RECENT RESULTS OF STUDIES OF MAGNETIC FIELD DISTRIBUTION AND NEUTRON SCALING ON PF-1000 AND PF-3 FACILITIES

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The recent results of studies of the magnetic field distribution and the neutron yield scaling in two largest plasma focus facilities, PF-3 and PF-1000 is done. The power-law 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. In the compression stage, the axial component of the magnetic field reaches several kG that comprises ~10 % of the azimuthal component. The presence of the B_z field is a powerful argument in favor of the existence of closed magnetic configurations, which play an important role in the generating of neutrons.

PACS: 52.58.LQ, 52.59.HQ

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 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 megamperes. At present, there are four PF facilities operating in this energy range: PF-3 at the Kurchatov Institute (Moscow), PF-1000 at the IPPLM (Warsaw), KPF-4 “Phoenix” at SPTI (Sukhumi), and the North Las Vegas Facility at the NSTec (Nevada). 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 [1]. 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 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 cm and 1.3 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) [2].

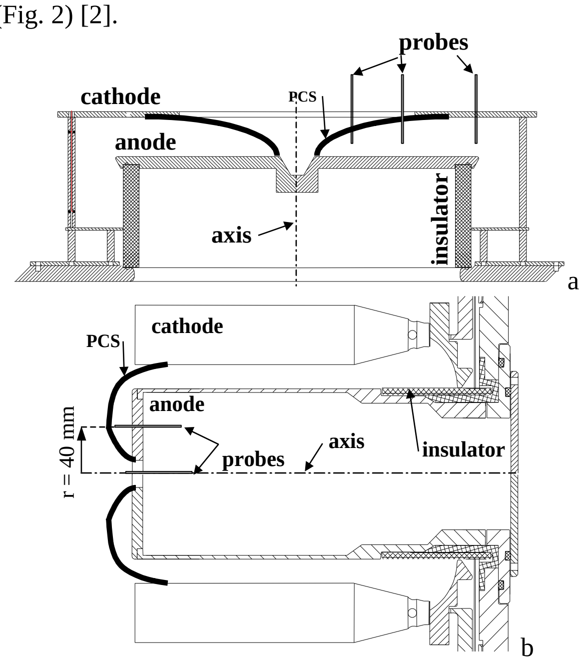

Fig. 1. Arrangement of magnetic probes in the (a) PF-3 and (b) PF-1000 facilities. The probes are installed at radii of 460, 260, 160 mm (PF-3), and of 40 and 13 mm (PF-1000)

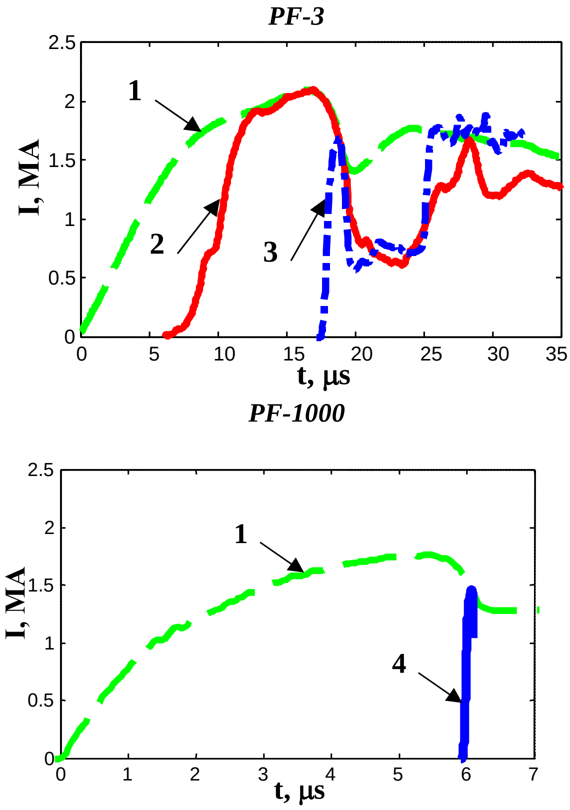

Fig. 2. Current oscillograms in optimal discharges: total discharge current (1) and currents measured at distances of 46 cm (2), 16 cm (3) and 4 cm (4) from the axis

