

Current and Perspective Applications of Dense Plasma Focus Devices

V.A. Gribkov

¹*A.I. Alikhanov Institute of Theoretical and Experimental Physics, ul. Bolshaya Cheremushkinskaya 25, 117218 Moscow, Russian Federation*

²*Institute of Plasma Physics and Laser Microfusion, ul. Hery 23, Warsaw 01-497, Poland*

Abstract. Dense Plasma Focus (DPF) devices' applications, which are intended to support the main-stream large-scale nuclear fusion programs (NFP) from one side (both in fundamental problems of Dense Magnetized Plasma physics and in its engineering issues) as well as elaborated for an immediate use in a number of fields from the other one, are described. In the first direction such problems as self-generated magnetic fields, implosion stability of plasma shells having a high aspect ratio, etc. are important for the Inertial Confinement Fusion (ICF) programs (e.g. as NIF), whereas different problems of current disruption phenomenon, plasma turbulence, mechanisms of generation of fast particles and neutrons in magnetized plasmas are of great interest for the large devices of the Magnetic Plasma Confinement – MPC (e.g. as ITER). In a sphere of the engineering problems of NFP it is shown that in particular the radiation material sciences have DPF as a very efficient tool for radiation tests of prospect materials and for improvement of their characteristics. In the field of broad-band current applications some results obtained in the fields of radiation material sciences, radiobiology, nuclear medicine, express Neutron Activation Analysis (including a single-shot interrogation of hidden illegal objects), dynamic non-destructive quality control, X-Ray microlithography and micromachining, and micro-radiography are presented. As the examples of the potential future applications it is proposed to use DPF as a powerful high-flux neutron source to generate very powerful pulses of neutrons in the nanosecond (ns) range of its duration for innovative experiments in nuclear physics, for the goals of radiation treatment of malignant tumors, for neutron tests of materials of the first wall, blankets and NFP device's constructions (with fluences up to 1 dpa per a year term), and ns pulses of fast electrons, neutrons and hard X-Rays for brachytherapy.

Keywords: plasma focus, fusion programs, radiation material science, nuclear medicine, radiobiology, dynamic quality control, microlithography, mine-clearing

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INTRODUCTION

Dense Magnetized Plasmas produced by different devices, such as plasma accelerators, Dense Plasma Focus (DPF), pinch facilities, etc., occupies a niche between the inertial plasma fusion devices (e.g. of the laser-produced implosion plasma types) and the installations with the magnetic plasma confinement (for example, of the tokamak type). This niche is established by characteristic times of physical processes and by the respective plasma parameters.

Besides its own fusion perspectives renovated during the last few years due to impressive experiments provided in Sandia Labs (U.S.A.) with multi-arrays pinching

assemblies it can serve as a very powerful source of various types of ionizing radiation.

Dense Plasma Focus device is a type of plasma accelerator producing nanosecond pulses of:

- Directed powerful hot ($T \sim 1$ keV) fast ($v > 10^7$ cm/s) dense ($n_{pl} \approx 10^{16} \dots 10^{19}$ cm⁻³) plasma streams,
- High-energy ion ($E_i \approx 0.01 \dots 100$ MeV) and electron ($E_e \approx 0.01 \dots 1.0$ MeV) beams
- Soft ($E_{hv} \sim 0.1 \dots 10$ keV) and hard ($E_{hv} \sim 10 \dots 1000$ keV) X-Rays and
- Fusion neutrons (monochromatic $E_n \sim 2.45$ and 14 MeV as well as broad-range ones - $2 \dots 11.3$ MeV)

These streams may irradiate a target with power flux density on its surface equal to 10^5 W/cm² (for neutrons), 10^8 W/cm² (for soft and hard X-rays), 10^{10} W/cm² (for fast ion streams and plasma jets) and up to 10^{13} W/cm² (for self-focused electron beams).

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

- It uses low charging voltage (~ 10 kV)
- It becomes a radiation source just for a few nanoseconds 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.

DPF having very short pulse duration of radiation simultaneously with very high energy contained in the pulse 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] (see Fig. 1):

1) Micro-volumes of activity of primary/secondary particles (e.g. spurs or blobs at water radiolysis) are overlapped within the irradiated volume

2) This overlapping occurs during a time interval that is short compared with the reciprocal physical or chemical process (e.g. diffusion or reaction times).

