Interelectrode high power density “dusty” warm matter for nuclear synthesis and hard X-rays lasing

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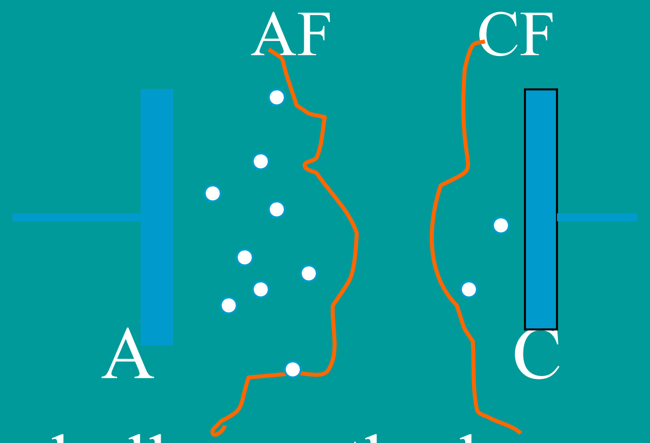
We study the random interelectrode media of high power density at low energy nanosecond vacuum discharges. These X-rays ensembles are created by an intense energy deposition into the cold solid density, low volume dusty “target“ collected at interelectrode space after voltage applied (clusters of different size from anode material). Hard X - rays emission efficiency, generation of energetic ions (up to ~1 MeV) and neutrons from collisional DD fusion, trapping and release of fast ions and/or X - rays by interelectrode ensembles are the subject of our study. The results of PIC simulaton using fully electrodynamic code KARAT, which recognized the essential role of virtual cathode and correspondent potential well formations are discussed.

Vacuum discharge physics : possible combination of number effects of high local power density



- hollow cathode, erosion
- mass transfer A/C $\sim 10^3$
- anode, cathode flare
- expansion AF and CF,
- nucleation, clusters

$\alpha_c \approx \rho_l / (\rho_l + \rho_v) \sim 0.2\text{-}\ 0.5$

meeting AF and CF: breakdown

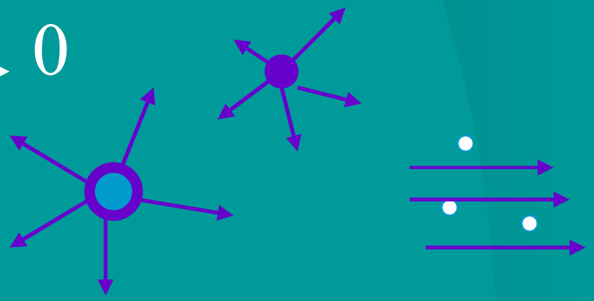
-solid density dusty “target”

-e-beams, collective effects or anomalous heating, j^2/σ_{lim}

$\sigma_{lim} \approx \omega_p / 4\pi$, $d \sim 0.01\text{-}1\mu m$

- $E / \Delta V \sim 10^7 – 10^8$ J/cm^3 ?

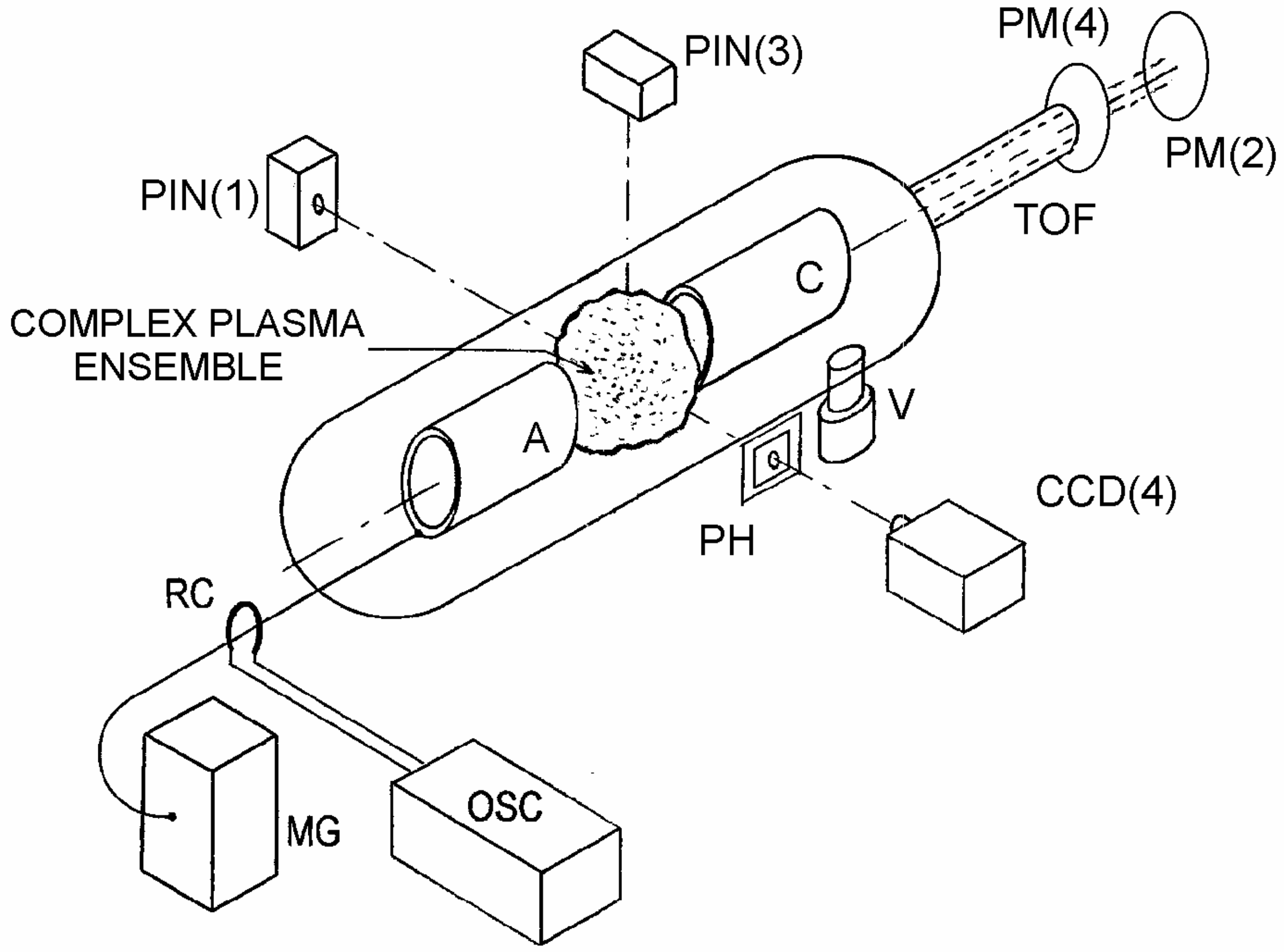
$\Delta V, \Delta t \to 0$



Scheme of experiment for hard x-rays bursts and DD nuclear synthesis

Kurilenkov, M. Skowronek, G.Louvet,A.A.Rukhadze,J.Dufty.

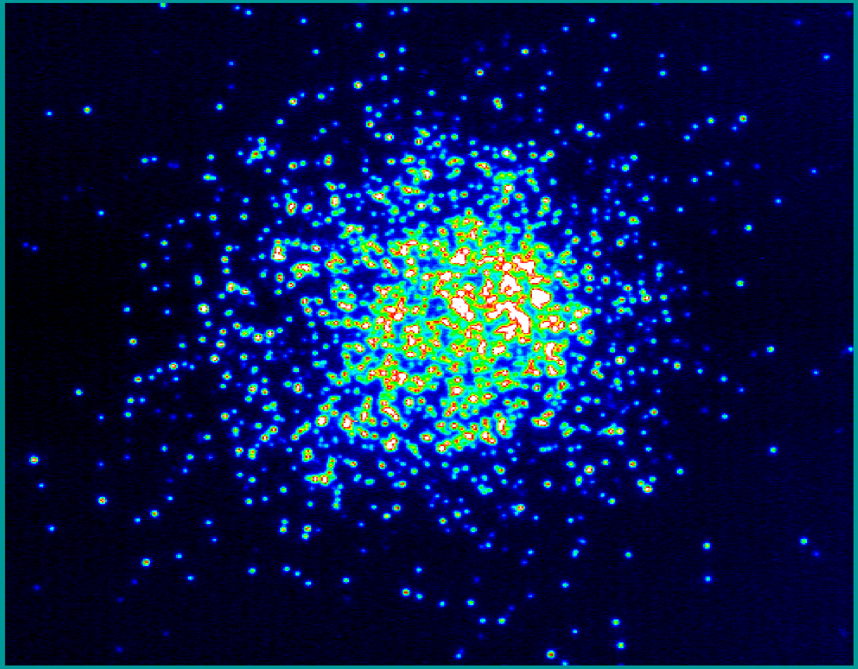
Journal de Physique 10 (2000) Pr5-409



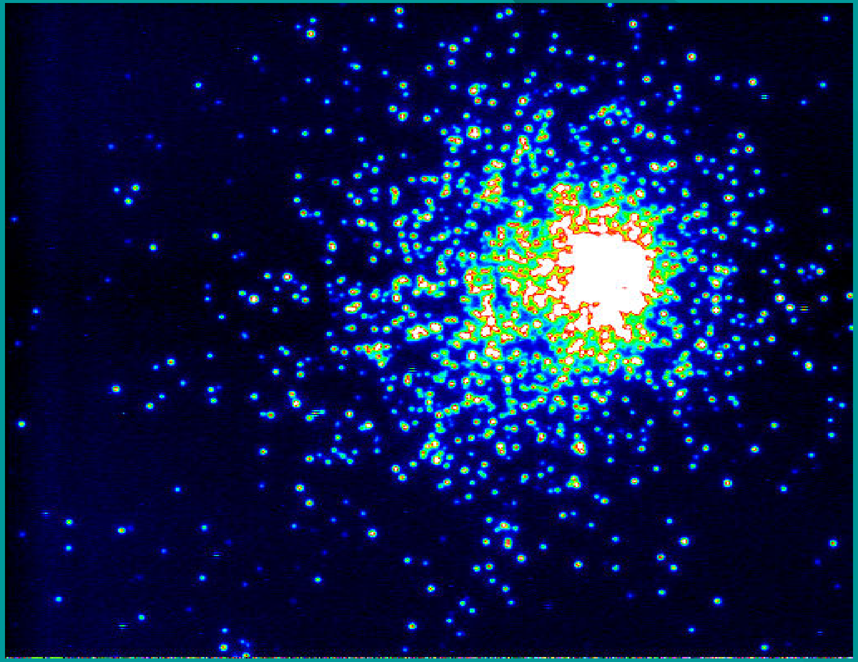
Parameters of discharge: ≈ 1 J of total energy, U=70keV, t=50 nsec I_{max} =1kA, TOF = 30cm $P_{min} \approx 10^{-7}$ mbar.

Collecting of x-rays «dust» from basic transparent ensemble (side-on view)

basic ensemble



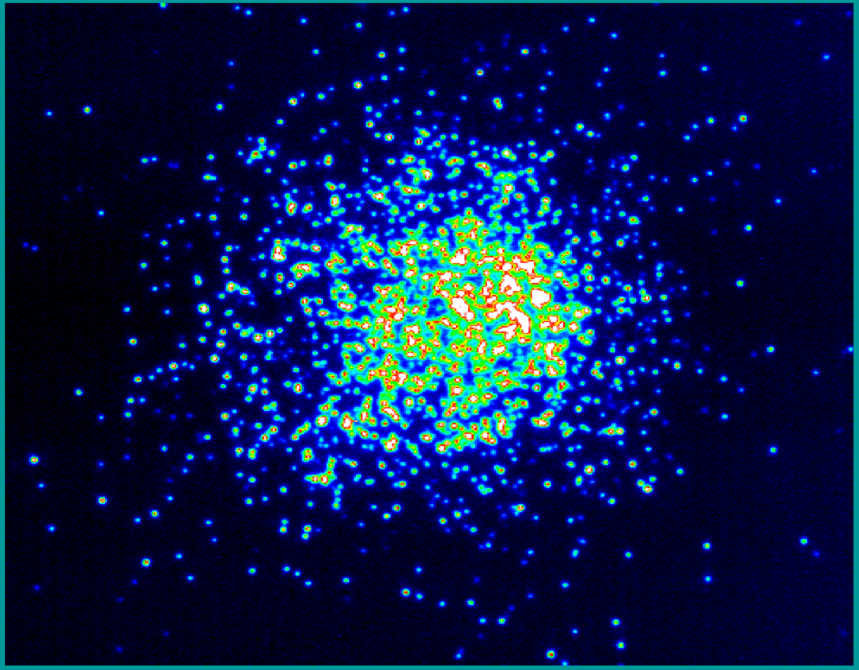
partial trapping of x-rays and fast ions

