PF-6 – an effective plasma focus as a source of ionizing radiation and plasma streams for application in material technology, biology and medicine

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Abstract A review of results on the design and operation of the new efficient Dense Plasma Focus device PF-6 of medium size (transportable) having bank energy of ca. 7 kJ and possessing a long lifetime is presented. New data on the interaction of the pulsed fast ion beams and dense plasma streams generated at this apparatus with various materials are given. These results are compared with the analogous information received at the biggest facility PF-1000. It is shown that it is possible to have about the same power flux density (in the range of 10^5–10^9 W/cm^2) in both devices however in different areas. Doses of soft X-rays produced by the device within the resists for the goals of microlithography and micromachining appear to be several times less that it is with the conventional X-ray tube. In biological application of this device, medium- and hard-energy X-rays are exploited in the field of radioenzymology. It was found that the necessary dose producing activation/inactivation of enzymes can be by several orders of magnitude lower if used at a high-power flux density in comparison with those received with isotope sources. In medicine, short-life isotope production for the goals of the positron emission tomography (medicine diagnostics) is possible by means of the fast ions generated within DPF. All these experiments are discussed in the framework of pulsed radiation physics and chemistry in its perfect sense thereto the criteria are formulated.

Key words Dense Plasma Focus • ion beam • plasma beam • X-ray beams • surface damage • microlithography • radioenzymology • positron emission tomography (PET)

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Introduction

New high-current pulsed technology [4, 5] makes it possible to create compact (portable and transportable) Dense Plasma Focus (DPF) devices [1] with reliable operation, a long lifetime (at the level of millions of shots) and the possibility of working in a high repetition mode [2, 3]. The main attribute of the DPF is a very high brightness of its hard radiations – fast electron and ion beams, plasma streams, X-rays and neutrons. The above-mentioned feature opens the possibilities for a number of important applications especially in the fields where pulsed action of hard radiation is important. The paper is devoted to the description of a new facility – the PF-6 machine – which is of industrial type device and recently put into operation at the Institute of Plasma Physics and Laser Microfusion, Warsaw. Several interesting applications tested with this and similar laboratory-type machines are presented.

Apparatus and diagnostics

The device under description – PF-6 – consists of 4 capacitors of KMK 30-7 type (30 kV, 7 μF, 10 nH,

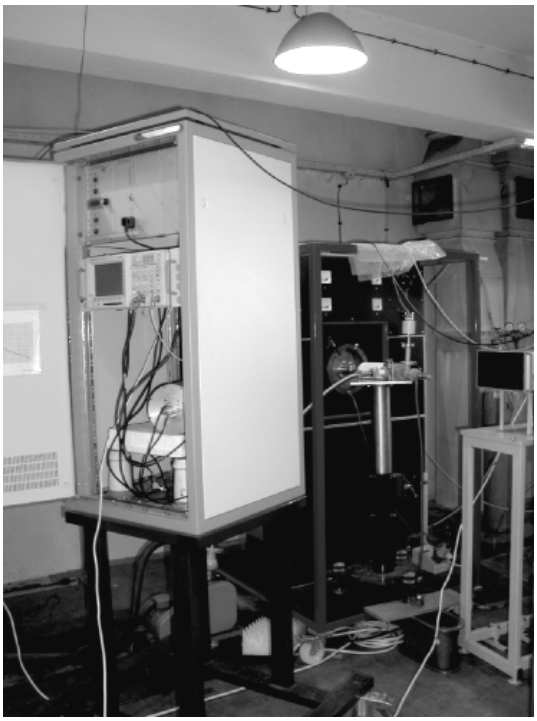

Fig. 1. Outward appearance of the PF-6 device.

350 kA each), 4 switches (pseudo-sparks TDI1-150k/25 – 200 kA, $>10^{11}$ A/s, jitter 4 ns), master spark forming 4 pulses of 60 ns duration with rise-time and slopes about 4 ns, connecting cables, current collector, DPF chambers, safe-guard systems, charger, pumps, working gas filling system, and a number of monitoring diagnostics. Total weight of the device itself is about 400 kg. The outward appearance of the device is presented in Fig. 1.

The most important element of the PF-6 device is its discharge chamber (Fig. 2) [2]. For each application depending on the kind of radiation to be used, these chambers have specific design. Thus, when the soft X-ray (SXR) emission is applied specific gases have to be used and a special outlet window must be done – preferably through on anode as it is shown in Fig. 2a [9]. For the ion beams/plasma streams (IB/PS) exploitation (in material science [8], or for short-live isotope production [13]) the anode has a specific design and an additional part for samples handling must be added to the chamber (see Figs. 2d and 2e). For hard X-ray (HXR) exploitation [7] depending on the spectra demanded, we must change foils covering the output windows (Fig. 2b). The neutron-optimized chambers are of simplest construction, but here its size depends on the current, which will flow through it (compare

