Time resolved x-ray emission from nanosecond vacuum discharge with virtual cathode

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Abstract. Design features and parameters of a modernized installation of inertial electrostatic confinement based on a low-energy nanosecond vacuum discharge (\(\sim 1\) J) are described when operating in diode geometry in the virtual cathode formation mode and the corresponding potential well. The device is used to study the processes of collisional DD synthesis in the interelectrode space, the processes of x-ray generation in complex plasma at various stages of the discharge: from the very initial stage, when the beam of autoelectrons only begins to irradiate the nonideal anode surface, to oscillating plasma configurations in later stages of the discharge. Here, the first steps were done to introduce x-ray spectral diagnostics, as well as to obtain the integral x-ray spectra for visualizations of interelectrode complex plasmas.

1. Introduction

The inertial fusion science [1, 2] contains a very old branch, which is called inertial electrostatic confinement (IEC) [3, 4]. IEC schemes rely on accelerating ions to a fusion relevant energy range 50–200 keV using electric fields [5, 6]. The accelerating fields can be provided by grids or virtual cathodes [3, 7]. Either spherical or cylindrical grids with high transparency are used with dc or low-frequency electric fields. In spite of demonstrating of significant neutron yields in a compact table-top size and rather inexpensive IEC devices, the resulting efficiency \(Q = E_{\text{fusion}}/E_{\text{input}}\) was still rather low (\(\sim 10^{-8}\)). Additional magnetic field is considering to improve IEC and make this scheme more reliable and perspective [3, 8, 9].

Oscillating plasmas were theoretically suggested as the basis of a possible IEC fusion scheme with potentially higher efficiency than at available ones [10, 11]. Oscillating ion cloud referred to as the periodically oscillating plasma sphere (POPS) may undergo a self-similar collapse in a harmonic-oscillator potential formed by uniform electron background [9]. Theoretical study has indicated that such a scheme is highly effective and may result in net fusion energy gain \(Q > 1\) even for DD fuel [12]. Experimental studies have confirmed the existence of the oscillating plasma at spherical geometry [13, 14]. POPS concept has favorable fusion power density scaling as well as an economical development way [14]. Meanwhile, some of theoretical results have indicated that there are absolute limits on the achievable compressions for POPS at spherical geometry for perfect space charge neutralization [15].
Simultaneously the cylindrical POPS-type system have been studied in experiments under IEC-scheme based on miniature nanosecond vacuum discharge (NVD) with deuterated Pd anode [16–20]. In these experiments, it has been demonstrated the version of a cylindrical virtual cathode (VC), where deuterium nuclei can be accelerated to energies of tens of keV at correspondent potential well (PW) [16,18]. In particular, POPS-like oscillations of deuterons in potential well of virtual cathode followed by pulsating neutron yield were recognized at early NVD experiments [16,18]. Such a discharge operation mode is a certain analogue of POPS-based IEC fusion [10,14] that was confirmed by a detailed numerical particle-in-cell (PIC) modeling of experiments with NVD by fully electrodynamic code KARAT [17,19]. Already at this stage in the experiments with NVD the potential wells of virtual cathode of tens of kilovolts, VC radius $r_{vc} \sim 0.1 \text{ cm}$, and the ion oscillation frequencies of about 80 MHz were implemented [16,17,20]. It corresponds to the extremely high power densities demonstrated at the present moment by the miniature IEC scheme.

The first results and discussion of the new experiments on DD fusion at IEC-scheme realized on the basis of NVD at the new experimental stand, NVD-2, have been presented recently [21]. It was an intermediate report related with construction of new experimental stand for studying the nuclear synthesis at the potential well of VC for IEC-scheme. Nevertheless, the first time-of-flight measurements have confirmed the DD neutron yield at ICF-scheme based on NVD [21]. The part of previous features of DD fusion at NVD [16–18] was reproduced also, in particular, POPS-like oscillations followed by measured pulsating neutron yield [21].