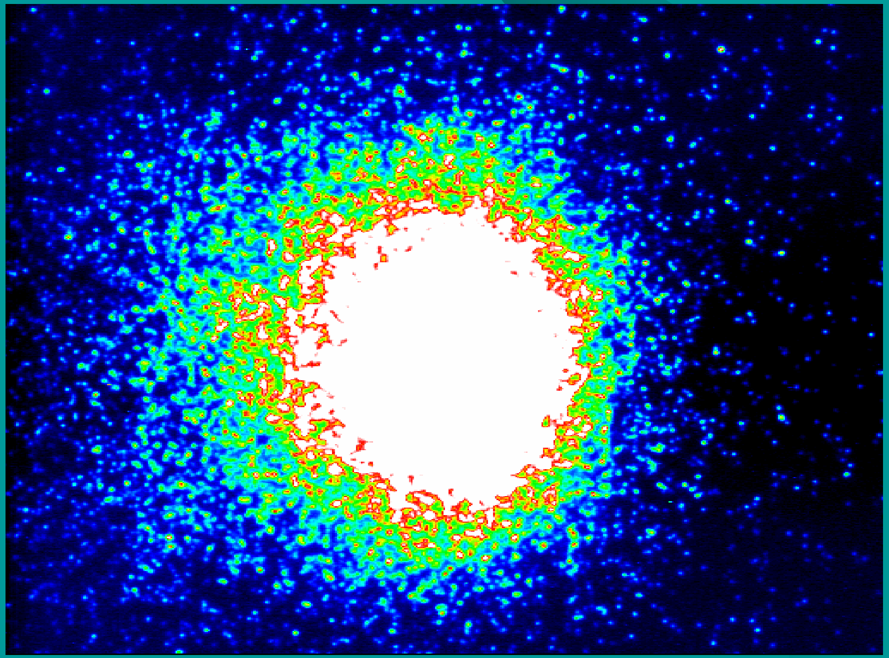


Transition from from basic "transparent" ensemble to dense self-organized ensemble

basic ensemble

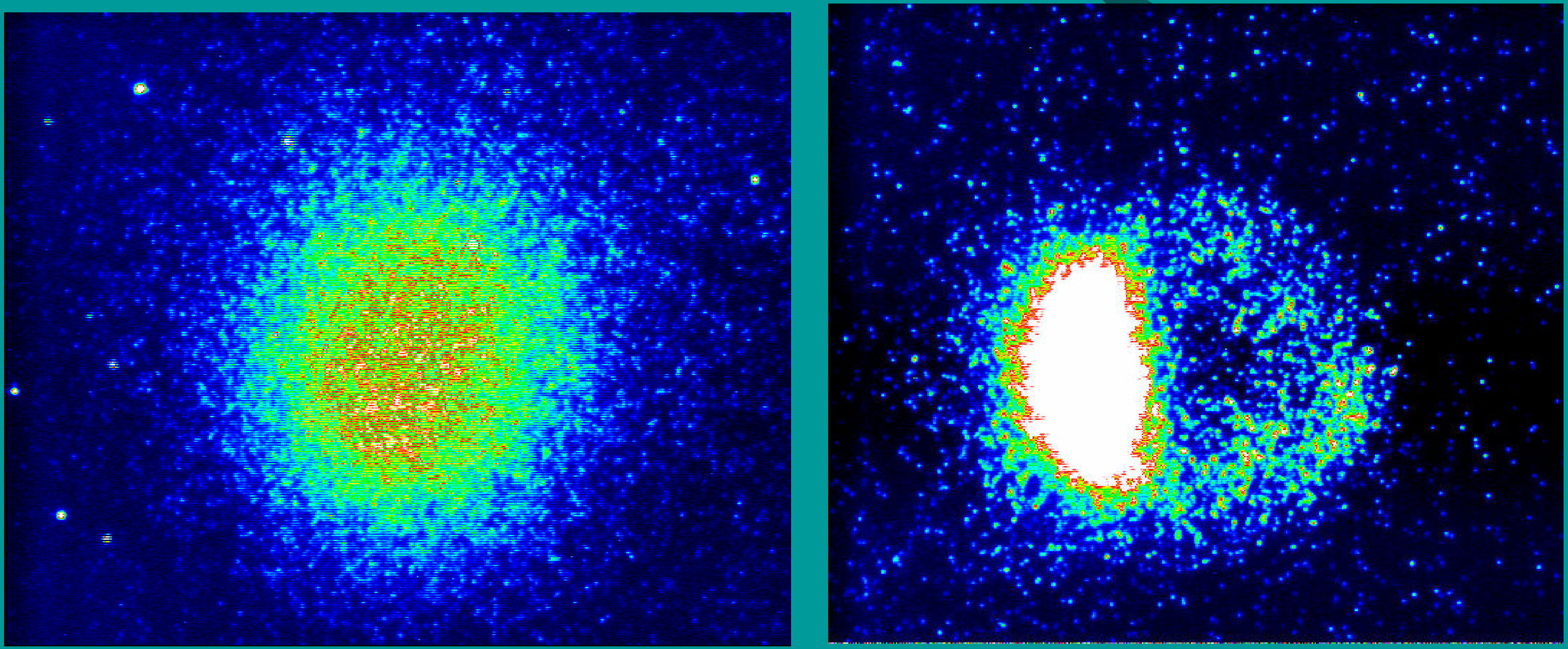
partial "trapping"of x-rays and total one for fast ions





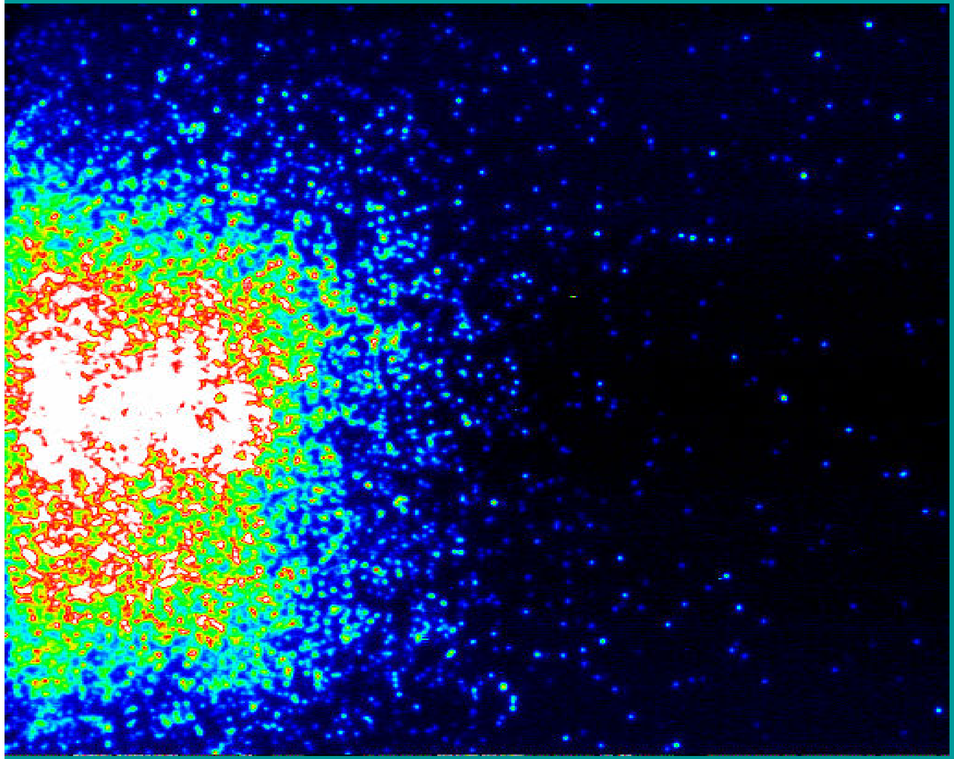
End-on view through the hollow cathode:

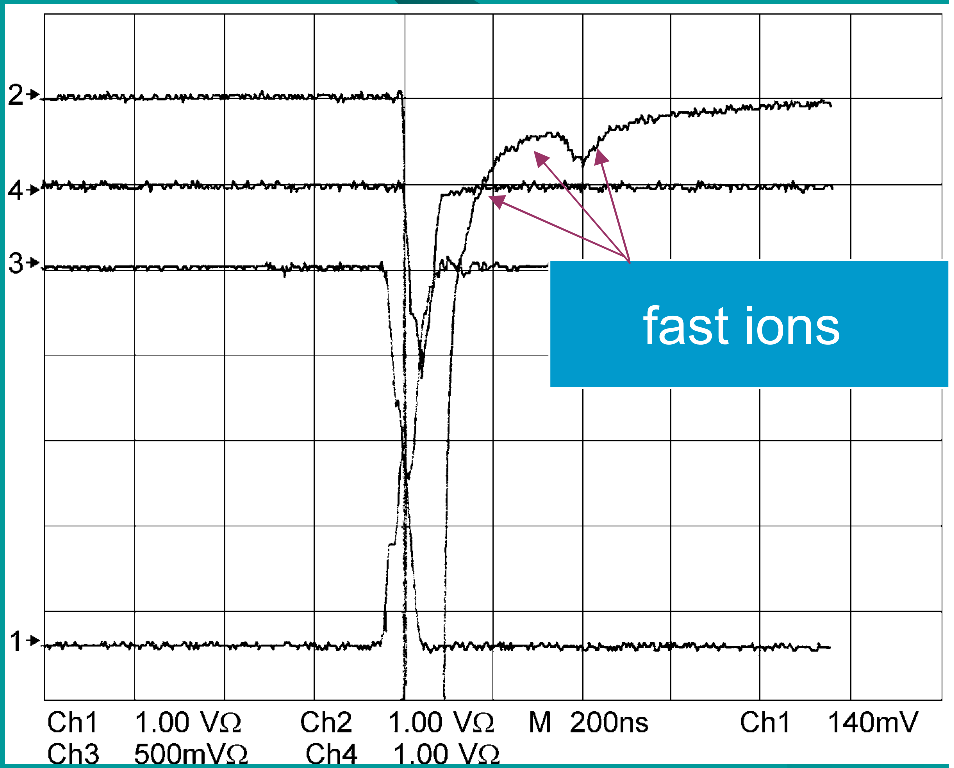
a) ensemble is outside of cathode b) or inside the cathode



Fast ions yield (TOF peak), $v_i \sim 10^8$ см/sec

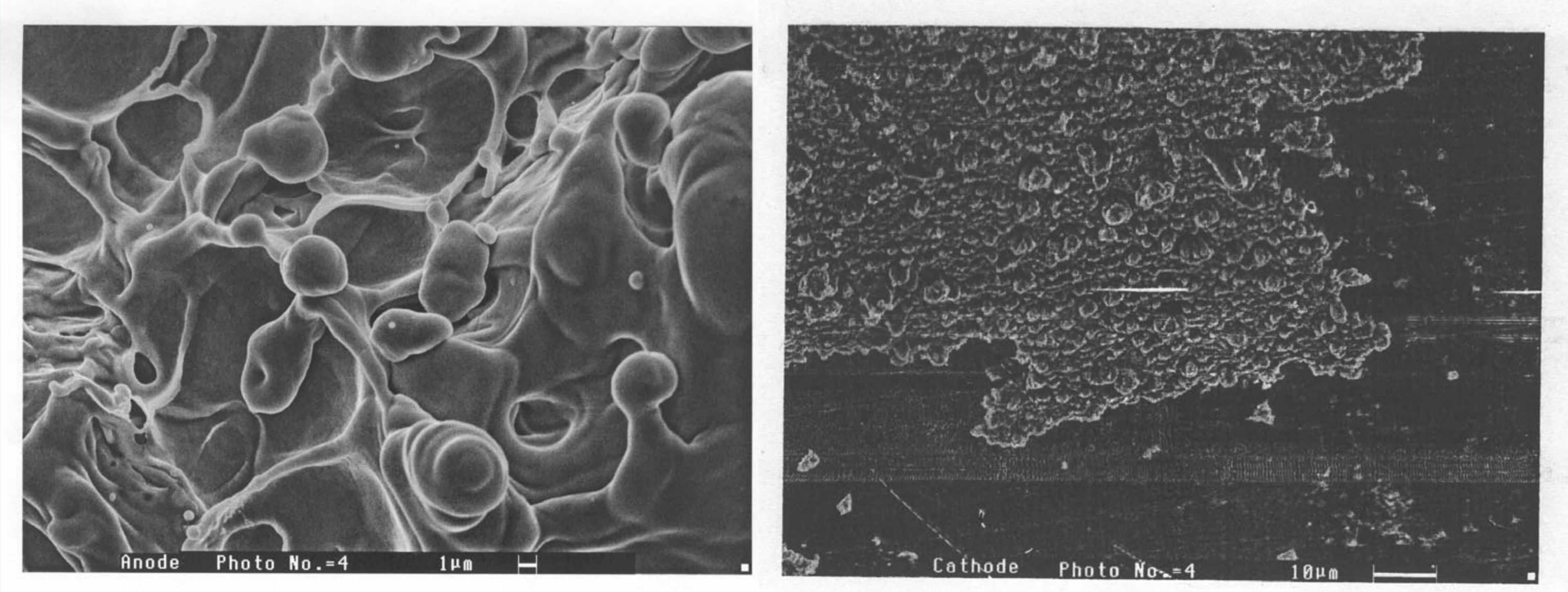
0306tri2_TOF





fast ions

Anode working edge (a) and internal surface of hollow cathode (b) accumulating anode material as nano - and microparticles along discharge shots



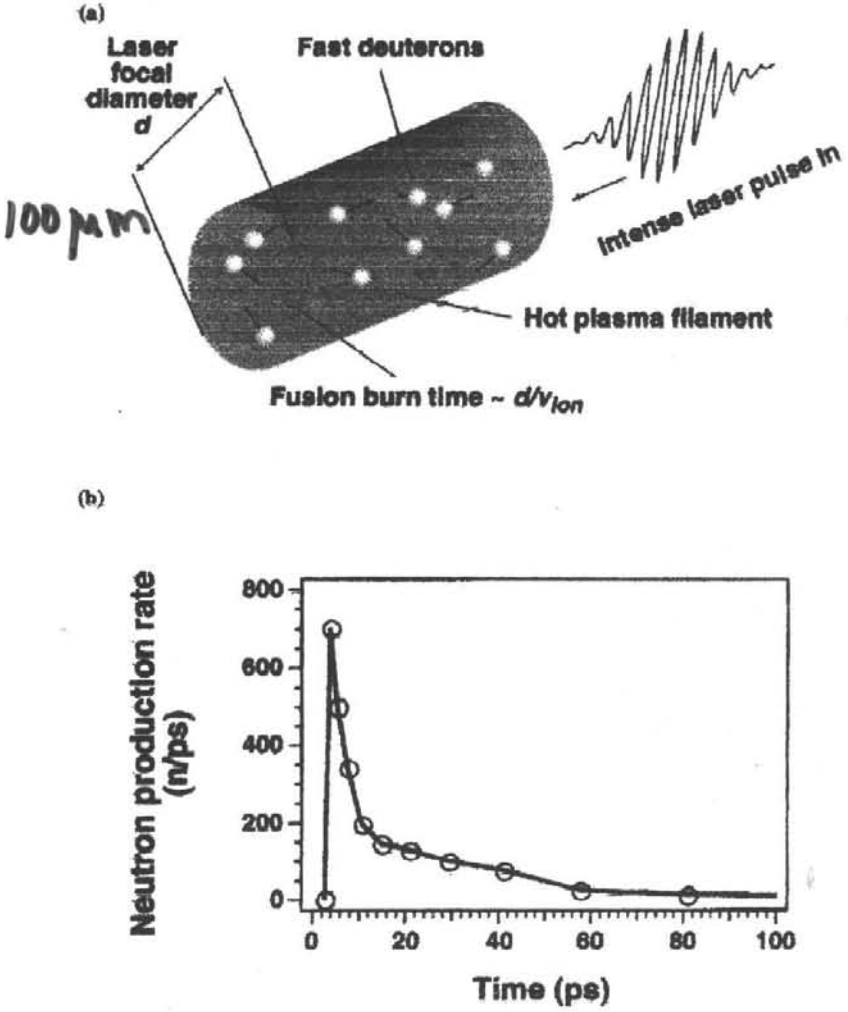


FIG. 1. (a) Experimental concept for an ultrafast neutron source. (b) Simulation showing the predicted neutron pulse width. The total pulse width is under 100 ps.

only with large-scale, low-repetition rate lasers. When large clusters (>1,000 atoms per cluster) are ionized, electrons undergo rapid collisional heating for the short time (<1 ps) before the cluster disassembles in the laser field[19]. Through various collective and nonlinear processes, the laser rapidly heats the electrons to a non-equilibrium state (with mean

