# PREFACE

Dear Colleagues,

We are delighted to host the 14th annual conference of the Israel Plasma Science and Technology Association (IPSTA). This is the second time that the Weizmann Institute of Science (WIS) is hosting the conference.

The Plasma Group at the WIS studies fundamental problems in plasmas subjected to high-energy deposition. Of particular interest are the interactions of nonequilibrium plasmas with strong, pulsed magnetic and electric fields, under a wide range of plasma and field parameters. An important aspect of the work is the continuing pursue of new diagnostic methods. The group also maintains the plasma-dedicated website http://plasma-gate.weizmann.ac.il/. Besides information on the research performed at WIS, it consists of useful links to plasma and atomic-physics databases, major plasma centers, and international conferences. Recently, a new web-based application, "Plasma Formulary Interactive", has become available. The application provides a comfortable access to evaluating, comparing, and plotting of a multitude of different plasma and atomic physics parameters.

One of the objectives of IPSTA is to foster international collaborations. This year, a special effort has been made in this direction. Three guests from large international plasma centers will give invited talks on diverse topics. Prof. Roger W. Falcone from U.C. Berkeley will talk on novel light sources and their applications, Prof. Gerhard G. Paulus of the Friedrich Schiller University, Jena, will talk on high-power laser-matter interaction, and Prof. Hartmut Zohm from the Max Plank Institute will address issues in magnetic-confinement fusion. In addition, a number of researchers from Kazan, Russia, will present their studies in technology-oriented subjects (both in the oral and poster sessions).

Due to the overwhelming demand for oral presentations we were unable to respond positively to all requests. Our decisions in composing the oral sessions were guided both by the scientific merit of the works and by the objective to have an appropriate representation of the various groups of the local plasma community. The scientific program consists of six invited lectures ($30 + 5'$), twelve contributed talks ($12 + 3'$), and more than forty poster presentations. Since we expect to have a vibrant poster session, it will be longer than usual (1h $45'$).

The Conference Book is organized as follows: On p. 3, the overall timetable is given, pp. 4–6 contain the list of oral (in the chronological order) and poster (in the alphabetical order by the *presenter's* name) contributions, while their abstracts appear on pp. 7–18 and pp. 19–46, respectively. For your convenience, the author index is given on pp. 47–48.

We wish you a successful and enjoyable conference.

Vladimir Bernshtam
Ramy Doron
Eyal Kroupp
Yitzhak Maron
Evgeny Stambulchik

(The Local Organizing Committee, Weizmann Institute of Science)

February 2012

# CONFERENCE ORGANIZATION

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## Sponsors of the Conference

- Weizmann Institute of Science
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IPSTA is affiliated with the Israel Vacuum Society.

# TIMETABLE

| | | | | |
|---|---|---|---|---|
| 08:00 | – | 08:45 | Registration | |
| 08:45 | – | 09:00 | Welcome Notes [Yosef Nir, Dean of the Faculty of Physics, WIS] | |
| **09:00** | – | **10:40** | Radiation-Plasma Interactions [Chair: Arie Zigler, HUJI] | |
| 09:00 | – | 09:35 | Next Generation Light Sources for the Study of Materials in Extreme Environments and Plasmas | FALCONE, Roger W. |
| 09:35 | – | 10:10 | Surface High-Harmonic Generation | PAULUS, Gerhard G. |
| 10:10 | – | 10:25 | Acceleration of Protons Using Nano Plasma | SCHLEIFER, Elad |
| 10:25 | – | 10:40 | High Accuracy X-Ray Transmission Gratings Spectroscopy Using a Novel Grating Scheme and Fabrication Method | EHRLICH, Yosi |
| 10:40 | – | 10:55 | Coffee Break | |
| **10:55** | – | **12:45** | Fusion and Beams [Chair: Zohar Henis, Soreq NRC] | |
| 10:55 | – | 11:30 | Plasma Physics on the Road to ITER and DEMO | ZOHM, Hartmut |
| 11:30 | – | 11:45 | Progress in ITER Disruption Modeling | STRAUSS, Hank |
| 11:45 | – | 12:00 | Antihydrogen Trapping and Resonant Interactions | SARID, Eli |
| 12:00 | – | 12:15 | Detailed Investigation of the Dynamics of Stagnating High-Energy-Density Plasma | ALUMOT, Dror |
| 12:15 | – | 12:30 | Sub-Microsecond Double-Gap Vircator | SHLAPAKOVSKI, Anatoli |
| 12:30 | – | 12:45 | First Demonstration of Optical Frequency Shot-Noise Suppression in Relativistic Electron Beams | NAUSE, Ariel |
| 12:45 | – | 14:30 | Lunch and Poster Session | |
| **14:30** | – | **16:10** | Astrophysical and Space Plasmas [Chair: Yakov Krasik, Technion] | |
| 14:30 | – | 15:05 | Fast Radiation Mediated Shocks | WAXMAN, Eli |
| 15:05 | – | 15:20 | A New Diffeomorphism Symmetry Group of Magnetohydrodynamics | YAHALOM, Asher |
| 15:20 | – | 15:55 | X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas | BEHAR, Ehud |
| 15:55 | – | 16:10 | Saturation of the Magnetorotational Instability by Stable Magnetoacoustic Modes | LIVERTS, Eduard |
| 16:10 | – | 16:25 | Coffee Break | |
| **16:25** | – | **17:45** | Basic Plasma Physics and Applications [Chair: Reuven Boxman, TAU] | |
| 16:25 | – | 17:00 | Neutral-Gas Dynamics in Low Temperature Plasmas | FRUCHTMAN, Amnon |
| 17:00 | – | 17:15 | Magnetically Induced Transparency in Cold Magnetized Plasma by Spatially Periodic Magneto-Static Field | GAD, Raanan |
| 17:15 | – | 17:30 | Application of Lowered Pressure Radio-Frequency Discharges for Modification of Properties of Inorganic Materials | ZHELTUKHIN, Victor |
| 17:30 | – | 17:45 | Initial Experimental Results of 95 GHz Gyrotron with Ferroelectric Cathode | EINAT, Moshe |
| 17:45 | – | 18:00 | Samuel Goldsmith Best Student Presentation Awards | |
| 18:00 | – | 18:30 | Cocktail Party | |

# IPSTA–2012

## NEXT GENERATION LIGHT SOURCES FOR THE STUDY OF MATERIALS IN EXTREME ENVIRONMENTS AND PLASMAS

**R.W. Falcone**

*University of California, Berkeley, USA*

I will discuss studies of material dynamics under conditions of rapid and intense energy deposition, as well as plasmas driven by laser driven shocks. The key to enabling these studies is a set of powerful x-ray sources that can be used for a variety of probe techniques, including spectroscopy and scattering. In particular, we utilize plasma x-ray sources, synchrotrons, and x-ray free electron lasers.

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## SURFACE HIGH-HARMONIC GENERATION

**G.G. Paulus**

*Friedrich Schiller University, Jena, Germany*

Plasma created at solid-state density surfaces by lasers of relativistic intensities may emit intense radiation at high-order harmonics of the frequency of the driving laser. The effect is due to the anharmonic oscillation of the plasma surface where the anharmonicity is caused by various relativistic effects. Accordingly, this mechanism is known as the relativistically oscillating mirror (ROM). We have performed experiments with our institute's 40-TW, 25-fs laser "JETI-40". By using a plasma mirror device with targets of different residual reectivity, the prepulse level can be adjusted in a wide range. Using an XUV spectrometer calibrated at a synchrotron, the absolute efficiency of ROM harmonic generation was measured. Efficiencies up to a few times $10^{-5}$ were observed. Even so this value corresponds to several $\mu J$ of pulse energy, it cannot be ignored that the harmonic yield is below expectations. Another observation has been that sharp harmonic lines are recorded only at the highest pulse contrast. Decreasing the pulse contrast results in harmonics with satellites. By comparison with theory, we were able to trace the effect back to a time-dependent denting of the plasma surface due to the light pressure of the driving laser pulse. This leads to a shift of the reflection point forth and back as the driving laser pulse evolves. As a consequence, the attosecond pulses emitted in each optical cycle are not equally spaced. In the spectral domain, this manifests in the observed splitting of the harmonic lines.

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M. Behmke, D. a.d. Brügge, C. Rödel, M. Cerchez, D. Hemmers, M. Heyer, O. Jäckel, M. Kübel, G. G. Paulus, G. Pretzler, A. Pukhov, M. Toncian, T. Toncian, O. Willi, *Controlling the spacing of attosecond pulse trains from relativistic surface plasmas*, Phys. Rev. Lett. 106, 185002 (2011).

## ACCELERATION OF PROTONS USING NANO PLASMA

**E. Schleifer**[1], I. Pomerantz[2], E. Nahum[1], S. Eisenmann[1], M. Botton[1] and A. Zigler[1]

*1 Hebrew University*

*2 Tel Aviv University*

The ability to generate fast protons from small and relatively inexpensive systems is of great importance to many applications such as medical radiation treatment and others. Target structuring is considered as one of the possible ways towards this goal. Nano-structured solid or quasi-solid targets attract significant attention. The presented scheme of using $H_2O$ “snow” nano-wires can relieve the demand for very high laser intensities, thus reducing the size and the cost of laser systems[1-4]. Usually ultra high intensity laser beams produce protons above the MeV energy level when the multi-terawatt scale laser facility provides intensity on the target which is at least $10^{18} - 10^{19}\,\mathrm{W/cm^2}$ and the beam irradiates targets such as thin-foils or gas jets. In this study, we examined the ability to achieve the same proton energy range with use of relatively modest
O1 laser intensity ($10^{17}\,\mathrm{W/cm^2}$) and a nano-structured $H_2O$ target. In this present experiment, we
3 used frozen $H_2O$ deposited on Sapphire, which were shaped as nanometer sized elongated wires with characteristic diameter in the range of 10-100 nm and length of several $\mu$m. In this setup, the plasma near the tip of the nano-wire is subject to locally enhanced laser intensity with high spatial gradients, and confined charge separation is obtained. Electrostatic fields of extremely high intensities are produced, and protons are accelerated to MeV-level energies. Nano-wire engineered targets will relax the demand of peak energy from laser based sources.

[1] A. Zigler, T. Palchan, N. Bruner, E. Schleifer et al., Phys. Rev. Lett. 106, 134801 (2011).
[2] A. Zigler, et al., Nucl. Instr. and Meth. A (2010).
[3] T. Palchan, S. Pecker, Z. Henis, S. Eisenmann, and A. Zigler, Appl. Phys. Lett. 90 041501 (2007).
[4] T. Palchan, et al., Appl. Phys. Lett. 91 251501 (2007).

