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Recent progress in 1 MJ Plasma-Focus research

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Abstract The paper reports on actual operational characteristics of the PF-1000 facility and it presents results of the first neutron experiments performed with a new set of large Mather-type electrodes, which were designed for shots up to 1000 kJ. Dynamics of a current-sheath was studied by means of two high-speed streak cameras and a two-frame camera. The last one was used for the side-on observation of the pinch column. The high-speed streak pictures were taken side-on behind slits oriented in the radial or axial direction. On the basis of the pictures taken behind the radial slit, average values of the radial compression and expansion velocities were estimated. Time-resolved X-ray signals were measured with PIN diodes covered by different filters, and they were compared with other traces (voltage waveforms, dI/dt signals, and neutron-induced pulses) in order to determine their correlation. The total neutron yield (Y_{tot}), i.e. the number of neutrons produced during a single discharge and emitted in various directions, was measured by means of several silver-activation detectors placed at different angles around the PF-1000 experimental chamber.

Key words neutron emission • plasma focus • scaling laws • soft X-ray radiation

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Introduction

Dense Plasma Focus (DPF) machines are pulsed discharges in which microinstabilities and turbulence lead to generation of powerful beams of electrons, ions, large emission of X-rays and of fusion neutrons when the filling gas is deuterium. The Plasma Focus (PF) belongs to the family of the dynamic Z-pinch. It is a non-cylindrical Z-pinch formed on the axis at the end of a coaxial electrode system of a plasma accelerator. Most realizations belongs to one of the two following geometrical types:

- Mather-type, characterized by a small anode aspect ratio (diameter/length < 1);
- Filippov-type, characterized by a large aspect ratio.

Plasma Focus produces a short living, rather dense plasma, the properties of which are dominated by the occurrence of macroscopic and microscopic instabilities. At present, DPF is one of the most efficient sources of neutron emission. Also scaling laws of neutron yield prepared on the basis of long experience with different devices of this type are very promising [1, 2]. Unfortunately, it was found that neutron emission saturates at an energy level of several hundreds kJ [3].

The main goals of our experiment were defined as follows:

- seek for conditions of good operation of the PF-1000 device at the energy level higher than 700 kJ for the first time;
- investigation of eventual neutron yield saturation with a maximum current I_{max};

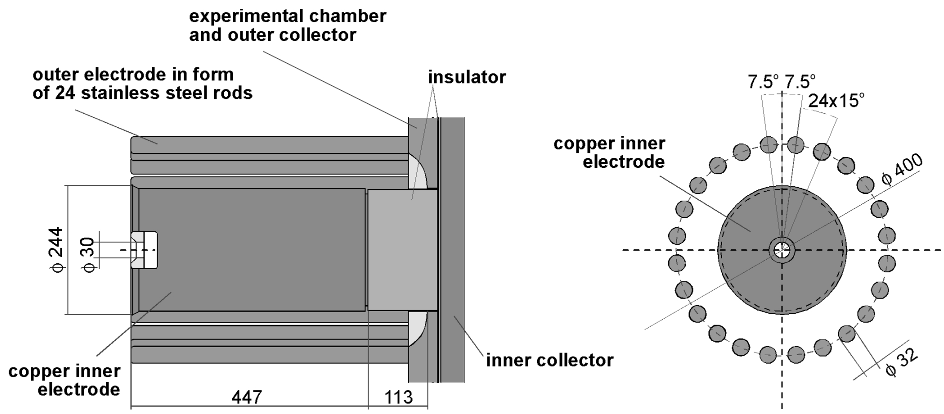

Fig. 1. Geometry and dimensions of the PF-1000 electrodes.

- seek for relations between Y_n and soft X-ray output;
- measurements of Y_n anisotropy for different filling gas pressure.

Experimental setup

Investigations described in this paper have been carried out on the PF-1000 plasma-focus device. Construction details of this device were presented in [5]. All geometrical dimensions are seen in Fig. 1. The outer electrode is formed of 24 stainless steel rods, which are 600 mm in length and 32 mm in diameter. The diameter of the outer electrode is 400 mm. The inner electrode is made of copper, its diameter is 244 mm. There is a hole (30 mm in diameter) at the end-on face of the inner electrode. The interelectrode gap between inner and outer electrode is 62 mm. The cylindrical alumina insulator has a diameter of 229 mm and its length is 113 mm. The PF-1000 condenser bank consists of twelve condenser modules each comprising twenty four 50 kV, 4.625 μF low inductance condensers connected in parallel. Summarizing, main parameters of the PF-1000 generator are: the charging voltage U_0 = 20–40 kV, the capacitor energy E_0 = 266–1064 kJ, and the quarter discharge time T = 5.4 μs.