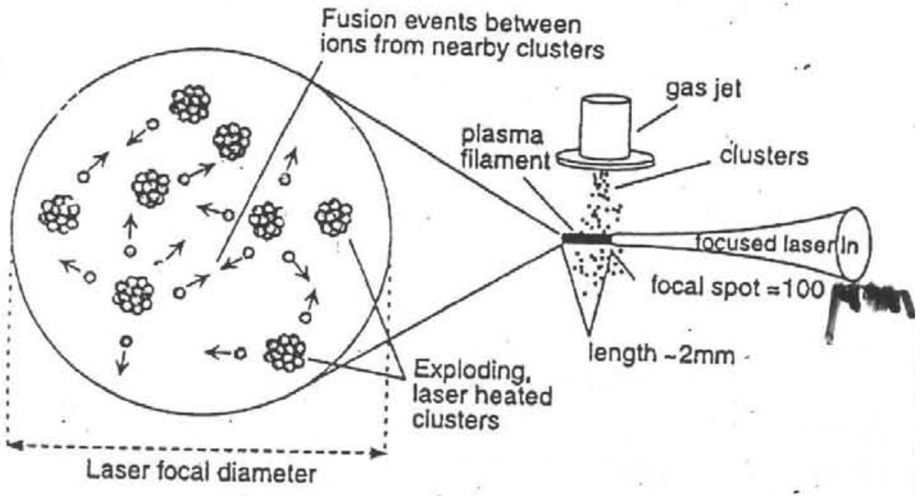
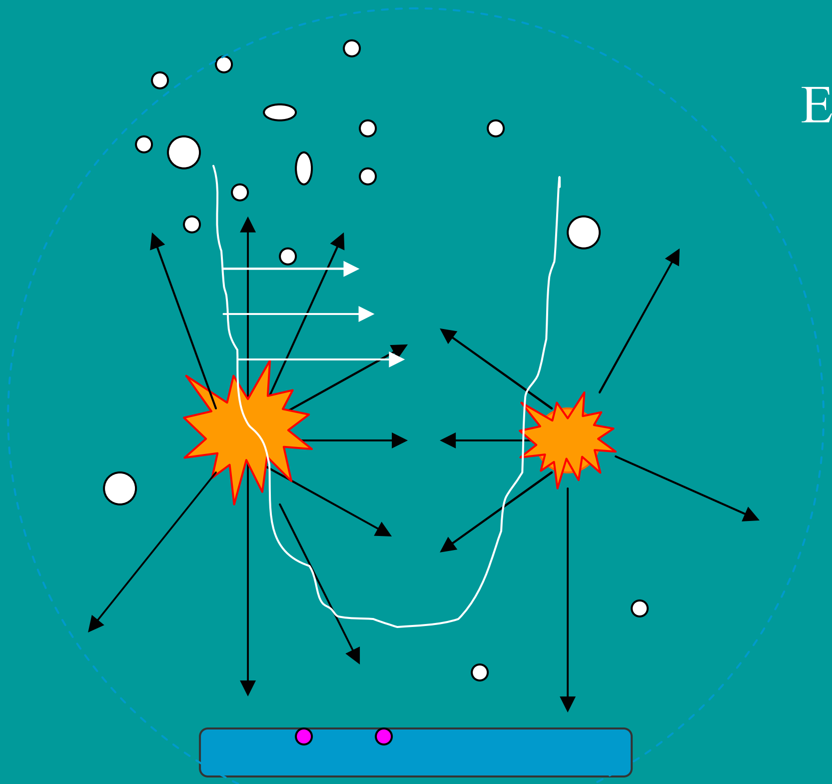


Figure 1 Layout of the deuterium cluster fusion experiment.

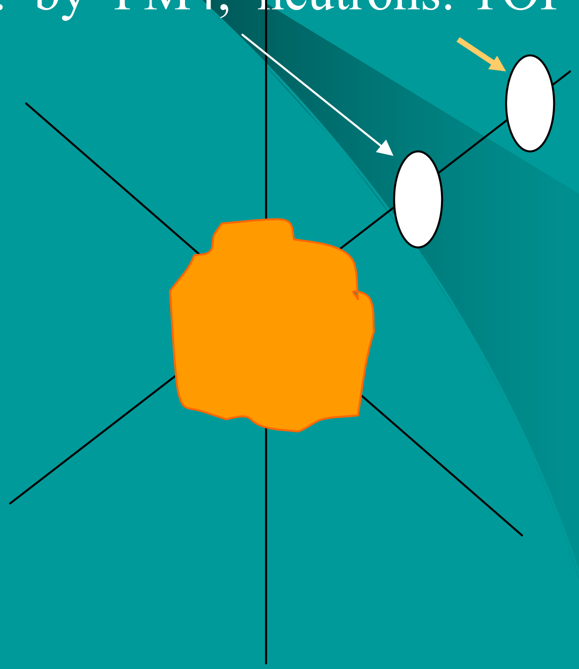
A T.Ditmire et al.*PRL* **84**(2000)634.

DD collisional synthesis. Possible mechanisms. Neutron yield study.



Deuterated Cu-Pd anode

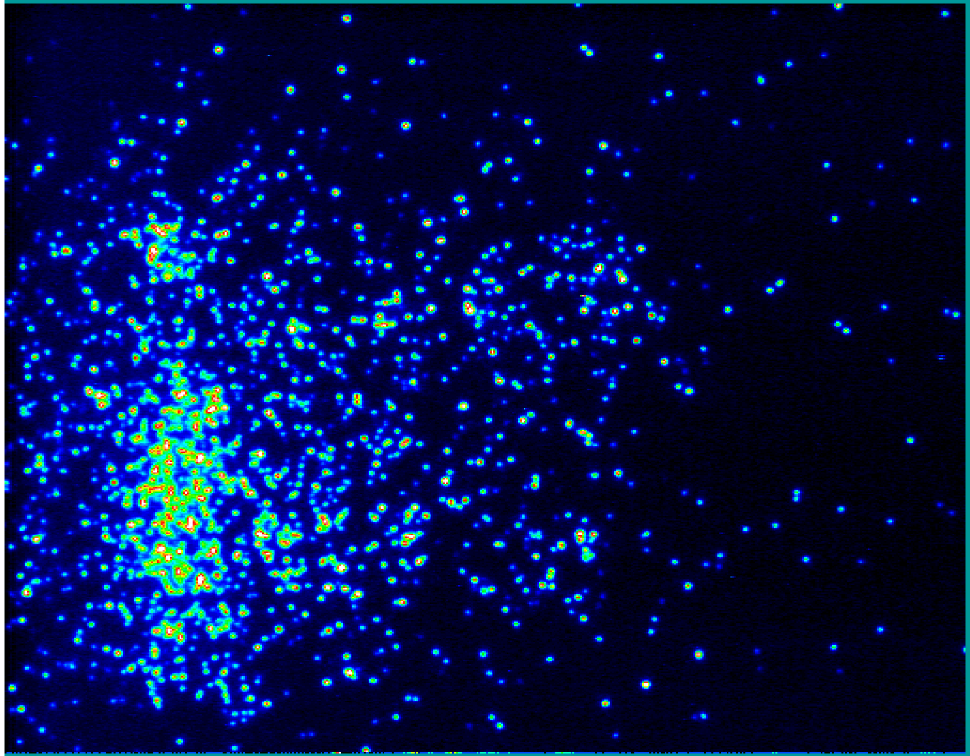
Extra x-rays: by PM4, neutrons: TOF by PM2

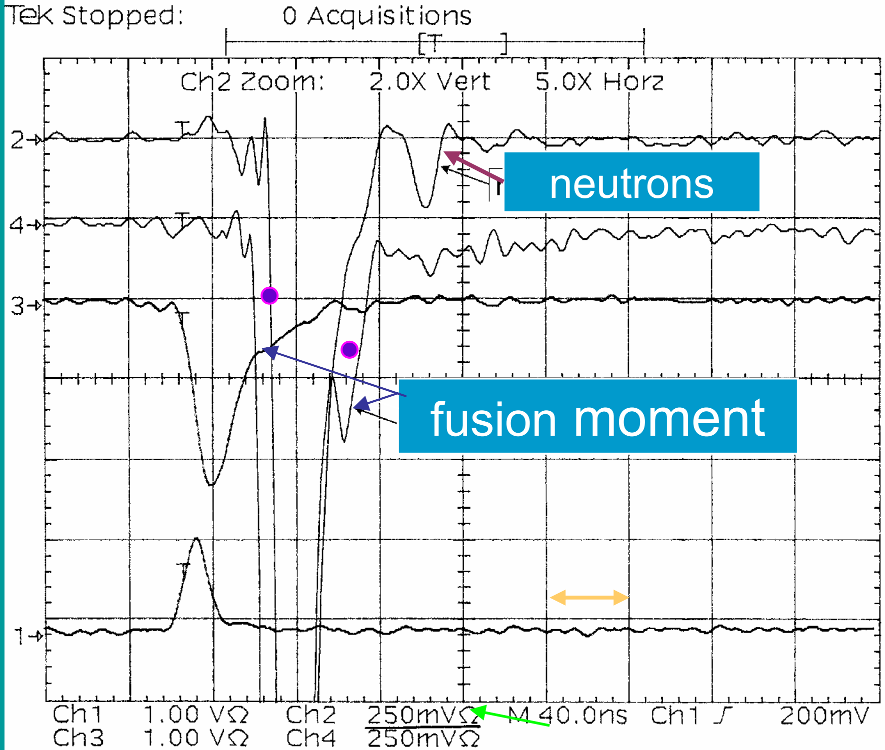


Yu.K.Kurilenkov, M.Skowronek. J.Phys.(Pramana, Indian Acad.Sci.) **61**(2003)1188

Observation of DD microfusion events accompanied by moderate neutron yield

D(D,n)He^3 → ~ 2,45 MeV neutrons, signature is 46, 6 nsec/m delayed signal at TOF (PM2 at channel 2)



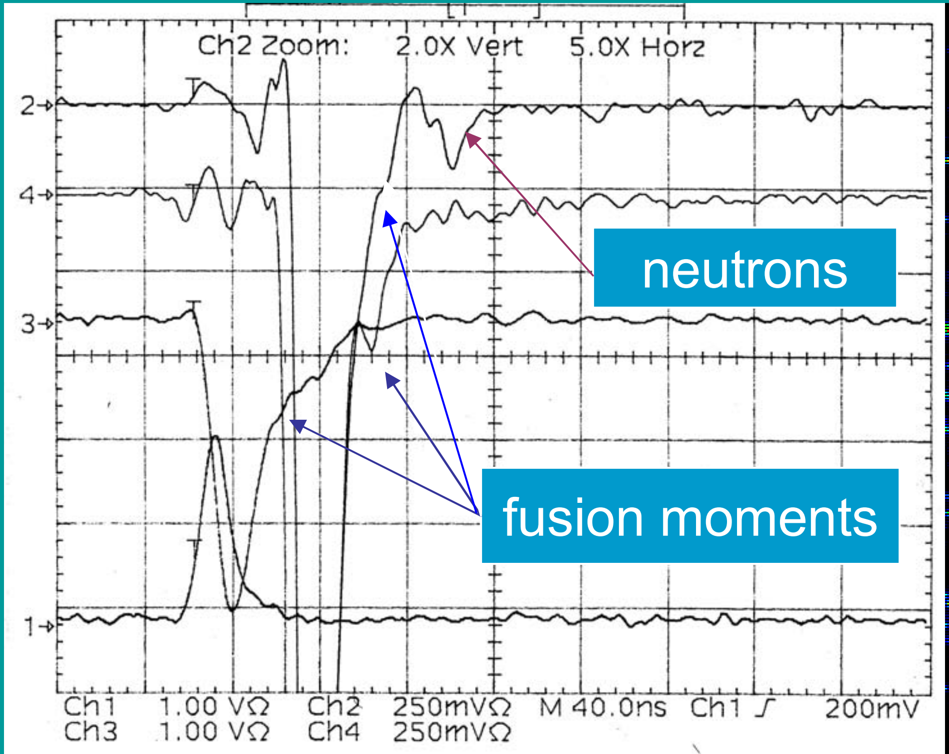


neutrons

fusion moment

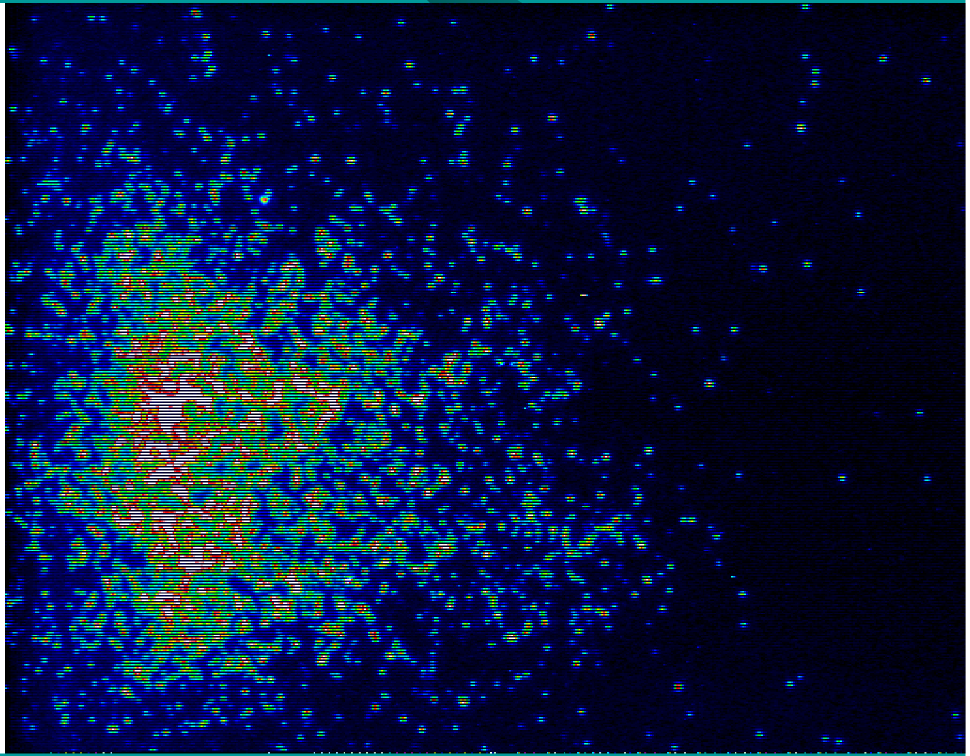
next shots from the same experimental seria. moderate neutron yield, neutron TOF signal at ch.2

