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**Prokhorov General Physics Institute**
**of the Russian Academy of Sciences**

# 21th International Workshop
# Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

CSCPIER

**Moscow, Russia, April 7-11, 2025**

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# 21th International Workshop Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

## Program

***Moscow, Russia, April 7-11, 2025***

# 21th International Workshop Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

***Moscow, Russia, April 7-11,* 2025**

## PROGRAM

***April 7,* (Monday) *2025***

**9:30-10:00 Gathering of the Workshop participants**

**10:00-10:15 Opening Ceremony of the CSCPIER-2025**

## SECTION 1. BASIC ASPECTS OF PLASMA SCIENCE. *7 April 2025 (Monday)*

10:15-10:45

**SIMULATION OF LIGHTNING DISCHARGES ON THE SCALE OF A LABORATORY EXPERIMENT AND RELATED ELECTROMAGNETIC PHENOMENA (*Invited*)**

E.V. Parkevich, K.V. Shpakov, A.I. Khirianova
*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*

10:45-11:00

**ON THE CHARACTERISTIC THRESHOLDS IN THE GENERATION OF HIGHLY IONIZED PLASMA IN PULSED NANOSECOND GAS DISCHARGES**

E.V. Parkevich, K.V. Shpakov, A.I. Khirianova, S.Yu. Gavrilov
*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*

11:00-11:15

**SNAKE-LIKE AND STRAIGHT-LINE IONIZATION WAVES FORMATION IN PLASMA JET OF A COAXIAL BARRIER DISCHARGE IN ARGON FLOW AT ATMOSPHERIC PRESSURE**

Yu. Akishev[1,2,3], S. Ermolaeva[3], M. Medvedev[1,3], A. Petryakov[1]
[1]*State Research Center of Russian Federation Troitsk Institute for Innovative and Fusion Research, Moscow, Troitsk, Russia*
[2]*National Research Nuclear University MEPHI, Moscow, Russia*
[3]The Gamaleya National Center of Epidemiology and Microbiology, Moscow, , Russia

11:15-11:30

**SMOOTH DECREASE OF SPECTRAL SERIES LINES INTENSITY WHEN APPROACHING THE IONIZATION THRESHOLD IN A DENSE EQUILIBRIUM PLASMA**

R.V. Dobrovenskis[1,2]
[1]*Moscow Institute of Physics and Technology, Russia, Dolgoprudny address, dobrovenskis.rv@phystech.edu*
[2]Joint Institute for High Temperatures (JIHT), RAS, Russia, Moscow

**11:30-11:45 Coffee Break**

11:45-12:15

**NONLINEAR PROCESSES ACCOMPANYING INTERACTION OF RELATIVISTIC BEAM WITH MAGNETIZED PLASMA (*Invited*)**

A.V. Arzhannikov[1,2]

*[1]Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences (BINP SB RAS), Novosibirsk, Russia*

*[2]Novosibirsk state university, Novosibirsk, Russia, press@nsu.ru*

12:15-12:30

**NONLINEAR ICR DYNAMICS OF SLOW IONS: A POSSIBILITY FOR OPTIMIZATION OF AN ELECTRODELESS ION THRUSTER**

M.A. Tereshchenko[1], I.A. Abramov[1,2]

*[1] Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*

*[2] National Research Center "Kurchatov Institute", Moscow, Russia*

12:30-12:45

**EFFECT OF MAGNETIC FIELD ON DECELERATION OF ION BEAM DUE TO CHERENKOV INTERACTION WITH ION-ACOUSTIC WAVES**

A.A. Shelkovoy[1], S.A. Uryupin[1,2]

*[1]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*

*[2]National Research Nuclear University MEPhI, Moscow, Russia*

12:45-13:00

**ON THE THIRD IONIZATION POTENTIAL OF TANTALUM ATOM**

R.E. Boltnev[1,2,3], A.V. Karabulin[1,2,3], I.N. Krushinskaya[2,3], A.A. Pelmenev[2,3], V.I. Matyushenko[2,3]

*[1]Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia*

*[2]Branch of Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, Russia*

*[3]Federal Research Center for Problems of Chemical Physics and Medicinal Chemistry, Russian Academy of Sciences, Chernogolovka, Moscow region, Russia*

13:00-13:15

**ION-ACOUSTIC SOLITONS IN A COLLISIONLESS NONISOTHERMAL PLASMA**

S. V. Kuznetsov

*Joint Institute for High Temperature of the Russian Academy of Sciences, Moscow, Russia*

13:15-13:30

**COMBINING A PLASMA DETECTOR AND CHROMATOGRAPH INTO A SINGLE ANALYTICAL CYCLE FOR DETERMINING THE COMPOSITION OF GASEOUS IMPURITIE**

S.S Sysoev[1], A.I. Saifutdinov[2]

*[1]St. Petersburg State University, Saint-Petersburg, Russia*

*[2]Kazan National Research Technical University named after A. N. Tupolev - KAI, Kazan, Russia*

**13:30-14:30 Lunch**

14:30-15:00

**FEATURES OF THE TRANSITION FROM A GLOW DISCHARGE TO AN ARC DISCHARGE WITH REFRACTORY AND NON-REFRACTORY ELECTRODES IN ATOMIC AND MOLECULAR GASES (*Invited*)**

A.I. Saifutdinov
*Kazan National Research Technical University named after A.N.Tupolev – KAI, Kazan, Russia*

15:00-15:15

**THE INFLUENCE OF ELECTRONEGATIVE GAS IMPURITIES ON THE FORMATION OF THE STRUCTURE OF A SHORT GLOW DISCHARGE IN HELIUM**

A.I. Saifutdinov, A.A. Saifutdinova
*Kazan National Research Technical University named after A.N. Tupolev – KAI, Kazan, Russia*

15:15-15:30

**THE PROPAGATION OF AN IONIZATION FRONT OF LOW-PRESSURE SURFACE-WAVE SUSTAINED DISCHARGE**

V.I. Zhukov, D.M. Karfidov
*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*

15:30-15:45

**PHYSICAL PROCESSES IN INDUCTIVELY COUPLED PLASMA AND THEIR IMPACT ON THE ACCURACY OF MASS SPECTROMETRY**

N.Sh. Jafar[1], T.K. Nurubeyli[1,2]
*[1]Institute of Physics of the Ministry of Science and Education of Republic of Azerbaijan, Baku, Azerbaijan*
*[2]Azerbaijan State Oil and Industry University, Baku, Azerbaijan*

15:45-16:00

**ON THE CHARACTERISTICS OF ELECTRON DIFFUSION AND DRIFT IN INERT GASES**

S.A. Maiorov[1], R.I. Golyatina[2], S.K. Kodanova[3], T.S. Ramazanov[3]
*[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
*[2]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
*[3]Institute for Experimental and Theoretical*

16:00-16:15

**EXPERIMENTAL DETERMINATION OF THE DEBYE LENGTH OF SCREENING AND ACCUMULATION OF ELECTRONS IN SEMICONDUCTOR NANOSTRUCTURES**

R. Yafarov
*Saratov branch of the Institute of Radio Engineering and Electronics named after V. A. Kotelnikov RAS, Saratov, Russia*

**16:15-16:30 Coffee Break**

16:30-17:00

**PROPERTIES OF NON-IDEAL PLASM *(Invited)***

A.D. Rakhel, A.S. Shumikhin
*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

17:00-17:15

**AB INITIO RECOMBINATION IN ULTRACOLD PLASMAS**

Yu.V. Dumin[1,2], L.M. Svirskaya[3,4]
*[1]Lomonosov Moscow State University, Moscow, Russia*
*[2]Space Research Institute of Russian Academy of Sciences, Moscow, Russia*
*[3]South Ural State University, Chelyabinsk, Russia*
*[4]South Ural State Humanitarian Pedagogical University, Chelyabinsk, Russia*

17:15-17:30

**TO THE SPECTRUM OF COLLECTIVE EXCITATIONS IN STRONGLY COUPLED PLASMA-LIKE LIQUIDS**

S.A. Trigger[1], S.A. Maslov[1,2]
*[1]Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow, Russian Federation*
*[2]Lomonosov Moscow State University, Moscow, Russian Federation*

17:30-17:45

**ATTRACTIVE - REPULSIVE GRAVITY: MASS DEFECT AND BINDING ENERGY**

S.A. Trigger
*Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow, Russian Federation*

17:45-18:00

**ON R.L. STRATONOVICH'S FORMULA FOR TRANSITION FROM DYNAMIC TO PROBABILISTIC MEASUREMENTS AND ITS CONNECTION WITH OPERATIONS ON DISTRIBUTION FUNCTIONS OF RANDOM VARIABLES**

M.Yu. Romanovsky[1,2,3]
*[1]PE Science and Innovation, Moscow, Russian Federation*
*[2]ANO National Center for Physics and Mathematics, ul. Parkovaya 1, str. 3, 607182 Sarov, Nizhny Novgorod region, Russian Federation*
*[3]Pirogov Russian National Research Medical University, ul. Ostrovityanova 1, 117997 Moscow, Russian Federation*

## SECTION 2 COMPLEX PLASMAS. *8 April 2025 (Tuesday)*

10:00-10:30

**ENERGY TRANSFER IN PLASMA CRYSTAL (Invited)**

A.M. Ignatov
*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*

10:30-10:45

**EQUATIONS OF STATE FOR LIMITED ONE-COMPONENT PLASMA**

D.I. Zhukhovitskii
*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

10:45-11:00

**NON-HERMITIAN SKIN EFFECT IN DUSTY PLASMA CHAIN STRUCTURES**

D. A. Kolotinskii[1,2], A.V. Timofeev[1,2,3]
*[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
*[2]Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*
*[3]National Research University Higher School of Economics, Moscow, Russia*

11:00-11:15

**EXCESS ENTROPY OF YUKAWA FLUID (COMPLEX PLASMA)**

S.A. Khrapak
*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

**11:15-11:30 Coffee Break**

11:30-12:00

**DYNAMICS OF DUSTY PLASMA IN A GLOW DISCHARGE IN HELIUM IN MAGNETIC FIELDS UP TO 1.5 T (*Invited*)**

L.G. Dyachkov[1], E.S. Dzlieva[2], L.A. Novikov[2], S.I. Pavlov[2], V.Yu. Karasev[2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Saint-Petersburg State University, Saint-Peterburg, Russia*

12:00-12:15

**CHANGES IN THE ARRANGEMENT OF DUST PARTICLES AND THE GEOMETRY OF DUST STRUCTURES UNDER THE INFLUENCE OF A MAGNETIC FIELD IN DIFFERENT TYPES OF DISCHARGES**

V.Yu. Karasev, E.S. Dzlieva, D.V. Yanisin, M.A. Gasilov,.A. Novikov, S.I. Pavlov
*Saint Petersburg State University, Saint Peterburg, Russia*

12:15-12:30

**ANALYSIS OF DUSTY PLASMA CHARACTERISTICS IN NOBLE GASES AT THE SAME CURRENT AND PRESSURE IN A GAS DISCHARGE TUBE**

S.A. Maiorov[1], R.I. Golyatina[2], E.S. Dzlieva[3], V.Yu. Karasev[3]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[3]*Saint Petersburg State University, Saint Petersburg, Russia*

12:30-12:45

**EXPERIMENTAL STUDY OF DUSTY PLASMA FORMATION IN A LOW-PRESSURE CAPACITIVE RF DISCHARGE**

M.E. Viktorov, S.V. Sintsov, D.A. Sergeev, I.M. Kraev, E.I. Preobrazhensky, A.V. Vodopyanov
*Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia*

12:45-13:00

**CHANGES IN THE STRUCTURE OF BIFEO3 NANOPARTICLES UNDER THE INFLUENCE OF MICROWAVE RADIATION FROM A POWERFUL GIROTRON**

Z.G. Ragimkhanova[1], G.B. Ragimkhanov[2], S.Kh. Gadzimagomedov[2], Gusein-zade[1,3], A.S. Sokolov[3], Z.A. Zakletskii[3], E.V. Voronova[3], N.N. Skvortsova[3]
[1]*MIREA – Russian Technological University, Moscow, Russia*
[2]*Dagestan State University, Makhachkala, Russia*
[3]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*

**13:00-14:00 Lunch**

14:00-14:30

**ACTIVE BROWNIAN MOTORS IN COULOMB SYSTEMS IN PLASMA, LIQUID AND SUPERFLUID HELIUM (*Invited*)**

O.F. Petrov
*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

14:30 -14:45

**STRUCTURES OF AN ACTIVE COULOMB PARTICLES IN GAS-DISCHARGE PLASMA**

Vasiliev M.M., Syrovatka R.A., Kononov E.A., Senoshenko R.V., Petrov O.F.
*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

14:45 -15:00

**MOTION OF AN ACTIVE BROWNIAN PARTICLE IN RF DISCHARGE PLASMA IN DIFFERENT DAMPING REGIMES**

X.G. Koss[1,2], K.A. Mizeva[1,2], A.V. Erilin[1,2], R.A. Syrovatka[1], D.A. Zamorin[1,2], M.M. Vasiliev[1], O.F. Petrov[1,2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

15:00-15:15

**DYNAMICS IN THE SYSTEM OF ACTIVE BROWNIAN PARTICLES IN GAS-DISCHARGE PLASMA UNDER EXTERNAL INFLUENCE**

R.V. Senoshenko[1,2], E.A. Kononov[1,2], M.M. Vasiliev[1], O.F. Petrov[1]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

15:15-15:30

**EXPERIMENTAL SIMULATION OF DUST PLASMA NEAR AN ATMOSPHERELESS SPACE BODY**

I.A. Shashkova, I.A. Kuznetsov, A.A. Kartasheva, S.I. Popel, G.G. Dol'nikov, A.N. Lyash, M.E. Abdelaal, A.V. Zakharov
*Space Research Institute of the Russian Academy of Sciences*(IKI)*, Moscow, Russia*

15:30-15:45

**ELECTROMAGNETIC SIGNATURES OF DUST-INDUCED DISCHARGES IN SIMULATED PLANETARY CONDITIONS**

M.E. Abdelaal[1,2], M.A. Zaitsev[2], I.V. Dokuchaev[2], I.A. Kuznetsov[2], A.N. Lyash[2], I.A. Shashkova[2], A.E. Dubov[2], A.A. Kartasheva[2], G.G. Dolnikov[2], A.V. Zakharov[2]
[1]*Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*
[2] *Space Research Institute of the Russian Academy of Sciences*(IKI)*, Moscow, Russia*

15:45 — 16:00

**LUNAR DUSTY PLASMA EXOSPHERE: DYNAMICS, LABORATORY SIMULATION AND MEANS OF PROTECTION**

I.A. Kuznetsov, I.A. Shashkova, A.A. Kartasheva , S.I. Popel, T.I. Morozova, G.G. Dol'nikov, A.N. Lyash, A.V. Zakharov, L.M. Zelenyi
*Space Research Institute of the Russian Academy of Sciences*(IKI)*, Moscow, Russia*

**16:00-16:15 Coffee Break**

16:15-16:45

**DUSTY PLASMA IN THE SOLAR SYSTEM: ATMOSPHERES OF PLANETS (*Invited*)**

S.I. Popel, Yu.S. Reznichenko, S.I. Kopnin, Yu.N. Izvekova, A.Yu. Dubinskii, L.M. Zelenyi
*Space Research Institute of the Russian Academy of Sciences*(IKI)*, Moscow, Russia*

16:45-17:00

**DUSTY PLASMA CONDITIONS IN SATURN'S MAGNETOSPHERE**

S.I. Kopnin[1], D.V Shokhrin[2], S.I. Popel[1]
[1]*Space Research Institute of the Russian Academy of Sciences*(IKI), *Moscow, Russia*
[2] *National Research University Higher School of Economics, Moscow, Russia*

17:00-17:15

**ON THE INFLUENCE OF MAGNETIC FIELD ON THE PROPAGATION OF LOW-FREQUENCY NONLINEAR DUST ACOUSTIC WAVES IN THE PLASMA OF SATURN'S MAGNETOSPHERE**

S.I. Kopnin[1], D.V. Shokhrin[2], S.I. Popel[1]
[1]*Space Research Institute of the Russian Academy of Sciences*(IKI), *Moscow, Russia*
[2] *National Research University Higher School of Economics, Moscow, Russia*

17:15-17:30

**NONLINEAR DUST ACOUSTIC WAVES NEAR THE SURFACES OF PHOBOS AND DEIMOS**

Yu.N. Izvekova, S.I. Kopnin, S.I. Popel
*Space Research Institute of the Russian Academy of Sciences*(IKI), *Moscow, Russia*

17:30-17:45

**DUSTY PLASMAS AT ACTIVE ASTEROIDS**

A.Yu. Dubinsky, Yu.S. Reznichenko, S.I. Popel
*Space Research Institute of the Russian Academy of Sciences* (IKI), *Moscow, Russia*

## SECTION 3 LASER PLASMAS. *9 April 2025 (Wednesday)*

10:00-10:30

**LASER SOURCES OF HIGH ENERGY PARTICLES AND RADIATION (*Invited*)**

N.E. Andreev[1,2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

10:30-10:45

**HIGH CURRENT RELATIVISTIC ELECTRON BEAMS FOR BRIGHT X-RAY AND GAMMA-RAY SOURCES**

M.E. Veysman[1], N.E. Andreev[1,2], I.R. Umarov1, V.S. Popov[1,2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology (State University), Dolgoprudny, Russia*

10:45-11:00

**GENERATION OF ELLIPTICALLY POLARIZED RADIATION BY GAS MEDIA IN TWO-COLOR LASER FIELDS**

S.Yu. Stremoukhov
[1]*Moscow State University, Moscow, Russia,*
[2]*National Research Center "Kurchatov Institute", Moscow, Russia*

11:00-11:15

**NONLINEAR RESPONSE OF ATOMIC GASES: ANALYTICAL TREATMENT IN THE FRAME OF THE NON-PERTURBATIVE APPROACH**

K.V. Lvov[1,2], S.Yu. Stremoukhov[1,2]
[1]*Lomonosov Moscow State University, Moscow, Russia*
[2]*National Research Center "Kurchatov Institute", Moscow, Russia*

11:15-11:30

**FEATURES OF THE FORMATION OF PERIODIC SUBWAVELENGTH MICROSTRUCTURES IN THE PROCESS OF FEMTOSECOND LASER WRITING IN THE VOLUME OF SOLID DIELECTRICS**

A.V. Bogatskaya[1,2], E.A. Volkova[3], A.M. Popov[1,2]
*[1]Lebedev Physical Institute, Russian Academy of Sciences, Moscow Russia*
*[2]Department of Physics, Lomonosov Moscow State University, Moscow, Russia*
*[3]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

11:30-11:45

**CONTROLLED LASER MICROSTRUCTURING IN THE VOLUME OF TRANSPARENT SOLID DIELECTRICS**

P.M. Nikiforova[1,2,3], A.V. Bogatskaya[1,2], A.M. Popov[1,2]
*[1]Lomonosov Moscow State University, Moscow, Russia*
*[2] Lebedev Physical Institute, Russian Academy of Sciences, Moscow Russia*
*[3] Moscow Technical University of Communications and Informatics, Moscow, Russia*

**11:45-12:00 Coffee Break**

12:00-12:30

**COUPLING OF WEIBEL MODE AND PLASMA WAVE IN RELATIVISTIC LASER PLASMA INTERACTION (*Invited*)**

M. Ghorbanalilu
*Department of physics, Shahid Beheshti University , Tehran, Iran*

12:30-12:45

**ADVANCED LASER MODE STRATEGIES FOR ENHANCED ELECTRON ACCELERATION IN NONLINEAR PLASMA**

M. Sedaghat, A. Amouye Foumani, A. Niknam
*Laser and Plasma Research Institute, Shahid Beheshti University, Tehran, Iran.*

12:45-13:00

**RESONANT INTERACTION OF HIGH-POWER LASER RADIATION WITH PLASMA AT A DOUBLED UPPER HYBRID FREQUENCY**

V.A. Turikov
*RUDN University, Moscow, Russian Federation*

13:00-13:15

**NONLINEAR SCATTERING OF A FEMTOSECOND LASER PULSE ON A DENSE, SMALL-SCALE PLASMA**

M.V. Sedov[1,2], A.A. Andreev[3], K.Yu. Platonov[4], L.A.
*[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
*[2]National Research Nuclear University MEPhI, Moscow, Russia*
*[3]Saint-Petersburg State University, St. Petersburg, Russia*
*[4]Saint-Petersburg State Polytechnik University, St. Petersburg, Russia*

13:15-13:30

**MODELING OF ELECTRON ACCELERATION PROCESSES IN DENSE PLASMA UNDER THE ACTION OF A RELATIVISTIC LASER PULSE WITH AN INTENSITY OF $10^{22}$ W/CM$^2$**

D. I. Gimaletdinova[1,2], M.V. Sedov[1,2]
*[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
*[2]National Research Nuclear University MEPhI, Moscow, Russia*

13:30 -13:45

**SPATIOTEMPORAL GOOS-HÄNCHEN EFFECT AT A LASER PULSE REFLECTION FROM BOUNDARY OF SUPERCRITICAL PLASMA**

A.A. Frolov
*P.N. Lebedev Physical Institute of RAS, Moscow, Russia*

**13:45-14:30 Lunch**

14:30-15:00

**INVESTIGATION OF EXTREME MATTER STATE WITH ENERGY DENSITY ~ 1 GJ/CM$^3$ GENERATED BY ULTRA-RELATIVISTIC LASER PULSES (*Invited*)**

M.A. Alkhimova[1], I.Yu. Skobelev[1], T.A. Pikuz[2]
[1]*Joint Institute for High Temperature, RAS, Moscow, Russia*
[2]*Transdisciplinary Research Initiatives, Osaka University, Osaka, Japan*

15:00-15:15

**GENERATION OF X-RAY ATTO-PULSES IN LASER PLASMA AND ITS AMPLIFICATION BY XFEL**

A.A. Andreev[1,3], K.Yu. Platonov[2]
[1]*Saint Petersburg State University, Saint Petersburg, Russia*
[2]*Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russia*
[3]*Ioffe Physico-Technical Institute, Saint Petersburg, Russia*

15:15-15:30

**FORMATION OF HIGH-ASPECT-RATIO NANOCAVITY IN LIF CRYSTAL USING A FEMTOSECOND OF X-RAY FEL PULSE**

S.S. Makarov[1], V.V. Zhakhovsky[1], S.A. Grigoryev[1], P. Chuprov[2], T.A. Pikuz[3], N.A. Inogamov[1,4], V.V. Khokhlov[1,4], Y.V. Petrov[4], E. Perov[1], V. Shepelev[2], T. Shobu[5], A. Tominaga[5], L. Rapp[6], S. Juodkazis[7,8], M. Makita[9], M. Nakatsutsumi[9], T.R. Preston[9], K. Appel[9], Z. Konopkova[9], V. Cerantola[9,10], E. Brambrink[9], J. Schwinkendorf[9], I. Mohacsi[9], V. Vozda[11], V. Hajkova[11], T. Burian[11], J. Chalupsky[11], L. Juha[11], N. Ozaki[12], R. Kodama[12,13], U. Zastrau[9], A.V. Rode[6], S.A. Pikuz[14]
[1]*Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow, Russia.*
[2]*Institute for Computer Aided Design, Russian Academy of Sciences, Moscow, Russia.*
[3]*Institute for Open and Transdisciplinary Research Initiatives, Osaka University, Osaka, Japan.*
[4]*Landau Institute for Theoretical Physics of Russian Academy of Sciences, Chernogolovka, Moscow Region, Russia.*
[5]*The facility at Material Science Research Center, Japan Atomic Energy Agency, Sayo, Japan.*
[6]*Laser Physics Centre, Department of Quantum Science and Technology, Research School of Physics, Australian National University, Canberra ACT 2600, Australia.*
[7]*Optical Sciences Centre and ARC Training Centre in Surface Engineering for Advanced Materials (SEAM), School of Science, Swinburne University of Technology, Hawthorn, Australia*
[8]*Tokyo Tech World Research Hub Initiative (WRHI), School of Materials and Chemical Technology, Tokyo Institute of Technology, Tokyo, Japan*
[9]*European XFEL, Hamburg, Germany.*
[10]*Università degli Studi di Milano Bicocca, Milano, Italy*
[11]*Department of Radiation and Chemical Physics, Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic.*
[12]*Graduate School of Engineering, Osaka University, Osaka, Japan*
[13]*Institute of Laser Engineering, Osaka University, Osaka, Japan*
[14] *HB11 Energy Holdings, Freshwater, Australia*

15:30-15:45

**FANO RESONANCE IN HIGH-ORDER HARMONIC GENERATION AND ITS CLASSICAL ANALOGY**

V.V. Strelkov[1,2], S.A. Bondarenko[2,3]
*[1]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
*[2]A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia*
*[3]National Research Nuclear University MEPhI, Moscow, Russia*

15:45-16:00

**EFFECT OF SHORT WAVELENGTH PUMPING IN HIGH HARMONIC GENERATION BY GALLIUM IONS IN LASER FIELD**

S.N. Yudin[1], A.I. Magunov[2,3], M.M. Popova[1,3]
*[1]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
*[2]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
*[3]Gaponov-Grekhov Institute of Applied Physics of the RAS, Nizhny Novgorod, Russia*

16:00-16:15

**THE EFFECT OF LASER PULSE DURATION ON THE DYNAMICS OF WATER MOLECULE COULOMB EXPLOSION**

S.N. Yudin, A.V. Bibikov, M.M. Popova, E.V. Gryzlova, A.N. Grum-Grzhimailo
*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

16:15-16:30

**ON SPATIAL LOCALIZATION OF COLD CESIUM ATOM ENSEMBLE IN BICHROMATIC LASER FIELD**

A.I. Magunov[1,2], V.G. Palchikov[2]
*[1]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
*[2]All-Russian Scientific Research Institute of Physical-Technical and Radiotechnical Measurements", Mendeleevo, Moscow region, Russia*

**16:30-16: 45 Coffee Break**

16:45-17:15

**CRYSTALLITE MOBILITY AND CORRESPONDING CHANGES IN SURFACE STRUCTURE UNDER WEAK (BELOW THE MELTING THRESHOLD) NANOSECOND IMPACT (*Invited*)**

N.A. Inogamov[1,2,3]
*[1]L.D/ Landau Institute for Theoretical Physics, RAS, Chernogolovka, Russia*
*[2] Joint Institute for High Temperatures, RAS*
*[3] Centre for Fundamental and Applied Research, N.L. Dukhov All-Russian Research Institute of Automatics, Moscow, Russian Federation*

17:15-17:30

**TREATMENT OF P- AND HIGHER ORDER ELECTRONIC SUBSHELLS IN STRONG-FIELD IONIZATION IN PARTICLE IN-CELL-SIMULATIONS**

A. A. Mironov[1], E. G. Gelfer[2], S. V. Popruzhenko[3,4]
*[1]Center for Theoretical Physics (CPHT), CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
*[2]ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Dolni Brezany, Czech Republic*
*[3]National Research Nuclear University MEPhI, Moscow, Russia*
*[4]Prokhorov General Physics Institute RAS, Moscow, Russia*

17:30-17:45

**QUANTUM-QUASICLASSICAL METHOD FOR ATOMIC PROCESSES IN STRONG LASER FIELDS**

V.S. Melezhik
*Joint Institute for Nuclear Research (JINR), Dubna Moscow Region, Russia*

17:45-18:00

**THE RABBITT SETUP IN THE LIGHT OF DIVERSE POLARIZATIONS**

M.M. Popova[1,2], S.N. Yudin[1], A.N. Grum-Grzhimailo[1], E.V. Gryzlova[1,2]
*[1]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
*[2]A.V. Gaponov-Grekhov Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia*

18:00-18:15

**COMPTON IONIZATION OF POSITRONIUM BY TWISTED PHOTONS**

Popov Yu.V.[1,2], Volobuev I.P.[1], Bornikov K.A.[3]
*[1]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
*[2]Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia*
*[3]Physics Faculty, Lomonosov Moscow State University, Moscow, Russia*

18:15-18:30

**ABRAHAM'S RADIATION FRICTION THRESHOLD FOR AN ELECTRON COLLIDING WITH A LASER PULSE**

A.V. Borovskiy [1], A.L. Galkin [2]
*[1]Baikal State University, Irkutsk, Russia*
*[2]Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, Russia*

## SECTION-3 LASER PLASMAS. *10 April 2025 (Thursday)*

10:00-10:30

**RELATIVISTIC LASER-DRIVEN PARTICLES BEAM ACCELERATION WITH THIN LIQUID TARGETS (*Invited*)**

K.A. Ivanov[1,2],S.A. Shulyapov[1], M.P. Filimonchuk[1,3], I.N. Tsymbalov[1,4], D.A. Gorlova[1], I.P. Tsygvintsev[5], M.S. Krivokorytov[6], R.V. Volkov[1], A.B. Savel'ev[1,2]
*[1]Physics faculty, M.V. Lomonosov Moscow State University, Moscow, Russia*
*[2]Lebedev Physical Institute of RAS, Moscow, Russia*
*[3] Joint Institute of High Temperatures of RAS, Moscow, Russia*
*[4] Institute for Nuclear Research of RAS, Moscow, Russia*
*[5]Keldysh Institute of applied mathematics of RAS, Moscow, Russia*
[6]Institute of Spectroscopy of RAS, Troitsk, Russia

10:30-10:45

**ENERGY-TUNABLE QUASI-MONOENERGETIC ELECTRON BEAM OBTAINING WITH LWFA**

E.M. Starodubtseva[1], I.N. Tsymbalov[1,2,] D.A. Gorlova[2], K.A. Ivanov[1,3], A.B. Savel'ev[1,3]
*[1]Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
*[2]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[3]*P.N. Lebedev Physical Institute, Moscow, Russia*

10:45-11:00

**INVESTIGATION OF BEAM-LOADING EFFECT IN LASER-WAKEFIELD ACCELERATION OF ELECTRON BUNCH AND ITS INFLUENCE ON ELECTRON BUNCH ENERGY SPREAD**

I.R. Umarov[1,2], N.E. Andreev[1,2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

11:00-11:15

**INHOMOGENEITIES EFFECT ON AUTORESONANT LASER ACCELERATION OF COLD ELECTRONS**

Iu.K. Gagarin[1], Ph.A. Korneev[1,2]
[1]*National Research Nuclear University "MEPhI", Moscow, Russia*
[2]*Lebedev Physical Institute of RAS, Moscow, Russia*

11:15-11:30

**INVESTIGATION OF THE PREPLASM OF A SOLID-STATE TARGET FOR PROBLEMS OF LASER ACCELERATION OF ELECTRONS AND IONS**

M.A. Rakitina[1], A.V. Brantov[1,2], S.I. Glazyrin[1,2]
[1]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[2] *Center for Fundamental and Applied Research, Dukhov Research Institute of Automatics (VNIIA), Moscow, Russia*

**11:30-11:45 Coffee Break**

## SECTION 5. SOLID STATE PLASMAS. *10April 2025 (Thursday)*

11:45-12:15

**FLUID-FLUID DECOMPOSITION IN BINARY DIPOLAR SYSTEM UNDER EXTERNAL FIELDS (*Invited*)**

E. Allahyarov[1,2,3]
[1] *Theoretical Department, Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Department of Physics, Case Western Reserve University, Cleveland OH, USA*
[3] *Theoretische Physik II: Weiche Materie, HHU Düsseldorf, Germany*

12:15-12:30

**INTERLAYER BOUNDARIES OF FERROELECTRIC SUPERLATTICES AS A SOURCE OF SOLID-STATE PLASMA FORMATION**

D.V. Kuzenko
*Scientific Research Institute "Reaktivelectron", Donetsk, Russia*

12:30-12:45

**POSSIBLE MECHANISM OF THE HIGHLY CONDUCTIVE STATE IN LOW-DIMENSIONAL SYSTEMS**

L.M. Svirskaya[1,2]
[1]*South Ural State Humanitarian and Pedagogical University, Chelyabinsk, Russia*
[2]*South Ural State University (National Research University), Chelyabinsk, Russia*

12:45-13:00

**MODELLING OF EDDY CURRENT EXCITATION DURING FEMTOSECOND LASER ABLATION OF METALS**

I.V. Oladyshkin, D.A. Fadeev
*A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia*

13:00-13:15

**PRODUCTION OF ULTRA-THIN NI NANONETWORK BY LASER ABLATION IN SUPERFLUID HELIUM**

E.V. Dvoretskaya, R.B. Morgunov
*Federal Research Center of Problems of Chemical Physics and Medicinal Chemistry RAS, Chernogolovka, Moscow region, Russia*

13:15-13:30

**ARC DISCHARGE PLASMA FOR THE SYNTHESIS OF NANOCARBIDES AND NANOCARBIDE-BASED COMPOSITES**

D.S. Nikitin, A. Nassyrbayev, I.I. Shanenkov, A.A. Sivkov
*National Research Tomsk Polytechnic University, Tomsk, Russia*

**13:30-14:30 Lunch**

## SECTION 4. GENERAL PLASMAS. *April 11 2025(Thursday)*

14:30-15:00

**GAS DISCHARGE PLASMA ANTENNAS, ARRAYS AND METASURFACES (*Invited*)**

N.N. Bogachev[1,2], M.S. Usachonak[3], V.P. Stepin[1], V.I. Zhukov[1], S.E. Andreev[1,2], I.L. Bogdankevich[1,2], L.V. Simonchik[3], N.G. Gusein-zade[1,2]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*MIREA - Russian Technological University, Moscow, Russia*
[3]*B.I. Stepanov Institute of Physics of the National Academy of Sciences of Belarus, Minsk, Belarus*

15:00-15:15

**EFFECTS OF AXIAL PLASMA DENSITY DISTRIBUTION ON THE CHARACTERISTICS OF A PLASMA ANTENNA**

V.P. Stepin[1], N.N. Bogachev[1], S.E. Andreev[1], I.L. Bogdankevich[1], V.I. Zhukov[1], D.M. Karfidov[1], M.S. Usachonak[2], N.G. Gusein-zade[1]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*B.I. Stepanov Institute of Physics of the National Academy of Sciences of Belarus, Minsk, Belarus*

15:15-15:30

**BROADBAND PLASMA ANTENNA**

I.M. Minaev, O.V. Tikhonevich
*Prokhorov General Physics Insttute of the Russian Academy of Sciences, Moscow, Russia*

15:30-15:45

**DYNAMICS OF THE RADIATION SPECTRUM UNDER THE COLLECTIVE STIMULATED CHERENKOV EFFECT IN DIELECTRIC AND PLASMA WAVEGUIDES**

A.V. Ershov, M.V. Kuzelev
*Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia*

15:45-16:00

**BEAM INSTABILITY IN A PLASMA MICROWAVE AMPLIFIER WITH COAXIAL GEOMETRY IN THE PRESENCE OF AN ABSORBER**

I.N. Kartashov, M.V. Kuzelev, A.V. Tumanov
*Moscow State University, Moscow, Russia,*

16:00-16:15

**NOISE AMPLIFICATION BY A RELATIVISTIC ELECTRON BEAM IN A DOUBLE COAXIAL PLASMA–METAL WAVEGUIDE**

A.E. Donets, V.I. Rogozhin, A.B. Buleyko, V.P. Bakhtin, A.G. Bykov, O.T. Loza, A.A. Ravaev
*JSC "SSC RF TRINITY", Troitsk, Moscow, Russia*

16:15-16:30

**DEPENDENCE OF PLASMA MASER EMISSION SPECTRA ON AZIMUTHAL PLASMA CONCENTRATION INHOMOGENEITY**

V.I. Rogozhin, A.E. Donets, A.B. Buleyko, V.P. Bakhtin, A.G. Bykov, O.T. Loza, A.A. Ravaev
*JSC "SSC RF TRINITY", Troitsk, Moscow, Russia*

**16:30-16:45 Coffee Break**

16:45-17:15

**OPTIMIZATION OF PLASMA ETCHING PROCESSES IN MICROELECTRONICS: APPLICATIONS OF PLASMA DIAGNOSTICS (*Invited)***

A.V. Miakonkikh
*NRC "Kurchatov Institute" – Valiev IPT, Moscow, Russia*

17:15-17:30

**MICROWAVE DISCHARGE IN WAVE FIELDS ON THE SURFACE OF SOLIDS**

Z.A. Zakletskii, S.E. Andreev, D.V. Malakhov
*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*

17:30-17:45

**STUDY OF DIODE PLASMA ON THE FORMATION AND PROPAGATION OF SHOCK WAVES DUE TO HIGH-CURRENT ELECTRON BEAM EXPOSURE**

L.M. Iusupova[1,2], E.D. Kazakov[2,3,4], S.I. Tkachenko[2,3]
[1]*National Research University "MPEI", Moscow, Russian Federation*
[2]*NRC "Kurchatov Institute", Moscow, Russian Federation*
[3]*Moscow Institute of Physics and Technology, Dolgoprudny, Russian Federation*
[4]*KIAM RAS, Moscow, Russian Federation*

17:45-18:00

**SHORTWAVELENGTH EMISSION FROM A HOT DENSE PLASMA**

V.P. Krainov[1], B.M. Smirnov[2]
[1]*Moscow Institute of Physics and Technology, Dolgoprudnyi, Moscow region, Russia*
[2]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

## SECTION 4. GENERAL PLASMAS. *April 11 2025 (Friday)*

10:00-10:30

**QUASI-STATIONARY MAGNET-INDUCED CONFINEMENT OF HIGH-ENERGY PLASMA FORMATION AT COLLISION OF CURRENT-CARRYING COMPRESSION PLASMA FLOWS (*Invited*)**

V.M. Astashynski, O.G. Penyazkov, P.N. Shoronov
*The A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Minsk, Belarus*

