IPSTA-2014

The 16th Israeli Plasma Science and Applications Conference

Program and Extended Abstracts

Faculty of Engineering, Tel Aviv University

February 5th, 2014
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This booklet is also available online at www.eng.tau.ac.il/IPSTA-2014

The cover page images belong to papers appearing on Pages 52, 9, 11, 23, 29, 7, 63, 35, 39 in this book, as indicated in the bottom right corner of each image.

Site Map

• All oral sessions are conducted in the Rosenblatt Auditorium.
• Posters are displayed in the Lobby.
• Coffee and refreshments are available in Room 106.
• Lunch is served in Room 104-5. Additional seating is available also in Room 106.
• According to the University instructions, drinks or food items are prohibited in the Rosenblatt Auditorium.
Dear Colleagues,

Welcome to IPSTA-2014, the 16th annual conference of the Israeli Plasma Science and Technology Association (IPSTA), at the Faculty of Engineering at Tel Aviv University.

IPSTA-2014 reflects the span and the depth of plasma studies in Israel. It covers topics ranging from fundamental, curiosity-driven scientific issues to practical engineering methodologies. As such, the interests of the IPSTA community include basic issues in plasma physics, atmospheric plasmas, astrophysics, as well as plasma processing, fusion research, radiation sources and particle beams, and pulsed power systems.

The IPSTA-2014 program includes 3 invited lectures, given by Igor Kaganovich (Princeton University), Victor Malka (Ecole Polytechnique), and Edl Schamiloglu (University of New Mexico), as well as 22 oral presentations and 15 posters. More than 70 participants have pre-registered leading up to the conference.

Professor Enrique Grunbaum, who initiated IPSTA-2014 at Tel Aviv University, passed away suddenly on Saturday, December 7, 2013 (note that up until just two days before, on Thursday afternoon, we were still having meetings regarding IPSTA-2014, after which Enrique notified us by e-mail that he had managed to raise additional funding for the students’ prizes!). Enrique was a prominent scientist in the fields of electron microscopy and material sciences, who also contributed voluntarily to scientific activities, such as of IPSTA. As a memorial to Professor Enrique Grunbaum and to his legacy combining science and voluntary public service, the IPSTA board has recently established the Enrique Grunbaum Award for Young Plasma Scientists, which will be given for the first time at IPSTA-2014.

The Samuel Goldsmith Award, as in previous years, will conclude the students’ competition at IPSTA-2014. In view of the increasing participation of students in this conference, 4 prizes will be awarded this year (2 for oral and 2 for poster presentations).

We would like to thank the Goldsmith family for the generous donation of the students’ prizes. We wish to thank also our other supporters, the offices of the Tel Aviv University R&D Vice President and of the Faculty of Engineering Dean, the Gordon center for Energy Research, and the Israeli Vacuum Society (IVS). Thanks to these generous supports, we can also have video records of the conference and a book of 2-page extended abstracts (both will be available online).

IPSTA-2014 wouldn't have come true without the devotion of the members of the IPSTA board, the IPSTA-2014 Organizing, Program and Advisory committee (listed in the next page). In particular, I would like to thank Rafi Jaffe and Yehuda Meir, my students, who have been my full partners in the "heavy lifting" of the IPSTA-2014 organization. Thank you all!

I hope that IPSTA-2014 will be a fruitful conference which will promote both plasma sciences and plasma scientists in Israel.

Best wishes,

Eli Jerby
IPSTA-2014 Committees

IPSTA-2014 Initiator

Enrique Grunbaum

Program Committee

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IPSTA-2014 Sponsors

- Office of the Vice President for Research and Development, Tel Aviv University
- Gordon Center for Energy Research
- Faculty of Engineering, Tel Aviv University
- The Israeli Vacuum Society (IVS)
The Enrique Grunbaum Award for Young Plasma Scientist

Prof. Enrique Grunbaum (1926-2013), was a prominent materials scientist, with important contributions in the fields of electron microscopy, epitaxial growth of thin films, and solar cells. Prof. Grunbaum served as a board member and treasurer of IPSTA until his last day, on December 7th, 2013. Prof. Grunbaum was the driving force behind the organization of many IPSTA conferences, and in particular the present one, IPSTA-2014, which he had initiated at Tel Aviv University.

As a memorial to Professor Enrique Grunbaum and his devotion to the IPSTA community, and in particular to its young members, the IPSTA board has recently established the Enrique Grunbaum Award for Young Plasma Scientists. The prize is donated this year by the Israeli Vacuum Society (IVS).

The objectives of the Enrique Grunbaum Award are to acknowledge and to encourage a young plasma scientist at the beginning of his or her career, provided that he or she has both scientific achievements in plasma science or technology, and a solid record of voluntary contribution to the IPSTA community. To be eligible, nominees must hold a Ph.D. degree for less than 7 years, and not yet hold a tenured position.

The Samuel Goldsmith Prizes for Best Students' Presentations

Professor Samuel Goldsmith (1935-2009) is remembered as a leading scientist in various fields related to plasma physics, and as a founder and leader of the Israel Plasma Science and Technology Association. Samuel was an involved citizen of the larger scientific community, and by all measures, an Israeli patriot.

Samuel was a great supporter of students and young researchers, and a welcoming host for new-comers. In this spirit, he initiated IPSTA in the mid 90's as an organized platform for the mutual support and solidarity among plasma scientists in Israel, and especially in order to empower the younger generation of this society.

The prizes donated by the Goldsmith family are awarded for the best presentations, either posters or orals, since both are considered as equally important. The criteria for the Goldsmith student competition are:

- the quality of the work presented, in terms of novelty, importance and relevance,
- the student's contribution to the work (especially if performed in a large group), and
- the clarity of the student's presentation.
# IPSTA-2014 Program

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## 08:45-09:00 Opening session

Greetings by the Faculty of Engineering Dean

Ehud Heyman  
*Tel Aviv University*

Welcoming remarks by IPSTA Chairman

Asher Yahalom  
*Ariel University*

The Enrique Grunbaum Award for Young Plasma Scientist

Reuven Boxman  
*Tel Aviv University*
**09:00-10:30  Session 1: Gas Discharge Physics**  
Chair: Yakov E. Krasik, *Technion - Israel Institute of Technology*

09:00-09:30  
**Nonlocal kinetic theory of plasma discharges**  
Igor Kaganovich (Invited), D. Sydorenko, A. Khrobrov, Y. Raitses, V. Demidov, I. Schweigert, A. Mustafaev  
*Princeton University*

09:30-09:45  
**Development of a pulsed glow discharge**  
Raymond L. Boxman, J. I. Muhamed, I. S. Falconer, A. Israel, A. E. Ross, D. R. McKenzie  
*University of Sidney, Tel Aviv University*

09:45-10:00  
**The force exerted by a fireball**  
Amnon Fruchtman, G. Makrinich  
*H.I.T. - Holon Institute of Technology*

10:00-10:15  
**Study of the lower ionosphere with VLF EM waves generated by lightning**  
Joseph Ashkenazy, A. Lipshtat, C. Price, I. Silber  
*Soreq NRC*

10:15-10:30  
**Temporally- and spatially-resolved measurements of the structure and the magnetic field distribution of an imploding plasma**  
Guy Rosenzweig, E. Kroupp, A. Fisher, Y. Maron  
*Weizmann Institute of Science*

**10:50-12:35  Session 2: High Power Microwaves and Millimeter Waves**  
Chair: Amnon Fruchtman, *H.I.T. - Holon Institute of Technology*

10:50-11:20  
**Trends in high power microwaves**  
Edl Schamiloglu (Invited)  
*University of New Mexico*

11:20-11:35  
**High power long-pulse operation of a millimeter wave FEL**  
Harry S. Marks, H. Kleinman, A. Nause, A. Gover, M. Einat, M. Kanter, D. Borodin, Y. Lasser, Y. Lurie, B. Kapilevich, B. Litvak, A. Yahalom, A. Friedman  
*Tel Aviv University, Ariel University*

11:35-11:50  
**Observation of plasma evolution in the interference switch of microwave pulse compressor**  
Leonid Beilin, A. Shlapakovski, M. Donskoy, Y. Hadas, Y. Krasik  
*Technion - Israel Institute of Technology*

11:50-12:05  
**Design and status of Tera-Hertz FEL in Ariel University**  
Aharon Friedman, A. Gover, M. Einat, A. Yahalom, E. Dyunin, D. Cheskis, Y. Lurie, Y. Vashdi  
*Ariel University*

12:05-12:20  
**Plasmoids excited by localized microwaves**  
Yehuda Meir, E. Jerby  
*Tel Aviv University*

12:20-12:35  
**A 6-kV, 130-ps rise-time pulsed-power circuit**  
Amit Kesar, L. Merensky, M. Ogranovich, A. Kardo-Sysoev, D. Shmilovitz  
*Soreq NRC*
14:10-15:40  Session 3 : Accelerators, Lasers and Wave Phenomena
Chair: Avi Gover, Tel Aviv University

14:10-14:40  Laser plasma accelerators: status and applications
Victor Malka (Invited)
Ecole Polytechnique, France

14:40-14:55  Optical emission spectroscopy of sputtering process in the plane plasma discharge
Alexander Axelevitch, B. Apter
H.I.T. - Holon Institute of Technology

14:55-15:10  Fluence and accelerating gradient in Bragg accelerator
Adi Hanuka, L. Schachter
Technion - Israel Institute of Technology

15:10-15:25  Cherenkov wake amplification by waveguide confined active medium
Miron Voin, Z. Toroker, W. Kimura, L. Schächter
Technion - Israel Institute of Technology

15:25-15:40  Investigation of converging strong shock wave generated by underwater electrical explosion of cylindrical and spherical wire arrays
Oleg Antonov, S. Efimov, D. Yanuka, V. Tz. Gurovich, Ya. E. Krasik
Technion - Israel Institute of Technology

16:00-17:30  Session 4 : Fusion Issues and Plasma Experiments
Chair: Ramy Doron, Weizmann Institute of Science

16:00-16:15  Tokamak toroidal rotation produced by MHD turbulence
Henry R. Strauss
HRS Fusion, USA

16:15-16:30  Active feedback stabilization of flute instability in a mirror trap
Ilan Be’ery, O. Seemann, A. Fisher, A. Fruchtman, A. Ron
Technion - Israel Institute of Technology

16:30-16:45  A retarding field analyzer for 2D energy distribution function measurement
Mike Hopkins, D. Gahan, S. Sharma
IMPEDANS Ltd., Ireland

16:45-17:00  Influence of the gas feed location on radial plasma source operation
Gennady Makrinich, A. Fruchtman, R. Boxman
H.I.T. - Holon Institute of Technology, Tel Aviv University

17:00-17:15  Cathode spot dynamics in a vacuum arc with an oblong roof shaped cathode in a magnetic field
Ben Sagi, I. I. Beilis, V. Zhitomirsky, R.L. Boxman
Tel Aviv University

17:15-17:30  Lifter experiments: induced force relation to the ion craft geometry
Moshe Einat, R. Kalderon, E. Adato
Ariel University

17:30-18:00  Closing session and farewell

The Samuel Goldsmith Student Prizes
**Poster Session**  
Chair: Isak Beilis (Chair), *Tel Aviv University*

**P1.** Generation of cumulative jets during underwater explosion of copper wires in the “X-pinch” configuration  
Doron Shafer, G. Toker, V. Tz. Gurovich, Y. Krasik  
*Technion - Israel Institute of Technology*

**P2.** Nonlinear wake amplification by active medium in a cylindrical waveguide  
Zeev Toroker, M. Voin, L. Schächter  
*Technion - Israel Institute of Technology*

**P3.** Synchrotron terahertz radiation from dense quasi-plane electron bunches  
Nezah Balal, V.L. Bratman, A.V. Savilov  
*Ariel University, Russian Academy of Sciences, Nizhny*

**P4.** Coupled cavities for terahertz gyrotrons  
V. Bratman, M. Einat, Roey Ben Moshe  
*Ariel University, Russian Academy of Sciences, Nizhny*

**P5.** Shaped beam and long pulse from a ferroelectric cathode with multi front electrode for gyrotron  
Yafit Orbach, M. Pilossof, R. Ben-Moshe, M. Einat  
*Ariel University*

**P6.** Titanium plasma-column generated by localized microwaves in air for TiO2 nano-powder deposition  
Simona Popescu, Eli Jerby  
*Tel Aviv University*

**P7.** Copper solenoid for continuous operation of a 95 GHz gyrotron  
Dmitri Borodin, H. Hirshbein, M. Einat  
*Ariel University*

**P8.** A novel investigation of the ion temperature and hydromotion of stagnating Z-pinch plasma using Stark-broadened line shapes  
Dror Alumot, E. Kroupp, E. Stambulchik, D. Osin, A. Fisher, Y. Maron  
*Weizmann Institute of Science*

**P9.** Effect of electrode materials (produced micro- and nano-particles) on the decomposition of methylene blue in aqueous solution by a submerged arc  
Violeta Yakubov-Tal, N. Parkansky, R. Boxman  
*Tel Aviv University*

**P10.** The BBGKY-hierarchy and the plasma-sheath transition  
Jorge Palacio Mizrahi  
*Technion - Israel Institute of Technology*

**P11.** Food cooking by microwave-excited plasmoid in air atmosphere  
Rafi Jaffe, E. Jerby  
*Tel Aviv University*

**P12.** Submerged pulse arc treatment of water with organic compound methylene blue  
Ariel Meirovich, N. Parkansky, R. L. Boxman  
*Tel Aviv University*

**P13.** Efficiency and optimal charge in Bragg accelerator  
Adi Hanuka, L. Schachter  
*Technion - Israel Institute of Technology*

**P14.** Temporal Evolution of Femtosecond Laser Induced Plasma Filaments  
Jenya Papeer, D. Gordon, Z. Henis, M. Botton, A. Zigler  
*The Hebrew University of Jerusalem*

**P15.** Non-Diffraction in Cold Magnetized Plasma  
Ziv Abelson, R. Gad, A. Fisher, S. Barad  
*Tel Aviv University*
Nonlocal Kinetic Theory of Plasma Discharges

Igor D. Kaganovich¹, Dmytro Sydorenko², Alexander V. Khrabrov¹, Yevgeny Raitses¹, Vladimir I. Demidov³, Irina Schweigert⁴, Alexander S. Mustafaev⁵

¹ Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543 USA
² University of Alberta, Edmonton, Alberta, T6G 2E9, Canada
³ West Virginia University, Morgantown, West Virginia, 26506, USA
⁴ Institute of Theoretical and Applied Mechanics, Novosibirsk, 630090, Russia
⁵ National Mineral Resources University, Saint-Petersburg 199106, Russia

SUMMARY

The purpose of the talk is to describe recent advances in nonlocal electron kinetics in low-pressure plasmas. Low-pressure discharges are widely used in industry as the main plasma sources for many applications including plasma processing, discharge lighting, plasma propulsion, particle beam sources and nanotechnology. Being partially-ionized, bounded, and weakly-collisional, the plasmas in these discharges demonstrate nonlocal electron kinetic effects, nonlinear processes in the sheaths, beam-plasma interaction, collisionless electron heating, etc. Such plasmas often have a non-Maxwellian electron velocity distribution function. The plethora of kinetic processes supporting the nonequilibrium plasma state is an invaluable tool, which can be used to adjust plasma parameters to the specific needs of a particular plasma application. We report on recent advances in nonlocal electron kinetics in low-pressure plasmas where a non-Maxwellian electron velocity distribution function was "designed" for a specific purpose: in DC discharges with auxiliary biased electrodes for plasma control, hybrid DC/RF magnetized and unmagnetized plasma sources, and Hall thruster discharges. We show using specific examples that this progress was made possible by synergy between full-scale particle-in-cell simulations, analytical models, and experiments.

Key words: nonlocal electron kinetic effects, nonlinear processes in the sheaths, beam-plasma interaction, collisionless electron heating.

1. INTRODUCTION

Low temperature plasmas (LTPs) are widely used in applications and are strongly affected by the presence of neutral species—chemistry adds enormous complexity to the plasma environment. Electron energies in such plasmas are of order a few electron volts with sufficient population of electrons with energies above the threshold energies of the excited states of neutral atoms and molecules. The power transfer from electrons to these atoms and molecules produces activated species (e.g., radicals, excited states, and photons). Due to the low degree of ionization, the mean energy of electrons and ions in such plasma considerably exceeds the temperature of the neutral species. This provides a unique set of conditions wherein plasma species can efficiently react with adjacent surfaces resulting in their beneficial modification. With such properties, low temperature plasmas are widely used in technological processes, ranging from manufacturing of semiconductor chips, solar and plasma-display panels, to the treatment of organic and bio-objects [1]. Examples of recent progress are described in Special Section of Physics of Plasmas "Electron kinetic effects in low temperature plasmas" [2].

The next logical step in the development of electron kinetics was not only explaining the observed kinetic phenomena but using this accumulated knowledge to explore ways of actively crafting electron energy distribution functions (EEDFs) to achieve required effects. This research is the focus of DOE funded Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems [3]. The complex dependence of different chemical reactions on electron energy places an extraordinary premium on optimally shaping EEDFs to influence the rate of interaction of a particular process. The ability to control the efficiency of the interaction of charged particles with their environment (gas atoms and molecules, or surfaces) depends on the ability to craft and control charged particles and photons distribution functions. Advancing LTP science requires the ability to control and to shape charged particles and photons distribution functions for beneficial treatment of surfaces, which is a challenging task considering the diversity and complexity of the variety of discharge conditions. However, improving the performance of these new plasma tools is still a significant challenge for plasma engineering. Exploitation of nonlocal plasma properties allows additional dimensions and flexibility in adjusting plasma parameters. A remarkable property of such plasmas is that changing conditions in one place may lead to unexpected changes far away in another part of the plasma. Additionally, plasmas with nonlocal EEDF allow independent and effective managing of electrons belonging to different energy ranges [4]. This, in turn, allows modification of the plasma properties in desirable ways, because different energetic groups of electrons are responsible for different processes, and their density modifications yield control over corresponding plasma processes. We report on recent advances in nonlocal electron kinetics in low-pressure plasmas where a non-Maxwellian EEDF was “designed” for a specific purpose.

2. THEORETICAL AND EXPERIMENTAL STUDY OF HALL THRUSTERS

In series of publications we studied plasma properties of Hall thrusters, see Ref.[5] and Refs. within. It was experimentally shown that plasma properties are affected by choice of wall material. For example, changing material from boron nitride to carbon-based materials yielded significant increase in electron temperature. Analytical and particle-in-cell simulation studies revealed that electron velocity distribution function (EVDF) in
Hall thruster is non-Maxwellian, anisotropic and enriched by electron beams emitted from the wall due to secondary electron emission, as evident from Fig.1.

![Figure 1. Complex structure of strongly anisotropic ($T_e = 12eV, T_i = 37eV$) electron velocity distribution function in the channel of a Hall thruster discharge (left) versus an isotropic Maxwellian EVDF (right) [5].](image)

3. THEORETICAL AND EXPERIMENTAL STUDY OF DC DISCHARGES WITH AUXILIARY ELECTRODES

Second example of a device with nonlocal plasma properties is a short dc discharge (several millimeters in length at the pressure of a few Torr, 10–100 μm for atmospheric pressure). The discharge consists of the cathode and anode sheathes and a negative glow plasma without a positive column. The plasma is created by the energetic electrons emitted by the cathode and accelerated by the near-cathode sheath to the energies above the ionization potential for the gas atoms. In contrast to semiconductor devices, plasma discharges can be used under harsh conditions related, for example, to high temperatures and radiation levels of damaged nuclear plants [6].

A dc discharge with a hot cathode is subject to current and voltage oscillations self-generated by plasma, which have deleterious effects on device operation. The oscillations can be inhibited by installing an auxiliary electrode, placed outside of the anode. By collecting a modest current through a small opening in anode, we show that the discharge becomes stable, in a certain pressure range. This method of avoiding current oscillations can be used, for example, for high current stabilizers.

4. THEORETICAL AND EXPERIMENTAL STUDY OF HYBRID DC/RF PLASMA SOURCES

Third example is a plasma etching device used for plasma processing applications. It is a radio frequency (rf) discharge with applied additional dc bias on one of the electrodes [7]. Experimental measurements of electron energy distribution function in a rf/dc discharge with 800 V dc voltage reveal the presence of a peak of super-thermal electrons with energy in the range of 40–400 eV [7]. The cathode in the experimental device could emit electrons thus producing an electron beam. We used a particle-in-cell code [8] to investigate acceleration of plasma electrons by an electron beam in a dc discharge with parameters close to those of Ref. [7]. The beam excites electron plasma waves via the two-stream instability. Simulations show that the two-stream instability is intermittent, with quiet and active periods. During the quiet periods, the beam propagates through the plasma with minimal perturbations. During the periods of activity of two-stream instability, the beam interacts with the plasma most intensively at locations where the global frequency of instability matches the local electron plasma frequency. There may be two resonance areas with intense oscillations usually near the edges of the plasma. These intense localized plasma oscillations produce peaks in the velocity distribution function similar to the ones measured in the experiment.

3. CONCLUSIONS

We show using specific examples that a lot of progress was made possible by synergy between full-scale particle-in-cell simulations, analytical models, and experiments in understanding and optimization of operation of several very important practical devices: Hall thruster for electric propulsion, dc discharge with thermionic emission for thermionic converters and high power current stabilizers, and rf/dc hybrid discharges for plasma processing applications (etching).

ACKNOWLEDGMENTS

This research was supported by U.S. Department of Energy and Air Force Office of Scientific Research.

REFERENCES


[3] See http://doeplasma.eecs.umich.edu/index.htm for the new Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems, which is funded by a five-year grant from the U.S. Department of Energy.


Development of a Pulsed Glow Discharge


School of Physics, University of Sydney, Sydney NSW, Australia.
* On sabbatical leave from Tel Aviv University: e-mail address boxman@eng.tau.ac.il

SUMMARY

The temporal development of the characteristic spatial features of the abnormal glow discharge was studied using high speed photography. It was found that the negative glow, Faraday dark space, and the positive column are all developed within a few $\mu$s.

Key words: abnormal glow discharge, Faraday dark space, negative glow, positive column

1. INTRODUCTION

Plasma assisted chemical vapor deposition (PACVD) is being investigated for depositing amorphous carbon films to support functional organic molecules, with the plasma produced by a pulsed abnormal glow discharge (PAGD). In the PAGD, the cathode glow covers the entire cathode, and increased current is accompanied by increased voltage [1,2]. High-speed photography has been previously used to investigate the shape and speed of propagating plasma discharges [3] as well as the spatial distributions of various atom and ion species in the discharges [4]. However, the negative glow and Faraday dark space were not previously investigated. Here we present preliminary results of a high-speed photographic study of the temporal development of the characteristic features of the PAGD, particularly the negative glow and the dark spaces, and show that they develop within a few $\mu$s’s.

2. METHOD AND RESULTS

The discharges were conducted between an 80 mm diameter steel disk cathode and a grounded 30 cm diameter test chamber anode, in argon gas. 20 $\mu$s, 11.7 kV pulses were applied to the cathode with a repetition rate of 100 Hz via ~2.5 m of coaxial cable.

The discharge was photographed with a Canon G15 camera in automatic mode (Fig. 1), and a Hamamatsu framing streak camera C4187/M4189/C8484 and a personal computer (PC) running Hamamatsu HPD-TA software. Framing camera gate pulses as well as the discharge voltage and current waveforms were recorded on an oscilloscope. The discharge was photographed in the framing mode, with 8 frames, each with an exposure time of 0.5 $\mu$s, and a frame interval of 1 $\mu$s, at maximum light amplification, integrated mode for 200 ms. Each of the images transferred to the PC was the integration of 20 images, each containing 8 frames, each acquired at a set time during the repetitive pulse. The raw black and white photographs were rendered in artificial color to highlight the light intensity distribution (Fig. 2).

Using the HPD-TA software, vertical light intensity profiles were collected for each frame, where each data point is the average of several pixels in the horizontal direction. Minima in the profile were identified as the center of the electrode, and the Faraday dark spaces on either side of the electrode. Maxima were identified as the center of the negative glow and the beginning of the positive column. The positions of these features were recorded and graphed (Fig. 3), to find the location of these features as a function of time (Fig. 4). It may be seen that the light intensity increased from frame to frame. Fig. 4 shows that the voltage pulse is flat-topped, while the current, measured in the pulse generator, initially has high amplitude oscillations, associated with transients in the cable connecting the generator to the electrode, followed by a period when the current rises from 0.13 to 0.25 A. During this period the light intensity increased, but the position of the various glow discharge features remained relatively constant.

3. CONCLUSIONS

The principle features of the pulsed abnormal glow discharge develop within a few $\mu$s of the start of each pulse. Their location is relative constant, while the emitted light intensity increases as the discharge current increases during pulse initiation.

REFERENCES

Figure 1. Time integrated photograph of a pulsed abnormal glow discharge in Ar on a steel electrode.

Figure 2. Sequence of eight 0.5 μs photographs (left) and a false color representation of the intensity field (right). 1st frame is lower left, and then progress up (2nd), right (3rd), down (4th), right (5th), up (6th), right (7th) and down to the 8th frame in the lower right.

Figure 3. Light intensity as a function of distance downward from the center of the electrode, y.

Figure 4. Discharge waveforms (left axis), camera gate pulses, and locations of the glow discharge features (right axis).
The Force Exerted by a Fireball

A. Fruchtman* and G. Makrinich

H.I.T. - Holon Institute of Technology, ISRAEL

SUMMARY

The force exerted by a fireball was deduced from the change of the equilibrium position of a pendulum and from the change in the pendulum oscillation period. That measured force was found to be several times larger than the force exerted by the ions accelerated across the double layer that is assumed to surround the fireball. The force enhancement that is expected by ion-neutral collisions in the fireball is evaluated to be too small to explain the measured enhanced force. Gas pressure increase, due to gas heating through electron-neutral collisions, as recently suggested [J. Appl. Phys. 109, 113305 (2011)], is examined as a possible source of the enhanced force.

Key words: fireball, double layer, ion-neutral collisions, gas heating.

1. INTRODUCTION

A fireball (plasma of a ball shape) is often formed near a positively biased electrode in a (usually) low pressure gas [1 – 6]. The generation of the fireball is believed to be associated with an excitation of a double layer around the fireball, across which part of the discharge voltage drops, and in which electrons acquire the energy for ionizing the gas [1]. One would expect the momentum of the particle flow outward of the ball to equal the momentum that the ions acquire while they are accelerated in the double layer. However, recent measurements [5, 6] show that the force exerted by the plasma flow is much larger than the force by the impinging ions. We suggested that the enhancement of the force could result from ion-neutral collisions in the fireball [5], similarly to what we demonstrated experimentally in magnetized plasma [6] and have shown theoretically to occur in cylindrical plasma that expands axially [7]. Stenzel et al. have recently suggested that it is neutral-gas heating that is the source of the enhanced force in their fireball experiment [5]. We will present measurements of the force exerted by the fireball, and will analyze these suggested mechanisms for force enhancement; ion-neutral collisions and gas heating.

![Figure 1: The radial plasma source and the diagnostic system.](image)

2. EXPERIMENT

A fireball is generated in cases when a DC voltage is applied between an anode and an electron-emitting cathode, both immersed in a low (several mTorr) pressure gas. The anode and cathode in our case were part of our Radial Plasma Source (RPS) [6]. The RPS was located at the center of a cross ISO 320 vacuum chamber which was pumped to a base pressure of 0.01 mTorr by a two-stage pump station.