(Channel 2 sensitivity is 250 mV)



neutrons

fusion moments

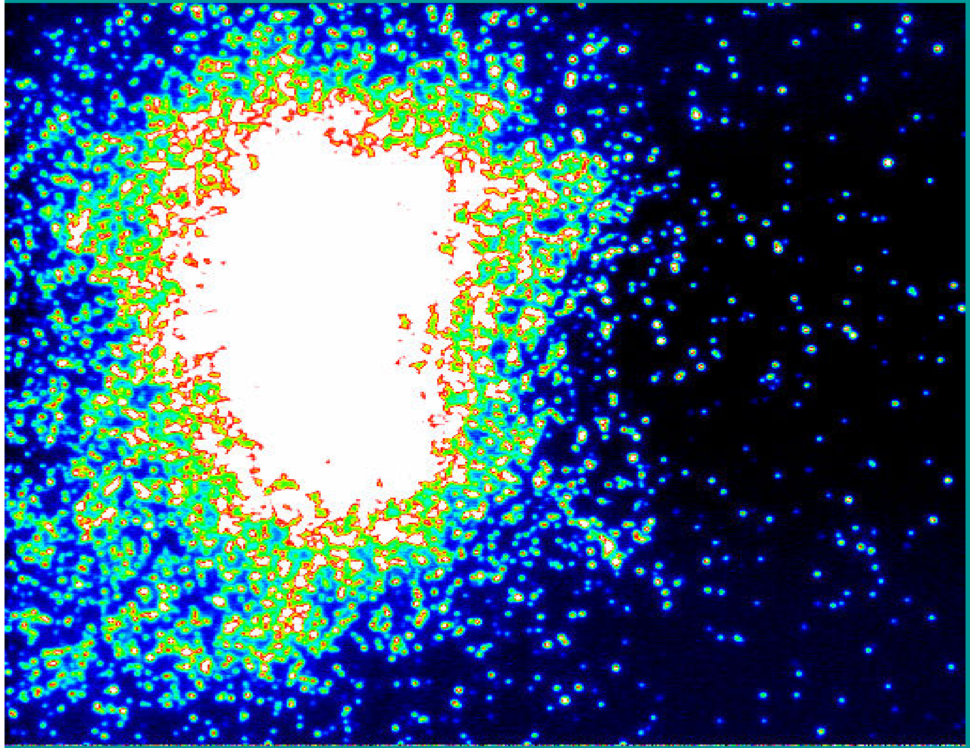


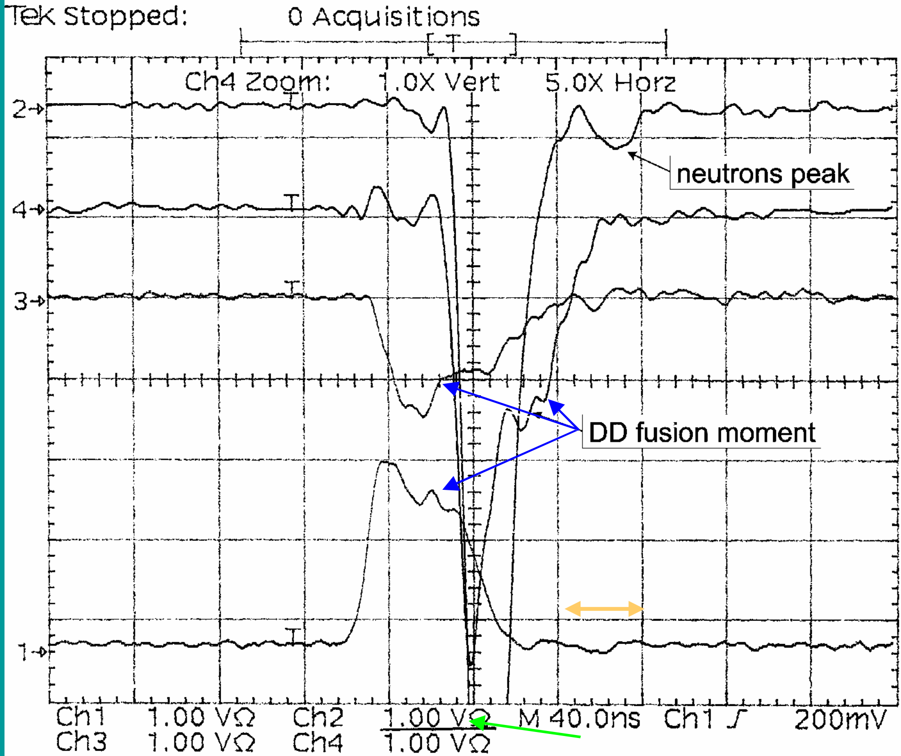
More dense aerosol ensemble with higher number of DD microfusion events

(Channel 2 sensitivity is 1 V)

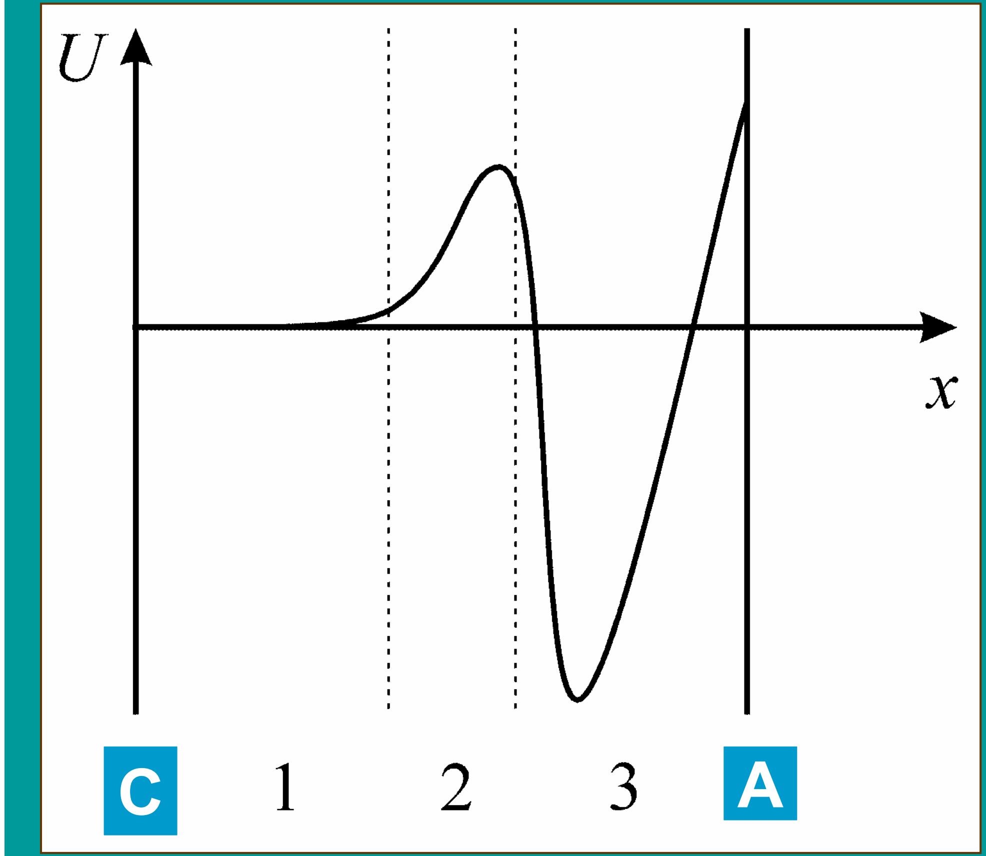
higher neutron yield, shot 1026d2 :

~ $10^6/4\pi$ per ≈ 1J .





Prehistory : Potential distribution in a vacuum diode with EEE at deep *nonstationary* potential well formation:



Deep nonstationary well during the drift of an electron beam with energy W downstream of the anode plate in vacuum:

$$e\varphi_W \sim W$$

(W. Poukey., N. Rostoker, *Plasma Physics* **13** (1971) 897).

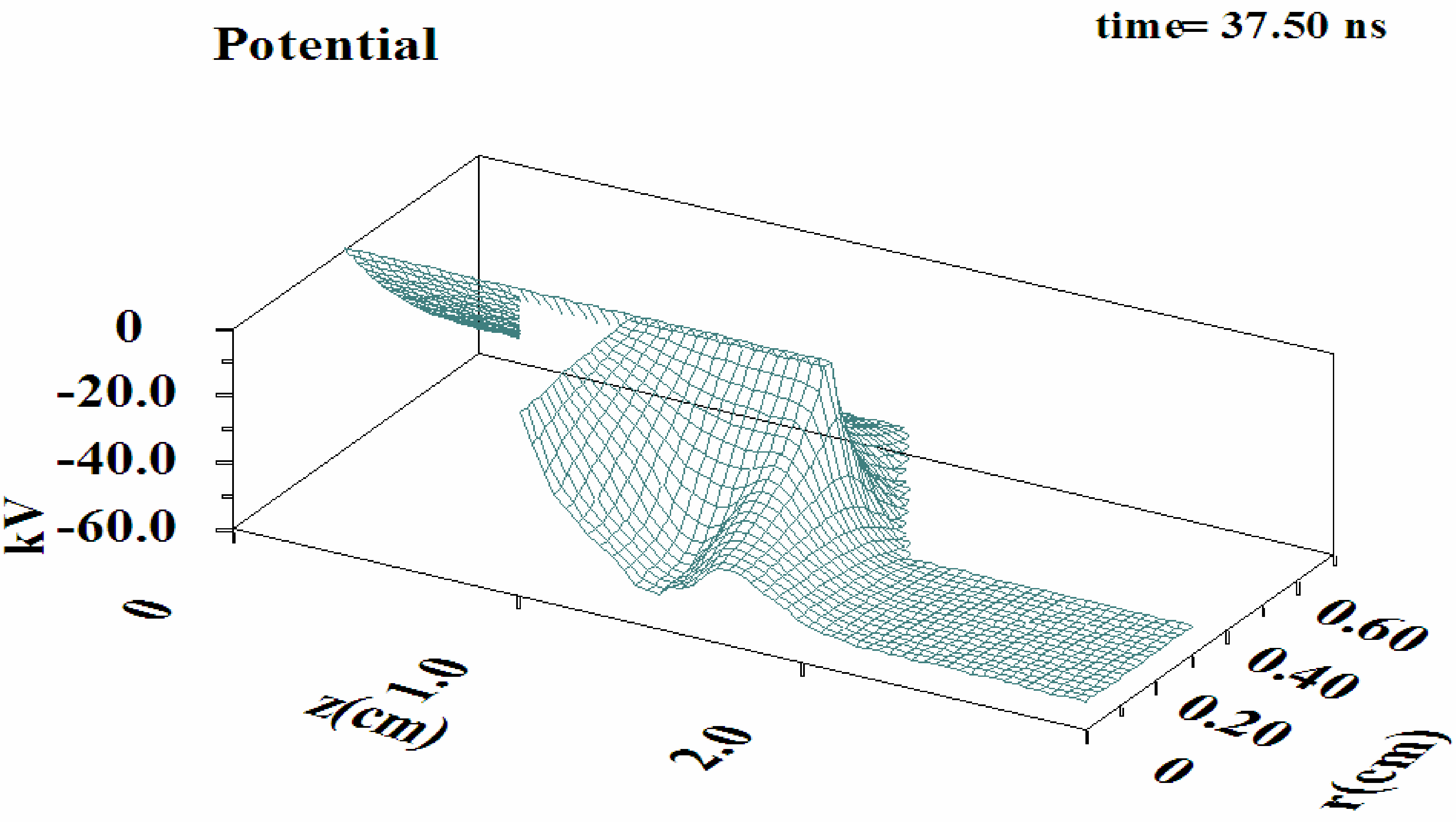
Unstable current carrying (external field applied)

1 – cathode flare plasma;
2 – charging plasma at flare front;
3 – deep nonstationary potential well.
C – cathode, A – anode

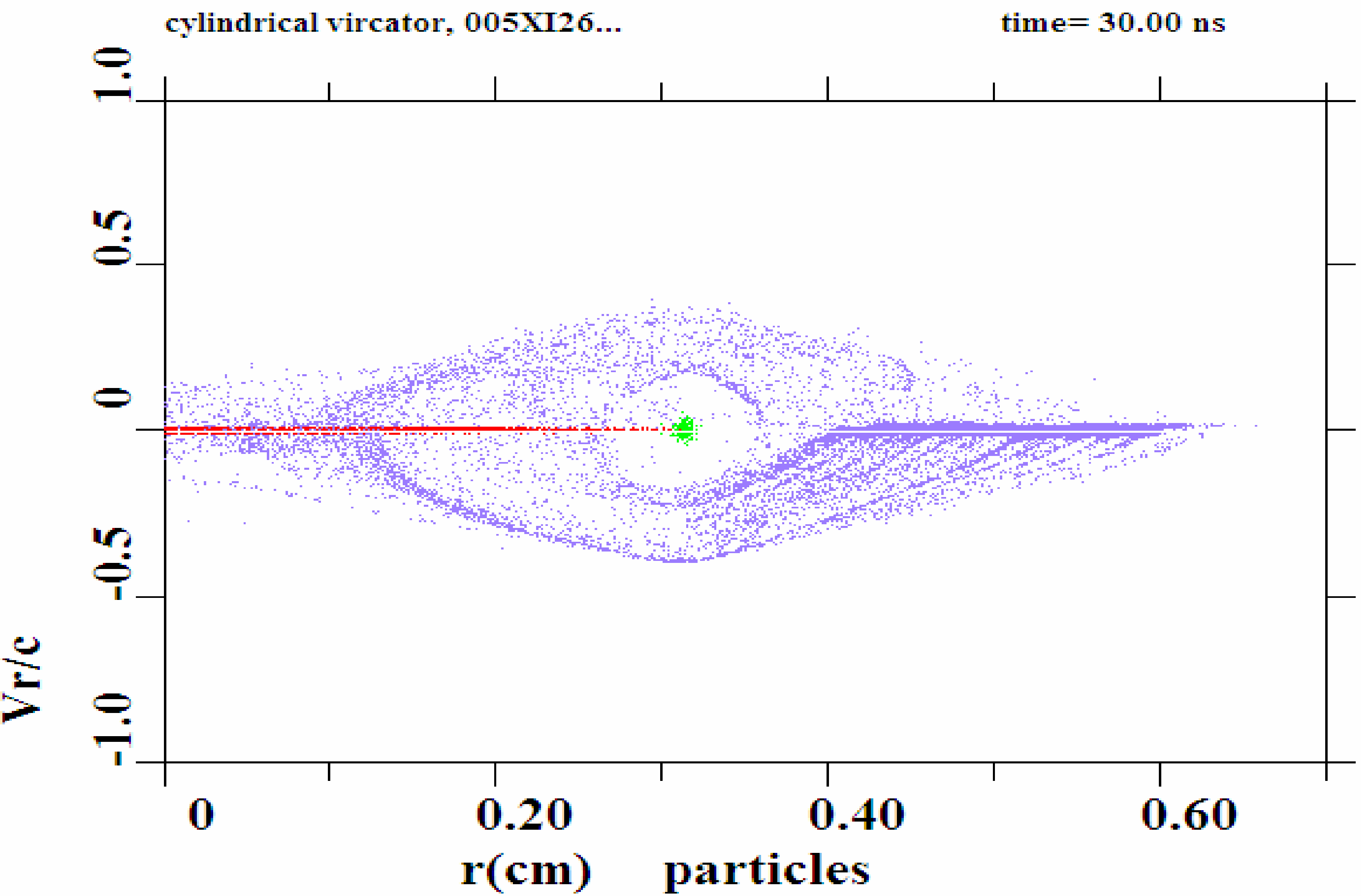
S.A. Barengolts, G.A. Mesyats*, and E.A. Perelshtein JETPh 118(2000)1358

