On pulsating DD neutron yield under inertial electrostatic confinement of complex plasma at miniature vacuum discharge

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Abstract. We continue to analyze the effects of deuteron oscillations in potential well of a virtual cathode under inertial electrostatic confinement based on nanosecond vacuum discharge. The goal of this paper is to present and discuss in detail available experimental results on pulsating DD neutron yield at this scheme. Also, the results of simulations for virtual cathodes and potential wells for particular experimental regimes of neutron yields are shown and discussed, as well as comparison with available similar scheme of periodical oscillating plasmas spheres for fusion.

1. Introduction

Inertial electrostatic confinement (IEC) was the very first approach in the long list of options, which were proposed and developed to solve the open until now problem of controlled fusion [1–3]. IEC schemes for fusion devices are studying starting from the beginnings of the fifties of last century both theoretically and experimentally [4]. Pioneers of the IEC were O Lavrent’ev [5–7] in the USSR and F Farnsworth in the USA (see [4,8,9] and references therein). However, 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 not developed properly. Just a couple of decades ago, interest in the IEC, mainly as in a simple source of neutrons, was renewed [10–16]. 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 [16] and recent book [4]).

The underlying problem is that for nonthermal systems like in IEC scheme, the Coulomb scattering cross sections are significantly larger than the fusion cross sections. Thus, it can take more energy to maintain the nonthermal distributions than the device produces in fusion power. More complete theoretical study (than initial ones based on the simple analytic models [17,18]) have indicated that if the ion distributions are close enough to thermal ones, net energy gains are possible, although the fusion power densities are small [15]. Oscillating plasmas close to thermal equilibrium were suggested as a possible fusion scheme in the theory [10,11]. A tiny oscillating ion cloud referred to as the periodically oscillating plasma sphere, or POPS, may undergo a self-similar collapse in a harmonic-oscillator potential formed by uniform electron background.
and achieve compression ratios and temperatures needed for fusion. Theoretical projections have indicated that such a scheme might be highly effective and may result in net fusion energy gain even for an advanced fuel such as D–D [10, 15]. However, in spite of demonstration of the oscillating plasma [12–14], until now POPS scheme have been studied much better in theory than experimentally [4].

In papers [19–22], there were studied processes of nuclear fusion in a compact IEC scheme, realized on the basis of a nanosecond vacuum discharge (NVD) of low energy ($\approx 1$ J). The yield of DD neutrons from the interelectrode space of NVD with deuterium-loaded Pd anode was represented and discussed earlier [19, 20]. A complete PIC simulation of the experimental conditions with the NVD [21, 22] was carried out with the help of an electrodynamic code KARAT [23, 24]. Particularly, there was revealed the essential role of formation of virtual cathode (VC) and deep quasi-stationary potential well (PW) corresponding thereto [20]. The PIC simulation has confirmed the fact that the experiment with NVD implements the well-known scheme of IEC [4, 5] having inverse polarity (last one have been considered in [8] theoretically earlier). 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, PIC simulations are showing that deuterons can also perform high-frequency harmonic oscillations in the potential well, which are manifesting in the experiment by the pulsating yield ($\approx 80$ MHz) of DD neutrons observed [19–22].

The goal of this paper is to present and discuss in more detail available experimental results on pulsating DD neutron yield at IEC scheme based on NVD. To understand better the fusion processes and available experimental data, PIC simulations of different regimes like shots with single neutron yield or pulsating neutron yield are presented, and specifics of VC and PW for particular neutron yields are analyzed. Some ways to achieve the positive energy output $Q > 1$ at IEC scheme under ion oscillations are discussed qualitatively also.
Figure 2. (a) Dynamics of x-ray yield for shots with triple (3 Pd tubes) anode in mode 1: peak of the extra x-ray on channel 4 (as well as the breaks on channels 3, 2) represents the fusion moment of DD reaction (sensitivity of channels 2 and 4 comes to 250 mV, channels 1 and 3—to 1 V; time scale is 40 ns/div). The time latency of the neutron peak at channel 2 corresponds to delay $\approx 46.6$ ns/m, i.e., to 2.45 MeV DD neutrons ($L_2 = 80$ cm; 0.05 cm of Cu before PM2).