The RPS, shown in Fig. 1, consisted of a ceramic insulator, a molybdenum anode, a magnetic-field generating solenoid (not used here), an iron core, a gas distributor, and a cathode. The ceramic insulator was composed of two annular disks connected with an axial segment. The outer diameter of each of the annular disks was 77 mm, the inner diameter was 30 mm, and the axial distance between the two disks was 5 mm. The RPS axial dimension was 30 mm. The molybdenum cylindrical anode was of 48 mm in diameter, 4.5 mm in height, and 0.25 mm in thickness. The empty cylindrical volume between those three parts plays a role of a gas distributor, through which the working gas was supplied through six holes in the ceramic insulator into the space between the two annular disks. The gas used was argon with a flow rate in all the experiments of 35 SCCM (Standard Cubic Centimeter per Minute) and, consequently, the pressure near the wall of the vacuum chamber was 5 mTorr. For the plasma generation we employed a cathode located 80 mm from the axis of the RPS.

The measurement system consisted of a flat Langmuir probe and a pendulum. The flat Langmuir probe was employed for measuring the ion particle flux flowing from the RPS, while the pendulum was used for evaluation of the force exerted by the ion and neutral flow out of the source. Both Langmuir probe and pendulum were located in the vicinity of the fireball. When the discharge was ignited in an unmagnetized mode at about 5 mTorr, a fireball appeared, as shown in Fig. 2. The size of the ball grew with the discharge current. The discharge current was 0.6A in Fig. 2a, 1.3A in Fig. 2b, and 1.4A in Fig. 2c, and the ball diameter varied from about 24mm in Fig. 2a to about 34mm in Fig. 2c. The ball was located for the lower currents as shown in Figs 2a and 2b, and when the current was increased to above 1.3A, the ball jumped to the location shown in Fig. 2c. We discuss mostly measurements taken while the ball was in the position shown in Fig. 2c.

While the fireball was in the position shown in Fig. 2(c), the pendulum sometime oscillated and sometimes was at a constant position. Both from the modified equilibrium position and oscillation period, we estimate the force exerted by the fireball to be 10⁻³ N.
3. THEORY
We first examined whether the source of the force could be the momentum carried by the ions accelerated by the potential drop inside the fireball. The maximal force that the ions could exert due to this acceleration is calculated to be more than 6 times smaller than the measured force. We then examined the possible enhancement of the force by ion-neutral collisions during their acceleration. The enhancement should be proportional to the square root of the number of collisions along the acceleration [6] and, consequently, to the neutral-gas density. The neutral-gas density that could result in momentum delivery to the ions that could explain the measured force is about 5×10^{22} m^{-3}. This density is more than 50 times larger than the estimated maximal neutral-gas density inside the fireball. We conclude that it is not likely that ion-neutral collisions are the source of the enhanced force.

A second possible mechanism for force enhancement is an increase of the neutral-gas pressure due to gas heating by the electron current. This mechanism was suggested by Stenzel et al for a pulsed fireball. An impulse is expected to be generated until pressure balance is achieved. In a steady-state, as in our experiment, a steady force can be formed by the gas flow only if there is a constant supply of gas into the fireball. We developed a model for a flowing gas into the fireball that is heated and then accelerated outward of the plasma ball. The heating of the gas by the electron current was estimated by using the parameters of the plasma according to a separate plasma model, and by employing the cross section for electron-neutral collisions. From the model we calculated the neutral-gas density and exiting velocity, the plasma density and the neutral-gas flux out of (and into) the fireball. While the calculated densities and neutral velocity seem reasonable, the neutral gas flow turns out to be larger than the gas flow rate in our experiment. Gas heating could therefore be the source of the enhanced force only if large flows are generated (possibly due to the heating).

4. CONCLUSIONS
The force exerted by the plasma-gas flow outward of a fireball was measured and was found to be much larger than expected by ions accelerated across a potential drop. Enhancement of the force by ion-neutral collisions seems to be too small to explain the measured force. Gas heating by the electron current could be the source of the force if a large gas flow into the fireball exists.

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Study of the Lower Ionosphere with VLF EM Waves Generated by Lightning

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SUMMARY

The lower ionosphere is investigated through its effect on VLF (3-30 kHz) EM waves radiated by lightning discharges. Signals from lightning return strokes thousands of km away are collected at two TAU observation stations and analysed. In order to model the received signal, a computer code, originally developed for calculating the propagation of VLF narrow band communication signals in the Earth-ionosphere waveguide, was adapted for simulation of the propagation of the waves radiated by a pulsed (wide band) natural source. Preliminary results show a fair agreement with observations.

Key words: Ionosphere, VLF, Lightning

1. INTRODUCTION

The ionosphere is the upper part of the atmosphere where fairly large concentrations of free electrons exist as a result of ionization by solar UV radiation and by energetic particles from the sun and from other outer space sources [1]. It is thus affected by solar variability (day/night, seasons, 11-year solar cycle), while solar storms can have an impact on scales of minutes, hours, or days. This is true in particular for the lower ionosphere (D-region), which extends from an altitude of roughly 60 to 80 km up to 100 km above surface, and which can be impacted also from below by natural phenomena (lightning, sprites, earthquakes), as well as by man-made sources (explosions, communication). While the lower ionosphere is too high to be reached by airplanes or balloons and too low for satellite, it can be studied using electromagnetic (EM) waves in the VLF range (3-30 kHz). Due to the presence of free electrons, the ionosphere is conductive and, as a result, the layer between it and the Earth acts as a waveguide within which VLF EM waves can propagate over distances of thousands of km. Thus, VLF received signals inherently contain information on the height and the profile of the conductive layer [2], and as such their measurement allow studying the lower ionosphere.

Existing VLF navigation and submarine communication narrow band transmitters have been used as sources for monitoring the ionosphere height. Nevertheless, their usefulness in research is somewhat limited due to their small number and their specific locations. Natural sources of VLF waves such as lightning discharges represent another possibility. According to recent satellite-based measurements, it is estimated that there are an average of ~45 lightning per second around the world [3], corresponding to ~2 lightning per second in a 5000X5000 km area. The return stroke phase of a lightning is characterized by a current of a few tens of kA, flowing through a (almost) vertical discharge channel of a few km, and lasting for a few tens of µsec [4]. Hence, it can be regarded as a system of a pulse generator and a radiating vertical antenna.

The goal of this recently initiated research is to study and understand the variability of the lower ionosphere above Israel and the eastern Mediterranean. This involves short term changes due to solar storms, sprites etc., and as well, long term changes due to the solar cycle and due to seasonal and climate changes. The research includes both observation and modelling.

2. METHODS AND RESULTS

2.1. Observations

Observations are performed at two TAU VLF field stations. The Sde-Boker station has a highly sensitive low noise VLF receiver, which combined with two orthogonal triangular large loops (18x9 m) has a sensitivity of 20fT (6µV/m) in the 0.35-50 kHz band. This system allows us to detect lightning signals from several thousands of km. The second station at Mt. Hermon has a smaller antenna (2.6x1.3 m) but is still very sensitive. The receiving system at each station includes also a GPS for time-stamping of the waveform transients, which are collected and recorded continuously. Then, synchronization with the world wide lightning location network (WWLLN) enables us to obtain a set of waveforms for which the locations of the source lightning is known in good accuracy.

2.2. Modelling

The long wavelength propagation capability (LWPC) code [5] is the state-of-the-art public domain program for simulating the propagation of VLF EM waves in the Earth-ionosphere waveguide. LWPC solves in the frequency domain for the far field of a short dipole (in terms of the wavelength) source above ground, and it takes into account the Earth curvature and the finite ground conductivities and dielectric constants along the path between the transmitting and the receiving locations.

As for the ionospheric plasma, it is far from being a homogeneous medium. Moreover, due to ionization by sun radiation, electron density increases during daytime, which causes the lower ionosphere to extend to lower altitudes. Since neutral density and, as a result, also the collision rate are larger at lower altitude, the conductivity is smaller at the boundary of the lower ionosphere during daytime. LWPC has a default plasma model of the ionosphere which takes these day/night differences into account, based on analysis of available
measurements. This model employs a conductivity that increases exponentially with height, \( \sigma(h) = \sigma_0 e^{\beta(h-h_0)} \). For daytime \( h' = 74\text{km} \) and \( \beta = 0.3\text{km}^{-1} \), while for nighttime \( h' = 87\text{km} \) and \( \beta \) varies between 0.3 and 0.8 \( \text{km}^{-1} \) in the 10-60 kHz frequency range. In addition, since during night the collision rate at the lower ionosphere is smaller, the program takes into account for the night case the effect of the geomagnetic field. This results in the lower ionosphere being an anisotropic reflector. LWPC allows for the modification or replacement of the default model. This will enable us to investigate the effects of short term phenomena such as solar storm or long term climate changes on the ionosphere.

We have successfully adapted LWPC for the modelling and simulation of the propagation of VLF waves from a pulsed source such as lightning. The first step is to acknowledge that the current moment \( M(t) \), obtained by spatial integration over \( J(r, t) \) - the current density distribution of the lightning return stroke, \( M(t) = \int_0^L J(r', t) dV' \), is the equivalent of the product of the current and the length of the antenna in the case of the short dipole source. From \( M(t) \) we get \( M(\omega) \) by Fourier transform. Then, LWPC is run for each frequency to obtain the spectrum of the field at the receiver, \( E_r(\omega) \) (or \( B_r(\omega) \)). Finally by inverse Fourier we get the signal at the receiver, \( E_r(t) \) (or \( B_r(t) \)).

### 2.3. Preliminary Results

We have applied a simple analytical model for the current moment of the lightning return stroke \[ M(t) = I_{r0} \left( \frac{v_0}{\gamma} \right) e^{a t - b t} \left( 1 - e^{-b t} \right), \] where \( I_{r0} \) is the amplitude of the return stroke current at the ground with a typical value of 20\,kA, \( v_0 e^{-\gamma t} \) is the pulse propagation velocity up the lightning channel with a typical value for \( v_0 \) of \( 8 \times 10^7 \text{m/s} \). The values of \( a, b, \) and \( \gamma \) are \( 2 \times 10^7 \text{s}^{-1}, 2 \times 10^5 \text{s}^{-1}, \) and \( 3 \times 10^5 \text{s}^{-1} \), respectively. Figure 1 shows the current moment pulse obtained with this model. We have used this current moment model, the LWPC program, and the procedure described above to simulate received signals at Sde-Boker from far away lightning discharges. Results were compared with recorded waveforms, for which the locations were identified by synchronization with WWLLN. A fair agreement was found. Figure 2 shows such a comparison. The magenta trace represents the waveform (a.u.) obtained from principle component analysis (PCA) of a few tens of signals received during night from distances of 2000-2050 km and azimuths of 0-10° (in south Ukraine). The black trace represents the simulated waveform for night ionosphere, a distance of 2025 km and azimuth of 5°.

![Figure 1. Lightning return stroke current moment model.](image)

![Figure 2. PCA of received signals at Sde-Boker during night from distances of 2000-2050 km and azimuths of 0-10° (magenta), and simulated waveform for night ionosphere, a distance of 2025 km and azimuth of 5° (black).](image)

### 3. CONCLUSIONS

A method to investigate the lower ionosphere through its effect on VLF (3-30 kHz) EM waves radiated by lightning discharges was described. Signals from lightning thousands of km away are collected at two TAU observation stations and analysed. A public domain computer code was adapted for simulation of the propagation in the Earth-ionosphere waveguide of the waves radiated by a pulsed (wide band) natural source. Preliminary results show a fair agreement with observations. The observational and modelling capabilities developed so far will be used to study the variability of the lower ionosphere above Israel and the eastern Mediterranean.

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Temporally- and Spatially-Resolved Measurements of the Structure and the Magnetic Field Distribution of an Imploding Plasma

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SUMMARY

Knowledge of the magnetic field distribution in imploding plasmas (such as a Z-pinch plasma) is of high importance due to the key role of the magnetic field in determining the characteristics of the plasma during implosion and stagnation. Various theoretical models and simulations of Z-pinch plasmas strongly rely on the magnetic field distribution for the predictions of the hydrodynamic and atomic processes in the plasma and of the energy coupling. Zeeman splitting measurements are limited to the relatively cold, low density plasma edge, since at the inner hot and dense plasma, the Doppler and Stark broadenings are larger than the Zeeman splitting.

In this talk I will present a technique that overcomes these limitations by recording the individual full line profiles of the left and right circularly polarized components of Zeeman-split emission lines. Employing this technique while viewing multiple chords through the plasma, can provide unambiguous determination of the magnetic field and current distribution in the plasma column.

Keywords: High-Energy-Density Plasmas, Z-pinch, Zeeman Splitting, Magnetic Field, Polarization Spectroscopy.

1. INTRODUCTION

Z-pinch implosions serve as intense sources of X-ray radiation that are of broad interest in the research toward inertial confinement fusion and the study of matter under high energy density. In such systems, a cylindrical plasma column (typically formed out of an array of fine wires or a puff of gas) radially implodes under the azimuthal magnetic field resulting from axially driven high currents.

The plasma properties, the processes of the energy conversion, the stability of the plasma during the implosion and stagnation and the properties of the radiation emitted, are considerably affected by the implosion dynamics. Therefore, studying the processes that govern the plasma implosion is crucial for improving the understanding of the various phenomena involved. These include the development of instabilities such as the Rayleigh-Taylor instability, the behavior of the magnetic field during the implosion phase and especially its penetration into the plasma, the flow of the current throughout the implosion, the process of matter being "overtaken" by the inward driving force and left behind the magnetic field front, and the propagation of pressure and polarization waves ahead of the magnetic field.

Several spectroscopic methods for the determination of magnetic fields are based on the Zeeman effect [1]. In the past, polarization spectroscopy has been used in our laboratory to obtain time-dependent measurements of the magnetic field distribution throughout the implosion phase of a moderate-density, gas-puff Z-pinch plasma [2]. In this method the relative contribution of the \( \pi \) and the \( \sigma \) polarizations (see below) to the spectral widths of observed emission lines were separated, serving to discriminate the Zeeman splitting against other broadening mechanisms, namely Stark, Doppler and opacity effects. However, Plasma conditions that are typical of high-energy-density (HED) systems render this technique impractical. The high densities and high ion velocities result in broad spectral line shapes that are dominated by Stark and Doppler broadenings, such that the relative contributions cannot be determined.

2. SPECTROSCOPIC METHOD

In a magnetic field the energy levels are split creating the Zeeman effect. The wavelength shift, \( \Delta \lambda \), is dependent on the magnetic quantum numbers \( m_s \) of the upper and lower states of the transition. The components of a transition for which \( \Delta m = 0 \) are called the \( \pi \) components; the \( \sigma \) components arise when \( \Delta m = \pm 1 \). The polarization of the components of a Zeeman spectrum depends on the viewing angle relative to the local magnetic field, \( \vec{B} \). When emission is viewed parallel to \( \vec{B} \), only the \( \sigma \) components are observable and the light is circularly polarized, right handed when \( \Delta m = +1 \) and left handed when \( \Delta m = -1 \) [3].

Discriminating between the \( \sigma+ \) and \( \sigma- \) components is achieved using a quarter-wave plate and a linear polarizer. The quarter-wave plate transforms the left and right handed circular polarizations into orthogonal linear polarizations, at \( \pm 45^\circ \) to its extraordinary axis. Placing a linear polarizer at these angles allows only one of the polarizations to pass. It is noteworthy that a disadvantage of this technique arises from the need to record the emission in the different polarizations, resulting in lower signal-to-noise ratios.

Contrasting X-ray [4] and visible images [5] of the Z-pinch plasma during stagnation, indicates that while bare nuclei, H⁻ and He-like ions reside within \( r \approx 0.5 \) mm, lower ionization levels exist at larger radii. The existence of these charge-state layers is the result of a temperatures gradient decreasing outwards from the hot core of the pinch.

This layer structure can be highly beneficial if emission lines from charge states which reside in distinguishable radii are found in suitable spectral proximity. The lines must not be too close so as to overlap naturally or when broadened. They must, however, be close enough to be measured simultaneously without sacrificing the spectral resolution required to discriminate between the \( \sigma+ \) and \( \sigma- \) components. Such line pairs were indeed found. The pair used thus far in this research consists of the 3811.35 Å line of O vi and the 3791.26 Å line of O iii. Abel inversion of the data showed that the O iii line extends to the outer surface of the pinch column, the O vi line only reaches radii up 5 mm smaller than that.
Ions residing in the outer surface of each layer emit light parallel to \( B \) at the appropriate radius. Therefore, measuring the spectral separation of the \( \sigma^+ \) and \( \sigma^- \) components of both lines simultaneously, each at its outermost chord, yields the magnetic field strength at two radii in a single measurement.

3. EXPERIMENTAL SYSTEM

The current generator is a 25 nH inductance, 5.5 µF capacitance and 80 kV voltage discharge circuit. A hollow cylindrical conduit (anode) is positioned inside the vacuum chamber co-axially with a nozzle (cathode) connected to a fast electromagnetic valve. Gas injected into the vacuum chamber fills the 9 mm A-K gap with a central jet, 3 mm in diameter, surrounded by a cylindrical shell with a diameter of 38 mm. When the voltage is applied across the A-K gap, gas breakdown and current conduction through the produced plasma are initiated, and the \( J \times B \) force compresses the gas inwards. The peak current provided by the system is \( \sim 1 \) MA, with a rise time of \(~500\) ns.

A new spectroscopic system, designed to measure both polarizations simultaneously, has been designed and its components are being manufactured. The spectroscopic system used as yet consists of a linear fiber array, made of 50 fibers, each measuring 200 µm in diameter and 4 m in length. Light from the plasma is imaged on one end of the array, with the other end imaged onto the entrance slit of a 1.26 m spectrometer equipped with a 2400 grooves/mm grating. The spectrometer is coupled to an intensified CCD camera (ICCD), equipped with a 1024 × 1024 pixels cooled CCD. Light from the plasma passed through a quarter-wave plate and a linear polarizer before reaching the fiber array. With this system each of the \( \sigma^+ \) and \( \sigma^- \) polarizations has been measured separately, by rotating the linear polarizer by 90°.

In addition, a UV-visible imaging system provides a 2D image of the plasma, taken concurrently with the spectroscopic measurement. Light from the plasma is imaged onto a second ICCD, with optical filters placed in its path.

4. RESULTS

Since each polarization had to be measured separately, the magnetic field strength was deduced from the shift of each component relative to the line center measured without the quarter-wave plate and polarizer.

Deducing the field strength from this shift was done by fitting a Zeeman split profile calculated within the LS approximation, where \( B \) and the broadening mechanisms are entered as parameters. The results are summarized in Figure 1. The outermost data point in each dataset is calculated from the total current flowing through the plasma, as measured by a \( B \) probe. These points are placed at the outer radii measured by the imaging system. The other two points were determined from spectroscopy as described above.

Figure 1. The magnetic field distribution in the plasma at different times, were \( t = 0 \) indicate peak X-ray emission. The boundary field for each dataset was calculated from the total current measured by a \( B \) probe and place at the outer radius of the column. The other two points were calculated from the Zeeman shift measured by the spectroscopic method.

5. CONCLUSIONS

The results obtained thus far show that while most of the current flows on the outer surface of the pinch column, penetration into the plasma is evident.

The need to determine the shift of each component meant relying on satisfactory reproducibility of the experiments and the line center position. Simultaneous measurements, made with the new soon-to-be-complete spectroscopic system, will serve to verify these results, improve their precision and provide additional data points for a more comprehensive time history of the current penetration into the plasma.

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Trends in High Power Microwaves

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SUMMARY

High power microwave (HPM) sources are hypoband (narrowband) coherent sources of electromagnetic radiation that have been under development for nearly 50 years. These sources are an outgrowth of the development of “modern pulsed power.” Such sources are intense, high perveance, relativistic electron beam-driven vacuum electron devices that follow a power-frequency scaling governed by $Pf^2$. The presentation reviews historical developments, describes the present state-of-the-art in the field, and describes recent trends for future development.

Key words: High power microwaves, Cherenkov radiation, oscillators, amplifiers, intentional electromagnetic interference.

1. INTRODUCTION

HPM sources are hypoband coherent sources of electromagnetic radiation that have been under development for nearly 50 years [1,2]. These are an outgrowth of the development of “modern pulsed power” [3]. Such sources are intense, high perveance, relativistic electron beam-driven vacuum electron devices that follow a power-frequency scaling determined as $Pf^2$. The frequency range over which HPM sources are researched range from $<1$ GHz – 1 THz.

2. HISTORICAL OVERVIEW

HPM sources began to appear in the mid-to-late 1960’s (see [2,4] for more details). They have two lines of genesis, one in the United States and one in the Soviet Union. The availability of high-current pulsed power accelerators led researchers, primarily plasma physicists, to revisit conventional electron beam-driven source concepts except this time using high-perveance electron beams. Plasma physicists led this line of research because these high-perveance relativistic electron beams have strong space charge fields, and plasma physicists are those who best understand particle-wave interactions under such extreme conditions, Fig. 1.

Figure 1. Plasma physicists dominated the development of HPM sources because of their understanding of particle-wave interaction when space charge is dominant [1].

The Early Years – the HPM Power Derby

The early years (late 1960’s – 1991) were dominated by a power derby between researchers in the United States and the Soviet Union. This was the era of big machines, exemplified by the Aurora machine at Harry Diamond Laboratories (Army Research Laboratory, Adelphi, MD) and the Gamma machine at the Institute of High Current Electronics, Tomsk, Soviet Union [4]. The Aurora accelerator, two stories tall and massive, was used to drive a vircator (virtual cathode oscillator), and the Gamma accelerator was used to drive a multi-wave Cherenkov generator. These devices output several GW of power at frequencies of a few GHz. These devices were, of course, single shot machines.

Pulse Shortening and Virtual Prototyping

The HPM power derby came to an end by the mid-1990’s. At the time the goals of source researchers were 1 kJ of output energy. That required generating 1 GW of power for 1 μs pulse duration. This was beyond what was achievable. Inevitably, plasmas generated within the electrodynamic interaction region, particularly plasma ions, moved sufficiently over a 100 ns time scale that they could affect the beam-wave interaction. This forced researchers to redirect their efforts and to study overmoded sources and to consider shorter pulse, higher repetition rate systems.

At about the same time that pulse shortening was recognized, virtual prototyping emerged as a reliable tool for designing HPM sources [5]. Prior to the early-mid 1990’s experimentalists tinkered; modeling and simulation attempted to match experimental results. Absolute agreement was poor. Today, no metal will be cut until simulation demonstrates optimal performance! Particle-in-cell (PIC) codes revolutionized the field. Developed by plasma physicists, these are 3D finite-difference-time-domain (FDTD) fully electromagnetic field solvers that incorporate relativistic dynamics. ICEPIC is a parallelized 3D development at the Air Force Research Laboratory (AFRL), Kirtland Air Force Base, New Mexico, and is the state-of-the-art in PIC. The university community in the United States primarily uses MAGIC (ATK/Mission Research, sponsored by AFOSR), although there are several commercial PIC codes that are competing very aggressively.

Virtual prototyping is now widely used all over the world and is the most reliable tool in designing new hypoband HPM source concepts. Recent work using virtual prototyping led to the invention of a novel cathode concept (electron emitter) [6] for relativistic magnetrons and was subsequently validated in experiments [7].
3. RECENT TRENDS
Three recent trends have been emerging in hypoband HPM source development: multi-spectral sources, phase coherent sources, and sources based on metamaterial and metamaterial-like slow wave structures (SWSs).

Multi-spectral Sources
The term “Multispectral sources” refers to enhanced frequency agility of HPM sources or to sources that can generate multiple frequencies simultaneously or switch frequency during a pulse. In [8] the authors demonstrate a mechanically tunable backward wave oscillator with 12% tunability in S-band from one-shot-to-the-next with multimegawatt power levels. In [9] the authors describe a Magnetically Insulated Line Oscillator (MILO) that is constructed of two half-cylinders of different radii, thus leading to the simultaneous generation of two frequencies in S-band (3.4 and 3.65 GHz) with gigawatt power level. In [10] the authors describe the use of a relatively low power externally injected signal to achieve mode switching in relativistic magnetron. By switching the operating mode the researchers were able to operate in different frequencies in S-band at near-gigawatt power level.

Phase Coherent Sources
Researchers at the Institute of High Current Electronics presented exciting results in phase coherence (reviewed in [4]). By splitting the output pulse forming line from their pulsed power accelerator they were able to simultaneously drive two short pulse superradiant backward wave oscillators. They demonstrated the coherent summation of the outputs and propose that if the phases are within about 25° it is sufficient to sum the powers, yielding an $N^2$ scaling (where $N$ is the number of sources being simultaneously driven). This notion of phase coherence is not as rigid as phase locking for radars, which requires that the source be in phase within <1°. This result was soon reproduced at the Northwest Institute of Nuclear Technology, Xi’an, China using two klystron-like relativistic backward wave oscillators (reviewed in [4]).

Metamaterial and Metamaterial-like Slow Wave Structures
An even more recent development is interest in metamaterial and metamaterial-like SWSs [11]. Metamaterials are promising artificial materials that have many unusual features, amongst which are negative refraction, backward Cherenkov radiation, surface waves propagating on the interface with ordinary material, etc. Unusual electrodynamic properties of metamaterials naturally call for investigations of their applicability as SWS elements in microwave vacuum electron devices. Their most attractive feature is that periodic metamaterials possess period $d$ much smaller than the wavelength $\lambda$, thus being able to support very low group velocities. If combined with large amplitudes of the longitudinal (to the direction of the beam propagation) electric field (and, hence, ensuring large Pierce parameter values), such materials could, in principle, find a unique place in the field of HPM sources, provided the issues associated with microwave breakdown are resolved.

This development has been motivated by renewed interest in HPM amplifiers as opposed to oscillators. HPM amplifiers offer the possibility of generating HPM pulses with richly varying temporal distribution, limited by the bandwidth of the amplifier.

4. CONCLUSIONS
HPM sources have been under investigation for nearly 50 years. This presentation will present an historical overview of the field, as well as the areas of future development.

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High-Power Long-Pulse Operation of a Millimeter-Wave FEL

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SUMMARY

The Electrostatic Accelerator Free Electron Laser in Ariel has been upgraded with several new features. It is now possible to remotely control the output reflectivity of the resonator and thereby vary both the power built up within the resonator and that emitted. This has allowed reliable operation of the laser at powers between 1-9kW (in the user room after attenuation in the transmission line). A voltage ramping device was installed at the resonator/wiggler to correct voltage drop due to electrons striking the walls of the beam line. This has allowed stable pulses of just over 50μs at high power with a chirp rate of ~70kHz/μs.

Key words: Electrostatic, FEL, Laser, Power Extraction, Long Pulse

1. INTRODUCTION

The Israeli Electrostatic Accelerator FEL is one of the few FEL oscillators besides the UCSB FEL [1] that can operate quasi-CW. It is most fitting for studying the physics of single mode laser oscillation and developing narrow line-width high power application in the mm-wave/THz regime, and it has displayed a record narrow line-width for FELs [2]. The laser was upgraded and reassembled, and is now providing high power long lasing pulses (up to 50μs) to a user room. A variable cavity radiation out-coupler was installed as the front mirror of the laser cavity. It is useful for realizing the concept of radiation power extraction maximization of an FEL oscillator [3]. A voltage ramp generator that was installed in the accelerator terminal made it possible to stabilize the voltage of the resonator/wiggler assembly during the laser pulse, and in this way to attain longer laser pulse operation. It also makes it possible to attain narrow laser line-width and controlled frequency chirp [4] that may be used for spectroscopic applications.

