On nuclear DD synthesis at the initial stage of nanosecond vacuum discharge with deuterium-loaded Pd anode

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Abstract. Earlier, there was demonstrated generation of DD neutrons in an interelectrode medium of a low-energy (∼1 J) nanosecond vacuum discharge with a hollow cathode and a deuterium-loaded Pd anode. There was revealed essential role of formation of a virtual cathode and a potential well corresponding thereto in the processes of collisional DD synthesis in the interelectrode space. In this work, we have obtained as a result of an experiment and discussed the neutron yield at the very initial stage of the discharge, when the beam of auto-electrons just starts to irradiate the non-ideal surface of the deuterium-loaded Pd anode.

1. Introduction
In the papers [1–4], there were studied processes of nuclear fusion in a compact scheme of inertial electrostatic confinement (IEC), realized on the basis of a nanosecond vacuum discharge (NVD) of low energy. The yield of DD neutrons from the NVD interelectrode space with deuterium-loaded Pd anode was represented and discussed earlier [1, 2]. A complete particle-in-cell (PIC) simulation of the experiments with the NVD was carried out with the help of electrodynamic code KARAT [3, 4]. Particularly, there was revealed the essential role of formation of virtual cathode (VC) and deep quasi-stationary potential well (PW) corresponding thereto [2]. The PIC simulation has confirmed the fact that the experiment with NVD implements the well-known scheme of IEC [5,6] having inverse polarity considered in theoretically [7]. Deuterons are accelerated in the PW up to the energies of dozens of keV, which ensures the DD nuclear fusion in head-on deuteron collisions at the moments of their collapse at the “bottom” of the PW. In particular, deuterons can also perform high-frequency harmonic oscillations in the potential well, which is accompanied in the experiment by the pulsating yield (≈80 MHz) of DD neutrons [1–4].

At the same time, the PIC simulation of the dynamics of all particles has demonstrated that during the first nanoseconds after the application of high voltage, a beam of auto-electrons from the cathode (having an energy of about 50 keV) reaches the surface of the deuterium-loaded anode and starts to interact with it. The initial stage of the discharge had been previously poorly studied, and was not sufficiently or just preliminary represented in the available publications [8]. This paper is devoted to the description and analysis of the novel experimental data on the
Figure 1. (a) Schematic of experiment for generating interelectrode complex plasma ensembles with nuclear burning: MG — Marx generator, R — Rogovskii coil, A and C — anode and cathode, PIN — instant PIN diodes, CCD — camera, PH — pinhole, PM2 and PM4 — photomultipliers, OSC — oscilloscope, TOF — time of flight tube, V — vacuum pump. (b) Example of CCD image of dilute (“transparent”) interelectrode ensemble; corresponding oscillograms are in figure 2(b).

NVD, related to the appearance of DD neutrons at the very initial stage of the discharge. The preliminary data presented earlier in [8] have been defined more accurately and verified also.

2. Experiment on IEC on the basis of NVD. DD neutrons at the initial stage of discharge

Let us remind of the fact that in the experiment we used a modified scheme of the IEC based on a miniature low-energy NVD with a deuterium-loaded palladium anode [1, 2]. From the standard IEC circuits with electrodes–meshes [6], we proceeded to the IEC comprising the distinctive features of the NVD physics, particularly, we have used a hollow Al cathode with a conical part and a Pd anode, which was periodically filled with deuterium in the process of electrolysis in heavy water. The general scheme of experiment and CCD image of particular interelectrode ensemble in hard x-rays are presented in figure 1 (see the details of experiment and the selected geometry of the base electrodes in [1, 2, 8, 9]; pulse duration of 50 ns, applied voltage of 70 kV, and maximum current of 1 kA). Such an IEC circuit with a reversed polarity [7] makes it possible to operate in vacuum, where beams of auto-electrons from the cathode will be formed when the voltage is switched on. The latter ones, interacting with the deuterium-loaded Pd anode, in the first, will create near the anode an erosion plasma containing deuterons and deuterium-containing clusters. Secondly, the electron beams, while flying into the anode space (through the “mesh” of thin Pd rods) and braking at its center, form a VC and the PW corresponding thereto. A deep potential well (dozens of kV) will play the role of a micro-accelerator, accelerating deuterons from the edges of the well to the energies of dozens of keV and making collided their counter-flows between each other on the discharge axis, that is on the “bottom” of the PW (this also applies to the nuclear “burning” of ions of complex elements with a charge $Z > 1$ [9]).

