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On the features of bursts of neutrons, hard x-rays and alpha-particles in the pulse vacuum discharge with a virtual cathode and self-organization

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Abstract. In this paper, we continue the discussion of the experimental results on the yield of DD neutrons and hard x-rays in the nanosecond vacuum discharge (NVD) with a virtual cathode, which was started in the previous article of this issue, and previously (Kurilenkov Y K et al 2006 J. Phys. A: Math. Gen. 39 4375). We have considered here the regimes of very dense interelectrode aerosol ensembles, in which diffusion of even hard x-rays is found. The yield of DD neutrons in these regimes is conditioned not only by the head-on deuteron-deuteron collisions in the potential well of virtual cathode, but also by the channel of "deuteron-deuterium cluster" reaction, which exceeds overall yield of neutrons per a shot by more than an order of magnitude, bringing it up to $\sim 10^7/(4\pi)$. Very bright bursts of hard x-rays are also represented and discussed here. Presumably, their nature may be associated with the appearance in the NVD of some properties of random laser in the x-ray spectrum. Good preceding agreeing of the experiment on the DD fusion in the NVD with its particle-in-cell (PIC) simulations provides a basis to begin consideration of nuclear burning "proton-boron" in the NVD, which will be accompanied by the release of alpha particles only. With this objective in view, there has been started the PIC-simulation of aneutronic burning of p-B¹¹, and its preliminary results are presented.

1. Introduction

This paper concerns the continuation of study and analysis of the database accumulated earlier on the yield of DD neutrons and hard x-rays in the nanosecond vacuum discharge (NVD) with a virtual cathode [1–4]. In particular, the interests represents some of the anomalous regimes registered earlier at NVD, beyond of the basic experimental and modeling data presented in the previous article of this issue [2]. We will consider the regimes of very dense interelectrode aerosol ensembles, in which some diffusion of even hard x-rays is found. The yield of DD neutrons in these regimes is conditioned not only by the head-on deuteron-deuteron collisions in the potential well (PW) of virtual cathode (VC) [2], but also by the channel of "deuterondeuterium containing cluster" reaction, which exceeds overall yield of neutrons per a shot by more than an order of magnitude (section 2). Very bright bursts of hard x-rays and their nature are represented and discussed in section 3. Apart from modeling and optimization of processes of the DD fusion in the NVD, we, as before, are also aimed at clarifying the possibilities of aneutronic burning of modern fuels, such as proton-boron, in the NVD, and its implementation

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in future experiments. Indeed, since the particle-in-cell (PIC) simulation has given previously completely adequate picture of the DD fusion in the NVD, looking forward, it is obvious that consideration of the problem of proton-boron burning should be started with the modeling of this process. With this objective in view, there has been began the PIC-simulation of nuclear burning of $p-B^{11}$, which is accompanied by the release of alpha-particles only and its preliminary results are presented (section 4).

Meanwhile, earlier in paper [5] have been described efficient way to operate inertial electrostatic confinement (IEC) devices, which appears to offer an avenue whereby IEC devices may be able to achieve high gain. In this scheme, the focused ion beam is replaced by an oscillating plasma sphere, which periodically compresses the plasma to very high density and temperature. This operating scheme is referred to as the periodically oscillating plasma sphere (POPS) [5]. Concerning to comparison of NVD data with POPS ones [5,6], started above in paper [2], we would like to add and remark that, in particular, the frequency of neutron yield oscillations observed in the vacuum discharge [1–4] comes to about $\nu \approx 77-83$ MHz, and coincides with extrapolation of POPS expression $\nu_{\rm POPS} \sim (\varphi/m_i)^{1/2}/r_{VC}$ [6] to A-C geometry and the potential well (PW) depth φ (m_i —deuteron mass, r_{VC} —virtual cathode radius). It seems that this agreement is not accidental and confirms the similarity to the POPS physics of some multiple fusion events (MFE) regimes of nanoseconds vacuum discharge [1–4]. The latter ones might provide at the collapse moments the ion densities $n_i \max \sim 10^{21} - 10^{22}$ cm⁻³ and compression of the ion subsystem of up to $\sim 10 \ \mu m$. The miniature size of virtual cathode, $r_{VC} \sim 0.1$ cm, as well as rather deep PW (like $\varphi \approx 50-55$ keV) correspond to the extremely high fusion power densities (~ φ^2/r_{VC}^4) demonstrated at the present moment by our system of the table-top IEC [1-4]. On the other hand, rather small absolute "reactor" volume, nanosecond scale of T_{pulse} , and losses restrict the value of total neutron yield, but keep it to be acceptable for some particular modern applications and, in particular, allows to consider the elementary cell (nuclear burning in potential well of NVD [2]) as a part of "fuel" array for any massively modular approach as suggested and discussed in [5,6]. In whole, the trapping of deuterons by interelectrode ensembles of clusters with deuterium, especially noticeable under the effects of the interelectrode cluster ensemble self-organizations (with the diffused x-rays inside), represents additional opportunities for the "reactor" optimization.

