PLASMA DYNAMICS AND PLASMA-WALL INTERACTION

COMMENTS ON RECENT ACHIEVEMENTS OF RESEARCH ON DENSE MAGNETIZED PLASMAS IN POLAND

M.J. Sadowski $^{1\text{-}2}$

^{1}***National Centre for Nuclear Research (NCBJ), Otwock-Świerk, Poland;***
^{2}***Institute of Plasma Physics and Laser Microfusion (IFPiLM), Warsaw, Poland***

This invited lecture presents author's comments on results of the experimental studies of dense and high-temperature plasmas, which were carried out in Poland during recent two years. Those studies were performed with the PF-360U device at NCBJ, and the PF-1000U facility at IFPiLM. There were investigated fast electron beams and soft x-rays, an influence of thin metal wires and/or an admixture of heavier gases, an influence of a shape of the anode end, as well as plasma micro-structures in a pinch column, i.e. plasma filaments and hot-spots (of electron densities > 10^{19} cm^{-3} and electron temperatures ranging several keV). The detailed studies concerned also the VR and x-ray emissions, estimates of local electron temperatures, and fast deuteron beams. Other experiments were devoted to investigation of plasma jets which can have dimensionless parameters corresponding to astrophysical objects. There are also presented some examples of the technological applications of PF discharges, studied in a frame of the Polish-Ukrainian scientific collaboration. The author's comments are followed by proposals of some future theoretical and experimental studies.

PACS: 52.50.Dg; 52.58.Lq; 52.59.Hq; 52.40.Hf; 52.70.-m

INTRODUCTION

The experimental and theoretical studies of high-temperature plasmas in Poland were initiated about 70 years ago. They were carried out mainly at the Institute of Nuclear Research (IBJ, later IPJ in Swierk n. Warsaw), which in 2011 was converted in the National Centre for Nuclear Studies (NCBJ). The Department of Plasma Physics and Materials Engineering (PV) was then split into the Plasma/Ion Beam Technology Division (FM2) and Plasma Studies Division (TJ5). In April 2018 the TJ5 department was combined with a Department of Detectors Physics and Plasma Diagnostics (TJ3). The results of earlier research on hot plasmas and controlled fusion were described in many papers and reported at international conferences, including those held in Kharkov [1-2].

Plasma research in Poland embraced various topics, e.g. laser experiments, tokamaks, technology etc., but the main aim of this invited talk was to present the author's comments on the studies of dense magnetized plasmas, which have been performed after the previous conference ICPPCF-2016, and to present some new proposals.

1. STUDIES OF FAST ELECTRON BEAMS AND SOFT X-RAYS FROM PF DISCHARGES

Initially some time-integrated visible radiation (VR) pictures were compared with x-ray pinhole images in order to identify plasma microstructures (Fig. 1).

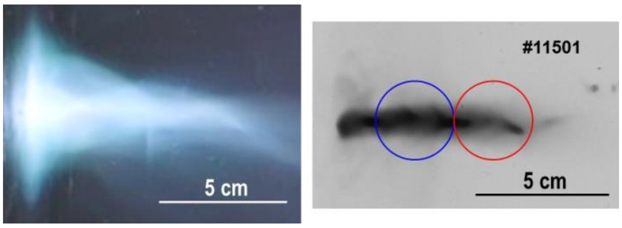

Fig. 1. Time-integrated VR picture and x-ray pinhole image of a PF-1000U discharge performed at U_o *= 23 kV,* p_0 *= 1.2 hPa (*D_2*+1% Ne) +* D_2 *puffing [3]*

During recent two years particular attention was focussed on detailed studies of fast electron beams (e-beams) and soft x-rays (SXR) emitted from high-current discharges of the plasma-focus (PF) type.

Measurements with x-ray pinhole cameras and filtered PIN diodes, which were carried out with the PF-360U device at NCBJ (Otwock-Swierk n. Warsaw) and the PF-1000U facility at IFPiLM (Warsaw), demonstrated that the x-ray pinhole images show fine plasma structures (filaments, hot-spots) in the pinch column. The most important observations of the x-rays and some estimates of local electron temperatures (T_e) were summarized in a lecture given at ICPPCF-2016 [3]. Measurements with different magnetic analysers proved that the fast e-beams can get energy up to hundreds keV, and their emission is correlated with the formation of hot-spots [4].

