PROGRESS IN DENSE MAGNETIZED PLASMA RESEARCH IN POLAND; A REVIEW

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Abstract

This invited talk describes recent dense magnetized plasma (DMP) experiments carried out with different Plasma-Focus (PF) facilities in Poland, which were investigated at energy levels ranging from 40 kJ to about 800 kJ. The most important results, which were obtained with MAJA-PF and PF-360 devices in Swierk, are presented. Also presented are some results obtained with PF-150 and PF-1000 facilities at IFPiLM in Warsaw. The main trends of the present DMP research are described and commented.

1. Introduction

Theoretical and experimental studies of DMP phenomena were started in Poland in the late 50s, initially with so-called multi-rod plasma injectors (RPIs). In the 60s there were initiated studies with the use of PF devices of the Mather-type. The first PF-20 and PF-150 facilities (of nominal energy ranging from 20 kJ to 150 kJ) were constructed at the Institute for Nuclear Research (IBJ) in Swierk, and later on they were investigated at the Military Academy of Technology (WAT) in Warsaw. Those early PF devices were used to study basic PF phenomena and to gain experience in experimenting with DMPs, and in particular to investigate fusion-produced neutron pulses. The most important results of those studies were reviewed at the previous Ukrainian Conference in Alushta in 1998 [1].

In the late 70s, at IBJ in Swierk, there was constructed the PF-360 facility of the nominal energy of 360 kJ, at 50 kV charging. That device was used to study dynamics of PF discharges and to optimize the fusion neutron yield. Basing on that experience, the IBJ team designed a new megajoule PF-1000 facility for WAT, which was put in the operation in Warsaw in 1994, as described in paper [1]. Meanwhile, in Swierk one of the previous RPI devices was converted in the MAJA-PF facility, which could be operated up to 60 kJ. The MAJA-PF device was designed especially for studies of the X-ray emission [2] and measurements of relativistic electron beams (REBs) [3].

In recent years the DMP studies in Poland have been concentrated at the MAJA-PF and PF-360 facilities in Swierk, as well as at the PF-150 and PF-1000 facilities in Warsaw. Some DMP experiments have been performed within a frame of the international scientific collaboration. Numerous DMP experiments, which were carried out by joint research teams from IPJ and IFPiLM, were reported at the previous Ukrainian Conference [1]. Therefore the main aim of this invited talk was to report and discuss only the newest results obtained in the recent two years.

2. Studies with MAJA-PF device

Recalling to the first observations of different polarization of some intense X-ray lines emitted from PF discharges [1-2], during recent years particular attention was paid to studies of these phenomena in the MAJA-PF facility. To make possible an accurate spectral analysis of the X-ray lines originated from highly ionized Ar-admixture, there were applied two almost identical crystal spectrometers with mutually perpendicular dispersion planes. To study REBs, which influence the X-ray emission, behind the main collector of the MAJA-PF device there were installed Cerenkov-type detectors and/or miniature magnetic analyzers. To measure fast ions, there was installed an ion pinhole camera equipped with nuclear-track detectors (NTDs) and/or scintillators. Fusion-produced neutrons were measured with silver-activation counters and scintillation detectors. To eliminate electromagnetic interference all diagnostic tools were connected through optical cables or coaxial cables protected with additional shields, as shown in Fig.1.

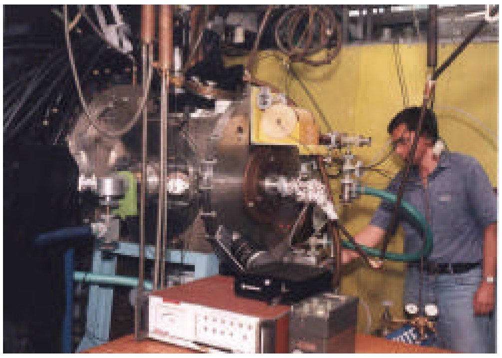

Fig.1. General view of the MAJA-PF experimental chamber, equipped with various diagnostic tools used for studies of X-rays, REBs, fast ions, and nuclear fusion products (fast protons and neutrons).

In two recent years DMP experiments within the MAJA-PF device were concentrated upon space-resolved studies of X-ray spectra [4]. It was proved that different parts of the registered spectral lines can be assigned to individual hot-spots identified in the time-integrated X-ray pinhole images, as shown in Fig.2.