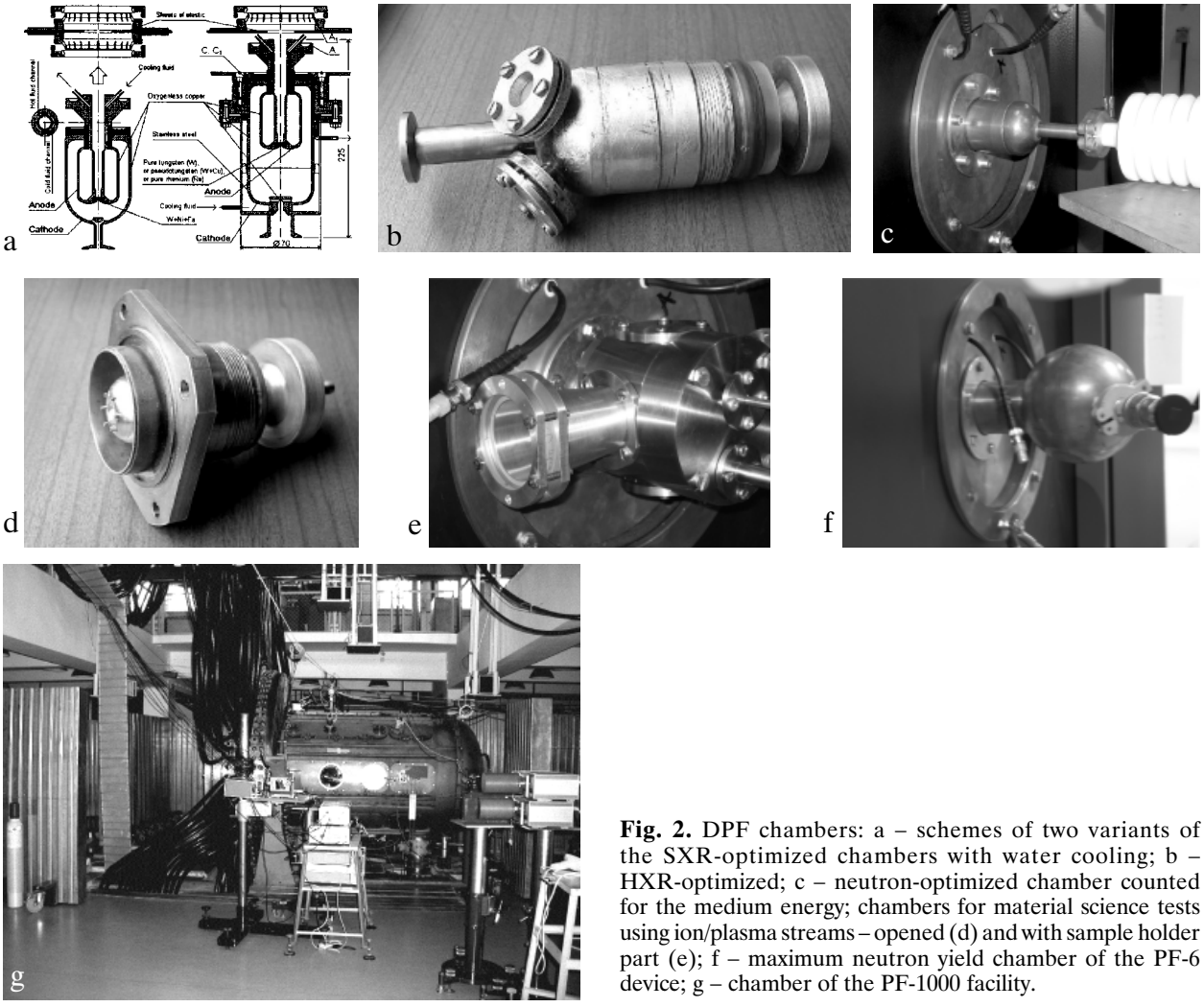

Fig. 2. DPF chambers: a – schemes of two variants of the SXR-optimized chambers with water cooling; b – HXR-optimized; c – neutron-optimized chamber counted for the medium energy; chambers for material science tests using ion/plasma streams – opened (d) and with sample holder part (e); f – maximum neutron yield chamber of the PF-6 device; g – chamber of the PF-1000 facility.

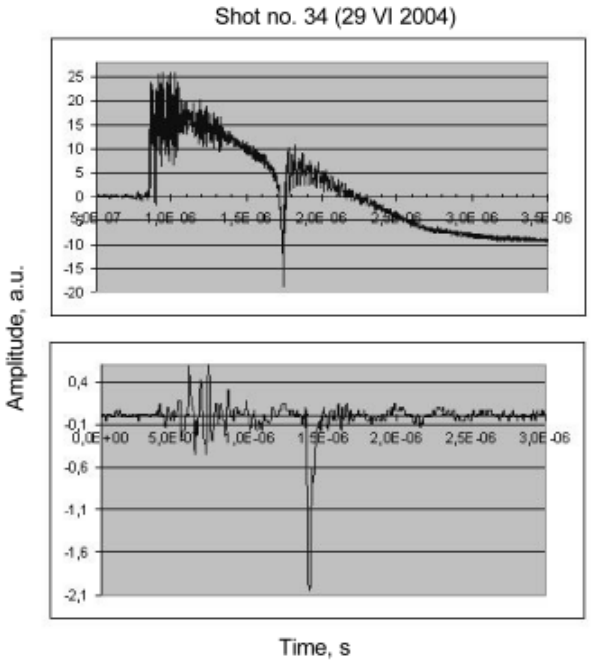

Fig. 3. Current derivative and hard X-ray + neutron signals at the PF-6 device.