## HIGH ACCURACY X-RAY TRANSMISSION GRATINGS SPECTROSCOPY USING A NOVEL GRATING SCHEME AND FABRICATION METHOD

**Y. Ehrlich**[1], M. Fraenkel[1], G. Hurvitz[1], Z. Shpilman[1], I. Levy[1], G. Sturm[2] and Y. Shaked[3]

*1 Plasma Physics Department, Applied Physics Division, Soreq NRC, Yavne 81800, Israel.*

*2 Applied Physics Division, Soreq NRC, Yavne 81800, Israel.*

*3 Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel*

Transmission-Grating Spectroscopy (TGS) is a powerful tool for wide-band spectroscopy of soft
x-ray source. Absolutely calibrated x-ray spectra can be acquired for soft x-ray source diagnostics
in the 100-3000 eV spectral range using transmission gratings and back-illuminated CCD cam-
era. Two main drawbacks of this tool are the overlapping of high diffraction orders, and grating
production imperfections causing grate difficulties in modelling the diffraction efficiency. Both O1
drawbacks can be overcome using a unique grating scheme made possible by the presented fabri- 4
cation method. High quality transmission gratings are produced using Focused-Ion-Beam (FIB)
technology which is used to fabricate high-quality free standing grating bars on TEM-grid based
substrates. The obtained gratings benefit from superb accuracy and high production flexibility.
Novel "eyes shape" sinusoidal grating scheme eliminates high diffraction orders. Double grating
combinations of identical or different parameters are easily fabricated, allowing advanced one-shot
application of transmission grating spectroscopy. These applications include spectroscopy with
different spectral resolution and bandwidth, improved dynamic range, and spectral calibration of
various x-ray optics elements.

## PLASMA PHYSICS ON THE ROAD TO ITER AND DEMO

**H. Zohm**

*Max-Planck-Institut für Plasmaphysik*

O21

Over the last decade, the world-wide fusion research programme has made large progress in understanding the physics of magnetically confined plasmas. Based on this progress, the next step experiment ITER is currently under construction in Cadarache, France, in a multi-national effort. The talk will first review the requirements to achieve nuclear fusion on earth and then discuss the progress made over the last years in the areas of confinement, stability and power exhaust from magnetically confined fusion plasmas. Examples of recent progress will be given from the ASDEX Upgrade tokamak device, operated by Max-Planck-Institut für Plasmaphysik in Garching, Germany. Finally, the prospects for demonstrating nuclear fusion as an energy source in ITER and finally in a demonstration reactor, DEMO, will be discussed.

## PROGRESS IN ITER DISRUPTION MODELING

**H. Strauss**

*HRS Fusion*

A critical issue with the ITER magnetic fusion effort is the electromechanical stresses produced by disruptions. In particular the concern is about the non axisymmetric “sideways” force. Simulational studies [Strauss 2010] of this problem are ongoing.

The disruptions thought to be the worst case consist of a vertical displacement event (VDE), which brings the plasma near the wall. Plasma and magnetic flux is scraped off until the effective reciprocal rotational transform q at the plasma edge drops to $q = 2$. The plasma then becomes unstable to an ideal MHD external kink mode, which produces current in the wall with toroidal mode number $n = 1$. This gives rise to a sideways force.

Our simulations of this process with the M3D code [Park 1999] have attracted some controversy. A controversial issue has been the effect of velocity boundary conditions on the magnitude of the sideways wall force. Usually M3D uses a standard boundary condition that $v_n = 0$ at the wall. It was argued [Zakharov 2010] that an absorbing boundary condition $v_n' = 0$, where the prime indicates a radial derivative, should be used instead. This has been tried, and indeed it gives a larger wall force. Effectively it acts as if the wall is made more resistive, so the magnetic field penetrates the wall more easily. However it is more reasonable to use a Robbins boundary condition $v_n' = v_n/d$. The parameter $d$ is the the wall thickness, which is the scale at which the velocity damps O2
to zero in the wall. Because $d$ is much less thanthe plasma radius, this gives $v_n$ approximately 0. 2
This has been verified numerically.

Another issue is the relative importance of “hiro current” [Zakharov 2008] rather than the standard halo current. Hiro current was invoked to explain the toroidal asymmetry of the toroidal current measured in JET. It has been shown that because div$J = 0$, only halo current can flow to the wall. The the toroidal asymmetry of the toroidal current can be fully explained with a correct understanding of halo current.

Another issue [Boozer 2011] has been the relatively low values of plasma resistivity and wall resistivity used in the simulations, for reasons of numerical stability and resolution. Simulations are in progress with more realistic values of these parameters. A preliminary result is that the plasma resistivity has only a weak result on the wall force, which is reasonable considering that an ideal MHD instability is producing the effect.

[Strauss 2010] H. R. Strauss, R. Paccagnella, J. Breslau, Phys. Plasmas 17, 082505 (2010).
[Park 1999] W. Park, E.V. Belova, G.Y. Fu, X. Tang, H.R. Strauss, L.E. Sugiyama, Phys. Plasmas 6, 1796 (1999).
[Zakharov 2010] Leonid E. Zakharov, Physics of Plasmas 17, 082505 (2010).
[Zakharov 2008] Leonid E. Zakharov, Phys. Plasmas 15, 062507 (2008).

## ANTIHYDROGEN TRAPPING AND RESONANT INTERACTIONS

**E. Sarid**

*NRCN, Israel and the ALPHA collaboration, CERN*

Trapping antihydrogen atoms was successfully demonstrated for the first time by the ALPHA collaboration at CERN [1]. The antihydrogen atoms were trapped in a minimum-B trap through the interaction between an inhomogeneous magnetic field (octupole and mirrors) and the magnetic moment of the neutral atoms. Long term confinement, for 1000 s, has been achieved [2], showing that even in a very shallow trap (less than 1 K), ground state antihydrogen atoms can be trapped.
O2 These results open the door to the development of spectroscopic measurements on anti-atoms that
3 will eventually allow precision tests of CPT theorem. The first resonant interaction that can be studied is positron spin flip (PSR) that causes trapped antiatoms to become un-trappable, causing their escape from the trap and producing an annihilation signal on the trap wall.

This work is supported by the ISF, Israel.

[1] G.B. Andersen et. al., ALPHA collaboration, *Trapped antihydrogen*, Nature 468, 673 (2010).
[2] G.B. Andersen et. al, ALPHA collaboration, *Confinement of antihydrogen for 1,000 seconds*, Nature Physics, 7, 558 (2011).

## DETAILED INVESTIGATION OF THE DYNAMICS OF STAGNATING HIGH-ENERGY-DENSITY PLASMA

**D. Alumot**[1], E. Kroupp[1], E. Stambulchik[1], D. Osin[1], A. Starobinets[1], V. Fisher[1], V. Bernshtam[1], L. Weingarten[1], Y. Maron[1], I. Uschmann[2] and A. Fisher[3]

*1 Weizmann Institute of Science*
*2 Friedrich-Schiller University, Jena, Germany*
*3 Technion – Israel Institute of Technology*

The thermalization and energy conversion to radiation of high-energy-density plasma is a topic of broad interest in laboratory plasmas and in astrophysics. We report an experiment where cylindrical neon plasma implodes radially until it assembles on axis, under magnetic fields produced by driving 500 kA during $\sim$ 500 ns (Z-pinch). Two spectroscopic systems with ultra-high-resolutions
O2 in spectrum, space, and time were built in order to study the stagnation process on axis. A major
4 emphasis has been put on simultaneous measurements of the spectra of two different optically-thin lines: satellites to Ly$\alpha$ and Ly$\delta$. The optical thinness is shown to be invaluable in diagnosing the ion velocity distribution, the electron density, and possibly the ion temperature. However, the low-intensity of such lines had to be overcome by the use of spherical crystals, which also yield axial imaging across the stagnation column. We demonstrate measurements that provide unique insight into the properties and dynamics of the stagnating plasma.

Examples are shown by the use of the temporal and spatial correlations between the shapes of the various lines to obtain subtleties in the distributions of the electron density and temperature in the stagnating column.

This research was supported by the Israel Science Foundation (grant No. 770/09).

## SUB-MICROSECOND DOUBLE-GAP VIRCATOR

**A. Shlapakovski**, T. Queller, Y. Bliokh and Y. Krasik
*Technion*

Investigations of a double-gap vircator driven by a 20 Ohm and 500 ns generator operating in the output voltage range 400–600 kV were carried out. The vircator generated microwave pulses with a peak power of up to 200 MW at $\sim 5\%$ efficiency and the frequency varied from 2.0 to 2.3 GHz depending on the cavity geometry. The limitations on the microwave pulse duration not related to the cathode plasma expansion are addressed. On the one hand, the microwave generation is terminated because of the plasma formation at the foil separating the cavity sections, so that the virtual cathode electron space charge is neutralized by the plasma ion flux. On the other hand, if O2
the electron beam energy deposition into the foil is reduced, a substantial delay in the start time of 5
the microwave generation appears, which has been studied in detail. With these limiting factors, the microwave pulse full duration varied from 100 to 350 ns; the maximal FWHM duration achieved in the experiments was $\sim 180$ ns. Measurements of the current transmitted through the vircator cavity indicated the existence of a virtual cathode in spite of the absence of microwave generation during the delay. The experimental dependence of the generation starting current on the diode voltage is presented and possible mechanisms behind the generation delay are discussed. Results of simplified numerical simulations are also presented.

## FIRST DEMONSTRATION OF OPTICAL FREQUENCY SHOT-NOISE SUPPRESSION IN RELATIVISTIC ELECTRON BEAMS

**A. Nause**, E. Dyunin and A. Gover
*Tel Aviv University*

We report first demonstration of optical frequency current shot-noise suppression in a relativistic e-beam. This process is made possible by collective Coulomb interaction between the electrons of a cold intense beam during beam drift, and is essentially a process of longitudinal beam-plasma oscillation. [1]

The fundamental current shot-noise determines the level of incoherent spontaneous radiation emission from electron-beam optical radiation sources and SASE-FELs [2]. Suppressing shot-noise would make it possible to attain spontaneous emission sub-radiance [3] and surpass the classical O2
coherence limits of seed-injected FELs. 6

The effect was demonstrated by measuring sub-linear growth as a function of current of the Optical Transition Radiation (OTR) emitted by the e-beam. This finding indicates that the beam charge homogenizes due to the collective interaction, and its distribution becomes sub-Poissonian.

