MEASUREMENTS OF PULSED ELECTRON BEAMS EMITTED FROM PLASMA-FOCUS DEVICES

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A dense plasma column, which is formed by a pulsed discharge within facilities of the Plasma-Focus (PF) type, is a source of the intense X-ray emission, pulsed electron beams and ion streams. Investigation of the electron beams can deliver information about development of plasma instabilities, which induce the formation of high-temperature plasma micro-regions in the form of hot-spots and/or filaments. The paper reports on recent studies of the pulsed electron beams within PF-type facilities.
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1. INTRODUCTION

The radial compression of a current sheath forms a dense magnetized plasma pinch column (plasma-focus). Numerous observations showed that inside the plasma region there are formed micro-regions (hot-spots) of a relatively dense ($>10^{20}$ cm^{-3}) plasma which achieves considerably high electron temperatures (> 1 keV). The whole PF pinch column, and particularly hot-spots are sources of intense X-ray emission as well as pulsed electron- and ion-beams [1, 2]. Measurements of the pulsed electron beams can in particular deliver information about the appearance of high-temperature dense plasma micro-regions as well as about instabilities of current filaments and local electromagnetic fields. The emission of directed electron beams is a reason of differences in the polarization of some X-ray spectral lines emitted from the investigated plasma. Therefore, simultaneously with the registration of the selected X-ray spectrum lines, we studied their correlation with pulsed electron beams emitted perpendicularly to the discharge axis as well as in the upstream direction.

2. TIME-RESOLVED MEASUREMENTS OF PULSED ELECTRON BEAMS WITH ČERENKOV DETECTORS

In order to determine emission dynamics of the pulsed electron beams one can apply detectors based on the Čerenkov radiation, because the emission of that is almost instantaneous (with a delay below 0.1 ns). Intensity of the Čerenkov radiation is very high and such detectors have very high temporal and spatial resolution. The Čerenkov radiation appears if a charged particle penetrates a transparent medium with a velocity v higher than the phase velocity of light u in this medium which is equal to c/n, where n is the refraction coefficient of the material in question. The condition can be written as:

$$v > u \quad \text{or} \quad \beta n > 1 \quad \text{where} \quad \beta = v/c$$

From this equation it can be seen that the emission of the Čerenkov radiation has an energy threshold. A comparison of refraction index values and corresponding minimal energy values for different materials show that to record electron beams of lower energy it is necessary to use radiators made of diamond or rutil.

In order to determine the spatial and temporal localization of hot-spots, the X-rays were measured from two chosen micro-regions: the first one placed in a close proximity of the electrode outlet (X_{NS}), and the second one (X_{SF}) placed at the distance of 20 mm along the z-axis. An example of time-resolved electrons signals and X-rays is presented in the oscillogram shown Fig 1.

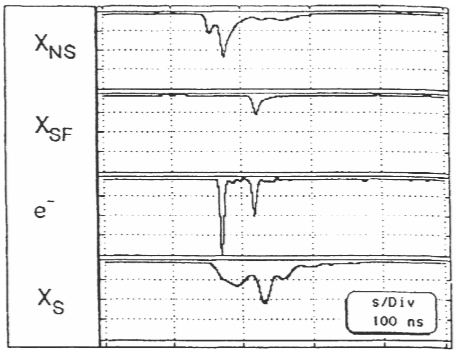

Fig. 1. Correlation of the soft X-ray pulses emitted from different hot-spots (near - X_{NS} and far - X_{SF}) with fast e-beams (e^-) and soft X-rays (X_S) registered from the whole pinch column

In that case the recorded X-ray pulses were evidently emitted from hot-spots formed in the selected micro-regions. Detailed studies of the correlation of the electron-induced signals and X-ray pulses confirmed the hypothesis that the observed emissions originate from the hot-spots simultaneously [3]. It should be noted that the life-time of observed hot-spots is about 7-10 ns. These hot-spots are formed successively along the z-axis (or near by) and they are responsible for the successive X-ray and electron pulses. The hot-spots are usually separated in space and time. It should also be noted that the Čerenkov detectors, which were placed at angles of 45° and 90° to the z-axis, have also revealed electron streams emitted in these directions.

The electron measurements, as performed in the direction perpendicular to the discharge axis, have shown that the pulsed electron beams appear about 100 ns before the voltage spike, as shown in Fig.2. This time corresponds to an instant when the current sheath appears in front of the electrode outlet. The emission of an intense electron pulse of energy > 80 keV, as observed in the radial direction, could be caused by some instabilities which develop in the current sheath.