(b) Dynamics of x-ray yield in mode 2 for the shot with 0.15 cm lower A–C distance than in part (a) shot. Few neutron peaks at PM2 (channel 2) correspond to periodic fusion moments registered by PM4, channel 4 ($L_2 = 50$ cm; 0.1 cm of Pb before PM2; sensitivity of channel 2 comes to 100 mV).

2. Experiment on DD fusion at IEC scheme based on miniature vacuum 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 [21, 22]. From the standard IEC circuits with electrodes in the form of meshes [4], 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 tubes, 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 [20, 25]; pulse duration of 50 ns, applied voltage of 70 kV, and maximum current of 1 kA). Remark, the erosion of Pd anode tubes during about 100–200 shots turned out not essential under chosen parameters of discharge (see below).

Meanwhile, the neutron yield itself from newly deuterated Pd anode is decreasing step by step after first 20–25 shots. 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 PM2 covered with a 0.5–2 mm Cu absorber. Time-of-flight (TOF) measurements of the DD neutron yield have been usually carried out using PM4 and PM2 (with scintillators) located on the same axis $Z$ as the electrodes at the maximum distances of $L_1 = 45$ cm and $L_2 = 50–90$ cm, respectively, see figure 1(a).

Such an IEC circuit with a reversed polarity [8] makes it possible to operate in vacuum, where beams of auto-electrons from the cathode will be formed when the voltage is applied. The auto-electrons, interacting with the deuterium-loaded Pd anode, in the first, will create near the anode an erosion plasma with deuterons and deuterium-containing clusters. Secondly, the electron beams, while flying into the anode space (through the “mesh” of thin Pd tubes) and braking at its center, form a VC and the PW corresponding thereto. A deep potential well
(a) Rather dilute ("transparent") and symmetric CCD image of an interelectrode ensemble for mode 3. (b) Dynamics of x-ray yield in mode 3 with 0.3 cm Pb plate before PM2. Monotonic pulsating neutron yield with the duration almost three time longer than period of voltage applied ($L_2 = 50$ cm).

(dozens of kV, see below) 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 $Z > 1$ [26]).

It should be underlined that the PM(2) and PM(4) signals are always delayed electronically by $\approx 35$ ns with respect to the instant 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 usually coinciding in real time). For the first particular, but typical case, figure 2(a), photomultipliers PM4 and PM2 were located at distances of 45 cm and 80 cm respectively (channels 4 and 2 presented in figure 2). 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 as extra x-rays, channel 3. Apart from the hard x-ray, basically bremsstrahlung one and some K$_\alpha$ lines (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), see figure 2(a). This delay represents a characteristic feature ("signature") of neutrons having energy of about 2.45 MeV from the $D + D \rightarrow n + He^3$ synthesis reaction (their arrival on the scintillator is detected by a photomultiplier PM2, channel 2, solid line). 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) [20, 22]. CCD image for this shot is dilute (or "transparent"). Some processes similar to anode erosion partially registered by CCD arising in turbulent and vortex two-phase flows containing microparticles [27, 28].

It should be noted that the IEC scheme, implemented on the basis of NVD [19–22], simplifies essentially a number of available IEC schemes [4], in particular, studied earlier in the LANL (Los Alamos) [12–14], where have been used a separate and rather complex injection of electron
beams from special sources to form VC and the PW related, 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 [29], which has particularly explained the appearance of fast ions in a number of the early conducted experiments [30]. In our case, the NVD configuration allows creating VC and quasi-stationary PWs [21,22] in the interelectrode space, which provides a sufficiently controlled collisional nuclear fusion. Remark, the experimental neutrons from the initial stage of NVD are presented and discussed in more detail in [31].

Thus, the features of single neutron yield, which is presented in figure 2(a) and discussed above, are typical ones for large number of shots in experiment with NVD [19–22]. Meanwhile, we may highlight another class of shots (like in figure 2(b) and similar ones below), titled earlier as the regime of multiple fusion events [19–22], where the few well-defined neutron peaks are registering simultaneously. In another words, below we will consider experimental regimes of pulsating neutron yields registering usually at the developed in time stage of NVD under slightly changed conditions of experiments.

