The Abdus Salam
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for Theoretical Physics

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School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

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Construction and Physics of the Dense Plasma Focus device

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Collaboration

- ICTP, Trieste, Italy
- International Centre for Dense Magnetized Plasma, Warsaw, Poland
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- Nanyang Technological University, Singapore
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OUTLINE

1. Introduction: DPF – constructions and principles of operation; pulsed radiation physics, chemistry, biology in its perfect sense
2. Apparatus and Diagnostics
3. Dynamics of plasma, beams of fast particles and ionizing radiations in Dense Plasma Focus devices
4. Conclusions

1. Introduction: DPF – constructions and principles of operation; pulsed radiation physics, chemistry, biology in its perfect sense

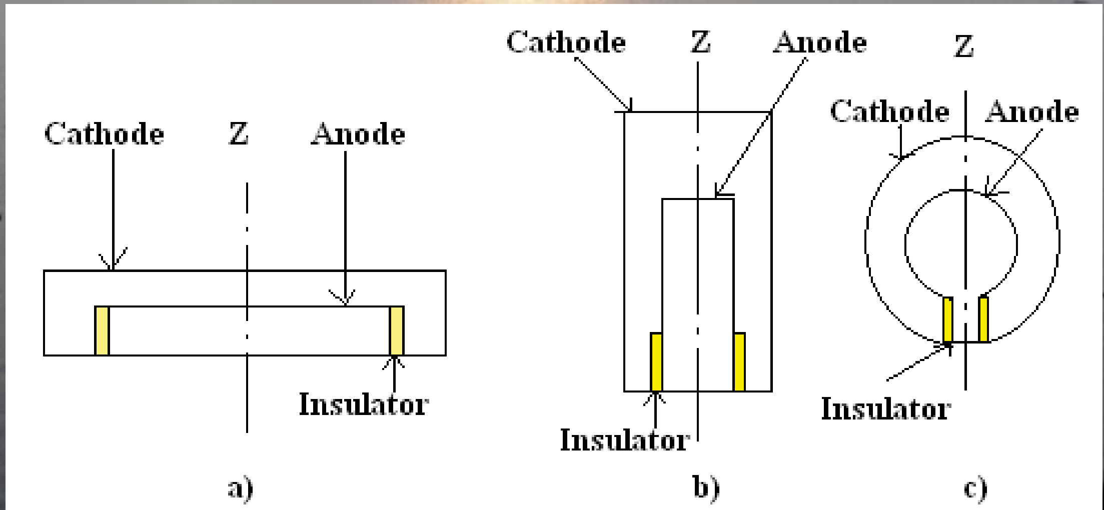
Dense Plasma Focus (DPF) device is a type of plasma accelerator that produces nanosecond pulses of:

- ***directed*** **powerful hot (T ~ 1 keV) fast ($v > 10^7$ cm/s) dense ($n_{pl} \approx 10^{16}…10^{19}$ cm^{-3}) plasma streams,**
- **high energy ion ($E_i \approx$ 0.01…100 MeV) and**
- **electron ($E_e \approx$ 0.01…1,0 MeV) beams**
- **soft ($E_{h\nu}$ ~ 0.1…10 keV) and**
- **hard ($E_{h\nu}$ ~ 10…1000 keV) X-rays and**
- **fusion neutrons (monochromatic E_n ~ 2.45 and 14 MeV as well as a broad-range - 2…11.3 MeV)**

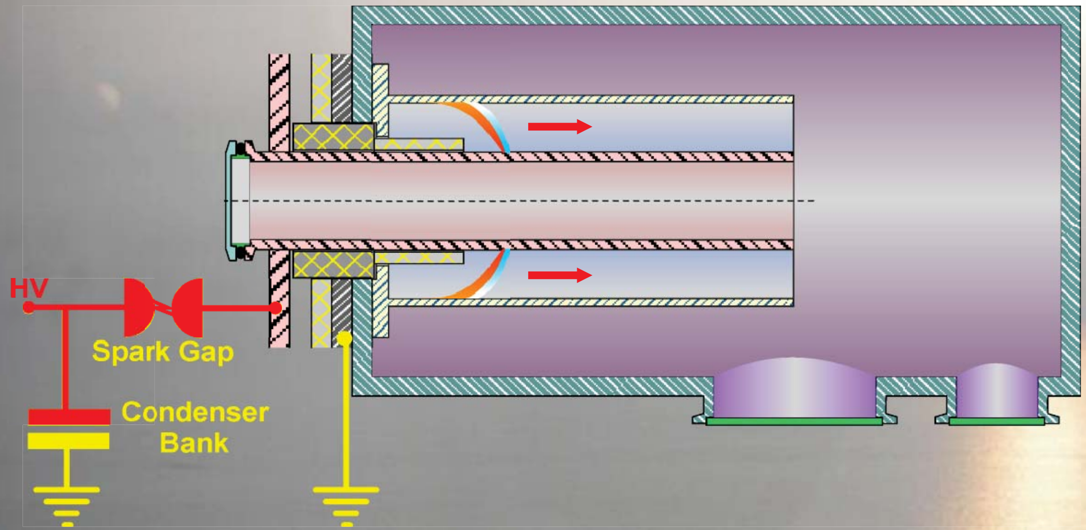
These streams may irradiate a target with power flux density on its surface equal to 10^5 W/cm^2 (neutrons), 10^8 W/cm^2 (soft and hard X-rays), 10^{12} W/cm^2 (fast ions and plasma jets) and > 10^{13} W/cm^2 (electrons)

DPF belongs to Z-pinch discharges in gas where a Lorentz force compresses plasma near the chamber axis

3 types of DPF chamber geometries are used at present time:

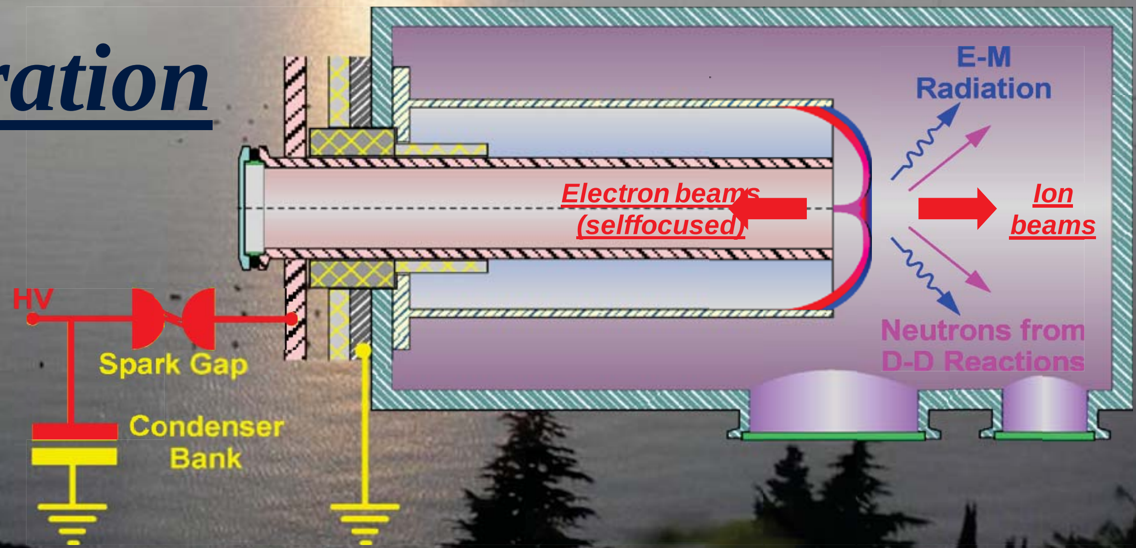


a) Flat (N. Filippov, KIAE); b) Extended (J. Mather, LANL); c) Spherical (VNIIEF)



MHD stage (current sheath acceleration and raking ("snow-plough")

Principle of operation



Kinetic stage (current abruption phenomena with subsequent acceleration of particles)

Compared with classical accelerators, fission reactors and isotopes DPF is an <u>ecologically more friendly radiation-producing device</u> because:

- it uses low charging voltage (~ 10 kV)

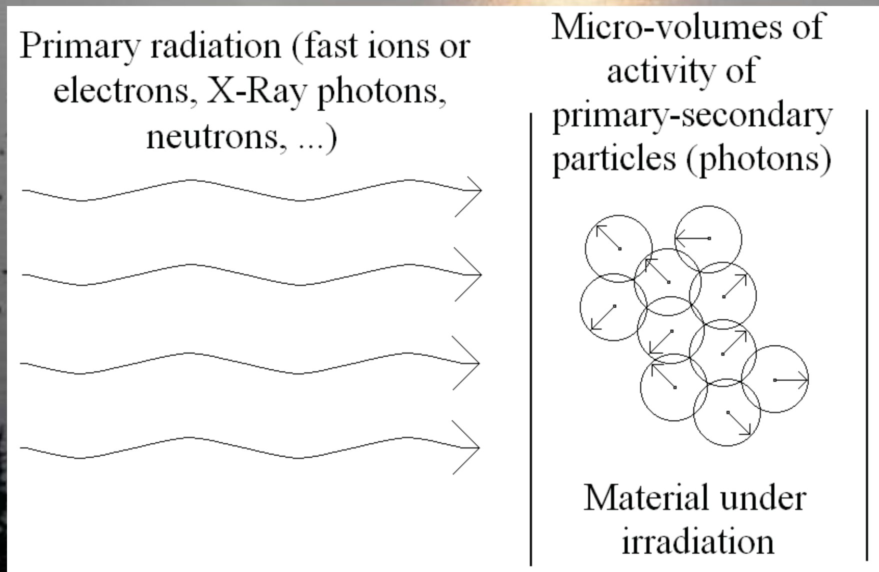
- it becomes a radiation source just for a few nanosecond and only on demands ("*<u>a push-button source</u>*")

- it is a radiation-safe device, i.e. it has no fission materials and doesn't need any *special containers* for the device's preservation

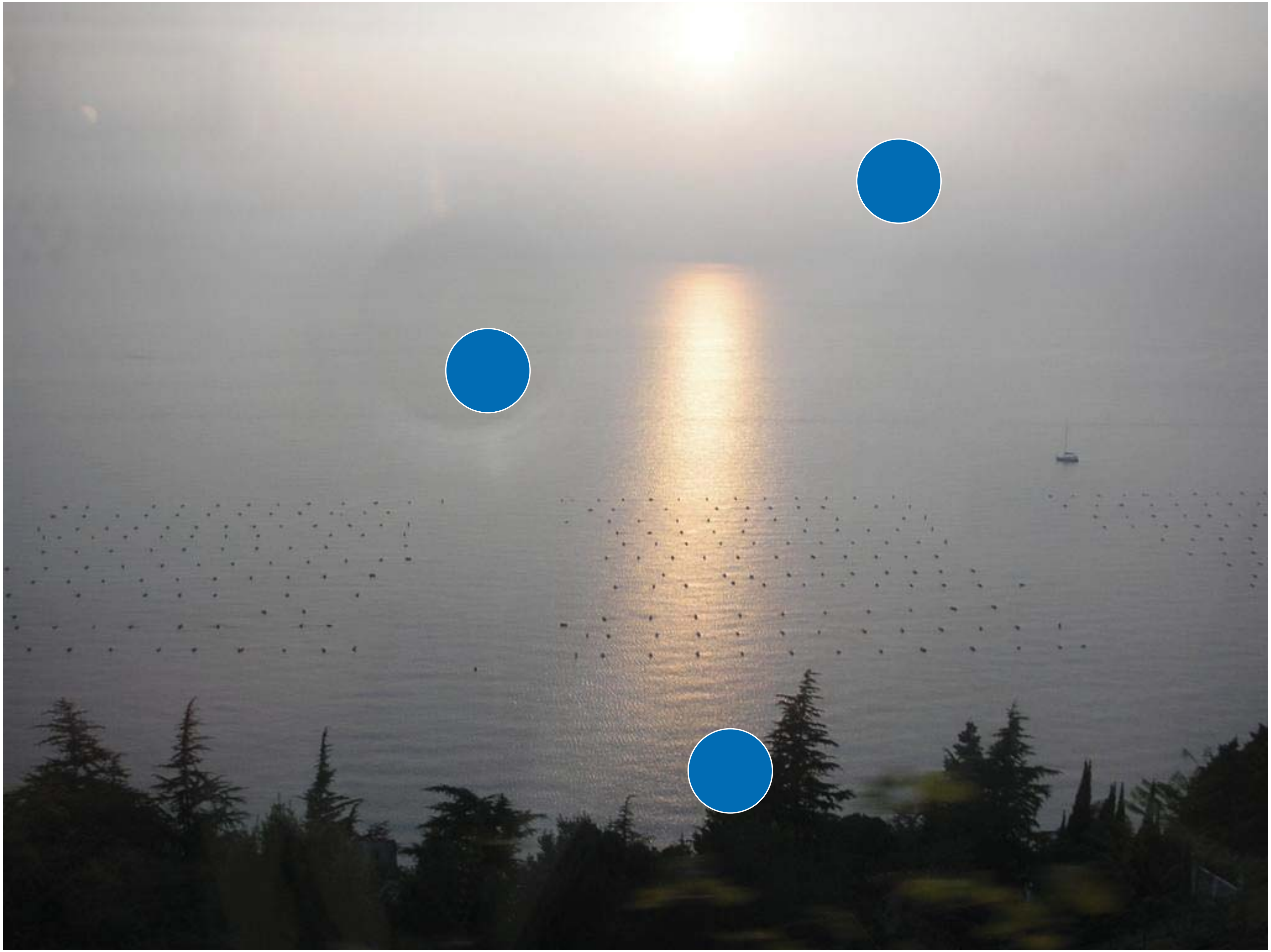
- it has no such a parameter as "*criticality*" – on the contrary to fission reactors