[1] A. Gover and E. Dyunin, Phys. Rev. Lett. 102, 154801, 2009.
[2] R. Akre, et al., *First lasing and operation of an ångstrom-wavelength free-electron laser*, Nature Photonics 4, 641 (2010).
[3] A. R. H. Dicke, Phys. Rev. 93, 99 (1954).

## FAST RADIATION MEDIATED SHOCKS

**E. Waxman**

*Weizmann Institute of Science*

O3 1

The shock waves driving the ejection of stellar envelopes in supernova (SN) explosions are "radiation mediated" (the post-shock energy density is dominated by radiation). The eruption of the shock wave from the stellar edge is accompanied by a luminous X-ray flash, a "SN breakout" flash, which carries unique information on the SN progenitor. The detection of such flashes over the past few years triggered an intensive study of the properties of fast, mildly- and highly-relativistic, radiation mediated shocks. I will describe the progress in understanding the structure of such shocks, the open questions, and the implications to our understanding of SN explosions, including their possible relation to cosmological gamma-ray bursts and X-ray flashes.

## A NEW DIFFEOMORPHISM SYMMETRY GROUP OF MAGNETOHYDRODYNAMICS

**A. Yahalom**

*Ariel University Center of Samaria*

O3 2

Variational principles for magnetohydrodynamics were introduced by previous authors both in Lagrangian and Eulerian form. In a previous work [1] Yahalom & Lynden-Bell introduced a simpler Eulerian variational principle from which all the relevant equations of magnetohydrodynamics can be derived. The variational principles were given in terms of six independent functions for non-stationary flows and three independent functions for stationary flows. This is less than the seven variables which appear in the standard equations of magnetohydrodynamics which are the magnetic field $B$ the velocity field $V$ and the density. In a more recent work [2] the number of needed functions was further reduced and it was shown that magnetohydrodynamics is mathematically equivalent to a four function field theory defined a by a Lagrangian. The four functions include two surfaces whose intersections consist the magnetic field lines, the part of the velocity field not defined by the commoving magnetic field and the density. The Lagrangian admits a newly discovered group of Diffeomorphism Symmetry.

[1] A. Yahalom and D. Lynden-Bell, *Simplified Variational Principles for Barotropic Magnetohydrodynamics*, [Los-Alamos Archives - physics/0603128]; J. Fluid Mech. 607, 235–265 (2008).
[2] A. Yahalom *A Four Function Variational Principle for Barotropic Magnetohydrodynamics*, EPL 89, 34005 (2010); [Los-Alamos Archives - arXiv:0811.2309].

## X-RAY SPECTROSCOPY OF ASTROPHYSICAL AND LABORATORY PLASMAS

**E. Behar**

*Technion*

The talk will describe some of the state of the art instrumentation for X-ray spectroscopy on board satellites. It will then focus on absorption measurements of outflows from supermassive black holes. Continuous ionization diagnostics, namely the Absorption Measure Distribution, has O3
proven useful in these observations to constrain the physics of the outflowing plasma, even when 3
no complementary spatial information is available. Both global galactic flows and local density variations can be estimated from these measurements and compared with astrophysical models. Relevant laboratory experiments will also be described as well as ways to harness high quality laboratory measurements to astrophysical diagnostics.

## SATURATION OF THE MAGNETOROTATIONAL INSTABILITY BY STABLE MAGNETOACOUSTIC MODES

**E. Liverts**, Y. Shtemler and M. Mond

*Ben Gurion University of the Negev*

The magnetorotational instability (MRI) of thin, vertically-isothermal Keplerian discs, under the influence of an axial magnetic field is investigated near the instability threshold. The nonlinear interaction of in-plane Alfvén-Coriolis (MRI) modes with stable vertical magnetoacoustic waves is considered. The transition of the Alfvén-Coriolis modes to instability occurs when the linearized
system has zero eigenvalue of multiplicity two. Such transition is characteristic of the Takens- O3
Bogdanov type bifurcation. As a result the nonlinear ordinary differential equation that describes 4
the evolution of the amplitude of the MRI mode near the threshold is of second order as opposed to first order equations (like the Landau-Ginzburg one) that characterize systems that bifurcate through a simple zero eigenvalue. Numerical solutions of that amplitude equation reveal that the MRI is saturated to bursty periodical oscillations due to the transfer of energy to the stable magnetosonic modes.

## NEUTRAL-GAS DYNAMICS IN LOW TEMPERATURE PLASMAS

**A. Fruchtman** and G. Makrinich

*Holon Institute of Technology*

While the plasma flow and transport in gas discharges are at the focus of research, the dynamics of the neutral-gas is often seen as a secondary issue. The nonlinear interaction between the the plasma and the neutral gas (which is composed usually of a larger number of particles) has however important and interesting effects. In recent years we have explored two such effects. The first effect is the modification of the neutral-gas density by the plasma. We have found that such a modification can have various and very different forms [1-3]. In addition to the expected neutral-gas depletion at the location of intense ionization, under certain conditions the neutral gas-density should surprisingly be larger where the ionization is larger. This unexpected effect has been coined
O4 neutral-gas repletion [3]. The second effect that will be described, an effect which we were able to
1 demonstrate experimentally, is the increase of the momentum delivered to plasma when the plasma ions collide with neutral-gas during their acceleration [4, 5]. The possible utilization of this effect for plasma thrusters will be discussed.

This research has been supported by the Israel Science Foundation Grant No. 864/07.

[1] A. Fruchtman, G. Makrinich, P. Chabert, and J. M. Rax, Phys. Rev. Lett. 95, 115002 (2005).
[2] A. Fruchtman, IEEE Trans. Plasma Sci. 36, 403 (2008).
[3] A. Fruchtman and J.-M. Rax, Phys. Plasmas 17, 043502 (2010).
[4] G. Makrinich and A. Fruchtman, Appl. Phys. Lett. 95, 181504 (2009).
[5] G. Makrinich and A. Fruchtman, Phys. Plasmas 16, 043507 (2009).

## MAGNETICALLY INDUCED TRANSPARENCY IN COLD MAGNETIZED PLASMA BY SPATIALLY PERIODIC MAGNETO-STATIC FIELD

**R. Gad**[1], J. Leopold[2], D. Fredkin[3], A. Fisher[1] and A. Ron[1]

*1 Technion*
*2 RAFAEL*
*3 UCSD*

Atomic Electromagnetically Induced Transparency (EIT) occurs when a resonance absorption line is made transparent by destructive interference between two atomic transitions [1]. A classical analog to EIT is when an opaque cold magnetized plasma is made transparent by a constant in time and varying in space magnetic field [2]. The physical mechanism responsible for this effect, is the coupling of longitudinal plasma modulation to the transverse components of the electromagnetic
O4 radiation, canceling the forces acting on the plasma electrons. The plasma frequency and the
2 electron cyclotron frequency are the classical analog to the atomic transition frequencies in quantum EIT. Controllable wave propagation parameters such as the transmission amplitude and the group velocity are inherent features of magnetically induced transparency [3].

In the present work, the theory is expanded and Magnetically Induced Transparency (MIT) is experimentally demonstrated [4].

[1] K. J. Boller and S. Harris, Phys. Rev. Lett., 66, 2593 (1991).
[2] G. Shvets and J. S. Wurtele, Phys. Rev. Lett., 89, 115003 (2002).
[3] M. Tushentsov and G. Shvets, IEEE Trans. Plasma Sci., 33, 23 (2005).
[4] R. Gad et. al., Phys. Rev. Lett., Nov 2011 (submitted).

## APPLICATION OF LOWERED PRESSURE RADIO-FREQUENCY DISCHARGES FOR MODIFICATION OF PROPERTIES OF INORGANIC MATERIALS

**V. Zheltukhin**[1], I. Abdullin[2] and I. Sagbiev[2]

*1 Kazan Federal University, Russian Federation*

*2 Kazan Technological University, Russian Federation*

Scientific foundation of operational, consumer and technological properties of inorganic materials such as metals, alloys, dielectrics, semi-conductors, thin films and powders regulation by superficial and volumetric modification using lowered pressure RF plasma processing are described. Physical and mathematical models of lowered pressure RF plasma influence on materials are presented. Results of experimental researches have shown that lowered pressure RF plasmas is effective in following processes:

- metals and alloys polishing with simultaneously increasing of microhardness, redistribution of residual tenses, removing of fissured and relief layers that conducts to rising in durability and service life of products; O4
- dielectric surface polishing with simultaneously removing of fissured and relief layers that leads to improvement of optical properties of a surface; 3
- metals and alloys gasing (nitriding, carbonization, oxidation, rare atoms penetration) to 200 microns by thickness, that results in increasing of durability and service life of products;
- metals and alloys (including aluminum) surface finishing clearance before plasma-ionic or galvanic deposition that conducts to improvement of adhesive properties of coverings;
- formations and modification of thin-film coverings, including multi-layer, to 500 microns by thickness;
- powder materials volumetric processing.

Examples of technological processes of inorganic materials processing at lowered pressure RF plasmas jet are shown.

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## INITIAL EXPERIMENTAL RESULTS OF 95 GHZ GYROTRON WITH FERROELECTRIC CATHODE

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Ferroelectric cathodes were intensively explored in the recent years, both for defining the emission physics as well as its applicability as source for electron tubes and other applications. The difficulties in the implementation of the cathode in microwave tubes were met and CRM, gyrotron, TWT and
O4 FEL interactions was reported based on ferroelectric cathode. Since the ferroelectric cathode is
4 based on plasma effect, the relatively high energy spread limits the operation frequency of the tube. Hence, the possibility to obtain higher frequencies remained questionable. In this experimental work a gyrotron was designed with operation frequency increased to the millimeter waves. A cylindrical cavity with a 7.6 mm diameter was integrated to a ferroelectric electron gun. The gyrotron was operated with $\sim 0.5\,\mu$s pulses and mm-wave radiation of frequency 95 GHz at TE02 mode was obtained. The magnetic field in the interaction region is $\sim 3.5$ T (first harmonic). Pushing the operation frequency obtained from ferroelectric cathode tubes towards the mm waves may leads to new possibilities for the use of the ferroelectric cathodes.

