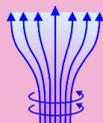




# The 19<sup>th</sup> Conference on Plasma and its Applications

February 5<sup>th</sup> , 2017, The Hebrew University of Jerusalem

## PROGRAM & ABSTRACTS



**Israel Plasma  
Science and  
Technology  
Association**

*affiliated with the Israel Vacuum Society*

האוניברסיטה העברית בירושלים  
THE HEBREW UNIVERSITY OF JERUSALEM



Edmond J. Safra Campus, Hebrew University of Jerusalem; Adiel Io (From Wikipedia, the free encyclopedia)

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## Table of Contents

<b>Organizing Committee</b> .....	4
<b>Program at a glance</b> .....	5
<b>AM-1 session</b> .....	7
Nathaniel J. Fisch <b>Invited</b> .....	7
Amnon Fruchtman .....	8
Menahem Krief .....	10
Yair Kurzweil .....	11
<b>AM-2 session</b> .....	13
Tsafir Armon .....	13
Adi Hanuka .....	15
David Yanuka .....	18
Vasily Yu. Kozhevnikov .....	20
<b>PM-1 session</b> .....	22
Victor Malka <b>Invited</b> .....	22
Ido Barth .....	24
Gilad Marcus .....	26
Jenya Papeer .....	27
<b>PM-2 session</b> .....	29
Guy Shafir .....	29
Miron Voin .....	30
N. Balal .....	32
Asher Yahalom .....	35

## Table of Contents

Marko Cvejić.....	37
<b>Poster session</b> .....	39
H. R. Strauss, P1 .....	39
Gilad Laredo, P2 .....	41
Roey Ben Moshe, P3.....	43
Adi Hanuka, P4 .....	45
Tal Queller, P5 .....	47
Alexei Baskin, P6.....	49
K.Gomberoff, P7.....	51
G. Makrinich, P8.....	53
A. Rososhek, P9 .....	55
V.L. Bratman, P10 .....	56
Seth Davidovits, P11 .....	59

# Organizing Committee:

Gilad Marcus – Hebrew University of Jerusalem,  
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Amnon Fruchtman – Holon Institute of Technology

Moshe Fraenkel - Nuclear Research Center - Soreq

Aharon Friedman - Ariel University

Start	End	Name	Title
8:00	9:00		early bird registration + coffee
9:00	9:10	Gilad Marcus + Asher Yahalom	Opening remarks
9:10	9:40	Nathaniel J. Fisch	<b>Invited:</b> Some Effects in Rotating Plasma
9:40	10:00	Amnon Fruchtman	Suppression of diamagnetism in partially-ionized high-beta plasma
10:00	10:20	Menahem Krief	The role of atomic physics in the modeling of the solar interior
10:20	10:40	Yair Kurzweil	Analytical methods for calculating detailed absorption spectra of hot LTE plasmas: theory and implementation
10:40	11:00		Coffee and snacks
11:00	11:20	Tsafrir Armon	Chirped nonlinear resonance dynamics in phase space
11:20	11:40	Adi Hanuka	Capturing Sub-Relativistic Particles in an Optical Booster
11:40	12:00	David Yanuka	Time resolved spectroscopy of light emission from a converging spherical shock wave in water
12:00	12:20	Vasily Yu. Kozhevnikov	Hybrid kinetic-liquid model of high-pressure gas discharge
12:20	12:35	Elections for the Israel Plasma Society board	Elections for the Israel Plasma Society board
			Princeton
			HIT
			HUJI
			NRCN
			HUJI
			NRCN
			HUJI
			HUJI
			Technion
			Technion
			Tomsk

Start	End	Name	Title	Start
12:35	13:35		Lunch	
<b>13:30</b>	<b>14:00</b>	<b>PM-1 session</b> Victor Malka	<b>Invited:</b> Manipulating relativistic electrons with lasers	CNRS
<b>14:00</b>	<b>14:20</b>	Ido Barth	Reducing Parametric Backscattering by Polarization Rotation	HUJI
<b>14:20</b>	<b>14:40</b>	Gilad Marcus	Resonance High Harmonic Generation in Plasma Plumes	HUJI
<b>14:40</b>	<b>15:00</b>	Jenya Papeer	Towards Generation of Long and Continuous Plasma Channels in Air	HUJI
<b>15:00</b>	<b>15:50</b>		<b>Posters + (coffee &amp; snacks)</b>	
<b>15:50</b>	<b>16:10</b>	<b>PM-2 session</b> Guy Shafir	Plasma wakefield generation by high power microwaves	Technion
<b>16:10</b>	<b>16:30</b>	Miron Voin	Spectral Analysis of a THz Radiation Source Based on High-Harmonic Interaction in a Hybrid Cavity	Technion
<b>16:30</b>	<b>16:50</b>	N. Balal	Expansion and Excitation of Plasma Oscillations in Modulated Electron Bunches Formed in Laser-Driven Photo-Injectors	Ariel
<b>16:50</b>	<b>17:10</b>	Asher Yahalom	Variational Principles and Applications of Local Topological Constants of Motion for Non-Barotropic Magnetohydrodynamics	Ariel
<b>17:10</b>	<b>17:30</b>	Marko Cvejić	Determination of the azimuthal magnetic field evolution in imploding magnetized plasma	Weizmann
<b>17:30</b>	<b>17:40</b>		closing remarks	

# Some Effects in Rotating Plasma

*Nathaniel J. Fisch<sup>1</sup>*

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Rotating plasma can exhibit certain unusual effects. These effects can be exploited in a variety of plasma devices, including Hall thrusters, plasma mass filters, and fusion confinement devices. In pulsed devices, rotating plasma exhibits unusual heat capacity effects. A very promising but highly speculative possibility is to exploit rotation to achieve magnetic confinement in a plasma torus, but with minimal toroidal current.

