On Correlations between Neutron Yield and Potential Well Dynamics at Electrostatic Confinement in Nanosecond Vacuum Discharge

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Abstract – Earlier, generation of energetic ions and DD neutrons from microfusion at interelectrode space of low energy nanosecond vacuum discharge have been demonstrated [1, 2]. Nevertheless, the physics of fusion processes and some results on neutron yield from database accumulated were understood poorly. At this work, the detailed PIC simulation of the discharge experimental conditions using fully electrodynamic code is presented. The dynamics of all charge particles was reconstructed in time and A–C space. The principal role of *virtual cathode* (VC) and corresponding single and double potential wells formations at interelectrode space are recognised. The calculated depth of *quasistationary potential well* (PW) of VC is about 50–60 keV, and the D^+ ions being trapped by this well are accelerating up to the same energy values that provides collisional DD nuclear synthesis. Correlation between calculated potential well structures (and dynamics) and neutron yield observed is available and discussed. In particular case, ions in the potential well undergo high frequency (~ 80 MHz) harmonic oscillations accompanied by correspondent regime of oscillatory neutron yield.

1. Introduction

In whole, efficiency of hard X-rays and fast ions generations at nanosecond vacuum discharge, as well as neutron generation turns out at least two orders of magnitude higher [1, 2] than for experiments on DD fusion driven by Coulomb explosion of laser irradiated deuterium clusters [3]. However, the complex physics of nanosecond discharge processes and mechanisms of microfusion were understood poorly that provoked interest to PIC simulations also [4]. Besides of representing the key points of general physical picture, computer modelling allows to clarify the details of experimental data obtained earlier, for example, appearing of double neutron peaks or pulsating neutron yield.

Remark, the model of collective ions acceleration [5] at vacuum discharge based on conception of *non-stationary* potential wells (PW) before the front of cathode flare at the regimes of non-stable current carrying was developed rather recently [6]. On the basis of this model the number of very early experimental data of A.A. Plutto and coauthors [7] on occasional anomalous ions acceleration were explained. Our preliminary results of PIC simulations of discharge conditions [2] have recognized that conception of PW is more universal, and namely *quasistationary* PW interelectrode space with depth up to ~ 80% of voltage applied provide electrostatic acceleration of ions up to the same energies. Correspondingly, head-on collisions of ions with energies of few tens keV is followed by DD nuclear synthesis transforming interelectrode space into something like reactor chamber.

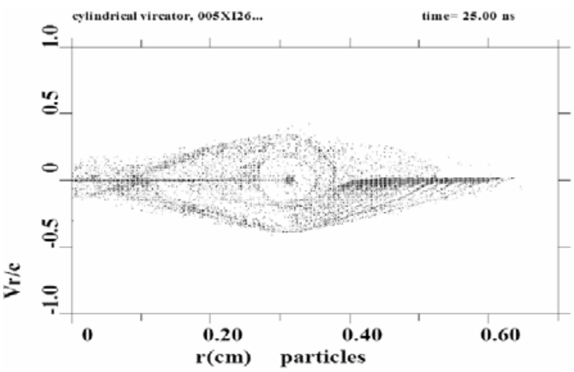

Fig. 1. Particle dynamics and virtual cathode (VC) formation (r – distance from discharge axis Z, V_r/c – particles velocities/velocity of light)

In fact, PIC modeling allows identifying experiment [1, 2] with rather old branch of plasma physics as inertial electrostatic confinement fusion (IECF) (see [8–12] and refs. therein). Pioneers of IECF were O. Lavrent'ev at USSR and F. Farnsworth at US, but due to different reasons, including rather low value $Q = E_{\text{fusion}}/E_{\text{input}} \sim 10^{-6}–10^{-5}$, this fusion conception was almost forgotten. Just at the beginning of 90-th interest to IECF was renewed at US and Japan mainly as to simple source of neutrons [10–12]. Moreover, on some experimental set-ups which are under study and construction at LANL new hopes have appeared to get $Q > 1$ [12] (as minimum in theory).