Time-of-flight measurements have been usually carried out using photomultipliers PM4 and PM2, located on the same axis as the electrodes, see figure 1(a). In figure 2 the oscillograms for two consequent shots are presented. For these particular cases photomultipliers PM4 and PM2 were located at distances of 45 cm and 80 cm respectively (channels 4 and 2 on the oscillograms...
Figure 2. (a) Dynamics of x-ray yield in mode 1: peak of the extra x-ray on channel 4 (as well as the breaks on channels 3, 2) represents manifestation of starting the DD reaction (sensitivity of channel 2 comes to 250 mV, time scale is 40 ns/div). The time latency of the neutron peak at channel 2 corresponds to \(\approx 46.6\ \text{ns/m}\) (i.e., to DD neutrons). The dashed lines correspond to the very initial stage of the discharge (see the discussion below). (b) Dynamics of x-ray yield in mode 2 for next shot with triple anode also (3 Pd tubes). The PM4 photomultiplier device specifically records the reaction moment itself as a reference point of the synthesis moment in time a small peak of extra hard x-ray or \(\gamma\)-emission due to the expansion and deceleration of the energetic products of DD reaction in surrounding matter, channel 4. In real time it coincides with the kink of the PIN diode signal being registered after the moment of synthesis by extra x-rays, channel 3. Apart from the hard x-ray, basically bremsstrahlung one (the first strong intensity peaks on channels 2 and 4), PM2 can record also a well reproducible signal (the second weak peak, channel 2) with a delay of about 46.6 ns/m relative to the DD synthesis moment, channel 4, figure 2(a). This delay represents a characteristic feature (“signature”) of neutrons having energy of about 2.45 MeV from the D(D,n)He\(^3\) synthesis reaction (their arrival on the scintillator is detected by a photomultiplier PM2, channel 2). The change in the distance between the plasma source and PM2 (nearer–farther) is accompanied by a corresponding time shifting of the instant of the appearance of the neutron peak on channel 2 (sooner–later) \([4, 8]\). It should be noted that the IEC scheme, implemented on the basis of NVD \([1–4]\), greatly simplifies a number of modern IEC schemes, in particular, available in the LANL (Los Alamos) \([10–12]\), where is used a separate and rather complex injection of electron beams from special sources to form the PW, making it just unnecessary. Let us also recall that the possible role of a non-stationary PW for accelerating ions ahead of the front of the cathode flare in the modes of unstable current transmission was considered in detail in \([13]\), which has particularly explained the appearance of fast ions in a number of the early conducted experiments \([14]\). In our case, the NVD configuration allows creating quasi-stationary PWs \([3, 4]\) in the interelectrode space, which provides a sufficiently controlled collisional nuclear fusion.

While the right-hand part of the oscillograph charts shown in figure 2(a) (after the 120th ns, channels 2 and 4) was previously represented and analyzed \([1–3]\), then the initial bursts of x-ray intensity (the left-hand part, up to before the 120th ns) has not been discussed yet. In fact, at the earliest stage of the discharge, we have sometimes observed correlated intensity peaks during...
Figure 3. (a) Dynamics of x-ray yield in mode 3 for triple anode (with more dense interelectrode ensemble, see CCD image below in figure 4(a), which is very similar to present mode). (b) Dynamics of x-ray yield in mode 4, when 0.1 cm lead plate was placed before photomultiplier PM2. Due to this absorber, channel 2 contains just DD neutrons peaks (from initial and further stages of discharge) as well as very hard x-rays from the fusion moments (due to deceleration of high energetic products of DD reaction). Correspondingly, sensitivities of channel 2 are essentially different at these figures (see text).

the time-of-flight mode (the left-hand part in figure 2(a), dashed line). These peaks are rather similar to the signals on the photo-multipliers from neutrons having energy of 2.45 MeV that were observed during the study of the collisional DD synthesis in the VC potential well forming during about 10 ns after the applied voltage pulse (the right-hand side of figure 2(a), solid lines). In particular, an analysis of x-ray intensities conducted from the sequence of peaks on channels 4 and 2 at the very initial stage of the discharge (figure 2(a), dashed arrows) shows that after the moment of synthesis registered at PM4, the DD neutrons initially come to the PM4 photomultiplier and are partially recorded by it (channel 4), and after that they are recorded on PM2 (figure 2(a), channel 2, dashed arrow). DD neutrons of the collisional synthesis that appear in the PW about 80 ns later are shown by a solid arrow (channel 2). Similar features are observed for next shot, figure 2(b).