3. Periodically oscillating ions. Pulsating neutron yield in experiment

Thus, coming back to the experiment, next feature of neutron yield is illustrated by the shot presented in figure 2(b), where the oscillograms manifest an essential pulsating neutron yield (channel 2, PM2, $L_2 = 50$ cm, sensitivity of 100 mV). Correspondent extra x-rays due to each DD fusion moment are registered like fractures at the PIN diode (channel 3) as well as PM4 varying signals of hard x-rays intensity. Typically, the hard x-ray intensity signal, channel 4, is modulated by the well-defined extra hard x-rays from fusion moments, but with a delay of $\approx 35$ ns in comparison with the instant signals of PIN diodes, channels 1, 3). The CCD image for this shot is dilute one, and presented in figure 1(b).

As shown earlier in paper [29], 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, $I_L$ is limiting Child–Langmuir current and $U$ is the potential applied. Since $I_L \sim U^{3/2}/d_{eff}^2$, then variation of $d_{eff}$ in our experiment [19,22] changes $I_L$ and, correspondingly, the value $T_{PW}$ ($d_{eff}$ is the
Figure 5. (a) More bright CCD image for more dense interelectrode ensemble for mode 5. (b) Dynamics of x-ray yield in mode 5 with 0.2 cm Pb plate before PM2 ($L_2 = 50$ cm); pulsating neutron yield (channel 2) with more irregular intensity than in figures 2(b) and 3(b).

effective interelectrode distance for non-planar electrodes) [32]. Thus, at rather large $d_{\text{eff}}$ we have $T_{\text{PW}} \approx T_{\text{pulse}}$, and just a single peak will be observed in experiments (like in figure 2(a) above). Decreasing $d_{\text{eff}}$ increases $I_L$ and lowers $T_{\text{PW}}$, and step by step at decreasing of $T_{\text{PW}} < T_{\text{pulse}}$ we get double [22], and multiple neutron yields, like in figure 2(b).

Regimes of pulsating neutron yields are shown also below in figures 3, 4 and 5 also. For these shots, in front of PM2 the lead plates have been used (0.2 cm thick, see figures 5, and 0.3 cm thick, see figures 3 and 4). These regimes were realized experimentally when interelectrode distance $d_{\text{eff}}$ have been reduced by 0.15 cm (see figure 5) and 0.2 cm (see figures 3 and 4) in comparison with distance for single neutron yield regime, see figure 2(a). Note that the hard x-rays intensities in PM2, channel 2, are strongly suppressed due to lead plates. The intensities of the neutron peaks registered is weakened partially also due to a possible reflection from the Pb absorbers located in front of PM2. Remark, the CCD image intensity is growing from very dilute, see figure 1(b), for shot with oscillograms in figure 2(a) to rather bright ones for shots presented in figures 5(b) and 6(b). Thus, in spite of rather irregular character, the neutron yield for shot in figure 5 is pulsating one.

Quite regular and well-defined pulsating neutron yield is presented by oscillograms in figures 3 and 4 for the shots with the same minimum value of $d_{\text{eff}}$. Note the well-defined modulation of x-rays intensities (PM4, channel 4) by the extra hard x-rays at the periodic fusion moments. Also, the CCD images for these shots are rather “transparent” ones. At the shot, presented in figure 5, the number of deuterium-containing clusters at PW is increased as well as the correspondent fraction of neutron yield due to the channel “accelerated deuteron—cluster” for reaction of DD synthesis. It should be reminded again that the typical hierarchy of related times at TOF measurements of the DD neutrons both for single and for multiple fusion events for particular fusion moment contains usually: the instant signal from channel 1 or channel 3 at the fusion moment $t_t$; next, electronically delayed signal at channel 4, $t_t + 35$ ns; and time-of-flight delayed neutron signal at channel 2, $t_t + 35$ ns + $t_{\text{TOF}}$, correspondingly [19, 22, 25, 33].