# Suppression of diamagnetism in partially-ionized high-beta plasma

*A. Fruchtman<sup>1</sup>, S. Shinohara<sup>2</sup> and D. Kuwahara<sup>2</sup>*

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Balance between magnetic pressure and plasma pressure is expected in fully ionized plasmas confined by a magnetic field. The magnetic force on the plasma is due to a current carried by the diamagnetic plasma. The magnetic field inside the plasma is then lowered by that current. In partially-ionized plasma, however, the plasma pressure is balanced not only by the magnetic field pressure but also by neutral-gas pressure. In that case the diamagnetic effect of the plasma, even if high beta, is expected to be lower. The suppressed diamagnetism is explained by the neutrals pressure replacing magnetic pressure in balancing plasma pressure. Diamagnetism is weakened if neutrals pressure is comparable to the plasma pressure

and if the coupling of plasma and neutrals pressure by ion-neutrals collisions is strong enough. We calculate the steady-state of a cylindrical low temperature magnetized partially-ionized plasma (such as radio-frequency plasma source). We solve for the radial dependencies of the plasma density, the neutral density, and the magnetic field profile. Neutral pressure gradient is established by neutral depletion under the plasma pressure. We demonstrate how neutral depletion competes with the diamagnetic effect of high beta plasma in balancing the plasma pressure. When neutral depletion and the diamagnetic effect are weak, linearization of the equations allows the derivation of analytical solutions. A parameter is identified, the size of which determines whether neutrals-pressure gradient or magnetic pressure balances the plasma pressure. Experimental results and preliminary theoretical modelling have been recently published [1].

[1] S. Shinohara, D. Kuwahara, K. Yano, and A. Fruchtman, *Phys. Plasmas* **23**, 122108 (2016).

# **The role of atomic physics in the modeling of the solar interior**

*Menahem Krief<sup>1</sup>, Alexander Feigel<sup>1</sup>, Doron Gazit<sup>1</sup>*

1. The Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel.

We discuss the special role of atomic physics of hot dense plasmas in local thermodynamic equilibrium in the modeling of the solar interior. We discuss the solar abundance problem which is a decade old open problem in the modeling of the sun, that has tremendous implications on astrophysics and cosmology. As it is widely believed that the challenging atomic calculations may be the source of the problem, we show how uncertainties, which must be quantified experimentally, due to line broadening or ion correlation effects may solve the problem. We also present a novel experimental method to measure Rosseland opacities at stellar interior conditions that were never achieved in the past in high energy density facilities. Such experiments may be used to quantify the uncertainties in Rosseland opacity calculations and may lead to a resolution of the solar opacity problem.

# **Analytical methods for calculating detailed absorption spectra of hot LTE plasmas: theory and implementation**

*Yair Kurzweil<sup>1</sup> and Giora Hazak<sup>1</sup>*

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In the recent years, we have developed efficient methods for the summation of the contributions to the spectrum of all unresolved-transition-arrays (UTA) [1] as well as partially resolved transition-arrays (PRTA) [2], sharing the same atomic potential. Unlike the standard Super-Transition-Array (STA) [3] and partially resolved-STA (PRSTA) [4], this novel technique preserves the full spectral structure of the underlying UTAs or PRTAs. As a consistency check we will show that the standard STA and PRSTA results are derivable by a systematic analytical coarse-graining of the spectrum obtained by our new method. In the presentation, we will demonstrate the capacity of our new method, as implemented in our "CRSTA" code [5-7].

[1] Bauche, C. Bauche-Arnoult and M. Klapisch, Advances

in atomic and molecular physics Vol. 23 pages 131-195.

[2] C. A. Iglesias and V. Sonnad, High Energy Density Phys. 8, 154 (2012), C. A. Iglesias, High Energy Density Phys. 8 260 (2012).

[3] A. Bar Shalom, J. Oreg, W.H. Goldstein, D. Shvarts and A. Zigler, Phys. Rev. A 40, 3183 (1989).

[4] Brian G. Wilson, Carlos A. Iglesias and Mau H. Chen High Energy Density Phys. 14, 67 (2015).

[5] G. Hazak and Y. Kurzweil High Energy Density Phys., 8, 290 (2012).

[6] Y. Kurzweil and G. Hazak High Energy Density Phys. 9, 548 (2013).

[7] Y. Kurzweil, G. Hazak, Phys. Rev. E 94 053210 (2016).

# Chirped nonlinear resonance dynamics in phase space

*Tsafrir Armon<sup>1</sup> and Lazar Friedland<sup>1</sup>*

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Passage through and capture into resonance in systems with slowly varying parameters is one of the outstanding problems of nonlinear dynamics. Examples include resonant capture in planetary dynamics, resonant excitation of nonlinear waves, adiabatic resonant transitions in atomic and molecular systems and more. In the most common setting the problem involves a nonlinear oscillator driven by an oscillating perturbation with a slowly varying frequency, which passes through the resonance with the unperturbed oscillator. The process of resonant capture in this case involves crossing of separatrix and, therefore, the adiabatic theorem cannot be used in studying this problem no matter how slow is the variation of the driving frequency. It will be shown that if instead of analyzing complicated single orbit dynamics in passage through resonance, one considers the evolution of a distribution of initial conditions in

phase space, simple adiabaticity and phase space incompressibility arguments yield a solution to the resonant capture probability problem. The approach will be illustrated in the case of a beam of charged particles driven by a chirped frequency wave passing through the Cherenkov resonance with the velocity distribution of the particles.