2. Regimes of maximal neutron yields

Single and pulsating DD neutron yields from NVD have been presented and discussed in detail above [2] (figures 2.3 and 5b, correspondingly). Another effect may appear if the concentration of clusters and micrograins is increased essentially but their mean sizes are decreased (we have $\sim 10^{-3}$ -10⁻¹ µm). In the experiment we may partially regulate the level of x-ray absorption and multiple scattering inside the ensemble of clusters by varying the interelectrode volume within a particular order of magnitude (by changing A-C distance, 0.5–0.1 cm) under approximately the same value of mass transfer from anode and under smooth variation of the pressure within the range 10^{-6} - 10^{-2} mbar. In the diffuse regime, $\lambda \ll l_{sc} \ll R$, the light that is being trapped in a disordered system may make a long random walk before it leaves the medium from the nearby surface area [7–13] $(l_{sc} = 1/N_0 Q_S$ —mean free path of photons due to scattering, R ensemble dimension, and λ —the wavelength; Q_S —scattering cross section, N_0 —volume density of scattering particles, $N_0^{-1/3} \gg \lambda$). Dense interelectrode ensembles at NVD seems to manifest the ability to "trap" partially even x-rays (figure 1, see the scheme and details of NVD experiment in [2]). Remind, the PM(2) and PM(4) signals are always delayed due to electron transit time of photomultiplier tube by ≈ 35 ns with respect to the signals from the PIN diodes, whereas channels 1 and 3 are synchronized with the PIN diodes. Thus, the maximum values of the PIN and PM of x-rays are coinciding in *real time* for "transparent" CCD ensembles [2]. The dynamics of x-ray radiation in the regime close to x-ray diffusion considerably differs from the



Figure 1. X-rays dynamics in regime 1: (a) Oscillograms of hard x-rays intensities and neutron yield (timescale is 40 ns/div.). X-ray yield from channels 1 and 3 is delayed in *real time* due to photons diffusion inside of cluster ensemble; (b) CCD image of related dense self-organized interelectrode ensemble with trapped fast ions and partially diffused x-rays (anode with 12 Pd tubes).

ordinary x-ray ensembles (transparent and disordered, as in figures 2,3 in [2]): the diffused lower energy x-ray photons (energy $\sim 3-8$ keV) are delayed to appear from the ensemble interior in comparison with very hard x-ray emission, which is not trapped practically (ch.2, $L_2 = 50$ cm, photon energy ≥ 60 keV, figure 1). Other "ball"-like ensembles with very low x-rays yield but bright CCD images are shown elsewhere [3, 4, 14].

The beginning of x-rays diffusion for the cluster ensemble of intermediate density (between presented in figure 1b above and figure 2a in paper [2]) is shown in figure 2 below. In fact, the maxima of signals from ch.2 and PIN diodes (chs.1,3 in figure 2) are looking as coinciding approximately on the oscillograms registered. But for proper comparison with lower energy x-rays yield (chs.1,3) in *real time*, the maximum of very hard x-rays (channel 2) have to be "shifted" to the left by ~ 35 ns (as shown schematically by dotted line with arrow). Thus, the observed diffusion-like delay with release of x-rays from the ensemble, registered by channels 1 and 3, comes to about ~ 40 ns (figures 1,2). More dense cluster ensemble (figure 1b) provides better diffusion of x-rays than in regime 2, figure 2, accompanied by lower intensity x-ray yield (chs.1,3) under more bright CCD image of ensemble. Obviously, that dense ensembles with diffused x-rays like in figure 1b have to trap totally also fast ions generated by PW.