Figs. 2c and 2f). Main feature of the chambers, however, is that they are made by a laser and e-beam welding technique, thus they do not contain any rubber o-rings and can be conditioned as the usual high-current industrial electronic device (chemical procedures, annealing, etc.) are. It can also be manufactured as sealed chambers with a special generator of working gas built-in. In this case, if a deuterium-tritium mixture is used the chamber may be counted as a closed radiation source. Side by side with this device we used for our applications a number of the laboratory-type devices – the biggest in the world working with deuterium PF-1000 facility (its chamber is shown in Fig. 2g), PF-150, and PF-60 [6].

The PF-6 device has been tested in various regimes within the energy range 2–7 kJ. Typical current derivative and HXR + neutron pulses are presented in Fig. 3. Calibration of our magnetic probe and the Rogowski coil has given us an absolute value of current. The highest magnitude for it (with the chamber of Fig. 2f) was equal to about 750 kA (voltage 23 kV).

To have data on parameters of the fast ion beams and plasma streams (velocity, angular distribution, power flux density, etc.), we used a number of diagnostics (track detectors, optical spectroscopy, etc.), but the most informative one was a frame optical camera. Examples of pictures taken with 1-ns time resolution in different moments of the discharge evolution is given in Fig. 4. One can see pinch formation and disruption, axial plasma jet and shock wave (SW) expansion, i-beam (IB) creation and transport, and interaction of these streams with a target resulted in the secondary plasma expansion from the target in the direction opposite to IB and jet.

Materials and analytic equipment

In radiation enzymology researches we used different enzymes, in particular an isolated and purified electrophoretically homogeneous angiotensin converting enzyme ACE (MW 180 kDa) from bovine lungs. We worked also with native horseradish peroxidase C (MW 44 kDa) purchased from Biozyme. In experiments on radiation material sciences we irradiated samples of an "Eurofer" alloy and a SiC composite material designed especially for use in the ITER tokamak, tungsten, an aluminum alloy, low-activated austenitic steel and some other materials. In microlithography experiments we applied a resist with chemical amplification SU-8.

Analysis of the irradiated sample was made as follows:

- in the case of radiation enzymology, the measurements of peroxidase activity was performed with a Shimadzu UV 120-02 spectrophotometer (Japan);
- activation of a carbon target irradiated by a beam of high energy ions, in the case of short-lived isotope production, was measured by a high-purity germanium detector (effectiveness 18%) connected with a multi-channel analyzer having a resolution of 2.04 keV;
- in material science experiment optical, electron and atomic force microscopes, elastic recoil deuteron analysis, X-ray microprobe technique as well as X-ray diffractometry were used;
- in X-ray nanolithography the irradiated resists were scanned by electron microscopy.

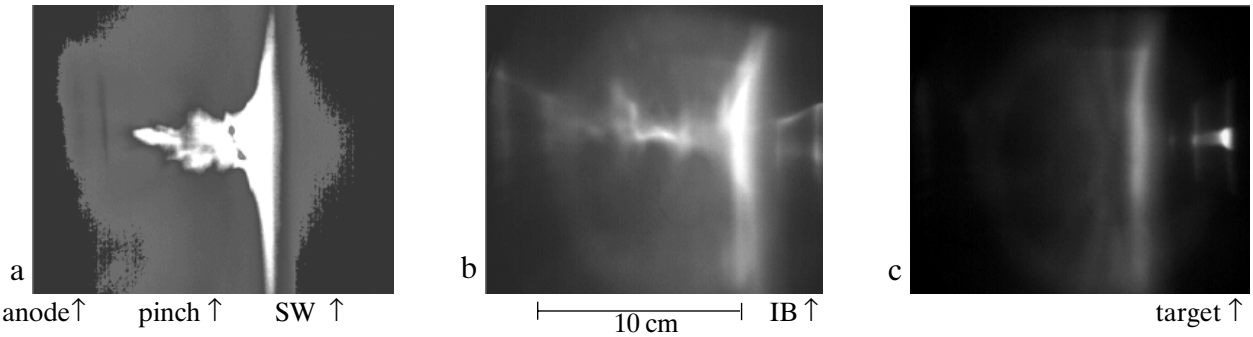

Fig. 4. Frame nanosecond self-luminosity photography of pinch plasma with the shock wave (SW) generated by the pinch (a), with the ion beam (IB) (b), and with the plasma produced at the irradiation of a target (c).

