Nuclear burning in a compact scheme of inertial electrostatic confinement as imitation of stellar nucleosynthesis. Experiment and PIC modeling

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Abstract. DD neutrons from microfusion in the interelectrode space of a table-top low energy nanosecond vacuum discharge with a deuterium-loaded Pd anode have been demonstrated earlier. The detailed particle-in-cell (PIC) simulation of the discharge experimental conditions have been developed using a fully electrodynamic code. The principal role of a virtual cathode and the corresponding deep potential well (PW) formed in the interelectrode space are recognized. The PIC modeling has allowed identifying the scheme of small-scale experiment with a rather old branch of plasma physics as inertial electrostatic confinement fusion. Deuterons being trapped by this well are accelerating up to the energies of a few tens of keV that provides the DD nuclear synthesis under head-on collisions. Meanwhile, any ions of other elements like He, C, O, Si (as main elements of different shells of stars) being placed in the PW (even with low $Z$ charges) have to be accelerated easily up to the head-on collisions energies, which are corresponding to the temperatures of ignition $T_{ign}$ for different shells. We conclude that hypothesis on some imitation of different stages of stellar nucleosynthesis by nuclear burning in the potential well of virtual cathode in vacuum discharge seems to be reasonable and stimulating in the future study of complex element burning including advanced fuel like p–B$^{11}$.

1. Introduction

This paper is related to the study of nuclear burning in a compact scheme of inertial electrostatic confinement (IEC) based on nanosecond vacuum discharge (NVD). This branch of fusion studies in the inertial confinement is alternative one to the hydrodynamic compression of matter at spherical target under pulse sources of energy such as laser or heavy ions beam [1–3]. Laser–target interactions, particle beam–target interactions, shock waves, high pressure and other studies of warm dense matter at large and medium scale facilities (see, for instance, [4, 5]) are supplemented successfully by small-scale experiments. For example, table-top experiments using femtosecond laser irradiation of clouds of clusters [6, 7] have demonstrated how x-rays, fast ions, and even neutrons can be generated. Apart from that, different states of matter under unusual conditions have been realized also during the study of the physics of vacuum discharges, where an extensive and various experience has been accumulated [8–11]. In fact, the solid density electrodes, vacuum environment, and fast and local energy deposition provide the framework to create and study high power density matter as well. For example, there are many ways to

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concentrate energy up to $10^4$ J/g in microscopic volumes of a cathode. These concentrations of energy result in microscopic explosions accompanied by emission of electrons, creating plasma, liquid droplets of metal and metal vapor [10,11].

The energetic ions and DD neutrons from microfusion in the interelectrode space of a low energy nanosecond vacuum discharge have been demonstrated recently [12–15]. The efficiency of hard x-rays and fast ions generation by nanosecond vacuum discharge, as well as the neutron generation, turned out to be higher than those for exciting experiments on the DD fusion driven by Coulomb explosion of laser irradiated deuterium clusters [6,7]. To understand better the physics of fusion processes, the detailed particle-in-cell (PIC) simulation of the discharge experimental conditions have been developed using a fully electrodynamic code. The principal role of a virtual cathode (VC) and the corresponding single and double potential well (PW) formed in the interelectrode space were recognised. The calculated depth of the quasistationary potential well (PW) of the VC is about 50–60 kV, and the deuterons being trapped by this well are accelerating there. Correspondingly, head-on collisions of deuterons with energies of a few tens of keV are followed by the DD nuclear synthesis, transforming the anode–cathode (A–C) interelectrode space into something like a fusion microreactor chamber. The PIC modeling allows the identification of the small-scale experiment [12–15] with a rather old branch of plasma physics, as inertial electrostatic confinement fusion (IECF) (see [16–27] and refs therein). Pioneers of the IECF were O Lavrent’ev [16,17,28] in the USSR and F Farnsworth in the USA (see [18,19,27] and ref. therein), but due to different reasons, including a rather low value for efficiency $Q = E_{\text{fusion}}/E_{\text{input}} \sim 10^{-8}$ or even less, this concept regarding fusion was almost forgotten. Just a couple of decades ago, interest in the IECF, mainly as in a simple source of neutrons, was renewed in the US and Japan [20–26]. Nowadays, a broad spectrum of research findings on the electrostatic confinement fusion is presented usually at the regular US–Japan workshops on the IEC (see, for example [26] and recent book [27]). Furthermore, some modern experimental set-ups being under study and construction at the LANL and other places provide new expectations to get $Q > 1$ [22–24] (as a minimum in theory [25]).

