The Abdus Salam
International Centre
for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2370-4

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

8 - 12 October 2012

Dense Plasma Focus: Current and Perspective Applications

Vladimir A. Gribkov

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

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

Strada Costiera, 11 - 34151 - Trieste - Italy • Tel. +39 0402240111 • Fax. +39 040224163 • sci_info@ictp.it • www.ictp.it
ICTP is governed by UNESCO, IAEA, and Italy, and it is a UNESCO Category 1 Institute

Dense Plasma Focus: 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. Applications under investigations and use:
   - Material sciences
   - Radiation chemistry/biology (enzymology)
   - Radiation medicine
   - Nanosecond Impulse Neutron Investigation System
2. Potential implementations
3. Conclusions

1. Applications under investigations and use:

- Radiation material sciences

DPF is usually supplied with a number of instruments **monitoring characteristics of its radiation types** ***during*** an irradiation ***process*** **with ns time resolution** and with **high angle, spatial, and spectral** precision

The same is true for the ***process of the interaction*** of these types of radiation with samples under tests (e.g. for the secondary plasma near the target)

These data can be **cross-correlated** with the results received ***a posteriori*** **by analytical instrumentation**

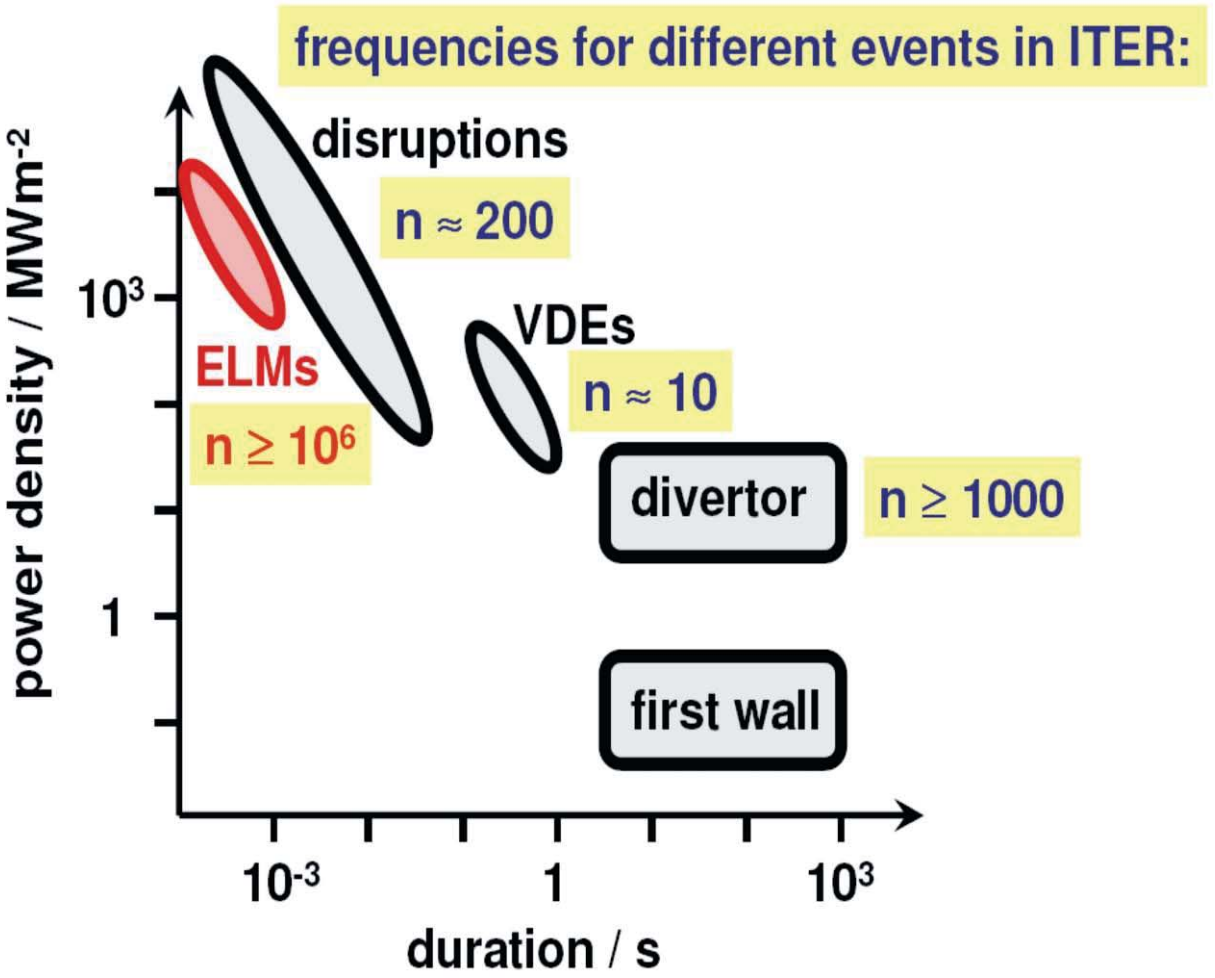
In our **material science** experiments the morphology of the irradiated sample's surfaces **after the irradiation** was investigated by ***optical, electron and atomic force microscopes***, as well as by an ***optical refractometer***

We applied also ***tribology*** *instrumentation,* ***weighing*** samples after irradiation, ***profilometry, elastic recoil detection analysis (ERDA), X-Ray microprobe (i.e. elemental), structural and diffraction analysis***, etc.

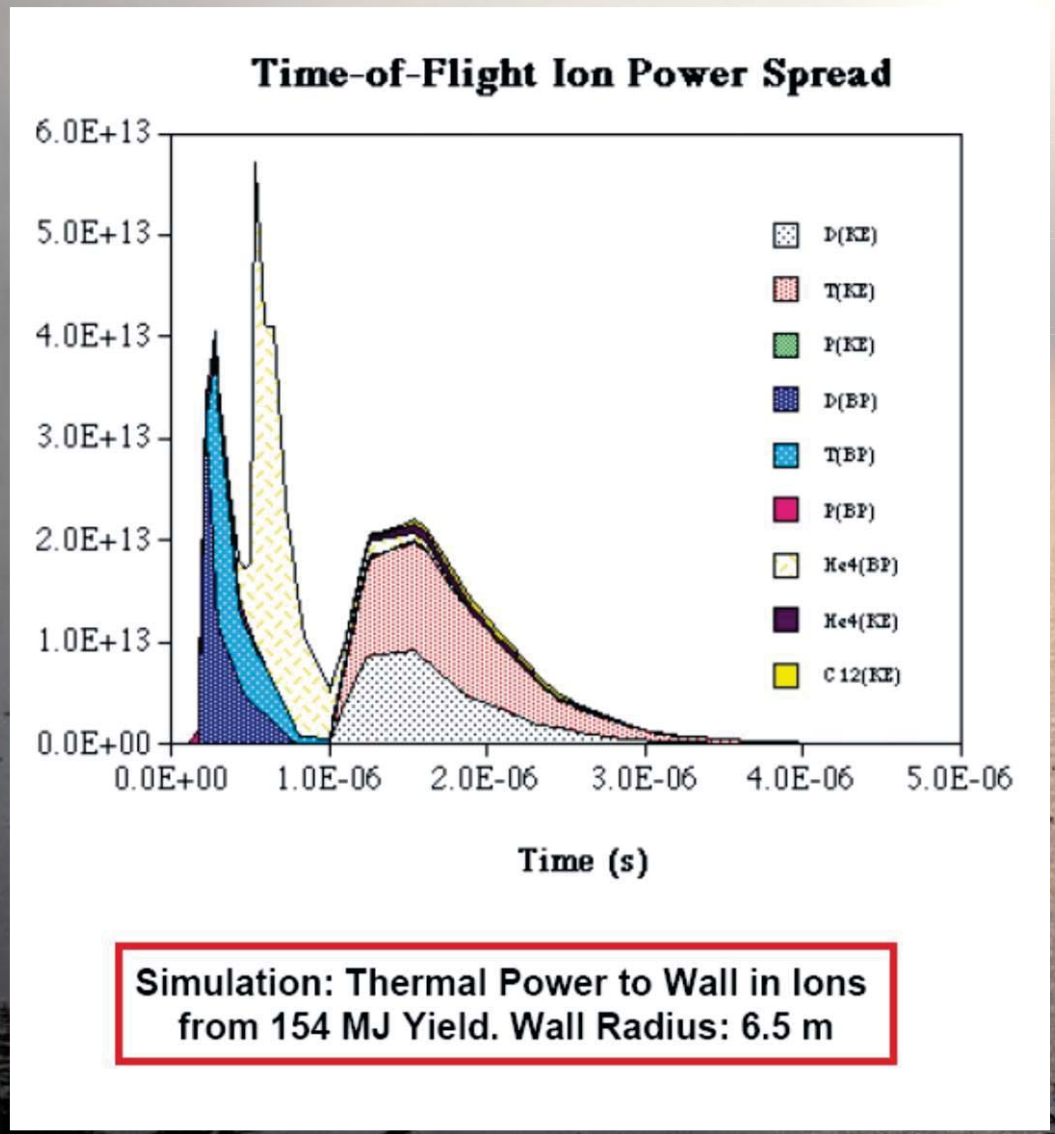
Inside and outside a chamber of modern full-scale fusion devices we have:

1) **First-wall** materials (Be for ITER and stainless steel for NIF)
2) **Divertor** materials (tungsten and carbon-based composites)
3) **Construction** materials (low-activated stainless steels, etc.)
4) **Optical** materials for windows (diagnostics)
5) Different types of **ceramics** (cables etc.)

Simulation of fusion relevant thermal loads



(according to Dr. J. Linke, Max-Planck-Institut fuer Plasmaphysik, Germany)



Simulation: Thermal Power to Wall in Ions from 154 MJ Yield. Wall Radius: 6.5 m

For direct-drive Laser FD:

- 1-2% X-Rays,
- 30% ions (50-50 fusion and debris),
- ~70% neutrons

Ions:

- 0.5 MeV, 0.5 μs,
- 8-20 J/cm^2 fluence,
- judged Significant Threat

X-Rays:

- < 10 keV,
- 1 J/cm^2,
- judged less significant threat

(according to Dr. T. Renk, Sandia National Laboratories, U.S.A.)

Comparative Table of Parameters of Radiation-Test Material Devices

Peak heat flux, P [W/m^2]: **- 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 [cm^2]
X-Rays [eV]
Neutrons [eV]
Neutrons/cm^2

DPF-generated **pulses** of the above **radiations types** (intrinsic to the main-stream fusion devices) and of **heat produced by them** have duration from a **few ns** till **a hundred μs** that makes them a very useful and cheap tool for different test modes of candidate radiation-resistive materials and for a modification of the sample's surface as well

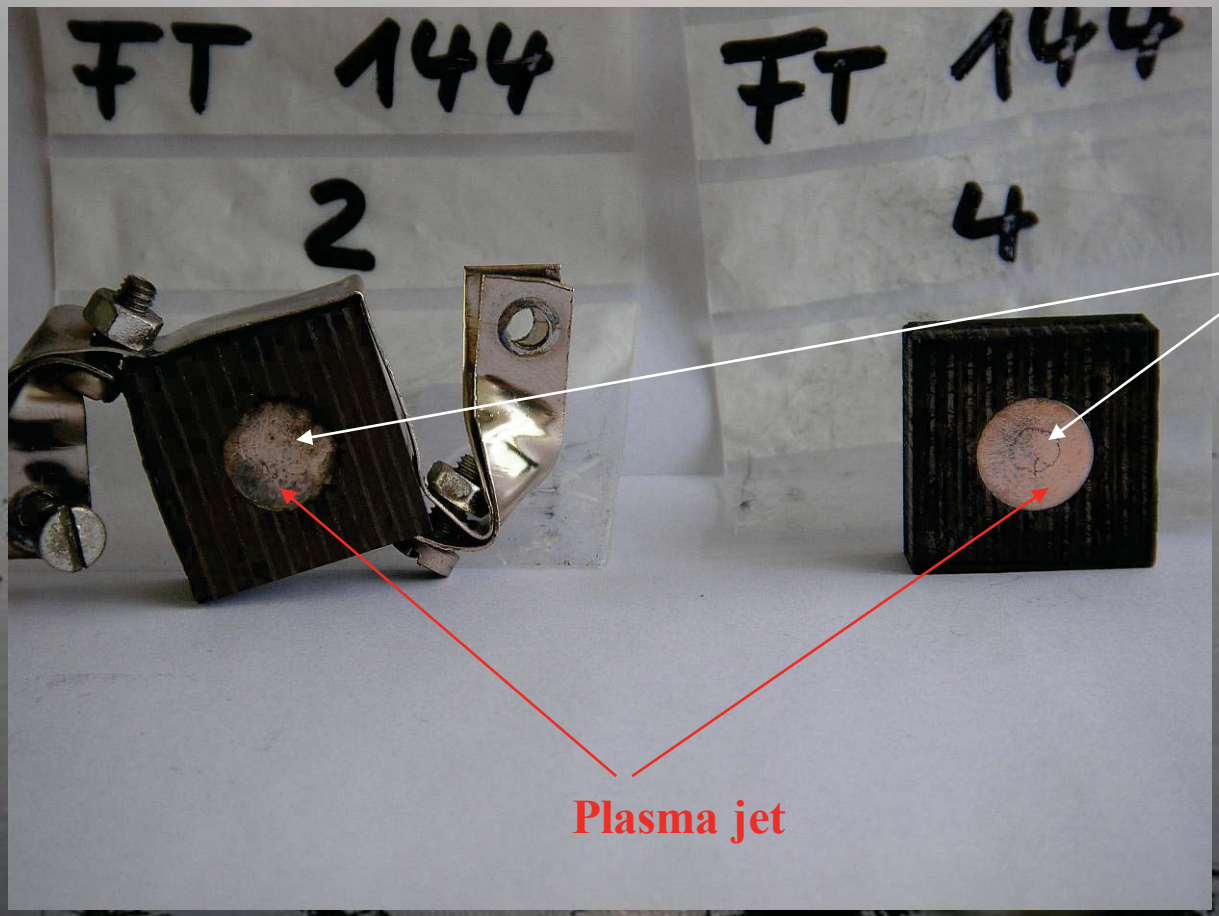
Based on a modern high-current technology these devices can operate with a **high repetition rate** (tested up to **15 cps**) with a **life-time** of their main discharge components **~ 10^7 "shots"**

A) RADIATION TESTS

1) Carbon-Fiber Composites (CFC) and tungsten (W) samples at PF-1000 (a part of a round-robin tests – at QSPA, MK-200, RHEPP-1, JUDITH – of ITER's divertor related materials)

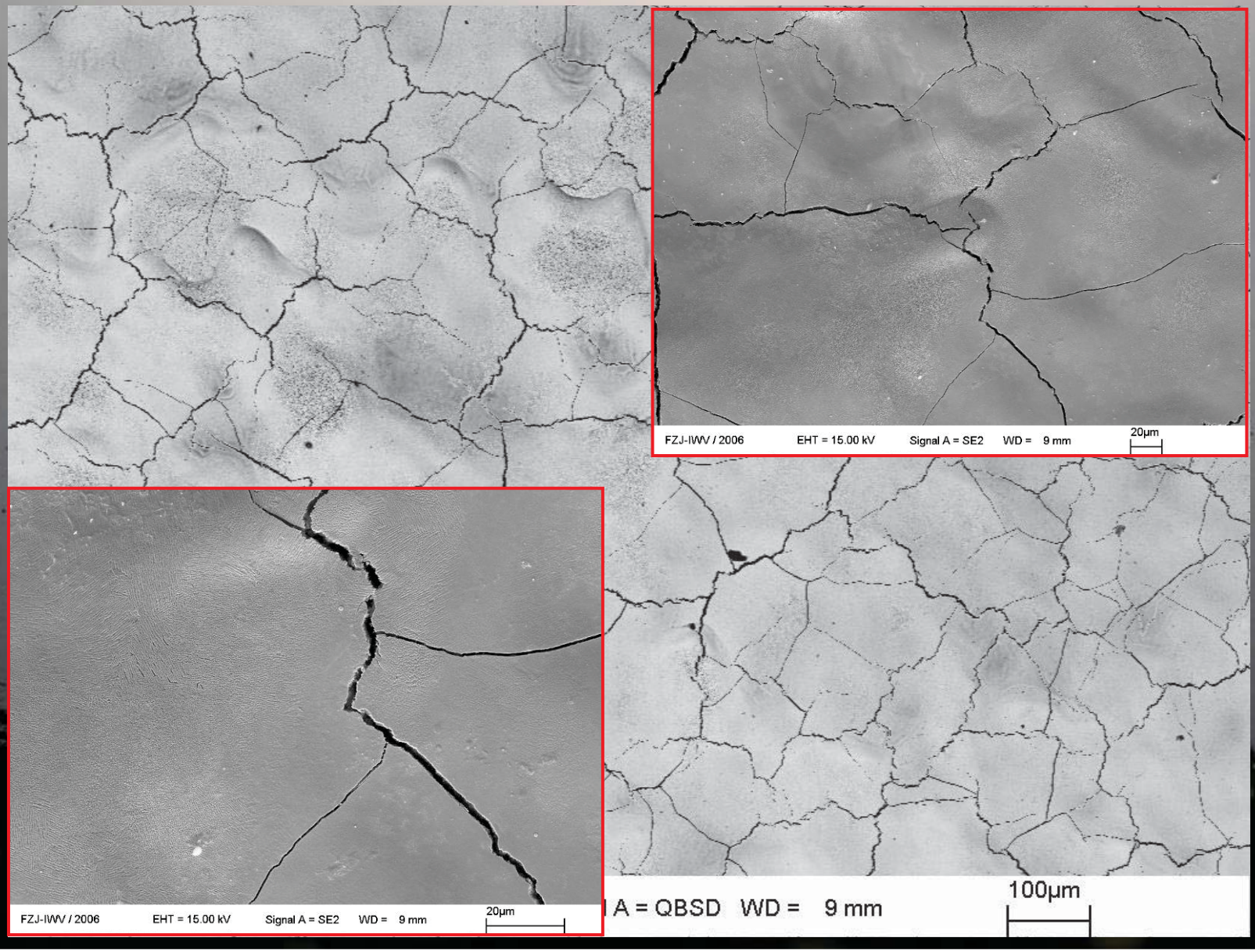
Virgin samples

Results of the irradiation of the above samples by streams of plasma and fast ions (cathode's side)