The equipment for electrical pulses measurement and triggering system consists of detectors situated on the experimental chamber and multi-channel fast, transient pulses capturing, control and analysis system (Fig. 2). To avoid the electrical discharge noises on cables, signals from detectors are transmitted by means of opto-links, and also the main control stand has its own electrical feeding source switched on during condenser bank discharge. The geometrical position of the detectors is as follows:

- current derivative probe (dI/dt) is mounted inside the outer collector;
- PIN1 visible light detector is situated in the diagnostic window and its observation region on the plasma-focus axis is placed at a distance of 20 mm from the central electrode face (Fig. 2);
- PIN2 – X-ray detector observes through 100 μm pinhole (covered with 20 μm Be) the same plasma region as PIN1 from another diagnostic window.

The registration setup of the plasma sheath luminosity was utilized to obtain the main triggering pulse to start all fast plasma diagnostics. In this way, in our experiment all detectors were switched on independently of the discharge current peculiarities and its stochasticity. It was also easy to change the triggering point in various discharges or to repeat the same diagnostic conditions in a subsequent discharge (if it was necessary, e.g. when the condenser bank energy was changed).

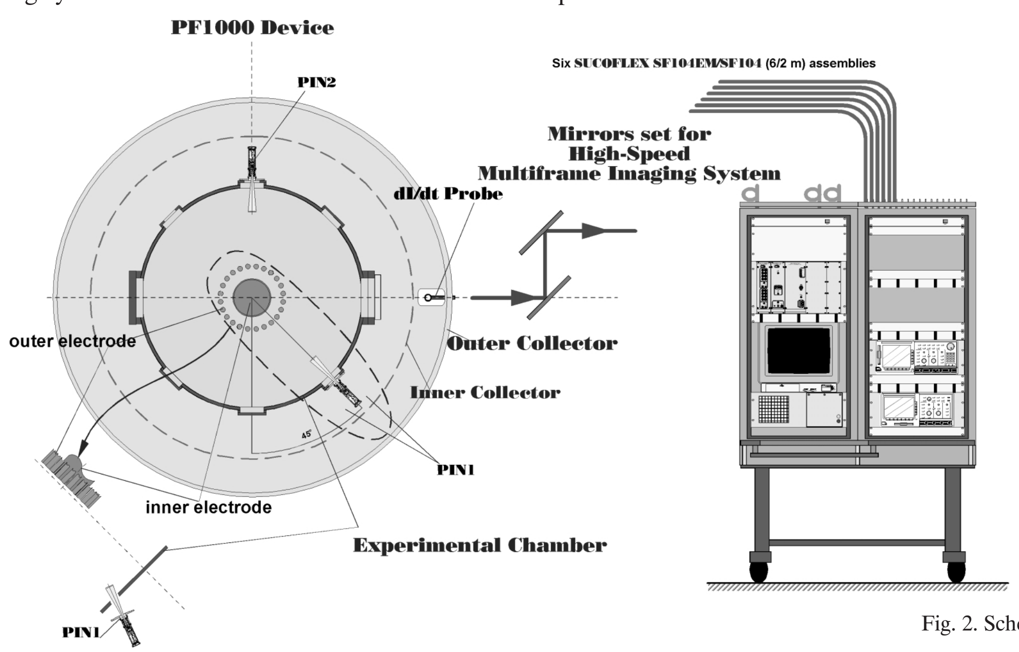

Fig. 2. Scheme of the diagnostic system.

