NUKLEONIKA 2001;46(Supplement 1):S65–S68

Studies of Plasma-Focus discharges within the PF-360 facility equipped with a planar D_2O-ice target

Jaroslaw Zebrowski, Jaroslaw Baranowski, Lech Jakubowski, Marek Sadowski

Abstract The paper reports on investigations of dense magnetized plasmas produced within a modernized PF-360 facility, which was operated with an additional planar cryogenic target placed in the front of the electrode outlet and covered with D_2O-ice layers. The main aim of these studies was to overcome the neutron saturation effect and to increase the maximum neutron yield from PF discharges by using fast deuteron beams. Such beams are usually emitted from a pinch region and can produce fast neutrons from D-D reactions during their interactions with the additional target.

Key words cryogenic target • ion-beams • neutron yield • plasma focus • X-rays

J. Zebrowski✉, J. Baranowski, L. Jakubowski, M. Sadowski
Department of Plasma Physics and Technology (P-V),
The Andrzej Soltan Institute for Nuclear Studies (IPJ),
05-400 Otwock-Swierk by Warsaw, Poland,
Tel.: +4822/ 7180611, Fax: +4822/ 7793481,
e-mail: zebrowski@ipj.gov.pl

Received: 23 October 2000, Accepted: 9 January 2001

Introduction

Many Plasma-Focus (PF) experiments, which were performed in different laboratories, showed an optimistic scaling of the neutron emission. These scaling laws for the fusion neutron yield (Y_n) from the Plasma-Focus facilities are described by the simple formulae:

$$Y_n \approx W_0^{\alpha} \quad \text{and} \quad Y_n \approx I_{max}^{\beta},$$

where W_0 is the initial energy input, I_{max} is the maximum value of the main discharge current, $\alpha = 2.0$–2.2 as well as $\beta = 3.3$–4.4 depend on a machine type and input energy value. For the PF-360 facility [3] it was found that $\alpha = 2.1$ and $\beta = 3.2$.

There were some papers, which suggested that it is possible to extend this scaling to a higher discharge current and initial energy values [1], but there is no experimental verification of this hypothesis so far. On the contrary, it was found that the promising scaling laws are valid only up to some critical levels, at which the neutron yield saturates (or even decreases) [2, 5]. The record neutron yields from the largest PF machines operated at 1 MJ level, reached about 10^{12} neutrons/shot only.

The PF-360 machine was built during the turn of the 70s and 80s [3]. Measurements of emission characteristics of charged particles, neutrons, and X-rays from the PF-360 device were carried out in the 90s [6–9]. For that purpose the use was made of various time-integrated and time-resolved diagnostic techniques. From shots performed at $W_0 = 171$ kJ the maximum neutron yield was about 2×10^{11} neutrons/shot. Since intense pulses of fast neutrons could be applied for different purposes, ranging from basic nuclear studies (e.g. the production of short living isotopes) to application-oriented research (e.g. fast neutron radiography), it was decided to continue neutron optimization studies.

Experimental setup

The PF-360 facility was equipped with coaxial electrodes made of pure copper. The inner and the outer electrodes of the Mather-type were 120 and 170 mm in diameter, respectively. The length of these electrodes was about 300 mm. The base of the inner electrode (anode) was embraced with a ceramic insulator of 80 mm in length. The main experimental chamber of the PF-360 machine was filled up with pure deuterium, the initial pressure varying from 6.0 to 12.0 mbar. The PF-discharges were powered from a capacitor bank of 288 μF (sometimes 270 μF). The charging voltage was limited to 30 kV for safety reasons, and the initial energy W_0 was equal to 130 kJ (and sometimes to 122 kJ from the 270 μF capacitor bank).

In order to increase the neutron yield, it was proposed to make use of fast deuterons. The directed beams of accelerated primary deuterons, which usually escape from the PF pinch column, contain a large number of fast deuterons, e.g. a moderate energy (about 70 kJ) PF-shot can emit 10^{15} deuterons of energy above 300 keV mainly in the downstream direction [4]. Such energetic deuterons can evidently be used for the production of fast neutrons from D-D reactions within a solid-state target containing deuterium, e.g. in the form of a heavy-ice layer. For that purpose the cryogenic target system might be applied and operate as a "cold nose" adopted to produce a thin heavy-ice layer. Such a system could contain an appropriate metal cylinder cooled down by blowing a liquid nitrogen stream. We used thermally insulated metal tubing, which might be adjusted along the z-axis of the PF-360 experimental chamber. In our case the cryogenic target was formed upon a thick copper plate, which was fixed to the front plate of the cold cylinders, as shown in Fig. 1.