It appears reasonable to try to combine the advantages of the interelectrode cluster ensembles with the multiple fusion events (figure 5b in [2]) and with the diffused x-rays under total trapping of deuterons (figure 1b). Namely, particular example of a cluster ensemble with similar combined features is shown in figure 3 as prototype of a table-top complex plasma microreactor. We observe a bright image of the cluster ensemble, but with very low hard x-ray yield under their essentiall diffusion (channels 1 and 3). The growing (left) part of the intensity curve from PM4 (channel 4) represents mainly both the DD neutrons, which are coming first on PM4 before PM2 (see the scheme of experiment, figure 1a in [2]) and some extra x-rays from multiple fusion events. The main part of intensity registered by PM2 (channel 2) represents the strong pulsating neutron yield as a manifestation of "waves" of the DD microfusion due to the periodic deuterons collapse, but on the essential background of "fast deuteron-deuterium clusters" target DD synthesis under deuterons trapping by ensemble ($L_2 = 90$ cm, 0.5 mm thick Cu absorber, channel 2 sensitivity is 1 V). The sensitivity of channel 4 ($L_4 = 45$ cm) is 2 times higher than that for channel 2.



Figure 2. X-rays dynamics in regime 2: (a) Oscillograms of hard x-rays intensities (shot almost without deuterium). In *real time* the yield of hard x-rays ($\sim 3 - 8 \text{ keV}$) in channels 1 and 3 is delayed in comparison with the instant yield of more hard x-rays (moment is indicated by dotted arrow), $\geq 60 \text{ keV}$, channel 2, shot without deuterium (see text); (b) CCD image of cluster ensemble with partial diffusion of hard x-rays (the ensemble of the intermediate density between those presented in figure 1b above and figure 2a in [2], anode with 12 Pd tubes almost without deuterium).

This means that photomultiplier PM2 has registered mainly the process of neutrons coming. Thus, the ensembles with more saturated x-ray images correspond to higher neutron yields due to essential or full stopping of deuterons by the deuterium clusters.

The efficiency of neutron production in our low-energy discharge (as well as hard x-rays) may be two orders of magnitude higher as minimum than that for fusion events driven by the laser irradiated clusters explosions (10⁴ neutrons for 120 mJ of laser energy [15, 16]), while the total estimated number of deuterons in the laser focal area [15] and those ejected from the anode into the interelectrode space at our single shot is of the same order (~ 10¹³–10¹⁴). This efficiency has been realised due to several reasons [1,3,4] and, in particular, due to the fact that for the experiments [15,16] with fusion driven by Coulomb explosion of clusters the collisional free path l_D for ions D⁺ is much longer than the plasma dimension (which comes to about laser focal diameter $d_{\text{focal}} = 200 \ \mu\text{m}$), $l_D \gg d_{\text{focal}}$. In our vacuum discharge, the smooth variation of the ratio between l_D and the cluster ensemble efficient radius, R_{ball} , is possible. As a result, it may include even the trapping of all the deuterium fast ions (figures 1,3) generated at PW inside the ensemble of cold grains, $l_D < R_{\text{ball}}$ ("dusty" stopping). Thus, it looks rather natural that the neutron yields, in fact, will be essentially higher for the ensembles with brighter CCD images, which have a lower transparency for x-rays and fast ions, meanwhile, just neutrons are leaving it (figures 1,3 above).

3. On anomalous hard x-rays bursts

It looks that the diffuse regime discussed above, $\lambda \ll l_{sc} \ll R$, is one of the manifestation of the principal feature of the dense ensemble of nanoclusters, namely: at decreasing of cluster sizes just the surface properties start to prevail. It should be remarked that the developed surface of nanoclusters may probably provide condition $l_{sc} < R$ even under small-angle scattering. To illustrate the prevailing of surface properties at decreasing of nanoparticles radii and increasing of their number, we may rewrite $l_{sc} = 1/N_0Q_S$ as $l_{sc} = V_{1clus}/V_{clusters} \cdot S_{1clus}$. (V_{1clus}, S_{1clus} —mean volume and surface of single cluster correspondingly; $V_{clusters}$ —relative volume of nanocluster