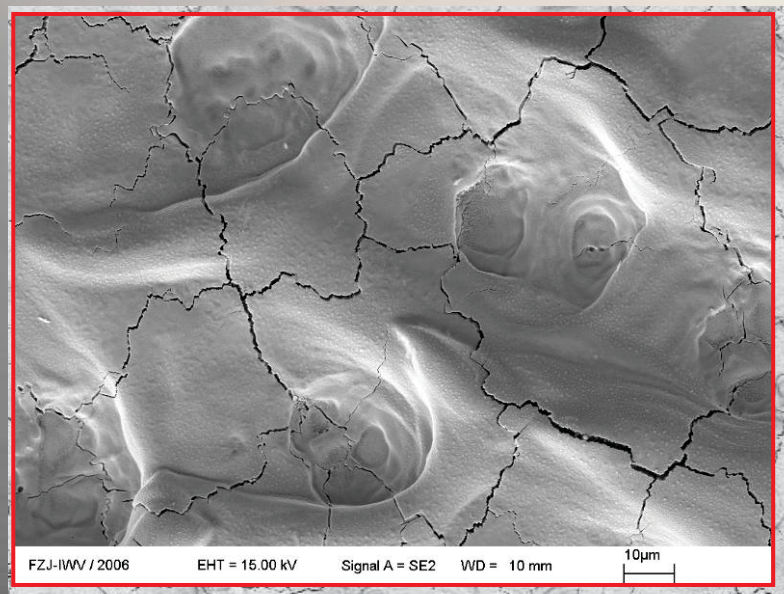
Front view

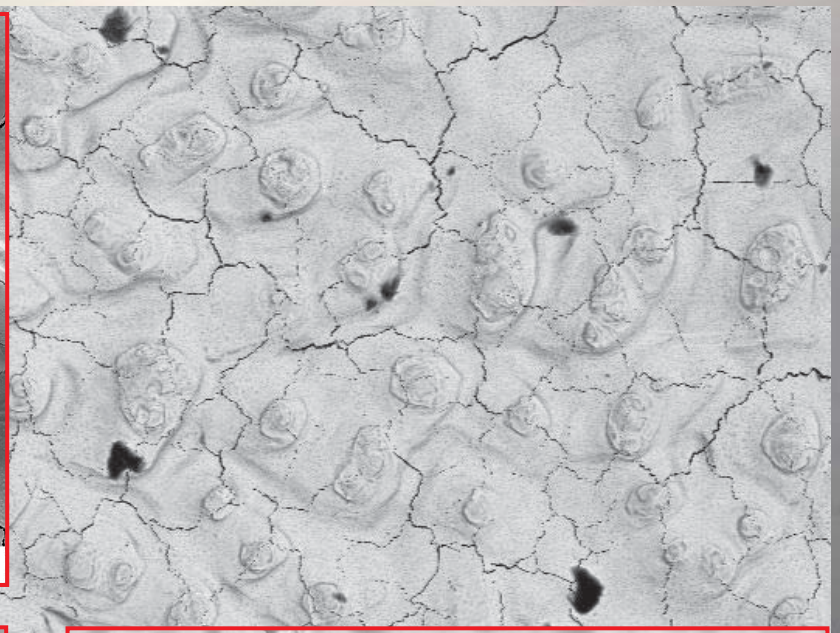
FT144-4, W

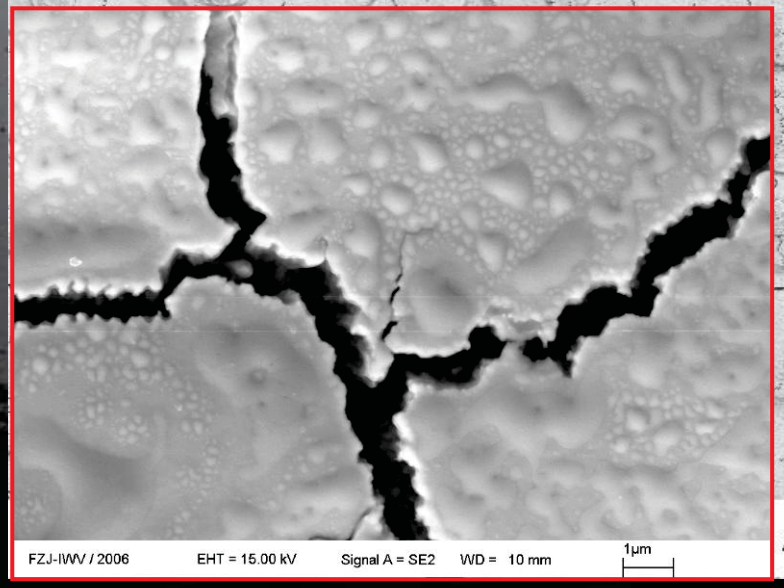

FZJ-IWV / 2006 EHT = 15.00 kV Signal A = SE2 WD = 9 mm 20µm
FZJ-IWV / 2006 EHT = 15.00 kV Signal A = SE2 WD = 9 mm 20µm
A = QBSD WD = 9 mm 100µm

FT144-1, W

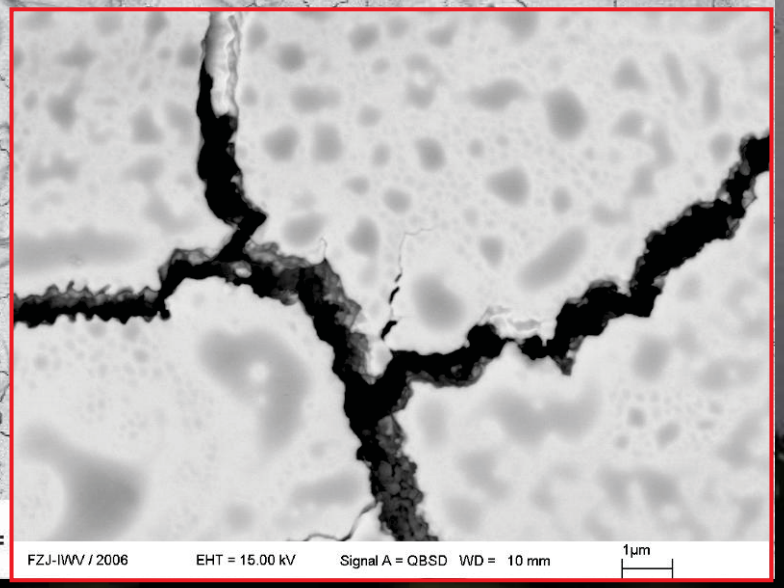
SEM



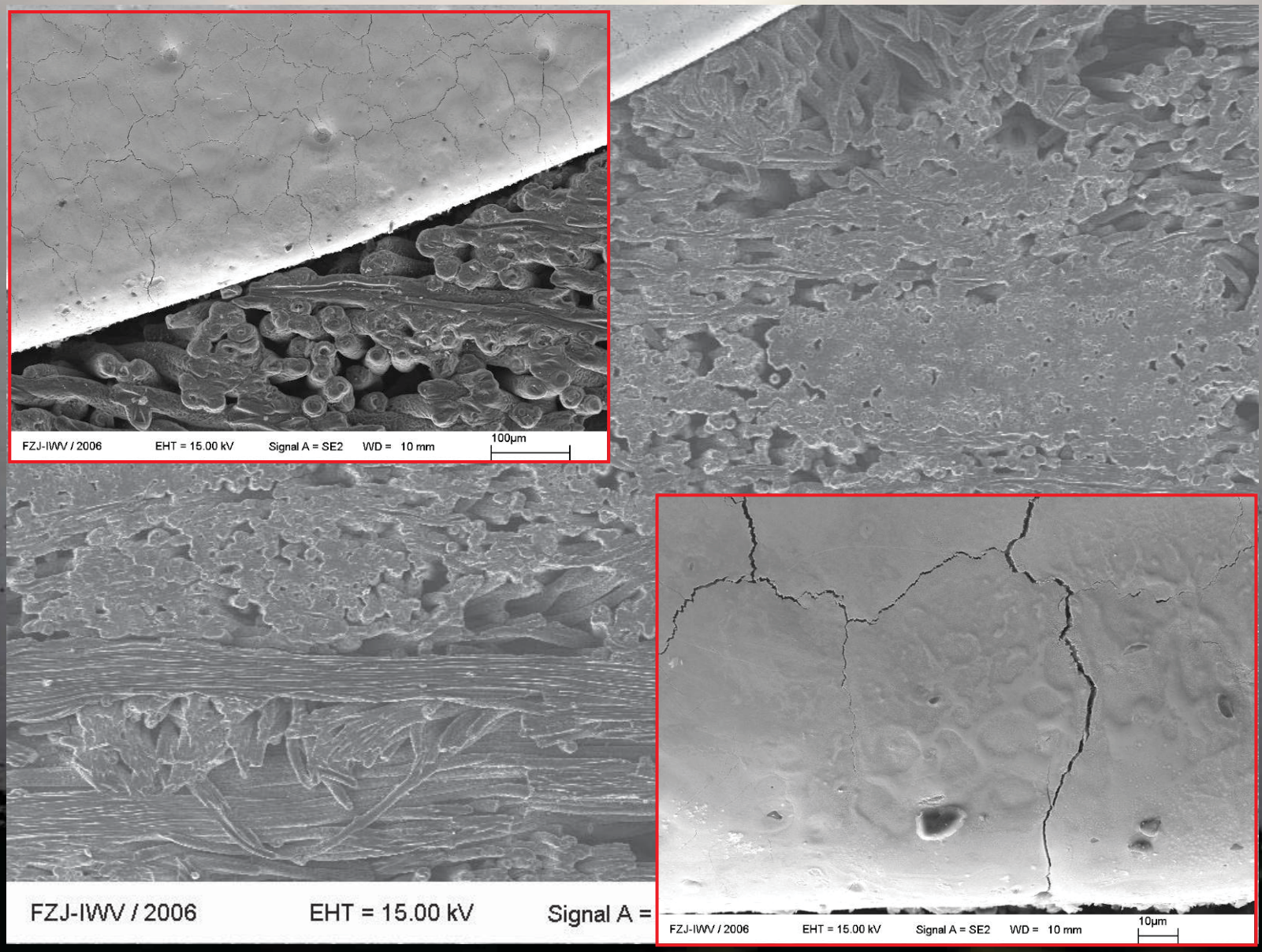




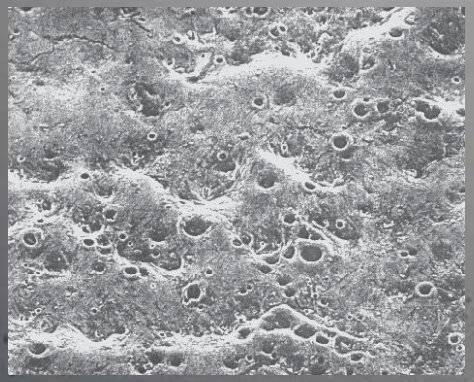
A =



FT144-1, CFC and W/CFC interface

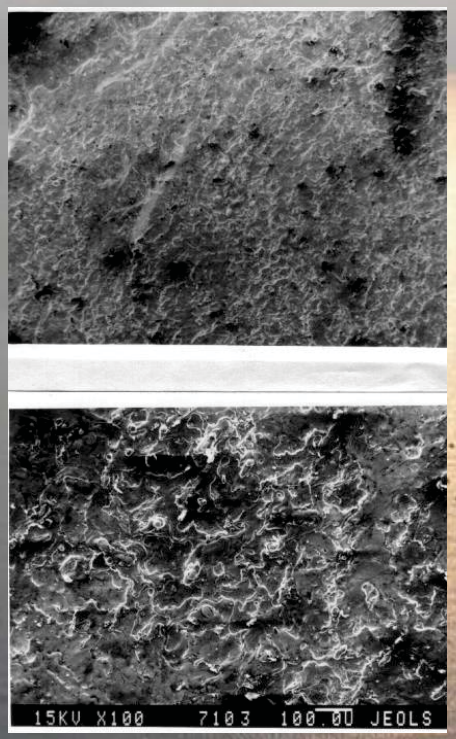


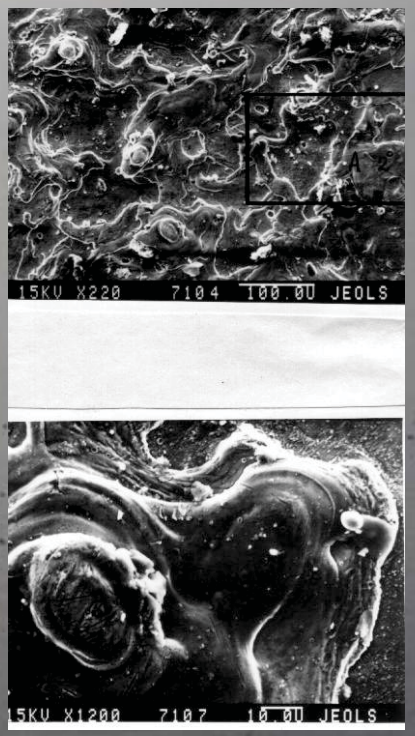
2) Low-activated austenitic steel (construction materials) irradiated at a cathode's side of DPF



10 μm

a)



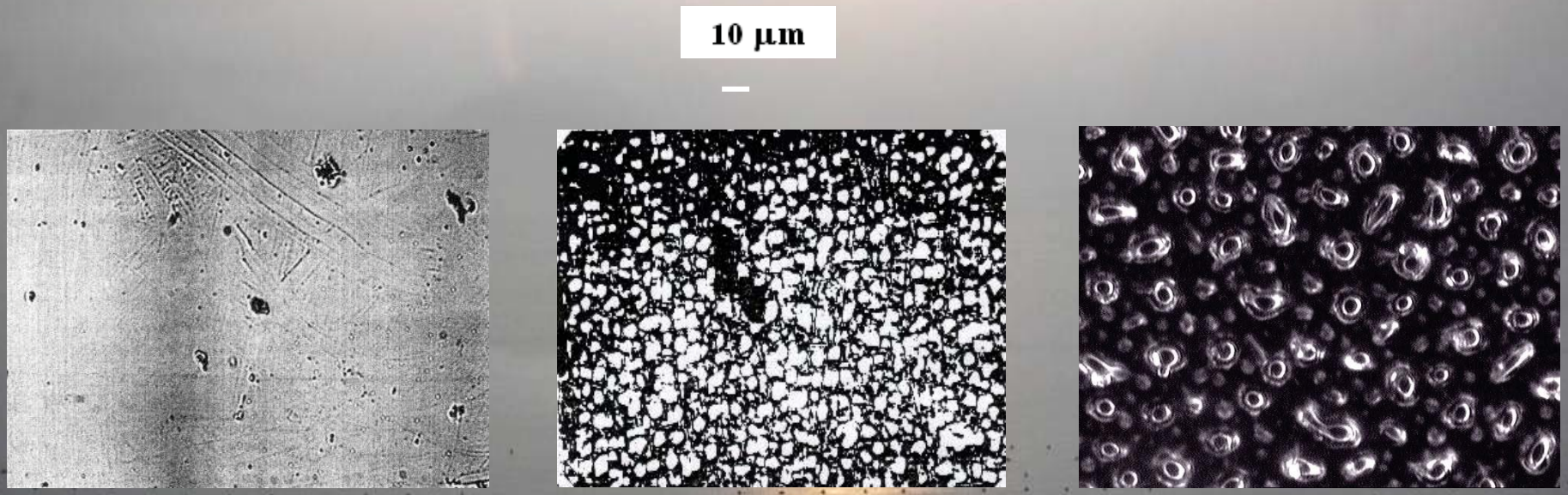


b)