10:30-10:45

**EXPERIMENTAL INVESTIGATION OF AN ABSORPTION OF THE ORDINARY POLARIZATION MICROWAVES IN A PLASMA FILAMENT**

E.Z. Gusakov[2], A.Yu. Popov[2], L.V. Simonchik[1], M.S. Usachonak[1]
[1]*Institute of Physics of NAS of Belarus, Minsk, Belarus*
[2]*Ioffe Institute, St-Petersburg, Russia*

10:45-11:00

**FEATURES OF ELECTRODYNAMICS OF HIGH-FREQUENCY DISCHARGE IN A MAGNETIC FIELD**

S.A. Dvinin[1,2], M.A. Korneeva[3], Z.A. Qodirzoda[4], O.A. Sinkevich[5], D.K. Solihzoda[4]
[1]*Lomonosov Moscow state university, Moscow, Russia*
[2]*RUDN university, Moscow, Russia*
[3]*National Research Centre "Kurchatov Institute" - NIISI, Moscow, Russia*
[4]*Tajik National University, Dushanbe, Tajikistan*
[5]*National Research University «Moscow Power Engineering Institute», Moscow, Russia*

11:00-11:15

**GENERATION OF RUNAWAY ELECTRONS IN LOW PRESSURE AIR FROM CAPACITIVE DISCHARGE PLASMA**

V.F. Tarasenko[1], E.Kh. Baksht[2], N.P. Vinogradov[2]
[1] *Institute of High Current Electronics SB RAS, Tomsk, RF, VFT@loi.hcei.tsc.ru*
[2] *Institute of High Current Electronics SB RAS, Tomsk, RF*

11:15-11:30

**TRICHEL PULSES IN NEGATIVE CORONA DISCHARGE: INSTABILITY AND BEHAVIOR NEAR THE GENERATION THRESHOLD**

E.Kh. Baksht, V.F. Tarasenko
*Institute of High Current Electronics SB RAS, Tomsk, Russia*

**11:30-11:45 Coffee Break**

11:45-12:15

**ON THE PROGRESS IN THE STUDY OF ANEUTRONIC PROTON – BORON FUSION IN A NANOSECOND VACUUM DISCHARGE (*Invited*)**

Yu. K. Kurilenkov[1,2], A.V. Oginov[2], S.N. Andreev[3], S.Yu. Gus'kov[2], I.S. Samoylov[1]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[3]*Moscow Institute of Physics and Technology National Research University, Dolgoprudny, Russia*

12:15-12:30

**ANEUTRONIC PROTON–BORON-11 REACTION IN QUASI-STATIONARY HIGH-DENSITY PLASMA**

E.G. Vovkivsky, A.Yu. Chirkov
*Thermal Physics Department, Bauman Moscow State Technical University, Moscow, Russia,*

12:30-12:45

**EVIDENCE OF PLASMA PHASE TRANSITION IN WARM DENSE CESIUM**

A.A. Filatkin[1,2], G.E. Norman[1,2,3], I.M. Saitov[1,4]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*
[3]*Higher School of Economics, Moscow, Russia*
[4]*University of L'Aquila, L'Aquila, Italy*

12:45-13:00

**ABOUT THE EFFECT OF CATHODE DISPERSION ON THE CHARACTERISTICS OF DIRECT CURRENT DISCHARGE**

M.M. Vasiliev, S.A. Maiorov, A. S. Svetlov, O.F. Petrov
*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

13:00-13:15

**OBTAINING AND REGULARIZATION OF A HEXAGONAL IRREGULAR COMPUTATIONAL GRID FOR PLASMA CALCULATIONS**

S.V. Ryzhkov, V.V. Kuzenov
*Bauman Moscow State Technical University, Moscow, Russia*

**13:15-14:30 Lunch**

14:30-15:00

**PROSPECTIVE SCHEMES OF RADIO-FREQUENCY PLASMA THRUSTERS (*Invited*)**

I.I. Zadiriev, E.A. Kralkina, K.V. Vavilin, G.V. Shvydkiy, A.M. Nikonov, V.S. Dudin
Lomonosov Moscow State University, Moscow, Russia

15:00-15:15

**OPTIMIZATION OF RADIO-FREQUENCY ION THRUSTER PROTOTYPE FOR OPERATION AS PART OF AN AIR-BREATHING ELECTRIC PROPULSION ENGINE IN ULTRA-LOW EARTH ORBITS**

V.S. Dudin, E.A. Kralkina, K.V. Vavilin, I.I. Zadiriev, A.M. Nikonov, G.V. Shvydkiy
*Lomonosov Moscow State University, Moscow, Russia*

15:15-15:30

**PLASMA OF THE EARTH'S LOWER IONOSPHERE IN THE YEAR OF MAXIMUM SOLAR ACTIVITY**

N.V. Bakhmetieva, G.I. Grigoriev, I.N. Zhemyakov, E.E. Kalinina, A.A. Lisov
*Radiophysical Research Institute Nizhny Novgorod State University, , Nizhny Novgorod, Russia*

15:30-15:45

**INVESTIGATIONS OF THE IONOSPHERIC DISTURBANCES DURING THE MAGNETIC STORM IN MARCH 2015 BY USING FORMOSAT-3/COSMIC SATELLITE RADIO OCCULTATION MEASUREMENTS**

V.N. Gubenko, I.A. Kirillovich, V.E. Andreev
*Kotelnikov Institute of Radio Engineering and Electronics RAS, Fryazino, Moscow region, Russia*

**15:45-16:00 Coffee Break**

16:00-16:30

**PLASMA-ACTIVATED WATER: A MULTIFUNCTIONAL MEDIUM FOR BIOMEDICAL AND NANOTECHNOLOGICAL APPLICATIONS (*Invited*)**

R.S. Pessoa[1], J. Karnopp[1], K.G. Kostov[2], C.Y. Koga-Ito[3]
[1]*Plasmas and Processes Laboratory (LPP), Aeronautics Institute of Technology (ITA), São José dos Campos, Brazil.*
[2]*Department of Physics, Guaratinguetá Faculty of Engineering, São Paulo State University (UNESP), Guaratinguetá, Brazil.*
[3]*Department of Environment Engineering, Institute of Science and Technology, São Paulo State University (UNESP), São José dos Campos, Brazil.*

16:30-16:45

**ENERGETIC PLASMA BUNCHES GENERATED UNDER AUTORESONANT INTERACTION IN A LONG MIRROR TRAP**

V.V Andreev, A.A Novitsky, A. Niamanesh
*RUDN University, Moscow, Russia*

16:45-17:00

**ECR HEATING IN A COAXIAL PLASMA SOURCE CERA-RX(C)**

A.V. Kalashnikov, A. Niamanesh
*RUDN University, Moscow, Russia*

17:00-17:15

**MODELING OF DIFFRACTION OF A PLANE ELECTROMAGNETIC WAVE ON A MICROSTRUCTURED PLASMA OF A HIGHLY IONIZED PULSED NANOSECOND GAS DISCHARGE**

S.Yu. Gavrilov, E.V. Parkevich, A.I. Khiryanova
*The Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*

17:15-17:30

**FORMATION OF ALUMINUM OXYNITRIDE CONTAINING MATERIALS IN THE PRESENCE OF MONO- AND POLYVALENT CATIONS UNDER A MICROWAVE DISCHARGE**

N.S. Akhmadullina[1,2], V.D. Borzosekov[2], T.E. Gayanova[2], V.V. Gudkova[2], N.G. Gusein-zade[2], A.V. Knyazev[2], A.A. Letunov[2], D.V Malakhov[2], E.D. Obraztsova[3], O.N. Shishilov[2,4], N.N. Skvortsova[2], A.S. Sokolov[2], V.D. Stepakhin[2]
[1]*A.A. Baikov Institute of Metallurgy and Material Science of Russian Academy of Sciences, Moscow, Russia*
[2]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[3]*Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*
[4]*MIREA – Russian Technological University, Institute of Fine Chemical Technology, Moscow, Russia*

17:30-17:45

**PREPARATION OF BIMETALLIC SUPPORTED CATALYSTS USING A MICROWAVE DISCHARGE**

O.N. Shishilov[1,2], N.S. Akhmadullina[3], V.D. Borzosekov[2], I.Yu. Vafin[2], E.V. Voronova[2], T.E. Gayanova[2], N.G. Gusein-zade[2], V.P. Logvinenko[2], D.V. Malakhov[2], E.D. Obraztsova[4], N.N. Skvortsova[2], A.S. Sokolov[2],V.D. Stepakhin[2]

[1]*Institute of Fine Chemical Technology, MIREA – Russian Technological University, Moscow, Russia*
[2]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[3]*A.A. Baikov Institute of Metallurgy and Material Science of Russian Academy of Sciences Moscow, Russia*
[4]*Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*

**17:45-18:00 Closing Ceremony of the CSCPIER-2025**

# 21th International Workshop Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

## Book of Abstracts

***Moscow, Russia, April 7-11, 2025***

# SIMULATION OF LIGHTNING DISCHARGES ON THE SCALE OF A LABORATORY EXPERIMENT AND RELATED ELECTROMAGNETIC PHENOMENA

E.V. Parkevich, K.V. Shpakov, A.I. Khirianova

*P.N. Lebedev Physical Institute of the Russian Academy of Sciences 119991, Moscow, Russia*

It is known that a lightning discharge in atmospheric air is accompanied by a variety of different electromagnetic phenomena and plasma formation processes rapidly developing in time and space within the framework of a single collective process. However, the unified physical picture of the corresponding processes is still undetermined due to the absence of numerous experimental and theoretical data on the features of the lightning discharge formation. Obtaining new knowledge in this direction is a priority for various scientific groups around the world. In the study, we report the results of the lightning simulation experiments obtained on a big high-voltage installation capable of generating electrical discharges up to 55 cm long at voltages of a million volts and currents of the order of kiloamperes. In the research we managed to localize the radiation sources and study in detail the temporal, spatial, spectral and angular characteristics of very-high-frequency (~10–100 MHz), ultra-high-frequency (~1–6 GHz) and hard X-ray (photons with energies in the range of 5–1000 keV) emissions, as well as determine their spatiotemporal correlation with the observed discharge structures. Based on the obtained results, a chronological map was constructed providing a comprehensive idea of the temporal nature and correlations of various electromagnetic emissions generated by an extended high-voltage discharge. The findings can be useful for solving applied problems related to the development of new methods of lightning protection and electromagnetic interference suppression, monitoring of thunderstorm phenomena and others.

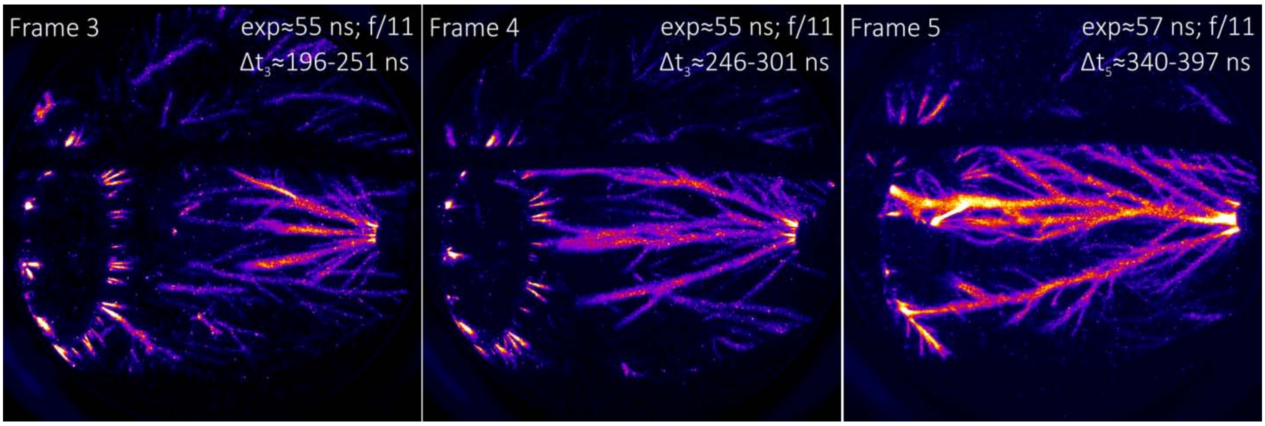


Fig. 1. The streamer evolution in the discharge development stage, when different electromagnetic emissions are registered.

## References

[1]. Parkevich E. V., et al. *Phys. Rev. E.* **105** (5) L053201 (2022).
[2]. Parkevich E. V., et al. *Phys. Rev. E.* **106** (4) 045210 (2022).
[3]. Parkevich E. V., et al. *Phys. Rev. E.* **108** (2) 025201 (2023).
[4]. Parkevich E. V., et al. *J. Appl. Phys.* **134** 153303 (2023).
[5]. Parkevich E. V., et al. *J. Appl. Phys.* **136**, 163302 (2024).
[6]. Parkevich E. V., et al. *J. Appl. Phys.* **136**, 173301 (2024).
[7]. Parkevich E. V., et al. *Phys. Rev. E.* **110** (6) 065204 (2024).

# ON THE CHARACTERISTIC THRESHOLDS IN THE GENERATION OF A HIGHLY-IONIZED PLASMA IN A PULSED NANOSECOND GAS DISCHRGE

E.V. Parkevich, K.V. Shpakov, A.I. Khirianova, S.Yu. Gavrilov

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We present the results of the investigation of the highly-ionized plasma generation in pulsed nanosecond gas discharges initiated in millimeter discharge gaps in air at atmospheric pressure. The main regularities in the generation of a highly-ionized plasma in the near-electrode regions at the early stage of its evolution are discussed. The transition from cathode and anode spots to growing highly-ionized spark channels with a complex filamentary microstructure is shown in details. Typical characteristics of microchannel plasma are demonstrated, and their influence on the integral properties of the discharge as a whole are discussed as well. In particular, it is shown that for about 1 ns microchannels can reach the stage of a fully-ionized plasma in atmospheric air, i.e. when plasma electron densities are as high as approximately $5\times10^{19}$ cm$^{-3}$. The thresholds for the generation of a highly-ionized plasma in a gas discharge medium are found together with the conditions, under which the formation of a complex filamentary microstructure starts in such a plasma. The thresholds were determined when varying the power of the energy input into the gas discharge medium and its pressure. Possible generation mechanisms of a highly-ionized plasma and the effects of its microstructuring are discussed. The results of the study can useful in improving methods of controlling plasma parameters in pulsed electrophysical systems and devices used in modern power industry, including systems with ignition of fuel mixtures depleted in oxygen.

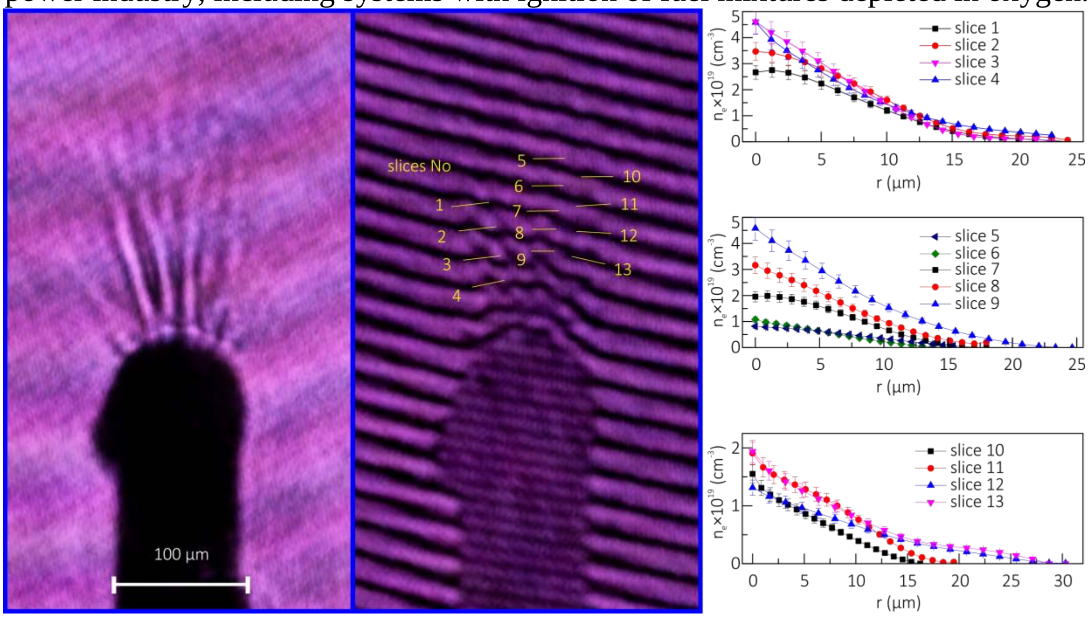


Fig. 1. The origination of thin plasma microchannels from a point anode (metal wire 100 μm in diameter) several nanoseconds after the electrical breakdown of a 2 mm air discharge gap.

The study was supported by the Russian Science Foundation (project no. 24-79-10167).

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# SNAKE-LIKE AND STRAIGHT-LINE IONIZATION WAVES FORMATION IN PLASMA JET OF A COAXIAL BARRIER DISCHARGE IN ARGON FLOW AT ATMOSPHERIC PRESSURE

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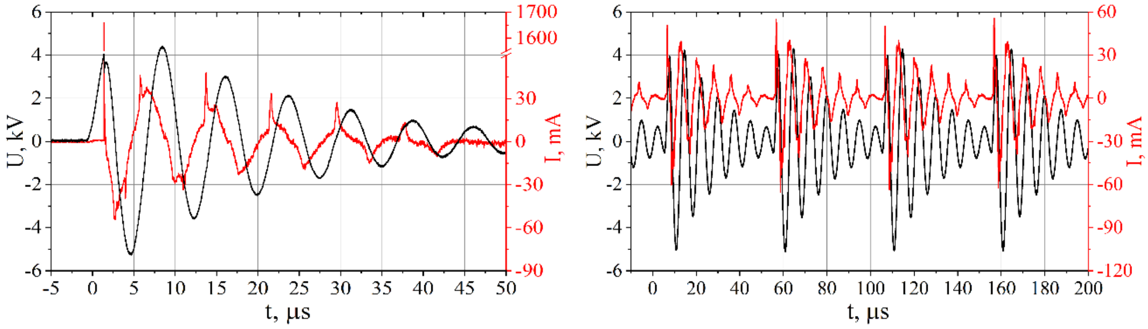
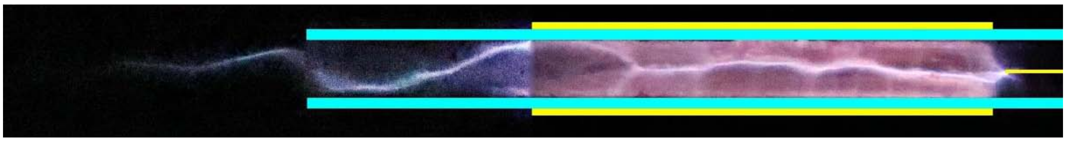
Currently, there are many papers devoted to studying the ionization waves in a barrier discharge in the form of a "snake" or straight-line streamers. However, all these works investigated the propagation of such ionization waves starting from the gas-discharge tube output. In this report, for the first time, the formation of ionization waves of the snake-like and straight-line streamers is traced, starting from its formation in the discharge zone within the tube. Their formation was traced using a high-speed ICCD camera. The coaxial barrier discharge in argon flow at atmospheric pressure was excited by successive trains of sinusoidal voltage, the frequency repetition of which was varied. A significant difference in the forms of ionization waves in dependence on the repetition frequency F was revealed. The snake-like and straight-line streamers are shown below for the repetition frequency F = 100 Hz and F=20 kHz.

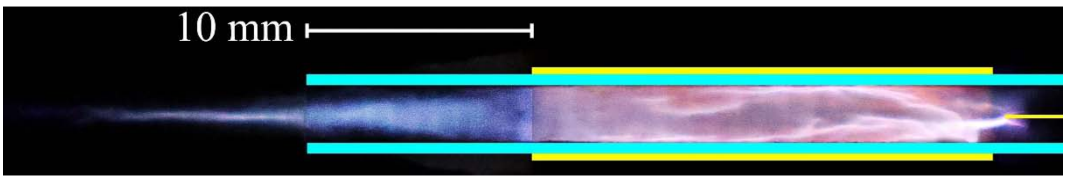



a) b)

Fig. 1. Voltage and current waveforms of sinusoidal zugs at two repetition frequency: a) F=1 kHz; b) F=20 kHz.



a)




b)

Fig. 2. Images of plasma structures in the quartz tube and plasma jet outside the tube. At short exposure time, weak diffuse glow of plasma jet is not detected. Flow direction is from right to left. a) F = 100 Hz. b) F = 20 kHz.

This work was supported by the Russian Science Foundation (grant No. 24-45-20006).

# SMOOTH DECREASE OF SPECTRAL SERIES LINES INTENSITY WHEN APPROACHING THE IONIZATION THRESHOLD IN A DENSE EQUILIBRIUM PLASMA.

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This report will examine the gradual weakening of spectral lines in dense plasma, how the intensity of spectral lines in a series decreases as the transition energy increases. The research is based on experimental data provided by Dmitry Kavyryshin, whose experiment is detailed in [1].

The issue at hand relates to the limitations of the statistical sum and the statistical weight of atomic levels. In the Coulomb field of a single atom, the statistical weight diverges with the square of the principal quantum number. The limitation on the number of excited atoms has been studied for many years by notable figures such as Bohr, Fermi, Planck, Larkin, and others [2,3]. This problem has been complex and has been under investigation for over a century.

In dense plasma, the main constraint on states in the statistical sum is the transition from two-body to many-body interactions. The concentration of excited atoms with a high quantum number of n decreases in dense plasma compared to dilute plasma. In simple term, this is because the large electron orbital radius (at high quantum number) leads to significant interactions with other ions, hindering the realization of higher energy levels.

To address these many-body interactions, molecular dynamics modeling was employed. Additionally, a code for identifying paired states, as described in [4], was utilized. During each step of the simulation, the nearest ion was located. If the energy of the electron and proton is below zero, they are considered a bound pair.

The experimental data align well with the theoretical predictions for d levels (fig.1) but do not fit as well for s levels. It has been suggested that the s level is not well-represented by any classical modeling. For instance, the orbital angular momentum of an electron in the s level is zero, while the classical thermodynamic average momentum of the electron is not zero.

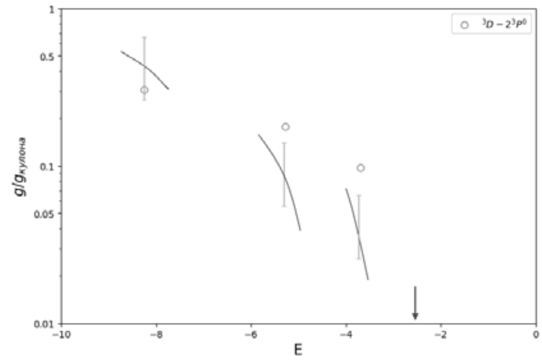


Fig. 1. Energy spectrum for triplet D levels. The line represents the modeling, while the circles indicate the experimental data points. The vertical axis shows the normalized concentration of levels, and the horizontal axis displays energy

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# NONLINEAR PROCESSES ACCOMPANYING INTERACTION OF RELATIVISTIC BEAM WITH MAGNETIZED PLASMA

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Interaction of a high current relativistic beam with a magnetized plasma is observed in open space and at modern experimental research facilities. Such interaction is realized due to two-stream instability on the frequency of Langmuir waves. At specific beam and plasma parameters, various nonlinear processes are accompanying this beam-plasma interaction. At the ratio of beam density to plasma density lower then $10^{-4}$, the amplitude of Langmuir waves is limited by nonlinearity in the weakly turbulent regime which is characterized these waves can be scattered on ion-acoustic oscillations [1, 2]. At the beam-plasma electron concentrations ratio above $10^{-3}$ the plasma oscillations achieve so high-level amplitude, that strong Langmuir turbulence develops and a rapid transfer of Langmuir waves across the spectrum to the region of large wave numbers is realized [3]. Under these conditions, electromagnetic wave emission near harmonics of the plasma frequency can arise due to scattering of Langmuir oscillations on forced fluctuations of the plasma density [4]. In the presence of a strong magnetic field in the plasma when the electron cyclotron frequency approaches to the Langmuir frequency, we have to describe this emission from the plasma according the spectrum of its upper-hybrid waves [5]. Experimental laboratory studies on the interaction of a high current beam with a magnetized plasma column were started at a beam pulse duration about 100 ns (INAR and GOL-1 facilities, see [6] and [7] respectively) and then they were conducted for the pulse duration ~ 10 µs (facilities GOL-3, see [8, 9] and GOL-PET, see [10 - 12]). We established in this experimental research that at the intense beam-plasma interaction regime with achieving high amplitudes of upper-hybrid waves, the energy deposition in the plasma under beam electron deceleration has achieved over 35% of the beam energy content both for the pulse duration ~ 100 ns (see [6]) and for the duration ~ 10 µs (see [8]). In turn, the detail measurements of escaping radiation fluxes at harmonic frequencies of plasma oscillations in frequency range 0.1-0.6 THz was measured at the facilities GOL-3 [9] and GOL-PET [10 - 12]. To analyze the nonlinear phenomena of the radiation flux generation, we conducted at GOL-PET facility measurements of the radiation fluxes escaping from the plasma in correlation with registration of the evolution of beam electrons energy distribution function due to the beam relaxation in the plasma.

Presented paper describes various nonlinear processes in time of the beam-plasma interaction for the experimental conditions mentioned above.

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# NONLINEAR ICR DYNAMICS OF SLOW IONS: A POSSIBILITY FOR OPTIMIZATION OF AN ELECTRODELESS ION THRUSTER

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Currently, the NRC "Kurchatov Institute" is developing a project for an electrodeless plasma rocket engine (EPRE) similar to the VASIMR project [1]. A distinctive feature of such electrodeless rocket engines is the heating of the plasma (working fluid) using ion cyclotron resonance (ICR). More precisely, in this scheme the helicon discharge creates a cold plasma, the ions of which must be heated as much as possible downstream by the left-hand polarized slow wave when crossing the ICR as the magnetic field decreases. Finally, in the magnetic nozzle the energy of ion gyration changes into the longitudinal energy. While plasma flows through the resonance zone, the total increment of ion energy density is the sum of two parts, one of which arises from the energy increments of single particles (dynamic part), and another is due to the distribution function change of the whole ensemble (kinetic part). In hot plasmas, the resonance dynamics of a great majority of ions is linear, which means that each individual energy increment is a sinusoidal function of the phase difference between Larmor gyration and electromagnetic oscillation at the entrance moment. This phase difference is random and therefore the averaged value of energy increment is zero. Thus, the ion heating has purely kinetic nature (i.e. diffusion in the velocity space) and it may be described using the absorption coefficients from the linear theory of plasma waves. On the contrary, in plasmas with almost cold ions, which is the case of VASIMR-like plasma thrusters, the kinetic heating mechanism tends to degrade. However, it turns out that ICR dynamics at low gyration velocities is essentially nonlinear, even in the small wave amplitude limit. This brings to a sizeable average energy increments; hence, such an alternative scenario of ion energization might be helpful in practice.

The theoretical consideration of nonlinear ICR dynamics showed that slow ions undergo bounces in the gyration energy between the initial value and the maximum value $W_{\perp\,\mathrm{max}}$ with the time period $t_\mathrm{b}$, where

$$W_{\perp\,\mathrm{max}} \sim 2\omega\left(\frac{4\pi m_\mathrm{i} e^2 P}{k_\parallel^5 c^2}\right)^{1/3}, \qquad t_\mathrm{b} \sim 3\left(\frac{m_\mathrm{i}^2 c^2}{\pi e^2 k_\parallel P}\right)^{1/3}.$$

Here $P$ is the wave power flux density, $k_\parallel$ is the longitudinal component of the wave vector and $\omega$ is the wave frequency. To make an electrodeless ion thruster more efficient than a chemical rocket engine, the average magnitude of acquired energy, which is certainly less than $W_{\perp\,\mathrm{max}}$, must be at least about several tens eV. One can see that practically the only way to raise the efficiency is to keep the value of $k_\parallel$ as small as possible. But the cold-plasma dispersion relation for the left-handed slow wave in the limit $\omega_\mathrm{ci} \to \omega$ ($\omega_\mathrm{ci} > \omega$) gives infinitely increasing $k_\parallel$:

$$k_\parallel^2 \approx \frac{2\omega_\mathrm{pi}^2 \omega^2}{c^2\left(\omega_\mathrm{ci}^2 - \omega^2\right)},$$

where $\omega_\mathrm{ci}$ and $\omega_\mathrm{pi}$ are the ion cyclotron and plasma frequencies. We can suggest the following solution. The ICR-section magnetic configuration should contain a sufficiently long segment of almost constant magnetic field, where the ions will spend a time $\sim t_\mathrm{b}/2$, and the optimal value for this field is about a third of a percent higher than that at the exact resonance $\omega_\mathrm{ci} = \omega$.

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# EFFECT OF MAGNETIC FIELD ON DECELERATION OF ION BEAM DUE TO CHERENKOV INTERACTION WITH ION-ACOUSTIC WAVES

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Ion beams are often used in studies of plasma properties in small tokamaks. The interaction of beams with plasma occurs under conditions when the temperature of electrons $T_e$ exceeds the temperature of ions $T_i$. Ion-acoustic waves can exist in non-isothermal plasma, and under the effect of a strong electric field $\mathbf{E} = (0, 0, E)$ the ion-acoustic turbulence (IAT) develops. Under these conditions, it is the Cherenkov interaction with ion-acoustic waves that determines deceleration if the ion beam velocity exceeds the velocity of ion sound $v_s$ [1]. Besides, in small tokamaks TUMAN-3M, TEXT-U, J-TEXT there is a magnetic field $\mathbf{B} = (0, 0, B)$, which can significantly change the trajectory of the beam ions and, thereby, affect the braking process [2].

Using the quasilinear equation for the ion beam distribution function, the equations for the velocity components $\mathbf{u} = (u_\rho, u_\varphi, u_z)$ are obtained. In this case, the ion beam density is considered to be small compared to the plasma density $n$, and for the distribution of ion-acoustic waves $N(\mathbf{k})$ in the wave number space $\mathbf{k}$ one can use the results of the Ref. [3].

The plasma parameters are chosen as follows: $T_e = 300$ eV, $T_i = 50$ eV, $n = 2 \times 10^{13}$ cm$^{-3}$. If the initial velocity of the beam is directed along the symmetry axis of the IAT, then the beam is decelerating in the same way as in the absence of the magnetic field [1]. Therefore, we consider the case when the initial velocity of the beam is directed across the symmetry axis. Figs. 1 (A) and (B) show the solution of the system for the ion beam velocity components for two values of $E/E_N$, where $E_N = 18$ V/cm is the field strength determined by the plasma parameters. In the figures, the value of coordinates is given in units $v_s/\nu_f = 0.4$ cm, where $v_s = 1.7 \times 10^7$ cm/s, and $\nu_f = 4.1 \times 10^7$ s$^{-1}$ is the frequency characterizing the deceleration of the ion beam. As can be seen from these figures, the beam ions move in a contracting spiral deep into the plasma. As they decelerate, their effective Larmor radius decreases, and the displacement along the magnetic field occurs. The ratio $E/E_N$ determines the efficiency of deceleration, and in addition, the number of turns along a spiral of decreasing radius that ions manage to make. In all cases, the deceleration stops when the velocity of the beam ions $u$ turns out to be equal to the velocity of the ion sound $v_s$.

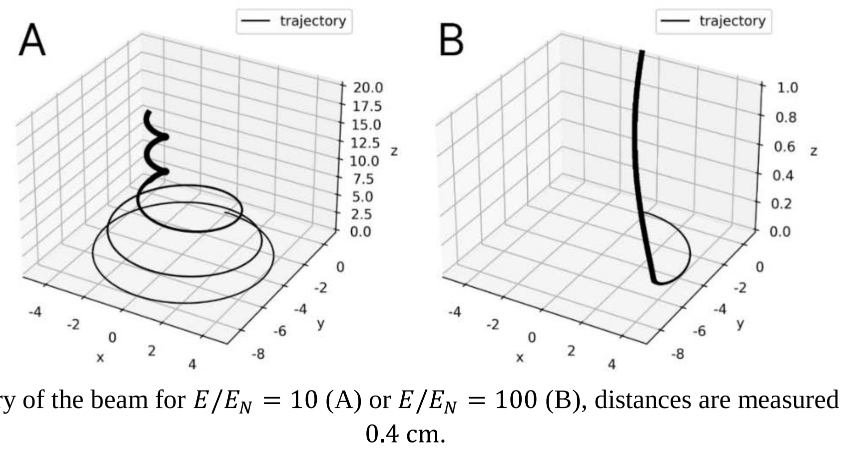


Fig. 1. The trajectory of the beam for $E/E_N = 10$ (A) or $E/E_N = 100$ (B), distances are measured in units $v_s/\nu_f = 0.4$ cm.

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# ON THE THIRD IONIZATION POTENTIAL OF TANTALUM ATOM

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It is known that triply-charged metal ions, $M^{3+}$, can form with a neutral helium atom, He, the bound complexes with the binding energy ≳ 1 eV [1]. In this case, $HeM^{3+}$ complexes can be metastable or even stable if the potential energy curves for the pairs He + $M^{3+}$ and $M^{2+}$ + $He^{+}$ intersect at a sufficiently high energy barrier to prevent rapid exothermic dissociation:

$$M^{3+} + He \rightarrow HeM^{3+} \quad (1)$$

One of the possible dissociation channels of such complex is its quenching by a neutral metal atom:

$$HeM^{3+} + M \rightarrow He^{+} + M^{2+} + M^{+} + e \quad (2)$$

It was found that this reaction is the main channel for the formation of helium ions in plasma formed during laser ablation of the metal target immersed in superfluid helium at the laser power density below the breakdown threshold of liquid helium [2]. This channel is accomplished observed exclusively for metals with a positive balance

$$IP3 - 24.59 - IP1 > 0 \quad (3)$$

where 24.59 eV is the first ionization potential of a helium atom, while IP1 and IP3 are the first and third ionization potentials of a metal atom, correspondingly.

We have detected the luminescence spectra of a plasma plume during laser ablation of a tantalum target immersed in superfluid helium. Observation of excited neutral helium atoms at the laser power density below the breakdown threshold of liquid helium points to formation of helium ions in laser plasmas [3]. From the NIST values for IP1 and IP3, 7.55 eV and 23.1 eV the energy disbalance 9.04 eV have been found [4]. Therefore, we suggest the real IP3 value for Ta atom should be significantly higher than 32.2 eV. Our analysis of the literature data supports this suggestion.

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignments # 124020600049-8, # 125012200612-2, # 075-00269-25-00).

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## ION-ACOUSTIC SOLITONS IN A COLLISIONLESS NONISOTHERMAL PLASMA

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The nonlinear motion of a collisionless nonisothermal plasma in the form of an ion-acoustic soliton is investigated in one-dimensional geometry based on two different approaches to describing the motion of the electron component of the plasma. The results of a more general kinetic method for studying the motion of nonisothermal plasma using the Vlasov equation for electrons are compared with the results of the classical approach [1], in which the dependence of the electron concentration on the scalar potential of the longitudinal field of the ion-acoustic soliton is determined by the Boltzmann distribution over the electron energy in the soliton potential field. The motion of plasma ions in both cases is described by the equations of cold hydrodynamics.

It is found that in the kinetic description of the motion of the electron component of plasma, taking into account the soliton displacement, the shape and propagation velocity of the soliton are determined by the following factors associated with electrons: the total charge and shape of the velocity distribution function of electrons trapped in the soliton potential well, the asymmetry of the velocity distribution function of passing electrons, and the discontinuity of its domain of definition caused by the presence of the potential well. It is shown that for small-amplitude solitons, when the electron energy in the soliton potential well is much less than the characteristic thermal energy of electrons, the dependence of the concentration of transient electrons on the scalar potential can be represented as an expansion in the value of the scalar potential in a series containing fractional powers multiples of ½. The last expansions in the series are a consequence of the discontinuity of the domain of definition of the distribution function for the velocities of transient electrons.

The distribution by velocities of electrons trapped in the soliton potential well is a function of the characteristics of the Vlasov equation, and when expanding the concentration of trapped electrons in a series in powers of the scalar potential, it also leads to the appearance of fractional powers multiples of ½ of the scalar potential.

The complex nature of the dependence of the electron concentration in an ion-acoustic soliton on the scalar potential in the kinetic description of the electron component of the plasma and the admissible arbitrariness [2] in the choice of the shape of the distribution function for the velocities of trapped electrons leads to a greater diversity of the family of ion-acoustic solitons than in the case of using the Boltzmann distribution for electrons, as is accepted in the classical approach [1]. It was found that if the shape of the distribution function for the velocities of trapped electrons is such that the terms with fractional powers in the expansion of the concentration of trapped electrons mutually cancel out with similar terms in the expansion of the concentration of passing electrons, then the soliton solution of the Poisson equation obtained in the kinetic approach coincides, up to small corrections proportional to the square of the ratio of the soliton velocity to the ion sound velocity, with the soliton obtained in the classical approach. However, unlike the classical soliton, the kinetic approach also shows the existence of a current of passing electrons in the ion-acoustic soliton, which is absent in the classical approach using the Boltzmann distribution. The current of passing electrons plays an important role in maintaining the plasma quasi-neutrality after the passage of an ion-acoustic soliton through it. Thus, the model using the Boltzmann distribution to describe the electron component is incomplete and limited for studying nonlinear motions of collisionless nonisothermal plasma.

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## COMBINING PLASMA DETECTOR AND CHROMATOGRAPH INTO SINGLE ANALYTICAL CYCLE FOR DETERMINING THE COMPOSITION OF GASEOUS IMPURITIES

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One of the promising applications of gas-discharge plasma with non-local characteristics is the development of gas impurity detectors [1-4] based on the plasma electron spectroscopy (PLES) method [1-4]. In recent years, significant progress has been made in the determination of complex impurities by the PLES method, including various types of hydrocarbons at both low and high pressures [1-4]. However, it has been shown that if the ionization energies of the impurity gases are close to each other, the characteristic peaks from fast electrons can overlap with each other, which can lead to difficulties in identifying gas impurities. The solution to this problem is to combine the PLES method and existing compact chromatographs with the aim of preliminary separation of gas impurities into components in a chromatographic column on a time scale and their subsequent analysis by the PLES method on an energy scale.