Figure 3. X-rays dynamics in regime 3: (a) Oscillograms of x-rays yield (channels 1 and 3) and neutron yields (channel 2) for specific interelectrode ensemble with trapped fast ions and x-rays ("triple" anode, dashed lines correspond to neutrons from initial stage of discharge [2], see the text for details of the experiment); (b) CCD image of the corresponding self-organized cluster ensemble (complex plasma microreactor), anode with 3 Pd tubes, pressure $P \sim 10^{-6}$ mbar.

ensemble). Then at cluster radius $r_{\rm clus} \to 0$ we have $S_{1{\rm clus}}/V_{1{\rm clus}} \to \infty$ and formally we have $l_{sc} \to 0$ that provides x-rays diffusion inside of the interelectrode nanoparticle ensemble (under $V_{\rm clusters} \approx \text{const}$ from shot to shot). Since the metallic nanoclusters are nanocrystalls of different structure [17], the specific role of exact Bragg reflection, scattering in volume interior as well as reflection by cold clusters shell (figures 1b,3b) as effective "ring resonator" [18] (or distributed Bragg reflector structure [19]) needs a separate further analysis.

It is not excluded that stochastic interelectrode cluster ensembles in vacuum discharge are of interest with respect to realizing some laser effects, namely at hard x-rays part of the spectrum. Many years ago V Letokhov has suggested a laser scheme with multiple scattering at stochastic resonator [7]. In this scheme the role of reflectors and scatterers is played by high number of disordered microparticles immersed into the "claude" of active medium. When the volume gain of diffuse photons overcomes the surface losses, lasing burst will take place. In the literature, this effect is often called as "photon bomb" [11], and this scheme in whole is named as stochastic or random laser. During the recent couple of decade the interest and studies of this scheme were renewed and increased, and multiple scattering as feedback for laser action has been studied experimentally, but mainly in the visible part of spectra [8–13].

Our experiment with the NVD has recognized partial or essential trapping of hard x-rays by ensembles of nanoclusters, as well as manifestation by the interelectrode media of some features of random laser [4, 20]. The solution of the system of equations, which describes diffusion of photons, shows that the laser generation threshold may be achieved when the volume gain becomes larger than the surface losses at some ensemble volume, which is above the critical size, or at $R > R_{cr}$ in the case of sphere [7]. Perhaps, the results of the shot presented in figure 4 are rather close to this situation, i.e. remind the burst of random laser for hard x-rays (with noncoherent feedback by energy [13]). It should be underlined that this shot in the real experiment was the next one after that presented in figure 3, where all hard x-rays (with 3– 8 keV) were practically trapped. It is not excluded that for one case (figure 3) the ensemble volume was smaller than critical one, and for another case—slightly higher (figure 4). Similar examples of hard x-rays trapping and bursts were also observed for the ball-like interelectrode ensembles [20, 21], where the regimes of amplification (superradiance) [18] or generation with



Figure 4. X-rays dynamics in regime 4: (a) Oscillograms with a strong hard x-rays (~ 60 keV) burst, channels 2 and 4, for the ensemble with the volume probably exceeding critical one (random lasing apparently). Moderate neutron yields on the "wing" (channels 2 and 4) are registered also (fusion moments are registered by extra x-rays peaks on channels 1 and 4); (b) CCD image of the ensemble with a strong hard x-rays burst (compare with volume of the CCD image for the trapped hard x-rays, figure 3b). CCD exposure is in the interlaced mode here. Anode with 3 Pd tubes, pressure $P \sim 10^{-4}$ mbar.

non-resonant feedback by energy [22] are recognizing partially.

As the PIC modeling shows, perhaps, the fast ions might be the source of pumping for the active media for this system. However, for reliable conclusion on realization of hard x-rays random lasing at the NVD, the quantitive hard x-rays spectroscopy will be needed in the future experiments as well as further analysis of all complex processes. The latter ones, in particular, concern the mechanisms of hard x-rays diffuse scattering and the reflection by the external nonhomogeneous shell from the cold metal nanoclusters and nanocrystalls (of different sizes and structures with deuterium [17]), the role of the ensemble self-organization, followed by the total x-rays trapping [4,20], localization of x-rays by the chains of nano- and micro-particles reminding localization of light in low disordered structures [23,24], as well as study of other random laser specifics [24,25] for x-ray spectral region. It should be remarked that astrophysical aspects and opportunities for the random laser realizations uder natural conditions were discussed in detail in the paper [13].