Oscillograms of the shot shown in figure 3(a) have been presented much earlier [1, figure 3] as well as CCD image of interelectrode ensemble also, but their left parts (in time) were not analyzed in detail. Meanwhile, we can notice here the similar small peaks (before main x-rays peaks from PM4 and PM2) as in figure 2. Oscillograms for the next shot where 0.1 cm Pb plate was installed before photomultiplier PM2 are shown in figure 3(b). This data looks very instructive. In fact, since 0.1 cm thick Pb absorber before PM2 is cutting photons with energies less than about 100 keV, we observe on channel 2 in figure 3(b) just neutrons from very initial stage (indicated by dashed lines) and further neutrons from collisional synthesis at PW (double peak due to double PW, apparently [4]) as well as very hard extra x-rays from the moments of this collisional DD synthesis (double peaks correspondingly also). The fusion moments in channels 1–3 in figure 3(b) are shown also as well as the TOF peak of neutrons from the initial stage (channel 4, PM4, dashed line) located in time before the neutron peak in channel 2 (since PM4 is between source and PM2). Underline, sensitivity of channel 2 in figure 3(b) is 200 mV, i.e. five time higher than for channel 2 in figure 3(a) (to compensate the absorbing and reflecting effects of Pb plate before PM2). Thus, neutron peak from channel 2
Figure 4. (a) CCD image of dense interelectrode cluster ensemble in mode 5. (b) Dynamics of x-ray yield in mode 5 for the shot which is the next after one presented in figure 3(b) (triple anode and 0.1 cm lead plate before photomultiplier PM2 also).

looks essentially stronger than similar one in figure 3(a). Note, the general structure of the signals from screened photomultiplier PM2 (very hard extra x-rays and DD neutrons) as well as signals from channels 1–3 in figure 3(b) are reproduced rather well from shot to shot at this experimental series. It is illustrated properly by the oscillograms for the next shot after that one presented in figure 3(b) shown below in figure 4 together with corresponding CCD image. We observe rather similar structures of DD neutrons peaks from the initial stage, double neutron peaks from DD fusion at PW as well as double extra x-rays from DD fusion moments, compare oscillograms in figure 3(b) and figure 4(b). Remark, the neutrons from initial stage and further neutrons from fusion at PW are shared clearly in time (figure 3(b) and figure 4(b), channel 2) and located almost symmetrically around very hard x-rays from DD fusion moments at PW.

The shots discussed above was made with an anode in which there were only three palladium tubes. Modified anode with twelve Pd tubes soldered to the end of the copper cylindrical base along its perimeter was also used in the experiments; oscillograms of the intensity of x-ray and neutrons are shown in figure 5(b). The first double peak of the neutrons in figure 5(b) is wider than the similar initial peak in figure 3(a), being approximately proportional to the increase in the surface area of Pd (during the transition from three to twelve tubes). Apart from the x-ray “dust” around the anode, it appears that the CCD image in the x-ray contains also overlapping regions of interaction of the electron beam with the surface of the palladium tubes, see figure 5(a). Let us note the modes that have yet been represented here above, figures 3(b) and 4(b), when the second photo-multiplier PM2 was closed with a lead plate 0.1 cm thick. In the present case, shot with 0.3 cm lead plate, the main x-ray maximum peak was suppressed also, and only DD synthesis moments and neutron peaks at the initial and subsequent stages of the discharge were fixed on channel 2 (figure 5(b), shot 0518D7). Remark, that very similar structures of neutron peaks at channel 2 with screened PM2 by 0.3 cm Pb plate as well as hard x-rays in channels 3–4 were presented earlier for shot with multiple fusion events also (figure 7 at [1], 12 Pd tubes anode, shot 0522D4). To complete this series, one more set of oscillograms from particular shot with 12 Pd tube anode is shown in figure 6(a), shot 0522D5. This shot was the next one after the shot 0522D4 (figure 7 at [1]), and their CCD images are similar also as well as the structures of DD neutrons and very hard x-ray peaks at channels 2 (0.3 cm Pb plate before PM4). Note, due to continuous row of Pd tubes at this anode type, the conditions
Figure 5. Dynamics of x-ray yield in mode 6: (a) CCD image of a cluster ensemble, together with bright overlapping regions of interaction of e-beam with a solid surface of 12 Pd anode tubes; (b) oscillograms of yield of x-rays (channels 1, 3 and 4) and neutrons (channel 2) for the anode with 12 Pd tubes and 0.3 cm lead plate before PM2 (see the text).