To implement this idea, a commercial compact chromatograph PIA [6] and a detector PLES connected to it were used in the presented work. The latter was based on a gas-discharge tube including a ring cathode and anode, as well as a cylindrical probe. Measurement of characteristic peaks from fast electrons generated as a result of Penning ionization reactions of impurity particles by metastable helium atoms was performed using a previously developed probe measuring system [6-8]. The distance between the electrodes was chosen such that a short (without a positive column) glow discharge was generated in it, i.e., negative glow plasma with non-local characteristics was generated in almost the entire discharge region.

Experimental studies on the registration of impurities were carried out using a mixture $He+C_3H_8$(400 ppm)+$CO_2$(200 ppm)+$N_2$ (500 ppm). In this case, two cases were considered: in the first, the mixture was not pre-separated in the chromatographic column, but immediately entered the discharge gap, and in the second, the mixture was passed through the chromatograph and then, separated on the time scale, the mixture entered the PLES detector. The results showed a fairly high efficiency in the possibility of registration.

This approach is in some sense similar to the chromatograph mass spectrometry method, whereby it is not the pulse that is measured, but the electron energy, which allows working at high pressures and refusing to create a deep vacuum, and therefore two-stage vacuum pumping systems. In other words, combining a chromatograph and a PLES detector will allow creating compact CHROMATO-PLES gas analytical systems that allow working on-site in real time.

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# FEATURES OF THE TRANSITION FROM A GLOW DISCHARGE TO AN ARC DISCHARGE WITH REFRACTORY AND NON-REFRACTORY ELECTRODES IN ATOMIC AND MOLECULAR GASES

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The paper presents the results of studying glow and arc direct current (DC) discharges, as well as the transition from a glow discharge to an arc within the framework of a self-consistent model based on an extended fluid description of plasma, which describes both the discharge gap and the electrodes in a unified way [1-4].

As a result of a series of numerical calculations within the framework of 2D axisymmetric geometry, studies of various modes of DC discharge in argon at atmospheric pressure with tungsten electrodes were carried out: from the Townsend and glow modes to the arc mode. For the discharge parameters in the normal glow mode, validation was performed using experimental data available in the scientific literature and our own electrophysical measurements, and for the arc mode, using our own studies. The effect of external boundary conditions on the electrodes, which describe the cooling conditions, on the volt-ampere characteristic of the discharge was demonstrated: the transition from the normal glow mode to the arc mode can occur with or without the formation of an abnormal glow mode. It was shown that, depending on the cooling conditions of the electrodes, two forms of arc discharge can be obtained: with a diffuse or contracted current spot [1-2]. Similar studies have been conducted for discharges in nitrogen and $CO_2$.

Within the framework of one-dimensional calculations, studies were conducted on the effect of evaporation of the electrode material (graphite and copper) on the characteristics of arc discharges in helium and argon. Based on the literature analysis, a set of elementary processes involving carbon atoms and molecules in the gas discharge gap was developed. The following types of particles were taken into account: neutral carbon particles (C, $C_2$, $C_3$), their ions ($C^+$, $C_2^+$, $C_3^+$), and excited states ($C^*$, $C_2^*$, $C_3^*$). For discharges with copper electrodes, in addition to Cu atoms and atomic copper ions ($Cu^+$), six effective excited states were considered. For discharges involving evaporated germanium or silicon, the formation of neutral atomic particles (Ge, Si) and one type of ions ($Ge^+$, $Si^+$) was taken into account [3].

Within the framework of simulations, it was shown that already in the transition mode from an abnormal glow discharge to an arc discharge, intense evaporation of atoms and molecules of the anode material — graphite, Cu or Fe — is observed. In the arc mode, a change in the plasma-forming gas is noted: the dominant ion becomes either the carbon ion or the Cu, or Fe ions, depending on the electrode material. When changing the combustion mode of an arc discharge in helium, such a transition is accompanied by the appearance of a potential jump. Additionally, an abrupt increase in the concentration of carbon (or Cu, or Fe) atoms and a sudden drop in the concentration of helium ions are observed. This is due, firstly, to the high concentrations of atomic particles of carbon or copper evaporated into the discharge gap, and secondly, to the low ionization energy and high impact ionization cross-sections of carbon or copper atoms compared to helium atoms. For an arc discharge in argon, such a transition occurs smoothly (monotonically) [4].

Additional numerical studies of the characteristics of discharges with a liquid (electrolyte) electrode were conducted, demonstrating the effect of water evaporation on the discharge characteristics.

Work supported by the RSF, grant No. 24-22-20091, https://rscf.ru/project/24-22-20091/.

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# THE INFLUENCE OF ELECTRONEGATIVE GAS IMPURITIES ON THE FORMATION OF THE STRUCTURE OF A SHORT GLOW DISCHARGE IN HELIUM

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The paper presents the results of probe diagnostics of the negative glow plasma of a short (without a positive column) glow discharge in helium with admixtures of electronegative gases ($SF_6$ and $SiH_4$). The formation of a peak from negative ions (immediately under the space potential) is shown on the slow (low-energy) part of the second derivatives of the probe *I–V* characteristics [1]. The results of the dynamic change in the second derivative are presented when a small admixture of electronegative gas is admitted in the time range from 1 ms to 100 s in a closed reactor and in a reactor with a weak flow of the plasma-forming mixture.

In addition, the results of peak formation on the high-energy part of the second derivative of the probe *I–V* characteristic are presented. The peaks are formed as a result of Penning ionization reactions of admixture gas molecules by metastable helium atoms and superelastic collisions.

For the experimental conditions considered, numerical calculations were performed on the features of plasma formation in a short glow discharge based on an extended fluid model taking into account the detailed kinetics of elementary processes in He + $SF_6$ and He + $SiH_4$ mixtures. As well as additional calculations within the framework of a hybrid model based on the electron kinetic equation [2] and within the framework of a hybrid model based on the PIC/MCC approximation [3]. The formation of negative ions is shown, which are collected in the middle of the negative glow region, forming the plasma structure. High-energy parts of the EEDF with the formation of beams from fast electrons are also presented.

Work supported by the RSF, grant No. 24-22-20091, https://rscf.ru/project/24-22-20091/

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# THE PROPAGATION OF AN IONIZATION FRONT OF LOW-PRESSURE SURFACE-WAVE SUSTAINED DISCHARGE

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The propagation of an ionization front of the gas discharge sustained by the microwave surface wave in a quartz tube filled with low-pressure argon was studied [1, 2]. A numerical model of discharge ionization front dynamics is developed in electrodynamics code KARAT [3] based on the PiC method which allows to study in detail the structure of the ionization front. In other works the discharge propagation numerical models based on the time independent Helmholtz equation for the complex electric field amplitudes and balance equations for particles and electron energy [4] and on the direct solution of the Maxwell equations along with the electron balance equation [5]. The microwave discharge sustained by the surface wave in a gas-discharge tube can be thought of as the ionization front propagating through the gas and leaving behind the plasma column sustained by the surface wave [2]. It was shown that the effect of the electric field enhancement in the plasma resonance region at the discharge front leads to a breakdown wave and high velocities (up to $8{\cdot}10^7$ cm/s at Fig 1.) of discharge propagation. The performed experiments are in good agreement with the numerical model. Simulation results show that the electric field strength in vicinity of the plasma resonance region increases with decreasing pressure under conditions of $\nu/\omega$ < 0.1 (≈ 0.1 when $p$ = 3 Torr), where $\omega$ is the angular frequency of microwave radiation and $\nu$ is electron-neutral collision frequency.

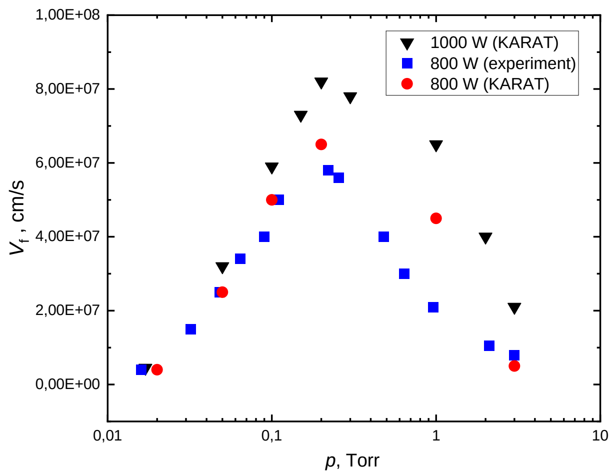


Fig. 1. Experimental dependence of the ionization front velocity $V_f$ on pressure *p*.

After ≈ 3Torr the mechanism of the fast propagation of the discharge front changes to a slower mechanism for the front propagation along the electron-density gradient due to the ambipolar diffusion. When the energy of the electrons in plasma resonance region exceeds 100 eV ($p$<0.1 Torr) the ionization rate decreased and front velocity drops.

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# PHYSICAL PROCESSES IN INDUCTIVELY COUPLED PLASMA AND THEIR IMPACT ON THE ACCURACY OF MASS SPECTROMETRY

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Inductively Coupled Plasma (ICP) is a highly intricate physical system involving key processes such as aerosol formation, ionization, ion extraction, and the transport of ions to the detector. These processes are governed by fundamental physical phenomena, including charge effects, plasma temperature redistribution, mass transport, and energy transfer dynamics. Each stage of the analysis is significantly influenced by the properties of the sample matrix. For instance, the matrix alters the droplet size distribution during aerosol formation, cools the plasma during ionization, and leads to the loss of lighter ions due to space charge effects during ion extraction and transport. Such matrix effects can compromise analytical accuracy and sensitivity [1-4].

To minimize these effects, it is essential to optimize plasma parameters, develop advanced ion introduction methods, and design more robust interfaces capable of mitigating space charge and thermal diffusion phenomena. Additionally, understanding the interplay between the sample matrix and plasma dynamics is critical for enhancing the precision and reliability of ICP-MS. These insights are fundamental to the advancement of analytical chemistry and plasma physics, laying the groundwork for innovative approaches in high-accuracy element and isotope analysis [5].

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# ON THE CHARACTERISTICS OF ELECTRON DIFFUSION AND DRIFT IN INERT GASES

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The problem of calculating kinetic characteristics during electron drift in inert gases in a wide range of the reduced electric field strength: 0.001 Td < E/N < 10000 Td is considered [1-3]. The drift velocity, average energy, longitudinal and transverse diffusion coefficients and ionization coefficient for the cases of a weak field and a moderately strong field E/N < 100 Td were calculated using the method of dynamics of many particles involving collisions in accordance with the Monte Carlo procedure. For the cases of strong and superstrong fields 100 Td < E/N <10000 Td, the results of calculations for two models of electron departure from the system were considered and analyzed: 1 - an avalanche model with multiplication; 2 - a model with the most energetic electron in the system leaving the wall during the act of ionization or transition to the runaway mode.

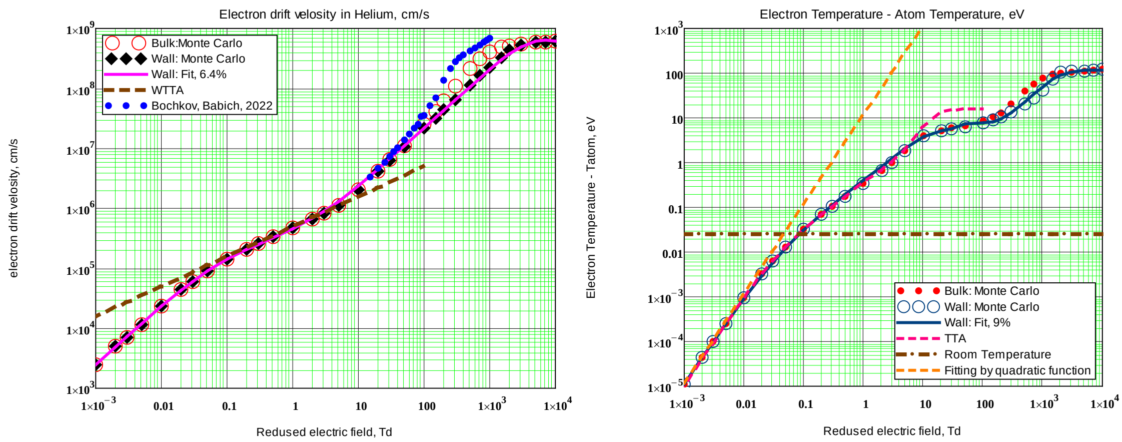


Fig. 1.left: Dependence of the electron drift velocity on the field strength for the avalanche and recombination models on the wall; right: Dependence of the electron heating on the field strength for the model with a wall.

As an example, Fig. 1a shows the graphs of the dependences of the helium electron drift velocity on the reduced electric field strength for the avalanche mode and the wall recombination mode, and Fig. 2b shows the electron heating values, which are defined as the difference between the electron temperature and the temperature of atoms. The figures also show approximation curves and curves obtained on the basis of a two-term approximation of the solution of the Boltzmann kinetic equation (TTA) using the collision cross sections from [4]. In superstrong fields E/N>200 Td, the electron runaway mechanism is taken into account, and the runaway coefficient is determined and calculated by analogy with the ionization coefficient.

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# EXPERIMENTAL DETERMINATION OF THE DEBYE LENGTH OF SCREENING AND ACCUMULATION OF ELECTRONS IN SEMICONDUCTOR NANOSTRUCTURES

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In heterostructures with tunnel-thin depleted layers, which represent a quantum barrier (QB) on an enriched base, when electric fields are applied, the transverse tunnel transport of electrons is more intense, the smaller the layer thickness and the higher the energy of the electron incident on the barrier [1]. An increase in the electron self-energy as a result of size quantization increases the transparency of the QB for electron tunneling. This transport mechanism agrees well with experimental data for heterostructures without plasma fluorination with depleted layer thicknesses from 5 to 20 nm (Fig. 1).

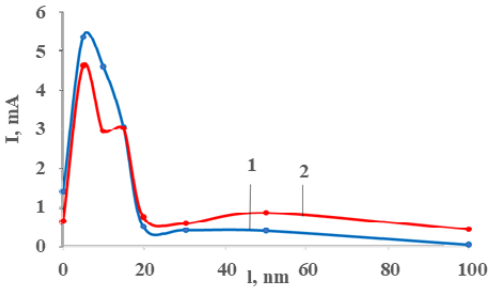


Fig. 1. Experimental dependences of transverse currents in 2 D heterostructures on the thickness of the depletion layer before (1) and after (2) treatment in $CF_4$ plasma

In heterostructures with different electron enrichment of layers, the transverse diffusion-drift current, the value of which is proportional to the gradient of the electron concentration between the layers, reduces the longitudinal current between the contacts. During plasma fluorination, the negative electrostatic potential forms a field in the near-surface region of the depleted layer between the contacts, penetrating to the depth of the Debye radius. Reducing the diffuse scattering at the boundary of the layers increases the longitudinal and transverse currents under the contact. This mechanism is realized at CB thicknesses in the range from 100 to 20 nm.

Reducing the thickness of the depletion layers increases the field strength of chemisorbed fluorine ions, which reduces transverse diffusion and slows down the formation of subsurface quantum-sized layers of the 2 D electron gas. Reducing the self-energy reduces the transparency coefficient for electron tunneling in the contacts. With a CB thickness equal to the Debye radius Ld, the transverse current is equal to the current in the absence of fluorine plasma treatment. With LD = $15 \cdot 10^{-9}$ m (Fig. 1), the electron concentration n is calculated using the formula [2]:

$$n = \varepsilon\varepsilon_0\, kT/q^2 L_d^{\ 2},$$

with ε = 12 - the permittivity of the medium, kT = 0.025 eV - the thermal kinetic energy of electrons at room temperature, q - the electron charge, yields a concentration value in the depleted layer $n = 9.3{\cdot}10^{17}$ cm$^{-3}$.

Experimental determination of the Debye radius allows one to control the concentration of charge carriers in nano-objects with a minimum number of other fundamental physical parameters.

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# PROPERTIES OF NON-IDEAL PLASMA

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Studying plasma with a degree of ionization of the order of unity, for which the Coulomb coupling parameter takes values of the order of unity, is a very complex problem for both theory and experiment. The coupling parameter is defined here as the ratio of the average potential energy of the Coulomb interaction of neighboring ions to their average kinetic energy. The complexity of studying such plasmas in theory is associated with the need to solve the quantum many-body problem due to the long-range Coulomb interaction between the charged particles constituting the plasma. The experimental difficulties in studying the strongly coupled plasma, that is also called non-ideal plasma, are associated with the high values of temperature and pressure at which such plasma exists in a state of thermodynamic equilibrium.

Recently, simultaneous measurements of thermodynamic functions and electrical conductivity of dense lead plasma were carried out in dynamic experiments [1]. In the experiment, a continuous transition of a metal sample to a plasma state was observed when heated by an electric current pulse at a supercritical pressure. This process was quasi-static and allowed the evolution of the thermodynamic state of the sample in the *PV*-plane (pressure, volume) to be detected. In addition to the two quantities, the internal energy and electrical conductivity were also measured during the experiment. Since the critical point of the liquid-gas transition and the critical density of the metal-nonmetal transition for lead had been determined earlier [2], the region in the *PV*-plane corresponding to gaseous nonmetallic states, i.e. plasma states, was known.

In this work, the measurement results [1] are compared with the calculation results by the chemical model of plasma [3]. The model is used primarily to determine the degree of ionization and plasma temperature, since these quantities are not currently measured in experiments, but they are necessary for interpreting the experimental results. We show that the results obtained from the chemical model [3] agree well with the entire set of the experimental data [1]. Based on this comparison we interpret the measured dependences. We check the accuracy of the long-predicted theoretically the universal dependence of the dimensionless electrical conductivity (i.e., the electrical conductivity divided by the electron plasma frequency) of fully ionized nonideal plasmas on the coupling parameter in the case the plasma is weakly degenerate, and the coupling parameter reaches values of the order of unity. We show that none of the existing theories of electrical conductivity of non-ideal plasma agree with the experimental data.

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# *AB INITIO* RECOMBINATION IN ULTRACOLD PLASMAS

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The efficiency of recombination is a crucial issue for the existence of ultracold plasmas, and the respective theoretical works [1, 2] were performed long before the experimental studies of such systems. Unfortunately, the straightforward numerical simulation of recombination in the non-ideal plasmas is a challenging task because of a huge difference in the characteristic temporal scales of the free and bounded motion of the electrons. To get around this problem, the rate of recombination is usually calculated by the two-step process: firstly, the electron partition function is simulated numerically and, secondly, it is used for the analytical estimates of the efficiency of formation of the bound states.

It is the aim of our report to present a new algorithm that enabled us to simulate the entire recombination process *ab initio* (*i.e.*, from the first principles). This method is based on the employment of the "scalable" reference frame [3], in which the effect of expansion of the plasma cloud is efficiently reduced to a kind of viscosity, enforcing the electrons to be captured in the field of the nearby ions. Such an approach was initially designed to simulate the evolution of electron temperature $T_e$ in the strongly-coupled regime [3], but it turned out to be well applicable also to the problem of recombination.

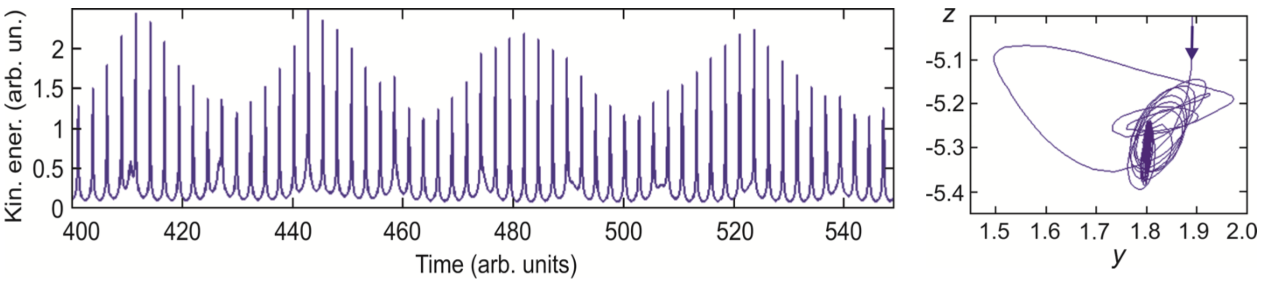


Fig. 1. Example of an electron trajectory captured in the vicinity of a nearby ion (right panel) and temporal behavior of the kinetic energy of plasma (a sample of 10 electrons and ions) after formation of two recombined states. The modulation of kinetic energy with two characteristic frequencies corresponds just to the motion of two captured electrons near the pericenters of their orbits.

As is seen in Fig. 1, the recombined states manifest themselves in the temporal behavior of the plasma kinetic energy as a series of equidistant peaks, whose maxima correspond to passage of the captured electron through the pericenter of its elliptical orbit around an ion. The fraction of the "quenched" (*i.e.*, avoiding the recombination) electrons in our simulations was found to be about 80%, which is in a surprisingly good agreement with the earlier modeling [4], where the criterion of recombination was introduced semi-empirically. Therefore, the *ab initio* simulations by our method can serve as a testbed for other approaches commonly used for the analysis of ultracold plasmas.

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# TO THE SPECTRUM OF COLLECTIVE EXCITATIONS IN STRONGLY COUPLED PLASMALIKE LIQUIDS

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In connection with the growing interest to phonon-roton excitations in Coulomb systems, the generalization [1] of Feynman-Cohen formula [2] for collective excitations in superfluid HeII is applied for systems at high temperature and with strong interparticle interaction. The basis for this use is an opportunity to extend the theory for Bose condensed systemstemperature on liquids at high temperatures in an assumption of a weak damping of oscillations [3]. The specific numerical results are found by use the relation

$$nS(p) = \frac{p^2}{2ME_{p-r}(p)} \coth\left[\frac{E_{p-r}(p)}{2T}\right], \tag{1}$$

where $n$, $p$, $S(p)$, $M$, $E_{p-r}(p)$ are the liquid density, transferred momentum, structure factor, mass of atom and spectrum of the collective excitations respectively. The existence of phonon-roton branch of excitations for liquid metallic hydrogen is predicted on the basis of the performed calculations (Fig. 1). The static structure factor for liquid metallic hydrogen in (1) has been calculated in [4] by molecular dynamics method.

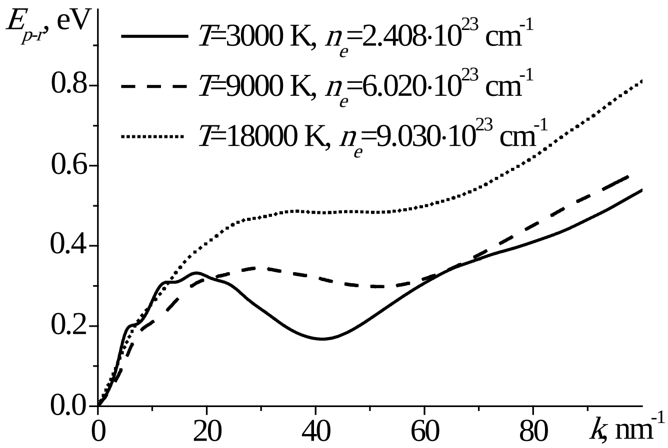


Fig. 1. Phonon-roton spectrum curves of collective $E_{p-r}(k)$ excitations as the function of transmitted wave vector for different characteristics of liquid-metal hydrogen.

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# ATTRACTIVE – REPULSIVE GRAVITY: MASS DEFECT AND BINDING ENERGY

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In connection with the recent experiment on the fall of antihydrogen in the gravitational field of the Earth [1], the general question of the equivalence of binding energy to the gravitational mass is posed and discussed. The problem appeared due to the statement "All mass is energy, but not all energy is mass" [2], based on the transversal photons massless nature . Various types of interactions responsible for binding energy of coupled particles composed on simpler particles are considered. Binding energy for the mass defect and for its massless form is discussed [3]. The hypothesis of the massless binding energy allows to formulate the concept of the prohibition of the transformation of massless energy into energy associated with the mass of particles by the Einstein relation. The problem of charge conjugation for the binding energy is discussed on the basis of paper [4]. Jeans instability for both forms of the binding energy is considered [5]. Existing experiments in the Penning trap and on the neutron-proton capture at the edge of precision confirm the mass nature of the binding energy for the electromagnetic and strong interactions. The quark-gluon interaction in proton makes a positive contribution to mass in the Lattice-QCD model and poses a question on universality of mass defect concept for various types of interaction. The need of further experiments is discussed.

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# ON R.L.STRATONOVICH'S FORMULA FOR TRANSITION FROM DYNAMIC TO PROBABILISTIC MEASUREMENTS AND ITS CONNECTION WITH OPERATIONS ON DISTRIBUTION FUNCTIONS OF RANDOM VARIABLES

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The applications of R.L.Stratonovich's formula [1] for the exact transition from dynamic measurements to probabilistic or thermodynamic measurements are considered. The connection of this formula with known expressions for operations on probability density functions of random variables is given. The application of the formula to the problem of determining the observed physical parameters: fields, potentials, moments - produced by (stochastically moving) charged particles of different multipolar types is demonstrated [2].

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# ENERGY TRANSFER IN PLASMA CRYSTAL

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The heat transfer in a plasma crystal is investigated with the help of the following model. In equilibrium, dust grains levitate at the same height forming a hexagonal grid in the horizontal plane. Assuming that all grains are of the same charge and mass, the linearized Langevin equation for small deviation of particles position from equilibrium is used.

The interaction between dust grains is described with the help of a potential function which is isotropic in the horizontal plane but nonreciprocal in the vertical direction, $U(\mathbf{r}) = U(\rho, z) \neq U(\rho, -z)$. For numeric purposes we use the interparticle potential calculated for an anisotropic plasma consisting of Maxwellian electrons and cold ions streaming downwards. Here, we are interested in a way the heat from the point source is distributed over the crystalline grid. Therefore, it is assumed that random force in the Langevin equation acts upon the central particle only.

The overall energy balance is analyzed. It is shown that the additional channel of energy exchange with an ambient plasma arises due the nonreciprocal interaction between dust grains. Unlike friction, the corresponding energy loss or gain may be attributed to a pair of interacting particles only but not to a single particle. The additional power channel is characterized by a function, $W(\mathbf{l},\mathbf{l}')$, of the positions of two dust grains which is expressed in terms of correlators between the displacement and the velocity of neighboring particles.

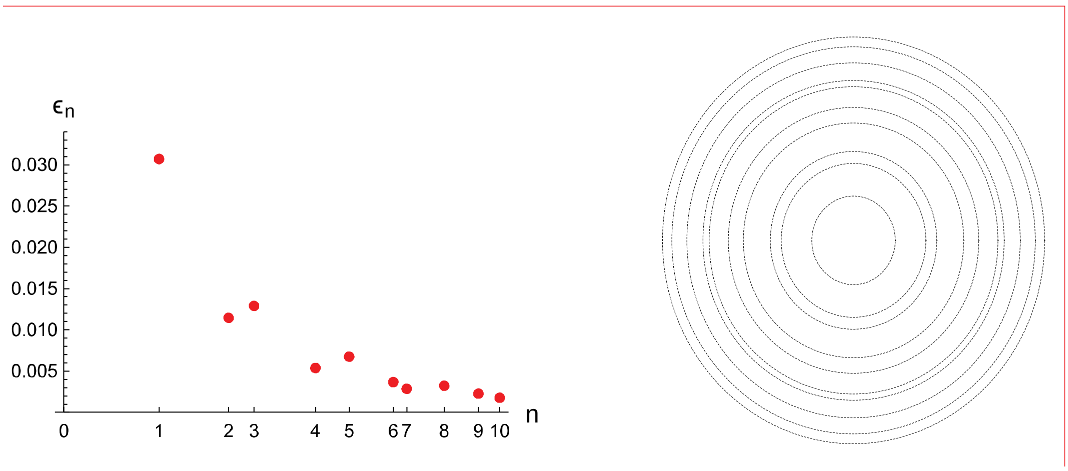


Fig. 1. Left: kinetic energy of particles vs distance to the central point. Right: collective energy exchange. Red solid lines correspond to pairs with *W>0*, blue dashed lines correspond to *W<0*.

An example of our findings is depicted in Fig.1. Left part of the figure shows the normalized average kinetic energy of the grains as a function of the distance to the origin. The most distinctive feature of this distribution is that it may be a non-monotonous function of the distance.

The right part of the figure schematically shows the structure of the function $W(\mathbf{l},\mathbf{l}')$. Neighboring grid points for which $W(\mathbf{l},\mathbf{l}') > 0$, i.e. there arises additional energy input from the streaming plasma, are connected with solid red lines. The bonds with $W(\mathbf{l},\mathbf{l}') < 0$ for which additional energy loss arises are shown by blue dashed lines.

# EQUATIONS OF STATE FOR LIMITED ONE-COMPONENT PLASMA

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An infinite system of massive charged point particles moving on the uniform background of a compensating charge is known as one-component plasma (OCP). The OCP limited by a spherical surface (specular reflection boundary condition is assumed) will be termed limited one-component plasma (LOCP). It was demonstrated in [1] that at high Coulomb coupling parameter $\Gamma = 500$, a solid core emerges in the LOCP containing $N > 2500$ particles, i.e., a transition to the thermodynamic limit at $N \to \infty$ occur. Note that at high $\Gamma$, the particles do not move outside the charge compensating sphere, so that a boundary condition is not necessary. In this work, LOCP is used to establish the equation of state (EOS) for the OCP in a wide range of $\Gamma$. To this end, we have performed molecular dynamics (MD) simulation of the equilibrium LOCP including from $2500$ to $50000$ particles to determine the dependence of the system excess potential energy $u_{\rm ex}$ per one particle on $N$, which appeared to by clearly resolved. This made it possible to obtain a reliable (accurate up to 0.1%) estimate for $u_{\rm ex}$ in the thermodynamics limit. Calculations in the range $0.003 \le \Gamma \le 1000$ showed that at $\Gamma < 0.03$, $u_{\rm ex}$ is fully compatible with the Debye–Hückel approximation, while at $\Gamma > 300$, $u_{\rm ex}$ approaches the Lieb–Narnhofer bound ($0.9$). In the range $0.1 \le \Gamma \le 100$, our results are in satisfactory agreement with the work [2], where Monte Carlo simulation of $10^6$ particles with periodic boundary conditions was performed (our $u_{\rm ex}$ is somewhat lower than that presented in this work). Also, at low $\Gamma$, they are rather inconsistent with earlier results of other authors.

In addition to $u_{\rm ex}$, two more quantities, namely, the excess energies of interparticle and particle–background interaction per one particle, $u_{p\rm ex}$ and $u_{b\rm ex}$, respectively, are found to be finite ( $u_{p\rm ex} + u_{b\rm ex} = u_{\rm ex}$ ). Both dependencies $u_{p\rm ex}(\Gamma)$ and $u_{b\rm ex}(\Gamma)$ are non-monotonic, $u_{b\rm ex}$ approaching maximum at $\Gamma \approx 0.03$ and $u_{p\rm ex}$, minimum at $\Gamma \approx 10$. They are shown to reach their limits $\lim_{\Gamma\to 0} u_{pex} = \lim_{\Gamma\to 0} u_{bex} = 0$ and $\lim_{\Gamma\to\infty} u_{pex} = 2\lim_{\Gamma\to\infty} u_{bex} = 0.6$ obtained analytically.

The compressibility factor for the particles is based on the introduced quantities: $Z_p = 1 + (\Gamma/3)(u_{p\rm ex} - 2u_{b\rm ex})$; from the above estimates, $\lim_{\Gamma\to 0} Z_p = 1$ and $\lim_{\Gamma\to\infty} Z_p = 0$. The particle EOS calculated from the MD energies was shown to match closely the EOS based on the virial of force from the same simulation. It was found that $Z_p > 0$ even at high $\Gamma$, which is a revision of the results [1]. At $\Gamma = 30$, $Z_p$ almost vanishes. Treatment of the full virial of force of the whole system leads to a conclusion that if an additional non-electromagnetic force is acting between the constituent particles of the background so that the total force between them vanishes then the compressibility factor for the whole system $Z = Z_p$. If they interact via the Coulomb potential then $Z = 1 + (\Gamma/3)u_{\rm ex}$, while $Z_p$ defines the EOS for a subsystem of the particles. Note that none of the quantities $Z$, $Z_p$, $u_{p\rm ex}$, and $u_{b\rm ex}$ reveal singularity in the vicinity of the OCP melting point, which is believed to be located at $\Gamma = 174$.

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# NON-HERMITIAN SKIN EFFECT IN DUSTY PLASMA CHAIN STRUCTURES

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The study of non-Hermitian physics has gained significant attention due to its ability to describe a wide range of open and dissipative systems [1]. In particular, non-Hermitian systems exhibit unique topological effects, among which the non-Hermitian skin effect (NHSE) is of paramount interest [2]. NHSE manifests as an anomalous accumulation of bulk states at the boundaries of a system due to asymmetric interactions. While this effect has been extensively studied in optical, photonic, and electronic systems, its realization in classical mechanical and plasma-based environments remains an open question.

In this work, a theoretical framework is developed to investigate the emergence of NHSE in a system of levitating dust particles confined in a vertical chain structure within a plasma discharge. The interaction between dust particles is effectively nonreciprocal due to ion wake effects and anisotropic plasma-mediated interactions. The presence of nonreciprocity in the system allows for the realization of NHSE, which leads to an exponential accumulation of kinetic energy at one boundary of the dust chain.

The mathematical model considers a discrete system of coupled harmonic oscillators with nonreciprocal interactions [3]. The dynamics of the system are governed by a set of equations incorporating a modified Coulomb potential with an additional ion wake-induced attraction, resulting in an asymmetric interaction matrix. The system is coupled to Langevin thermostats to simulate the influence of plasma background fluctuations. The resulting equations of motion can be mapped onto a non-Hermitian Schrödinger-like equation, enabling the characterization of NHSE in terms of complex eigenvalues and nonorthogonal eigenstates.

It is shown that the nonreciprocity-induced NHSE leads to an exponential increase in the kinetic temperature of dust particles localized at the boundary of the chain. This effect is robust against moderate perturbations in particle charge and interaction strength, indicating its topological protection. The findings provide a new perspective on the behavior of complex plasma systems and suggest that dusty plasma chains serve as a promising platform for studying non-Hermitian physics in classical settings.

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# EXCESS ENTROPY OF YUKAWA FLUIDS (COMPLEX PLASMA)

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The entropy of strongly coupled Yukawa fluids is discussed from several perspectives [1]. First, it is demonstrated that a vibrational paradigm of atomic dynamics in dense fluids can be used to obtain a simple and accurate estimate of the entropy without any adjustable parameters. Second, it is explained why a quasi-universal value of the excess entropy of simple fluids at the freezing point should be expected, and it is demonstrated that a remaining very weak dependence of the freezing point entropy on the screening parameter in the Yukawa fluid can be described by a simple linear function. Third, a scaling of the excess entropy with the freezing temperature is examined, a modified form of the Rosenfeld-Tarazona scaling is put forward, and some consequences are briefly discussed. Fourth, the location of the Frenkel line on the phase diagram of Yukawa systems is discussed in terms of the excess entropy and compared with some predictions made in the literature. Fifth, the excess entropy scaling of the transport coefficients (self-diffusion, viscosity, and thermal conductivity) is re-examined using the contemporary datasets for the transport properties of Yukawa fluids. The results could be of particular interest in the context of complex (dusty) plasmas, colloidal suspensions, electrolytes, and other related systems with soft pairwise interactions.

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# DYNAMICS OF DUSTY PLASMA IN A GLOW DISCHARGE IN HELIUM IN MAGNETIC FIELDS UP TO 1.5 T

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For the first time, rotation of dust particles in helium was observed in strong magnetic fields up to 1.5 T. This may be due to the fact that the dust structure is formed not in the striation, but inside the conical insert, which narrows the current channel and stabilizes the discharge. The dust structure rotation velocity was measured in the entire range of magnetic field changes from 0 to 1.5 T. As in neon under similar conditions [1, 2], rotation occurs counterclockwise, if we look in the direction of the magnetic field, in the entire range of its change. However, in this case, the dependence of the rotation velocity on the magnetic field differs significantly from what was observed in neon. We have observed a sharp maximum of the rotation velocity (in absolute value) at magnetic field 0.1 T up to 33 rad/s. Then it quickly drops to 11 rad/s at 0.2 T and continues to drop at a slow pace to 3 rad/s at 1 T. After this, the velocity begins to increase (in absolute value) and reaches 35 rad/s at 1.5 T.

To explain such a dependence of the dust structure rotation velocity on the magnetic field, we performed a calculation based on the assumption of two rotation mechanisms: ion drag and neutral gas drag. The rotation velocity component associated with ion drag can be calculated based on our work [3]. The second mechanism (neutral gas drag) is associated with the assumption of some expansion of the current channel inside the conical insert below its narrowest point (upper end) and the appearance of a radial current component. Nedospasov [4] showed that the radial component of the eddy current in the striation causes the neutral gas to rotate, and along with it the dust particles. We assume the same mechanism of action of the discharge current radial component inside the insert, with the only difference being that it is directed from the discharge tube axis to the wall, while the eddy current radial component in the striation at the level of the dust structure has the opposite direction. With some reasonable assumptions about the nature of the expansion of the current channel inside the insert, it is possible to explain the observed dependence of the rotation velocity of dust particles on the magnetic field.