[Reference] Armon, T. and Friedland, L. (2016) 'Chirped resonance dynamics in phase space', *Journal of Plasma Physics*, 82(5).

# Capturing Sub-Relativistic Particles in an Optical Booster

*Adi Hanuka<sup>1</sup> and Levi Schächter<sup>1</sup>*

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Progress during the last decade in wall-plug to light efficiency of lasers makes them serious competitors to current microwave driven accelerators for high energy physics as well as for medical applications. One of the aspects which makes the optical system significantly different comparing to microwave machines is the *trapping* condition.

For realistic gradients ( $E_0 = 1-10 \text{ GV/m}$ ), the typical value of the normalized longitudinal field  $a \equiv eE_0\lambda / mc^2$  is much smaller than unity, as compared with the case of a conventional RF photo-injector ( $\lambda = 10 \text{ cm}$ ), where typically  $a \approx 1$ . Consider as an example the case of  $\lambda = 1 \mu\text{m}$  and zero initial energy, the required gradient to capture sub-relativistic particles in a uniform structure is of the order of 3 TV/m. For comparison, in the microwave regime the trapping gradient is: 20MV/m, for which, evidently,

the electrons become relativistic within a few wavelengths. Consequently, in the optical regime, there is a need for a tapered structure to maintain local phase synchronicity with the particles.

In this work, we present a longitudinal tapering of the structure to maximize the trapping efficiency. We further solve the dynamics of the trapping process with\without longitudinal space-charge effects for both the resonant particle and a distribution of particles. Throughout our analysis, we assume that the vacuum tunnel's radius (internal radius) is constant and only single mode operation is considered. Also, since we are interested not only on the effect of the field on the electrons but also vice-versa, it is assumed that the relation between interaction impedance and the phase-velocity is known and is determined locally (adiabatic tapering).

We investigate the resonant particle dynamics, and analyze the effect of the initial phase and energy distribution on the trapped electrons for a distribution of particles. We suggest a few different trapping criteria, together with several types of phase and energy distributions. The figure below describes two

potential types of tapered structures, each keeping either the external or the internal radius uniform.

# **Time resolved spectroscopy of light emission from a converging spherical shock wave in water**

*D. Yanuka<sup>1</sup>, A. Rososhek<sup>1</sup>, S. Efimov<sup>1</sup>, M. Nitishinskiy<sup>1</sup>, and Ya. E. Krasik<sup>1</sup>*

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Time-resolved spectroscopic measurements of light emission from plasma formed in the vicinity of a converging spherical strong shock wave (SSW) have been carried out. The shock wave was generated by an underwater electrical explosion of a spherical wire array made of either Al or Cu. The obtained spectra, together with hydrodynamic and radiative-transfer simulations, can be used to calculate the parameters of water at that location, and for the characterization of the SSW convergence symmetry. According to the simulation, water density, temperature, and pressure should be larger than  $\sim 3 \text{ g/cm}^3$ ,  $\sim 1.4 \text{ eV}$  and  $\sim 2 \times 10^{11} \text{ Pa}$ , respectively, at radii  $< 25 \text{ }\mu\text{m}$  with respect to the origin of the SSW implosion. It was also shown that

the obtained time-of-flight of the SSW and emission spectra agree well with the results of the simulation.

# Hybrid kinetic-liquid model of high-pressure gas discharge

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As is known the direct solution of Boltzmann kinetic equation is of great interest for theoretical investigation of various gas discharges. Such approach gives the most important information about the discharge and its evolution by providing electron and ion distribution functions at given time point. The complete numerical solution of Boltzmann equations for multi-component gas discharge plasma is quite challenging even for one-dimensional problems due to high computational costs. That is the reason why gas discharges are usually described in terms of simplified moments models with drift-diffusion approximation or particle-in-cell (PIC) approaches with Monte-Carlo collisions. Main disadvantage of these techniques is that the description of fast particles (e.g. runaway electrons) is considerably difficult, especially for high pressures and strong overvoltages. For example, PIC method operates with restricted ensemble of macroparticles, so

the accurate description of small portion of particles (like electrons with high energies) is simply unfeasible.

Here we present the novel hybrid theoretical approach for the simulation of discharges in dense gases. Within its framework, both plasma hydrodynamics and kinetics methodologies are used in order to describe the dynamics of different components of low-temperature discharge plasma simultaneously. As a demonstration of current model advantages, we apply it to consider one-dimensional coaxial relativistic gas diode. Namely, in terms of our model it was shown that electrons power spectrum contains a group of electrons with the so-called "anomalous" energies (above the maximal applied voltage value) that were not correctly predicted before, but do exist in various experiments.

# Manipulating Relativistic Electrons with Intense Laser Pulses

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Laser Plasma Accelerators (LPA) rely on the control of the electronic motion with intense laser pulses [1]. The manipulation of electrons with intense laser pulses allows a fine mapping of the longitudinal and radial components of giant electric fields that can be therefore optimized for accelerating charged particle or for producing X rays. To illustrate the beauty of laser plasma accelerators I will show, how by changing the density profile of the gas target, one can improve the quality of the electron beam, its stability [2] and its energy gain [3], or by playing with the radial field one can reduce its divergence [4]. I'll then show how by controlling the quiver motion of relativistic electrons intense and bright X-ray beams are produced in a

compact and elegant way [5,6]. Finally, I'll show some examples of applications [7].

[1] V. Malka, Phys. of Plasmas 19, 055501 (2012)

[2] E. Guillaume et al., Phys. Rev. Lett. 115, 155002 (2015).