2. METHODS AND RESULTS

The significant performance upgrade was attained by accomplishment of the following major tasks:
1. Reassembly of the wiggler for improving transport, using a new method for magnets pairing optimization [5]
2. Development of a 3-grid variable transmission mirror for controlled radiation out-coupling.
3. Development of a remotely controlled voltage ramp generator for stabilizing the resonator/wiggler potential during the laser pulse and for controlling laser frequency chirp. The ramp generator is connected between the resonator/wiggler assembly and the high voltage terminal (that are isolated from each other). The ramp voltage generator can produce a voltage ramp of up to 25kV during the electron beam pulse duration.

Lasing results

Every laser oscillator has an operating point of maximum output emission power as a function of its resonator out-coupling coefficient [6]. In our FEL it is possible to study the non-linear process of FEL power extraction efficiency [3] taking advantage of the new variable out-coupler device. Fig. 1 displays measurements of radiation power output as a function of the output coupler reflectivity. The graph represents the maximum power measurements over repetitive pulses.

Considering the single pass attenuation in the transmission line from the resonator exit to the user room (~60% power loss) the maximum stable output power measured at the exit of the resonator was just over 21kW. This corresponds to a power extraction efficiency of approximately 1.4% out of the 1.4MeV, 1.1A electron beam.

Applying a positive voltage ramp between the resonator/wiggler assembly and the terminal it was possible to keep the wiggler-potential nearly stable during the electron beam pulse while the terminal voltage drops due to beam current leakage in the terminal. A stable lasing pulse of up to 50μs was so far attained (Fig. 2). The laser pulse radiation spectrum was measured using heterodyne detection. Fourier transform of the IF signal indicated single mode operation at a stable frequency of 101.850GHz during the pulse duration.

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Figure 1. Radiation power measured in the user room vs. reflectivity of the cavity output-coupler.

Figure 2. Radiation power signal from the FEL operating at beam energy 1.4MeV and current 1.12A. Voltage ramping of up to 25kV was applied to keep the wiggler voltage constant during the pulse.
Observation of Plasma Evolution in the Interference Switch of Microwave Pulse Compressor

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SUMMARY

The evolution of light emission from the plasma which is formed to release microwave energy from the resonant S-band pulse compressor was studied using fast-framing optical imaging with 4QuikE camera. The compressor comprised a cavity filled with pressurized air and an H-plane waveguide tee as an interference switch; it generated output pulses of up to 7.4 MW peak power and ~8 ns duration in 2.766 GHz frequency. The plasma generation in the switch was initiated by a Surelite laser. From the obtained typical size of the plasma and its velocity of expansion along the electric field, the density of the plasma was estimated. Its influence on the power of microwave output pulses was determined numerically: results are in good agreement with the experiments.

Key words: microwave pulse compression, gas plasma discharge.

1. INTRODUCTION

The method of resonant pulse compression is a promising approach to high-power microwave generation [1]. In a resonant compressor, the RF energy generated by a primary source is stored in a high-Q cavity providing high power gain, and the fast extraction of the stored energy is achieved using an interference switch. Usually, a switch represents an H-plane waveguide tee with a shorted side arm; it is closed during energy storage and rapidly opened by initiating a plasma discharge in a gas filling the system.

In spite of significant progress in the development of high-power compressors with plasma switching [2], so far, there is no clear understanding of the processes which govern plasma formation under a strong RF electric field in pressurized gases, and which ultimately determine compressor output power. An ideal switch would provide a rectangular waveform of an output signal with the power corresponding to that of a traveling wave component in the cavity; this is, however, not the case in existing compressors. In high-power compressors operating at high background gas pressures, the plasma is characterized by a high rate of electron-neutral collisions. There is much research related to microwave gas breakdown in these conditions; however, they did not consider the process of plasma formation in connection with the microwave energy release from the cavity.

In this work, the dynamics of plasma formation in an interference switch is studied with the use of a fast-framing 4QuikE camera (frame duration of 2 ns). This allows one to observe the evolution of the light emission from the plasma during the formation of the compressor output pulse. The dimensions of the plasma and velocity of its expansion along the electric field were used to estimate the plasma density and simulate the compressor microwave output.

2. EXPERIMENTAL RESULTS

Experiments were performed using a common configuration of the compressor with the standard WR284-waveguide-based parts. For the compressor cavity, a 40 dB directional coupler was employed, so that the power of the traveling wave component of the cavity field could be easily measured. The H-tee side arm was shorted by a deformable copper membrane. The membrane deformation was adjusted for the coincidence of the compressor resonant frequency (f = 2.766 GHz) with the closing frequency of the tee. The compressor was charged by the magnetron generating input pulses of 200 to 450 kW power at up to 2.4 μs duration. For the energy release, the Surelite laser (532 nm wavelength, ~50 mJ energy per ~7-ns optical pulse) was used to initiate the plasma generation at the quarter guide wavelength (~40 mm) from the membrane. Both the side-view and top-view imaging of the discharge were performed. The optical setup for the case of side-view imaging is shown in Figure 1. For fine focusing and calibration of the image dimensions, an optical target with a graduated pattern was placed at the observation plane; the obtained resolution is ~7.4 μm/pixel.

![Figure 1. Setup for fast-framing imaging of the laser-triggered microwave plasma discharge in the compressor.](image)

Experiments were carried out at different pressures of the dry air filling the system and different input power. The power that the compressor cavity withstands without a self-breakdown increased with increasing pressure; the output power of the compressor increased accordingly. The maximum output power of ~7.4 MW was obtained at the pressure of 3·10³ Pa when the input power was ~420 kW and the power of the cavity field traveling wave component was ~21 MW. The instantaneous output power and cavity power calculated from the oscilloscope traces of RF voltages are shown in Figure 2 in the nanosecond time scale. One can see that the FWHM of the output pulse is ~8 ns and the maximal
The calculated transmission efficiency of power extraction is ~35%. At lower pressures, power extraction is less efficient.

Figure 2. Instantaneous power of the output (dark) and cavity signal at the maximal peak output power recorded.

For each framing image of light emission, the corresponding camera synchro-pulse and the compressor microwave output pulse were recorded. The time shift $\Delta_{\text{pw}}$ of the beginning of the 2-ns frame with respect to the start of the microwave extraction was determined for each recorded image. The side-view images obtained at $2 \times 10^3$ Pa pressure are shown in Figure 3; the input power in this case was ~310 kW. One can see the dynamics of the plasma formation. At $\Delta_{\text{pw}} = -5.1$ ns, i.e., before the beginning of the microwave extraction, the plasma has small dimensions (0.5 mm length and 0.1 mm width). With the increase in $\Delta_{\text{pw}}$, one obtains the increase in dimensions of the plasma, mainly along the direction of the RF electric field, and at the shift $\Delta_{\text{pw}} = 8.5$ ns corresponding to the peak in the output power, the plasma occupies almost all the diameter of the output window, 5.7 mm. One can also see a sharp light emission boundary from the cavity waveguide side and diffuse boundary from the membrane side.

The images of Figure 3 and obtained top-view images allow one to conclude that the discharge channel represents a filament-like structure. Let us note here that in the most of top-view images only one filament (point) was seen, but in a smaller number of discharges, two, three, and even four filaments were obtained as well. The diameter of the point-like filaments was in the range of 0.2-0.6 mm.

Using the obtained results of optical imaging of the plasma formation, one can estimate roughly the main plasma parameters. From the evolution of the image dimensions, the average drift velocity of the discharge channel propagation along the electric field can be estimated as $V_d \approx 5 \times 10^5$ m/s. This velocity is connected with the effective electron-neutral collision frequency $\nu$ as $V_d = eE/n\nu$ [3] where $E$ is the amplitude of the RF electric field in the discharge location. For $E \approx 7 \times 10^6$ V/m (this corresponds to the cavity signal measured), the estimate for the effective collision frequency is $\nu \approx 2.5 \times 10^{12}$ s$^{-1}$. Now, assuming that the width of the bright part of the plasma image shows the effective thickness of the skin layer $\delta$ and using simple formulas connecting the conductivity $\sigma$ of strongly collisional plasma with the skin depth, on one hand, and the electron density $n_e$, on the other hand, $\sigma = e^2/4\pi\varepsilon_0\varepsilon\delta = e^2n_e/m\nu$, one can estimate the plasma density. Taking $\delta = 2 \times 10^{-2}$ cm, one obtains $n_e \approx 2 \times 10^{17}$ cm$^{-3}$.

With these data, the efficiency of power extraction from the compressor was determined numerically using CST simulation. Namely, the system was represented as an H-plane tee with the shorted side-arm, which is closed at the operating frequency $f = 2.766$ GHz. The calculated transmission coefficient $S_{11}$ between collinear arms was then $\approx 47$ dB. Then, the filament of a conductive gas crossing the side-arm waveguide normally to its wide walls, in the center, at the quarter guide wavelength from the shorting plane was introduced. The conductivity was taken to correspond to the estimated $n_e$, the constant of $2.3 \times 10^6$ $\Omega$ m along 6 mm in the center and exponentially decreasing toward the walls. With such a conductive gas filament, in the operating frequency, the calculation gives $S_{11} = -10$ dB, which is in satisfactory agreement with the efficiency of power extraction obtained in the experiments at $2 \times 10^3$ Pa pressure.

Figure 3. Side-view images recorded at $2 \times 10^3$ Pa pressure with 4QuikE camera at different time shifts $\Delta_{\text{pw}}$. The exposure time is 2 ns; the camera gain is close to maximal.

3. CONCLUSIONS

For the first time, nanosecond dynamics of plasma formation in an interference switch of a high-power microwave pulse compressor has been experimentally observed. The plasma has the form of filaments expanding along the RF electric field. Using the data of fast-frame imaging, the parameters of the plasma – density and collision frequency – have been estimated. Numerical calculations of the efficiency of power extraction from the compressor cavity with such plasma filament well agree with the compressor output power and the power of the traveling wave in the cavity before switching measured in the experiments.

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Design and Status of Tera-Hertz FEL in Ariel University

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SUMMARY

We describe the Free Electron Laser being constructed in Ariel University. The FEL is designed based on a 5.5-6.5 MeV photo cathode gun currently being built in UCLA. The gun is designed to produce single pulses of 300 pico coulomb with an energy chirp that will compress them down to less than 100 femto seconds at the entrance to the wiggler. The wiggler period will be 2cm. This sets the radiation frequency at 2.5 - 5.5 THz. The short duration of the electron pulse sets the radiation emission process at the superradiance regime where the energy is proportional to the square of the charge rather than the charge. Our simulations show an output of at least 150KW instantaneous power with a pulse width of about 7 pico seconds.

The gun will also produce a pre-bunched beam train of 10-12 pico seconds width with a bunching frequency of 1.5 Tera Hertz. With chirping, this pulse can be compressed to match the frequency of the FEL radiation. This will produce a higher instantaneous pulse of longer duration than the single pulse operation mode.

We will discuss the possibility of using that same accelerator to generate shorter wavelength coherent radiation. One of the considered schemes is compression of the pre-bunched beam to a bunching period of 5 microns and using a 95 GHz gyrotron instead of a wiggler to generate 5 micron (infra red) high intensity radiation. Because of the bunching, operation in the high gain regime is expected.

We will also discuss and demonstrate the current status of the project.

Key words: Free Electron Laser, FEL, wiggler, tera hertz

1. INTRODUCTION

The Tera Hertz Free Electron Laser is being built based on a compact (60cm) RF LINAC. The RF LINAC is being built in UCLA and is based on an innovative concept of hybrid photo-cathode gun [1]. It short length is possible due to the fact that the photo cathode is embedded in the RF cavity of the LINAC.

The electrons are emitted directly in the acceleration field and bunched by subsequent bunching cavities in an integral structure.

Fig. 1 describes the FEL in general details: The laser beam is injected into the gun from the front at a slight angle to the electron beam. The gun creates a chirped pulse which compresses as it drifts, until it reaches a width of 100 femto seconds at the entrance to the wiggler. The interaction with the electrons occurs inside an over-modes wave guide. At the end of the wiggler section the electron beam is separated from the radiation, and the radiation is transmitted to the users.

2. MODES OF OPERATION

The FEL is designed to work in two modes: a single pulse mode in which super-radiance is observed due to the width of the mode being much less than one period of the radiation [2,3]. Fig. 2 shows the profile of the electric field at the exit of the wiggler. As expected, the field is concentrated around the electron beam. The field looks almost like a TEM$_{00}$ Gaussian. Hence it will propagate as a gaussian beam who's waste is at the wave guide exit.

The second mode of operation is periodic bunching superradiance from a short train of pulses [4]. The method of creating it is by modulating the laser hitting the cathode. Femto seconds laser are designed with a frequency chirp. The frequency increases with time. By splitting the laser beam, delaying one of the beams, and then merging them, one gets a light beam with beats in its intensity. The interfering beams create at the cathode light intensity modulation and corresponding current emission modulation at the beat frequency. A typical beat frequency is 1.5 THz. By introducing the correct chirp into the beam, it is possible to assure that the beam arrives at the interaction section with the correct modulation frequency.

3. DETECTION METHODS

Detecting a short, high power THz signal is not a trivial issue. We will use two methods for the detection;

The first method is to use a fast electro-optic crystal. The crystal is set within two polarizers. When a laser is shined on the crystal, and the polarizers are crossed, no light passes. Once a THz field is applied to the crystal it rotates the polarization and light passes through. That light is modulated by the Tera Hertz signal. An electro optic prism is then used to transform the light from the time domain to a longitudinal domain. With this method we will be able to get a time resolution of less than 100 femto seconds.

The second method is to create a narrow bandwidth antenna with a Josephson junction (super-conducting) in its center. The antenna resonant frequency is modified by a dc voltage applied to the junction. Thus, it is possible to scan frequencies and receive amplitude and phase of each frequency. The signal is then reconstructed with a Fourier Transform.
REFERENCES


Figure 1: A general view of the Tera-Hz FEL

Figure 2: Electric field profile at the wave guide exit
Plasmoids Excited by Localized Microwaves

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SUMMARY

This paper reviews several types of plasmoids excited by localized microwaves from various materials. These plasmoids, in forms of fire-columns and fireballs, are ejected from hotspots induced by localized microwaves in a mechanism of thermal-runaway instability. They are characterized as low-temperature dusty plasmas originated from the molten substrates. Assuming partial local thermal equilibrium, a numerical simulation incorporated with the experimental measurements enables us to find the effective dielectric permittivity from the microwave reflections hence to estimate the electron density. Related studies and potential applications of the microwave-generated plasmoids are discussed (e.g. for material identification, powder solidification, food cooking, and combustion).

Key words: plasmoid; localized microwaves; thermal runaway; hotspot, fireball.

1. INTRODUCTION

Localized microwaves were demonstrated as a means to eject plasmoids directly from various substrates in air atmosphere [1]. The localized microwave heating (LMH) involves a thermal runaway instability which generates a hotspot. The plasma ejected from the hotspot in a form of a fire-column may further evolve to a buoyant plasmoid [2] (similarly to ball-lightning in nature). This paper reviews several experimental studies of microwave-excited plasmoids and discusses their potential applications.

2. METHOD AND RESULTS

A typical experimental setup shown in Fig. 1a includes rectangular cavity fed by 1 kW, 2.45 GHz microwave energy. A movable electrode guides the microwaves locally to the substrate [3]. Cutoff vanes enable diagnostics, such as optical spectroscopy, small-angle X-ray scattering (SAXS) and visual observations. Incident and reflected waves are recorded for further analyses. The upper collector is used for ex-situ analyses of the plasma products.

Various substrates, such as silicon, glass, copper, titanium, and copper-based powder, were used in order to eject plasma. A fire-column ejected directly from the substrate may feed an adjacent buoyant fireball as shown in Fig. 1b.

Figure 1. The experimental setup (a) used to excite fire-columns and fireballs (b) [1, 2].

The microwave reflection measurements (Fig. 2) show the impedance variations during the various stages of the process, from a cold substrate to a fire-column ejection and further to a buoyant fireball as presented in Fig. 2b.

Figure 2. Microwave reflections during the excitation in scalar (a) and Smit-chart presentations (b) [2].

The substrate material is evidenced in the plasma by the specific emission of the silicon and copper elements in the optical spectrum shown in Figs. 3a and b, respectively [4]. Hydroxyl and nitric oxide radicals may also be generated in the plasmoid, as shown in Fig. 3a. Their line shape reveals the excitation temperature of the plasma in the range of ~0.5 eV. This result coincides with Boltzmann plot analyses of the substrate’s lines, assuming partial local thermal equilibrium (pLTE). The continuum radiation in Fig. 3b represents the blackbody radiation from the substrate.

Figure 3. Optical spectral emissions of plasmoids ejected from silicon (a) and from copper powder (b).

Nano-particles and droplets made of the substrate materials were found in all the plasmoids examined in this study. A mean radius of \( r_d \sim 60 \text{nm} \) with a number density of \( n_d \sim 10^5 \text{ m}^{-3} \) was revealed in-situ by SAXS analyses of silica particles [2]. This finding coincides with ex-situ SEM observations of the macro-particles accumulated upon the substrate emitter and the collector as shown in Fig. 4. EDS analysis validates the silicon content of the particles. Dusty plasma features were also observed in various other substrate materials, such as copper and titanium.

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Figure 4. Dust originated inside plasmoid. (a) Silicon sphere and (b) aggregated particles on the collector [2].

The charging process of the dust particles by the electrons in the plasma contributes to the plasmoid’s conductivity and effective dielectric permittivity [5]. The latter is reduced in our case to [2]:

$$\varepsilon_r \approx 1 + \frac{\omega_p^2}{\omega^2 + i \omega \tau} \left[ -1 + \frac{v}{k \ell_0} \left( \frac{v}{\omega} - \frac{1}{k \ell_0} \right) \right] g$$

(1)

where $\ell_0 = (\pi r_n)^{1/3}$ is the dust-electron mean free path, $\omega_p = \sqrt{4 \pi n_e m_e e^2 / \varepsilon_0}$ is the plasma frequency, $\varepsilon_r$ is the vacuum permittivity, $v = V_e \sigma N_e$ is the collision frequency, and $\omega$ and $k$ are the microwave angular frequency and wavelength respectively, and $g$ is a spatial profile. The thermal velocity is $v_e = \sqrt{kT_e / m_e}$, where $T_e$ and $n_e$ are the electron temperature and density, and $e$ and $m_e$ are the electron charge and mass respectively.

A 3D model of the plasmoid in the cavity uses the dielectric permittivity in Eq. 1 in order to relate the measured microwave reflections to the electron density and to the actual position of the plasmoid, as observed experimentally. An electron density estimate of $n_e \sim 10^{18}$ m$^{-3}$ is compatible with the ~0.3 reflection coefficient observed in Fig. 2b. The phase change of the reflection is attributed to the position and intensity variation of the plasmoid, in a negative feedback manner (the more energy absorbed, the electron density increases and the dielectric loss increases according to Eq. 1). The charging process of the dust particles by the electrons in the plasma contributes to the plasmoid’s conductivity and effective dielectric permittivity [5]. The latter is reduced in our case to [2]:

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3. RELATED STUDIES

Our other studies related to the microwave-excited plasmoids include:

Material identification
The light emitted from the plasma is used to identify the solid substrate. This microwave-induced breakdown spectroscopy (MIBS) technique is proposed as a low-cost substitute to the laser based technology (LIBS) [4].

Powder solidification
In this study, we apply LMH and localized plasma in order to solidify small amounts of metal powder in a repetitive manner for 3D printing and additive manufacturing [6].Currents induced in the metal powder and electric discharge between the metallic particles may enhance the microwave heating process up to the melting temperature.

Food cooking
In this technique [7] microwave-excited fireballs are used to cook food effectively (see Jaffe et al in these Proceedings).

Thermite ignition
Chemical reactions, hard to ignite otherwise, can be initiated easily inside the fireball, and as a result contribute to the total heat emitted. A thermite mixture composed of aluminium and iron oxide is ignited by this plasmoid [8]. Once ignited, this fuel can also react underwater due to its zero oxygen balance.

Direct conversion of solids to nano-powders
The dust generated directly from the substrate by the plasma consists of nano particles (e.g. Fig. 4). These are deposited as a nano-powder on the collector. In particular, nano-powders produced directly from titanium [9] are of interest for photovoltaic and solar cell applications.

4. CONCLUSIONS

Plasma can be excited by localized microwaves in atmospheric pressure in forms of fire-columns and fireballs. This dusty plasma, consisting of the substrate’s elements, exhibit relatively low temperatures and electron densities. The dust produced is composed of macro-particles that contribute to the effective dielectric permittivity of the plasma. This form of plasma opens new possibilities for microwave based processes as presented above.

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A 6-kV, 130-ps Rise-Time Pulsed-Power Circuit

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SUMMARY

Drift-step-recovery diodes (DSRDs) are used ~1-ns high-voltage opening switches by pumping them slowly in the forward direction and then pulsing them quickly in the reverse direction. The fast opening occurs when the reverse current discharges the carriers that were stored in the DSRD junction during the forward cycle. Typical forward and reverse timescales are tens and a few nanoseconds, respectively. While a state-of-the-art MOSFET may pulse the DSRD at a rise-rate of about 20 A/ns, the DSRD itself can be used to pulse another DSRD at a rise-rate of about 60 A/ns. We report enhanced performance by this method resulting in a high-voltage nanosecond pulse. This pulse was then further sharpened by driving a fast avalanche diode. A 6-kV, 130-ps rise-time, with a rise rate exceeding 40 kV/ns circuit is presented.

Key words: drift-step recovery diode, power semiconductor diode switches, pulse generation.

1. INTRODUCTION

Nanosecond and sub-nanosecond pulses having high peak power combined with high-speed bursts can be used in applications such as through-wall imaging, underground detection, biological research, and in high energy density physics experiments. While technologies such as spark-gaps and pulse compression by nonlinear transmission lines (NLTs) can reach tens to hundreds of kilo-volts in the sub-nanosecond regime, the pulse repetition frequency (PRF) of these technologies is limited to the sub-kilohertz range. A pulse compression technique featuring a compact all-solid-state circuit with air-coils is presented, where a PRF of 100-kHz in burst mode is demonstrated.

Drift-step-recovery diodes (DSRDs) are used as ~1-ns high-voltage opening switches by pumping them slowly in the forward (anode to cathode) direction, I_MAX, and pulsing them quickly with current in the reverse direction, I_R, [1]. Fig. 1 shows an illustration of the DSRD operation, where the DSRD is pumped and pulse via an inductor, L, and is connected in parallel to a load, R_L. The fast opening occurs when the reverse current discharges the carriers that were stored in the DSRD junction during the forward cycle, i.e.,

\[ \int_{t_0}^{t_1} I_F \, dt = \int_{t_1}^{t_2} I_R \, dt \quad . \]

The load peak voltage, V_L, is correlated to the diode turn-off time between t_2 and t_3 and to the reverse peak current, I_MAX, by

\[ \max(V_L) \sim L \frac{I_{\max}}{t_3 - t_2} \sim \frac{I_{\max}}{R_L} \quad . \]

For a given charge at the DSRD junction, and for its given turn-off time, it follows from Eqs. (1) and (2), that in order to increase the load peak voltage it is desirable to increase I_MAX by increasing the rate of the diode reverse pulsing, dI_R/dt.

While a state-of-the-art MOSFET may pulse the DSRD at a rise-rate of about 20 A/ns, the DSRD itself can be used to pulse another DSRD at a rise-rate of about 60 A/ns, as shown in Table 1. Here, we describe this method and report an enhanced performance resulting in a high-voltage nanosecond pulse.

![Figure 1. Illustration of the DSRD operation.](image)

Table 1. Fast opening switches.

<table>
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</tbody>
</table>

Silicon avalanche shaper (SAS) diodes are fast-closing switches capable of producing high-voltage pulses with a rise time of around 100 ps [1]. The fast avalanche effect occurs when a high voltage ramp of the order of a few kilovolts per nanosecond is applied to the diode in the reverse direction. Thus, DSRDs are good candidates for driving SAS diodes. A pulsed-power circuit having multi-compression stages comprising of MOSFETs, DSRDs, and a fast avalanche diode is described below [2].
2. EXPERIMENTAL SETUP

The experimental circuit is presented in Fig. 2. It consists of four compression stages. The first and second stages consist of two power MOSFETs (Qa = Qb = DE475-102N21A by IXYS RF) and two DSRDs (DSRD1 = DSRD2 rated to 3 kV, 120 A), connected in parallel. The third compression stage consists of a 6 kV, 120 A DSRD (DSRD3). The DSRDs were assembled at Soreq NRC using stacks of recovery diodes. The fourth stage consists of a shaping head (SH) constructed at Soreq NRC, using a fast avalanche diode and a peaking capacitor (C1 = 1 pF). A function generator was connected to the circuit input and an input trigger of duration ΔT was applied. The load was Rl = 50 Ω.

The circuit operation is described in [2]. The parameters of the air coils were L1a = L1b = 120 nH, L2a = L2b = 100 nH, L3a = L3b = 90 nH, and L4 = 40 nH. The parameters of the capacitors were C1a = C1b = 4 nF, C2a = C2b = C3 = 100 nF, and C4 = 200 pF.

Figure 2. The 6 kV, 130 ps rise-time pulsed-power circuit.

3. RESULTS

The circuit shown in Fig. 2 was operated with an input trigger duration of ΔT = 120 ns. The supply and bias voltages were VCC = 300 V, V1a = 106 V, V1b = 110 V, and V2 = 86 V. Fig. 3 shows the circuit signals throughout their compression stages. The output of the second compression stage, where DSRD2 and the fourth compression stage were disconnected and the load was connected to point “C” via a 0.73 μF capacitor, is shown in Fig. 3(a). Following a charging of the coils between -140 ns and -20 ns, the signal peaked to 3.0 kV with a rise-time (10%-90%) of 2.06 ns and a full-width at half maximum (FWHM) points of 3.97 ns.

The output of the third compression stage, where only the fourth compression stage was disconnected and the load was connected to point “C” via the 0.73 μF capacitor, is shown in Fig. 3(b). As shown, the presence of DSRD2 contributed to further peaking of the signal up to 5.0 kV with a rise-time of 1.96 ns and a FWHM of 2.27 ns.

The output of the fourth compression stage is shown in Fig. 3(c). The PRF was 1 kHz. Following some 1 ns of slow ramp to ~1 kV, the signal then peaked to 6.17 kV. The rise-time in this case was calculated between 20% and 90% of the signal and was 130 ps. The maximum rise rate of the voltage was 41.4 kV/μs. The peak signal at a repetition frequency of 3 kHz (continuous operation) was 5.81 kV. The circuit was then operated in burst mode at a repetition frequency of 100 kHz. Fig. 3(d) shows a trace of the output in this mode. The comb of pulses was 5.8 kV with a rise-time (20%-90%) of 140 ps and a maximum rise rate of 37.6 kV/ns.

Figure 3. The circuit signals throughout its compression stages.