Those observations enabled more accurate estimation of local plasma parameters in the identified hot-spots to be performed. Taking into account relative intensities of resonance and inter-combination He-like argon lines, the electron concentration in the hot-spots was estimated to be from 5×10^{20} cm^{-3} to 2.2×10^{21} cm^{-3}. On the basis of relative intensities of the satellite lines and resonance lines, there were also estimated local electron

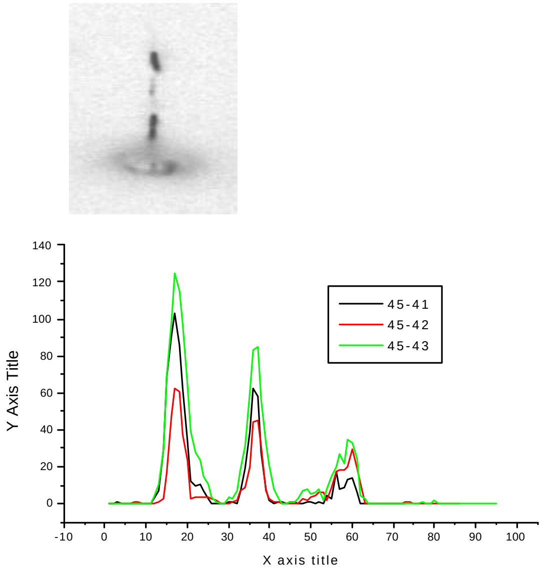

Fig.2. X-ray pinhole picture (top) and spectra of highly ionized Ar-lines (bottom), as registered with the spatially resolving spectrometer. Three different curves correspond to the individual hot spots, which were numbered successively, starting from the anode end.

temperatures, ranging from about 250 eV to about 600 eV [4]. The local parameters obtained from the spectra registered with two crystal spectrometers (with the different orientation of the dispersion planes) were slightly different. Therefore, it was concluded that to make correct estimations of the local parameters one must take into account polarization effects as well as the excitation of He-like ions by fast electron beams.
In the recent MAJA-PF experiments particular attention was paid to studies of REBs emitted in the upstream direction [3], and fast ions emitted along the z-axis [5]. Using the ion pinhole camera and CN-type detectors, there were registered ion images, as shown in Fig.3.

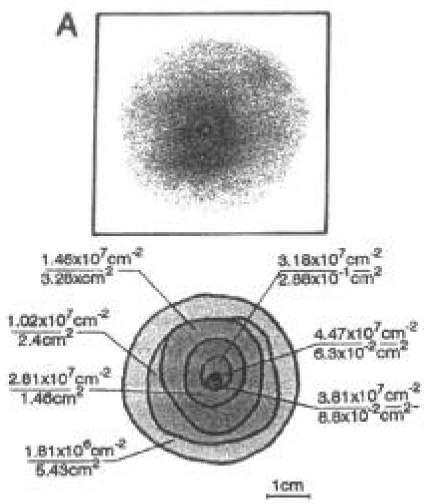

Fig.3. Pinhole images and corresponding density maps of fast ion beams, as obtained within the MAJA-PF experiment: A – from 3 shots with no absorption filter upon the detector (E_d > 80 keV); B – from 3 shots with a 3-mm-thick Al-filter on the detector (E_d > 220 keV).

Quite recent MAJA-PF experiments have confirmed that high-energy (> 1.0 MeV) deuteron microbeams are emitted within a narrow cone oriented along the z-axis, and that such microbeams are produced by different microsorces, which can be identified with hot-spots [6].

3. Experiments with PF-150 facility

Several series DMP experiments were performed with the PF-150 device operated at IFPiLM in Warsaw. That device was equipped with Mather-type electrodes of 100 mm and 50 mm in diameter, and 200 mm in length, powered at 41 kJ / 28 kV. The main experimental chamber of the PF-150 device and some diagnostic tools are shown in Fig.4.