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# CHANGES IN THE ARRANGEMENT OF DUST PARTICLES AND THE GEOMETRY OF DUST STRUCTURES UNDER THE INFLUENCE OF A MAGNETIC FIELD IN DIFFERENT TYPES OF DISCHARGES

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The magnetic field in the moderate and strong ranges affects the gas-discharge plasma, changing the conditions both in the gas discharge and in the dust trap [1-5]. For example, the geometry of the striation in the positive column of the DC changes significantly, the homogeneity of the 2D of the RFE discharge is disrupted, and in the case of the RFI discharge it can change the nature of the energy input into the discharge [6]. Both directly and indirectly, all these processes affect the geometry of dust structures and their internal structural properties.

The presented report discusses the change in the geometry of dust structures and the order of particle arrangement in them in different types of discharges and a wide range of changes in the imposed magnetic field. It also considers the influence of the dynamics of dust plasma rotation on the studied properties of dust structures, in particular, different mechanisms causing uniform and non-uniform rotation. The values of the parameters at which a significant change in the characteristics of dust structures occurs are noted.

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# ANALYSIS OF DUSTY PLASMA CHARACTERISTICS IN NOBLE GASES AT THE SAME CURRENT AND PRESSURE IN A GAS DISCHARGE TUBE

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The kinetic characteristics of dusty plasma in inert gases in a DC discharge are analyzed. For the case of a discharge in a tube 2 cm in diameter at a gas pressure of 0.33 Torr and a current of 1.5 mA [1], the drift velocity, Townsend energy coefficient, average energy, ionization coefficient, and fraction of energy input into gas excitation and ionization are calculated using the Monte Carlo collision simulation method of many particles. Cases of uniform and stratified discharge are considered. Estimates of the wall potential and plasma density are obtained, and a comparison with the experiment is made.

Usually, in experiments with dusty plasma in a DC gas discharge at low pressure, the positive column is stratified. Therefore, two calculations were performed for each gas: electron drift in a constant homogeneous field [2] and drift in a strongly inhomogeneous periodic field with an amplitude of the order of the average field value [3]. The Table shows the results of the corresponding calculations. For comparison, the values of drift calculations in a homogeneous field are shown in parentheses.

| **Gas** | E, **V/cm** | E/N, **Td** | W, ***km/s*** | $eD_\perp / \mu$ **eV** | $T_{eff}$ **eV** | α/N, **Å²** | φwall, **V** | Ne, **cm⁻³** |
|---|---|---|---|---|---|---|---|---|
| He | 8.5 | 78 | 124(167) | 8.0(7.7) | 5.8(7.3) | 0.067(0.065) | 40(40) | 7.5e8 (5.6e8) |
| Ne | 6 | 55 | 122(137) | 9.1(9.3) | 6.7(7.3) | 0.061(0.056) | 32(32) | 7.7e8(7.2e8) |
| Ar | 4.5 | 41 | 38(40) | 6.9(6.6) | 4.0(4.0) | 0.022(0.010) | 17(17) | 2.5e9(2.4e9) |
| Kr | 7 | 64 | 45(48) | 6.9(5.3) | 3.5(3.5) | 0.069(0.044) | 17(16) | 2.1e9(2.0e9) |
| Xe | 5 | 45 | 26(27) | 4.9(4.8) | 2.8(2.8) | 0.041(0.018) | 13(12) | 3.7e9(3.5e9) |

The main factors influencing the dust subsystem at the same current and pressure, but different gases, are: 1) when the type of gas changes, the value of the average field in the positive column changes; 2) stratification of the positive column greatly affects the characteristics of the discharge; 3) sputtering of the cathode leads to the appearance of metal vapor in the noble gas.

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# EXPERIMENTAL STUDY OF DUSTY PLASMA FORMATION IN A LOW-PRESSURE CAPACITIVE RF DISCHARGE

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A new experimental setup for studying dusty plasma dynamics has been created at the IAP RAS. It has been experimentally shown that using acetylene as a carrier gas for carbon atoms in a low-pressure capacitive RF discharge plasma results in the formation of plasma-dust clouds with dust particles smaller than a micrometer. Using the PIV method, the spatial distribution of the dust microparticles velocity illuminated by a flat laser beam formed by the laser knife system has been measured. The average velocity of dust particles in the plasma has been determined to be about 7 mm/s. Various modes of dust clouds formation have been studied, including the formation of dust voids and self-excitation of dust plasma waves.

The work has been carried out within the framework of the scientific program of the National Center for Physics and Mathematics in the direction 10 “Experimental Laboratory Astrophysics and Geophysics”.

# CHANGES IN THE STRUCTURE OF $BIFEO_3$ NANOPARTICLES UNDER THE INFLUENCE OF MICROWAVE RADIATION FROM A POWERFUL

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The unique properties of ferrite-based nanomaterials are due to the occurrence of size effects during their synthesis [1]. This leads to their peculiar structural changes - lattice constant, compared to massive solid samples [2]. The content of the main phase in the studied BiFeO3 powder is at least 90%. The crystallite size is from 40 to 50 nm. The powder is highly agglomerated, consists of nanoparticles. The size of the agglomerates is from hundreds of nanometers to a micron.

Processing of nano-sized BiFeO3 powders was carried out on the specialized stand using a pulsed powerful gyrotron (microwave radiation power up to 0.8 MW, pulse duration up to 8 ms, frequency 75 GHz) [3]. The conditions for the development of a microwave discharge, and the evolution of process parameters in the reactor are described in detail in [4].

Microwave radiation initiates the development of plasma-chemical exothermic processes in the reactor in air, in which substances of the original powder participate, and the synthesis of new substances occurs with their subsequent cooling (hardening) [5]. During the process, the surface of the powders was heated to (2200 – 1800) ± 200 К [6]. Grains with regular edges, spherical in shape, were formed, most likely, during the liquid phase by recrystallization. As a result, nano-sized particles were transformed into spherical micro-sized particles (up to 100 µm) with a complex structure. On the surface of such particles, inclusions (dark color) in the form of rectangles and polyhedrons with dimensions up to 3 microns are found (Fig. 1). When the particles cooled, cells similar to Bénard cells formed on their surface. The report will also provide the element composition of the resulting material.

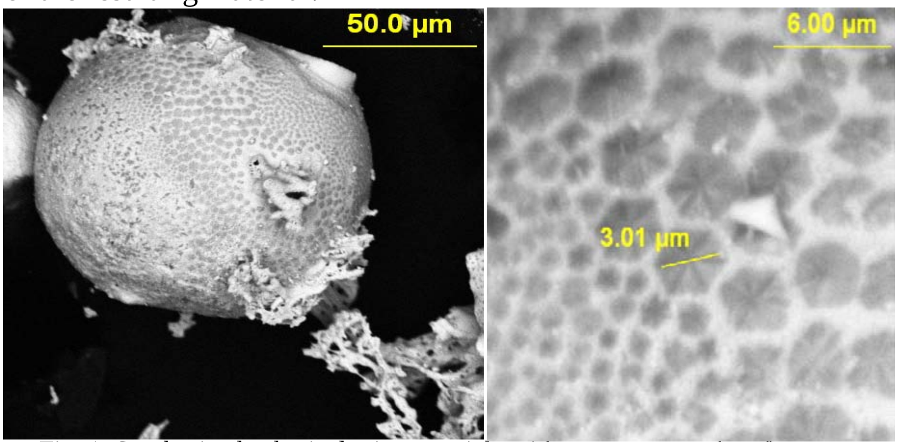


Fig. 1. Synthesized spherical micro-particle with nanostructured surface.

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# ACTIVE BROWNIAN MOTORS IN COULOMB SYSTEMS IN PLASMA, LIQUID AND SUPERFLUID HELIUM

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The work presents the results of experimental study of the dynamics of active Brownian particles in low-pressure plasma, viscous liquid and in superfluid helium.

When laser radiation is applied to charged (Coulomb) Brownian particles of micron size levitating in plasma, viscous liquid or superfluid helium, complex particle motion can be observed if the particles absorb the radiation energy. Such particles can be considered as active Brownian motors whose motion is controlled by radiation, and the mechanism of active Brownian motion itself is associated with photo- or thermophoresis (in plasma and liquid), or with the occurrence of quantum turbulence (in superfluid helium). Active Brownian motors are able to obtain energy from external sources (laser radiation), store it and spend it on their own motion in the medium, which can lead to their self-organization and evolution.

The active Brownian motion of light-absorbing and strongly interacting particles far from equilibrium suspended in a gas discharge under laser irradiation was studied, when the character and intensity of the active motion depend on the effect of radiation. Active Brownian motion has been attributed to photophoresis, i.e., absorption of laser radiation on the surface of a particle creates a radiometric force, which, in turn, sets it in motion. Active Brownian motion of charged particles was experimentally observed during the transition of a monolayer of particles from a crystal-like state to a liquid state [1].

Emulsions of complex composition were experimentally obtained and their dynamics initiated by laser irradiation was studied [2]. The oil-in-water emulsion consisted of monodisperse oil droplets with a diameter of 65 μm containing magnetite nanoparticles with a size of about 10 nm and was placed in an aqueous solution of a surfactant. The experimentally observed active Brownian motion of emulsion droplets was the result of intra-droplet motion of magnetite nanoparticles absorbing laser radiation.

Active Brownian motion and evolution of structures due to quantum effects were experimentally observed for the first time for micron-sized particles levitating in superfluid helium [3]. The active Brownian motion of the particles was induced by quantum turbulence when the particles absorbed laser radiation. The intensity of Brownian motion associated with quantum vortices increased by 6-7 orders of magnitude compared to the values from Einstein's formula. The structures of particles in the state far from thermodynamic equilibrium and their evolution to more complex organized structures with lower entropy were observed.

Thus, the structures of active Brownian motors in the experiments described above in Coulomb systems in plasma, viscous liquid and superfluid helium can be regarded as dissipative structures, i.e. stationary systems, far from equilibrium, in which active Brownian motion, self-organization and evolution are induced by laser radiation.

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# STRUCTURES OF AN ACTIVE COULOMB PARTICLES IN GAS-DISCHARGE PLASMA

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In recent years, active Brownian motion has attracted much interest in physics, biology, and other fields [1-4]. While classical Brownian particles are in thermal equilibrium with their environment, active Brownian particles are able to convert energy from external sources into their own kinetic energy [7, 8]. Thus, the structures formed by such particles are far from thermodynamic equilibrium. Due to the ability to export entropy to the environment, the structures of active Brownian particles show the ability to self-organization and evolution (in the sense of growth of their complexity).

In the present work, we experimentally studied the behavior of single active Brownian particles, small clusters and extended structures formed by them. It is shown that as a result of absorption of laser radiation of different intensities interacting active Brownian particles, small clusters and extended structures formed by them. Brownian particles show the formation of complex dynamics (from random, Brownian, to directed, in particular, vortex motion) and complication of structures [9-12].

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# MOTION OF AN ACTIVE BROWNIAN PARTICLE IN RF DISCHARGE PLASMA IN DIFFERENT DAMPING REGIMES

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Entropy and other tools used within the framework of dissipative systems physics are universal, and they can be successfully applied to study the evolution of active Brownian systems [1]. To study the influence of buffer gas pressure on the dynamics of an active Brownian particle in the plasma of an RF discharge, this paper uses the approach proposed in [2] - the calculation of the mean first-passage time dynamic entropy (mean first-passage time, MFPT). With the help of this approach, one can describe the motion of a single active Brownian particle using several parameters (such as the fractal dimension of its trajectory and the size of the localization area) and compare different modes of motion [3].

The dynamics of a single active particle in a medium is a combination of translational Brownian motion and directional motion combined with random rotation (reorientation); this describes an overdamped mode of particle motion. However, in low-viscosity media, a decrease in the friction force makes the inertial effects important, that can significantly change the dynamics of active particles. In this case, the particle enters the underdamped mode of motion. When all these effects should be taken into account, the particle moves in the transient mode.

An experiment was conducted to study the evolution of active Brownian systems. A voltage with a frequency of 13.56 MHz was applied to an RF electrode with a parabolic shape cavity in argon, creating a RF discharge. Spherical plastic particles with partial molybdenum coating were injected into the near-electrode zone. The particles were charged by electron and ion fluxes and levitated above the center of the electrode. The particle motion was recorded using a high-frequency video camera. During the experiment, the buffer gas pressure in the discharge was varied (1 Pa, 10 Pa, and 30 Pa), influencing the regime of motion of the active particle. The overdamped, underdamped and crossover regimes of motion were obtained. The dependence of the mean first-passage time dynamic entropy on the coarsening parameter, the value of the fractal dimension of the particle trajectories, and its localization area were obtained.

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# DYNAMICS IN THE SYSTEM OF ACTIVE BROWNIAN PARTICLES IN GAS-DISCHARGE PLASMA UNDER EXTERNAL INFLUENCE

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A unique property of active Brownian particles is their ability to convert external energy into their own directed motion [1]. Active particles can be of different kinds and form systems far from thermodynamic equilibrium. One of the most common active systems in nature is colloidal plasma containing charged micro- and nanoparticles [2]. In gas-discharge plasma, such systems of active Brownian particles are able to mass- and energy exchange with their surrounding medium. Also, one of the characteristic properties of metal-coated microparticles is their interaction with surrounding plasma medium [3]. During their stay in the gas-discharge plasma, such particles can absorb the incoming radiation energy from outside and come to active motion [4].

The dynamics in the plasma-dust system of active Brownian particles in a DC glow discharge with a composite cathode (copper, nickel and aluminium) under the action of laser radiation has been experimentally investigated. The formation of active dust particles in the discharge strata due to electrode erosion was observed. The dependence of dispersibility and rate of condensation of active particles on the cathode material used was detected.

For all observation times coordinates of synthesised active particles were obtained and their trajectories were reconstructed. Their main dynamic characteristics were also calculated: velocities, kinetic energies, mean-square displacement (MSD) dependences versus time were plotted.

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# EXPERIMENTAL SIMULATION OF DUSTY PLASMA NEAR AN ATMOSPHERELESS SPACE BODY

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Laboratory simulation of dust plasma is important for understanding physical processes related to the dynamics of charged dust particles in plasma, as well as for designing and preparing space missions to the surface of the Moon and to other atmosphereless bodies of the Solar System. Previous missions to the surface of the Moon have shown that the behavior of charged dust particles of micron and submicron sizes has a negative impact on the operation of scientific instruments, corrupts measurement results.

The study presents a laboratory experiment on creation of charged dust particle flows with diameters from 10 microns to 100 microns from silicon oxide, which is a part of lunar regolith.

The results of such studies can be useful for studying the behavior of charged dust particles near the surface of atmosphereless space bodies. The obtained information can be used in the future for the development of protection against the negative impact of charged dust in space experiments.

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# ELECTROMAGNETIC SIGNATURES OF DUST-INDUCED DISCHARGES IN SIMULATED PLANETARY CONDITIONS

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Electromagnetic discharges in dust storms play a crucial role in planetary atmospheric dynamics, particularly in the thin $CO_2$ -rich atmosphere of Mars [1]. The Electromagnetic Analyzer (EMA) of the Dust Complex (DC) on the ExoMars mission was designed to detect transient electromagnetic pulses associated with charge buildup and breakdown within Martian dust storms [2]. This work presents an experimental investigation conducted under laboratory conditions to simulate dust-induced discharges and validate the EMA frequency range selection [3].

Our experiments were carried out in a vacuum chamber replicating Martian atmospheric pressure with $CO_2$ gas flow at pressures up to 4 bar. Charged desert sand particles were suspended in a 3D-printed discharge chamber, and breakdown events were monitored. The breakdown voltage was recorded and analyzed in the context of Paschen's law. The spectral characteristics of the registered discharges revealed dominant frequency components (Fig.1) within the selected EMA range, confirming theoretical predictions based on pulse rise times (~1-10 μs) and Fourier spectral analysis.

These findings demonstrate that the EMA device is optimized for capturing Martian electromagnetic noise while mitigating terrestrial radio-frequency interference. The results contribute to our understanding of electrostatic and electromagnetic processes in planetary dust environments, enhancing the interpretation of future Mars observations.

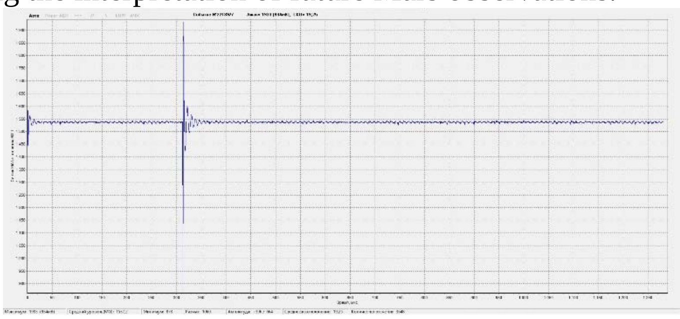

Fig. 1. Electromagnetic Signals Registered from Dust Discharge Events

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# LUNAR DUSTY PLASMA EXOSPHERE: DYNAMICS, LABORATORY SIMULATION AND MEANS OF PROTECTION

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The problem of the dynamics of lunar dust particles and the formation of the Moon’s plasma-dust exosphere is a pressing challenge for researchers and engineers, especially in light of the preparation for manned missions and the development of lunar infrastructure. Contemporary studies require a deep understanding of the mutual influence of the Moon’s plasma-dust environment on spacecraft systems and infrastructure objects, making the investigation of protection methods of utmost importance.

This work examines modern methods for laboratory modeling of dust particle dynamics and dusty plasma behavior, as well as develops techniques for diagnosing and protecting against the negative impacts of dust and plasma. The study includes a detailed analysis of experimental data and the development of protective strategies aimed at enhancing the reliability of equipment operating in the conditions of the lunar exosphere.

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# DUSTY PLASMA IN THE SOLAR SYSTEM: ATMOSPHERES OF PLANETS

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Dusty plasma processes are reviewed for atmospheres of planets. In particular, dusty plasma cloud formation is described in the ionospheres of the Earth and Mars. For this purpose, the self-consistent model [1, 2] of the ionosphere for grain growth, sedimentation, and charging is used. It has been shown that summer conditions in the polar ionosphere, which are characterized by an ambient air temperature below 150 K and presence of supersaturated water vapor, facilitate the formation of dusty plasma structures in the Earth's mesosphere related to noctilucent clouds and polar mesospheric summer echoes. The ionospheric plasma composition can change significantly in the regions occupied by these structures. Depending on photoelectric properties of the grains, their presence may lead to excess, or decrease in, electron number density and complex behavior of ion number density. The model for dusty plasma clouds observed at altitudes of about 100 km in the mesosphere of Mars involves additionally effects of deceleration of dust particles because of the absorption of condensed $CO_2$ substance to them. An altitude distribution of particles constituting mesospheric clouds on Mars has been calculated within the proposed self-consistent model. It has been shown that an important factor for the formation of dusty plasma clouds in the ionosphere of Mars is the Rayleigh-Taylor instability, which limits both the maximum size of dust particles that can form dusty plasma clouds and the maximum thickness of the dusty plasma clouds. Formation of dusty plasmas in the Earth's ionosphere at 80-120 km altitudes during high-speed meteor showers and its detectable manifestations are discussed. Emphasis is given to ground-based observations such as detection of low-frequency (<50 Hz) ionospheric radio noise, ground-based observations of infrasonic waves, amplification of the intensity of green radiation at 557.7 nm from a layer at the 110–120 km altitude in the lower ionosphere [3], and the formation of the periodic structures named dunes, which were observed in the form of a set of almost horizontal stripes of green emission at some altitude in the altitude range of 90-110 km [4]. The physical processes responsible for these manifestations are considered. Dust and dusty plasma play significant role in the atmosphere and ionosphere of Mars. Electrification in dust events such as dust devils and dust storms can presumably lead to electric fields large enough for discharges to take place and for existence of oscillations in the Schumann cavity. The role of dust and dusty plasma in the excitation of the Schumann oscillations on Mars is discussed and comparison with the situation of the Schumann oscillations in the atmosphere of the Earth is provided [5]. The role of dust in the atmospheres of other planets of our Solar system is discussed.

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# DUSTY PLASMA CONDITIONS IN SATURN'S MAGNETOSPHERE

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It is well known that dust particles entering plasma can significantly influence and, under certain parameters, determine the properties of such plasma. The plasma of Saturn's magnetosphere may contain enough dust particles to be considered as the dusty plasma. There are many sources of dust particles in Saturn's magnetosphere. One of these sources may be Saturn's satellites. Among them, Enceladus occupies a special place. An important source of dust particles in Saturn’s magnetosphere is Enceladus, one of the largest satellites of Saturn, known for its ice geysers (ice volcanoes, cryovolcanoes). Dusty plasma in the vicinity of Enceladus was discovered in the Cassini mission. Research in this mission also pointed to its possible reason: the Cassini spacecraft discovered fountains of dust particles and small particles of water ice (which can also be interpreted as dust particles) many hundreds of kilometers high, gushing from four cracks in the area of Enceladus’ south pole.

Plasma in Saturn’s magnetosphere has a number of features differing it from other space systems, the active research of which is currently underway (for the Moon and Mars). For example, measurements of the parameters of electrons in Saturn’s magnetosphere, obtained as part of the Voyager and Cassini missions, showed the coexistence of two types (hot and cold) electrons. It turned out that the velocities of electron populations obey the so-called kappa-distribution.

In this work the dusty plasma is considered in Saturn's magnetosphere at different distances from Saturn. Particular attention is paid to the conditions of the dusty plasma in the vicinity of Saturn's satellite Enceladus. The situations of positive and negative charges of dust particles are investigated. The parameters of dusty plasma are discussed as a function of various environmental parameters, in particular the parameters of electrons obeying the kappa-distribution.

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# ON THE INFLUENCE OF MAGNETIC FIELD ON THE PROPAGATION OF LOW-FREQUENCY NONLINEAR DUST ACOUSTIC WAVES IN THE PLASMA OF SATURN'S MAGNETOSPHERE

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For the conditions of dusty plasma in Saturn's magnetosphere, consisting of ions satisfying the Boltzmann distribution law, two types of electrons (cold and hot, obeying the κ-distribution) and charged dust particles, we have considered the situation of low frequencies not exceeding the dust Larmor frequency. For this situation, the nonlinear Zakharov–Kuznetsov equation for dust-acoustic perturbations has been obtained, which distinguishes it from the situation, when the gyrofrequency of dust particles is so small that the frequencies of dust acoustic waves significantly exceed it, and, e.g., in the two-dimensional case, nonlinear dust-acoustic perturbations are described by the Kadomtsev–Petviashvili equation. The situation considered also differs from the situation of nonlinear dust-acoustic waves in dusty plasma in Moon's exosphere, when the role of particles captured by the wave is large and the nonlinearity in the Zakharov–Kuznetsov equation is nonanalytic. In the situation of Saturn's magnetosphere considered here, the role of κ–distributions characterizing electrons is not so important and, therefore, the resulting nonlinear equation turns out to be the classical Zakharov–Kuznetsov equation.

In this work, partial solutions of the Zakharov–Kuznetsov equation have been found in one-dimensional and three-dimensional spherically symmetric cases. It has been shown that the characteristic spatial size of solitons strongly depends on the direction of propagation of solitons with respect to the direction of the magnetic field. In the case of one-dimensional solitons, the larger the angle, the larger the characteristic width of the soliton. In the case of a threedimensional soliton propagating along a magnetic field, the characteristic transverse size greatly (thousands and sometimes hundreds of thousands of times) exceeds its longitudinal size.

As for possible observations of the considered solitons in future space missions, despite their small (but finite) amplitudes, such observations in Saturn's magnetosphere are apparently possible, as indicated by observations of lower hybrid solitons in Earth's magnetosphere in the FREJA experiment. To carry out such observations by future spacecraft aimed at Saturn, equipment similar to that located on the FREJA spacecraft is needed, which allows high-precision measurements of electric fields in outer space.

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# NONLINEAR DUST ACOUSTIC WAVES NEAR THE SURFACES OF PHOBOS AND DEIMOS

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Phobos and Deimos are atmosphereless cosmic bodies with weak gravity. Their surfaces consist of small grains of regolith unbound to each other, formed as a result of micrometeoroid bombardment. The presence of weak gravity makes these objects attractive for manned flights, and also enhances the role of dust, since even a weak disturbance leads to the formation of a massive dust cloud above the surface. The surfaces of the satellites of Mars are charged by the electromagnetic radiation of the Sun and the plasma of the solar wind. When interacting with solar radiation, the surfaces of Phobos and Deimos emit electrons due to the photoelectric effect, which leads to the formation of a layer of photoelectrons above the surface. The appearance of photoelectrons also results from their emission by dust particles present above the surface, due to the interaction of the latter with electromagnetic radiation of the Sun. Dust particles located on the surface or in the near-surface layer absorb photoelectrons, photons of solar radiation, electrons and ions of the solar wind. All these processes lead to the charging of dust particles, their interaction with the charged surfaces of Phobos or Deimos, the rise and movement of dust. In this regard, the study of dusty plasma near the surface of Phobos and Deimos is of great importance. In this system the propagation of dust acoustic waves is possible, the excitation of which (and the formation of nonlinear wave structures) can, for example, occur in the vicinity of the terminators of the satellites of Mars. We study the corresponding nonlinear solutions in the form of solitons and periodic dust acoustic waves.

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# DUSTY PLASMAS AT ACTIVE ASTERIODS

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The dusty plasma system in the vicinity of an active asteroid is considered. It is demonstrated that during the formation of a dusty plasma system in the vicinity of an active asteroid, not only electrostatic interactions are important, but also processes associated with the gas flow from areas of the asteroid surface containing water. In this case, it turns out to be possible to interpret micrometer-sized dust gains as the particles levitating above the surface of the asteroid. Fine (nano-sized and submicron) particles do not become levitating and are carried away by the gas flow from the surface of the asteroid. The behavior of dust particles in the near-surface layer of an asteroid is described by equations characterizing their dynamics and charging [1]:

$$m_d \frac{d^2 r_d}{dt^2} = q_d E + m_d g_0 + F_{fg}, \tag{1}$$

$$\frac{dq_d}{dt} = I_e(q_d) + I_i(q_d) - I_{ph}(q_d) + I_{e,ph}(q_d), \tag{2}$$

where $F_{fg}$ is the force acting on a dust particle from the side of gas flow, the direction of this force coinciding with the direction of the gas flow, and the absolute value being determined by the Epstein formula [2]: $F_{fg} = \left(\frac{4}{3}\right)\pi a^2 n_s m_{(H_2O)} u_s^2$.

It is shown that the specific features of the formation of the plasma-dust system above the surface of an active asteroid (in comparison with the typical atmosphereless cosmic bodies such as the Moon, Mercury, the satellites of Mars, etc.) are mainly associated with two factors, the influence of water and the influence of the processes of interaction of dust with the gas flow. At the same time, water can have a certain effect on the plasma-dust exosphere above the surface of an ordinary (non-active) asteroid.

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# LASER SOURCES OF HIGH ENERGY PARTICLES AND RADIATION

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Intense beams of photons and particles in the MeV energy range are effective tools in many areas of research, such as the creation and diagnostics of matter in extreme states, nuclear physics and materials science, as well as in other applications. Various processes of laser-plasma acceleration of electrons are considered, starting with the mechanism of wakefield acceleration in the regime of self-modulation of a laser pulse [1].

A more efficient concept for creating sources of γ-radiation and neutrons based on the generation of relativistic electrons in the regime of direct laser acceleration is currently being discussed. PW-class laser systems capable of generating sub-picosecond and femtosecond pulses focused to ultrarelativistic intensity, are good candidates for creating high-current beams of ultra-relativistic electrons in an extended plasma with a density close to critical [2, 3], which was confirmed in experiments [4].

The dependences of the parameters of laser-generated electron bunches on the laser radiation intensity and plasma density for subpicosecond and femtosecond laser pulses are obtained and analyzed taking into account current and future experiments [4, 5, 6]. The results obtained indicate a way to improve the efficiency of a wide class of secondary laser sources, such as sources of electrons, positrons, betatron and bremsstrahlung radiation [7], and sources of protons and neutrons for various purposes [8, 9].

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# HIGH CURRENT RELATIVISTIC ELECTRON BEAMS FOR BRIGHT X-RAY AND GAMMA-RAY SOURCES

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Action of sub-petawatt and petawatt laser pulses on long length near-critical density plasma obtained by supersonic ionization of low-density aerogel foams can lead to production of high current relativistic electron beams with charges up to several mkC for electrons with energies higher than several MeV [1,2]. Sunch beams can generate bright fluxes of high energy X-ray or gamma ray photons due to betatron radiation [3] and (or) also due to bremsstrahlung [2] when passed through metallic foil. Using theoretical analysis and numerical simulations (see Fig. 1), we investigate the possible optimisation of laser and plasma parameters in order to maximize the number of generated high energy photons and discuss the respective requirements and scalings, including scalings for electrons energies and charges [3,4].

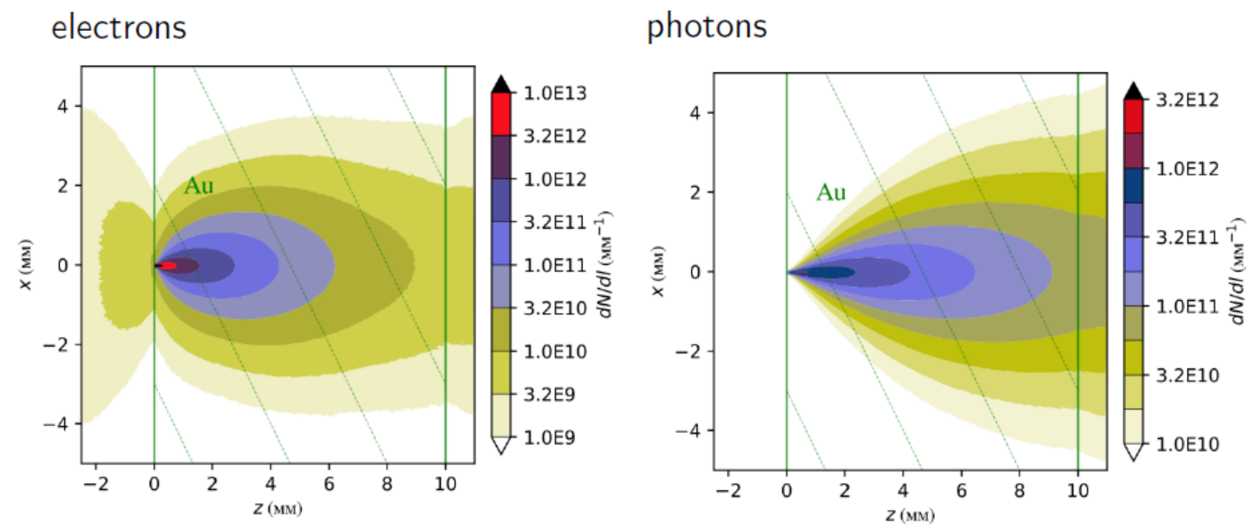


Fig. 1. Spectra of electrons and gamma–rays on the back side of Au converter for differentconverter thicknesses z, for PHELIX [1] laser installation, GEANT4 and PIC simulations [5],laser energy $W_L = 17.5$J, intensity$I_L = 2.5\ 10^{19} W/cm^2$, duration $\tau_L = 700$ fs, laserspotsize$D_L = 15 \times 11\ \mu m$, relation of electrons concentration to critical one $n_e/n_c = 0.65$.

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# GENERATION OF ELLIPTICALLY POLARIZED RADIATION BY GAS MEDIA IN TWO-COLOR LASER FIELDS

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High-harmonic generation in gaseous media interacting with intense laser fields is one mechanism for obtaining coherent short-wavelength radiation [1]. Such radiation, possessing elliptical polarization, opens up opportunities for studying the magnetic and polarization-sensitive properties of matter [2]. At the same time, the nonlinearity of the radiation generation process dictates the need to develop methods for controlling the polarization properties of generated high-order harmonics. Moreover, such methods must take into account the peculiarities of the nonlinear optical response of the medium at both the microscopic (atomic) and macroscopic (propagation effects) levels of description of such interaction, including under conditions of phase and quasi-phase matching [3].

Here we present the results of our research on the generation of coherent elliptically polarized radiation in gaseous media through interaction with two-color laser fields, composed of the fundamental and second harmonic of a laser source. This work examines the cases of both linearly and circularly polarized components within these fields. Furthermore, we propose techniques for controlling the polarization state of the resulting radiation.For this study, we have used the interference model presented in [4] and non- perturbative theory of the single-atom response calculation discussed in [5].

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# NONLINEAR RESPONSE OF ATOMIC GASES: ANALYTICAL TREATMENT IN THE FRAME OF THE NON-PERTURBATIVE APPROACH

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The nonlinear susceptibility of a medium is a necessary parameter of the traditionally used propagation models of laser radiation (FME, UPPE, NLSE, etc.) [1], which make it possible to theoretically study various experimentally observed nonlinear optical laser-matter interactions. The nonlinear susceptibility of a medium is determined, in general, phenomenologically, by matching the theoretical model with the obtained experimental data [2-4].

The quantum-mechanical non-perturbative approach [5] is used to calculate gaseous medium polarization. This method does not suffer from the limitations of perturbation theory and takes into account all laser field orders of interaction between a laser field and an atom. Through the natural expansion in the laser field of the matrix elements contained in the medium polarization, the analytical expression is obtained for the nonlinear susceptibility of an arbitrary order of a gaseous medium, which is essential for calculating the nonlinear polarization present in each model of laser radiation propagation. The proposed approach can be combined with experimental studies in order to search for promising gaseous media, including synthetic, with the improved efficiency of higher-order harmonic generation and with the wider generated spectrum.

The transition from domination of a single nonlinear susceptibility term at a given harmonic to comparable contributions of multiple high-order susceptibilities at mid-infrared wavelengths is observed. The laser intensity, at which this transition occurs, decreases with the laser wavelength. However, the direct channel remains predominant over the cascade one through the nonlinear susceptibilities of a lower order.

Analytical expression for the nonlinear susceptibility derived here are valid only in the case of low excitation of the ground state by the laser field. Otherwise, obtaining the same clear expressions seems to be a sophisticated and even unfeasible task. Then numerical solution of the dynamics equations for energy level populations solves the problem, but only a harmonic signal (consisting of a number of frequency components) can be retrieved. The numerical approach provides an opportunity to study the nonlinear properties of a gaseous medium in cases of resonant excitation or when a medium is irradiated with a two-color laser field, including the case of two mid-infrared fields and the case of a mid-infrared + terahertz field.

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# FEATURES OF THE FORMATION OF PERIODIC SUBWAVELENGTH MICROSTRUCTURES IN THE PROCESS OF FEMTOSECOND LASER WRITING IN THE VOLUME OF SOLID DIELECTRICS

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In this work we perform 3D self-consistent numerical simulations of a focused laser pulse exposure in fused silica volume. The model combines the second-order wave equation solution with the rate equation for the electrondensity in the conduction band. Our results indicate that a dense plasma formation near the focal plane effectively scatters and reflects the laser pulse. The coherent interference between the incident and scattered laser waves creates regions of intense field ionization, resulting in periodic plasma nanostructures along both the $\rho$- and $z$-axes [1,2]. We also examine the impact of Kerr nonlinearity, which leads to pulse self-focusing.

The effect of electrondefocusing on the laser beam propagation can be observed in Figure 1, which shows the dependence of the mean radius of the laser pulse during its propagation for different pulse intensities. We calculate this radius, using the following formula:

$$\langle\rho(t)\rangle = \frac{\int E^2(\rho,z,t)\rho^2 d\rho dz}{\int E^2(\rho,z,t)\rho d\rho dz}. \quad (1)$$

Black curve corresponds to the low energy pulse propagation in the absence of dense plasma formation. It can be seen that an increase of pulse energy leads to increase in the observed beam size and a shift in the position the focal plane (minimum value of $\langle\rho\rangle$). The effect of pulse focusing due to the Kerr effect can be also observed in Fig.1, but its role is insignificant. The calculations showed that the role of cubic nonlinearity is more pronounced at a 515 nm wavelength, which allows obtaining higher electron densities in the near-focal region.

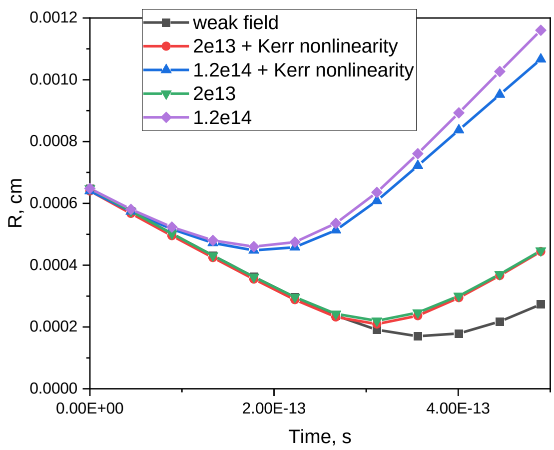


Fig. 1. The radial size of the pulse $\langle\rho\rangle$ during its propagation for different pulse intensities with and without accounting Kerr nonlinearity. Time scale corresponds to the pulse movement from the initial point ($z_0 = 75$ mkm) to the focal plane ($z_f = 0$). Plasma-free focal spot radius is $\rho_0 = 2.5$ mkm, pulse duration is 50 fs.

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# CONTROLLED LASER MICROSTRUCTURING IN THE VOLUME OF TRANSPARENT SOLID DIELECTRICS

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In recent decades, there have been significant efforts to study the key features of microscale surface and volumetric modifications of dielectric materials caused by focused femtosecond laser pulses.Subsequent studies on the physics of volume nanograting formation carried out by several scientific groups have revealed several main mechanisms. These include electron plasma wave coupling with incident light waves,formation of nanoplasmas due to local field enhancements, followed by self-ordering into nanoplanes,and ultrafast self-trapping of exciton-polaritons.