At that stage of the work, the stand NVD-2 was not fully completed by tools for diagnostics of different processes, including x-ray spectral diagnostics. The present work has two goals. The first, is the measurement of the emission spectra of the interelectrode plasma of NVD in the x-ray spectral range. Earlier, these measurements were not carried out, and the quanta of x-ray were estimated only on the basis of data on calibration of p-type–intrinsic–n-type (PIN) semiconductor diodes or with the help of various absorbers. The second, is obtaining of integral images of interelectrode ensembles in x-ray. The latter is important for further investigation of the correlation found earlier between the type of interelectrode ensembles and the corresponding nature of the yield of x-rays and neutrons [22], including the role of self-organization effects of ensembles. Thus, this paper presents the further developing results of NVD-2 stand, where the first steps were done to introduce x-ray spectral diagnostics. Also, the integral x-ray spectra were recorded and visualizations of particular interelectrode complex plasmas in x-ray were obtained.

2. Experimental set-up and diagnostics

Based on the results of the accumulated data analysis and modeling, ways of the optimization of electrophysical processes in an NVD have been determined [21]. The provision of conditions close to the propagation of transverse electromagnetic (TEM) wave in the diode gap makes it possible to increase the lifetime of the potential well, to increase the emission yield without increasing the storage energy of the generator, to reduce the effect of anode erosion on the change in the geometric parameters of the diode, to slow the depletion of the surface layer and the anode edge.

To ensure higher parameters of the potential well (conditions of electrostatic confinement and acceleration of deuterons [23,24]), a high-voltage pulse source was modernized (figure 1). It is worth noting that the implemented design completely retained the previous function of the NVD generator [21]. It allows, if necessary, to load the discharge gap by the initial pulse of the Marx generator by changing the switching scheme. Such a possibility is useful when comparing simulation results with the experiments in some boundary variants of load geometries, electrode materials, etc [22–24].

A calibrated spectrometer based on matched pairs of silicon PIN diodes, thin filters of specified density, high-frequency signal separation blocks and signal lines is used to obtain spectra
Figure 1. (a) Schematic view of the NVD-2 stand: A—anode; C—cathode; P—pinhole (50 µm Ta); XRC—x-ray camera; D1,3,4,5—x-ray PIN diodes of spectrometer; HV—high-voltage input into the diode chamber. (b) General view of experimental stand, with Fe and Pd anodes variants and hollow Al cathode with conical part (funnel) in insert.

Figure 2. (a) Typical spectral sensitivity of PIN diode. (b) Spectral sensitivity of the difference channel for the Fe–V pair of balanced filters, as example.

in the x-ray range with high time resolution (≈ 2 ns). The spectrometer allows recording the time dependence of the pulsed x-ray emission spectrum in the energy range from 1.5 to 50 keV. The characteristics of the PIN diodes used make it possible to carry out spectral measurements of pulsed flows of short duration and high steepness of signal rise.

The spectral sensitivity of the diode is determined by the thickness of the “dead” layer of the input window of the sensitive element (SE) of the diode, the thickness of the sensitive area of the SE, and the diameter of the detector input window. The typical spectral sensitivity of single diode and an example of spectral sensitivity for difference channel are shown in figure 2.

The detector current is proportional to the flux density of x-ray quanta. The selection of spectral subbands is carried out by the well known balanced Ross filter method [25]. The entire energy range under study is divided into separate spectral intervals, each of which corresponds to its difference channel consisting of two detectors with different filters. The thickness and material of the filters are selected on the basis of spectral sensitivity calculation of the difference
channels from the transmission curves of the filters on each channel and the sensitivity of the detector (PIN diode).

The filter transmission curves are calculated by the following formula:

\[ I = I_0 e^{-\mu \rho D} \]

where \( I \) is the intensity of the x-ray of the energy \( E \) behind the filter, \( I_0 \) is the intensity of the x-ray of the energy \( E \) in front of the filter, \( D \) is the filter thickness, \( \mu = \mu(E) \) is the total mass absorption coefficient of the x-ray radiation in the filter material being the function of energy, \( \rho \) is the linear density of the filter material substance.

The above-mentioned foil filters, in combination with the known spectral sensitivities of the difference channels, make it possible to carry out measurements in the ranges of the spectrum limited by the values of 1.56, 4.97, 5.46, 7.11, 8.33, 9.66, 17.04, 20.00, 29.20 and 50.24 keV; \( S_{\text{Eff}} = (0.8–13) \times 10^{-17} \text{ C/quantum} \).