## EXPERIMENTAL CHARACTERIZATION OF SILICA PLASMOIDS EXCITED BY LOCALIZED MICROWAVES

**A. Balaish**, Y. Meir and E. Jerby

*Tel Aviv University*

This paper reviews characteristics of microwave-excited plasmoids (fireballs) measured by synchrotron small-angle X-ray diffraction (SAXS) and by scanning-electron microscope (SEM), and presents new experimental results obtained by Langmuir probe, microwave scattering, and optical spectroscopy. The plasmoids are created in these experiments by directing localized microwave energy at 2.45 GHz into a solid substrate (e.g. silicon or glass) hence creating a hotspot from which the plasmoid is blown up to the air atmosphere within the microwave cavity. Spontaneous emission of microwaves from the plasmoid is measured near the electron plasma frequency ($< 1$ GHz) and at 4.9 GHz, the second harmonic of the microwave-excitation frequency. The plasma characteristics of these plasmoids (electron density and temperature) are estimated, and their dusty-plasma features are introduced. The resemblance of these plasmoids to the natural ball-lightning is reviewed, and their potential applications, such as for direct conversion of solids to powders, are proposed.

P 1

## GROWTH OF INTERCHANGE INSTABILITY IN A MIRROR TRAP

**I. Be'ery**[1], A. Lifshitz[1], A. Fisher[1], A. Ron[1] and A. Fruchtman[2]

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The interchange instability in mirror traps is a textbook example of plasma instability. While the linear regime of the instability has been extensively studied, the non-linear regime is mostly unexplored, both theoretically and experimentally. Optical photography and tomography have been used to study the evolution of cold, high density Hydrogen plasma in a small mirror machine. We demonstrate the effects of Finite Larmor Radius, conductive wall, and mirror ratio on the stability of the largest wavelength interchange modes. Introduction of radial electric field induces $E \times B$ rotation which can have stabilizing or destabilizing effect, based on the direction relative to the ion diamagnetic rotation.

P 2

## INERTIAL CONFINEMENT IN THE MODEL OF PARTICLES INTERACTING AT HIGH ENERGIES

**S. Bondarenko** and K. Komoshvili

*Ariel University Center*

P 3

We discuss an application of effect of inertial confinement for the gas of charged particles interacting at high energy. We formulate this problem as a problem of determination of an equation of state of the gas of slow ("internal") particles which stays under the pressure of fast ("external") particles. In general, the processes like that are non-equilibrium. Therefore, we reformulate our problem as a equilibrium one for the "internal" particles in some additional potential field created by "external" particles. The interaction of these "external" energetic particles with the slow particles we describe similarly to the type of interactions arose in high energy physics. Namely, the amplitude of these interactions we choose to be proportional to the rapidity of the external particles in the frame related to the particles inside some region. In this formulation we found the equation of state for the "internal" particles, we also solved the Euler's equation in shock wave description of the process finding a self-similar solution for the equations and, finally, we solved Boltzmann equation for self-consistent field (Vlasov's equations) in linear approximation determining an electrical properties of collisionless plasma.

## TITANIUM SUBMERGED ARC BREAKDOWN OF METHYLENE BLUE IN AQUEOUS SOLUTIONS

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*Tel Aviv University*

P 4

The pulsed submerged arc is a high-current electrical discharge between two electrodes in a liquid, in which the electrical current is conducted via a plasma bubble consisting of vaporized and partially ionized liquid and electrode materials. Low voltage, low energy submerged pulsed arcs between a pair of 99.5% Ti electrodes with a pulse repetition rate of 100 Hz, energies of 2.6-192 mJ and durations of 20, 50 and 100 microseconds were used to remove 10mg/L methylene blue (MB) contamination from 40 ml aqueous solutions, to which 0.5% $H_2O_2$ was added. The removal $ln(C_0/C_t)$ was considered as a function of treatment time $T_t = T_p + T_a$, where $C_0$ and $C_t$ are the MB concentrations initially and after total time $T_t$, respectively, $T_p$ is the arc processing time, and $T_a$ is the aging time needed to complete the MB decomposition after the arc processing. The effects of the treatment on the pH of solution and on the Zeta-potential of the particles formed as a result of the electrode erosion were studied. It was shown that using the submerged arc treatment with Ti electrodes and addition of 0.5% $H_2O_2$ produced a value of G50 (the volume of treated water per unit energy expenditure at 50% degradation of MB) which was more than 200 times larger than obtained with other plasma methods.

## MODIFIED WIRE ARRAY UNDERWATER ELECTRICAL EXPLOSION

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*Technion – Israel Institute of Technology*

The results of experimental and numerical research of cylindrical wire array underwater electrical explosion and generation of extreme state of water in the vicinity of implosion axis by converging strong shock wave with improved efficiency of energy transfer to converging water flow will be reported. It will be shown that in the case of a Cu wire array, the addition of the outer metal reflector increases the pressure, density, and temperature of the water in the vicinity of the implosion axis $\sim 1.38$, $\sim 1.07$ and $\sim 1.33$ times, respectively. The influence of the reflector material and its radial distance with respect to the wire array on the water parameters in the vicinity of implosion axis was investigated. In addition, it was found that the shock wave reflection at the axis of implosion results in the water boiling and bubbles formation. Finally, the application of Al wire cylindrical array explosion with stainless steel reflector results in Al combustion and, respectively, in additional energy delivered to the converging water flow which generates up to $\sim 540$ GPa pressure in the vicinity of the implosion axis.

P 5

## TOWARDS RECOMBINATION-PUMPED H-LIKE N X-RAY LASER

**I. Gissis**, A. Rikanati, I. Be'ery, A. Fisher and E. Behar
*Technion*

The recombination pumping scheme for soft X-Ray lasers has better energy scaling, than the collisional-excitation pumping scheme. Implementation of an H-like Nitrogen recombination laser, at $\lambda \sim 13.4$ nm requires initial conditions of at least 50% fully stripped Nitrogen, $kT_e \sim 140$ eV and electron density of $\sim 10^{20}$ cm$^{-3}$. In order to reach population inversion, the plasma cooling to below 60eV should be faster than the typical three-body recombination time. The goal of this study is achieving the required plasma conditions using a capillary discharge z-pinch apparatus. The experimental setup includes a 90mm alumina capillary coupled to a pulsed power generator of $\sim$ 60 kA peak current, with a rise time of $\sim 60$ ns. Various diagnostic techniques are applied to measure the plasma conditions, including X-ray diode, time-resolved pinhole imaging and time-resolved spectrometry analysed with a multi-ion collisional-radiative atomic model. For optimization of the plasma conditions, experiments were done in different capillary radii and different initial gas pressures. The results show a fast cooling rate to below 60 eV, demonstrating the feasibility of capillary discharge lasers.

P 6

## HIGH-CURRENT ELECTRON BEAM GENERATION IN THE DIODE WITH DIFFERENT CATHODES

**J. Gleizer**, T. Queller, Y. Bliokh, S. Yatom, V. Vekselman and Y. Krasik

*Physics department, Technion*

P 7

Results of experiments on generation of electron beams with current density $j_e \sim 200$ A/cm$^2$ at accelerating voltages of $\leq 200$ kV and pulse duration of several hundreds of nanoseconds in a diode with different type of cathodes (carbon, aluminum and carbon fiber-epoxy) are reported. Different electrical, optical, x-ray and spectroscopic diagnostics were applied in this research. The best diode operation (pulse duration, electron beam cross-sectional uniformity) was obtained with carbon fiber-epoxy cathode. It was shown that the electric field threshold for beginning of the electron emission is $\leq 15$ kV/cm and that this cathode can sustain $\sim 3000$ generator pulses without any degradation in its emission properties. The phenomenon governing the electron emission is flashover plasma which is formed along the surface of the carbon fiber-epoxy capillaries during the fast rise time of the accelerating voltage. Spectroscopic investigations of this cathode were carried out and cathode plasma density and temperature were determined. In addition, it was shown that the electron beam injection into the drift tube, placed in external magnetic field, with current amplitude exceeding its critical value leads to the virtual cathode formation and change in the cross-sectional electron beam current density radial distribution because of reflection of inner electrons from the virtual cathode.

## DIAGNOSTICS OF DIELECTRONIC PROCESSES IN LASER PRODUCED SAMARIUM PLASMA

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*2 Hebrew University*

P 8

Spatially-resolved time-integrated X-ray spectra of laser produced samarium plasma were recorded, in the spectral range from 7 to 10 Å. The spectrum of samarium is characterized by the prominent pattern of transitions $3d{-}nf$ ($n = 4$ to 7) belonging to Co-like ($Sm^{35+}$), Ni-like ($Sm^{34+}$) and Cu-like ($Sm^{33+}$) ions. Spectral lines of Mn-like ($Sm^{37+}$) to Zn-like ($Sm^{32+}$) were identified. The appearance of these ionization stages as a function of distance from the target was measured. Transfer of the dominant ion stages to lower stages with increasing distance from the original target surface was demonstrated, probably indicating dielectronic recombination. The Hebrew University Lawrence Livermore Atomic Code was used to generate emission spectra for comparison with the experimental ones. A radiation-hydrodynamics code coupled to three non-Local Thermal Equilibrium ionization and equation of state models with different approaches for dielectronic processes was used to model the plasma. The simulated plasma ionization and electron densities and temperatures were found to be consistent with the experimental results.

## BORON NITRITE PLASMA MICRO LENS FOR LASER PRE-PULSE SUPPRESSION

**Y. Katzir**

*Hebrew University*

We demonstrate a technique for ASE and pre-pulse suppression for high power lasers. ASE and pre-pulse contrast ratio increased by one order of magnitude while transmitting 93% of the pulse energy by propagating the pulse through a boron nitrite plasma microlens. The microlens was created by ablating a boron-nitrite (BN) disk with a central 0.5 mm hole target with an 2.5 J/cm$^2$ 7 ns Nd:Yag laser. The produced preformed plasma exhibiting different focal lengths for the high intensity main pulse and low intensity prepulse leading to the significant increase in main pulse vs. prepulse ratio. P 9

## THIRD HARMONIC GENERATION BY A LOW INTENSITY LASER PULSE IN A CORRUGATED DISCHARGE CAPILLARY

**Y. Katzir** and Y. Ferber

*Hebrew University*

Quasi phase matching (QPM) and increase of laser interaction length was promoted by periodically modulated plasma guide formed by a discharge current ablating the inner capillary walls. The phenomenon was demonstrated through the use of third harmonics. For Ti:Sapphire laser pulses propagating through 1cm long corrugated discharge capillaries, with an axial corrugation period of 200 $\mu$m the third harmonic was generated at intensities as low as $10^9$ W/cm$^2$. P 10

## DESIGN OF A MAGNETRON INJECTION GUN FOR A 670 GHZ GYROTRON

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P 11

A 670-GHz, 300-kW gyrotron with a pulsed solenoid is presently under development at the University of Maryland. The gyrotron will operate at the fundamental cyclotron resonance. The pulsed solenoid will provide magnetic fields in the range of $27 - 28$ T. Design of a magnetron-type electron gun for such a gyrotron is done by using available numerical codes, EGN2W, TRAK, and MICHELLE. The beam voltage and current are 70 kV and 15 A, respectively. Simulation results will be presented.