to form VC and corresponding PW are not optimal and interpretations of oscillograms is not always unambiguous as in the case of the triple (transparent) anode.

It should be noted that placing a piece of paraffin between the PM4 and PM2 photo-multipliers simultaneously weakens the intensities of both small neutron peaks registered on channel 2 by the PM2 photo-multiplier (figure 6(b), no lead plate before PM2). This fact also speaks in favor of the general (neutron) nature of these peaks. It is not excluded that the neutron peak from the very initial stage of the discharge is fixed in the microreactor mode also (figure 11 in [8]).

In general, from the analysis of the available data array, it can be concluded that the very initial stage of the discharge can also be accompanied by a neutron yield that varies from shot to shot in a more random way as compared to the synthesis in the second stage, when in the interelectrode space the VC and the corresponding PW are formed. In addition, the large surface area of the deuterium-loaded Pd anode (during the transition from three Pd tubes to twelve ones) reveals a larger neutron yield at the initial stage.

Let us recall that hydrogen or deuterium saturated palladium (a special case of our anodes in the NVD) is a potential energy accumulator, the interest in which (and its accompanying effects) has increased in the last decade (see, for example, [15–23]). Thus, measurements of neutron scattering at small angles have revealed that dislocations in the Pd lattice can absorb a large amount of hydrogen (deuterium), and the micro-regions of absorption themselves have a cylindrical geometry [16]. The anomalies in electronic transport and the magnetic properties of deformed hydrogenated Pd foils were explained in terms of local (filamentary) superconductivity [17] associated with condensation of trapped hydrogen (deuterium) into the metallic phase (∼10^24 cm^-3) [18] in the dislocation nucleuses. Moreover, some experiments [19] also indicate the possibility of the existence of ultra-dense deuterium (∼8 × 10^28 cm^-3). The possibility of DD synthesis with weak laser action on ultra-dense deuterium formed in pores with Fe_2O_3 was investigated in [20], and the time-of-flight measurements have revealed the characteristic products of DD synthesis. In such a way, the observations listed above provide grounds to assume that the power impact of internal electron beams at the very beginning on
the non-ideal surface of the deuterium-loaded Pd anode of the NVD can also not pass without a trace [21].

3. Surface morphology of Pd anode

With reference to the initial stage of the NVD, we can rely up to the moment only on the time-of-flight measurements. The mechanism of possible DD synthesis in the “electron beam–deuterium-loaded Pd” system is far from being obvious, and here our main goal is to represent the experimental data and we confine ourselves to a just qualitative discussion of possible synthesis scenarios. In the first place, it can be assumed that micro-pores, microcracks, dislocations (filled with deuterium) and the like on the surface of the anode represent a natural set of micro-channels (figure 7) for possible micro-synthesis near the surface of the anode under the action of electron beam irradiation at the initial stage of the NVD. Extrapolation of fusion power density scaling $P \sim 1/r_{VC}^4$ in IEC-like device with oscillating deuterons [4, 11] for the case of very small values of $r_{VC}$ shows that at $r_{VC} \to 0$ the synthesis efficiency is formally increases appreciably [8].