For an integrated x-ray visualization of the discharge area, a digital x-ray camera with a vacuum inlet flange of the KF40 type is used. The x-ray image is converted to the visible image by means of a Gd\(_2\)O\(_2\)S: Tb phosphor screen on a fiber optic plate with aluminum shielding layer of \( \approx 1 \mu\text{m} \) thick, then transferring the image to a backlight-type sensor by a contact method, which minimizes losses. The size of the working area of the x-ray camera sensor is \( 13 \times 17 \text{ mm}^2 \), the spatial resolution of the x-ray camera on the screen is not worse than 20 \( \mu\text{m} \).

3. X-ray radiation measurement in several spectral intervals by the method of Ross filters with a time resolution

For x-ray measurements a pulsed x-ray spectrometer is used based on Si x-ray PIN diodes. Selection of spectral regions is carried out by Ross filter method [25]. In this case, the entire energy range is divided into separate spectral intervals, each of them corresponds to its difference channel, which consists of two calibrated diodes with different filters selected for sensitivity (figure 3). Then, in each difference channel, the energy flux density of the x-ray radiation is transformed into an electrical analog (current pulses at the output of the x-ray PIN diodes).

The spectrometer is designed to record the time dependence of the spectrum of pulsed x-ray radiation in the energy range from 2 to 50 keV. The spectrometer used makes it possible to
Figure 4. (a) Signal waveforms of four PIN diodes in the adjusted for optimal performance diode gap: ch1—D4 with Fe 38.48 µm; ch2—D3 with Co 32.86 µm; ch3—D5 with Fe 2\times19.24 µm; ch4—D1 with V 2\times37.96 µm. Start time of the oscilloscope is shown by an arrow. (b) Calculated two difference channels (ch2 − ch1 and ch3 − ch4) for matched detector pairs.

3.1. Fe-anode
On the oscilloscope channels, signals of four PIN diodes (two pairs) were recorded, closed by filters made of their selected materials of a given thickness. The pair of detectors, selected by sensitivity, forms one difference channel, see figure 2(b). For the registration of the K$_\alpha$ Fe-56 line, the difference channels (Co–Fe) and (Fe–V) were chosen with filters closest to the calculated optimum with thicknesses of 32.86 (Co), 38.48 (Fe), 2 \times 37.96 µm (V), see figure 3(b).

The conversion into the total number of quanta in a given spectral interval was carried out as follows. Based on the amplitudes of the difference channel signals and the known matched load (50 Ω), the detector current was calculated. The total charge passed through the detector was calculated by integrating the current during the pulse time. Using the calibration efficiency of detectors (absolute), the number of quanta in a given spectral interval incident on the sensitive surface area of the detector was calculated. The total number of quanta was estimated in assumption of point and isotropy of the source, as well as the geometric factor determined by the diameter of the tantalum collimators of spectrometric diodes (2.5 mm in diameter) and the distance to the object (12.5 cm). See example of calculating the x-ray yield for shot shown in figure 4 in table 1. The results for several shots (numbered as F010, F007, F025) in form of histogram are shown in figure 5.

3.2. Pd-anode (13 tube)
For the detection of the K$_\alpha$ Pd-106 line, the three difference channels B1 (Sn–Gd), B2 (Mo–Sn) and B3 (Y–Mo) with the filters closest to the calculated optimum are selected with thicknesses of 70.33 (Gd), 145.4 (Sn), 157.3 and 27.89 (Mo), 82.37 µm (Y). Thus, a scan of three spectral intervals is realized: one with K$_\alpha$ Pd-106, and two others on both sides of it (table 2). The same processing procedure, as for Fe anode, is carried out. Results for shots (numbered as F028, F030, F031) in series I and shots (numbered as F033, F034, F035) in series II are shown in figure 6.
Figure 5. Histogram of the x-ray output in two spectral ranges: the range containing K$_\alpha$ Fe-56 (left); range, not containing K$_\alpha$ Fe-56 (right).

Table 1. Example of calculation of the x-ray yield for shot shown in figure 4: $E_{ph}$ means the spectral interval; $S_{Eff}$ is the quantum efficiency (averaged); $U_{max}$ is a signal amplitude; $t_{pulse}$ is a pulse duration; $\Gamma$ is a geometric factor; $Q$ is the transferred charge; $N_{PIN}$ is the number of quanta incident on the sensitive area of PIN diode; $N_{total}$ is calculated total number of generated quanta.

