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# Energy transformation in Plasma Focus discharge with wire and liner as a load

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**Abstract** We present the results of experiments focused on energy transformations during the implosion of the hydrogen current sheath towards an Al wire (120 µm in diameter) positioned on the top of the inner electrode of the PF-1000 plasma focus facility at the IPPLM in Warsaw. A wire corona is formed at the current sheath impact and ~60 ns after the impact a soft X-ray pulse is emitted. Its spectrum contains AlVI-XII lines accompanied by their satellites. The amount of emitted energy is recorded by two filtered PIN diodes and thermoluminescent dosimeters and depends on symmetry of the current sheath and quality of the current sheath focus. The mean value of energy of keV photons emitted in the runs done without the wire (~1 J) is higher than the energy obtained with the wire (~0.4 J). A time delay between the impact of the current sheath and X-ray pulse, the plasma focus dynamics and soft X-ray emission are interpreted by an axial magnetic field generation and transformations.

**Key words** plasma focus • X-ray source • XUV spectroscopy

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## Introduction

Papers [1, 2] described the relative stable plasma corona and X-ray pulses of H- and He-like Al ions produced due to impact of the hydrogen plasma current sheath to the Al wire (120 µm in diameter), which was positioned on the top of the inner electrode of the plasma focus PF-1000 operated at currents ~1.5 MA. In this contribution, a temporal correlation of the PIN diode signal with the streak camera record is discussed for one shot No. 00-11-28-3, and the results obtained in a series of runs carried out with and without the wire are compared. This research was realized in the frame of a programme of the International Center on Dense Magnetized Plasmas.

## Experiment and diagnostic results

The plasma focus device PF-1000 at the Institute of Plasma Physics and Laser Microfusion in Warsaw was operated at energy of 250–300 kJ. The electric current reached the maximum of 1.3–1.5 MA during the pinch phase. The Al wires of 120 µm diameters and 2 cm length were located in front of the central electrode at an initial pressure of 5–8 torrs of hydrogen.

The plasma was studied by means of two time resolving soft X-ray PIN detectors filtered with 1.5 µm Al and 10 mm Be foils, a time-integrated XUV grazing-incidence (2–25 nm) spectrometer, a mica crystal (below 0.7 nm) spectrometer, a streak camera in the visible range of wavelengths and thermoluminescent dosimeters.

During the pinch phase of the current sheath the soft X-ray pulse is emitted at the time of minimum of the current derivative. Energy of this pulse (as registered with the filtered PIN diode) varies shot to shot and is dependent on the quality of the current sheath compression. The FWHM of the X-pulse, as observed for the shots with and without wire, reaches

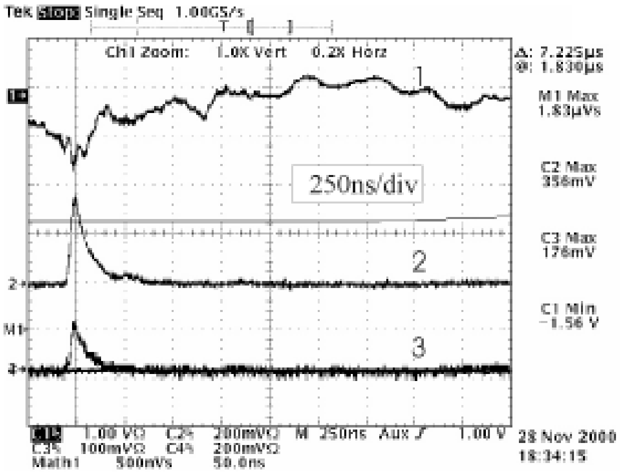


**Fig. 1.** (Shot 00-11-28-3) Oscillogram: trace 1 – current derive, trace 2 – signal from the PIN detector filtered with a 1.5 μm Al foil, trace 3 – signal from the PIN detector filtered with a 10 μm Be foil.

~ 50–100 ns. The current derivative and PIN diode signals registered for the shot No. 00-11-28-3 are presented in Fig. 1.

The streak camera records confirmed an important influence of the wire upon the plasma-focus phase duration. This duration in shots without a fiber is usually lower than 100 ns, and presence of the wire increases this period over 1 μs. In the streak camera record of the shot No. 00-11-28-3 with the Al wire (Fig. 2) one can distinguish four phases. The first one is the implosion of the hydrogen current sheath with a velocity of ~ $1.5\times10^5$ $ms^{-1}$ towards the wire. The second phase is the beginning of the plasma focus, when a plasma corona is formed around the wire with a diameter of ~7 mm and duration ~60 ns. The third phase corresponds to the corona minimal diameter of 2 mm (during ~60 ns) in the temporal correlation with an X-ray pulse and the current derivative minimum. The forth phase is characterized by a slow and regular increase in the corona diameter (with velocity of $5\times10^3$ $ms^{-1}$) from 4 mm to 20 mm during about 1.3 μs.