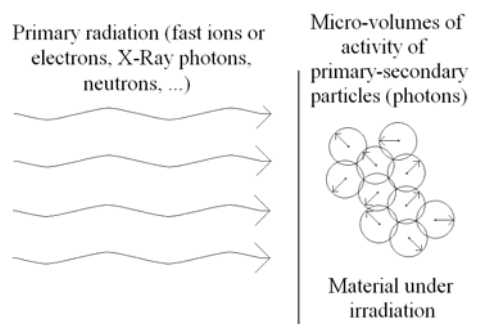


FIGURE 1 Scheme of interaction of primary quasi-particles' radiation with matter in the case of pulsed radiation physics in the perfect sense of the term

In this case the interaction of radiation with matter obeys a collective character, and this collective action can create volumetric synergetic effects, e.g. it can produce *instantly* a high *concentration*, *temperature* or *pressure* of a substance in micro-spheres of activity of secondary particles (i.e. in the whole reaction volume), etc. [2].

APPARATUS

Contemporary powerful neutron sources of the DPF type [3] can, not only generate neutron pulses being *short* by its duration (in the nano-second range) and providing a *very high neutron yield*, but they may have a long life-time ($\sim 10^7$ pulses) and a high repetition rate (up to 50 cps). Our devices PF-1000, PF-6 (IPPLM), PF-10 (ITEP) and ING-102, ING-103 (Fig. 1), have levels of energy in its capacitor storage from 0.1 till 1,000 kJ with a current maximum in the range 0.15...3.0 MA and a quarter period of the discharge from 0.4 till 7 μ s. The medium-energy transportable devices (2-7 kJ) can generate in one pulse of 7...15-ns duration from 10^8 up to 10^9 2.5-MeV neutrons under operation of the device with pure deuterium or till 10^{11} 14-MeV neutrons at the deuterium-tritium mixture respectively. They have sealed chambers (so it can be treated as “closed or sealed radiation source”), low size and weight (1 m³ and <400 kg), comparatively low cost, etc. Fig. 2 presents as an example the PF-10 device installed in a room having long length to ensure perfect time-of-flight (TOF) measurements.



FIGURE 2 PF-10 device (ITEP)

This device belonging to the Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia, has energy storage 10 kJ at 23-kV initial voltage.

It should be mentioned here that we have also a *portable* modification of the DPF of this new generation [4] weighing only 15 kg. Its neutron yield being irradiated during the 2-ns pulse is about 10^7 14-MeV neutrons per pulse.

EXPERIMENTS IN DMP PHYSICS

All processes in these devices are investigated with ns temporal, high spatial, angular and spectral resolution. Neutron radiation has been investigated by activation counters, bubble detectors, and fast photomultipliers with scintillators (S+PM). The last technique was used simultaneously for hard X-rays. A typical oscilloscope trace taken by a photomultiplier positioned at a distance 0.8 m from the chamber of PF-10 is presented in the Fig. 3. Fig. 4 presents pictures of pinch, ion beam and secondary plasma from the irradiated target taken by a frame camera in a visible range. In Fig. 5 (PF-1000, IPPLM, Poland) one may see a set of oscilloscope traces taken in a single shot by means of a number of diagnostics [5].

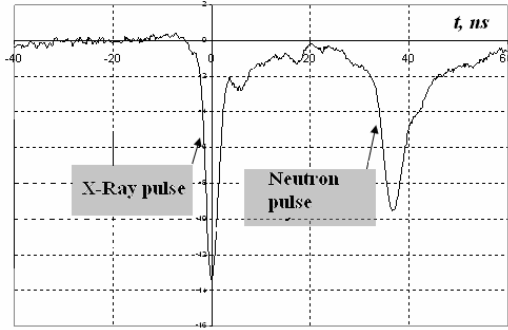


FIGURE 3 Oscilloscope trace of pulses of hard X-Rays and neutrons (PF-10)

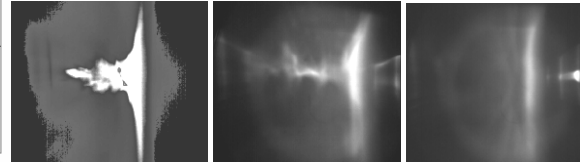


FIGURE 4 Pictures of pinch with shock wave (SW), ion beam (IB) and secondary plasma (SP) taken by a frame camera in a visible range