2. RESEARCH ON INFLUENCE OF A THIN METAL WIRE ON PF PINCH COLUMN

Next experimental studies concerned an influence of a thin metal wire immersed in a PF pinch column [5]. The Al-wire (of 270 μm in diameter and 10 cm in length) was placed along the PF-1000U electrodes axis by means of a holder, which was fixed without any connection with the anode.

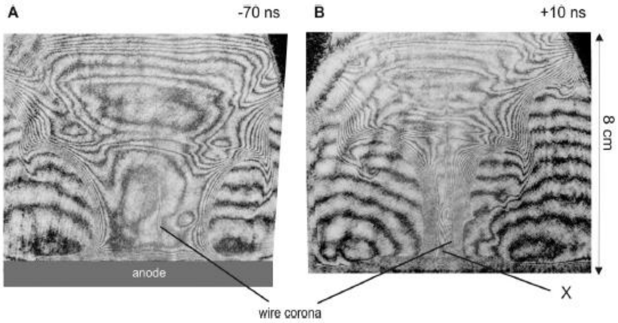

Fig. 2. Interferometric images recorded for shot #10633: (A) during the implosion of the current sheath and formation of the Al-wire corona, (B) during the formation of the internal plasmoid

Detailed measurements of the voltage waveforms, current derivative, and the total discharge current vs. time, were performed for discharges of 350 kJ energy, at the maximal current reaching 1.5…1.7 MA. Time-resolved SXR in the energy range of 0.7…15 keV were measured with a Si-PIN diode filtered with a 10-μm-thick Be-foil.

Time-integrated x-ray pictures were taken with a pinhole camera equipped with the identical Be-filter. The use was also made of a sophisticated laser interferometer system which made it possible to obtain up to 15 frames during a single discharge [6]. The interferometric images of the PF-1000U discharges were recorded at different instants and analysed in details (Fig. 2).

The ultraviolet (XUV) radiation from PF discharges was detected by means of a multi-channel plate (MCP) without any filter, which could record photons of energy > 10 eV [5]. A comparison of the XUV and inteferometric images provided additional and valuable information about transformations of the pinch column (Fig. 3).

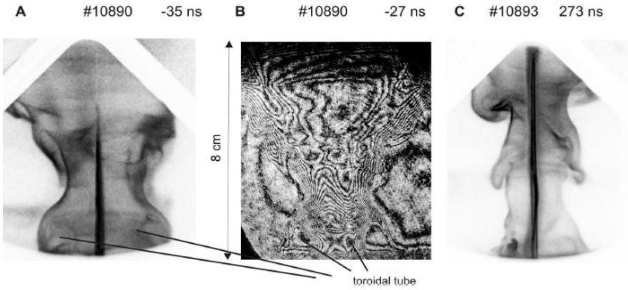

Fig. 3. Images of a plasma column and the wire corona: (A) a XUV frame, and (B) an interferometric image, taken during the first SXR and neutron pulse: (C) another XUV frame taken at the late phase of the XUV emission [5]

An important finding was the observation that the insertion of the Al-wire does not prevent the formation of dense plasmoids and the production of fusion-neutrons during transformations of the PF column, if the corona is not broken [5].

The next experiments with the Al-wire placed along the pinch axis in the PF-1000U facility were performed at the helium-filling [7]. Such discharges have also produced pinches containing spontaneously organized structures of the helical-, toroidal- and plasmoidal-type, but dynamics was considerably slower. The production of hard x-ray (HXR) pulses was different, since in the D-shots they were generated mainly during the instability evolution, while in the He-discharges they were emitted during the formation of the first internal plasmoid [7].

In author's opinion the use of a metal wire is not a good method for the optimization of PF discharges, since the introduction of relatively cold metal ions reduces the neutron yield (Y_n). It might be reasonable to perform experiments with the use of a frozen-deuterium wire, which might be completely vaporized and increase the deuterons density, as in some Z-pinch experiments [8].

3. STUDIES OF INFLUENCE OF N_2 ADMIXTURE ON EVOLUTION OF A D_2 PINCH COLUMN

The next series of experiments concerned research on an influence of a heavier gas (e.g. nitrogen) admixture on dynamics of a pinch column [9]. Detailed interferometric measurements enabled different phases of the pinch transformation to be investigated (see Fig. 4).