Applications

Results of radiation material science

Our first results (PF-60 device [6]) gave us the possibility to distinguish three regimes of sample irradiation, which produce different net results [8]:

(i) "implantation regime" of the streams interaction with a target ($q \approx 10^5$–10^7 W/cm^2, where q is the power flux density of the streams on the sample surface);
(ii) "detachment mode" of irradiation, i.e. with screening of the sample surface from plasma jet action by a secondary plasma cloud ($q \approx 10^7$–10^8 W/cm^2), and
(iii) "broken implantation" type of irradiation ($q \approx 10^8$–10^{10} W/cm^2).

Of importance here is that the above broken implantation takes place in spite of the fact of relatively low absolute fluence of the ion-beam irradiation. But the ion-beam pulse occupies the time interval short compared with the typical diffusion and thermal conductivity times.

New experiments were performed using both a small PF-6 device and a PF-1000 facility. Analysis made by optical microscopy has shown that in spite of the fact that the PF-6 device is much smaller than our main facility used in material tests – PF-1000 – the character of action here is quite similar to our previous experiments performed with the large device. Also strong macroscopic damage (in fact destruction of the back side of SiC sample produced by a shock wave penetrating it at the PF-6) gives rise to the same conclusion. It results from the fact that we can put our samples much closer to the plasma and beam generation zone in the PF-6 chamber. Of course the area of the intensive action here is much smaller compared with the PF-1000 device.

At the PF-1000 facility, we irradiated a tube made of low activated austenitic steel 25Cr12Mn20W and positioned along the chamber axis. The closest part of the tube was irradiated at the highest power flux density as it was in the (iii) above-mentioned regime. We investigated a relief of the surface both inside and outside of the tubes. Also we have traced the damage along the tubes according to the decrease of the power flux density of radiation. Micro-hardness of the surface layer was measured in all cases. An example of the relief of the surface seen by means of optical microscope with different magnifications is presented in Fig. 5. The tube-like geometry of our target and its positioning gave us the possibility to investigate results of plasma and ion beam action onto the target in dependence on the power flux density in a single shot. We saw the wave-like relief, many droplets, influxes and ridges. The farther from irradiation source the smaller is the typical size of the elements of the surface relief. The micro-hardness of the irradiated tubes was increased at the surface. This is important for the technology of hardening of surface layer in hard-to-reach parts of different components of machines.

Fast ions in positron emission tomography

PET consists of three elements: production of positron-emitting isotopes, synthesis of biological molecules