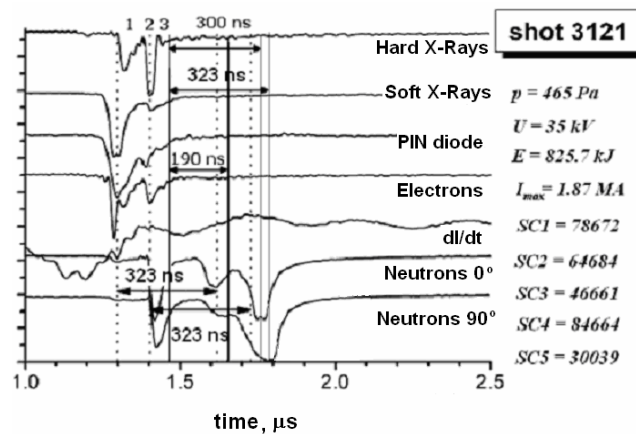


FIGURE 5 Oscilloscope traces taken in a single shot of the PF-1000 facility

RADIATION MATERIAL SCIENCE

A DPF is a very well diagnosed facility usually supplied with a number of instruments monitoring the main 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 those samples under test. These data can be cross-correlated subsequently with the results obtained *a posteriori* by analytical instrumentation.

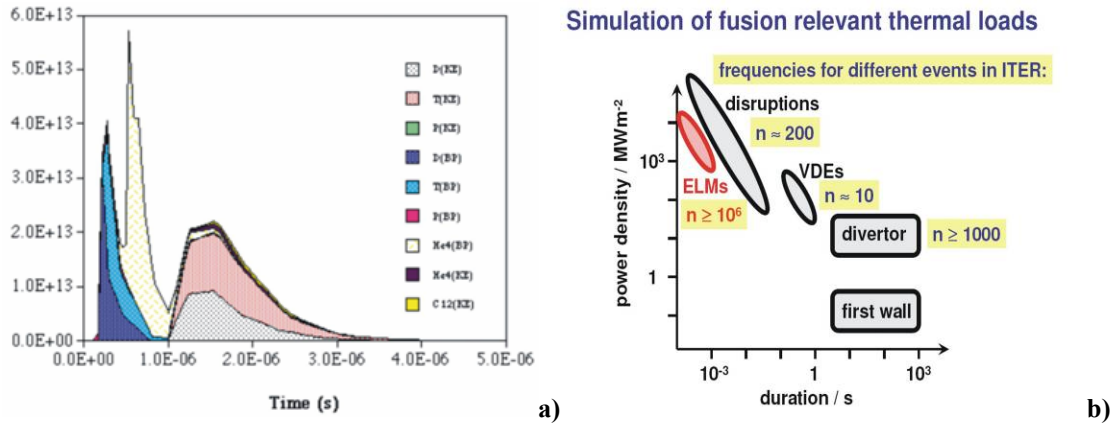
In our materials science experiments the morphology of the irradiated samples' surfaces after the irradiation was investigated by optical, electron and atomic force microscopes, as well as by an optical reflectometer. We applied also various tribology instruments, weighing samples after irradiation, profilometry, elastic recoil detection analysis (ERDA), X-Ray microprobe (i.e. elemental), structural, phase, and diffraction analysis, etc. (see, e.g. [6]).

Inside and outside a chamber of a contemporary full-scale fusion device we have:

- 1) First-wall materials (Be for ITER and stainless steel for NIF)
- 2) Divertor materials (tungsten and carbon-based composites for ITER)
- 3) Construction materials (low-activated stainless steels, ceramics, etc.)
- 4) Optical materials for windows (diagnostics and beams transmission paths)

5) Different types of plastics (cables, etc.).

Typical time intervals and parameters acting onto the materials inside the mainstream fusion devices are presented in Fig. 6 (a) for ICF and for MPC (b):



Simulation: Thermal Power to Wall in Ions From 154 MJ Yield. Wall radius: 6.5 meters Time-of-Flight Power Spread

FIGURE 6 Time intervals and power acting in the mainstream fusion devices – ICF (a) and MCF (b)

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 μ s that makes them a very useful and cheap tool for different test modes of candidate radiation-resistant materials and for a modification of the sample's surface.