2. Virtual cathode and potential wells

Figure 1 represents example calculations of particle dynamics at cylindrical geometry, and explains the appearance of VC. Related with VC examples of PW are shown at Figs. 2 and 3 for different times of discharge pulse (A–C configuration follows from these figures easily). Remind, that at experiment [2] cylindrical Cu anode (∅ = 0.6 cm) has a set of thin hollow Pd deuterated tube (∅ = 0.1 cm) attached to anode end-on, and hollow cathode was constructed from Al. At PIC calculations Pd tubes were modeled by semi-transparent "foil". Some anode "erosion plasmas" were added also (small sphere at the centre of "void" at Fig. 1, where $V_{RMI}/c = 0$ and $r \approx 0.3$ cm). When voltage applied, electron beams were extracted from internal surface of cathode ($r \approx 0.4$–0.6 cm) and accelerated up to $v_{e\text{-max}} \approx 0.3$–$0.4c$ near Pd tubes ($r = 0.3$). Interaction of electron beams with tubes provides erosion of system ($Pd + D_2$) and ejection (implosion) of deuterium and palladium vapors into near anode axis area (accompanied by their partial nucleation at real experiment). Further, since the current I_A exceeds at experiment the limiting Langmuir value $I_A > I_L$ [13], cumulative convergence of head-on e-beams at the axis (inside of space restricted by Pd tubes) provides total deceleration of electrons (as well as partial reflection of electrons outside, $V_r/c > 0$), and VC do appear (at $r \approx 0.1$ cm).

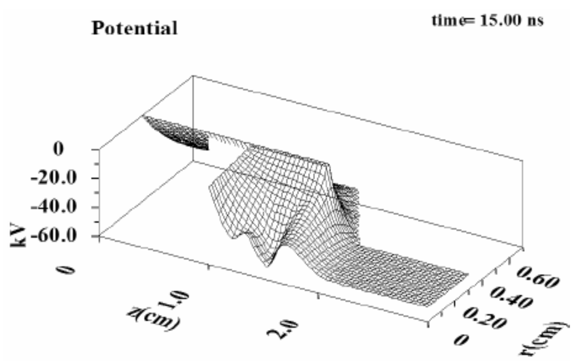

Fig. 2. Double potential well (PW), appearing at the first part of impulse of voltage applied

Due to VC, negative potential about few tens keV will appear at the axis (at $Z \approx 1.2$–1.8 cm), and internal part of near anode area will be fulfilled by accelerated ions (Fig. 1, horizontal line $V_r/c \approx 0$ at $r = 0$–0.3 cm interval. This line will be spitted (in ion scale of velocities) at $r = 0$ into two converged at axis Z branches of ions with velocities $V^i_r/c = \pm 0.5 \cdot 10^{-2}$ (at $r \to 0$). PW is evaluating in time and can transformed from double one (Fig. 2) into broad single one (Fig. 3). Well depth turns out up to 80% of voltage applied. Ions, being accelerated from different edges of PW to axis Z, represent head-on fluxes at $r \to 0$ with velocities 20–50 keV. Apparently, it explains collisional DD fusion observed in real experiment (in real case we have to take into account collisions with neutrals, deuterium clusters and deuterated anode itself also) [2]. Area of Z and r at the half-width of PW contains practically isotropic distribution of fast ions (volume of "reactor"). Ions density has a maximum at the bottom of PW ($Z \approx 1.5$ cm) and typical shape is shown in Fig. 4 (absolute values of n_i under modeling will depend of parameters of "anode plasma").