It should be reminded that the source of D$^+$ ions for the DD synthesis in the PW of NVD is the erosion anode plasma or, more accurately, warm dense matter from deuterium-loaded Pd anode, created by electron beams in the discharge at the anode within $\sim$10 ns when the voltage applied. The physics of the DD synthesis in the potential well of virtual cathode is clarified in principle, in particular, due to the PIC simulations [14]. The very initial stage of discharge (1–3 ns), when the electron beam extracted from the cathode just comes to the anode and starts to interact with the deuterium-loaded Pd, is still not investigated properly. Meanwhile, besides of the DD collisional fusion, the opportunity of burning of different complex elements in the PW is not obvious and still not studied properly also.

The paper is organized as follows. The experiment on the DD synthesis in the nanosecond vacuum discharge of low energy is described briefly in section 2. The main physical results of the PIC modeling of the experimental conditions are given in section 3. Some particular specifics of the neutron yield observed at the nanosecond vacuum discharge are considered in section 4. The features of burning of complex elements and relationship with stellar nucleosynthesis are discussed in section 5. Section 6 relates to the discussion and some concluding remarks.

2. Experimental set-up. DD microfusion and neutron yield

The source of complex plasma (figure 1) consists of a cylindrical vacuum chamber with a diameter of 50 mm, which has three windows covered by a 70 µm Mylar film. The chamber is connected to a vacuum pump (to $10^{-6}–10^{-7}$ mbar) continuously operating during a series of discharges. Two electrodes are situated on one axis: a cylindrical anode and a hollow cathode of different shape. The effective distance between the electrodes varies with a step of 0.1 mm in a range of 2–7 mm. The source includes a coaxial high voltage cable (with an impedance of 50 Ω) connected
Figure 1. (a) Schematic of the experiment for generating interelectrode complex plasma ensembles with nuclear burning: MG—Marx generator, RC—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 dense self-organized interelectrode ensemble with trapped fast ions and partially diffused x-rays (see [29]).

Figure 2. X-ray dynamics in regime 1: (a) x-ray CCD image for the transparent low density interelectrode ensemble with DD fusion accompanied by a moderate neutron yield; (b) Extra x-ray spark in channel 4—manifestation of the beginning of nuclear reactions (sensitivity of channels 4, 2 is 250 mV; time scale is 40 ns/div). The delay of the neutron peak in channel 2 corresponds to ≈46.6 ns/m (or 2.45 MeV neutrons due to the DD fusion).

to the four-step Marx generator sending a 50 ns pulse with a voltage of 70 kV to a load of 50 Ω. Commonly, the current comes up to 1 kA. Three Mylar windows provide for measuring x-rays in three perpendicular directions (in the plane approximately coinciding with the anode edge, figure 1a). Another window and/or time of flight (TOF) tube provide measuring through the edge of the hollow cathode (along cylindrical axis Z, figure 1a). Calibrated PIN diodes with a signal buildup rate from 1 to 2 ns were used for measuring x-ray yield. X-ray CCD images of the interelectrode ensembles were recorded through a pinhole aperture (smaller than 0.1 mm) made in a 1 mm thick lead plate. An Al foil with a thickness of less than 100 µm covered the aperture for recording hard x-rays only.
Generation of 2.45 MeV neutrons due to the DD syntheses reactions at the interelectrodes x-ray ensembles (similar to those shown in figures 2a and 3a) was observed in the experiments with a modified Cu–Pd anode deuterated by electrolysis in heavy water (6 h at 100 mA) [14,15]. We recall that channels 1 and 3 (see figure 1) measure the x-ray intensity with a maximum sensitivity within the range of 5–15 keV. Harder x-rays (>60 keV) were usually recorded using a photomultiplier PM(2) covered with a 2 mm Cu absorber. Time of flight (TOF) measurements of the DD neutron yield were performed using PM(4) and PM(2) (with scintillators) (see figure 1) situated on the same axis Z as the electrodes at the maximum distances of $L_4 = 45$ cm and $L_2 = 50–90$ cm, respectively (channels 4 and 2 on the oscillograms similar to those shown in figure 2b, $L_2 = 80$ cm). It should be underlined that the PM(2) and PM(4) signals are always delayed electronically 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). Along with the common hard x-rays, mainly bremsstrahlung x-rays (first broad peak in channel 2) due to passing of autoelectron beams through the cluster ensembles, PM(2) also records a well reproducible signal (second weak peak) with a delay of about 46.6 ns/m from the fusion moment fixed by PM(4) as well as by the PIN diode at channel 3 (figure 2b). This is a typical picture (“signature”) for 2.45 MeV neutrons from the DD fusion. Photomultiplier PM(4) records the instant of the DD reaction as a reference time (it should be reminded that in real time it coincides with the kink of the PIN diode signal, as it can be seen in figure 2b, channel 3). The second small peak in the scintillator in front of PM(2) corresponds to the neutron yield of the reaction $D + D = n + ^4$He (see figure 2b). The change of the distance between the plasma source and PM(2) (longer or shorter) is accompanied by the corresponding time shift of the second (neutron) peak (to the right or left, correspondingly). The next shot with rather similar features of the above described oscillograms is shown in figure 3 (see section 4 also). The CR-39 plates were used simultaneously with the TOF scheme as well. The plate processing gave a varying number of tracks depending on the number of shots [12,13].

