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FEATURE PAPER

On possible formulation of problems of a Dense Plasma Focus used in material sciences

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Abstract The paper describes various possibilities at can be given by the use of dense plasma focus (DPF) device in material sciences. Main distinguishing features of such a device – availability of several different types of hard radiation and its high power flux density – determine the niche of applications of this type devices in the field. Some directions of materials investigation and treatment, which can be developed at present time, are discussed.

Key words cumulative plasma streams • dense plasma focus • electron beam • ion beam • material sciences • neutrons • X-rays

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Introduction

A dense plasma focus (DPF) device is one of the most efficient pulsed power compressors used in plasma physics research and applications at present time. It has several successive stages of the power amplification during its operation [1]:

- storing energy from the mains within a capacitor bank during a charging phase (typically seconds or minutes),
- the conversion of this energy into hot plasma ($\leq$1 keV), into kinetic energy of current/plasma sheath and cumulative stream, having a speed of $\leq 10^8$ cm/s, and into a magnetic field ("plasma inductive storage system") during the run-down phase after electrical circuit switching (current rise-time $\sim 10^{-7}$–10^{-5} s),
- the transformation of the above magnetic energy into pulses of more or less directed streams and beams of plasma, fast ions, relativistic electrons, and neutrons, as well as soft and hard X-rays after the current disruption (pulse width $\sim 10^{-9}$–10^{-7} s). Typical energy spectra of the fast particles and photons extend up to several MeV.

From the very beginning it should be stressed that some tasks of material sciences cannot be resolved with the help of the present day DPF devices. Between them there are a long time duration interaction of particle and photon streams with a target (pulses longer that 10^{-6} s), the accumulation of a high neutron dose within samples (with fluxes of more than 10^{17} neutrons/cm^2), large surface irradiation (of several m^2), etc. Isotopes, fission reactors, as well as various types of accelerators and other cumbersome and ecologically dangerous sources of the ionising radiation should be used for such aims.

At the same time the DPF device has two main features distinguishing it from other devices. And namely – availability of a combination of several different types of hard radiation (hot plasma, a high speed plasma cumulative stream, fast electron and ion beams, soft and hard X-ray flashes, neutron pulses) and their high power and brightness – determine the class of problems that can be resolved with its help [5].

Special attention should be paid to the fact each device, generating so many types of the hard radiation, is ecologically clean in comparison with the above mentioned sources. Indeed, a DPF installation uses for its charging a relatively low voltage (of the order of 10 kV) in its power supply system (in a comparison with classical accelerators), whereas high-energy (MeV) particles are generated inside the device because of collective phenomena taking place within the plasma. Such a device becomes a source of the hard radiation only for a short period of time not exceeding 1 μs, and only after charging of its capacitor bank. Thus it does not demand a special container for its keeping (as it is in the case of radioactive isotopes), and it cannot be stolen or dangerously lost. Finally, at any case its activity cannot be higher than a certain limit (as it can be in the case of a fission reactor).

In a view of the above-mentioned specific features of a DPF, it should be pointed out that this device has a particular advantage for problems of material sciences of a specific type. Between them there are issues of such a type where a powerful action (direct or indirect, e.g. by means of shock waves) or a combined irradiation of the target by beams of different nature, are demanded.

Outward problems

Usually researchers (and in particular theoreticians) working with a dense plasma focus pay main attention to parameters of the hot plasma and fast particles generated at the final stage of the current sheath (CS) run-down phase, near the DPF chamber axis. In spite of the fact that namely these characteristics determine future irradiation parameters of beams acting on a specimen of the constructing material, which is positioned inside the chamber, there is a demand for accurate investigations and a consistent description of the processes taking place outside the pinch. Let us list and comment some of them, the most important ones from the point of view of the material sciences problems.

Cumulative stream

As it is well known, a conical flow (which takes place in a DPF chamber near the anode at the final stage of the CS run-down phase) can produce an axial stream because of a cumulative process [10]. This process is a specific mechanism of the power densification, when kinetic energy (initially stored in the whole plasma content of the collapsing CS) transfers to the axial stream, which contains only a small part of the total number of particles coming to the axis. Thus a velocity of the axial stream can be much higher than that of the collapsing CS. In [9] it is shown that in a non-stationary process of such a type, taking place in ideal gas, the velocity of the cumulative stream can be 4 times higher than that of the CS (about 2.0×10^7 cm/s). The hot plasma of the DPF with a deuterium as a working gas by its behaviour is very close to the ideal gas model. But the formation of this stream can be possible only in cases when an angle of the collapsing conical flow exceeds 30°.