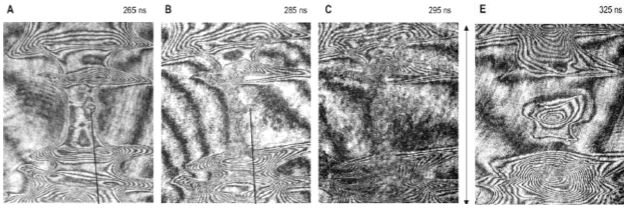

Fig. 4. Interferometric images corresponding to different phases: (A) implosion of a constriction, (B) the minimal constriction diameter, (C) expansion and HXR emission, (E) pinch interruption (formation of separate plasmoids). The presented part of the pinch column is 5 cm in length

Measurements of the XUV radiation, as performed with the framed MCP, provided interesting information about filamentation of the pinch column (Fig. 5).

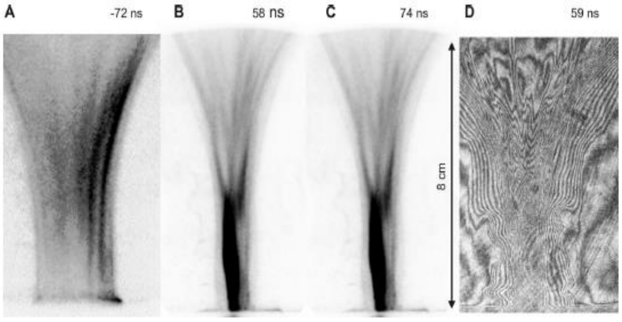

Fig. 5 XUV images recorded at various instants: (A) -72 ns, (B) +58 ns, (C) +74 ns, and the interferometric image (D) which shows some filaments in the top corners

It was found that the current filaments, as recorded during the implosion and the pinch phase, had 1…2 mm in diameter and the electron density ranging $(3…7)\cdot10^{24}\,m^{-3}$. Reconnections of magnetic field lines (originating from such current filaments) induced strong electrical fields, which could accelerate electrons and ions to energies of hundreds kiloelectronvolt [9]. These processes influenced also on the DD fusion reactions rate and neutron yields.

In author's opinion the current filaments, which can easily be observed in discharges with the application of a heavier gas admixture, are indeed responsible for the generation of strong magnetic fields. Transformations of these magnetic fields can induce strong local electric fields responsible for the acceleration of ions and electrons, but one should also take into account local disruptions of filaments, when the separation of electrical charges in dense plasma can also induce very strong local electric fields [10]. Such disruptions (filaments necks) can form point-like sources of fast deuteron beams.

4. STUDIES OF FILAMENTATION PHENOMENA

The studies described in Section 3 were followed by detailed observations of current filaments in the pinched column of PF-1000 discharges at the D-filling and D-puffing [11]. There were observed many plasma filaments and hot-spots (lasting > 50 ns), which moved within a plasma stream. For the first time there were observed very small "plasma balls" outside the pinch column, which appeared during the early discharge phases (Fig. 6).

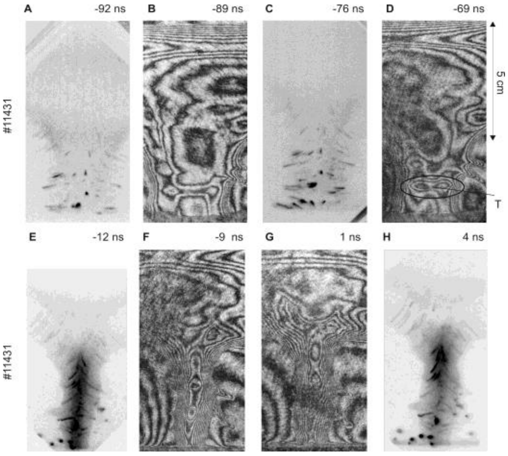

Fig. 6. XUV and interferometric images of early phases: (A-D) during the current sheath implosion, (E-H) during the emission of the 1st peaks of x-rays and neutrons [11]

Many tiny plasma filaments and "plasma balls" were also observed in the XUV frames recorded during the late phases 100…200 ns of the PF-1000 discharges [11]. Similar observations were performed at D-filling and H-puffing, as well as at H-filling and D-puffing, but in general the described micro-structures were more distinct when a heavier gas admixture was applied [11].