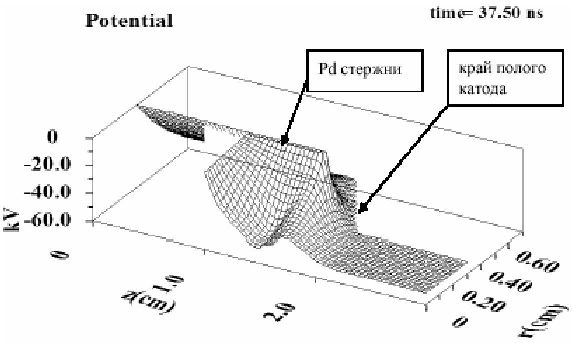

Fig. 3. Typical single potential well (by axis Z) (at 37.5 ns of calculated time, PW minimum corresponds to $Z \approx 1.5$ cm)

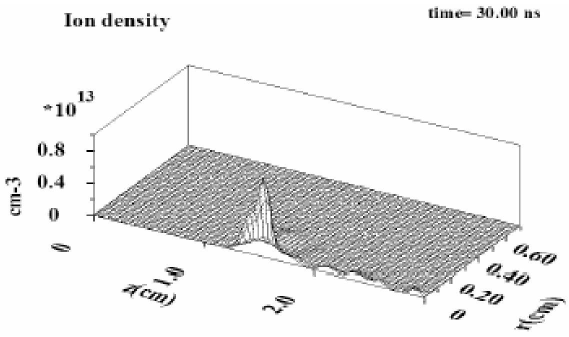

Fig. 4. Example of averaged density of fast ions in potential well (along discharge axis Z; $Z = 1$ – edge of Cu anode)

3. Specifics and regimes of neutron yield

PIC simulations have assist in understanding of some effects observed in experiment [2] earlier. For example, the shapes of some non-maxwelian distribution functions are in correlation with registered in experiment "plateau" at histograms for fast ions tracks. Another example, well reproducing at experiment at simulations double potential wells on the first stage of discharge (like in Fig. 2; remark, double PW – by Z-axis, and weakly double by r, last one takes place and for single PW by Z). Looks probable, that appearing of double wells might explain double neutron peak have observed sometimes in experiment (like in Fig. 5, ch.2). We can see that PW time of life is about $T_{PW} \approx 20$–25 ns, and after that VC have to be neutralized ($T_{PW} >> \omega^{-1}_{pi}$) by flux of ions. Since total pulse of voltage is about 50 ns, there is keeping conditions for VC appearing in experiment ($I_A > I_L$), and new PW will appear being double one also. Ions collisions at this PW will be manifested by second double neutron peak registered on Fig. 5. Remind that appearing of single-, double-, and multiple PW and non-maxwellian distributions of ions are typical features of systems with IECF. Earlier, the study of correlation between PW structures and neutron yields have recognized that not only well depth, but namely potential instability in time defines neutron yield at ions beams interactions [10].

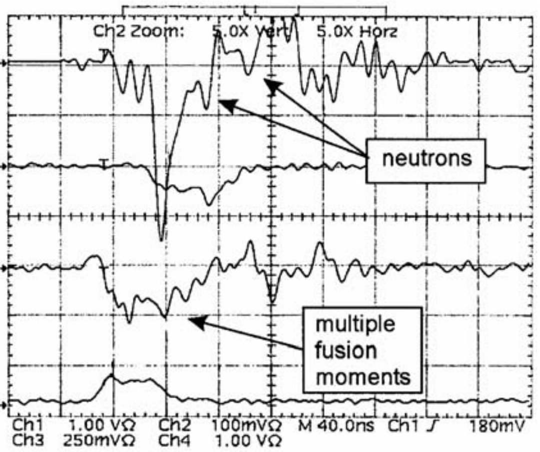

Fig. 5. Oscillogrammes of hard X-rays yield (channels 1, 3 and 4) and neutrons yield (double peaks, channel 2) (see text and [2])

In our experiments also not only PW structure, but dynamics of potential structures will define character of neutron yield. In a result, three types of observed neutron yield could be recognized at experiment [2]: 1) single peaks (like on Figs. 2, 5 in [2]), 2) multiple intermittent neutron yield (two and more neutron peaks, Fig. 5 above, and Figs. 3, 7 in [2]), 3) oscillatory or pulsating neutron yield (like on Figs. 4, in [2], as well as on Fig. 6 below).

