Magnetic field measurements on PF-1000 and PF-3 facilities: current sheath structure and neutron scaling

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Abstract. The comparative analysis of the magnetic field distribution, the dynamics and structure of the plasma current sheath, and the neutron yield scaling in two largest plasma focus facilities, PF-3 and PF-1000 is done. The power-low dependence of the neutron yield on the current in the imploding plasma sheath has been demonstrated experimentally. For the first time the presence of the B_z magnetic field components is experimentally shown.

Key words: plasma focus (PF) • magnetic probe • current sheath • neutron scaling

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Introduction

Study of the mechanisms for generation of neutron and X-ray emission in megajoule and submegajoule facilities is one of the priority directions in the development of plasma focus (PF) systems. Interest in these studies is motivated by the important problem of creating a high-power neutron source. The empirical scaling $Y_n \sim I^4$, where Y_n is the neutron yield and I is the amplitude of the current pulse, reliably operates in the discharge energy range from several kilojoules (kJ) to a few hundred kilojoules.

In order to further increase the neutron yield, it is necessary to carry out experiments on large facilities with currents of several megaamperes. At present, there are four PF facilities operating in this energy range: PF-3 at the Kurchatov Institute (Moscow, Russia), PF-1000 at the Institute of Plasma Physics and Laser Microfusion (IPPLM, Warsaw, Poland), KPF-4 "Phoenix" at SPTI (Sukhumi, Abkhazia), and the North Las Vegas Facility at the NSTec (Nevada, USA).

This study is devoted to the comparative analysis of the magnetic field distribution, the dynamics and structure of the plasma current sheath (PCS), and the neutron yield scaling in two of the above facilities, PF-3 and PF-1000.

Experimental results

The dynamics and structure of the PCS in different discharge stages was studied using absolutely calibrated magnetic probes [3]. The PF-3 and PF-1000 facilities belong to the two different types of PF systems: Filippov and Mather types, respectively. The difference in the geometry of the systems dictated differences in the

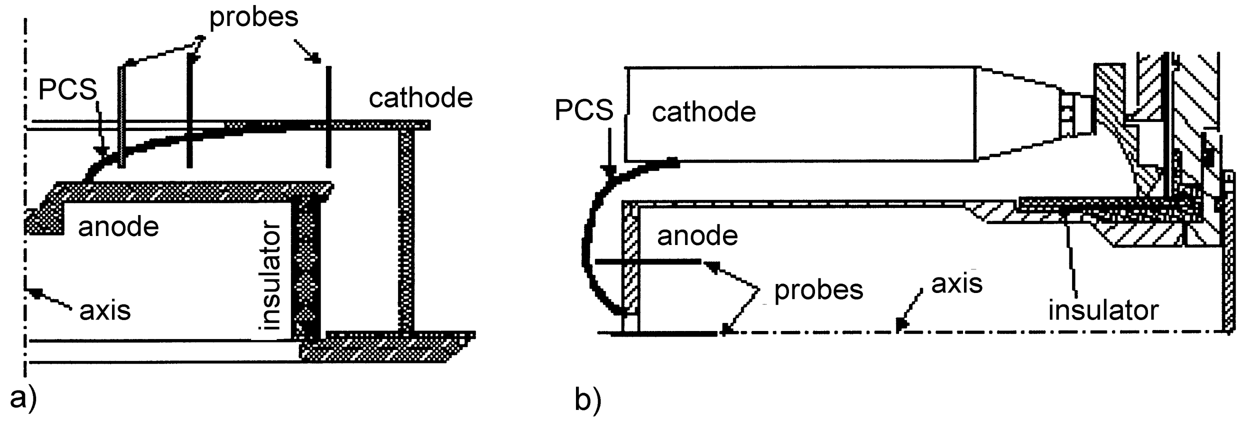


Fig. 1. Arrangement of magnetic probes in the (a) PF-3 and (b) PF-1000 facilities. The probes are installed at radii of 460, 260, 160 mm (PF-3), and of 40 and 13 mm (PF-1000).