[3] C. Thaury Scientific Report, 10.1038, srep16310, Nov. 9 (2015)

[4] C. Thaury et al., Nature Comm. 6, 6860 (2015)

[5] K. Ta Phuoc et al., Nature Photonics 6, 308-311 (2012)

[6] S. Corde et al., Review of Modern Phys. 85 (2013)

[7] I. Andriyash et al., Nature Comm. 5, 4736 (2014)

# Reducing Parametric Backscattering by Polarization Rotation

*Ido Barth<sup>1</sup> and Nathaniel J. Fisch<sup>1</sup>*

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When a laser passes through underdense plasmas, Raman and Brillouin Backscattering can reflect a substantial portion of the incident laser energy. This is a major loss mechanism, for example, in employing lasers in inertial confinement fusion. However, by slow rotation of the incident linear polarization, the overall reflectivity can be reduced significantly. Particle in cell simulations show that, for parameters similar to those of indirect drive fusion experiments, polarization rotation reduces the reflectivity by a factor of 5. A general, fluid-model based analytical estimation for the reflectivity reduction agrees with simulations. However, in identifying the source of the backscatter reduction, it is difficult to disentangle the rotating polarization from the frequency separation based approach used to engineer the beam's polarization. Although the backscatter reduction arises similarly to

other approaches that employ frequency separation, in the case here, the intensity remains constant in time.

[Reference] I. Barth and N. J. Fisch, Phys of Plasmas **23**, 1021006 (2016)

# **Resonant high harmonics and the role of phase matching**

*Noa Rosenthal<sup>1</sup> and Gilad Marcus<sup>1</sup>*

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Resonance high order harmonic in plasma plumes is an exciting phenomenon, predicted long time ago, but discovered only recently. Explanations for the resonance enhancement of a single harmonic rely either on the single atom response or on the collective process of phase matching. In this work, we try to discriminate between the two possibilities by measuring the coherent lengths of all the harmonics and compare them. Information about the coherent lengths of the harmonics, allow us also to demonstrate quasi phase matching enhancement of the harmonics yield.

# **Towards Generation of Long and Continuous Plasma Channels in Air**

*J. Papeer<sup>1</sup>, Z. Henis<sup>2</sup>, M. Botton<sup>1</sup>, D. Gordo<sup>3</sup> and A. Zigler<sup>1</sup>*

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A powerful femtosecond laser pulse undergoing beam filamentation leaves channels of ionized air in its wake. These plasma channels have typical diameter of  $\sim 100\mu\text{m}$ , length of less than 1m and initial plasma density of  $10^{16}\text{cm}^{-3}$  which decays on a timescale of 3ns. The short length, lifetime and shot to shot instability present a limitation towards many promising applications of these plasma channels.

We experimentally demonstrate concatenation of several plasma filaments. By controlling the shot to shot randomness, the number and the position of the filaments along the optical beam we arranged the plasma channels so that each channel will be initiated immediately after the previous channel has been

exhausted. This technique allows generation of a long "broken" plasma wire in air. In our proof of principal experiment, we concatenated several plasma filament, so that the distance between two sequential filaments was shorter than 4mm and the initial plasma density along the entire channel was measured to sustain above  $10^{15}\text{cm}^{-3}$ .

Lifetime of these plasma filaments is demonstrated to be extended by more than an order of magnitude. Plasma lifetime prolongation is achieved by properly timed irradiation of the filament with a relatively low intensity nanosecond laser pulse. The typical relaxation time is extended tenfold. We reveal the physical mechanism behind the prolongation of plasma life time and demonstrate the preferential conditions for lifetime extension.

The combination of these two methods will allow generation of long, coexisting plasma channels with high electron density. This approach may pave the way towards many potential applications of femtosecond beam filamentation previously proposed in the literature.

## **Plasma wakefield generation by high power microwaves**

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We present preliminary results of experimental research of plasma waves, driven by a short duration (0.5 ns), high power (>500 MW) microwave (10 GHz) beam generated by backward oscillator operating in super-radiance mode. The goal of this research is to investigate the effect of the ponderomotive force effects in the plasma, exerted by the electromagnetic wave non-linear interaction on the plasma electrons. In the experiment, the microwave beam was focused using dielectric lens inside an 80 cm long, 25 cm diameter, Pyrex chamber, filled with air at different pressures. The focused microwave beam generates a dense plasma at focus plane, and exerts a force on the plasma electrons, forming plasma waves that interact with the microwave beam at sub-ns time scales. Results of this interaction will be presented.

# **Spectral Analysis of a THz Radiation Source Based on High-Harmonic Interaction in a Hybrid Cavity**

*Miron Voin<sup>1</sup> and Levi Schächter<sup>1</sup>*

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THz frequency region is commonly considered as a gap in the range of available radiation sources. While multiple schemes for such sources were evaluated during the last several decades, there is still a lack of efficient and practical devices. Virtually all possible radiation source paradigms were studied by various research groups around the world, including lasers, solid-state electronics, vacuum electronics, photomixing, and even mechanical excitation. One of the widely exploited approaches to the problem, scaling down of conventional vacuum electronic devices (VED), is associated with an inherent difficulty of miniaturization of complex arrangements – cathodes, focusing systems, slow-wave structures, collectors, and vacuum windows.

We consider a novel concept of a miniature VED, targeting coherent electromagnetic wave generation in the THz range, but not limited to the latter. While in a traditional VED a preformed mono-energetic electron beam is interacting with a slow-wave structure or a resonant cavity, the hybrid cavity under consideration allows for interaction of electron bunches oscillating in a Penning trap-like static field configuration integrated with a resonant cavity, formed partially by the trap's electrodes and partially by a dielectric Bragg structure. As a first step, we analyze the energy exchange spectrum between the oscillating bunches and the cavity eigenmodes. While the dielectric breakdown limits the maximal frequency of bunches' oscillations to order of 0.1 GHz, a significant high-harmonic interaction with longitudinal cavity modes above the fundamental is possible for a large, comparable with the cavity dimensions, oscillating dipole. Proper design of the cavity may allow for interaction of a selected high harmonic of bunch oscillations with a single longitudinal mode of the cavity, providing conditions for an energy-efficient generation for a virtually monochromatic THz wave.