In author's opinion the observed plasma micro-structures, visible in the XUV frames, can hardly be identified in the interferometric images due to their small dimensions and too small gradients in the electron density. The observed tiny plasma filaments can have various directions (from quasi-axial to quasi-radial), what probably depends on the direction of an Ampere force (of the discharge current and its own magnetic field) or a Hall current (depending on the main discharge electric- and magnetic-fields). It should be remind that the quasi-axial filaments inside the pinch column were for the first time observed many years ago in other PF and Z-pinch experiments [12, 13]. The author is convinced that research on plasma-current filaments and hot-spots should be continued, and new efforts should be undertaken to develop corresponding physical models.

In a frame of the Czech-Polish scientific collaboration there were performed studies of transformations of the ordered internal plasma structures during the acceleration of fast charged particles in PF discharges [14]. The collected data provided detailed information about pinch dynamics and other characteristics (Fig. 7).

The reported studies confirmed that the 1st neutron pulse is produced by fast deuterons accelerated by transformations of the internal plasma structures, and it is emitted during formation of the 1st plasmoid, while the subsequent neutron pulses are generated later, during the development of strong instabilities.

In author's opinion these statements are consistent with conclusions from earlier experiments performed within other PF facilities [15], but new information is provided by high-quality intereferometric images.

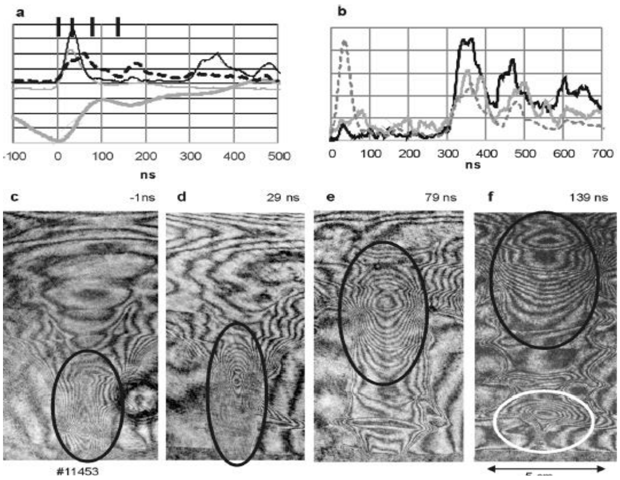

Fig. 7. Waveforms: (a) dI/dt (thick grey), SXR (thin grey), HRX (thin black), neutrons (dashed), (b) signals from scintillation detectors: downstream (black), upstream (grey), and side-on (dashed); Interferometric images: (c) formation of a plasmoid, (d-f) formation of necking [14]

5. INVESTIGATION OF AN INFLUENCE OF A CONICAL TIP PLACED IN THE ANODE-CENTRE

The next PF-1000 experiments concerned research on an influence of a shape of the anode end. A metal conical tip was fixed at the centre of the anode end-plate [16]. It changed the formation of the pinch column and its characteristics (Fig. 8).

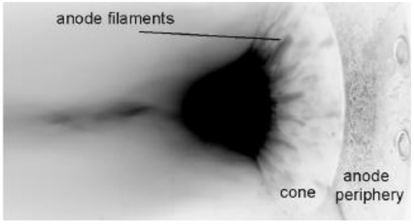

Fig. 8. VR picture, showing that current filaments had quasi-stabile positions upon the anode surface, and the pinch column had a distinct micro-structure

Measurements of the *I(t)* and *dI/dt* waveforms, the SXR and HXR peaks, as well as detailed studies of the pinch structure by means of the laser interferometer, were also performed (Fig. 9).