Typical **stationary** potential well at interelectrode space under available experimental conditions. PIC simulations

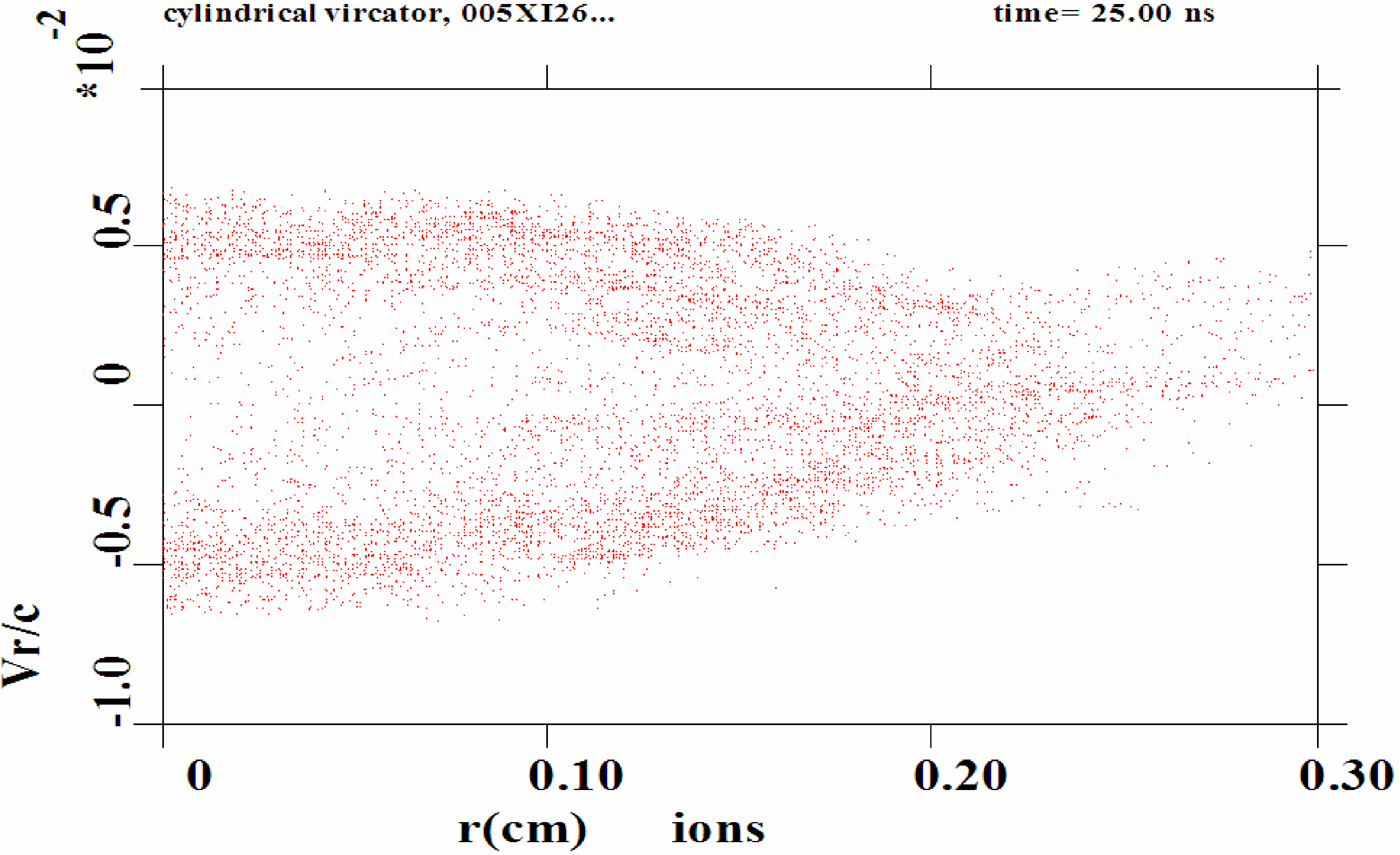
(the deepness of well is up to 80% of voltage applied)



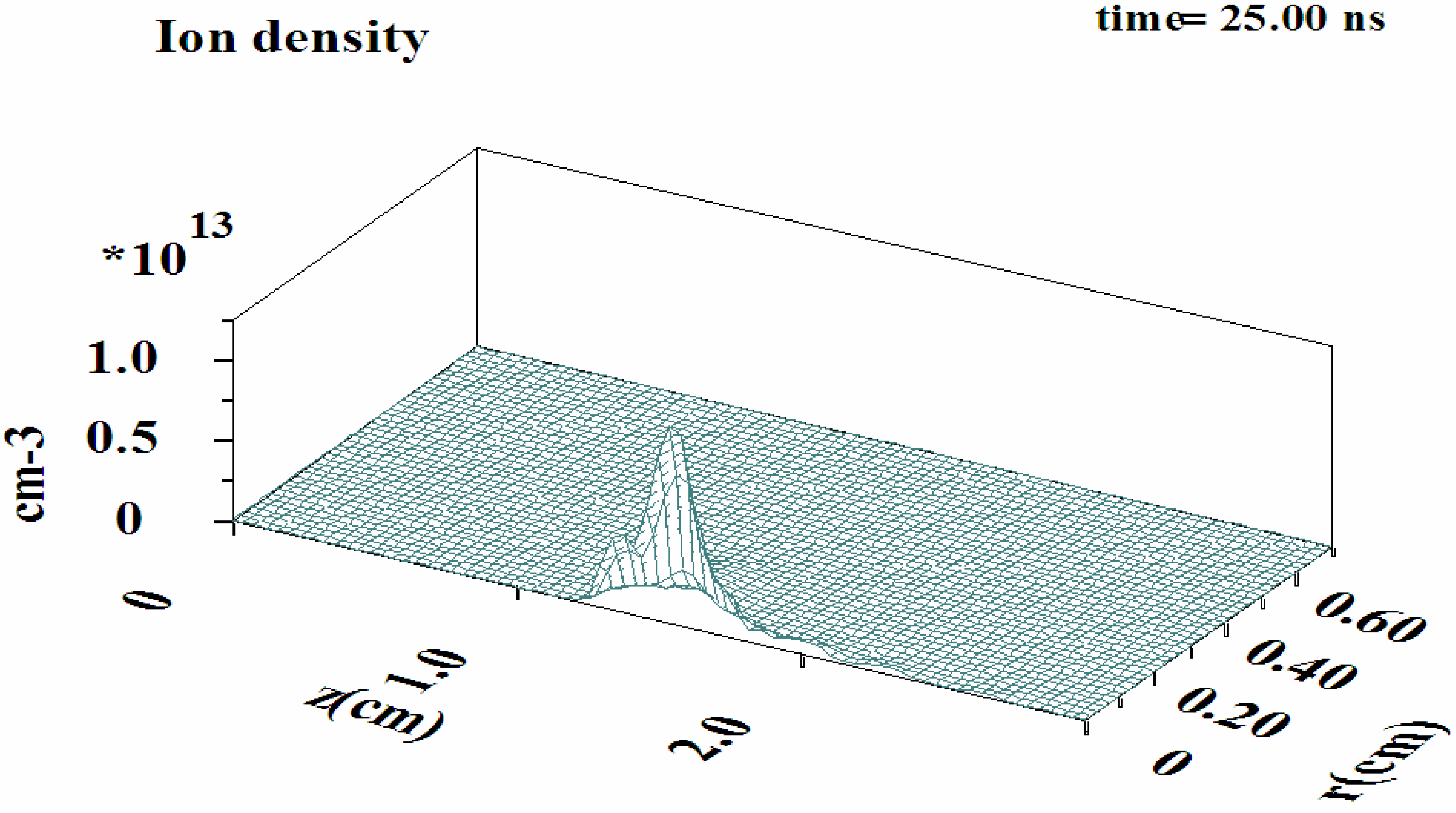
Phase portraite of particles under virtual cathode formation (blue – beam electrons, red – ions accelerated by virtual cathode, green- anode plasma). PIC simulations.



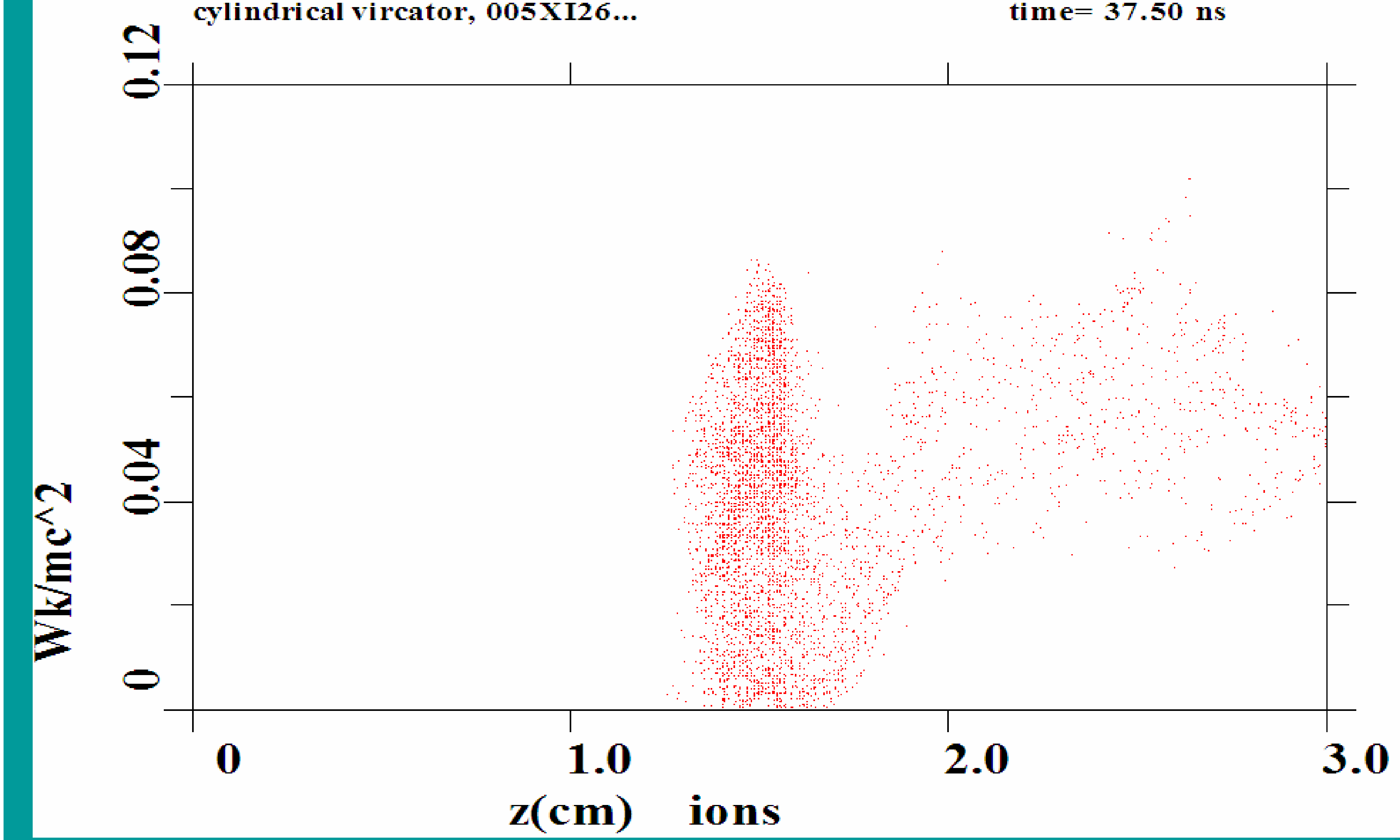
Radial velocities of deuterium ions as function of radius (W_i^{max} = 52 keV, W_i^{mean} = 21 keV)



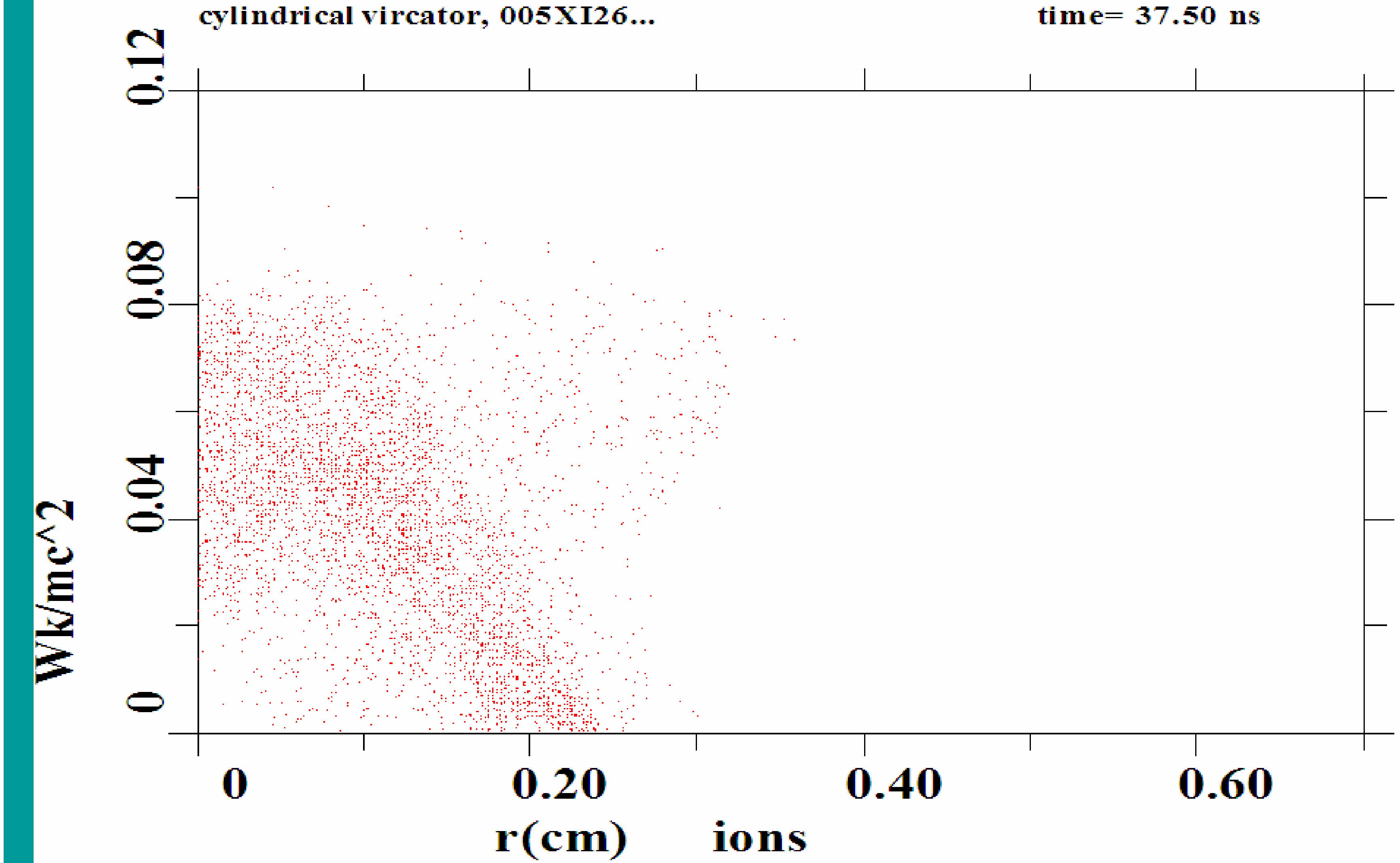
Particular density of deuterium ions, accelerated by virtual cathode and concentrated at the bottom of potential well