# **Expansion and Excitation of Plasma Oscillations in Modulated Electron Bunches Formed in Laser-Driven Photo-Injectors**

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Short dense electron bunches with a moderately relativistic electron energy formed in photo-injectors, can be effectively used for generation of coherent spontaneous THz radiation. In order to significantly increase the radiation energy and frequency a number of authors have proposed to use a preliminary spatial modulation of electron density in such sources. According to [1, 2] the modulation can lead to excitation of plasma waves and formation of sharp spikes in the bunch. This prediction was done on the basis of an analytical solution for 1D (plane) model of the bunch that surprisingly well coincided with results of GPT simulations and experiments carried out for charged threads with small aspect ratio (bunch

radius/modulation period). The match of findings sounds awesome, as is obvious that a displacement of the particles in a 1D model of the bunch does not lead to the appearance of the returning forces and plasma oscillations. The above coincidence is the result of the implicit assumption on maintaining the modulation period that is justified only for the opposite situation of small aspect ratio. In this case Coulomb interaction of electrons significantly decreases at the one period; all the periods are approximately equivalent and the value of the period stays constant. As for quasi-plane bunches with large radii, Coulomb repulsion is nearly constant and can only weaken the modulation. We have revised these effects for a moving 1D electron layer with a finite width corresponding to the length of a cylinder bunch and with an arbitrary density distribution taking into account changing of modulation period. In contrast to theory of [1, 2] the derived formulas and the corresponding GPT simulations confirm the validity of the above simple physical expectations.

Modulated bunches in the form of treads and disks can be used for significant efficiency enhancement of THz

sources based on the Doppler frequency-up-shifted coherent spontaneous radiation of bunches. At a relatively small change in particle energy the periodicity in 1D layers is conserved during their expansion despite strong Coulomb repulsion; however, the period of modulation increases and its amplitude decreases in time. At a large change in energy, the uniformity of periodicity is broken due to different relativistic changes of longitudinal scales along the bunch: the “period” decreases and its amplitude increases from the rear to the front boundary. Nevertheless, long modulated bunches can provide significantly higher power and narrower spectrum of radiation than short single bunches with the same charge.

[1] P. Musumeci, R. K. Li, and A. Marinelli, "Nonlinear Longitudinal Space Charge Oscillations in Relativistic Electron Beams," *Phys. Rev. Lett.*, vol. 106, no. 18, p. 184801, 2011.

[2] P. Musumeci, R. K. Li, and K. G. Roberts, E. Chiadroni, "Controlling nonlinear longitudinal space charge oscillations for high peak current bunch train generation," *Phys. Rev. ST Accel. Beams*, vol. 16, no. 10, p. 100701, 2013.

# Variational Principles and Applications of Local Topological Constants of Motion for Non-Barotropic Magnetohydrodynamics

*Asher Yahalom<sup>1</sup>*

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Variational principles for magnetohydrodynamics (MHD) were introduced by previous authors both in Lagrangian and Eulerian form. In this paper, we introduce simpler Eulerian variational principles from which all the relevant equations of non-barotropic MHD can be derived for certain field topologies. The variational principle is given in terms of five independent functions for non-stationary non-barotropic flows. This is less than the eight variables which appear in the standard equations of barotropic MHD which are the magnetic field  $\vec{B}$  the velocity field  $\vec{v}$ , the entropy  $s$  and the density  $\rho$ . The case of non-barotropic MHD in which the internal energy is a function of both entropy and density was not discussed in previous works which were concerned with the

simplistic barotropic case. It is important to understand the rule of entropy and temperature for the variational analysis of MHD. Thus, we introduce a variational principle of non-barotropic MHD and show that five functions will suffice to describe this physical system.

We will also discuss the implications of the above analysis for topological constants. It will be shown that while cross helicity is not conserved for non-barotropic MHD a variant of this quantity is. The implications of this to non-barotropic MHD stability is discussed.

[1] Asher Yahalom “Simplified Variational Principles for non-Barotropic Magnetohydrodynamics”. (arXiv: 1510.00637 [Plasma Physics]) J. Plasma Phys. (2016), vol. 82, 905820204 © Cambridge University Press 2016 doi:10.1017/S0022377816000222.

[2] Asher Yahalom “[Simplified Variational Principles for Stationary non-Barotropic Magnetohydrodynamics](#)” International Journal of Mechanics, Volume 10, 2016, p. 336-341. ISSN: 1998-4448.

[3] Asher Yahalom “[Non-Barotropic Magnetohydrodynamics as a Five Function Field Theory](#)”. International Journal of Geometric Methods in Modern Physics, No. 10 (November 2016). Vol. 13 1650130 (13 pages) © World Scientific Publishing Company, DOI: 10.1142/S0219887816501309.

[4] Asher Yahalom “A Conserved Local Cross Helicity for Non-Barotropic MHD” Accepted to Geophysical & Astrophysical Fluid Dynamics.