As have been shown earlier by 2D PIC simulations for NVD conditions [21, 22, 25], the experimentally observed pulsating neutron yield regime (like presented one in figures 3, 4, 5) is due to the periodic collapses of deuterons at the PW bottom (during their oscillations in potential
Figure 6. (a) CCD image of dense and partially self-organized interelectrode cluster ensemble (complex plasma microreactor) for mode 6. (b) Oscillograms of x-rays yield (channels 1, 3 and 4) and neutron yield (channel 2) for specific ensemble with trapped deuterons and partially diffused x-rays ($L_2 = 50$ cm, 0.5 mm Cu before PM2; channel 2 sensitivity is 1 V, channel 4—500 mV).

well under $T_{PW} \ll T_{pulse}$). This regime is suggestive of the advanced and stimulating conception of periodically oscillating plasma spheres (POPS) earlier developed properly in theory [10, 11], but have been demonstrated in the experiment just under very moderate conditions for some ions [12–14]. It was suggested to abandon the standard scheme of the IEC, 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 grids). Ions then will undergo radial harmonic oscillations with any amplitude in the potential well formed, and at the moments of maximal compression the high fusion power density will be provided. At the present moment, in spite of the POPS attractiveness and demonstration in principle (just for $\text{He}^+$, $\text{Ne}^+$ and $\text{H}_2^+$ ions), the PW depth reported was still < 1 keV, and the POPS frequencies comes to $\nu_{\text{POPS}} < 1$ MHz (the applications, economy, and limitations are discussed in details in [12–14]). Generally speaking, the theoretical POPS are particular and well-defined case or analogue of the experimental regime of multiple fusion events [19, 20, 33] at vacuum discharge. In fact, at the experiment with NVD with deuterated Pd anode we have PW depth $\varphi \approx 50$ kV namely for deuterons, and the frequency of neutron yield oscillations observed in the vacuum discharge [19–22] comes to about $\nu \approx 77–83$ MHz ($\varphi$ is about 60–80% of voltage applied). This value coincides with extrapolation of POPS expression $\nu_{\text{POPS}} \sim (\varphi/m_i)^{1/2}/r_{VC}$ [13] to A–C geometry and the potential well depth $\varphi$ at NVD ($m_i$ is deuteron mass, $r_{VC}$ is virtual cathode radius). It seems that this agreement is not accidental and confirms the similarity of the POPS physics and some multiple fusion events regimes of nanosecond vacuum discharge in cylindrical geometry (see figures 3–6) [19–22].

Note, instead of special injections of electrons into a spherical device to produce a VC as in [12–14], nanosecond vacuum discharge with hollow cathode provides itself (after voltage is applied) an automatic extraction of electron beams from the surface of conical part of cathode, figure 7(a) and their further acceleration and converging injection into the anode area on the axis to form a VC, figure 7(c). By analogy with the POPS expressions, we may estimate the fusion power $P_{\text{fusion}} \sim \varphi^2 \theta^2 f^2 (\sigma v)_l / (2\pi e^2 r_{VC}^2)$ 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 $r_{\text{max}}/r_{\text{min}}$, $f = n_i/n_e$, $\langle \sigma v \rangle$ 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 of oscillations [10,11]). Assuming that $\phi \approx 50$ kV and $r_{\text{VC}} \approx 0.1$ cm, as well as $f^2 \sim 1$, $\theta < 10^2 \cdot 10^3$, $l \approx 0.5$ cm, we get the yield of $\sim 10^4 \cdot 10^5$ neutrons for a single collapse of deuterons at the discharge axis (or for one period of deuterons oscillations), that is in agreement with the value of experimental neutron yield, (see figure 3(b)).

Thus, as have been noticed earlier in [12–14], specific advantage of the IEC systems like the POPS, or the multiple fusion events [19–22,33] is the favorable scaling of fusion power density with decreasing of set-up size.

