The Abdus Salam
International Centre
for Theoretical Physics

2369-15

CIMPA/ICTP Geometric Structures and Theory of Control

1 - 12 October 2012

Dense Plasma Focus: Construction, Physics, Current and Perspective Applications

Vladimir A. Gribkov

A.I. Alikhanov Institute of Theoretical & Experimental Physics
Moscow
Russian Federation

Dense Plasma Focus: Construction, Physics, Current and Perspective Applications

Vladimir A. Gribkov

A.I. Alikhanov Institute for Theoretical and Experimental Physics, Rosatom, Moscow, Russia

A.A. Baikov Institute of Metallurgy and Material Sciences, Russ. Ac. Sci., Moscow, Russia

The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

Collaboration

- ICTP, Trieste, Italy
- International Centre for Dense Magnetized Plasma, Warsaw, Poland
- Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
- M.V. Lomonosov Moscow State University, Moscow, Russia
- All-Russ. Research Inst. of Automatics, Moscow, Russia
- Nanyang Technological University, Singapore
- Moscow Physical Society, Moscow, Russia
- ACS Ltd., Warsaw, Poland
- Tallinn University, Tallinn, Estonia

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. Applications under investigations and use:
   - Material sciences
   - Radiation chemistry/biology (enzymology)
   - Radiation medicine
   - Nanosecond Impulse Neutron Investigation System
5. Potential implementations
6. Conclusions

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

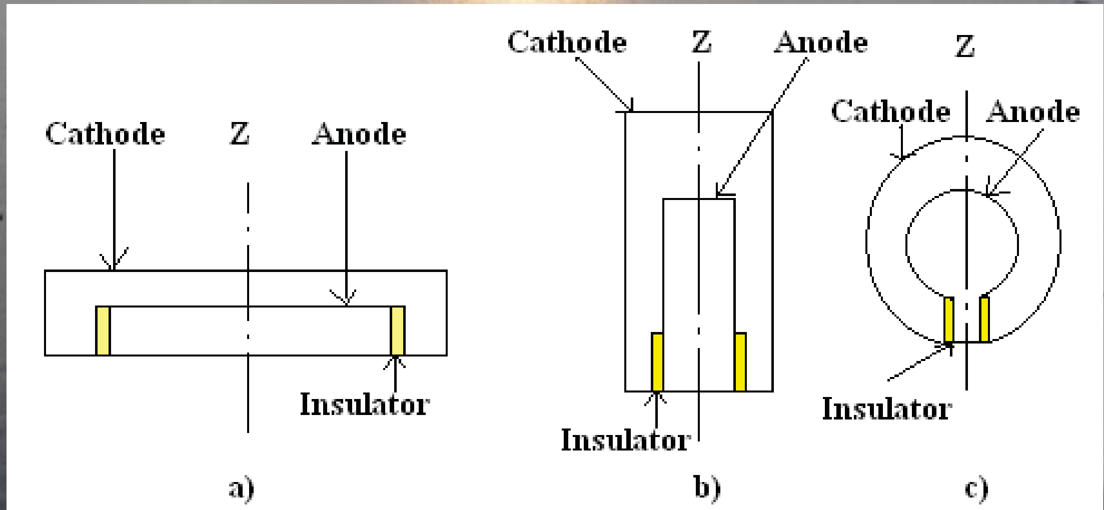
Dense Plasma Focus (DPF) device is a type of plasma accelerator that produces nanosecond pulses of:

- *directed* powerful hot ($T \sim 1$ 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 ($E_{h\nu} \sim 0.1...10$ keV) and
- hard ($E_{h\nu} \sim 10...1000$ keV) X-rays and
- fusion neutrons (monochromatic $E_n \sim 2.45$ 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

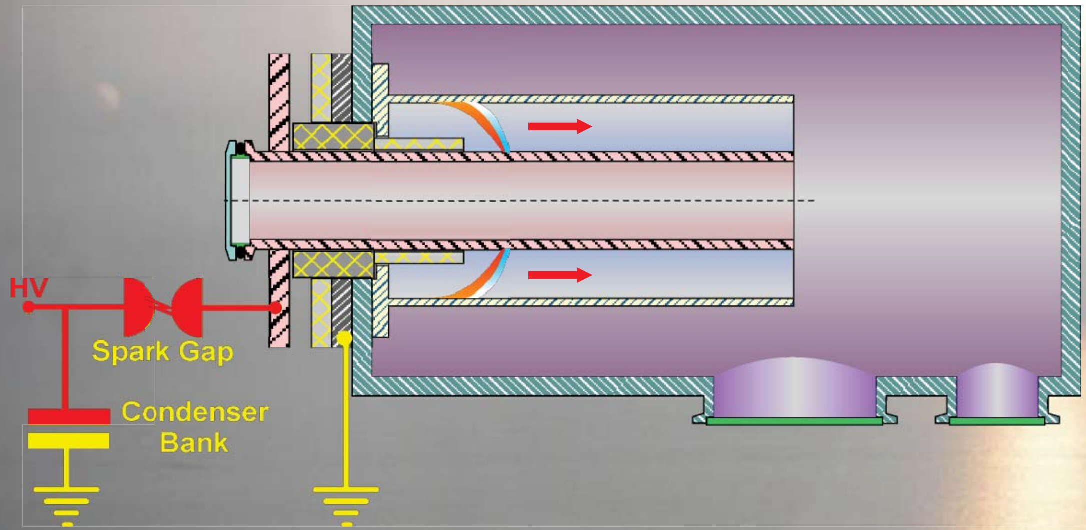
3 types of DPF chamber geometries are used at present time:

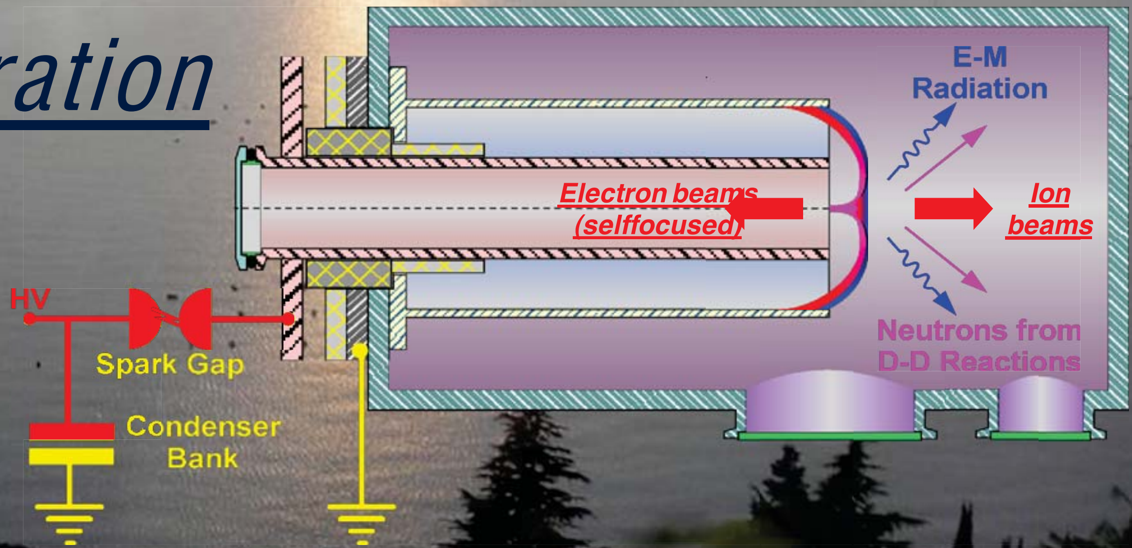


a) Flat (N. Filippov, KIAE); b) Extended (J. Mather, LANL); c) Spherical (VNIIEF)

Principle of operation

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





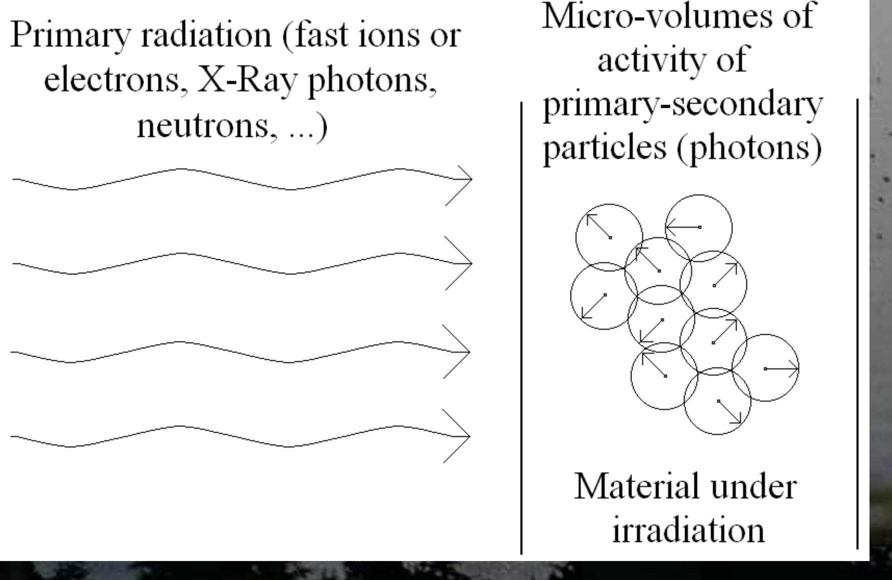
Kinetic stage (current abruption phenomena with subsequent acceleration of particles)

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

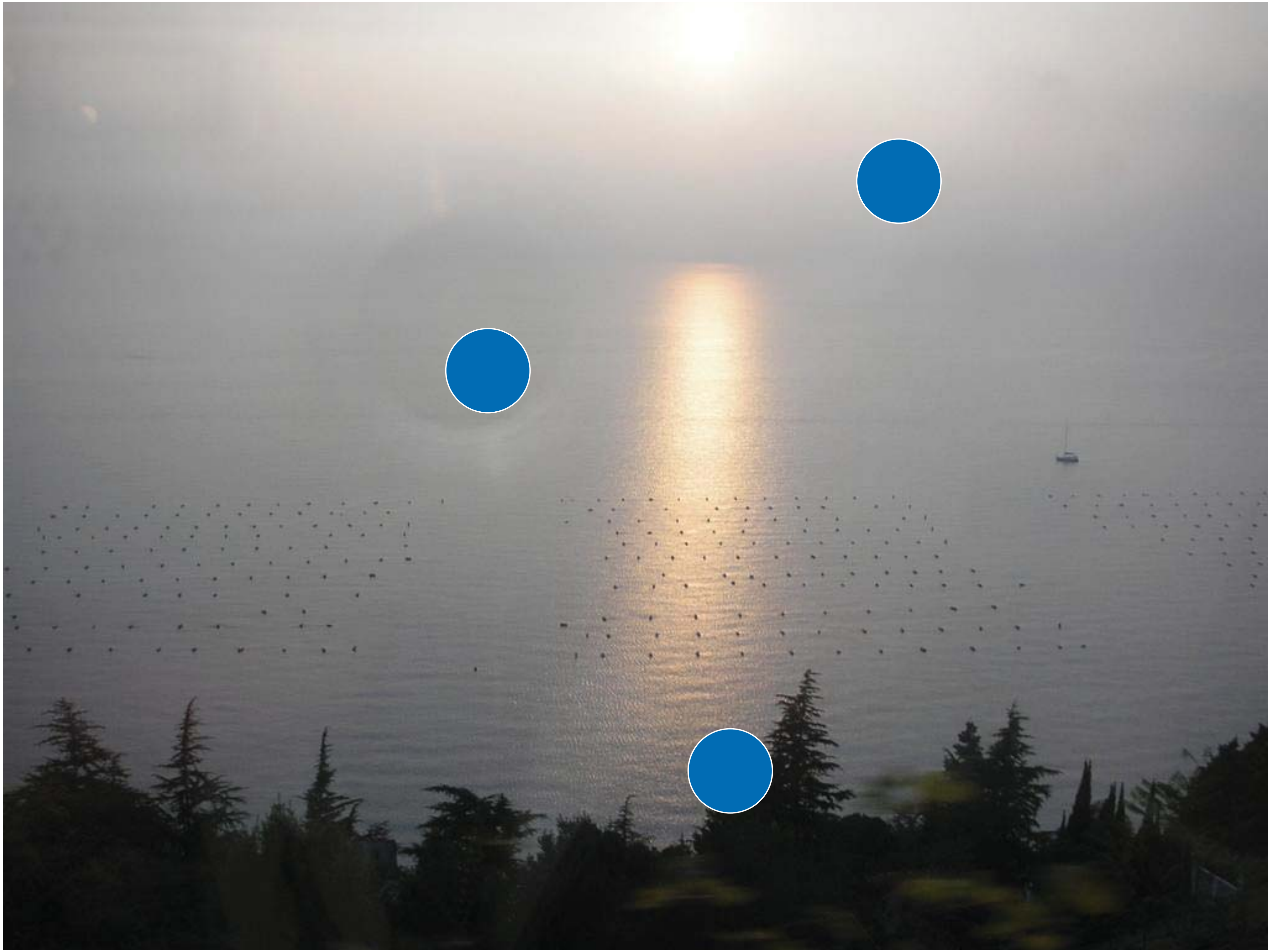
- it uses low charging voltage (~ 10 kV)
- it becomes a radiation source just for a few nanosecond and only on demands ("*a push-button source*")
- it is a radiation-safe device, i.e. it has no fission materials and **doesn't need any** *special containers* **for the device's preservation**
- it has no such a parameter as "*criticality*" – on the contrary to fission reactors