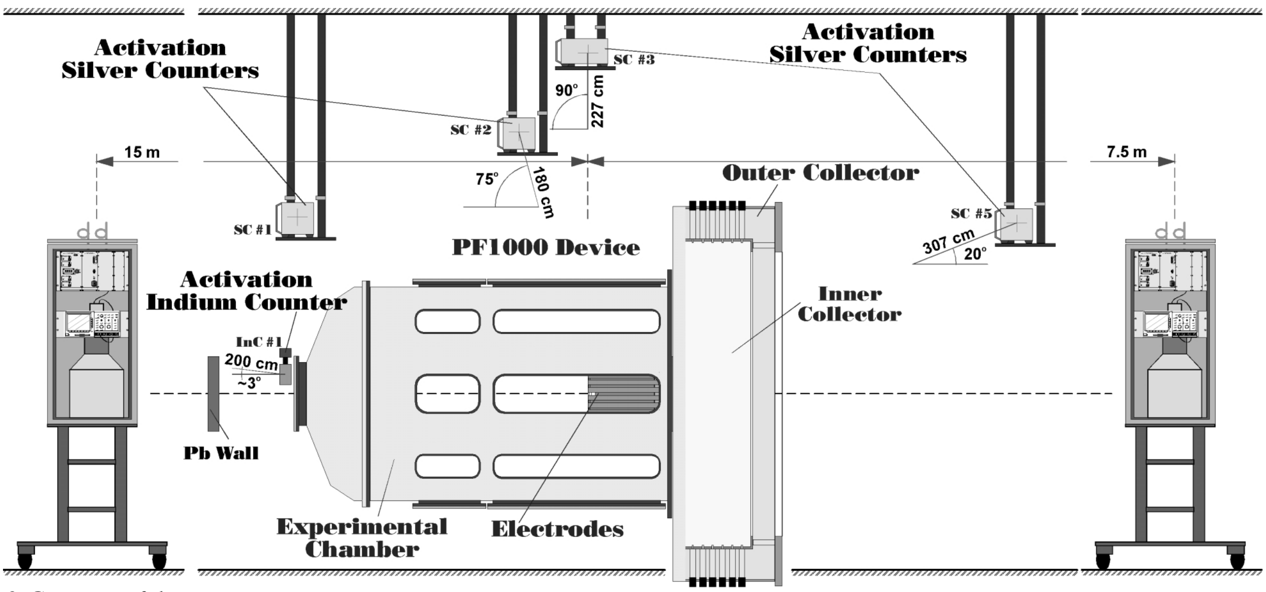

Fig. 3. Geometry of the neutron counters.

Three independent streak and frame cameras are used in one shot to observe the plasma-focus region:

- the frame, optical camera QUADRO – which gives two subsequent frames at a time distance of 50 ns;
- slow streak camera FENIX II (time base equal to 2 μs);
- fast streak camera IMACON type (time base equal to 300 ns).

Neutron and hard X-ray emission were measured by means of three independent types of detectors:
- four silver activation counters situated spatially at various distances from the source and various angles to the axis of the electrodes (see Fig. 3);
- two indium activation counters situated along the axis and perpendicular to it, respectively;
- a scintillating probe located at a distance of 15 m from the inner electrode face to measure time-resolved signals induced by neutrons and hard X-ray radiation.

The neutron detectors were calibrated using an Am-Be neutron source of an activity of 1.5×10^7 neutrons/s.

Results of the experiments

Exemplary frame camera pictures taken in a so called “good” shot and corresponding signals from the scintillation probe are presented in Fig. 4. Fig. 5 presents equivalent pictures and signals obtained in a “bad” shot. The pictures in Fig. 4 reveal a well formed, long (~4 cm in length) and narrow (~0.6 cm in diameter) pinched plasma column with the highest brightness on its axis. The “good” shot (Fig. 4) was performed at the discharge energy equal to 1070 kJ and neutron yield amounted to 2.06×10^{11} in this shot. The time resolved signals (from Rogowski coil, two PIN diodes, dI/dt probe) as registered in the good shot are presented in Fig. 6. One can see two separate and sharp X-ray pulses (50 ns one after another) revealed by the PIN diodes in this shot. The streak camera pictures, taken through a narrow vertical slit situated at a distance of 2 cm from the inner electrode face, demonstrate that the imploding current sheath underwent a proper accelerated motion toward the axis.

Bad shots generally happened when the discharge voltage was not properly adjusted to the filling pressure (was too low or too high). Pictures taken in such shots by both the frame and streak cameras showed that the plasma sheath was not well formed and its dynamics was not high (Fig. 5). The neutron yield decreased significantly in such shots and was two-three orders of magnitude lower than in the good ones. Also the current derivative signals did not show any sharp dip which is characteristic for good pinching.