Last but not least, the shot with bright CCD image and pulsating neutron yield is presented in figure 6. The number of deuterium-containing clusters at potential well is increased essentially for this shot as well as the correspondent fraction of neutron yield due to the channel “accelerated deuteron–cluster” for reaction of DD synthesis. In fact, sensitivity of channel 2 here is 1 V, i.e. ten times lower than for shots presented in figures 2(b), 3(b) and 4(b). Thus, the neutron yield is highest for this type of shots $[\sim 10^7/(4\pi)]$, where the channel “accelerated deuteron–cluster” for neutron yield is prevailed. The density of nano-clusters is so high that even rather hard x-rays are partially trapped and diffusing at inter electrode ensembles of this type. Discussions of x-rays diffusion at dense cluster ensembles in NVD [26] as well as some other effects and processes related [27,28,34,35] are beyond of the scope of this paper.

Thus, we may conclude that well reproduced pulsating neutron yields due to deuteron oscillations in the field of virtual cathode is observing at NVD experiment under very different densities of interelectrode cluster ensembles, that provides different neutron yield correspondingly.

4. PIC simulations of virtual cathodes and potential wells at NVD

KARAT is a versatile relativistic, fully electromagnetic 1D, 2D and 3D version code based on the PIC method and aimed at the solution of non-stationary electrodynamic problems having complicated geometry and involving electron and ion beams [23,24]. A finite difference scheme with overstepping on the rectangular shearing grid is used to solve Maxwell’s equations. It is suited to the simulation of devices such as vircators, free electron lasers, gyrotrons, backward-wave oscillators, etc. The code has several features useful for modeling phenomena associated with electron and ion beam devices, laser–plasma interaction and so on. It is appropriate for the modeling of phenomena in laboratory and space plasmas simulated either by macro particles or by hybrid models.

The PIC modeling developed earlier for compact NVD conditions, where IEC scheme have been realized, have clarified the general picture of physical processes related with DD neutron generation, in particular, the appearing of VC and correspondent PW. Last one is playing the role of micro accelerator for deuterons, and their head-on collisions at PW bottom are followed by DD neutron generation. Some other specifics of IEC scheme like non-Maxwellian distribution functions for ions, appearing of double potential wells (related with observed double neutron peaks), oscillating ions at PW and some other effects registered in NVD with deuterium-loaded Pd anode have been clarified or understood better due to PIC simulations [19,21,22,25].

In this section, we concern the comparison of the structures of virtual cathodes and potential wells for two different regimes of neutron yield discussed, i.e single and multiple (pulsating) neutron yields. In particular, in figure 7 the results of PIC simulations of VC and correspondent phase portraits of particle dynamics for both cases are shown. Experimental values of voltage applied 70 kV (with front about 1 ns), current 1 kA, pulse duration 50 ns, section 2, as well as real A–C geometry and distance between electrodes for different shots are used in simulations. Phase portrait in figure 7(d) represents the case where VC position was distorted in comparison with usual particles dynamics for single neutron yield, see figure 7(c). It is the result of very
Figure 7. Results of PIC simulation of VC: (a) for the shot with oscillograms of x-rays shown in figure 2(a) (single neutron yield); (b) for shot under smaller A–C effective distance with oscillograms of x-rays shown in figure 4(b) (pulsating neutron yield); (c, d) correspondent phase portraits of particles with formed virtual cathodes presented above (the blue dots show electrons accelerated as approaching the Pd tubes to $V_{r_{\text{max}}} \approx 0.4c$ ($r \approx 0.3$ cm), and the red horizontal line $V_r/c \approx 0$ (in the interval $r = 0$ to 0.3 cm) shows accelerated deuterons, the resolved head-on branches of accelerated deuterons are shown elsewhere [21, 25] ($c$ is light velocity; the erosion “anode plasma” is the small green area at the center, where $V_r/c = 0$ and $r \approx 0.3$ cm).