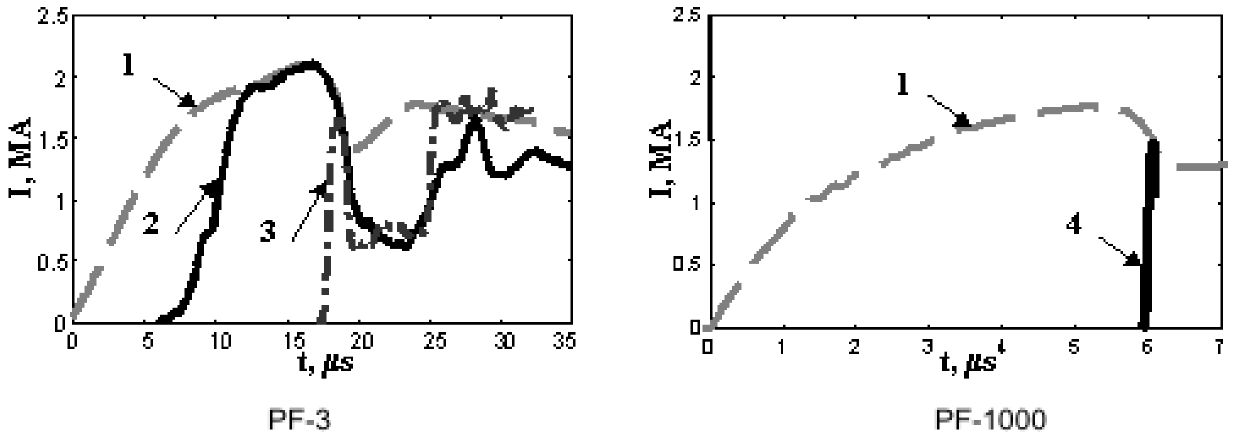


Fig. 2. Current oscillograms in optimal discharges: total discharge current (1) and currents measured at distances of 46 cm (2), 16 cm (3) and 4 cm (4) from the axis.

measurement schemes (Fig. 1). In PF-3, the probes were introduced from the cathode side at different distances from the axis, due to which it was possible to study the dynamics of the PCS in different stages of its long-term radial compression, from its rise above the anode edge near the insulator ($R = 46$ cm) up to its implosion onto the axis. In PF-1000, the stage of radial compression is much shorter. Here, attention was focused on studying the PCS structure in the developed stage of radial compression. The probes were introduced from the side of the high-voltage anode at a distance of 4 and 1.3 cm from the system axis.

In the first series of experiments, we studied the efficiency of current transportation onto the axis. It was demonstrated that, in the optimal regimes accompanied by a high neutron yield, the current in both facilities was almost entirely compressed into the pinching region (Fig. 2).

At the same time, for nonoptimal regimes, especially in the stage of discharge chamber "training" (degassing), the fraction of the current compressed onto the axis may comprise less than one-half of the total discharge current (Fig. 3). Experiments carried out on PF-3 have shown that leakage currents can appear both

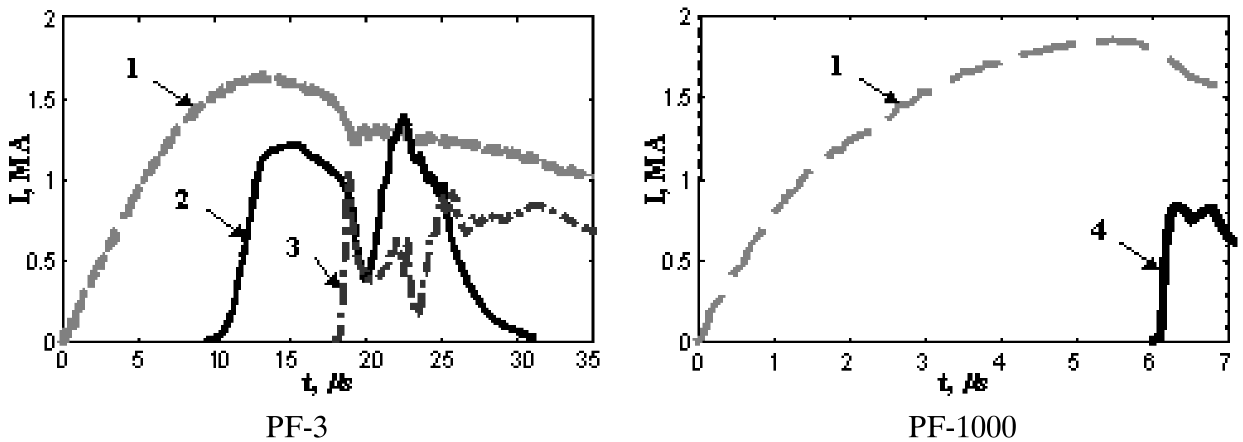
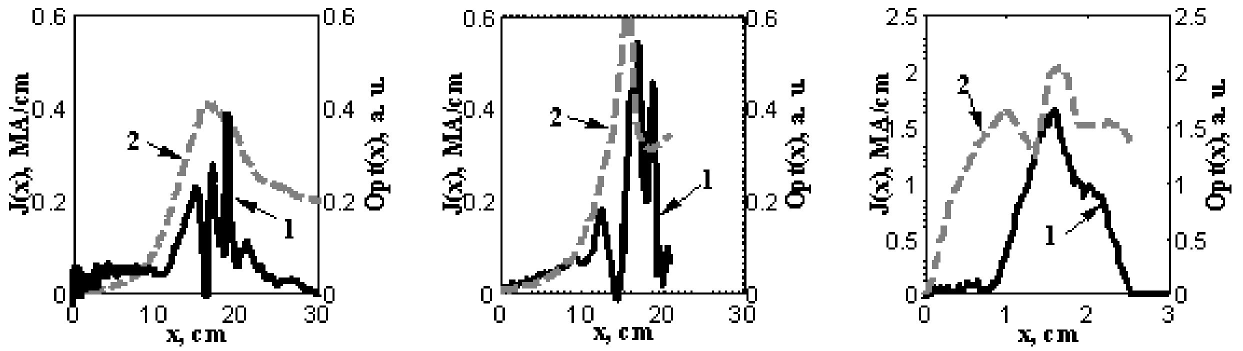