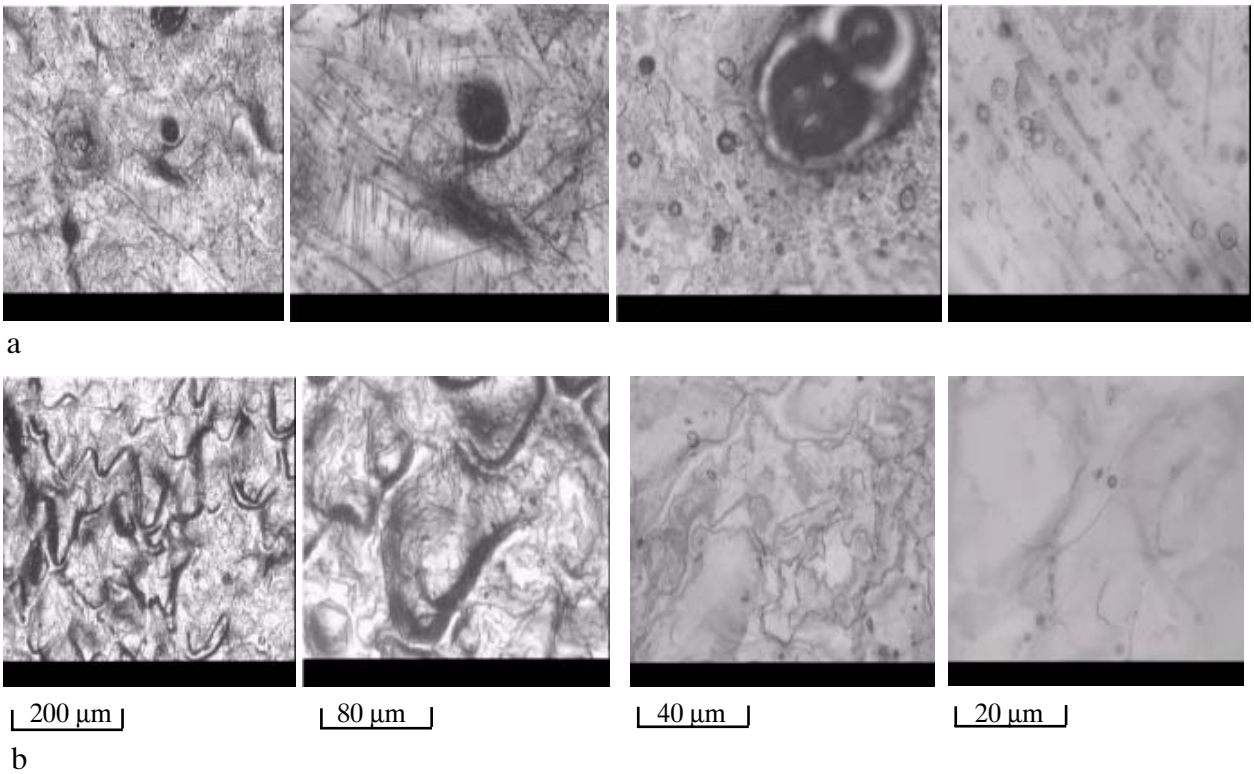

Fig. 5. Parts of the internal and external surfaces of the specimen #8 at the middle zone of the tube (optic microscopy with different magnification).

labeled with the above positron emitters, and scanning of the human body. DPF, in which ions are accelerated by collective effects, may prove attractive as an alternative to cyclotrons for the production of positron emitting isotopes, in particular, because of its potentially lower cost and lower level of system complexity. We made experiments on the production of the ^{13}N short-lived isotope (9.97 min) by fast ions generated by the DPF discharge [13] using the reaction

(1) $$^{12}C(d,n)^{13}N$$

The main objectives of our work were: (1) to determine the activity induced by fast deuterons impinging on the solid target; (2) to calculate the production throughput of the positron emitting isotope ^{13}N. Our results, received with the PF-150 operated at the 20-kJ energy level, are as follows.

The target was based on soot melted in polyurethane, which resulted in the flexibility and durability as well as recitation of the shock wave, which proceeded from the plasma focus. The "threshold" for this reaction lies in the relatively low energy range (~600 keV). The target was placed 30 cm from the face of the inner electrode. Activation of targets was measured with the high purity germanium detector having an efficiency of 18% and a 16-thousand channel analyzer (MCA) with a 2.04-keV resolution (determined for 1332 keV). Energy and effectiveness of calibration were based on a special calibration source. A natural radiation background was subtracted.

Figure 6 shows a typical spectrum obtained from MCA, the peak of energy 511 keV being emphasized. The following equation was used for the activity evaluation:

(2) $$A = \frac{N}{t \cdot \varepsilon \cdot \gamma \cdot f \cdot f'} + \frac{\sigma}{t \cdot \varepsilon \cdot \gamma \cdot f \cdot f'}$$

where: A – activity; N – number of registrations under the pick; t – measurement time; ε – effectiveness of registration; γ – effectiveness of delay; f – correction factor represented the difference between sample activation and its measurement; f' – correction factors represented the disintegration of a sample during measurement; σ – counting error. The exemplary result of the measurements for a shot having a good neutron yield is shown in Table 1. The number of ions ejected from DPF and evaluated from Eq. (2): $N_{od} = 1.01 \times 10^{13}$. This result has shown that the DPF of the above level of energy, working with a frequency of 10 Hz, can produce within 100 s (1/6 of the isotope half-lifetime) an amount of the isotope ^{13}N having activity ca. 30 MBq. Note that for the tomographic diagnostics of the human