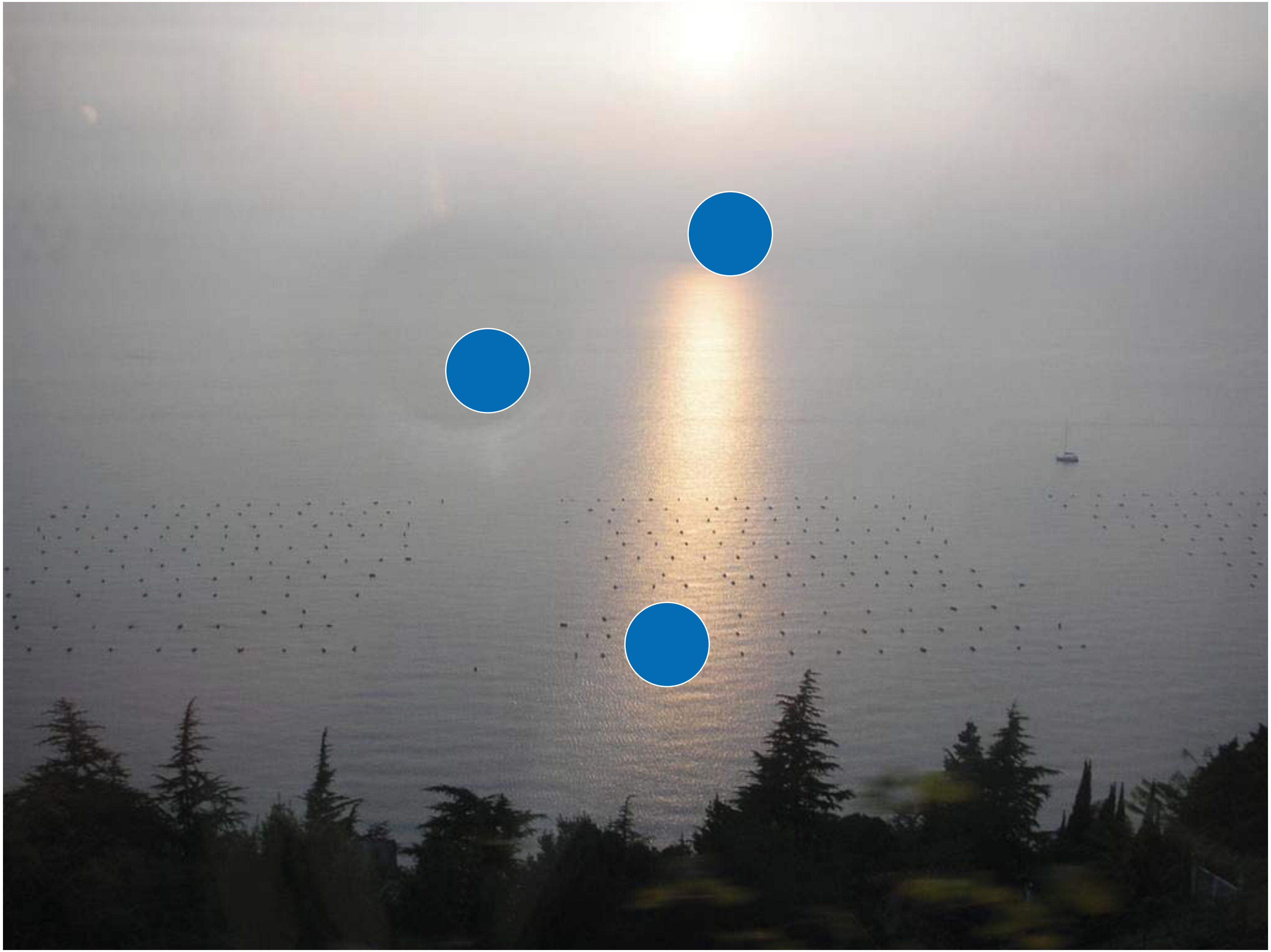
Having a very *short pulse duration* of radiation together with a very *high energy* contained in the pulse, DPF can be used in *pulsed radiation physics, chemistry, biology… in <u>the perfect sense</u> of this term,* i.e. when <u>two prerequisites hold true concurrently</u>:

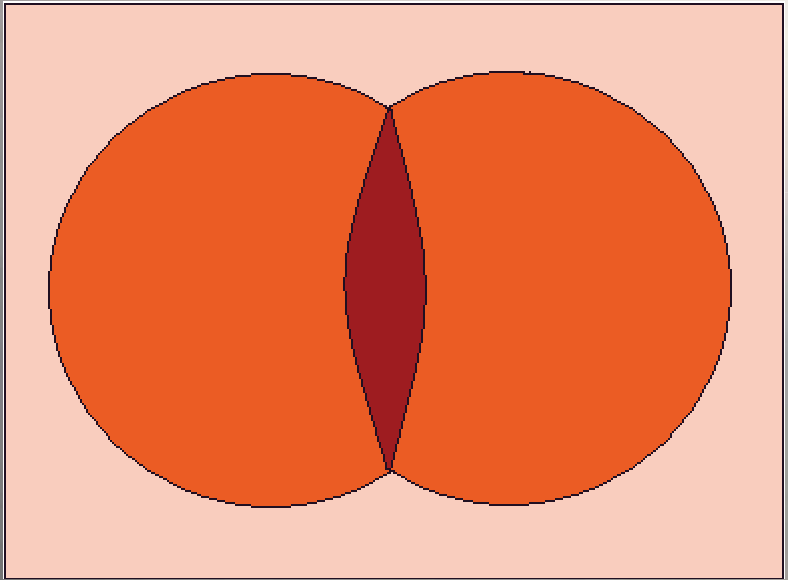
1) Micro-volumes of activity of each primary/secondary particle are <u>overlapped</u> within the irradiated volume



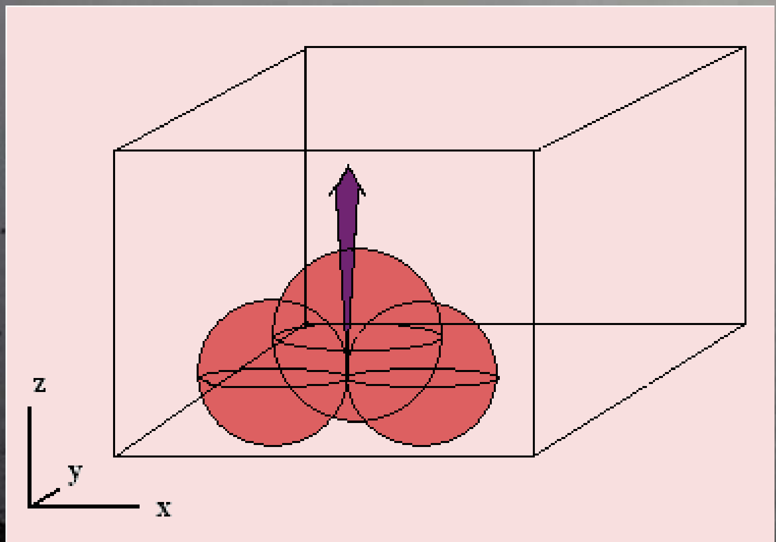
2) This overlapping occurs during a time interval, which is <u>short compared with the reciprocal phys./chemical process</u>







Collision of two shock waves with the parameters' increase in the collisional zone



3-D collision of 3 shock waves with a formation of a cumulative stream (jet)

This collective action can create many volumetric effects, e.g. it can produce a very high concentration of particles

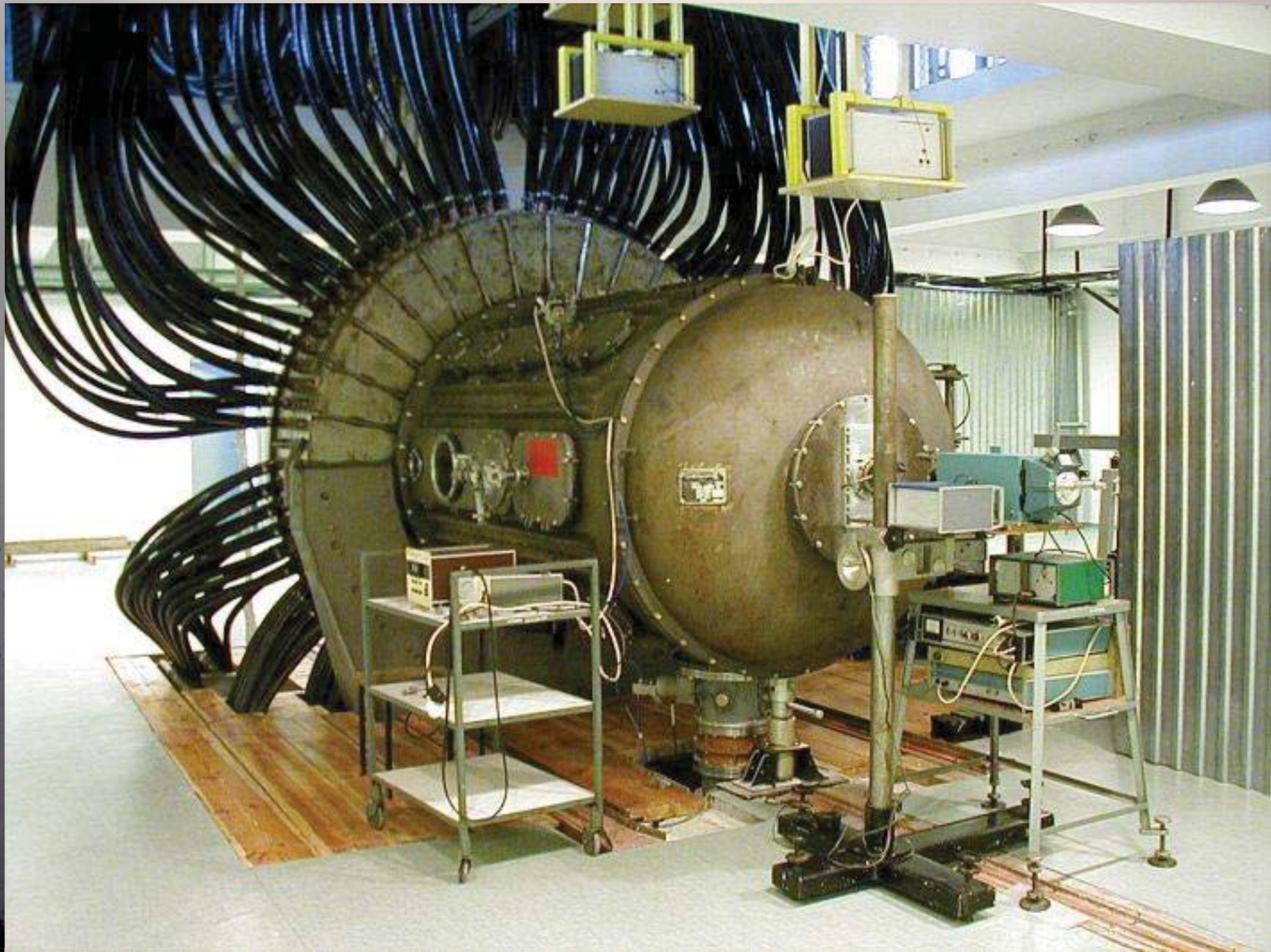
Taking into consideration *absolute X-ray and neutron yields* of DPF of medium sizes (with energy ~ 1.0-100.0 kJ in a bank) and *efficiency* of their generation here it must be noted that there do not appear to be sufficient reason to use these devices when one need large fluences of the above radiations

However due to a very short pulse durations with still substantial output and small size of the irradiating zone these sources have *unprecedented brightness* and are able to produce *a very high power flux density* of the penetrating radiations on the target

