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ORIGINAL PAPER

Stabilizing of Z-pinch and Plasma Focus discharges due to thick wires

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Abstract This paper presents the results of the diagnostics observing the impact of the plasma sheath imploded in mega-ampere Z-pinch or plasma focus devices onto the Al or C wires of 30–300 μm in diameter fixed in the center axis. The discharges were operated with a maximum current of 1.5–3 MA at two devices, PF 1000 at IPFLM in Warsaw, and Stand 300 at RRC Kurchatov Institute in Moscow. At the plasma impact the 10–50 ns XUV pulse was emitted in K-shell lines from the ring or helical-like forms on the surface of the wire corona. The scenario of the production of the non-equilibrium intensities of the C and Al H-like and He-like lines is discussed considering fast transformation of magnetic field, electron beams acceleration, total ionization of the ions and fast recombination in dense and magnetized wire corona.

Key words plasma focus • X-ray source • XUV spectroscopy • Z-pinch

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Introduction

Recently, a review of the fast Z-pinches was published in [6], where the physics of evolution, stability, simulations and applications in detail were described. To the important questions belong the suppression of the instability development and production of the non-thermal high energy particles and keV radiation. With both the above mentioned questions a spontaneous generation of a magnetic field is closely related, mainly its axial component. In the Z-pinch experiments with Al and C wires of 30–2000 μm in diameter the dense plasma corona and the temporally random pulse of XUV lines were observed in correlation with the fast transformation of the corona surface (sometimes helical-like form) [1, 4]. The stabilizing factor for suppression of the instability development seems to be the solid state of the axis part of the wire, high plasma density and a strong magnetic field.

In this paper the emission of the non-thermal K-shell pulse and suppression of the instability development induced by the impact of the current sheath onto the thick wire are presented and discussed. These experiments were realized at the mega-ampere devices – PF 1000 at IPFLM in Warsaw and the Stand 300 at RRC Kurchatov Institute in Moscow.

Experiments

Plasma focus

Experiments were performed with a PF-1000 plasma focus device at the Institute of Plasma Physics and Laser Microfusion in Warsaw with Al or C wires fixed to the inner electrode face to its axis.

In the first series of experiments the Al wire of 30, 80 or 230 μm in diameter and 1.5 cm in length were studied at an initial pressure of 5–8 Torrs of hydrogen. The results were reported in papers [7, 8].

At the moment of the current sheath impact onto the wire, the non-thermal keV X-ray pulse with the FWHM of 10–30 ns was emitted from the whole surface of the corona. Time integrated emission spectra of highly charged Al ions were registered. The axial dimensions of the plasma source emitting H and He-like Al lines is about 5 cm longer than the wire length and the surface of this source seems to be helical (Fig. 1). In the spectrum the satellites of the resonance lines were identified belonging to the highly stripped Al ions – from Li-like to F-like. After the impact of the imploded current sheath onto the wire and X-ray emission, a relative stable plasma corona has been formed around the wire with a life-time of ~1 μs and a diameter of ~2 μm.

In the second series of experiments, C fibers (100 and 300 μm in diameter, and 3 cm in length) were studied at an initial pressure of 2–3 Torr of hydrogen in the chamber at the same configuration as the Al wire. The results were summarized in the publication [5].

After the current-sheath impact onto the fiber, the XUV pulse has been emitted with the FWHM of ~50 ns. The X-ray emissions originate only from the part of the fiber corona surface (Fig. 2) which is of a cylindrical volume with the diameter of ~0.6 mm and the length of ~15 mm. In the spectrograph records the lines with non-equilibrium intensities of the H- and He-like C lines and the He-, Li- and Be-like O lines have been recorded, (Fig. 3), with electron temperature ~50 eV and electron density $\sim 10^{25}$ m^{-3}. From the streak camera records it was possible to determine the parameters of the stable corona – the diameter about 2–3 mm and the life-time approximately 500 ns.

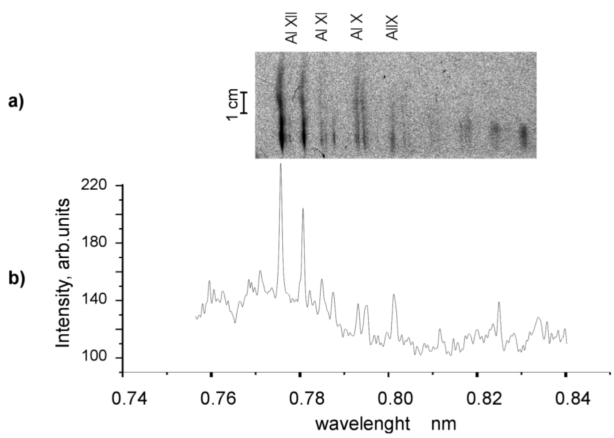

Fig. 1. Record from shot No. 98-12-3-01. a) Spectrum with spatial resolution along the wire. b) Intensities of the He-like lines.

Stand 300

At the S-300 machine at the RRC Kurchatov Institute the liner of array system type (cylindrical form, 1 cm in diameter, 60 tungsten wires each of 6 μm in diameter and 1 cm in length) was imploded onto the Al wire (120 μm in diameter). The evolution of the liner implosion was described in papers [2, 3]. The pinch phase with a minimum diameter of 1.5–3 mm was formed at 160–180 ns after the current onset. During this pinch phase the soft X-ray pulse was emitted with the FWHM of ~20 ns from the inner layers of the pinch of the form like "rod" with "clouds" (see Fig. 4). The rod with helical-like surface was located in the pinch axis. The keV Al K-shell lines imagined in the spectral records had been emitted probably from the clouds (Fig. 5). It seems that the clouds were formed by plasma streams exploded from the rods. From the Al K-shell line intensities of the spectrum electron temperature of 200–500 eV and electron densities of 10^{27}–10^{28} m^{-3} were evaluated.

