

# OPTIMIZATION OF INITIAL GAS DISTRIBUTION IN PLASMA FOCUS DISCHARGES

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## INTRODUCTION

As the increasing number of plasma focus (PF) installations turns to be operated at power supply energies ( $W$ ) above 100 kJ, new factors become evident to come into play that prevent obtaining the neutron yields ( $N$ ) predicted by the well-known scaling  $N \sim W^2$ . This is mainly due to the fact that with an increasing energy there is no increase in the current flowing in plasma filament compressed on the axis of a discharge system proportionally to  $W$ , and a part of discharge current starts to flow at the periphery [1]. It is also known that the main condition of matching the moment when the discharge current reaches its peak value and the moment when the plasma (current) sheath coincides with the axis leads to a perfectly certain ratio of PF-system parameters which can vary with optimization of discharge conditions:  $V^2 C^2 / r^2 l^2 P = \text{const}$ , where  $V$  and  $C$  are, respectively, the initial voltage and capacity of a capacitive energy accumulator,  $l$  is the accelerating electrode length,  $r$  is the radius of internal electrode (anode), and  $P$  is the initial working-gas pressure. This ratio shows that with changing power supply parameters it is necessary that either the discharge system sizes or the working gas pressure should be appropriately changed. It is more preferable to carry out matching by varying the working gas pressure  $P$ , for in this case there is no need to perform complicated work associated with changes in the accelerator sizes.

There are two optimum points on initial pressure in the PF discharges. If pressure is relatively low, then the formation of uniform plasma sheath takes place. The latter effectively carries away the gas from the initial region of discharge volume, that essentially increases the electrical strength of internal electrode gap required for peaking the discharge power at a final stage [2]. As the pressure rises, the discharge dynamics at the final stage of PF formation as well as the mechanisms of neutron generation become optimized [3]. However, in practice, the pressure can be increased only up to a certain limit, following which a noticeable deterioration in operating conditions of the installation occurs.

## 1. EXPERIMENTAL INSTALLATION OF RESEARCH TECHNIQUE

One of the ways to optimize the PF system in the neutron yield is to create profile gas distributions, where the working gas density in the vicinity of insulator is lower than the one in the region of PF formation. For this purpose, PF discharges have been investigated on the installation CPF-1M ( $W \sim 40$  kJ,  $V \sim 25$  kV,  $T/2 \sim 7$   $\mu$ s) at pulsed neutral-gas supply conditions with the use of an electrodynamic valve. The studies were performed by two methods shown schematically in Fig. 1.

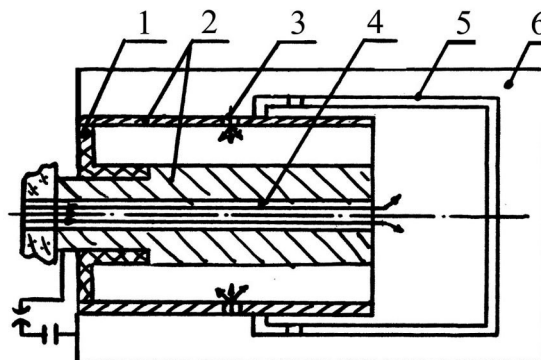


Fig.1 The scheme of the installation CPF –1M  
1 - insulator; 2 - electrodes; 3 - gas radial filling;  
4 - axial filling; 5 - a tip; 6 - vacuum volume

In the first case, the gas (deuterium) was let in radially in the middle part of a coaxial-type discharge system, through 30 holes, each of 4 mm in diameter, in a cylindrical external electrode with a diameter of 130 mm. The internal electrode was 80 mm in diameter; the electrode length was 240 mm. The insulator was made of alundum. Before being filled with gas, the vacuum chamber was pumped out to a pressure of  $< 10^{-5}$  torr.

Voltage and discharge current, time and integral parameters of X-rays and neutron radiation, energy spectra of ion beams generated in the PF have been measured in the experiments. The discharge was photographed in visible and X-ray regions of the spectrum.

The quantity of gas in the discharge volume and its distribution along the axis were controlled within certain limits by varying the delay ( $\tau$ ) between the moment of valve opening and the onset of discharge.

## 2. EXPERIMENTAL RESULTS AND DISCUSSION

PF-discharge characteristics have been investigated in a wide range of delays. At given experimental conditions the PF discharge was observed in the delay  $\tau$  range between 1.0 and 2.5 ms. At  $\tau = 1.0$  to 1.4 ms the discharge behavior is similar to that at a low pressure regime with a steady-state gas filling of the vacuum chamber [2, 4], the only difference being that the singularity here exists for a longer time of  $\Delta\tau = 0.6 \dots 0.8$   $\mu$ s.

As it can be seen from the voltage and current oscillograms in Fig. 2, a succession of discharge current disruptions and the corresponding voltage spikes up to 100 ... 120 kV take place.