Let us consider first two types of neutron yields. As shown in [6], time taken to form VC (or decay time of potential) is about $T_v \approx C_d U/I_L$, where C_d – diode gap capacitance; U – potential. Since $I_L \sim U^{3/2}/d^2_{\text{eff}}$, then variation of d_{eff} in our experiment [2] changes I_L and, correspondingly, the value T_v (d_{eff} – effective interelectrode distance for non-planar electrodes) [13]. Thus, at rather large d_{eff} we have $T_v \approx T_{\text{pulse}}$, and just single peak will be registered at experiment (first type). Decreasing of d_{eff} increases I_L and lowering T_v, and step by step at decreasing of $T_v < T_{\text{pulse}}$ we get double-, and multiple neutron yield (second type). At $U = 50$ кeV, $I_A/I_L \approx 1.5$, $C_d \approx 300$ pF [2] we have $T_v \approx 28$ ns, that is not far from the time taken to form VC for the case presented on Fig. 5.

Third type of neutron yield represents special interest. At $I_L \to I_A$, if electron distribution in VC would be close to uniform one and well would still available, then ions oscillations at PW will be close to regime of harmonic oscillator. At the moments of maximum periodic compression of ionic subsystem the reaction DD will take place, and neutron yield will be as pulsating one (typical example is Fig. 6, ch.2 below or Figs. 4, 6 at [2]). Period of oscillations of neutron yield is about 12–13 ns at experiment [2] ($T_v << T_{\text{pulse}}$), and it represents now mainly the frequency of harmonic oscillations D^+ in PW (Fig. 3) instead of T_v (like at the first type of neutron yield). In fact, pulsating neutron yield is reproducing at experiment just at decreasing d_{eff}. Thus, in summing up, neutron yield as single peak is a result of single collapse of ions at the well bottom at neutralization of VC in regime $T_v \approx T_{\text{pulse}}$, and second type of yield is intermediate one between single and multiple oscillatory yield at $I_L \to I_A$ (Fig. 6).

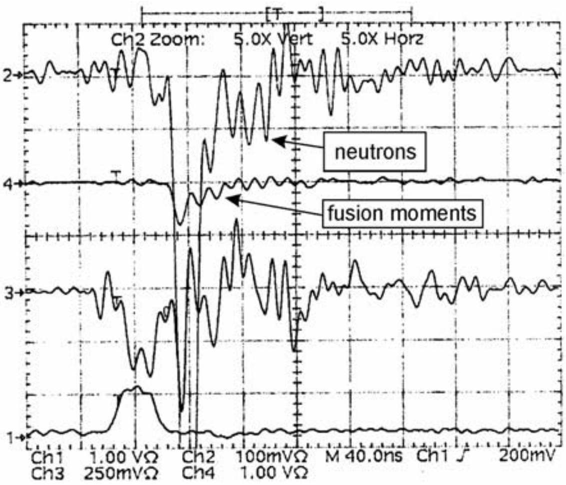

Fig. 6. Oscillograms of hard X-rays intensities (channels 1, 3 and 4) and pulsating (oscillatory) regime of neutron yield (channel 2, see text). Intensity of channel 4 is modulated by the moments of DD reactions