4. PIC modeling of proton-boron burning

It should be reminded that the neutron-free reaction of proton– boron nuclear burning accompanied with the yield of three alpha particles $(p + B^{11} \rightarrow \alpha + {}^{8}Be^* \rightarrow 3\alpha)$ is of great fundamental and applied interest (radioactive elements are also practically absent here) [26–30]. Controlled synthesis of $p-B^{11}$ would mean, in particular, the principal possibility of establishing of a transforming source of electricity, possessing advantages over the known sources of energy [26]. Since the energy output is carried out in this scheme exclusively due to the charged particles, in principle, it enables the direct conversion of the kinetic energy of the alpha particles into electricity [27]. However, as is well known (see, for example, [29]), the implementation of the synthesis of $p-B^{11}$ requires such extreme plasma parameters that are difficult to achieve. However, attempts to achieve the required parameters are taken, and interest in the problem is growing [26–30]. Besides of hard plasma-focus attempts [26, 27], in a recent paper [28], the reaction of proton-boron has been demonstrated successfully in the interaction of the proton



Figure 5. (a) Geometry of electrodes at PIC modeling of proton-boron burning (to the left: anode—red, cathode—blue) and position of particles in the interelectrode space at the 20^{th} nanosecond (blue—electrons, red—boron ions, yellow—protons, green—erosion plasma with boron and protons); (b) Velocities of particles as a function of their position along the radius (phase portrait) of the anode–cathode geometry being studied (formation of virtual cathode (VC) in the area of $r \leq 0.1$ cm at slow-downing of the electrons, proton beams and boron ions being accelerated in the potential well to the discharge axis).

beam with laser boron plasma. Also, even higher alpha-particle yield (up to $\sim 10^9$) have been obtained under boron-proton fusion induced in boron-doped silicon target by low contrast nanosecond laser [31].

The PIC modeling using KARAT code is carried out in the axially symmetric approximation. Voltage pulse with leading front of 5 ns and amplitude of 100 kV is applied to the diode along the coaxial. Then evolutions of the voltage at the coaxial inlet and the voltage between the anode and the virtual cathode (VC) are calculated. On the part of the cathode there is provided self-consistent emission of electrons. The latter, while passing through the "translucent" anode modeled as a foil, create plasma and continue their movement towards the axis, where they are forming the virtual cathode. Boron ions and protons are accelerated in the potential well (PW) of the virtual cathode in the direction of the axis, where their density and energy of head-on collisions are increasing, which actually leads to the appearance of alpha particles. For the calculations there is used a block, in which fusion reaction $p+^{11}B$ is simulated; besides, a separate block of ⁸Be decay is used at that.

An example of simulation of discharge in the KARAT code at the current actual operating discharge parameters (U = 100 kV, I = 1 kA) is represented below. As usual, from the conical part of the cathode (electrode geometry is seen in figure 5a) there is provided self-consistent emission of electrons, which are shown as the blue dots. At the initial moment, p–B plasma is "loaded" in the area of anode foil (green area behind the end of the anode shown in red color) (hereinafter, the dots throughout the figures designate the following: blue—emitted electrons; green—plasma electrons; yellow—protons, red—boron ions B¹¹ with a charge of +3; He⁴ +2, ⁸Be^{*}, He⁴ +1 are omitted here and will be presented elsewhere [32]. figure 5a demonstrates in RZ coordinates the geometry of electrodes, forming, together with the potential well (PW) of virtual cathode, an open electrostatic trap.

The phase portrait of the particles (figure 5b) shows the process of acceleration of electrons nearly up to $V_r/c \sim 0.5$, and then their slow-downing almost on the discharge axis with formation of the virtual cathode ($V_r/c \sim 0$) and the potential well corresponding to it. Boron ions and





Figure 6. Energy of particles as a function of their position along the radius (figure 5b) (blue—electrons, red—boron ions, yellow—protons, green—erosion plasma).