Recently, a new concept of volume nanograting formation was first introduced [1] and then studied numerically and experimentally in [2-4]. This method proposes the interaction of incident and reflected(scattered)light waves in the prefocal area of the beam (within the duration of a laser pulse), generating a standing wave and the corresponding ionization wave in the material. In the listed works the reflected wave was formed by denseprefocal plasma. Due to the fact that this plasma canbe of anyshape, the reflected wave is not plane and,therefore,the resulting nanogratinghas a complexgeometry. What is more, prefocal plasma formation requires high powers.

The idea of this work is to placean opaque metal layer at the dielectric-air interfacebehind the laser beam focus areawhich provides effective reflection of the laser radiation, thus forming a standing wave of ionization and eliminating the need for dense focal plasma formation. The ionization occurs in bundles of standing wave, forming a plasma lattice with a period that is equal to the period of the standing wave in the medium. At the end of the laser pulse, areas with a different refractive index form in the material at the site of plasma formations. Numerical modeling allows us to identify the conditions under which this nanostructuring process can occur.

We propose a simple theoretical model describing the reflection and formation of plasma structures depending on the relative position of the metallic wall and the focal plane, thereby changing the intensity of the interference pattern.

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# COUPLING OF WEIBEL MODE AND PLASMA WAVE IN RELATIVISTIC LASER PLASMA INTERACTION

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Stream instabilities arising from an anisotropic electron velocity distribution function (EVDF) are analyzed within the optical-field ionization mechanism of a monatomic dilute gas irradiated by a circularly polarized laser beam in a fully relativistic regime. It is demonstrated that a relativistically rotating electron beam is generated by the interaction with the circularly polarized laser field. Before collisions thermalize the electrons, the plasma undergoes Buneman and Weibel instabilities following ionization. These instabilities are shown to propagate with wave vectors **k** perpendicular to the streaming direction.

The theoretical analysis reveals that at the threshold of the relativistic regime, the instabilities are aperiodic and evolve independently. However, as the laser intensity increases , the two instabilities become coupled. This coupling process enhances the growth rate of the Weibel instability while reducing the growth rate of the Buneman instability.

# ADVANCED LASER MODE STRATEGIES FOR ENHANCED ELECTRON ACCELERATION IN NONLINEAR PLASMA WAKE

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Laser wakefield acceleration (LWFA) is a promising technique for compact accelerators due to its high gradients. High-quality electron beams can be produced in the "bubble" regime, where a high-intensity laser pulse propagating through low-density plasma generates GeV-scale beams over centimeters [1]. Techniques like colliding pulse, density gradient, and ionization injection have improved electron injection stability [2-4]. However, challenges remain in increasing charge and controlling beam parameters such as emittance, dark current, and energy spread. Achievable charge depends on factors like beam loading, propagation length, and pulsedefocusing. While increasing laser spot size or reducing plasma density can enhance charge, these methods face limitations, such as higher laser power requirements. Alternatively, multiple co-propagating pulses have been explored to increase charge [5,6].This report introduces a novel approach using Hermite-Gaussian laser pulses to enhance electron bunch charge in the nonlinear regime. Simulations compared Gaussian and first-order Hermite-Gaussian pulses with identical initial energy: 30 fs duration, 0.8 μm wavelength, normalized vector potential $a_0 = 4$, and spot size $w_0 = 18$ μm. The plasma had a 50 μm density ramp leading to $n_0 = 6 \times 10^{18}$ cm$^{-3}$. The simulation window, moving at light speed, measured 70 μm longitudinally and 120 μm transversely, with a 1250 × 200 grid and four macroparticles per cell. Fig. 1(a) compares energy spectra for both pulse types.It is evident that, in the case of the Hermite pulse, not only have the electrons been accelerated to higher energies, but the amount of charge injected from the plasma background has also increased. Fig.1 (b), shows the θx distribution at t = 3.09 ps, where $\theta x = \tan^{-1}(P_x/P_z)$ represents the x-dimension inclination angle, with $P_x$ and $P_z$ being the particle momentum in the transverse and axial directions, respectively. As can be seen from the figure, the number of particles moving approximately parallel to the axis, i.e., those with small |θx| values, is higher for the Hermite-Gaussian pulse.

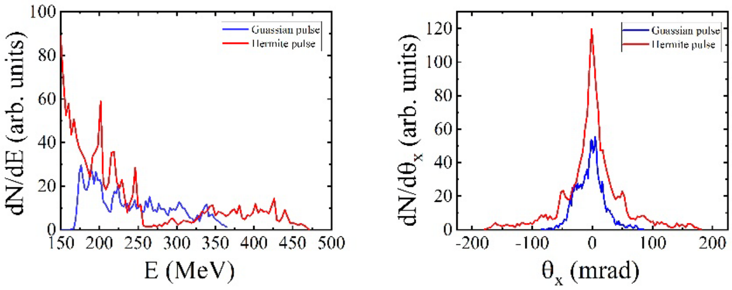


Fig. 1. (a) Energy spectrum, (b) θx distribution of the self-injected electron bunch at t = 3.09 ps. The red and blue curves correspond to the first-order Hermite pulse and the Gaussian pulse, respectively.

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# RESONANT INTERACTION OF POWERFUL LASER RADIATION WITH PLASMA AT DOUBLE UPPER HYBRID FREQUENCY

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A strong external magnetic field can have a significant effect on the development of parametric instabilities during the interaction of powerful laser radiation with plasma [1]. At the same time, under resonant conditions, a laser wave can transmit significant energy to plasma electrons [2]. The study of such an interaction for laser radiation at an upper hybrid frequency was carried out in [3] using one-dimensional particle-in-cell simulation. It has been shown that a laser wave of extraordinary polarization transforms into an electrostatic mode when passing through the upper hybrid resonance region. Such an electrostatic wave translates its energy into the kinetic energy of electrons. This report presents the results of a numerical simulation of the interaction of a laser wave with a plasma layer in the resonance region at twice the upper hybrid frequency. This heating method is often used in tokamaks and in other systems with magnetic plasma confinement. The decisive role in this case is played by parametric decaying processes. However, due to a significant difference in the radiation power and radiation frequencies, these processes for laser heating in a strong magnetic field can be greatly changed, due to the influence of nonlinear effects and relativism. Modeling was carried out using an electromagnetic relativistic PIC code. Numerical experiments show that when a certain threshold value of the amplitude is reached, stimulated combination scattering of laser radiation in the resonance area is excited. With amplitudes much smaller threshold, Bernstein electrostatic modes arise. When a pulse passes from the smaller magnetic field, a reflected electromagnetic wave occurs at the upper hybrid frequency. A similar wave was observed in the work [4] when heating the plasma in the tokamak at a doubled upper hybrid frequency. In this case, threshold values for the amplitude of microwave radiation could be reduced by locking daughter waves in the resonance region [5]. From the results of the modeling presented in this report it follows that, as the initial laser pulse amplitude increases, the energy of the electrostatic field of the upper hybrid plasmons grows. This leads to an increase in the efficiency of transmitting the energy of radiation to the electrons of plasma. It was shown that the energy set of electrons is significant only on condition that the cyclotron frequency is close to plasma and slightly exceeds it. In the case of a high excess of the cyclotron frequency relative to the plasma fraction of the transmitted energy, it was significantly reduced. With the growth of the magnetic field gradient an increase in the threshold value was observed. For large radiation amplitudes, a self-modulation of the reflected wave arose with the subsequent formation of cascade modes.

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# NONLINEAR SCATTERING OF A FEMTOSECOND LASER PULSE ON A DENSE, SMALL-SCALE PLASMA

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When the amplitude of the laser field is significantly larger than the internal fields of the target, the characteristic time of the velocity change of the scattering electron ceases to be estimated by the laser period and becomes very small in the relativistic case, producing ultrashort pulses of the scattered field with an interval of half the laser period between them [1]. Some of the electrons leave the laser target and are accelerated by the laser field, which is accompanied by intense secondary radiation. For targets whose dimensions are less than half the wavelength of the laser radiation, all electrons of the target are affected by a laser field of the same sign, so that the secondary radiation of such targets resembles the radiation of a single electron, except for the duration of the scattering pulse. In this work, we numerically investigate the angular and temporal properties of the secondary coherent radiation produced by the scattering of relativistic linearly polarized laser pulses from spherical targets with a radius of 0.25 – 0.5 μm consisting of liquid argon. The EPOCH code [2] with 3D geometry was used for the calculations; the degree of argon ionization was calculated in the code in a self-consistent manner.

Fig. 1 shows the density of hot electrons in the cluster, whose distribution is determined by the nature of the electron trajectories. Fig. 1a shows that the main factor forming the electron trajectory is the laser wave field.

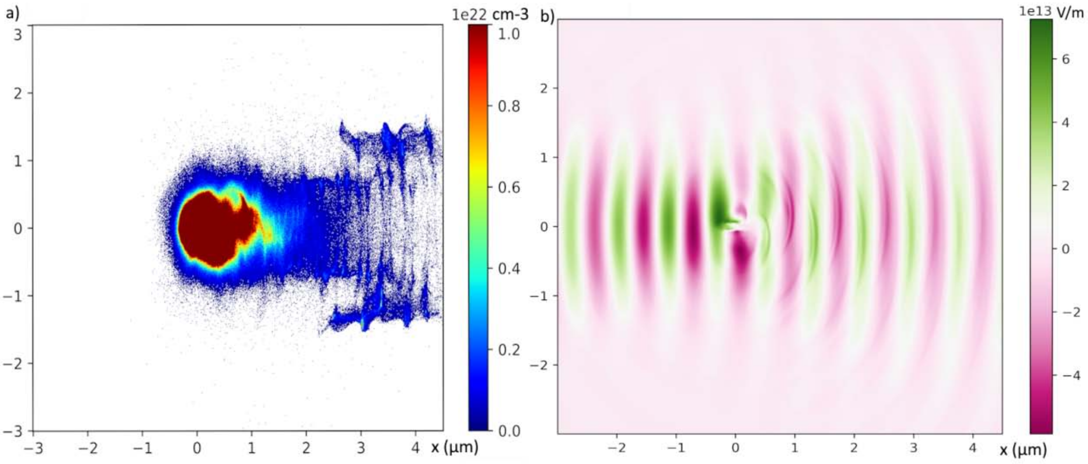


Fig. 1.2D cross-section of the spatial distribution of a) the density of hot electrons (E>1 MeV) of an Ar cluster with a radius of 250 nm.Intensity 1020 W/cm2; b) the electric field components of the laser and the scattered fields. Time – 60 fs from the moment the laser pulse hits the cluster.

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# MODELING OF ELECTRON ACCELERATION PROCESSES IN DENSE PLASMA UNDEER THE ACTION OF A RELATIVISTIC LASER PULSE WITH AN INTENSITY OF $10^{22}$ W/CM$^2$

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Laser Wakefield Acceleration (LWFA) [1] and Direct Laser Acceleration (DLA) [2] are two different mechanisms for accelerating electrons in subcritical density laser plasma. LWFA uses a wake wave excited by a laser pulse in the plasma. The DLA mechanism accelerates electrons in an ion channel that the laser pulse breaks through in the plasma or plasma bubble due to betatron resonance.

In this paper, the effect of plasma density on electron acceleration under the action of a laser pulse with an intensity of $10^{22}$ W/cm² is investigated using PIC code EPOCH [3]. As a target we used fully ionized argon (gas density of $10^{19}$-$10^{22}$ cm$^{-3}$). Fig. 1 shows the electronic spectrum for the range of densities considered in the simulation.

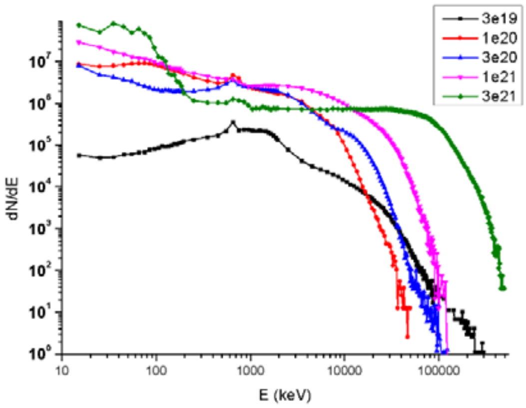


Fig. 1. Electron spectra depending on plasma density

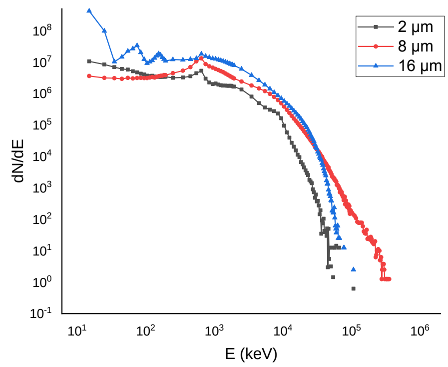


Fig. 2. Electron spectra depending on the laser pulse radius

In the study, the dependence of laser pulse absorption on plasma density was examined. We determined electron spectra and angular distributions. Fig. 2 shows the electron spectrum depending on the laser pulse radius. For a plasma density of $10^{20}$ cm$^{-3}$, the dependence of the beam intensity of the initial radius of the laser pulse was analyzed, and how the pulse radius changes over time was determined.

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# SPATIOTEMPORAL GOOS-HÄNCHEN EFFECT ATA LASER PULSE REFLECTION FROM BOUNDARY OF SUPERCRITICAL PLASMA

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When a light beam of finite width is incident on the boundary of an optically dense medium, its reflection takes place, which is accompanied by the lateral shift of the beam relative to the position determined by geometric optics. This phenomenon was called the Goos-Hänchen (GH) effect. If we consider the incidence of an optical pulse with finite time duration on a matter, then together with the lateral spatial shift of the reflected pulse, we can expect the appearance of a temporal analogue of the GH effect, namely, the time delay of the reflected pulse.

In this article, we consider the incidence of *s*- and *p*-polarized laser pulse on the boundary of supercritical plasma and show that, in addition to the lateral spatial shift, the reflection of the pulse is also accompanied by its time delay, and this time delay can significantly exceed the period of the laser field. The dependence of the delay time on the incidence angle of the laser pulse, its polarization, and plasma density is studied. It is shown that in a sufficiently dense plasma, the delay time of the reflected pulse is always less than the period of laser radiation. If the electron density is close to the critical value, then the delay time can be equal to several periods of the laser fieldoscillations, but does not exceed its duration. It is shown that thetime delay of the reflected*s*-polarized laser pulseis maximum,for its normal incidence. When a*p*-polarized laser pulse is reflected, the maximum value of the delay time depends on the plasma density. The time delay of the reflected *p*-polarized pulse is maximum forthe grazing incidence in dense plasma and forthe small incidence angles in near-critical plasma (Fig.1).

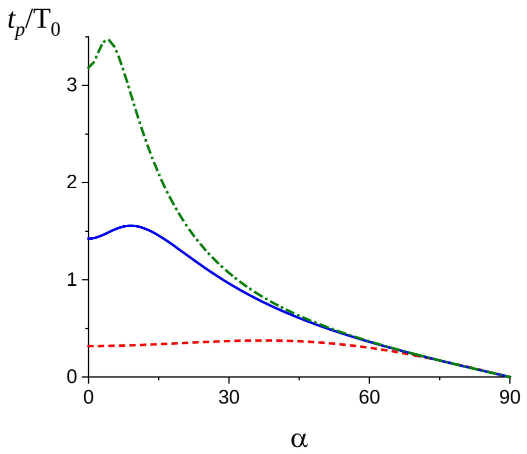


Fig. 1.The delay time of the reflected *p*-polarized laser pulse ($t_p$) as the function of the incidence angle αfor various electron densities, where $T_0$ islaser period. Dashed, solid and dash-dotted curves correspond to the following values of the dimensionless electron density$N_{0e}/N_{cr}$=2, 1.1, 1.01,where$N_{cr}$is critical density.

It should be noted that the time delay of the reflected laser pulse is due exclusively to the dependence of the plasma permittivity on frequency, and this effect is absent for media with a constant refractive index.We note once more that the time delay of the reflected pulse is explained by the fact that the laser pulse is not reflected at the boundary, but penetrates deep into the plasma to the depth of the skin layer. That is, the time during which the laser pulse travels the distance of the order of the skin depth determines the time delay of the reflected pulse. The important feature of the time delay of the reflected laser pulse is that it has the maximum value at almost normal incidence, when the lateral shift is very small value.

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# INVESTIGATION OF EXTREME MATTER STATE WITH ENERGY DENSITY ~ 1 GJ/CM$^3$ GENERATED BY ULTRA-RELATIVISTIC LASER PULSES

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Nowadays, the study of nature and properties of plasma formed under the influence of ultra-intense laser pulses is of great interest, both from the point of view of fundamental knowledge about the nature of our universe and from the point of view of practical application as a powerful emission source of X-ray, gamma and corpuscular radiation in medicine and applied problems. Plasma formed under the influence of high-contrast laser radiation with an intensity of ~ $10^{21}$ - $10^{22}$ W/cm$^2$ is characterized by short lifetimes of ~ 1 - 3 ns in the extreme state, high energy densities and temperatures of the order of 2-5 keV. One of the most important approaches for investigating the extreme matter state and its emission properties is X-ray spectroscopy with high spectral resolution. It enables the measurement of the most important plasma parameters, the estimation of the degree of ionization and the efficiency of energy conversion into X-rays (energy 0.5–25 keV, wavelength range 0.5–19 Å) and the investigation of various nonlinear effects that occur in ultra-relativistic laser plasmas. In this work, the results of the application of X-ray spectroscopy approaches to the study of steel foil plasmas(atomic number Z = 26) generated by femtosecond laser pulses with an intensity of $\geq 5 \cdot 10^{21}$ W/cm$^2$ are presented. The aim of the experiment was to investigate the emission properties of plasma during the interaction of thin 5μm steel foils with femtosecond high-contrast pulses of sub-PW power. X-ray focusing spectrometers (FSSR) [1]based on spherically curved alpha quartz crystals were used to measure the plasma parameters. A comprehensive analysis of the X-ray emission spectra measured in the experiment with high laser contrast showed the effect of relativistic broadening of the laser plasma [2]. The possibility of the formation of a plasma with an energy density of ~ 1.2 GJ/cm$^3$ and a pressure of 12 Gbar in the interaction region was demonstrated [3].

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# GENERATION OF X-RAY ATTO-PULSES IN LASER PLASMA AND ITS AMPLIFICATION BY XFEL

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Recently the generation of multi-KeV photon pulses of ultra-short duration in laser plasma [1-4] and its amplification [5] with help of XFEL was considered, where interacting relativistic electron bunches can be produced by standard accelerator or Peta-watt laser. The investigations were done with help of analytical modelling and numerical simulations by EPOCH and PUFFIN codes [6,7].

In this research, with the similar technic, we investigated a wider parameter range, at which generation and significant amplification of ultrashort pulses with duration up to a few atto-second can be realized. In particular, we modelled the process of amplification of ultrashort X-ray Gaussian pulse of duration $\tau_a$ = 4 as by electron bunch of the length 0.3 micron and charge $10^{-11}$ C, with electron energy 1.5 GeV propagating in the undulator with the number of periods (of length $\lambda_w$ =1.7 cm) N = 120 and magnetic field $a_w = eH\lambda_w / m_e c^2 = 0.75$. The results of the simulations have shown the possibility of the amplification of the normalized amplitude of electric field of incoming ultrashort pulse $a = eE\tau_a / 2\pi mc$ up to the order of magnitude, from $a = 10^{-3}$ till $a \sim 10^{-1}$ at almost keeping of its short duration, because after amplification pulse duration was about 6 as. Analytical estimations of the duration of the amplified pulse on the base of harmonics expansion and the known amplification increment for any monochromatic component gave the result close to the simulation data. It was also shown, that for significant amplification of all harmonics cooperating ultrashort pulse, electron bunch should have big enough energy spread and small angular divergence (emittance) about a few $nm \cdot rad$ .

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# FORMATION OF HIGH-ASPECT-RATIO NANOCAVITY IN LIF CRYSTAL USING A FEMTOSECOND OF X-RAY FEL PULSE

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Sub-picosecond optical laser processing of metals is actively utilized for modification of a heated surface layer. But for deeper modification of different materials a laser in the hard x-ray range is required. Here, we demonstrate that a single 9-keV x-ray pulse from a free-electron laser can form a µm-diameter cylindrical cavity with length of ~1 mm in LiF surrounded by shock-transformed material [1]. The plasma-generated shock wave with TPa-level pressure results in damage, melting and polymorphic transformations of any material, including transparent and non-transparent to conventional optical lasers. Moreover, cylindrical shocks can be utilized to obtain a considerable amount of exotic high-pressure polymorphs. Pressure wave propagation in LiF, radial material flow, formation of cracks and voids are analyzed via continuum and atomistic simulations revealing a sequence of processes leading to the final structure with the long cavity. Similar results can be produced with semiconductors and ceramics, which opens a new pathway for development of laser material processing with hard x-ray pulses.

[1]. https://doi.org/10.48550/arXiv.2409.03625

# FANO RESONANCE IN HIGH-ORDER HARMONIC GENERATION AND ITS CLASSICAL ANALOGY

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High-order harmonic generation (HHG) of intense laser field is a promising tool to obtain coherent extreme ultraviolet radiation (XUV) in femtosecond or attosecond time domain [1]. However, the typical efficiencies of the HHG process remain below the level required for many applications. One of the ways to increase the efficiency is using resonances of the generating particles. A very pronounced resonant enhancement of HHG was observed in plasma plume and in xenon. Moreover, resonant features were also observed in XUV generated in argon and helium. In these studies they observed enhanced generation of XUV with frequency close to the frequency of a transition from an autoionizing state (AIS) to the ground state of the generating atom or ion. Several theoretical approaches were suggested to describe this phenomenon. In particular, paper [2] generalizes the non-resonant HHG theory [3] to the case when the generating particle has an AIS. It was shown that the XUV spectrum emitted by such a system is a product of the non-resonant spectrum and the resonant factor, similar to the one found by Fano [4]

In this paper we integrate numerically the Schrödinger equation for the model helium atom irradiated by intense few-cycle laser pulse and find the emitted XUV spectra. They demonstrate resonant peaks at the frequencies of transitions from the doubly-excited AIS to the ground state. We study [5] the properties of these peaks depending on the laser pulse duration and find that the decay of the AISs due to photoionization by the laser field affects them. Moreover, we consider the classical system of two coupled oscillators and find that both the quantum (the atom with AIS in the field) and the classical (the coupled oscillators with friction) systems demonstrate Fano-like resonant peak described by an essentially complex asymmetry parameter. We find a remarkable similarity in the behavior of these systems and conclude that the classical system of coupled oscillators with friction is an analogy of the AIS having an extra decay channel in addition to the autoionization one.

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# EFFECT OF SHORT WAVELENGTH PUMPING IN HIGH HARMONIC GENERATION BY GALLIUM IONS IN LASER FIELD

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Over the last few years, convincing experimental evidence has been obtained for the enhancement of individual harmonics in high-order harmonic generation (HHG) by intense laser radiation in plasmas produced on the surface of metal targets [1]. The enhancement is explained by multiphoton resonance at a strong transition from the ground state of the ion to the autoionization state (AIS) [2]. Theoretical confirmation of the resonance mechanism requires the use of a realistic model of the atomic system that takes into account its spectroscopic structure.

We report the results of a theoretical study of HHG by a Zn-like $Ga^+$ ion irradiated by a laser pulse with parameters that yielded impressive enhancement of the seventh harmonic (7H) intensity in measurements with a gallium plasma target [3]. In previous calculations [4], an approach based on the expansion of the solution of the time-dependent Schrödinger equation in a limited basis of discrete states of the free ion was used. The obtained effect of the enhancement of 7H relative to neighboring harmonics at its resonance with the excitation energy of the AIS $3d^9 4s^2 4p$ from the closed inner shell 3d of the ground state at the laser wavelength $\lambda_L$ = 397 nm turned out to be much weaker than that observed experimentally. In this regard, the expansion basis was significantly expanded by adding highly excited discrete states and the continuum states of the $Ga^+$ ion. However, this did not eliminate the significant discrepancy between the calculated results and the experimental data.

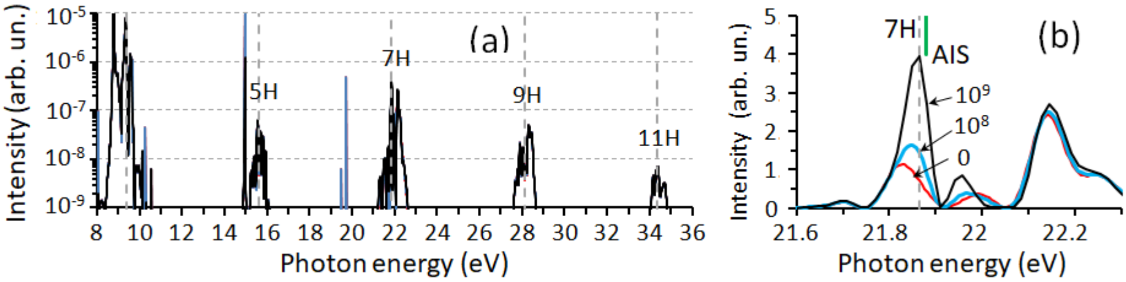


Fig. 1. The HHG spectrum of the $Ga^+$ ion in the range of 3H-11H (a) and the details of the 7H line (b),

More effective was the inclusion of additional resonant pumping by radiation at the wavelength $\lambda_{XUV} = \lambda_L/7$, formed in the plasma medium during the laser pulse.

Figure 1 shows the results of calculating the HHG spectrum for different values of the short-wavelength radiation intensity $I_{XUV}$ indicated in units of W/cm$^2$ near arrows in Fig. 1b. With its relatively moderate value of $10^9$ W/cm$^2$, a multiple increase in the 7H yield is achieved compared to multiphoton pumping by a laser field with the peak intensity of $1.6 \times 10^{14}$ W/cm$^2$ and the FWHM pulse duration of 30 fs. The effect of an additional increase in the harmonic intensity disappears rapidly with detuning from resonance. The obtained results indicate the importance of the processes during the formation of radiation in the medium and their influence on the nonlinear microscopic response of the generating atomic system.

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# THE EFFECT OF LASER PULSE DURATION ON THE DYNAMICS OF WATER MOLECULE COULOMB EXPLOSION

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The powerful ultrashort pulses generated by the modern laser facilities have made it possible to study the dynamics of molecular bonds [1]. We previously developed and tested a theoretical model [2] of the Coulomb explosion of water molecules for pulse parameters close to the realized experimentally: photon energy ω=1 KeV, duration 20 fs, fluence $2\times10^{11}$ ph/μm$^2$.

In the simulation, three types of transitions between the states of the molecule and molecular ion were taken into account: photoionization, Auger transitions, fluorescence. We used the Monte Carlo method with classical dynamics of atoms on five potential energy surfaces which were obtained by the original code [3].

In this research, we explore the effect of the radiation beam duration (while the fluence remains constant) on the observable quantities. It was found (fig. 1a, Q – charge of oxygen ion, N – events) that the instant intensity of radiation strongly affects the nature of the temporal evolution of the charges in the molecule: the yields of ions with higher charges rise with the pulse duration increase.

For a short (5 fs) pulse duration (fig. 1b), and therefore high radiation intensity, there are an overwhelming number of charge trajectories passing through the double core-hole state ($1s^2$). That leads to rapid molecular decay, when the geometry of neutral water does not have time to relax, and, in addition, to a high kinetic energy of fragments.

Longer pulses lead to characteristic changes in the pattern of Newton diagrams: the appearance of more events with proton pulses directed into a positive half–plane, which is a consequence of the dication unfolding into an energetically favorable position — a straight line, resulting to more isotropic diagram (for 20 fs) (fig. 1c).

For a longer duration (50 fs), there are very few double core-hole state events, but the Newton diagram clearly shows an "inner circle" (fig. 1d) with the minimum kinetic energy of the first separated proton – this is the dissociation to channel $OH^+ + H^+$.

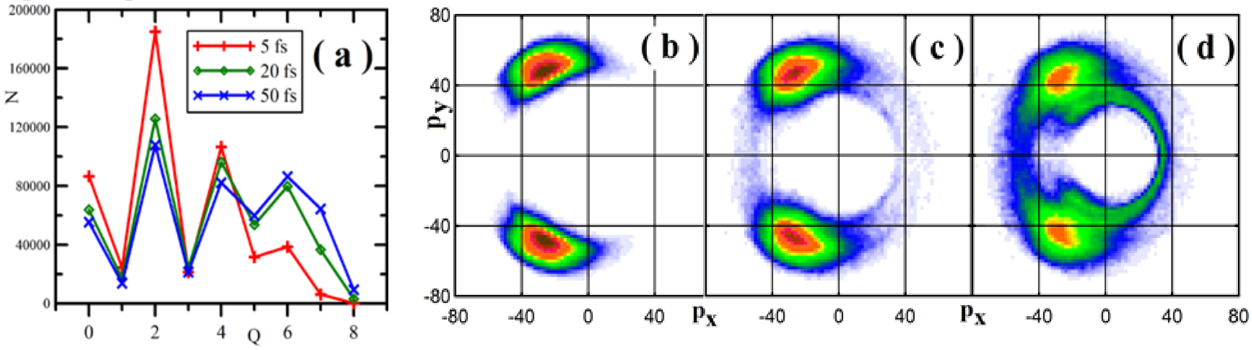


Fig. 1 Charges diagram (a), Newton diagrams for duration 5 fs (b), 20 fs (c) and 50 fs (d).

Thus, the study of the effect of the radiation pulse duration allows us to take a deeper look at the dynamics of molecular bonds.

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# ON SPATIAL LOCALIZATION OF COLD CESIUM ATOM ENSEMBLE IN BICHROMATIC LASER FIELD

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Magneto-optical traps (MOT) are often used in high-precision frequency standards on cold alkali and alkaline-earth atoms. They allow efficient laser cooling and trapping of atoms. However, there are limitations in their application, associated, for example, with the inertia of the magnetic field, as well as with the need to take into account and control the residual magnetic field in the region of interaction of cold atoms with the probe field of the "clock" laser. Recently, a purely optical scheme free from the above-mentioned disadvantages of MOT was proposed [1]. Its idea is based on the possibility of forming a potential created by the fields of two standing laser waves with a frequency difference of $\Delta\nu_{12}$, holding atoms in a spatial region with linear dimensions $\Delta L = c/(2\Delta\nu_{12}) \sim 1$ cm at $\Delta\nu_{12} \sim 10$ GHz. This scheme can be implemented for atoms whose interaction with the field corresponds to a two-level system [2].

The report discusses the possibility of spatial localization of a cloud of cold cesium atoms in a bichromatic laser field. Spectroscopic features (the hyperfine structure (HFS) splitting of the $6^2S_{1/2}$ ground state $\Delta\nu_g \approx 9.19$ GHz and the small relative radiative width of the cooling optical transition 6s $\leftrightarrow$ 6p $\gamma/\Delta\nu_g \approx 5.7\times10^{-4}$) exclude the applicability of the two-level approximation. In this regard, a four-level scheme with two independent optical transitions between the HFS components for the $D_1$ and $D_2$ lines (with $6^2P_{1/2}$ and $6^2P_{3/2}$ excited states, respectively) is considered. A serious problem is to eliminate the conditions for the transition of the atom to "dark" polarization states, in which there is no interaction with the laser field. Using the density matrix formalism, equations are obtained that describe the macroscopic motion of a Cs atom in a bichromatic laser field. Estimates of the parameters of the holding potential are made depending on the intensities and frequencies of the laser components.

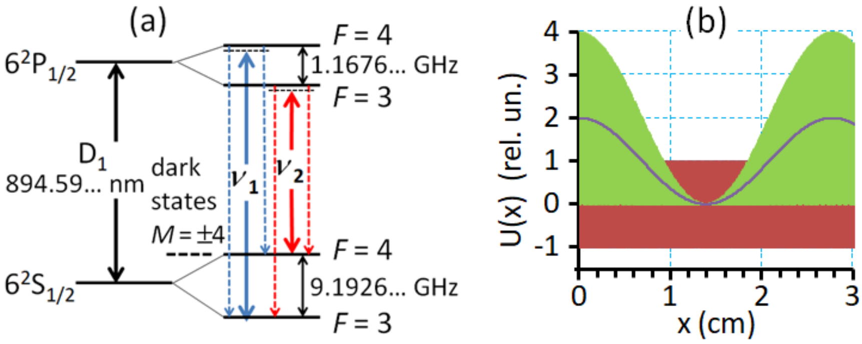


Fig. 1. (a)The HFS and transitions for the $D_1$ line of Cs with the "dark" magnetic sublevels $M = \pm4$ of the ground state . (b) The shape of macroscopic potential for an atom in bichromatic standing waves with frequency detuning $\Delta\nu_{12}$=10.3 GHz. The bright-green area corresponds to the square of a standing wave superposition of frequency components with equal amplitudes (dark-brown area). The solid curve is averaged over the scale of wavelengths.

Figure 1a presents the scheme of the cooling $D_1$ line optical transitions between the HFS levels of Cs in a bichromatic laser field with collinear polarization. In figure 1b the shape of macroscopic potential for an atom in bichromatic standing waves with equal contributions is shown.

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# CRYSTALLITE MOBILITY AND CORRESPONDING CHANGES IN SURFACE STRUCTURE UNDER WEAK (BELOW THE MELTING THRESHOLD) NANOSECOND IMPACT

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We consider the mechanisms of surface relief formation on bulk copper samples after the influence of nanosecond laser pulses [1].Intensity of the laser pulse is rather weak - below melting threshold.It has been experimentally established that after irradiation on the surface of the samplesin local areas near grain boundaries, a characteristic system of protrusions / depressions is formed.Deformation nature of the formed relief was established.Traces of plastic deformation development are experimentally detected in the thin near-surface layer near grain boundaries.

Molecular dynamic modelling has shown that the main physical reason for the development of the relief under consideration isanisotropy of thermal expansion of differently oriented grains (crystallites) during cyclic heating to pre-melting temperature.It has been established that thermomechanical stresses arising in the near-surface layerexceed the yield strength of the material, which leads to irreversible plastic deformation.The accumulation of structural changes with increasing energy density and number of pulses is shown.The results obtained are important for understanding the mechanisms of surface degradation of well-polished polycrystal metals under cyclic pulsed thermal loading.This study allows to improve the operational durability of metal optics.

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# TREATMENT OF P- AND HIGHER ORDER ELECTRONIC SUBSHELLS IN STRONG-FIELD IONIZATION IN PARTICLE-IN-CELL SIMULATIONS

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Strong-field ionization is an important effect for applications in laser-plasma interactions at very high intensities, which includes potential use for in situ laser intensity measurements at the focal spot [1] and injection of electrons in laser wake-field acceleration [2]. The particle-in-cell (PIC) method is the state-of-the-art approach to studying such interactions theoretically. It allows for accurate simulation of plasma effects and can be combined with Monte-Carlo routines for the inclusion of stochastic quantum effects such as strong-field ionization. For practical realizations of the latter, one has to impose strong assumptions: single electron ionization and sequential ionization order, meaning that the ion is considered to be always in the ground state, and the outermost electron is extracted. The existing implementations also rely on additional approximations, such as neglecting the dependence on the magnetic quantum number *m* in the ionization rates [3].

We analyze the precision of the approximations for strong-field ionization used in PIC codes [4]. We show that the dependence on the magnetic quantum number *m* of electrons on, e.g. on a *p*-subshell, can lead to a significant change in the simulation outcome. However, we identify that the sequential ionization approximation appears to be the most stringent for simulation precision. We suggest an algorithm that allows accounting for both the dependence on the *m* number and the dominant nonsequential ionization pathway in PIC codes. We also discuss the impact of barrier suppression ionization. We illustrate these findings with simulations for an argon target impinged by a strong laser.

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# QUANTUM-QUASICLASSICAL METHOD FOR ATOMIC PROCESSES IN STRONG LASER FIELDS

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In our works [1-3], a quantum-quasiclassical approach was proposed and implemented for the quantitative description of the interaction of neutral atoms with laser radiation, taking into account non-dipole corrections arising due to the spatial inhomogeneity of the electromagnetic wave **kr** and the presence of a magnetic component in it. Non-dipole corrections in the interaction of an atom with laser radiation lead to “entanglement” of the variables of the center of mass (CM) and electrons in a neutral atom and, as a consequence, to its acceleration. We studied this effect, as well as the accompanying processes of excitation and ionization of the hydrogen atom in strong ($10^{12}$ - $2 \times 10^{14}$) W/cm$^2$ linearly polarized short-wave (5 eV$\leq h\nu \leq$ 27 eV) electromagnetic pulses with a duration of about 8 fs.Two mechanisms of atomic acceleration have been established: through single-photon and two-photon excitation of the atom.It is shown that the one-photon mechanism leads to a linear dependence of the atomic velocity at the end of the laser pulse on the laser intensity, and the two-photon mechanism leads to a quadratic dependence [2]. The report focuses on our latest results obtained for elliptical polarization of a laser pulse [4]. The effect of polarization on excitation, ionization and acceleration of an atom is investigated. It is shown that when interacting with a circularly right-polarized electromagnetic pulse, the atom accelerates and "twists" - acquires an orbital momentum with a projection m=+1 on the direction of its motion (see Fig. 1). In this regard, it should be noted that despite the almost thirty-year history of studying twisted photons and electrons, obtaining twisted atoms is a challenging experimental task. So far, only one experiment has been carried out in which twisted helium atoms were obtained using a specially designed diffraction grating [5].