| $E_{ph}$ (keV) | $S_{Eff}$ (C/quantum) | $U_{max}$ (V) | $t_{pulse}$ (ns) | $\Gamma$ | $Q$ (pC) | $N_{PIN}$ (quanta) | $N_{total}$ (quanta) |
|---------------|-----------------------|---------------|-----------------|---------|---------|---------------------|---------------------|
| 5.46–7.11     | $7.3 \times 10^{-17}$ | 0.06          | 4.1             | $2.5 \times 10^{-5}$ | 4.94    | 67 800              | $2.7 \times 10^9$   |
| 7.11–7.71     | $5.9 \times 10^{-17}$ | 0.02          | 3.4             | $2.5 \times 10^{-5}$ | 1.36    | 22 900              | $9.2 \times 10^8$   |

4. X-ray imaging
A camera based on a complementary metal-oxide semiconductor (CMOS) sensor with a fiber optic plate and a scintillator-based x-ray converter (P43) with a protective 1 $\mu$m thick Al coating was used to record the integrated x-ray radiation in the 2–30 keV range. An enlarged image of the object was projected with a pinhole of 100 $\mu$m in diameter onto a scintillation screen with a diameter of 13 mm, which was additionally protected from the background flare by a 15 $\mu$m Be filter (for the entire area of the sensor).

X-ray images for the case of Fe-anode (see figure 1(b), insert), Al-cathode funnel and “anode tip–cathode face plane” distance parameter $d = 0.0 \pm 0.1$ mm are shown in figure 7. Here and further images are processed: a “dark” image containing background noise of the matrix and
Table 2. Difference channels in the experiment with Pd-anode.

| Channel, detector | Relative sensitivity | Filter material | Filter thickness (µm) | Difference channel |
|-------------------|----------------------|-----------------|----------------------|--------------------|
| Series I          |                      |                 |                      |                    |
| Ch1, D4           | 1.48 ± 0.02          | Sn              | 38.48                | B1                 |
| Ch2, D3           | 1.44 ± 0.02          | Gd              | 145.4                | B1                 |
| Ch3, D5           | 1.06 ± 0.04          | Sn              | 145.4                | B2                 |
| Ch4, D1           | 1                    | Mo              | 157.3                | B2                 |
| Series II         |                      |                 |                      |                    |
| Ch1, D4           | 1.48 ± 0.02          | Y               | 82.37                | B3                 |
| Ch2, D3           | 1.44 ± 0.02          | Mo              | 27.89                | B3                 |
| Ch3, D5           | 1.06 ± 0.04          | Sn              | 145.4                | B2                 |
| Ch4, D1           | 1                    | Mo              | 157.3                | B2                 |

Figure 6. Histogram of the x-ray output in three spectral ranges: the range in the center is containing Kα Pd-106; left and right ranges do not contain Kα Pd-106.

artifacts of the scintillation screen (hot spots) is subtracted. Color pictures—images in pseudo colors. The color scale (LUT Jet) is applied to the grayscale image.

The case of a Pd multi-tube anode with three “removed” tubes, the anode was oriented with a single “breach” to the camera. In this case, the images show the outlines of the tubes with
Figure 7. X-ray images of discharge with Fe anodes: (a) solid anode, “triangular” glow zone in the center; (b) multi-tooth Fe-anode (8 teeth), cathode funnel with side window facing the chamber, $d = 0.0 \pm 0.1$ mm.

Figure 8. X-ray images of discharge with Pd-anode (13 minus 3 tubes), cathode funnel, $d = 0.0 \pm 0.1$ mm. The gap in the tubes faces the camera: (a) shot with bright region formation in the gap between the tubes, (b) shot with the bright globular formation near the end sections of the tubes.

shadows on the background of the object glowing in the x-ray. The aluminum cathode funnel is fairly transparent for the detected radiation, in comparison with palladium tubes, and its contours are not clearly visible. However, in cases where the cathode funnel extends beyond the end face of the anode ($d > 0$), the recorded image in the gap is more intense, which corresponds to recording without absorption of a part of the quanta on the thickness of the Al cathode wall. The luminous regions in the x-ray region have a symmetrical shape, with variations both in the region between the tubes and at their cutoff on the axis of the electrode system closer to the cathode, forming approximately globular luminous regions (see, for example, shots presented in figure 8).