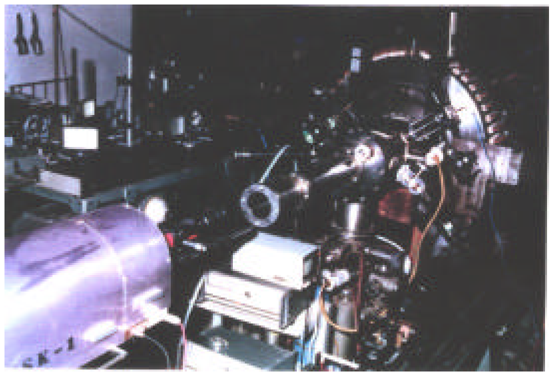

Fig.4. General view of the PF-150 facility with some equipment used for optical and corpuscular measurements.

To investigate dynamics of VR and X-ray emission the use was made of a multi-frame imaging system consisted of two VR measuring channels (DUPLO high-speed camera) and two separate X-ray framing modules [7]. The VR and X-ray frames were synchronized in pairs, and their exposition times were about 1 ns. The synchronization with PF discharges was realized by means of fast photo-diodes, which observed current-sheath (CS) motion. Electrical signals were stored with a TDS784A digital oscilloscope, and frames were elaborated with an automatic image capturing and processing system (AICPS). The VR pictures and corresponding X-ray images demonstrated correlation of fine structures formed within the pinch column, as shown in Fig.5.

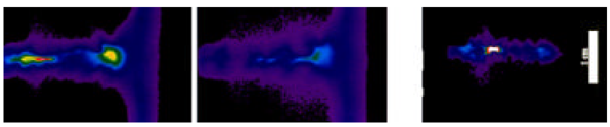

Fig.5. Two VR pictures and the X-ray image registered during a single PF shot. The first picture was taken at 31 ns, and the second at 41 ns, while the X-ray image (on the right) was obtained at 28 ns. The correlation of intense emitting regions and hot-spots can be analyzed.

Several series of measurements performed with the multi-frame imaging system made possible to collect experimental data on internal structure of the PF pinch column and regions emitting intense X-ray pulses, as shown in Fig.6.

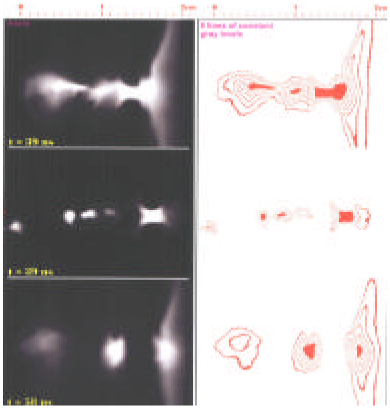

Fig.6. The first VR picture and corresponding X-ray picture (from the top), which were taken at t = 39 ns, in a comparison with the second VR picture registered at t = 58 ns. Corresponding isodensity maps (the right column) facilitate to observe the spatial microstructure and motion of the most intensively emitting regions.

Another series of DMP experiments with PF-150 device was devoted to studies of solid targets made of thin metal or carbon fibers, which were placed on the z-axis at the electrode outlet [8]. Using the diagnostic equipment described above it was proved that the interaction of the low-mass CS layer with the fiber target produces almost uniform corona plasma, which is relatively stable during the whole CS collapse phase. Simultaneously, using an XUV spectrometer, a Czech team from CVUT in Prague registered various spectral lines belonging to OV-OVII and CV-CVI ions, as well as high-intensity continuum. The H-like carbon lines as well as He-like resonance lines have been observed with the carbon fiber only. These experimental results are of relevance for research on X-ray lasers.

4. New experiments with PF-360 facility

Several extensive series of DMP experiments were carried out with a modernized PF-360 facility operated in Swierk (see Fig.7).

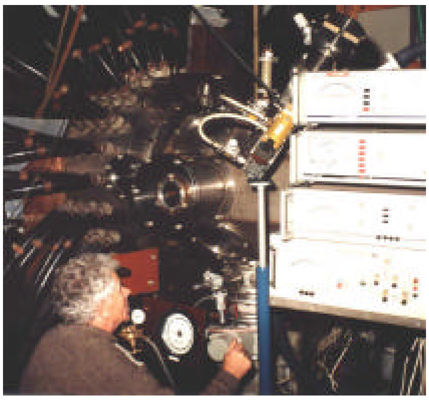

Fig.7. General view of the modernized PF-360 facility equipped with the new diagnostic equipment designed for measurements of X-rays and neutron pulses.