Fig. 3. Current oscillograms in nonoptimal discharges: total discharge current (1) and currents measured at distances of 46 cm (2), 16 cm (3) and 4 cm (4) from the axis.



PF-3, R = 46 cm PF-3, R = 26 cm PF-1000, R = 4 cm

Fig. 4. Profiles of the (1) current density and (2) plasma glow across the PCS in different discharge stages.

at the very beginning of the discharge (when a fraction of the current has not yet detached from the insulator) and during the PCS propagation toward the axis. In this case, closed current loops separated from both the pinching region and the power supply can form [3].

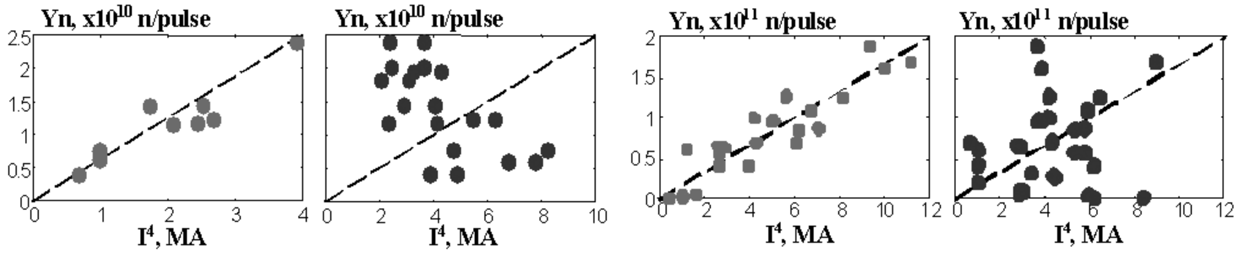
The efficiency of current transportation toward the axis is determined by the snowplowing efficiency, which in turn depends on the PCS quality. The PCS structure was studied using a magneto-optical probe [1], which, in addition to the magnetic signal, also recorded the PCS optical radiation. It has been found that the PCS structure depends substantially on the discharge stage. The initial discharge stages are characterized by a loose PCS structure; in this case, the current is distributed over almost the entire PCS thickness. As the PCS approaches the axis, it becomes more compact, a pronounced shock wave forms, and the current begins to flow mainly in the region of the magnetic piston (Fig. 4).

Neutron measurements have demonstrated that the neutron yield correlates with the magnitude of the current flowing in the PCS and is practically independent of the total discharge current (Fig. 5). In both facilities, the dependence of the neutron yield on the PCS current agrees well with the scaling $Y_n \sim I^4$.

It should be noted that, for the same discharge currents, the neutron yield in PF-1000 is higher than that in PF-3. We also note that the scaling for PF-3 was constructed using magnetic probes installed at a relatively large distance (≥ 16 cm) from the axis. Obviously, the current flowing in the PCS can decrease appreciably as the sheath approaches the axis. Moreover, the measured neutron yield in PF-3 may be affected by the scheme of neutron measurements, because an appreciable fraction of the pinch (up to 70%) may occur in a dip in the central part of the massive anode [3] and, thereby, be screened from the detector recording radiation at an angle of 90° to the system axis. Possible differences in the mechanisms for neutron generation should also be taken into account; in particular, in PF-3, the neutron flux is almost isotropic, which indicates the thermonuclear nature of these neutrons. Certainly more detailed analysis, including the involvement of the results of the time of flight measurements is required which will be done in the next studies.

Along with conventional thermonuclear and acceleration mechanisms for neutron generation, the mechanism related to the trapping of accelerated ions in closed magnetic configurations has attracted considerable interest [2]. This mechanism assumes the presence of a sufficiently strong axial magnetic field. However, no direct measurements of the field B_z have been performed as yet. We attempted to perform such measurements on PF-1000 facility by using probes with the correspondingly oriented turns of the measurement coil. Unfortunately, the coil of the axial probe always has a “parasitic” area sensitive to the azimuthal component of the magnetic field and we failed to extract a pure B_z signal. Therefore, we used a combination of two probes, an azimuthal one, located at a standard distance of 40 mm from the axis, and an axial one, located at a distance of 13 mm. Figure 6 shows the results of these measurements.