## ANODE THICKNESSES INFLUENCE ON THE ION CURRENT IN A VACUUM ARC WITH REFRACTORY ANODE

**Y. Koulik**, I. Beilis and R. Boxman

*Tel Aviv University*

P 12

The time dependent ion current density $J_i$ was measured in a hot refractory anode vacuum arc (HRAVA) sustained between a consumed water-cooled cylindrical Cu cathode and non-consumed cylindrical W anodes with thickness $d = 5, 10, 15, 20, 30$ mm separated by a 10 mm gap. Arc currents of $I = 130, 150, 175, 200$ A were applied for period of 90 s. $J_i$ was collected using a negatively biased probe at distances $L_i = 50, 80, 110, 140$ mm from the electrode axis. The active probe surface was oriented perpendicular or parallel to the plasma flow direction. When the arc was ignited, $J_i$ sharply increased and then increased slowly, passed through a peak and finally at time $t_{ss}$ reached a steady state $J_{i,ss}$. When d was increased from 5 to 30 mm, $t_{ss}$ increased from 12 to 48 s ($I = 200$ A) and from 20 to 69 s (I=150 A), weakly dependent on probe orientation. When d was increased from 5 to 15 mm, $J_{i,ss}$ decreased from $\sim 80$ to $\sim 69$ mA/cm$^2$ ($I = 150$ A) and from 125 to 105 mA/cm$^2$ ($I = 200$ A) for $L_i = 50$ mm (perpendicular probe). With $I = 200$ A, $L_i = 50$ mm, $d = 15$ mm and the parallel probe, the peak $J_i$ was $\sim 32$ mA/cm$^2$ and $J_{i,ss}$ was $\sim 18$ mA/cm$^2$, while for perpendicular probe these values were $\sim 180$ and 110 mA/cm$^2$ respectively. $J_{i,ss}$(perpendicular) exceeded $J_{i,ss}$(parallel) by a factor of $5.2 - 6.7$, depending on $L_i$ and $I$.

## TOMOGRAPHY OF LASER-PRODUCED SOLID-DENSITY PLASMAS

**E. Kroupp**[1], E. Stambulchik[1], Y. Maron[1], U. Zastrau[2], V. Hilbert[2], T. Kämpfer[2], R. Loetzsch[2], I. Uschmann[2], E. Förster[2,3] and H.-P. Schlenvoigt[4]

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Studies of warm dense matter (WDM) are an emerging and challenging field that is at the crossroads of condensed matter physics and plasma physics. WDM phenomena are at heart of several frontier researches of modern science. The WDM state nowadays is routinely created in laboratory in the interactions of intense laser or particle beams with solid-density matter. If the energy of the beam is deposited to the target sufficiently fast ($\lesssim 1\,\mathrm{ps}$), the target during this time does not expand significantly, thus remaining at a solid-state density. Because of the high density, only short-wavelength radiation may escape the inner parts of the target. Due to this reason, the inner-shell x-ray emission is an important instrument to yield valuable information about such plasmas. P
Formerly, the temperature and K$\alpha$-yield radial distributions in laser-produced solid-density plasmas 13
were measured using the 1D spatial imaging x-ray spectroscopy [1]. However, the integration along the z axis results in a weighted averaging of the spectra observed by accumulating photons emitted from different depths of the target. In other studies, sandwich targets were used to achieve axial resolution, although new complications arise due to the layer bonding and contact effects. Ultra high resolution (spatial and spectral) doubly-curved GaAs crystals were used to record the K$\alpha$ emission of thin Ti foils at different angles, in order to reconstruct the 3D intensity dependence of the line emission. The experiments were done on two different high-power laser systems. Preliminary results will be presented.

[1] U. Zastrau, P. Audebert, V. Bernshtam, E. Brambrink, T. Kämpfer, E. Kroupp, R. Loetzsch, Y. Maron, Yu. Ralchenko, H. Reinholz, G. Röpke, A. Sengebusch, E. Stambulchik, I. Uschmann, L. Weingarten, and E. Förster, Phys. Rev. E 81, 026406 (2010).

## INFLUENCE OF EMISSION MECHANISM ON RUNAWAY ELECTRONS GENERATION

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*Technion*

P 14

The results of particle-in-cell numerical simulations of the influence of emission mechanism (field emission or explosive emission) during the nanosecond high-voltage discharge in nitrogen at atmospheric pressure are presented. It is shown that the runaway electrons are generated in two stages when only field emission occurs. In the first stage, runaway electrons are composed of the electrons emitted by the cathode and producing gas ionization in the vicinity of the cathode. This stage is terminated with the formation of the virtual cathode, which becomes the primary source of runaway electrons in the second stage. Also, it is shown that runaway electrons current is limited because of shielding of field emission by the space charge of the emitted electrons and because of the formation of a virtual cathode.

In the case when the electron field emission transfers to explosive emission, it is shown that the time when the explosive emission turns on influences significantly the generation of runaway electrons. Namely, the turn-on of explosive emission prior to the formation of the virtual cathode leads to an increase in the current amplitude of the runaway electrons and in a decrease in its duration. Conversely, an explosive emission turn-on after the formation of the virtual cathode and during the high-voltage pulse rise time does not influence the generation of runaway electrons significantly. Finally, if the explosive emission turns on during the fall of the high-voltage pulse and also after the virtual cathode formation, one obtains additional runaway electrons generation.

## ACTIVE FEEDBACK STABILIZATION OF THE FLUTE INSTABILITY IN A MIRROR MACHINE USING PARALLEL COILS

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P 15

Plasmas confined in mirror machines are unstable even at low beta (plasma pressure/magnetic pressure), mainly because of the flute instability. One possible way to stabilize the plasma is to use active feedback to correct the plasma shape in real-time. A 2-dimensional MHD simulation was used to investigate a system consisting of feedback coils parallel to the magnetic field, immersed in the plasma around the hot core. When current is driven through the coils, the plasma moves to conserve magnetic flux. An algorithm for determining the feedback currents is shown to stabilize the system with zero residual current.

## SELF AMPLIFICATION VS ENHANCED SUPER-RADIANCE IN SINGLE PASS FREE-ELECTRON LASERS FOR THE THZ SPECTRAL RANGE

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Self amplified spontaneous emission and enhanced super-radiance are discussed and compared as possible configurations for the construction of a single-pass, compact FEL source for THz radiation. Numerical simulations carried out using the 3D space-frequency approach demonstrate the charge squared dependence of the radiation power in both cases, the characteristic typical to super-radiant emission. The comparison reveals a higher efficiency of an enhanced super-radiance FEL, which can be achieved if drive electron beam bunches with the length of about the radiation wavelength long or shorter are available at a proper energy chirping.

P 16

## BREAKDOWN SPECTROSCOPY INDUCED BY LOCALIZED MICROWAVES FOR MATERIAL IDENTIFICATION

**Y. Meir** and E. Jerby

*Tel Aviv University*

This paper introduces a localized microwave based technique for direct excitation of plasma from solid materials for the sake of their identification by atomic emission spectroscopy. The microwave energy is concentrated on the material surface by an open-ended coaxial applicator. The evolved $\sim$ 1-mm$^3$ hotspot is slightly evaporated and excited as plasma. An optical spectrometer measures the atomic emission spectrum, hence enabling the material identification, as in the known laser-induced breakdown spectroscopy (LIBS) technique. The experimental results demonstrate the conceptual feasibility of the localized microwave induced breakdown spectroscopy as a low-cost MIBS substitute for the LIBS for material identification in scenarios in which a direct contact with the material to be identified and its slight destruction are permitted.

P 17

## THERMITE FLAME IGNITION BY LOCALIZED MICROWAVES

**Y. Meir** and E. Jerby
*Tel Aviv University*

P 18

This paper presents a method to ignite pure thermite powder, which is usually hard to ignite. In this method, microwave energy is supplied locally to the powder, creates a confined hotspot, and consequently initiates a self-propagating combustion process in the entire powder volume. The coupled thermal-electromagnetic interaction evolved within the powder prior to its ignition is simulated theoretically, taking into account the powder's temperature-dependent parameters. The simulation results show a thermal-runaway instability and localized heating within a confined hotspot, induced mostly by the microwave's electric-field component. The experimental setup employs accordingly an open-end applicator implemented by a miniature solid-state microwave-drill device inserted into the thermite powder as a local igniter. The experimental results show ignition and flame ejection within $\sim 3$ seconds at 2.1-GHz, 100-W microwave injection, in agreement with the theoretical model. The dependence of the minimal microwave power on the exposure time required to reach combustion is identified. The optical spectrum of the flame is analyzed using the Boltzmann-plot method. Practical aspects and potential applications of this mechanism, such as rust conversion, self-propagating high-temperature synthesis (SHS), energy production, and propulsion are indicated.

Y. Meir and E. Jerby, *Thermite-powder ignition by electrically-coupled localized microwaves*, to be published in Combustion and Flames.

## TOMOGRAPHIC RECONSTRUCTION OF INCOMPRESSIBLE FLOW

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P 19

In many plasma experiments facilitating tomography the reconstruction problem is under-determined, meaning there are many possible solutions consistent with the measurements. If the sampling rate is fast relative to the typical evolution time, the known physical dynamics of the system can be used as additional reconstruction constraints. We demonstrate that incorporating the requirement of incompressible flow can improve significantly the fidelity of the reconstructed sequence. The incompressibility of the reconstruction is assured by requiring the conservation of the density moments. A consequence of the density moments' conservation is the conservation of the density histogram throughout the reconstructed sequence.