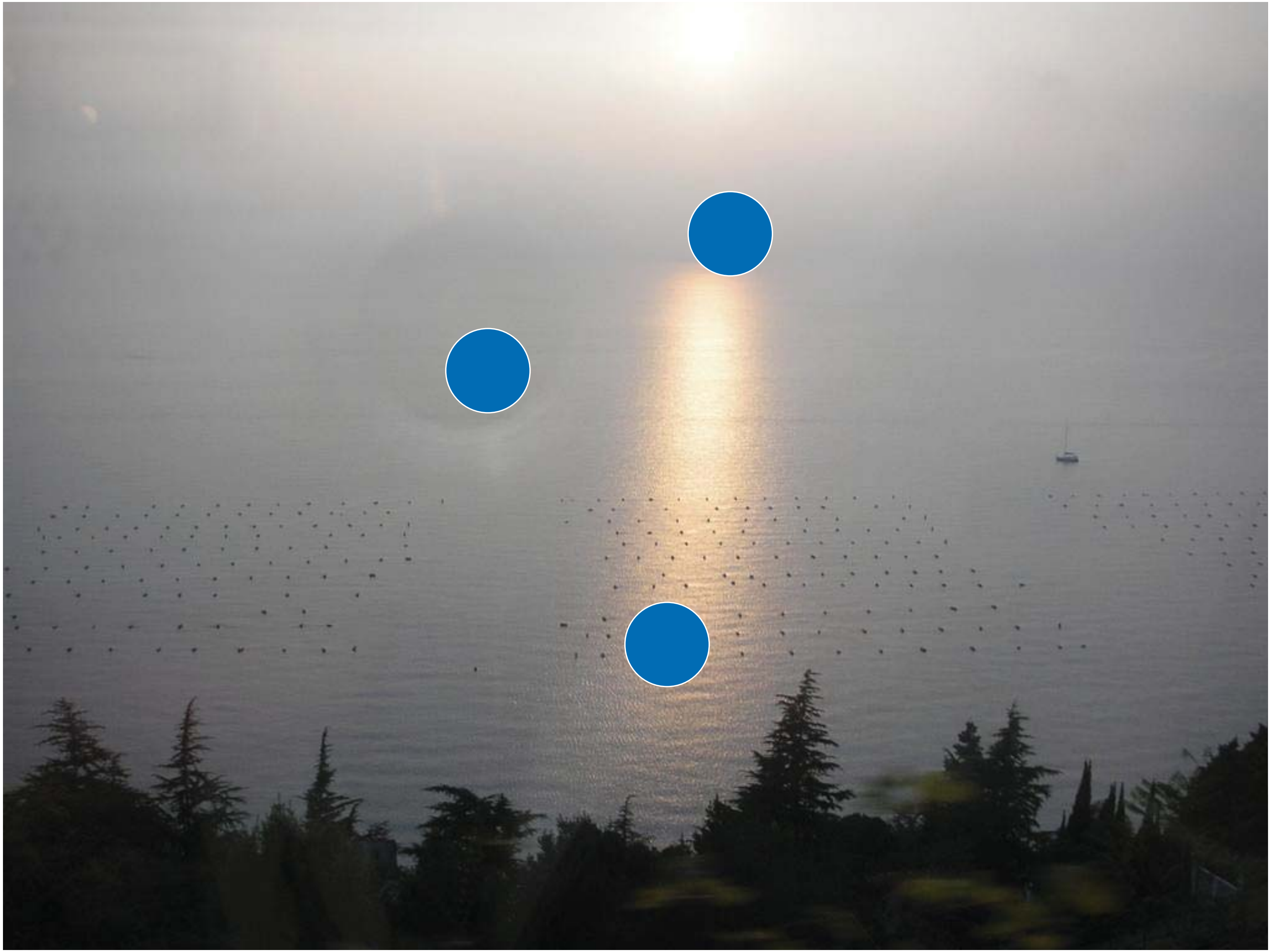
Having a very *short pulse duration* of radiation together with a very *high energy* contained in the pulse, DPF can be used in ***pulsed radiation physics, chemistry, biology… in*** *the perfect sense of this term,* i.e. when two prerequisites hold true concurrently:

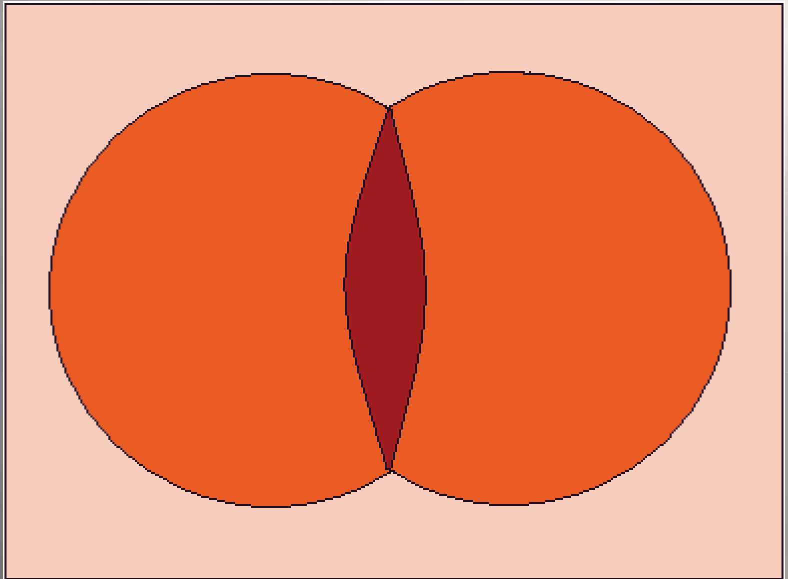
1) Micro-volumes of activity of each primary/secondary particle are overlapped within the irradiated volume



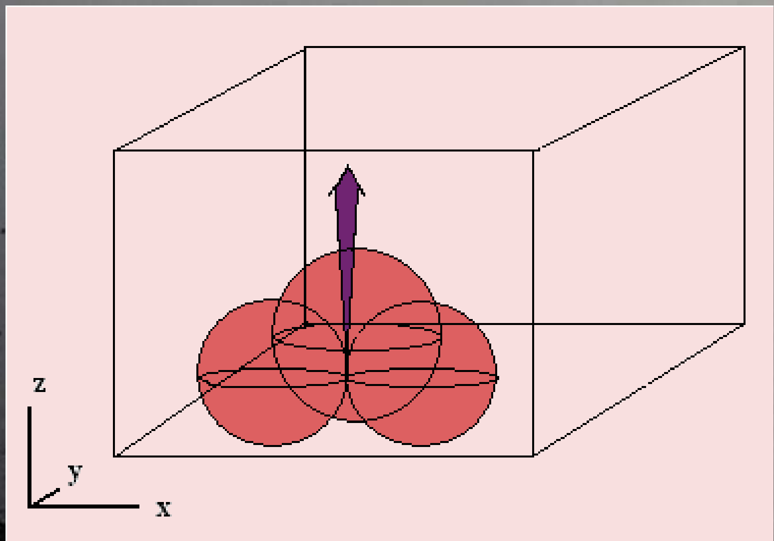
2) This overlapping occurs during a time interval, which is short compared with the reciprocal phys./chemical process







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

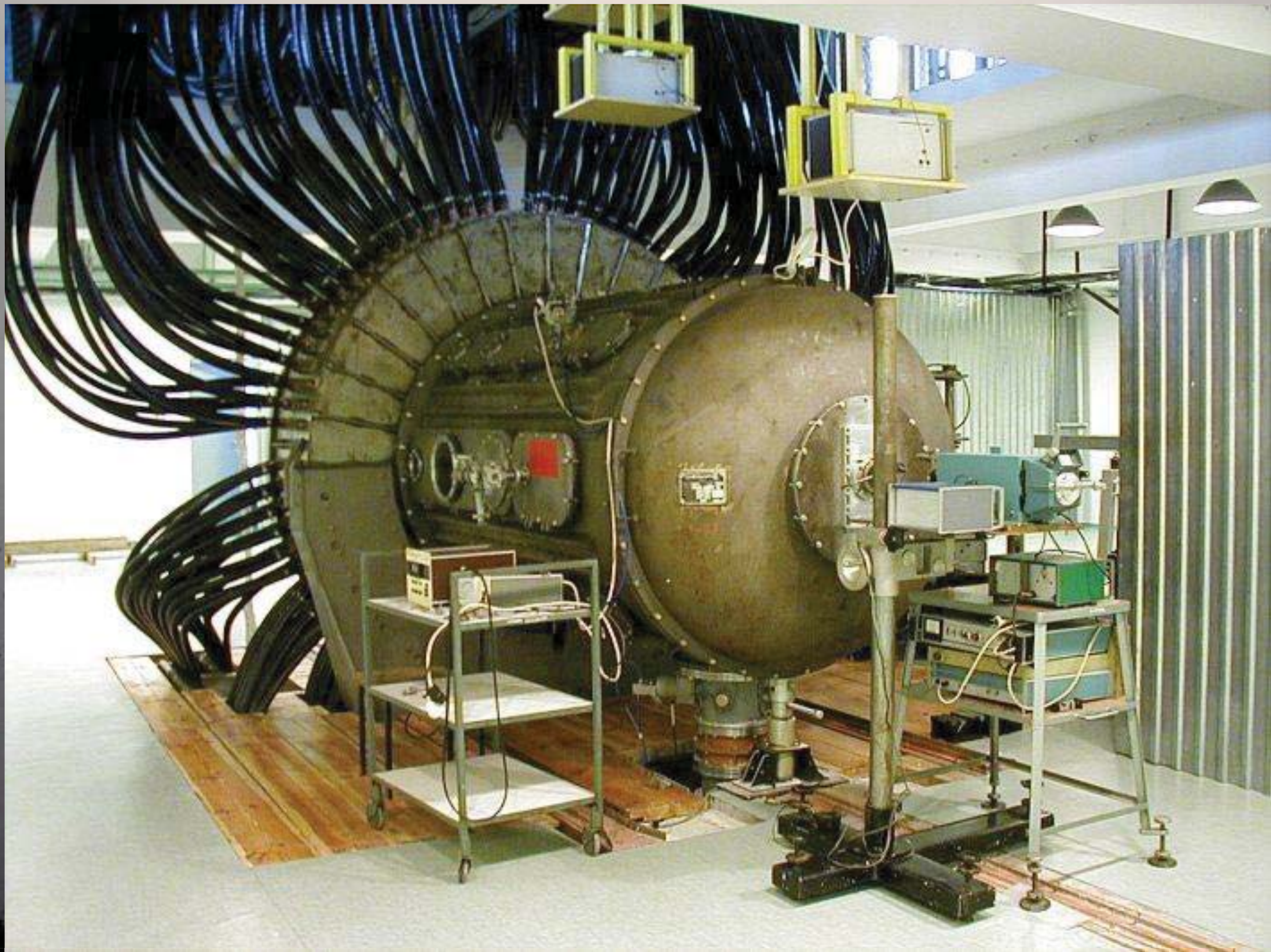
Taking into consideration *absolute X-ray and neutron yields* of DPF of medium sizes (with energy ~ 1.0-100.0 kJ in a bank) and *efficiency* of their generation here it must be noted that there do not appear to be sufficient reason to use these devices when one need large fluences of the above radiations

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

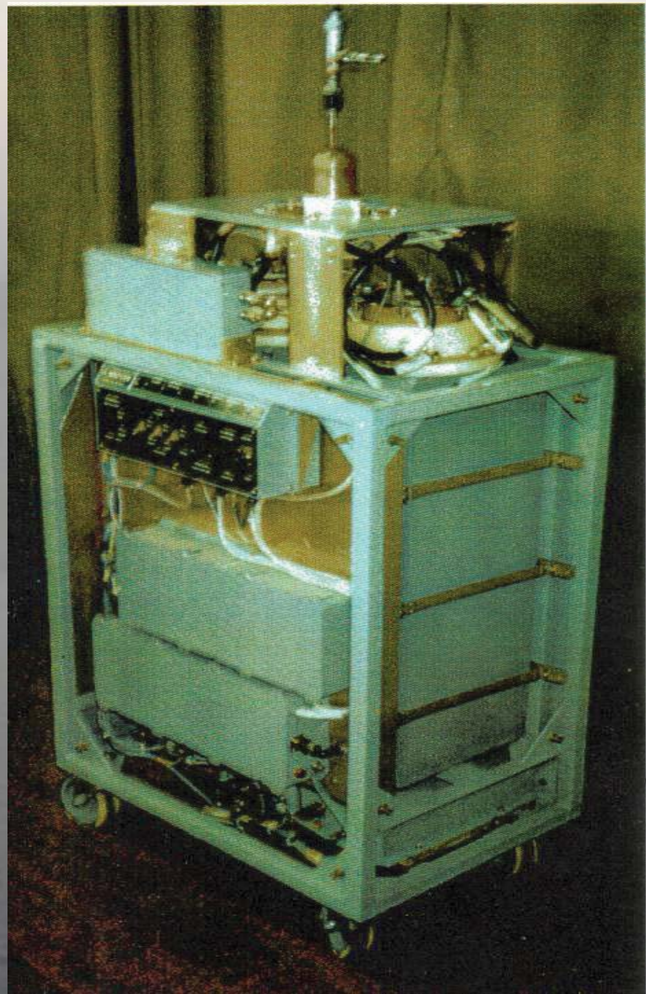
Besides these devices are small, cheap and simple in operation