30, 100, 220 and 1200 magnification

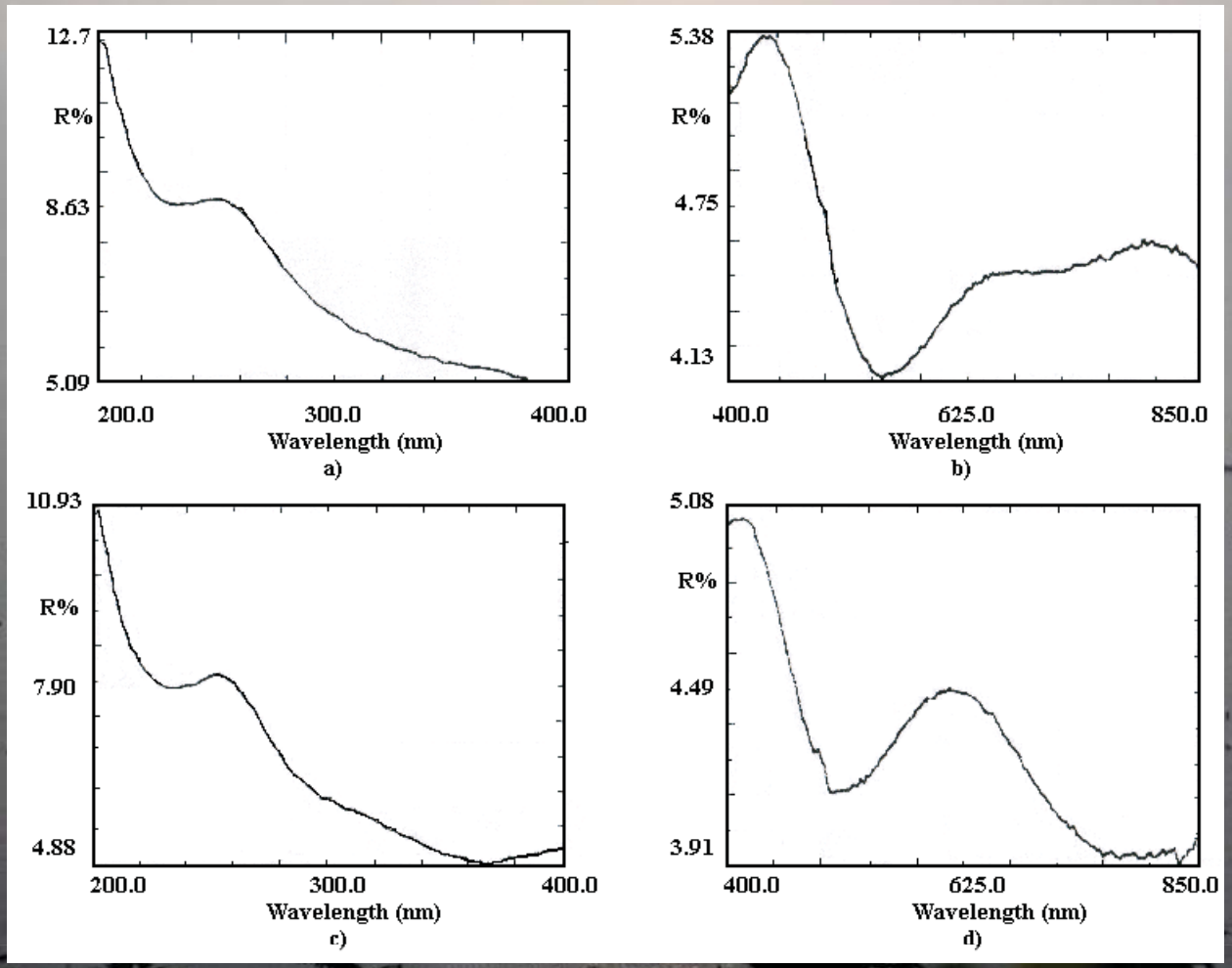
Optical (a) and electron (b) microscopy of irradiated specimens

3) Optical materials (cathode's side)

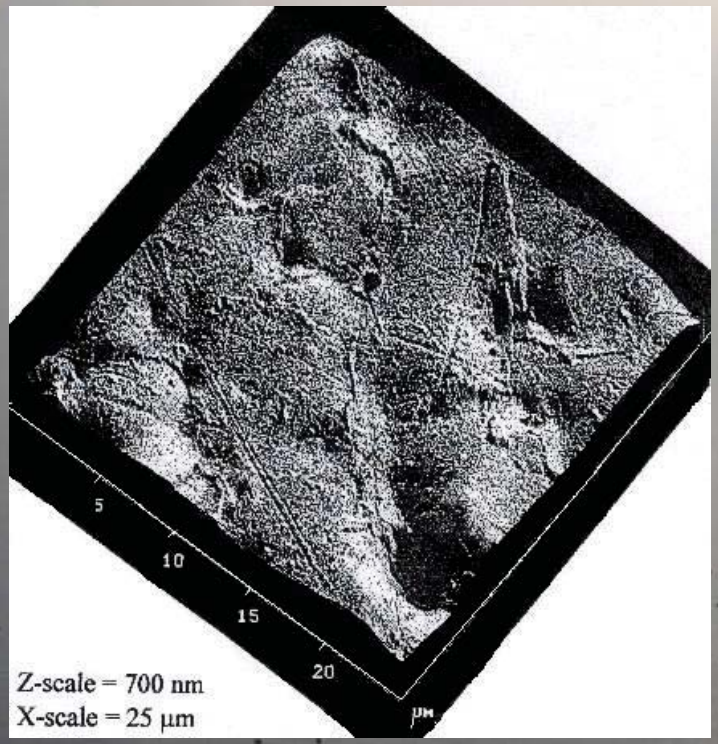


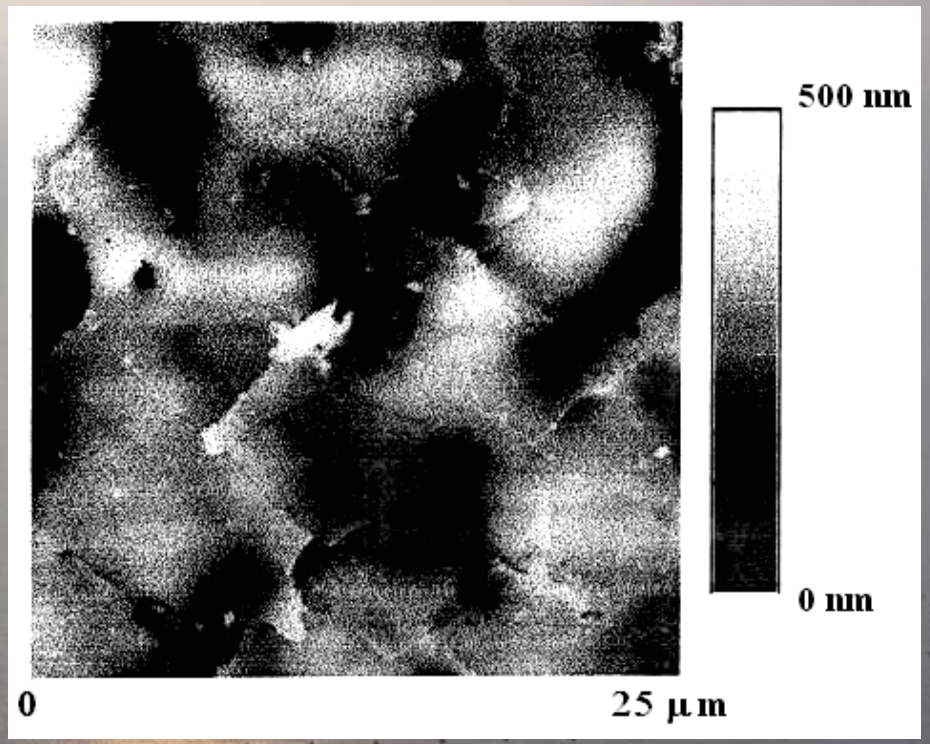
Optical microscopy of surfaces of samples of quartz (a), sapphire (b) and topaz (c) irradiated by a beam of fast (~ 60 keV) hydrogen ions

Reflectometry



Reflection coefficient of a sapphire sample surface versus wavelength after irradiation





a) b)

Atomic force microscopy of sapphire and quartz specimen's surfaces after a single-pulse irradiation

4) Electron microscopy of specimen's surface irradiated by a fast electron beam (anode's side)

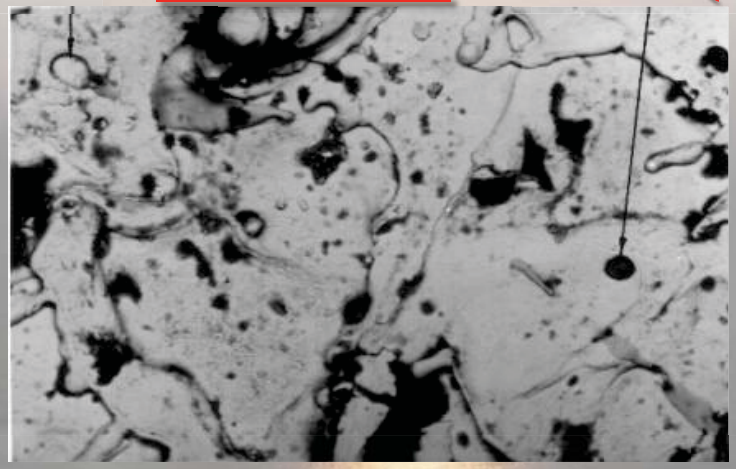
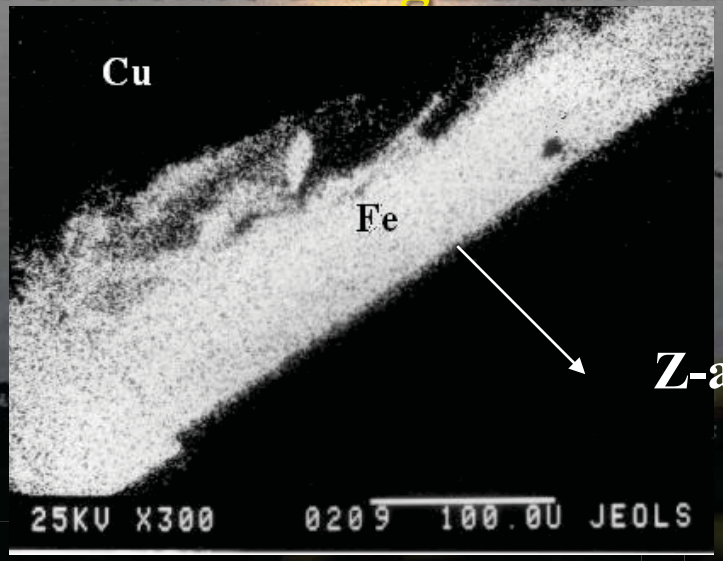
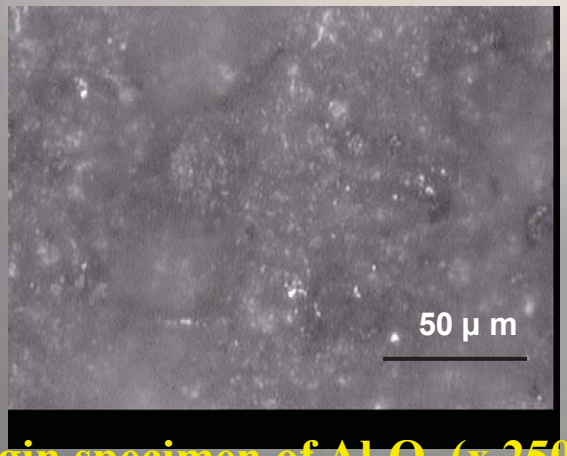


Image of an anode surface (Cu) taken in secondary electrons: light zones give an evidence of high deuterium concentration



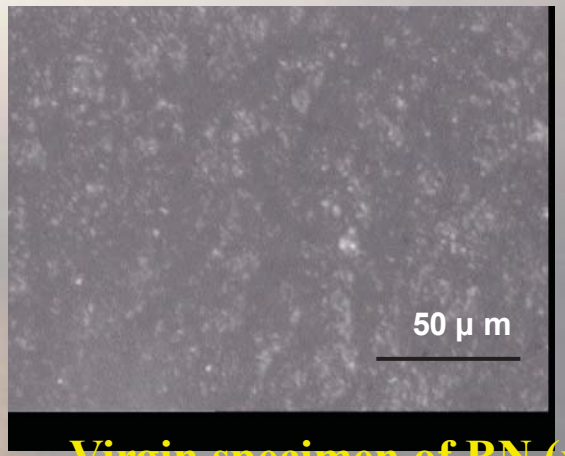
Section of an anode near its surface taken in a *K-alpha* line of Fe

5) CERAMOGRAPHY

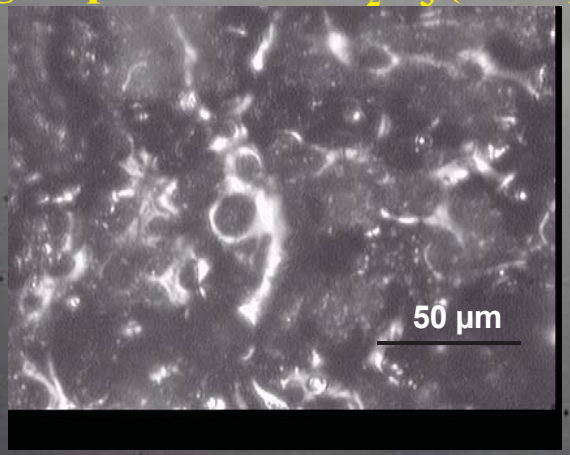


Virgin specimen of Al_2O_3 (x 250)

a)

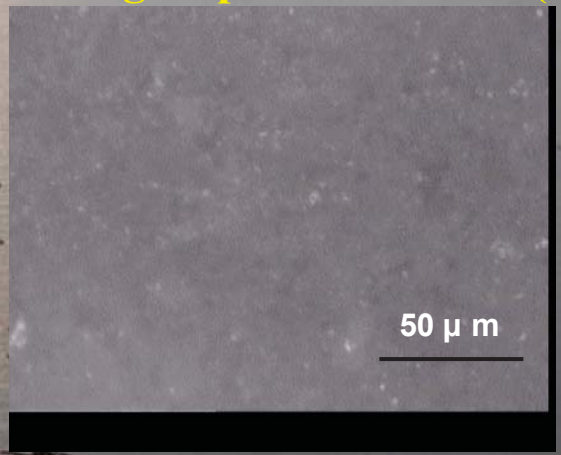


Virgin specimen of BN (x 250)



Specimen of Al_2O_3 (No. 3, x250)

b)



Specimen of BN (No. 2, x 250)

Optical microscopy of central parts of the specimens

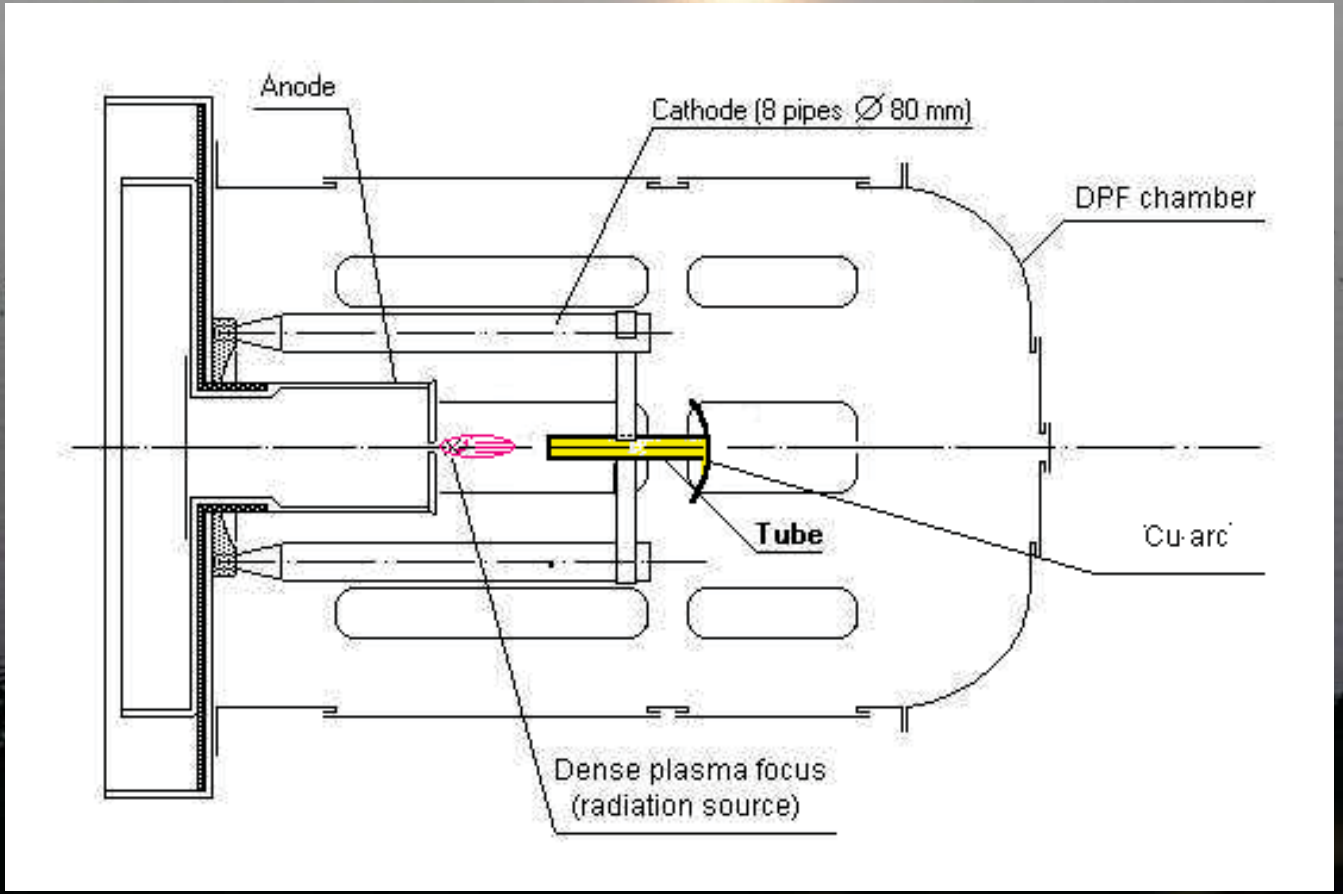
Distance between the DPF anode and the specimen is 30 cm