In fact, a typical example from the x-rays data base of images of interelectrodes aerosols dusty matter with lower neutron yield of $10^3/4\pi$ (and rather low total x-ray yield) is shown in figure 2a. Namely, rather low x-ray yield allows us to register more accurately the moment of microfusion events. The next example of interelectrode ensemble with slightly more dense x-ray images is shown in figure 3 (specifics of the initial stage of this regime are discussed at the end of section 3). The value of the neutron yield from the random interelectrode media is variable, and turns out to be about $10^3/4\pi$ per shot for the “transparent” CCD ensembles (like those presented in figures 2a, 3a) and up to $\sim10^7/4\pi$ (assuming isotropic yield) for rather dense and partially self-organised interelectrode ensembles (like those in figure 1b above or figure 6a in [12] and figure 7b in [14]) at $\approx1$ J of total energy deposited to create all the discharge processes at the single shot.

3. PIC simulations. Virtual cathode and potential well formation

The complex physics of nanosecond discharge processes and the mechanisms of microfusion were poorly understood, and motivated the interest in complementary PIC (particle-in-cell) KARAT simulations [14,30]. In addition to representing the key points of the general physical picture, computer modelling allows clarification of the details of the experimental data. To explain the nature of fusion in the experiments with nanosecond vacuum discharge [12–14], just a limited number of PIC 2D calculations results are presented and discussed below. First, the discharge geometry and particle dynamics are shown in figure 4a. Next, figure 4b represents a phase portrait, and demonstrates the appearance of the VC. An example of the PW related with the VC is shown in figure 5a (the present PIC simulation performed for voltage applied $U = 100$ kV, meanwhile the results of the PIC modeling for experimental value $U = 70$ kV [14,15] qualitatively are the same ones). For the PIC calculations, anode Pd tubes were modeled by a
Figure 3. X-ray dynamics in regime 2: (a) x-ray CCD image for the low density interelectrode ensemble with the DD fusion accompanied by neutron yield; (b) Extra x-ray spark in channel 4—manifestation of the beginning of nuclear reaction (sensitivity of channels 4, 2 is 250 mV; time scale is 40 ns/div). The delay of the neutron peak in channel 2 corresponds to approximately 46.6 ns/m (or 2.45 MeV neutrons due to the DD fusion). The dotted lines correspond to the initial stage of discharge (see sections 4 and 6).

The PIC modeling shows that the area of Z and R at the half-width of the PW contains in the experiment almost isotropic distribution of fast ions with mean energy of about 25–30 keV [14]. The system of Pd tubes is open and allows to run away from the PW for some of ions along axis Z (figure 4a). The PIC simulations allow providing the optimization of the electrodes geometry, as well as testing new geometries. Looking at the calculated energy of electrons and ions as function of their radii positions [15], we may underline that A–C geometry chosen in the experiment is an efficient way to transform the energy of the electron beams into the energy of fast ions of the same value, but in another part of the interelectrode space.

The PIC simulations have assisted in understanding some effects observed in the experiments.
earlier [12,13]. For example, the shapes of some PIC non-Maxwellian distribution functions are in correlation with a “plateau” in histograms for the fast ions tracks observed in the experiments (see figure 8 in [12, 13]). Another example is the double potential wells at the first stage of discharge obtained during the PIC simulations. It looks very probable that the appearance of double wells might explain the double neutron peak observed sometimes in the experiment (as in figure 5 [14]). We can see that the PW lifetime in the experiment is about \( T_{PW} \approx 20 - 25 \) ns, and after that the VC has to be neutralized by the flux of ions. Since the total pulse \( T_{pulse} \) of voltage is about 50 ns, there are sufficient conditions for the VC appearing in the experiments again \( (I_A > I_L) \), and a new double PW will appear \( (T_{pulse} > T_{PW} \gg \omega_{pi}^{-1}) \). Ion collisions in this PW will be manifested by a second double neutron peak like have been registered earlier (see figure 5 in [14]). It should be noted that the appearance of single-, double-, and multiple PWs and non-Maxwellian distributions of ions are typical features of the systems with the IECF [32].