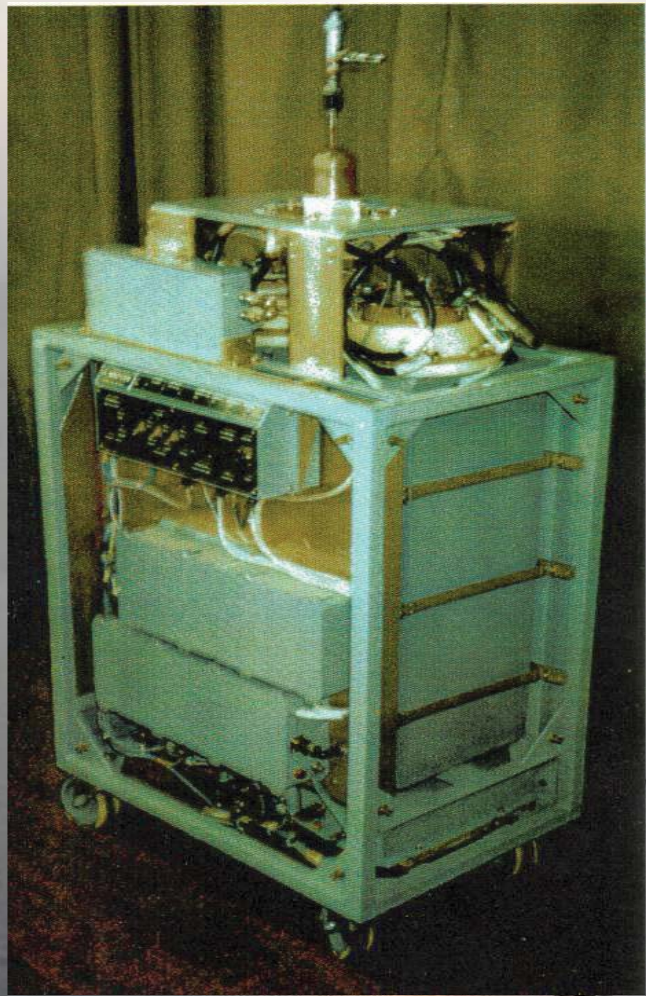
Besides these devices are small, cheap and simple in operation

Thus DPF gives an opportunity to make heavy science with light technology

2. APPARATUS & DIAGNOSTICS

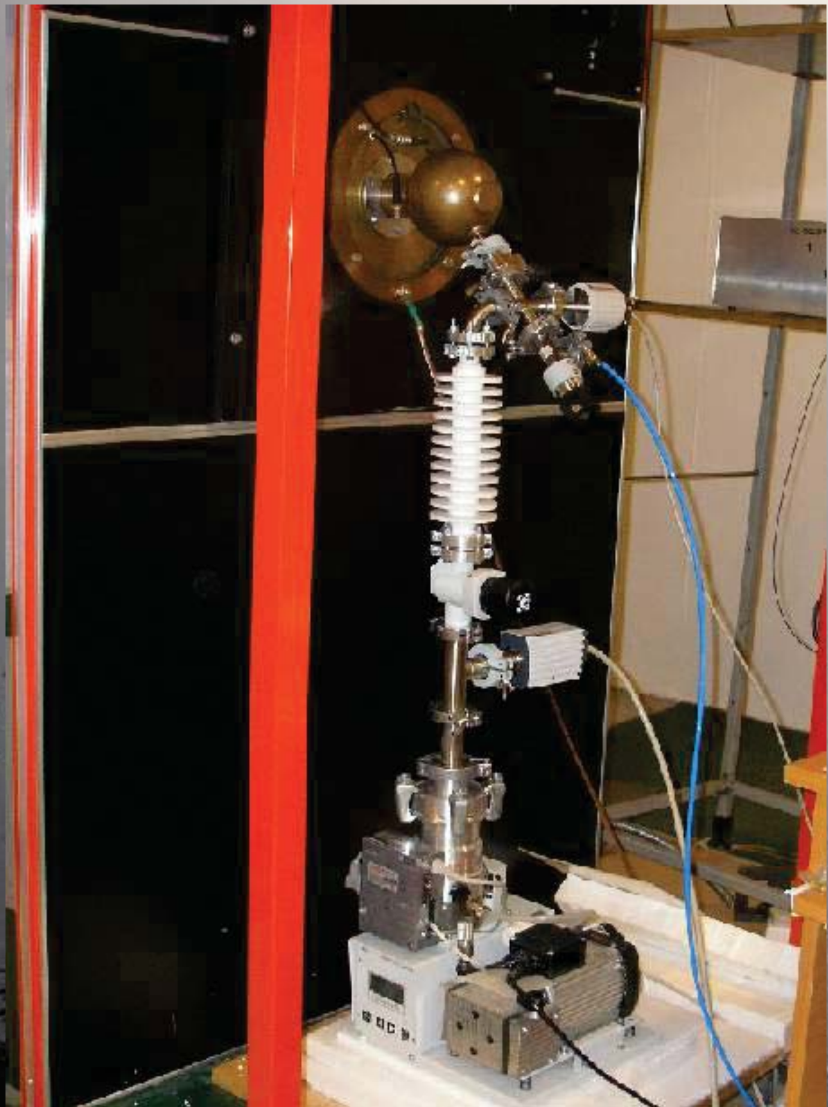


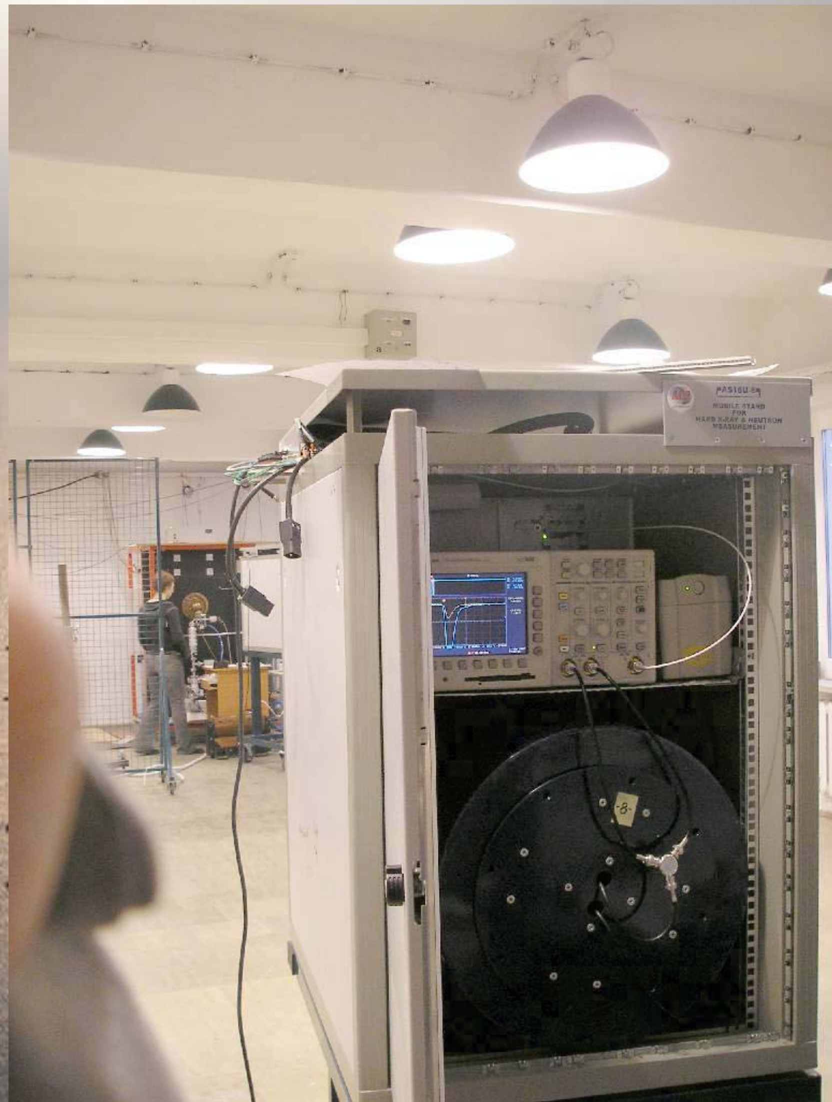
PF-1000 facility: 1.2 MJ, 3 MA, 6×10^{11} *D-D* n/pulse
(IPPLM + ICDMP)



Base transportable device ING-103: 4 kJ, 400 kA, 2×10^{10} *D-T* n/pulse, weight – 200 kg (VNIIA)

<u>Transportable device PF-6</u>: 7 kJ, 750 kA, 10^9 *D-D or* 10^{11} *D-T* n/pulse, weight – 400 kg (IPPLM + MPS)



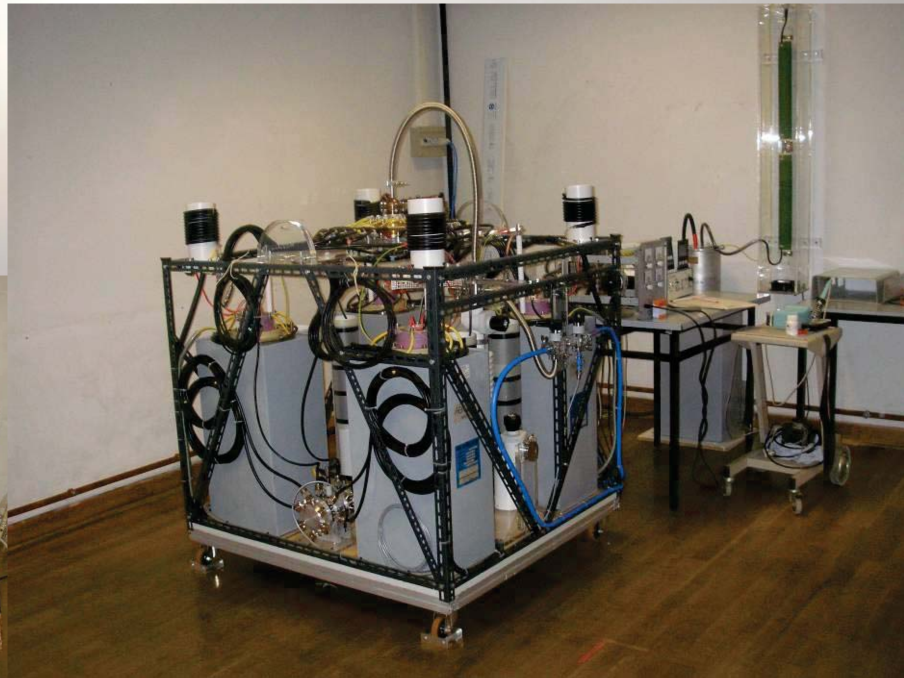


Neutron-producing chamber at its operation in PF-6 device with circa 1 cps

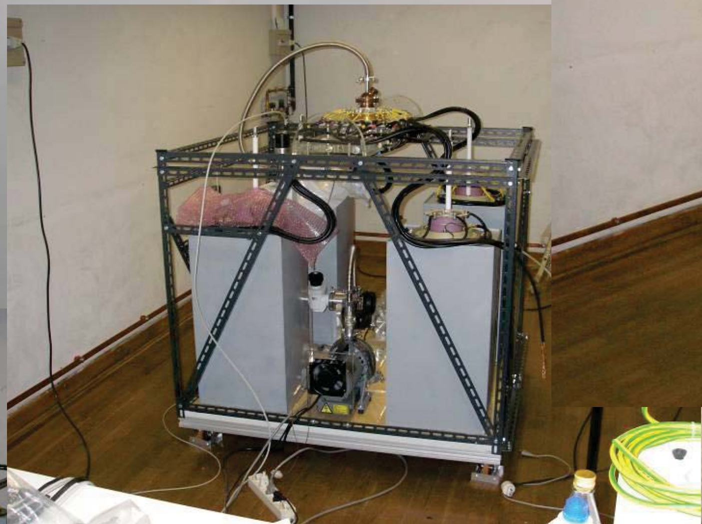
<u>Transportable device PF-10:</u> 5 kJ, 350 kA, 3×10^8 *D-D* n/pulse, weight – 150 kg (ITEP+MPS)

Transportable device PF-5M: **5 kJ, 350 kA,**
3×10^{8} *D-D* n/pulse, weight – 250 kg
(IMET+MPS)

NX2 device improved by a number of elements (e.g. PSs) for a long life-time:
3 kJ, 450 kA, 14.5 kV, 5×10^8 *D-D* n/pulse
(NIE + MPS)