It follows from the results of other measurements that the PCS velocity in this region is $\sim 2 \times 10^7$ cm/s, i.e., the PCS should reach the second probe about 130 ns after the appearance of the signal from the first probe. However, the signal from the second probe occurs just after 65 ns and is preserved on a moderate level over about 60 ns, and then increases abruptly. The instant at which this signal increases coincides with the calculated time of the PCS arrival at the second probe. In our opinion, this increase corresponds to the detection of the azimuthal component of the magnetic field (or a combination of the two components). The previous



PF-3 **PF-1000**

Fig. 5. Neutron yield Y_n as a function of the current measured by magnetic probes (on the left) and the total current at the instant of neutron generation (on the right). The dashed line shows the dependence $Y_n \sim I^4$.

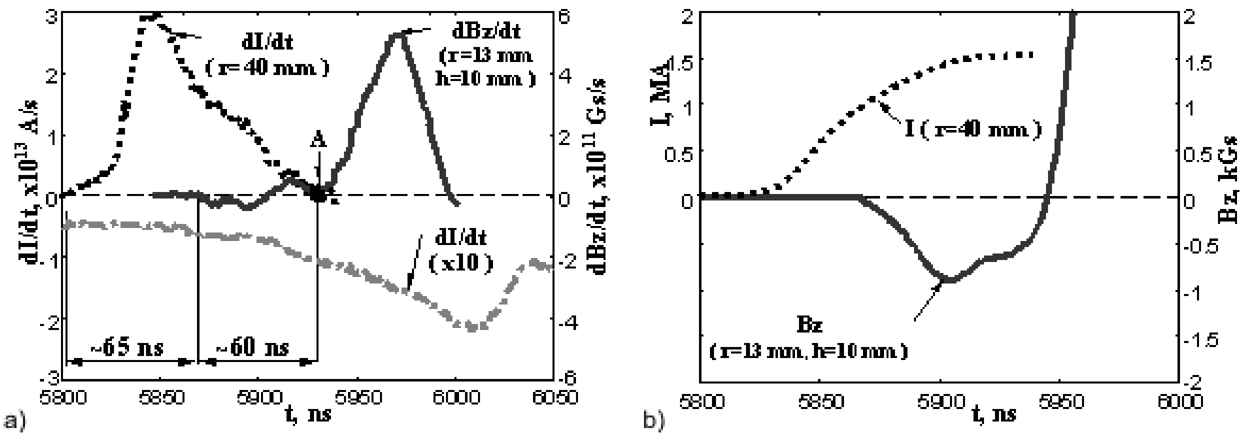


Fig. 6. Results of measurements of the azimuthal and axial magnetic field components on the PF-1000 facility: (a) derivative of the total current, *dI/dt*, the current derivative, measured by the azimuthal probe at radius 40 mm, *dI/dt* (r = 40 mm), and derivative of induction of the axial magnetic field, *dBz/dt*, and (b) current within radius 40 mm, *I*, and induction of the axial magnetic field, *Bz*.

(moderate) signal cannot be explained as the "precursor", because it has the polarity, which is opposite to the polarity of the $dB\varphi/dt$ signal. Moreover, in each probe we use two small-size coils wound in opposite directions (clockwise and counter-clockwise) and placed in a common case. The use of two coils provided simultaneous recording of two signals of opposite polarity, which allowed one to extract the useful signal caused by variations in the magnetic field against the background of possible electromagnetic disturbances. The circumstances set forth above allow us to make the assumption that this signal is caused by the axial field.

It follows from Fig. 6b that the corresponding magnetic field is ~ 1 kG. Probably, this is the axial magnetic field that arises during the compression of the axial magnetic flux at the front of the supersonic shock wave. As this flux is further compressed when the PCS collapses onto the axis, the magnetic field can increase substantially. We plan to perform additional measurements of the axial field by using a probe with an improved design.

Summary and conclusions

Comparative analysis of the magnetic field distributions measured using magnetic probes of different design at two large facilities, PF-3 and PF-1000, at discharge energies of up to 500 kJ has made it possible to reveal the following specific features. Regimes in which the entire discharge current is transported onto the system axis have been obtained on both facilities. The power-low dependence of the neutron yield on the current in the imploding PCS has been demonstrated experimentally. In both facilities, this dependence agrees well with the known scaling $Y_n \sim I^4$. Efficient snowplowing of the discharge current onto the axis is the necessary, but insufficient condition for achieving a high neutron yield, which depends, first of all, on the mechanism of neutron generation that prevails in a particular regime. It has been demonstrated that, in the optimal regimes, the PCS structure in the final stage of compression approaches the ideal snowplow model, in which the current mainly flows in the magnetic piston. The longitudinal (axial) magnetic field has been detected for the first time. The presence of this field may have an appreciable effect on the mechanism of neutron generation.

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