In order to determine the neutron scaling law we proceeded in the following way: a series of shots was performed with a constant filling gas pressure, increasing voltage. The higher voltage resulted in increased discharge current. For

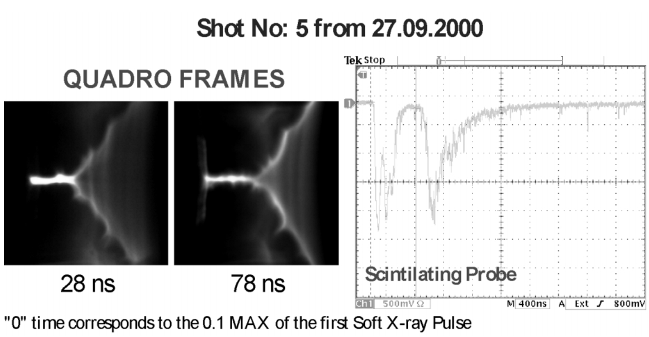

Fig. 4. Frame camera pictures and time resolved scintillating probe signals for “good” shot.

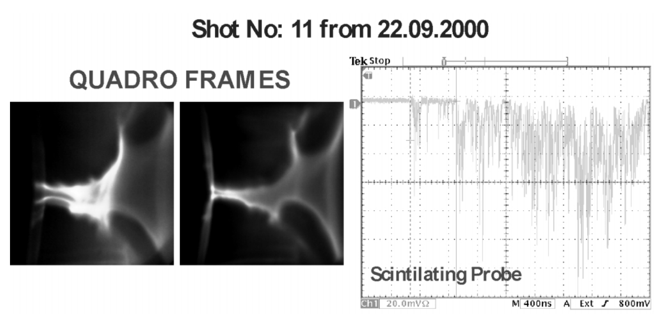

Fig. 5. Frame camera pictures and time resolved scintillating probes signals for “bad” shot.

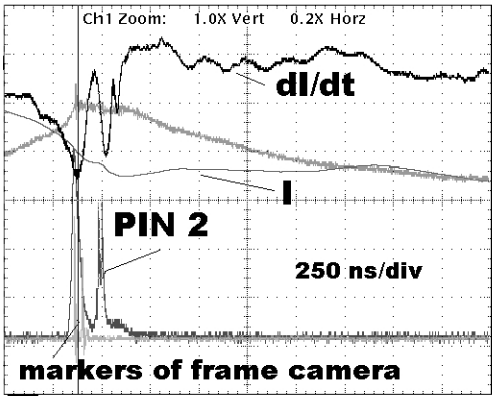

Fig. 6. The time resolved signals (from Rogowski coil, two PIN diodes, dI/dt probe).

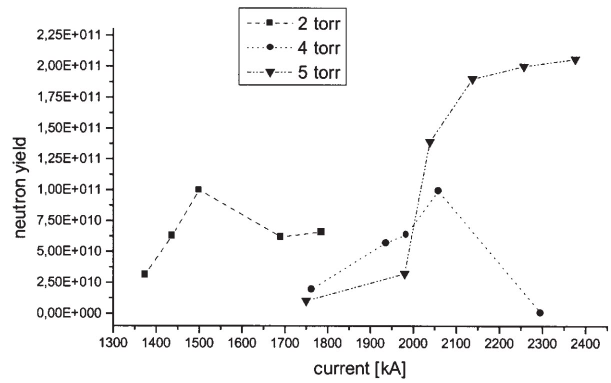

Fig. 7. Neutron yield *vs.* maximum current.

each filling pressure value, a maximum neutron yield was determined and plotted *vs.* discharge current (Fig. 7). It can be seen that for fixed pressure the neutron yield curve exhibits a maximum and that for currents lower or higher than a certain level (depending on pressure) the neutron yield vanishes. There is also some optimistic message from Fig. 7. We hope that, as a result, of increasing the filling pressure it will be possible to gain much higher neutron yield.

Fig. 8. shows the correlation between the neutron yield and the total X-ray energy output as measured using the PIN diodes equipped with a pinhole covered with a 1.5 μm Al foil. Each diagram in this Figure relates to one value of the filling pressure. Assuming that X-ray energy output is proportional to the total plasma internal energy we can conclude that the neutron output for each shot is well 'coupled' to this energy. Our suggestion is that this fact should be taken into account in a more detailed analysis of neutron production mechanism in plasma focus discharges in the megajoule range.