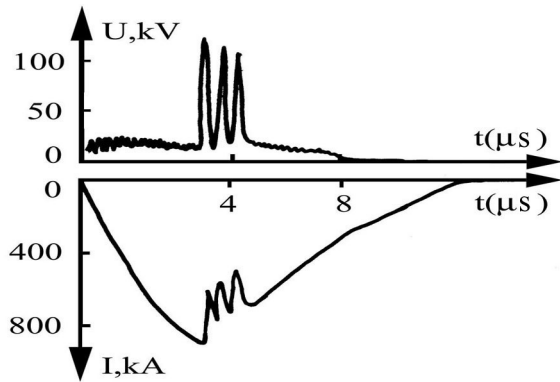


Fig. 2. Typical waveforms of voltage (upper) and current (lower) of the plasma focus discharge.

At this stage, intense bursts of hard X-rays are registered. The integral pinhole-camera pictures taken in hard X-rays from the end of the discharge system (Fig. 3) display that the hard X-rays are emitted not only in the near-axis region of the anode.

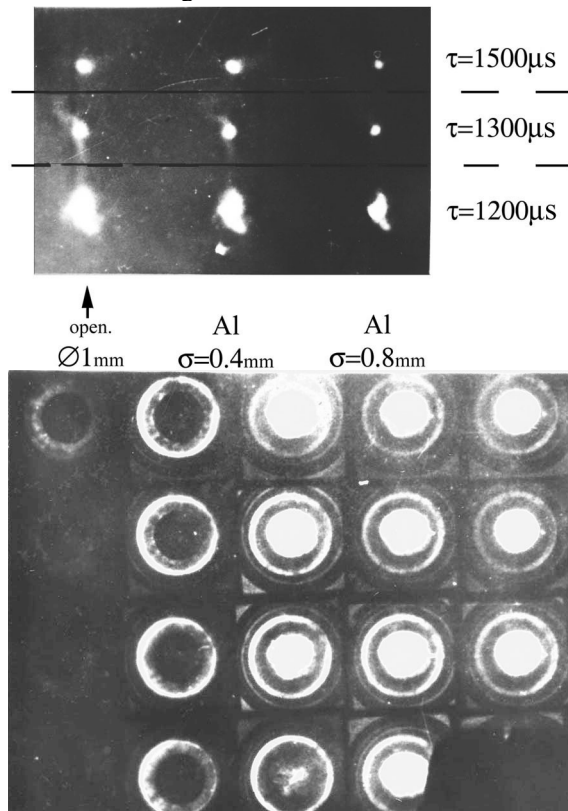


Fig. 3 (top) Pinhole-camera pictures in hard X-rays (viewed from the end) obtained at various delays  $\tau$ . From left to right: an open hole with a diameter of 1 mm; aluminium foil closed hole (foil thickness  $\delta=0.4\text{mm}$ ;  $\delta=0.8\text{mm}$ ) (bottom) Framing pictures of the discharge (viewed from the end). The interval between the frames  $\sim 0.5\ \mu\text{s}$ .

Well-localized or diffuse sources of hard x-rays bremsstrahlung can be seen on different parts of the end of the internal electrode. This points to the fact that kinetic instabilities are excited as early as at the stage of radial compression of the current sheet which emerges at the end of the internal electrode to the region with a decreasing neutral-gas density. In this case, the current sheet is split into separate filaments. The instabilities at

the nonlinear stage transfer the plasma to a turbulent state. This results in an abnormally high (of about  $10^{-1}$  Ohm) resistance of the current channel. Plasma electrons and ions get accelerated to high energies in the arising strong electric fields. The pinhole-camera measurements (3 input holes, each being 1 mm in diameter) using various absorbing filters give the average energy of the main portion of beam electrons to range between 30 and 100 keV.

A similar picture of inhomogeneous luminescence of the end of the internal electrode is also observed in the framing pictures of the discharge (Fig.3 bottom). It is seen that there is no axial localization of plasma and it consists of separate filaments.

As  $\tau$  increases, the gas distribution, set at short delays, with the density maximum in the middle part of electrodes (place of gas filling) and with the density fall-off in the vicinity of the insulator and at the end of electrodes, gradually changes. As a result of gas accumulation in the closed initial region of the discharge volume, the gas density grows close by the insulator. In this case, the «singularity» duration on volt-ampere curves and the amplitude of voltage spike decrease. Almost in the whole range of delays ( $\tau = 1.1 \dots 2.2\ \mu\text{s}$ ), the neutron yield remains at a level of  $< 10^9$  neutrons/discharge at  $W \sim 40\ \text{kJ}$ , and it was lower than at conditions with a constant gas filling of chamber at the same energy.

The results show that the distribution of neutral gas with a reduced density in the initial part of the discharge volume is optimum for creating conditions when the interelectrode space behind the accelerated plasma sheath acquires and retains an electrical strength high enough to maintain a rather long existence of the «singularity» ( $< 1\ \mu\text{s}$ ). During this time, the discharge power reaches a value of  $> 10^{11}\ \text{W}$ . On the other hand, low density in the region of radial current-sheet compression does not allow to form an axisymmetrical PF with the highest possible current density in it. As a result, it appears impossible to form a dense cumulative plasma jet required for the effective beam-target mechanism of neutron production [3].

