

# Theoretical and experimental study of inertial gases admixtures influence on the hard x-ray emission of plasma focus

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**Abstract.** This paper studies the influence of inertial gases admixtures (Ar, Kr, Xe) to deuterium in plasma focus (PF) chambers. Experiments were realized in PF chambers with discharge currents of 350, 650 and 1000 kA. The measurements of the hard x-ray (HXR) emission were carried out by the scintillation detector SSDI38 with time resolution of 2.5 ns. Experiments show the existence of optimum amount of inertial gases, which corresponds with the atomic number of added gas. At the optimum amount of inertial gas and deuterium in PF chamber, the HXR yield rises up to 10 times in comparison with HXR yield only for deuterium filling. This work shows the dependence of HXR emission on PF device stored energy. The mechanism of inertial gases admixtures influence that leads to rise of HXR yield has been discussed. The mechanism concerns with different behavior of deuterium ions and ions of inertial gases during the pinch decay phase when the discharge current compression force has reduced. Inertial gas ions locate near the axis of the pinch and deuterium ions go to the near plasma area. Local positive charge in plasma forms on this axis because of multiply charged ions of inertial gases. Then electrons gather to the axis area and electron density increases. This electrons form high current electron beam under the influence of the induced electromotive force during the pinch decay phase. HXR emission is generated after the electron beam interaction with the anode target in PF chamber.

## 1. Introduction

Hard x-ray (HXR) emission of the plasma focus (PF) device potentially has a wide range of applications: dynamic defectoscopy, x-ray radiography, study of the radiation effects in different materials and others [1–3]. This dictates the necessity of PF chambers HXR emission parameters (pulse duration 3–10 ns, energy density to 1–4 J/cm<sup>2</sup>, local maximum of spectrum in 40–60 keV range, spectrum maximum energies up to 300–500 keV) study. Investigations in this area show the regimes that provide the increase of HXR yield. As it is noted in [4,5], the admixture of the inertial gas in PF chamber leads to increased HXR yield of the device. The aim of this work is to research this subject in terms of theory and experiment.

## 2. Experimental setups

All-Russia Research Institute of Automatics develops generators based on the PF chambers. Chambers allow multiple refilling of working gas and allows us to study the effect of inertial gases admixtures to deuterium in PF chamber.



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**Table 1.**

Filling	$Q_{\text{in}}/Q_D$
ING-103 7.0% Ar	1.35
ING-103 2.5% Kr	0.92
ING-104 4.5% Ar	0.85
ING-104 1.7% Kr	0.63
ING-104 1.0% Xe	0.55

Experiments of the HXR yield measurement were carried out at two experimental facilities ING-103 (360 kA) and ING-104 (650 kA) with Mather type PF chamber and spherical type PF chamber respectively. The admixture was composed of 1–10% of argon, krypton or xenon and 99–90% of deuterium respectively. The total working pressure was 10–13 Torr. To detect HXR pulses, we used an SSDI38 scintillation detector with a time resolution of about 1.5 ns. SSDI38 was located at the distance 0.5–3 meters from the axis of the PF chambers. Thicknesses of the copper cathode and anode were 2.5 mm in both PF facilities. Thus, bremsstrahlung passes through copper before it reaches the scintillation detector. Soft x-ray emission does not pass through the copper walls of the chamber. The SSDI38 detects only the hard component of x-ray emission with photon energies higher than 60 keV. The absolute neutron yield was measured using SIVN61 neutron detector based on the moderation of fast neutrons to thermal energies and activation of a silver foil with the subsequent detection of  $\beta$  particles generated as a result of the radioactive decay of the produced silver isotopes.