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

2. APPARATUS & DIAGNOSTICS

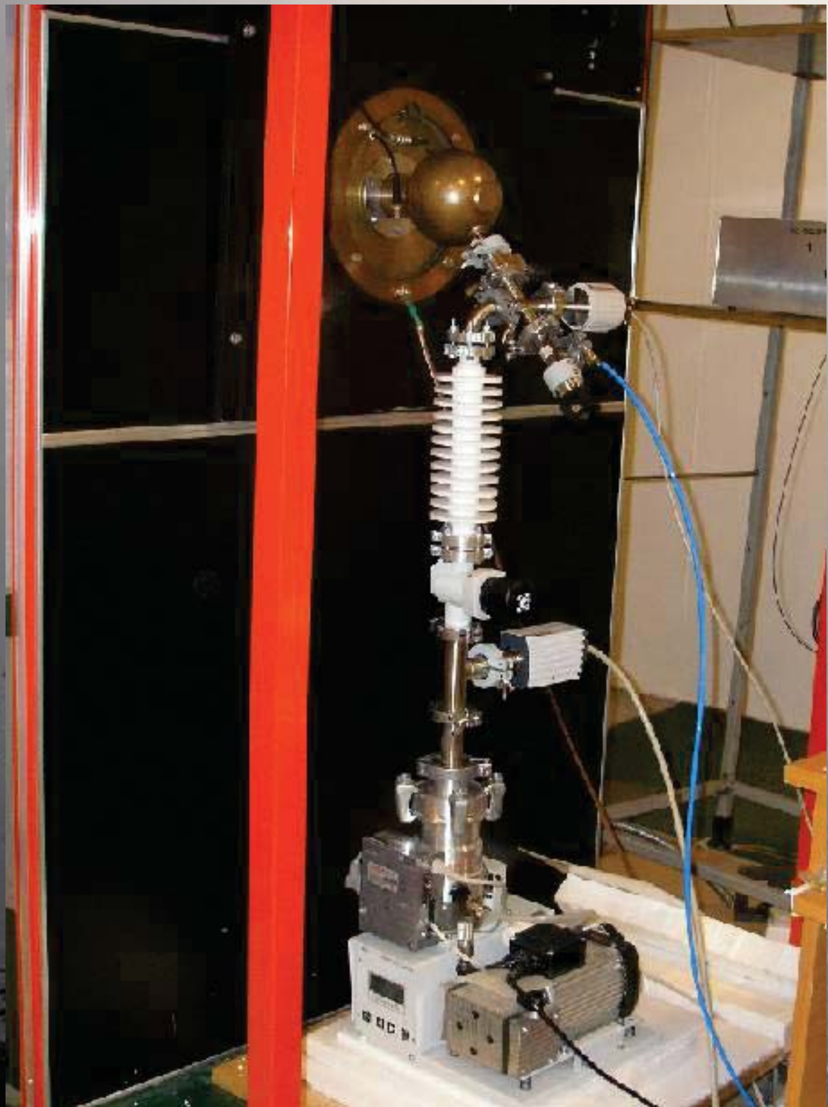


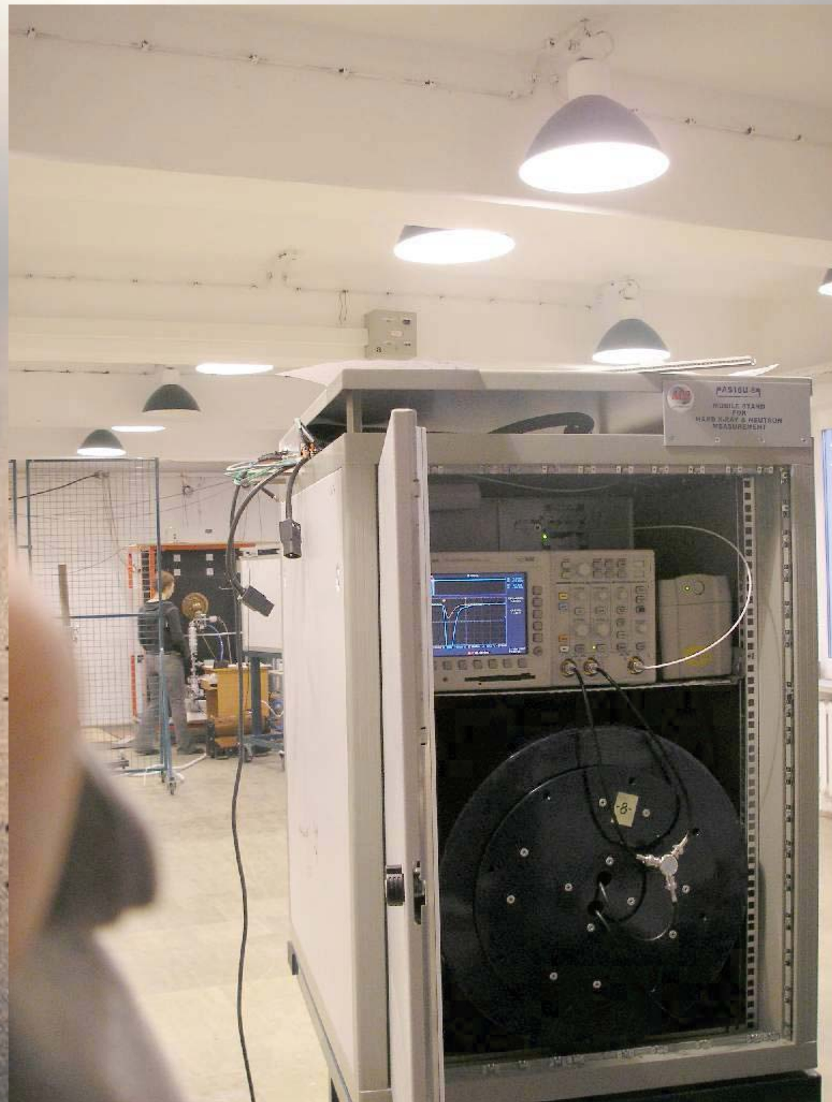
PF-1000 facility: 1.2 MJ, 3 MA, 6×10^{11} *D-D* n/pulse
(IPPLM + ICDMP)



<u>Base transportable device ING-103:</u> 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)**



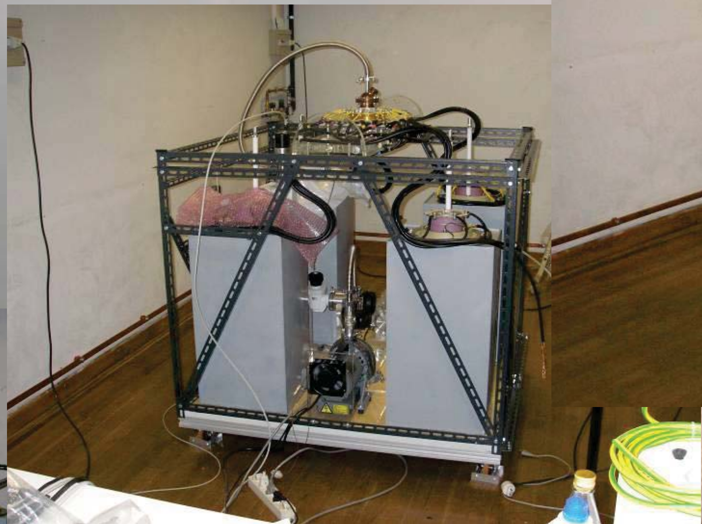


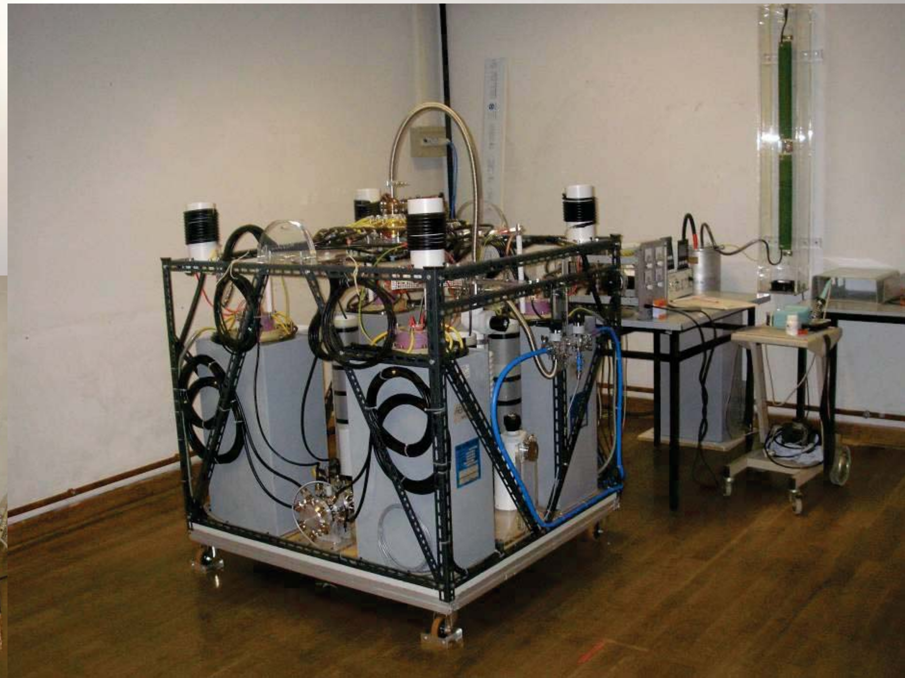
Neutron-producing chamber at its operation in PF-6 device
with circa 1 cps

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

<u>Transportable device PF-5M:</u> 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)



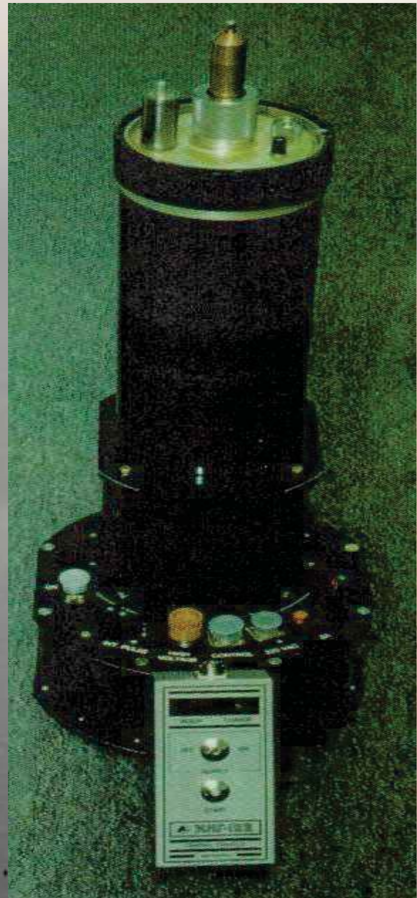


September

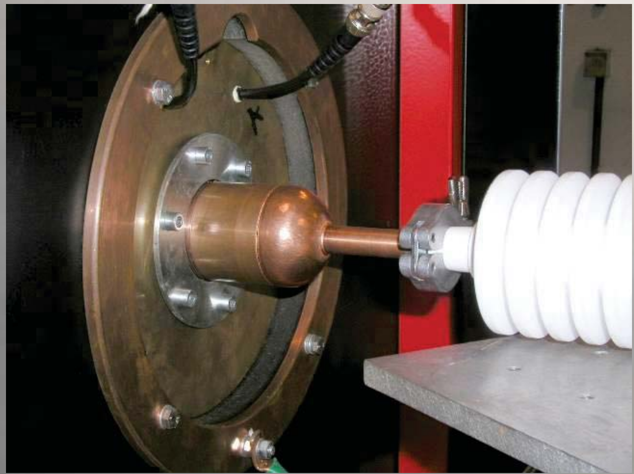
June

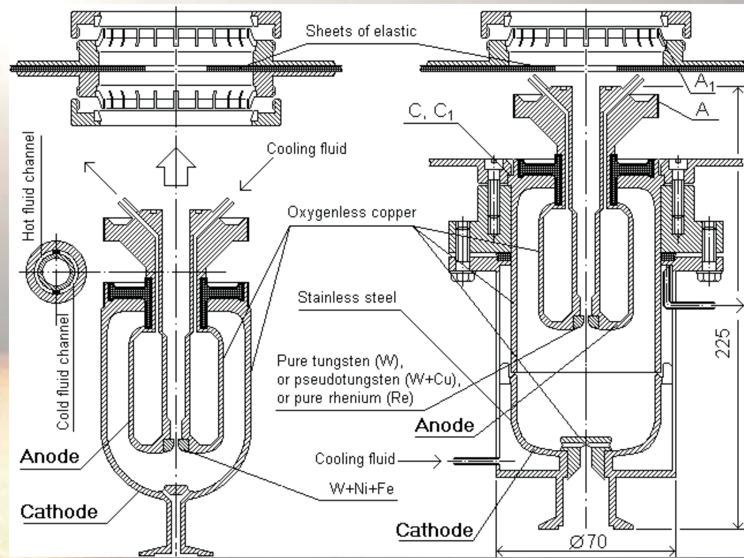
February 2007

Transportable device "Bora": 5 kJ, 350 kA, $2{\times}10^8$ *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:

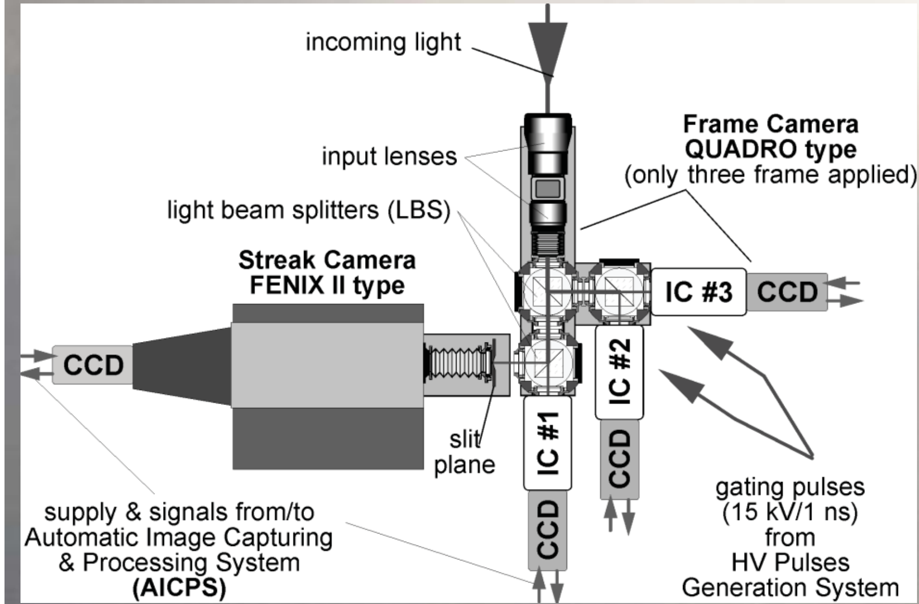
- fast electron and ion beams (including charged fusion reactions products),
- plasma streams,
- soft and hard X-ray radiation, and
- neutrons