	ITER Cadarache France	NIF LLNL, USA	PF-1000 IPPLM, Poland	PF-10,PF-5M PF-6, RF and Poland	QSPA Kh-50 Ukraine	MK-200 Troitsk, RF	RHEPP-1 Sandia Lab, USA	JUDITH Jülich, FRG
heat flux [W/m^2]: - normal operation - disruptions - VDEs - ELMs	10^6 10^{11} 10^9 10^7	10^{13}	* $10^{11}-10^{16}$ (10^{18} for fast el.)	* $10^{10}-10^{13}$ (10^{17} for fast electrons)	$0.6 \cdot 10^{10}$ or $1.1 \cdot 10^{10}$	10^{11}	10^{12}	10^{10}
Duration P [s]	$10^{-4}-10^{-3}$	10^{-7} - 10^{-6} (?)	$*10^{-4}$	$3 \cdot 10^{-5}$	$\geq 10^{-4}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-7}$ (?)	$10^{-4}-10^{-3}$
T_{pl} (surface) [eV]	10^3	10^{2-3}	$*10^3$	$*10^3$	10^2	10^2	-	-
Duration T_{pl} [s]	$10^{-4}-10^{-1}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	$\geq 10^{-4}$		-	-
$E_i D_{fast}$ [eV]	10^5	$10^2/10^6$	$*10^5-10^7$	$*10^5$	-	$\sim 10^3$	$8 \cdot 10^5$	-
Duration E_i [s]	$\geq 10^{-4}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	-	$2 \cdot 10^{-5}$	$2 \cdot 10^{-7}$	-
$E_e, fast$ [eV]	10^5-10^7	?	$*10^5-10^6$	10^5	-	-	-	$1.5 \cdot 10^5$
Duration E_e [s]	$\geq 10^{-4}$?	$2 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	-	-	-	$10^{-4}-10^3$
Irrad. surface [cm^2]	$\sim 10^7$	$\sim 10^6$	10^1-10^3 (0,1)	1 (0.01)	10^2	1-30	10^2	$0.04-10^2$
X-Rays [eV]	10^5-10^7	10^1	$*10^0-10^6$	10^0-10^5	-	-	-	$1.5 \cdot 10^5$
Neutrons [eV]	$1.4 \cdot 10^7$	$1.4 \cdot 10^7$	$2.5 \cdot 10^6$	$*1.4 \cdot 10^7$	-	-	-	-
Neutrons/ cm^2	10^{13}	10^{14}	10^{10}	$*10^{10}$	-	-	-	-

TABLE 1 Comparative characteristics of devices used in the round robin tests

They can simulate almost all parameters expected in ITER and NIF facilities contrarily to other devices as shown in Table 1. This Table represents a comparative analysis of devices used during a round robin tests organized by the Institute of

Plasma Physics and Laser Microfusion, Poland. Devices used were from 5 countries whereas samples were given by Forschungszentrum, Germany. Scheme of plasma and ion beams in DPF irradiating samples are shown in Fig. 7 whereas SEM photo of irradiated samples (tungsten plus carbon-based composite) are in Fig. 8.

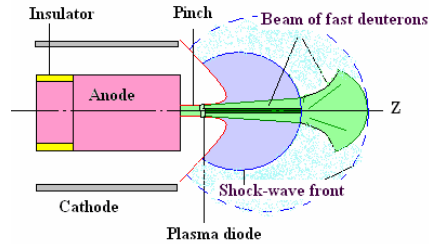


FIGURE 7 Scheme of streams on DPF

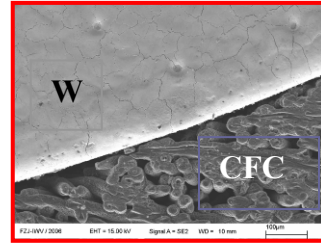


FIGURE 8 SEM photo of the irradiated sample

We have provided also comparative radiation tests of optical (Fig. 9) and ceramic (Fig. 10) materials.

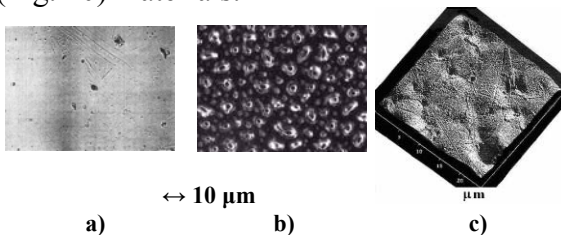


FIGURE 9 Quartz (a), topaz (b) (optical microscopy) sapphire (c, atomic force microscopy) irradiated in the same conditions

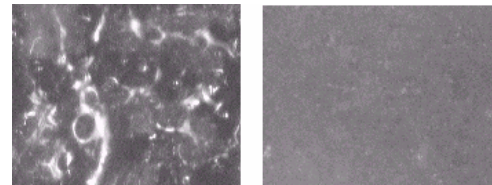


FIGURE 10 Specimens of Al_2O_3 and BN and irradiated in the same conditions (optical microscopy)

DPF can be used for improvement of the sample characteristics, in particular, in the hard-to-reach parts of a specimen (e.g. in the internal surface of a tube) as it is shown on Fig. 11 for the surface's micro-hardness.