## FERROELECTRIC CATHODE WITH DUAL FRONT ELECTRODE

M. Einat, **Y. Orbach**, R. Ben-Moshe, M. Pilossof and H. Hirshbein

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Ferroelectric cathode with dual front electrode experimental study is conducted. The two electrodes are triggered separately in complementary timing. During the operation and plasma formation of one, the second is in the relaxation process and vice versa. This configuration has the potential to increase the possible pulse repetition rate and duty-cycle of the ferroelectric cathode. The experimental setup and first results are presented. P 20

## MICROWAVE DIAGNOSTICS OF FEMTOSECOND LASER-GENERATED PLASMA FILAMENTS

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*Hebrew University*

Intense laser pulse propagating in atmospheric conditions will self focus and generate long, plasma formations called plasma filaments. We present a simple non intrusive experimental method allowing a complete, high temporal resolution measurement of filament conductivity. The method is based on filament interaction with low intensity microwave radiation in a rectangular waveguide. The suggested diagnostics allow a complete single shot temporal analysis of filament plasma decay with resolution better than 0.3 ns and high spatial resolution along the filament. The experimental results are compared to numerical simulations, and an initial electron density of $7 \times 10^{16}$ $cm^{-3}$ and decay time of 3 ns are obtained. The experimental technique is used to evaluate variations in plasma conductivity along the filament and to monitor plasma relaxation in nitrogen and oxygen at atmospheric pressure. Our results amply on a non uniform distribution of electron density along the filament produced by the focusing-defocusing sickles of the laser pulse undergoing filamentation. Comparison of filamentation in air to filamentation in oxygen and nitrogen provides the ability to recognize recombination and attachment dominant plasma decay regimes. P 21

## PARAMETERS OF EXPLOSIVE EMISSION PLASMA DURING S-BAND RELATIVISTIC MAGNETRON OPERATION

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P 22

Research results on the parameters of explosive emission plasma generated during the operation of a relativistic S-band magnetron powered by Linear Induction Accelerator ($\sim 450\,$kV, $\sim 5\,$kA, $\sim 150$ ns) are presented. Time- and space-resolved characteristics of the cathode plasma were calculated using data obtained by non-intrusive spectroscopic measurements. These parameters were compared with the explosive emission plasma parameters generated in a cylindrical magnetically insulated diode configuration, under the same amplitude applied voltage and current. A significant difference in the parameters of the plasmas in these two configurations was observed, and a possible explanation which associates it to the heating of the plasma by the oscillating electromagnetic field in the magnetron's interaction space is given.

## NON-LTE EQUATION OF STATE FOR SIMULATIONS OF LASER PLASMA INTERACTION

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*2 Tel Aviv University*

P 23

In this work we present equation of state (EOS) for the free and bound electrons in non-LTE (Local Thermodynamic Equilibrium) conditions typical for laser-plasma interaction. In order to characterize the plasma we solve stationary rate equations for the populations of the bound electrons (since the Saha-Boltzman distribution is not adequate in non-LTE). For this purpose we use screened hydrogenic average atom approximation with l-splitting. Having found the bound state populations and ionization degree, we evaluate the pressure and internal energy. The bound electrons pressure is calculated using the quantum mechanical stress tensor formula. This electronic EOS is added to the cold and ionic terms of QEOS model and then implemented to a 1D hydro-radiative code. The simulation results are compared to those with other EOS models.

## SUB-MICROSECOND RESPONSE TIME FOR MILLIMETER WAVE AND THZ DETECTOR BASED ON INEXPENSIVE NEON PLASMA INDICATOR LAMPS

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The electromagnetic spectrum between 3 mm and 30 $\mu$m becomes very attractive for applications in medicine, communications, home land security, and space technology. This is because there is no known ionization hazard for biological tissue, and atmospheric attenuation of terahertz (THz) radiation is low compared to infrared and optical rays. The lack of inexpensive room temperature detectors in this spectral region makes it difficult to develop detection and imaging systems.
Miniature Neon indicator lamps were found to be very good detectors in the millimeterwave (MMW) and THz, known as Glow Discharge Detectors (GDD). The detection mechanism of the GDD is P
based on slight change of the current between the two electrodes of the lamp due to the electric field 24
of the electromagnetic radiation incident to the GDD. The dominant mechanism was found to be enhanced cascade ionization rather than diffusion current. The former increases the current while the former decreases it. The response time of the plasma is on the order of nanoseconds; however the response time of the GDD is limited by the electronic circuit. Recently we were able to detect fast signals on the order of 100 nsec using commercial miniature plasma neon lamps operating in the abnormal glow mode. The advantages of such plasma detector are: room temperature detector, high dynamic range, broadband, easy to operate, commercially available, and very inexpensive detector about \$0.2 – \$0.5 each. Some applications of millimeter waves require fast envelope detection. Examples of such applications include measuring the time of flight, radar detection, direct detection of short pulses, and real time imaging.

## MAGNETIC FIELD PENETRATION INTO A LOW-RESISTIVITY MULTI-ION-SPECIES PLASMA

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A rapid, non-diffusive, penetration of a magnetic field ($\sim 8\,$kG) into a low resistivity plasma (with an initial electron density of $\sim 2\times10^{14}$ cm$^{-3}$ and electron temperature of $\sim 6\,$eV) has previously been observed [1]. However, due to the limited resolution of previous observations, the details of the magnetic field profile and plasma dynamics during the penetration remained vague. This P
study was aimed at reducing these ambiguities by improving the resolution of the observation. 25
To this end a new, indirect, method for observing the magnetic field has been developed, which relays on extracting the magnetic field from the velocities of trace element ions accelerated by the field. Observation of the magnetic field on a spatial resolution approaching the electron skin depth (nearly an order of magnitude higher than previously obtained resolution) has been obtained. The new measurements show that the magnetic field penetrates some of the plasma and repels the rest of it while keeping the profile of the magnetic field front nearly unaltered, at least during the time it progresses the width of its front. It was also shown that the electron density evolution agrees with the ion dynamics expected from the magnetic field profile obtained.

[1] R. Arad, K. Tsigutkin, A. Fruchtman, J. D. Huba, and Y. Maron, Phys. Plasmas 10 (2003).

## MODIFICATION OF THE SURFACE NANOLAYERS CERAMIC-METAL MATERIALS USING LOW PRESSURE RF PLASMAS

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It is known that reliability of a metal-cutting tools and its lifetime are defined by a surface coating condition. One of perspective ways of materials characteristics improvement is processing by a stream of low energy ions (50 – 100 eV), created in low pressure (13.3 – 133 Pa) radio-frequency (RF) plasma. Formation of the surface nanolayers on tungsten-cobalt samples by low pressure RF plasma treatment were studied.

Experiments were spent on RF plasma source with plane-parallel electrodes at frequency of 13.56 MHz. Mix of argon and propane-butane fraction in the ratio volume fractions of 70% of argon and 30% of propane-butane was used for surface saturation by carbon.

Samples were made as plates $9 \times 9$ mm by sizes and of 3 mm by thickness. The surface of plates
P was polished before plasma treatment. Researches were spent at various time from 40 up to 240 s,
26 pressure from 13 up to 133 Pa, gas expense up to 0.2 g/s, discharge power from 0.5 up to 5 kW.
Surface of specimen is exposed to ion bombardment of 10 – 100 eV by energy 0.3 – 1 A/m$^2$ by ionic current density.

Studying of surface layers spent by X-ray photoelectron spectroscopy, Auger-electron spectroscopy and electron microscope researches, microhardness measurement. It was found that modified nanophase layers up to 70 – 670 nm by thickness depending on plasma treatment time are formed, also microhardness of materials from 16 up to 22 GPa were increased. These changes occur due to influence of plasma ions with energy 10 – 100 eV on base material that provides intensive diffusion of structure defects and atoms from superficial nanolayers in deep layers. As a result a crystal lattice is changed, corrosion and wear resistance and hardness of materials are increased.

On the basis of the research the technology of hardening of ceramic-metal medical stomatologic mills from tungsten-cobalt alloy by low pressure RF plasma was developed.

## SURFACE MODIFICATION OF METALS BY RADIO-FREQUENCY PLASMA OF REDUCED PRESSURE

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Improving the quality, reliability and durability of products is the major task of the manufacturing industry. One effective method to improve the quality of engineering products is a modification of properties of working surfaces exposed to various media in operation. The results of experimental studies of the processes of wear and failure of various products during operation showed that the product reliability and service life depend, and often completely determined by the state of the surface layer.

The proposed method of surface modification of products is based on the principle of plasma generation by radio-frequency (RF) electromagnetic fields in the medium of the plasma-supporting gas and plasma interaction with the surface of the workpiece. First, this treatment removes surface contamination, including oxide films, process lubricants, etc, which are inevitably present on the surface of materials. Second, as a result by treatment the surface roughness of metals decreases as the ion impact concentrates on apex of microroughness during the ion bombardment. Third, the ion bombardment in the RF plasma treating achieves healing of the metal surface microcracks, P
the elimination of fissured and relief layers, the formation of compressive residual stresses in the 27
surface layer of the sample, etc. Fourth, the bombardment allows improving the inner structure of metals through the reallocation of defective layers. Gas saturation of surface with the formation of the carbides and nitrides can be achieved when using the mixture of argon with propane-butane gas or nitrogen as a plasma-supporting gas. The use of plasma-chemical gas leads to a change in the chemical composition of the metal surface layer. As a result by treatment occurs the formation of nanophase near-surface layers deep into the sample, etc. The proposed technology makes it possible to treat products ranging from standard general-purpose tools (cutters, drills, multiflute drills, reamers) to sophisticated prefabricated elements, such as the facing cassette milling heads, gear-cutting tool, combination tool, etc.

Thus, the RF plasma treating of metals and alloys leads to increase the corrosion resistance, microhardness, wear resistance of products made from these materials. These changes are the result of diffusion of plasma-forming gas atoms, structural defects created by RF plasma in the surface nanolayer.

## CREATING A NANOMODIFIED TEXTILE MATERIALS WITH ANTIBACTERIAL PROPERTIES BY NON-EQUILIBRIUM LOW-TEMPERATURE PLASMA MODIFICATION

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Modification of the silver nanoparticles can impart antimicrobial and bacteriostatic properties of the textile materials, stimulate the immune system, metabolism and cell regeneration. These properties make modified textile materials are indispensable for the production of sports clothing and outfit, thermal underwear, textiles for medical purposes.

The problem of textile materials consisting of synthetic fibers is hydrophobic, inert surfaces, which prevents impregnation of textiles colloidal solution of silver nanoparticles.

One promising areas of application of silver nanoparticles on textile materials is modification using plasma treatment. Non-equilibrium low-temperature plasma efficiently and stably change the surface properties of the sample, does not impair the volumetric (including the physical and mechanical) characteristics, does not cause destruction of the material. By changing the parameters and the type of plasma-forming gas can be controlled the composition of the chemically active
P particles and, consequently, the nature of the impact the high-frequency capacitive discharge of the
28 textile material.