That facility was equipped with new Mather-type electrodes of 170 mm and 120 mm in diameter, and 300 mm in length. The PF discharges were powered at 122 kJ / 30 kV or 166 kJ / 35 kV. Different diagnostic techniques were applied to study time-integrated and time-resolved characteristics of charged particles and neutron pulses. In order to increase a neutron yield from PF discharges it was proposed to make use of fast deuterons, which escape from the PF pinch region mainly in the downstream direction. For this purpose there was designed a special cryogenic target, which consisted of a thick copper plate cooled down by an inner flow of liquid nitrogen [9]. When such a planar target was placed at an appropriate distance from the PF electrode outlet, and a small amount of "heavy water" (D_2O) was injected into the main experimental chamber, the front surface of the target was covered with a thin layer of a "heavy ice". Such planar D_2O-ice targets, bombarded by fast deuteron beams, could produce additional neutrons from DD fusion reactions. Some optimization measurements, which have been performed within the PF-360 facility, demonstrated that a considerable increase in an average neutron yield could be achieved, as shown in Fig.8.

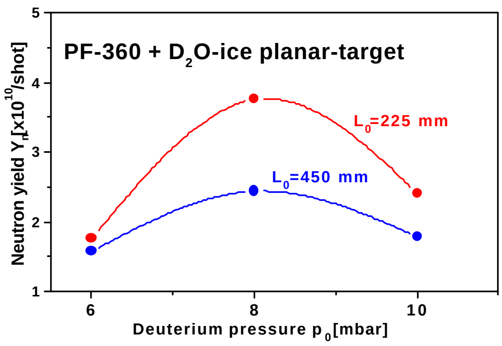

Fig.8. Average neutron-yield versus the initial pressure, as measured for PF experiments with the planar cryogenic target. The PF shots were performed at U_0 = 30 kV, W_0 = 130 kJ, and different positions of the target. The best results were achieved when it was placed at a distance of 225 mm from the electrode end.

Simultaneously with the time-integrated neutron measurements there were also performed time-resolved studies by means of calibrated scintillation detectors. It was confirmed that the fusion-produced neutrons are emitted in several pulses, which are correlated with the discharge current peculiarity and hard X-ray peaks, as shown in Fig.9.

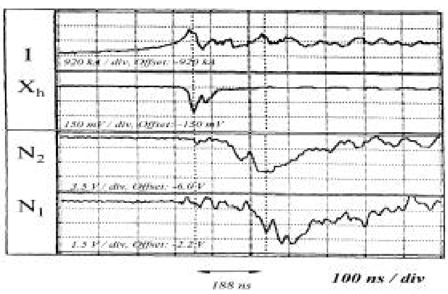

Fig.9. Typical time-resolved signals from two neutron scintillation detectors, as obtained for PF shots with the planar cryogenic target at W_0 = 130 kJ. For a comparison there are also shown the discharge current (I), and hard X-rays (X_h) waveforms.

To increase the fusion neutron yield it was also proposed to make use of accelerated deuterons moving in the radial direction [10]. For this purpose there was designed another needle-like cryogenic target consisted of a thin copper tube, which was placed on the PF pinch axis. When that needle-like target was cooled down with liquid nitrogen and covered with a D_2O ice layer, one could also observe an increase in the neutron emission [9]. The application of such a target did not changed CS dynamics considerably, but it disturbed the CS collapse region and the formation of PF pinch column, as can be seen in Fig.10.

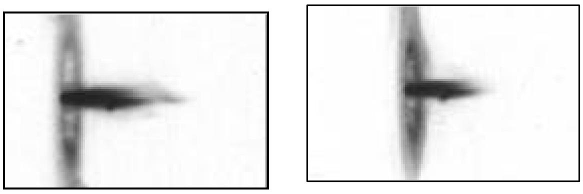

Fig.10. Soft X-ray pinhole pictures, as taken during a single PF discharge performed within the PF-360 device equipped with the needle-like D_2O-ice target. It can be observed that the target (placed slightly off the pinch axis) disturbed the PF pinch region.

In spite of that influence, the use of the needle cryogenic target made also possible to rise the fusion neutron emission up to $Y_n = 2.2 \times 10^{10}$ neutrons/shot under determined experimental conditions. Details of these DMP experiments are described in another paper to be presented at this conference [11].