The model of collective ion acceleration [33] at a vacuum discharge, based on the concept of nonstationary potential wells (PW) before the front of the cathode flare in the regimes of non-stable current carrying, was developed earlier [34]. On the basis of this model the explanations were given for the early experimental data [35, 36] on occasional anomalous ions acceleration. Our results of the PIC simulations for real electrodes geometry and vacuum discharge conditions of the experiment [12, 13] using electrodynamic KARAT code [14, 37] have recognized that the concept of PW is more universal and represents the basis for the IEC fusion reactor: namely, a quasistationary PW in the interelectrode space with depth of up to \( \sim 80\% \) of the applied voltage provides for radial electrostatic acceleration of ions up to the same energies. Correspondingly, head-on collisions of ions at the axis with energies of a few tens of keV are followed by the DD
nuclear synthesis, transforming the interelectrode space into the reactor chamber.

4. Pulsating neutron yield. Neutrons at the very initial stage

Coming back to the experiment, next possible feature of neutron yield is illustrated by the shot presented in figure 5b. The CCD image for this shot (see [15]) is very similar to that presented in figure 3b, but the oscillograms manifest an essential pulsating neutron yield (channel 2, PM2, L_2 = 50 cm, sensitivity of 100 mV, figure 5b). Correspondent extra x-rays due to each DD fusion event are registered as fractures both at the PIN diode (channel 3) and PM4 signals of hard x-rays intensity (the right parts of these x-ray intensity curves are modulated by the same moments of fusion with a delay of ≈35 ns in comparison with the instant diodes signals, chs 1,3). The intensity of the neutron peaks registered is weakened partially due to a possible reflection from the 2 mm Pb absorber located in front of PM2.

As shown in [34], the time taken to form the VC and PW (or the decay time of potential) is about $T_{PW} \approx C_d U/I_L$, where $C_d$ is the diode gap capacitance and $U$ is the potential. Since $I_L \sim U^{3/2}/d_{eff}^2$, then variation of $d_{eff}$ in our experiment [12,14] changes $I_L$ and, correspondingly, the value $T_{PW}$ ($d_{eff}$ is the effective interelectrode distance for non-planar electrodes) [31]. Thus, at rather large $d_{eff}$ we have $T_{PW} \approx T_{pulse}$, and just a single peak will be observed in experiments (like in figures 2,3 above). Decreasing $d_{eff}$ increases $I_L$ and lowers $T_{PW}$, and step by step at decreasing of $T_{PW} < T_{pulse}$ we get double, and multiple neutron yields (like in figure 5b). It should be reminded that the typical hierarchy of related times at TOF measurements of the DD neutrons both for the oscillograms in figures 2b, 3b and for multiple fusion events (MFE, figure 5b) [12,13] for particular fusion moment contains usually: the instant signal from ch.1 or ch.3 at the fusion moment $t_f$; next, electronically delayed signal at ch.4, $t_f + 35$ ns; and time of flight delayed neutron signal at ch.2, $t_f + 35$ ns + $t_{TOF}$, correspondingly [12–15].

The pulsating neutron yield regime (figure 5b) due to the periodic collapses of deuteron at the PW bottom (during their oscillations in the PW, $T_{PW} \ll T_{pulse}$) is suggestive of the interesting and stimulating conception of periodically oscillating plasma spheres (POPS), developed earlier in theory and in the experiment [20–24]. It was suggested to abandon the standard scheme of the IECF, where particular ion beams interact with each other, and use in addition the injection of electrons into the grids (in order to get a uniform electron background inside of the cathode.
Ions then will undergo radial harmonic oscillations with any amplitude in the potential well formed, and at the moments when maximal compression high fusion power density will be provided.

Generally speaking, the POPS are particular and well-defined cases or analogs of the multiple fusion events (MFE) [12, 13] at vacuum discharge. At the present moment, in spite of the POPS attractiveness and demonstration in principle (just for He\(^{+}\), Ne\(^{+}\) and H\(_{2}\)\(^{+}\) ions), the PW depth reported is still \(\leq 1\) keV, and the POPS frequency comes to \(\nu_{\text{POPS}} \leq 1\) MHz (the applications, economy, and limitations are discussed in details in [22–24]). In our experiment with vacuum discharge with deuterated Pd anode we have PW depth of 50–60 kV namely for deuterons, and frequency of deuteron oscillations \(\nu_{\text{MFE}} \approx 80\) MHz (analog of \(\nu_{\text{POPS}}\)) with accompanied pulsating DD neutrons yield.