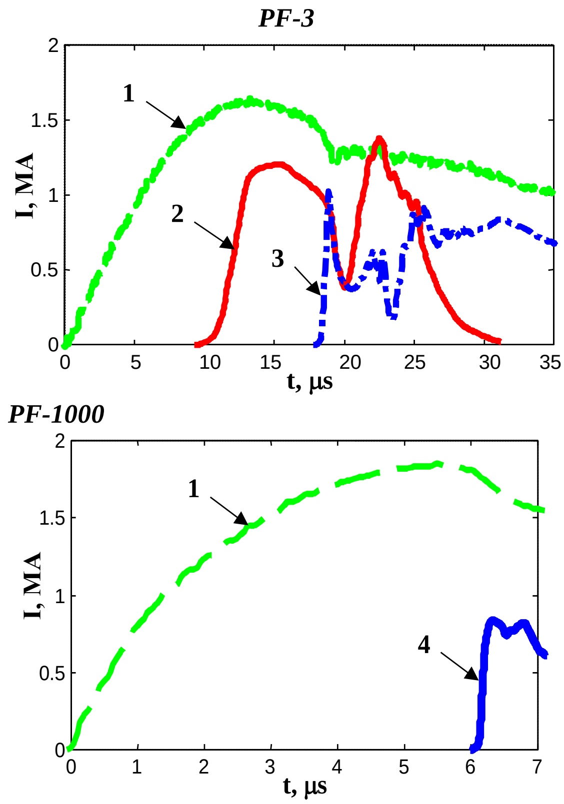

Fig. 3. Current oscillograms in nonoptimal discharges: total discharge current (1) and currents measured at distances of 46 cm (2), 16 cm (3) and 4 cm (4) from the axis

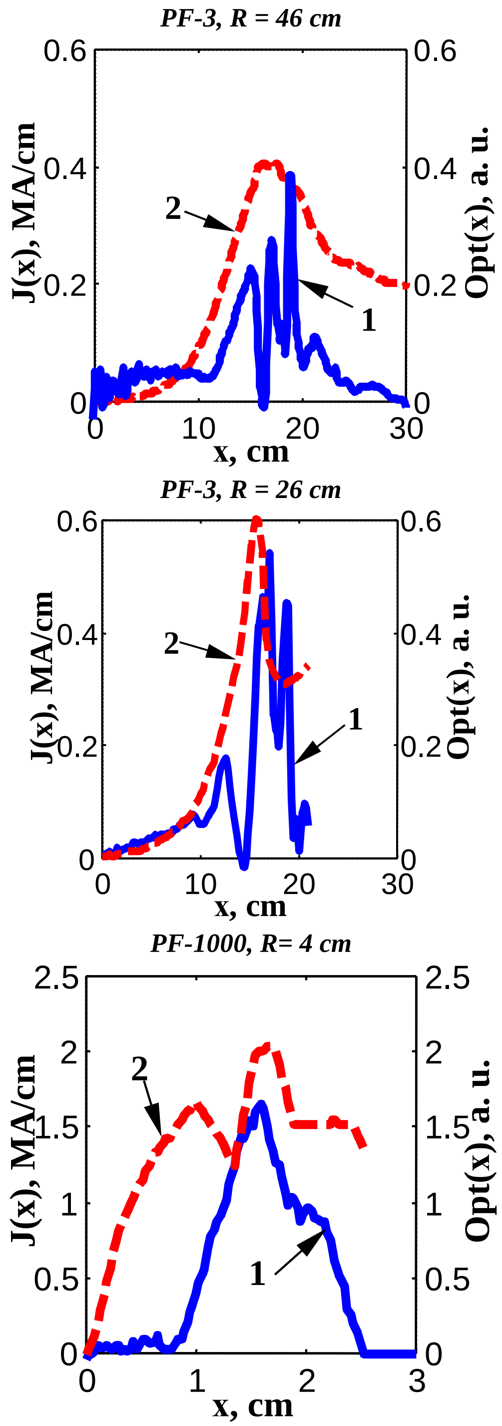

Fig. 4. Profiles of the (1) plasma glow and (2) current density across the PCS in different discharge stages

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 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 [1].

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 [3], 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 [1] 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.

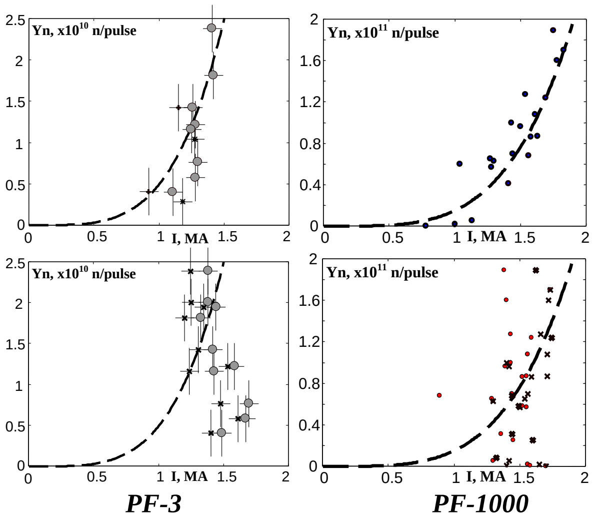

Fig. 5. Neutron yield Y_n as a function of the current measured by magnetic probes (on the left) and the total current at the instant of neutron generation (on the right). The dashed line shows the dependence $Y_n \sim I$

In recent years, 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 [4]. 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. As a rare example we can mention the paper [5] in which the results of measurements of B_z field with the help of Faraday rotation were reported. We attempted to perform such measurements on PF-1000 facility by using probes with the correspondingly oriented turns of the measurement coil. We used a modified combined probe allowing one to simultaneously measure not only the azimuthal and axial components of the magnetic field, but also plasma optical emission.