September



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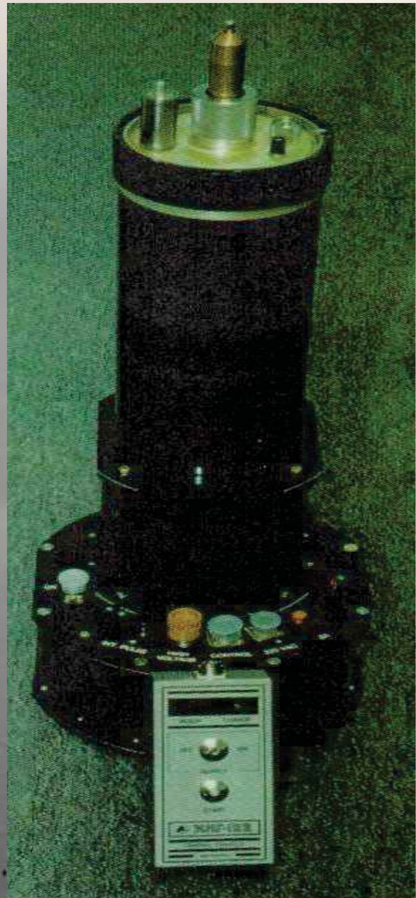
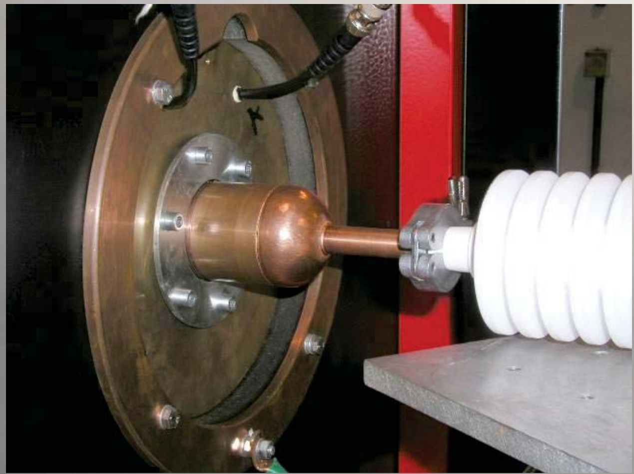
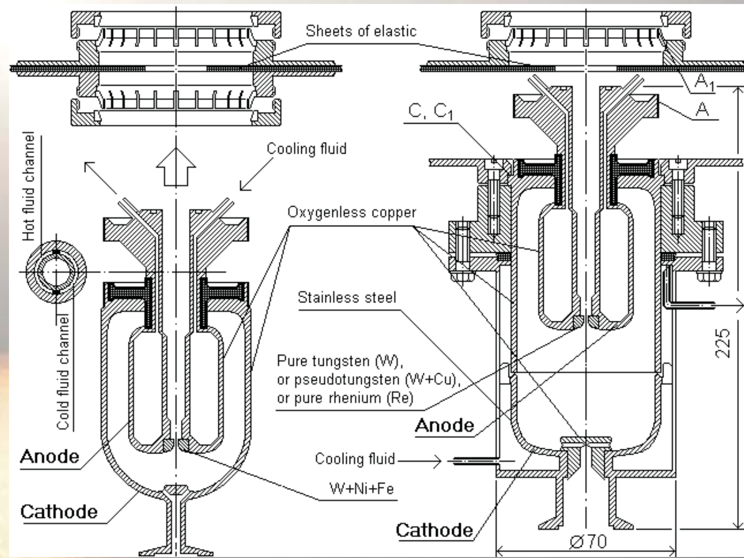
February 2007

Transportable device “Bora”: 5 kJ, 350 kA, 2×10^{8} *D-D* n/pulse, assembling stages (ICTP + MPS)



<u>Portable device ING-102:</u> 100 J, 150 kA, 10^8 *D-T* n/pulse, weight – 15 kg (VNIIA + MPS)





DPF chambers of transportable devices (VNIIA + MPS + IPPLM + ICDMP)

Being invented in the 50's DPF is the most well-diagnosed plasma device at present time

To have data on parameters of:

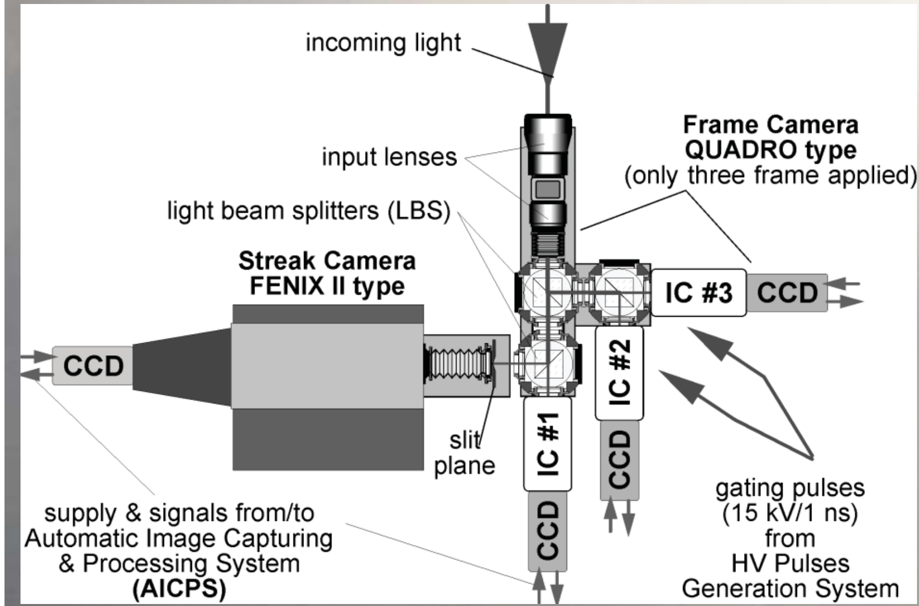
- **fast electron and ion beams (including charged fusion reactions products),**
- **plasma streams,**
- **soft and hard X-ray radiation, and**
- **neutrons**

i.e. on their current magnitude, velocity, spectrum, angular distribution, absolute yields, fluence, power flux density, etc.

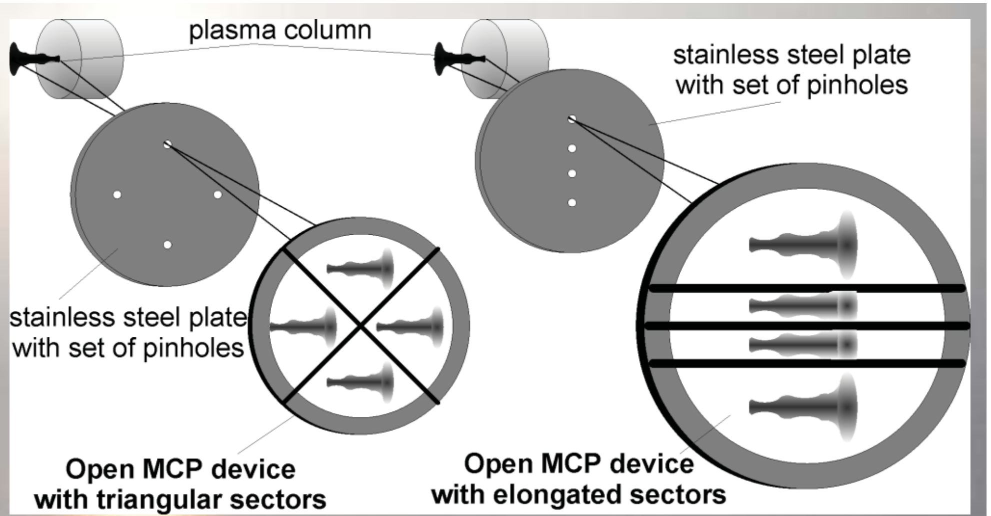
we use a number of diagnostics, having about 1-ns temporal, few micrometers spatial, high spectral and angular resolution

Among these diagnostics we use the following tools:

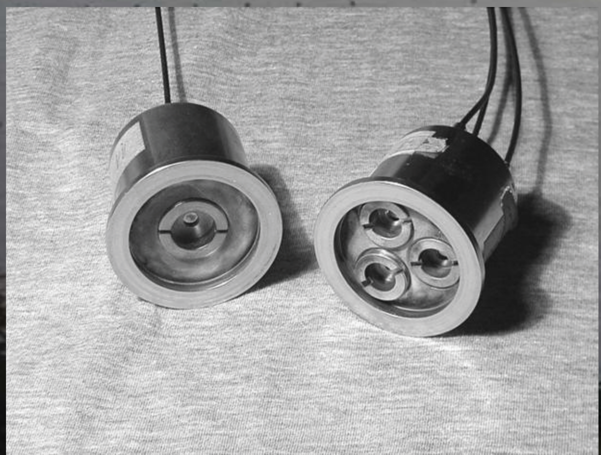
- magnetic probes, Rogowski coil and voltage divider;
- 1-ns 16-frames laser interferometry;
- 1-ns 4-frame photography and a streak camera for registering visible and X-ray plasma luminescence;
- 5 channels of 0.3-…1.3-ns PM tubes + scintillators;
- Čerenkov detectors;
- visible and X-ray spectroscopy;
- activation counters (several blocks placed at dissimilar angles to the source) with different activated elements (silver, indium, copper, etc.);
- calorimeters and bolometers;
- X-ray PIN detectors,
- ion plastic track detectors, etc.



Optical 4-frame camera

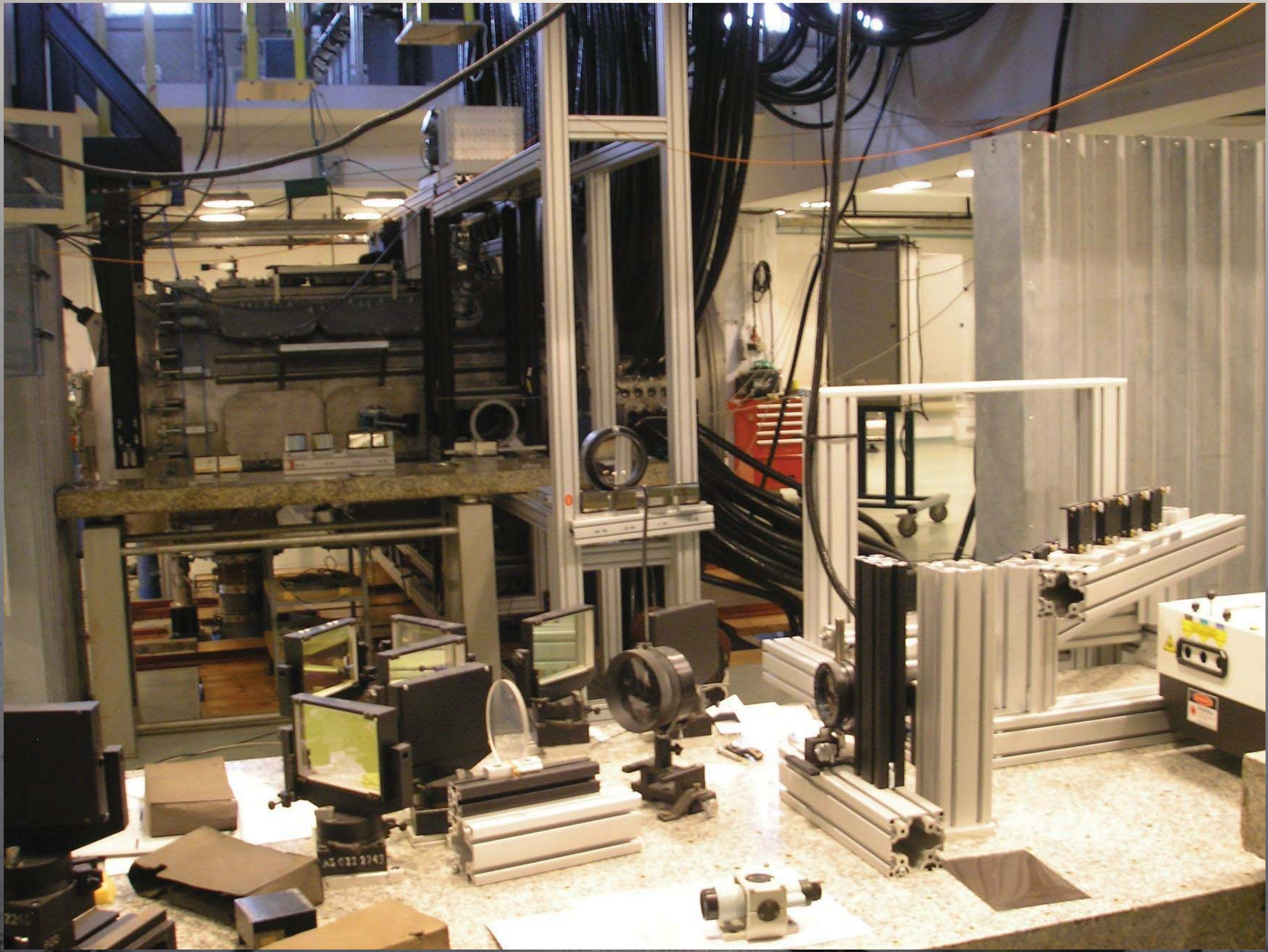


4-frame soft X-ray camera



Cerenkov detectors

Ion track detectors



Laser with interferometer and a system of mirrors

Besides after experiments we provide investigation of irradiated samples with the following analytical instrumentation:

- **optical, electron scanning and atomic force microscopy,**
- **various tribological methods (including e.g. nanohardness measurements),**
- **elastic proton recoil detection analysis,**
- **X-ray micro-elemental, structure and phase analysis,**
- **luminescence response, etc.**