3. CONCLUSIONS

The concept of cascaded compression by DSRDs, where a signal enhancement from 3 kV to 5 kV was demonstrated in Fig. 1. Furthermore, two DSRDs in the second compression stage were jointly timed to drive the third compression stage. Since the output of the third compression stage to a 50 Ω load was 5 kV with a rise-rate of about 2 ns, we estimate from Eq. (2), with the inclusion of some switching losses, that the DSRD in the third compression stage was pulsed by the second stage at a rise-rate of the order of 100 A/μs. This rise-rate and rise-time are almost an order of magnitude better than those that can be achieved by a state-of-the-art MOSFET, as shown in Table 1.

The use of an all-solid-state technology with air-coils allowed the demonstrated PRF of 100 kHz in burst mode. This repetition rate is some two orders of magnitude higher than those that were reported by other sub-nanosecond pulse sharpening technologies such as spark-gaps and NLTLs. A higher PRF of about 1 MHz is feasible by this technology.

The concepts presented here can be utilized to drive powerful DSRDs by using more units in parallel, together with additional DSRD compression stages. Thus, it may facilitate the driving of faster DSRDs and avalanche diodes made of advanced semiconductor materials such as GaAs and SiC.

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Laser Plasma Accelerators: Status and Applications

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SUMMARY

Compact accelerators based on laser plasma cavities, which support hundreds of GV/m electric field, deliver today electron beam with unique parameters. In 2004 quasi mono-energetic electron beams have been produced in the bubble regime by focusing intense laser beam in under-dense plasma targets. This efficient bubble regime of acceleration is now currently working in many laboratories over the world. In 2006 stable and quasi mono-energetic electron beams have been demonstrated at LOA using by colliding two laser pulses in under-dense plasma. This last approach is very promising for future applications because of the stability of the electron beams and the easy control of their parameters. The very high brightness and shortness (fs) make them very attractive for many applications. I will present the different regimes of acceleration and relevant applications that have been recently considered at LOA: For medicine to treat the cancer by radiotherapy, for fundamental studies in radiobiology (short-time-scale), for chemistry (radiolysis in the femtosecond range), for material science in automobile and aeronautic industries (for non-destructive dense matter inspection by gamma radiography), and finally for accelerator physics.

Key words: Laser, accelerators, plasmas, relativistic interaction.

1. INTRODUCTION

The discovery of the superconductivity in mercury cooled with liquid helium has opened a very active field of research. After decades of effort, researchers have been able to produce new superconductors working at “higher” temperatures. Even if there remain open fundamental questions, mastering superconductivity has allowed the discovery of tremendous applications for example in magnetic resonance imaging for medicine or in accelerators with the use of superconducting cavities. In parallel, since the first 1.26 MeV Hg ion beam experiments performed by Lawrence, accelerators have gained in efficiency and in performance. With a market of more than 3 Billion dollars per year, accelerators are used today in many fields such as cancer therapy, ion implantation, electron cutting and melting, food irradiation, and non-destructive inspection. The most energetic machines that deliver particle beams with energies greater than 1 GeV, represent only 1% of the total number of accelerators. They were developed for fundamental research, for example for producing intense X-ray beams using Free Electron Laser (FEL). Higher energy accelerators are crucial to answer important questions regarding the origins of the universe, of the dark energy, of the number of spatial dimension, etc. Recently the largest available accelerator, the Large Hadron Collider has revealed the properties of the Higgs boson. Since the electric field value is limited because of electrical breakdown in metallic cavities, accelerators become more and more gigantesque. Since the accelerating field in superconducting radio-frequency cavities is limited to about 100 MV/m, the length of accelerators has to increase in order to achieve higher energy gain (figure 1). To overcome this size issue the use of an ionized medium (a plasma) that can sustain extreme electric fields appears naturally.

2. METHOD AND RESULTS

The pioneering theoretical work performed in 1979 by Tajima and Dawson [1] showed how an intense laser pulse can excite a wake of plasma oscillations through the laser ponderomotive force that pushes out electrons from high to low intensities regions (figure 1). The charge separation associated to these plasma density wakes produce a strong longitudinal electric field. In their proposed scheme, relativistic electrons were injected externally and were accelerated through the high electric field sustained by relativistic plasma waves driven by lasers. With more intense laser pulses, non-linear plasma waves have allowed to drive accelerating gradient that can easily overcome hundreds of GV/m [4]. Since then, plasmas have been recognized as a promising accelerating media. Thanks to the continuing efforts of the community, major breakthroughs have shown the possibility to produce stable and high quality electron beams with controllable parameters. Controlled injection is mandatory for producing high quality electron beams. It is particularly challenging, in laser plasma accelerators, because the length of the injected bunch has to be a fraction of the plasma wavelength, with typical values in the [10–100 microns] range. In this case, electrons witness the same accelerating field, leading to the acceleration of a monoenergetic and high quality bunch. Electrons can be injected if they are located at the appropriate phase of the wake and/or if they have sufficient initial kinetic energy. Different schemes have been demonstrated and allow control of the phase of injected electrons. The scheme of principle of two of them, the bubble and the colliding laser pulses schemes, is shown on figure 2. In those two schemes, the focused laser energy is concentrated in a very small sphere, of radius shorter than the plasma wavelength. The ponderomotive force expels radially electrons from the plasma, forming a positively charged cavity behind the laser, and surrounded by a dense region of electrons. In the bubble case, self-injection occurs when electrons flow along the cavity boundary and collide at the bubble base. The transverse breaking occurs providing a well-localized region of injection in the cavity. Since the injection is well localized, at the back of the cavity, it gives similar initial properties in the phase space to injected electrons. The trapping stops automatically when the charge contained in the cavity compensates the ionic charge, leading to the generation of a quasi-mono-energetic electron beam that was experimentally demonstrated in 2004. Finally, the rotation in the phase-space also leads to a shortening of the spectral width of the electron beam. Electron beam quality is also improved because electrons that are trapped behind the laser do not interacted anymore with the electric field of the laser. The scheme of principle of the bubble/blowout regime is illustrated on figure 2.
In 2006, stable and tuneable quasi-mono-energetic electron beams were measured by using two laser beams in the colliding scheme with a counter propagating geometry. The use of two laser beams instead of one offers more flexibility and enables one to separate the injection from the acceleration process. The first laser beam the pump beam (the injection beam) is used to heat electrons during its collision with the pump beam and, after the collision has occurred, to drive the relativistic plasma that will accelerate the trapped electrons as shown on figure 2. This concept has been recently validated in an experiment, using two counter-propagating pulses where very high quality electron beams have been produced with a very good shot-to-shot stability. Importantly it has been shown that this approach allows a control of the electron beam energy which is done simply by changing the delay between the two laser pulses.

3. CONCLUSIONS

Extremely intense electric fields that result from the collective motion of electrons have been produced with intense laser beams. The control of motion of plasma electrons issue from this accelerating structure has allowed to generate a stable and tuneable electron beam that open perspectives for societal applications, in material science for example for high resolution gamma radiography, in medicine for cancer treatment, in chemistry, and in radiobiology. They appear also as a powerful tool for future and compact Free Electron Laser, Compton, Betatron, or Bremsstrahlung X rays sources.

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REFERENCES

Optical Emission Spectroscopy of Sputtering Process in the Plane Plasma Discharge

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SUMMARY
The results of spectroscopic investigation of plane plasma discharge and sputtering processes in the triode system are presented. The forced electric discharge with currents of 1-4 A at argon pressure of 1 mTorr was studied using the emission spectroscopy method. The spectra of plasma discharge were observed in the 200-1100 nm wavelength range. The silver target was used for sputtering. It was found that a part of sputtered particles is ionized in plasma. The emission spectrum of the ionized silver species was observed as a function of target voltage while sputtering. It was shown that the number of ionized silver species depends on the energy of argon ions.

Key words: Plane plasma discharge, Optical emission spectroscopy, Silver sputtering.

1. INTRODUCTION
Sputtering is one of the most useful methods for thin films deposition. It is widely used in the semiconductor, photovoltaic, and microelectronic industries [1-3]. A low-pressure plane plasma discharge is one of the novel techniques for thin films growth in recent years. Low pressure plane plasma discharge enables fine control on most of the sputtering parameters, as well as high growth rate. A wide range of materials may be sputtered using this novel method. Other advantages of this method are its high reproducibility and perfect stoichiometry of deposited films. The low-pressure plane plasma discharge may be realized in the triode sputtering system [4].

The main goal of the research presented below was to understand the relation between the plane plasma discharge parameters and ionized species presenting in plasma while sputtering. Also, it is of interest the presence of the ionized particles of sputtered material in the plasma. In the present research we investigated in-situ the dynamic changes of the plane plasma behaviour while sputtering the metal targets using spectroscopic measurements of the emissivity of species in plasma.

2. EXPERIMENTAL DETAILS
Experiments with low-pressure plane plasma discharge and sputtering of silver targets were done using a laboratory setup equipped with a standard two-stage vacuum system providing a residual vacuum of 2-3×10⁻⁵ Torr. The sputtering system consists of a thermo-emissive cathode made from the tungsten, an anode from tantalum placed opposite to the cathode, a water-cooled sputtering target-holder arranged in parallel with the cathode-anode axis, and a substrate-holder placed opposite to the target. Two external coaxial electromagnetic coils create a homogeneous magnetic field in the vacuum chamber. This field confines the plasma discharge between cathode and anode enabling decrease a working pressure while sputtering. A more comprehensive description of this sputtering system is given in our previous work [7].

The experimental setup, based on the triode sputtering system, is presented in figure 1.

Figure 1. Experimental setup.

The spectral characteristics of plasma and various species which going through plasma while sputtering were observed using OSM-400 spectrometer of "Newport". The optical signals were transferred from the vacuum chamber to the spectrometer using the fibre optic cable and the fibre optic vacuum feedthrough of "Accu-Glass", providing a homogeneous transmission in the spectral range of 200-1000 nm.

First, the emission spectrum of heated cathode in residual vacuum and at the argon pressure of approximately 1 mTorr was recorded. Then, we recorded spectra of the plane plasma discharge with varied plasma current and through the sputtering process of the silver target with varied voltage applied to the target.

2. RESULTS AND DISCUSSION
The spectra, recorded in our experiments, represent superimposition of spectra of different sources: heated tungsten cathode, plasma discharge, recombination and relaxation processes through sputtering of metal targets. It is interesting to note, that the increasing of argon pressure inside the vacuum chamber up to 1 mTorr does not affect the spectrum, recorded without sputtering process, since the...
thermal radiation of heated cathode cannot ionize the gas, filling the vacuum chamber.

Figure 2 represents experimental spectra of the plane plasma discharge at different voltages between cathode and anode at different discharge currents without sputtering.

![Figure 2](image)

**Figure 2.** Emissivity spectra of the plane plasma discharge in argon recorded at different plasma currents.

Increase of intensity of spectral peaks with increase of anode-cathode voltage, shown in figure 2, indicates increase of the amount of ionized argon atoms in the plasma. This effect can be used to control of sputtering process. As shown in figure 3, applying sputtering voltage to the silver target decreases the intensity of spectral peaks, thus indicating decrease of amount of the ionized argon species in plasma.

![Figure 3](image)

**Figure 3.** Dependence of ionized argon species on the applied voltage while sputtering.

Figure 4 represents (squares and black curve) experimental dependence of the intensity of spectral line at 328.1 nm wavelength on the voltage, applied to sputtering target. This spectral line indicates the appearance of ionized silver species in plasma.

It was found that a part of sputtered neutral atoms moving to the substrate is ionized. Quantity of ionized silver particles depends nonlinearly on the applied sputtering voltage and has a maximum at about 1600 V. In our opinion, this ionization is caused by secondary electrons, emitted from the sputtering target. The inset in figure 4 shows the coefficients of third-order polynomial (red curve) model, describing the dependence of the silver ionized species quantity on the sputtered voltage.

![Figure 4](image)

**Figure 4.** Dependence of the silver ionized species quantity on the sputtered voltage in the plane plasma sputtering at low pressure.

3. CONCLUSIONS

The results of in-situ spectroscopic studies of the sputtering process in plane plasma discharge has been presented. It was found that the amount of ionized argon species strongly depends on the voltage applied to the plasma. This quantity significantly decreases while sputtering due to transfer of their energy to the sputtering target and appropriate recombination processes. It was also found that the part of neutral silver atoms is ionized during sputtering. The proposed spectroscopic method can be effectively used to study processes occurring in plasma.

REFERENCES


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Fluence and Accelerating Gradient in Bragg Accelerator

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SUMMARY

We present the first steps of the design of the optimal parameters for the accelerator of a full Bragg X-Ray free electron laser. Aiming to a future source of coherent X-ray radiation, operating in strong Compton regime, we contemplate the system to be the seed for an advanced light-source or compact medical X-ray source. Here we focus on the design of the maximum gradient.

Key words: XFEL, Bragg, Compton, Light source, Fluence.

1. INTRODUCTION

X-ray sources based on Compton scattering of a laser from a relativistic counter-propagating electron beam have been recently drawn increasing interest due to several potential advantages over magnetostatic FEL’s, such as: compact size, low-cost operation, and reduced e-beam energy requirement. Any novel acceleration concept intended to exceed the performance of radio frequency (RF) based accelerators must demonstrate gradients of the order of 1 GV/m or higher, as well as a reasonable efficiency.

Recent work [1] demonstrated that x-ray radiation emitted by relativistic electrons scattered by a counter-propagating laser pulse guided by an adequate Bragg structure (weak Compton regime) surpasses by about 2 orders of magnitude the energy generated by a conventional free-space Gaussian-beam configuration, given the same e-beam and injected laser power in both configurations.

Based on this configuration, this work presents preliminary results of a design study for the accelerator of full Bragg configuration based X-FEL operating in the collective regime.

2. DESCRIPTION OF THE SYSTEM

The full system consists of 3 components (Figure 1.): an optical injector bunches the electrons to Accelerator Bragg structure which supports a TM_{01} mode. The co-propagating laser which accelerates the electrons is dumped at the end. Next, the electrons are transported to second Bragg waveguide that acts as an EM wiggler. This structure supports a TEM laser at vacuum core (TM mode at the Bragg layers) counter-propagating to the e-beam. This generates X-ray radiation (Inverse Compton scattering).

The Accelerator parameters to be examined are: Bragg structure, laser (TM mode) and optimal number of electrons in train of M micro-bunches. The EM wiggler parameters to be examined are: Bragg structure, laser (TEM-TM mode) and the XFEL process. In this work we discuss optimal optical accelerator parameters only.

A planar Bragg waveguide [2] consists of dielectric layers surrounding a sub-wavelength vacuum region which is symmetric relative to the central plane. The clearance is a vacuum region of width 2D_{in}, surrounding alternating periodic layers. For a single mode operation: D_{in}=0.25\lambda \rightarrow 0.55\lambda. The layers are made of two lossless dielectric materials. First layer has a relative dielectric coefficient \varepsilon_1. For an optical accelerator having a vacuum core, surrounding layers must have an effective dielectric coefficient, smaller than unity i.e. \varepsilon_{eff}<1 thus the need of a Bragg structure.

![Figure 1. Schematic of an all-Bragg system. On the left, the Bragg accelerator supports a co-propagating TM_{01} mode which accelerates the electron beam. The latter is injected into another Bragg structure which supports a TEM mode (inside the vacuum core) counter-propagating to the electrons that as a result generate x-ray radiation.](image)

There are many parameters that must be taken into consideration in a practical design. Three important parameters are gradient, efficiency and optimal accelerated charge (see additional abstract "Efficiency and Optimal charge in Bragg accelerator" in this proceedings).

3. ACCELERATING GRADIENT

Maximum electric field, sustained by the structure before breakdown, is limited by the fluence at the vacuum-first layer interface and the pulse duration.

$$E_{\text{max}} = \frac{2F}{\varepsilon_0 c \tau_p v_m} = G_0 \left[1 + \left(\frac{\phi_b}{c D_{in}}\right)^2\right]$$

(1)

where G_0 is the accelerating field gradient, v_m is the energy velocity in the system and \tau_p is the duration of the electromagnetic pulse. Dielectrics damage involves heating of conduction band electrons by the incident radiation and transfer of this energy to the lattice. Damage occurs via conventional heat deposition resulting in the melting and boiling of the dielectric material. Thus, we consider threshold fluence (energy/area) of the material which depends on the pulse duration (F). An empirical fluence threshold of fused silica is given [3] by

$$F = \begin{cases} 1.44 \times 10^2 \tau_p \text{[psec]} > 10 \\ 2.5 \times 10^2 \tau_p \text{[psec]} < 10 \\ 2 \times 10^3 \tau_p \text{[psec]} < 0.4 \\ \end{cases}$$

(2)
Since the laser pulse propagates at the group/energy velocity whereas the electrons virtually at the speed of light in vacuum, the former’s duration is

$$t_g = \frac{L_{laser}}{c} = \frac{L}{c} \left( \frac{1}{\beta_\gamma} - 1 \right) + \frac{L_{beam}}{c}$$  (3)

where \(L_{beam} = (M - 1) \lambda_\gamma \), \(M\) represents the number of micro-bunches in the train and \(\lambda_\gamma\) is the laser wavelength in vacuum. The geometric length of the structure is

$$L_{geo} = \gamma m e c^2 / e G_0 \quad \text{where} \quad \gamma = \sqrt{\beta_\gamma^2 - 1}$$

is the relativistic factor. As an example, for a laser wavelength of 1 micron and radiation wavelength of X-ray (0.1nm), we get \(\gamma = 50\). At this point no emittance requirement is considered in the calculation.

Due to the constraint imposed by the fluence and for the specified energy \((\gamma = 50)\), the maximum accelerating gradient depends on 2 parameters: the clearance of the structure \((D_{int})\) and the number of micro-bunches in the train \((M)\). Note the interdependence between the various parameters requires a self-consistent solution: the laser field depends on laser pulse duration, which in turn depends on the train’s total charge and the gradient itself.

![Figure 2. Gradient Vs. number of microbunches in the train. Red line for \(D_{int}=0.25\lambda_\gamma\) and green line for \(D_{int}=0.55\lambda_\gamma\) multiplied by a factor such that at \(M=1\) both curves coincide for \(G_0(D_{int}=0.25\lambda_\gamma)\). There is a critical value around \(M=1000\).](image)

A self-consistent solution is illustrated in Figures 2 and 3. For \(M<10^3\) microbunches, the gradient is virtually independent of \(M\) – see Figure 2. For larger values of \(M\) the gradient decreases for the same clearance. Figure 3 shows that it is advantageous to operate with the smallest possible vacuum tunnel – leading to maximum gradient of less than 0.5 [GV/m]. Further simulations show it is better to use lower dielectric coefficient for the first layer and in order to achieve a gradient of 1GV/m we need to replace the Silica, with a material whose typical fluence is higher by a factor of 3.5 – assuming the pulse dependence is the same.

**Figure 3. Gradient Vs. clearance of accelerator structure. Red line for single bunch and green line for \(M=10^4\). As the clearance wider, the gradient drops.**

### 4. CONCLUSIONS

1. Maximum accelerating gradient is evaluated self-consistently based on the constraints imposed by the pulse duration and the fluence. It depends on two parameters: the clearance of the structure \((D_{int})\) and the number of micro-bunches in the train \((M)\). As the vacuum clearance is widened, the gradient drops and there is a critical value around \(M=1000\).

2. For a train of microbunches, two constraints must be satisfied: laser pulse duration must be longer than the macro bunch length. The laser’s envelope must be tapered to compensate for the beam loading, ensuring uniform gradient acceleration of all micro-bunches.

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Cherenkov Wake Amplification by Waveguide Confined 
Active Medium

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SUMMARY

A relativistic electron bunch traveling along a waveguide filled with dielectric will produce an electromagnetic wake following the bunch, when the Cherenkov condition is satisfied. The wake is a superposition of infinite number of Bessel harmonics, all propagating with phase velocity equal to velocity of the bunch and having different frequencies defined by the waveguide geometry. If the dielectric is active, similar to a laser medium, the Bessel harmonics with frequencies close to the active resonance of the medium would be amplified resulting in a monochromatic wake many wavelengths behind the trigger. Another train of bunches may be accelerated by this amplified wake. The gradient is limited by breakdown and saturation of the medium. Linear analytic model for the wake enhancement is considered and some simulation results are presented.

Key words: Gaseous active medium, Stimulated radiation, Laser acceleration.

1. INTRODUCTION

In the category of structure-less acceleration schemes there are two main conceptual mechanisms which may be divided according to the initial origin of the energy: in one case, an intense laser pulse [1] is injected in filled plasma and the particles are accelerated by the trailing space-charge wake. Obviously, the initial energy required for acceleration is stored in the laser pulse. In the second paradigm, the laser pulse is replaced by an intense electron beam [2], [3] as the energy source the acceleration itself is again facilitated by the emerging space-charge wake. We are considering a third possibility - to store the energy within the medium and the particles may gain energy at the expense of the latter. The proof of principle experiment of the concept for a structure-less configuration was performed at Brookhaven National Laboratory accelerator Test Facility (BNL-ATF) in 2006 [4]. Its essence was to velocity modulate a 45MeV electron beam by a 0.5GW CO2 laser in a wiggl[5]. After 2.5m drift the velocity-modulated beam emerging from the first module becomes density-modulated and it is injected in a second module which consists of a 30cm long vessel filled with CO2 mixture identical with that of the CO2 laser at 0.25atm. This mixture could be excited by a (30-40keV) discharge circuit. Comparing the electrons’ spectrum with the discharge on and off, a significant fraction (more than 10%) of the electrons gained about 200keV corresponding to an accelerating gradient of less than 1MV/m.

In the paradigm considered here: (i) Rather than energy being transferred from the medium to the same bunch that stimulates the medium, the energy is transferred to the Cherenkov radiation which in turn may be used to accelerate a different train of electron bunches trailing many wavelengths behind. (ii) The active medium is confined in a cylindrical waveguide such that the multiple reflections facilitate significant enhancement of the wake. See schematic of the concept in Fig. 1.

2. ESSENCE OF THE MODEL

Magnetic vector potential associated with a charge ring of radius $R_c$ located at $z = z_s$ at $t = 0$ is

$$A(r, \tau_s) = \frac{Q_s v_s}{2\pi} \sum G_i (r, R_c) \frac{d\omega}{2} \frac{\exp(j\omega \tau_s)}{\omega^2} - p_i^2 - \omega^2 \sqrt{v^2 + \omega^2} / c^2$$

$$G_i (r, r') = \frac{J_0(p_i r / R_c)J_0(p_i r' / R_c)}{R_c^2 J_1^2(p_i) / 2}, \quad \tau_s = t - (z - z_s) / v$$

In the time domain the waves’ propagation depends on Cherenkov condition $\tau \cong \epsilon, -\beta^+ > 0$. When the condition is satisfied, the moving charge is followed by an electromagnetic wake, which is a superposition of infinite number of Bessel harmonics.

$$A_i = -\frac{Q_s v_s c^2 \omega_i}{2\pi} \sum G_i (r, R_c) \frac{1}{\pi \omega_i} \sin(\omega_i \tau_s) h(\tau_s),$$

where $\omega_i c = p_i c^2 / R_c |\tau|$ and $h(z)$ is the Heaviside step function.

For simplicity sake we describe the active medium by a single resonance as

$$\epsilon(\omega) = \epsilon_i + \epsilon_r / (\epsilon_r + 2j\omega\omega - \omega^2)$$

Figure 1. Schematic of the conceived concept. A trigger bunch generates a weak wake that is amplified by the medium which in turn accelerates a trailing bunch. Beam loading is exaggerated in the drawing.
Plasma frequency in equation (3) may be found from classic laser theory [6] as \( \omega_p^2 = -4c\alpha\Delta\omega \), where \( \alpha \) is the spatial growth rate for a resonance plane wave in the same medium.

We provide an analytic solution for the electric field of the wake in time domain based on the magnetic vector potential (1) with dielectric constant substituted by the function (3). It is shown that when the waveguide geometry is selected such that the frequency of one of the wake modes is close to the medium resonance frequency \( \omega_{c,s} = \omega_0 \), the growth rate for this mode of the wake is
\[
\Delta\omega_s = \left( \frac{\Delta\omega_0}{4} \right) \left( 1 - \sqrt{1 + 8c\alpha / \Delta\omega_0} \right)
\]

While the gain for a plain wave in the same medium is
\[
\exp(az)\hat{h}(z)
\]
the gain for the resonant mode of the wake may be approximated for two limit cases as
\[
\begin{align*}
&\left\{ \exp\left[ (t - z) / c\alpha / \varepsilon \right] \hat{h}(t - z / v) \quad \varepsilon \gg 4c\alpha / \Delta\omega_0 \\
&\exp\left[ (t - z) / c\alpha / \varepsilon \right] \hat{h}(t - z / v) \quad \varepsilon \ll 4c\alpha / \Delta\omega_0
\end{align*}
\]

The model is presented in more detail in our recent publication [7].

3. NUMERICAL SIMULATIONS

Numerical simulations are carried out for a single resonance of CO\(_2\) mixture (\( \lambda_0=10.6\mu m \)) at a pressure of order of 10atm, waveguide of ~50mm radius and a trigger bunch of a total charge of \( 10^5e \) at \( \gamma=600 \).

![Figure 2. Spectrum of \( E_z \) for first 1000 modes. The geometry is such that only one mode satisfies the resonance condition \( \omega_{c,s} = \omega_0 \). In the other case \( \omega_{c,s} < \omega_0 < \omega_{c,s+1} \).](image)

At a certain distance behind the triggering bunch the Cherenkov wake is dominated by single harmonic facilitating conditions for acceleration of appropriately placed trailing bunch. Fig. 2 shows the spectrum of \( E_z \) in the vicinity of resonance when a total of 1000 modes are considered. Its peak near resonance \( \omega_{c,s} \approx \omega_0 \) is evident regardless whether the geometry is properly selected such that
\[
p_s = \omega_0 R_s \sqrt{v_t - \beta^2} / c
\]
is exactly satisfied or only approximately satisfied such that
\[
cp_{so} / R_s \sqrt{v_t - \beta^2} \leq \omega_0 \leq cp_{so} / R_s \sqrt{v_t - \beta^2}
\]. Fig. 3 shows the growth of the wake behind the trigger for both cases.

![Figure 3. Amplitude of \( E_p \) behind the trigger bunch (time-domain) employing 1000 Bessel harmonics in case of resonance \( \omega_{c,s} = \omega_0 \) (blue-squares) and off resonance (red-circle). The intensity in the latter case is lower by several orders of magnitude and there is clear indication of interference.](image)

4. CONCLUSIONS

A linear analytic model for Cherenkov wake enhancement in a cylindrical waveguide filled with CO\(_2\) laser mixture at 10atm is provided. Modes of the wake close to the resonance of the active medium at 10.6\( \mu m \) are amplified by the latter. A trailing train of electron microbunches located behind the trigger in phase with the enhanced wake will be accelerated by the latter.

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Investigation of Converging Strong Shock Wave Generated by Underwater Electrical Explosion of Cylindrical and Spherical Wire Arrays

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SUMMARY

Recent results of experiments on underwater wire array explosions, by various timescale generators, together with one-dimensional hydrodynamic simulation results, are presented. Electrical and optical diagnostics were used to obtain energy deposition to the wire array and time-of-flight of the converging strong shock wave, respectively. Using this data one-dimensional hydrodynamic simulations were done to calculate water parameters at the vicinity of the implosion. These extreme parameters characterized by pressure up to $2 \times 10^{12} \text{ Pa}$, temperature up to $8 \text{ eV}$, and water compression up to 7, in case of spherical wire array explosion. In addition it was shown that energy deposition to the water flow strongly depends on the timescale, moreover one may achieve larger water parameters at the vicinity of the implosion by increase the timescale of the explosion (timescale of the generator), even with decreasing of the stored energy.