small $d_{\text{eff}}$ used for this shot in experiment, see figure 7(b), where the size of VC increased: $r_{\text{VC}} \approx 0.15–0.2$ cm, in figure 7(d), instead of $r_{\text{VC}} \approx 0.1$ cm in figure 7(c). Potential wells for two limiting cases of neutron yield discussed are presented in figures 8(a) and 8(b), correspondingly. Related profiles (cross-sections) of PW at $z = 1.5$ cm, near minimum, and at $z = 2.5$ cm are presented in figure 8(c) and figure 8(d). PW for shot with single neutron yield, see figure 8(a), is more narrow and deeper than for pulsating one, see figure 8(b). Thus, PW for regime of pulsating neutron yield, figure 7(b), is essentially broader, but not so deep in comparison with PW, see figure 8(a), for standard A–C geometry with single neutron yield, like for shot in figure 2(a). Meanwhile, anode–cathode distance and geometry of anode space with oscillations of chosen groups of deuterons inside is shown in figure 9(a).
Figure 8. Potential well of a virtual cathode: (a) for the shot with x-ray oscillograms shown in figure 2(a) (single neutron yield); (b) for the shot under smaller A–C effective distance with oscillograms of x-rays shown in figure 4(a) (pulsating neutron yield); (c) and (d) are correspondent cross-sections of PW (near minimum, at \( z = 1.5 \) cm, and at \( z = 2.5 \) cm) presented in parts (a) and (b) above.

Additional PIC simulation of ion dynamics was made by XZ version of the code KARAT in potential model to illustrate deuteron oscillations. 2D simulation region consists of outer grounded circle with radius 1 cm and inner coaxial circle with radius 0.5 cm under negative potential 100 kV. In initial moment along \( Z \) direction the proton bunch is injected with small energy 10 eV. Duration of bunch is 0.1 ns and total charge of ions is \( 10^9 \) elementary charges. This construction for ions is the potential well with flat bottom, that is rather similar to PW profile shown in figure 8(d). In electric field of electrodes ions are accelerated and reach cathode transparent for ions. When crossing the cathode, deuterons are deflected on angle uniformly distributed in the range \( \pm 5^\circ \). Inside cathode ions move under self electric field. To prevent the deposition of ions on the outer electrode at the time of the first pass of center part the cathode potential is increased on 5%. Trajectories of chosen groups of ions in XZ plane accumulated during 200 ns of time of well-defined oscillations are shown in figure 9(b). We observe that the ion scattering, accompanied by appearance of tangential component of ion velocity, provides the very smooth rotation of oscillations in XZ plane around axis \( Y \). Thus, under assumptions chosen, it seems that effects of ions scattering are accumulating by non-additive manner.
5. Concluding remarks

POPS-like oscillations of deuterons in potential well of a virtual cathode followed by pulsating neutron yield (called as multiple fusion events in paper [19]) were recognized at early NVD experiments [36, 37]. Evidently, in our steady-state plasmas in NVD device, the POPS-like oscillations are primarily a mechanism to resonant heat the ions rather than for coherent compression ratios as originally envisioned for POPS [10, 38]. Also, our system with the deep PW satisfies the stability conditions discussed in [8, 38] since ion “temperature” turns out comparable to the electron injection energy [22, 25]. Stability of large-amplitude plasma oscillations in IEC devices was predicted earlier in [11].

Note, in [38] 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 our NVD with cylindrical geometry, we avoid some restrictions or limits caused by geometrical convergence in sphere [38]. Also, 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 deuteron oscillations (through pulsating neutron yield [19, 22]) turn out rather stable.

As underlined earlier in paper [13, 14], a critical advantage for a POPS-like based fusion device is its favorable scaling of fusion power, which increases with the inverse of the virtual cathode radius. This attribute provides an economical development path for the POPS concept since each next generation device will be smaller and more efficient than the previous one [13]. It also leads to a modular, high mass power density device that should be economically competitive. It was noted that even a fusion power plant or advanced space propulsion can be considered if breakeven is achieved [13]. In fact, the very small size of virtual cathode, \( r_{VC} \sim 0.1 \text{ cm} \), as well as rather deep PW (like \( \varphi \approx 50–55 \text{ kV} \)) correspond to the extremely high fusion power densities (\( \sim \varphi^2/r_{VC}^2 \)) demonstrated at the present moment by the miniature table-top IEC scheme based on NVD [19–22].