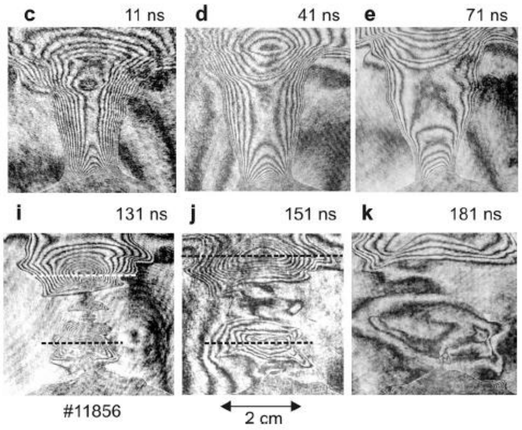

Fig. 9. Interferometric images of different phases of a discharge with the anode conical ending: (c-e) the stagnation phase, (i-k) a decay of the internal plasmoids

The use of the metal tip facilitated motion of current filament upon the anode surface, and influenced the pinch formation, and dynamics of the internal plasma micro-structures. For a comparison, during the reported experiments, there were performed 16 shots without any anode-tip and 29 shots with the conical tip [16]. The average value of Y_n increased from $(0.8 \pm 0.3) \cdot 10^{10}$ to $(5.3 \pm 2.0) \cdot 10^{10}$, but a jitter in Y_n was also increased.

In author's opinion the observed increase in Y_n could be induced by changes in the dimensions and dynamics of the pinch column, but one should remember about erosion of the anode surface and an inflow of metal ions. It should also be noted that conical tips were applied in earlier PF experiments [17], to produce more stable hot-spots, which served as local sources of fast electrons and x-rays.

6. STUDIES OF VR, X-RAYS (FOR ESTIMATES OF LOCAL T_E), AND FAST DEUTERONS

The earlier studies of the VR and x-ray emission from PF discharges (see above) were followed by more detailed investigation of the optical spectra, x-ray pulses, and fast deuteron beams [18]. The optical emission spectroscopy (OES) was applied to record the Balmer D-lines and lines of impurities (Fig. 9).

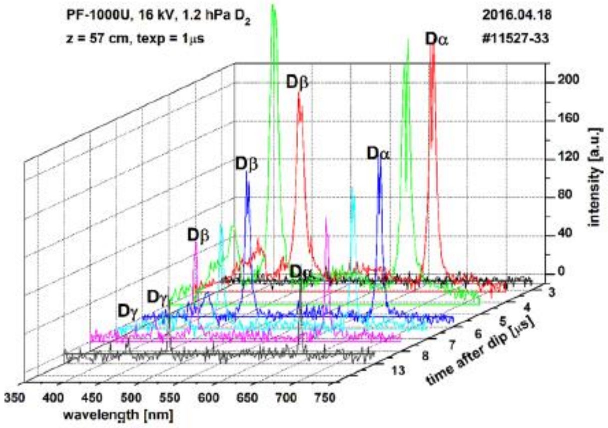

Fig. 10. OES spectra recorded vs. time after a current dip

Attention was focused on time-integrated and time-resolved measurements of the SXR emission. X-ray signals were collected by two pairs of filtered PIN diodes which observed the chosen regions of the pinch column (see as shown in Fig. 1). The SRX signals were compared, and T_e values (averaged over the observation regions) were estimated. They depended on experimental conditions, i.e. the pressure and composition of working gas (Fig. 11).

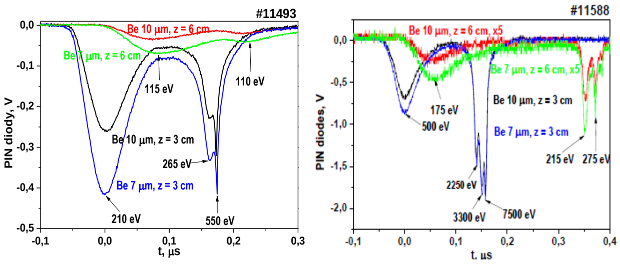

Fig. 11. X-ray signals from two pairs of PIN diodes and different shots: (left) at 1.2 hPa D_2 + D_2 puffing, (right) at 1.2 hPa (90 %D_2+10 %Ne) + (75 %D_2+25 %Ne) puffing

The research described above was followed by detailed studies of fast deuterons and fusion-neutrons [20]. The measurements of the characteristic discharge waveforms were supplemented by the laser interferometry and measurements of deuteron beams, which were performed by means of pinhole cameras equipped with nuclear track detectors (Fig. 12).