High-speed multi-frame laser interferometry [6] has shown that indeed the velocity of the stream is close to 10^8 cm/s, and its energy content is about 10% of the whole initially stored energy. Because of this figure and of the fact that deuterons with the above velocities have energy of the order of 10 keV, this stream becomes a useful tool for the material science (implantation, destruction, etc.). Future researches in this field should concentrate on the detailed investigation of the parameters of the stream, conditions of its formation and consistent theoretical description of its dynamics. Additional problem of the cumulative stream is an investigation of a shock wave generated in the residual gas above the pinch, as well as its reverse influence on the stream characteristics.

Relativistic electron beam (REB)

Detailed investigations of it with high temporal and spectral resolution [2] as well as with the accurate absolute measurements have given a possibility to describe its dynamics. At the same time it was shown [4] that efficiency of its generation can reach 20%, and during the interaction with the anode surface this REB can form a strong shock wave (SW) inside the anode plate. Both REB itself and formed by it SW can produce strong modification of the materials positioned at an anode [7]. Again as in the above case there are no good experiments as well as the consistent description of the REB extraction from the pinch and its transportation to the samples, in particular in different anode configurations (flat, conical hole, cylindrical cavern, etc.). Modification of the materials characteristics as well as destruction tests (e.g. modelling of the emergency regimes of tokamak devices – run-away electrons, saw-tooth and disruptive instabilities, SW modification of materials, etc.) are the main goals of the REB use in material sciences.

Ion beams

In contrast to many other experiments with a DPF its ion beams are investigated namely outside the pinch. Yet here we have also several serious problems. At first, because of the facts that within the DPF chamber near the pinch we have a non-zero pressure of a working gas and a very high magnetic field, all measurements can be reliable only for ions that have an energy exceeding a certain limit (about 100 keV). Furthermore, if during these experiments a special slit ("skimmer") is used, then the question arises – what is a degree of a representation of the initial ion spectrum in a space after this slit. Possibility of the total current transportation by ion beam at a certain stage of the DPF dynamics during a short period of time is still an intriguing problem of the device.

But not only questions of the ion energy distribution and the total number of particles in these beams are very important for tasks of material sciences. An angular distribution of the ion beams leaving the pinched plasma and its dependence on the DPF parameters, are in the centre of attention. Solution of these problems will help in main goals of a DPF use in the ion implantation technique, generation of short living isotopes (e.g. for Positron Emission Tomography (PET) diagnostics of patients), etc.

X-rays

For discussions of various possible applications, the X-ray spectrum generated in a DPF can be subdivided into 3 ranges: near 1 keV (hot plasma thermal luminescence), 10–100 keV, and above 100 keV. The last one arises as a result of the REB slowing down at the anode material whereas the second one is a combination of both processes.

The first type of the radiation (soft X-rays) is mainly used at present time in a nano-lithography and micro-machinery. The second and third – in military electronics testing. But it should be taken into consideration that X-ray flashes of high intensities appear in any material science experiments (ion implantation, destruction, etc.), and their action superimposes on, or precedes the main radiation treatment (e.g. ion implantation) process. Relatively new branches of the use of short X-rays pulses in material sciences are dynamic defectoscopy of mechanisms during their operation as well as medico-biological applications, such as X-ray microscopy, activation of enzyme [3], etc. In all these applications it is of great importance to know an angular distribution of the radiation, size of the source, pulse duration and its absolute yield. Experimentally the main problem is an interpretation of the results received with an X-ray flash of very short duration and very high brightness, as well as the calibration of measuring instruments under these conditions.

It should be mentioned here that the efficiency of each of the above types of radiation can be of the order of 10, 0.1 and 0.01%, respectively. Considering also a very small size of the sources ($\sim$1–100 μm) and the possibility to generate a relatively narrow spectral band of this luminescence at the outlet of a DPF device, it is evident that such a source can be used in many applications demanding an X-ray laser.

