Polarization of X-Ray Lines Emitted from Plasma-Focus Discharges; Problems of Interpretation

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Abstract: In high current pulse discharges of the Plasma Focus (PF) type, inside the collapsing pinch column, there are formed local micro-regions of high-density and high-temperature plasma, so-called hot spots. Individual hot spots are separated in space and time. Each hot spot is characterized by its specific electron concentration and temperature, as well as by the emission of X-ray lines with different polarization. When numerous hot spots are produced it is impossible to determine local plasma parameters and to interpretate the polarization effects. To eliminate this problem this study was devoted to the realization of PF-type discharges with single hot spot only. It has been achieved by a choice of the electrode configuration, which facilitated the formation of a single hot spot emitting intense X-ray lines. At the chosen experimental conditions it was possible to determine local plasma parameters and to demonstrate evident differences in the polarization of the observed X-ray lines.

1. Introduction

In Plasma-Focus (PF) type discharges, when a current-sheath layer arrives to the coaxial-electrode ends and its part undergoes the radial compression, there is created a dense magnetized plasma column. Inside this pinch column, due to various instabilities (mostly of the m = 0 type), there are formed high-density microregions, so-called “hot spots”. The local electron concentrations in the hot spots can exceed 10^{20} cm^{-3}, and the local electron temperatures can achieve values above 1 keV. It was proved experimentally that the hot spots are created successively, as the maximum plasma density in the collapsing current-sheath moves from the electrode outlet along the z-axis, with an axial velocity of about 3×10^7 cm/s [1]. The individual hot spots are usually separated in space and time, although they can also form some clusters at and off the z-axis.

The observed hot spots are sources of intense X-ray emissions, as well as sources of pulsed electron- and ion-beams emitted on the opposite directions [2-3]. The generation of pulsed electron beams, inside or in a close proximity of the hot spots, is combined with a violation of the maxwellian distribution of electron velocities. The interaction of such electron beams with electrical fields of plasma ions is probably a reason of the polarization of the emitted X-ray lines.

2. Experimental setup

Studies of the polarization of different X-rays lines emitted by PF-type discharges has been carried out at the Andrzej Soltan Institute for Nuclear Studies in Swierk, Poland, for many years [4-5]. The experimental observations have been performed mostly within the MAJA-PF facility, which was equipped with coaxial electrodes of the Mather type. The experiments have been carried out at the initial charging voltage U_o = 35 kV, the condenser bank energy equal to 45 kJ, and the maximum discharge current amounting to 500 kA. The X-ray spectra have been measured by means of two crystal-spectrometers, which were placed side-on, perpendicularly to the z-axis, but with their dispersion planes rotated mutually by 90^o.

For PF discharges performed within deuterium with some argon admixture, there were registered X-ray lines corresponding to highly ionized argon ions, and particularly the ArXVII–^{1}P resonance lines, the ArXVII–^{3}P intercombination lines as well as the ArXVI satellite lines. Comparing a ratio of intensities of the resonance- and intercombination-lines (I_r/I_i), as measured from the spectra registered by both crystal spectrometers, it was possible to determined differences in the polarization of the considered X-ray lines.

Simultaneously with the X-ray studies, there have been performed measurements of pulsed electron beams, which were emitted in the upstream direction through an axial channel within the inner coaxial electrode and the main collector plate. Time-resolved measurements of the pulsed electron beams have been carried out by means of Cerenkov-type detectors equipped with radiators made of rutil crystals [6]. Energy spectra of the emitted electron beams have been measured with a small magnetic spectrometer. Miniature scintillation detectors, which were placed at chosen points of the registration plane of the magnetic spectrometer, have enabled temporal correlation of electrons of the determined energy values to be investigated. Those measurements have demonstrated that the emitted electron beams are well correlated with the appearance of the successive hot spots. The energy spectra of the investigated electron beams have ranged from several dozen keV to several hundreds keV. It is evident that the individual hot spots can emit the pulsed electron beams with some stochastic jitter and within different energy ranges.

3. Experimental results

The simultaneous studies of the pulsed electron beams and X-ray pulses, as emitted from the hot spots, have confirmed that correlation and evident differences in the polarization of various X-ray lines. The I_r/I_i ration, which was determined for the selected argon lines on the basis of the X-ray spectra registered with the two crystal spectrometers with mutually perpendicular dispersion planes, has appeared to be different considerably [5]. Also the statistics, which was made for numerous PF experiments, has confirmed the polarization effects, as shown in Table 1.