1 irradiation pulse

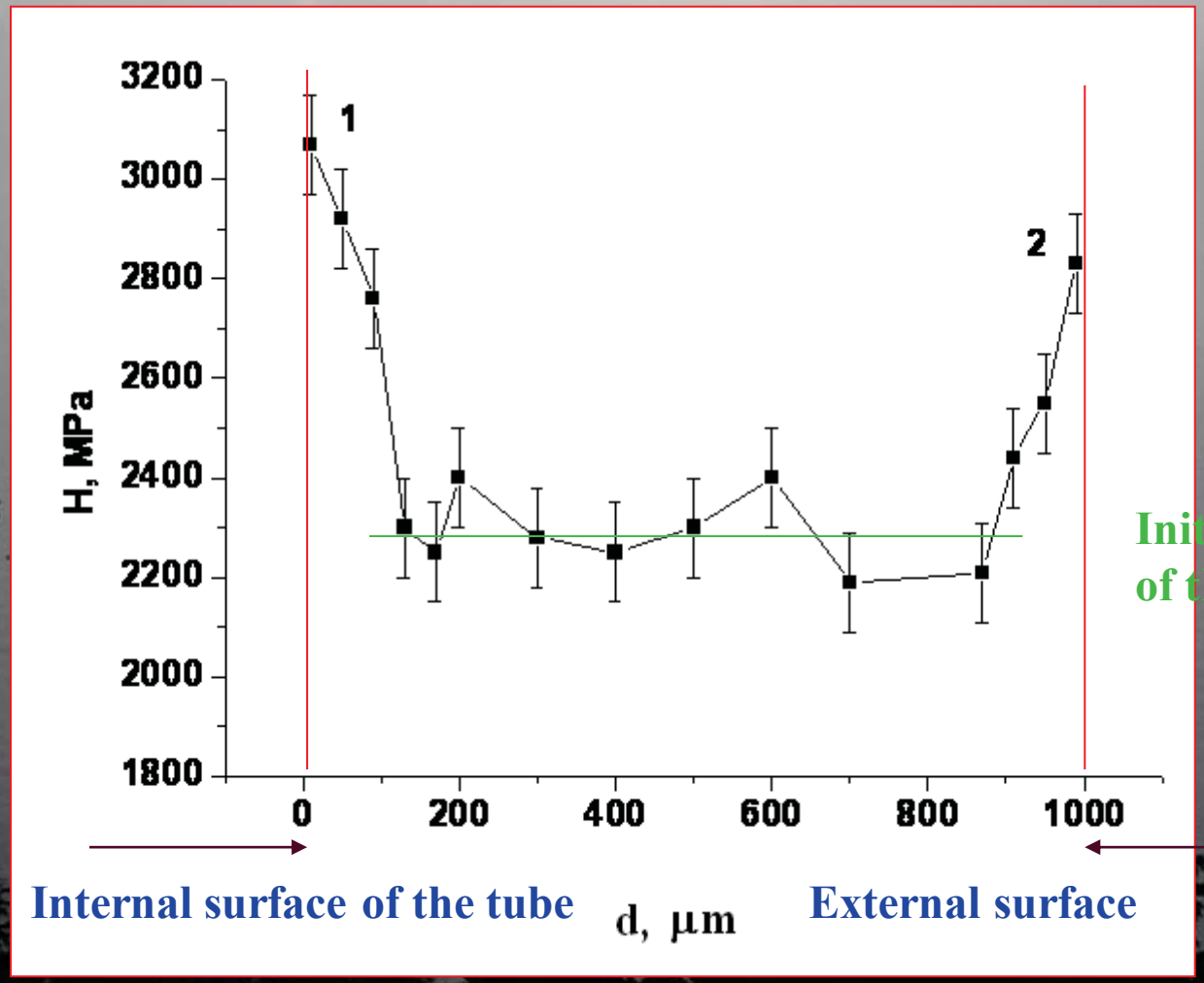
$\Delta m\ (BN)/\Delta m\ (Al_2O_3) \approx 1.7$

B) RADIATION-BASED IMPROVEMENTS OF HARD-TO-REACH COMPARTMENTS

(internal surfaces of tubes)



Micro-hardness

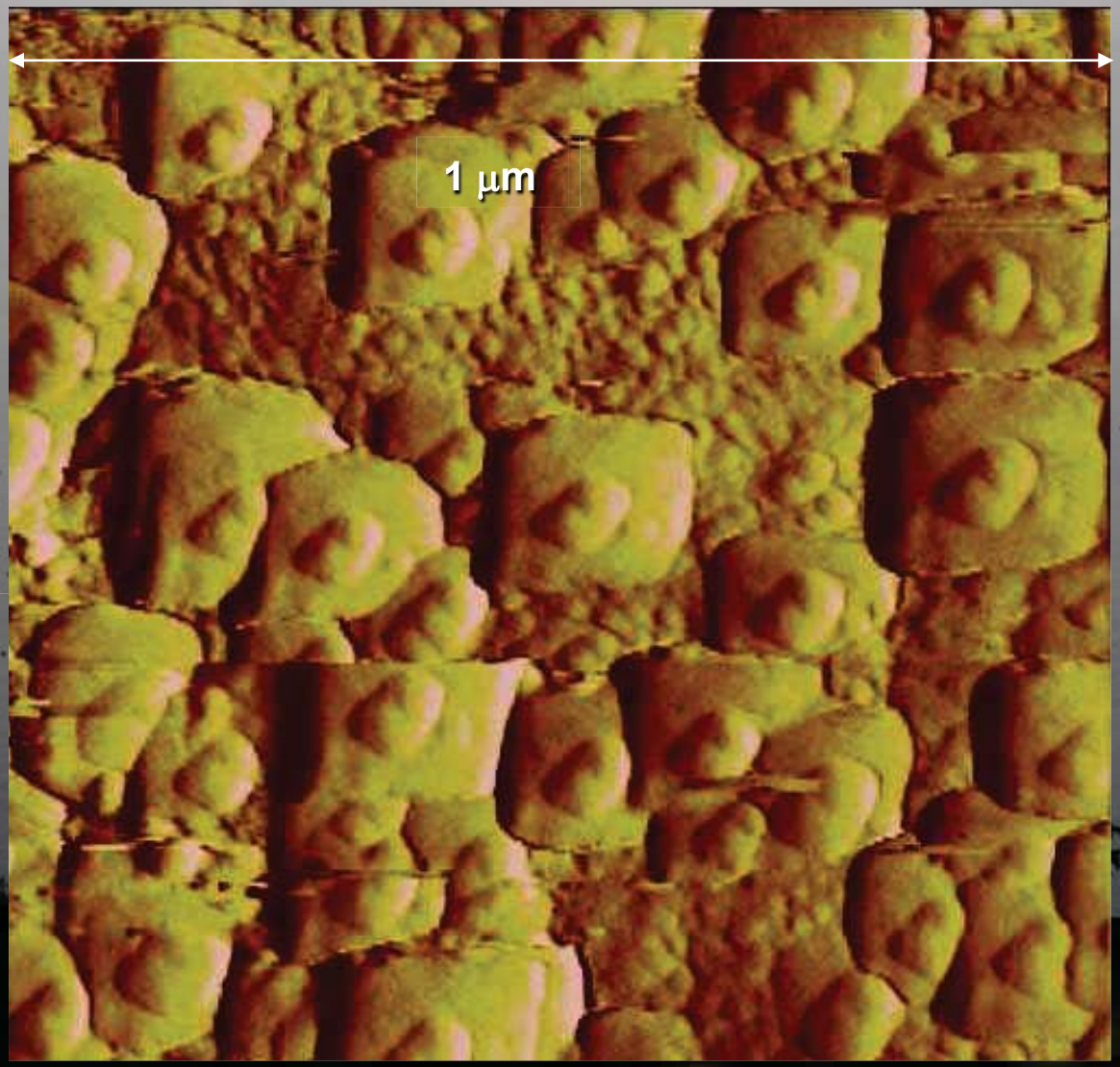


C) PRODUCTION OF NANOSTRUCTURES ON A SURFACE

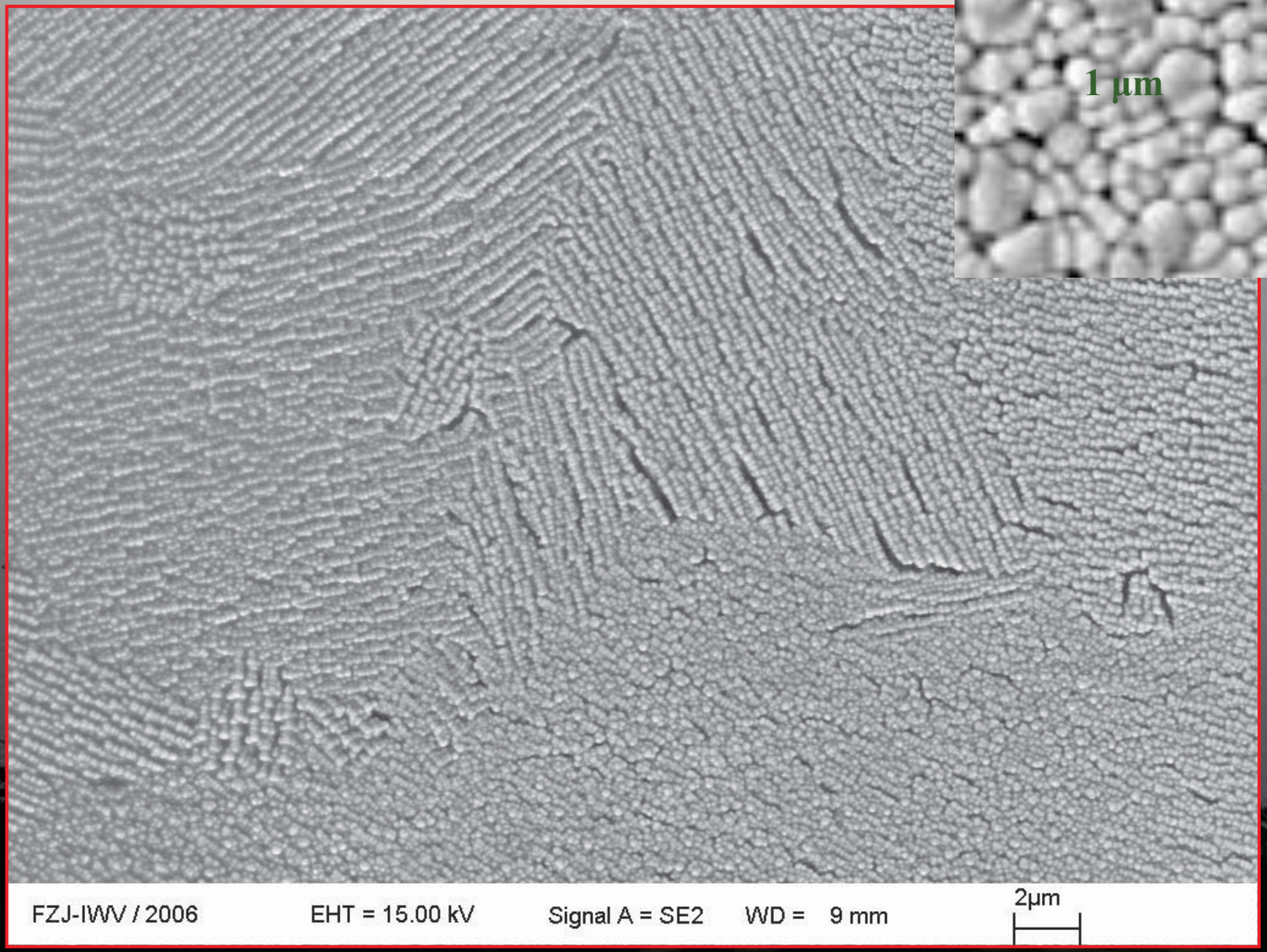
(atomic-force and scanning electron microscopy)

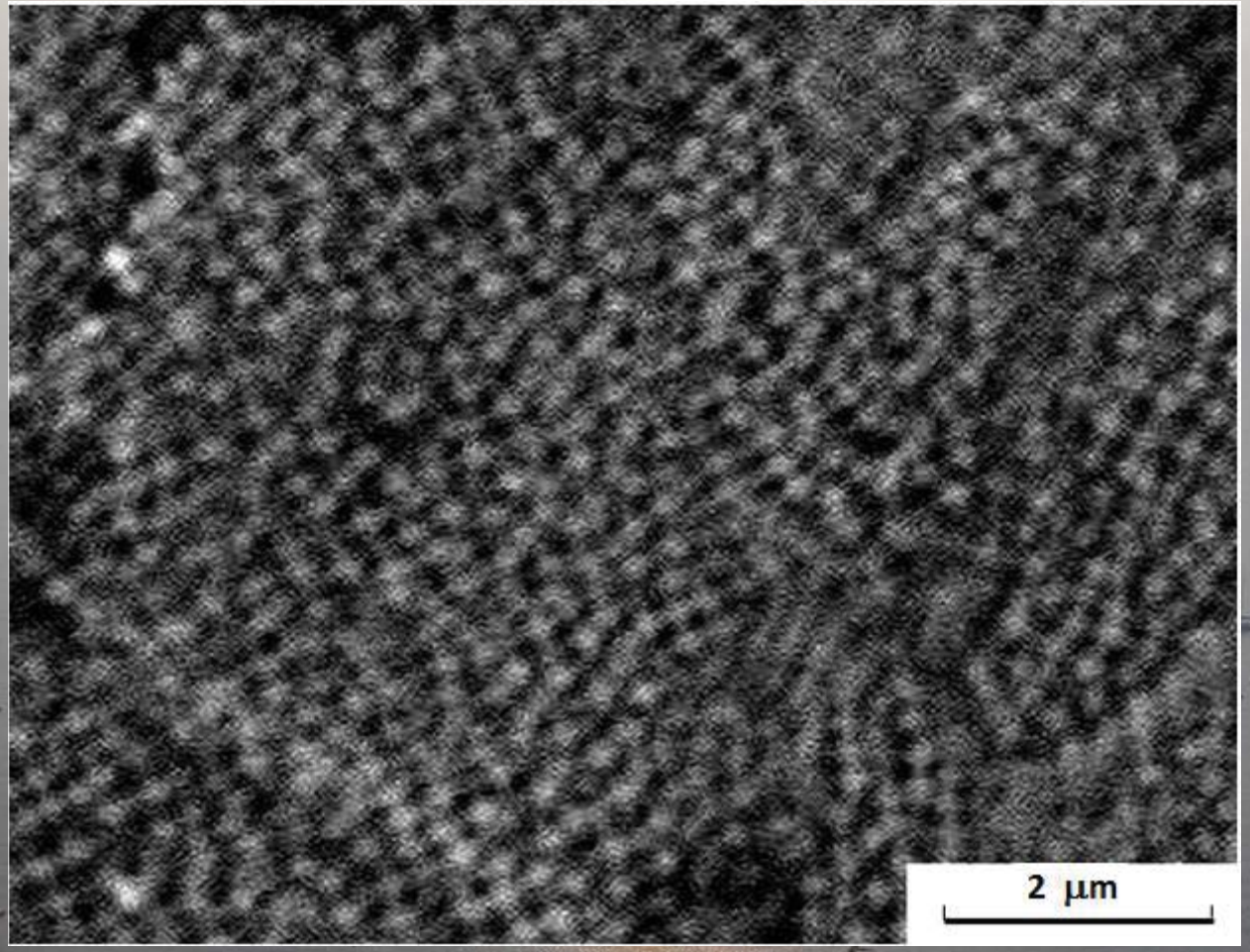
1 pulse

Scale in Z-direction 200 nm



FT144-4, W, high magnification



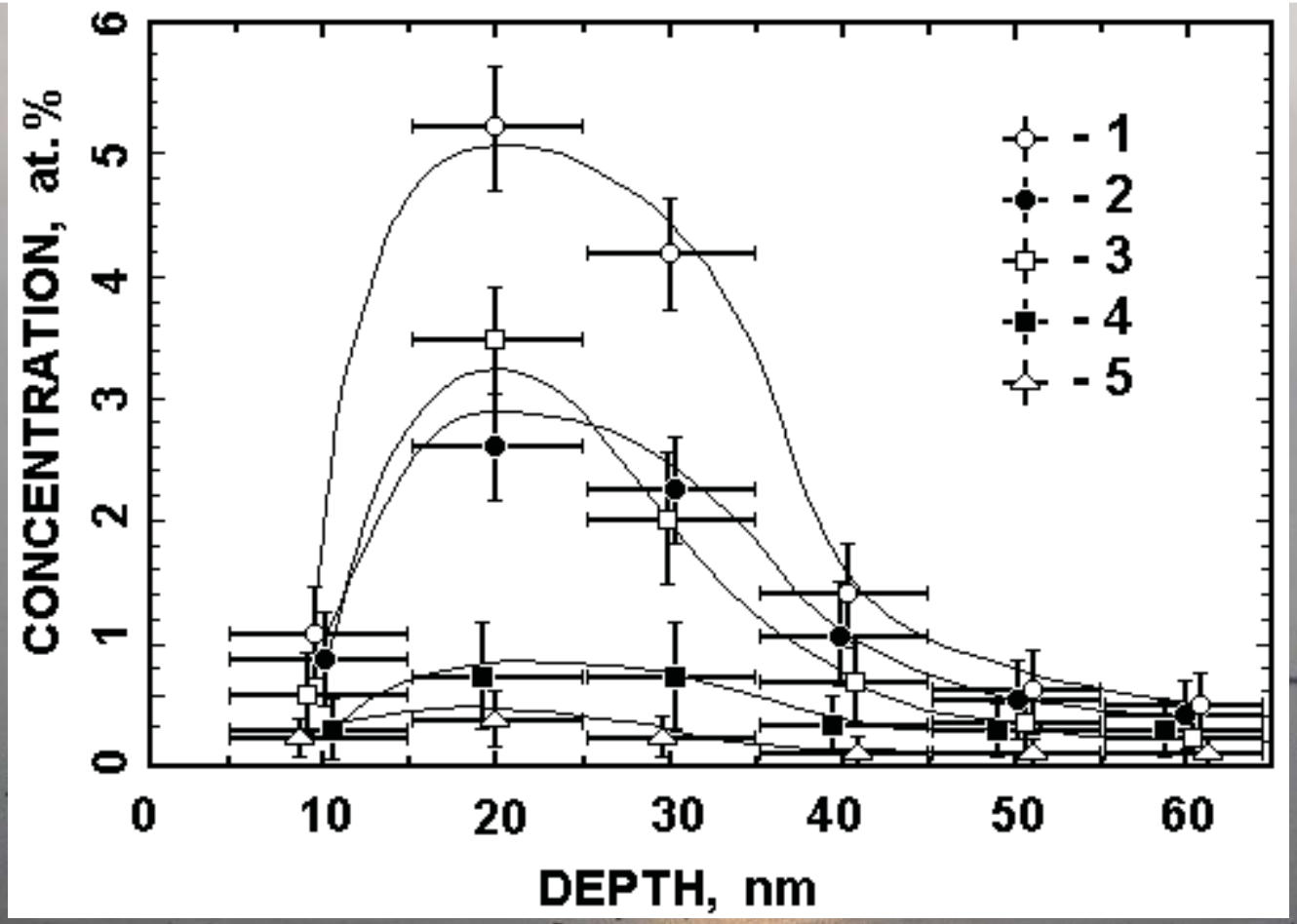


Part of surface of the irradiated sample manufactured of pure iron; a single-pulse irradiation at PF-5M device (IMET) with $P > 10^{10}$ W/cm^2, SEM