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

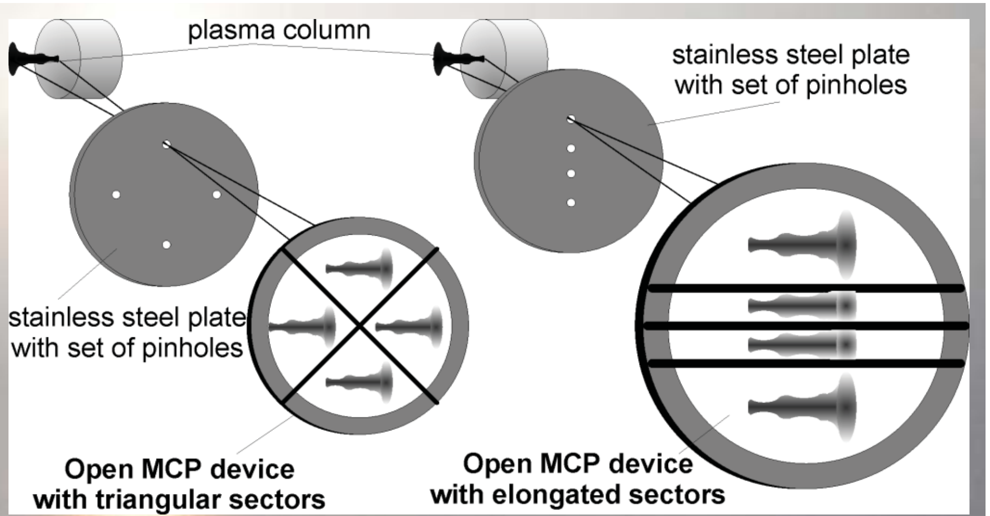
we use a number of diagnostics, having about 1-ns temporal, few micrometers spatial, high spectral and angular resolution

Among these diagnostics we use the following tools:

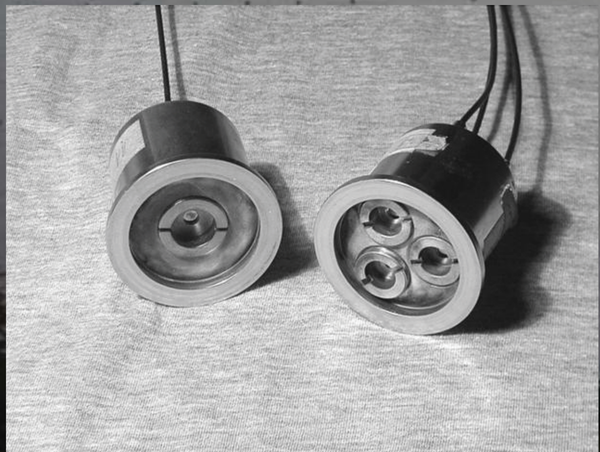
- magnetic probes, Rogowski coil and voltage divider;
- 1-ns 16-frames laser interferometry;
- 1-ns 4-frame photography and a streak camera for registering visible and X-ray plasma luminescence;
- 5 channels of 0.3-...1.3-ns PM tubes + scintillators;
- Čerenkov detectors;
- visible and X-ray spectroscopy;
- 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

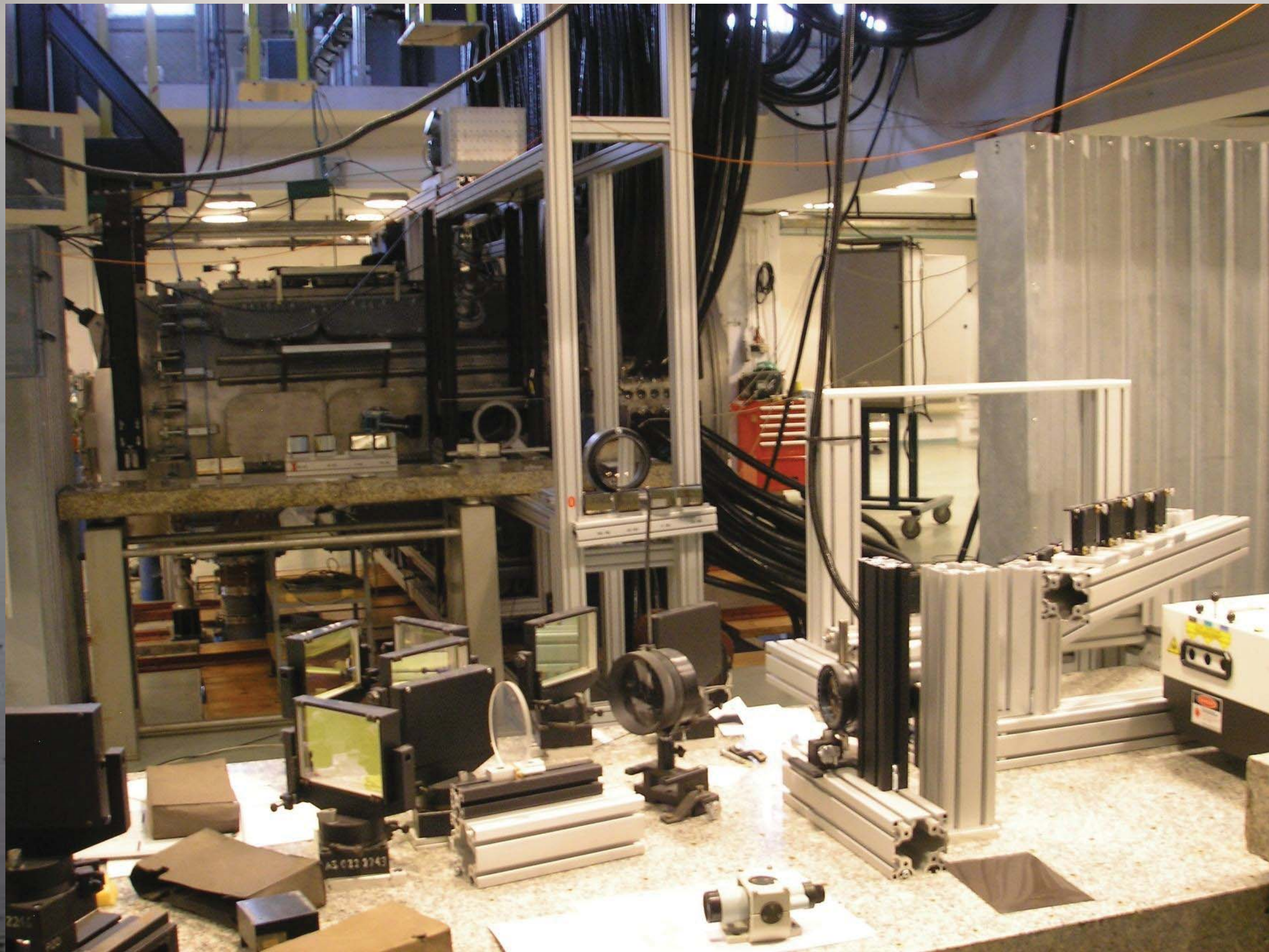


4-frame soft X-ray camera



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.

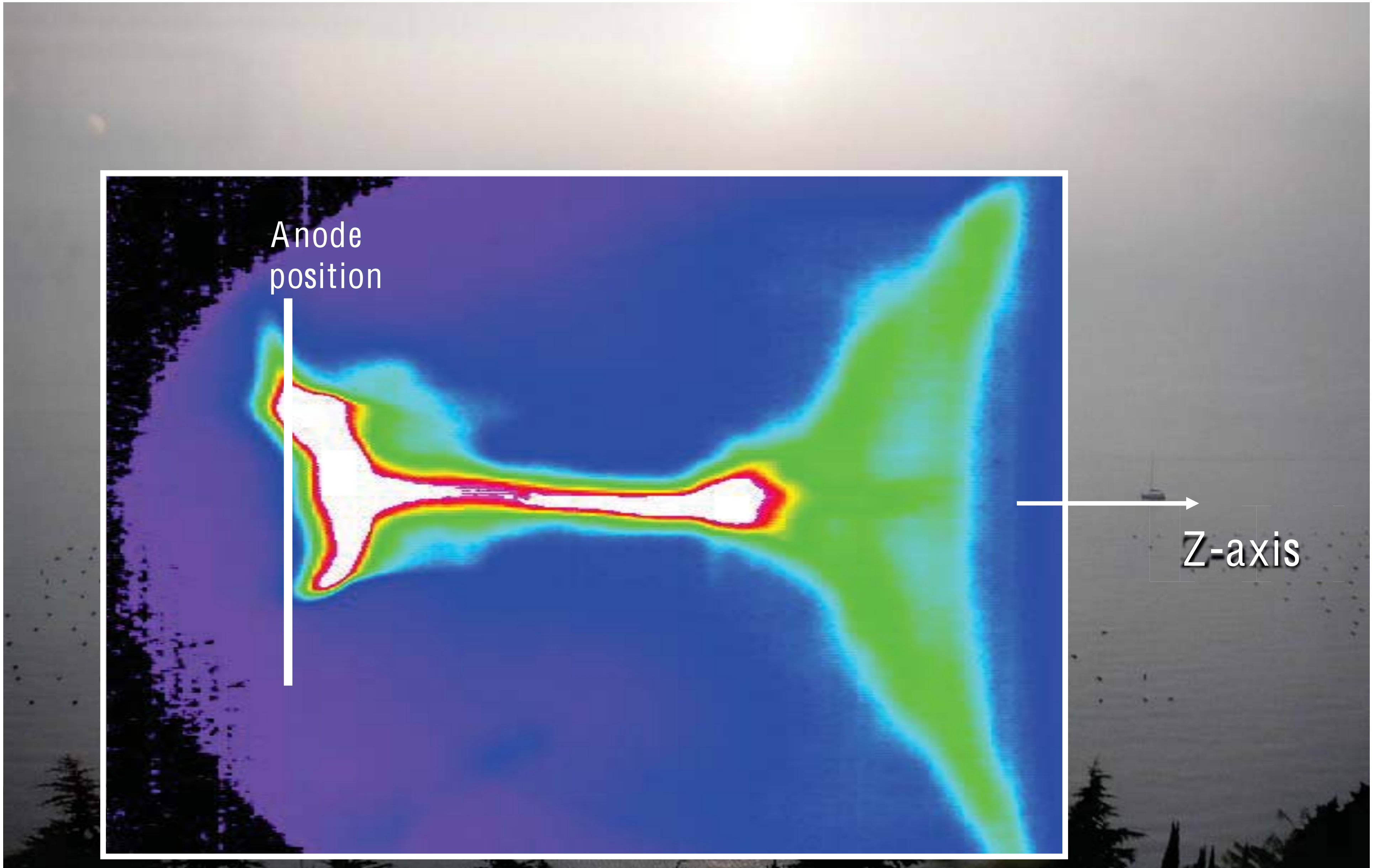
As a rule all experiments were supported by intensive numerical modeling using FLUKA and MCNP codes

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

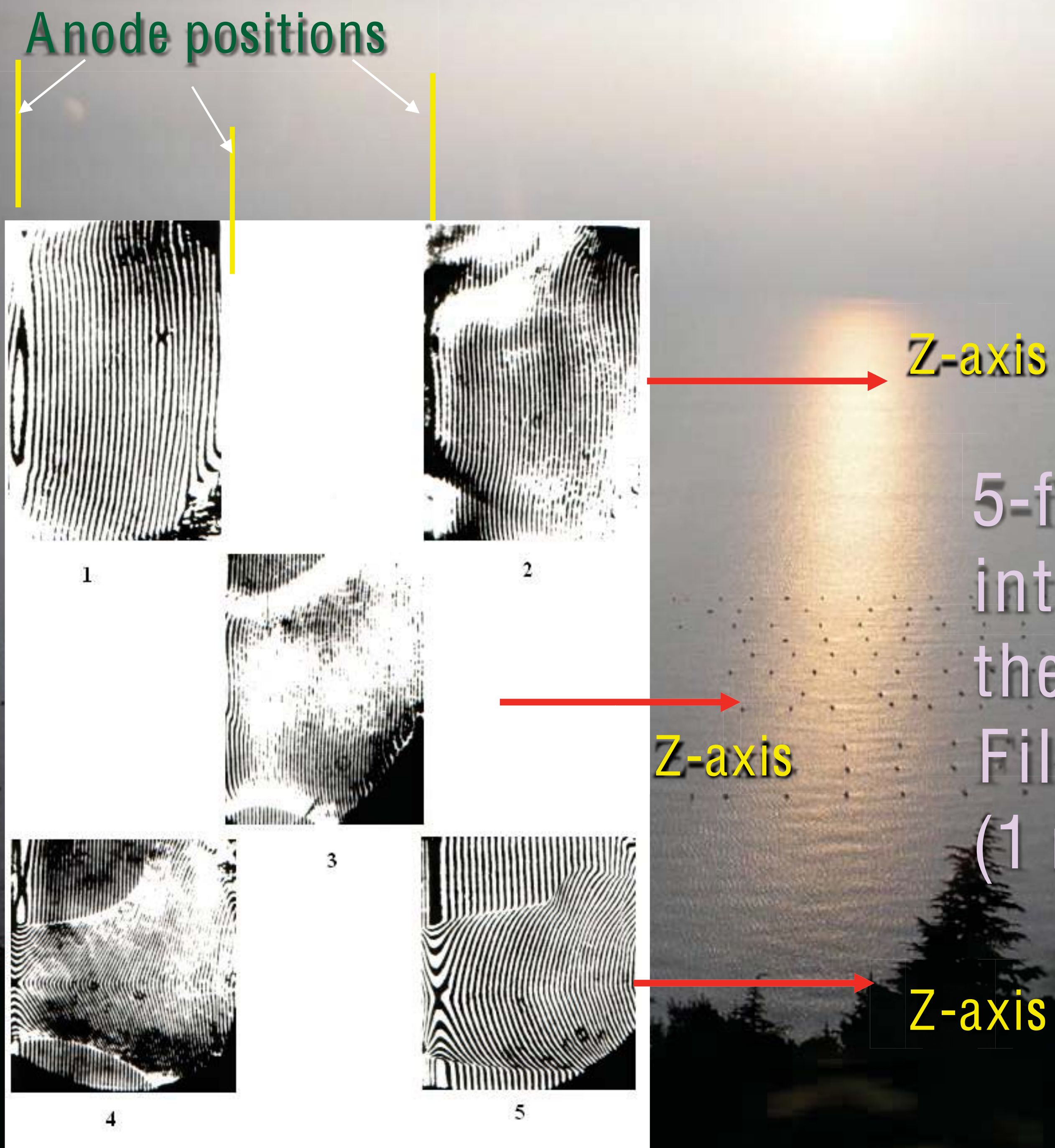
3. Dynamics of plasma, beams of fast particles and ionizing radiations in Dense Plasma Focus devices