Neutrons

Depending on the working gas a DPF device can generate neutrons of the relatively narrow spectral bandwidth ($\leq$10%) centred at 2.45 or 14 MeV. Because of its fusion origin and of very short pulse duration, these flashes can be used in certain experiments related to fusion reactor technology problems (e.g. tokamak chamber or premise characterisation, neutron diagnostics calibration, etc.). It is of special importance that pulses with so short duration (down to several ns) give the possibility to use the Time of Flight (TOF) technique. Having a deep penetration depth the DPF neutrons have also a potential opportunity to be applied for the material characterisation of thick objects. Between them there are: a search for drugs and explosives, oil bore-hole prospecting, investigations of tubes conditions and characterisation of liquids flowing inside them, making "instant" 2-D pictures additive to the X-ray radiography, etc.). Main outward problems here are the investigation of real neutron fluxes, their spectra and a degree of flux anisotropy.

Concluding this section it should be pointed out that the whole list of material science problems to be solved with these types of hard radiation is produced by a DPF device. It consists of the following types of applications depending on the power flux density of the irradiation used:

- characterisation of materials and objects (including the dynamical ones),
- surface and bulk modification of materials,
- destruction tests.

Inward problems

DPF devices of both known types (with Filippov and Mather electrode geometry) were investigated and improved intensively during more than 40 years [1]. Yet in their application for material sciences there is a room for further work. Here we shall mention the main important directions of present scientific and technological research.

The first problem is the scaling of DPF devices above 1 MJ and down to 100 J. Up to now no installation did work exceeding those limits. Works that have to be done here are connected with:

- physics of the initial surface breakdown along the DPF insulator, including probably pre-ionisation of the gas near the insulator, treatment of the insulator surface with a laser, adequate geometry of the anode connectors, high frequency current oscillations at this stage, etc.,
- conditioning set of shots (impurity elimination from the electrodes and insulator, treatment of the insulator and anode surfaces, etc.),
- adequate (and probably new) geometry and a proper choice of materials for electrodes and insulator,
- new perspective technologies of the DPF assembling (laser and e-beam welding, vacuum chamber cleaning and treatment, etc.),
- working gas parameters, such as pressure (including gas-puff), gas mixture content, influence of surface adhesion layers, etc.,
- charging voltage value and shaping of the discharge current, etc.

The second point is related to the well-known problem of the ion current saturation [12]. There is a difference with the case of the classical plasma accelerators where special injectors supply a necessary quantity of ions through the net-like anode. Here the mechanism of the ion component of supporting of the high current within the contact of a fast moving current sheath at the anode surface (so-called "dynamical CS contact") is a self-regulating foam-like layer, saturated by molecules of the working gas [7]. This issue has a particular importance in connection with the first problem of scaling. Indeed, it is extremely difficult to organise such a layer on an anode surface in big devices. In a small DPF chamber, just in contrary to this, several mono-molecular layers (usually existing on the internal chamber surface) contain much more particles that the whole number of molecules within the working gas filling the chamber.

Many technological questions of the above mentioned types can be resolved by using noble gases for the DPF filling, and in particular their different mixtures with nitrogen and hydrogen isotopes. This idea constitutes the third important field of internal DPF problems. In previous studies it was very difficult to prepare an experiment to examine a proper percentage of different components of the working gas. That was because of the fact that the so-called conditioning shots take a long time (several days or even months) to produce a foam film on the anode surface, saturated by working gas molecules. But now, it can be done with the devices of high efficiency high repetition rate, based on a new technology [8]. With these installations, having repetition rate up to 10 Hz, all tests of such a kind can be carried out in minutes.

But at the same time, this fourth point initiates the problem of an anode material survival (fifth task). High life-time of the chamber (and the anode central part in particular) becomes the most important material science problem, related to the DPF itself. Many tests of radiation resistive materials and especially of various pseudo-alloys (as an anode) insert should be done.

In addition to the above-mentioned problems – scaling, high efficiency, high repetition rate, and long lifetime – there should be pointed out the problem of transportability of DPF devices. Fortunately, already several works have been done devoted to the creation even a portable DPF device.