The results of change of hydrophilic properties of the knitted materials after plasma activation:

- for the knitted material N°1 (65.3% cotton, 34.7% polypropylene) the value of capillarity: before plasma treatment – 20 mm, after plasma treatment – 34 mm; time of spreading droplets: before plasma treatment – 156 s, after plasma treatment – 18 s.
- for the knitted material N°2 (62.5 % wool, 35.6% polyester, 1.9% spandex) the value of capillarity: before plasma treatment – 0 mm, after plasma treatment – 165 mm; time of spreading droplets: before plasma treatment – $\infty$ s, after plasma treatment – 20 s.

Treatment of the textile materials blended composition using the non-equilibrium low-temperature plasma leads to hydrophilization of their surface (increasing the value of the capillarity, reduction of the time of spreading droplets), activation of textile fibers, which allows silver nanoparticles to settle on the surface of the fibers, preventing them agglomeration. After impregnation with silver nanoparticles and drying plasma re-processing of textile materials leads to stable fixation of silver nanoparticles on the textile fibers. This makes it possible to obtain textile materials with uniformly distributed fixed and stable silver nanoparticles in the surface layer of materials.

## PROSPECTS OF USING PLASMA TREATMENT FOR IMPROVING THE SURFACE PROPERTIES OF ARAMID FIBERS

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In the field of automobile and aircraft manufacturing there is a tendency to design lighter, more compact components. So there appears the need to replace metals in shipbuilding, aerospace, automotive and other industries where weight reduction and the cost of a product is required with an increase in its strength, corrosion and thermal resistance, etc. So today more and more becoming the preferred choice of synthetic fiber materials as the basis for the creation of composite materials (CM). One of the options such raw materials are aramid fibers. Aramid fibers Rusar-S (Scientific Production Enterprise "Termoteks") refer to the threads of the third generation and have a very high physical and mechanical properties. They are used in the production of heavy duty CM, whose service life is 15 – 20 years depending on operating conditions. Problem of using aramid fibers as a reinforcing material is hydrophobic, the inertion of its surface, thus preventing of interphase interaction with the matrix material and obtaining monolithic CM. P 29

Processing of low-pressure plasma in a high-capacitive discharge (HCD) let to change the hydrophilic properties of aramid fibers with an increase of capillarity, which is essential in creating ultra-light high-strength CM. The results of influence of plasma activation on hydrophilic properties of aramid fibers:

- for fiber Rusar-S (1): the average value of capillarity before plasma treatment – 5.7 mm, after plasma treatment – 181.7 mm;
- for fiber Rusar-S (2): the average value of capillarity before plasma treatment – 5.3 mm, after plasma treatment – 103.3 mm.

Using plasma treatment of aramid fibers can increase their wettability by working liquid in 31.8 times for the mark Rusar-S (1) and in 19.5 times for the mark Rusar-S (2) in comparison with the control samples without plasma treatment.

## RESEARCH OPPORTUNITIES FOR TECHNICAL FABRICS WITH ANTI-ADHESIVE PROPERTIES USING PLASMA MODIFICATION

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P 30

Technical textiles are widely used for the production of conveyor belts, rubber hoses, flat and V-belts, upholstery seats and the interior lining of cars, for tents, shells, balloons and inflatable hangars, garages, and folding camping hiking, automobile and aircraft tires; in as filter screens. To reduce the adhesion of filling material on the basis of technical fabrics for the procurement of raw rubber is required to further processing with release formulations. Fabrics are either impregnated or duplicated with film material, or covered with various emulsions based on polymers of low molecular weight rubbers [1]. Non-equilibrium low-temperature plasma (NLP) allows you to adjust the specified properties of fibrous materials without destruction, provides the ability to eliminate the processing of various chemical substances, and changes the adhesive properties of the surface depending on the parameters of the plasma modification. In connection with this interest is the impact on the NLP fabrics for technical purposes, including on the basis of natural and synthetic fibers. The object of the study performed technical fabrics ChLH (51% cotton, 49% of PEF) produced by "Krez", Elabuga. Insulating fabric cushioning ChLH is used in the tire industry between steel cord and rubber, therefore, is to make the necessary antiadhesive properties of the technical fabrics to the rubber. Treatment of the samples was carried out at high plasma installation of capacitive discharge. Evaluation of the surface properties of the object of research carried out by changing the capillary tissue according to a standard method according to GOST 3816 - 81.

[1] Gushchina M.N. *The new woven protective material for the rubber industry*, in M.N. Gushchina, N.M. Kolotilova *Technical Textiles* - 4 (2002).

## INFLUENCE OF LOW PRESSURE RF PLASMAS ON COPPER POWDER MECHANICAL PROPERTIES

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Copper powders are widely applied at manufacturing details of cars and devices used in aviation and rocket technics that forces scientists to create new copper powders with the certain mechanical, physical and chemical properties, capable to provide operational characteristics. One of the most perspective methods of increasing of mechanical properties of powder materials is the low pressure radio-frequency (RF) plasma treatment, which allows to vary both temperature of processing and ionic stream characteristic. Influence on mechanical properties of copper powder by low pressure RF plasma treatment was studied.

Experiments were spent on RF plasma source at frequency of 1.76 MHz. Researches were spent at various pressure from 13 up to 133 Pa, gas expense up to 0.2 g/s, consumption power from 2 up to 12 kW. Studying of copper powder spent by X-ray structural analysis (X-ray diffractometer DRON-2), mechanical properties as temporary resistance, elongation and ultimate strength was defined under normal condition on tearing machine. P 31

It was found that particles of a copper powder becomes an additional electrode. Therefore at its surface the same as in near-electrode areas of RF discharges a positive charge layer is formed. Passing through positive charge layer ions are accelerated and take an energy up to 100 eV. At impact on surface copper particles ions pass the got kinetic energy and recombination energy to superficial atoms of a copper powder and modify its superficial layer. In case of using argon mixture with nitrogen, oxygen or carbohydrates in powder nanophase layers nitrides, oxides, carbides were found. On the basis of the research established that low pressure RF plasma treatment positively affects to pressing and sintering of copper powders due to grains sizes reduction and their quantitative increasing that in turn tends material mechanical properties increasing.

# THE NUMERICAL MODEL OF DISTRIBUTION OF LOW-ENERGETIC ION STREAM ON A SURFACE OF WOOLEN FIBERS DURING MODIFICATION IN THE RADIOFREQUENCY GAS DISCHARGE

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P 32

The modification of woolen fiber in radiofrequency gas discharge improves their processing characteristics: improves coloring value, accelerates lightening, etc. A sheepskin hair covering samples were used in experiments. The treatment was performed in radiofrequency gas discharge with the following properties: frequency 13.56 MHz, pressure 26.6 Pa, argon consumption 0.04 g/s, ionic stream density 0.3 – 0.6 A/$m^2$, ionic energy 30 – 90 eV. Occurred as the result of radiofrequency gas discharge modification, changes in hair cuticle structure are clearly demonstrated by REM data. Examining the samples, virgin and modified with increasing intensity of modification, we can observe the accumulation of cuticle defects. These defects touch mainly the cuticle cell ledges and become apparent:
- mode 1 - as exfoliation from matrix and minor damage of the cuticle cell upper edge;
- mode 2 - as significant exfoliation and thinning of the cuticle cell upper edge;
- mode 3 - the cuticle upper edges are covered with chips and unbent outside.

To determine the mechanism of the impact of low-energetic ion stream, forming in underpressure radiofrequency discharge, on the fur hair covering, the mathematical model of surface low-energetic ionic bombardment was developed. At first modeling stage the three-dimensional geometric model of hair was developed. The fiber shaft was shaped as an elliptic cylinder, with the semiaxis ratio 2:3 and maximum lateral dimension 40 micron. The cuticle was simulated using the surfaces, described with the trigonometric functions. The cuticle cells are shaped as set of surfaces with specified height step and rotation around the fiber shaft angle (900). The height of upper and lower sections is specified. At second modeling stage the theoretical experiment was performed, to study the cuticle geometry influence on the bombarding low-energetic ion trajectory in process of radiofrequency plasma modification of fur sheepskin hair covering. As the base of this experiment the model of low-energetic ionic stream interaction with flat material relief surface [1] was used

For numerical estimate of process computer imulations, based on the Monte Carlo method, were performed. The movement of 50,000 ions to the charged surface of geometric model was simulated. It was determined, that the distribution of low-energetic ionic stream on the surface during radiofrequency gas discharge modification of fur hair covering is not uniform. The substantial growth of ionic stream density, when the energy of ions remains constant (30 – 90 eV), ensures the selective impact of radiofrequency discharge on the cuticle ledges. Due to this growth the processes of etching are realized. Also the possible reason of the cuticle edge bend is the presence of localized thermal impact effects.

[1] Sagbiev, I.R. *The underpressure jet radiofrequency discharge in modification processes of constructional material surface nano-layers*, Dissertation, Master of Science in Technique, Kazan, 2009.

## MICRO-PLASMA EFFECT IN METAL-POWDER MICROWAVE-HEATING INTERACTION

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This paper presents various microwave interactions with metal powders, including a micro-plasma effect, leading to the powder heating, melting, consolidation and solidification. Experimental results show metal powder solidification in forms of spheres and rods in a $1 - 10$ mm range. A theoretical model of the localized microwave interaction within metal powders shows microwave propagation and dissipation effects (unlike in solid metal) that give rise to several heating mechanisms. In particular, the coupling effect caused by the induced complex permeability leads to magnetic heating even in powders made of non-magnetic metals (e.g. copper and aluminum) due to the Eddy currents induced in the powder particles. However, a numerical analysis suggests that the enhanced electric field between the metallic particles excite electric discharges (micro-plasma) that initiate the heating process, as observed also experimentally. The results presented here lead to the development of a microwave-plasma technique for stepwise formation of $>$ 1-mm metal structures, as a low-cost partial substitute for laser-based technologies for rapid prototyping (RP) and additive manufacturing (AM) systems.

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## A SPACE- AND TIME-RESOLVED TABLE-TOP HARD X-RAY SOURCE

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Space and time-resolved x-ray radiation was produced using a high-voltage $\sim 5$ ns pulse duration table-top spiral generator. The generator supplies a high-voltage pulse with amplitude of up to $\sim 150$ kV to the vacuum diode with needle-like cathode and anode electrodes. A guiding external magnetic field produced by Helmholtz coils was used to decrease the size of the anode surface that produces x-rays by electron bombardment. A high resolution x-ray detector coupled to the system was used to capture x-ray shadow images of an underwater exploding wire. The obtained x-ray images have time and space resolution of $\leq 5$ ns and $< 100$ microns, respectively.