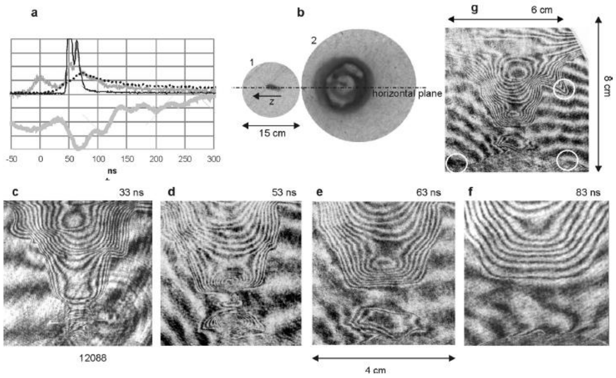

Fig. 12. Waveforms: (a) current derivative (thick grey), SXR (thin grey), HXR (black), fusion neutrons (dashed); (b) Deuteron images (> 360 keV, at 60^0 and 0^0); Interferograms: (c) before the x-ray and neutron pulse, (d) during the pinch interruption, (e-g) after that

The most important was the statement that the fast deuterons are emitted as numerous beams from different pinch regions and tops of plasma lobules, formed outside the dense plasma column. Trajectories of these deuterons are strongly deflected by local magnetic fields.

In author's opinion the described studies are consistent with earlier ion measurements, but should be followed by more detailed investigation. The SXR signals should be taken from smaller plasma regions, which can be defined by appropriate pinholes. The emitted ions should be measured in more details in order to determine their mass- and energy spectra, as well as their dependence on the experimental conditions.

7. STUDIES OF DEUTERIUM AND HELIUM PLASMA JETS IN PF DISCHARGES

The recent studies of dense magnetized plasmas concerned also the generation of so-called plasma jets [21-22]. The scientific collaboration of the Polish and Russian teams enabled the formation of a dense plasma jet to be observed (Fig. 13).

Fig. 13. Time-integrated picture of a plasma jet generated in the PF-1000U facility by a discharge #11541 at p_0 = 1.2 hPa D_2, U_0 = 16 kV, and I_{max} = 1.4 MA

Those studies showed that such plasma jets can have dimensionless parameters, i.e. the Mach-, Reynolds- and Pécklet-numbers as well as density contrasts ($n_{jet}/n_{ambient}$), similar to those observed in astrophysical objects [21]. It was also shown that the simulation of some astrophysical jets in a laboratory is possible with the use of different PF facilities (in Moscow, Warsaw, and Sukhumi) [22].

Recently, more detailed studies of the influence of gas conditions on parameters of plasma jets generated in the PF-1000U facility have been performed and summarised in a new paper [23].

In author’s opinion such experiments are of primary importance for further simulations of astrophysical phenomena, but one should take into account considerable differences in parameters of plasmas generated within various PF machines. An attempt should be undertaken to obtain the best consistence of characteristic parameters.

8. APPLICATIONS OF DENSE PLASMA STREAMS FROM PF DISCHARGES

During recent years the experimental studies, which concerned applications of plasma streams produced by PF discharges, were performed in a frame of the bilateral Polish-Ukrainian scientific collaboration. As an example one can mention investigation of plasma interactions with tungsten samples in the PF-1000U facility [24], but it should also be noted that studies of plasma-surface interactions were also carried out with other plasma facilities, e.g. the RPI-IBIS in Swierk [25] and QSPA in Kharkov [26, 27]. Other examples of the material studies are reported in another presentation at the ICPPCF-2018 [27].

9. SUMMARY AND CONCLUSIONS

The detailed comments on described research activities have been given in the previous sections. The most important comments can be summarised as follows: 1. A thin axial metal-wire can slightly increase an averaged Y_n, but an inflow of metal ions changes other emission characteristics; 2. Filaments and hot-spots constitute important forms of the internal plasma structures, and they should be further investigated experimentally and theoretically; 3. The use of a conical tip upon the anode improves slightly parameters of the pinch column, but the problem is strong erosion of this tip surface; 4. The ordered internal plasma structures in PF discharges have already been investigated, but more experimental data and theoretical analyses are still needed; 5. Simultaneous measurements of x-rays, e-beams and fast ions, coupled with detailed interferometric studies, have already been performed, but their precision should still be improved; 6.