The optimum neutron yields as a function of maximum current I_{max} and as a function of condenser bank energy W_{bat} is presented in Fig. 9. Two maximum values of neutron yields for each pressures equal to 2, 4, and 5 Torr were taken into account. From this, rather rough interpolation, it follows that the scaling formulas are in good agreement with the earlier published results [4].

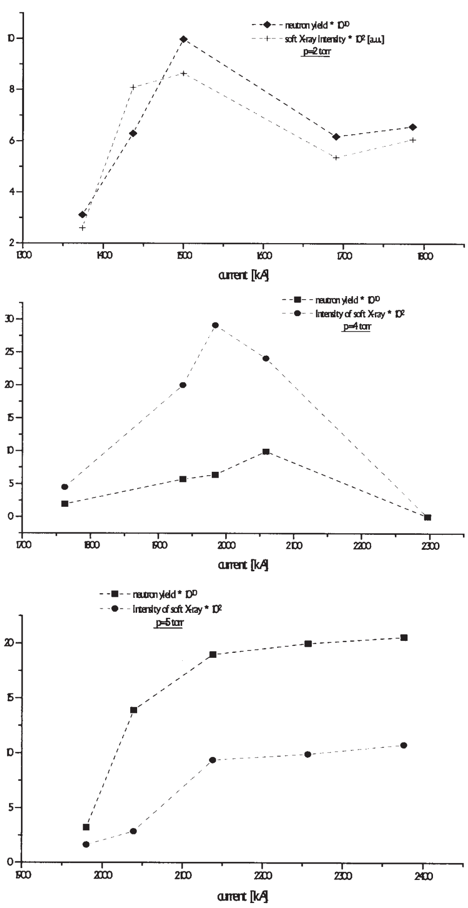

Fig. 8. Neutron yield and soft X-ray output *vs.* maximum current for different pressures.

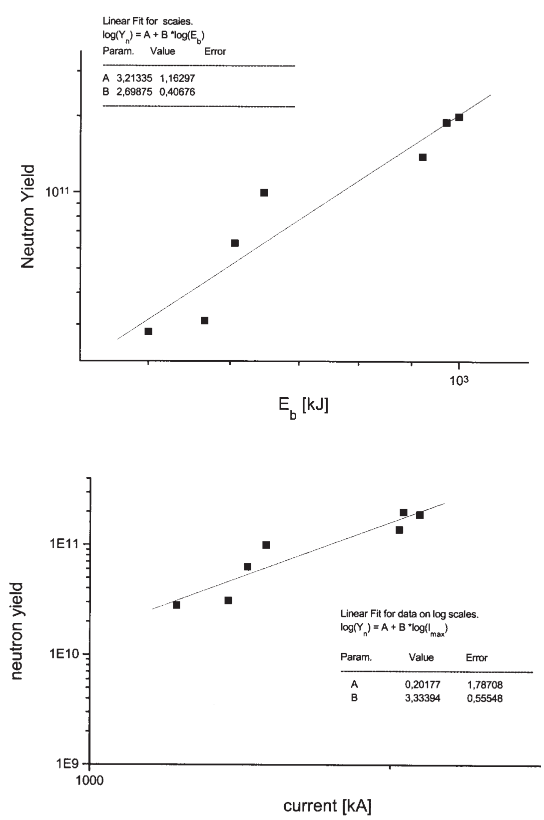

Fig. 9. Scalling laws of neutron yield obtained from results of the first neutron experiment on PF-1000.

Conclusions

Results of the first experiment at the 1 MJ energy level in the Plasma Focus investigation are optimistic:

- the PF-1000 device is working properly for energy up to 1 MJ although maximum current values achieved are not as high as expected;
- the neutron scaling is $Y \sim I_{max}^{3.3}$;
- lack of Y saturation for $I < 2.3$ MA (the question is, whether will it exist for $I > 2.3$ MA);
- correlation of the soft X-ray output and neutron yield has been found.

A future neutron experiment strategy for the PF-1000 facility should concentrate on an optimal matching of the generator characteristics to the load (testing new electrodes better coupled to condenser bank energy) to achieve higher maximum current values. Application of new types of diagnostics like interferometry, X-ray back-lightning and X-ray frame cameras is also foreseen. In future experiments we intend to increase the gas pressure up to 6 and 8 Torr to prove whether the neutron yield will still grow up as a function of maximum current.

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