Key words: Shock Wave, Plasma, Electrical Explosion

The subject of Warm Dense Plasma and High Energy Density physics is important for researchers among many fields like: physics of giant planets [1], equation of states (EOS) [2], and the conductivity of matter at extreme conditions [3]. The subject of warm dense matter (WDM) attracts continuous attention due to the interesting physical phenomena involved and important technical applications. Several approaches that require stored energy in the range of $10^7$-$10^8 \text{ J}$, such as multi-stage light gas guns, Z-pinch, powerful lasers, and intense heavy ion beams, are used to generate this state of matter, characterizing by a pressure $\geq 10^{11} \text{ Pa}$. Recent research showed that underwater electrical explosion of a wire array can be used as an alternative method to generate WDM with $\leq 2 \times 10^{10} \text{ Pa}$, using generators with only several kJ stored energy. This method is based on the implosion of the converging strong shock wave (SSW) generated by the underwater electrical explosion of either cylindrical or spherical wire arrays. Assuming uniformity of the converging SSW and based on 1D-HD simulations, coupled with the EOS of water, the experimentally measured time-of-flight of the SSW, and the energy deposited into the water flow, in the case of cylindrical wire arrays explosions [4-7] the water in the vicinity of the implosion axis ($r=2.5 \mu m$) were estimated as $540 \text{ GPa}$, $3 \text{ eV}$, and $4.2 \text{ g/cm}^2$, respectively.

The recent results of experiments on underwater electrical explosions of spherical wire array were presented a significant increase in the water parameters in the vicinity of implosion origin. In this research sub-microsecond ($\sim 300 \text{ ns}$, $\leq 500 \text{ kA}$, $\sim 6 \text{ kJ}$) and microsecond timescales generators ($\sim 1 \mu s$, $\leq 300 \text{ kA}$, $4 \text{ kJ}$) were used for explosion of spherical Cu-wire arrays which was accompanied by generation of converging spherical SSW. Convergence of these SSWs results in extreme state of water in the vicinity of implosion origin. In experiments (see Fig. 1 for typical experimental setup), the time of flight of the SSW, the discharge current and voltage (see Fig. 2) were measured and were used in 1D hydrodynamic simulation, coupled with EOS database, for calculating water parameters at the implosion vicinity of the symmetry with additional demand that the energy delivered to the water flow does not exceed $\sim 13\%$ of the total energy delivered to the exploded wire array. The time-of-flight of the generated SSW was obtained three independent methods, namely: by light emission from the water in the vicinity of origin, by light emission of the optical fiber placed in equatorial axis of the sphere (see Fig. 3), and by cut-off of the laser light guided by the optical fiber.

Figure 1. (a) Experimental setup. F1 is the optical filter. (b) External view of the wire array of 30 mm in diameter and composed of 40 Cu wires each of $114 \mu m$ in diameter.

Figure 2. Waveforms of (a) discharged current and the voltage and (b) deposited power and energy. The wire array, consisting of 40 Cu wires, each $100 \mu m$ in diameter, was 40mm in diameter.

In the case of spherical wire array, the results of these simulations which assume uniformity of the converging SSW, showed that in the vicinity of implosion origin (the diameter of this region is $\sim 12 \mu m$) the pressure, temperature and density reached extreme values of $\sim 2 \times 10^{12} \text{ Pa}$, $\sim 8 \text{ eV}$ and $\sim 7$, respectively.
respectively. In additional, a strong evidence of large energy density was obtained by destruction of different targets (thin rods made of carbon, copper and aluminum) placed in equatorial plane of the spherical wire array.

![Figure 3](image1.png)

Figure 3. Typical waveform of light-emission from the optical fiber. The wire array, consisting of 40 Cu wires, each 100µm in diameter, was 40mm in diameter. Here \( t=0 \) is the time of the beginning of the discharge current.

It was shown that in spite of a smaller stored energy in microsecond timescale generator, the parameters of water in the vicinity of implosion are superior to those obtained in the case of sub-microsecond timescale explosion (see Fig. 4). The latter is related to magnetic pressure which becomes significant (transfers more energy to the generated SSW) at a longer timescale.

![Figure 4](image2.png)

Figure 4. Time evolution of the radial position of a 100GPa pressure in water generated by (1) µs timescale and (2) sub-µs timescale underwater electrical explosions of a 30-mm Cu wire array, with respect to the first moment when the pressure at the front of the SSW becomes ≥100GPa.

Finally, the preliminary results on measurements of the pressure using different pressure probes (manganin and carbon resistors) placed in the vicinity of the origin of the implosion will be presented as well.

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Tokamak Toroidal Rotation Produced by MHD Turbulence

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SUMMARY

Toroidal rotation in tokamaks can be produced by MHD turbulence. Three conditions must be met: (1) a normal component of magnetic field penetrates the wall bounding the plasma, (2) there is a vertical up – down asymmetry, and (3) a spectrum of MHD toroidally varying perturbations is present. These conditions can be found during disruptions, which occur in all tokamaks, and are expected to occur in ITER. The rotation is a concern for ITER, because of a possible resonance between the rotating MHD perturbations and the conducting structures surrounding the plasma. The rotation can also occur in turbulent events driven by the pressure gradient at the plasma edge. This may help explain the intrinsic toroidal rotation observed in many tokamaks.

Key words: rotation, MHD, ITER, turbulence, tokamak.

1. INTRODUCTION

Toroidal rotation during disruptions has been observed in several tokamak experiments such as JET [1], NSTX[2], and Alcator C-Mod[3]. This rotation is a concern for the ITER experiment under construction, because of a possible resonance between the rotating MHD perturbations and the conducting structures surrounding the plasma.

It is shown that rotation in tokamaks can be produced by MHD turbulence [4]. Three conditions must be met: (1) a normal component of magnetic field penetrates the wall bounding the plasma, (2) there is a vertical up – down asymmetry, and (3) a spectrum of MHD toroidally varying perturbations is present.

These results are established by simulations using the M3D [5] code as well as by theoretical analysis.

2. METHOD AND RESULTS

As noted in the Introduction, there are three conditions to produce rotation. When the magnetic field penetrates the wall containing the plasma, conservation of toroidal angular momentum applies to the plasma and wall together, so the plasma is able to have a net rotation. In the simulations and theory, the vertical asymmetry is provided by an instability, a vertical displacement event (VDE), which occurs in many disrupting plasmas. The VDE can occur when the plasma is vertically elongated and the wall surrounding the plasma is resistive. It causes the plasma to drift vertically and destabilizes the plasma to current driven kink instabilities. The third requirement is a spectrum of toroidally varying perturbations, which are the kink instabilities. These events constitute a disruption and are simulated with M3D, using a model ITER initial equilibrium. During this type of disruption, force is exerted by the plasma on the wall. This has been simulated and analysed [6]. The new results are the numerical simulation and analysis of the rotation.

An example from a simulation is shown in Fig. 1. On the left is the poloidal magnetic flux which has been vertically displaced by the VDE. The magnetic field is aligned with the poloidal flux contours and penetrates the boundary. On the right in the figure are contours of the toroidal velocity. It has regions of positive and negative flow, and there is a net flow.

Rotation can also be produced by pressure driven instabilities known as edge localized modes (ELMs). The mechanism is similar to the case of the kink mode disruptions.

An example of an ELM simulation is shown in Fig. 2. This shows an isosurface plot of plasma density, along with flow streamlines. The streamlines have a toroidal component, and there is a net toroidal flow. In many tokamaks an intrinsic
toroidal rotation is observed [7]. These tokamaks are also unstable to ELMs which occur periodically. It is possible that MHD turbulence during the ELMs is a cause of the observed intrinsic rotation.

3. CONCLUSIONS

It is shown that under certain conditions, MHD turbulence arising in tokamak disruptions and ELMs can generate the toroidal rotation observed in experiments. Further work is planned to assess the impact of the rotation on ITER.

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Active Feedback Stabilization of Flute Instability in a Mirror Trap

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SUMMARY

The flute instability in a table-top mirror machine has been drastically diminished by active feedback system consisting of optical probes, digital signal processor, and needle electrodes. MHD spectroscopy of the system with stable plasma shows a smooth temporal response spectrum and negligible spatial phase between sensors and actuators. Using local feedback algorithm, we demonstrated a large suppression of \textit{m}=1 mode and significant suppression of the \textit{m}=2 mode. Higher spatial and temporal components of the flute instability are slightly enhanced by the feedback.

Key words: mirror machine, feedback, flute, instability.

1. INTRODUCTION

Axi-symmetric mirror machines are the simplest magnetic confinement devices, and as such could be attractive for fusion machines, ions separation, and more. However, mirror machines suffer from particle loss due to the flute instability. Feedback stabilization has been proposed as a remedy for large-scale plasma instability, but it has been implemented almost solely in toroidal devices. The purpose of the current research is to supress the flute in mirror machine by active feedback.

2. METHOD AND RESULTS

A table-top, axi-symmetric mirror machine is filled with hydrogen plasma from a capillary gun [1]. The plasma density is $10^{11}$-$10^{12}$ cm$^{-3}$ and the temperature is 1-3 eV. Six optical collimators coupled to photodiodes at the periphery of the plasma are used to sense the plasma spatial variations. These sensors are fed into a digital processing unit, and the calculated feedback is fed to amplifiers and then to needle electrodes immersed in the plasma. The electrodes induce $E \times B$ drift, predominantly in the radial direction [2]. The overall response time of the feedback system is 5 \(\mu\)s.

Open loop response of the system was measured by the MHD spectroscopy method [3]. Applying periodic \textit{m}=1 signal to the actuators at various frequencies and measuring the resulting periodic signal in the sensors (figure 1) yielded the frequency response curve (figure 1). This curve is smooth, with no resonances, and shows relatively large response even for periods 5 times smaller than the flute typical growth time of 100-200 \(\mu\)s. The angular phase between the actuators’ input and the sensors’ output is relatively small – about 6\(^\circ\) for period of 60 \(\mu\)s. Smooth frequency response and the small phase enable the use of a simple ‘local feedback’ algorithm. In this feedback, the voltage between two adjacent electrodes is proportional to the deviation of the sensor located between these electrodes from the mean of the sensors.

The results of this feedback, averaged over several experiments are demonstrated in figure 2. Without feedback, the dominant flute perturbation is the \textit{m}=1 mode. The introduction of positive feedback destabilizes all the modes. Negative feedback reduces the amplitude of the \textit{m}=1 mode to less than half relative to the case without feedback. The \textit{m}=2 also reduces but only by 10\%, and the \textit{m}=3 increases by a similar amount. The inability of the feedback to cope with the higher modes is expected from the Nyquist theorem. The power spectra of the sensors’ time series for the three cases draws a complementary picture: the positive feedback increases the power at all frequencies relative to the case without feedback, while the negative feedback reduces the power at lower frequencies and increases the power at higher frequencies. The lower frequencies in this case corresponds to the growth rate of the \textit{m}=1,2 flute modes, while the higher frequencies are close to the response frequency of the feedback system.

Figure 1. Left – output of the 6 sensors to periodic stimulation of the plasma. The sensors are spaced in the vertical direction for clarity. Right – the frequency response of the system.
3. CONCLUSIONS AND FUTURE WORK

The flute instability in axi-symmetric mirror machine has been drastically diminished by the use of active feedback system with 6 sensing elements and 6 actuators. Using very simple, local-proportional feedback algorithm, the m=1,2 flute modes have been significantly stabilized. Higher spatial and temporal frequencies are excited by the feedback, but these are stabilized by finite Larmor radius effect [4]. The visible light sensing technique and the immersed electrodes actuators are not applicable to hydrogen plasma with temperature exceeding few 10’s of eV. The next goal of this research is to heat the plasma with ion cyclotron RF and use feedback methods relevant to fusion devices.

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A Retarding Field Analyzer for 2D Energy Distribution Function Measurement.

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SUMMARY

The retarding field energy analyser (RFEA) is a multigrid structure which uses a scanning voltage, \( V \) bias, to retard ions and determine the ion energy distribution function (IEDF) of the ions from the first derivative of the current collected with respect to the retarding bias voltage. The total ion flux is obtained by integrating the IEDF over the full energy range. The technique is well established in the literature and is available as a product from Impedans Ltd. The standard RFEA obtains the 1D IEDF so that ions arriving at an angle will appear to have only an energy perpendicular to the RFEA surface and their angular energy is not recorded. The purpose of this research is modify a standard RFEA so that it records the IEDF as a function of elevation angle. In the current work we set our angle resolution at 3 degrees and measure the IEDF between zero and 45 degrees, which is the largest acceptance angle that ions can enter the RFEA. This work is important in measuring ion angle in etch applications and beam applications.

Key words: Ion energy, Ion angle, Ion flux, RFEA, Etch.

1. INTRODUCTION

The RFEA has been widely used to measure ion energy distributions in a range of plasma applications. In recent times adding RF filters to the RFEA has allowed it to float on a biased substrate and measure the IEDF at the substrate location [1]. This has increased the importance of the RFEA in etch applications. However a major drawback of the RFEA is that it measures the IEDF perpendicular to the grid surface and ignores the energy of ions parallel to the surface. Previous studies [2] looked at using a set of nested hemispherical grids and a segmented collector to measure the angle resolved energy distribution function. The structure was complicated to build, needed differential pumping and had to float on the biased electrode. The resolution was about 5% or an ion angle of 6 degrees. Ions entered the RFEA via a pinhole. The complexity of the design was such that it was not suitable as a commercial RFEA that could be placed in standard chambers.

2. METHOD AND RESULTS

In the present work we use a simple retarding field energy analyser with two aperture grids biased at \( V \) bias and \( V \) bias – \( V \) angle. When \( V \) angle is zero, ions that have energy close to \( V \) bias and zero energy parallel to the grids will drift across the field free region and be collected at the collector which is biased negatively to collect all positive ions that exit the second aperture grid. However ions with any parallel energy will drift sideways and not be collected. Increasing \( V \) angle to 2% of \( V \) bias means that ions with parallel energies in the range 0-2% of \( V \) bias will, in general now make it across the aperture gap. Thus, increasing the size of \( V \) angle results in an increase of the collected current of ions with energy close to \( V \) bias. By analysing the collected current as a function of both \( V \) bias and \( V \) angle it is possible to determine the IEDF as a function of both perpendicular energy and elevation angle entering the RFEA.

3. CONCLUSIONS

We have shown a simple method to measure the ion angle in a standard RFEA with a 3 degree resolution.
Influence of the Gas Feed Location on Radial Plasma Source Operation

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SUMMARY

The influence of the gas feed location on the discharge of a radial plasma source (RPS) was studied experimentally. Three gas feed locations were tested: (1) in the anode area, (2) at the middle of the acceleration channel where the magnetic field is maximal, and (3) through diffusing into the source from the chamber in which the RPS is located. The plasma diagnostics included a Langmuir probe and a balance force meter. For all three gas feeds, the electric force exerted on the balance force meter was found to be enhanced by ion-neutral collisions. Contrary to our expectations, when the gas was fed at the location of the maximal magnetic field, the momentum was found to be smaller, only half of the momentum found when the gas was fed near the anode. The ion current was smallest when the gas was fed at the middle of the acceleration channel, which explains why the momentum was low. The maximal momentum was then carried by the flow from the feed location near the anode. Surprisingly, the momentum was only slightly smaller when the gas source was only diffusion from the chamber.

Key words: momentum, discharge, gas feed.

1. INTRODUCTION

Ion flux and the force exerted by the plasma flow are important characteristics of flowing-plasma sources. We have shown recently that if ion-neutral collisions occur during the acceleration of the ions by the electric field, the total momentum gained by the ion-neutral flow (and thus the exerted force) is enhanced considerably [1]. In the present work, an attempt was made to increase the number of ion-neutral collisions in the region of the acceleration channel where the electric field is largest, by feeding the gas directly into that region. The influence of this gas feed location on the momentum gained by the flow was examined. Additionally, the flow momentum (and exerted force) was determined when the gas was fed through the chamber surrounding the RPS.

2. METHOD AND RESULTS

An existing RPS [1] with a gas distributor near the anode (“anode distributor”) was modified to include a second gas distributor near the middle of the acceleration channel (“middle distributor”), where the applied magnetic field is maximal. The electric field was measured to be largest where the magnetic field is maximal [2]. The modified RPS, shown in Fig. 1, consisted of a ceramic insulator, a molybdenum anode, a magnetic field generating solenoid, an iron core, two (anode and middle) gas distributors and a cathode. The gas was fed into the discharge either through: (1) the anode distributor, (2) holes of the middle distributor or, (3) from the chamber in which the RPS is located by diffusion. For the specified gas flow rate of 70 sccm and a discharge current of 1.1 A, the electric force, ion current and discharge voltage were measured when the magnetic field intensity was varied from 130 G to 420 G. The ambient gas pressure, measured at a distance of 50 cm from the RPS axis, was a constant 8.2 mTorr. The radial electric force and radial ion drift current were measured using a balance force meter and a Langmuir probe. The methodology of the measurements and designs of the balance force meter and the probe were previously described in detail [1].

From the measurements it was found that the electric force, ion current and discharge voltage increased when the intensity of the magnetic field was increased. Contrary to our expectations, when the gas was fed through the middle distributor, the force was found to be smaller, only half the maximal force found when the gas was fed through the anode distributor. In contrast, when the gas was fed through diffusion from the chamber, the force was approximately the same as when fed through the anode distributor, but the discharge voltage was about 30% larger than for anode distributor. The ion current was smallest when the gas was fed at the middle of the distributor, which explains why the force was low.

To analyse the force increase due to ion-neutral collisions, we define an enhancement factor as the ratio between the measured force and the maximal possible force when there are no neutrals, for the ion current and discharge voltage,

\[ \gamma = \frac{v_0 F_E}{\sqrt{2} e V_{ac} / m} \]

where \( \gamma \) is the enhancement factor, \( F_E \) is the electric force, \( I_i \) is the ion drift current, \( V_{ac} \) is the accelerating voltage between the anode and the probe location, and \( v_0 = \sqrt{2eV_{ac}/m} \), where \( e \) is the elementary charge and \( m \) is the ion mass.
The enhancement factor versus magnetic field intensity is presented in Fig. 2. It is seen in the figure that for all three feed locations, the enhancement factor was larger than unity. Therefore, the electric force was enhanced for all feed locations by ion-neutral collisions. The enhancement factor slightly increased with the magnetic field and saturated at a magnetic field of 400 G. The enhancement factor was considerably larger when the gas was fed through the anode distributor. For the diffusion feed, the enhancement factor was less than for the anode feed. This can be explained by the larger value of the discharge voltage, and as result, also a large value of the accelerating voltage. The feed through the middle distributor had the smallest enhancement factor of the three feed locations. Since the force increase depends on ion-neutral collisions, it seems that when gas was fed through the anode distributor, the ions experienced more collisions.

3. CONCLUSIONS

For gas feed at three locations, it was found that the electric force was enhanced by ion-neutral collisions. Contrary to our expectations, when the gas was fed at the location of the maximal electric field, the force was found to be smaller than when the gas was fed near the anode. Feeding from the chamber resulted in a force approximately the same as with the anode feed.

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Cathode Spot Dynamics in a Vacuum Arc with an Oblong Roof Shaped Cathode in a Magnetic Field

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SUMMARY

The dynamics of a vacuum arc cathode spots (CS's) on the surface of an elongated "roof-top" shaped aluminium cathode were investigated, in the presence of an external magnetic field. The dependence of the spot motion on the cathode slope, magnetic field, and arc current was analysed using a high speed video camera. The CS velocity and surface distribution were calculated. It has been found that as the magnetic field and arc current were increased, the spot velocity increased linearly. An "extended group spot" phenomenon was observed, where several group spots can co-exist and join each other.

Key words: vacuum arc, cathode spot, magnetic field, cathode geometry, slope angle.

1. INTRODUCTION

The vacuum arc is used as a metal plasma source. In filtered vacuum arc deposition (FVAD), the plasma is filtered from droplets of molten cathode material, known as macro-particles, by magnetic separation. Typical FVAD systems have a relatively small plasma output beam cross-section. However many applications such as wafer metallization in microelectronic industry, transparent conductive coatings for large flat panel displays or energy conserving coatings on architectural glass require uniform coatings over large areas. Therefore operation with a large cathode area is important.

The plasma originates from cathode spots (CS's), which are high current density areas, typically no larger than $10^{-3}$ cm in size [1]. Controlled motion of the CS using a magnetic field is commonly used to influence erosion uniformity on the cathode surface, and plasma beam uniformity [2].

When a transverse magnetic field (TMF), i.e. parallel to the surface, is applied in a vacuum arc, the CS moves in the "retrograde" –jxB direction [3,4]. Also, if the magnetic field is inclined to the cathode surface, the direction of CS motion is deflected from the retrograde direction towards the direction of the acute angle formed by the field line and its projection on the cathode surface. This is known as the "acute angle rule".

The magnetic field influence on the CS motion for retrograde motion has been reviewed [5] and an explanation was developed considering the cathode plasma flow in the TMF [6]. Several cathode geometries combined with a magnetic field orientation to manipulate the CS motion and its desired location in arc deposition systems were suggested, but not investigated [2]. In the present work, spot motion was investigated for an oblong roof cathode. This design is a conceptual elongation in one direction of the truncated cone cathode, so that a large scale plasma beam can be generated, and eventually coupled to a magnetic filter [2].

2. METHOD AND RESULTS

Method. The CS motion was monitored with a PHANTOM V310 high speed video camera (HSVC). The HSVC was set to record at 6000 frames/s with 256X1280 pixels. The Al "roof-top" cathode had sloped surfaces as shown in Fig.1. Luminous group spots were observed with diameters of 0.3-3-mm [5,6].

Fig.1. Roof-top cathode geometry

The average group spot velocity in the x-direction ($V_x$) on the cathode slope area and the CS surface distribution between roof and slop surfaces were obtained from the movie data.

In order to determine $V_x$ a number of spot trajectories on the cathode slope surface were selected throughout each movie. For each set of system parameters (slope angle, arc current and magnetic field flux) 36 such trajectories were measured and $V_x$ was obtained for both slope surfaces. The spot surface distribution was calculated in the following manner: each movie was paused every 500 frames (roughly 35 frames from each movie). In each of these selected frames, the location of the cathode spots was identified by their pixel coordinates (X, Y), and this location was designated as either "slope" or "roof". The numbers of CS's recorded on the roof area were designated as $N_{roof}$ and the numbers of CS's recorded on all of the slope areas was $N_{slope}$. The total number of spots is $N_{tot}=N_{roof}+N_{slope}$. The fraction of spots on the slope ($K_{slope}$) and on roof ($K_{roof}$) surfaces is respectively:

$$K_{slope} = \frac{N_{slope}}{N_{tot}} \quad K_{roof} = \frac{N_{roof}}{N_{tot}}$$

Results. Several cathode slope angles ($\alpha=17^\circ,40^\circ,46^\circ$) with magnetic fields B=5, 9 and 14mT, and arc currents 150, 200, 300 and 400A were examined.

1. Dependence on magnetic field. The spot or group spot (GS) velocity $V_x$ increased with the magnetic flux approximately linearly, as seen in Fig. 2 for an arc current of 200A. A similar result was obtained on the both slopes. This general behaviour was observed previously [3,5] and agrees with theoretical predictions [6].

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The effect of the magnetic field on the spot surface distribution can be seen in Fig. 3. As the magnetic field was increased more spots move to the roof of the cathode from the slope areas. The tendency of the CS's to occupy the roof area depended on the axial component of the magnetic field while their presence over the slope areas was depended by a transverse component of magnetic field.

According to the measurements as the arc current increased the CS's slope surface fraction, \( K_{\text{slop}} \), increased. This trend was observed for all slope angles. This means that when the current was increased, more CS's moved from the roof surface to the cathode slope areas.

**II. Dependence on arc current.** The spot velocity increased with the arc current for each \( \alpha \) as can be seen in Fig. 4. The measured data indicate that this dependence is linear for \( \alpha=17 \), but not at other slope angles. Lower \( V_x \) was measured for the higher \( \alpha \) (40° & 46°). Similar results were observed on both slope surfaces.

When \( \beta-300\)A sometimes several EGS’s co-exist on the cathode slope, and they move together. When there are multiple EGS’s on the cathode surface, their velocity was lower than that observed for a single EGS. For example, \( V_x=11\)m/s was measured for a single EGS while \( V_x=7\)m/s was measured in the same experiment but when 2 EGS’s were present (\( \alpha=40^\circ, I=300\)A).

**3. CONCLUSIONS**

(1) Cathode spot velocity linearly increased with arc current and applied magnetic field and agree with that published previously and also with theoretical predictions. (2) The fraction of the CSs number on the roof increased with the magnetic field, and decreased with the arc current. (3) It was found that several group spots can be joined spatially and this formation was called as an extended group spot.

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Lifter Experiments: Induced Force Relation to the Ion Craft Geometry

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SUMMARY

'Lifter' is a nickname for a levitating device based on Biefeld-Brown effect. With this fascinating effect, levitation can be reached without moving or rotating elements. Static high voltage is applied between asymmetric electrodes, ion wind flows from the small electrode to the big electrode, and in return, a force towards the small electrode is generated. The lifter is studied experimentally in this work. A set of experiments is conducted trying to clarify the relation of the ion craft geometry to the induced force. The results show clear relations of the generated force to the model structure and dimensions. As the asymmetry is stronger, the force is stronger. According to the experimental results, a set of preferred parameters is given to strength the effect. Choosing the geometrical properties properly led to improvement of factor ~6 in the generated force. Nevertheless, some results provide contradictions to earlier theoretical models describing the effect and reveal unresolved questions regarding this effect.

Key words: Lifter, Biefeld-Brown effect, Levitation, Ion wind, Ion craft,

1. INTRODUCTION

Although the Biefeld-Brown effect was discovered over 80 years ago [1], only limited number of publications were published in the scientific literature describing it. This effect occurs when a device with two asymmetric electrodes is connected to a few kV voltage in atmospheric pressure. Ionization of the air occurs and ion current is following between the electrodes. As a result, a force is obtained pushing the device towards the small electrode, regardless of the voltage polarity. Levitation can easily be obtained without any moving parts. The scientific attention drowned to explain this fascinating effect was very little for many years. But unlike other effects, building a setup demonstrating this effect can be done by rather simple means. Therefore, at the recent years many amateurs built a 'home-made' setup and uploaded a 'youtube' movie demonstrating the effect with the nickname 'Lifter'. Most of the physicists and engineers seeing these movies are first fascinated by it, and then categories it as some kind of either photomontage or magician trick. But with some patient, after watching many of these movies, one's healthy curiosity must rise. They can't all be fraud. So we have decided to check it out in laboratory conditions and perform a controlled experiment. First, a levitating model was built imitating models seen in the movies. After few failure models, indeed the fascinating effect of levitation without any moving parts was obtained in the lab [2]. Two asymmetric electrodes fixed on balsa wood sticks, connected to a voltage power supply were levitating in a stable manner.