Moreover, instead of special injections of electrons into a spherical device to produce a VC as in [22–24], nanosecond vacuum discharge with hollow cathode provides itself (after voltage is applied) an automatic extraction of electron beams from the cathode surface and their further acceleration and converging injection into the anode area on the axis to form a VC (figure 4). By analogy with the POPS expressions, we may estimate the fusion power \(P_{\text{fusion}} \sim \varphi^2 \theta^2 f^2 < \sigma v > l/2\pi e^2 r^2_{\text{VC}}\) at the volume of nuclear burning for a reactor with cylindrical geometry, where \(\varphi\) is the well depth, \(\theta\) is the radial ion plasma compression ratio \(r_{\text{max}}/r_{\text{min}}\), \(f = n_i/n_e\), \(r_{\text{VC}}\) is the radius of VC, \(<\sigma v>\) is the averaged cross-section, and \(l\) is the length of the cylinder (here \(P_{\text{fusion}}\) is the total power integrated over a single period [20, 21]). Assuming that \(\varphi \approx 60\) kV and \(r_{\text{VC}} \approx 0.1\) cm, as well as \(f^2 \sim 1\), \(\theta \leq 10^3\), \(l \approx 0.5\) cm, we get the yield of \(\sim 10^5\) neutrons for a single collapse of deuterons at the discharge axis (or for one period of deuterons oscillations). Thus, specific advantage of the IECF systems like the POPS, as have been noticed earlier in [22–24], or the MFE [12, 13] is the favorable scaling of fusion power density (with decreasing set-up size), which is increased with decreasing of \(r_{\text{VC}}\) and increasing of the PW depth [15].

The PIC modeling of particle dynamics and processes in vacuum discharge shows qualitatively, in particular, what is going there during the first 1–2 ns after voltage applying. During this time the electron beam extracted from the cathode is reaching the deuterium-loaded anode and starts to interact with the Pd surface. In comparison with the later on processes of virtual cathode and potential well formation, this relatively fast initial stage of discharge in our experiment is still poorly understood. In whole, the essential part of the oscillograms from the database accumulated contains the specific and correlated in time TOF peaks (figure 3b) yet before the main x-rays burst [15]. Thus, it seems that the beginning of the interaction of the electron beams with the Pd anode loaded with deuterium is possible to be connected with appearing of some indicators of the DD synthesis (see figure 3 above and figure 3a below [29], dashed lines). We may conclude from the detailed TOF analysis of the available experimental data that the initial stage of discharge may be also accompanied by a certain neutron yield, which is changing in a more random manner from shot to shot in comparison with the yield from synthesis in the PW at the second stage of the discharge. There is still no obvious answer to the question about mechanism of the DD synthesis at the initial stage of the discharge (some of the qualitative explanations are discussed in [15]).

It should be remarked that the palladium-hydrogen (deuterium) systems themselves are interesting both from fundamental and applied points of view, in particular, as the systems that could be utilized for energy storage (surfaces, nanocrystals, vacancy- and dislocation-rich materials, thin films, multilayers, and clusters as the systems of major interest are addressed in the review [38]). Small angle neutron scattering measurements of deuterium dislocation trapping in Pd have recognized rod-like trapping geometry [39], as well as the fact that the dislocations in the H(D)-cycled Pd can absorb large amount of hydrogen (deuterium) [40]. Anomalies in the electron transport and magnetic properties in a deformed loaded Pd foil were interpreted in...
terms of filamentary superconductivity attributed with the condensation of the trapped hydrogen (deuterium) into a metallic-like phase ($\sim 10^{24}$ cm$^{-3}$) within the dislocation core [41]. (This metallic phase has been also predicted [42]). Spectra of collective excitations at deuterium-loaded Pd were considered in [43], and have shown that excitation of the hydrogen subsystem as a result of the electron bombardment is specified by the generation of plasmons in the crystalline lattice, which are localized in the vicinity of hydrogen (deuterium) atoms. Further, very recent studies of dense hydrogen have shown that even ultra-dense material may exist, called ultra-dense deuterium (with the bound DD distance of 2.3 pm, corresponding to density $\sim 8 \times 10^{28}$ cm$^{-3}$, which was estimated directly from the experiment [44, 45]). The possibility of the DD fusion under relatively weak laser beam was investigated, and time-of-flight (TOF) particles detection recognized all particles expected from the DD synthesis [44, 45]. The lattice assisting nuclear reactions and the key role of the effective screening potential (as a factor of intensification of the DD reaction) are discussed also [46–48]. In particular, the transparency of the Coulomb barrier is $\text{Pd}/\text{D}_2 > 10^{50}$ for deuterium atoms (just in the states 2p, 3p or higher) that are in the same crystallographic niche of Pd lattice filled with free conduction electrons as the corresponding value of free deuterium molecules [48]. In this case, the discharge process of releasing nuclear energy of 24 MeV in the almost aneutronic reaction $\text{DD} \rightarrow \text{^4He}^*$ might be performed with the consequent release of virtual photons [48].