Some PF experiments with the application of an additional gaseous target, which were performed in Stuttgart several years ago [12], showed that such a target can influence dynamics of the CS collapse as well as the production of fusion neutrons. Recently, several PF experiments with additional gas-puffed targets have also been carried out within the PF-360 facility [9]. In order to produce such targets in the pinch region, the inner electrode of the PF-360 machine was modified and equipped with a fast-acting electromagnetic gas-valve, similar to that used previously [12]. Several series of PF discharges, as performed with the additional deuterium-puffed targets, showed that one could operate the PF-360 machine at lower initial filling pressures. When the gas-valve operation was optimized (i.e., the valve was activated about 400 µs before the main discharge initiation), a relatively high neutron yield $Y_n = 2.5 \times 10^{10}$ neutrons/shot was achieved. The details of these gas-puffed experiments are also to be presented in another paper at this conference [11].

5. Optimization studies with PF-1000 facility

The large PF-1000 facility [13], which is operated at IFPiLM in Warsaw, was for the first time used for wire-target experiments analogous to those performed previously with Z-Pinch machines [14]. During those experiments the PF-1000 facility was run with the old Mather-type electrodes powered at a 250-300 kJ level [15]. Particular attention was put to the interaction of the collapsing CS layer with thin Al wires of various diameters (ranging from 30 µm to 230 µm) and 15 mm in length, which were positioned on the PF pinch axis. For diagnostics the use was made of high-speed streak- and frame-cameras, X-ray pinhole cameras, and PIN diodes covered with 1.5-µm-thick aluminized Mylar-foils. It was observed that a relatively stable DMP column could be formed and lasted for about 280 µs, as shown in Fig.11.

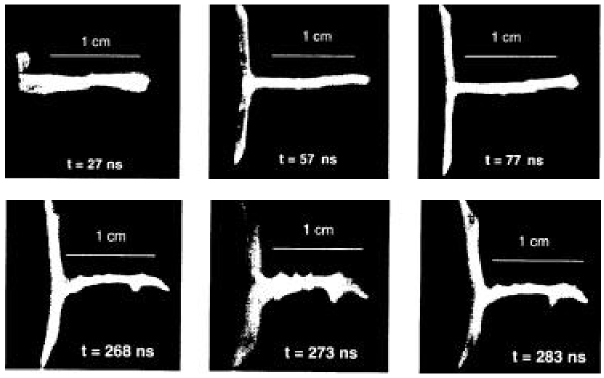

Fig.11. High-speed frame pictures, which were taken side-on during a single PF discharge with the target made of the Al wire of 80 mm in diameter. The shot was performed at p_0 = 3.7 hPa H_2 and W_o = 267 kJ [15].

Other large-scale DMP experiments, with the use of the PF-1000 facility, have been carried out through joint teams from IFPiLM and IPJ [16-21]. The facility has recently been equipped with new large Mather-type electrodes of 400 mm and 231 mm in diameter, and 600 mm in length. To make possible detailed studies of CS dynamics, X-rays, and fusion-produced neutron pulses, that machine was also equipped with new diagnostic tools, as shown in Fig.12.

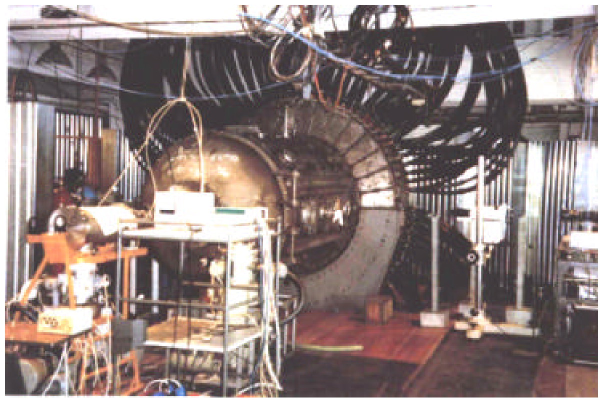

Fig.12. General view of the PF-1000 facility with the new diagnostic equipment, designed for optimization measurements of the X-ray, ion, and neutron emission.