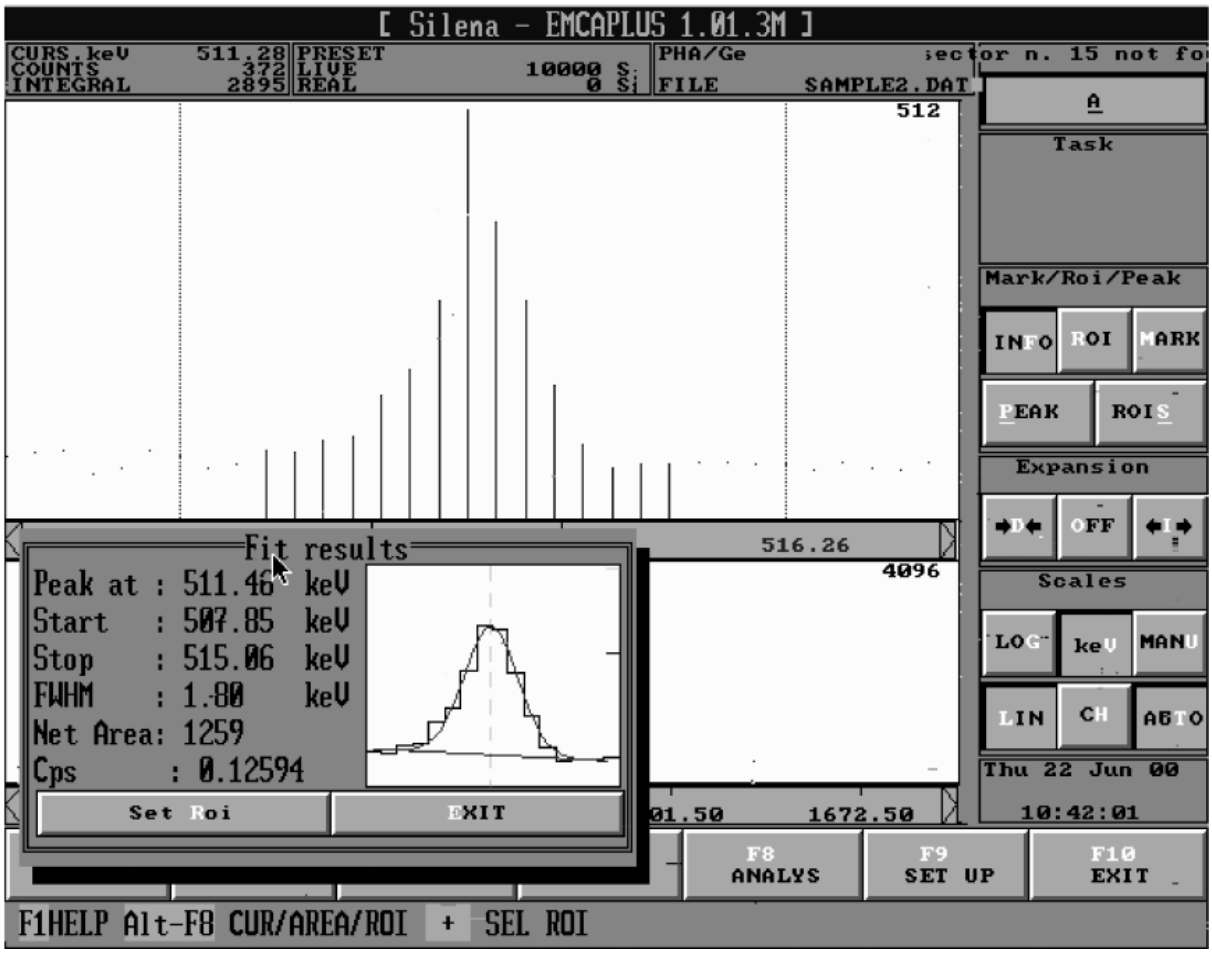

Fig. 6. Spectrum of gamma photons emitted from activated carbon target; photo pick with energy 511 keV has been expanded and analyzed in the left down corner.

Table 1. Results of carbon target activation with ion beams obtained from the plasma focus

Nuclear reaction	Induced activity, Bq	Measurement error σ, %
$^{12}C(d,n)^{13}N$	28.0×10^3	3

head with the help of this method the necessary quantity of the isotope determined by its activity is 10 MBq.

Soft X-rays in the X-ray proximity lithography

Being a source of soft X-rays (SXR) of high efficiency (ca. 10%) and having a very small size of its radiation zone (200 μm down to 2–3 μm) the DPF may be successfully used in X-ray microlithography [9] (working gas – Ne, irradiated wavelength $\lambda \sim 10$ Å). We have demonstrated that this source can produce the necessary exposure of the resist with chemical amplification SU-8 for several hundred shots (~500) at its operation with a repetition rate of 3.5 Hz. Our quantitative analysis and parallel experiment made with the conventional X-ray tube have shown that the dose received was several times less than those, which is necessary at the usage of the X-ray tube. An example of the nanostructure manufactured is presented in Fig. 7.

Medium and hard X-rays in radiation enzymology

In these experiments, different enzymes were irradiated *in vitro* with various doses, dose power, number of shots, and by various spectral ranges of the radiation. In this new set of experiments, we have received results supporting a tremendous difference in enzyme activation/inactivation after its irradiation by X-rays from the DPF and from a conventional isotope source (γ-source ^{137}Cs) [7]. It appears that working with DPF we have about the same phenomena as in the case of the isotope but at doses 4 orders(!) of magnitude less. However, the power flux density difference in these two

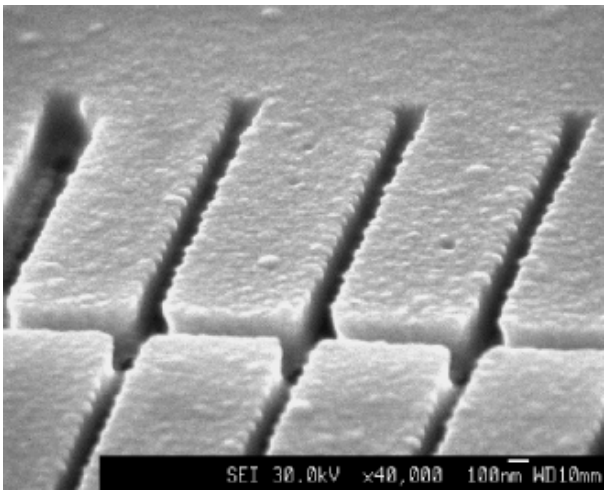

Fig. 7. Nanostructure received with the photoresist SU-8 for 500 DPF shots.