This powerful irradiation of different samples has a couple of quite unexpected consequences

First we found out that **the content of hydrogen isotopes** which were implanted by force method into the bulk of material with concentration much higher compared with the solubility limit **was decreased with an increase of the number of shots**; this feature is of great importance for future fusion reactors in the context of hydrogen retention by plasma-facing elements

We associate this phenomenon with **a strong enlargement of *the surface area*** of the samples due to the acquired nanostructures that results in an accelerated **diffusion (release) of gas from solid materials *back into the reactor's chamber***



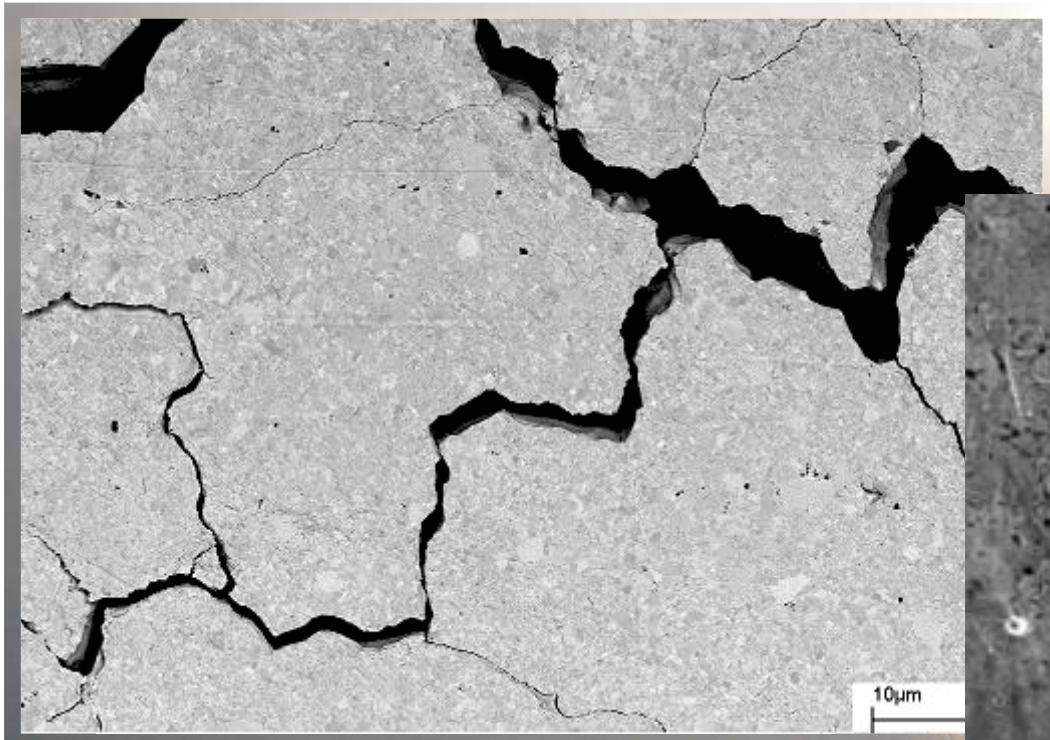
Deuterium concentration distribution in the surface layer of austenitic 25Cr12Mn20W steel after irradiation by high powerful plasma jet and fast ion beam

Elastic Recoil Detection Analysis (ERDA) processed with a **Rutherford Universal Manipulation Program (RUMP)**:

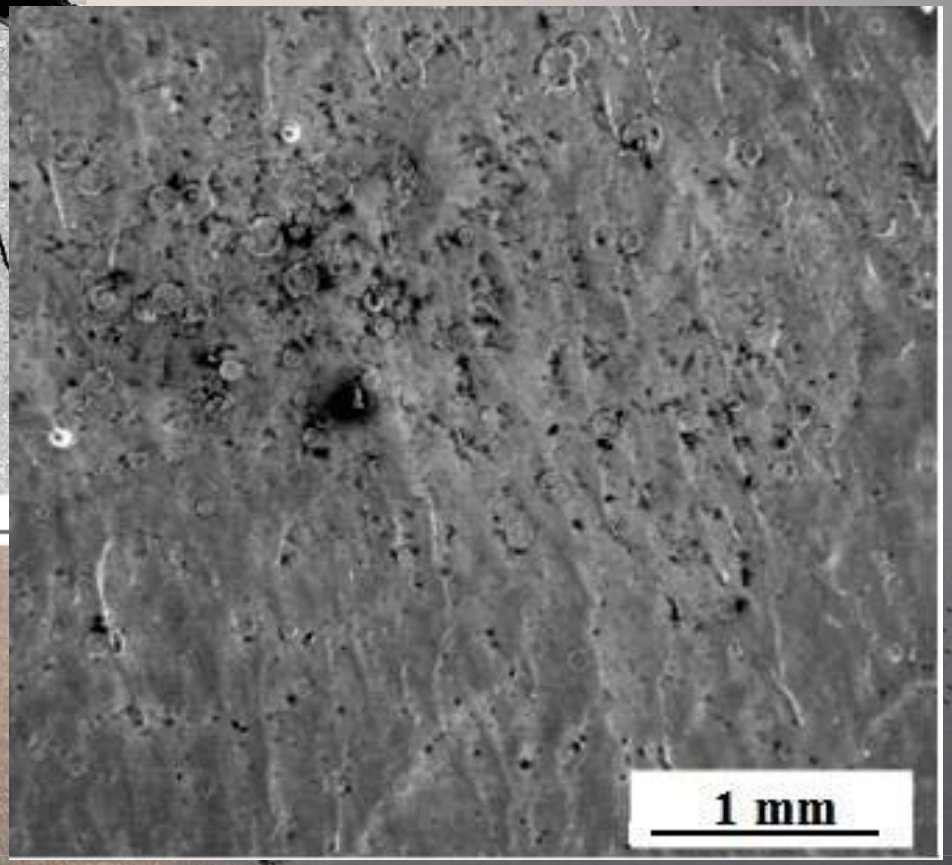
1 - 1 pulse, **2** - 2 pulses, **3** - 4 pulses, **4** - 8 pulses, **5** - 16 pulses

Second effect which was observed in these experiments is connected with the damageability of these materials

In particular, when our samples of tungsten (same as above) and pure iron (same as in the last picture) were irradiated by the above streams of rather ***lower*** power flux density – about $P \sim 10^7 \ldots 10^9$ W/cm^2 (i.e. on the "border" of sample's surface melting or with low melting of it) we saw well-defined cracking and porosity of them correspondingly (see below)



Surface of tungsten irradiated by a single pulse of HP/FI at PF-1000 with P ~ 10^8 W/cm^2, SEM



Surface of pure iron irradiated by a single pulse of HP/FI at "Bora" with P ~ 10^9 W/cm^2, optical microscopy

D) DINAMIC QUALITY CONTROL

(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:

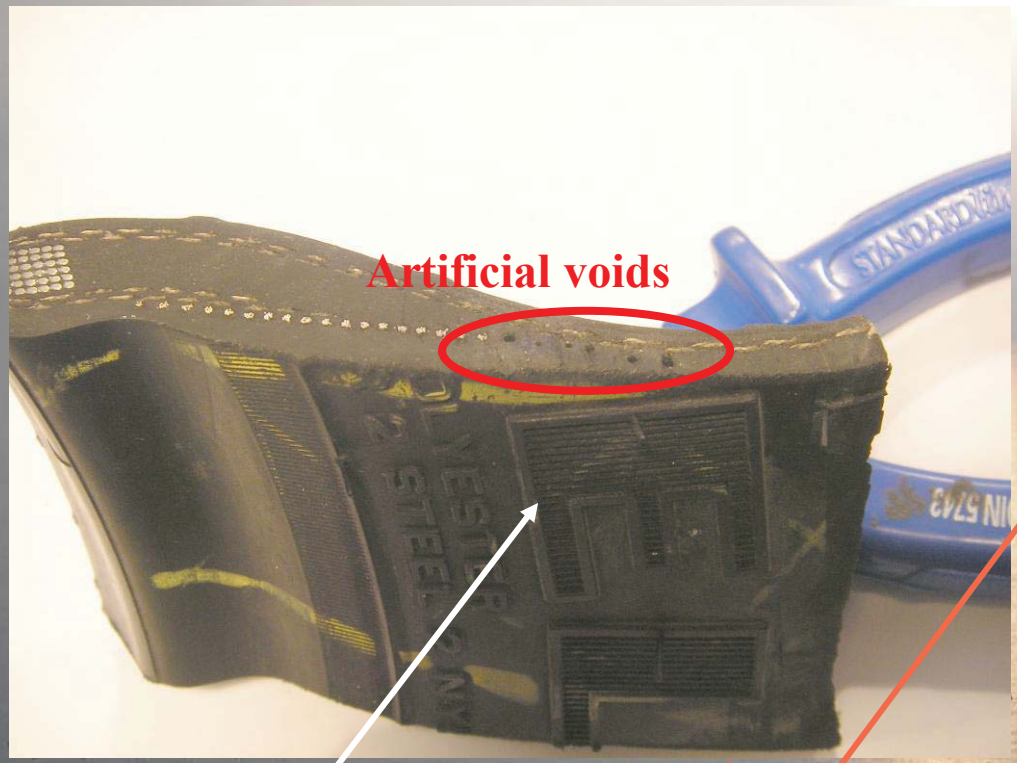
- pulse duration of X-Rays (ns)

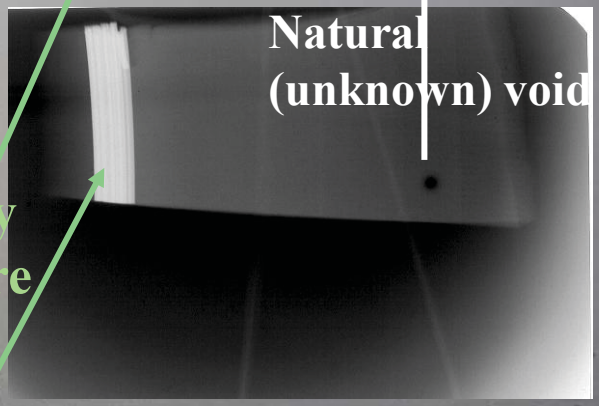
- size of the source of X-Rays and its remoteness from an object (< 100 μm, 10 cm – a few meters)

- diffraction (wavelength, distance)

- contrast degree of an object's detail to be visualized (spectrum of hard X-Rays)

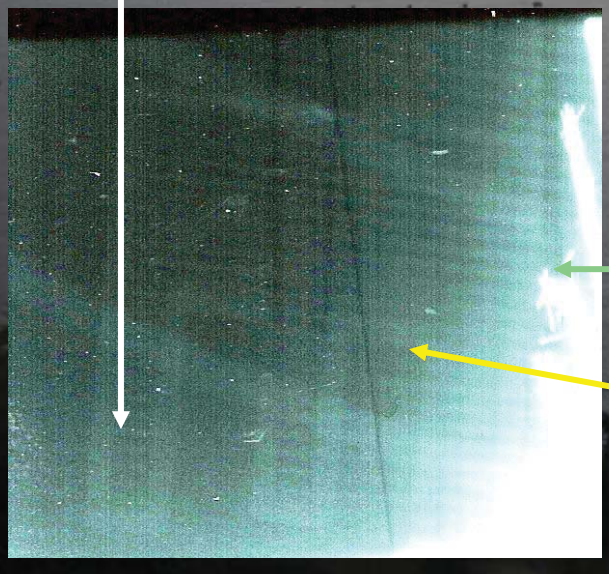
Theoretically for DPF it could be ~ 1 μm in a 10-cm distance



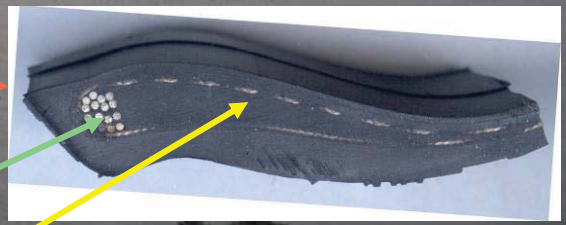


X-Ray
picture

Relief of “E” letter



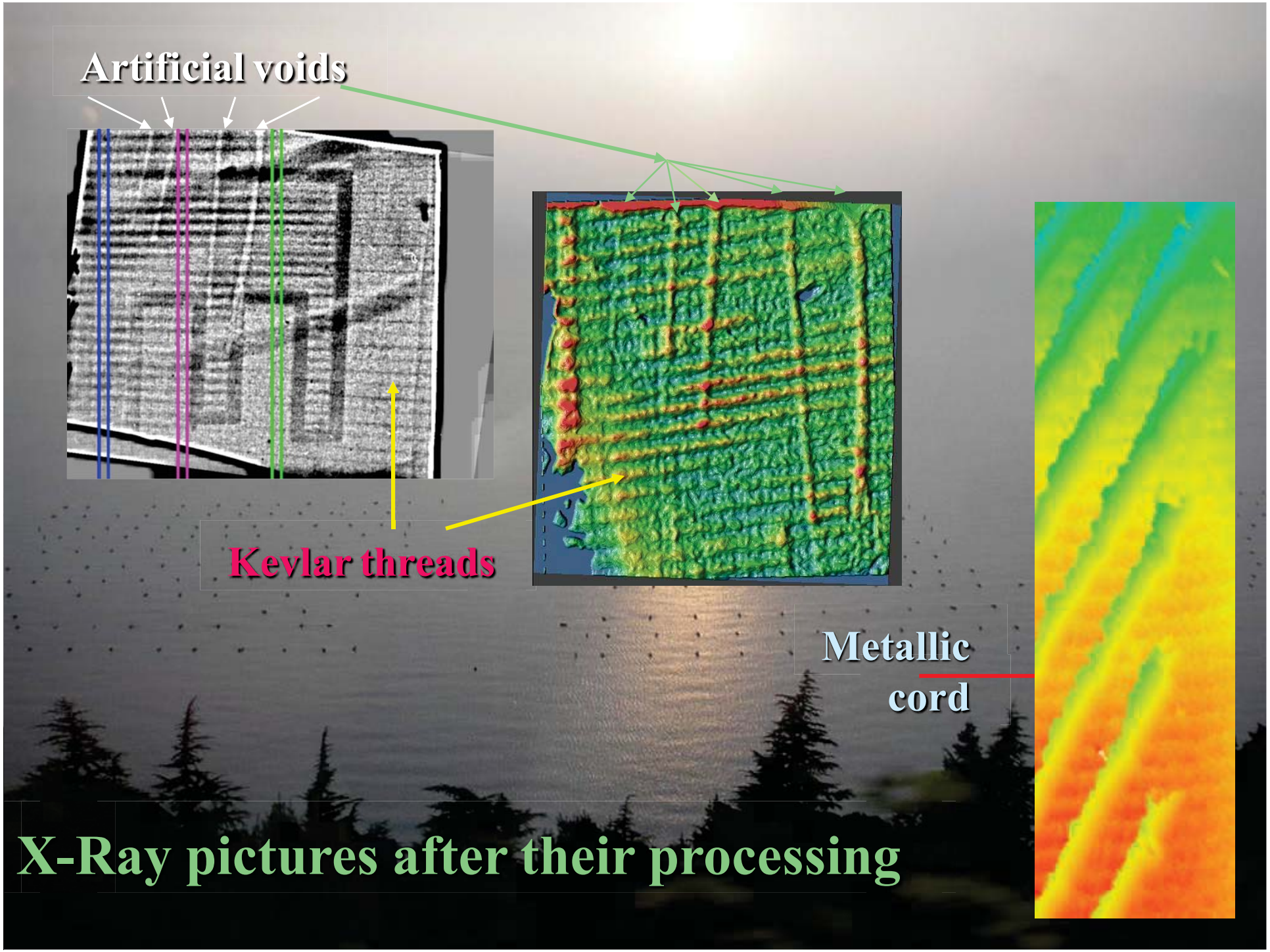
Visible
light



Metallic cord

X-Ray
picture

Kevlar threads

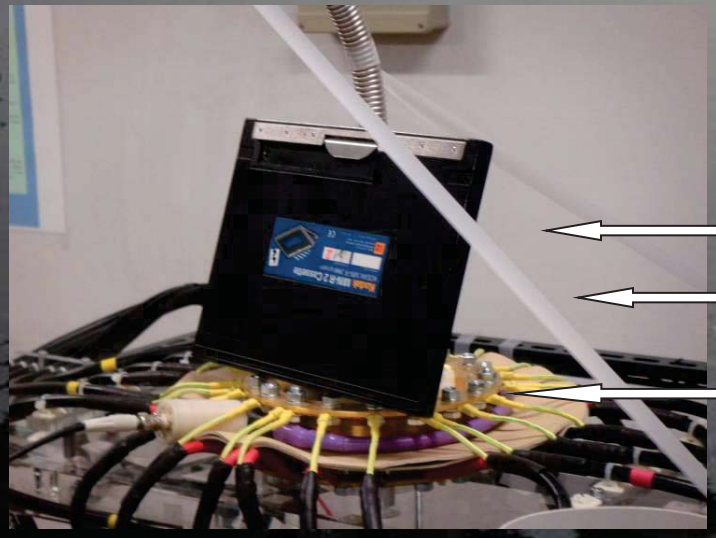


X-Ray pictures after their processing

Fan

DPF chamber

a)