Fig. 6 shows signals from probes arranged at the radius 40 mm.

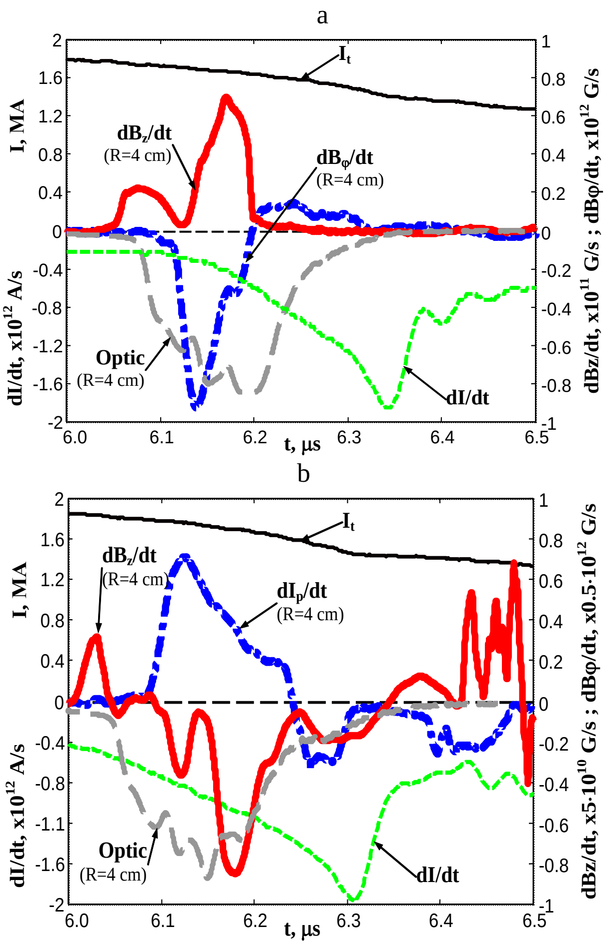

Fig. 6: Signals from the B_z and B_φ channels of the probes having different relative sensitivities of the B_z channel: $K_z(B_\varphi)/K_z(B_z)$ = (a) 0.231 (shot no. 9347) and (b) 0.055 (shot no. 9348). Here, "Optic" in panel (a) stands for the signal from the optical channel of the probe (in arb. units). R_{probe} = 40 mm; Z_{probe} = 10 mm; Y_n = 1.24×10^{11} and 9.3×10^{10} n/shot for shot nos. 9347 and 9348, respectively

The signals were recorded in two successive discharges with identical initial conditions and close neutron yields. For a given signal $U(t)|_{(Bz+B\varphi)}$ recorded from the B_z channel, the actual value of the axial component of the magnetic field depends substantially on the relative sensitivity of the B_z coil to different component of the magnetic field.

Fig. 7 shows the B_z and B_φ fields recovered from the signals shown in Fig. 6 according with technique described in [6]. One can see that, in spite of essential difference in the origin signals, the behavior of Bz field is identical for both pulses. It appears ~60…65 ns before the arrival of the PCS and increases to ~0.4 kG. According to the calibration results, the B_z field in front of the PCS is directed from the anode to the cathode. After the arrival of the PCS, the B_z field changes its sign and reaches a value of ~4 kG.

It should be noted that the probe actually records the change in the magnetic field, ΔB. When recording the azimuthal component, we can assert with a high degree of accuracy that $\Delta B_\varphi = B_\varphi$, whereas in recording the axial component, we cannot be assured that, before the arrival of the PCS, the B_z field at the location of the probe was zero. If we assume that the initial B_z field is nonzero and is directed positively (from the anode), then the negative signal from the B_z channel can be caused by expulsion of the magnetic field by the PCS plasma.