Discussion

The results of the diagnostics of the impact of the current sheath onto the fiber obtained at both high-current devices can be summarized as follows:

1. At the impact of the current sheath onto the wire, the short ~20 ns pulse was emitted in K-shell lines of the wire element.
2. The intensities of the emitted lines and the presence of dielectronic satellite lines are related to the non-equilibrium plasma parameters.
3. These non-thermal high energy radiation was emitted from the corona surface (often of ring or helical-like structures).
4. After the current-sheath impact, the relative stable corona has been formed around the wire. The plasma corona was composed of a dense and cold plasma and its life time was much longer than the duration of the XUV pulse and pinch phase.

These results could be interpreted as follows:

At the moment of the current sheath impact, the wire corona radius was rapidly decreased and the magnetic field

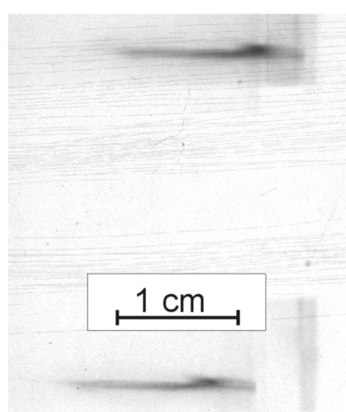

Fig. 2. Record from shot No. 00-3-29-1. Pinhole camera pictures. Fiber corona filtered with 10 μm-thick Be-foil (up) and with 20 μm-thick Be-foil (down).

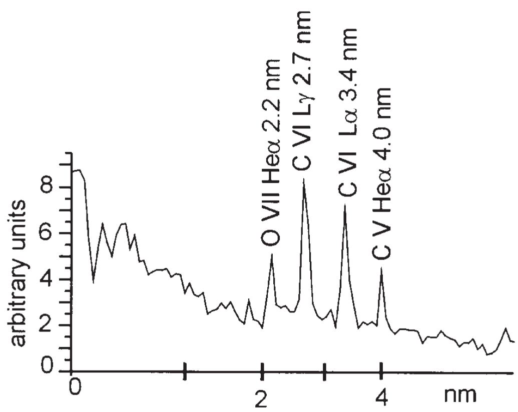

Fig. 3. Record from shot No. 00-3-23-3. XUV emission, as registered within the range of 2–5 nm.

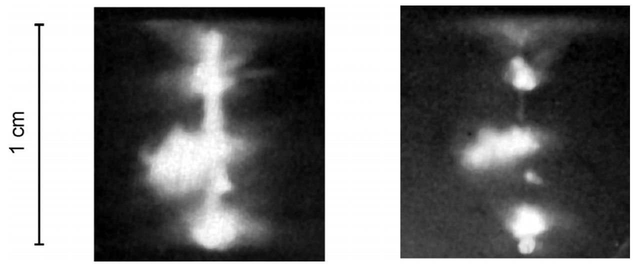

Fig. 4. Record from shot No. 99-12-3-1 (array implosion onto the Al wire). Record of the pinhole camera filtered with a) 1.5 μm-thick mylar foil and b) 12 μm-thick mylar foil.

rapidly increased. Dominant part of the electric current in the front of the current sheath was probably caught in the wire corona and changed the configuration of the magnetic field. The voltage of the induced electric field can be simply estimated from the temporal derivative of the magnetic flow. The final energy of accelerated electrons (~ keV) could be sufficient for total ionization of the ions in the wire corona. Then, the XUV pulse has been emitted during the fast recombination.

It seems very probable that the reason for the depression of instability development can be the solid state of the axis part of the wire. The dense and cold non-ideal plasma depressed fast energy transformations.

The important consequence of this behavior leads to the phenomena of the XUV lasing. The electron beams could realize not only the total ionization of the ions in the corona surface but also the recombination scheme of pumping of inverse population of the second and third levels of the H-like ions.

Conclusions

The diagnostics showed that after the current sheath impact the pinch phase was developed and the ~20 ns pulse in the H- and He-like lines of the wire element was emitted from the surface of the wire corona often of helical-like form. The fast transformation of magnetic fields, induction of the electric field and accelerated electron beams are probably the reasons for this K-shell emission. In both types of experiments, the dense and relative stable plasma was formed probably as a consequence of the solid state of the wire inside the corona. It seems interesting to study these phenomena for fusion and X-ray laser research applications.

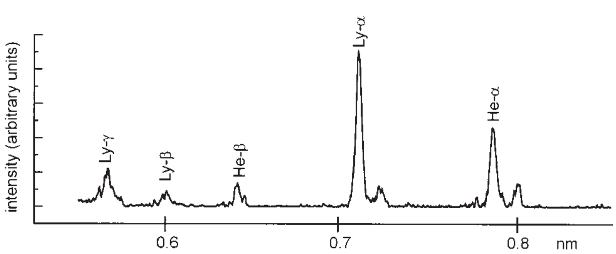

Fig. 5. Record from shot No. 99-12-6-1. H- and He-like Al lines in the spectrum of the soft X-ray pulse.

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