In particular, it allows to consider this elementary cell (nuclear burning in potential well of NVD [20]) as a part of “fuel” array for any massively modular approach as suggested and discussed earlier in [13, 14].
Note, ion–ion relaxation does not take place during the time of ion collapse, and real IEC-systems with ion oscillation frequencies $\nu = 10–100$ MHz are corresponding to a nonequilibrium states of colliding ions [39]. It should be stressed that the positive fusion output $Q > 1$ at IEC with POPS-like oscillations could be produced just in a result of multi-repeated initiation of fusion reactions in the periodically generated plasma under a head-on collision of ion bunches in the center of system. In this case, the gain in each individual act of synthesis at “non-igniting” plasma is much less than unity. Meanwhile, the summation of relatively small gains over the all periodic short “burning” time during the whole time of operation cycle $\tau$ would provide $Q > 1$.

Two aspects should be distinguished under discussion of the prospects of systems with electrostatic confinement as a powerful source of thermonuclear neutrons and even as systems with a positive energy output. The first, it is providing of conditions for creation and support of an effective potential well, with completely separated charges of the ion flux and the electrons of virtual cathode. An effective way to support such a potential well is to use, in combination with an electrostatic trap, an external magnetic field. This idea originally suggested in [40] was developed in [41] where proposed to surround an IEC electrostatic PW with a polyhedral cusp magnetic field in order to improve electron confinement [18]. Such a hybrid scheme was called as Polywell [41]. In this case, the energy deposited into the system will be spent on maintaining the electric field during the period of the first or several first ion oscillations, and their subsequent oscillations will occur in the field of VC of magnetized electrons. According to various estimates, this requires a magnetic field with a strength of about 10 kT [4,41]. Generally speaking, Polywell scheme can be realized both in the geometry of spherical and cylindrical electrostatic traps [42,43]. In [38], the possibility of forming of PW with the separation of the volume charges of ions and electrons of VC without the application of a magnetic field was studied. It is shown that in the case of the spherical geometry of an electrostatic trap, such PW can be formed only under conditions of a special time profiling of the ion and electron fluxes and their precise synchronization, which is a rather difficult task. It is not excluded, that it was one of the formal reason to interrupt the further experimental study of POPS scheme in spherical geometry [13]. The use of a cylindrical electrostatic trap with axial injection of electrons is proposed in [38] as a more realistic way. However, the possibility of achieving a high concentration of particles of converting ion fluxes, which is a key problem for any scheme with inertial confinement, is much lower for the cylindrical geometry of the trap than for the spherical one. Namely, for PW with separation of volume charges, as underlined in [38], the most favorable scaling mentioned above can be applied for the power of thermonuclear reactions that corresponds to the maximum density of ions participating in the burning process.

The second aspect of the effective operation of systems with IEC is the number of ion oscillations during the lifetime of the potential well. For a cylindrical electrostatic trap, i.e. for the geometry of the NVD considered in this work, in the most favorable case of PW with a separation of volume charges and in the approximation of adiabatic compression of deuterium ions, the condition for exceeding of the released energy of the DD fusion reactions over the energy deposited in the system was obtained [39] (an analogue of Lawson criterion [44] for breakeven). For the potential well of 100 kV, this condition is $\tau\nu^2 > 3 \times 10^{13}$ s$^{-1}$ ($\tau$ is the duration of the operation cycle at a single deposition of energy, $\nu$ is the frequency of deuteron oscillations; perhaps it is appropriate to recall here a very old saying: “A drop sharpens a stone not by force, but by the frequency of its fall”, Giordano Bruno). Thus, according to the criterion for a positive energy yield of DD-reaction, for example, when the oscillation frequency is $\nu = 100$ MHz, the duration of the operation of IEC-installation with direct injection of ions must exceed about 3 ms [39,45]. Nevertheless, in spite of rather optimistic character of this estimation, the time “gap” is rather essential one between $\tau \sim 100$ ns (see figures 3, 4, 5) which is available now at the present NVD experiment with oscillating deuterons and total operation time $\tau > 3$ ms needed for breakeven.
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