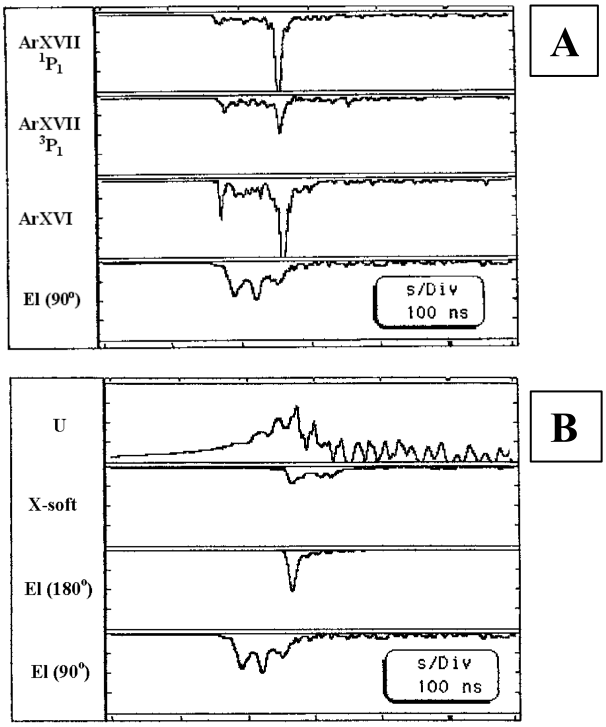

Fig.2. Correlation of time-resolved signals corresponding to the highly ionized argon lines with electrons pulses emitted at the angle of 90° to the z-axis (A), as well as with other characteristics of the investigated discharge (B).

The emission of directed electron beams is a reason of differences in the polarization of some X-ray spectral lines emitted from the investigated plasma. In order to study temporal changes in the selected X-ray lines the detection systems of the spectrometers were modified, so that the X-ray films were replaced by sets of miniature scintillators of the NE102A type. Those scintillation detectors could record the chosen spectral lines separately. Therefore, simultaneously with the registration of the selected X-ray spectrum lines, we studied their correlation with pulsed electron beams emitted perpendicularly (at 90^0) to the discharge axis [4] as well as in the upstream direction (at 180^0), towards the anode opening (see Fig.2). One can easily see that the maximum emission of the considered spectral lines, i.e. the resonance line ArXVII-$^1P_1$, the inter-combination line ArXVII-$^3P_1$, and the averaged satellite line ArXVI, appears during the over-voltage peak (U). This effect is accompanied by a dip (peculiarity) in the discharge current and the emission of the "soft" X-rays (X-soft) as well as fast electrons directed towards the anode – E1 (180°). It should be noted that the beginning of the emission of the investigated X-ray lines correlates well with the appearance of pulsed electron beams emitted perpendicularly to the discharge axis. The considered spectral lines and the radial-oriented electron beams appear about 100 ns before the main current dip. In this instant the current sheath is pushed from the inter-electrode gap into the region in front of the electrode ends. The emission of the X-ray lines as well as fast electrons in this moment is probably induced by Rayleigh-Taylor instabilities developing inside the moving current sheath. It has been found that the emission of highly ionized argon lines is well correlated with the appearance of successive hot-spots and the emission of electron beams from them.

During simultaneous measurements of fast ions, as performed by means of a time-of-flight method, an analysis of their correlation with pulsed e-beams made possible to determine an energy distribution of deuterons, as shown in Fig.3.

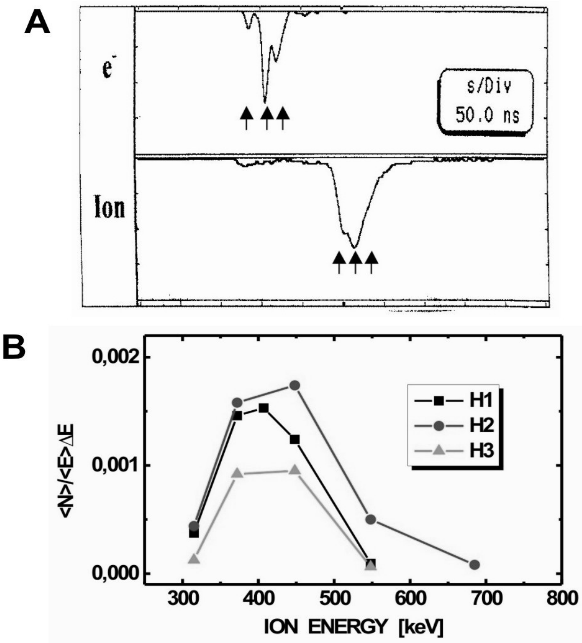

Fig.3. A - Three electron induced signals, in the comparison with three successive (superimposed) ion signals, B - Energy distribution of deuterons, as computed from ion signals registered from different hot-spots.

3. TIME-INTEGRATED MEASUREMENTS OF ELECTRON BEAMS WITH MAGNETIC SPECTROMETERS

In order to investigate electron beams of energy below the Čerenkov threshold, and to determine the whole energy spectrum of electrons emitted from plasma, one can also apply magnetic spectrometers. If a collimated electron beam penetrates through a constant and uniform magnetic field, it may be deflected by a given angle (e.g. 180°). Since a radius of the deflection is proportional to the electron velocity (energy) values, using an appropriate magnetic field it is possible to record electrons within a chosen energy range (e.g. 5-700 keV). The deflected electron beams can be recorded, e.g. upon an X-ray film, which makes possible to determine the time-integrated energy spectrum of electrons even from a single discharge, as shown in Fig.4.