TABLE 1

Averaged I_r/I_I ratio		Cylindrical crystal	N		N	Spherical crystal	N
A		2.08	12	1.92	6	1.87	12
B	Without spatial resolution	1.44	13				
	With spatial resolution (average)			1.57	12	1.32	12

Table 1 gives the averaged I_r/I_i ratio as determined for N discharges of the PF type, as measured by means of two crystal spectrometers with different orientation of the dispersion plane: A – parallel to the pinch axis, and B - perpendicular to that. The results presented above show that for the spectrometer equipped with the cylindrical crystal, with the dispersion plane parallel to the discharge axis (case A), the I_r/I_I ratio appears to be statistically larger than that for the spectrometer with the dispersion plane perpendicular to the z-axis (case B). This ratio amounts to 2.08 (in the case A) and to 1.44 (in the case B). From the measurements performed with the spatial resolution this ratio amounts to 1.92 (A) and 1.57 (B), respectively. Those values were determined by averaging spectra obtained from different hot spots. Similar differences were observed for the spectrometer with the spherical crystal, i.e. 1.87 (A) and 1.32 (B). It should, however, be noted that in the described studies there were taken into consideration only those results, which corresponded to the linear part of the blackening curve. It means that some spectral lines, with the exposition lower than 20% or higher than 80% of the maximal blackening, have not been taken into account.

It should also be noted that the hot spots, which are sources of the intense X-ray pulses, are usually formed at different instants and in different places along (and nearly) the z-axis, in the region of about 20-30 mm in length. The input optical systems, which were used in the applied X-ray spectrometers, have made possible to record the X-ray emission from the axial region of about 15 mm in length. It means that the recorded X-ray radiation could originate from several hot spots. On the other, it was proved that each hot spot has its specific electron concentration, its specific electron temperature and its characteristic I_r/I_i ratio [7]. Therefore, the measurement integrating the X-ray emission from several hot spots is not able to deliver accurate information about local values of plasma parameters, since it gives averaged characteristics only. Some differences in the viewing fields of the both crystal spectrometers could also be a reason that the recorded X-ray emission originated from slightly different hot spot assemblies. For a detailed analysis one should also take into account that the observation ranges for various X-ray spectral lines could be slightly different [8]. The problems mentioned above have appeared during the analysis of different X-ray spectra, which were recorded at almost identical experimental conditions. The main reason of the observed differences has evidently been a stochastic jitter in the formation of the hot spots along the discharge axis, as shown in Fig.1.

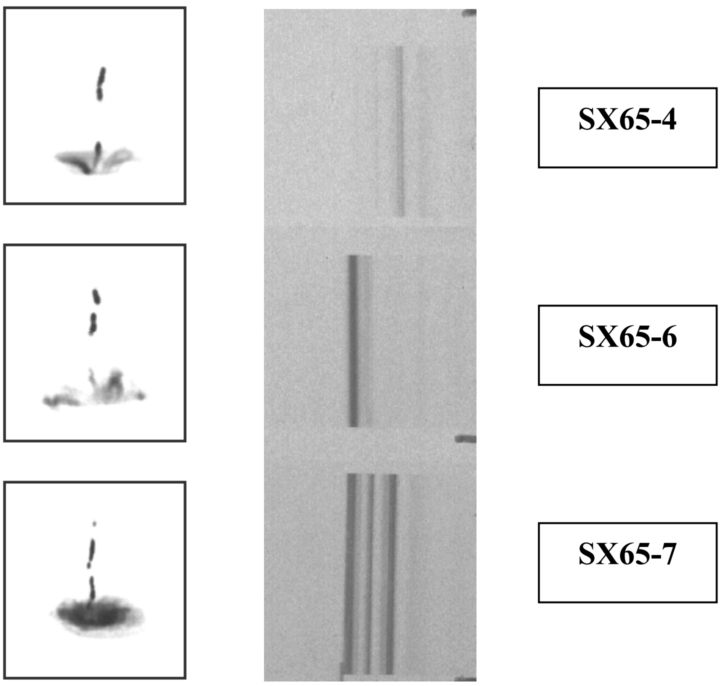

Fig.1. Comparison of X-ray spectra recorded at the same experimental conditions, but with some stochastic jitter in the formation of hot spots along the pinch axis, as shown on X-ray pinhole pictures in the left column.

The spectrum obtained from a shot SX65-4 shows mainly the ArXVI satellite lines, while in the spectrum recorded for the SX65-6 shot the most intense appears to be the resonance line. The spectrum obtained from the SX65-7 shot shows the intense emission within the whole spectral range. A comparison of the X-ray spectra recorded under identical experimental conditions shows that they depend considerably on the positioning of hot spots in relation to the viewing field of the spectrometer. That question has already been discussed in details in the previous paper [8].

In order to facilitate the correlation analysis, the best solution would be to perform PF discharges producing only a single hot spot, emitting intense X-ray lines. Recently, to achieve this aim there have been undertaken some efforts by changing a front-plate insert in the inner electrode. The inserts made of iron, in which a conical channel was drilled, have reduced a number of the produced hot spots, but some increase in the spatial jitter of hot spots (along the z-axis) has been observed. For the described electrode configuration the succesive discharges were irreproducible, and there was observed a strong erossion of the electrodes, as shown in Fig. 2a.