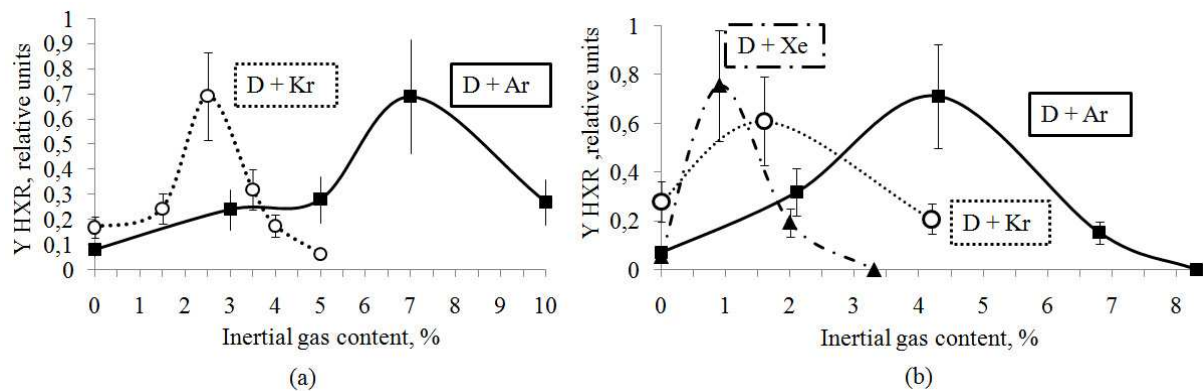
Results of ING-103 and ING-104 HXR yield measurements show that the inertial gas admixture increases the HXR yield about 3–7 times (figure 1). The maximum increase was 10–15 times when the content of inertial gas was optimum (5% for Ar, 2.5% for Kr, 1% for Xe). Furthermore, the neutron yield did not change in case of inertial gas admixtures to deuterium in comparison with pure deuterium filling. Estimation of the total positive charge of inertial gas ions  $Q_{\text{in}}$  and total positive charge of deuterium ions  $Q_D$  in PF chamber shows that  $Q_{\text{in}}/Q_D$  tends to unity.  $Q_{\text{in}}/Q_D = eZ_{\text{in}}N_{\text{in}}/eZ_DN_D = Z_{\text{in}}p_{\text{in}}/Z_Dp_D$ , where  $Z_{\text{in}}$  and  $Z_D$ —atomic number of inertial gas and deuterium respectively,  $N_{\text{in}}$  and  $N_D$ —number of inertial gas and deuterium ions respectively,  $p_{\text{in}}$  and  $p_D$ —pressure of inertial gas and deuterium in PF chamber after filling respectively. Results of positive charges evaluation are shown in table 1.

Proposed wording of criterion: maximum HXR yield in PF chamber is provided when positive charge in plasma from inertial gas is equal to positive charge in plasma from deuterium ions.

### 3. Mechanism of the inertial gas ions influence on the HXR emission parameters

It was noted in publications that mechanism of the inertial gas ions influence on the HXR emission could be connected with the failure of current front that corresponds to the sharp rising of plasma radial speed [4]. Current contracts on the axis without the increase of plasma density. This creates conditions for the generation of high-power electron beam, which is generated by the magnetic field energy stored in PF chamber. In addition, the inertial gases influence is associated with increase of radiation losses in plasma. However, experiments showed that on the VNIIA's PF chambers axis the dense pinch was formed (neutron yield did not change). The effect of HXR yield increase is required to be explained in agreement with experimental data. Probably the mechanism connected with failure of the current front observed in PF chambers of Filippov geometry [1].

To describe the processes let us consider the pinch decay phase. HXR generation takes place at the final phase of the pinch evolution [6]—instabilities and pinch decay. At this time, the



**Figure 1.** Dependence of HXR yield on inertial gas content in deuterium filling: (a)—ING-103 generator, (b)—ING-104 generator.

area with anomalous resistance that significantly exceeds the resistance of formed hot pinch appears near the PF chamber axis. Therefore, discharge current redistributes between axis area (with anomalous resistance) and near-plasma area. Let us focus on the processes that take place with deuterium ions and inertial gas admixture ions during the pinch decay phase. Firstly, they undergo the compression by the force of the discharge current. Secondly, ions move apart from the axis because of their thermal velocities and they can leave the pinch area. This is possible because the average electrons and ions temperatures in the pinch are equal to 1 keV [1]. Electron and ion temperature equality could be explained by their long time of interaction with each other before the pinch forms (acceleration and compression phases). During these phases, electrons and ions obtain high velocities and swap energies in a thin layer of hot moving sheath.