0.4

particles

r(cm)

Ó

0.8

Figure 7. Potential well of the virtual cathode as possible micro-"reactor" for $p^{-11}B$ nuclear burning.

protons are drawn by the field from the green area of the erosion plasma and accelerated in the PW to the discharge axis (figure 5b). Transformation of the energy of the electron beam into the energy of boron ions and protons is well illustrated in figure 6. It can be seen that the protons, while approaching the axis of the discharge, reach the same maximum energy (figure 6) that the electrons have when approaching the anode grid provided of Pd rods (figure 5b). The energy of boron ions in the PW bottom is proportional to their charge Z = +3, as shown in figure 6, i.e. it is almost three times higher in relation to the protons (the part of boron ions are leaving the open trap and accelerating futher at A-C gap, $r \approx 0.2 - 0.3$ cm, figures 5a,6).

Meanwhile, PIC modeling have recognizing that transfer from electrodes geometry shown in figure 5a above to almost pure cylindrical geometry of cathode allows to optimize some of the key parameters of nuclear burning at NVD, for example, the shape and the deepness of potential well [32]. It should be noted that the quoted depth of the PW (figure 7) turns out to be greater than the applied voltage, and the choice of exactly such regimes using the KARAT code probably will allow increasing the synthesis efficiency at the new experiment without the need for a major increase of voltage.

Momentary position of boron ions and protons will correspond to their oscillating around the axis Z (at cylindrical geometry of cathode) in the PW (figure 8a). The changing in time energy of the isolated groups of protons and boron ions in the RZ plane is shown in figure 8b. Probabilities of $p-B^{11}$ synthesis (and alpha-particles bursts related) will be sharply increasing in certain moments of "thickening" of the trajectories of protons and boron ions (for maximum energies of individual groups during the collapse of the particles on the bottom of the potential well), which takes place at about 7, 9, 11, 13, 15, 17 and 19 nanoseconds approximately (figure 8). This operating example illustrates only the possibilities of using the KARAT code to describe and optimize the $p-B^{11}$ synthesis conditions in the potential well of the NVD on the future experiment, and the presented result allows us to be oriented in the processes, but it is still far from the optimum.

It should be reminded that the cross-section of proton-boron reaction is changing almost by thirteen orders of magnitude when the temperature of the ions in the plasma changes from 10 keV to 100 keV [33]. At the same time, in the future experiment we will be interested in the area in the vicinity of the narrow peak of $p-B^{11}$ cross-section at an energy of 148 keV (where it



Figure 8. (a) Marked groups of protons (index r) and boron ions (index y), which are oscillating at potential well around Z axis (figure 7); (b) Energy of the same groups of protons and boron ions as a function of time in the process of oscillations in potential well (within the interval 0-20 nanoseconds).

is close to the DD reaction cross-section), which is achievable in the above quoted PW even for single boron ions.

The well-known schemes of controlled thermonuclear fusion [34, 35] do not allow achieving such temperatures, while the scheme with inertial electrostatic confinement (IEC) is one of the few where such energies of ions are quite possible [36, 37]. The instructive conclusion was given at the recent 14th US-Japan Symposium on the IEC [38] by R. Hirsh, one of well-known veteran in research on thermonuclear fusion in the USA [39]. As he mentioned, it is not impossible that the practical fusion requirements "...will be most probably met by a compact and neutron-free IEC-scheme...", and "...proton-boron plasma must be non-Maxwellian..." [38].

Phase portrait for particles dynamics in cylindrical geometry is given in figure 9a. Distribution functions (DF) of proton energy are shown on figure 9b (DF for boron ions are the same ones qualitatively). Non-Maxwellian "tail" of fast particles is typical for the particles accelerated in the potential well. This tail increases Gamov factor, and defines the increasing of efficiency of nuclear burning at NVD. It should noted that the ion distribution function with non-Maxwellian "tail", presented above in figure 9b, is typical one for our PIC simulations of recent years and when used in respect of the entire physics of the IEC on the basis of the NVD [3]. Therefore, summing up the experience accumulated at this stage, we can assume that it is quite probably that the requirements of practical synthesis in the future will be really satisfied by a compact IEC scheme (in consonance with [38]), in which the proton-boron plasma will be non-Maxwellian one. However, the last word will be said by further experiments.

We will add that one of the necessary directions for further development of theoretical research in this area is numerical modeling of stimulation of nuclear reactions, as well as x-ray and alpha particle transfer with using the kinetic units of one-dimensional spherical [40, 41] and cylindrical [42–45] codes designed for simulation of physical processes in a plasma with inertial confinement.