In that case D-D fusion, neutrons should be produced mainly by fast deuterons propagating along the z-axis. The main metal plate was connected with a Dewar-type tubing fixed in a special adapter flange. It enabled the target plate to be positioned on the z-axis, at a chosen distance from the PF electrode outlet. The target plate could be cooled down from inside by a flow of liquid nitrogen, which might be supplied through an additional tubing inserted into the mentioned axial Dewar tube.

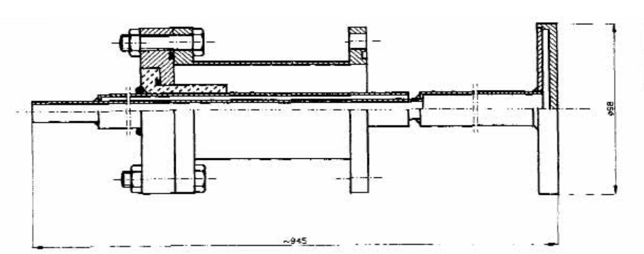

Fig. 1. Scheme of the planar cryogenic-target system, which was designed for the PF-360 experimental chamber. The metal cylinder with the "empty slice" part can be cooled down by vaporization of the liquid nitrogen stream, which can be injected through the thin axial tubing.

In order to ensure the deposition of a heavy-ice layer on the target plate only, other surfaces of the target system were protected with an additional thermal shield. To make possible the formation of a heavy-ice (D_2O) layer upon the target plate in the experimental chamber there was installed an additional vacuum valve, which supplied a small amount of heavy water. A thickness of the D_2O-ice layer was varied within the range from 0.3 to 2 mm by a change in amount of the injected heavy water and cooling medium flow. A scheme of the planar target positioning is presented in Fig. 2. When the described cryogenic target was placed on the z-axis near the coaxial electrode outlets, fast deuterons from the collapsing current sheath could bombard the heavy ice layer and a considerable increase in the fusion neutron production of beam-target origin should be achieved. In order to estimate which part of the total PF-360 neutron yield is of a beam-target origin there are needed some additional neutron anisotropy measurements. The described cryogenic target, before its installation within the PF-360 experimental chamber, was tested within an auxiliary vacuum stand. After successful tests, the target system was installed within the PF-360 facility and there were prepared different diagnostic tools for measurements of charge particles, neutrons, and X-rays. Time-integrated measurements of neutron emission were performed with two calibrated silver-activation counters placed at different distances from the main axis of the coaxial-electrodes. Time-integrated measurements of the X-ray emission were carried out with two VAJ-type radiometers. The X-ray emission measurements were also performed with a pinhole camera equipped with a thin beryllium filter. Time-resolved measurements of X-ray peaks were carried out by means of filter-scintillator sets coupled through optical cables with photomultiplier heads. Time-resolved neutron signals and very hard X-ray signals were measured with two scintillator-photomultiplier probes placed side-on, at a distance of 2.7 and 3.8 m from the electrodes outlet, at different angular positions.

Experimental results

Several series of PF shots were performed with the use of the planar cryogenic target, when it was placed on the z-axis of the PF-360 machine, at different distances from the electrode ends. The most important observations were the measurements of neutron yield, which were performed at different positions of the planar cryogenic target and at vari-

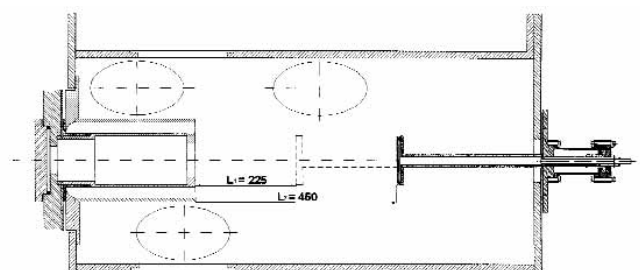

Fig. 2. Positions of the planar cryogenic target inside the main experimental chamber of the PF-360 facility.