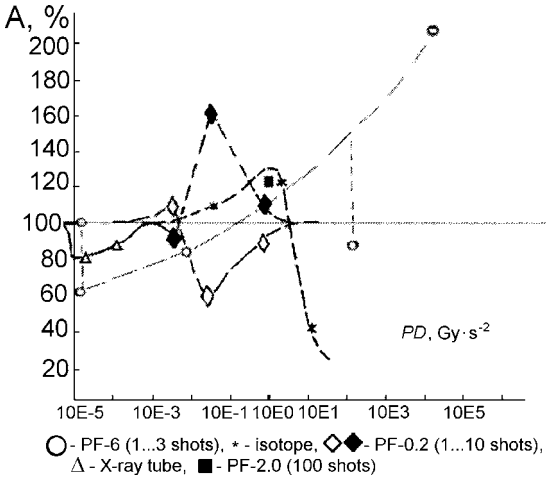

Fig. 8. Enzymes activity rating vs. a product of dose and dose power (⋆ – isotope sources, △ – classical X-ray tube, ○ – PF-6, ◆◇■ – all another DPF devices).

irradiation experiments was about 7–8 orders of magnitude in favor of DPF. The results on enzymes activity vs. the product of dose and dose power are presented in Fig. 8.

Discussion

In all these cases we have high radiation power of SXR, HXR, ion and plasma streams. On the contrary, the classical "pulsed radiation physics and chemistry" [10–12] usually deals with relatively "weak" beams of radiation (low power flux density), and it operates only by terms of "doses" (D). In those cases, it is important only the absolute number of ionizing particles or photons, which interacts with the object independently of each other.

At the same time, during the last 4 decades physics of high energy density (and corresponding chemistry) was born. But it develops mainly as a laser-matter interaction, where photons of near-visible energy range were exploited. In this case all effects usually have a two-dimensional (surface) character. This is because photons of classical powerful lasers (Nd-glass, CO_2, etc.) are absorbed by a solid target surface in a depth much lower than a micrometer. Speaking in terms of radiation chemistry, they have a very high linear energy transfer (LET) factor. However, this field starts to spread recently into beams of particles and photons of higher energy range, i.e. into penetrating radiation. In this case, the interaction acquires volumetric properties. We shall concentrate our attention, namely, on the latter case discussing the above described physical and chemical phenomena.

New generation of powerful sources of ionizing radiation, and the DPF between them [1], can generate pulses of energetic photons and particles not only having short duration (in the nanosecond range or shorter), but providing a very high energy injection. Sources of the penetrating radiation of this type create a very high energy density within a volume. This feature distinguishes them from lasers, which act mainly on the surface. With

this fact a new quality is created, which ensures an action of the pulses upon the corresponding physical and chemical processes during the time interval short compared with the duration of the processes themselves. Moreover, the power of these modern sources appeared to be so high that they can create a very high concentration of individual micro-volumes of interaction or secondary particle activity within the irradiated substance. Namely, these micro-volumes (e.g. spurs and blobs at water radiolysis), being of the characteristic size of the mean free path of primary or secondary particles (e.g. solvated electrons), may overlap each other (see Fig. 9a). And, as it was already mentioned above, this overlapping is produced for the time interval short compared with the duration of the process induced. It is clear that in this case the interaction will have a nonstationary and non-equilibrium character. We shall count the processes, taking place in these conditions, as the pulsed radiation physics (chemistry, biology…) processes in its perfect sense.

Thus, analyzing all the above processes from this point of view we may see that in the (iii) regime of material irradiation we have multi-fold overlapping of ion interaction volumes, that takes time interval short compared with thermal conduction and diffusion processes as it is shown in Fig. 9a. That is why we have so strong damages of our samples in spite of the relatively low absolute number of particles per square cm. Similarly, in the case of microlithography almost total overlapping of micro-volumes filled with photo-electrons inside the upper layer of the photoresist (as it is in Fig. 9b) takes place for the time interval short compared with the chemical processes and diffusion. This results in a decrease of the necessary dose for the resist exposure in several times as it was proved by its irradiation from a conventional X-ray tube.

Taking into consideration the volumetric action of high-power penetrating radiation, we may expect that because of practically instant enveloping of the whole volume, these hard radiations may produce cumulative volumetric effects of the type presented in Fig. 9c. Viz. at an "instant" irradiation of a volume of an explosive gas mixture (e.g. $H_2 + O_2$) a large number of fast cumulative streams will be produced here because of 3-D collisions of shock waves. It may enlarge mixing and matter supply, which can results in a strong increase of this volumetric explosion.

In this connection, the important question arises – whether these nanosecond flashes of X-ray radiation can be used for the low-dose X-ray diagnostics of patients or just contrarily for the low-dose X-ray therapy of patients? Doubts in the positive reply to the issue are connected with the fact that decreasing the dose by several times with the DPF use results in the dose power increase by several orders of magnitude, and nobody knows possible consequences of such a step. Experiments with various bio-materials must be done to resolve this problem.