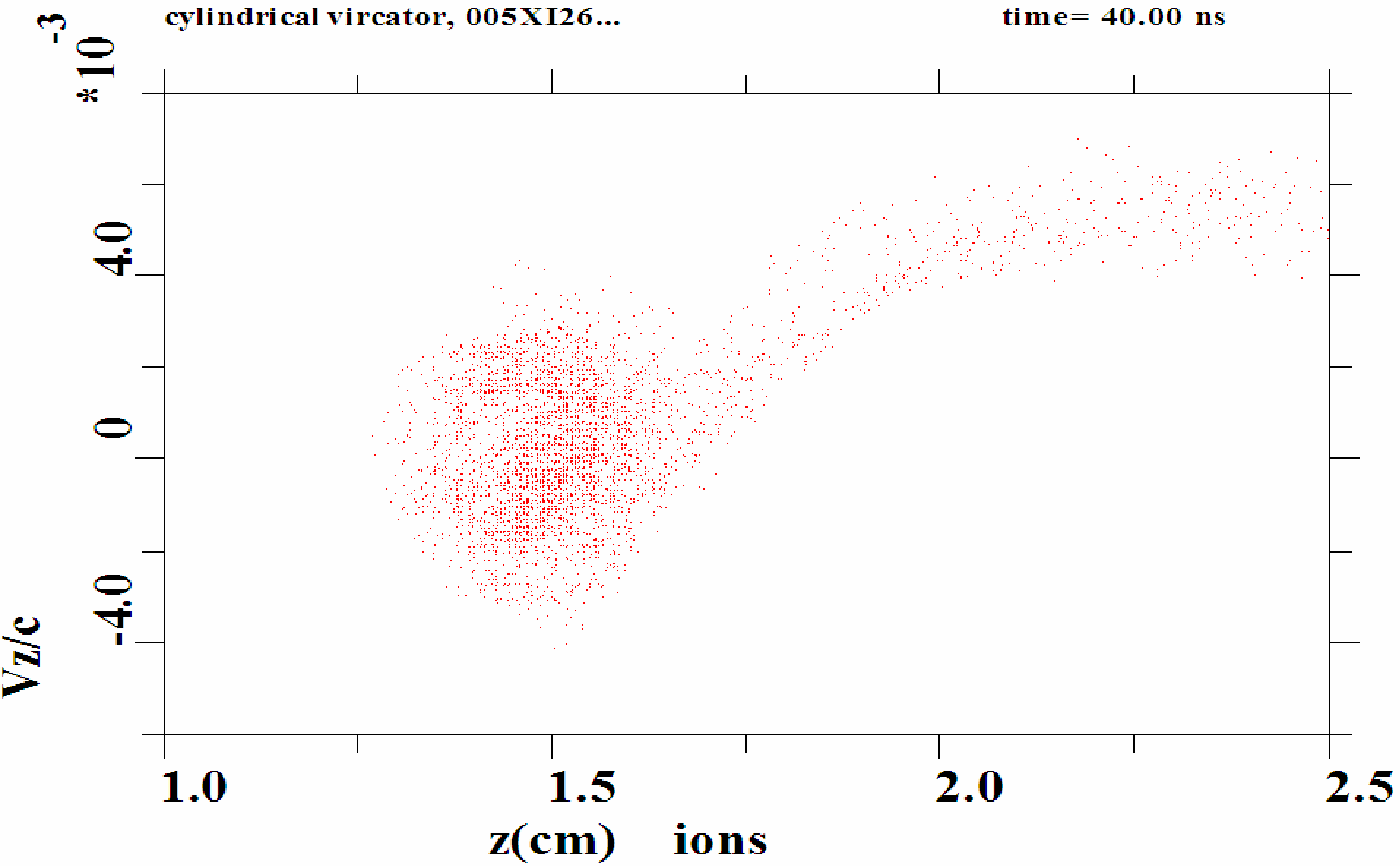
Energy of ions as function of their axial position (near the minimum of potential well, z= 1.5)



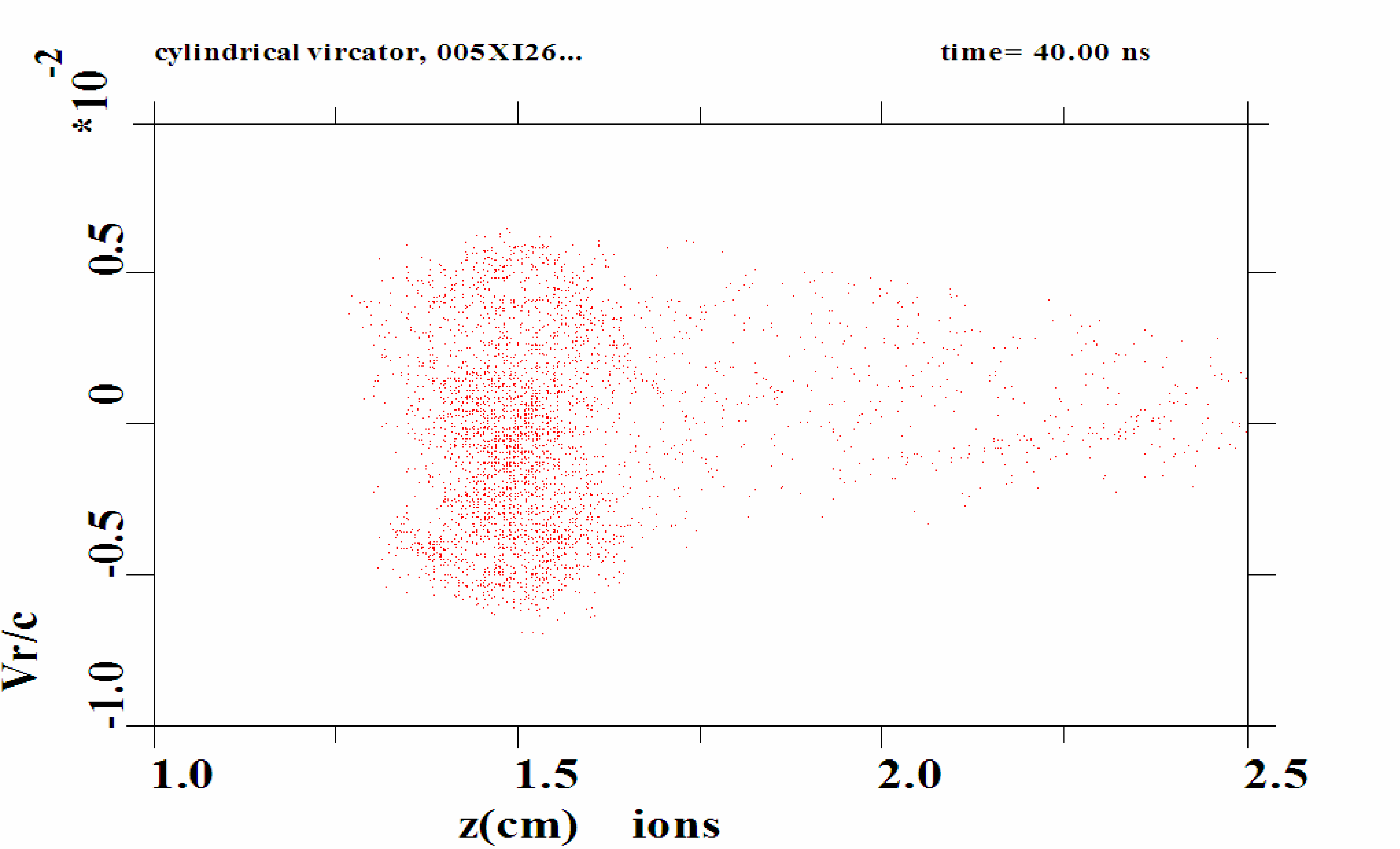
Energy of ions as function of their radial position



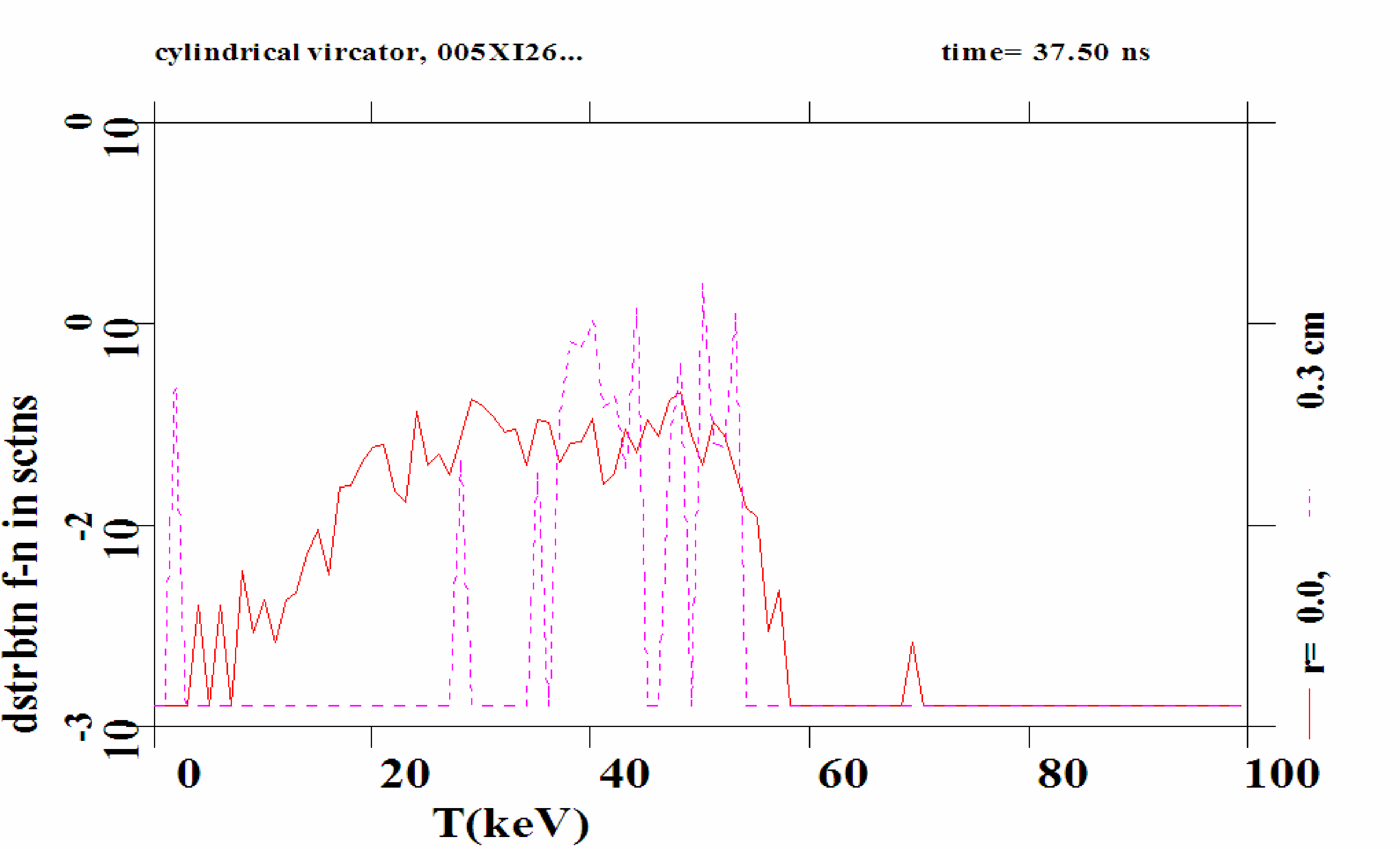
Axial velocities of ions in the “chamber”



Radial velocities of deuterium ions at the "chamber" (W_i^{max} = 50 keV, W_i^{mean} = 14 keV)



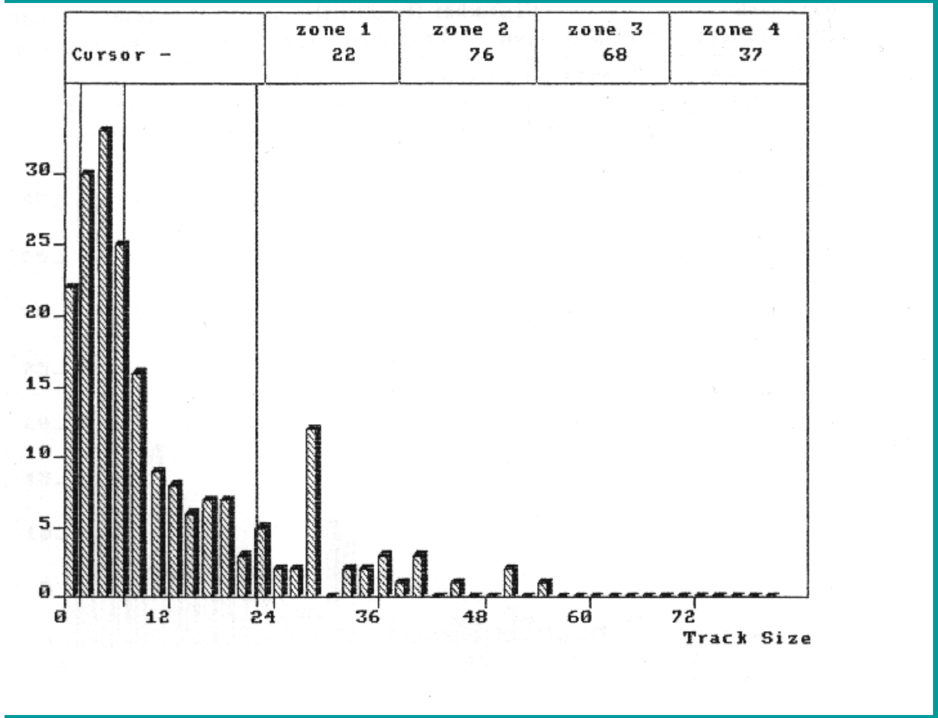
Distribution functions for ions at the axis (r=0) and near the upper edge of potential well (r=0.3)