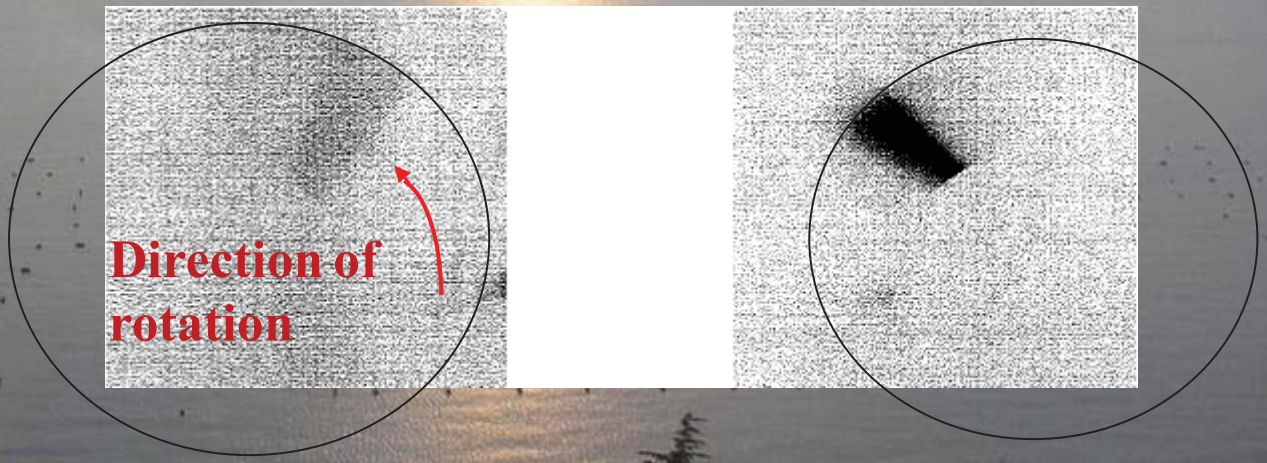
X-Ray film in a cassette

Fan (beyond the cassette)

DPF chamber

b)

Experiment in dynamic quality control



a) b)

X-Ray pictures of the fan's wing in dynamics (a), 1 shot of DPF, and in a static state (b), 7 shots of DPF

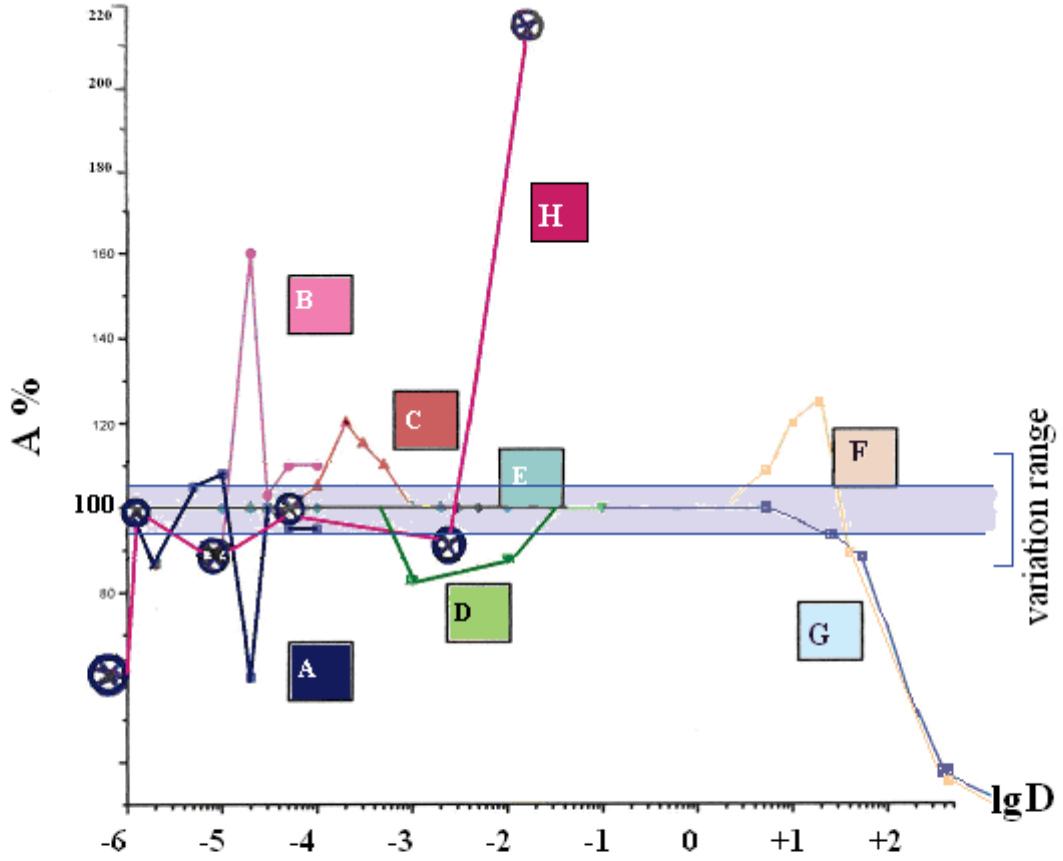
- Radiation chemistry/biology: radioenzymology

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})

But with DPF the effects appear at ***power flux density*** difference in these two irradiation experiments equal to about ***7-8 orders*** of magnitude

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



A, B – "PF -0.2", Cu filter; ***C*** – "PF-2", Cu filter;

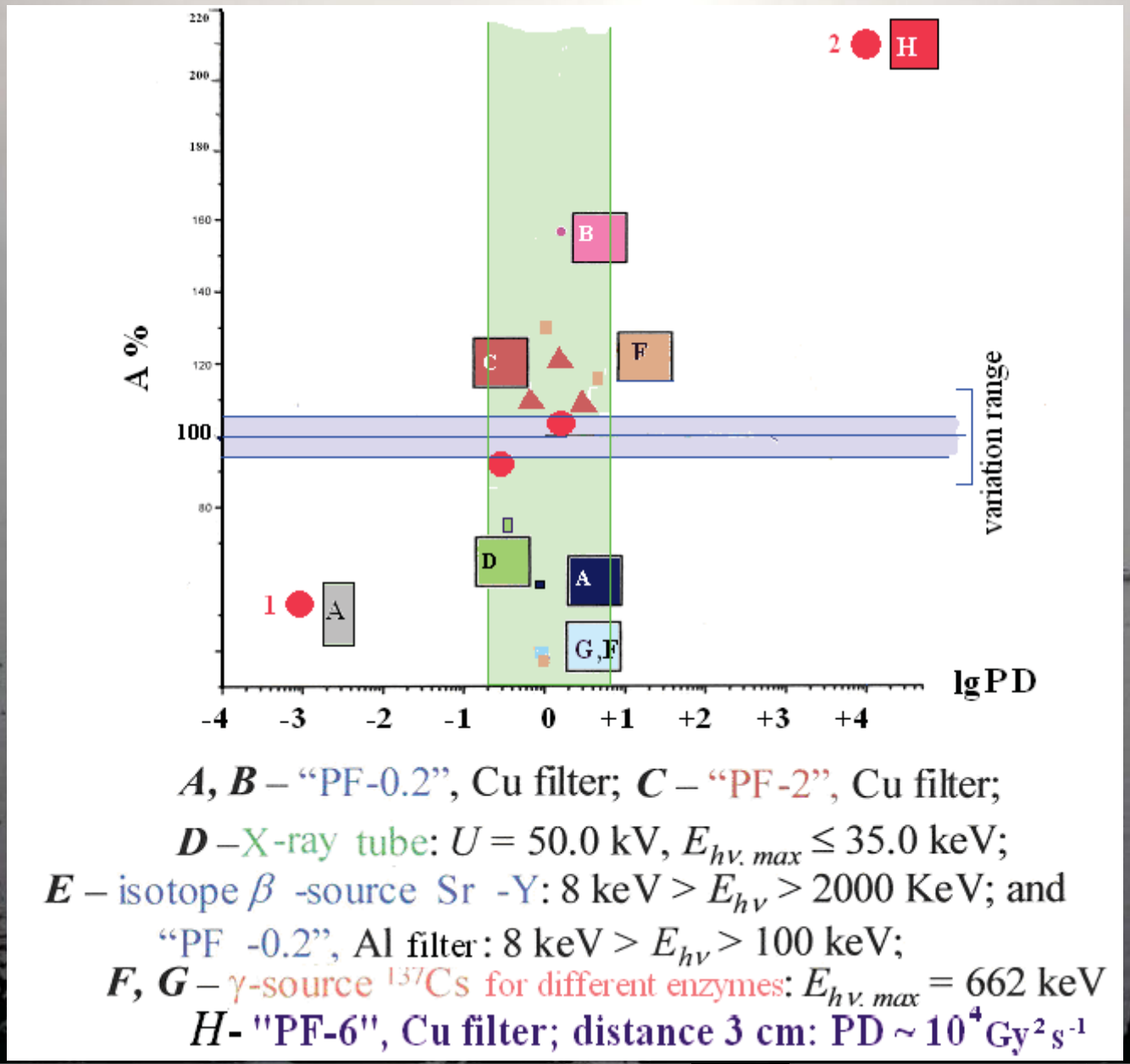
D – X-ray tube: $U = 50.0$ kV, $E_{hv.\,max} \leq 35.0$ keV;

E – isotope β -source Sr -Y: 8 keV > E_{hv} > 2000 KeV; and "PF -0.2", Al filter: 8 keV > E_{hv} > 100 keV;

F, G – γ-source ^{137}Cs for different enzymes: $E_{hv.\,max} = 662$ keV

H - "PF-6", Cu filter; distance 3 cm: PD ~ 10^4 $Gy^2 s^{-1}$

Activity of enzymes versus irradiation dose



A, B – "PF-0.2", Cu filter; ***C*** – "PF-2", Cu filter;

D – X-ray tube: $U = 50.0$ kV, $E_{hv.\,max} \leq 35.0$ keV;

E – isotope β -source Sr -Y: 8 keV > E_{hv} > 2000 KeV; and "PF -0.2", Al filter: 8 keV > E_{hv} > 100 keV;

F, G – γ-source ^{137}Cs for different enzymes: $E_{hv.\,max} = 662$ keV

H - "PF-6", Cu filter; distance 3 cm: PD ~ 10^4 $Gy^2 s^{-1}$

Activity of enzymes versus a product of *DP*

In these experiments we changed distances from a source till the test-tubes with enzymes, a number of irradiating shots as well as filters on the DPF chamber window, which screened pulses of X-Rays

Our preliminary conclusion is that in this case we have a synergetic effect achieved due to ***simultaneously produced a high concentration of free radicals in the vicinity of an enzyme molecule and an excitation of metallic ions within this molecule***

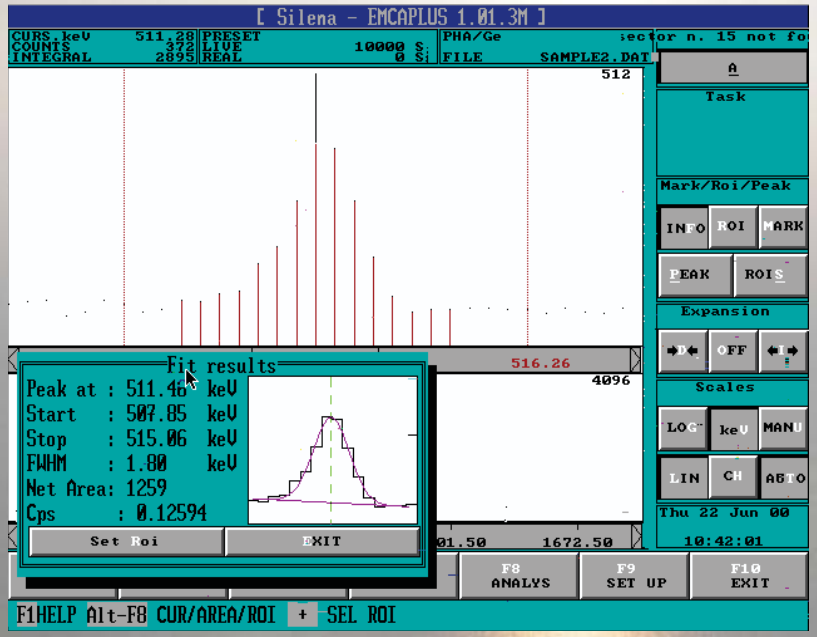
Thus in pulsed radiation hygiene a **product of dose and dose power is crucial**

- Radiation medicine

a) Fast ions in positron emission tomography

Positron emission tomography (PET) is one of several methods currently exploiting nuclear physics principles for health – so-called **"nuclear medicine" (NM);** generally PET consists of three elements: ***production*** of ***positron-emitting isotopes***, ***synthesis of biological molecules*** labeled with the above positron emitters, and ***scanning of a human body***

The most commonly used at present time as PET tracers are the isotopes C^{11}, N^{13}, O^{15}, and F^{18} ($T½$ =20.03 min, 9.97 min, 2.03 min and 109 min correspondingly) , because they can be introduced into biological molecules without altering the composition of these molecules



Spectrometric picture of the electron-positron pair annihilation produced in a reaction $C^{12}(d,n)N^{13}$ using deuterons from DPF

This result has shown that the DPF of the level of energy 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

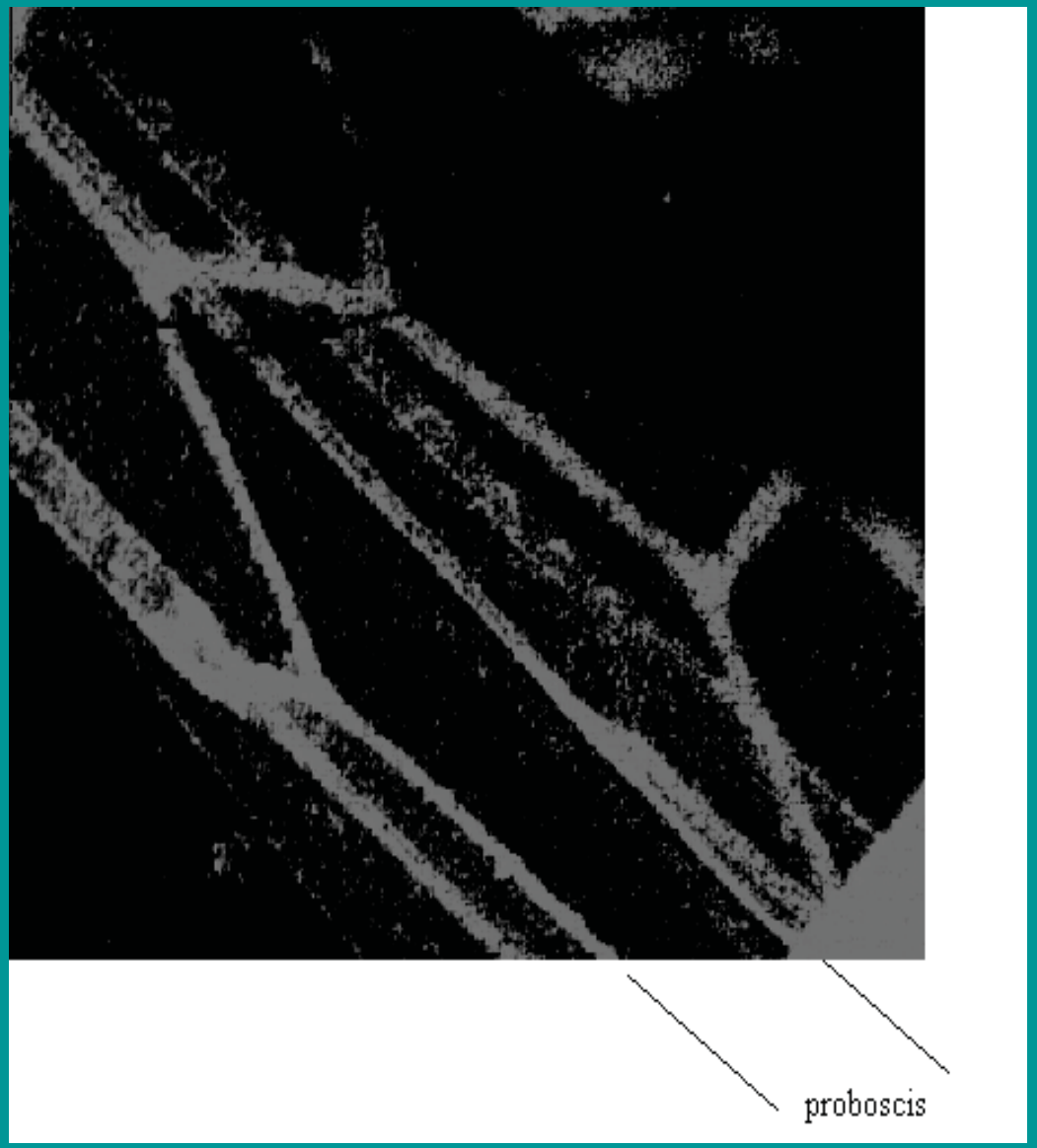
c) Micro-radiography

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*** depending on working media used