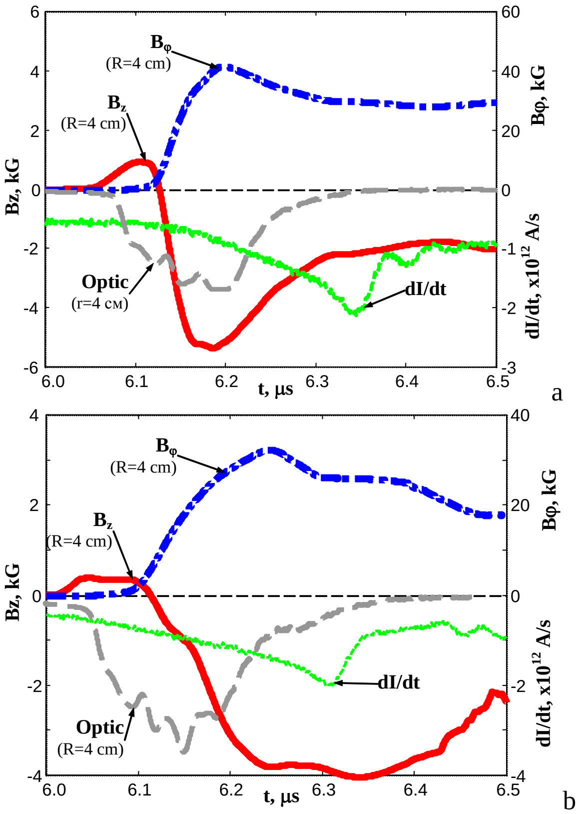

Fig. 7. Time dependences of the B_z and B_φ fields at the radius of 40 mm, calculated from the probes signals shown in Fig. 6 for $K_z(B_\varphi)/K_z(B_z)$ = (a) 0.231 (shot no. 9347) and (b) 0.055 (shot no. 9348). Here, "Optic" in panel (a) stands for the signal from the optical channel of the probe (in arb. units)

The presence of an initial axial field with a magnitude of several kG can be explained, e.g., in terms of the model proposed in [7]. In principle, taking into account that the axial component of the magnetic field comprises ~10 % of the azimuthal component, the axial magnetic field with a magnitude of several kG can be produced by the current flowing along a helix with a relatively small pitch angle. There is some indirect evidence of the existence of such a helical current structure. For example, helical instability of the PCS outer boundary was observed in the frame photographs taken in the stage of PCS compression [8].

Therefore, the first pulse in the probe signal can be caused by the compression of the axial magnetic flux at the shock front. Even for a small degree of ionization of the working gas in front of the PCS (≥1 %), the observed PCS velocity of ~2 × 10^7 cm/s at a magnetic field of ~5 kG exceeds the Alfvén velocity, i.e., we are dealing with a shock-wave propagation of the PCS with an Alfvén Mach number of $M_A > 1$.

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-law 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 the B_z field is a powerful argument in favor of the existence of closed magnetic configurations, which play an important role in the generating of neutrons. On the other hand, it is necessary to take into account that the presence of the axial magnetic field in front of the PCS can hinder the pinching process and prevent the achievement of the maximum plasma and current densities. At least, this is evidenced by the results of experiments in which an external longitudinal magnetic field was applied [9, 10].

This research has been supported by the Russian Foundation for Basic Research (project nos. 11-02-01212 and 11-02-90303) and by the research program no. LA08024 of the Ministry of Education, Youth and Sport of the Czech Republic.

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Article received 23.10.12

ПОСЛЕДНИЕ РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЙ РАСПРЕДЕЛЕНИЯ МАГНИТНОГО ПОЛЯ И НЕЙТРОННОГО СКЕЙЛИНГА НА УСТАНОВКАХ ПФ-1000 И ПФ-3

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Представлены результаты последних исследований распределения магнитного поля и скейлинга нейтронного выхода на двух крупнейших плазмофокусных установках ПФ-3 и ПФ-1000. Экспериментально показана степенная зависимость нейтронного выхода от величины тока в сжимающейся плазменной оболочке. Впервые экспериментально показано наличие B_z-компоненты магнитного поля. В стадии сжатия величина аксиальной компоненты магнитного поля достигает нескольких кГс, что составляет ~ 10% от величины азимутальной компоненты. Наличие B_z-поля является весомым аргументом в пользу существования замкнутых магнитных конфигураций, играющих важную роль в механизме генерации нейтронов.

ОСТАННІ РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ РОЗПОДІЛУ МАГНІТНОГО ПОЛЯ І НЕЙТРОННОГО СКЕЙЛІНГА НА УСТАНОВКАХ ПФ-1000 І ПФ-3

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Представлено результати останніх досліджень розподілу магнітного поля і скейлінга нейтронного виходу на двох найбільших плазмофокусних установках ПФ-3 та ПФ-1000. Експериментально показана ступенева залежність нейтронного виходу від величини струму в плазмовїй оболонці, що стикається. Вперше експериментально показано наявність B_Z-компоненти магнітного поля. У стадії стиснення величина аксіальної компоненти магнітного поля досягає декількох кГс, що складає ~ 10 % від величини азимутальної компоненти. Наявність B_Z-поля є вагомим аргументом на користь існування замкнутих магнітних конфігурацій, що мають неаби яку роль у механізмі генерації нейтронів.