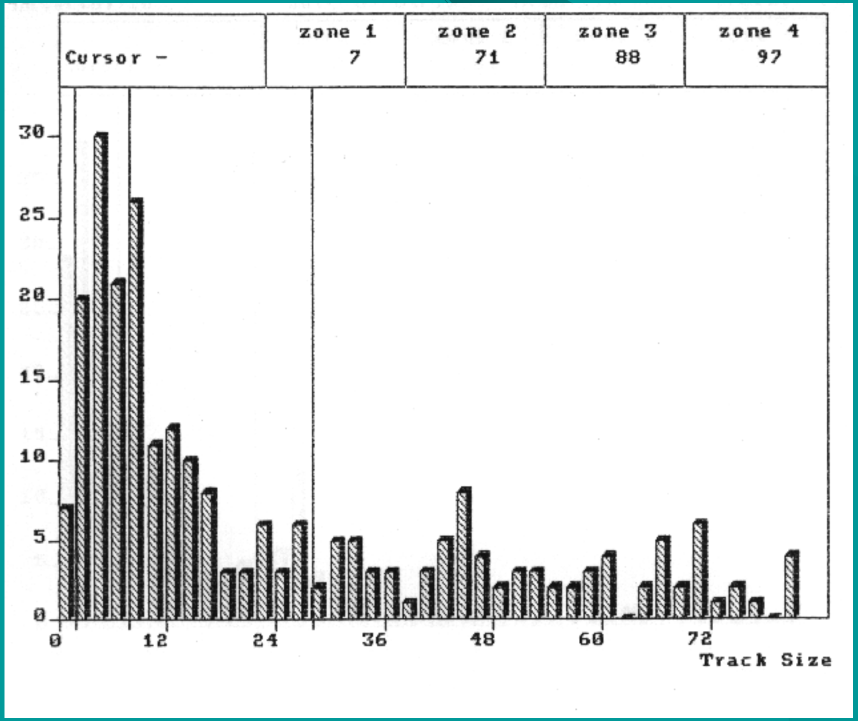


Number of fast ions tracks versus CR-39 track sizes (~ ions energies). « Plateau » at energy distribution of fast ions at early experiments

Standard anode: maxwellian plasma

Modified anode for high energy (up to ~ 3 MeV) tail of ions: non-maxwellian plasma

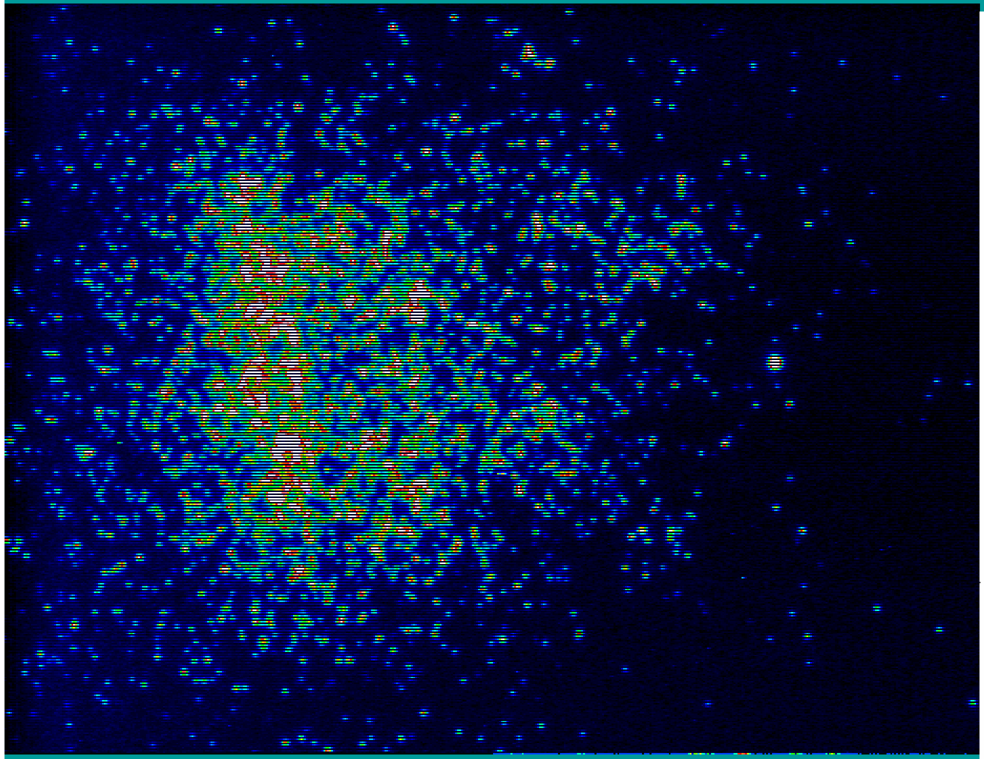


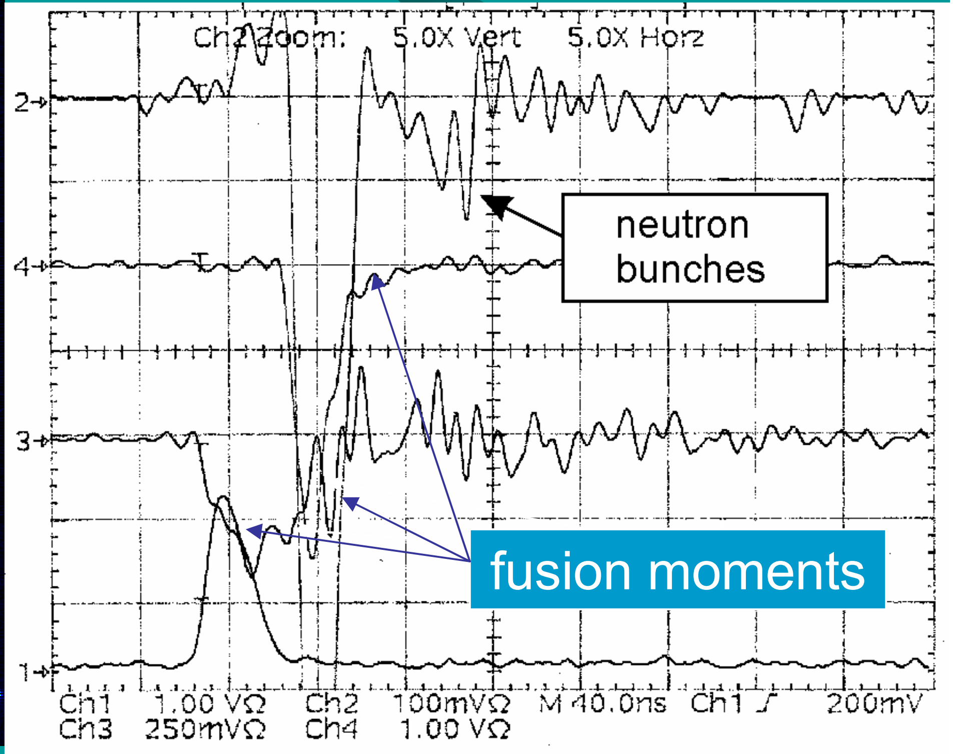


In summary, besides of single fusion neutrons peaks for dilute ensembles, two specific types of interelectrode ensembles with neutron and x-rays yields are recognized at experiment.

Type 1: multiple fusion (*pulsating* neutron yield)

0525tri7





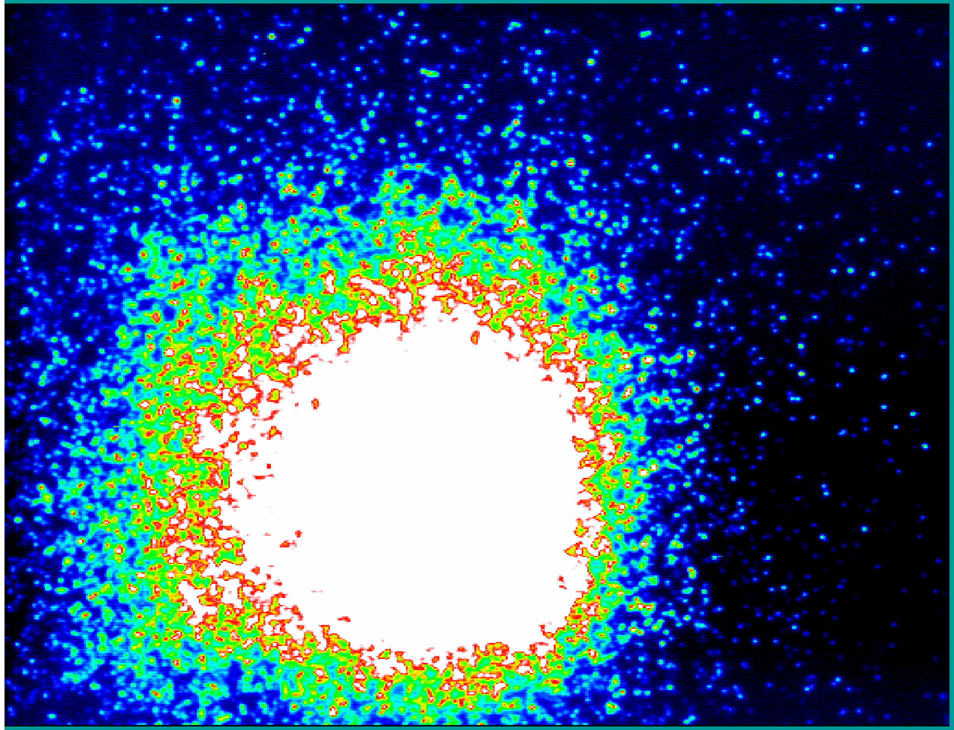
neutron bunches

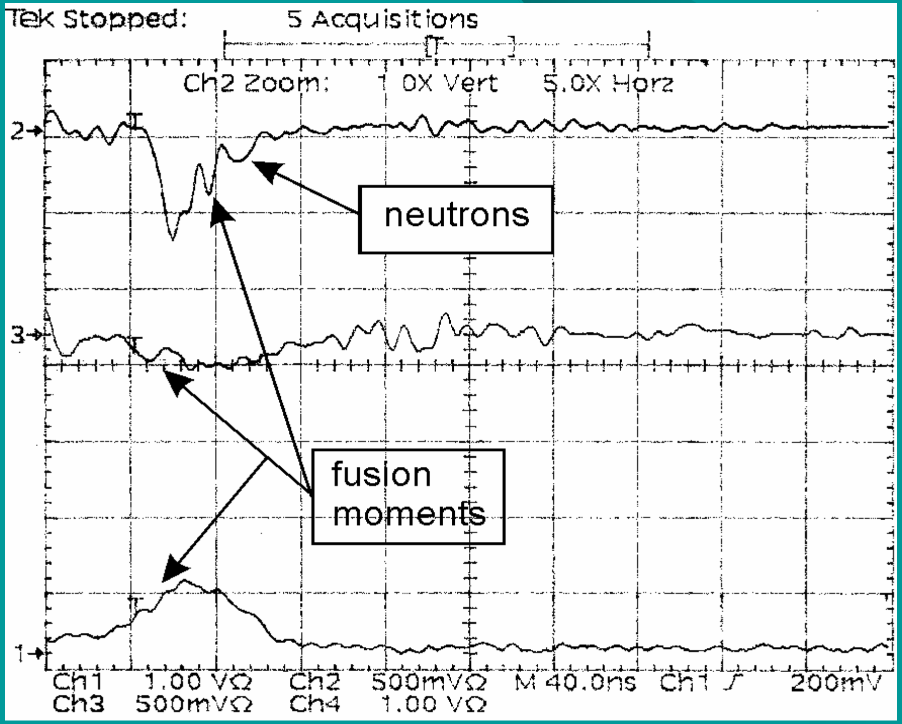
fusion moments

Type 2: dense ensembles with total *trapping of fast ions and partially « diffused » hard x-rays* (inside of cluster ensemble)

Diffusion (delay) of lower energy hard x- rays (ch.1,3). Release of harder x-ray. Enhanced neutron yield from the « ball » (sensitivity of ch.2 is 500 mV, 0426D1)