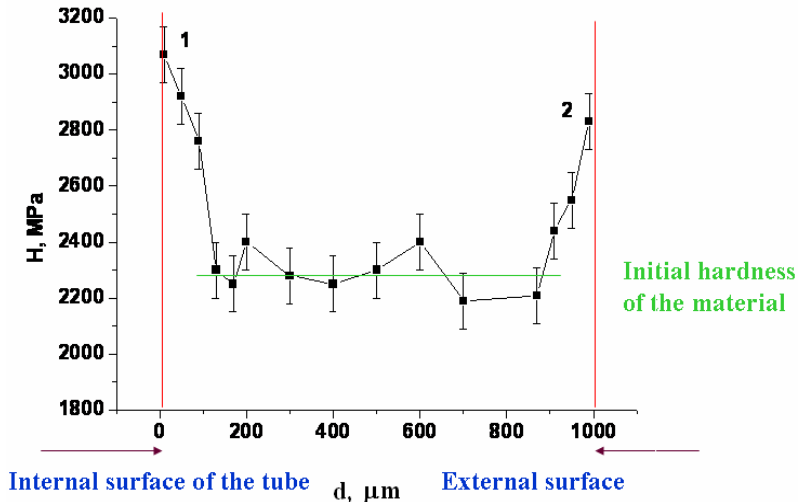


FIGURE 11 Micro-hardness distribution in a cross-section of a tube's wall

DPF devices may also produce various nano-structures on the surface depending on the specificity of the irradiation's regime (Fig. 12).

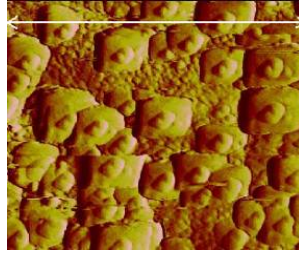


FIGURE 12 Nanostructures produced by DPF on the sample's surface (scale – 1 μm)

DYNAMIC QUALITY CONTROL

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

- Pulse duration of the X-Rays (a few ns)
- Size of the X-Ray source and its remoteness from an object (< 100 μm ; 10 cm...a few meters respectively)
- Diffraction (wavelength, distance)
- Contrast degree of an object's detail to be visualized (depending on spectrum of hard X-Rays).

Theoretically for a DPF it could be $\sim 1 \mu\text{m}$ at a 10-cm distance for a rotation speed of 6,000 rpm.

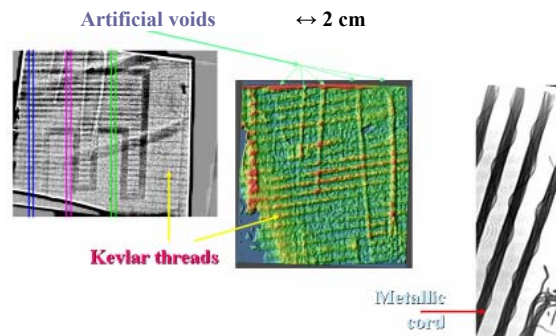
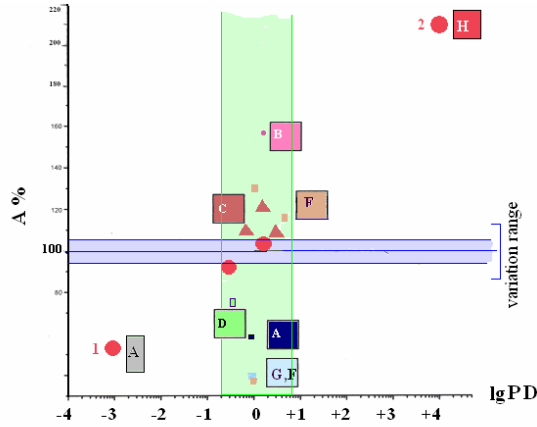