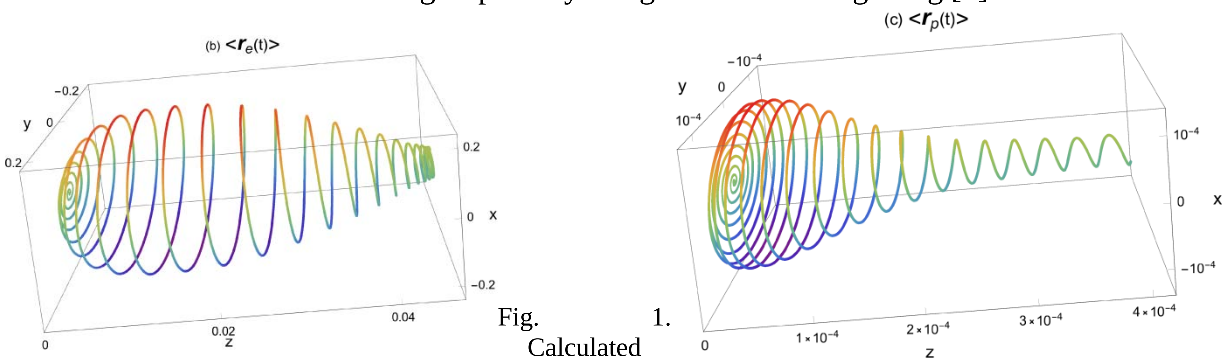


Fig. 1. Calculated trajectories of an electron <$\mathbf{r}_e(t)$> (b) and a proton <$\mathbf{r}_p(t)$> (c) in a hydrogen atom interacting with a circularly polarized laser pulse propagating along the Z axis, with a duration of 8 fs, $10^{14}$ W/cm$^2$ and ω=0.48 a.u.[4]. The variables X, Y and Z are given in a.u. .

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# THE RABBITT SETUP IN THE LIGHT OF DIVERSE POLARIZATIONS

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The RABBITT setup [1] used for characterization of HHG pulses is usually considered for linearly polarized light, since the generated HHG spectra have been only linearly polarized for many years. Recently, significant progress has been made in generating circularly and elliptically polarized high harmonics [2,3], therefore, there is a need for a systematic investigation of polarization effects in RABBITT experiments. We report our theoretical studies of the polarization effects in photoelectron angular distributions (PADs) for various combinations of "XUV+IR" field components polarization: "linear+linear" (a) & "linear+circular" (b) & "circular+linear" (c) with crossed propagation directions, and "circular+circular" (d) with parallel propagation directions.Theoretical findings are supported by numerical simulations of neon ionization by 15, 17 and 19 harmonics with 800 nm seed IR field. In Fig. 1, the obtained PADs for the sideband 20 are presented. We used two previously approbated methods: time-dependent perturbation theory and amplitude coefficient/rate equations [4].

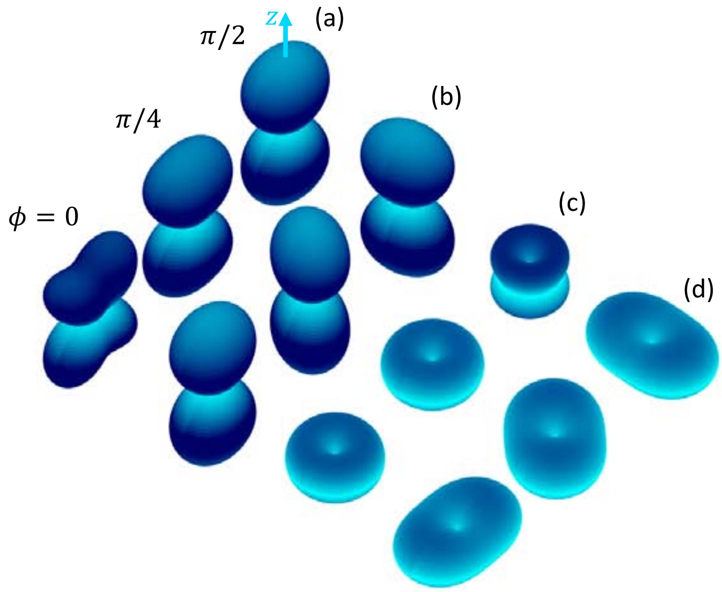


Fig. 1. PADs for the "XUV+IR" field components polarization described above at three different phases of IR field.

We have found that: I) time-delays can be measured without recording angle-differential spectra only in schemes (a) and (c); II) only scheme (c) possesses the axial symmetry III) circular dichroism can only be achieved in scheme (d); IV) PADs in schemes (a) and (c), if one considers ionization from atomic s-shell, become independent from the target atom.

The presented observations may be helpful for planning of future experiments.

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# COMPTON IONIZATION OF POSITRONIUM BY TWISTED PHOTONS.

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The process of Compton decay of positronium by a twisted photon is considered in the $A^2$ approximation. In the case of an incoming Bessel cylindrical wave and an outgoing photon plane wave, the matrix element of such decay is closely related to a similar matrix element for an incoming plane electromagnetic wave. Within the framework of standard scattering theory taking into account the momentum conservation law, it is shown that in the expression for the probability of this process almost all the most important characteristics of the cylindrical wave of a twisted photon are lost. Moreover, it is shown that the differential probability of positronium decay by a twisted photon is equal to the probability of decay by a plane-wave photon with a certain momentum moving at a certain angle to the z axis, averaged over the azimuthal angle of the incident photon [1].

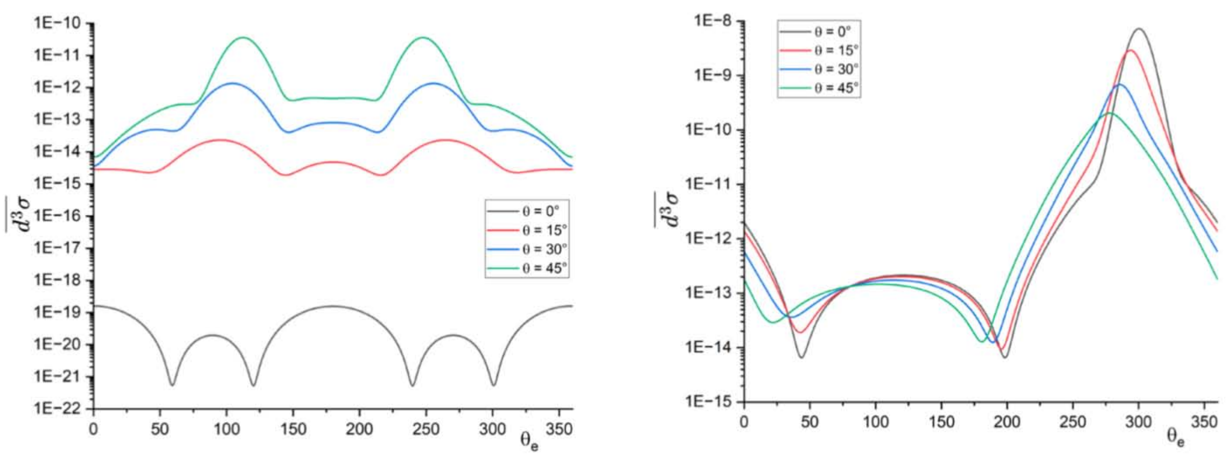


Fig. 1. Averaged differential cross section in atomic units as a function of the electron scattering angle $\theta_e$. $\omega$= 5 keV, electron energy $E_e$= 27.2 eV, coplanar kinematics. The opening angles $\theta$and the corresponding curves are shown in the figures. Left panel: scattering photon angle $\theta_1 = 0^\circ$, right panel: $\theta_1 = 60^\circ$.

As an example, in Fig. 1, the differential cross sections are displayed for the cases of different opening angles of twisted photons. This study demonstrates that incorporating the momentum conservation law into the plane-wave matrix element removes the dependence of the matrix element (probability, cross section) on the projection $m$ of the orbital angular momentum and the impact parameter, which, from a physical standpoint, should play an important role in the case of a cylindrical wave. This conclusion is also supported by papers of other authors.

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# ABRAHAM'S RADIATION FRICTION TRESHOLD FOR AN ELECTRON COLLIDING WITH A LASER PULSE

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In the "Gaussian field - Abraham radiation friction" model, a radiation friction threshold is determined that limits from below the kinetic energy of the counter-propagating electron at a fixed peak intensity of the laser pulse. For the relative peak intensity γ with respect to the relativistic one, it is shown that with increasing γ, the threshold condition for the kinetic energy of the counter-propagating electron is weakened according to the law $\sim\gamma^{-1/4}$, and the main reason for the deceleration is associated with the growth of the second derivative of the longitudinal velocity of the electron $\ddot{v}_z$ according to the law $\sim\gamma^{3/2}$.

It is shown that the calculations of radiation friction in the Landau-Lifshitz model [2-4] do not give a noticeable Abraham friction. And the calculation in the model [5] (transversely inhomogeneous laser field with a flat phase front - Abraham force) strictly corresponds to the radiation friction threshold.

Thus, the Landau-Lifshitz model significantly underestimates the radiation friction threshold.

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# RELATIVISTIC LASER-DRIVEN PARTICLES BEAM ACCELERATION WITH THIN LIQUID TARGETS

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We report the results on the generation of highly energetic electron beam with low divergence with only 2 TW femtosecond laser system interacting with under-critical plasma of liquid targets with small initial thickness. The advantage of liquid target is the high spatial stability over long operation time and fast surface renewal allowing to operate at high repetition rate of laser pulses (up to kHz level). Three type of liquid target shapes were considered: a cylindrical continuous liquid jet, isolated microdroplet and thin liquid sheet. The under-critical plasma slab was formed by acting onto the targets by an intense nanosecond prepulse with peak intensity ~$10^{12}$ W/cm$^2$, coming in a few nanosecond time window relative to the main accelerating femtosecond pulse with peak intensity up to 7x$10^{18}$ W/cm$^2$. Isolated droplets were additionally optically shaped by a weak nanosecond prepulse to form a thin liquid structure due to material propulsion. By means of optical shadowgraphy supported by numerical hydrodynamic simulations the density profile of the preformed plasma was established. Particle-In-Cell modelling revealed the complex mechanism of particles energy gain which may be attributed to Direct Laser Acceleration and subsequent transition to Self Modulated Laser Wakefield Acceleration [1,2].

Experimentally with the use of the liquid targets the electron beam with energy up to 20 MeV and divergence below 0.1 rad was registered, see Figure 1(a). The shot-to-shot beam pointing stability is below 0.15 rad, see Figure 1(b). Evaluation of the beam charge with nuclear technique and direct measurements by Faraday cup have shown that in the range above 1 MeV the charge reaches record-breaking level of 500-700 pC. Advantages and limitations of the liquid targets are discussed.

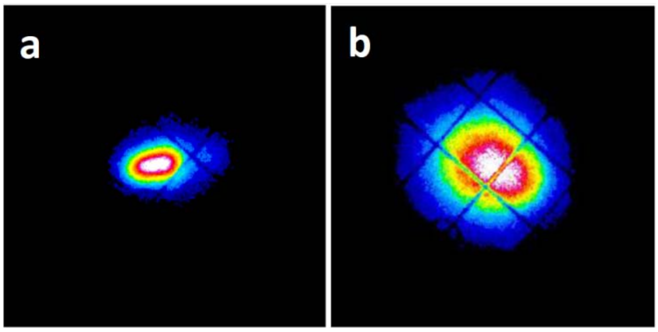


Fig. 1. Single shot electron beam stamp (a). Averaged over few hundreds shot electron beam stamp (b).

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# ENERGY-TUNABLE QUASI-MONOENERGETIC ELECTRON BEAM OBTAINING WITH LWFA

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Laser plasma electron acceleration is one of the most promising applications of ultraintense lasers. Laser wakefield acceleration (LWFA) is the most widespread laser plasma acceleration mechanism [1]. This mechanism can be implemented to generate electron beams with energies in the range of tens MeV that are valuable for a variety of applications, such as investigation of the photonuclear reactions near thresholdand high-resolution microscopy.

We have obtained the generation of energy-tunable quasi-monoenergetic electron beams by interrupting the acceleration process at different stages by introducing a sharp density spike created by a laser-induced blast wave [2]. Electron beams with tunable energies ranging from 6 to 12 MeV and an energy spread of 2 to 3 MeV were achieved by this approach experimentally (see fig. 1). Additionally, we conducted an extensive analysis of the 1D quasi-linear model of LWFA to elucidate this effect [3]. The analytical model provides a theoretical framework for understanding the generation of quasi-monochromatic energy-tunable electron beams through LWFA. It demonstrates that energy tuning occurs during the deceleration phase. The analytical modelprovides accurate estimates of the electron beam parameters.

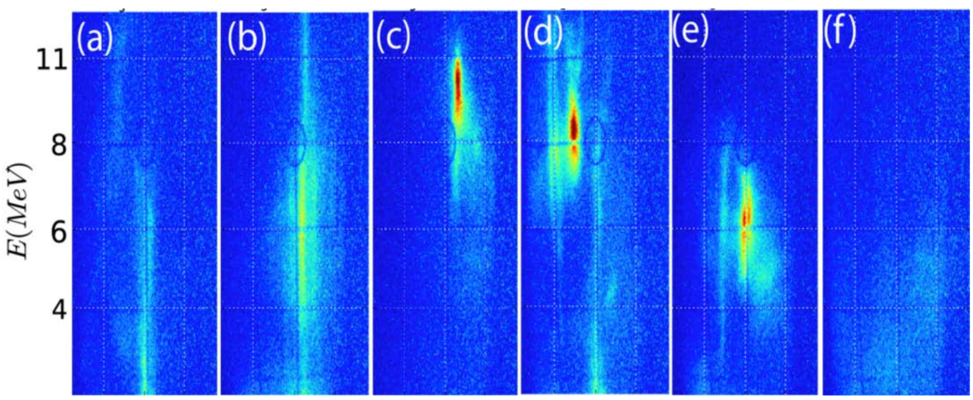


Fig. 1. Electron spectra obtained in the experiment in a single shot for different shock front positions – x=425λ (a), x=440λ (b), x=460λ (c),x=470λ (d),x=485λ (e)and without shock (f).

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# INVESTIGATION OF BEAM-LOADING EFFECT IN LASER-WAKEFIELD ACCELERATION OF ELECTRON BUNCH AND ITS INFLUENCE ON ELECTRON BUNCH ENERGY SPREAD

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The development of an efficient method for the acceleration of charged particles is one of the priority tasks of modern physics. Laser-plasma interaction based accelerators are among the most promising candidates for solving this problem of efficient acceleration, since they make it possible to generate accelerating fields with amplitudes several orders of magnitude higher than it is possible in conventional accelerators. The success of laser-plasma accelerators depends to a large extent on their ability to provide quasi-monoenergetic acceleration of short electron beams to high energies [1-3] while maintaining low emittance. One of the limitations of laser-wakefield acceleration is related to the intrinsic current of the accelerated beam due to its motion in the plasma (beam-loading effect) [4]. This feedback effect modifies the accelerating field in which the accelerated bunch propagates, which limits the possible accelerated charge and also influences its final energy spread [5]. Therefore, taking this effect into account is a very important task, especially if the goal is to produce accelerated beams with as small an energy spread as possible.

Based on the theory as well as on the self-consistent nonlinear modeling, the influence of the beam-loading effect on the acceleration process of electronbunch has been investigated. It was analyzed how different parameters of the bunch, such as its size and charge, affect the accelerating field due to this effect. A method for optimizing the initial parameters of the bunch of accelerated electrons for efficient laser-plasma acceleration in terms of finite energy spread is proposed.

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# INHOMOGENEITIES EFFECT ON AUTO-RESONANT LASER ACCELERATION OF COLD ELECTRONS

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Acceleration of electrons with intense laser beams in underdense, strongly magnetized plasma is studied in the auto-resonance regime. The magnetic field of the several kilotesla scale is assumed to be generated using an auxiliary laser driver in specially designed capillary targets [1], which corresponds to a solenoidal-like geometric profile. The properties of the magnetic field are crucial for an experimental implementation of the discussed acceleration mechanism.

As demonstrated in previous studies [2-4], a unique resonance condition (auto-resonance) can be achieved when a plane electromagnetic wave interacts with a charged particle in the presence of a sufficiently strong magnetic field directed along the propagation direction of the wave.However, this regime is very sensitive [5] to factors such as the interaction geometry, magnetic field inhomogeneities, initial electron distribution, laser focusing and collective effects in plasma, which are essential to any experiment.

For a magnetic field with a Gaussian transverse profile, the optimal field strength can be estimated based on the spatial scale of the inhomogeneity. Analytical expression for an optimal amplitude is derived assuming inhomogeneity scale to be much smaller than the transverse size of the accelerating electron trajectory. This qualitative estimate can be corrected to show a good quantitative agreement with the numerical results.

High energies of accelerated electrons can be achieved with relativistically intense laser pulses, which are usually focused to a small spot resulting in a nonuniform laser field distribution. According to the conducted numerical investigation, laser focusing leads to a resonance shift and a decrease in electron energies. However this effect does not eliminate the possibility of an effective acceleration.

Besides electromagnetic field inhomogeneities, collective effects in plasma also play an important role in an effective generation of ultrarelativistic electrons in the considered setup. The laser electron acceleration in plasma with these effects taken into account was studied numerically in two-dimensional geometry using the particle-in-cell code Smilei [6]. Simulations show an existence of optimal setup parameters, particularly density and size of the magnetized plasma, which can be appropriately chosen to increase the energy gained by an electron.

Finally, simulations considering all mentioned effects taken into account were performed. To obtain a realistic model, a solenoidal magnetic field was applied to a plasma cloud. Though in the considered setup with all the effects taking place, the dephasing is stronger, it appears still possible to create an ultrarelativistic electron bunch. Electrons can be accelerated to even higher energies, when the laser pulses with increased intensity are used, which may partially compensate for the negative effects of the considered inhomogeneities.

This work was supported by the Russian Science Foundation (agreement # 24-22-00402).

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# INVESTIGATION OF THE PREPLASM OF A SOLID-STATE TARGET FOR PROBLEMS OF LASER ACCELERATION OF ELECTRONS AND IONS

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This work is devoted to modeling the interaction of a laser pulse with solid targets in order to find optimal plasma parameters. The influence of the target material and thickness, as well as the laser pulse parameters on the resulting density profiles is considered. Optimal parameters of the plasma formed on the leading edge of the target will make the acceleration of charged particles more efficient.

Short laser pulses with relativistic intensity make it possible to effectively accelerate electrons and ions of a plasma target to high energies, which opens up prospects for the creation of compact charged particle accelerators with a wide range of practical applications [1,2]. The accumulated energy and the number of accelerated particles are determined not only by the laser pulse, but also by the target itself. Using an additional nanosecond laser pulse, it is possible to create an extended plasma on the irradiated side of the target, which opens up the possibility of manipulating the target parameters. In this work, the dynamics of the expansion of finite-thickness targets is analyzed depending on the laser pulse parameters and the properties of the target itself for laser pulses with energies of up to several millijoules. We simulated the expansion of the target under the action of a nanosecond laser pulse and obtained density profiles of the preplasm formed on the irradiated side of the target. The simulation was carried out using the hydrodynamic code FRONT [3], which solved a system of two-temperature hydrodynamics, including the equation of continuity and the equation of motion of plasma density, as well as equations for the internal energy of electrons and ions. The calculations were carried out in three-dimensional (cylindrical) geometry.

During the calculations, laser pulses with an intensity from $10^{11}$ W/cm$^2$ to $10^{14}$ W/cm$^2$ and a duration from 1 to 5 ns were used. Aluminum, iron and tungsten were considered as the target material.

The preplasm density profile can be roughly represented as the sum of two exponentials, one of which describes the plasma near the target, and the other describes the sub-critical plasma. The characteristic gradient of plasma density of an aluminum target, close to the critical one, is about 0.2-0.3 microns for the minimum density of the invested energy used in the simulation (about 0.3-0.5 kJ/cm$^2$) and reaches saturation in the region of ~ 0.4 microns at an energy density above 5 kJ/cm$^2$. In the case of targets made of iron and tungsten, the characteristic gradient of near-critical plasma is about 0.1-0.2 microns and does not change for given energy densities. The characteristic gradient of low-density plasma of an aluminum target increases from 7.5 to 20 microns. These values are 15-20% higher than in targets made of iron and tungsten. The obtained calculations will allow us to carry out kinetic modeling of the acceleration of electrons and ions from these targets in order to optimize the parameters of the laser pulse.

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# FLUID-FLUID DECOMPOSITION IN BINARY DIPOLAR SYSTEM UNDER EXTERNAL FIELDS

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A 50:50 mixture of polarizable materials was simulated under an external field applied perpendicular to both flat (2D) and wavy film surfaces. The study revealed various patterns in how these materials distribute themselves, depending on the mixture's overall density, the strength of the applied field, and the characteristics of the wavy surface. When strong dipole interactions were present, the mixture in flat films separated into micro-clusters with an interesting structure: higher-permittivity materials concentrated in the center, while lower-permittivity materials formed the outer layer. The material density inside these clusters was higher than in the spaces between them. In some cases, the higher-permittivity materials arranged themselves in crystal-like patterns separated by lines of the lower-permittivity materials. Most interestingly, the dipoles inside the clusters pointed in the opposite direction of the applied field – a reversal phenomenon that our team previously reported for single-material systems in our earlier work. An example of this behavior is shown in Figure 1.

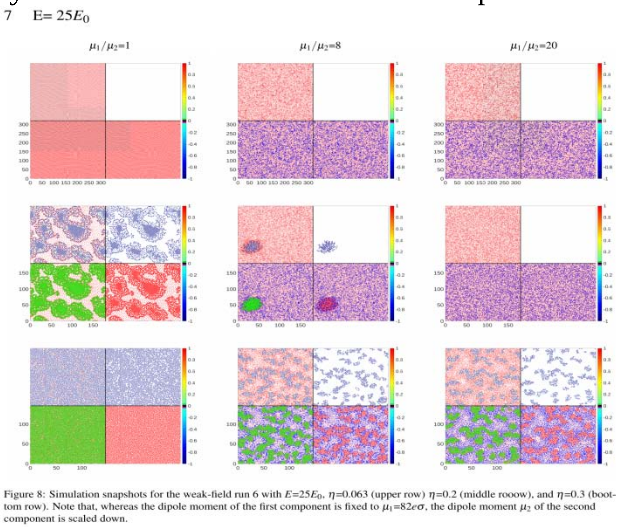


Fig. 1. Simulation snapshot for E=25MV/m,η=0.3.

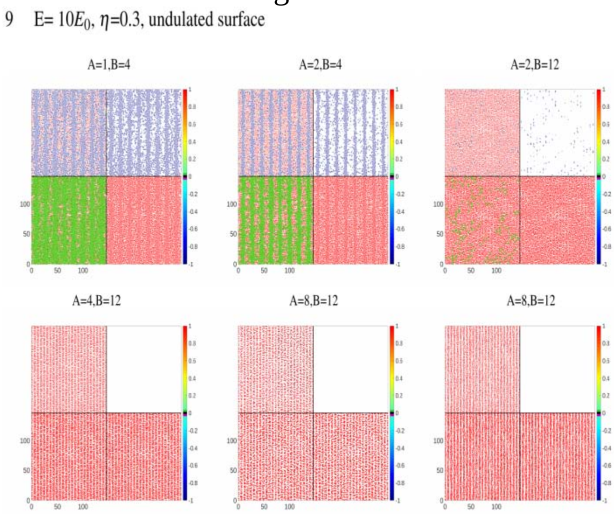


Fig. 2. Simulation snapshot for E=10V/m,η=0.3, A=2.

Our simulations of the mixed materials on wavy surfaces revealed several interesting findings. First, the particles avoided settling at the highest points (hills) and lowest points (valleys) of the surface due to mutual repulsion, making these positions unstable. Instead, they gathered on the slopes - both uphill and downhill areas. Second, we observed a clear separation pattern on these slopes, where the higher-permittivity particles became surrounded by the lower-permittivity ones, see Figure 2. Third, when we used specific numbers and heights of waves, the particles formed strip-like linear clusters that ran parallel to the wave direction. We found we could control both the number of particles in each linear cluster and the spacing between clusters by adjusting the overall particle density and the strength of the applied field.

Our research findings could be used to design surfaces that control how particles separate in mixed materials. This work also provides insights into how dipolar proteins might reorganize themselves on cell membranes.

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# INTERLAYER BOUNDARIES OF FERROELECTRIC SUPERLATTICES AS A SOURCE OF SOLID-STATE PLASMA FORMATION

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The establishment of the fact of solid-state plasma formation at the metal-ferroelectric interface led to the creation of fundamentally new electron sources – cathodes with high current density [1]. Further advances in improving the emission characteristics of such cathodes were previously considered either by varying the chemical and phase composition or by creating special temperature conditions for activating the domain structure [2]. In this paper, it is proposed to investigate the formation of solid-state plasma of interlayer boundaries of ferroelectric superlattices based on oxygen-octahedral ferroelectrics with the perovskite structure $BaTiO_3$, $SrTiO_3$, $PbTiO_3$, $PbZrO_3$, $KNbO_3$, $KTaO_3$, $SrZrO_3$ as a source of solid-state plasma. It is known that the emission capacity of ferroelectrics depends on their electronic structure, domain structure and crystallographic parameters. In addition, the formation of plasma, including solid-state plasma, is necessary for the occurrence of strong electron emission. The condition for the occurrence of plasma can be obtained from an estimate of the Debye screening radius of a substance with a dielectric constant ε and a charge carrier concentration *n* at a temperature *T* [3]:

$$\lambda_D = \sqrt{\frac{\varepsilon \cdot k_B \cdot T}{n \cdot e^2}}, \#(1)$$

where $k_B$ is the Boltzmann constant, *e* is the electron charge. For ceramics $BaTiO_3$ and $Pb(Zr,Ti)O_3$, the temperature dependence of the Debye screening radius $\lambda_D$ (relative to $\lambda_D$ at the Curie temperature $T_C$) was determined from impedance spectroscopy data for the case of dominance of free electron scattering on phonons at high temperatures, when the charge mobility is $\mu \sim T^{-3/2}$. Moreover, for $Pb(Zr,Ti)O_3$ the complex dielectric permittivity was measured at a frequency of 1 kHz, and for $BaTiO_3$ at different frequencies: 0.3, 1, 50, 100 kHz (Fig. 1).

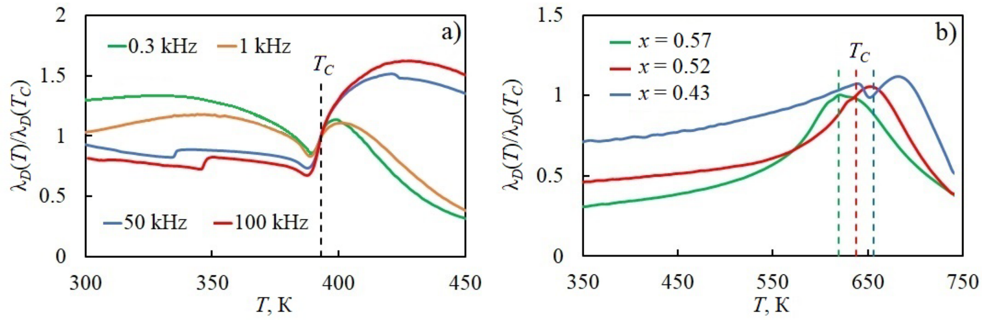


Fig. 1. Temperature dependence of the relative Debye screening radius for $BaTiO_3$ (a) and $Pb(Zr_xTi_{1-x})O_3$ (b) ceramics. $T_C$ – Curie temperature for ferroelectrics

When approaching the phase transition in $T_C$, the Debye radius changes, and for $BaTiO_3$ and $Pb(Zr,Ti)O_3$ this dependence has a different form, which is associated with the different contribution to the total electrical conductivity of the ionic and electronic conductivity mechanisms. For a superlattice of these ferroelectrics, the emergence of electron plasma and current emission will be determined by the correlation of the Debye radii of its components.

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# POSSIBLE MECHANISM OF THE HIGHLY CONDUCTIVE STATE IN LOW-DIMENSIONAL SYSTEMS

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One of the characteristic features of low-dimensional systems is the possibility of an abrupt transition to a highly conductive state under the influence of external impacts (pressure, temperature, density changes). Such systems include, for example, thin layers and one-dimensional conducting capillaries of rapidly frozen metal-ammonia solutions [1,2], polymer nanotubes and nanofibrils [3], polymer composites [4], etc.

The emergence of a high conductivity state (HCS) can be considered as a result of an incomplete but significant shutdown of the interaction of current carriers with elementary excitations in quasi-one-dimensional systems, regulated by the laws of conservation of energy and quasi-momentum [5,6]. In particular, in the case of one-dimensional motion of a band electron with the dispersion law

$$E(k) = E_0 - 2|t| cos\ ka, \tag{1}$$

and a phonon with a dispersion law

$$\omega_q = \frac{2u}{a}\left|sin\frac{qa}{2}\right|, \tag{2}$$

the establishment of the HCS is facilitated by the sufficient narrowness of the electron energy band $\Delta E_e$ compared to the phonon energy band $\Delta E_{ph}$ ($\Delta E_e < 0.01. eV$), the presence of the maximum electron velocity

$$v_{max} < u \tag{3}$$

and a significant value of the effective mass $m_0^*$ of current carriers

$$am_0^* u > \hbar, \tag{4}$$

where $u$ is the speed of sound, $\hbar$ – reduced Planck constant.

Within the framework of the multi-electron polar model of the Shubin-Vonsovsky crystal, the possibility of the existence (along with plasmons and other quasiparticles) of specifically solid-state collective excitations determined by the integral of intra-atomic Coulomb repulsion U and the integral of transfer $t_{g_1 g_2}$ of electrons between neighboring lattice sites is taken into account [7]. For gapless excitations, the effective mass of quasiparticles (homeopolarons and ionisons) has the form

$$m^* = \frac{\hbar^2}{ta^2\left(1 \mp \frac{U}{4t}\right)}, \tag{4}$$

the minus sign is for the homeopolaron, the plus sign is for the fully polar ionison.

Taking into account the interaction of current carriers with polar excitations may be important for the mechanism of realization of HCS in materials that are promising for inorganic and organic electronics.

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# MODELLING OF EDDY CURRENT EXCITATION DURING FEMTOSECOND LASER ABLATION OF METALS

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The interaction of intense optical pulses with metals is accompanied by inhomogeneous electron heating and interband transitions. It can lead to the excitation of bulk eddy currents due to the Biermann battery effect [1], caused by misaligned gradients of free electrons' pressure and density (see the schematic picture on Fig. 1). We study both analytically and numerically subpicosecond dynamics of free electrons in metals under typical conditions of laser ablation and show that eddy currents significantly heat electrons and provide convective heat transfer at subwavelength scales. In particular, eddy currents accompanying low-frequency magnetic field propagates inside the metal quite fast according to the magnetic diffusion equation, so that the estimated heating depth reaches several hundred nanometers. Considered additional heating of electrons should modify the initial conditions for further material melting and acoustic shock wave generation.

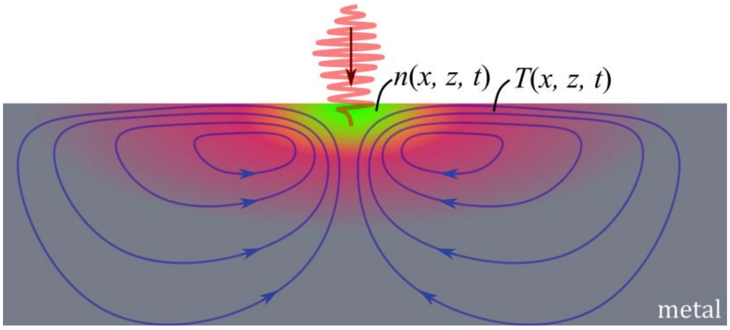


Fig. 1. Schematic picture of eddy currents excitation after laser irradiation of metal. Green and red colors show the areas of increased free electron density and thermal energy, respectively. Blue lines show free electron velocities.

The prerequisites for the Biermann effect manifestation arise even in purely electronic subsystem of laser-irradiated solids before any heat exchange with the crystal lattice. For example, it was established experimentally that femtosecond laser irradiation of gold leads to electron heating up to the temperature of 5 eV and more than twice increase of free electron density at incident optical fluences of 3 J/cm$^2$ [2]. The measured dependencies of electronic temperature and density on pump intensity are significantly different: while the temperature increases roughly linearly, free electron density remains almost constant at low intensities and then experiences significant increase. It means that their spatial distributions over the irradiated spot are indeed different, and so the temperature and density gradients are misaligned.

The diffusion-type equation has been derived for the magnetic field and eddy current propagation inside the medium, and it has been shown analytically and proved numerically that the magnetic diffusion is much faster than the classical electronic thermal conductivity. Basing on the available data for several metals and alloys, it has been predicted that eddy currents excited inside the metal are sufficiently strong to heat the material at least up to the melting temperature. The convective heat transfer provided by these currents has also been estimated and found to be important on subwavelength spatial scales.

The work was supported by the Russian Science Foundation, project № 25-22-20019.

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# PRODUCTION OF ULTRA-THIN NI NANONETWORK BY LASER ABLATION IN SUPERFLUID HELIUM

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Magnetic nanostructures such as nanowires, nanoparticles and nanoballs are widely used in biophysics and medicine to develop models of neurophysical systems and capture rare living cells from mixtures, as well as in magnetic logic and magnetic memory devices. The aim of the work is to create and analyze a Ni nanonetwork at different stages of its formation from individual nanowires to a continuous film and to establish the influence of the topological parameters of the nanonetwork on its magnetic properties [1].

A nanonetwork was grown from crystalline Ni in a superfluid helium environment using laser ablation (Fig. 1.). The network is a system of ultrathin Ni nanowires with a diameter of less than 4 nm and Ni nanoballs with a diameter of less than 50 nm. The duration of the ablation time significantly affects the structure and properties of the resulting Ni nanonetwork. At short ablation times, the nanomesh consists mainly of nanowires and exhibits a rectangular magnetic hysteresis loop, while an increase in the ablation time leads to an increase in the concentration of nanoballs and their diameter, which are formed as a result of winding a large number of nanowires on each other, which is the reason for a decrease in the rectangularity of the hysteresis loop. By analyzing the magnetic properties of the Ni nanomesh at different ablation stages, the contribution of nanowires and nanoballs to the magnetic moment of the nanomesh was established. The composition of the system can be determined from the change in the magnetic hysteresis loop and the temperature dependence of magnetization.

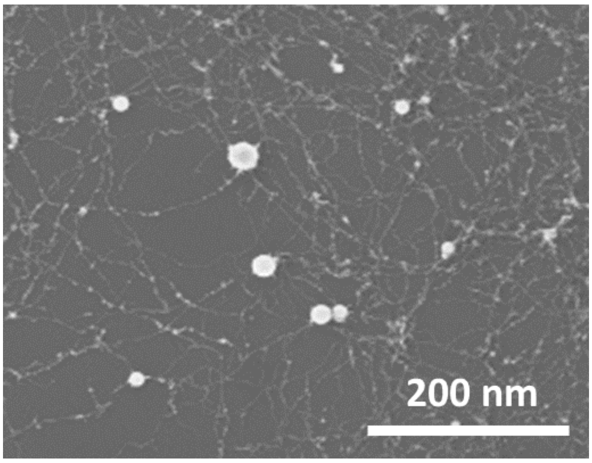


Fig. 1. SEM image of Ni nanonetwork after 60 min ablation

The magnetocrystalline anisotropy of Ni nanowires and Ni nanolayers is close to the magnetic anisotropy of bulk magnetic Ni known in the literature. A significant decrease in the coercive force in the nanomesh is observed compared to the theoretically predicted value for a system of isolated non-interacting microwires at an early stage of ablation, when mainly nanowires are present.

The work was carried out within the framework of the state assignment of the Federal Research Center of Problems of Chemical Physics and Medicinal Chemistry RAS 124013100858-3.

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# ARC DISCHARGE PLASMA FOR THE SYNTHESIS OF NANOCARBIDES AND NANOCARBIDE-BASED COMPOSITES

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Carbides such as SiC, $B_4C$, WC, TiC, etc. have high hardness, wear resistance and heat resistance, which makes them in demand in various industrial fields [1]. One of the ways to improve the properties of carbides is to apply their nanostructures. Obtaining nanosized carbides is a complex task because it requires the application of high temperatures, pressures and crystallization rates, which are difficult to achieve using traditional chemical technologies. One of the most promising applications of nanosized carbides is their use as a reinforcing component of metal matrix composites [2].

Plasma dynamic synthesis is a universal method for obtaining both carbide nanopowders and metal matrix composites based on them. The advantages of such a process (high *pT* parameters in the plasma structure, crystallization rates $>10^7$ K/s, process time up to 1 ms) allowed to carry out the synthesis of nanosized carbides as well as multicomponent and high-entropy carbide. We have performed selective synthesis of powders and coatings made of carbides $Hf_xTa_{1-x}C$ with predefined stoichiometry, crystal structure, and properties [3]. The chosen plasma dynamic technique has been also used to synthesize high-entropy carbide $TiZrNbHfTaC_5$ and the corresponding carbonitrides (N up to 8wt%) in the form of single -crystalline nanoparticles [4]. By varying the experimental system conditions, we have demonstrated not only the production of pure powders, but also the ability to apply different precursors.

In addition, to obtain metal matrix composites, an *in situ* approach was implemented, which implies the introduction of reinforcing carbide particles directly into the metal matrix during the production of these components. The basic principle of the developed method of metal matrix reinforcement with carbides is shown in Fig. 1 (on the example of the Al-$B_4C$ system).

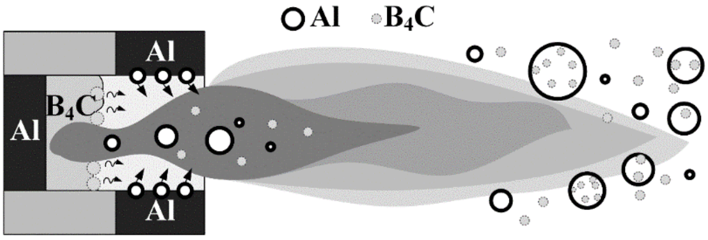


Fig. 1. Principle of production of dispersed Al-$B_4C$ composite

The properties of the obtained powders provide a higher level of mechanical and thermophysical properties of bulk composite products. For example, a unified strategy for obtaining bulk aluminum matrix composites has been demonstrated. When producing bulk samples, the unique structure of as-prepared powder materials is a key factor in achieving a high degree of densification (up to 99 %) and improved physical and mechanical properties (103-215 HV) compared to samples from commercially available MMC components (47-62 HV).