Neutrons leave the « ball » at the same time or earlier than diffused x-rays

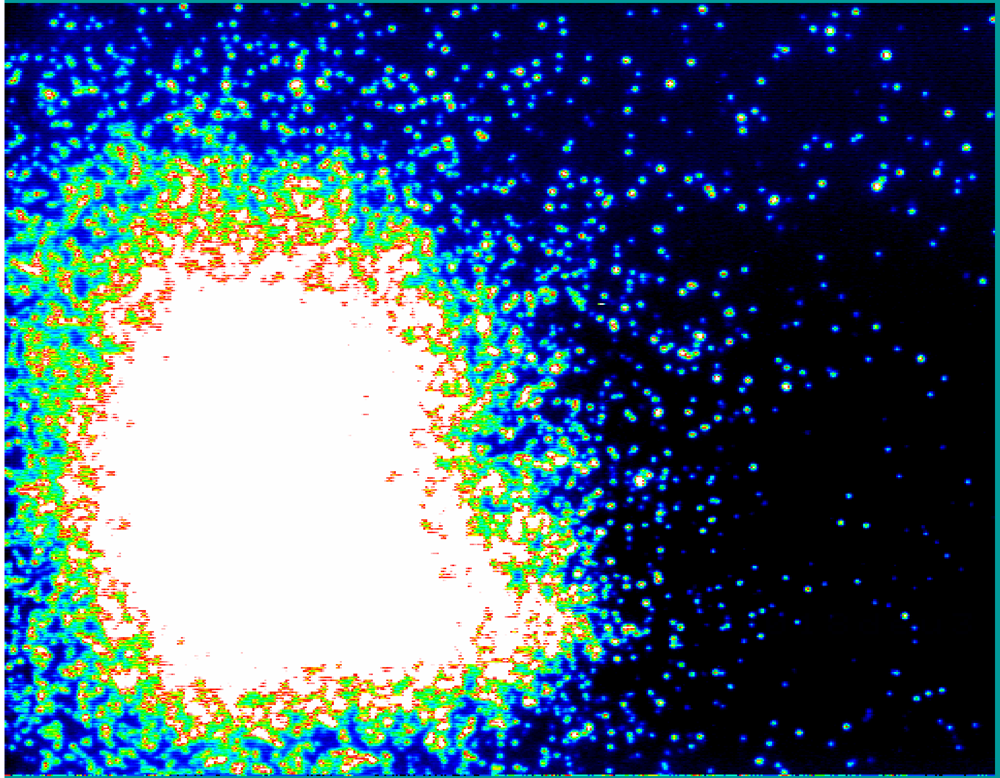


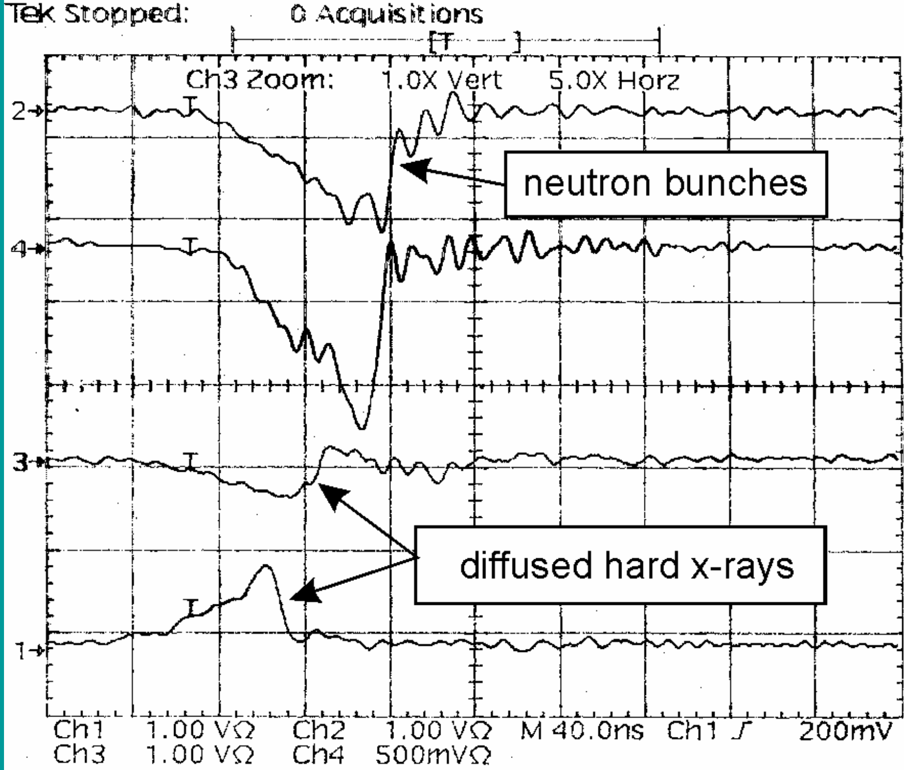


Combination of advantages of types 1 and 2: essential x-rays diffusion and manifestation of higher pulsating neutron yield (due to *multiple fusion events)*

(rare example of « microreactor »-like regime)

1018D3, ch.2 -1 V, ch.4- 500 mV



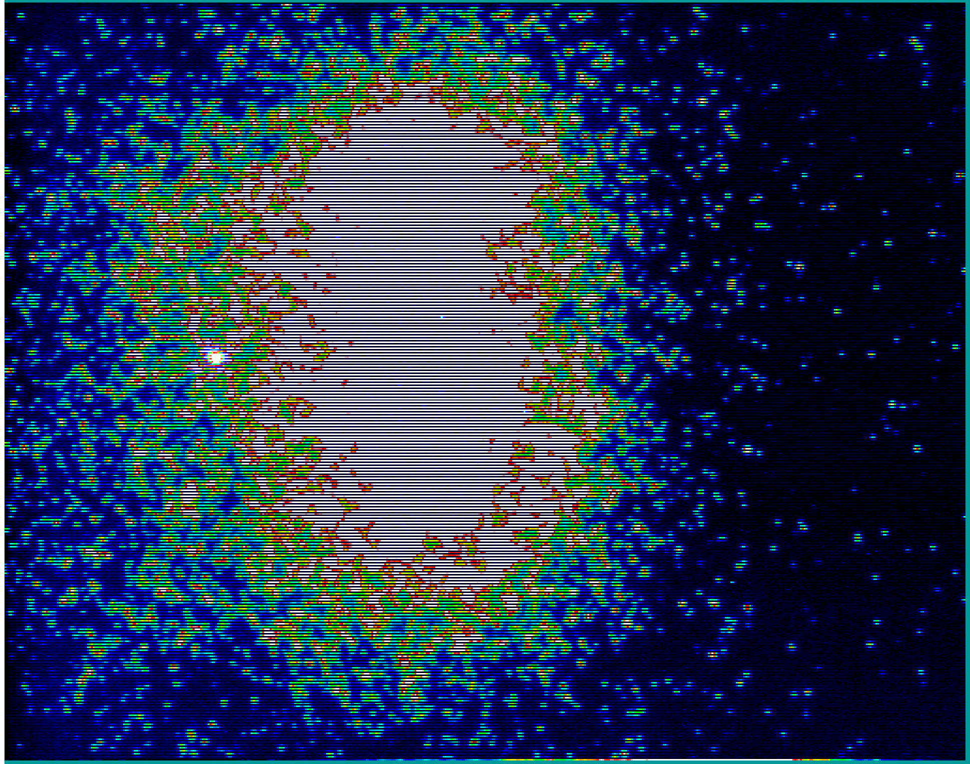


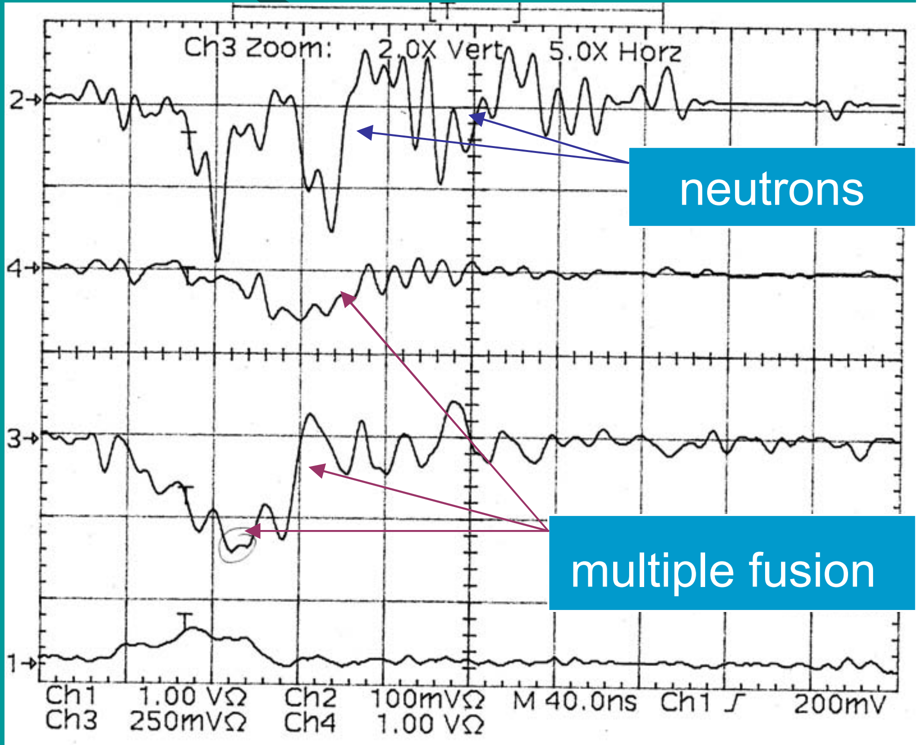
neutron bunches

diffused hard x-rays

Typical example of ensemble with well-defined « modulation » of x-rays intensities at ch.3 and ch.4 by extra x-rays due to multiple fusion events accompanied by intermitent neutron yield

(0522D4, PM2+Pb)





neutrons

multiple fusion

Estimation of neutron yield from DD fusion

Beam-beam, beam –neutrals and beam- clusters channels of fusion

Estimation from PIC modeling (just beam-beam channel)

$N_{neutrons} = n_i^2 < \sigma \upsilon > V \tau \sim 10^4 - 10^5 / 4\pi$ (per 1 J)

Our experiment : $N_{neutrons} \sim 10^5 – 10^7 / 4\pi$

(under assumption that yield is isotropic one !)

Yu.K.Kurilenkov, M.Skowronek, J.Dufty. J.Phys.A: Math&Gen v.39 (2006) 4375

Fusion power density, P_{fusion} , at rather similar systems with inertial electrostatic confinement (IECF). Example of periodically oscillating plasma spheres (POPS) with frequency

$\omega_{POPS} \sim (2 \varphi / r_{VC}^2 \; m_i)^{1/2}$ $\mathbf{P_{fusion} \sim \varphi^2 < \sigma \upsilon > / r_{VC}}$

J.Park, R.A.Nebel *et al* Phys.Plasmas 12, 056315 (2005)

Current experiments at LANL

Schematic of particular Inertial Electrostatic Confinement Fusion (IECF) device

J.Park, R.A.Nebel *et al* Phys.Plasmas **12,** 056315 (2005)

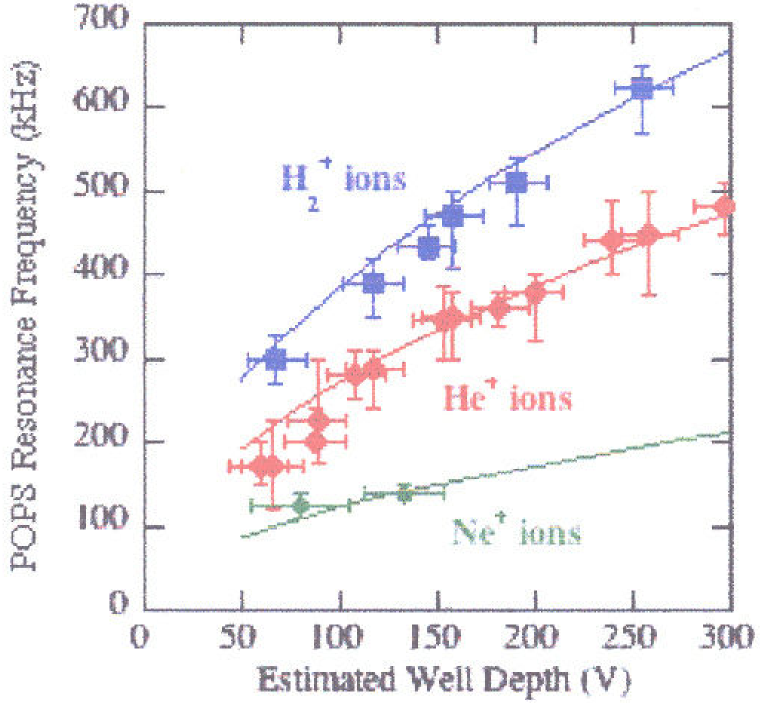


FIG. 4. Comparison between the experimentally measured resonance frequencies due to POPS oscillation (points) and the theoretical calculations (lines) as a function of potential well depth in the virtual cathode and ion mass. (Reproduced from Ref. 19.)

Phys. Plasmas **12**, 056315 (200

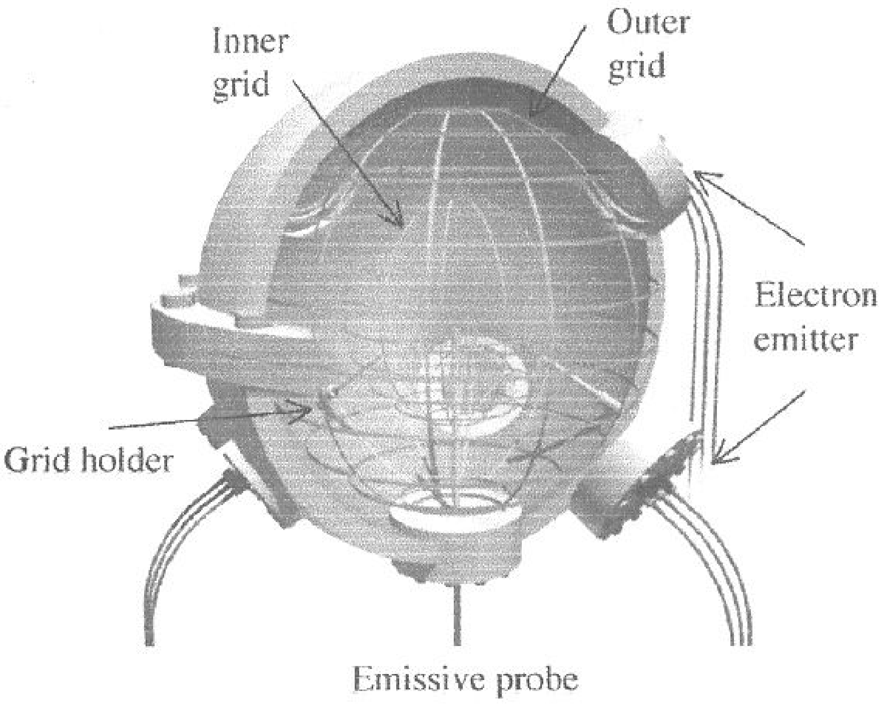


FIG. 1. Schematic of the INS-e device.

Attractivness of IECF schemes (by J.Nadler)

- non-Maxwellian Ion Energy Distribution
- non-linear scaling of reaction rate with current
- plasma target fusion specifics
- non-ignited plasma
- compact size and low reactor rate

Concluding remarks:

-The estimated value of the **neutron yield from DD microfusion** in the interelectrode space at small-scale experimental set-up is variable and amounts to ~ 10^{5}- $10^{7}/4\pi$ per shot (under isotropic approximation) under ≈ 1 J of total energy stored to create all discharge processes. **PIC simulations confirm the same order of neutron yield** for used electrodes geometry.

-In a **limiting case of total trapping of fast deuterium ions** by the dense "dusty cloud" of clusters under partial hard x-rays diffusion inside, pulsating neutrons yield have maximum values (*table-top complex plasma "micro reactor"*) being up two order of magnitude higher than for experiments on DD fusion driven by Coulomb explosion of laser irradiated deuterium clusters (T.Ditmire et al. *PRL* 84(2000)634).

-Cylindrical VC (PIC simulations): multiple DD collisional fusion as manifestation of collective ions acceleration by *stationary potential well of virtual cathode* immersed into complex interelecrode media .

- many questions remain: scaling of fusion power density, channels of fusion with prevail neutron yield, stochastic, anisotropy of particles and x-rays yields, beam-clusters and self-organization effects, etc.

Yu.K.Kurilenkov, M.Skowronek, J.Dufty. J.Phys.A: Math&Gen v.39 (2006)4375