Thus, we may assume that the latter few examples imply that new results and ideas might be also relevant to possible triggering of the lattice-assisted DD reactions under irradiation of deuterium-loaded Pd anode surface by auto electron beams at the initial stage of vacuum discharge [15]. However, we are just at the beginning of the study of these phenomena.

5. Nuclear burning at potential well of virtual cathode as imitation of stellar nucleosynthesis

Generally speaking, apart from the deuterons acceleration, the potential well (like presented above in figure 5a) is a tool to accelerate any kind of ions of complex elements. We may suggest that collisional nuclear synthesis for ions of complex elements at the depth of the PW have to be followed by generation of new elements, and their ions, in turns, again have to be captured and accelerated by the PW being the fuel for the next stage of nuclear burning to produce heavier elements, and so on. However, the hypothesis that nuclear burning in the deep potential well of virtual cathode at vacuum discharge might imitate the role of gravity at stellar nucleosynthesis needs an experimental verification.

Earlier, the analysis of surface morphology of Pd anodes used in the experiments with the nanosecond vacuum discharge has been started [15]. Further analysis of the Pd anode used in the experiment was performed at the next stage of the study; in particular, we would like to clarify the component contents of different parts of the anode surface along the Pd tubes. The anode with three Pd tubes with marked particular areas (1–6) along the tube chosen for analysing is shown in figure 6a.

The part of the surface from area 1 (at the end of the tube) is presented in more detail in figure 6b. The spectra of characteristic emission from different parts of this surface (figure 6b) obtained under irradiation by electron beam with energy of 30 keV are shown in figure 6c. The total area of each peak in figure 6c is proportional to the number of atoms of particular element. As we see from figure 6c, at the area of point 1 (figure 6b) we have almost pure Palladium. At the area of point 2, inside of deep pore, the elements C, O, Na, Mg, Al, Si, S, Cl, K, Ca have appeared. At the area of point 3, figure 6b (intermediate between the pore and well-defined Pd surface), the same elements are available like in the pore, but in lower quantities. We may conclude that on the electrode surface all the elements are accumulating inside of the deep pores mainly. For area 6 (figure 6a), we observe qualitatively the same relation of elements content in the pores and beyond the pores as for area 1 (both these areas are irradiated essentially by
auto electron beams along the discharge). At areas 3 and 4 the elements content inside of the pores and beyond them is practically the same.

Thus, the question arises: does there a generation of new elements take place along the experimental shots at the vacuum discharge with potential well, or do we observe just the result of accumulating of some impurities in the pores from any discharge camera parts, electrode materials, and so on. It should be reminded that we have analyzed above the anode with three Pd tubes (“triple” anode, figure 6a), which have been used at discharge widely under regular deuteration of this anode by electrolysis at heavy water. The analysis has been continued for other electrodes and for different regimes of their work at the discharge. It has been recognized, in particular, that appearing of new light elements in the pores takes place just under sufficient filling the Pd anode with deuterium.

In fact, for the second Pd anode with the same geometry but under much lower average concentration of deuterium, the spectra of characteristic emission from different parts of the Pd tubes surface (in the pore or beyond the pore) turned out to be very similar to each other (not shown here). The average concentration of deuterium in this anode was no fewer than two orders of magnitude less in the Pd tubes due to much higher number of shots after standard single charge of Pd anode by deuterium. Thus, the element content inside the pores and beyond them in any parts of the Pd tube for the second anode turns out to be practically the same (like in areas 3 and 4 for the first anode presented in figure 6a above). In other words, new elements are not appearing along the discharge shots without proper filling of the Pd tubes with deuterium, although all the details of camera construction and electrodes (as possible potential sources of impurities) were the same ones. Also, no generation of new elements were observed under the shots with the new anodes which were still not loaded with deuterium.