5. Concluding remarks

In whole, the DD synthesis discussed above has been realized in the framework of warm dense matter created under the interactions of auto electron beams coming from a cathode with a deuterium-loaded Pd anode. In one case (in the second stage of discharge when virtual cathode do appear), the anode erosion and ionization of part of the deuterium atoms provide



Figure 9. (a) Velocities of particles as a function of their position along the radius) of the anode-cathode cylindrical geometry (formation of rather long virtual cathode (VC) in the area of $r \leq 0.2$ cm at deceleration of the electrons; proton beams and boron ions are accelerating in the potential well, figure 7, to the discharge axis Z for head-on collisions; protons—red, boron ions—yellow, the remaining symbols as in figure 5); (b) Local functions of proton energy distribution under higher voltage U = 150 kV (for different radii r = 0, 0.2, 0.3 cm, figure 7). Total distribution function is shown as icon inside.

for appearing of deuterons at the edge of the deep potential well. Their further acceleration by the PW and the head-on collisions at the bottom of the potential well are followed by the DD synthesis and neutron yield related. Simultaneously, the anode erosion partially provides the filling of the PW with the deuterium clusters or deuterated Pd clusters [17](dense interelectrode ensembles). Thus, in addition to the particle-particle syntheses, the channel of the DD synthesis like "deuteron–deuterium cluster" have to be considered, since the VC is located sometimes inside of a "cloud" of burning "dust" nucleated (or ejected) from the anode material (this effect still has not been included in the PIC modeling). Neutrons from very initial stage (figure 3, dashed lines) have been discussed in [2].

Meanwhile, the time of appearing of interelectrode ensembles is rather short (~ 10 ns), that allow suggest the explosive character of expansion of anode material into vacuum. Thus, coming back to our surface morphology data obtained along experiment with discharge [4], some of the craters on the Pd anode surface created at vacuum discharge (figures 17,18 in [4]) have to be interpreted as manifestation of specific anode ectons of nuclear origin (just cathode ectons, or explosive centers [46], are especially well-known and studied at present time). Underline, the large craters (~ 10 μ m) on Pd anode surface observed earlier [4] are rather similar to the same size craters registered at electron beam (energy 30 keV, current < 1 μ A) bombardment of deuterated Pd foils, where statistically significant emissions of DD-reaction products (3 MeV protons and 1 MeV tritons) was registered also [47, 48]. It is not excluded, that not only the usual anode erosion, but mass ejection assisted by anode ectons which is originated from surface DD microsynthesis provides also the creation of dense interelectrode ensembles namely. (Similar processes arising in turbulent and vortex two-phase flows containing macroparticles as well as ablation of metals have been studied intensively [49–52]). However, the available stage of study does not allow us to share properly the possible standard explosive evaporation of anode material by electron beam [46] (or any superheating effects under fast energy deposition [53]) from scenario of triggering any nuclear reactions on deuterium-loaded Pd anode surface by electron beams at the process of vacuum discharge. In the latter case, the appearing of neutrons at very initial stage of discharge and explosive fulfillment of interelectrode space by nanoclusters (similar

ones to studied at paper [17]) are correlated strongly. By the way, these small clusters with lattice structure of different kind and with hydrogen (deuterium) solubility [17] probably are playing the crucial role for Bragg x-rays reflections in our dense interelectrode nanocluster ensembles, providing partial diffusing of x-rays inside of dense ensemble as well as x-rays reflection inside by dense external cluster shells (resulting to x-rays "trapping" discussed above).