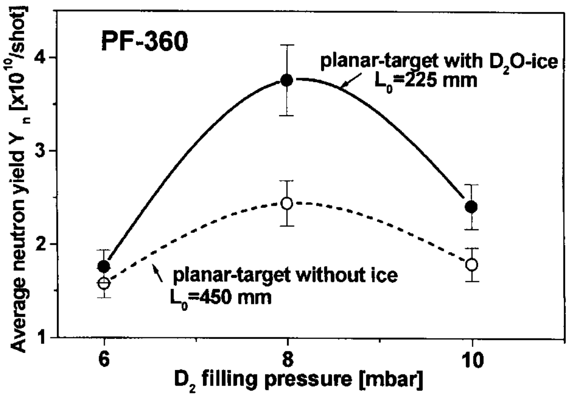

Fig. 3. Average neutron yields as a function of the initial deuterium pressure. The measurements were performed with the D_2O-ice planar target at different axial position. The initial conditions of PF-360 discharges were U_0 = 30 kV and W_0 = 130 kJ.

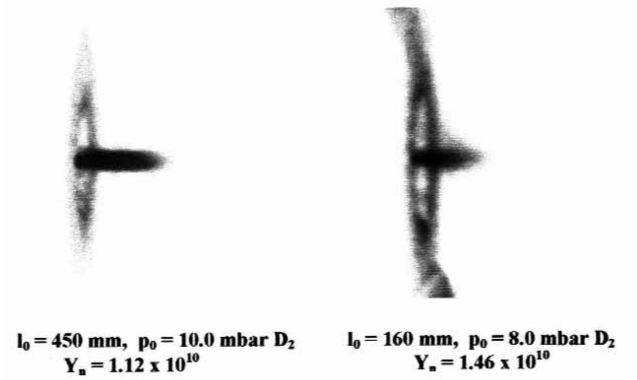

Fig. 4. X-ray pinhole pictures taken side-on for shots with the planar cryogenic target, which was placed in different axial positions. The PF-360 discharges were performed at U_0 = 30 kV, and W_0 = 130 kJ. The left picture shows the pinch region, when the planar target without cooling was applied, and the right one was taken with the target covered with the D_2O-ice layer.

ous initial filling-pressures, ranging from 6.0 to about 12.0 mbar D_2. The neutron yields were averaged over the series of successive (mostly 5) PF shots performed under identical experimental conditions. A considerable increase in the average neutron yield (from 2.4×10^{10} to 3.8×10^{10}) under the determined experimental conditions (p_0 = 8.0 mbar D_2, U_0 = 30 kV, W_0 = 130 kJ) was observed during the performed optimization series. When the neutron yields were averaged over the series of the PF discharges carried out at U_0 = 30 kV, and W_0 = 130 kJ, the optimal position of the target was found at a distance l_0 = 225 mm from the electrodes ends, as shown in Fig. 3.

The X-ray emission from the PF pinch column did not change considerably when the planar cryogenic target was placed in different axial positions, but not too close to the electrode outlet. The X-ray pinhole pictures, as taken side-on for shots with the cryogenic planar target, showed a complex inner structure of the pinch, as shown in Fig. 4. It can be easy seen, that the target placed far from the electrode ends (at l_0 = 450 mm) did not influence the pinch formation. The target covered with the heavy-ice layer and placed close to the electrode ends (at l_0 = 160 mm) could induce some changes in the formation of the X-ray emitting plasma column, but they did not seem to be of importance. It should also be noted that a comparison of the voltage and current-waveforms showed that the position of the planar cryogenic target did not influence PF discharges considerably. It was valid, when the target was placed not too close to the electrode outlet, i.e., at a distance l_0 > 80 mm. Simultaneously with the time-integrated neutron measurements there were also performed time-resolved studies by means of scintillation detectors. They confirmed that the fusion-produced neutrons are emitted in several pulses, which are correlated with the discharge current peculiarity and hard X-ray pulses. The time-resolved measurements within the PF-360 machine revealed the appearance of one and sometimes two neutron pulses. In the case of the mentioned two-peak emission the successive neutron pulses were identified with two different phases of the neutron production, i.e. with the maximum compression and with the m=0 instability development, as in other large PF experiments [2]. Some examples of time-resolved neutron, X-ray, and discharge current signals are presented in Fig. 5.