Scientific literature exploration showed that the theory describing this effect is still immature. Early ideas suggested different explanations of unknown physics, but recent works rejected these ideas and described the force as an outcome result of ion wind [3-8], an electrohydrodynamic (EHD) effect. Few experiments were carried out to support these theories and fair agreement between the theoretical prediction and the experiments was reported for the described setup. In this experimental study, parametric measurements were done trying to relate the generated driving force of the Biefeld-Brown effect to the structure of the model. Such experimental results may help understanding the nature of the force, and even reveal ways to maximize the effect. Indeed, such relations between the model structure and the generated driving force were experimentally found as described further on. Also, some contradictions to the earlier suggested EHD models are found experimentally.

2. METHOD AND RESULTS

In order to demonstrate the levitation effect a model was built from balsa wood, aluminium foil and copper wire as seen in Fig. 1. Already at the end of this experiment a clear observation is made: this device creates a wind downwards. It is easily felt and seen. To demonstrate it small objects were placed in the device vicinity and the generated wind blow them away. Also a smell is noticed that can be related to ionization. Experienced experimentalist indicated that it is the smell of Ozone, but it was not further checked.

Following the levitation experiments a setup was made to explore the behaviour of the device in different environments. It was placed in a closed system and the forced induced on system itself was monitored. No force was measured out of the closed system. Also, it was entered into a vacuum environment. In vacuum, also, no force was measured. These experiments relate the effect to ion wind and exclude mysterious theories.
3. CONCLUSIONS

In this experimental study, parametric measurements of the Biefeld Brown effect were done relating the generated force to the structure of the ion craft. Clear observations are:

a) Levitating device without any moving/rotating parts is easily obtained in asymmetric electrodes geometry.
b) The force is always towards the small electrode disregarding the voltage polarity and grounding.
c) Wind is obtained towards the big electrode.
d) The size of the electrodes influence the force: smaller small electrode and bigger big electrode both yields higher force.
e) Structures with similar potential distributions but with different electrode area induce different forces, related to the electrode area.

The experimental results reveal ways to maximize the effect:

1) Decreasing the distance between the foil to the copper wire,
2) Narrowing the copper wire diameter,
3) Increasing the number of foils,
4) Ruggedizing the device,
5) Increasing the height of the foil,
6) Stretching tight the small electrode to avoid vibrations,
7) Polarity – ground to the big electrode and positive voltage to the small electrode are superior.

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Generation of Cumulative Jets during Underwater Explosion of Copper Wires in the “X-pinch” Configuration

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SUMMARY
The results of experiments with underwater electrical explosion of 0.1 mm diameter copper wires in X-pinch configuration are presented. A pulsed generator producing a ~30 kA-amplitude current with a ~65 ns rise time was used for the explosion of the wires. Shadowgraph and shearing interferometry techniques were applied for optical diagnostics. Evidence of fast-moving copper jets, originating from the location of the intersection of the exploding wires, is reported. Simultaneous measurement of the expansion of the wires, shock waves, and copper jets showed that the dynamics of the jets strongly resemble the classic problem of a collision of two planes, producing two consecutive cumulative jets.

Key words: wire explosion, X-pinch, cumulation, strong shock waves

1. INTRODUCTION
The research of electrical explosions of X-pinch configuration of wires in vacuum is attracting much attention due to the interesting physical phenomena involved in the formation of an extremely hot (>1 keV) and dense (~10^{22} m^{-3}) plasma spot at the location of the intersection of the wires. The process of wire explosion is accompanied by the ablation of the wire material, and its ionization and compression toward the axis by the global gradient force j×B of the magnetic field, where B is the self-magnetic field of the discharge current with current density j. This configuration of the magnetic field causes the ablated plasma to collapse onto the axis of the angle bisector, forming jet-like structures as described by Zakharov et al. These two oppositely-aligned jets are ejected in the directions where the wires cross at acute angles.

Unlike wire explosions in vacuum, underwater electrical wire explosion (UEWE) is characterized by the confinement of the exploding wire by the surrounding water, preventing the fast radial expansion of the wire (radial expansion velocity \( V_r \approx 10^3 \) m/s in water versus ~10^7 m/s in vacuum). In addition, the process of parasitic plasma surface discharge, typical for wire explosions in vacuum, does not take place in UEWE due to the high (~3×10^7 V/m) threshold of the electric breakdown field in water, thus keeping a large density discharge current flowing through the wire. As a result, a much larger energy density deposition (up to several hundreds of eV/atom) is achieved.

This work presents the experimental results of underwater electrical explosion of wires in the X-pinch configuration. The dynamics of the resulting jets in water is found to be quite different from that in vacuum, because of the low compressibility of water. In vacuum, the effect of the generation of cumulative jets is quite weak, as described in the review by Sokolov.

2. METHODS AND RESULTS
The X-pinch was made of two crossed copper (Cu) wires (~58° between the wires), each with a diameter of 0.1 mm and length of 40 mm. The wires were stretched between the cathode and anode electrodes, and immersed in water in a stainless-steel chamber having quartz windows for optical observation. The wires were exploded by a current pulse with an amplitude of \( I \leq 30 \) kA (\( j \leq 3×10^{12} \) A/m^2) and rise time of ~65 ns, produced by a high-current generator. Two optical diagnostic techniques were used: shadow imaging and shearing interferometry. For shadow imaging, a CW laser (532 nm, ~100 mW) was used as a source of backlight, and a 4QuikE intensified camera was used for capturing the images with a frame time of 5 ns at different time delays \( \tau_d \) with respect to the beginning of the discharge current. The Mach-Zehnder scheme was used for shearing interferometry.

A series of shadow and shearing interferograms images of an X-pinch in water (see Figs. 1 and 2) was recorded at different time delays \( \tau_d \). Similarly to the experiments performed in vacuum, in the case of underwater X-pinch configurations, the generation of two jets lying along the acute angle bisectors was observed. In this case the generation of these jets can be described by a process of cumulation, similar to the effect of jet formation in a weakly-compressible medium. The fast radial expansion of the wires begins at the location of the intersection of the wires. This leads to the generation of a quasi-spherical shock wave (SW). The front of this SW is interacting, but is not overlapping, with the fronts of cylindrical SWs, which are generated by the radial expansion of the wires. As a result, a region of a high pressure \( P_{SW} \) is created behind the interacting fronts of these SWs. The jets are propagating in opposite directions, with an average velocity of \( V_j \approx 2.5×10^3 \) cm/s.
The collision of the exploding wires generated by underwater electrical explosion in the X-pinch configuration creates fast-moving cumulative jets similar to those generated by the collision of metal slabs, accelerated by the chemical explosion. The properties of these jets are determined by the parameters of the electrical explosion and their interaction with the water, compressed by the SW generated by the exploded wires. This method of generation of cumulative jets and their interaction with low-compressible media is significantly simpler than common methods, and allows the application of optical diagnostics for the observation of the dynamics of the jets.

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Nonlinear Wake Amplification by Active Medium in a Cylindrical Waveguide

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SUMMARY

Cerenkov wake amplification can be used as an accelerating scheme, in which a trigger bunch of electrons propagates inside a cylindrical waveguide filled with an active medium and generates an initial wake field. Due to the multiple reflections inside the waveguide, the wake is amplified significantly compared with a wake in a boundless medium. When the wake is strong and reaches saturation, it can accelerate a second train of bunch of electrons trailing behind the trigger bunch. Here, we calculate numerically the nonlinear dynamics of the wake and population inversion density for CO₂ active medium. We calculated both numerically and analytically the dependence of the saturation time and the value of the saturated wake on the accelerator parameters. Our model indicates that it is feasible to obtain gradients as high as GV/m in a cm⁻¹ waveguide volume.

1. INTRODUCTION

One of the key parameters in e-beam accelerators is the value of the electric field in the longitudinal direction known also as the gradient. So far, there are two major conceptual schemes of accelerators that have been studied both theoretically and experimentally. The first one, electrons are accelerated by a plasma wave that is produced by the interaction of an intense laser pulse in plasma [1]. In the second case, an intense e-beam generates a wake in a plasma which in turn accelerates the electrons [2].

In this paper we present a new scheme which compromises one structure to accelerate electrons and does not require external input of high intensity laser pulse [3-5]. Thus, such structure can accelerate e-beams more efficiently than structures that are based on the injection of high intensity laser pulses.

In this scheme an active medium inside a metallic cylinder is used to accelerate e-beams. Initially, a triggering bunch of electrons generates a wake which has an electric field component in the longitudinal direction. In turn, the latter is amplified by the active medium via the stimulated emission process. As the wake field is amplified, the population inversion in the active medium is reduced and as a result the spatial gain also decreases. When the spatial gain is zero, the wake reaches saturation and it can accelerate a second bunch of electrons trailing behind the triggering bunch.

Previous study of this scheme used linear model [3,4] and simplified non-linear model [5]. In the linear model, where a constant population inversion density is assumed, the wake is exponentially amplified. Since the propagating wake in the cylindrical waveguide propagates in an oblique angle, it reflects multiple times with the boundaries. Thus, the effective propagating length of the wake is longer than if the wake was propagating in a boundless medium. As a result, the effective gain of the wake is enhanced.

The simplified nonlinear model [5] assumes the propagation of one electromagnetic mode, it does not account for the multiple reflections of the wake from the waveguide boundary and only the dynamics of the polarization field was considered. While these approaches predicts qualitatively the saturation process the present approach is by far more quantitative.

In this paper we extend the previous linear model and include the nonlinear dynamics of the active medium. The extended model can describe the wake saturation level and the interval of time in which the wake reaches to saturation.

2. METHOD AND RESULTS

The accelerator structure that we consider is made of a cylindrical metallic waveguide of radius R filled with an active medium. Initially, a short bunch of electrons, the trigger bunch, is injected to the structure. Assuming azimuthal symmetry, that bunch of electrons satisfies the Cerenkov condition excites transverse magnetic (TM) modes which propagate behind it and have electric fields in the longitudinal direction, E, and in the transverse direction, E, and magnetic field in the azimuthal direction, H.

Specifically, the dynamics of the wake is governed by the Ampere's

\[ \nabla \times \vec{H} = \varepsilon_0 \varepsilon_r \frac{\partial \vec{E}}{\partial t} + \frac{\partial \vec{P}}{\partial t} + \vec{J} \]  

(1.1)

and Faraday's law

\[ \nabla \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t} \]  

(1.2)

where \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon_r \) is the dielectric constant of the medium excluding the population inversion dynamics, and \( J \) is the current density of the electron bunch.

The active medium is modelled semi-classically as two levels system within the framework of the dipole approximation. The response of the active medium to the wake is through the polarization fields \( \vec{P} \),

\[ \frac{d^2 \vec{P}}{dt^2} + \Delta \omega_0 \frac{d \vec{P}}{dt} + \omega_0^2 \vec{P} = -\frac{N}{N_0} \varepsilon_0 \varepsilon_r \vec{E} \]  

(1.3)
where the plasma frequency of the active medium is
\[ \omega_p = \omega_0 \sqrt{\frac{2N_0 \mu_0}{3e_k h \alpha_b}}. \]
Here, \( \omega_0 \) is the resonance frequency of the active medium, \( N_0 \) is the initial population inversion density, \( h \) is the reduced Planck constant, and \( \mu_0 \) is the dipole moment. Finally, the dynamic of the population inversion density (PID), \( N \), is
\[ \frac{\partial N}{\partial t} = \frac{2}{\hbar \omega_0} E_x \frac{\partial P}{\partial t}. \]

These generated TM modes from the bunch also known as the wake field travel at the same speed of the trigger bunch, \( \beta c \), where \( c \) is the speed of light in vacuum. Moreover, most of the wake is amplified by the active medium through the stimulated emission process at the resonance frequency of \( \omega_0 \). Hence, the dynamics of the wake and the active medium can be described by the slowly varying envelope approximation with \( T = t - z / \beta c \) dependence.

In addition, due to the resonance frequency of the active medium it is possible to amplify single TM mode when the waveguide dispersion coincide with the electron bunch dispersion. In another words the single mode condition is
\[ \left( \frac{\omega_0}{c \sqrt{\epsilon_c}} \right)^2 - \left( \frac{p_x}{R} \right)^2 = \left( \frac{\omega_0}{\beta c} \right)^2. \]

where \( p_x \) are the roots of the Bessel function \( J_n(p_x) = 0 \). As an indicative example we study wake amplification in CO2 gas mixture with the same set of parameters as in Ref. [3]. Figure 1a shows the envelope dynamics of the normalized longitudinal wake on the axis, \( E_x \), the normalized PID, \( \overline{N} \), and the bunch profile (dashed curve), \( \beta \) as function of the normalized time \( \tau = T_0 / t' \). Here, the wake is normalized with respect to \( E_0 = \frac{\hbar \omega_0 N_0}{2 e_0 J_n'(p_x)} \). Figure 1b shows the wake in physical units of V/m (blue curve) and the normalized bunch profile (red curve) as function of \( t = t' / \beta c \). At this point there is not any effective amplification or the medium is transparent and the wake reaches to saturation.

However, as the wake is amplified the PID will be depleted as a result of the stimulated emission (right hand side of Eq. 1.4) till it will be reduced to zero at \( \tau = \tau_{sat} \). At this point there is not any effective amplification or the medium is depleted. Hence, the gain of the medium is constant and the wake can be amplified exponentially.

Figure 1a shows the envelope dynamics of the normalized longitudinal wake on the axis (solid curve) , \( E_x \), the normalized PID (dashed dotted curve), \( \overline{N} = N / N_0 \), and the bunch profile (dashed curve) , \( \beta \) as function of the normalized time \( \tau = T_0 / \beta c \). Here, the wake is normalized with respect to \( E_0 = \frac{\hbar \omega_0 N_0}{2 e_0 J_n'(p_x)} \).

3. CONCLUSIONS

We presented nonlinear model of wake amplification which extend the linear model of Ref. [3]. The extended model enables to calculate numerically the value of the saturated wake and the saturation length.

In the studied example of CO2 gas mixture, it has been shown that it is possible to have in the nonlinear regime flat gradient of the order of GV/m for cm size waveguide. This gradient can be used to accelerate a second trailing bunch of electrons.

To summarize, wake amplification by active medium can produce high gradients in a relatively small size structure without using an external high intensity laser pulse.

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Synchrotron Tera-Hertz Radiation from Dense Quasi-Plane Electron Bunches

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SUMMARY

It has been theoretically shown that electron bunches from linear accelerators with laser-driven photo-injectors even at moderate particle energy can be effectively used for radiation in homogeneous magnetic field of strongly directed, very short and powerful THz electromagnetic pulses with broad frequency spectrum. Radiation fields and their spectra can be presented in a very simple analytical form using fields of an arbitrary moving charged plane. This method can be also effectively used for study of other prospective methods of high-frequency generation (cyclotron and undulator radiation, wave scattering and others) with taking into account of self-action and interaction of electron layers inside the bunches. A broadband radiation with frequencies up to (1-3) THz can be effectively generated by electrons with energy (4-6) MeV in magnetic field (4-10) kOe.

Key words: laser-driven photoinjector, coherent spontaneous radiation, terahertz.

1. INTRODUCTION

Appearance of accelerators with laser-driven photo-injectors caused a renaissance of the ideas on using preliminarily prepared compact electron bunches for generating powerful high-frequency electromagnetic radiation, which were very popular in 1950s. Ultra-dense bunches of ultrarelativistic electrons with charge of the order of 1 nC and duration of (0.01-10) ps are used now not only in FELs of various frequency ranges, but also in various sources of the so-called coherent spontaneous radiation or/and super-radiation of short electron bunches. Most of works in the latter field is focused on providing a narrow-frequency-bandwidth generation in undulators that is often a difficult task because of very fast Coulomb repulsion of electrons in dense bunches. It should be emphasized that an opposite case of very short and broadband spontaneous synchrotron or undulator radiation from bunches can be also fairly interested for a number of applications and presumably easier in realization [1].

The longitudinal sizes of the electron bunches from photo-injectors are often of the order of the wavelengths of terahertz radiation while their transverse sizes are usually much larger than the wavelengths. Correspondingly, in this paper, we develop the idea of using coherent spontaneous radiation of short quasi-plane bunches mainly with respect to production of powerful THz electromagnetic radiation from electrons with a moderate energy moving in moderate magnetic fields. Radiation of a quasi-plane source is strongly directed already in free space and can be used for selective excitation of waveguide/mirror electrodynamical systems.

The important features of radiation of quasi-plane bunches can be studied on the simple 1D model using the formulas for arbitrary moving charged plane [2]. These formulas are also successfully used in a number of papers for study of interactions of ultra-powerful laser pulses with matter which lead in particular to fast particle acceleration and generation of ultra-short extremely powerful and high-frequency electromagnetic pulses [3].

In this presentation, the fields and spectra for a charged plane or a layer which moves, while retaining parallel to itself, with arbitrary relativistic velocities of the particles are obtained for fixed and self-consistent motion of charges along Larmor arcs in a short section of magnetic field.

2. THE FIELDS OF A MOVING CHARGED PLANE AND A PLANE LAYER

The radiation of a thin bunch can be estimated from the field of a charged plane consisting of particles which move synchronously along the same arbitrary trajectories (Fig.1). The corresponding formulas [2] are much simpler than well-known expressions for the Lienard-Vichert potentials. In particular, they do not diverge at any distance from the plane and readily give the self-radiation force acting on the plane. Together with a simple expression for Coulomb field it allows easy taking into account of interaction between thin

Figure 1. 1D bunch of electrons moving along identical trajectories creates the field that propagates in ±z - directions with speed of light and is compressed/stretched in passing/counter directions.
elementary layers in a wide layer. Using this method we have studied the coherent synchrotron radiation of a bunch with particles entering a transverse magnetic field perpendicularly to the plane with the same ultrarelativistic Lorentz-factors \( \gamma \) and moving along a short Larmor arcs \( \theta \sim 1/\gamma \) (Fig. 1). In the instantly accompanying reference system, where \( \nu'_z(t') = 0 \), one has uniform Coulomb fields \( E_z \) at the both sides of the plane and symmetric transverse fields whose fronts move from the plane with speed of light in \( \pm z \) - directions [4]. If the velocity component \( \nu'_z(t') \) represents a pulse of arbitrary duration, one observes two field layers of the same value and duration which propagate in opposite directions from the plane. The motion of the particles in the}\( z \)-direction causes asymmetry of the transverse fields. In the laboratory system, these field layers are contracted and increased by amplitude in the passing direction and stretched and decreased in the counter direction (Fig. 1).

For ultrarelativistic electron energy and small Larmor arcs the field of radiation from the moving plane can be presented in an especially simple form. If electrons entering the magnetic field have only \( z \)-component of velocity, the passing field presents a strong quasi-rectangular video-pulse which is many times Doppler-compressed in time in comparison with the pulse of transverse velocity. Its duration is equal to the small delay of electrons relative to the radiated wave during particle motion which is caused both by the curvature of the electron path and difference of particle velocity from speed of light.

Like for a single electron, the bandwidth of radiation spectrum is of the order of \( \gamma^2 \Omega \), however, its spectrum is located at low frequencies (Fig. 2). Increase in the value of the Larmor arc described by particles, leads to the enhancement of the total radiated energy, but diminishes a fraction of radiation at high frequencies. The total energy radiated in forward direction can be found by integration of the \( z \)-component of the Poynting vector or by integration of equations of electron motion under action of the magnetic field and radiation force. The obtained very simple and universal formulas can be used for estimation of radiation from an infinitely thin electron disk. Let us consider the disc with a large charge 1 nC and typical area 1 mm\(^2\) consisting of electrons with a moderate particle energy 6 MeV \( (\gamma \approx 13) \) in a moderate magnetic field \( H = 10.7 \text{ kOe} \). In this case, the time of particle motion along Larmor arcs with the angle \( 1/\gamma \) is about of 5 ps while the duration of radiated pulse is equal to 20 fs only. Then, the infinitely thin disc with initial energy of the 6 mJ radiates a pulse with energy and average power of about of 20 \( \mu \text{J} \) and 1 GW, respectively. For the arc with larger angle 0.2 the time of electron motion is 13 ps, the radiation pulse duration is 130 fs and energy is 120 \( \mu \text{J} \) with approximately the same average power of about 1 GW, but certainly at lower frequencies.

The field of a plane layer can be represented as an integral of the fields of elementary thin layers. Estimations show that for motion in the short field it is possible to neglect both Coulomb repulsion of the elementary layers and their interaction through the radiation field. In the case of the same electron energies in the elementary layers the total field is a superposition of pulses of identical shape which come to the point of observation one after another with amplitudes proportional to the current value of the electron density in the bunch. The radiation spectrum of the layer (Fig. 2) is the product of spectra of an infinitely thin plane and a density function.

3. CONCLUSIONS

The studied THz source based on using short quasi-plane electron bunches with a very large charge which can be presumably formed in photo-injector linacs may provide fairly powerful and high-frequency radiation even at moderate electron energy and magnetic field. According to the theory, the radiation with frequencies up to (1-3) THz can be effectively generated by electrons with energy (4-6) MeV in magnetic field (4-10) kOe. The main conditions for the generation of high frequencies in such situation are small electron pulse duration and sufficiently sharp limitation of small region of electron motion in short magnetic field. Then the electrons radiate short powerful pulses with a broadband spectrum. Unlike the synchrotron radiation of point-like electron bunches, the maximum of radiation for the quasi-plane bunch is situated at low frequencies. It allows, in particular, generating unipolar video-pulses which could be useful for specific pump-probe experiments. The radiation pattern of the quasi-plane bunch provides also a selective excitation of waveguide modes.

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Coupled Cavities for Terahertz Gyrotrons

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SUMMARY

The replacement of conventional gyrotron cavity on a system of two coupled cavities can provide significant efficiency enhancement in terahertz frequency range due to decreasing diffraction Q-factor and reducing Ohmic losses in the walls. In this presentation, electrodynamical systems with a relatively smooth profile have been studied both analytically and numerically based on the well-known non-uniform string equation. It is shown that a very simple system with a waveguide coupling whose diameter is by only a small fraction of the wavelength larger than the cavity diameters can provide a favourable ratio of the field amplitudes in the cavities and needed discrimination of the parasitic normal mode.

Key words: terahertz frequency range, gyrotron, coupled cavities.

1. INTRODUCTION

A very attractive method for mastering terahertz frequency region using weakly relativistic high-harmonic Large Orbit Gyrotrons [1] essentially suffers from high Ohmic losses in the walls of the conventional cavities. This problem is very important because of a relatively low impedence of interaction of weakly relativistic electrons with the operating mode at high cyclotron harmonics and caused by this necessity to use long cavities possessing diffraction Q-factors much high than Ohmic Q-factors. A possible way for solution of the problem is to replace the conventional cylindrical gyrotron cavity on a more complicated system in the form of two cylindrical cavities coupled through a cut-off waveguide [2] or, as was recently proposed in papers [3, 4], through a wide waveguide in which the wave of coupling is far from cut-off and propagates with a large group velocity under a small angle to the axis of the system. Gyrotrons with such electrodynamical systems represent self-exciting gyroklstrons with a feedback. In such an oscillator one can provide an accurate modulation of electrons by transverse velocities in the first cavity, a compact azimuthal particle bunching on Larmor circles in the waveguide coupling (drift space) and an effective energy extraction from the bunched electron beam into the operating mode in the second cavity. At the same length of interaction of the electrons with the resonance terahertz field the system of coupled cavities can possess significantly higher useful diffraction losses and even smaller parasitic Ohmic losses in comparison with the conventional cylindrical cavity. Correspondingly, the output efficiency and radiation power of the terahertz gyrotron with the coupled cavities can be many times higher [3,4]. Due to the potential importance and non-trivial character of this result we study in this presentation electrodynamical properties of such systems in detail. Unlike [3,4], we analyse a simpler and probably more practical case of a regular waveguide coupling whose radius is only slightly larger than cavity radii. In this situation, normal axial modes of the coupled system can be found from the well-known non-uniform string equation [5], which is equivalent to the geometric-optic approach. An analytic solution of the corresponding boundary problem for the simplest geometry allowed finding the conditions when the normal mode with a smaller amplitude in the first cavity (what is favourable for high output efficiency) has higher diffraction Q-factor and smaller starting current, respectively, and due to it confidently wins the competition with the second normal mode. These solutions were also checked using the completely electromagnetic code CST Microwave Studio.

2. BOUNDARY PROBLEM

Let us consider a modification of the “new” electrodynamical system [3, 4] with a regular wide waveguide in the drift space. We study analytically a case with regular cylindrical cavities (1 and 2) opened into the wide drift space (d) (Fig. 1). When the waveguide radius profile, R(\(\zeta\)), is sufficiently weakly varying function of axial coordinate, one can neglect transverse mode conversion on small irregularities of the profile. For our situation it means that all the jumps in waveguide diameters (Fig. 1) are at least much smaller than the operating wavelength. If, nevertheless, the Q-factor of the electrodynamical system is large enough it is possible to consider the axial field structure fixed, non-dependent on the parameters of the electron beam, and to use for description of the axial field structure the so-called non-uniform string equation [5]:

\[ f'' + \frac{1}{\zeta} f' = 0 \]  

(1)

with radiation boundary conditions \( f' \big|_{\zeta=0} = 0 \) and \( h(\zeta) \) is the axial wavenumber for the cross-section \( \zeta \) and \( h(\zeta) \) are the axial wavenumbers in the output waveguides. Due to continuity of transverse electric and magnetic fields the function \( f(\zeta) \) and its derivative are continuous. The described boundary problem is very similar to the problem for the 1D stationary Schrödinger equation for a particle in a field with two rectangular pits separated by a deeper pit which provides the above-barrier wave reflection. A specific feature of the electrodynamical problem for a gyrotron is closeness of partial cavity frequencies to the cut-off frequencies of the corresponding waveguides that leads to the smallness of axial wavenumbers inside the cavities (the Brillouin rays inside the cavity propagate almost perpendicular to the axis). The most important is the case of the normal modes with one variation in the cavities. It is important, that at sufficiently large Fresnel parameters for the cavities, even jumps in the waveguide diameter at the transitions from the
cavities to the output and drift waveguides which are small in comparison with the wavelength can lead to large jumps in axial wavenumbers and to high reflections. Correspondingly, such small jumps can provide high cavity diffraction $Q$-factors. Like the field of the main axial mode in the closed cylindrical cavity, the field distribution inside of both coupled cavities is very close to the arc of sinus. At the same time the field in a long enough drift space has many variations (Fig. 1).

Using the ratios of the axial wavenumbers in the cavities and in the waveguides as small parameters we find the complex normal frequencies for the coupled system:

$$\omega_{1,2} = \Omega_1 + \Omega_2 \pm \frac{\Omega_1 - \Omega_2}{2} \sqrt{1 + \sigma^2}.$$  \hspace{1cm} (2)

Here $\sigma$ is the normalized complex parameter of coupling of the cavities (the coupling coefficient divided by the difference of partial frequencies, $\Omega_{1,2}$) which simply depends on lengths and radii of all the sections. At weak coupling, $|\sigma| \ll 1$, the complex normal frequencies are close to the partial ones. In opposite case, they essentially depend on the coupling. The ratio of the amplitudes for the normal modes is also determined by the coupling parameter $\sigma$. Varying lengths and radii of the cavities while maintaining their frequencies approximately equal to each other we get that at relatively strong cavity coupling and short first cavity there is an opportunity to simultaneously provide a favourable ratio of the field amplitudes in the first and second cavities of about 0.2-0.4 for one of the normal waves (Figure 1). The diffraction $Q$-factor for this mode is lower than that for the first axial mode of the conventional gyrotron cavity. At the optimal electron current such conditions allow significant enhancement of the efficiency for the operating mode. Analytic solutions were checked using both numerical solution of the non-uniform string equation (1) and simulations on the basis of the code CST Microwave Studio. These methods allow studying of more complicated profiles and also the second of them is applicable for an important situation of a small cavity Fresnel parameters.