FIGURE 13 X-Ray picture of a tire after its procession

RADIATION BIOLOGY

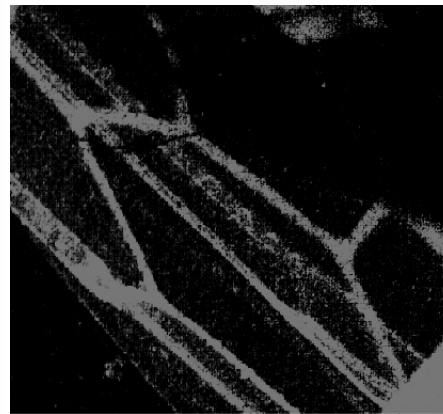
A) Radio-enzymology

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 to 5 orders (!) of magnitude) *difference in doses for the enzyme activation/inactivation* by their X-Rays irradiation between a DPF and an isotope source (Cs^{137}) [1]. But the effects appear at *power flux density* difference in these two mentioned irradiation experiments about 7-8 orders of magnitude larger for a DPF. We found that the *proper characteristic of the short-pulse radiation action* is a product “dose \times dose power”, namely: $D \times P$. It appears that for this parameter almost all points are collected in the range $10^{-1} \dots 10^{+1} \text{ Gy}^2/\text{s}$.



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: $8 \text{ keV} > E_{hv} > 2000 \text{ KeV}$; and
 “PF -0.2”, Al filter: $8 \text{ keV} > E_{hv} > 100 \text{ keV}$;
F, G – γ -source ^{137}Cs for different enzymes: $E_{hv, max} = 662 \text{ keV}$
H - “PF-6”, Cu filter; distance 3 cm: $PD \sim 10^4 \text{ Gy}^2 \text{ s}^{-1}$

FIGURE 14 Dependence of the enzyme activation or inactivation on the product of dose×dose power



10 μm proboscis

FIGURE 15 Soft X-Ray (~1-keV photons) picture of mosquito proboscis in its open state taken for live insect

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

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

B) 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 ($\sim \mu\text{m}$) of plasma produce soft X-Rays with photon energies tunable within the range $\sim 0.1 \dots 5.0$ keV depending on working media used in DPF. Two examples of these tests are shown in pictures (Fig. 15 and 16) where X-Ray films were visualized by an optical microscope *Swift Instruments International S.A.* with lenses 10/0.25, 25/0.4 or 40/0.65.



FIGURE 16 Mimosa’s leaf at the moment of its closing (pumping out of water)

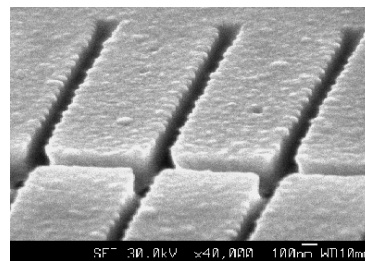


FIGURE 17 SEM image of a mask on the SU-8 photoresist

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 golden mask (SEM picture, Fig. 17). These experiments can be done in the so-called “*proximity X-Ray lithography*” scheme. 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 a classical X-Ray tube. Spatial 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 purpose of micro-radiography of live bio-objects in the sub-micrometer and nanometer ranges in the course of their vital functioning. It is produced by irradiation of them with soft X-Rays in the regime of their *inertial* confinement (i.e. at their evaporation by the irradiating X-Rays; however an image taken by ns-pulses will visualize their initial state before their blow off).

Evidently it can be also used in X-Ray proximity lithography and micro-machining.

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} ($T_{1/2} = 20.03$ min, 9.97 min, 2.03 min and 109 min respectively), because they can be introduced into biological molecules without altering the composition of these molecules. We used, for production N^{13} , deuterons generated by a DPF according to the reaction (“threshold ~ 600 keV): $\text{C}^{12}(\text{d},\text{n})\text{N}^{13}$. A spectrometric picture of the electron-positron pair annihilation produced in the subsequent annihilation reaction is shown in Fig. 18.

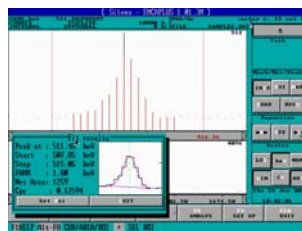


FIGURE 18 Spectrometric picture of the electron-positron pair annihilation produced in a reaction $\text{C}^{12}(\text{d},\text{n})\text{N}^{13}$ using deuterons from DPF

This result shows that a DPF of a 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 of N^{13}) an amount of the isotope N^{13} having total activity ~ 30 MBq.