4. Comparisons and concluding remarks

Pulsating regime (Fig. 6) looks similar to waiting specifics at the conception of periodically oscillating plasma spheres (POPS), developing at the last decade in theory and in experiment [11, 12]. There was suggested to cancel from standard scheme of IECF, where particular ion beams interact with each other, and use injection of electrons into grids additionally (in order to get uniform electron background inside cathode grids). Ions will undergo harmonic oscillations by radius with any amplitude at the potential well appeared, and at the moments of maximal compression high fusion power density will be provided $P_{\text{fusion}} \approx 3\varphi^2\theta^2 f^{\,2} < \sigma\upsilon > /2\pi e^2 r_{\text{VC}}$, where φ – well depth; θ – level of compression; $f = n_i/n_e$, r_{VC} – radius VC, $<\sigma\upsilon>$ -averaged cross-section (here P_{fusion} is integrated the total power over single period [11]). Typical POPS frequency is $\nu_{\text{POPS}} \sim (2\varphi/m_i)^{1/2}/r_{\text{VC}}$. Analysis of POPS physics have shown that potential well depth about ~ 60% of voltage applied is enough for realization of conception of reactor in oscillating systems. However, at the present moment in spite of POPS demonstration in principle, PW depth is still ≤ 1 кeV, and POPS frequency $\nu_{\text{POPS}} \leq 1$ MHz (applications, economy, limitations are discussed in detail at [12]).

Generally speaking, POPS are particular and well-defined case or analog of discussed multiple fusion events (MFI) at vacuum discharge [2]. In fact, instead of special injections of electrons into spherical device to produce VC at [12], nanosecond vacuum discharge with hollow cathode provides (after voltage applied) automatic extraction of electron beams from cathode and their further acceleration and injection into anode area on the axis to form VC (Fig. 1) [1, 2]. By analogy with POPS expressions we may estimate fusion power density $P_{\text{fusion}} \approx 9\varphi^2\theta^2 f^{\,2} < \sigma\upsilon > l/2\pi e^2 r^2{}_{VC}$ at the volume of nuclear burning for reactor with cylindrical geometry [2] (l – length of cylinder). If to assume $\varphi \approx 60$ кeV and $r_{\text{VC}} \approx 0.2$ cm, as well as $\theta^2 f^{\,2} \sim 1$, we get the yield $\sim 5 \cdot 10^6$ neutrons for single collapse (or for one period of oscillations) of D^+ ions at the discharge axis (or for one period of oscillations). Thus, favorable scaling with decreasing of set-up size of fusion power density, which is increased with decreasing of r_{VC} and increasing of PW depth, represents specific advantage IECF systems (like POPS [12] or MFI [2]). As have been discussed above, during the total time of voltage pulse we may get from single to 4–5 moments of deuterium ions collapses at the axis (depending of relation between T_{v} and T_{pulse}). It will be accompanied by the correspondent number of neutrons peaks in real experiments (see Figs. 5, 6 above and [2]) with total neutron yield related.

Remark, the frequency of neutron yield oscillations in vacuum discharge [2] is about ≈ 77–83 MHz, meanwhile, extrapolation of POPS expressions [12] on A–C geometry and PW depth gives $\nu_{\text{POPS}} \approx 78$ MHz. Seems, this agree is not occasional and confirms similar to POPS physics available at some regimes of nanoseconds discharge. Miniature size ($r_{\text{VC}} \approx 0.2$ cm) as well as rather deep PW like $\varphi \approx 50$–55 кeV are correspond to extremely high fusion power densities demonstrated [2, 14] at the present moment for similar IECF systems. From the other size – small absolute volume, nanosecond scale of T_{pulse} and losses restrict the total neutron yield, but keep one acceptable for some applications.

Note, the calculation of real neutron yield (besides of another channels of DD reactions) have to be performed with taking into account periodic compressions of ionic subsystem. It might provide at the collapse moments the ion densities essentially higher than presented in Fig. 4 above (for similar POPS conditions the calculated value $n_{\text{i max}} \sim 10^{19}$ cm^{-3}, and r_{min} at the compression moment is ~ 60 microns [11]). Besides of it, VC sometime is located inside of "cloud" of burning "dust" of anode material, that still have not been included into PIC modeling. Negative and positive aspects of electrodes erosion, as well as the fact that PW sometimes is fulfilled by clusters of deuterium, needs separate discussion. Trapping of fast ions by ensembles of clusters (including deuterium ones as potential targets), especially noticeable under effects of ensemble self-organizations (dusty stopping) represents additional opportunities as well as complexity for "reactor" optimization.

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