The analysis of many experimental measurements has shown that the investigated electron beams had energies ranging from several keV to about 600 keV. The recorded images and corresponding energy spectra have appeared to be not very smooth and they have suggested that individual micro-sources emit electrons within relatively narrow energy bands. Such electron pulses could evidently be emitted by individual hot-spots.

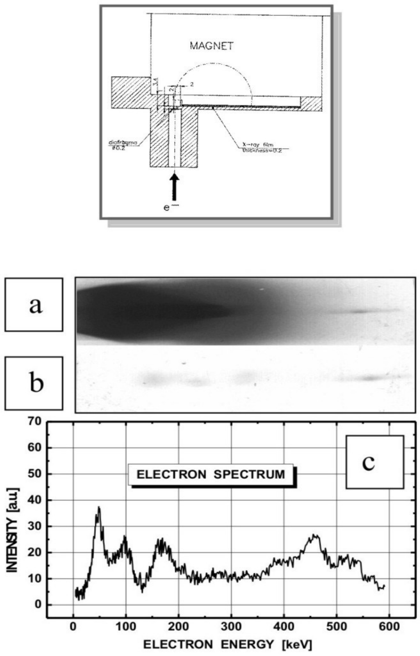

Fig.4. On the top – a scheme of the magnetic spectrometer. On the bottom – the electron energy spectrum recorded on X-ray film for a single PF shot: (a) as registered on the first emulsion layer, (b) as registered behind a filter, (c) the corresponding electron spectrum

4. TIME-RESOLVED MEASUREMENTS OF ELECTRON BEAMS WITH MAGNETIC SPECTROMETERS

In order to study temporal changes in the emission of electron beams within selected bands of the energy spectrum, the use was made of miniature scintillation detectors, which were installed in chosen points of the image plane of the magnetic spectrometer. Those detectors produced light pulses corresponding to electrons of the energy values with accuracy of ±10%. In our experiments the chosen values were: 20, 50, 200 and 500 keV, respectively. An example of the corresponding signals is presented in Fig.5.

The obtained results have confirmed that in the observed energy bands the electron spectrum has a multi-spike structure. Taking into consideration the shape, width and time instants, when the electron-induced X-ray pulses appear, a comparison with the images recorded with X-ray pinhole camera can be performed. Such a comparison confirms that individual electron peaks really correspond to different hot-spots. It can also be stated that these hot-spots emit electron beams within defined energy bands, what has been suggested by the measurements of the integrated electron-energy spectra.

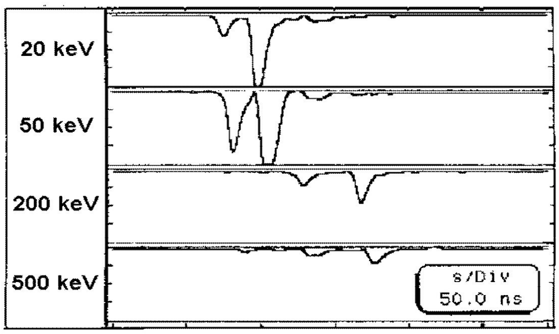

Fig.5. Time-resolved electron signals within different energy bands. The pulses seem to correspond to different hot-spots with various emission characteristics

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ИЗМЕРЕНИЯ ИМПУЛЬСНЫХ ЭЛЕКТРОННЫХ ПОТОКОВ, ЭМИТИРОВАННЫХ ИЗ УСТАНОВОК ТИПА ПЛАЗМЕННЫЙ ФОКУС

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Шнур плотной плазмы, формируемый импульсным разрядом на установках типа плазменный фокус (ПФ), является источником интенсивного рентгеновского излучения, импульсных электронных пучков и потоков ионов. Исследование электронных пучков может дать информацию о развитии плазменных неустойчивостей, которые вызывают формирование высокотемпературных плазменных микрообластей в виде «горячих пятен» и/или волокон. Работа посвящена последним результатам изучения импульсных электронных пучков, генерируемых в установках типа ПФ.

ВИМІРИ ІМПУЛЬСНИХ ЕЛЕКТРОННИХ ПОТОКІВ, ЕМІТОВАНИХ ІЗ УСТАНОВОК ТИПУ ПЛАЗМОВИЙ ФОКУС

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Шнур щільної плазми, формований імпульсним розрядом на установках типу плазмовий фокус (ПФ), є джерелом інтенсивного рентгенівського випромінювання, імпульсних електронних пучків і потоків іонів. Дослідження електронних пучків може дати інформацію про розвиток плазмових нестійкостей, що викликають формування високотемпературних плазмових мікрообластей у виді «гарячих плям» і/або волокон. Робота присвячена останнім результатам вивчення імпульсних електронних пучків, генерируємих в установках типу ПФ.