3. CONCLUSIONS

The developed theory allow a deeper understanding of the electrodynamical properties for THz gyrotrons with coupled cavities and demonstrate the opportunity for possible simplification of wide waveguide coupling for such systems.

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Shaped Beam and Long Pulse from a Ferroelectric Cathode with Multi Front Electrode for Gyrotron

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SUMMARY

A gyrotron based on ferroelectric cathode with various models of cathodes were designed and built. Each model has different electrodes with different configuration. The results indicate that the operation of the cathode with two or more front electrodes in synchronism allows extension of the pulse duration and high PRF operation with flexible duty cycle. In a dual front electrode version, two electrodes are triggered separately in complementary timing. During the operation and the plasma formation of one electrode, the second is in a relaxation process and vice versa. A pulse repetition rate of ~3MHz with 50% duty cycle was obtained from each electrode, reaching an overall 100% duty cycle, forming a continues ~7 µs current pulse. This configuration has the potential to extend the pulse duration towards long pulses and continues operation. The cathode was used as a source for 25 GHz gyrotron generating a ~7 µs radiation pulse. The electron beam shape was measured photographed at the cathode surface and on a phosphorescent screen far from the cathode to examine the beam profile. The results showed that the shape of the beam is affected by the shape of the electrode. An annular electron beam was received, fitting the needs of a typical gyrotron tube.

Key words: Gyrotron, ferroelectric cathode.

1. INTRODUCTION

The ferroelectric cathode (FE) has been investigated in the recent years as a cold electron source for many uses including microwave and millimetre waves applications [1]. Recent achievements extended the use of this unique cathode to S-band relativistic magnetron [2] and 95 GHz gyrotron [3]. While a thermionic cathode can emit long pulses and even continuous beam, plasma cathodes are typically limited to short pulses operation. The main limiting factors are the gap closure that limits the pulse duration, and the plasma relaxation time that limits the pulse repetition frequency (PRF). Earlier attempt for extension of the pulse duration is reported in the work of Advani et al. [4], where 5 µs single pulse is achieved from a 11.4 cm diameter annular ferroelectric cathode. This cathode was designed for a gyrotron but it was not implemented into a tube, and radiation was not obtained. A similar problem of extension the pulse duration in different plasma cathode, based on explosive emission, was addressed by Engelko [5]. Multi-point ignition was used to overcome the plasma limitation, generating a 30 µs current pulse length. Again, this demonstration included electron gun but radiation from tube was not reported. Afterwards this method was implemented with FE cathode by Gleizer et al. [6], obtaining single pulses of ~6 µs. In this experiment also electron beam is reported but radiation is not. Radiation from FE tube is reported by Hadas et al. [2], where an S-Band magnetron with FE cathode was compared to the same tube with explosive emission cathode. The use of the ferroelectric cathode extended the duration of the radiated pulse in ~30% to 100 ns, and increased the microwave power in ~10%. It is clearly determined in this experiment that the FE cathode is ~30% more efficient in comparison to explosive emission in the tested tube. In other studies demonstrating the integration of ferroelectric cathode in electron tubes a PRF of 3 MHz and duty cycle of up to 50% gyrotron was measured with 150 ns pulses. However, FE cathode tubes with long pulses were not reported.

In this work a various models of FE cathodes are presented. the construction of the cathode with two or more front electrodes enables high PRF with flexible duty cycle. When the duty cycle is tuned to 100% long pulses are obtained as described hereinafter. The beam profile far from the cathode was examined. The results showed that the shape of the beam is affected by the shape of the electrode. An annular electron beam was received, fitting the needs of a typical gyrotron tube.

2. METHOD AND RESULTS

The experiment was based on a ferroelectric cathode made of a 2.5 mm thick and 18 mm diameter barium titanate (BaTiO3) ceramic plate. The non-emitting rear side of the cathode was coated with a 17.5 mm diameter metal electrode, while the front side was coated with a different shaped electrode for each part of the experiment. First, a dual electrode has been tested. A cathode was coated with two separated metal 6.60×1.7 mm rectangle electrodes with a gap of 2.5 mm between them as shown in Fig. 1. Each one of the electrodes was wired and triggered independently. The cathode was implanted into a 25GHz gyrotron tube.

The electron gun was connected to the gyrotron tube. Each electrode was separately triggered with a sequence of 300 ns pulses with complementary timing (Fig. 2a). The duty cycle of the sequences was gradually varied from ~7% to ~50% and the PRF was varied from 0.25 MHz to 1.6 MHz. From each trigger pulse a collector current pulse and a radiation pulse were obtained. Therefore the duty cycle and the PRF of the collector current pulses were doubled as shown. As the PRF was further increased to ~1.6 MHz for each electrode with ~50% duty cycle (3.2 MHz for the
Figure 3. The cathode schematic.

In a second experiment the cathode was coated with a ring shaped electrode, as shown in Fig. 3(a) and a tripled bow electrode, as shown in Fig. 3(b). The cathode surface was photographed during the plasma excitation and a phosphorescent screen was used to examine the beam profile far from the cathode. Fig. 4-5 shows the results of photographing the cathode surface during plasma excitation (Fig. 4) and the combination of images of the electron beam hitting a phosphor screen for the ring electrode (Fig. 5a) and for the tripled bow electrode (Fig. 5b).

3. CONCLUSIONS

In this experiment it is shown that two electrodes in close proximity to each other, only 2 mm gap, can be operated without mutual interruption. By triggering each electrode with separated switches, a high PRF is achieved with flexibility in the possible duty cycle from 0% to 100%. When operating each electrode in 50% duty cycle in complementary timing, a unified long pulse comprised of the pulses from the two cathodes is obtained; much longer than a pulse from a single cathode. In this experiment the total pulse length was 7.5 µs, and it was limited by the high voltage switches, which have finite number of possible sequent pulses. Also photographing the electron beam has shown that it is possible to control the beam shape by the changing the front electrode shape.

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Titanium Plasma-Column Generated by Localized Microwaves in Air for TiO$_2$ Nano-Powder Deposition

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SUMMARY

A plasma column ("fire-column") of titanium in air is generated by localized microwaves at 2.45 GHz. The fire-column is investigated by optical spectroscopy and microwave impedance analyses, and by small-angle X-ray scattering (SAXS). The TiO$_2$ nanoparticles are deposited by the fire-column on a copper or glass substrate, and analysed by scanning-electron microscopy (SEM) and by X-ray diffraction (XRD). The optical spectroscopy shows typical lines of titanium. The nanoparticles of titanium dioxide deposited on the substrate in a powder form are observed in various crystalline structures. Applications of this technique, such as air cleaning and energy conversion, are discussed.

Key words: plasma column, fireballs, localized microwaves, titanium nano-powders.

1. INTRODUCTION

Titanium dioxide is synthesized nowadays by various techniques using spark plasma sintering, microwave plasma torches, arc discharges, hydrothermal processes, and other chemical methods [1]. This work, however, presents the synthesis and deposition of nano-particles and nano-powders of TiO$_2$ in transition mixed phases of brookite-anatase-rutile by the microwave fire-column technique [2].

2. METHOD AND RESULTS

In the experimental setup described schematically in Fig. 1, a movable titanium electrode is brought into contact with the upper edge of a titanium metal plate (the emitter). The localized microwave energy at 2.45 GHz creates a hotspot that melts the titanium and initiates a fire column. The dusty plasma evolved is accumulated on the deposition substrate.

Figure 1. The microwave cavity (a), the fire column (b), and the entire experimental setup (c).

Following [3], the electron density is found from plasma impedance measurements (Fig. 2) as $n_e \sim 5 \times 10^{18}$ m$^{-3}$.

Figure 2. Microwave reflection measurements enable estimates of the electron density [3].

The optical emission spectrum of the fire column is measured by an AvaSpec-3648 spectrometer. A typical result shown in Fig. 3 reveals the titanium Ti-I and Ti-II lines at wavelengths in the range of 400–800 nm.

Figure 3. A typical emission spectrum of the fire-column.

Small-angle X-ray scattering (SAXS) analyses (performed at the ESRF synchrotron as in [2]) yield the dusty plasma parameters. The radius of gyration $R_g$, obtained by the IRENA SAXS unified fit analysis [4], ranges from ~3 nm for small particles to ~22 nm for agglomerated particles. The particles size distribution shown in Fig. 4 is obtained by the inverse Fourier transform of the scattered intensity $I(Q)$ versus the scattering vector $Q$ [2]. The size distribution of
the nanoparticles within the plasma and the particles density are still under study.

Figure 4. Small-angle X-ray scattering (SAXS) analysis of the titanium fire-column (following [2]).

SEM observations of the TiO₂ depositions show different forms of titanium dioxide on the collector and on the emitter (Fig. 5). The titanium dioxide obtained on the collector shows various crystalline morphologies, including elongated, hexagonal, and spherical forms, of the rutile (Fig. 5a), brookite (Figs. 5b and 5c), and anatase (Fig. 5d) phases. The particles found on the emitter are arranged in hexagonal, lamellar and column morphologies, which correspond to the brookite (Figs. 5e and 5f) and rutile (Figs. 5g and 5h) phases.

Figure 5. SEM images of TiO₂ nano-powders obtained in deposition periods of ~ 2 minutes on the copper substrate (a-d) and on the titanium emitter (e-h).

The XRD investigation (Fig. 6) identifies the anatase, brookite, and rutile crystalline phases of titanium dioxide (whereas the most abundant form is anatase).

3. CONCLUSIONS

The deposition of TiO₂ in air atmosphere is demonstrated by a technique involving microwave-generated plasma [2]. TiO₂ nanoparticles are observed in the diameter range of 10-150 nm by SEM and SAXS. The TiO₂ crystalline structures observed by SEM and XRD are anatase, brookite and some rutile.

Figure 6. XRD diffraction patterns of TiO₂ deposited on copper substrate.

This technique shows several advantages over the current methods, including its relatively faster nano-powder deposition, the processing in air atmosphere, the relatively low cost, the controllable layer thickness, and the versatility of the deposition substrate material (copper, glass, etc.)

Potential applications of this technique are considered for photovoltaic (PV) and solar-cell manufacturing, as well as for air cleaning, water purification, and photo-catalysts [5].

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Copper Solenoid for Continuous Operation of a 95 GHz Gyrotron

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SUMMARY

A copper solenoid for a 95 GHz Gyrotron is presently under development at Ariel University. The Solenoid provides a magnetic field of 1.8 T within the interaction region with homogeneity of ±0.5% at 40mm length. The solenoid is designed from six concentric cylindrical segments of copper foil winding, and one correction segment for achieving the desired homogeneity. Spacing of 5mm between the segments was left as a water cooling channel. Electromagnetic simulations of the magnetic fields and the electron trajectory was performed by CST and MatLab codes, and will be presented together with thermo-mechanical simulations, performed by COMSOL code.

Key words: Gyrotron, Copper Solenoid, 95 GHz, 1.8 Tesla.

1. INTRODUCTION

Gyrotrons [1, 2, 3] are dominant devices used for generation of millimeter wave radiation. In the gyrotron interaction region the electrons rotate due to a magnetic field and transfer energy to an electromagnetic wave within the cavity. The frequency of the radiation corresponds to the angular electron oscillations. Higher operating frequencies require higher magnetic fields. The magnetic field is aligned with the axial component of the electrons motion, and its homogeneity determines the performance of the gyrotron [4, 5]. Therefore the elements used to generate the magnetic field are key components in its operation.

The magnetic field within a gyrotron is typically obtained by several means: pulsed magnet [6], superconducting magnet [7, 8], and permanent magnet [9, 10]. The superconducting magnet requires cryogenic cooling which complicates the system. It also results in long turn-on time [10], therefore it is not suitable for gyrotron which a fast turn-on time is required. Permanent magnets induce constant magnetic field, but their weight is high [10]. Pulsed magnets cannot work longer than a few milliseconds.

Accordingly, the turn-on time, weight and price are the main advantages of water cooled DC solenoid, over the other alternatives. The main disadvantage of water cooled DC solenoid is the relatively high power consumption and problems of heat dissipation. In this work a water cooled DC solenoid for continuous operation of a 95 GHz gyrotron is presented.

1. METHOD AND RESULTS

The final simulated results of the magnetic field profiles are seen in Fig. 1, magnetic field homogeneity of ±0.34% over a length of 40mm is obtained. Velocity ratio and average guiding center radius meet the requirements. The solenoid is operated by a DC current of 725A. In order to reduce the power consumption and concentrate the magnetic flux into the cavity a solenoid with an iron shell [11, 12] was selected, shaped with tapered ends [13] as seen in Fig. 2. The required homogeneity was realized using a correction segment. CST simulation was used to optimize the solenoid and iron shell physical dimensions for the required field.

The solenoid is composed of six concentric cylindrical segments of copper foil winding and two additional correction segments. In each of the cylindrical segment there are 30 layers of foil copper windings with a 0.3 mm thickness and 0.05mm Kapton insulation layer. The length of the segments increases with radius. The correction segments are wound on copper tube which is electrically isolated from the cavity. Each segment has 7 layers with a distance of 34mm between.

![FIG. 1: Simulation of the magnetic field induced by the solenoid having a 40 m length homogeneity for the gyrotron interaction.](image)

3. CONCLUSIONS

A DC solenoid for a 95 GHz gyrotron is designed an fulfil the electromagnetic and thermal requirements.
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A Novel Investigation of the Ion Temperature and Hydromotion of Stagnating Z-pinch Plasma Using Stark-Broadened Line Shapes

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In imploding plasmas, there is a severe lack of detailed experimental data on the thermalization processes that govern the ion temperature at the stagnation phase, and on the energy delivered to radiation. Here, I report on a novel spectroscopic system, used to determine the temporally- and spatially-resolved ion temperature and total ion kinetic energy, as well as the electron temperature and density. We use a neon puff-on-jet Z-pinch, imploding under a 500-kA, 500-ns current pulse, and observe a hot-and-dense plasma core stagnating on axis for ~10 ns. A two-spectrometer diagnostic system is employed, simultaneously recording two groups of optically-thin lines: He-like satellites to Lyα and high-n H-like Lyβ and Lyγ lines, with ultra-high resolutions in spectrum, time and space. This novel system is a highly useful experimental tool, which provides invaluable, never-before-attainable insight into the dynamics of the stagnating plasma. The ion temperature is obtained as a function of time, by analyzing the ion-correlation affected shapes of the Stark-broadened high-n lines. The total Doppler width of the singlet satellite line yielded the total ion kinetic energy. The intensity ratio of two groups of triplet lines gives the electron density. The ion temperature is found to be substantially lower than the hydrodynamic-motion energy, the dissipation time of which is determined as well.

Keywords: High-Energy-Density Plasmas, Z-pinches, X-ray Spectroscopy.

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Effect of Electrode Materials (Produced Micro- and Nano-particles) on the Decomposition of Methylene Blue in Aqueous Solution by a Submerged Arc

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SUMMARY

The pulsed submerged arc (SA) can decompose contaminant molecules in water. Recently, SA decomposition of Methylene Blue (MB) contamination in aqueous solutions was demonstrated. It was shown that the particles eroded from the electrodes influence the decomposition efficiency. However, no comparative studies of effects of the particles eroded from Fe, Cu and Ti electrodes were conducted. The objective of this work was to determine the effects of Fe, Cu and Ti electrodes on the efficiency of MB decomposition in aqueous solutions. Electrode pairs of the same material and combinations of these materials were used. Solutions were treated using a SA with the electrodes in the presence of H$_2$O$_2$, and then were aged. The treated solutions were examined by absorption spectroscopy. The produced particles were studied by SEM, XRF and XRD.

In the presence of H$_2$O$_2$ in the solutions, SA treatment with Cu/Fe, Cu/Ti, Ti/Cu, Ti/Ti, Fe/Fe, Ti/Fe and Fe/Ti electrodes was more effective than with Fe/Cu or Cu/Cu electrodes. One week aging of the solutions treated in the presence of H$_2$O$_2$ with all electrode pairs very effectively decontaminated the solutions, reaching a decontamination ratio close to 99% (and it was only 89 and 72% for Fe/Cu and Cu/Cu electrodes, respectively). According to the XRD analysis, titanium peroxide was formed by SA treatment with Ti electrodes on the surface of particles eroded from the electrodes. We believe that Ti peroxide forms on the surface of eroded particles during SA treatment and gradually oxidizes MB during aging. A similar process can proceed on the surface of the particles eroded from Fe electrodes owing to Fe-peroxide compounds formed in Fenton chemistry during discharge.

1. INTRODUCTION

Plasma processes to treat water proceed by several mechanisms such as radical reactions, shock waves, ultraviolet radiation, ionic reactions, electron processes and thermal dissociation [1-4]. The pulsed submerged high-current and high voltage electrical discharge, i.e. a discharge between two electrodes in a liquid, referred to as an electro-hydraulic discharge [1], has been shown to oxidize many organic compounds [5-9]. The pulsed low voltage submerged arc (SA) can decompose contaminant molecules in water. Recently, SA decomposition of Methylene Blue (MB) contamination was demonstrated [2,9]. However, similarities and differences of the effects of particles eroded from different electrodes on decontamination efficiency have not been studied. The objectives of this research were determining and comparing these effects for the particles eroded from Fe, Cu and Ti electrodes. Electrode pairs of the same material and combinations of these were used.

2. METHOD AND RESULTS

Pulsed arcs were applied between low carbon (0.2%) steel 99.5% Ti and 97% Cu electrodes. Electrode pairs of the same material and combinations of these materials were used in a setup which was previously presented [2]. 40 ml samples of 10mg/l MB solutions, most containing 0.5% H$_2$O$_2$, were SA treated with the above electrodes. All solutions were prepared using deionised water. The SA comprised discharging a 15 μF capacitor charged to 80 V, and hence storing energy of 1.8 mJ, momentarily contacting and separating the electrodes, which were submerged in the solution. This was accomplished by mounting one of the electrodes on a vibrator, with vibration frequency of 100 Hz and amplitude of ~0.5 mm. This produced arc pulses with a 100 Hz repetition frequency, which was applied to the solution for 1-5 min.

The SA treatment was followed by aging of the treated liquid, i.e. storing it in the dark. The decontamination was monitored by absorption spectroscopy, specifically of the 664 nm MB absorption peak [10]. The eroded particles were examined by SEM, XRF and XRD.

Effect of electrode materials on MB removal during aging was studied using 48 μJ SA pulses for treatment during two minutes of the MB solution with 0.5% of H$_2$O$_2$ added before treatment. Fig. 1 shows influence of different electrode pairs on kinetics of the MB removal in the case. The removal for all used electrode pairs increased rapidly at first, and then slowed. MB removal reached 97-99% for aging solutions treated with Ti/Ti, Cu/Fe, Ti/Cu, Cu/Ti, Fe/Fe, Fe/Ti, and Ti/Fe electrode pair, and it was only 89 and 72% for Fe/Cu and Cu/Cu electrodes, respectively. Aging time for reaching the removal more than 90% increased in a series: Cu/Fe, Cu/Ti, Ti/Cu, Ti/Ti, Fe/Fe, and Fe/Ti, Ti/Fe.

Effect of SA treatment time on MB removal during aging was studied by arcing the MB solution during 1-5 min by 16mJ pulses with 10 μs duration of SA with Ti electrodes. Fig.2 presents influence of the SA treatment time on kinetics of the MB removal during aging. It is seen that, as in the previous case, the removal increased up to saturation (maximum) with aging time for all treatment times. The time of reaching the maximum removal decreased with treatment time.

The effect of H$_2$O$_2$ on the removal ratio is associated with Fenton reaction in the case of Fe/Fe electrodes [10] and with formation of Ti oxide and peroxide on the surface of the eroded particles in the case of Ti/Ti electrodes. Fenton reaction provides formation of OH$^-$ radicals (Fe$^{2+}$ is generated by SA from electrodes):

$$\text{Fe}^{2+} + \text{H}_2\text{O}_2 = \text{Fe}^{3+} + \text{OH}^- + \text{OH}^+$$
**3. CONCLUSIONS**

10 mg/L MB aqueous solutions were decomposed during both SA treatment and followed aging. During aging the removal, at first, rapidly increased, and then slowed up to saturation for all used electrode pairs and SA treatment duration. The degradation rate depended on material electrodes and electrode erosion, and also on treatment time, pulse energy and duration, and on aging duration.

MB degradation during aging occurred with higher rate (by factor ~2-3) for arcing with dissimilar electrodes one of which is Cu. The effect may be explained by MB catalytic oxidation by peroxide compounds supported and non supported by Cu oxides, CuO nanoparticles or the mixtures of CuO and other oxides.

The particles eroded from electrodes defined the type and concentration of oxidative species and the level of removal ratio after SA treatment. Decrease of the oxidative species concentration with SA treatment time leads to the low limited removal ratio for the electrodes.

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The BBGKY-Hierarchy and the Plasma-Sheath transition

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SUMMARY

An analysis of the problem of describing the ion dynamics in the sheath and pre-sheath regions is made. The analysis is based on the BBGKY-Hierarchy for the joint distribution functions of plasma ions and electrons which allows understanding the dynamical correlation between those particles near to and inside the sheath region. In previous treatment of this problem several authors have analysed the ion dynamics through the use of the Boltzmann equation applied exclusively to the ions. In such treatments, the electron dynamics is in certain sense decoupled from the ion dynamics, the only coupling being through the mean electric field created for both types of particles. The BBGKY-Hierarchy allows analysing simultaneously the correlated dynamics of plasma ions and electrons.

Key words: BBGKY-Hierarchy, cluster expansion, one-particle distribution function, joint distribution function, sheath, pre-sheath.

1. INTRODUCTION

When plasma is in contact with a wall, a boundary layer is formed between them. This layer consists of two regions: One in which the plasma is quasi-neutral and is called the pre-sheath, and a second one between the pre-sheath and the wall which is a region of net positive charge and is called the sheath. This layer is formed due to the large mobility of the plasma electrons, which allows the plasma electrons to escape from the plasma and to reach the wall faster than the plasma ions. In this way the plasma acquires a positive potential with respect to the wall. The potential gradient induces an electric field which confines the plasma electrons while stimulates the flow of ions toward the wall until a steady state is reached. The usual treatment of the plasma wall interaction [1, 2, 3] considers the ion dynamics independently of the electron dynamics and the only coupling between them is through the average electric field produced by both distributions of charges. This, in turn, affects those distributions in a self consistent manner. However it is clear that the dynamics of plasma ions and electrons have to be correlated in this boundary layer. In the present work the mutual correlation between the dynamics of plasma ions and electrons is studied by means of the BBGKY-Hierarchy by using the joint probability distribution functions and decomposing them in clusters or correlation patterns.

2. METHOD AND RESULTS

The BBGKY-Hierarchy [4,5] is a coupled set of differential equations for the joint distribution functions of a system of particles which interact through a given potential. The joint distribution functions are decomposed in clusters or correlation patterns. Each correlation pattern includes a correlation function and/or the one-particle distribution function. A perturbation method allows selecting the appropriate correlation functions for the problem under consideration. In this way the Hierarchy is cut and one obtains a closed system of integro-differential equations for the one-particle distribution function and for the correlation functions.

By assigning appropriate boundary conditions the problem can, in principle, be solved.

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Food Cooking by Microwave-Excited Plasmoid in Air Atmosphere

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SUMMARY
This study presents a cooking technique by a microwave-excited plasmoid ("fireball") in air atmosphere. The stable plasmoid is generated by localized microwaves from a liquid solution (e.g., salty water), and brought into direct contact with the food to be cooked. Experiments yield relatively rapid surface cooking of meat chunks within such plasmoids. Another approach is presented using a similar setup, in which the plasmoid serves as a means to convert microwave energy to heat, where the latter is conveyed indirectly by heat conduction to the food items. This method resembles a stovetop burner, with possible advantages of higher efficiency and the ability to use less conventional fuels, also possibly utilizing exothermic reactions. These techniques can be combined with direct microwave heating, as a hybrid microwave-plasmoid cooking within the same chamber, or as standalone methods devoid of microwave-food interactions. Experimental schemes and results are presented and discussed. Concerns regarding the presence of nanoparticles and free radicals in the direct fireball-cooking scheme are examined, but not definitively resolved. Energy consumption aspects are considered, and the feasibility of energy production by exothermic reactions is demonstrated. Future realizations of this technology are presented as well.

Key words: Microwave plasmas, microwave ovens, cooking, food browning, food safety.

1. INTRODUCTION
Microwave ovens, extensively used for volumetric food cooking and thermal processing, are well known for their quick, low-cost, easy-to-use, and safe heating of food [1]. Microwave cooking is preferred over conventional heating also because of its lesser effect on the original taste, and for various health-oriented reasons (such as [2]).

Plasma is used for fast sterilization in a non-toxic etching process which provides dry and low temperature conditions [3]. The utilization of microwave-excited gaseous plasma for rapid cooking, presented in [4-5], also adds color and texture to the food. Plasma can be generated more easily by localized microwaves both from solid and liquid substrates in forms of fire-columns and fireballs in air atmosphere [6]. However, these plasmoids are categorized as complex dusty plasma, and may contain nano-particles [7] which may be harmful for the food quality and even make it inedible [8]. Additionally, the fireballs tend to contain free radicals [6], which could present yet another health concern [9] that must be assessed and addressed.

In this study [10], we present three techniques for fast cooking of food items by microwave-excited fireballs ejected from salty water by localized microwaves. We present the experimental setups and results, with attention to safety issues and energy efficiency. The potentials and limitations of these plasmoids for cooking of food are discussed.

2. MATERIALS AND METHODS
In all three conceptual schemes, microwave energy is radiated into a cavity containing a conical water injector, which functions also as an electrode. The water substrate thus injected creates a plasmoid, which in turn converts the microwave energy and chemical energy of the substrate to heat. The three cooking schemes are described in Figure 1, the first being sole direct plasma cooking, the second hybrid plasma-microwave cooking, and the third indirect plasma cooking.

The microwave cavity is fed by a 2.45-GHz, 0.8-kW magnetron via an impedance-matching tuner, which measures the incident and reflected waves (amplitude and phase) as well. A thermal camera is used to measure the temperature of the food.

An optical spectrometer is used to analyze the spectral emissions of the plasmoid.

Figure 1. Conceptual schemes for direct (a) and indirect (b) cooking by microwave-generated plasmas [10]. The hybrid scheme of both microwave and plasma heating is accomplished by inserting the food to plasma within the cavity.

The cooked food’s surface is analyzed by ex-situ environmental scanning electron microscopy (ESEM) and its elemental content is revealed by energy dispersive spectroscopy (EDS) analysis. This analysis aims to assess the presence of nano-particles in the cooked food, as well as to examine the effect of the plasma cooking on the meat’s surface in comparison to other cooking methods.

In this study, chicken breast filet cubes of ~1.5 cm, weighing 3.5 g each, are used as the subject of the cooking experiments, inserted into the chamber on a ceramic skewer.
3. RESULTS

The microwave induced plasmoid is shown to be capable of cooking food effectively, where the cooking properties are dependent on the method, power, and exposure time.