Particular attention was paid to time-integrated measurements of X-rays [17-18] and to spectroscopic studies of the X-ray emission from highly stripped admixture-ions [19]. To avoid a strong modification of PF discharges, an admixture of Ar-gas to the working gas (H_2) amounted to a few percent only. Using a mica crystal spectrometer of the FSSR-2D type, there were registered space-resolved K-shell spectra. Those spectra were compared with results of model computations, giving a good agreement, as shown in Fig.13.

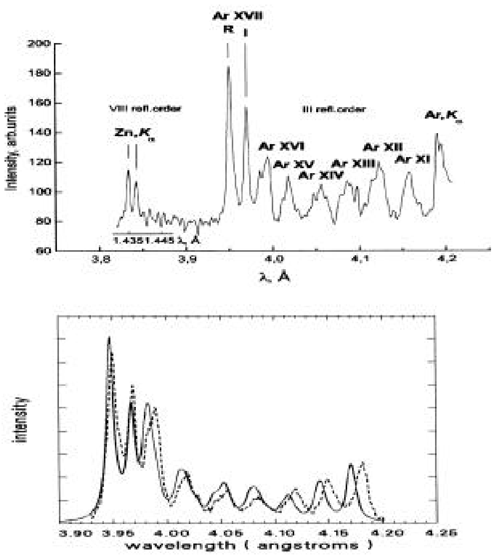

Fig.13. Comparison of the experimental spectrum of Ar ions with some results of computations, which were performed on the basis of a collisional-radiative model including effects from hot electrons [19].

The very recent PF-1000 experiments have been carried with the use of new Mather-type electrodes of 400 mm and 231 mm in diameter, and 600 mm in length. The recent PF discharges were performed at energy levels ranging from 500 kJ to about 800 kJ [18, 20]. The dynamics of a CS layer was studied with high-speed cameras, as shown in Fig.14.

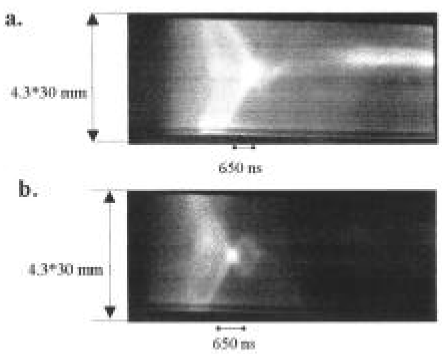

Fig.14. Streak pictures of the collapsing current-sheath in the PF-1000 machine, as taken through a slit placed at a distance of 1 cm from the electrode outlet plane. The PF shots were performed at p_o = 3.9 mbar D_2, U_o = 30 kV and W_o = 600 kJ [20].

On the basis of smear VR-pictures an average velocity of the radial compression has been determined. Using an X-ray pinhole camera there was studied the formation of "hot-spots". Also studied were fast (> 80 keV) ion beams emitted along the z-axis. The ion images registered with SSNTDs confirmed the emission of bunches of fast ion beams. Research on the neutron yield optimization has just been started, and the new results are to be presented soon [21].

6. Summary and conclusions

This invited talk can be summarized as follows:

- The recent experiments within the MAJA-PF device delivered valuable information about polarization of the X-ray emission and about correlation between X-ray pulses and charge-particle emission.
- Recent studies carried out with the PF-150 device, operated at 35-40 kJ, delivered new information about dynamics of PF discharges, as well as the X-ray and XUV emission.
- The recent DMP studies with the PF-360 facility, operated at 120-130 kJ with additional cryogenic targets, proved that accelerated primary deuterons (moving in axial and radial directions) could be used to produce fusion neutrons from D_2O-ice layers.
- Recent DMP experiments, performed with the use of the fast-acting gas-valve in the PF-360 device, proved that the gas puffing into the PF pinch region could influence dynamics of the radial compression phase and the neutron emission.
- The recent large-scale DMP experiments with the PF-1000 facility, performed up to 600 kJ, delivered valuable data on X-ray spectra and dynamics of the current-sheath at high discharge currents.

One can conclude that to optimize the X-ray and neutron emission from DMP discharges further studies with various targets (solid fibers, cryogenic layers, and gas-puffed targets) are needed. Such experiments are to be continued with medium-scale PF devices, before these techniques are used in the largest PF facilities.

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