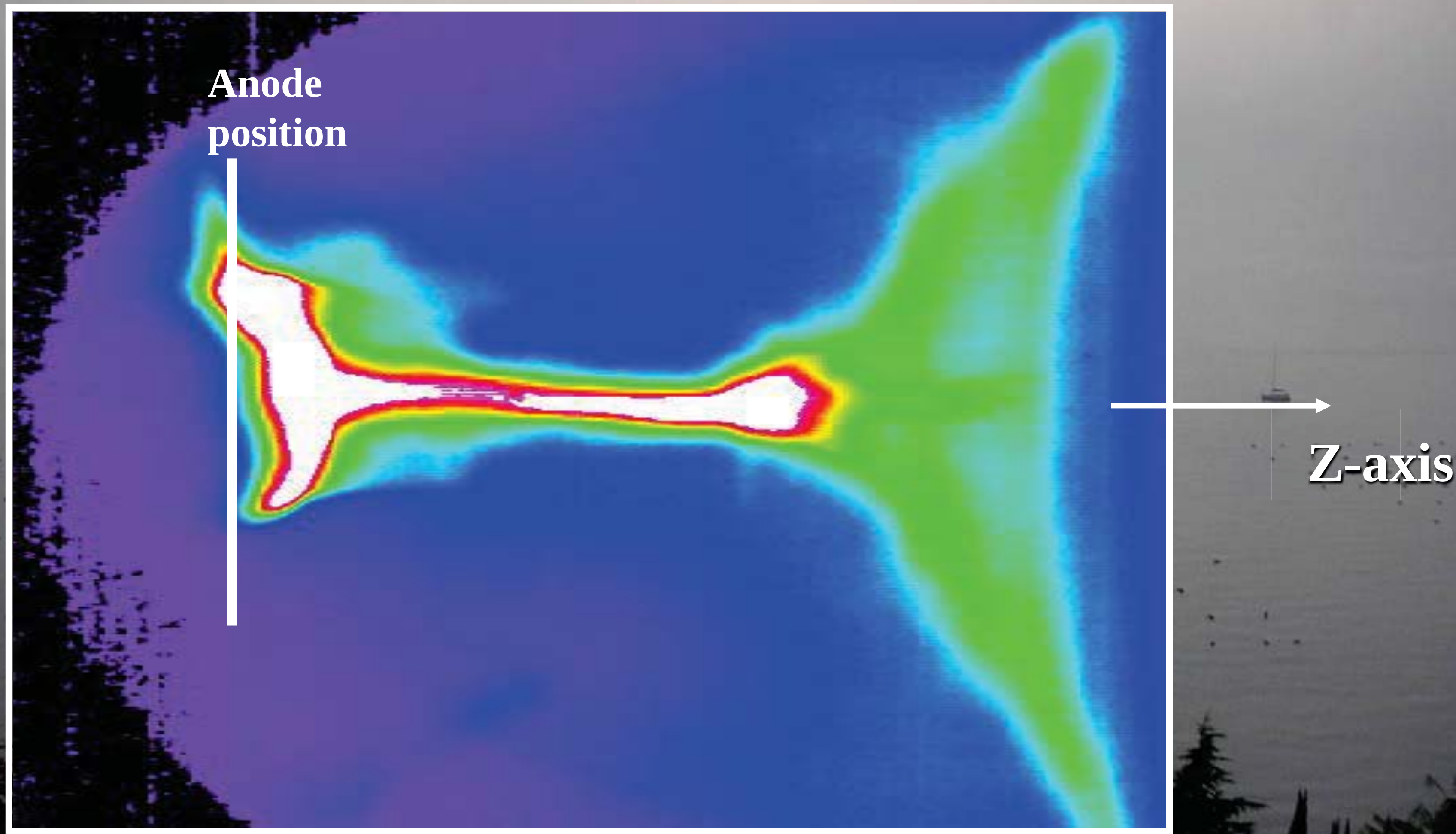
As a rule all experiments were supported by intensive numerical modeling using FLUKA and MCNP codes

Two optical microscopes for use in radiation material science experiments at ICTP

3. Dynamics of plasma, beams of fast particles and ionizing radiations in Dense Plasma Focus devices

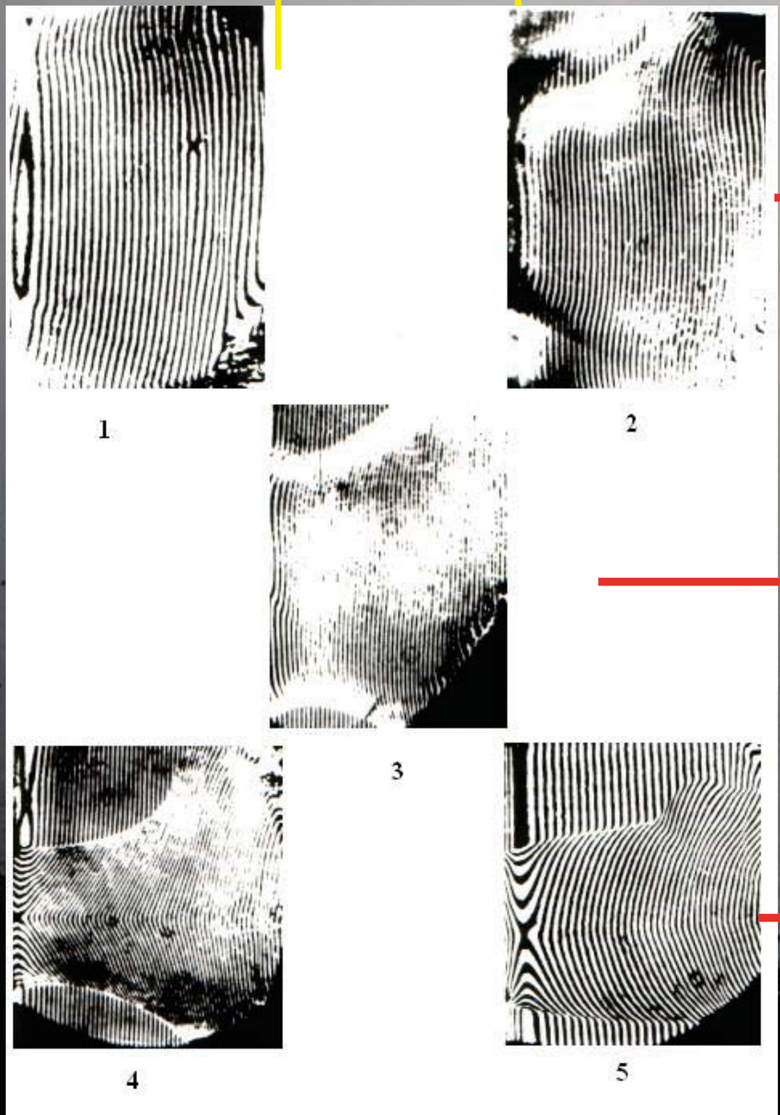
Our measurements made by visible streak and 4-frame cameras as well as SXR 4-frame cameras and 16-frame laser interferometry have shown that at a high neutron yield the plasma compression process develops symmetrically, and the velocity of the Plasma Current Sheath is in the range 2…3×10^7 cm/s

Collapsing process of the PCS is preceded by a Shock Wave contraction about Z-axis, then it finishes by a formation of a straight plasma column



1-ns time exposure frame picture of the pinch plasma (self-luminescence in visible light)

Anode positions



Z-axis

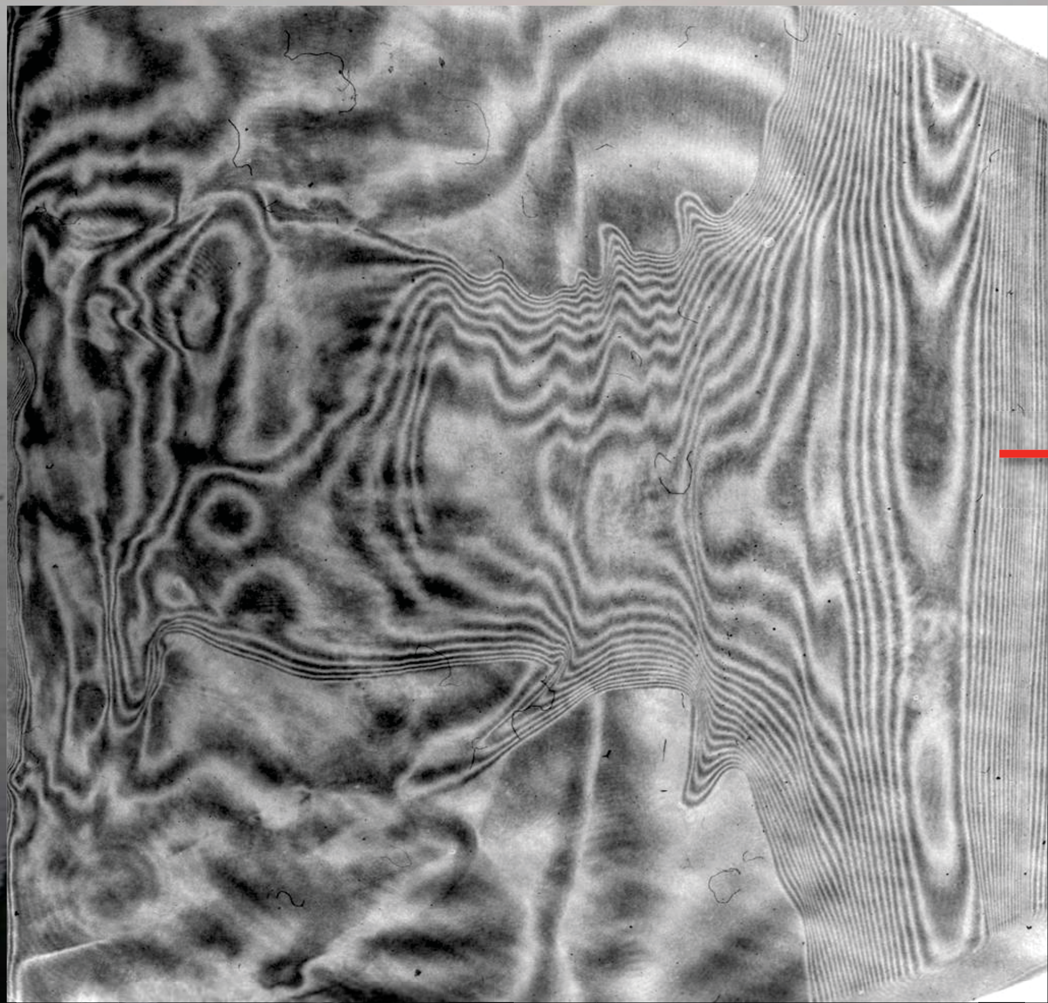
Z-axis

Z-axis

5-frame laser interferometry at the DPF of Filippov geometry (1 ns – 16 ns)

16-frame laser interferometry at the DPF of Mather geometry – PF-1000 (1 ns – 10/20 ns)

Laser interferometry of the pinch plasma in Mather geometry (1-ns time exposure)



Z-axis

anode ↑ pinch column↑ current sheath↑

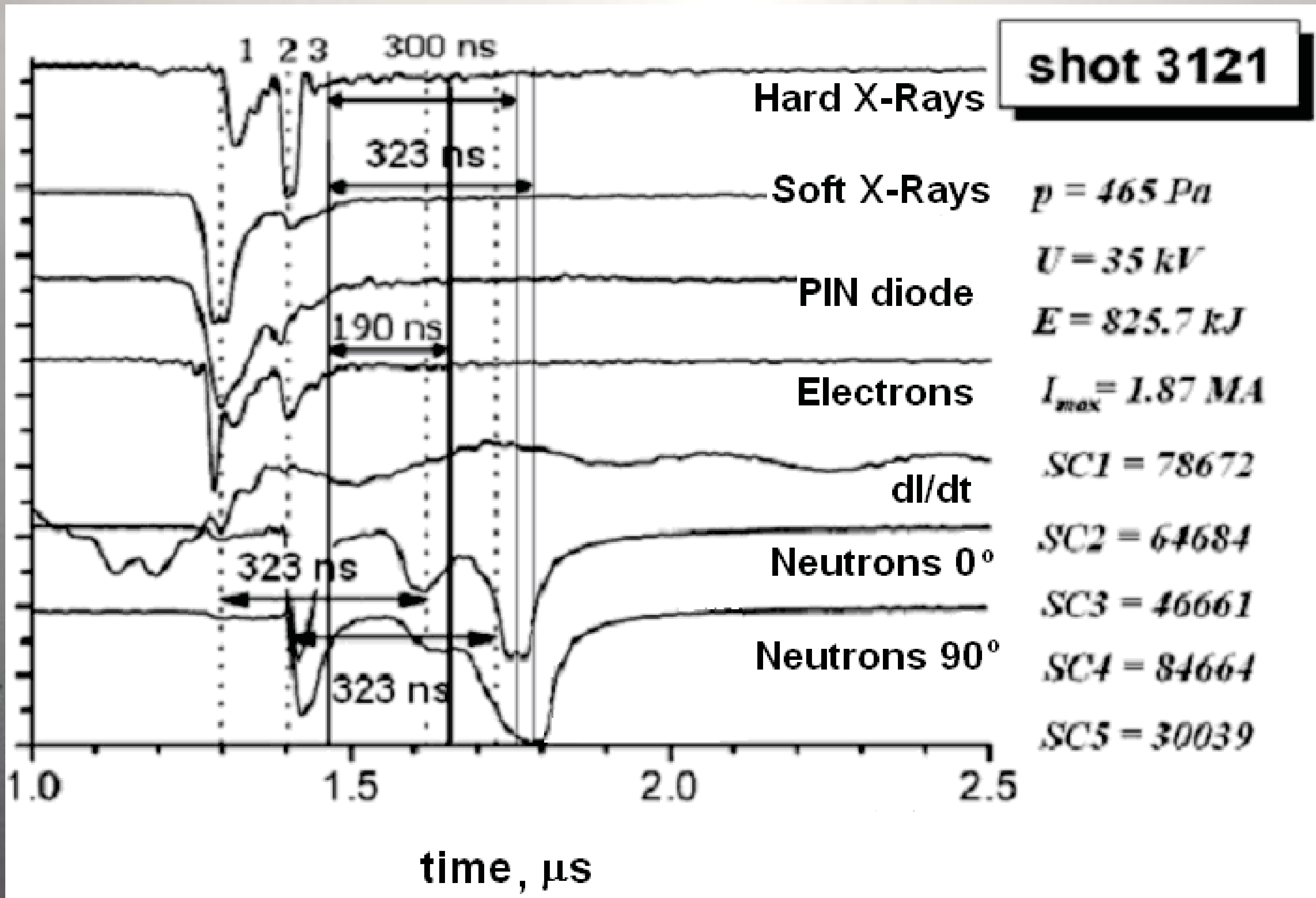
Implosion speed measured by the above three methods gave us a lower estimate of the plasma temperature T in the dense plasma pinch provided that the ordered kinetic energy of the PCS is converted into the chaotic plasma particle motion: $(mv^2)/2 = 3/2(kT)$, and that additional plasma heating takes place because the final adiabatic plasma squeezing