Furthermore, we may compare the element contents of the surface of the Cu edge of the anode basis (where deuterating Pd tubes were attached) “before” (figure 7a) and “after” (figure 7b) curtain number of shots with generation of DD neutrons. We see that for the second case the concentration of C and O has been increased essentially. Apart from that, new peaks of Si and S have appeared (figure 7b), in particular, with prevailing of Si isotopes (the latter one needs further detailed study). Thus, along the discharge shots we observe appearing of particular peaks growing by intensity at spectra of characteristic x-rays emission. These peaks are associated with appearing of new elements during the nuclear burning in the potential well. It should be remarked that these elements might be originated not only from the initial deuterium in the Pd tubes, but, generally speaking, with involving of some available impurities of C and O into the burning in the PW also.

Elements content of Al cathode surface has been also studied. As an example, the spectrum of characteristic x-ray emission from the middle of conical edge of cathode is shown in figure 8. Apart from C, O, Na, Mg, Al, Si, S, Cl, K, and Ca at different areas of cathode surface, there were found also Pd, Cu, Zn, Fe and Mn in different proportions. The main material of cathode, Aluminum, is prevailed (> 96%). The appearing of Cu (up to 2–3%) and Zn (up to 0.1%) is apparently associated with the copper anode basis, where the Pd tubes were attached. Of a separate interest is an experimental fact that ratio Mn/Fe is changing noticeably at different cathode areas, nevertheless being everywhere as Mn/Fe > 1. It should be noted that the cathode itself represents in whole something like the diagnostic tool or container for the products of nuclear burning in the deep PW. At the cathode edge we have 1.28% of Mn, and 0.98% of Fe.

Ratio Mn/Fe at different parts of cathode is up to 3 or more, and at particular places on the cathode surface we observed just small “ice lands” of Mn. We may suggest that ratio Mn/Fe > 1 observed for all parts of the cathode surface might be explained by capture of the DD neutrons with energy of 2.45 MeV by iron, i.e Fe(n,p)Mn reaction, along the large number of the discharge shots. Cross-section for this reaction becomes noticeable at neutron energies of \(\sim 1\) MeV or higher [49].
Figure 6. (a) SEM picture of “triple” Pd anode at elastically reflected electrons; (b) Shown in more details area 1 (from figure 6a) from the anode surface chosen for analysis of the component content. The analysis took place at points 1,2,3 from square of 1×1 microns; (c) Spectra of characteristic x-rays emission from points 1,2,3 (on figure 6b). Number of color lines corresponds to the numbers of point investigated.

In whole, taking into account all the experimental data obtained (including the generation of many light elements), we may assume that the deep potential well of virtual cathode at nanosecond vacuum discharge (as microreactor for collisional nuclear synthesis) reproduces or
imitates in some sense the role of gravitation at stellar nucleosynthesis, which provides shell by shell nuclear burning of different elements [50]. In fact, evolving stars build up nuclear ash of increasing atomic weight in their cores. If the temperature becomes high enough, $T_{\text{ignition}}$, the ash formed by the last burning stage becomes the fuel for the subsequent stage of evolution, and so on. It should be reminded that schematically cross-section of the star looks like an “onion”, consisted from the shells of different elements, and each shell, starting from the first external one, is the nuclear fuel for creation (by products of burning) of the next interior shell, and so on. In particular, the following sequence for stellar nucleosynthesis in massive stars takes place [50]: fuel H $\rightarrow$ main product He ($T_{\text{ignition}} \sim 1$ keV), further, He $\rightarrow$ (O,C) ($T_{\text{ignition}} \sim 10$ keV), C $\rightarrow$ (Ne,Mg) ($T_{\text{ignition}} \sim 40$–70 keV), Ne $\rightarrow$ (O,Mg), O $\rightarrow$ (Si,S) ($T_{\text{ignition}} \sim 140$–200 keV), Si $\rightarrow$ Fe ($T_{\text{ignition}} \sim 300$–500 keV) [50]. Let us compare the temperatures of ignition presented above for different elements with the energies of head-on colliding ions, accelerated in a potential well with the depth of, for example, about $U \sim 100$ kV (like in figure 5a). We conclude, that any ions of elements like He, C, O, Si (as main elements of different shells of the stars) being placed in the PW as presented in figure 5a (even with low charges $Z = +2$ to $+4$) have to be accelerated rather easily up to the head-on collisions energies, which correspond approximately to the temperatures of their ignition for different shells [50] (it should be reminded that the energy of ions at the depth of the PW will be $\sim ZU$ [34]).