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## GAS DISCHARGE PLASMA ANTENNAS, ARRAYS AND METASURFACES

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As early as 1888, G. R. Hertz used ionized media to transmit and receive electromagnetic waves in his experiments with a spark transmitter and a dipole emitter. Although the concept of using an ionized medium (plasma) as an antenna was patented by J. Hettinger in the USA in 1919 (application 1917) [1], active research into plasma antenna-feeder devices began at the end of the 20th century [2-4]. At present, research into plasma antennas has not lost its relevance and is carried out by many scientific groups in different countries [5]. Plasma in such devices can be used as a conducting or reflecting element, as well as a control element. This paper provides an review of the main types of gas-discharge plasma antennas, systems and metasurfaces being studied for use in telecommunications, radar and other systems.

The main advantages of such antennas over traditional metal antennas are the ability to quickly turn on/off (low radar visibility) and electronically change parameters on a millisecond time scale: shape, frequency, directivity pattern and gain. Electrical control of the parameters and characteristics of a plasma antenna is achieved by changing the plasma parameters (concentration, collision frequency, shape and size of the plasma column). Plasma is especially attractive for developing antenna arrays, which allow for rapid beam control at lower costs compared to active phased arrays.

Paper presents the physical foundations of the operation of plasma antenna-feeder devices, as well as the classification of types of plasma antennas and the features of their operation. Antennas, systems and metasurfsces using different gas-discharges are considered. The basic methods of creating, measuring and modeling this plasma in antenna devices and systems are described. Special attention in the review is paid to the issue of the influence of plasma sources and the heterogeneity of plasma parameters on the characteristics of plasma antenna-feeder devices. The problems, challenges and promising areas of research into plasma antenna-feeder devices, including metasurfaces, are discussed.

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# EFFECTS OF AXIAL PLASMA DENSITY DISTRIBUTION ON THE CHARACTERISTICS OF A PLASMA ANTENNA

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One of the areas of development in plasma physics and radio physics is the creation of plasma antennas. This class of antennas is distinguished by the ability to dynamically control their radio frequency characteristics by modifying the magnitude and spatial distribution of electron density in gas-discharge regions. This study examines the effect of electron density distribution in the plasma of the radiating body of an asymmetric dipole antenna. [1-3].

The antenna consisted of a standard gas-discharge tube from a commercial fluorescent lamp (160 mm in length, 12 mm in diameter), filled with argon at a pressure of 1–3 Torr and mercury vapor at a pressure of approximately 0.01 Torr, with a disk-shaped screen 200 mm in diameter. The discharge in the tube was initiated by a portion of the power transmitted through the antenna at a frequency of 443 MHz (a microwave discharge on a surface wave). Using a cylindrical microwave cavity (E11 mode), an estimation of the axial distribution of the volume-averaged electron [4 - 6]. density in the plasma column of the antenna was performed. It was shown that the electron density decreases linearly with distance from the base of the radiating body, with a coefficient of 0.5 $cm^{-3}/cm$. Along the length of the tube, the density decreases fivefold.

The obtained experimental results are in good agreement with the results of numerical modeling performed using the electromagnetic code KARAT in a 2.5D geometry. The simulation employed the finite-difference time-domain (FDTD) method for calculating the electromagnetic field and the Particle-in-Cell (PIC) method. In the numerical modeling, for argon pressures ranging from 0.1 Torr to 1 Torr, a steady-state discharge regime was achieved. The electron density values, as well as their longitudinal and radial distributions, were obtained. Additionally, the plasma current values and the field distributions inside the gas-discharge tube and in the near-field region were determined.

The obtained distributions were used to evaluate the radio frequency characteristics of the antenna through its simulation in the COMSOL Multiphysics environment. The transition from a uniform electron density distribution to the experimentally obtained axially decreasing distribution causes only a slight change (no more than 5°) in the main lobe direction of the antenna's radiation pattern. However, it leads to a significant decrease in radiation directivity (by approximately 30%) and an increase in the main lobe width by 45°.

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# BROADBAND PLASMA ANTENNA

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The broadband plasma antenna is based on a gas discharge tube. The plasma in the antenna is generated by one-sided excitation of an extended RF discharge supported by a propagating azimuthally symmetric mode of a surface wave [1]. A special feature of this excitation method is the ability to change the length of the plasma region (plasma column $L_{st}$) by varying the ioniser power $P_i$ [2.3]. The antenna achieves broadband by changing the length of the radiating element – the plasma column. The antenna functions when the plasma density $n_e > n_{cr}$ along the entire length of the plasma column, where $n_{sr}$ is determined from $\omega_p \geq \sqrt{2}\,\omega_i$ ($\omega_p$ - plasma frequency, $\omega_i$ - ioniser frequency). The resonant length of such an antenna varies as the length of the plasma column changes from $L_{st}$ min to $L_{st}$ max. This antenna can therefore receive and transmit in the wavelength range corresponding to plasma column lengths. The efficiency of such a radiator (plasma column) depends on the electron density distribution both along the axis of the plasma column and along its radius. Studies of the density distribution along the axis of the plasma column have been carried out.

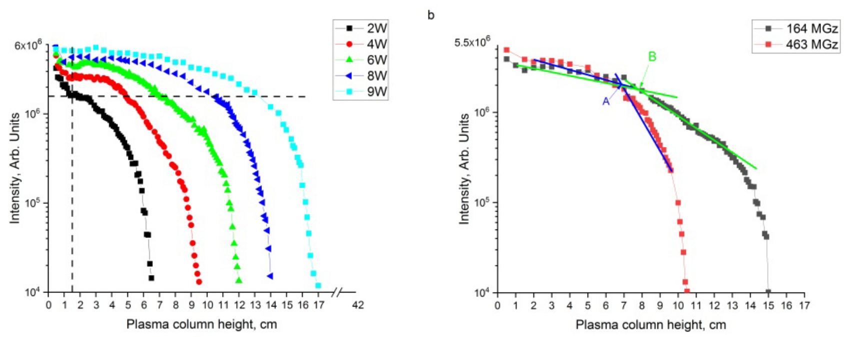


Fig. 1. a) Distribution $n_e$ along the tube axis depending on $P_i$;

b) Distribution $n_e$ along the tube axis as a function of frequency at $P_i$ = 5W

The results of a study of the characteristics of a plasma antenna (plasma column) along the axis of a gas-discharge tube at two ionizer frequencies of 164 MHz and 463 MHz are presented. Figure 1a shows the distribution of the ne density along the tube axis for various values of the $P_i$ power (plasma column length), Figure 1b shows the distribution of the ne density along the tube axis for one $P_i$ value at frequencies of 164 MHz and 463 MHz. The results obtained made it possible to determine the boundary of the active region of the plasma column (p.A and p.B Fig.1b) where the condition $\omega_p \geq \sqrt{2}\,\omega_i$ is still fulfilled.

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# DYNAMICS OF THE RADIATION SPECTRUM UNDER THE COLLECTIVE STIMULATED CHERENKOV EFFECT IN DIELECTRIC AND PLASMA WAVEGUIDES

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In the case of beam instability in the regime of the collective stimulated Cherenkov effect, the main mechanism of saturation of instability is a nonlinear frequency shift caused by a decrease in the average electron velocity of the beam due to the transfer of its kinetic energy to excited waves [1,2]. This process is described by the equations for the amplitudes of electromagnetic waves $E_s$ and the amplitudes of Langmuir beam waves $\rho_s$

$$\frac{dE_s}{d\tau} = -\nu\rho_s,$$
$$\frac{d\rho_s}{d\tau} - i\tilde{\Delta}_s\rho_s = -\nu E_s, \qquad (1)$$
$$\Delta_s = \frac{\omega_s - k_s u + \Omega_b}{\Omega_b} + W, \qquad W = \frac{1}{2}s\sum_{s=S\min}^{S\max}\left(|E_s|^2 - |E_{0s}|^2\right),$$

where $s \in [S_{\min}, S_{\max}]$ is the wave number, $\nu = |\delta\omega|/\Omega_b$ is a small parameter, $\delta\omega$ is the increment of linear theory, $\Omega_b$ is the frequency of the Langmuir beam wave, $u$ is the beam velocity, $\tau = \Omega_b t$ is the dimensionless time. When the dispersion law of electromagnetic waves is close to linear (as in the case of quasi-TEM waves of a coaxial waveguide with a dielectric), the nonlinear disorder is determined by the formula $\Delta_s = (s_0 - s)/s_0 + W$, where $s_0 = \Omega_b/[k_0(u - c_0)]$ is the number of the resonant wave, $c_0 < u$ is the phase velocity. The dynamics of the radiation spectra (functions $|E_s|$ for time points $\tau = 50, 100, 200, 300, 400$) is shown in the Figure 1.

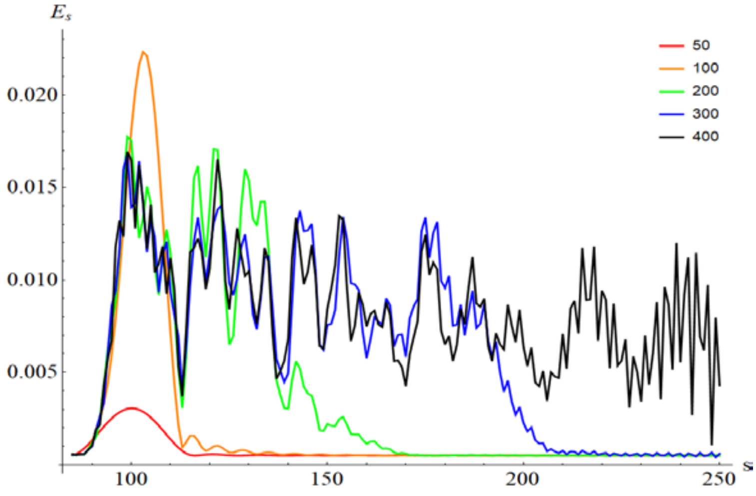


Fig. 1. Dynamics of the radiation spectra

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# BEAM INSTABILITY IN A COAXIAL GEOMETRY PLASMA MICROWAVE AMPLIFIER WITH AN ABSORBER

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The beam-plasma instability development in a plasma microwave amplifier with an absorber uniform along the length of the system is considered in a coaxial geometry. The addition of an absorber to the system is due to the need to suppress parasitic feedback. In this case, the presence of an absorber leads to a modification of the system`s electrodynamic properties. Beam-plasma instability Increments are calculated, parameter regions are determined when self-excitation of the amplifier does not occur. Efficiency modification of conversion of electron energy into energy of amplified wave and effect of absorber on it are estimated.

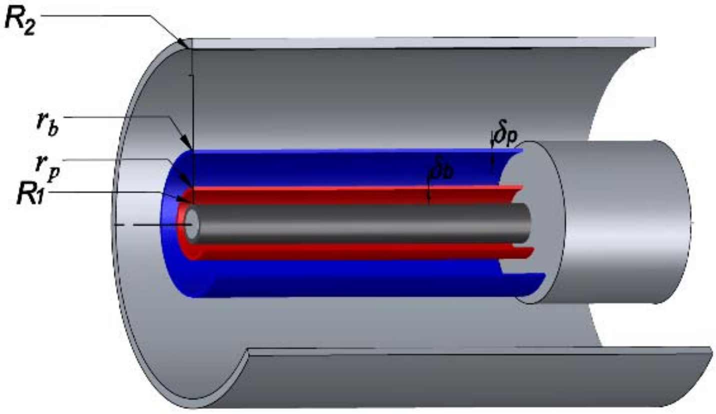


Fig. 1.A schematic of the microwave plasma amplifier: absorber is located along the inner rod along the entire length of beam-plasma interaction area.

In a system without absorber, there is a well-known dispersal equation [1]

$$\left[\omega^2-\omega_p^2\frac{\chi_0^2}{k_{\perp p}^2}\right]\left[(\omega-k_z u)^2-\omega_b^2\gamma^{-3}\frac{\chi_0^2}{k_{\perp p}^2}\right]=\Theta\omega_p^2\frac{\chi_0^2}{k_{\perp p}^2}\omega_b^2\gamma^{-3}\frac{\chi_0^2}{k_{\perp p}^2}. \quad (1)$$

It can be easily solved; thus, increments can be found. Direct modification of coefficients in this equation is a nontrivial task, but assuming that absorption is small, we can determine corrections to increments using energy flux into the absorber [1]

$$\delta k_{z1,4}=\frac{\dfrac{dP_{r1,4}(z)}{dz}}{2P_{z1,4}(z)}=\frac{\omega R_1}{2c}\frac{\operatorname{Re}\left(\dfrac{1}{\sqrt{\varepsilon}}\right)\left|\dfrac{d\Psi}{dr}(R_1)\right|^2}{\operatorname{Re}k_{z1,4}\displaystyle\int_{R_1}^{R_2}\left(\left|\frac{d\Psi}{dr}(r)\right|^2-\frac{l^2}{r^2}\left|\Psi(r)\right|^2\right)rdr}. \quad (2)$$

The presence of an absorber leads to a decrease of the amplification increment and an increase of decrements for backscattered wave from the radiating horn. Thus breaking the feedback loop that leads to self-excitation.

Energy dissipation in the absorber and reflection from the output end of the amplifier reduces the efficiency to

$$\eta=\eta_0\frac{\Delta P_{z1}}{\Delta P_{z1}+\Delta P_{r1}}\left(1-\left|\kappa_{14}\right|^2\right)=\eta_0\frac{\left|\operatorname{Im}k_{z1}\right|-\delta k_{z1}}{\left|\operatorname{Im}k_{z1}\right|}\left(1-\left|\kappa_{14}\right|^2\right), \quad (3)$$

where $\eta_0$ is efficiency in the system without absorber calculated according to [2]

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# NOISE AMPLIFICATION BY A RELATIVISTIC ELECTRON BEAM IN A DOUBLE COAXIAL PLASMA-METAL WAVEGUIDE

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The work of a plasma maser, in which a double coaxial waveguide is used as an amplifying section, is investigated. The outer and inner electrodes of the waveguide are metallic, and the role of the middle electrode is played by tubular plasma. The dependence of the microwave radiation field amplitude on the amplifying section, containing plasma, length L is obtained. This dependence allows us to determine the optimal length L = 40 cm, at which the amplitude of microwave radiation is maximum, as well as the initial noise level at the input of the plasma maser. This noise turned out to be of the order of megawatts, which coincides with the results obtained earlier for the configuration of the plasma maser without inner electrode [1].

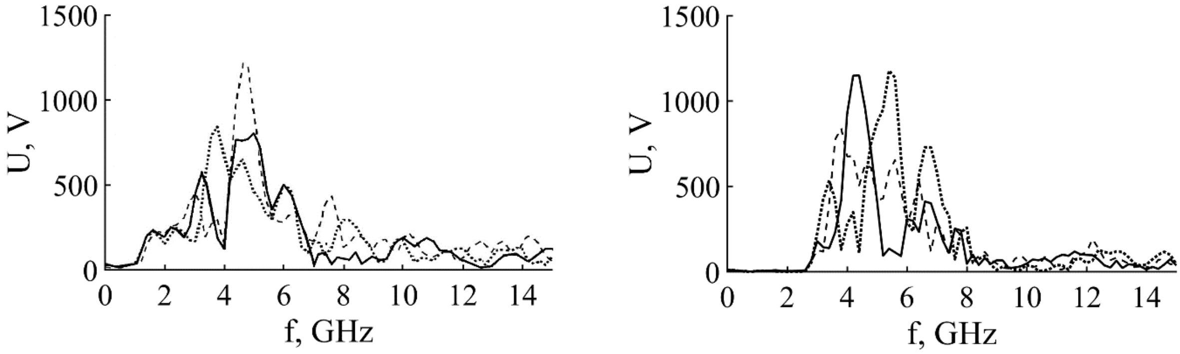


Fig. 1. Series of plasma maser emission spectra obtained under identical conditions respectively at the optimum length of the amplifying section without internal electrode L = 35 cm (left) and with internal electrode L = 40 cm (right).

The radiation spectra of the plasma masers in the configurations with and without inner electrode at the optimal amplifying section lengths are shown in Fig. 1. The transformation of a plasma coaxial waveguide into a double plasma-metal waveguide does not significantly affect the plasma wave amplification factor and radiation characteristics. The presence of the inner electrode does not affect the frequency range of the amplified waves, which depends mainly on the plasma concentration. The radiation amplitude is maintained at correspondingly optimal lengths of the various configurations. On the other hand, the presence of the inner electrode increases the limiting vacuum current of the REB transport and the optimal working current of the plasma maser, allowing to increase the radiation power, and also helps to solve technical problems essential for the creation of pulsed-periodic plasma masers [2].

The research was performed under the State Contract № H.4к.241.09.23.1050 dated April 10, 2023.

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# DEPENDENCE OF PLASMA MASER EMISSION SPECTRA ON AZIMUTHAL PLASMA CONCENTRATION INHOMOGENEITY

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The work of an axially symmetric plasma maser operating in the noise amplifier mode was investigated. The tubular plasma was created by source based on an annular thermal cathode. The plasma concentration, which is one of the main factors influencing on the spectral composition of the plasma maser radiation, was measured using the Langmuir probe [1]. The measurements showed that the plasma concentration lies in the range $(1…5) \cdot 10^{13}$ $см^3$ at various points along the length and azimuth of the plasma tube.

It was found that the width of the radiation spectrum significantly depends on the degree of azimuthal inhomogeneity of the plasma concentration. With a homogeneous in azimuth plasma, the spectrum width of 3…4 GHz remains (Fig. 1), and a concentration change makes it possible to change the central frequency of the radiation from 4 to 13 GHz.

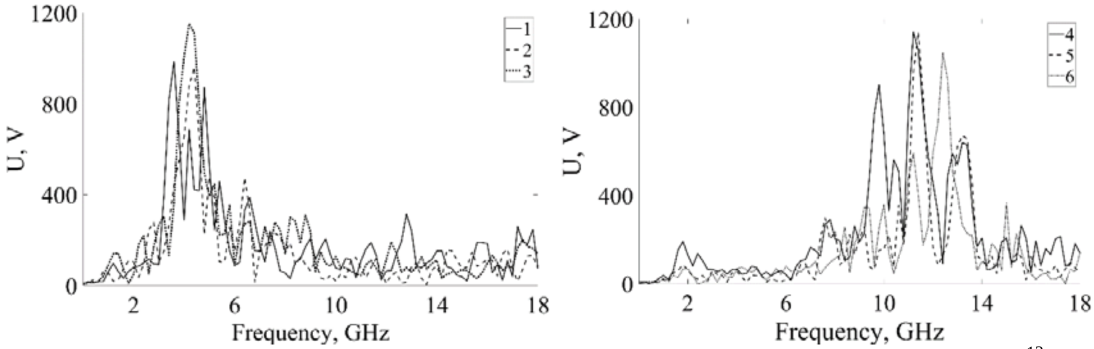


Fig. 1 Emission spectrum of a plasma maser for different plasma concentrations: left $n_e = 1{\cdot}10^{13}$ cm-3; right – $n_e = 3{\cdot}10^{13}$ cm-3 (plasma concentration is homogeneous in azimuth)

The azimuthal inhomogeneity of the plasma concentration with a factor of ~ 2 leads to a broadening of the spectrum of the radiation frequencies to 100% of the central frequency, Fig. 2 [2].

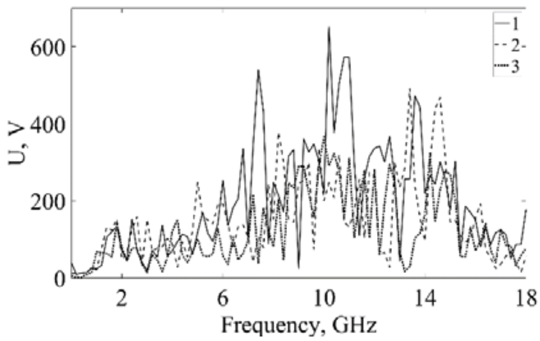


Fig. 2 Emission spectrum of a plasma maser (plasma concentration is inhomogeneous in azimuth)

The results show that the application of the sectionalized direct incandescence thermocathode provides the possibility of electronic control of the width of the plasma maser radiation spectrum.

The research was performed under the State Contract № Н.4к.241.09.23.1050 dated April 10, 2023.

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# OPTIMIZATION OF PLASMA ETCHING PROCESSES IN MICROELECTRONICS: APPLICATIONS OF PLASMA DIAGNOSTICS

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Plasma etching processes in microelectronics occupy a dominant position due to the possibilities of implementing anisotropic and high-aspect etching. Recently, a significant breakthrough in the capabilities of microstructuring has been the development of processes with an atomic scale of accuracy, in particular, atomic-layer etching [1]. The latter required the development of processes with high requirements for selectivity between surface activation reactions and parasitic sputtering. The report will highlight the possibilities of optimizing the composition of plasma components and ion energy distribution functions. The results obtained by the Langmuir probe and optical emission spectroscopy methods, as well as modelling of the kinetics of reactions in plasma and the ion energy distribution function will be presented.

Technological plasma imposes a number of restrictions on the application of diagnostic methods, for example, probe methods should be used under the condition of maintaining the probe in a stationary state (etching of probe and deposition of non-conducting films are inhibited). Plasma diagnostic data are necessary for experimental and theoretical studies of technological processes in low-temperature plasma. Of interest here are the values of electron temperature, electron and ion concentration, ion concentration, and ion energy distribution function. Modelling technological processes from first principles, using the reactor design and external discharge parameters as input data, encounters significant difficulties associated with unreliable ideas about cross-sections, particle loss constants on the walls, etc. In addition, such models must be self-consistent, since the propagation of electromagnetic fields in the plasma depends on the electron concentration, which in turn depends on the kinetics of ionization processes; in addition, it must be understood that the flow of reaction products from the plate being processed is comparable in order of magnitude to the flow of the plasma-forming gas.

The accuracy of modelling can be significantly increased by using diagnostic data, such as the electron temperature and the concentration of active particles [1], as input parameters for modelling. Carrying out diagnostics in the presence of processed microstructures [2] allows us to estimate the resulting loading effects, changes in the etching rate and other parameters depending on the proportion of open windows in the etching mask. The ever-increasing requirements for the accuracy of microstructuring have led to the development of deposition and etching processes of atomic-scale accuracy (atomic layer deposition and atomic layer etching), which defines new tasks for diagnostics of technological processes. On the one hand, methods for precise control of etching and deposition processes on the surface are needed, which can be implemented using the spectral ellipsometry method [3]. On the other hand, in atomic layer etching processes, to achieve high synergy values, it is necessary to control the width of the energy spectrum of ions reaching the sample surface [4], which requires the development of appropriate measurement tools, such as the Retarded Field Energy Analyzer (RFEA). In addition, the literature discusses the possibility of predicting such distributions theoretically based on in situ diagnostic data (virtual sensor).

The research was carried out within the framework of the State assignment of the National Research Center "Kurchatov Institute".

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# MICROWAVE DISCHARGE IN WAVE FIELDS ON THE SURFACE OF SOLIDS

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Subthreshold microwave discharge is an interesting object of research. The majority of modern studies are devoted to microwave subthreshold discharge in free space, but the most interesting are questions and problems of interaction of such discharges with various solid objects [1,2].

In this paper we investigate the microwave discharge excited in a powder of silver microparticles at different microwave intensity and ambient pressure. Under these conditions, the discharge propagation velocity, its effect on the target cube are determined, and the plasma deposition processes are investigated.

The work is of interest to specialists in the field of microwave discharges and plasma materials science.

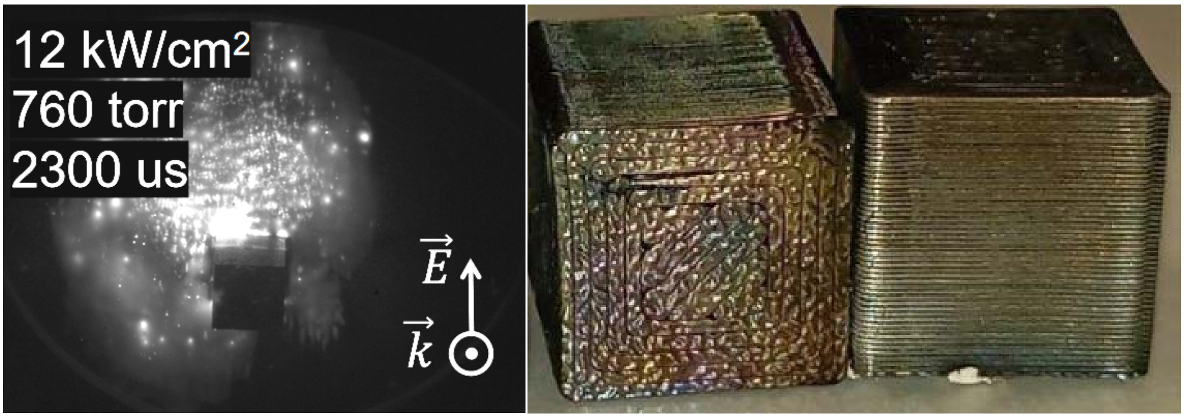


Figure 1 - Left) Image of wavefield discharge at 2300 μs after microwave breakdown; Rigth) Image of cube surface after plasma treatment

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# STUDY OF DIODE PLASMA ON THE FORMATION AND PROPAGATION OF SHOCK WAVES DUE TO HIGH-CURRENT ELECTRON BEAM EXPOSURE

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This study examines the effect of diode plasma on the formation and propagation of shock waves when exposed to a high-current electron beam of the Kalmar installation (beam current up to 35 kA, diode voltage up to 350 kV) on solid targets. The results of recent studies have shown that deformation waves can occur after a considerable time after exposure to an electron beam (~ 100 ns). It is possible that their formation may be influenced by diode plasma, since, according to some experiments, this area has rather extreme parameters. [1]

Numerical modeling of the processes in the diode gap was carried out for estimates within the framework of one-dimensional magnetic hydrodynamics. Based on the simulation results, it was revealed that an area of increased pressure appears in the plasma column, which eventually shifts towards the axis of symmetry.

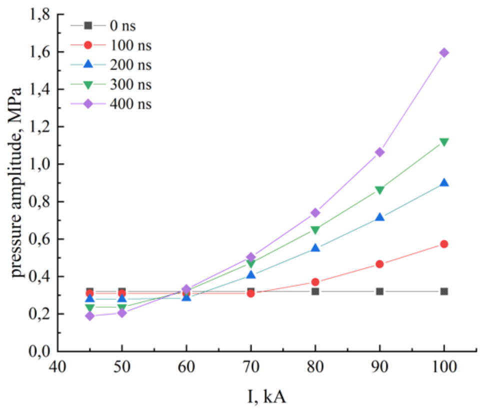


Fig. 1. The dependence of the maximum value of the gas-dynamic pressure in the plasma column on the amplitude of the current at different time points. The graph shows the time that is counted from the moment of the beginning of the conduction current.

Figure 1 illustrates the dependence of the maximum value of the gas dynamic pressure in the plasma column on the amplitude of the current. With a small current amplitude (up to 60 kA), the pressure value decreases over time. However, at higher currents, the amplitude of the gas dynamic pressure increases over time, and as the amplitude of the current increases, the amplitude of the pressure increases significantly.

An increase in plasma pressure in the column will generate an increase in pressure on the target surface, which can lead to the formation of secondary compression waves or shock waves propagating inside the target. Thus, it can be assumed that the processes occurring in a diode plasma can have a significant impact on the development of shock wave processes in solid targets.

The work was carried out within the state assignment of NRC "Kurchatov Institute"

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# SHORT WAVE-LENGTH EMISSION FROM A HOT DENSE PLASMA

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We calculate the photorecombination emission intensity, which determines emission from a hot plasma at thermodynamic equilibrium at a noticeable degree of ionization. In the case of air, the contribution of the short-wavelength emission in the range 60–100 nm to the total emission power is about 90%.Above 10 kK, this contribution is temperature-independent. The subject of this work is emission from a dense plasma with a noticeable degree of ionization, which is generated by an external source, with focus on the plasma in a conductive lightning channel when an electric current passes through it in the return stroke stage, i.e., at the maximum electric current. Such a plasma is formed via excitation and ionization of gas or vapor consisting of atoms with a partially filled electron shell. We consider distinctive features of such a plasma and emission from it.

Consider emission from an ionized gas. At a noticeable degree of ionization, it is determined by collisions of electrons and ions and leads to the formation of bound states of electrons and ions. The characteristic electron energy is taken to be considerably lower than the corresponding atomic energy, as is the case in a real plasma. The bremsstrahlung emission from the plasma then continuously transforms into recombination emission as the transition frequency increases.

The results are presented in Fig. 1. The emission intensity of an air plasma was calculated for atmospheric pressure and a temperature $T$ = 20 kK. The plasma was assumed to be optically transparent, so the emission intensity was taken to be proportional to its volume.

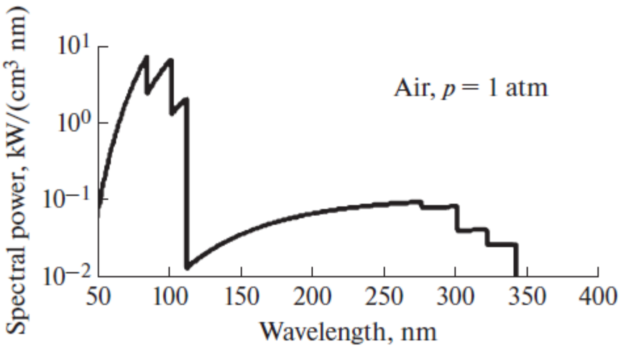


Fig. 1. Spectral power of the short-wavelength emission from an equilibrium air plasma at a pressure of 1 atm and temperature of 2 × 104 K according to Eq. (1).

The spectral dependence of the electron–ion photorecombination emission power per unit plasma volume per unit wavelength (W/(cm$^3$ ·nm)) is shown in Fig. 1 (see in detail Ref. [1]):

$$\frac{dP_\lambda}{d\lambda} = \frac{32\sqrt{2\pi^3}\alpha^2 e^6 N_e^2}{3\sqrt{3T}\sqrt{mT}} \sum_k \frac{g_k}{\lambda^2}\left(\frac{2J_k}{\mathrm{Ry}}\right)^{5/2} \times \exp\left(-\frac{2\pi c\hbar/\lambda - J_k}{T}\right)\eta\left(2\pi c\hbar/\lambda - J_k\right). \quad (1)$$

Here $\eta(x)$ is the Heaviside function.

As follows from Fig. 1, an air plasma is an effective VUV source between 60 and 100 nm. The emission power in this wavelength range exceeds the visible emission power. It follows from the above analysis that one can make a pulsed VUV source for certain wavelengths using appropriate gases or metal vapors that can be excited by electric current pulses. In such a case, a spark discharge is used as an energy source.

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# QUASI-STATIONARY MAGNET-INDUCED CONFINEMENT OF HIGH-ENERGY PLASMA FORMATION AT COLLISION OF CURRENT-CARRYING COMPRESSION PLASMA FLOWS

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During the last 20-25 years, evident amount of the papers were published, which are dedicated to the development of new techniques of thermonuclear synthesis realization, such a Magneto-inertial fusion (MIF). To realize MIF in the thermonuclear facilities being developed, the implosion liner compresses target magnetized plasma to thermonuclear parameters [1-2]. The most interesting proposal in this respect envisages application of a coaxial plasma accelerator with the profiled solid electrodes, in which multiple plasma jets of relatively small power are being injected into the main accelerating channel. The main accelerating channel and plasma injectors possess independent high-voltage power supplies [2].

The efficiency of such a system creates justified doubts, since the plasma gun works under the current transfer mode by electron. In such a system with a rise in discharge currents the electrons become magnetized and can't flow transversely the accelerating channel but drift along the anode. As a result, near the anode a powerful potential jump is formed, which leads to anode destruction and ingress of admixtures into plasma and disrupt regular plasma flow in the channel itself. In order for eliminate current drift along the anode surface it is necessary to realize ion current transfer mode of the accelerator operation, which is brought out clearly in the papers of Prof. A.I. Morozov.

At the our works a fundamentally new approach to generate and confine high-energy plasma during the collision of opposite-directed current-carrying supersonic compression plasma flows, which are generated by quasi-stationary high-current plasma accelerators operated at the mode of ion current transfer, have been proposed and demonstrated for the first time [3-4].

Collision of compression flows generated by quasi-stationary high-current plasma accelerators of magnetoplasma compressor type (MPC) was shown to lead to the generation of a spherical plasma formation confined by self-magnetic field without gaps with $\beta \sim 1$ (approximate parity of magnetic pressure and plasma pressure), which is induced in a self-consistent way at oncoming interaction of current-carrying compression flows. In this case due to viscous dissipation (thermalization) of colliding compression flows, transition of their kinetic energy into internal energy of spherical plasma formation takes place, ensuring extremely high values of charged particle concentration and plasma temperature in the collision area.

The experiments conducted showed that the magnetic field formed during the collision of current-carrying compression flows has a complex structure, which is a superposition of fields excited by currents flowing in different directions. In particular, interferometric studies of the compression flows collision have shown the presence of discontinuities in interference fringes around the collision region, which indicate the presence of a high gradient in the plasma refraction values at the boundary of the compression flow – the collision region.

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# EXPERIMENTAL INVESTIGATION OF AN ABSORPTION OF THE ORDINARY POLARIZATION MICROWAVES IN A PLASMA FILAMENT

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It is known, that in experiments on electron-cyclotron resonant heating (ECRH) a large number of various anomalous effects (anomalous backscattering, anomalously accelerated ions) are observed [1-2]. How it was shown in [3], similar effects (anomalous absorption) can be exited at non-monotonous density profile for pump wave of ordinary polarization. The experimental investigation of microwave absorption at plasma filament at magnetic field level higher than the ECR for half-frequency of pump is under investigation in this work.

A plasma filament is created by homemade pulse HV power supply in a quartz tube (inner diameter 22 mm) filled with argon at a pressure of about 1-2 Pa and placed in magnetic field of up to 57 mT. The maximal average plasma density in the filament is slightly exceeded $2\times10^{16}$ $m^{-3}$ and electron temperature is about 1 eV. The tube with plasma passes through a waveguide with a cross section of $72\times34$ $mm^2$ perpendicular to wide walls. Pulses of microwave power (up to 1000 W) at a frequency of 2.38 GHz are supplied to the plasma by this waveguide. Thus, there is an ordinary polarized wave in plasma. The presence effect of a strong anomalous absorption of incident power in a plasma filament depending on the magnetic field, plasma density and microwave power is demonstrated. The threshold nature of this effect is shown. It is obtained, that its efficiency is about 30-40 % and is accompanied by an increase of electron temperature up to 5 eV and of electron density about one order of magnitude. The scenario of pump wave decay into upper-hybrid and Langmuir waves was propose. The agreement of calculated threshold of this absorption (about 80 W) with experimental one – 50 W is demonstrated.

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# FEATURES OF ELECTRODYNAMICS OF HIGH-FREQUENCY DISCHARGE IN A MAGNETIC FIELD

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Discharges in a magnetic field [1, 2], including discharges at electron cyclotron resonance and helicon discharges, have several advantages when creating technological installations operating at low gas pressure. To analyze processes in technological installations using this type of discharge (for example, discharges in a magnetic trap [3], [4]), it is necessary to compare calculations of the spatial distribution of the electromagnetic field and calculations of the wave's spectra in the geometry used in experimental installations in a wide range of plasma parameters.

In this paper, such a comparison is made for a discharge in a resonator. The paper calculates the dispersion characteristics of waves propagating in a flat symmetric three-layer waveguide partially filled with magnetoactive plasma with a magnetic field directed parallel to the boundary. Calculations are made of changes in the spectra of waves propagating along and the magnetic field. As an example, Fig. 1 shows the calculations of the dependence of the wave numbers of waves in the waveguide across the magnetic field. The numbers in the figure indicate different modes [5] of waves that can propagate in the waveguide: 1 – surface waves, 2 – volume waves, 3 – dielectric waveguide waves, 5 - quasipotential waves. The influence of electron pressure on wave's spectra is discussed.

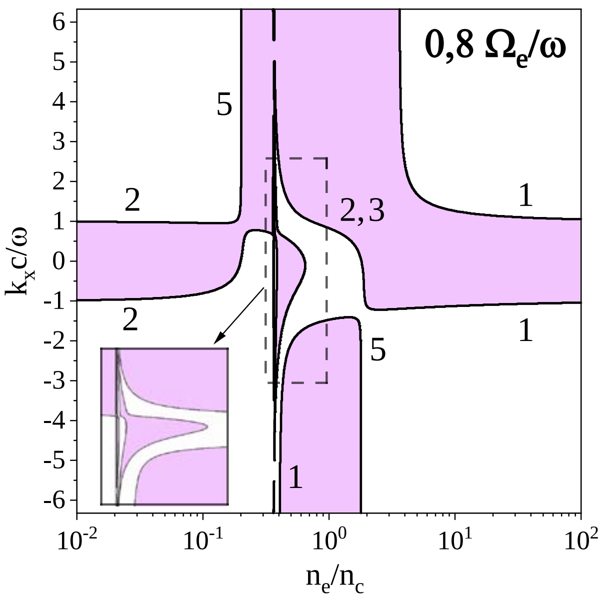


Fig. 1. Calculated values of dimensionless waves propagation constants of across the magnetic field $k_z c/\omega$ as functions of the electron density for different values of the ratio of the cyclotron frequency to the field frequency: $\Omega_e/\omega$ = 0.8. Field frequency 2.45 GHz.