B) X-Ray medical diagnostics

The spectrum of X-Rays generated by a DPF has the following specific features:

1) It is enriched by soft and medium-energy X-Ray components (0.1...5.0 and 5...50 keV), which results in the possibility of simultaneous visualization of soft tissues and hard elements (bones) of a body (same as in the above case of tires – rubber, metallic and synthetic cords).

2) Small size of the source (0.3 down to 3 μm), which gives high spatial resolution.

3) Very high power, which results in a *low-dose* formation of an image (effect of the overlapping of micro-volumes filled with photoelectrons within the film).

NANOSECOND NEUTRON INVESTIGATION SYSTEM (NINIS)

Two important issues encountered in the non-intrusive inspection of buried materials by neutron methods 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 proposed to bring into play a neutron source based on a DPF, which can make the practice as “a single-shot interrogation procedure”. Scheme of such an experiment based on elastic neutron scattering by different nuclei is presented in Fig. 19.

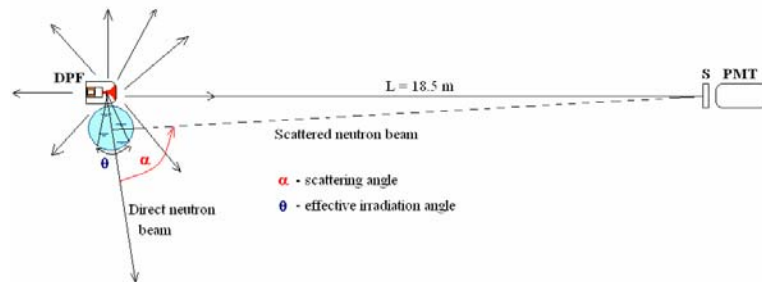


FIGURE 19 Scheme of a single-shot interrogation technique based on elastic scattering of neutrons generated in ns-pulses by DPF. Target – a 1-litre bottle of methanol.

We present some results on these tests. Calculations have shown that on the oscilloscope trace taken at 18.5 meters we have signals from the direct neutron beam, neutrons elastically scattered by the bottle with methanol (C^{12} and O^{16} nuclei), and by a high-pressure cylinder with deuterium (H^2) placed near the DPF chamber. The delay-times in relation to hard X-Ray pulse (HXRP) and direct neutron pulse (NP) are correlated with the angles between directions of straight-forward and scattered neutron beam propagation.

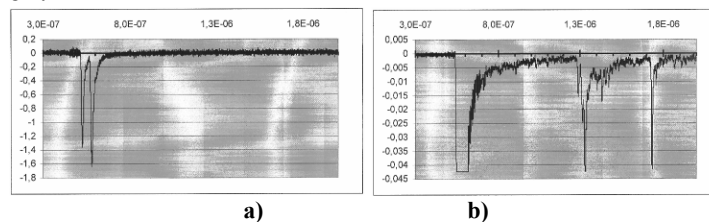


FIGURE 20 Oscilloscope traces of HXRP and NP taken with the bottle of methanol at two distances – at 1 m (a) and 18.5 m (b, c) from DPF chamber

Amplitude analysis of the registered pulses appeared to be in a very good agreement with cross-sections and kinematics of the neutron scattering.

POTENTIAL APPLICATIONS

A) Tritium inventory investigations

A DPF may use small (< 1 liter) *sealed* chambers supplied with the D-T-mixture generator, which can be a “built-in” device. 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. During these shots we may provide measurements of an influence of *Be* on neutron yield of DPF. Then we can investigate the results of *fast ion/plasma, fast electron/soft X-Rays* irradiation of samples, influence of neutrons upon *Be* sample, *tritium absorption, re-deposition of Be*, etc. in this very cheap and convenient configuration

B) Characterization of neutron fields around ITER or NIF

Using this *small source of 14-MeV neutrons* (A 1-m^3 device on wheels with the neutron-irradiating zone having a characteristic size $\sim 1\text{ cm}^3$), which irradiates a neutron pulse represented in space by a *spherical shell of $\sim 0.5\text{-m}$ thickness*, we can use a time-of-flight method to characterize a neutron field of ITER (or NIF) at each stage of its assembling. For this we have to move DPF along the ITER chamber circumference after each successive step:

- Foundation construction
- Magnet installation
- Assembling of the chamber
- Neutral-beam heating guns attaching, etc.