Primarily let us calculate the maximum distance of deuterium and inertial gases ions going away from the axis. Average thermal velocities for deuterium, argon and krypton calculated from the thermal energy of particles in plasma are  $3.8 \times 10^7$  cm/s,  $0.6 \times 10^7$  cm/s and  $0.4 \times 10^7$  cm/s respectively. Time of HXR generation varies from 3 to 10 ns for PF devices with stored energy from 3 to 30 kJ respectively [6]. This time is determined by the time of electron beam generation in the pinch instability. Based on ions thermal velocities in the pinch instability we can assess the distance of ions going away during the time of electron beam generation. It allows assessing the distribution of ions during this time. We assume the average time of electron beam generation in instability  $t_{\text{gen}} = 7$  ns. Then the distances for deuterium, argon and krypton are 2.7 mm, 0.4 mm and 0.3 mm respectively.

Distinctive pinch radius is equal to 0.5–1 mm [1, 2]. During the pinch decay phase, its radius can be 0.3–0.5 mm in local places of instability rises [3]. During the  $t_{\text{gen}}$  deuterium ions have enough time to leave the pinch area and go to near-plasma area. Density of near-plasma is several orders of magnitude lower than density of plasma in pinch, so near-plasma doesn't disturb ions to go away from axis. Inertial gas ions stay in pinch area. Wherein electrons could go away at the great distance during  $t_{\text{gen}} = 7$  ns.

Then let us focus on the compression action of the discharge current that determines ions velocities directed to the chamber axis. We use two-dimensional magneto hydrodynamic (MHD) model [7] to calculate this velocities. The results show that ions velocities are  $6.0 \times 10^6$  cm/s (radial),  $2.5 \times 10^6$  cm/s (axial) and  $6.0 \times 10^6$  cm/s (radial),  $2.0 \times 10^6$  cm/s (axial) for generators ING-103 and ING-104 respectively. The value of velocities is determined now of the current–plasma sheath collapse to the pinch formation on the axis. This moment notes by MHD program. Phases of stable, hot pinch and pinch decay go after the phase of collapse. At this stages ions velocities caused by discharge current don't exceed their value at the collapse phase. Results of

calculation show that ions velocities weakly changed for PF generators with different discharge currents.

Maximum value of the radial plasma velocity was  $6.0 \times 10^6$  cm/s that coincides with thermal velocity of argon ions. In assumption of equal grab efficiency in plasma–current sheath, deuterium ions and inertial gas ions, the argon ions velocity by discharge current that directed to the axis matches with thermal velocity directed from the axis. Thus, argon ions remain in place into the pinch near axis. For deuterium ions, their thermal velocity is much higher than velocity caused by compression. They can leave a pinch area during  $t_{\text{gen}}$ .

Since studied processes occurred at the pinch decay phase, we needed to consider the discharge current distribution between pinch area and near-plasma area. Significant part of discharge current could redistribute on near-plasma area because of the anomalous resistance [6]. There are only 5–10% of total current in the pinch. Values of the radial ions velocities decreased in comparison with calculated values in MHD model. Spatial distribution of deuterium ions and inertial gas ions at the pinch decay phase is determined by their thermal velocities and will limit near-plasma area with most part of discharge current (1–2 mm from the chamber axis).

Based on such argumentation let us show the total description of the mechanism of inertial gas ions influence on the increasing of the HXR yield. Let us consider the case of experimental data—4.5% Ar and 95.5% D.

After the filling in PF chamber:

$$N_D/N_{\text{Ar}} = p_D/p_{\text{Ar}} = 0.955/0.045 = 21,$$

$N_D$ —amount of deuterium ions,  $N_{\text{Ar}}$ —amount of argon ions,  $p_D$ —deuterium pressure in chamber after filling,  $p_{\text{Ar}}$ —argon pressure in chamber after filling.

After the pinch decay starts (when deuterium and argon ions densities redistribute) deuterium ions go away from the chamber axis on  $l_D = 1.5$  mm and argon ions locate in area near axis with radius  $l_{\text{Ar}} = 0.4$  mm.