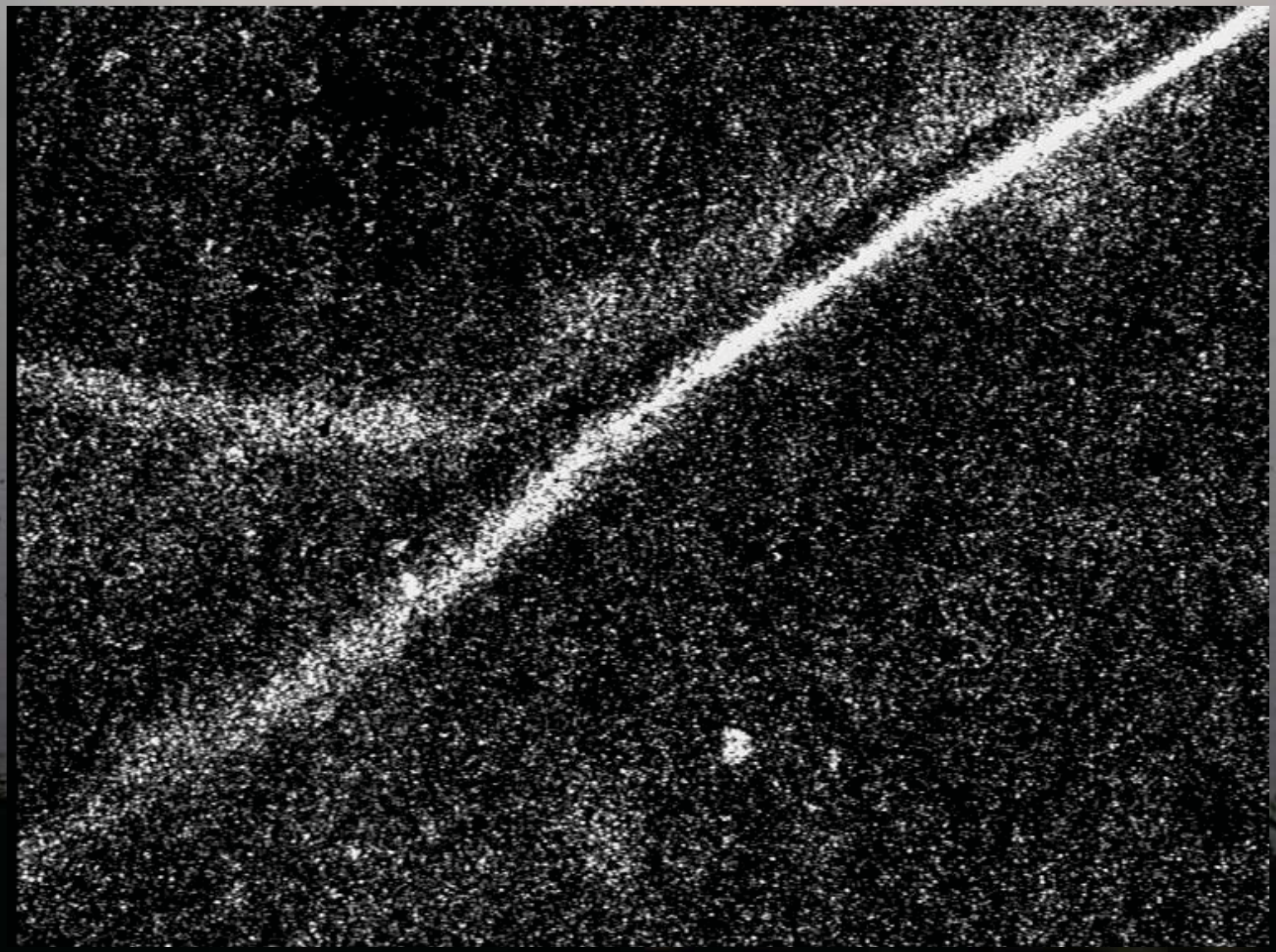
A few examples of the tests are shown in the pictures where X-Ray films are presented with their visualization by an **optical microscope** ***Swift Instruments International S.A.*** with lenses 10/0.25, 25/0.4 or 40/0.65 or by **scanning electron microscope**

A mosquito proboscis in its “open” position



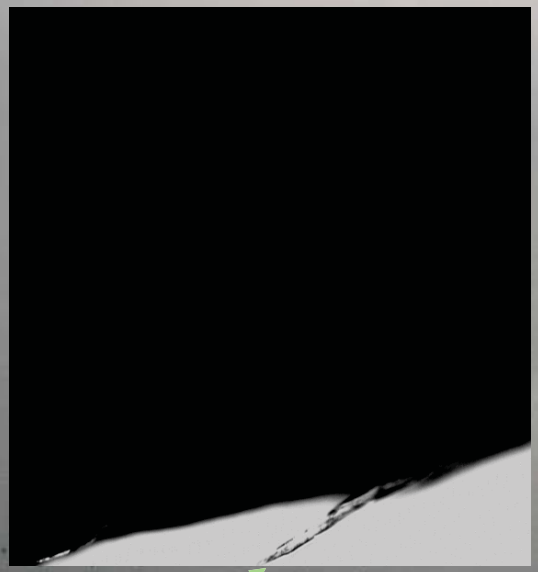
10 μm

An intermediate phase of the closing process of a mimosa leaf

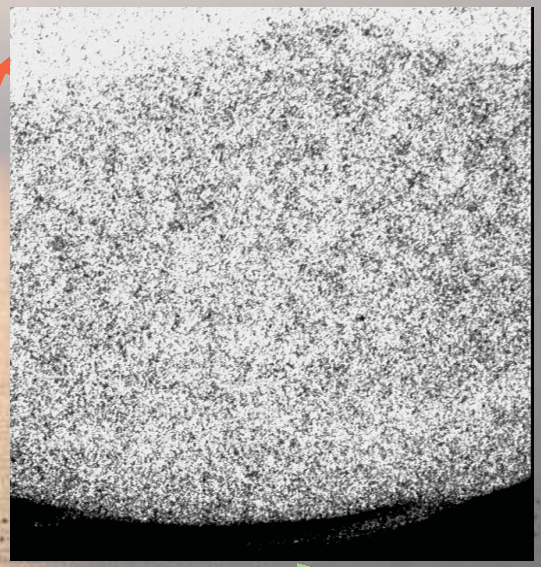


Three pictures of a bird's feather – direct optical image and SXR visualizations of it

Visible light



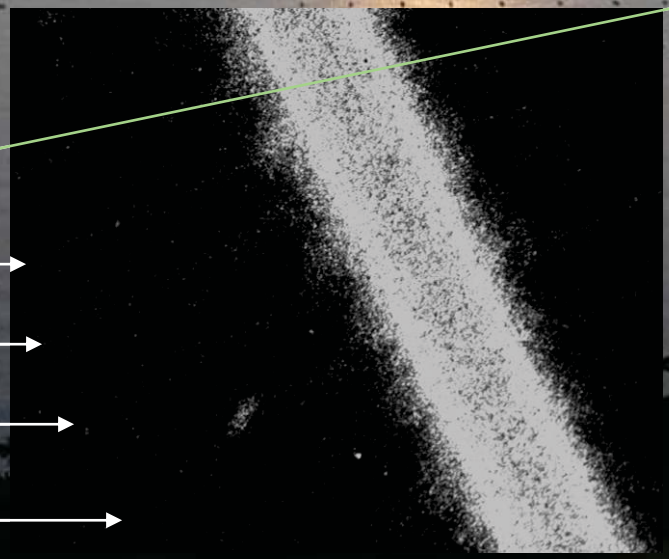
Feather's stem (of a tube-like structure)



Soft X-Rays

Feather's fragment

Secondary structure of the feather (not seen in visible light)



Soft X-Rays

In all these pictures spatial resolution of images was circa 1 μm, which has been specially tested by photographing of a golden wire of 15 μm thickness (with and without phase contrast)

When one needs a spatial resolution better than this various ***photoresists*** should be used instead of X-Ray films

We have tested SU-8 photoresist with chemical amplification to visualize a special golden mask

All these experiments can be done in the scheme of the so-called ***"proximity X-Ray lithography"***

A dose necessary to produce the image on this resist appeared to be **several times (almost 10 times) less** than it was estimated for and checked by classical X-Ray tube; resolution in this case was 50 nm

We also investigated by these technique diamond-like films, embryo of reptiles as well as organs of various insects, a butterfly, etc.

From the above-mentioned one may see that 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 by irradiation of them with soft X-Rays **in the regime of their inertial confinement**

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

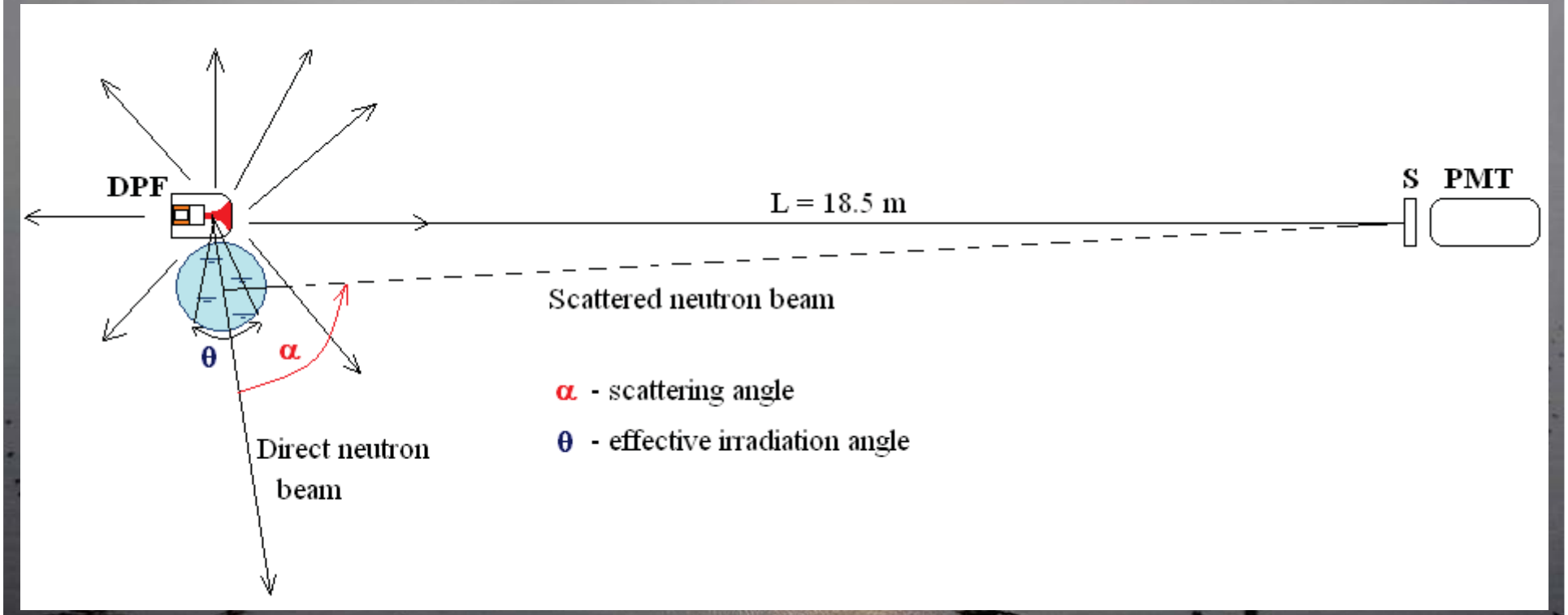
Two important issues encountered in the non-intrusive inspection of buried materials by neutron methods with using isotopes or classical accelerators:

- ***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"***

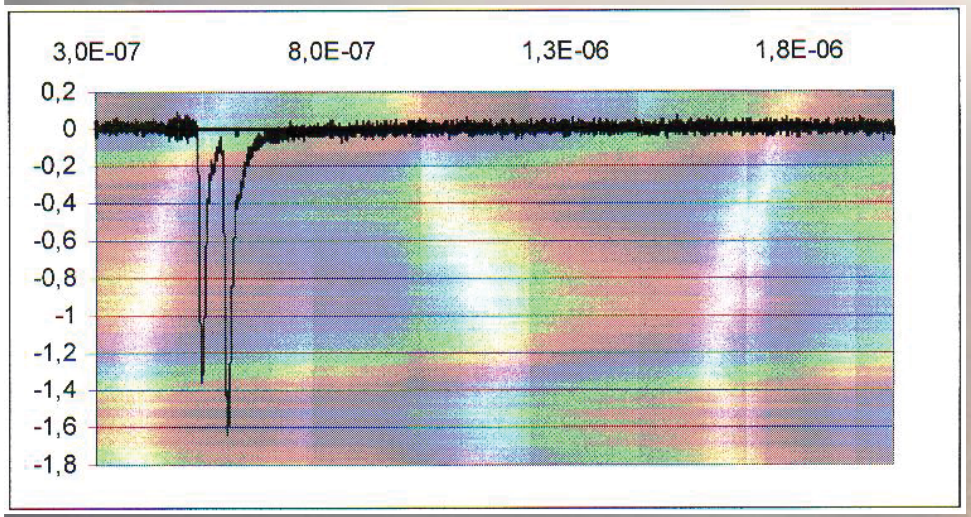
Scheme of the experiments

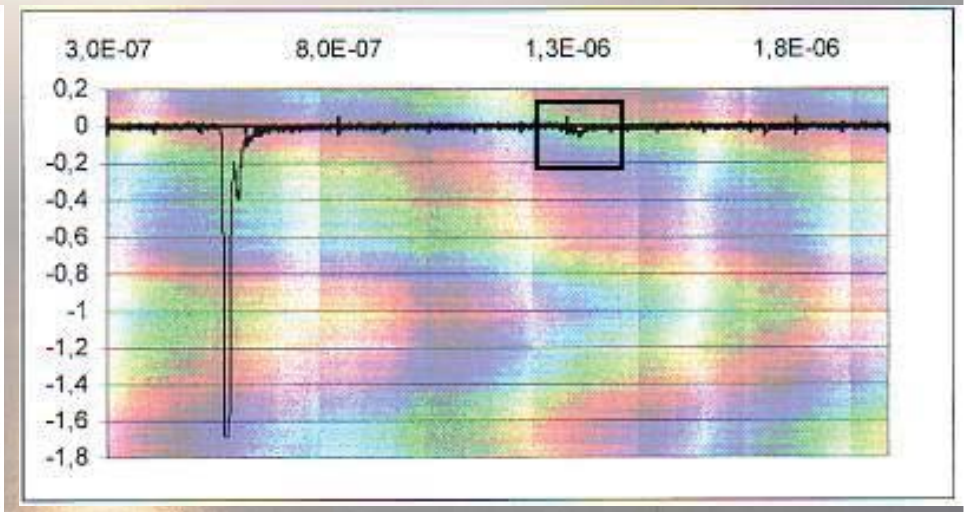


Target – a 1-litre bottle with methanol (CH_3OH)

