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Physics of High Energy Density with Use of Penetrating Radiation: Examples Based on Dense Plasma Focus Experiments

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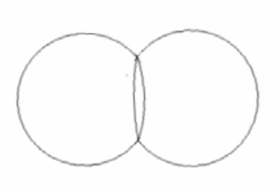
1. Introduction

Physics of high energy density (PHED) was developed during last four decades mainly in the context of interaction of high-power laser radiation with matter (see e.g. [1]). However absorption of this radiation in solid targets takes place at depths, which are much less than the working wavelength of the lasers due to a high-frequency skin-effect (by another words in terms of radiation chemistry – with a very high factor of its Linear Energy Transfer – LET). And because of the fact that these wavelengths of the lasers belong to a visible range a vast majority of effects of this PHED's branch bears a *surface* (two-dimensional – 2-D) character.

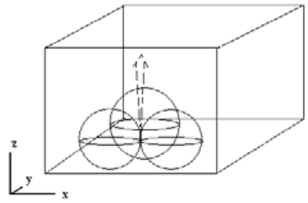
On the other hand new facilities based on the pulsed high-current discharges and generating very powerful pulses of penetrating radiation give a possibility to spread this branch of science onto volumetric (3-D) effects. Between the devices, generating high-power electron and ion beams, soft and hard X-Rays, and neutrons as well the most powerful are those based on a high-current discharge through gas or multi-array liners. Dense Plasma Focus (DPF) is one of the opportunities in this field. The report presents last results received with two types of devices – PF-1000 facility (of 1 MJ energy range), which is the biggest in the world DPF working with deuterium for the neutron production, and with the new very efficient type of the DPF machines having energy circa 10 kJ – PF-6 and PF-10 devices, which may have a high repetition rate and in that way designed for different applications.

2. Prerequisites of pulsed radiation physics

To exploit this new field by the most effective way it is necessary to fulfil during the process of interaction of penetrating radiation with matter *two conditions concurrently*, namely: the effective micro-volumes of the activity of primary or secondary particles (e.g. spurs at water radiolysis) must *overlap* – at least partially – each other, and this event have to take place during a *time interval short compared* with a process to be pursued. For this condition a source of radiation must be very powerful and its pulse duration has to be in the range of nanoseconds. In this case we shall ensure a situation of *pulsed radiation physics (PRP) (or chemistry - PRC) in its perfect sense*. At a usage of the nanosecond very powerful pulses of penetrating radiation all events will attain volumetric, non-diffusive, non-stationary, and non-equilibrium character resulted in a number of collective (synergetic) effects. It can be seen from the following example. Imagine that we shall produce two *adjacent* shock waves (SW) *simultaneously* (Fig. 1a). In this case in a region of there intersection parameters of gas (plasma) will be much higher than in each of them although velocity will be decreased.



a)



b)

Fig. 1 Collision of two and three shock waves

However a mutual collision of three waves (Fig. 1b) – a strongly pronounced 3-D effect – can produce additionally a cumulative stream having velocity 3-4 times higher [2]. If it will be done within an explosive blend (e.g. in $H_2 + O_2$) before the moment of transformation of the SWs into detonation ones this *volumetric* explosion compared with a point initiation will be enhanced due to an increase of gas parameters and faster mixing of chemical agents.

3. Apparatus

Main parameters of our devices are as follows – *PF-10*: 48 μF; 450 kA; 9,6 kJ; *PF-6*: 28 μF; 760 kA; 7,4 kJ; *PF-1000*: 1320 μF; 3 MA; 810 kJ [3, 4]. All of them have Mather type electrodes. However small devices are equipped with specialized chambers each optimized for a certain type of radiation (neutrons, X-Rays…). Our experiments with these machines are devoted both to fundamental problems of Dense Magnetized Plasmas and applications in different fields of science and technology. We present here a few examples of the researches.

4. Generation of neutrons and hard X-Rays in PF-1000

In Fig. 2 hard X-Ray (HXR) signals gave us information about fast (~100 keV) powerful electron streams generated in the PF. Being registered along Z-axis (*a,* 0°) and perpendicular to it (*c,* 90°) they are moved forward by their time-of-flight (TOF) of the 7-m distance (23.3 ns). Neutron pulses seen in the picture provide data on powerful streams of fast (also ~100 keV) ions.