Total positive charge at the pinch decay phase:

$$Q_{\text{tot}} = Q_{D\text{pinch}} + Q_{D\text{near}} + Q_{\text{Ar pinch}},$$

$Q_{\text{tot}}$ —total positive charge in plasma,  $Q_{D\text{pinch}}$ —positive charge from deuterium ions located in pinch area,  $Q_{D\text{near}}$ —positive charge from deuterium ions located in near-plasma area,  $Q_{\text{Ar pinch}}$ —positive charge from argon ions located in pinch area. Since deuterium ions contribute to the total positive charge in two areas it is necessary to assess their charges in two areas—they will be proportional to volumes of the areas. We consider the pinch area equal to the average radius of argon ions location (0.4 mm). So near the axis amount of deuterium ions will be inversely proportional to  $l_{\text{Ar}}^2/l_D^2 = 0.07N_D$  (if the height of plasma column  $h$  in two areas is the same). In near-plasma area amount of deuterium ions is accordingly  $0.93N_D$ . Total positive charge:

$$Q_{\text{tot}} = eZ_D N_D (1 - l_{\text{Ar}}^2/l_D^2) + eZ_D N_D l_{\text{Ar}}^2/l_D^2 + Z_{\text{Ar}} N_{\text{Ar}}.$$

Ratio of charge in near-plasma area (first term) to charge in axis area (second and third terms):

$$Q_{\text{tot}} = 0.93eN_D + 0.07eN_D + e18N_D/21.$$

Positive ions charge divides equally between near-plasma area and axis area. Charge densities in these areas:

$$n_{\text{near}} = Q_{\text{near}}/(l_D^2 h) = 0.93eN_D/2.25h = 0.41eN_D \text{ C/mm}^3,$$

$$n_{\text{pinch}} = Q_{\text{pinch}}/(l_{\text{Ar}}^2 h) = 13.33eN_D \text{ C/mm}^3,$$

**Table 2.**

Filling	Normalized HXR Yield
H2 5 Torr	19.6
H2 10 Torr	1.0
H2 13 Torr	3.0
H2 10 Torr + 0.5 Torr Ar	133.6
D2 10 Torr	24.4
D2 10 Torr + 0.5 Torr Ar	83.2
Ar 4 Torr	14.4

$n_{\text{near}}$ —positive charge density in near-plasma area,  $n_{\text{pinch}}$ —positive charge density in axis area.

So near the axis a region creates with charge density 20 times more than charge density in near-plasma area because of the argon ions. The some numbers of electrons should come to this region to provide positive charge compensation. They could come to region with excess positive charge near axis and compensate it due to high velocities of electrons during  $t_{\text{gen}} = 7$  ns. Electron density  $n_e$  on the PF chamber axis rises up to 20 times too. It occurs at the pinch decay phase when the area with anomalous resistance has appeared (induced electromotive force (EMF) [6]. Electrons on the axis are accelerated by the EMF and create an electron beam directed to the anode.

Electron beam current  $I$  rises up to 20 times because of the electron density rising:

$$I = en_e v_e S,$$

where  $n_e$ —electron density,  $v_e$ —electrons velocity,  $S$ —beam area.

Therefore, HXR yield rises proportionally to the electron beam current [8]:

$$W_{\text{HXR}} = kUI^2 Z_{\text{target}} t_{\text{gen}},$$

$W_{\text{HXR}}$ —HXR yield,  $U$ —accelerated voltage,  $I$ —beam current,  $Z_{\text{target}}$ —atomic number of the target on the anode top (or atomic number of the anode material),  $t_{\text{gen}}$ —time of electron beam generation,  $k$ —proportionality coefficient.

From the mechanism above it is clear that inertial gas ions give the main contribution to the effect of HXR yield rising. Probably working gas (deuterium) helps to catch inertial gas ions to the current-plasma sheath and accelerate them to the pinch area. Changing deuterium to hydrogen and adding inertial gases admixtures can lead to the PF chamber working with high HXR yield and without neutron emission. This can be interesting for some applications of PF devices. In addition, PF work with pure hydrogen should give low HXR yield. These assumptions are tested experimentally on ING-103 generator with working gases like hydrogen, deuterium, hydrogen and deuterium with argon and pure argon. Charging voltage was 18 kV. There were not less 10 shots in every series of experiments. Results are shown in the table 2.

So on deuterium with argon we obtained 3 times increase of HXR yield, on hydrogen with argon 7 times increase and lack of neutron emission. HXR yield on pure argon is rather small.

#### 4. Conclusion

This work represents the mechanism of inertial gas influence on HXR yield of PF devices based on processes at the pinch decay phase. The mechanism has agreement with experimental data and allows us to find PF regime without neutron emission and with high HXR yield.

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