It appears to be within the limits of $T \cong 0.5\ldots2.0$ keV

Density estimations based on the Bennett equation $H^2/8\pi = 2nkT$, provided that the whole current measured flows through the dense pinch, gives a figure $1.3\cdot10^{19}$ cm^{-3} for $T \cong 1$ keV

Supposition that only 70% of the total current flows through the column gives it around 10^{19} cm^3

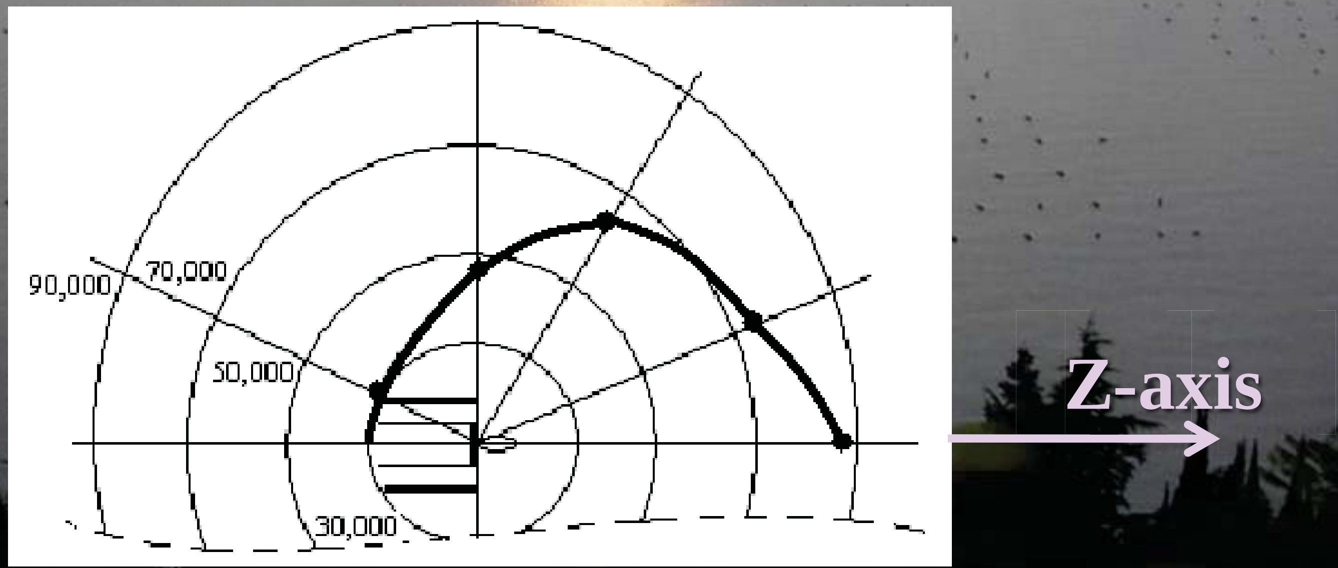
Interferometry and spectroscopy support these estimations



Collection of the data from 5 neutron counters, 4 PM tubes, PIN diode, Cerenkov detector, and Rogowski coil (PF-1000 facility)

Angular anisotropy of neutron emission was measured by the above-mentioned 5 silver activation counters

The anisotropy of the neutron emission has “normal” character (i.e. it is characterized by a preferential direction of neutron irradiation at 0° to Z-axis) and it is rather high – namely it is 1.8 for the ratio $Y_{0°} / Y_{90°}$ and it is equal to 0.65 for the ratio $Y_{90°} / Y_{180°}$



Two hard X-ray and neutron pulses are observed in most cases during a single DPF shot

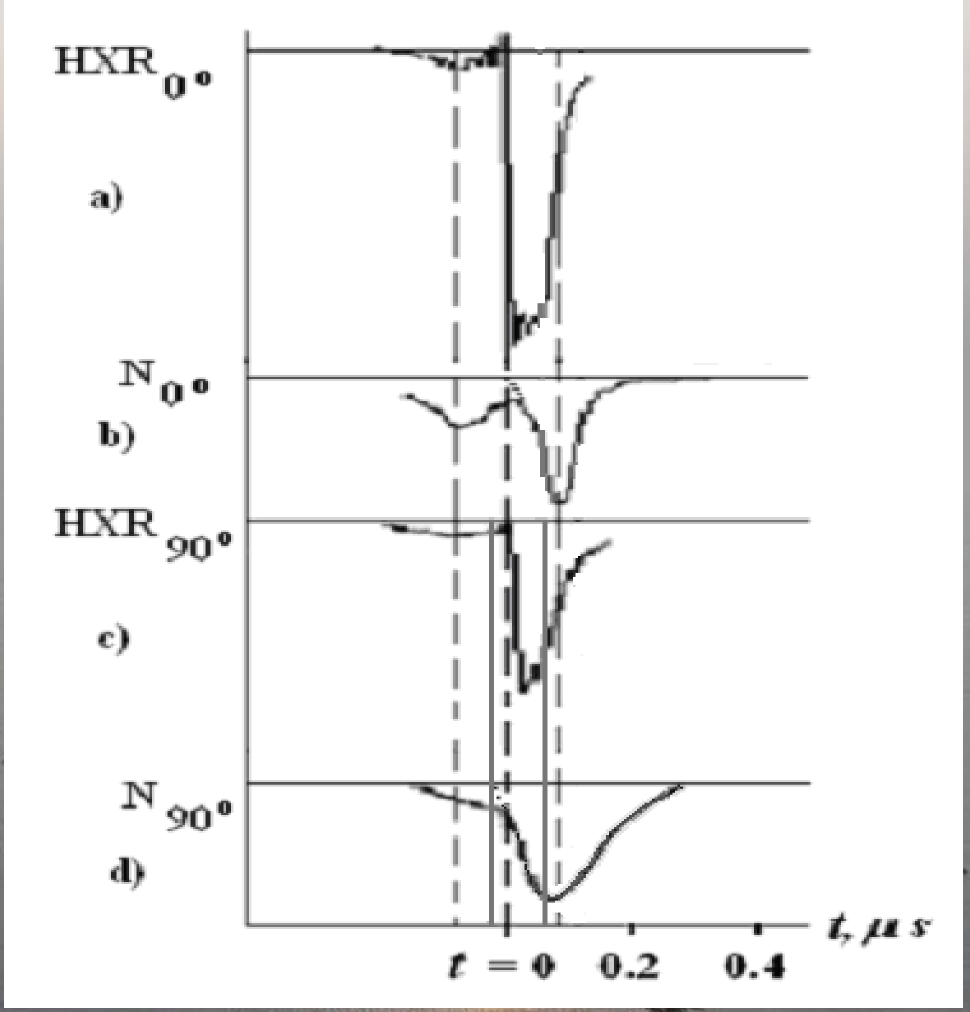
Both second pulses are higher by amplitude from 4 through 20 times than the first ones

Hard X-ray pulses have usually a very sharp rise-time whereas neutron pulses are of a bell-like shape

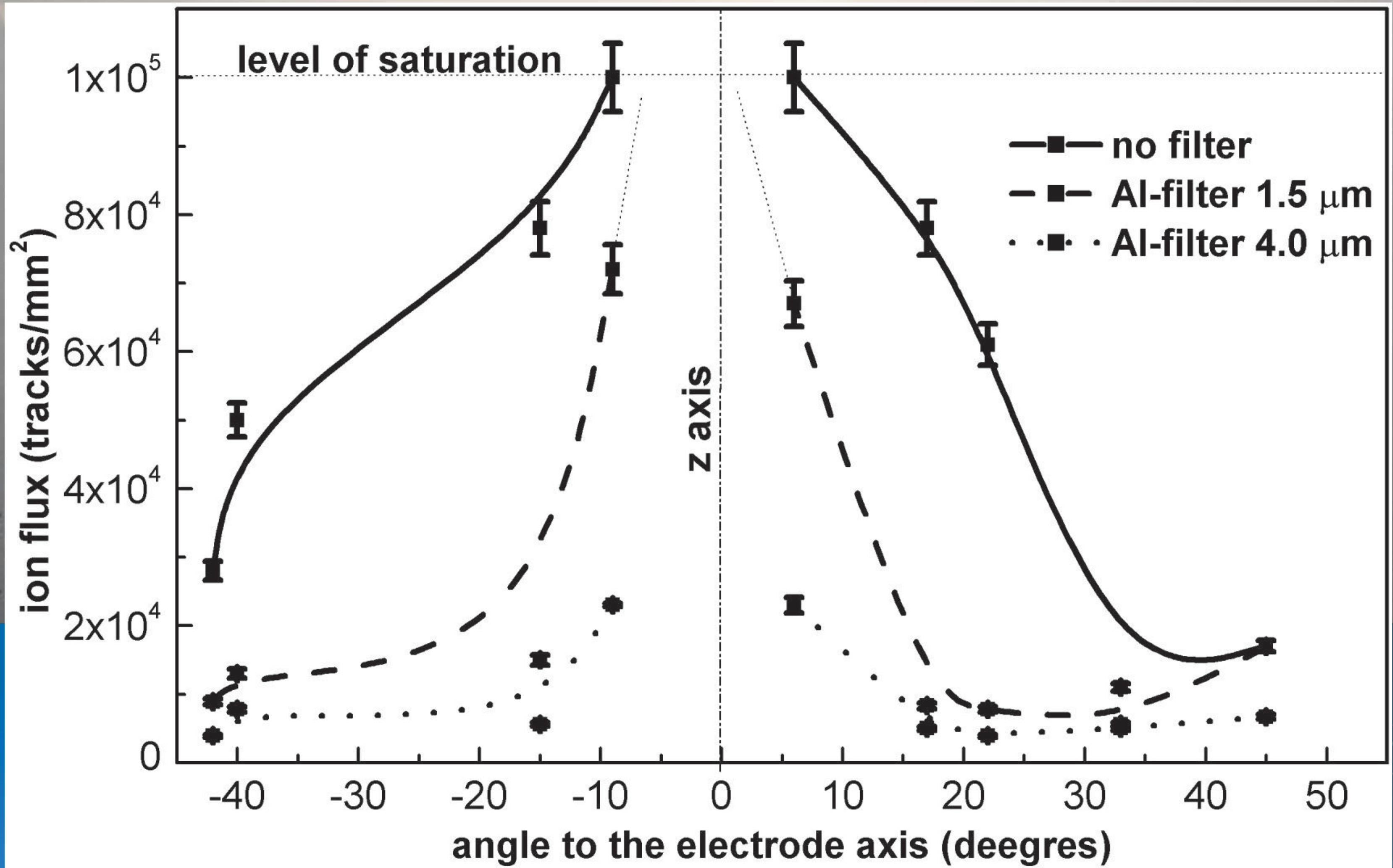
Durations of each neutron pulse (FWHM) as well as the interval between them at their registration in the “head-on” direction depends on the size of the particular device and lies in the limits from 10 through 150 ns

Also depending on the sizes of the devices the first neutron pulse has larger longevity thus in the range of the DPF bank energy from 0.1 through 800.0 kJ the duration increases from 1.5…2 ns till 150 ns, roughly proportional to the current value.