In the second place, it is possible that the electron beam can play, in some individual cases, the role of a trigger for local nuclear micro-explosions. Indeed, defects in the palladium crystal lattice with a high local pressure ($\approx 180$ GPa [22]) represent a unique tool for producing hydrogen (deuterium) in the metallic phase (dislocation is a kind of a potential trap, causing deuterium to condense). Irradiation of clusters of ultra-dense deuterium, if such will be formed during the process of electrolysis, may be accompanied by separate points of nuclear micro-synthesis near the anode surface and by explosive release of anode material.

Preliminary study of the morphology of the Pd anode surface reveals a large number of different kinds of micro-pores and microcraters of various sizes (two typical fragments of the Pd anode surface are shown in figure 7). Analyzing the Pd surface, it can be seen, that in addition to the fairly ordinary pores and craters in figure 7(a) that are arising during the interaction of the electron beam with the anode surface, relatively large individual craters also appear $\approx 10$ $\mu$m, see the left-hand part of figure 7(b). Perhaps, their formation at the anode surface indicates to the possible nuclear nature of some anode ectons (explosive centers [23]). This is indirectly supported by the recent independent experiment on “stimulation” of nuclear reactions

Figure 6. (a) Dynamics of x-ray yield in mode 7 for a shot with an anode of 12 palladium tubes and 0.3 cm lead plate before PM2. (b) Dynamics of x-ray yield in mode 8 (triple anode), when a piece of paraffin was placed between photomultipliers PM4 and PM2.
during irradiation of deuterium-loaded palladium foils with an external electron beam [24, 25]. In this experiment, there was registered yield of some DD reaction products (protons having energy of $\approx 3$ MeV) under the impact of microampere beam of electrons having energy of 30 keV on the surface of the deuterium-loaded palladium foil. The formation of more number of pores and microcraters (10–12 $\mu$m in size) was noted only in the case of filling the foils with deuterium; filling with hydrogen did not cause these effects [24]. The large microcraters in these experiments [24, 25] are very similar in shape and size to the crater registered on the surface of the Pd anode in the NVD shown in the left-hand part of figure 7(b).

4. Concluding remarks

Summarizing, let us note that in the experiment with the NVD during the time-of-flight regime, there was observed the appearance of neutrons with an energy of 2.45 MeV from the DD synthesis, which possibly is realized in various ways at the initial and quasi-stationary stage of the NVD. The physics of the collision DD synthesis in the potential well of VC in a miniature low-energy NVD was substantially clarified by the PIC simulations [3, 4, 8, 9]. The analysis of time-of-flight signals in the experiments with the NVD allows us to conclude that, at the initial stage there is also possible a certain yield of DD neutrons. This yield changes more randomly from the shot to the shot as compared to the collisional DD synthesis in the later formed PW [8, 9]. In fact, the auto-electron beam might play the role of a trigger for the micro-synthesis processes on the surface or in the volume of deuterium-loaded Pd anode. Qualitatively, a similar result (a statistically significant yield of the DD-reaction products and large craters) was obtained during the irradiation by a low-current electron beam of targets from Pd/PdO:D$_x$ [24, 25].

Overlapping of the discussed above synthesis mechanisms at the initial stage of the NVD is also not excluded, and should be the subject of further study. It should be noted that further analysis is required also for both more exotic explanations for the possibility of generation of DD neutrons at the initial stage of the NVD, such as the build-up of oscillations [26, 27] in the entire volume of the Pd anode, stimulated by irradiation of a beam of auto-electrons, and possible DD
synthesis, caused by the influence of the Pd lattice itself, filled with deuterium, on the fusion of deuterium nucleuses [28] under the external irradiation. Some similar processes arising in turbulent and vortex two-phase flows containing microparticles [29, 30] as well as other related phenomena [31, 32] are beyond of discussion here.

From the other side, it is also possible that the hit of auto-electron beam at the moment of its arrival at the anode partially inside the anode Pd tubes themselves can also form a short-lived VC of very small dimensions. In this case, the general scenario of generation of DD neutrons at initial stage of NVD discharge will include the overlapping of whole spectrum of the most diverse effects, and which one will dominate under certain conditions is not yet clear. Thus, of great interest are also further modeling of new effects [33], associated with the interaction of beams of auto-electrons with the deuterium-loaded palladium anode tubes (including processes inside of Pd tubes also) as well as the novel independent experiments related with interaction of energetic electron beams with deuterium-loaded palladium or other deuterium-loaded metals.

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