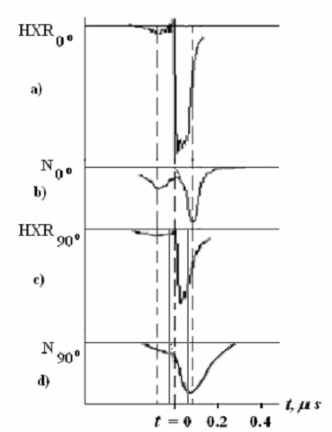


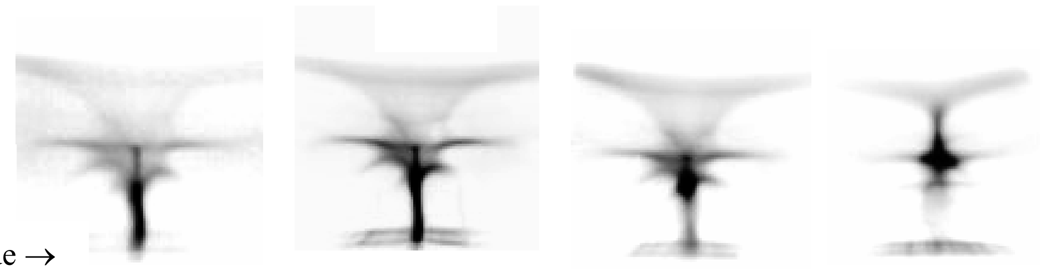
Fig. 2 Hard X-Ray pulses (*a* and *c*) versus neutron pulses (*b* and *d*) taken at 0° and 90° to Z-axis after moving them forward according to their real (HXR) and assumed (N) time-of-flight

At these traces we've done the same procedure for both neutron (N) emission pulses for their TOF (*b,* 0° and *d,* 90°) provided that *these neutron pulses consist of exactly 2.5-MeV neutrons* (232 ns). It is clearly seen that the *first pulses* of both HXR and N emissions are almost *coincided in both cases* (0° and 90°) after their correction by TOF. It means that in the PF-1000 device runaway electrons are accelerated during or slightly earlier in comparison with a so-called first compression phase as in other devices [2], and neutron emission produced during this period of time (i.e. in the first pulse) has an energy spectrum centered at 2.5 MeV.

Contrary to it second N pulses in the two directions start and have their peaks during a decay time (droop) of the HXR pulses. Moreover the second pulse maximum *in the head-on case* comes earlier than those one in the *side-on case* and it "runs over" the HXR pulse. It means (and we might expect it from our anisotropy measurement and literature) that the spectrum of neutrons irradiated at 0° has higher energy than the neutrons propagating at 90°. The start moment of the second pulse of the hard X-Rays (t = 0) being very sharp precisely coincides with the appearance of the disruption at plasma column (Fig. 3).

↔

anode →



1 – t_1 = + 5 ns **2** – t_2 = + 15 ns **3** – t_3 = + 35 ns **4** – t_4 = + 87 ns

Fig. 3 Experimental images of the current cutoff phenomenon (marked by a sign ↔) taken by the optical image camera with 1-ns time resolution

Analysis has shown [5], that the results of these experiments are in favor of neutron emission model based on ion beam-plasma interaction with *three important features*: 1) *plasma target* is *hot* and confined during *a few "inertial confinement times"*; 2) *ions* of the main part of the beam are *magnetized* and *entrapped* about the pinch-plasma target for a longer period than the *characteristic time of the plasma inductive storage system*; and 3) *ion-ion collisions* – fusion and Coulomb ones – are *both* responsible for neutron emission.

5. Applications of DPF in radiation material science, dynamic quality control, X-Ray microlithography, radiation enzymology, and interrogation of illicit materials

In radiation material sciences when irradiating some materials (candidate ones for a fusion reactor) by deuterium plasma streams ($v \cong 3 \cdot 10^7$ cm/s) and the above fast ion beams ($v > 3 \cdot 10^8$ cm/s) we have found several unexpected effects. The two examples from them are a violation of detachment effect when power flux density of the streams is ca. 10^9 W/cm^2, and a deuteron implantation profile peaked *inside the bulk* of the specimens at irradiation of them by the above nanosecond pulses. Interpretation of both effects are based on the fact that the time interval of injection of ions in these experiments having a very high LET were short compared with periods of cooling of secondary plasma and diffusion of the ions within the samples [6].

In works made within the frames of semiconductor industry (soft X-Ray proximity lithography) and dynamic quality control (hard X-Ray radiography of rotating tyres) we have found that an irradiation dose necessary to expose films and photo-resists is several times less than with a conventional X-Ray tube [7]. An explanation was found on the base of a *collective* action of secondary photoelectrons generated by soft X-Rays (SXR) in these photo-materials. Because of compression of the SXR radiation in time (~1 ns) and space (~1 μm) this pulse produces overlapping of micro-spheres filled with the electrons as it was mentioned above.

The soundest phenomenon of this type has been investigated in a sphere of radiation enzymology [8]. We found here in PRC an appearance of inactivation or super-activation of enzymes *in vitro* at doses of X-Rays ($h\nu \sim$ 8 keV) 4 orders of magnitude lower than at the irradiation by isotopes. We interpret these results on a base of a synergetic action of excitation of metallic ions existed in enzymes and very high concentration of free radicals surrounding the enzyme's molecule. This effect can be ensured only by a very high intensity of the source thus we have to take into account at these radiation effects not only doses but also dose power.

Last example refers to an elaboration of a method of a nanosecond *single-shot* detection of illicit materials based on elastic and inelastic scattering of neutrons [9]. Due to a very high brightness of neutron pulses generated by DPF and their nanosecond duration (PRP) we acquire the following new operating characteristics: very high signal-to-noise ratio, possibility to use time-of-flight method with short (a few meters) base, spatial resolution of tens cm, and eventually a very fast interrogation time, determined only just by a registration system.

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