This monitoring will give information on main neutron scatterers in the facility, can predict final neutron field during the full-scale ITER experiment, and (what is very important) can show possible “hot-spots” where neutron flux will be the highest one.

C) Neutron tests of materials which are perspective for NIF and ITER

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 with a repetition 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. Indeed if in the DPF facility the pinch current would be about 6 MA its neutron yield would exceed 10^{13} of 2.5-MeV neutrons/pulse. It will give $>10^{15}$ 14-MeV neutrons at the operation of the DPF with the deuterium-tritium mixture as a working gas. Taking into consideration a possible geometry of the near-pinch anode part of the DPF of this energy level it is easy to estimate that 1 dpa can be succeeded during an operational year in a volume of about 1 liter with the irradiation area $\sim 0.1\text{ m}^2$. But for all that a DPF must work with a repetition rate 3-4 cps with the irradiating zone positioned 0.1 m apart from specimens.

These figures for a facility designed with the use of the above-mentioned new technology look feasible since at our recent PF-6 device [7] we reached current circa 750 kA only with 4 capacitors with the overall energy bank $E_c = 7$ kJ and neutron yield Y_n about 10^9 neutrons per pulse with deuterium as a working gas. According to our experience in scaling law for bank parameters we may expect the needed figures for the same type of DPF-based neutron test facility on the level of a few hundred kJ. For this aim its main elements should be changed 10 times during the year of the tests, which gives the cost of such a device on the level of about 10 millions US \$ only.

Thus DPF can fill a niche in this very important field.

D) Nuclear physics

A DPF is favorably differed 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 a DPF 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 characteristic time, during which the overall number of neutrons (i.e. the above-mentioned concentration of them) will be injected (created), diffuse and multiplied within the 1-cm zone of uranium, is namely of the order of 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:

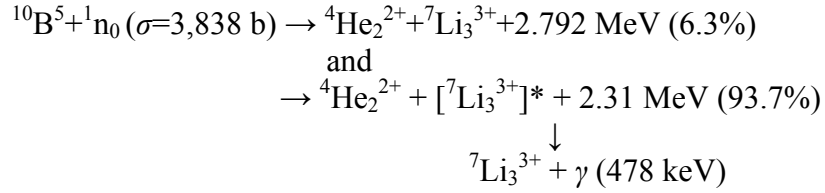
- A possibility to increase the rate of the initiation of chain reactions in a sub-critical assembly by a volumetric action.
- An opportunity to increase “burning out” of fission fragments inside the assembly *during the DPF neutron pulse*.

Important opportunities appear here also for the fusion-fission hybrid schemes [8].

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

Proposals to use neutrons for destruction of malignant tumors appeared immediately after the discovery of neutrons. Since those times (30’s of previous century) many clinics try to reach in this direction a success working with various methods.

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* or *epithermal* neutrons with Boron atoms ^{10}B introduced beforehand in a human tissue (such as widely used now BPA and DSH):



Mean-free-paths (MFP) of lithium nuclei and alpha-particles within human tissues are equal to 6 and 9 μm 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 a DPF has here the following original opportunities:

1) DPF devices of the medium size (5-10 kJ) can ensure the necessary dose in about 3 hours working with a moderator (to produce epithermal neutrons) if it will be operated with a rep rate of 100 cps with D_2 or with 1 cps with a D-T mixture. It is a satisfactory time interval for auto-transplantation treatment [9].

2) One can expect here a number of various synergetic effects if a DPF will be used either with *fast neutrons of ns-pulse duration* (due to a shock-like action of such pulses) or at the *combined application of fast neutrons and hard X-Rays*.

Possible reasons for these foreseen effects are:

- A *simultaneous rupture* of both spirals of DNA during the ns period of time by a high-density neutron flux.

- A *threshold-like behavior* of radiation damage of malignant cells inside a high-concentration neutron field.

Both these opportunities open ways to a low-dose therapy of cancer.

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 [10].

CONCLUSIONS

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

Thus it can simulate and help in investigations of many damage features existed in 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. It is important to mark that 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 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 applied in low-dose medical X-Ray diagnostics as well as in micro-radiography. It looks promising to use a DPF for irradiation malignant tumors in

BCNT by thermal neutrons as well as in a therapy by fast neutrons, in particular in combination with hard X-Ray photons generated by it in the same shots; it 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 beryllium re-deposition taking place under typical thermonuclear fusion conditions by a very cheap and efficient way.

DPF devices based on 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

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