The mica crystal (2D focusing spherical, space resolved) spectrometer, equipped with a 10 μm Be filter, was located in the radial position to the Al wire. The record of He-like lines of Al ions and their satellites from Li- to F-like ions is shown in Fig. 3. The He-like lines were emitted from the region corresponding to the surface of the wire corona of ~2 cm in length and ~1 mm in width, while the most intensive F-like satellite line was obtained from a larger region of ~6 cm in length and 5–7 mm in width. The spot of the K-shell Cu lines is produced by an impact of electron beams upon the central Cu-electrode. The XUV spectrum in the range 0.7–10 nm is composed of AlXII – AlVI lines.

A multi-channel detection system, which was based on commercially produced Si-photodiodes and TLDs with a dynamic range of ≈($1\times10^{-9}$–20) Gy, was used to perform accurate measurements of X-ray energy. The total X-ray energy per 4π solid angle, which was emitted from the PF-1000 facility powered of 600 kJ, was about 20 mJ in the spectral range (10–15) keV.

## Discussion

The total mass of the Al fiber (~ 300–400 mg) dominates the mass of the hydrogen current sheath (~7 μg). The total energy was calculated from filtered PIN signal, under assumption of the isotropic radiation in the 4π solid angle. The presence of the fiber decreases the total energy of keV photons from 1 to 0.4 J.

The kinetic energy of the hydrogen ions in the imploding current sheath reached ~100 eV and the total kinetic energy of the current sheath was about 70 J. In Figs. 1 and 2 (for the same shot No. 00-11-28-3) one can see the development of the current sheath implosion towards the wire and the plasma corona evolution in the correlation with the X-ray emission. The plasma corona starts its radiation in the visible range after the current sheath impact and the kinetic energy transformation, but the soft X-ray pulse starts ~60 ns later in the correlation with the phase of a minimal diameter of the plasma corona. The kinetic energy of the current sheath transforms only partially onto the thermal energy necessary for the ionization of the wire corona, and partially probably into a compressed axial magnetic field. The helical configuration could stabilize the magnetic confinement of the corona.

The Al K-shell emission in experiments with the Al fiber must be produced by keV non-thermal electrons. For their acceleration the generation of the kV electric fields by a fast (~10 ns) transformation of magnetic fields of 10–100 T is necessary. On the basis of the differences of the source dimensions of the both helium-like Al lines and their satellites the ion velocity was evaluated to be ~ $3\times10^5$ $ms^{-1}$. This velocity could be achieved due to the kV electric field. The fast ions can penetrate the colder plasma, recombine and catch electrons in upper energy levels and emit satellite lines after ~50 ns in the distance of a few cm from the source of their origin.

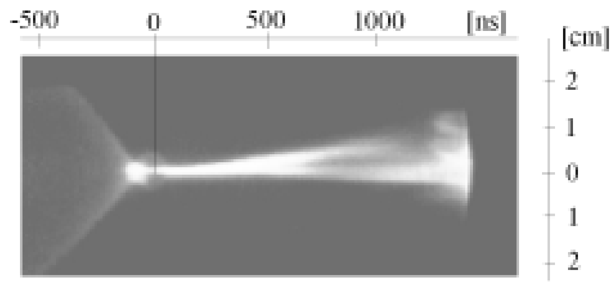


**Fig. 2.** Streak camera picture taken for shot 00-11-28-3.

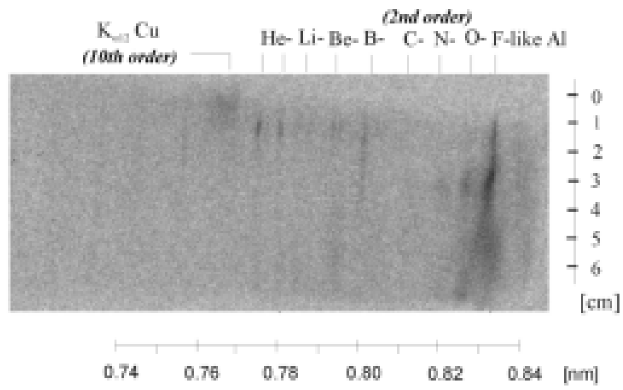


**Fig. 3.** Soft X-ray spectrum registered for shot 00-11-28-3.

The soft X-ray pulse is probably induced by a fast transformation of the internal axial magnetic field onto a helical magnetic configuration. The following stationary behavior of the wire corona could be explained by a limited diffusion of magnetic lines and high conductivity of the plasma.

## Conclusions

An impact of the current sheath onto the wire surface generated a relative stable plasma corona and the soft X-ray emission. The total power of X-rays produced without wire was evaluated to be ~10 MW and that with the wire ~5 MW. The total energy of keV photons emitted in the shots performed without wires (~1 J) was higher than that emitted with the wire (~0.4 J). The relative stable plasma corona with the slow increasing diameter and life time ~1.5 μs was probably confined by a frozen magnetic field. The soft X-ray pulse was emitted during a weak pinch of the plasma corona, about ~60 ns after the current sheath impact, on the form of He-like Al lines and their satellites. The time delay can be interpreted by the partial transformation of kinetic energy of the imploded current sheath to the helical configuration of the magnetic field (with compressed axial magnetic components). The fast transformation of this configuration (in a few tens of ns) could produce a kV electric field which could accelerate electrons and ions and generate the soft X-ray radiation.

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