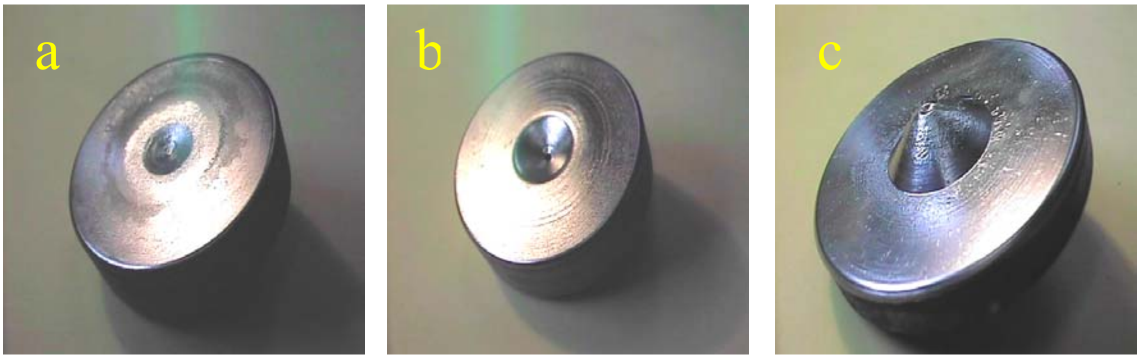

Fig.2. Pictures showing the erossion of the inserts in the central (inner) electrode, which were used in order to produce PF discharges with a single hot spot: a) – a concave conical pit, b) – a concave conical pit with the axial hole for the extraction of electron beams, and c) – a crowned quasi-conical prominence.

The described insert with the axial channel, which was used for the extraction of the electron beams emitted in the upstream direction, has evidently stabilized these beams, and it has reduced the erosion of the electrode end, as shown in Fig. 2b. On the contrary, the front-plate inserts made of iron with an axial quasi-conical prominence (Fig. 2c), in spite of relatively strong erosion by many discharges, have ensured the formation of a PF pinch column with a single hot spot in the viewing field of the X-ray spectrometers. An example of the X-ray pinhole picture of the single hot spot and X-ray spectra, which were obtained by means of the two crystal spectrometers, have been presented in Fig.3.

It should be noted that the dispersion plane of the first crystal spectrometer (A) was oriented parallel to the PF pinch axis, while that of the second crystal spectrometer (B) was perpendicular to the same axis. In the case B the spatial resolution was achieved due to the application of a spherically bent crystal. The measured ratio of the resonance and inter-combination lines (I_r/I_i), as determined on the basis of the recorded spectra, was equal to 4.09

in the case A, and 1.39 in the case B. Those values have demonstrated that the polarization of the analyzed X-ray lines has differed considerably.

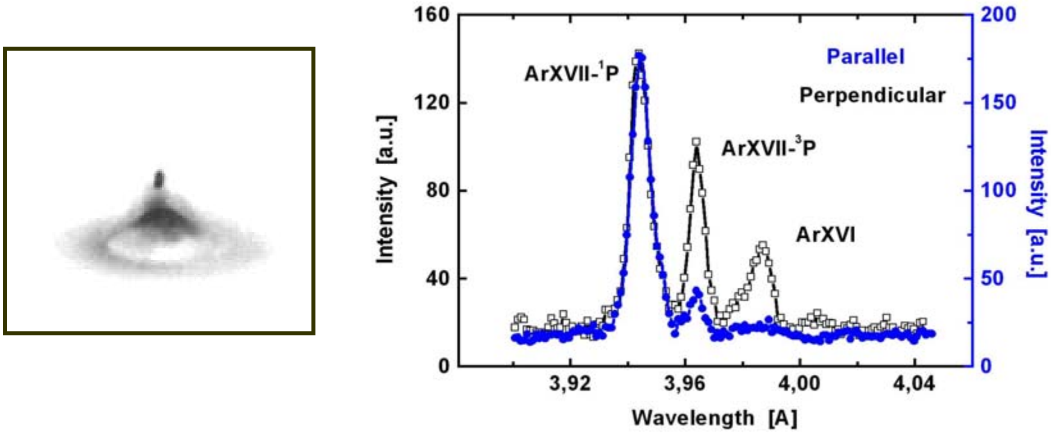

Fig.3. X-ray pinhole picture of a single hot–spot and spectra of the X-ray radiation emitted from that, as recorded by means of the two crystal spectrometers with mutually perpendicular dispersion planes (A and B).

In conclusion it could be stated that the results obtained for PF discharges with the single hot spot have confirmed the previous observations on the polarization of the X-ray radiation from PF-type discharges.

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