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## PLASMA FORMULARY INTERACTIVE

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Plasma Formulary [1,2] is an interactive, Web-based application that provides a comfortable access to evaluating, comparing, and plotting of a multitude of different plasma and atomic physics parameters, grouped by the unit dimensions. A special attention is devoted to the Stark broadening which is calculated with a good accuracy for transitions between degenerate atomic levels using the quasi-contiguous approximation [3]. The list of the entities calculated encompasses over one
P hundred entries and is easily expandable.
35 The application is built using open-source components and is compatible with a majority of modern browsers.

[1] http://plasma-gate.weizmann.ac.il/pf/
[2] E. Stambulchik and Y. Maron, *Plasma Formulary Interactive*, JINST 6, P10009 (2011).
[3] E. Stambulchik and Y. Maron, *Stark effect of high-n hydrogen-like transitions: Quasi-contiguous approximation*, J. Phys. B: At. Mol. Opt. Phys. 41, 095703 (2008).

## THE LITHIUM WALL FUSION AVENUE

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Several issues may be show-stoppers in attaining a working fusion energy device: Disruptions, wall
P erosion, size, etc. During the last ten years or so, there are activities around the world to show
36 how liquid metal walls in tokamaks may solve the above problems in a fundamental way. The most promising results have been obtained using liquid lithium covered limiters and divertors at several laboratories in the PPPL (USA), China, and elsewhere.

## INVESTIGATION OF A PLASMA WAVE-GUIDE FOR LASER ELECTRON ACCELERATION

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The strong electro-magnetic fields generated by high power lasers ($> 10^{18}$ W/cm$^2$) enable the acceleration of particles up to relativistic energies on a millimeter scale [1-4]. Common approaches of electron acceleration make use of capillary discharge and laser self-focusing in gas jets as waveguides. In an effort to improve the electron energy distribution and acceleration efficiency, a new approach for creating a waveguide, based on a small scale z-pinch, was recently proposed in collaboration between the Weizmann Institute of Science and the Jena Friedrich Schiller University, Germany. In contrast to the capillary approach, where radial probing is prohibited due to the capillary walls, the z-pinch method is not restricted to axial diagnostics. In terms of future applications, the z-pinch approach also offers longer operation cycles since it saves the need for capillary replacement. The axial and radial electron density profiles of the z-pinch are crucial for the laser electron acceleration. The effects of different gas nozzle designs, pre-ionization, and application of an external, axial magnetic field on the spatial symmetry of the imploding plasma column are studied. The evolution of the electron density profile has been determined by spectroscopy using Stark broadening and continuum emission, as well as interferometry. P 37

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## STUDY OF HEATERLESS THERMIONIC HOLLOW CATHODE FOR LOW POWER PLASMA THRUSTERS

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P 38

Hollow cathode based on thermionic electron emission serves as crucial component in electric propulsion systems where this cathode used as source of electrons for propellant ionization and ion beam neutralization. In this research, a novel design of the hollow cathode without the heater was studied in the diode mode operation. The simplicity of the cathode design and its unique ignition characteristics (few ms) are attractive features for microsatellite and nanosatellite propulsion applications. However, physical processes involved in the cathode ignition, heating and main discharge formation are still poorly understood.

In this report, the study of the physical processes accompanying the heaterless thermionic hollow cathode ignition, heating and DC operation will be reported. The research was carried out using various diagnostic methods (single and double Langmuir probes, biased Faraday cup, electron energy retarding analyzer, Penning probe and spectroscopy). The cathode operation characteristics and plasma parameters were determined versus the discharge current, cathode-anode gap and Xe flow rate.

## RESULTS OF X-RAY ABSORPTION SPECTROSCOPY IN A NANOSECOND DISCHARGE IN PRESSURIZED GAS

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The properties of high-energy runaway electrons generated during a nanosecond discharge in an air filled diode at pressures up to $3 \times 10^5$ Pa were studied using x-ray absorption spectroscopy. The results of studies of the discharge at different pressures and with different lengths of cathode-anode gap allow an insight into the factors that influence the energy distribution of runaway electrons. Energy distribution functions for runaway electrons produced in Particle-in-Cell simulation were used to create the x-ray attenuation curves via a computer-assisted technique simulating the generation of x-ray by energetic electrons. The simulated attenuation curves were compared to experimental results.

## SIMULATION OF INTERACTION BETWEEN LOWERED PRESSURE RF PLASMA AND SILVER NANOPARTICLES

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Radio-frequency (RF) plasma at lowered pressure is effectively used in various technological processes, including deposition of silver nanoparticle on fur [1]. Therefore mathematical model of silver nanoparticles interaction of with lowered pressure RF plasma is developed. RF plasma at pressure $p = 13.3 - 133$ Pa, generator frequency $f = 1.76$ MHz, discharge power $P_d = 0.5 - 4$ kW, gas consumption $G <$ 0.2 g/s possesses following characteristics: ionization degree less than $10^{-4} - 10^{-7}$, electronic concentration $n_e \sim 10^{15} - 10^{19}\mathrm{m}^{-3}$, electronic temperature $T_e = 1 - 4$ eV, temperature of atoms and ions in discharge $T_a = (3-4) \times 10^3$ K, in plasma stream $T_a = 350 - 700$ K [2]. Diameter of silver nanoparticles is equal up 5 to 9 nm that is much less then Debay length $\lambda_D \sim 7 \times 10^{-5}$ m. Because of continuum conditions aren't carried out, it is necessary to use molecular dynamic methods for modeling of nanoparticles interaction with plasma [3]. Due to $Ag^+$ nanoparticles concentration is less then $10^5$ $\mathrm{m}^{-3}$ one particle activation process excepting others particle influence is considered. The model is constructed in the assumption that nanoparticles moves in plasma stream so that ions are motionless in the local system of coordinates connected with nanocorpuscle, but electrons fluctuate in phase with electric field intensity changing. Elementary cell of $n_e^{-1/3}$ by linear size, containing one charged silver particle is considered. One nanoparticle contains approximately $10^4 - 10^5$ silver atoms and ions. Energy $\sim 7.5$ eV is emited at electron recombination with $Ag^+$ ion. This energy is in almost three times more than the energy needed for evaporation of silver atom out of surface. Nanoparticle charge is decreased at each electron collision with the particle, but its energy is increased due to recombination energy and kinetic energy of electron. Therefore nanoparticles is heated to melting temperature at first, and heated up to evaporation temperature after that. When nanoparticle is loss positive charge, it is charged negatively. Limit negative charge of nanoparticle is found. Nanoparticles neutralization and recharge times as well as its residual volume are calculated.

P 40

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## SIMULATION OF LOWERED PRESSURE CAPACITY COUPLED RADIO-FREQUENCY DISCHARGE AT BIG INTERELECTRODE DISTANCES

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RF discharge at lowered pressure $p = 13.3 - 133$ Pa and interelectrode distance of 20 – 30 cm is effectively applied to processing of a leather-fur marterials [1]. Models of RF discharges at average and low pressures and at interelectrode distances $d = 3 - 5$ cm in detail are investigated [2]. Properties of RF discharges at the big interelectrode distances (more than 10 cm) practically are not investigated.

Therefore one-dimensional mathematical model of RF discharges at lowered pressure is constructed. The basic characteristics of a positive column and of a positive charge layer such as concentration of electrons and ions, electronic and gaseous temperature, electric field in plasmotrone with big interelectrode distance is allowed to estimate the model.

P The mathematical model includes equations of a continuity for electronic and ionic gases, heat
41 conductivity of atomic and ionic gas and Poisson equation for electric potential together with
corresponding boundary and initial conditions.

The comparative analysis of efficiency of various finite difference schemes which is applied for decision such tasks, a simple iterative method and a delayed factors method for a linearization of nonlinearities is given.

As a result of calculations the basic characteristics of a positive column and positive charge shell of lowered pressure RF discharge at big interelectrode distance are established.

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## CALCULATION OF GAS DYNAMICS FLOWS OF HIGH FREQUENCY PLASMA IN LOW PRESSURE AND SOLUTION FOR FLOW AROUND BODY PROBLEM

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Model of lowered pressure RF plasma flow at $Kn = 0.001 - 0.1$ is described. The model is based on the statistical approach. Results of calculations of neutral component of plasma is shown for undisturbed flow as well as for flow with specimen.

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## PHYSICAL MODEL OF LOWERED PRESSURE RF DISCHARGE INFLUENCE ON FOOTWEAR CARDBOARDS

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Processing at lowered pressure RF discharge (LPRFD) is allowed to improve operational properties of footwear cardboards [1]. Footwear cardboards represent the system consisting of various substrata (natural polymers such as leather and paper waste), connected by adhesive inter-layers which is glue (synthetic polymers). The cross-section size of structural elements is about 10 – 15 microns, longitudinal size is about 40 – 60 microns.

Footwear cardboards is composed from collagen which is the main component of leather, cellulose which is the main component of paper and the glutinous polymeric material. These materials are electrets. Therefore they are able to electrize spontaneously and to keep an electric charge for a long time. Due to electronic gas fluctuations in oscillating electric field a spatial charge shell (SCS) is formed near sample surface therefore the sample gets potential 70 – 100 V [2]. Spatial charge shells near opposite sample size is pulsed in an antiphase with each other. Therefore instantaneous potentials of the opposite sides of the sample is also increased and decreased in an antiphase with each other. The amplitude of a potential difference between the opposite sides of the sample reaches 120 – 160 V. Thickness of footwear cardboard samples is equal h = 0.9 – 2.5 mm, therefore, an alternative electric field of $\sim (4.8 - 17.6) \times 10^4$ V/m appears inside samples. Because of electronic and ionic streams are arrived in porous volume of sample from plasma, breakdown is occurred inside pores and capillaries. Charged particles resulting breakdown are recombined on an internal surface of pores and capillaries and released energy 15.76 eV for argon. Energy action is led to conformational changes of polymer molecules, dipole reorientation, change of crystallinity degree, ordering of an amorphous phase, splitting of fibres that proves to be true experimental data. Thus, breakdown occurrence inside pores and capillaries is a main reason of volumetric modification of footwear cardboards in LPRFD.

The work is supported by RFBR (projects No. 10-01-00728a, 11-01-00864-a) and MES RF (contract No. 14.740.11.0080).

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