The generation of dense plasma jets in PF facilities has been studied, but some optimization of this process is still needed; 7. Applications of dense plasma streams for material engineering have been investigated, but they should still be further developed.

On basis of the reported results the author has proposed to perform new PF experiments with the use of a frozen-deuterium fibre. Also proposed are further detailed studies of filaments and hot-spots. Since these phenomena do not preserve the cylindrical symmetry, it is necessary to apply a 3D mhd-code or to develop a more sophisticated model, e.g. kinetic approach. Transformations of other internal plasma structures require also a theoretical analysis. More precise measurements of x-rays, e-beams and fast ions should also be performed, and the generation of plasma jets should be studied in more details. Applications of PF facilities for material engineering should be extended on new materials. It would be reasonable to realize such advanced studies in a frame of research activities at the International Centre for Dense Magnetized Plasmas.

ACKNOWLEDGEMENTS

The reported studies were supported by Grants MSMT LTT17015, LTAUSA17084, GACR 16-070365, IAEA CRP RC-19253, and SGS 16/223/OHK3/3T/13 in Czech Republic, the RSF Project No. 16-12-10051 in Russia, IAEA CRP RC-23071 in Poland and the financial resources allocated by the Polish Ministry of Science and Higher Education for inter-national co-financed projects at IFPILM in years 2017-2018.

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Article received 13.09.2018

КОММЕНТАРИИ О ПОСЛЕДНИХ ДОСТИЖЕНИЯХ В ИССЛЕДОВАНИИ ПЛОТНЫХ ЗАМАГНИЧЕННЫХ ПЛАЗМ В ПОЛЬШЕ

M.J. Sadowski

Представлены комментарии автора о результатах экспериментальных исследований плотных и высокотемпературных плазм, которые проводились в Польше в течение последних двух лет. Эти исследования проводились на установках ПФ-360U в Национальном центре ядерных исследований и ПФ-1000U в Институте физики плазмы и лазерного микросинтеза. Особое внимание уделялось изучению быстрых электронных пучков и рентгеновского излучения, влияния тонких металлических проволок и/или смеси тяжелых газов, влияния формы анода, а также плазменных микроструктур в пинче, т.е. плазменных нитей и горячих точек с электронной плотностью > 10^{19} см$^{-3}$ и электронными температурами порядка нескольких килоэлектронвольт. Детально описано также исследование видимого и рентгеновского излучений, оценки локальных электронных температур и пучков быстрых дейтронов. Другие эксперименты были посвящены изучению плазменных струй, которые имеют размеры соответствующие астрофизическим объектам. В рамках польско-украинского научного сотрудничества представлены некоторые примеры технологического применения ПФ-разрядов. Автор предлагает некоторые теоретические и экспериментальные идеи для последующих исследований в этой области.

КОМЕНТАРІ ПРО ОСТАННІ ДОСЯГНЕННЯ В ДОСЛІДЖЕННІ ГУСТИХ ЗАМАГНІЧЕНИХ ПЛАЗМ У ПОЛЬЩІ

M.J. Sadowski

Представлено коментарі автора про результати експериментальних досліджень щільних і високотемпературних плазм, що проводилися в Польщі протягом останніх двох років. Ці дослідження проводилися на установках ПФ-360U у Національному центрі ядерних досліджень та ПФ-1000U в Інституті фізики плазми і лазерного мікросинтезу. Особливу увагу приділено вивченню швидких електронних пучків і рентгенівського випромінювання, впливу тонких металевих дротів і/або суміші важких газів, впливу форми анода, а також плазмових мікроструктур у пінчі, тобто плазмових ниток і гарячих точок з електронною густиною > 10^{19} см$^{-3}$ і електронними температурами близько декількох кілоелектронвольт. Детально описано також дослідження видимого та рентгенівського випромінювань, оцінки локальних електронних температур і пучків швидких дейтронів. Інші експерименти були присвячені вивченню плазмових струменів, які мають розміри, що відповідають астрофізичним об'єктам. У рамках польсько-українського наукового співробітництва представлені деякі приклади технологічного застосування ПФ-розрядів. Автор пропонує деякі теоретичні та експериментальні ідеї для подальших досліджень у цій області.