Interactions, materials

Referring to the section: "Inward problems" we have to point out that investigations of the interaction of all the above mentioned streams and fluxes with targets, should give a very important information both on illumination conditions and its influence on the resulting material parameters. These types of works are in its beginning, and only a few experiments have been done with a DPF. We shall mention here several important points to be taken into account during such an activity.

Changing a distance between the irradiated samples and a source, we can change sequence of the irradiating streams, e.g., positioning a specimen material near the pinch will result in the irradiation of it at the beginning by a cumulative stream of plasma, and after about 50–100 ns it will receive a beam of fast ions. But if we place the sample at a distance larger than 10 cm from the anode, then the situation may be changed into opposite one. Fast ions (100 keV) will come to the cold surface (to disrupt all surface molecular bonds necessary for adhesion), and afterwards we have a stream of low energy (5–10 keV) ions for implantation and for a cover film creation.

Different plasma/ion beams compositions can be achieved not only by the mixture of gases used for the chamber filling, but also by a creation of the "heterogeneous pinch". It can be done, e.g. by the material injection (as an axial stream inside the pinch) by a laser pulse. The last method gives a possibility to use any material – not only gases.

Power flux density is an important factor for interaction processes. Because we may reach here fluxes in the range up to 10^{13} W/cm^2, a detailed analysis should be done in every particular case, e.g., the "detachment effect" may be modified as the high power beams may heat the previously evaporated metal clouds up to high temperatures, thus making them transparent for these beams.

For theoreticians it is a challenge to make a correct description of the process of the REB interaction with condensed matter, taking into consideration parameters and processes of different types, namely:

- over-Alfven current transportation and interaction,
- magnetisation of electrons and generation of various plasma instabilities during the beam penetration into a target,
- heated plasma expansion at the presence of strong X-rays of thermal and slowing-down emission (radiation gas-dynamics),
- thermal and shock waves penetration inside the solid target, etc.

Side by side with this problem there are many other tasks. Between them a correct formulation of initial boundary conditions for the process of each stage, establishing of a set of equations for the plasma-wall interaction process (with variable coefficient of sputtering, possibility of description of self-similar regimes of evaporation, kinetic processes within the near-wall plasma, etc.) and others. Establishing of a correct procedure for numerical calculation of the equation set is a present day problem.

A very important point is a specimen material. It should be elaborated, treated, irradiated, and investigated afterwards. All parameters of the illuminated samples are interesting – the final composition, structure and characteristics. Here problems of such a kind like the molecules implantation, gas diffusion, lattice relaxation, etc., are under investigation. There are several time scales for the processes – the metastable phase creation ($\sim 10^{-10}$ s), irradiation time (10^{-9}–10^{-6} s), diffusion and relaxation times (10^{-4}–10^{0} s), etc. Measurements should overcome the whole range of the time intervals.

A final characterisation of specimen materials properties after the irradiation demands optical microscopy, SEM, X-ray element and structure microanalysis, micro-hardness, wear and tear, as well as other characteristic measurements.

Diagnostics and monitoring

There are only a few reports devoted to the investigation of the process of the plasma/beams interaction with samples during their modification [11]. But it is of special importance in material science works of such a kind. Indeed, only a detailed analysis of the local mechanisms and microscopic parameters can give an understanding and subsequent control of the material modification. The main characteristics to be measured at the sample surface are plasma and sample temperature fields, plasma density, material and plasma pressure, local electrical and magnetic fields, particle and electromagnetic waves flux density, diffusion processes, melting and evaporation dynamics, particle scattering and secondary effects, fluctuations of these parameters, etc. But investigations of these processes and characteristics near the condensed matter surface are very difficult. In this region we have usually a very dense plasma, non-transparent for its own luminescence and laser light, and moving with a high velocity.

Thus for these studies we need to elaborate diagnostics of new types: soft X-ray backlighting, very high intensities laser beams, micro-probe technique, miniature pressure meters, etc., and all these diagnostics should have a temporal resolution from ns till fs, and spatial resolution of the order of micrometers. It can be done on the basis of a miniature DPF working with a noble gas (e.g. neon), piezo-electric films, etc. These devices must provide measurements with temporal and spatial scales of a kinetic type.

Side by side with these methods it is very preferable to supply a permanent monitoring of beam parameters. All these measurements should give us spectral, temporal, spatial and absolute characteristics of the streams used for the specimen irradiation.

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