6. Discussion and concluding remarks

Thus, at the present moment, we may conclude that 2.45 MeV neutrons have been observed at the time-of-flight study from the DD synthesis, which is realized probably by different manner at the initial and stationary stages of nanosecond vacuum discharge within just 50 ns [12–15]. Remark, the shape of the typical peak of extra x-rays at fusion moment (figure 2a, channel 4) and the shape of neutron peak (channel 2) are not occasional ones. This is a signature of available physics of fusion in our device—the collapse of fast deuterons at the potential well bottom (case $T_{\text{PW}} \approx T_{\text{pulse}}$). If to decrease efficient anode-cathode distance in experiment we will get $T_{\text{PW}} \ll T_{\text{pulse}}$ regime [14] and periodically collapsing deuterons at PW with corresponding pulsating neutron yield (figure 5b). The physics of the collisional DD synthesis at small-scale low energy vacuum discharge with deuterium-loaded Pd anodes have been clarified definitely, but the number of questions answered does produce new ones. In particular, nuclear burning with generation of light elements in a potential well of vacuum discharge, registered experimentally, needs further studying and corresponding computer modelling. On the other side, our results obtained indicate a real opportunity of aneutronic p-B$^{11}$ fusion at vacuum discharge as well [29].
Figure 8. Spectrum of characteristic x-ray emission from the middle of the conical edge of Al cathode after the number of shots in vacuum discharge with the DD synthesis.

If sufficiently deep potential well (like in figure 5a) would be realized at experiment with the NVD under slightly higher voltage than in [12, 13, 51]. Also, the processes of homogeneous condensation during the expansion of a metal vapors in vacuum, the formation of clusters, solid nanoparticles and so on [52–54] at interelectrode space deserves special study.

The physics of the very initial stage at the beginning of e-beam interaction with deuterium-loaded Pd anode and mechanisms of the DD synthesis observed (figure 3b, dashed line) are not as clear as for the stage of the VC and PW formation, described in detail by the PIC simulations. Meanwhile, namely during the recent few years, the special interest to the systems like “electron beam–deuterium loaded Pd” has been increased and some experimental data and related models have appeared. In particular, the model of stimulation of DD reaction by electron beams at loaded Pd surface has been developed [43]. Nevertheless, well-defined experiments related represent the main interest. In particular, statistically significant emissions of the DD-reaction products (3 MeV protons and 1 MeV tritons), as well as high energy alpha particles have been registered under electron beam stimulation of the D-desorption from Pd/PdO:Dx targets [47, 55]. Electron beam (energy 30 keV, current < 1 µA) bombardment is accompanied by formation of numerical pores (from Pd through the PdO) with diameters in the range of 100–2000 nm, while the surface that has not been subjected to the e-beam bombardment shows smooth PdO structure. It should be underlined that no larger pores (> 350 nm) or craters have been found in the reference Pd/PdO:Hx samples after the electron beam. Hopefully also that the lattice assisting the nuclear reactions models, taking into account the effective screening potential as a factor of intensification of the DD reaction [46–48], will be developed further up to the self-consistent stage. One should say, an important direction for further theoretical research related is numerical modeling of nuclear reaction stimulation in the considered system, having the properties of inertial confinement. Such simulations can be performed, for example, using one-dimensional [56–60] or two-dimensional (axis-symmetry) codes for the modeling of physical processes in the cylindrical geometry of the plasma with inertial confinement.

The energy-generation mechanisms in the stellar interiors (mentioned briefly in section 5 above) give a satisfactory general picture for the formation of most light elements, starting from hydrogen. This picture agrees rather well with the observed high relative abundances of these elements that it appears to be substantially correct. However, many details still
remain to be sorted out [50]. It is clear that nuclear burning in a potential well is not able to reproduce any extremely complicated and developed chains of burning processes during the stellar nucleosynthesis. Moreover, remind we have vacuum and nanoseconds in experiment instead of extremely high pressures and billion years in real stars. Nevertheless, starting from deuterium (loaded into Pd anode), the experiment with the NVD recognizes the appearing of main set of light elements, i.e. imitates the results of stellar nucleosynthesis. Iron-group formation from the products of O$^{16}$ burning (silicon burning) is a very complex stage of stellar nucleosynthesis [50]. So, the appearing of iron on cathode edge is still not clear at the laboratory experiment, although further capture of DD neutrons by Fe with generation of Mn (observed at the experiment, figure 8) looks rather probable. Anyway, the hypothesis regarding imitation of some stages of stellar nucleosynthesis by the nuclear burning in a potential well of virtual cathode in vacuum discharge (presented and discussed preliminary earlier in [61]) seems to be useful and stimulating in the future. Meanwhile, it should be developed and tested by further experiments as well as by the PIC modeling of nuclear burning of complex elements in the deep potential well of virtual cathode at vacuum discharge [29].

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