One of them is our work in pulsed radio-enzymology. Analysis has shown that in these experiments our ionization zones (mainly blobs) are overlapped. This means that the density of radiolysis water products is highly increased during the period of X-ray pulse (Fig. 9d). Furthermore, this overlapping takes place during the time interval (few nanoseconds), of the order of time intervals (10^{-12}–10^{-8} s) of the creation of water radiolysis products. However, it is much less than the end of reactions with radicals (10^{-6} s). Therefore, all the products instantly start to diffuse and interact with enzyme molecules (not with each other, as an enzyme molecule is very large). At the same time, the X-ray radiation excites the metallic atoms present

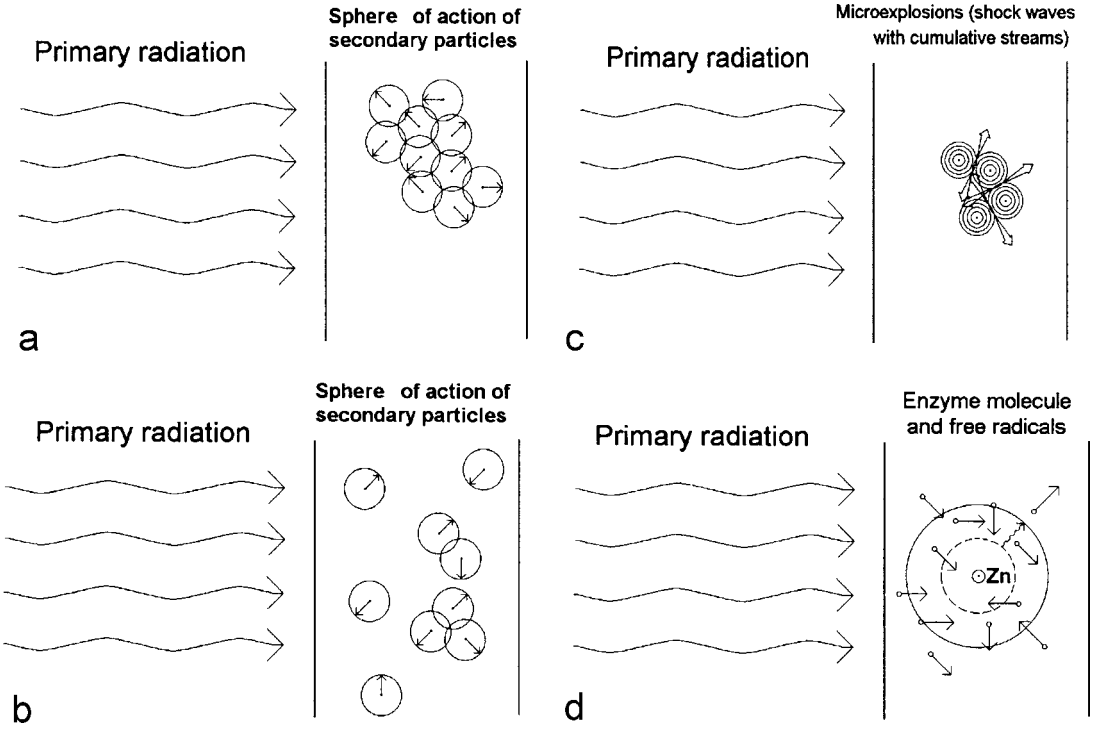

Fig. 9. Schemes of pulsed – in the perfect sense of the word – action of penetrating radiation upon matter.

in the enzymes [7]. This synergetic action of the two mechanisms may be responsible for the effect.

It is important to note here several points of general nature connecting with all the above-mentioned experiments. Microdosimetry in these experiments is a problematic point. It seems to be not important in the microlithography, it is of evident significance especially in radioenzymology. It is clear that additional more refined experiments (spectroscopy of high spectral resolution, picosecond laser probing, X-ray back-lighting, etc.) produced with sub-ns and sub-μm temporal and spatial resolution can help in deeper understanding of the phenomena found.

Another important issue to be investigated in the future is effective "temperature" and its distribution and evolution. Non-steady-state (in fact extremely transient) character of the processes under investigation presumes that in some cases (for sure during time intervals, typical for the fine temporal structure of the DPF X-ray pulses – 10^{-13}–10^{-11} s) temperature of plasma inside micro-volumes (Maxwellian distribution functions of particles participating in processes) has no time to be established. And this is on the condition that just on the contrary, these time intervals are perfect for "inertial" confinement of matter or at least of concentration of the active particles.

Conclusion

The DPF devices based on the modern high-power pulsed technology can operate reliably with record power flux density of penetrating radiation. Their application in pulsed radiation physics and chemistry gives promising results (in particular, it reduces necessary doses), which have to be verified in more detailed experiments exploiting better spatial and temporal resolution.

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