# Determination of the azimuthal magnetic field evolution in imploding magnetized plasma

*Marko Cvejić<sup>1</sup>, Dmitry Mikitchuk<sup>1</sup>, Eyal Kroupp<sup>1</sup>, Ramy Doron<sup>1</sup>, Yitzhak Maron<sup>1</sup>*

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We investigate the fundamental phenomena of magnetic-field flux and magnetized plasma compression by plasma implosion. In the experiment, we employ a cylindrical configuration, in which an initial axial quasi-static magnetic flux (up to 0.4 T) is pre-embedded in an argon gas column. A high-power electric discharge (300 kA, rise time 1.6  $\mu$ s) ionizes the gas and generates an azimuthal magnetic field, creating a pressure that radially compresses the plasma inward together with the axial magnetic field embedded in it. Here, we present non-invasive spectroscopic measurements of the azimuthal magnetic field. Systematic measurements, performed for different initial axial

magnetic fields ( $B_z$ ), show that with increasing initial values of  $B_z$ , less current is flowing through the imploding Ar plasma shell. For  $B_z(t=0) = 0.4$  T, only  $\sim 1/4$  of the current is flowing through the imploding Ar plasma. Measurements at large radii, outside the imploding plasma shell, reveal that in the presence of  $B_z$ , most of the current flows through a surrounding dilute plasma that is not imploded.

# **JET tokamak disruption simulations and implications for ITER**

*H. R. Strauss*  
HRS Fusion

Disruptions in the JET tokamak are a main predictor of expected disruption behavior in the ITER experiment. A major concern is the asymmetric electromechanical force generated on the wall. It was estimated [1] that the wall force in ITER might be 20 times the wall force in JET. 3D MHD simulations of JET disruptions have been carried out with the M3D [2] code. The simulations suggest that the wall force in ITER will be less than the wall force in JET! The simulations were initialized with JET data, and were in reasonable agreement with JET time history data. A typical JET disruption starts with a thermal quench, caused by MHD instability, which occurs on a rapid timescale. This is followed by a slow asymmetric vertical instability (AVDE), in which the plasma drifts toward the wall. The timescale for the AVDE is the resistive wall magnetic penetration time  $\tau_{wall}$ . Data compared with experiment include the plasma vertical

P-1

displacement, toroidal current asymmetry [1], and halo current [3]. The wall force is largest when the plasma reaches the wall. It persists until the plasma current is quenched, in the current quench time  $\tau_{CQ}$ . In JET the ratio of current quench time to resistive wall time is  $\tau_{CQ} / \tau_{wall} \approx 4$ . In ITER, the situation is different. It is expected that  $\tau_{CQ}$  in ITER is about 4 times larger than in JET, while  $\tau_{wall}$  is at least 60 times larger. In ITER, the plasma does not have time to reach the wall before the current is quenched, nor is there a significant wall force.

[1] S.N. Gerasimov, et al., Nucl. Fusion 54 073009 (2014).

[2] W. Park, et al., Phys. Plasmas 6 1796 (1999).

[3] V. Riccardo, et al., Plasma Phys. Control. Fusion 46, 925 (2004).

# Particle Confinement by a Radially Polarized Laser Bessel Beam

*Gilad Laredo<sup>1</sup>, Levi Schächter<sup>1</sup> and Wayne D. Kimura<sup>2</sup>*

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The stable trajectories of a charged particle in an external guiding field is an essential condition for its acceleration or for forcing it to generate radiation. Examples of possible guiding devices include a solenoidal magnetic field or permanent periodic magnets in klystrons, an undulator in free electron lasers, the lattice of any accelerator, and finally the crystal lattice for the case of channeling radiation. We demonstrate that the trajectory of a point-charge in a radially polarized laser Bessel beam may be stable similar to the case of a positron that bounces back and forth in a potential well generated by two adjacent atomic planes. While in the case of channeling radiation, the transverse motion is controlled by a harmonic oscillator equation, for a Bessel beam, the transverse motion is controlled by the Mathieu

Poster session

15:00-15:50

P-2

equation. Some characteristics of the motion will be presented.

## **Optimization of a second-harmonic gyrotron in conditions of mode competition**

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Gyrotron operation at a cyclotron harmonic frequently suffers from parasitic excitation at lower harmonics. The corresponding modes having lower starting currents are excited first and after that suppress the operating mode in non-linear regimes. It is well-known that despite such severe mode competition excitation of a desired mode and suppression of dangerous modes can be still obtained by varying the value of magnetic field, beam voltage and/or electron pitch factor during transient process [1]. Such opportunity was theoretically studied in this work for a second-harmonic W-band gyrotron with the operating TE021 mode. In such a gyrotron the resonance magnetic field for parasitic TE211 mode with one axial variation of the cavity field is significantly lower than for the

P-3

operating mode, but in a relatively short gyrotron cavity the excitation at the third axial mode - the TE<sub>213</sub> mode or running wave at low wave reflections from the collector end of the cavity - is a very serious problem. This parasitic mode and the operating one have close resonant fields and approximately the same starting currents at different radii, position and velocity spreads of the electron beam. Detailed study of the mode competition on the basis of direct solutions of Maxwell equations for the field in the cavity and force equations for particles based on the well-known 3D CST Particle Studio code demonstrates the possibility of the single mode second-harmonic operation at the currents not larger than 75% from the optimum value. It corresponds to a very large loss in gyrotron efficiency and output power. Improvement of this situation in pulsed operating regimes requires too fast changes of control parameters. However, according to simulations the efficient optimum regime can be achieved for CW operation using suitable adiabatic change of control parameters.