Later we shall discuss all the data in connection with the largest in the world PF-1000 facility (IPPLM, Poland)



Hard X-Ray pulses (a and c) versus neutron pulses (b and d) taken at 0° and 90° to Z-axis after moving them forward according to their real (HXR) and assumed (N) time-of-flight (PF-1000)



Angular distribution of ion streams (PF-1000)

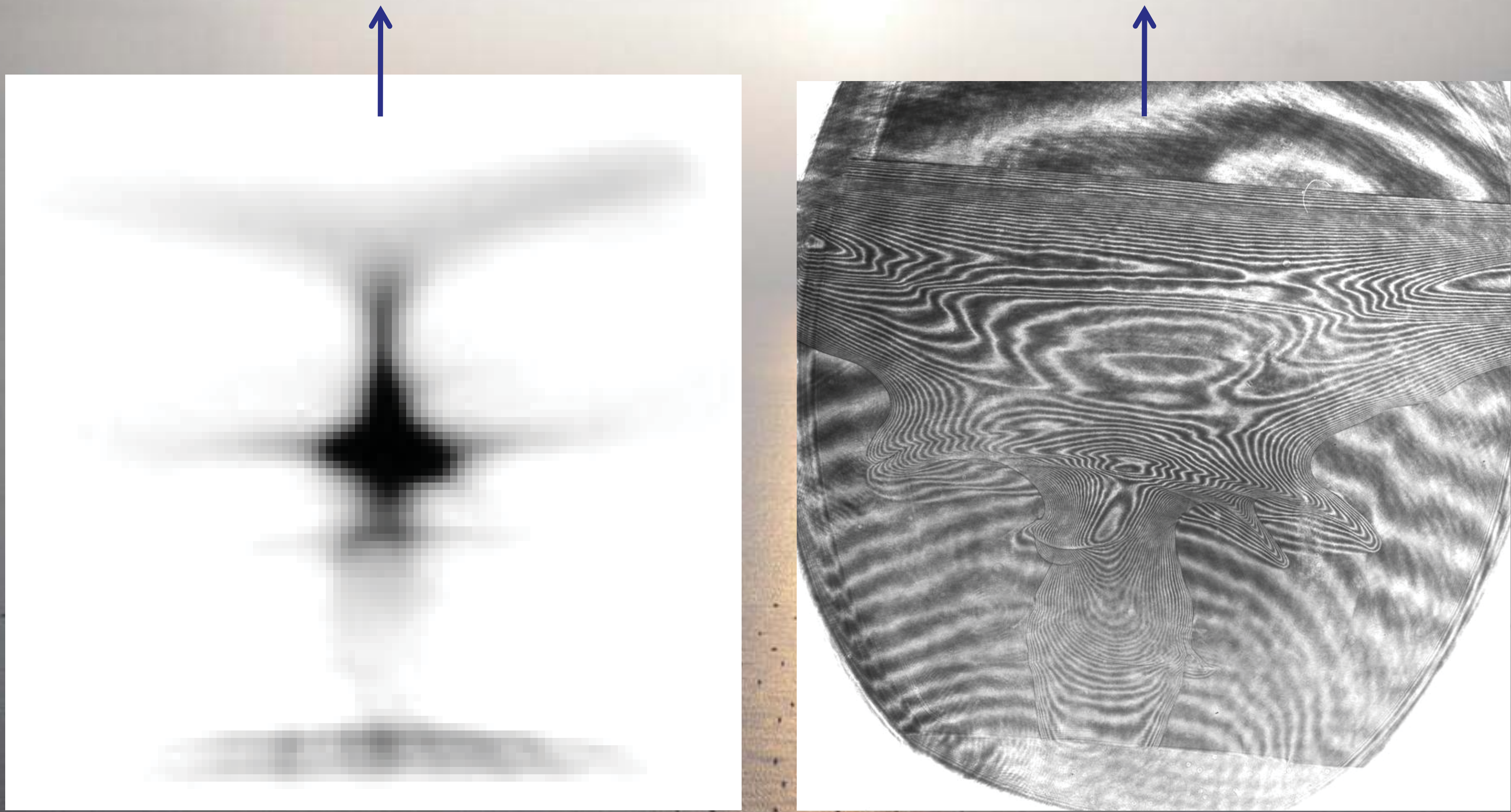
The pinch's column during the first neutron pulse is straight and has a height of 10 cm with a radius of 0.5 cm (a so-called the first compression phase)

Later on this plasma column is widened and disturbed by instabilities

All pinch parameters start to fall down with the characteristic time of the order of the above plasma confinement time

Strong perturbations of plasma sheath surface can be found in all frame images of it (both self-luminescence and interferometric)

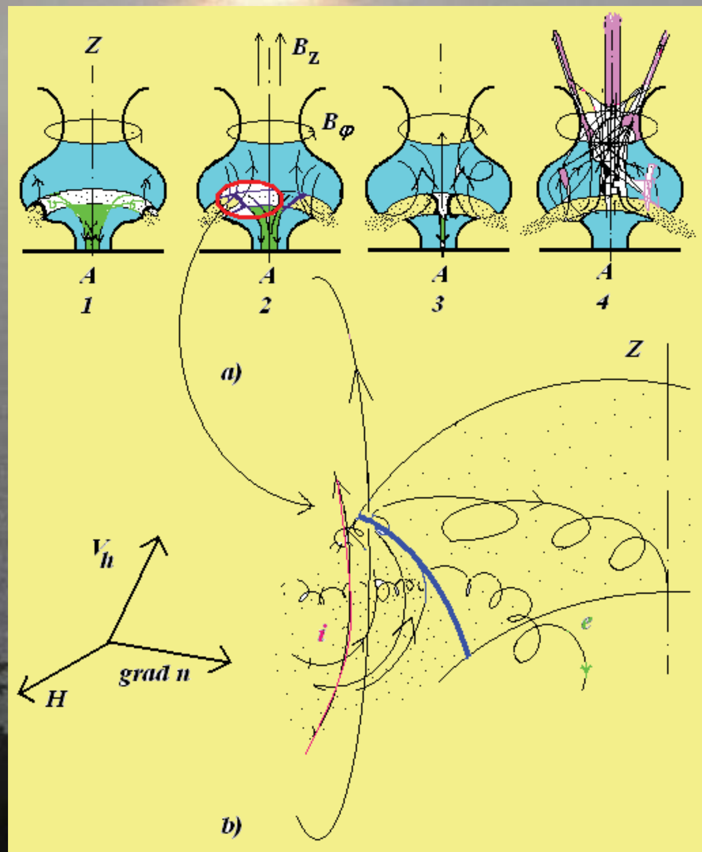
The pinch breaks usually in one-two (or sometimes several) regions along the column. According to our analysis the data received give an evidence of the virtual plasma diode creation across the pinch



1-ns self-luminescence and interferometric pictures of the pinch during development of MHD instability (and the plasma-diode formation) on the plasma column

At the current maximum the main part of electric energy stored previously in the bank is concentrated as magnetic energy near the pinch column, i.e. in the “plasma inductive storage”

Then we have a disconnection of the current and formation a plasma diode on the pinch according to the following scenario:



For a DPF the Gyrating Particle Model is valid: the pinch is presumably a hot-plasma target to be irradiated by fast ion beam generated within a DPF after current abruption and *magnetized* inside the pinch

Pinch diameter determines the maximum value of magnetic field:

$$B = 0.2\, I/r = 2 \text{ MG}$$

where I = 2 MA and r = 0.45 cm (for PF-1000 facility)

It means that the Larmor radii for fast (100 keV) electrons and deuterons are correspondingly:

$$r_e \geq 3.37(W_\perp)^{1/2}/\, B_\perp \text{ and}$$

$$r_d \geq 204\, (W_\perp)^{1/2}/B_\perp$$

where transverse energy $W_\perp$ is in eV, $B_\perp$ in Gauss, and r in cm

It gives estimations for their minimal values:

$$r_e \geq 5\times10^{-4} \text{ cm and}$$

$$r_d \geq 3 \times 10^{-2} \text{ cm}$$

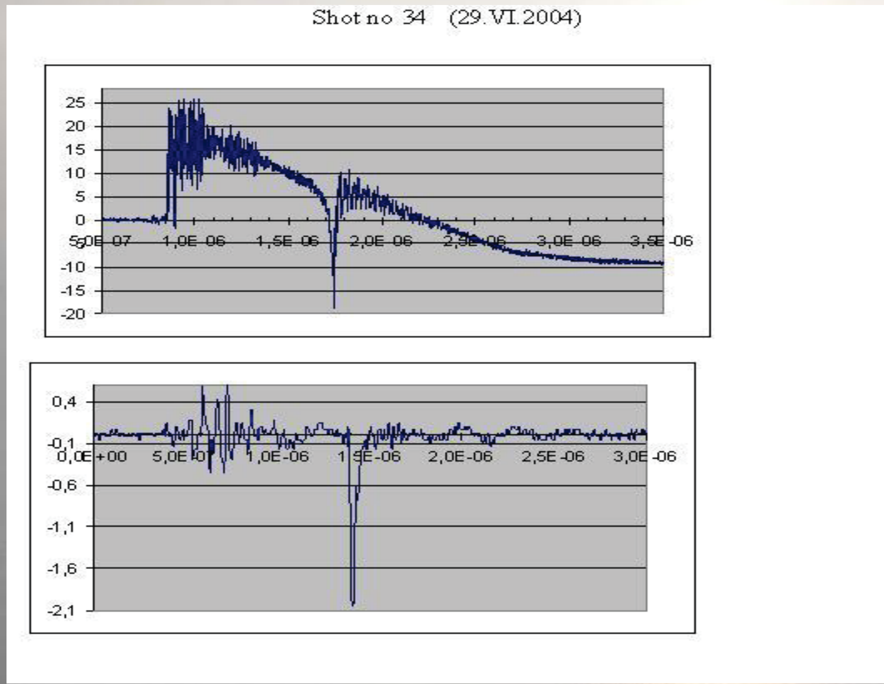
They are much less than the pinch diameter

It opens opportunities for:

-a creation of the above-mentioned plasma diode;

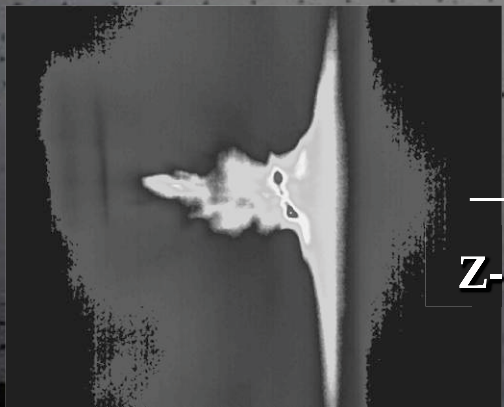
- for magnetizing the electron beam and subsequently for the substitution of the electron beam by the beam of fast ions (carrying circa the whole discharge current);

- for magnetization of these fast ions about the pinch column and for production of neutrons in the frame of the Gyrating Particle Model