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 $2...3 \times 10^7$ cm/s

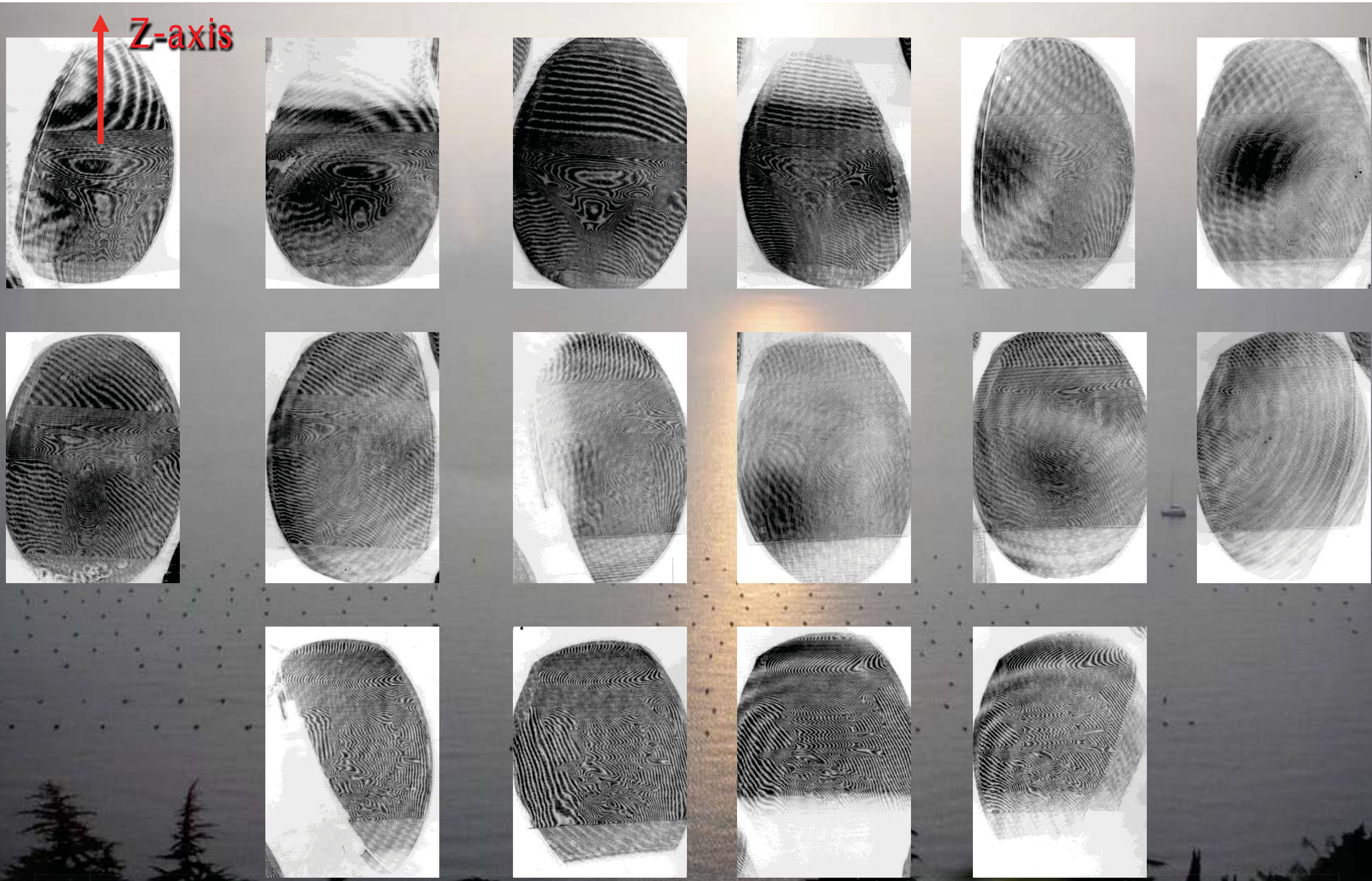
Collapsing process of the PCS is preceded by a Shock Wave contraction about Z-axis, then it finishes by a formation of a straight plasma column



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

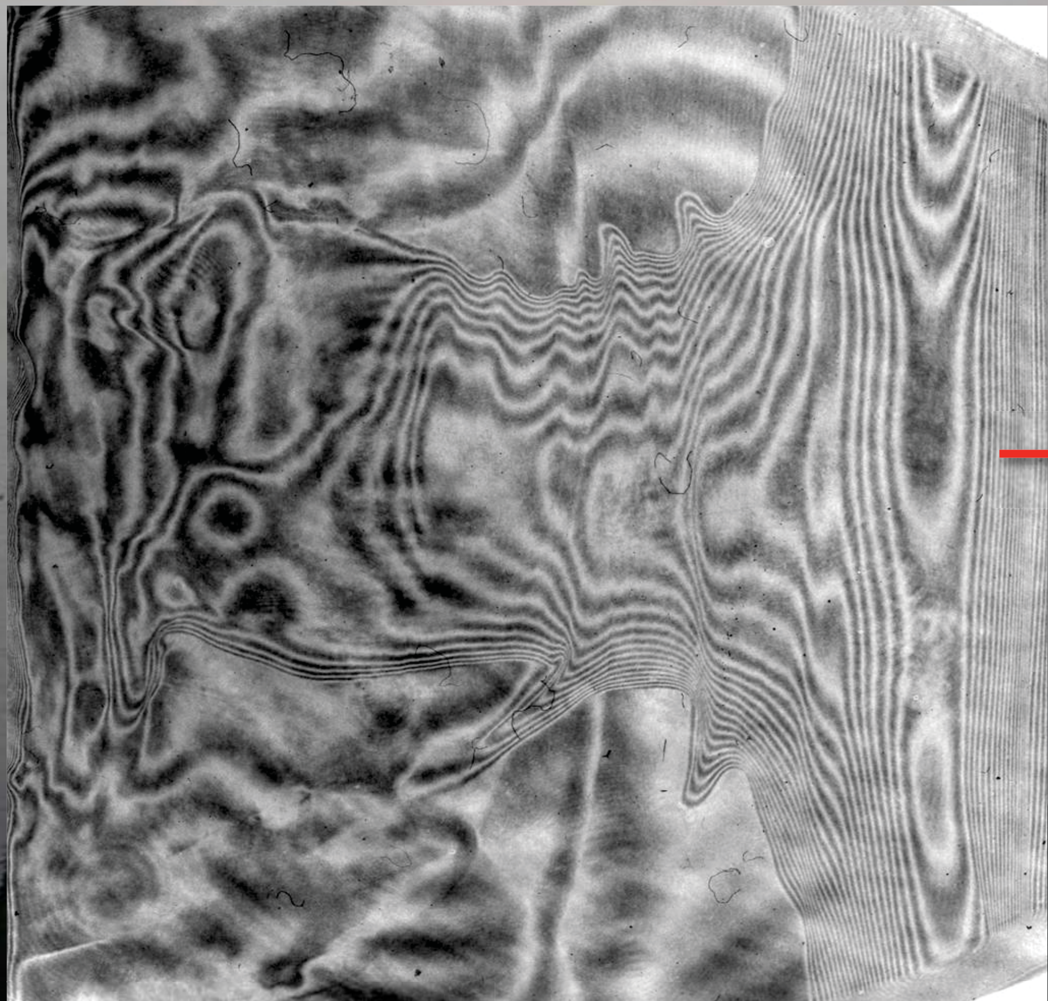


5-frame laser interferometry at the DPF of Filippov geometry (1 ns – 16 ns)



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)



anode ↑ pinch column↑ current sheath↑

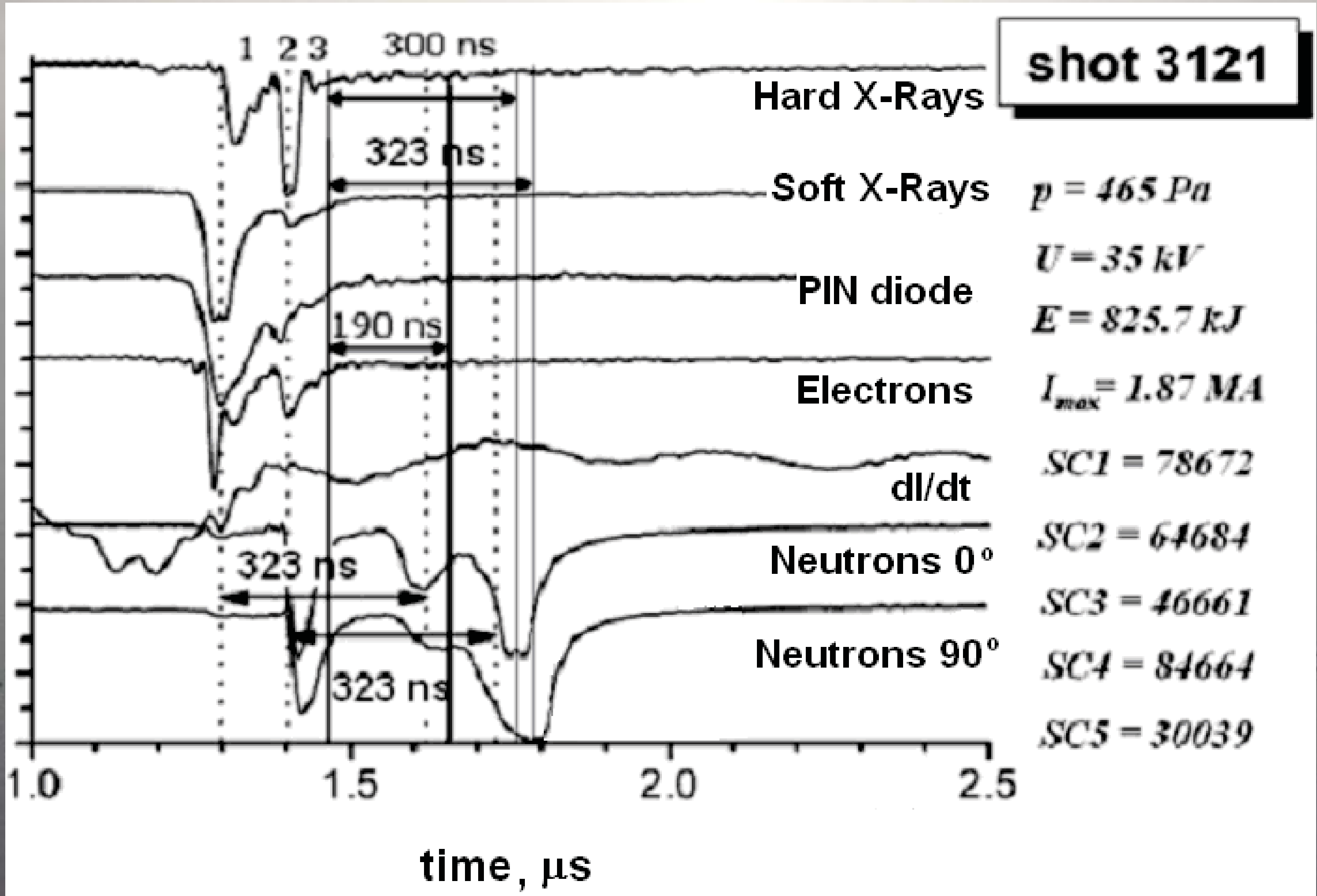
Implosion speed measured by the above three methods gave us a lower estimate of the plasma temperature T in the dense plasma pinch provided that the ordered kinetic energy of the PCS is converted into the chaotic plasma particle motion: $(mv^2)/2 = 3/2(kT)$, and that additional plasma heating takes place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

It appears to be within the limits of $T \cong \mathbf{0.5 \ldots 2.0\ keV}$

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 $1.3 \cdot 10^{19}$ 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}

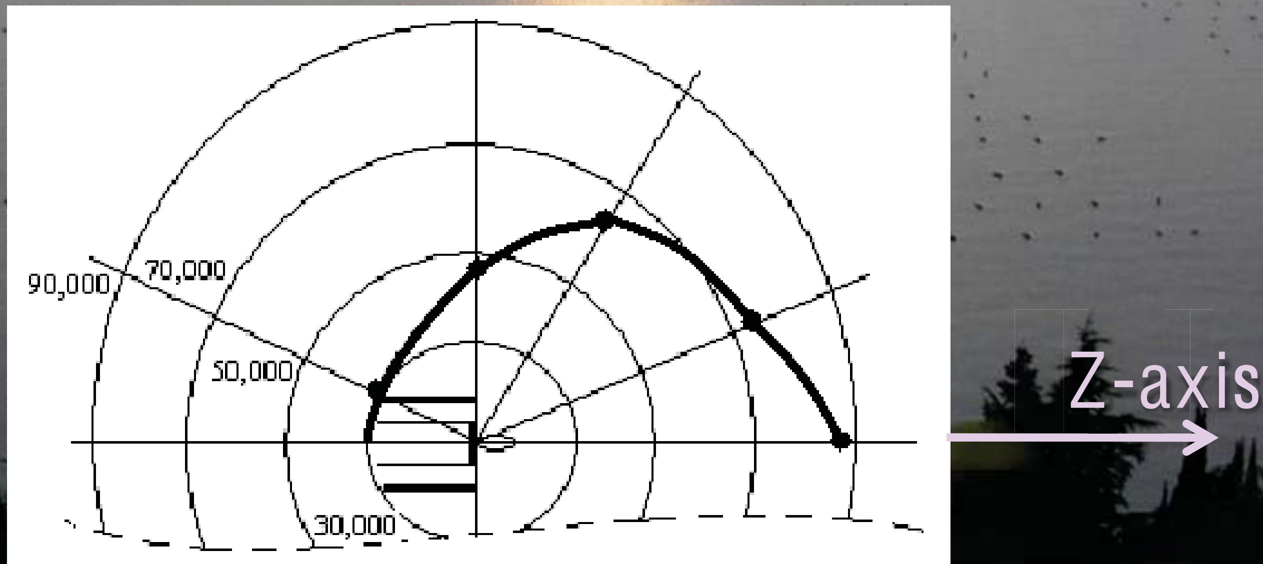
Interferometry and spectroscopy support these estimations