Comparison of the wave~~'s~~ spectra and spatial distributions of the electromagnetic field in the resonator showed their satisfactory agreement. The obtained results can be useful in the development of technological devices using radio frequency and microwave discharges.

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# GENERATION OF RUNAWAY ELECTRONS IN LOW PRESSURE AIR FROM CAPACITIVE DISCHARGE PLASMA

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One of the important issues that arises when studying pulsed discharges in the Earth's atmosphere at high altitudes above sea level, in particular when formation red sprites [1] is the generation of runaway electrons.

In this paper, it is shown for the first time that a runaway electron beam (REB) is registered during the formation of miniature analogues of columnar red sprites in the laboratory. Runaway electrons were registered in air at pressures of 0.4 and 1 Torr from plasma initiating plasma diffuse jets (PDJs), which had no contact with metal electrodes. The conditions for the generation of PDJs formed by streamers (ionization waves) and their properties are described in detail in [2-4]. This study was carried out on a setup in which a collector with a time resolution of up to 100 ps was mounted in the quarts tube. The setup diagram is shown in Fig. 1.

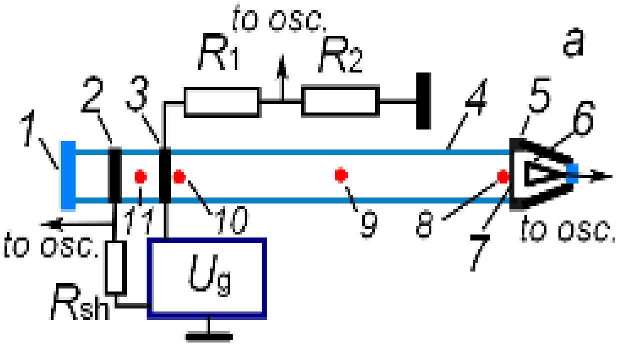


Fig. 1. Schematic diagram of the setup. *1* – left end flange made of caprolon, *2* and *3* – 1 cm wide external ring electrodes made of 100 µm thick foil, *4* – quartz tube with an internal diameter of 5 cm and a wall thickness of 2.5 mm, *5* – collector body, *6* – receiving part of the collector with a diameter of 2 cm, *7* – nickel grid, *8-11* – discharge regions from which radiation was fed through a light guide to a silicon photomultiplier (SiPM). $R_1$ and $R_2$ are the resistances of the TT-HVP 2739 voltage divider, $R_{sh}$ is the shunt resistance, $U_g$ is the NPG-18/2000N pulse generator of negative polarity.

The conducted studies have shown that, when forming plasma diffuse jets by a pulse-periodic capacitive discharge, a beam of runaway electrons is generated in the absence of contact between the initiating plasma and the metal cathode. It has been established that under these conditions the REB is ahead of the PDJ front and is registered by the collector before its arrival. The obtained results show the possibility of generating runaway electron beams from columnar red sprites when negative streamers directed upward from the Earth's surface arise.

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# TRICHEL PULSES IN NEGATIVE CORONA DISCHARGE: INSTABILITY AND BEHAVIOR NEAR THE GENERATION THRESHOLD

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When a negative voltage is applied to an electrode with a small radius of curvature and a corona discharge is ignited in air, a pulsed discharge mode is realized in a certain voltage range – the so-called Trichel pulses (TP) [1]. This phenomenon has been the subject of numerous studies, both experimental and theoretical. However, some issues remain uncertain. Thus, a number of studies report of measuring the current at the stage preceding the TP. In this case, the current value in different studies fluctuates from 0.1-1 nA [2] to (~0.1-1 μA) [3-5].

In our work, we investigated the stage preceding the TP. The negative corona was ignited in the "point – plane" gap. Measurements of the discharge current and voltage were performed using oscillography. Since the level of the studied current was $10^5$-$10^7$ times lower than the value of the TP current, a damping capacitor connected in parallel to the megohm input of the oscilloscope was used to protect the oscilloscope from overvoltage. The damping capacitor did not affect the measurement of quasi-stationary current. At the same time, information about the appearance of the TP was saved. A 0.1 Mohm resistance or the megohm input of the oscilloscope was used as a current shunt. The studies showed that under the experimental conditions (centimeter gap, ~20 µm point radius, and atmospheric pressure air), the current before the onset of the TP was not detected with an accuracy of ±0.2 nA.

In addition, it was discovered for the first time that in a certain voltage range, the TP mode after its initiation becomes unstable and periodically changes to a pulseless mode with a current of $\lesssim$ 1 μA (Fig. 1).

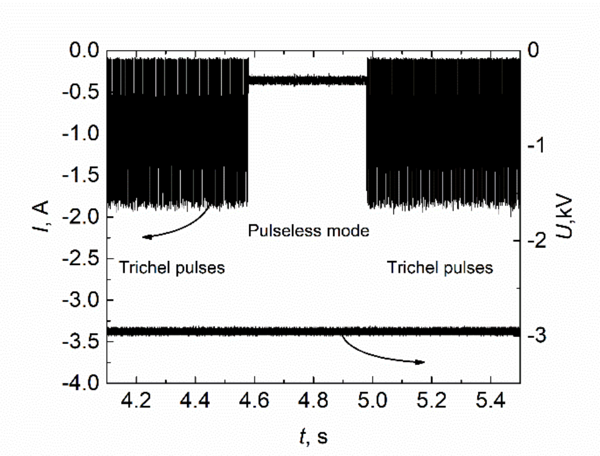


Fig. 1. Waveforms of corona discharge current and gap voltage.

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# ON PROGRESS IN THE STUDY OF ANEUTRONIC PROTON-BORON FUSION IN A NANOSECOND VACUUM DISCHRGE

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Earlier, during the experiment and PiC modeling, the possibility of ion confinement and ion acceleration to energies of tens of keV by the field of a virtual cathode in an inertial electrostatic confinement scheme with reverse polarity was revealed. This scheme was implemented on the basis of a miniaturized nanosecond vacuum discharge (NVD) of low energy, in which both DD neutrons and α–particles from the aneutronic proton-boron reaction were observed experimentally [1]. In this work, in search of ways to optimize proton–boron (pB) synthesis in HBP, we study the scaling of pB synthesis power depending on the size of the virtual cathode (or the inner radius of the anode space). In fact, the previously obtained favorable scaling of the DD fusion power for oscillating plasma [2-4], which increases with inverse radius of the virtual cathode (VC), also stimulates this work. The obtained results of PiC modeling using the KARAT code [5] show that the number of proton-boron reactions in the anode space of NVD increases with increasing of anode space, in contrast to scaling DD synthesis, and the yield of α-particles turns out to be proportional to the value of the anode radius (or VC size) in the range $R_A \approx 0.1 - 0.5$ cm. However, the number of proton-boron reactions reaches a certain saturation with increasing $R_A$ at a fixed time of high voltage and the amount of energy supplied [6]. New experimental data on the release of α–particles from pB reaction, obtained in the resumed experiment with NVD, will also be presented and discussed. In general, the yield of alpha particles increased by more than two orders of magnitude compared to the first experiments [1], and confirms the trend found by PiC modeling in the yield of pB reaction in the NVD with an increase in the radius of the virtual cathode. Thus, the formation of a more voluminous potential well (wider in radius and extended along the discharge axis) [6], with pronounced oscillations of protons and boron ions in it, provides a noticeable increase in the yield of α–particles.

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# ANEUTRONIC PROTON–BORON-11 REACTION IN QUASI-STATIONARY HIGH-DENSITY PLASMA

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The potential feasibility of using energy from the p–$^{11}$B reaction is amplifying interest in the development of efficient thermonuclear fusion methods. The aneutronic p–$^{11}$B nuclear fusion reaction is currently being intensively studied in laser experiments [1-2], and the concepts of systems based on magnetic confinement (even tokamak [3]) and magneto-inertial systems (e.g. dense plasma focus [4-5]) are also considered.

In present study, combined non-stationary scenarios with fuel refill are analyzed. The ratio of fuel components is taken to be $x_B = n_B/n_p \sim 0.15–0.2$ ($n_B$ is the density of boron ions, $n_p$ is the density of protons). It is shown that achieving a positive energy yield apparently requires a combination of features of inertial systems (compression of fuel to a high density $n \sim 10^{30} - 10^{31}$ m$^{-3}$) and magnetic confinement (supply of fuel and energy to the reaction zone, confinement time exceeding the inertial expansion time). Plasma ignition occurs when the ratio $P_{fus}/P_{br} > 1$, where $P_{fus}$ is the thermonuclear fusion power and $P_{\mathrm{br}}$ is the bremsstrahlung radiation power. Estimations indicate that achieving this condition requires heating ions to a temperature of $Ti \sim$ 200 keV and electrons to $T_e \sim$100 keV. The gain in Maxwellian plasma is $Q \sim 5$, and taking into account the accumulation of fusion “ash” (alpha particles), the gain $Q < 1$.

The factors limiting the gain are considered, which are mainly associated with the ratio of the reaction rate, bremsstrahlung losses, and energy exchange between ions and electrons. The calculation technique is based on non-stationary balance equations for particles and energy. Potential possibilities for increasing Q in non-Maxwellian plasma [6] are shown (taking relaxation into account). Possibilities for removing “ash” are discussed

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# EVIDENCE OF PLASMA PHASE TRANSITION IN WARM DENSE CESIUM

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Equation of state and dielectric propeties of cesium at high pressures 1--1000 GP are calculated using quantum molecular modelling within the framework of the density functional theory. PBE (Perdew, Burke, Ernzerhof) parametrization of exchange-correlation functional is implemented. The existence of plasma phase transition in cesium, when an abrupt change of conductivity accompanies a sharp increase in density, is predicted. The indicators are emergence of wide metastable branches of isotherms, with significantly higher mean ion charge of cesium plasma in comparison to stable ones, and huge overlapping of these branches in volume.

# ABOUT THE EFFECT OF CATHODE DISPERSION ON THE CHARACTERISTICS OF DIRECT CURRENT DISCHARGE

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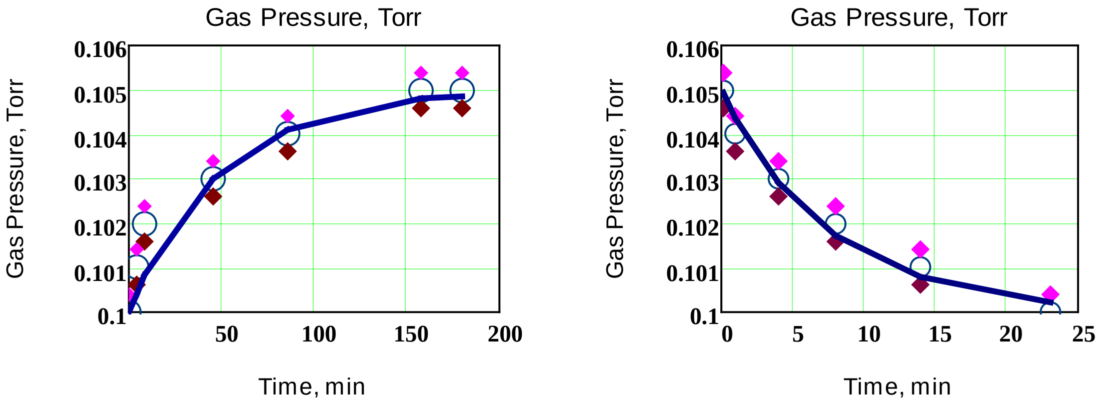
In the cathode layer of a direct current discharge at reduced gas pressure, ions acquire energy of the order of 200 - 300 eV and therefore, when they hit a metal cathode, they knock out an atom from it with a high probability, i.e., cathode sputtering occurs. In this paper, an analysis of experiments on measuring the time dependences of pressure and voltage in the direct current mode in the tube when the discharge is turned on and the pressure drop when the discharge is turned off is performed. After the discharge is ignited, the atoms sputtered from the cathode accumulate in the tube volume until the reverse process of removing atoms due to their deposition on the walls, doping the cathode with metal ions compensates for its entry due to cathode sputtering (see Fig. left: markers – experiment, line – analytical fit).




The right figure shows similar data on the dependence of the gas pressure in a sealed tube after the discharge is switched off. In this case, the sputtered atoms of the metal cathode are deposited on the walls of the tube and the cathode, and the gas pressure becomes equal to the initial value of 0.1 Torr. The paper presents the results of modeling the characteristics of the discharge in inert gases with a small admixture of metal vapors, provides estimates of the characteristic times of pressure and voltage change in the direct current mode, and constructs a mathematical model for determining the concentration of the admixture in the presence of gas pumping in the constant pressure mode [1-3].

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. 075-00269-25-00).

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# OBTAINING AND REGULARIZATION OF A HEXAGONAL IRREGULAR COMPUTATIONAL GRID FOR PLASMA CALCULATIONS

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The paper proposes a method for transition from a tetrahedral to a hexagonal irregular computational grid. A variant of an elliptical grid "regularizer" has been developed, which is based on a "mechanical analogy" and is based on solving the linear equations of elasticity theory. A brief analysis of the advantages and disadvantages of irregular and regular grids has been performed. The initial results of rebuilding and "regularization" of the computational grid are presented, as well as the distribution of the "angular" criterion for assessing its quality. Several mathematical models based on irregular computational grids were created by authors previously [1-10]. Refinement and improvement of the numerical methods are given in this work.

This research has been supported by the Ministry of the Science and Higher Education of the Russian Federation (Russian Minobrnauki), Project No. FSFN-2024-0011.

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## PROSPECTIVE SCHEMES OF RADIO-FREQUENCY PLASMA THRUSTERS

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The results of an experimental study of promising schemes of electric thrusters (ETs) based on a radio-frequency (RF) discharge are presented. The schemes of gridless ETs based on a capacitive RF discharge in crossed fields and a helicon discharge, as well as a gridded ion thruster with an external magnetic field are considered. The main dependences of the characteristics of the listed laboratory models of ETs on the external parameters of the discharges are obtained and analyzed.

It is shown that when organizing a capacitive RF discharge in the Hall thruster (Stationary Plasma Thruster [1]) geometry, a quasi-stationary potential jump is localized at the discharge channel outlet, accelerating ions. The energy of ions flowing out of such gas discharge chamber (GDC) depends on the type of the external discharge circuit: for DC closed and open circuits, it reaches values of about 350 eV and 70 eV, respectively. In the case of DC open discharge circuit, it is possible to extract an ion beam compensated by electrons without using an external cathode-compensator.

It has been experimentally determined that when an external longitudinal magnetic field is applied to an inductive RF discharge in a cylindrical GDC, directed flows of electrons and ions exiting from the outlet at the end of the GDC are formed. The energy and density of particles in these flows have clearly expressed non-monotonic dependences on the induction of the external magnetic field, and in the absence of an external magnetic field, directed flows of particles from the studied helicon source were not observed. It has been shown that, among other factors, such results are caused by the excitation of plasma waves inside the GDC.

For a gridded RF ion thruster operating in a pulsed mode, the possibility of increasing the extracted ion current at a given average RF power over time compared to the continuous mode is demonstrated. This increase is achieved by extracting the ion current through the ion-optical system at the deionization stage, when the RF power supplied to the discharge is zero.

Based on the results of the examination of the indicated promising electric propulsion schemes, conclusions were made about the possibility of their use to obtain thrust on spacecraft and their strengths and weaknesses were analyzed in comparison with existing electric propulsion schemes.

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# OPTIMIZATION OF RADIO-FREQUENCY ION THRUSTER PROTOTYPE FOR OPERATION AS PART OF AN AIR-BREATHING ELECTRIC PROPULSION ENGINE IN ULTRA-LOW EARTH ORBITS

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Nowadays, the pace of exploration of near-Earth space has increased significantly. Only 10 years ago the number of all artificial Earth satellites was about two thousand, but now the same number of spacecrafts (SC) is launched annually, and the plans of the largest corporations like SpaceX and Amazon in the next decade include the launch of several tens of thousands more SC.

In this regard, there is a danger of global contamination of the developed near-Earth orbits of medium altitudes (500-2000 km) with space debris, which may be irreversible [1] since an adequate method for cleaning space orbits from debris has not yet been invented by mankind.

The only reasonable solution in such conditions is to conquer ultra-low Earth orbits (ULEO, 160-250 km). Besides the low cost of space launches, chipper non-radiation-resistant functional equipment and better signal-noise ratio, the decisive advantage of ULEO is the presence of the residual atmosphere, leading to the decay of any space debris from these orbits in about a month. However, it is necessary to equip the spacecraft with a thruster capable of operating non-stop for many years constantly compensating the resistance of the planet's residual atmosphere.

The world community has already formed a general concept of an Air-Breathing Electric Propulsion Engine (ABEPE) to solve the problem of the lack of fuel on board for long-term maintenance of the satellite in orbit [2]. ABEPE consists of an air intake, which provides a flow of the working fluid (outboard atmospheric gases) into the gas-discharge chamber of the electric propulsion thruster (EPT), which creates the necessary thrust and receives power from solar panels. However, most of the existing and tested to date types of EPT operate on the noble gases xenon or krypton and fundamentally cannot operate on chemically active gases nitrogen and atomic oxygen, which are predominant in ultra-low orbits [3], due to their cathodes design.

In this regard, one of the main candidates for the role of an electric propulsion thruster for ultra-low orbits is a Radio-Frequency Gridded Ion Thruster (RF GIT), since it is cathodeless and is capable of using chemically active gases as a working fluid, is characterized by a long service life and has the highest ion exhaust velocity which is also important for compensating the resistance of the particle flow hitting the spacecraft at the first cosmic velocity.

This paper presents the results of the RF GIT optimization for operation on gases of the residual atmosphere of ultra-low Earth orbits. Measurements of the operating parameters of the thruster prototype are performed and the estimates of the energy consumption for maintaining a spacecraft in the orbits are made. To improve the thruster operating parameters longitudinal external magnetic field was imposed on the discharge, the generator operating frequency and the length of the gas-discharge chamber were varied. The experimental results are compared with the calculations.

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# PLASMA OF THE EARTH'S LOWER IONOSPHERE IN THE YEAR OF MAXIMUM SOLAR ACTIVITY

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High solar activity provides high plasma density (electron concentration). As a result, the conditions for propagation of HF and VHF radio waves are improved. In the ionogram shown in Fig. 1 (left), the critical frequency has reached 13 MHz, and as a result, radio waves with a frequency of up to 40 MHz can propagate along a 3000 km long path [1]. On the contrary, geomagnetic perturbations caused by solar disturbance lead to a sharp decrease in critical frequencies and degradation of the conditions for propagation of radio waves.

The paper contains results of studies of the lower ionosphere (60–130 km) using the method of resonant scattering of radio waves on artificial periodic irregularities (APIs) of the ionospheric plasma [2,3]. We present results of recent observations of sunset-sunrise phenomena in the plasma and neutral component during high solar activity based on the study of the ionosphere by the API technique.

APIs created by powerful HF radio emission from the SURA heating facility (56.1°N; 46.1°E). The observations were carried out on June 27–29, 2023 (average monthly sunspot number W=160.5), October 4–5, 2023 (W=134.2) and September 23–24, 2024 (W=141.4) under conditions of high solar activity. The irregularities were created by the emission into zenith of a powerful radio wave of extraordinary or ordinary polarization at frequencies of 4.3, 4.7 or 5.6 MHz by the SURA facility transmitters. Radio wave probing of irregularities was carried out at the same frequencies by radio waves of the same polarization. The amplitudes and phases of signals scattered by artificial irregularities were measured. On this basis, data on variations in the amplitude and relaxation time of the scattered signal in height and time, the velocity of the vertical plasma motion, and the temperature of the neutral component were obtained.

Sunset-sunrise asymmetry of the D-region, caused by the peculiarities of the change in the coefficients of attachment and detachment of electrons from neutral molecules, was confirmed. During sunset an increase in the heights of scattered signals in the D region was observed with a gradual disappearance of the APIs at night, which is typical for the transition to the night state of the ionosphere. At sunrise a sporadic E layer ($E_s$ layer) often developed, improving the conditions for the creation of APIs and probe radio waves scattering. Manifestations of internal gravity waves with specific periods from several minutes to several hours were found in variations of the relaxation time of the scattered signal, the velocity of vertical plasma motion and the temperature of the neutral atmosphere.

The work was carried out under Russian Science Foundation project No. 25-27-00031.

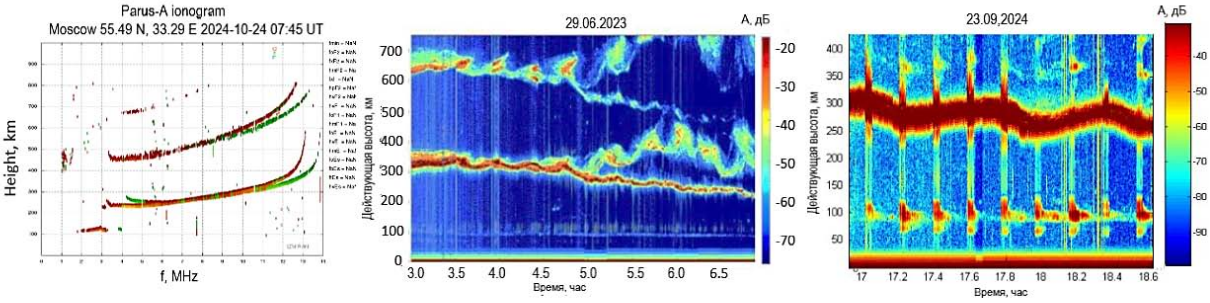


Fig. 1. An example of ionogram in period of high solar activity (left), altitude-temporal variations of the amplitude of ionosphere and API scattered signals during sunrise June 29, 2023 (center )and sunset September 23, 2024 (right).

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# INVESTIGATIONS OF THE IONOSPHERIC DISTURBANCES DURING THE MAGNETIC STORM IN MARCH 2015 BY USING *FORMOSAT-3/COSMIC* SATELLITE RADIO OCCULTATION MEASUREMENTS

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Results of about 50 sessions of sounding the Earth's high-latitude (> 65°N) ionosphere conducted on March 17–18, 2015 in the *FORMOSAT-3/COSMIC* radio occultation experiment for two ranges *L1* (~19.0 cm) and *L2* (~24.4 cm) of decimeter (DM) waves are analyzed. Coronal mass ejections (CMEs) that reached the Earth's magnetosphere during the specified time period provoked a strong magnetic storm of the *G4*-class (*G4* = *Kp* – 4), in which the maximum values of the *Kp*-index were equal to 8. This storm caused significant fluctuations in the characteristics of DM radio waves on the sounding paths: navigation (*GPS*) satellites – low-orbit (*FORMOSAT-3/COSMIC*) satellites. The most noticeable variations in the power of DM signals were observed in the *E*-region at altitudes below ~110 km. Here, the oscillations of the power of DM signals with vertical sizes <2 km (diffraction scales) during the main phase M2 of the magnetic storm reach values of +2.5 and –3.0 dB. A correlation found between the fluctuations in the refractive attenuation and in the power of radio waves indicates the decisive contribution of layered inhomogeneities to the observed power variations with vertical sizes >2 km. The studies conducted in the Earth's ionosphere are important for analyzing the dynamics of space weather, and are also of practical interest in the problems of ensuring radio communications and navigation.

The work was carried out within the framework of the state order of the Kotel'nikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences.

# PLASMA-ACTIVATED WATER: A MULTIFUNCTIONAL MEDIUM FOR BIOMEDICAL AND NANOTECHNOLOGICAL APPLICATIONS

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Plasma-activated water (PAW) has emerged as a versatile medium with broad applicability due to its unique chemical composition, formed through interactions between gaseous plasma and liquid water [1]. The generation of reactive oxygen and nitrogen species in PAW enables its use across various fields, including biomedicine, materials science, and environmental engineering [2]. Its antimicrobial and anticancer properties have been extensively explored in medical applications, ranging from biofilm eradication and wound healing to disinfection and targeted cancer therapies [3]. In parallel, PAW has demonstrated significant potential in nanotechnology, particularly in thin film synthesis and surface modification.

Recent advances have highlighted PAW's effectiveness in atomic layer deposition (ALD), where it serves as a novel oxidant, enhancing thin film growth. The use of ex-situ prepared PAW increased the growth per cycle (GPC) of $Al_2O_3$ films by up to 19%, comparable to energy-enhanced ALD. PAW was generated using a pin-to-liquid system and analyzed alongside aqueous solutions of $O_3$, $H_2O_2$, and $NO_3^-$. Experimental results showed that PAW outperformed individual species, with $NO_3^-$ playing a key role. A kinetic model suggested additional reactive pathways, underscoring PAW's potential for optimizing ALD processes in microelectronics, protective coatings, and biomedical applications.

This presentation provides an overview of PAW's emerging applications, focusing on its role in biomedical engineering and nanotechnology. The discussion will highlight recent experimental results, emphasizing the physicochemical mechanisms underlying PAW's reactivity and its impact on material synthesis and biological interactions. By bridging plasma science with technological advancements, PAW represents a promising tool for next-generation applications in healthcare and advanced materials.

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# ENERGETIC PLASMA BUNCHES GENERATED UNDER AUTORESONANT INTERACTION IN A LONG MIRROR TRAP

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A significant area of research in the field of plasma bunch generation with an energetic electron component is the study of interactions between magnetoactive plasma particles and electromagnetic radiation. One possible type of such interaction is autoresonant particle acceleration, which can be realized in both traveling wave and standing wave regimes [1]. The mechanism for sustaining cyclotron autoresonance in a standing wave field by varying the external magnetic field over time or space is known as gyromagnetic autoresonance (GA) and has been experimentally demonstrated [2, 3]. In this study, we implement a scenario that integrates the generation of plasma bunches with an energetic electron component under GA interaction conditions and their accumulation in a magnetic trap of an extended probkotron [4]. The primary objective is to determine the optimal operational parameters that ensure maximum efficiency in electron capture and acceleration, as well as to establish the retention duration of the generated plasma bunches within the operational capabilities of the electrophysical test facility. The analysis is based on a detailed investigation of the spatiotemporal and spectral-angular distribution of both bremsstrahlung (BR) and characteristic radiation (CR), which are emitted by plasma bunches when interacting with gaseous and solid targets. X-ray spectrometry and radiometry in the energy range up to 1000 keV were carried out using two identical X-ray detectors (BDEG, NaI(Tl), 40×40). For CR detection in the soft X-ray range, X-123-CdTe and Si-Pin-X-123 spectrometers were employed, with energy resolutions of no worse than 1.5 keV and 139 eV, respectively. X-ray imaging of the generated plasma bunches in the longitudinal direction was performed using a compact scintillation camera (Ximea xiRAY, MH110XC-KK-FA), which features direct phosphor visualization, high resolution, high sensitivity, and low noise levels in the 7–100 keV energy range. Additionally, a pinhole camera with Super HR-U (FUJIFILM) X-ray films was used for further imaging. The energy analysis of BR was conducted with a registration time window of 150 μs, covering both the acceleration phase (lasting 500 μs) and the confinement phase (up to 10 ms). It was demonstrated that the energy spectrum of BR photons, which reflects the electron distribution function within the bunch, exhibits significant variations when measured along and across the magnetic field. Furthermore, transformations in the spectrum were observed when transitioning from the acceleration phase to the confinement phase. Analysis of the X-ray images and variations in CR line intensities from the gas target provided insights into the influence of the magnetic field variation rate during the GA stage on particle capture in the acceleration mode, which is directly related to the number of energetic electrons retained in the electron vortex. The observed CR lines from the chamber walls enabled an assessment of the integral particle losses, accounting for losses occurring both during the GA phase and the confinement phase. The obtained results are compared with numerical simulations based on a developed theoretical model [5].

The research was carried out within the State Assignment of Ministry of Science and Higher Education of the Russian Federation (theme No. FSSF-2025-0001).

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# ECR HEATING IN THE COAXIAL PLASMA SOURCE CERA-RX(C)

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The study presents experimental and modeling results on the investigation of soft X-ray radiation from the volume of the compact ECR plasma source CERA-RX(C), an original design [1]. The CERA-RX(C) source consists of a cylindrical half-wave coaxial resonator operating at a pump wave frequency of 2.45 GHz. The microwave power supplied to the resonator varied in the range of 0.01–10 watts. Under these conditions, the plasma's electron component predominantly undergoes azimuthal drift in the space between the electrodes of the coaxial resonator, caused by the radial inhomogeneity of the magnetic field within the resonator. The design features of the plasma source's magnetic system allow for adjusting the radial position of the ECR zone, thereby providing conditions for the effective deposition of hot electrons onto the lateral surface of the axial electrode of the resonator. To localize the azimuthal deposition of electrons, the axial electrode of the resonator was supplemented in its central part with a radially oriented target electrode, which is a molybdenum cylinder (3 mm in diameter and 3 mm in height). The spatial localization of the X-ray radiation region is determined the linear size, shape of the target and the spatial spread of the electron trajectories.

The experimental setup is equipped with various control and measurement systems and diagnostic tools. The energy composition and spatial localization of X-ray radiation from the target was registered by a semiconductor detector based on a Si(Li) crystal and a CCD matrix. To optimize the operation of the CERA-RX(C) source and explore the possibility of improving its efficiency, a numerical model was constructed in accordance with the particle-in-cell method [2, 3], enabling three-dimensional simulation of ECR heating process. The simulation of X-ray radiation from the target electrode based on the Monte Carlo method. The calculations were performed for a system geometry corresponding to the actual experiment.

The optimal parameters of the source were determined, the maintenance of which ensures optimal heating and transport of the hot electron component of the plasma to the target. Experiments conducted under pulsed microwave generation conditions revealed a delay in the detection of X-ray of less than 2 μs from the moment of pulse application, with their presence persisting for up to 10 ms after the pulse ended. Varying the microwave power supplied to the resonator from 0.01 W to 1.5 W resulted in a change in the maximum energy of gamma radiation from the target, ranging from 20 keV to 50 keV.

Additional experiments conducted using various dosimetric equipment and methods estimated the exposure dose rate to be approximately 30 R/h at a distance of 0.3 meters from the source, with a maximum gamma-photon energy of 50 keV.

This indicates the effectiveness of the electron heating mechanism and the retention of hot electrons in the source. The experimental results obtained are consistent with numerical modeling.

The research was carried out within the State Assignment of Ministry of Science and Higher Education of the Russian Federation (theme No. FSSF-2025-0001)

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# MODELING OF DIFFRACTION OF A PLANE ELECTROMAGNETIC WAVE ON A MICROSTRUCTURED PLASMA OF A HIGHLY IONIZED PULSED NANOSECOND GAS DISCHARGE

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In this paper, we simulated the diffraction of a plane electromagnetic wave by a microstructured plasma of a highly ionized pulsed nanosecond gas discharge. The development of methods for solving and modeling the direct problem of diffraction on a microstructured plasma makes it possible to increase the accuracy of reconstructing the structures of phase microobjects using interferometry, which is widely used in the experiment [1]. The modeling in the work was carried out using the Rytov method, which is particularly sensitive to phase contrast [2]. The structure under consideration is a round cylinder consisting of 30-40 filaments with a smoothly changing permittivity profile. The overall size of the structure is about 300 microns in diameter, the diameter of one microstructure is 20 μm. The maximum electron density achieved in each filament is approximately $5\times10^{19}$ $cm^{-3}$. The wavelength of the probe radiation is 532 nm. The obtained diffraction patterns are in good agreement with the experimental data obtained in the article [1].

The study was supported by the Russian Science Foundation (project no. 24-79-10167).

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# FORMATION OF ALUMINUM OXYNITRIDE CONTAINING MATERIALS IN THE PRESENCE OF MONO- AND POLYVALENT CATIONS UNDER A MICROWAVE DISCHARGE

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For the last decade we have been developed a new approach for plasma chemical synthesis of micro- and nanodispersed materials of different types. The approach is based on the use of MW discharge, which occurs in the mixtures of metal and dielectric powders when they treated with short (2-8 ms) and high-power (up to 350 kW) pulses of MW irradiation (75 GHz). The experimental setup is described in details in [1]. The developed approach was utilized to prepare the material containing aluminum oxynitrides (AlONs) [2]. AlON is considering to be a perspective substance for making protective glasses and phosphors [3].

Considering that recently we are staying focused on synthesis of AlON containing materials doped with different mono- and polyvalent cations, and herein we describe our latest results. The mixtures of metal aluminum, $Al_2O_3$ and AlN with an addition of corresponding nitrate (Na, K) or oxide (Mg, Ca, Zr, La, Ce) were used as starting mixtures. The Al:$Al_2O_3$:AlN molar ratio was set to 1:2:1, 2:2:1 or 4:2:1, the content of dopant was 2.0 at. % vs. aluminum in $Al_2O_3$+AlN. The mixtures were put in a plasma chemical reactor (fig. 1a) and treated with pulses of MW irradiation (8 ms/400 kW). The Ni wire grid was set up as shown in fig. 1a to initiate a non-self-sustaining breakdown and intensify plasma chemical process It was found that AlON formation can be promoted by addition of mono- and divalent cations of alkali and alkali earth metals (Na, K, Mg, Ca – as an example see fig. 1b) while polyvalent cations are less effective in that way.

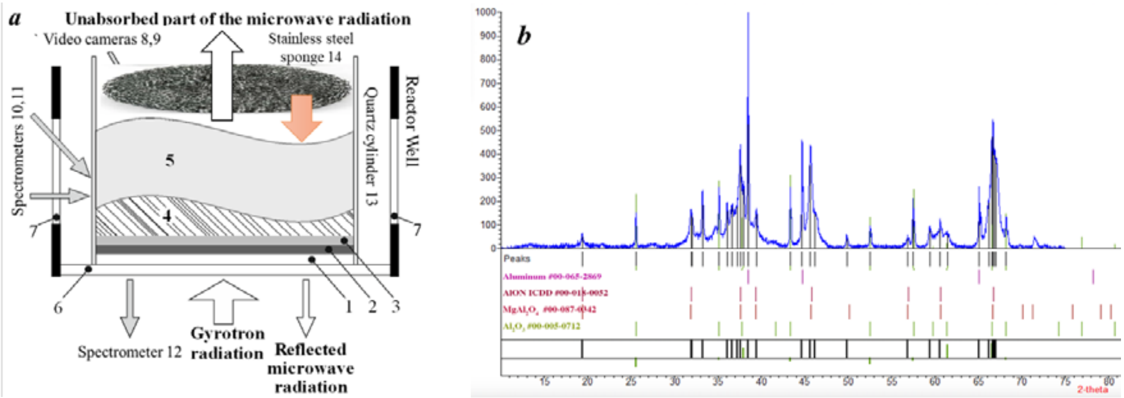


Fig. 1. (a) Plasma chemical reactor; (b) XRD pattern for Al/$Al_2O_3$/AlN + 2%MgO mixture after treatment.

The work was carried out within the framework of the State Assignment No. FFWF-2022-0001 «Study of innovative synthesis of micro- and nanoparticles with controlled composition and structure based on a microwave discharge in gyrotron radiation».

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# PREPARATION OF BIMETALLIC SUPPORTED CATALYSTS USING A MICROWAVE DISCHARGE

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Developing a new approach for plasma synthesis of micro- and nanodispersed materials via MW discharge, which occurs in the mixtures of metal and dielectric powders when they treated with short (2-8 ms) and high-power (up to 350 kW) pulses of MW irradiation (75 GHz), we realized that it can be applied to preparation of metal nanoparticles supported by alumina, silica, titanium dioxide etc. [1]. Supported metal NP's are of great interest due to their catalytic properties [2]. Very recently we extended the approach to the synthesis of bimetallic catalysts.

The experimental setup consists of the high-power gyrotron, plasma-chemical reactor and diagnostic complex, which includes the optical emission spectrometers and high-speed camera [3]. In a typical experiment a mixture of $\gamma$-$Al_2O_3$ powder with the particles size in the range of 40-160 µm and metal powders (Ni+Co, Ni+Mo, Ni+W) was put in a plasma chemical reactor (fig. 1a) and treated with the pulses of MW irradiation (8 ms/400 kW). The Ni wire grid was set up as shown in fig. 1a to initiate a non-self-sustaining breakdown and intensify plasma chemical process. Mass ratio of Ni and second metal was 1:2 or 1:4, total metals content was 15 w/w % or 20 w/w %. In all the cases the treated particles of $Al_2O_3$ were found to be covered with small (< 100 nm) particles of both metals (fig. 1b), which confirms the transfer of metals from initial metal particles. It may be proposed that the transfer occurs via the gas phase. The prepared materials were tested as catalysts for oxidative desulfurization of alkanes and showed moderate activity.

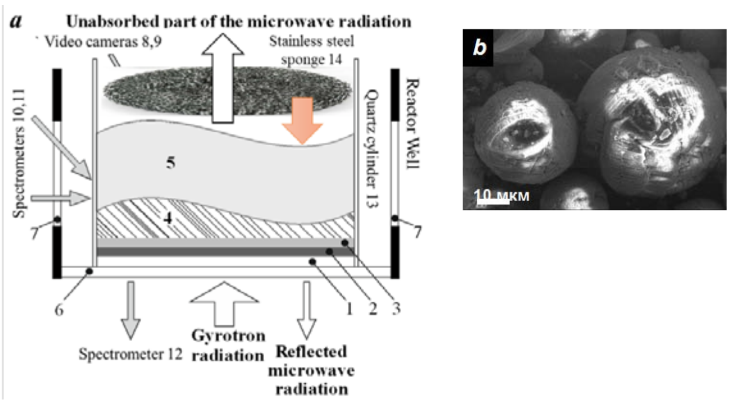


Fig. 1. (a) Plasma chemical reactor; (b) SEM image and EDS elemental maps for sample $Al_2O_3$/15%(Ni+Co)(1:2).

The work was carried out within the framework of the State Assignment No. FFWF-2022-0001 «Study of innovative synthesis of micro- and nanoparticles with controlled composition and structure based on a microwave discharge in gyrotron radiation».

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