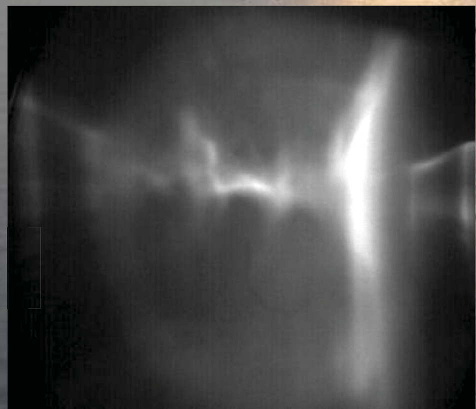


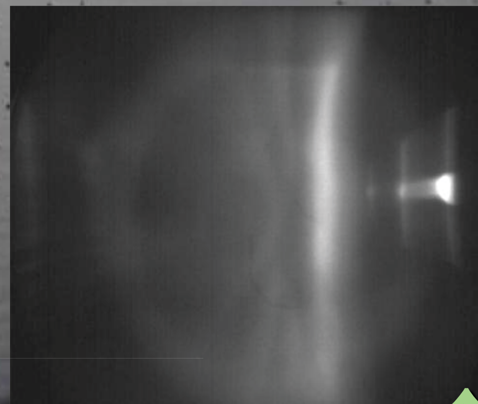
dI / dt

Hard X-rays and neutrons



Z-axis



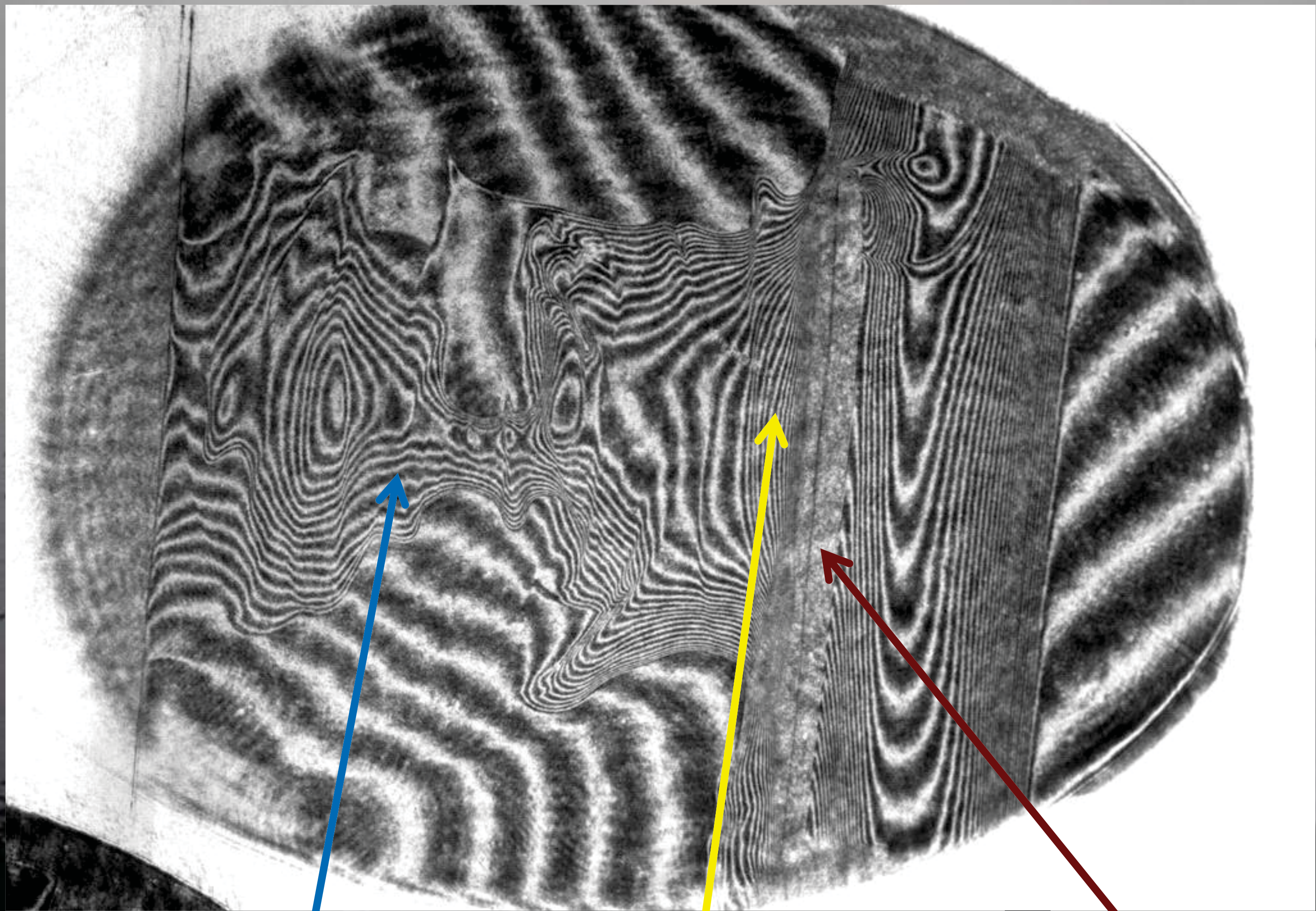


SW ↑

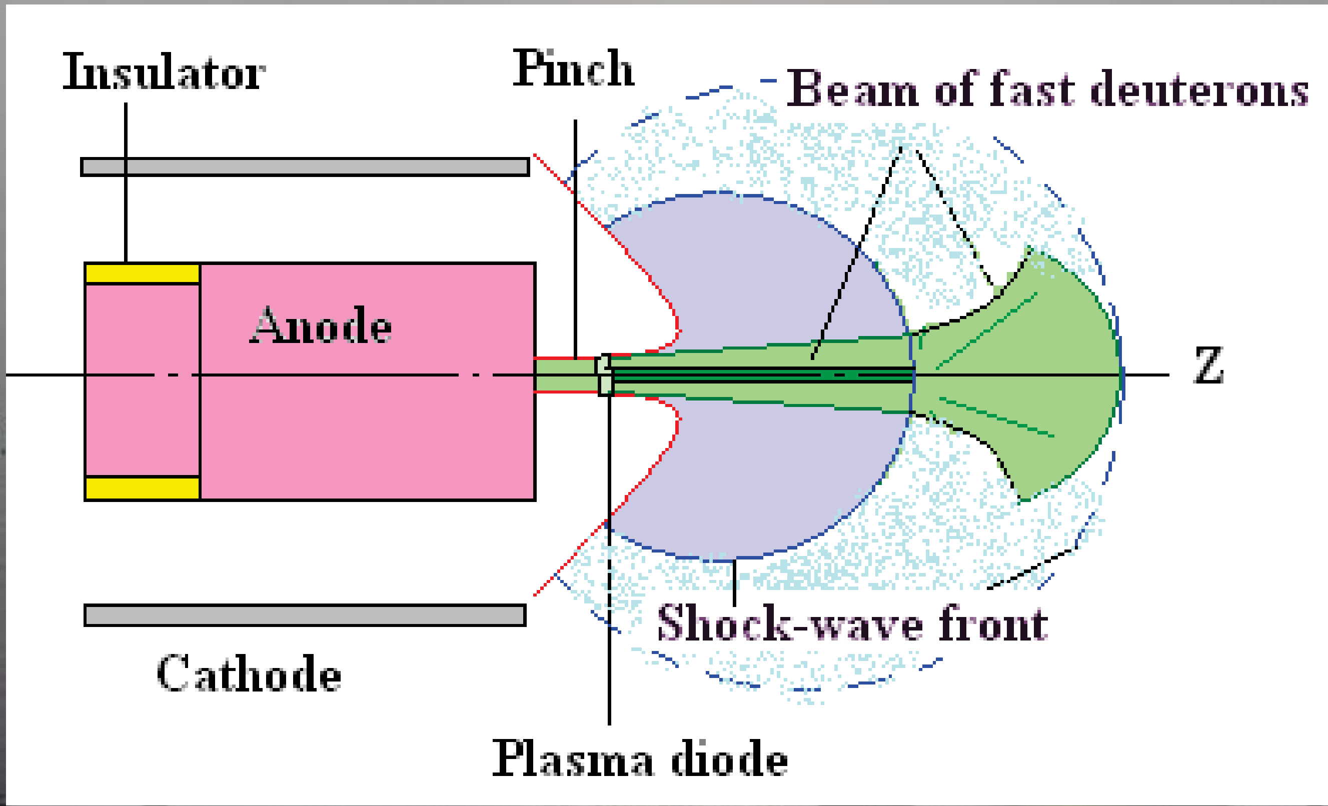
IB ↑

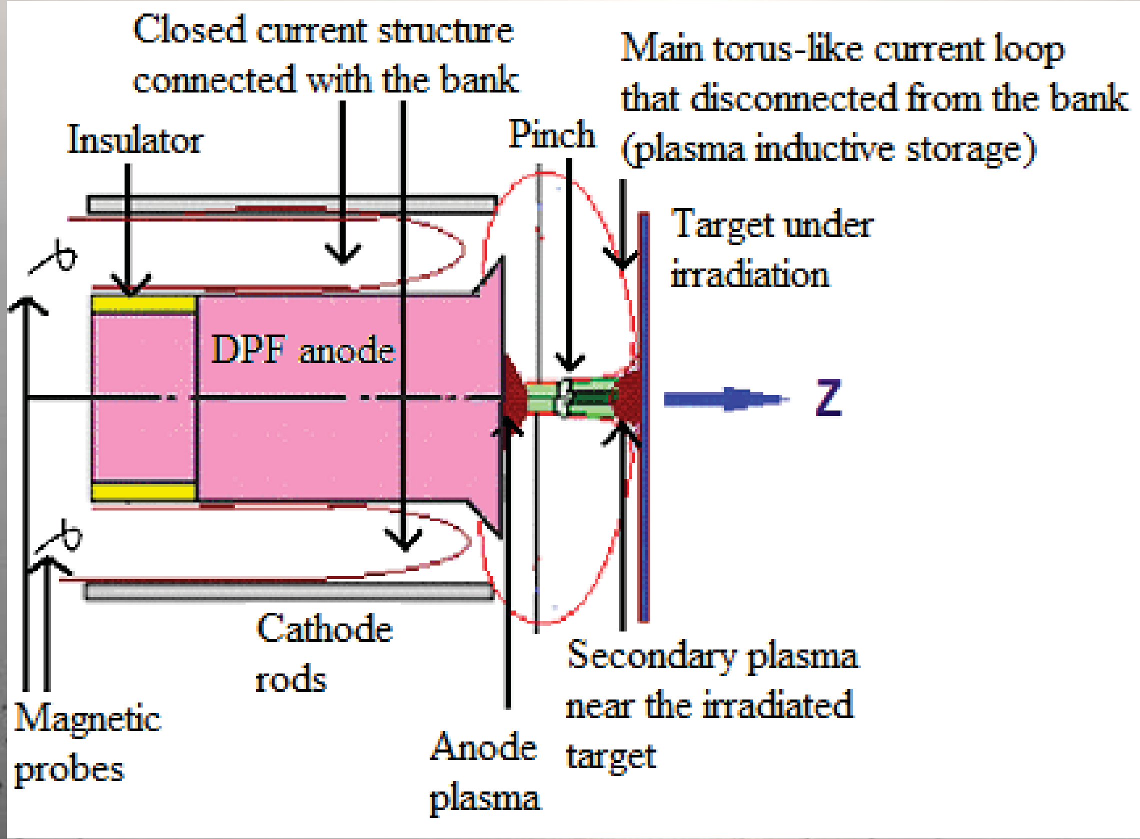
target↑ with IB and secondary plasma

Interferometric frame picture of interaction process (1-ns time exposure)



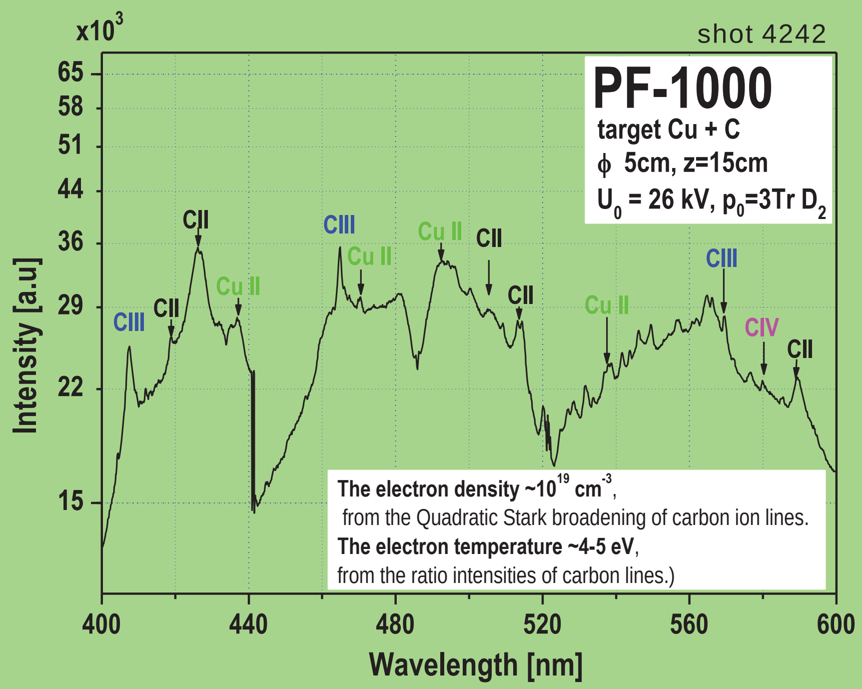
Scheme of dynamics of plasma streams and of fast deuterons beams in the PF-1000



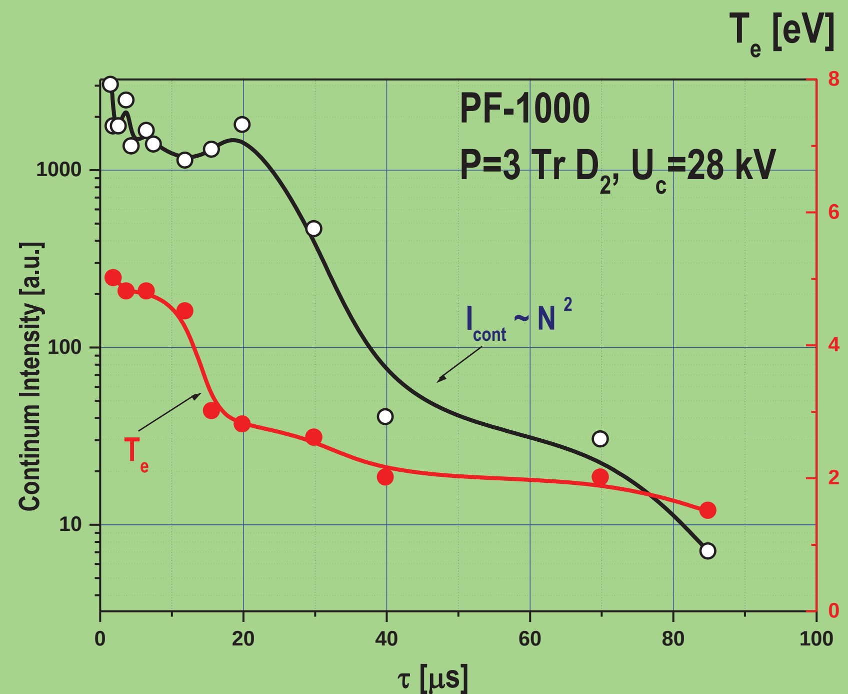


A schematic showing current loops configurations inside the DPF after secondary breakdown between ends of cathode rods and anode's edge

Spectrum of secondary (target's) plasma



Time evolution of main parameters of the secondary plasma



4. CONCLUSIONS

Our experiments on the diagnostics of the physical processes taking place in the Dense Plasma Focus device has shown that:

1) The discharge evolution can be separated into two main stages – the MHD and the kinetic ones
2) In the first stage a plasma column with density ~ 10^{19} cm^{-3} and temperature ~ 1 keV is formed which is subsequently presents a hot plasma target
3) At the second stage magnetic energy converts into beams of fast electrons and then fast ions
4) Fast electrons produce hard X-Rays whereas fast ions been magnetized produce neutrons


Thank you!