Radius of the DPF chamber is 3 cm, diameter of the bottle with methanol – 10 cm

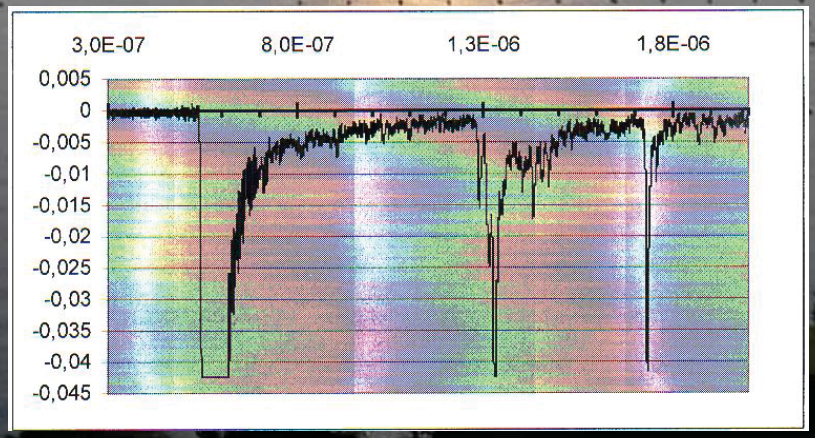
NINIS tests with ethanol





X-Rays↑ 1.0 m X-Rays↑ 18.5 m ↑neutrons

↑neutrons X-Rays ↓

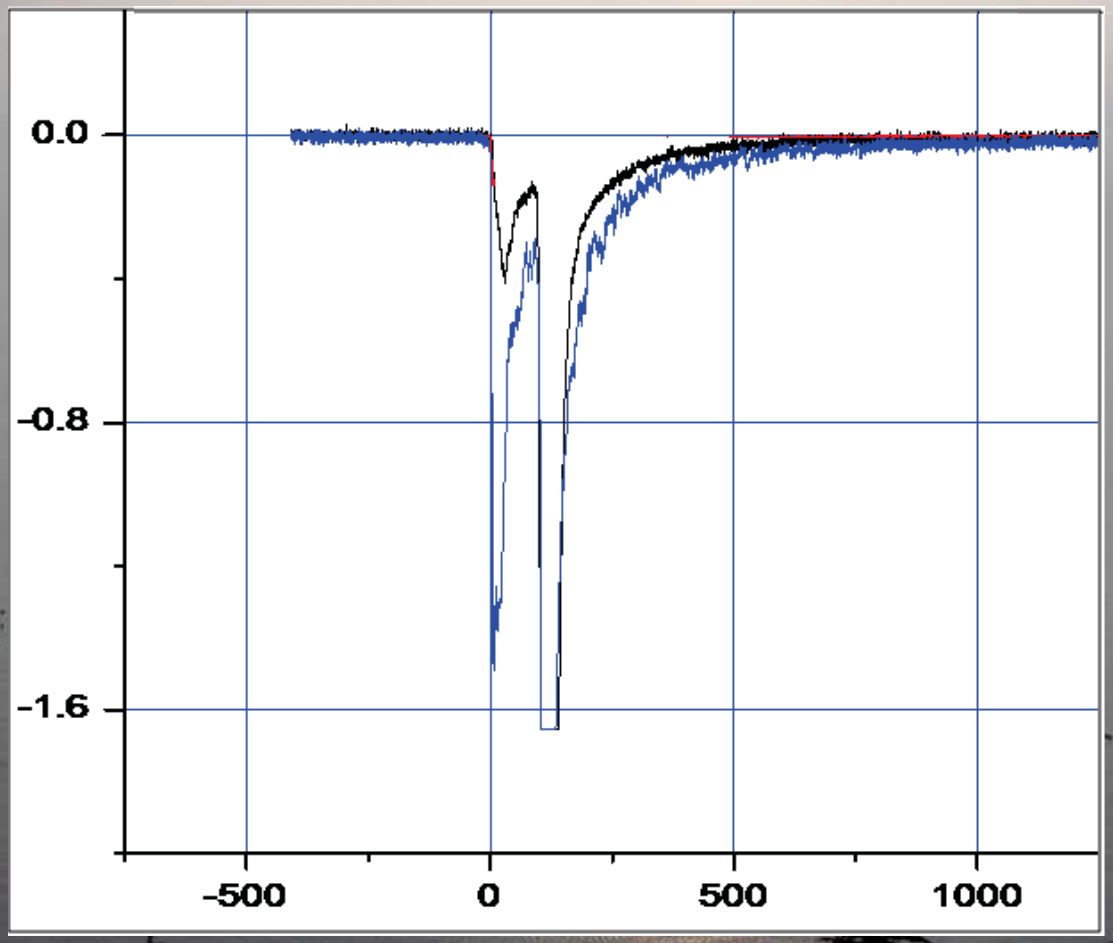


18.5 m

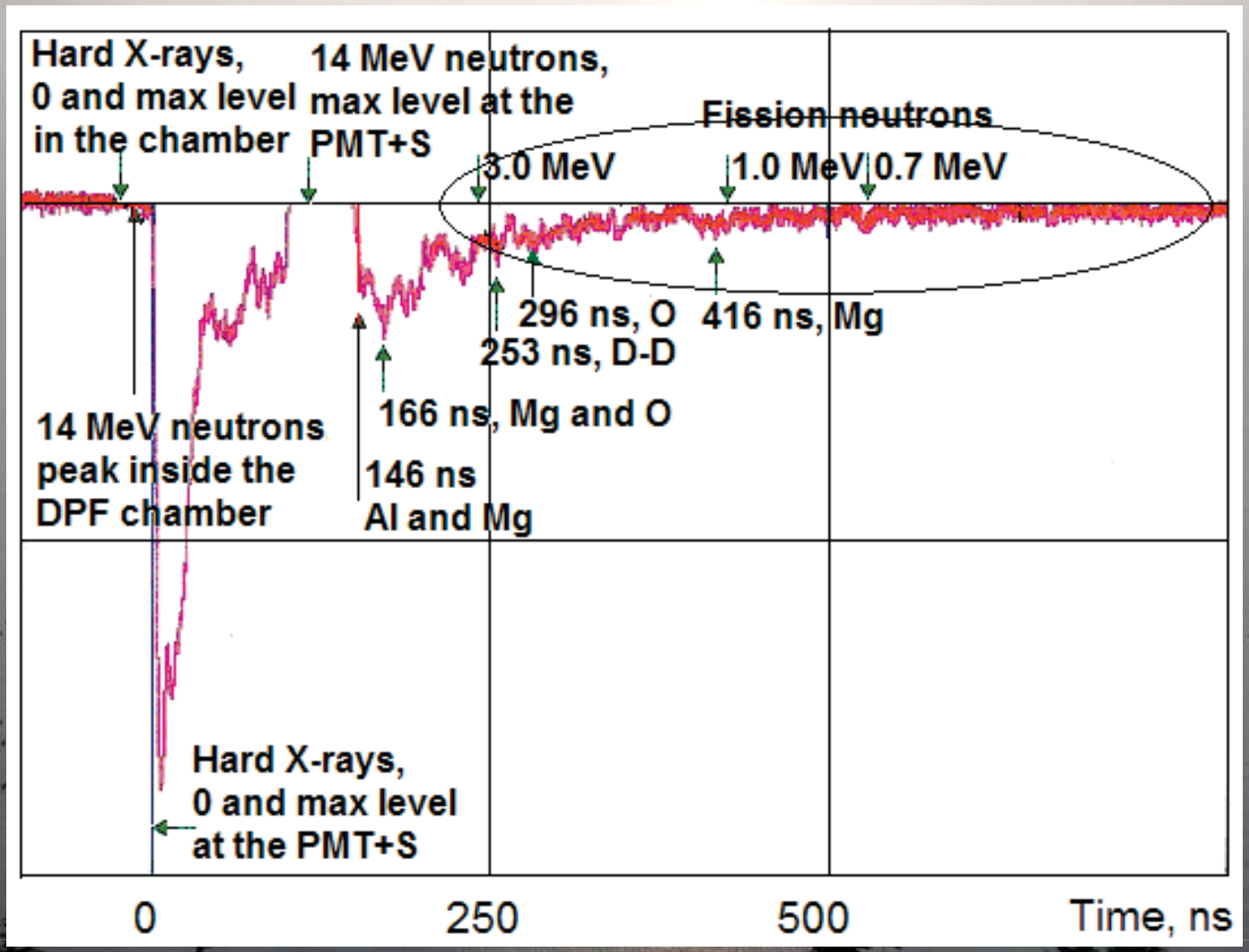
neutrons scattered by methanol ↑

↑ neutrons scattered by a 10-liter HPC with deuterium (150 atm)

A single-shot nanosecond neutron pulsed technique for the detection of fissile materials



Two oscilloscope traces overlapping one another: one is taken without fuel element (the black one, smooth) and another one is taken with fuel element EK-10 (the blue one with multiple peaks)



A result of the subtraction of oscilloscope traces with attribution of different peaks and comparison with results of MCNP modelling calculations

2. 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) Nuclear physics

DPF favorably differs from the classical neutron sources by a very short pulse of neutron emission and its intensity. These features make this device very interesting for its use inside the *active sub-critical multiplicative core*

It might help to investigate ***dynamical response*** of the booster by the "instant" neutron pulse. That is because the "initiating" neutron pulse in the case of the DPF use will be much shorter than the overall duration of the output neutron pulse of the whole sub-critical assembly

However it is very likely that one may attain something more. Indeed let's look for typical temporal and spatial scales of the processes under investigation

Simple estimations show that the ***overall number of neutrons*** (the above-mentioned concentration of them) will be **injected and multiplied within the 1-cm zone of uranium *namely during* the DPF neutron pulse**

The primary neutrons (side by side with secondary neutrons) will produce ***fission fragments***. Mean free path of the fission fragments at their deceleration in uranium is circa 10 μm. It means that ***each fission fragment*** will occupy **precisely the same micro-volume as the single primary neutron**

In these conditions it will be very interesting to check:

- a possibility to ***increase the rate of the initiation*** of chain reactions in a sub-critical assembly ***by volumetric action***

- an opportunity to ***increase "burning out" of fission fragments*** inside the assembly ***during the DPF neutron pulse***

e) Thermal and fast neutrons and X-Rays in Boron Neutron Capture Therapy (FU + IPPLM + ICTP)

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**):

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

and

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

$$\downarrow$$

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

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

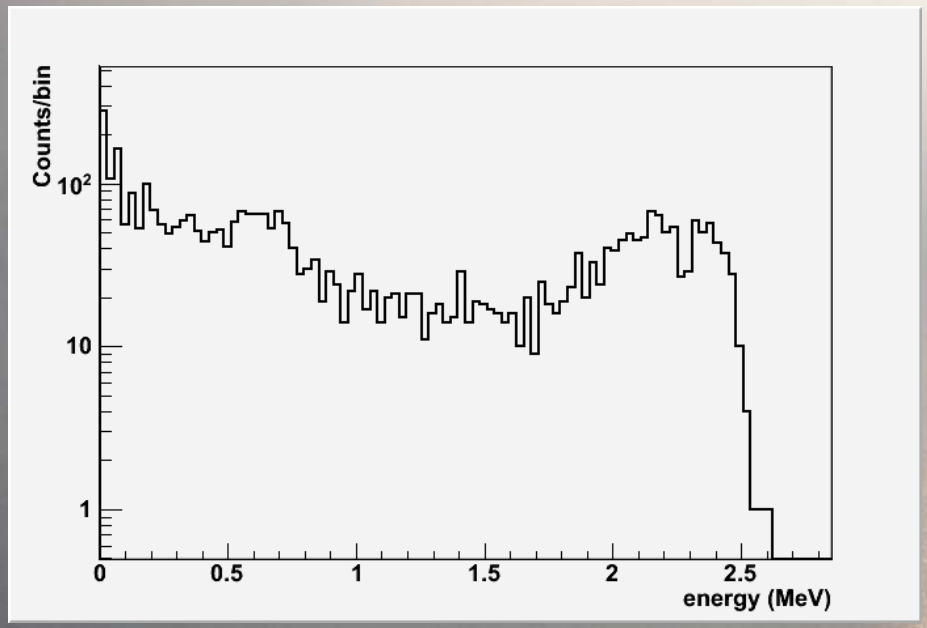
2) One can expect here **synergetic effects** if DPF will be used either with just **fast neutrons of the ns pulse duration** or at the ***combined application of fast neutrons and hard X-Rays*** for a suppression of malignant cells

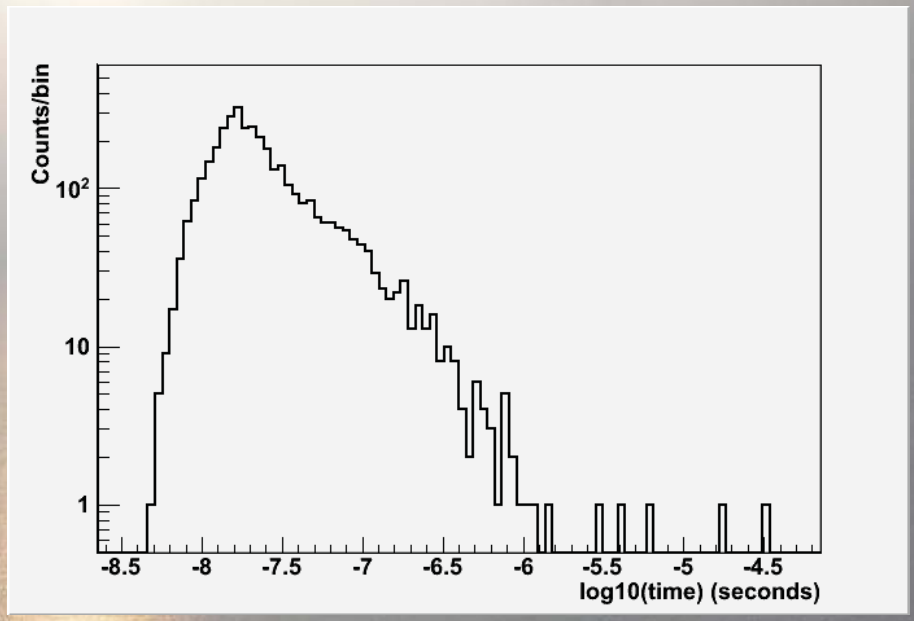
Possible reasons to expect these effects namely in malignant cells enriched with boron to higher degree compared with sound cells are:

- a *simultaneous destruction* of both spirals of their DNA during the ns period of time by a high-density neutron flux ("shock-like action" at a double-strand rupture)

- a *threshold-like behavior* of radiation damage of malignant cells inside a neutron field having a higher concentration namely in a tumor with overlapping of micro-volumes of free radicals and nuclear reaction products

Both these opportunities open ways for low-dose therapy of cancer





a) **b)**

Neutron energy spectrum (a) and time profile (b) obtained by simulating a monochromatic pulse of 10 ns of 2.45-MeV neutrons in the small chamber of the "Bora" device with 15 cm FluentalTM moderator

f) Brachytherapy

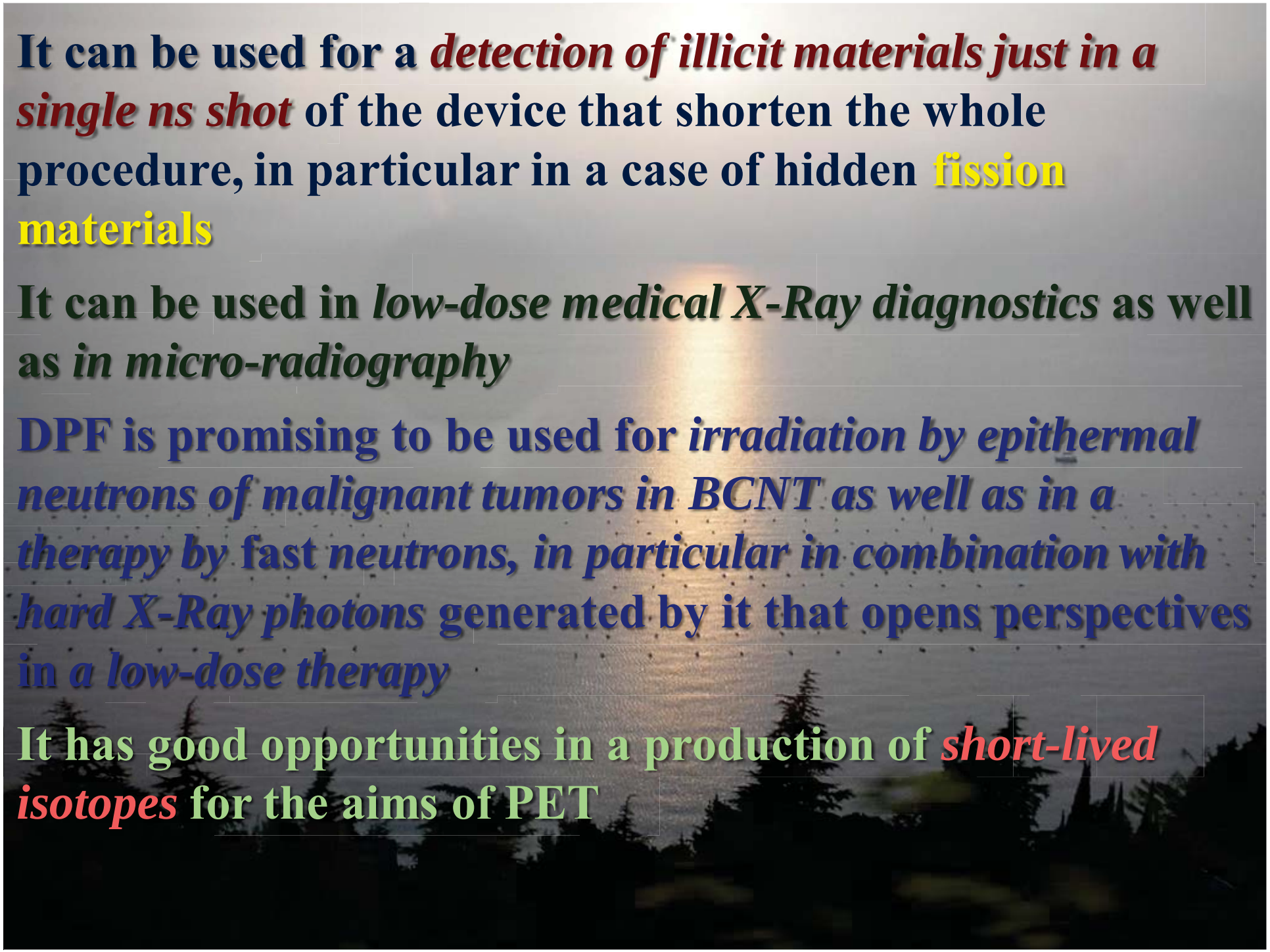
Because electron beam (with electron's energy about 100 keV) generated in DPF can be transported along large distances (~ 1 meter) inside the anode's tube due to the back-current induced in the tube's wall it can be used for brachytherapy both by the ***e-beam itself*** and by ***hard X-rays*** generated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

6. CONCLUSIONS

Our experiments has shown that DPF side by side with its own fusion perspectives can successfully be used right now in a number of applications in **biology, medicine, material sciences, express NAA**, etc.

Thus it can simulate and help in investigations 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


It can be used for a detection of illicit materials just in a single ns shot of the device that shorten the whole procedure, in particular in a case of hidden fission materials
It can be used in low-dose medical X-Ray diagnostics as well as in micro-radiography
DPF is promising to be used for irradiation by epithermal neutrons of malignant tumors in BCNT 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

DPF has attractive perspectives for application in nuclear physics, in particular in combination with sub-critical assemblies

Future perspectives of DPF are connected with small *sealed DPF chambers* giving opportunities to investigate such complicated problems like tritium inventory and berillium re-deposition taking place under typical thermonuclear fusion conditions in a very cheap and efficient way

DPF devices based on the modern high-power pulsed technology can produce *"instantaneous"* powerful impact upon materials and may help in investigation of *transient* and *non-steady-state* phenomena in a very broad range of experiments


Thank you!