[1] G. S. Nusinovich, Introduction to the Physics of Gyrotrons (Johns Hopkins Studies in Applied Physics) Johns Hopkins University Press, 2004

# Critical Behavior in Bragg Dielectric Structures

*Adi Hanuka<sup>1</sup> and Levi Schächter<sup>1</sup>*

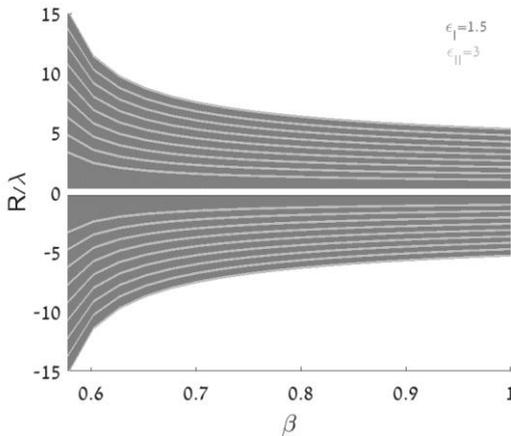
1. Technion – Israel Institute of Technology, Haifa 32000, Israel

There is a growing demand for compact optical components that can be integrated on-chip, to increase portability and potentially reduce the cost and complexity of today's systems. Bragg structures offer variable characteristics and design flexibility for applications in re-configurable integrated optics. Variety of tunable optical functions can be realized with on-chip Bragg reflector.

In this study, we introduce a new tapering concept in which the inner core tunnel is kept constant, while the adiabatic tapering is facilitated by varying the thickness of all the Bragg layers, and especially the first layer. As a result, the tapering is neither linear nor exponential but rather determined by the local phase velocity imposed by the specific application considered.

P-4

With regards to confinement, we show that a single propagating mode, leaks not due to a finite number of layers, but because it reaches a critical point where the confinement condition is not satisfied. At this point, a longitudinal propagating power is transformed into transverse radiation. This concept could be advantageous depending on the application; transforming the vertical into longitudinal flow might be useful for coupling or combining laser beams for high energy applications, and conversely, for sensors and spectrometry. This critical point phenomenon is described in a general formulation for any configuration, which can be exploited to achieve controllable on-chip mode manipulations.



# **Three-Dimensional Interferometric Characterization of a Gas-Puff Laser-Target for the Measurement of the Laser- Wave-Induced Stark Effect in Plasma**

*D. Naimark<sup>1</sup>, T Queller<sup>1</sup>, E. Kroupp<sup>1</sup>, E. Stambulchik<sup>1</sup> and  
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Polarized x-ray emission from the interaction of a high-intensity laser ( $5 \times 10^{16}$  W/cm<sup>2</sup>) with a specially designed gas target will hopefully allow, for the first time, the measurement of the Stark effect due to the harmonic electric field of a laser light wave. This knowledge may help to resolve the disagreement between the predictions of different theoretical models of line-shapes simultaneously affected by the plasma micro-fields and the external laser field [1,2]. We describe the characterization of the 3D density distribution of such a gas-puff laser-target, using 2D interferometry. Special fast valve and nozzle have been

P-5

designed and built, forming an approximately 5-mm-wide and 0.5-mm-thick gas-sheet target. The target was designed such as to produce the sharpest possible density gradients along the laser-beam direction, and as homogeneous density profile as possible in the perpendicular directions. The relatively moderate perpendicular density gradient is an important characteristic of the target, since it enables the use of the target for a wide range of densities with a simple translation of the target relative to the laser. A Mach-Zehnder interferometer was used for obtaining orthogonal, time resolved, path integrated phase maps of the gas-puff, which were then used to reconstruct its three-dimensional density distribution.

[1] E. Stambulchik. Review of the 1st Spectral Line Shapes in Plasmas code comparison workshop. *High Energy Density Phys.*, 9(3):528–534, 2013.  
doi:10.1016/j.hedp.2013.05.003.

[2] E. Stambulchik, A. Calisti, H.-K. Chung, and M. Á González. Special issue on spectral line shapes in plasmas. *Atoms*, 2(3):378–381, August 2014.  
doi:10.3390/atoms2030378.

# **Why is the broad line region similar in all active galactic nuclei? — The effect of radiation pressure on astrophysical plasma**

*Alexei Baskin<sup>1</sup>*

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Approximately 10% of galaxies host an active galactic nucleus (AGN) that emits strong radiation in the whole electromagnetic range (e.g. quasars). AGN are characterized by broad emission lines. The lines show similar properties from the lowest luminosity ( $10^{39}$  erg/s) to the highest luminosity ( $10^{48}$  erg/s) AGN. What produces this similarity over such a vast range of  $10^9$  in luminosity? Photoionization is inevitably associated with momentum transfer to the photoionized gas. Yet, most of the photoionized gas in the broad-line region (BLR) follows Keplerian orbits, which suggests that the BLR originates from gas with a large enough column density for gravity to dominate. The photoionized surface layer of the gas must develop a pressure gradient due to the incident radiation force. I

P-6

will present solutions for the structure of such a hydrostatic photoionized-gas layer in the BLR. The gas is stratified, with a low-density highly-ionized surface layer, a density rise inwards and a uniform-density cooler inner region, where the gas pressure reaches the incident radiation pressure. This radiation pressure compression (RPC) of the photoionized layer leads to a universal ionization parameter  $U \sim 0.1$  in the inner photoionized layer, independent of luminosity and distance. Thus, RPC appears to explain the universality of the BLR properties in AGN.

[Reference] A. Baskin, A. Laor, and J. Stern, *Mon. Not. R. Astron. Soc.* 438, 604 (2014)

## **Autoresonance of the $m=2$ diocotron oscillations in a non neutral plasmas**

*K.Gomberoff<sup>1</sup>, H.Higaki<sup>2</sup> and C. Kaga<sup>2</sup>*

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The existence of autoresonances for  $m=2$  diocotron oscillations of non-neutral electron plasmas in a uniform magnetic field was predicted by particle-in-cell simulations and it was confirmed in experiments. The obtained results in experiment and in simulations show deviations from the for the threshold amplitude standard power law dependence on the sweep rate. The threshold amplitude approaches a constant at a lower sweep rate when there is a damping force. Autoresonance is obtained also in simulations with the application of a chirped external drive around the second harmonic frequency of the mode.