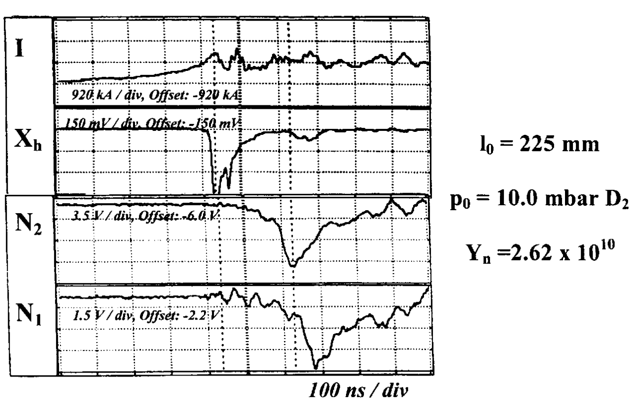

Fig. 5. Examples of time-resolved waveforms of the discharge current (I), hard X-rays (X_h) and neutron signals (N_1 and N_2) obtained from the scintillator-photomultiplier neutron probes. The measurements were performed for the PF-360 facility operated with a D_2O-ice planar target at U_0 = 30 kV and W_0 =130 kJ.

Summary and conclusions

The most important results of the neutron yield studies described above can be summarized as follows:

- Measurements of the neutron emission with the presence of the planar cryogenic target demonstrated a considerable increase in the average neutron yield (from 2.4×10^{10} to 3.8×10^{10}) under the determined experimental conditions.
- Technical conditions for the application of such cryogenic targets in the PF-360 facility require further investigation and optimization.
- Optimization measurements of the neutron emission, with the use of the planar D_2O-ice target, should be performed also in other PF facilities of higher energy. In such a case, a new neutron scaling law for the cryogenic target discharges could be estimated.

Acknowledgments This work was partially supported by the US-AF EOARD contract no. F61775-99-WE088 (SPC99-4088).

References

1. Brzosko JS, Degan JH, Filippov VV, Freeman BL, Kiuttu GF, Mather JW (1997) Comments on the feasibility of achieving scientific break-even with a Plasma Focus machine. In: Panarella E (ed) Proc 2nd Symp: Current Trends in Int Fusion Research. Plenum Press, New York, pp 11–32
2. Herold H, Jerzykiewicz A, Sadowski M, Schmidt H (1989) Comparative analysis of large Plasma Focus experiments performed at IPF-Stuttgart and at IPJ-Swierk. Nucl Fusion 29:1255–1269
3. Jerzykiewicz A, Bielik M, Jakubowski L et al. (1985) Neutron, ion, X-ray emission from a 360 kJ plasma focus device. Nucl Fusion, Suppl 25:591–599
4. Sadowski M (1996) Ion beam from high-current PF facilities. In: Proc Int Conf BEAMS'96. Prague, Czech Republic 1:170–173
5. Sadowski M (1998) Studies of neutron emission from different Plasma-Focus facilities in Poland: a review. J Moscow Phys Soc 8:1–11
6. Sadowski M, Szydlowski A, Zebrowski J, Al-Mashhadani EM (1992) Investigation of charged particle and X-ray pulses emitted from PF-type discharges. In: 19th EPS Conf Controlled Fusion and Plasma Physics. Innsbruck, Austria 1:691–694
7. Sadowski M, Zebrowski J (1998) Diagnostic methods of experimental studies on emission of pulsed deuteron and electron beams from the PF-360 facility. J Tech Phys 39:115–120
8. Sadowski M, Zebrowski J, Al-Mashhadani EM (1993) Time-integrated and time-resolved measurements of X-rays and charged particles from PF-360 facility. In: Third Int Conf Dense Z-Pinches. London, UK. AIP Conf Proc 299:224–250
9. Zebrowski J, Baranowski J, Sadowski M, Skladnik-Sadowska E, Garkusha I, Makhlay V (1997) Study of ions, electrons, and X-rays emitted from PF-type discharges. In: Int Symp PLASMA'97. Jarnołtówek, Poland 1:129–132