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

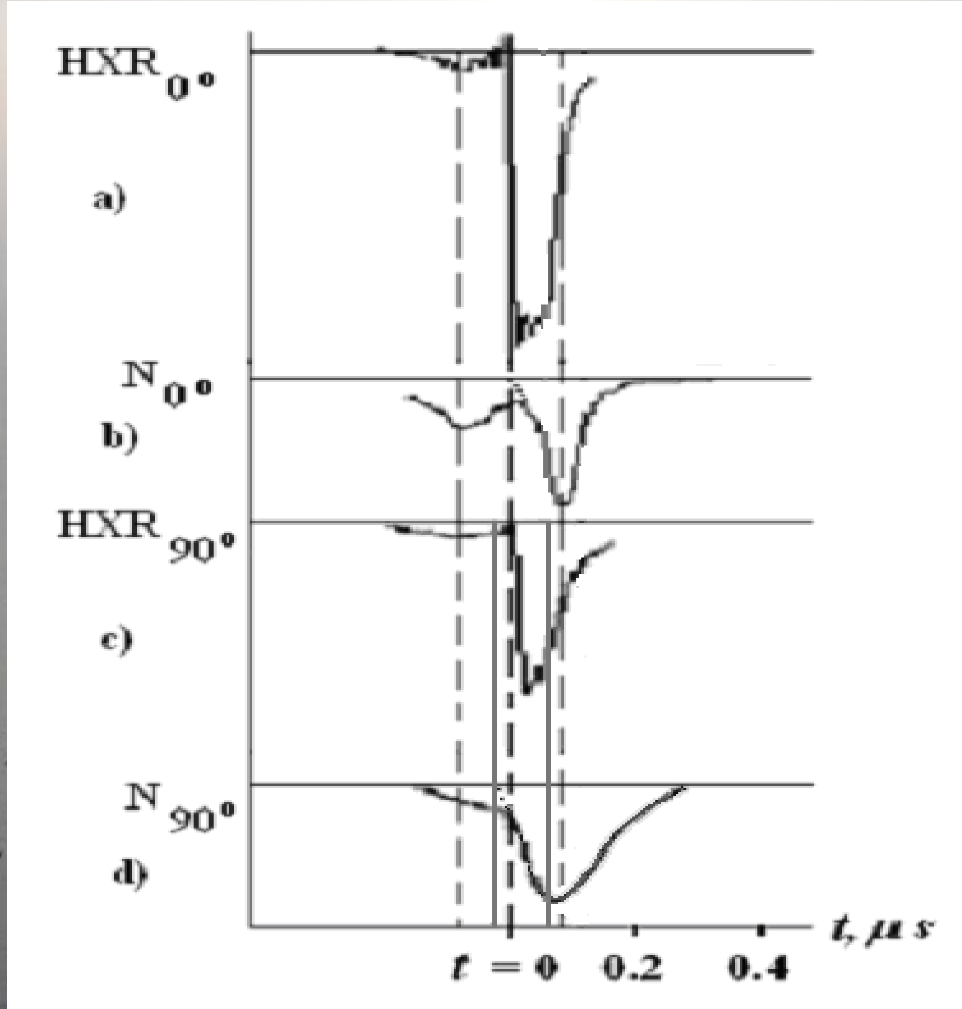
Both second pulses are higher by amplitude from 4 through 20 times than the first ones

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

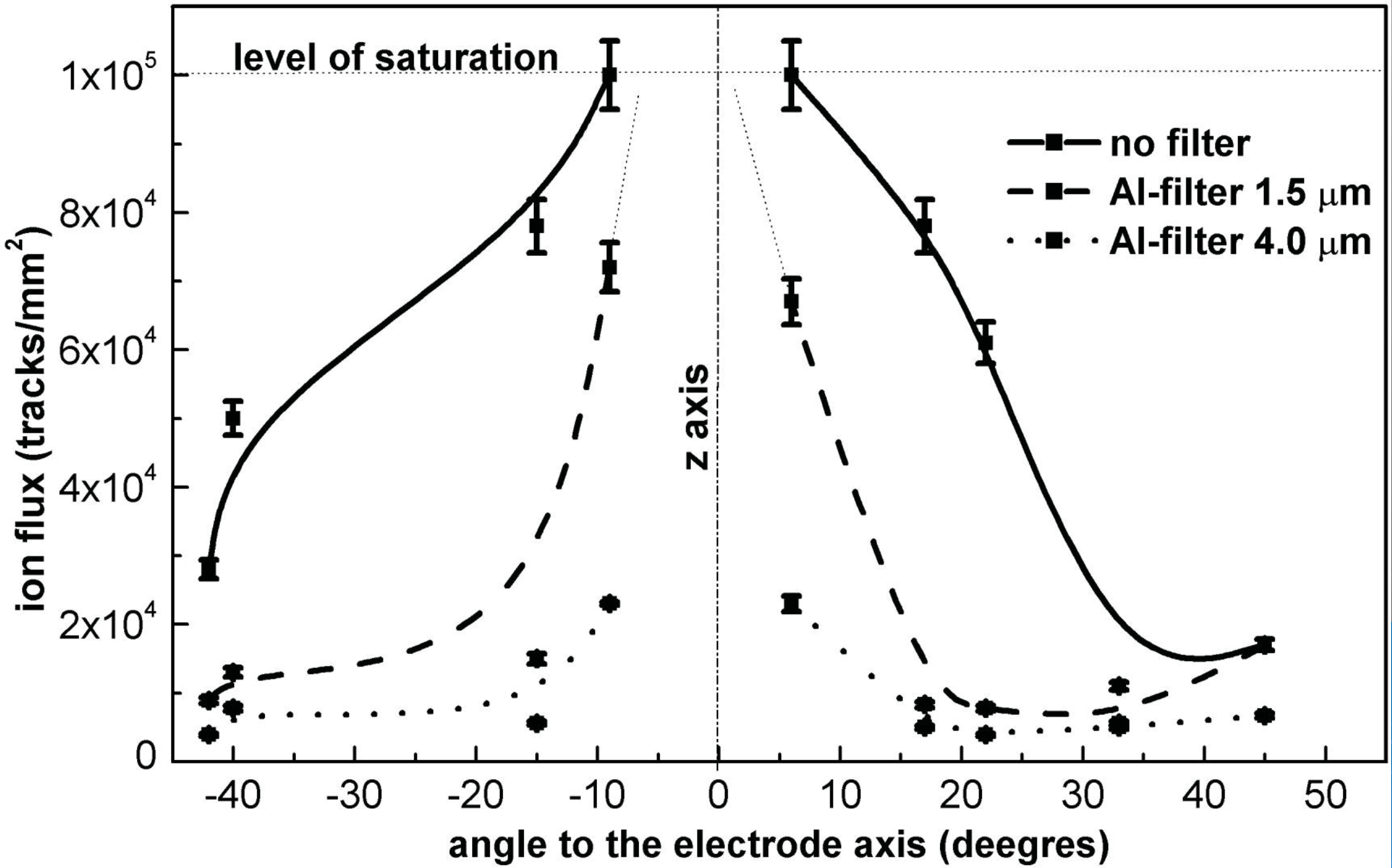
Durations of each neutron pulse (FWHM) as well as the interval between them at their registration in the **“head-on”** direction depends on the size of the particular device and lies in the limits from 10 through 150 ns

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)

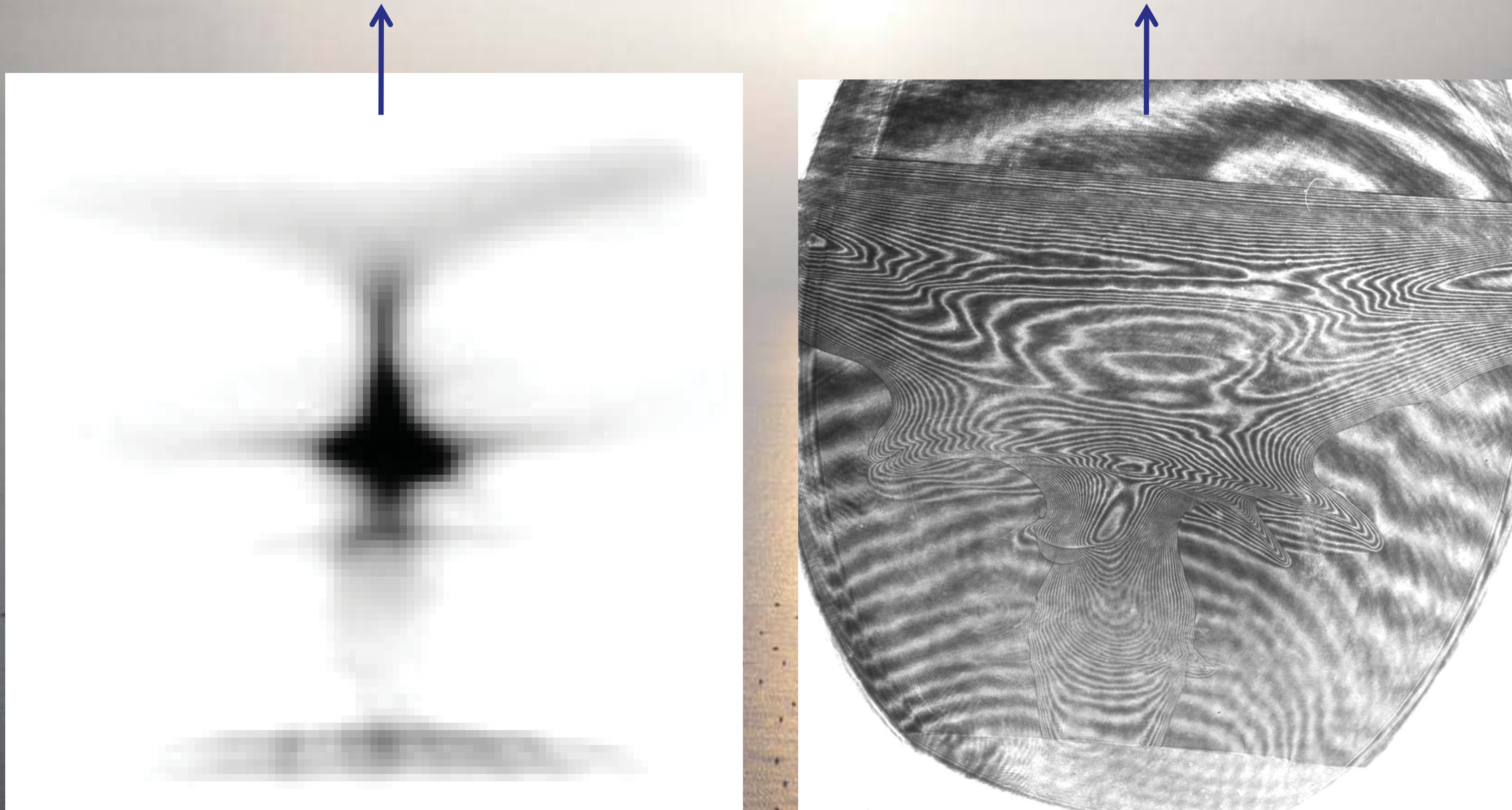
The **pinch's column during the first neutron pulse is** straight and has a height of 10 cm with a radius of 0.5 cm (a so-called the first compression phase)

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)

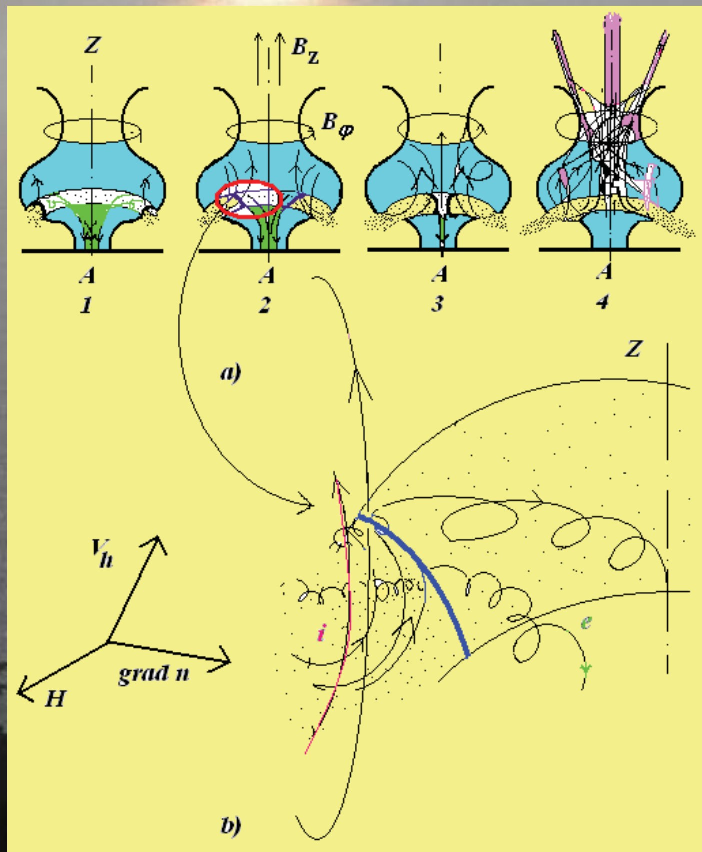
The pinch breaks usually in one-two (or sometimes several) regions along the column. According to our analysis the data received give an evidence of the virtual plasma diode creation across the pinch



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:

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

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:

$$r_e \geq \mathbf{5} \times 10^{-4} \text{ cm and}$$

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

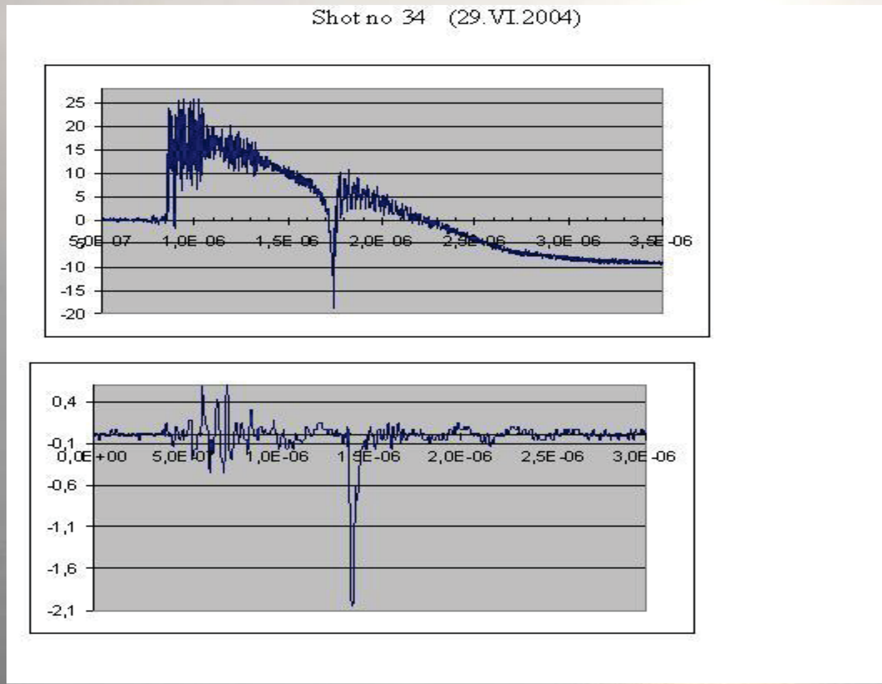
They are much less than the pinch diameter

It opens opportunities for:

-a creation of the above-mentioned plasma diode;

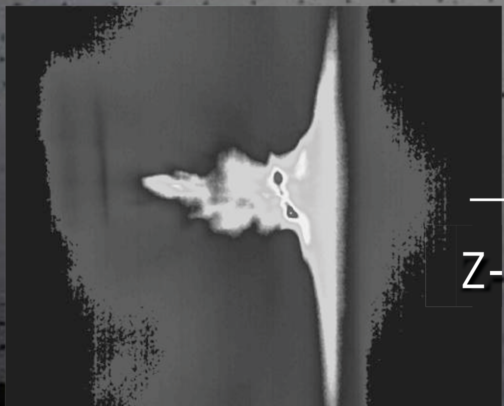
- for magnetizing the electron beam and subsequently for the substitution of the electron beam by the beam of fast ions (carrying circa the whole discharge current);

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

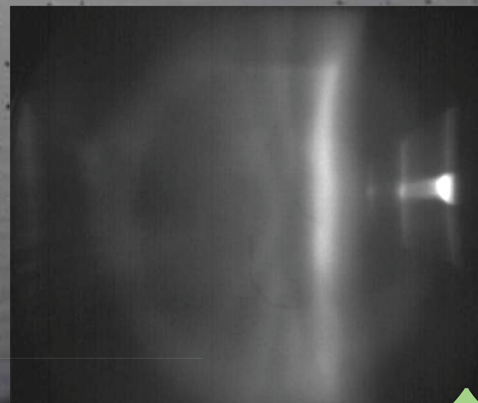


dI / dt

Hard X-rays and neutrons



Z-axis

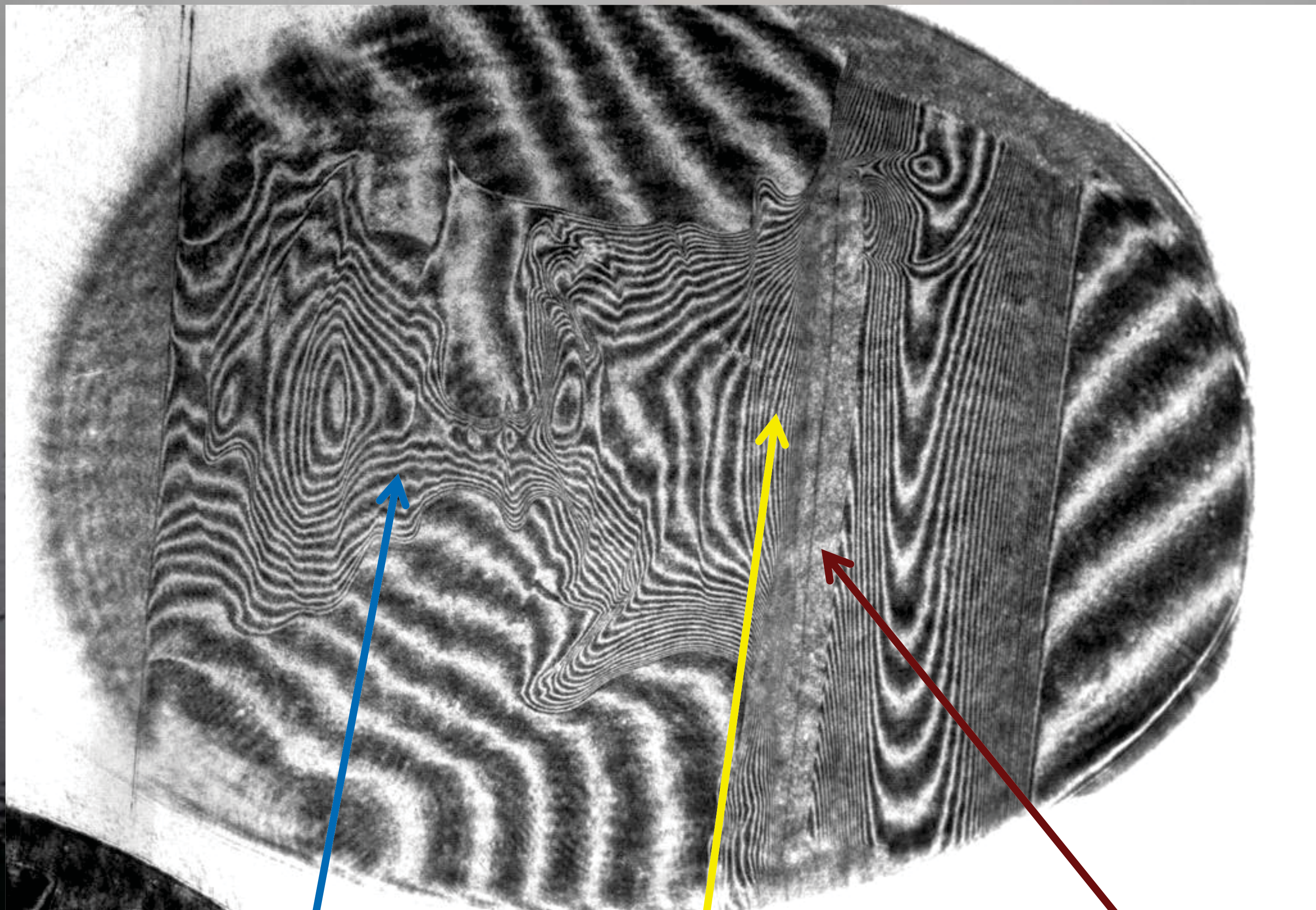


SW ↑

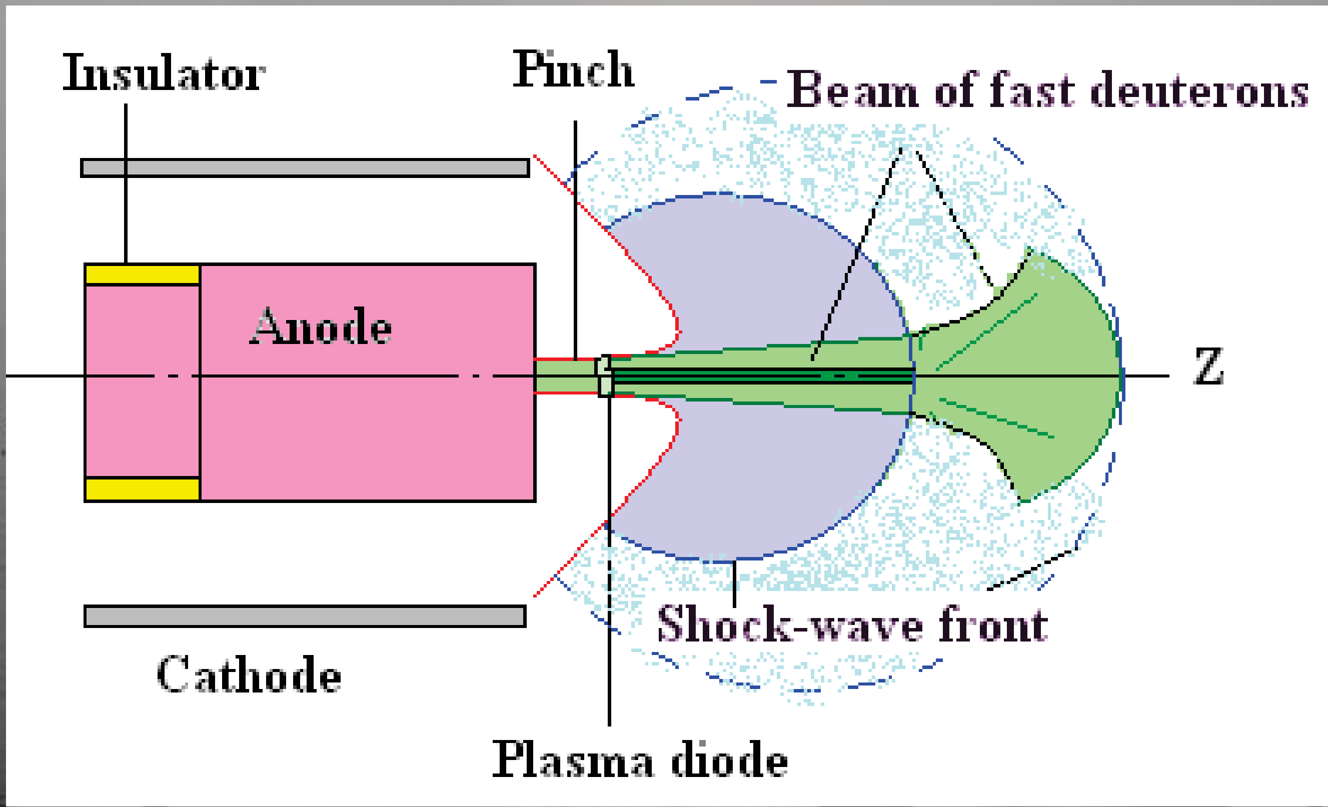
IB ↑

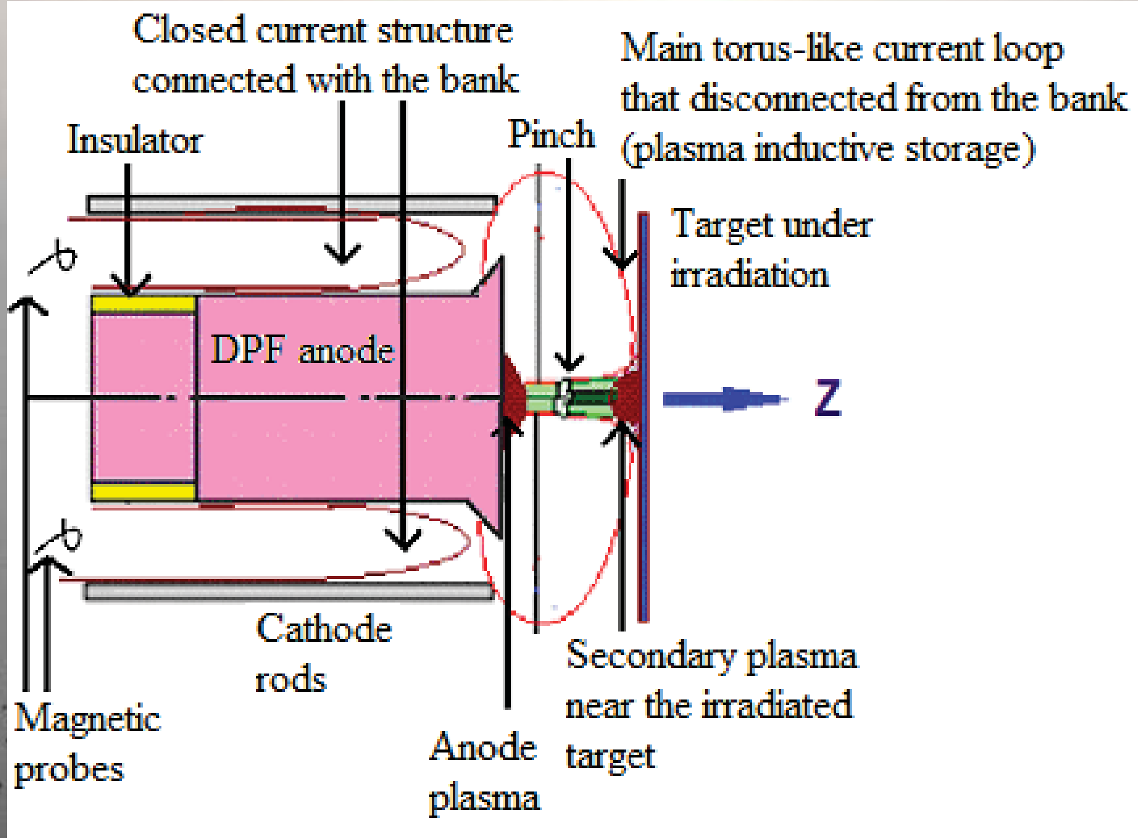
target↑
with IB and secondary plasma

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



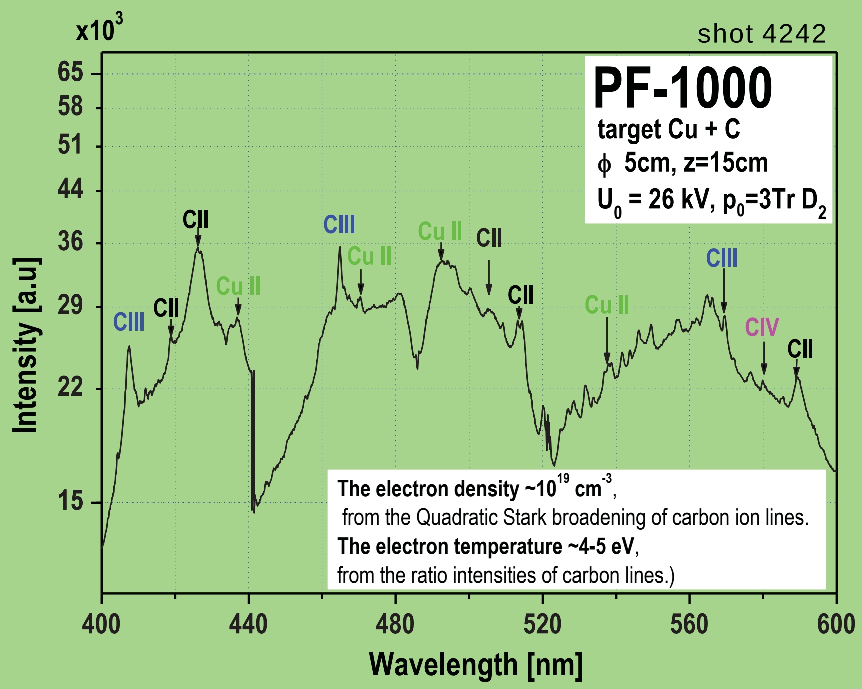
Scheme of dynamics of plasma streams and of fast deuterons beams in the PF-1000