In the following series of experiments the method of gas inlet into the discharge volume was modified so that the gas density should gradually increase from the insulator to the end of electrodes. With this purpose, a hollow copper cylindrical tip 5 with a diameter of 140 mm was added to the former design of the discharge system. The bottom of this tip was set at a distance of  $\sim 70\ \text{mm}$  from the internal electrode end. The gas came through the  $\text{Ø} 12\text{-mm}$  axial channel in the internal electrode and, being reflected from the tip bottom, it uniformly filled the internal electrode volume.

The gas pressure variation with time in the initial and final regions of interelectrode volume has been investigated previously [5].

Fig.4 shows the time behavior of pressure curve for the pressure  $P_0 = 3\ \text{atm}$  in the subvalve volume of the electrodynamic valve. It is seen that the pressure at both points of initial (1) and final (2) regions of acceleration space grows linearly up to 3.5 torr, approximately.

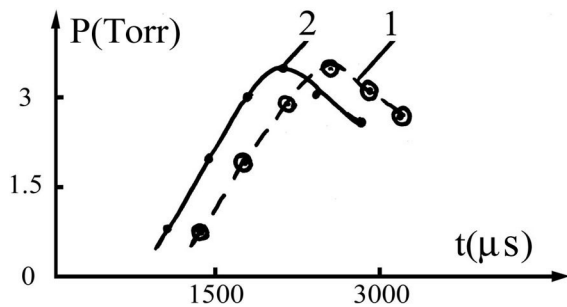


Fig. 4

Fig.5 gives the plot of neutron yield as a function of delay in the same time scale as the pressure curves in Fig.4.

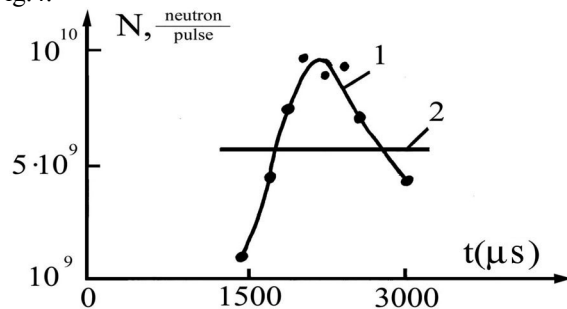


Fig. 5.

- 1 - neutron yield with axial pulsed gas filling. Each point is averaged over 10 discharges.
- 2 - neutron yield at steady-state gas filling of vacuum chamber  $P=3,5$  torr (deuterium).

From comparison between the curves in Figs.4 and 5, it can be seen that the neutron yield grows together with an increasing amount of gas coming into the discharge volume. Discharge regimes have been defined at optimum delays. These regimes are characterized by a high reproducibility of neutron yield as compared with a radial gas filling. The maximum neutron yield has increased up to  $1.5 \cdot 10^{10}$  neutrons/discharge, this being comparable with the values corresponding to the scaling ( $N \sim W^2$ ) for a power of 40 kJ.

At  $\tau \sim 2.5$  ms, when the gas distribution along the electrode length becomes almost uniform, the neutron yield begins to decrease. When pressure nearby the insulator exceeds pressure at the end of the internal electrode, the neutron yield value becomes lower than at steady-state gas filling.

Fig. 6 shows the signals from the type SNFT-3 photomultiplier with a scintillator, recording neutron radiation and hard X-rays, the time-of-flight lag being R

$= 6.5$  m. The energy spectrum of ions accelerated in the PF was investigated using a magnetic analyzer [3]. This analyzer can detect ions in a wide energy range (from 10 keV up to 2 MeV) with a high time resolution. Generation of intense ion beams of energy  $E \sim 0.8$  MeV is always synchronous with sharp bursts of hard X-rays high amplitude.

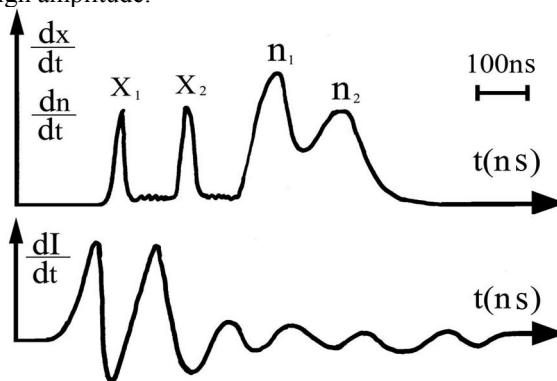


Fig.6. Pulses from hard X-rays ( $X_1$  and  $X_2$ ) neutron radiation's ( $n_1$  and  $n_2$ ).

## CONCLUSION

Thus, the axial method of working gas filling allows one to optimize both the initial and the final phases of the discharge with the result that a rather high and well reproducible neutron yield is obtained. This method of gas filling also made it possible to investigate discharge regimes (steady-state gas filling of chamber) at conditions of additional introduction of various impurity components (Xe, Ar), without deteriorating dynamic properties of the discharge, which have an appreciable effect on radiation energy release in the PF.

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