[1] K. Gomberoff, H. Higaki, C. Kaga, K. Ito, and H. Okamoto, Phys. Rev. E.94. No 4, (2016) DOI: 10.1103/PhysRevE.94.043204

P-7

[2] H. Higaki, Y. Abo, K. Ito, H. Okamoto, and K. Gomberoff, *Non-Neutral Plasma Physics IX*, edited by Y. Soga, A. Sanpei, and H. Himura, AIP Conf. Proc. No. 1668 (AIP, Melville, NY, 2015), p. 050006

# **Influence of Ambient Gas Pressure on a Hall Thruster Operation**

*G. Makrinich<sup>1</sup> and A. Fruchtman<sup>1</sup>*

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The influence of the ambient gas pressure on a Hall thruster operation was studied experimentally. Argon gas was used. For discharge currents of 1.5 A and 1.9 A, a magnetic field intensity of 160 G and gas flow rate through anode of 20 Standard Cubic Centimeter per Minute (SCCM), the thrust, the ion current, the discharge voltage, and the accelerating voltage (potential drop across the acceleration channel) were measured versus the ambient gas pressure. The ambient gas pressure was varied from 3.3 mTorr to 16.5 mTorr by using an additional gas flow inlet in the vacuum chamber. The thrust was decreased with the ambient gas pressure for both discharge currents, for 1.5 A from 5.0 mN to 2.5 mN and for 1.9 A from 5.9 mN to 4.5 mN. The current utilization, estimated from the measured ion current and discharge current,

P-8

decreased from 0.23 to 0.15 when the ambient gas pressure increased from 3.3 mTorr to 16.5 mTorr, for both discharge currents. The discharge voltage also decreased with the ambient gas pressure, from 130 V to 90 V, for both discharge currents. These findings are similar to those in our previous research of the Radial Plasma Source<sup>1</sup> (RPS). The decrease in performance is probably related to the neutral gas density inside the acceleration channel being higher for a higher ambient gas pressure because the ambient gas probably penetrates the acceleration channel from the exit of the Hall thruster. The thrust per ion however increases when the pressure increases. This will be discussed.

[1] Makrinich G. and Fruchtman A., "Electric Force and Ambient Gas Pressure", 18-th IPSTA Conference, Israel, March 2016.

## **Underwater electrical explosion of Al and Cu single wires**

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Comparison between single Al and Cu wires underwater electrical explosion and generated cylindrical strong shock waves (SSW) will be presented. Experimental research was carried out using nanosecond timescale generator (120 kV, 50 kA, 70 ns). The discharge current was measured by a current viewing resistor and the resistive voltage was calculated from the measured voltage by a capacitive voltage divider accounting for inductive voltage. These data were used for calculation of deposited energy into exploding wire. The wire and generated SSW radial expansions were studied using fast multi-frame system and a streak camera. These data allowed to determine the pressure behind the SSW front and to make conclusion regarding combustion of Al wire and possible additional energy delivered to the water-flow by this process.

## **Non-relativistic hollow electron beam for W-band Backward-Wave Oscillator**

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4. Nizhny Novgorod State University, Nizhny Novgorod, Russia

Slow-wave devices are widely used as medium-power sources of short-millimeter and sub-terahertz waves. In order to increase the CW or average power of these devices, the use of spatially distributed electron beams, mostly sheet beams, is widely studied last few years. Another feasible and maybe somewhat simpler configuration is hollow rectilinear thin-wall electron beams interacting with the slow waves of azimuthally-symmetric operating waveguides, similar to that of relativistic high-current microwave oscillators. Like in the case of sheet beams, the use of hollow electron beams permits a significant decrease in current density and heating of the microwave structure. To study this

P-10

option, a W-band Backward-Wave Oscillator (BWO) with operating voltage of 30-32 kV has been designed. Oscillator utilizes the microwave structure with a rectangular corrugation (groove depth is close to quarter wavelength); the lower axi-symmetric TM<sub>01</sub> mode is used as the operating one. The electron beam with an outer diameter of 1.6 mm is formed in Pierce-like electron gun with thermionic cathode and magnetic compression of 100 and then guided in the magnetic field of 0.7 T. In the preliminary electron-optical experiment, 0.7-A hollow beam with wall thickness of about 0.3 mm was produced and guided in slow-wave structure, and 0.3 A were intercepted by cutoff narrowing at the cathode side of the structure, while simulations predict beam wall thickness of 0.15 mm and current of 1 A. The difference between simulations and experiment can be caused by a large cathode surface roughness which results in an increased velocity spread of electrons. Nevertheless, simulations based on the averaged equations and 3D PIC-code CST predict that BWO with the existing beam can provide relatively high output power up to 300 W and wideband frequency tuning.

Poster session

15:00-15:50

P-10

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# **Ionization enhanced turbulence in compressing plasmas and sudden dissipation**

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Turbulent plasma flow, amplified by rapid 3D compression, can be suddenly dissipated under continuing compression. This sudden dissipation comes about because the plasma viscosity is very sensitive to temperature. The viscosity is also very sensitive to the plasma ionization state. We show that increasing plasma ionization state during compression is associated with much stronger turbulence growth, compared to the case with no ionization during compression. Additionally, we show that ionization during compression can prevent the sudden dissipation phenomenon.

## Notes

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