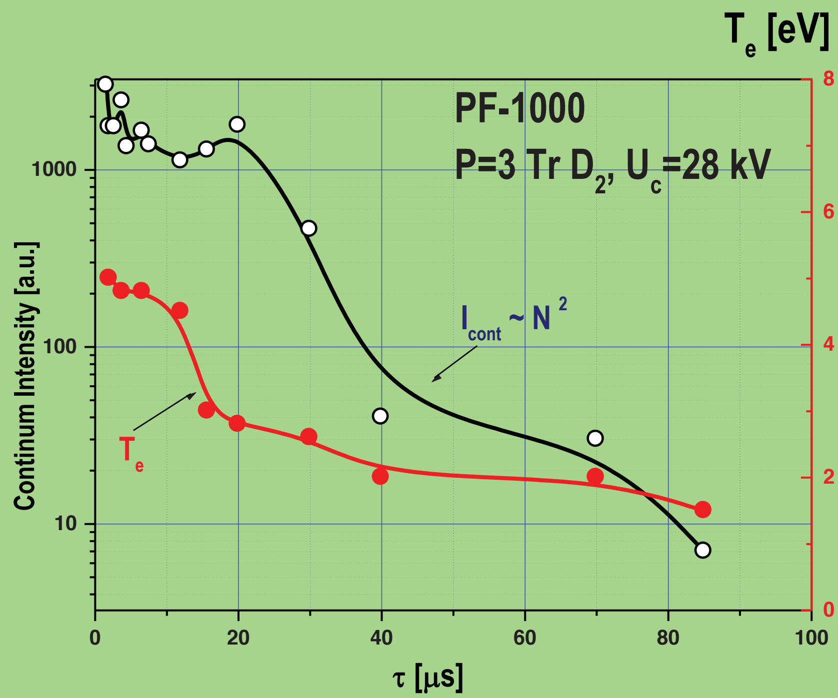


A schematic showing current loops configurations inside the DPF after secondary breakdown between ends of cathode rods and **anode's edge**

Spectrum of **secondary (target's)** plasma



Time evolution of main parameters of the secondary plasma



4. Applications under investigations and use:

- Radiation material sciences:

a) TESTING OF THE MATERIALS PERSPECTIVE FOR FUSION REACTORS:

- first wall and divertor materials (W, CFC, Be...)
- construction materials (low-activated stainless steels)
- optical materials (diagnostics and ICF chamber windows)
- cables and coil materials (ceramography)

Comparative Table of Parameters of Test Devices

Peak heat flux, P [W/m²]: - normal operation - disruptions - VDEs - ELMs
Duration P [s]
T_{pl} (surface) [eV]
Duration T_{pl} [s]
$E_{i,\ D\ fast}$ [eV]
Duration E_i [s]
$E_{e,\ fast}$ [eV]
Duration E_e [s]
Irrad. surface [cm²]
X-Rays [eV]
Neutrons [eV]
Neutrons/cm²

b) RADIATION-BASED IMPROVEMENTS OF MATERIALS' PROPERTIES (INCLUDING HARD-TO-REACH COMPARTMENTS)

- surface modifications (production of nitride phases, structure changes, ...)
- production of thin films on a substrate
- phase changes
- creation of nanostructures, etc.

by means of different working gases used in the DPF chambers or by sputtering of solid target materials with the help of fast electron or ion beams

c) DINAMIC QUALITY CONTROL

(e.g. for stressedly-deformed compounds – car tires)

Spatial resolution of the image of a mechanism's detail (turbine's blade, car tire, piston of a car engine, etc.) taken *during its operation* by a flash of the hard X-Ray radiation from DPF determined by:

- pulse duration of X-Rays (ns)
- size of the source of X-Rays and its remoteness from an object (< 100 μm, 10 cm – a few meters)
- diffraction (wavelength, distance)
- **contrast degree of an object's detail to be visualized** (spectrum of hard X-Rays)

Theoretically for DPF it could be ~ 1 μm in a 10-cm distance

- Radiation chemistry/biology: radioenzymology

In these experiments enzymes were irradiated *in vitro* with various doses, dose power and spectral range by X-Ray photons

We have found here a very large (4 orders (!) of magnitude) *difference in doses for the enzyme activation/inactivation* by their irradiation with X-Rays from DPF compared with the same procedure using an isotope source (Cs^{137})

We found that the *proper characteristic of the short-pulse radiation action* is a **product "dose × dose power": $D \times P$**

- Radiation medicine

a) Fast ions in positron emission tomography

Positron emission tomography (PET) consists of <u>three elements</u>: *production* of *positron-emitting isotopes*, *synthesis of biological molecules* labeled with the above positron emitters, and *scanning of a human body*

The DPF of the level 15 of energy 18 about 20 kJ working with a frequency of 10 Hz can produce for the time period of *100 seconds* (1/6 of the half-life time) an amount of the isotope N^{13} having total activity ~ *30 MBq*

b) X-Ray medical diagnostics

Spectrum of X-Rays generated by DPF has the following specific features:

1) Enriched soft and medium-energy X-Ray components (0.1…5.0 and 5…50 keV), which results in *simultaneous visualization of soft tissues and hard elements* (bones) of a body (same as in the case of tires – rubber, metallic and synthetic cords)

2) Small size of the source (0.3 mm down to 3 μm), which gives a *very high spatial resolution* of an object

3) Very high power, which results in a low-dose formation of an image

c) Micro-radiography

Using a so-**called "phase-contrast technique" DPF** may be applied for micro-radiography of tiny object (e.g. bio-objects) of low contrast

It has to be exploited in the regime of hot-spots generation when very small zones (~μm) of plasma produce soft X-Rays with photon energies *tunable within the range* ***~ 0.1…5.0 keV***

This method is reliable for the goals of micro-radiography of live bio-objects in the sub-micrometer and nanometer ranges in a course of their vital functioning produced in the regime of their inertial confinement

- Nanosecond Impulse Neutron Investigation System (NINIS) for detection of hidden objects

Two important issues encountered in the non-intrusive inspection of buried materials by neutron methods with using isotopes or classical accelerators:

- *low signal-to-background ratio* and
- *long duration of measurements at a detection procedure*

That is why these methods demand to produce *a huge number of "shots" (>10^7 shots)*

We have proposed to bring into play a neutron source based on a *plasma focus (DPF)*, which generates *very powerful pulses of neutrons of the nanosecond (ns) duration* and can convert the procedure into *"a single-shot interrogation"*

We demonstrated it with explosives and fissile materials

5. Potential implementations

a) Tritium inventory

DPF may use small (~1 liter) *sealed* chambers with the D-T-mixture generator “built-in”

In this case we may install inside this chamber a *Be* sample (in the anode or cathode parts of it) and produce say 1000 shots

Then we can investigate the results of *fast ion/plasma* or *fast electron/soft X-Rays* irradiation of samples, *tritium absorption*, *re-deposition of Be*, etc. in this very cheap, safe and convenient configuration

b) Neutron fields characterization around ITER

Using this *small neutron source* (~1-m^3 device with the neutron-irradiating zone ~ 1 cm^3), which have a neutron pulse appearing in space as a *spherical shell of ~ 0.5-m thickness*, we can use a time-of-flight method to characterize a neutron field of ITER at each stage of its assembling moving DPF along the ITER chamber circumference after each step:

- foundation construction
- magnet installation
- assembling of the chamber
- beam-heating guns attaching, etc.

c) *Neutron tests* of materials perspective for ITER and NIF

Simple estimations have shown that the DPF device being assembled on the base of new high-current technology working in the energy range of the order of a few hundred kJ and with a rep rate of the order of a few cps can fulfill the demands to produce a 14-MeV neutron radiation dose ~ 1 dpa per one year

For this aim its main elements should be changed 10 times, which gives the cost of such a device on the level of about 10 millions US $ only

Thus DPF can fill the niche in this very important field

d) Thermal and fast neutrons and X-Rays in Boron Neutron Capture Therapy

Therapeutic effect is reached due to a very high **Linear Energy Transfer (LET)** of the nuclear reaction ***products***, which are generated at the interaction of thermal neutrons with Boron atoms ^{10}B introduced beforehand in a human tissue (**BPA and DSH**):

$$^{10}B_5 + {}^1n_0\ (\sigma = 3\ 838\ \mathbf{b}) \rightarrow {}^4He_2^{2+} + {}^7Li_3^{3+} + 2{,}792\ MeV\ (6.3\%)$$

and

$$\rightarrow {}^4He_2^{2+} + [{}^7Li_3^{3+}]^* + 2{,}31\ MeV\ (93.7\%)$$

$$\downarrow$$

$$^7Li_3^{3+} + \gamma\ (478\ keV)$$

Mean-free-paths (MFP) of lithium nuclei and alpha-particles within human tissues are equal to 6 and **9 μ** respectively, what makes a release of their energy to be practically local in the vicinity of a zone of neutron's absorption

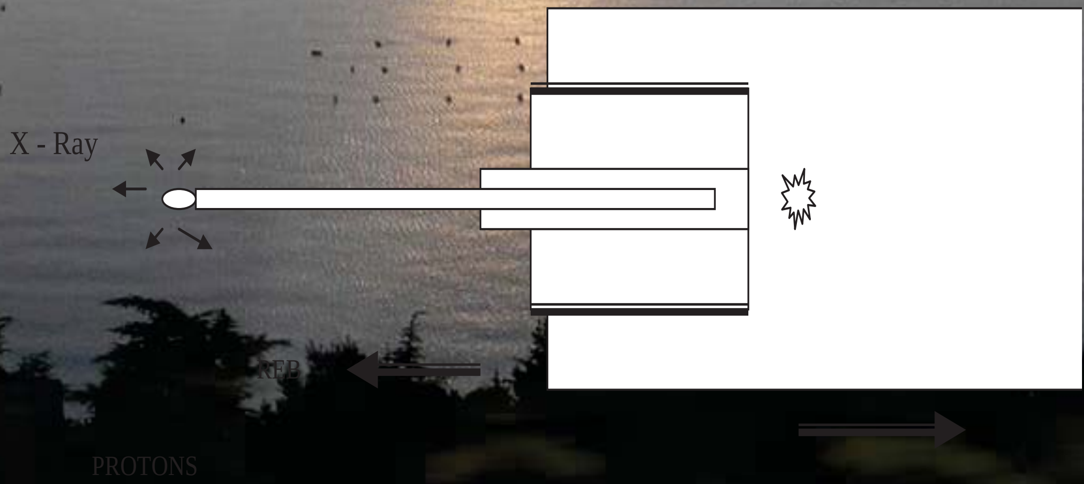
Our analysis has shown that DPF has here the following opportunities:

1) DPF devices of the medium size (5-10 kJ) can ensure the necessary dose in about 3 hours working with a moderator (epithermal neutrons) if it will be operated with a rep rate of 1 cps with a D-T mixture

2) One can expect here synergetic effects if DPF will be used either with just fast neutrons of the ns pulse duration or at the *combined application of fast neutrons and hard X-Rays* for a suppression of malignant cells

e) Brachytherapy

Because electron beam (with electron's energy about 100 keV) generated in DPF can be transported along large distances (~ 1 meter) inside **the anode's tube due to the back-**current induced in **the tube's wall it can be used for brachytherapy** both by the *e-beam itself* and by *hard X-rays* generated by it on a proper target:



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

Our experiments has shown that DPF can successfully be used right now in a number of applications in biology, medicine, material sciences, NAA, etc.

In particular it can simulate and help in investigations of many *damage features* existed in the contemporary main-stream fusion devices and accelerators such as phase changes, brittle destruction and cracks, melting, evaporation and re-deposition of materials under tests, etc. *during (with ns and μm resolution)* and *after (by analytical equipment) irradiation*

And these types of damage are produced here *namely by the same types of radiation* that existed in modern fusion devices

This device can be implemented for modification of materials to impart them better characteristics

DPF can also be used for a *detection of illicit materials just in a single ns shot* of the device that shorten the whole procedure, that is important in particular in the cases of hidden fission materials or fast moving objects

It can be used in *low-dose medical X-Ray diagnostics* as well as *in micro-radiography* and *micro-lithography*

DPF is promising to be used for *irradiation by epithermal neutrons of malignant tumors in BNCT as well as in a therapy by* fast *neutrons, in particular in combination with hard X-Ray photons* generated by it that opens perspectives in *a low-dose therapy*

It has good opportunities in a production of *short-lived isotopes* for the aims of PET


Thank you!