5. Concluding remarks

The method of x-rays detection using PIN diodes and Ross filters was chosen in connection with high sensitivity and time resolution, the possibility of direct calculating the energy characteristics of radiation and the ease of implementation. Other methods giving the x-ray spectrum directly, for example, Bragg spectrographs on crystals, in our case are not suitable because of the relatively low flash intensity in one shot. Accumulation for a large number of shots is associated with a
risk of changes in the electrodes of the discharge gap as the number of shots increases up to few hundreds ones needed for spectrograph on crystals. Of course, we understand that the histograms presented in figures 5 and 6 are different from the real x-ray spectra. However, the results obtained give us the first quantitative representations of the spectra of the complex NVD plasma in the x-ray area.

The integral x-ray images obtained in this work (examples are shown above in figures 7 and 8) confirm and supplement the fact of formation of an inhomogeneous or partially ordered complex plasma in the pre-anode region, already known on the basis of the previous CCD images obtained in early experiments [16–18]. At the same time, the method of registration of x-ray images used in this work allows us to exclude a part of false signals also. This method of x-ray images recording will be used in the further experiments with NVD-2 to determine the role of self-organization of interelectrode ensembles of clusters and nanocrystals in the processes of generation, propagation, “trapping” or release of x-ray emission [22], as well as under the study of efficiency of DD neutron generation and other products of nuclear burning in the IEC scheme based on NVD [24].

Next, we can extend the analysis of some available previous experiments on x-ray registration at NVD in the light of the present data obtained on x-ray spectra. Earlier we discussed the possibility of “trapping” of a not very hard x-ray (∼3–8 keV) by interelectrode ensemble of nanoparticles in NVD [22,26]. Example of a rather bright ensemble with a strong and anisotropic outburst of a hard x-ray was shown in [26] (it was a shot with Fe anode, which followed by another shot [26], where the x-ray was almost trapped by the complex plasma ensemble). We have not measured the x-ray spectra in [26], but one can try to estimate the energy region of photons fixed by PIN diodes (channels 1 and 3 in previous oscillograms in [26]). The line spectrum of cold iron does not exceed 7.1 keV, and the arrangement of PIN diodes in the air at some distance from the source made it possible to detect photons with energies of about or more than 5 keV. Thus, the line spectrum is limited to an interval of about 5–7 keV, plus a certain “background” will be created by x-ray bremsstrahlung. In the NVD experiment with Fe anode we are dealing with a “cloud” of atoms, molecules, iron clusters and it is permeated by fast electrons, ions, and x-rays, all with energies up to about 50 keV [27]. These factors, apparently, can ensure the excitation and ionization of the K-electron with the subsequent appearance of the fluorescent line $K_{α} Fe$-56, 6.4 keV. Seems, the present measurements of Fe spectra (see figure 5) do confirm this scenario for previous experiment [26].

Remark, relatively recently astrophysics actively discussed the hard x-ray radiation recorded by the IBIS telescope from the molecular cloud Sgr B2 in the region of the galactic center [28–30]. It was shown that the observed x-ray emission could be emitted in the past by the supermassive black hole Sgr A* and is reflected distantly from it by the molecular gas of a massive cloud at a distance of 350 light years in the form of a fluorescent line of $K_{α} Fe$-56. Coming back to present experiments, we observe the fluorescent line $K_{α} Fe$-56, emitted from interelectrode cloud of complex self-pumped plasma. Thus, looking forward, some laboratory astrophysics [24] and some similar effects [31, 32] based on the processes in NVD with VC seems reasonable also.

Note, the previous experiments with a Pd anode have recognized both x-ray trapping and, rather rare, the strong bursts of x-rays [22] in the tougher part of the x-ray spectrum, apparently corresponding to $K_{α} Pd$-106 (21.177 keV) (PIN diodes in [22] do not react to them as strongly as for the Fe anode in [26], since the maximum of their sensitivity is just in the region of $K_{α} Fe$-56, and at higher energies of photons it falls). Also, PIC simulations [20,24] show that for shots with Pd anode where the polydisperse plasma was formed in the virtual cathode field in NVD, there are all the same favorable factors for transfer of the Pd K-electron to the continuum (24.350 keV) as for the case of Fe anode discussed above. Present data obtained on x-ray emission for Pd anode (see figure 6) partially confirm it but, in whole, the situation looks more complex than for Fe anode. Thus, the hypothesis of the appearance of a fluorescent line $K_{α} Pd$-106 as well
as the nature of strong hard x-ray bursts [22] require further verification and appropriate x-ray measurements in NVD-2.

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