When using the direct plasma cooking method (isolated from microwave irradiation as in Fig. 1a) the chicken cube is in direct contact with the fireball, and so is rapidly cooked. As shown in Figs. 2a, b, this result demonstrates the surface only cooking, as well as a certain degree of scavenging, which increases with exposure time. The thermal image of the chicken in Fig. 2c shows temperatures in excess of 500 K.

![Figure 2: The outer surface (a), cross section (b), and thermal imaging (c) of chicken cooked by direct plasma. Chunks cooked by microwave irradiation only (d), and by irradiation followed by direct fireball (e).](image)

Cooking a similar chunk with microwave irradiation only reveals the bulk cooking effect, leaving the surface raw and unappealing (Fig. 2d). If this chunk is then cooked by direct fireball exposure, the surface becomes cooked as well, along with a certain degree of browning (Fig. 2e). This demonstrates the hybrid cooking method [10].

In the indirect fireball cooking method, the copper pan is heated by the plasma fireball. Figure 3 depicts the temperature evolution of water in the pan, as well as the absorbed microwave power and radical temperature.

![Figure 3: (a) Temperature evolution of water in cooking pan, during fireball and fire-column modes, as depicted in inset. (b) Absorbed microwave power (green) and radical temperature (red) of the plasma corresponding to (a).](image)

The results show cooking comparable to that of a regular stovetop burner. For fireballs excited from salty water the efficiency is roughly 50%, and adding sucrose (C12H22O11) to the solution increases the efficiency to about 75%.

ESEM examination of the surface of the cooked chicken shows many salt (NaCl) grains, roughly 5 μm in diameter, but no metallic nano-particles. Also, the fireball cooking exerts a large amount of thermal stress on the chicken’s surface in comparison to microwave irradiation and even direct exposure to butane flame. This is expressed in high degrees of cratering, as well as annihilation of fiber formations on the surface.

4. CONCLUSIONS

The direct fireball cooking method presents a technique for rapid cooking and browning the surface of foods. It can be extended to a more complete cooking by using a hybrid with microwave irradiation. Concerns of nano-particle and free radical contamination have not yet been fully resolved.

The indirect method functions as a stovetop burner, displaying potential for higher efficiency (possibly even >1 microwave-to-heat energy conversion) and use of uncommon fuels, such as granulated sugar.

Future realizations of this technology could include a dual function microwave oven with a built-in additional plasma cooking chamber, using the hybrid method discussed.

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Submerged Pulse Arc Treatment of Water with Organic Compound Methylene Blue

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SUMMARY

Pulsed submerged arc (SA) treatment generates plasma vapour bubbles submerged within liquid, creating free radicals and oxidative species which cause the decomposition of the organic dye Methylene Blue (MB). The SA treatment was carried out in the reactor by 48 ml electrical discharges in a liquid between multiple movable electrodes, which are contacted repetitively. 600 ml deionized water (DI) and tap water solutions containing MB in a 10 mg/L concentration, were SA treated by using Fe electrodes with filtering cycle in intermissions between treatments (except for one reference unfiltered experiment). The treated solutions were examined by absorption spectroscopy. It was found that cyclic filtration greatly increases decomposition of MB (95.376% vs 24.719% for 8 minutes treatment in tap water), as well as treatment time (65-95.376% in tap water, 54.667-96.922% in DI water for 2 and 8 minute treatment time respectively). In addition there is a negligible difference between DI and tap water (40% for short treatment times and 0.4-3.6% for long ones), suggesting that conductance of water plays no major part in MB decomposition by SA. Effects of aging of the SA treated cyclically filtered solution seem also non consequential as high levels of MB decomposition were measured several days post treatment. For treatment times of 6 and 8 minutes, the range of MB decomposition was 91-97%, levels usually obtained with the addition of H₂O₂ prior to treatment (which was not done in this experiment).

Key words: submerged arc, Methylene Blue, decomposition, absorbance.

INTRODUCTION

[1] Many dyes and their breakdown products are toxic, one such dye is Methylene blue - MB. Due to aromatic rings present in dye molecules, conventional biological treatment does not effectively eliminate them. Dyes are generally not removed from wastewater by conventional treatment systems. It has been shown that plasma technologies can treat water using several mechanisms such as radical reactions, shock waves, ultra-violet radiation, ionic reactions, electron processes and thermal dissociation. It is suspected that these factors, singularly or synergistically, may be responsible for concurrently oxidizing trace contaminants and disinfecting microorganisms in water. In particular, the submerged pulsed high-current and high voltage electrical discharge, i.e. a discharge between two electrodes in a liquid, sometimes referred to as an electro-hydraulic discharge. However low voltage submerged arc-SA removal of (MB) from aqueous solutions has been reported recently and used in this experiment. The electrodes were constructed from iron, because of the possibility of producing Fenton's reagent (H₂O₂, Fe²⁺), which very effectively oxidizes organic compounds.

METHOD

The SA treatment was carried out by a power supply utilizing a 15 µF capacitor to generate 48 mJ electrical discharges. The experimental system is a large scale unique adaptation to contact mode SA. The electrodes used were multiple movable iron bolts weighing about 533 gr, laying on a much bigger circular Fe construction to which the power supply is attached, and repeatedly coming into contact with it while submerged inside a solution.

2 mediums were examined, 600 ml DI water and tap water solutions containing MB with 10 mg/L concentration. Cycle filtering was conducted between every 2 minutes of treatment time, consisting of simple liquid-solid separation using cleaning paper, with 20ml samples being taken before returning the solution to the system for further treatment. One reference solution was sampled after 8 minutes treatment time without filtration or pause during treatment.

The treated solution samples were examined several times in different hours post treatment, and were covered in foil paper to reduce natural decomposition.

The examination was done by absorption spectroscopy - a stellarNet spectrophotometer, all measurements were done with a glass cuvette using the SpectraWiz computer program with temperature compensation and about 200 ms integration time settings. The results were displayed graphically as in

![Figure 1. Typical absorbance spectrum for SA treated methylene blue, peak is around 670 nm.](image)
figure 1. And peak absorbance values were used to calculate removal%.

Based on the Beer-Lambert law of:
\[ A = \varepsilon \cdot l \cdot c \]

When \( A \) is the absorption, \( \varepsilon \) the extinction coefficient, \( l \) the optical path, and \( c \) the concentration, a removal percent can be calculated by:
\[ \text{Removal}\% = \left( 1 - \frac{A_{\text{sample}}}{A_{\text{reference}}} \right) \times 100\% \]

The removal percent being the decomposition of MB due to treatment.

RESULTS AND DISCUSSION

As seen in figure 2, the removal percent greatly increases for longer treatment times, suggesting that oxidative and/or highly active radicals are formed in the process as function of processing time and are the main cause of MB decomposition as evident also by figure 1 (decrease of absorbance for longer times), because MB natural decomposition is negligible as the reference absorbance is nearly the same throughout the testing. This point can also be seen in figure 3, in addition that the change is negligible depended on aging time for all curves save the one representing unfiltered solution. A comparison between the solutions themselves shows that for longer treatment times there is no significant difference.

A comparison between filtered and unfiltered tap water solutions treated for 8 minutes can be seen in figure 4. It appears that decomposition of MB in unfiltered solution varies greatly with aging time.

CONCLUSIONS

Cycle filtering increases MB decomposition exponentially, and is more efficient as longer the SA treatment time is.

Water conductivity does not play a dominant part in the process, meaning that organic contamination might be removed by this SA process regardless of water contents.

REFERENCES

Efficiency and Optimal charge in Bragg accelerator

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SUMMARY

We present the first steps of the design of the optimal parameters for the accelerator of a full Bragg X-Ray free electron laser. Aiming to a future source of coherent X-ray radiation, operating in strong Compton regime, we contemplate the system to be the seed for an advanced light-source or compact medical X-ray source. Here we focus on the design of the maximum efficiency.

Key words: XFEL, Bragg, Compton, Light source, Fluence.

1. INTRODUCTION

X-ray sources based on Compton scattering of a laser from a relativistic counter-propagating electron beam have been recently drawn increasing interest due to several potential advantages over magnetostatic FEL’s, such as: compact size, low-cost operation, reduced e-beam energy requirement. Any novel acceleration concept intended to exceed the performance of radio frequency (RF) based accelerators must demonstrate gradients of the order of 1 GV/m or higher, as well as a reasonable efficiency.

Recent work [1] demonstrated that x-ray radiation emitted by relativistic electrons scattered by a counter-propagating laser pulse guided by an adequate Bragg structure (weak Compton regime) surpasses by about 2 orders of magnitude the energy generated by a conventional free-space Gaussian-beam configuration, given the same e-beam and injected laser power in both configurations.

Based on this configuration, this work presents preliminary results of a design study for the accelerator of full Bragg configuration based X-FEL operating in the collective regime.

2. DESCRIPTION OS THE SYSTEM

The full system consists of 3 components (Figure 1.): an optical injector bunches the electrons to Accelerator Bragg structure which supports a TM_{01} mode. The co-propagating laser which accelerates the electrons is dumped at the end. Next, the electrons are transported to second Bragg waveguide that acts as an EM wiggler. This structure supports a TEM laser at vacuum core (TM mode at the Bragg layers) counter-propagating to the e-beam. This generates X-ray radiation (Inverse Compton scattering).

The Accelerator parameters to be examined are: Bragg structure, laser (TM mode) and optimal number of electrons in train of M micro-bunches. The EM wiggler parameters to be examined are: Bragg structure, laser (TEM-TM mode) and the XFEL process. In this work we discuss optimal optical accelerator parameters only.

A planar Bragg waveguide[2] consists of dielectric layers surrounding a sub-wavelength vacuum region which is symmetric relative to the central plane. The clearance is a vacuum region of width 2D_{vac}, surrounding alternating periodic layers. For a single mode operation: D_{vac}=0.25\lambda \rightarrow 0.55\lambda . The layers are made of two lossless dielectric materials. First layer has a relative dielectric coefficient \epsilon_1. For an optical accelerator having a vacuum core, surrounding layers must have an effective dielectric coefficient, smaller than unity i.e. \epsilon_{eff}<1 thus the need of a Bragg structure.

![Figure 1. Schematic of an all-Bragg system. On the left, the Bragg accelerator supports a co-propagating TM_{01} mode which accelerates the electron beam. The latter is injected into another Bragg structure which supports a TEM mode (inside the vacuum core) counter-propagating to the electrons that as a result generate x-ray radiation.](image)

There are many parameters that must be taken into consideration in a practical design. Three important parameters are gradient (see additional abstract “Fluence and Accelerating gradient in Bragg accelerator” in this proceedings), efficiency and optimal accelerated charge.

3. EFFICIENCY

Given the accelerating gradient G_a which was evaluated self-consistently, we calculate the optimal number of electrons in a microbunch injected into the acceleration module. Optimum charge occurs for maximum efficiency of the acceleration process.

i. Single bunch: In the single bunch case (M=1), the efficiency of the acceleration process may be determined by

\[
\eta = \frac{\Delta U_{\text{kinetic}}}{U_{\text{EM}}} = 4\eta_{\text{max}} \frac{q}{q_0} \left(1 - \frac{q}{q_0}\right)
\]  

where \(q_0 = G_a / \kappa\) is the charge for which the wake generated by the bunch balances the laser gradient. Maximum value of efficiency, occurring for \(q_{\text{opt}} = q_0 / 2\) is set by the projection of the total deceleration \(\kappa_i\) on the fundamental mode \(\kappa : \eta_{\text{max}} = \kappa / \kappa W_{\text{l}}\). In the case of a dielectric planar Bragg with a vacuum tunnel of 2D_{vac} along which a point charge propagates, the wake coefficient associated with the decelerating field is
\( \kappa = E^{\text{dec}} / q = 1/(4 \varepsilon_0 D_{\text{lum}}) \); \( \kappa_i = x \kappa \) is the wake coefficient of the first mode, where \( W_i \) is the weight function of the first mode. In other words, \( \kappa_i \) represents the beam-loading namely the wake projection on the fundamental mode.

**ii. Train of microbunches:** For the case of a train of \( M \) microbunches, the beam-loading causes different micro-bunches to experience a different effective accelerating gradient. In order to eliminate this effect, the laser pulse must be tapered according to

\[
G(t) = G_0 + \frac{L}{\tau_p} \kappa_\text{lab} (M - 1) .
\]

\( q_{\text{lab}} \) is the charge in one micro-bunch; all micro-bunches are assumed to be identical. It is assumed that for sufficiently large number of \( M \) the weight function of the first mode is 1, i.e. \( \kappa_i \sim \kappa \). The electromagnetic energy injected into the system may be readily calculated using

\[
U_{\text{emb}} = \int_0^t dP_q(t) = \int_0^t \frac{L^2}{Z_{\text{eff}}} G^2(t)
\]

(3)

together with Eq. (4), the efficiency in this case is given by:

\[
\eta = \frac{\Delta U_{\text{beam}}}{U_{\text{emb}}} = \eta_{\text{max}}(M = 1) \frac{12M\eta(1-\eta)}{1 + \beta_p L_{\text{beam}}/L_q}.
\]

(4)

By neglecting geometric length dependence on the charge (since it doesn’t change dramatically), the optimal charge is

\[
q_{\text{opt}}(M) = q_0 \frac{3 + 3(M - 1)(M + 2)}{(M - 1)(M + 2)} = q_0 \xi(M)
\]

(5)

Several facts are evident: (i) Maximum efficiency value depends on 2 parameters: the clearance and number of microbunches in a train. Figure 2 illustrate the efficiency and its maximum. (ii) For the case of a single bunch (\( M=1 \)) we get \( \xi(M-1)=0.5 \) and get the maximum efficiency which was calculated explicitly for single bunch. (iii) Comparing to the latter case, the efficiency may be more than doubled for \( M \sim 50 \). (iv) Figure 2 shows weak dependence of the maximum efficiency on the vacuum clearance and strong dependence on the number of micro-bunches.

The projection of the wake on the fundamental \( (W_i) \) increases with number of microbunches in the train (since higher frequencies are suppressed). Therefore, we should be able to enhance to some extent the efficiency for \( M>1 \), and increase the amount of charge accelerated. In this simulations we haven’t considered that point.

Another perspective of the energy conversion efficiency is the amount of charge accelerated and its distribution among the various numbers of micro-bunches. The number of electrons in a train as a function of number of micro-bunches is almost constant \(~4.5 \times 10^2\). Thus, for larger values of \( M \), number electrons in a microbunch drops. Figure 3 reveals weak dependence of \( q_{\text{lab}} \) and \( Mq_{\text{lab}} \) on the vacuum clearance.

**4. CONCLUSIONS**

1. For a train of microbunches, two constraints must be satisfied: laser pulse duration must be longer than the macro bunch length. The laser’s envelope must be tapered to compensate for the beam loading, ensuring uniform gradient acceleration of all micro-bunches.

2. Maximum efficiency value (~15%) depends on two parameters: weak dependence on the vacuum clearance and strong dependence on the number of micro-bunches.

3. Optimal number of electrons to be accelerated is determined by the laser field, and maximum efficiency requirement. For \( M=1000 \), the number electrons in a microbunch is \(~500\), while total number of electrons in the train is almost constant. There is weak dependence of \( q_{\text{lab}} \) and \( Mq_{\text{lab}} \) on the vacuum clearance.

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Temporal Evolution of Femtosecond Laser Induced Plasma Filaments

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SUMMARY

We present high resolution, time-resolved measurements of the relaxation of femtosecond laser induced plasma filaments. A simplified model of relaxation rate equations is proposed and compared to a more accurate simulation and previously used analyses techniques. We introduce an additional nano-second laser pulse that heats the initial electrons generated by femtosecond filament and dramatically extends typical plasma relaxation time.

1. INTRODUCTION

Ultra short laser pulses with power above a critical value, (for air) propagating in transparent media self focuses and generates a thin plasma filament on the wake of its propagation. This plasma forms a conducting path that can be used for many potential applications [1]. The initial free electron densities obtained in air filaments reaches values above \(10^{15} \text{ cm}^{-3}\), at such densities electron relaxation is dominated by the capture by parent ions, leading to a decrease of the electron density by two orders of magnitude within a few ns. It is generally assumed that at electron density values below, attachment by neutral oxygen molecules becomes the main recombination process giving rise to an exponential decay.

2. METHOD AND RESULTS

In this work, we present high resolution, single shot, time-resolved measurements of the relaxation of laser induced plasma filaments in air and in \(N_2\) gas. Plasma electron density and its temporal evolution are measured by monitoring the interaction of the plasma filament with low intensity continuous wave (CW) microwave (MW) propagating in a rectangular single mode waveguide [2]. By confining the interaction to a single mode of the waveguide we force the MW radiation to interact with the small plasma filament instead of diffracting around it, with low measurable effect (as would be the case in free space).

The plasma temporal decay is measured by disrupting the microwave signal and comparing the disruption pattern to a theoretical curve computed by air chemistry analyses [3]. This method enables a direct measurement of plasma filament generated by a single laser shot over complete process of plasma relaxation with spatial resolution along the filament of 0.5 cm and temporal resolution of 0.3 ns. By comparing measurements in Air to \(N_2\), we estimated the role of electron attachment to neutral \(O_2\) molecules and showed the importance of \(O_2\) recombination to the plasma filament relaxation.

Plasma temporal evolution, measured in the experiment, is compared to a numerical simulation of plasma relaxation in atmospheric conditions. The simulation is based on the CHMAIR code [3], that follows the evolution of a large number of species at a single spatial location. The model solves coupled rate equations for the densities of over 20 species, including molecular, atomic, ionic, and excited state species. Fig. 1 compares the time evolution of the simulated electron density and the experimental microwave signal. Best agreement between the two is achieved for initial electron density of \(n_0=1.6 \times 10^{14} \text{ cm}^{-3}\), for air and \(10^{15} \text{ cm}^{-3}\) for \(N_2\).

The agreement between the obtained and simulated signal is strongly effected on initial electron density. The change of 5% in the initial density leads to a significant deviation between the temporal profiles of the experimental and simulated signals. This demonstrates the capability to evaluate the electron density simply by observing the temporal profile of the MW signal.

In order to evaluate the contributions of main decay processes, the experimental curves are also compared to a simple set of relaxation rate equations, following the analyses previously presented by Tzortzakis et al. [4] and Ladouceur et al. [5]. Plasma relaxation was described by a simplified rate equation

\[
\frac{dn}{dt} = -\beta n^2 - \eta n
\]

(1)

here \(n\) is the electron density, \(\beta\) the dissociative recombination rate coefficient and \(\eta\) is the attachment rate coefficient. In air, the recombination term is dominant at electron density above \(10^{15} \text{ cm}^{-3}\) and is responsible to electron lost at the beginning of plasma relaxation, while at later time, when the electron density is relatively low, electron attachment to \(O_2\) molecules becomes the main decay mechanism. Electrons lost through attachment can be neglected in pure \(N_2\) resulting in much slower decay rate of electron population in \(N_2\) compared to Air for time later than a few ns. This effect can be clearly seen from examining the signals presented at Fig.1. The comparison between plasma decay in air and in nitrogen clearly shows the effect of electron attachment.
Fig 1. Experimental data and calculations. A second peak that appears at t=13ns at the experimental curve is an artifact caused by a parasitic reflection of MW in the waveguide, therefore experimental data points at 12ns<t<25ns were excluded from the fit. The experimental data is averaged over 50 laser shots.

We now introduce a simplified model that includes the contribution of $O_4^+$ and is sufficient to capture the physics of filament relaxation. The reactions and rate coefficients are summarized in eqs. 2-4.

$$\frac{dn}{dt} = -\beta n_o n_{O_4^+} - \eta n_e - \gamma n_{O_4^+} n_e$$  \hspace{1cm} (2)

$$\frac{dn_{O_4^+}}{dt} = -\beta n_o n_{O_4^+} - \alpha n_{O_4^+}$$  \hspace{1cm} (3)

$$\frac{dn_e}{dt} = -\gamma n_{O_4^+} n_e + \alpha n_{O_4^+} - \eta n_e$$  \hspace{1cm} (4)

Eqs. (2-4) are solved numerically for various initial electron concentrations. Best agreement to the experiment is achieved for $n_e(0)=1.4 \times 10^6 \, \text{cm}^{-3}$, as can be seen at Fig. 2, in good agreement with CHMAIR simulation. Comparison between the changes in numerical density of $O_4^+$ to the decrease in density of $O_4^+$ during the period of 1-10ns (see Fig.3) demonstrates the importance of recombination with $O_4^+$ to electron lost at densities below $2 \times 10^6 \, \text{cm}^{-3}$.

The sensitivity of our experimental technique to variations in electron density, and its high temporal resolution enables us to study filament interaction with additional nanosecond laser pulse. We have demonstrated the increase in plasma relaxation time and the triggering of laser induced breakdown by heating the filament with additional nanosecond laser pulse. The results clearly indicate on extension of filament relaxation time from a few ns to ~20 ns. At specific experimental conditions it is demonstrated that free electrons generated in the filamentation process can act as seed electrons and trigger avalanche breakdown of the medium under the effect of the heating laser.

3. CONCLUSIONS

In conclusion, we present a simple non intrusive method to measure the temporal evolution of plasma electron density in plasma filament. Contribution of various relaxation processes is studied thru simulation and a simplified model that is sufficient to capture the main physics of the relaxation process is proposed thus eliminating the need of complex simulations for experimental data interpretation. Our studies indicate that recombination with $O_4^+$ plays an important role in filament relaxation. In addition we have experimentally demonstrated a mechanism that allows one to extend plasma life time thus increasing filament length toward possible applications.

REFERENCES

Non-Diffraction in Cold Magnetized Plasma

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SUMMARY

Cold magnetized plasma possesses an anisotropic permittivity tensor with a unique dispersion relation that for adequate electron density and magnetic field, results in non-diffraction of a right hand circular polarized beam. In the present work, we demonstrate experimentally, for the first time, indication of non-diffraction of a microwave beam in plasma. For plasma possessing the necessary parameters and a wave below the cyclotron frequency, a significant increase in the received signal has been measured in plasma relative to non-ionized gas. Extensive work has been performed to characterize this signal increase and to confirm that it is an inherent effect of non-diffraction.

Key words: Non-Diffraction, Magnetized Plasma.

1. INTRODUCTION

Non-diffraction, a phenomenon in which electromagnetic waves propagate without diffraction through a medium has been demonstrated recently in a variety of systems, including photonic crystals [1], atomic systems [2] and nano-structures [3]. Although the mechanism varies between systems, the result is a substantial decline in the expansion profile of the finite-size wave in comparison to free-space.

Unlike self-focusing, in which the electromagnetic wave induces a change in the refractive index of the media, in the case of non-diffraction the electromagnetic wave has little effect on the refractive index of the medium. The non-diffraction effect occurs due to unique intrinsic characteristics of the medium.

Zhang et al. [4] have proposed cold magnetized plasma as such a medium which shall demonstrate almost diffractionless propagation of the electromagnetic waves in the direction of the magnetic field. The reason is that magnetized plasma possesses a unique dispersion relation which under the correct conditions will induce non-diffraction of right hand circular polarized electromagnetic waves below the cyclotron frequency.

In this work, experimental evidence for the existence of non-diffusive propagation of electromagnetic radiation in cold magnetized plasma is demonstrated for the first time. Initially, the theoretical basis for the occurrence of the non-diffraction effect shall be briefly reviewed. Next, the experimental system shall be presented and finally, a small example of the experimental results providing evidence for non-diffraction will be presented and discussed.

The dependence of the dispersion relation on the angle of propagation is a unique feature of the plasma, quite different from other media, which leads to the effect of non-diffraction. Zhang et al. proposed [4] to review Equi-Frequency Contour (EFC) plots of plasma to examine the effect. Thus, an EFC plot has been derived and is displayed in Figure 1a. From these results it is clear that the RHCP (Right Hand Circular Polarized) wave can only propagate through the plasma for small angles in respect to the magnetic field direction, unlike the LHCP wave, which can propagate at almost all angles.

![Figure 1. Top - Comparison between EFCs of different electron densities. These EFCs were calculated for a frequency of 7.9 GHz, an external magnetic field of 0.35 T and an electron density of (a) $10^{12}$ cm$^{-3}$ and (b) $10^{11}$ cm$^{-3}$. Note that for (b) the EFC is similar to the EFC in vacuum, allowing propagation at all angles. Bottom - Numerical COMSOL simulation of propagation of a beam generated from a slit for a plasma of respective density.](image-url)
2. METHOD AND RESULTS

In this series of experiments, pulsed cold magnetized Argon plasma was produced by a double folded Boswell type paddle-shaped antenna. This plasma was produced within a vacuum chamber, consisting of a central glass tube of 40 cm long and of a diameter of 17 cm. The measurements were performed at an axial magnetic field of approx. 0.4T corresponding to the electron cyclotron frequency of 11 GHz. The experimental measurements were at electron temperature of few eV and the plasma electron density obtained during the period of interest was $10^{12}$ cm$^{-3}$ corresponding to a plasma frequency of 9 GHz. Tapered Circular Polarized antennas were used for transmission and reception of the microwaves. The transmitting and receiving antennas were positioned internally, inside the plasma chamber. Initially, it was necessary to obtain a positive indication for the existence of non-diffraction in plasma. Thus, first experiments in which transmitting and receiving RHCP antennas that were placed on opposite sides on the main axis of the plasma chamber displayed a significant increase in the measured signal for plasma compared to the signal obtained for non-ionized gas.

As presented in Figure 2, a 100 μs, 7.9 GHz pulse has been transmitted through the plasma, and has been transmitted in the identical configuration, without ionization. A substantial increase is observed in the received signal for plasma. Such an effect of signal strengthening poses direct evidence for the existence of non-diffraction in plasma.

Throughout this work, experiments have been performed to characterize this effect, to provide additional evidence in support of our argument and also to disqualify any alternative phenomena that could account for such a signal increase. It is important to mention that the signal increase occurs almost immediately after the return from cutoff and for a brief period. Measurements of the plasma density at this period have shown that the density in this time is approx. $10^{12}$ cm$^{-3}$. Upon examination of the EFC pattern, it can be realized that the non-diffraction effect is no longer dominant at electron densities lower than $7.7 \times 10^{11}$ cm$^{-3}$. Interestingly, this is approximately the point where the microwave transmission frequency is equal to the plasma frequency. A further decrease in density leads to a change in sign for an element in the permittivity tensor from negative to positive. It has been determined [5-6] that such a negative element in the permittivity tensor holds remarkable consequences for the electromagnetic properties of the material. An example is given in Figure 1 in which a comparison is presented between EFCs of different electron density.

3. CONCLUSIONS

As was previously presented, this effect of signal increase occurs only at the densities predicted by the theoretical model and for a variety of frequencies. Additional experiments have confirmed a direct dependence of the effect on transmission power and it has been observed that the ratio of signal increase is greater for antennas with greater beam divergence. The effect has also been confirmed in aspects of spatial pattern and for a reflected beam.

In addition, the effect features and additional experiments performed have helped to confirm that the signal increase is not generated as a result of reflections, rotation of the polarization plane, improvement of antenna matching by the plasma, interference on the signal or density gradients within the plasma. This effect of non-diffraction is essentially limited, by the absorption of the wave by the plasma. To summarize, this is the first time evidence has been provided for the existence of non-diffraction in cold magnetized plasma, all measurements show that this effect is indeed an indication of diffractionless propagation. Perhaps plasma may also display additional optical effects previously witnessed in other systems.

REFERENCES


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