Collapses of deuterons at the PW bottom are illustrated properly by the features of neutron yield for "transparent" ensembles (figures 2,3 in [2]). The total trapping of fast deuterons observed in the experiment [4] would increase the neutron yield essentially. A related examples of a self-organized cluster ensembles were shown in figures 1b and figure 3 above. The last shot and the ensemble registered by the CCD is similar to the ensemble presented in figure 6 in [1] and manifests a high level of pulsating neutron yield also ($\sim 10^7/4\pi$). Fast deuterons and even few keV hard x-rays are trapped there, and just neutrons are leaving these sorts of interelectrode ensembles (a prototype of complex plasma microreactor). It should be noted that the appearing of collisions of fast ions with deuterium clusters target inside of the PW will increase the efficiency at the beginning, but further the growing role of this channel of the DD reaction will restrict certainly the efficiency in whole at the level of $Q_{\rm lim} \sim 0.1-0.02$ [54]. Our estimate of NVD efficiency is about $Q = 10^{-6}-10^{-4}$, which corresponds to the level of neutron yield for different regimes. Meanwhile, the fusion power density at the moments of deuterons collapse on the bottom of potential well is rather high $\sim 1-10$ MW/cm³. Qualitatively, these extremely high approximate values are in agreement with favorable scaling of fusion power density (for POPS-like systems) which increases with the inverse of virtual cathode radius [3,6].

Recent books on IEC are deep and instructive in different ways [55, 56]. The authors of early paper [57], where IEC were considered theoretically, have concluded, in particular, that "...it may be possible to produce in this way small regions of thermonuclear plasma for study". To overcome the main problem of net energy producing at IEC devices, oscillating plasmas with local thermodynamic equilibrium (LTE), referred as POPS, have been suggested by D Barnes and R Nebel [5], and further experimental studies have confirmed the existence of oscillating plasmas [6]. Both oscillating and steady-state plasmas in LTE [5] have very favorable fusion power density scaling mentioned above as a critical advantage [6,58]. Also, related energy gain calculations have recognized that net energy gain are possible [59]. However, after R Nebel and J Park left LANL to EMC2 company, unfortunately, we observe some gap in any news on POPS scheme (recent resulting paper on EMC2 activity during few past years also there is no mention of POPS [60]).

Meanwhile, first stage of our searching experiment on DD syntheses at NVD with deuteriumloaded Pd anode and the database accumulating have been started and completed at the end of last century [21,61,62]. However, more clear understanding of physical processes resulting to DD fusion at NVD experiment and our place in IEC study have appeared just after starting of broad 2D PIC modeling [1,3]. In particular, POPS-like oscillations of deuterons in potential well of virtual cathode (called as multiple fusion events in [1]) followed by pulsating neutron yield were recognized at early NVD experiments [21, 62]. Remark, it have been predicted and underlined in [6], that each next generation of POPS-like device will be smaller and more efficient. Seems that our data obtained on DD fusion at miniature NVD device are almost by chance and by independent manner turned out close to this limit on the threshold of a new century [21, 62]. Apparently, in our steady-state plasmas in NVD device (similar to one considered in [57]), the POPS-like oscillations are primarily a mechanism to resonant heat the ions rather than for coherent compressions [58] as originally envisioned for POPS [5]. Also, our system with the deep potential well satisfies the stability conditions discussed in [57, 58] since ion temperature turns out comparable to the electron injection energy (see figure 6). Stability of large-amplitude plasma oscillations in IEC devices was predicted earlier in [63]. Note, in paper [58] a systematic approach is taken in order to determine how to best inject electrons into an IEC system like

POPS or steady-state device. Concerning NVD, remind, electron injection in our discharge is going on from cathode surface to Pd tubes anode space automatically when the voltage is applied, and observed deuterons oscillations (through pulsating neutron yield [1,3]) turns out rather stable (like in figure 5b at [2] or figure 4 at [1]).

Thus, at the present moment, we may conclude that the physics of the collisional DD synthesis at small-scale low energy vacuum discharge with deuterium-loaded Pd anodes have been clarified definitely, however, strongly interdisciplinary character of study of nuclear burning at NVD is still missing the detail consideration of some essential questions. These are the nature of very fast appearing of nanocluster ensembles in A-C space, neutrons from very initial stage of discharge, self-organization of interelectrode clusters ensembles under VC formation in current-carrying NVD, general problems of Pd anode erosion, discharge stochastics and so on. On the other side, our results obtained indicate also to the real opportunity of aneutronic $p-B^{11}$ fusion in vacuum discharge, if sufficiently deep potential well (like that in figure 7) would be realized in the experiment with the NVD under slightly higher voltage than earlier [1,3,4]. Last, but not the least, both the study of hard x-ray random laser [20] and looking for potential opportunities of the laboratory astrophysics [64] based on the strong hard x-rays bursts modeling of some astrophysical phenomena [13] are just at the beginning.

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