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PLASMA FOCUS AS A SOURCE OF INTENSE RADIATION AND PLASMA STREAMS FOR TECHNOLOGICAL APPLICATIONS[1]

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Dense Plasma Focus, a device invented more than 30 years ago, is until now one of the most bright and efficient source of ionizing radiation (neutrons, soft and hard X-rays, electron and ion streams). Being relatively cheap and flexible (energy stored in condenser battery and driving the phenomena from 0.2 kJ up to 1MJ) DPF fits very well to a number of applications in different fields e.g. nanotechnology, material science, defectoscopy, biology, medicine etc.. Already investigated and existing applications of DPF, as well as those of future potential are presented and discussed in the paper. Specific demands for radiation sources based on DPF principle to be used in above mentioned fields, problems encountered and methods how to overcome them are briefly indicated.

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1 Introduction

Dense Plasma Focus (DPF) has been known for more than 30 years as a remarkable source of hot and fast plasma streams ($T_e \sim 1$ keV, $v_{pl} \sim 10^5$ m/s), different types of ionizing radiation – fast electrons and soft/hard X-rays (10^{-1} – 10^3 keV), fast ions (up to 10 MeV) and neutrons (2.45 or 14.0 MeV). These sorts of radiation are produced at the high-current discharge in a chamber filled with various gases at pressure of a few Torr. Efficiency of the source is quite high. It can reach about 10% for soft X-rays and fast particles, whereas for secondary particle beams like hard X-rays, neutrons and other fusion products the yield is followed to the classical laws. A DPF is a source of extremely high brightness due to its very short pulsed character and small sizes of the plasma source of radiation. It is very well fitted to a number of applications, in spite of the fact that a quite complicated picture of physical processes ruling a generation of radiation still is not understood completely. A possibility of working with DPF on a low energy level and at relatively low cost of the related equipment (even modern one) produces a unique opportunity to organize various types of activity - scientific, educational, as well as the one oriented to various applications. At the same time the biggest DPF device is one of the most advanced tool for some basic scientific investigations.

In any of the above mentioned types of activity, but in particular for technological applications, DPF facilities should be reliable with high rep rate and long lifetime, and they should

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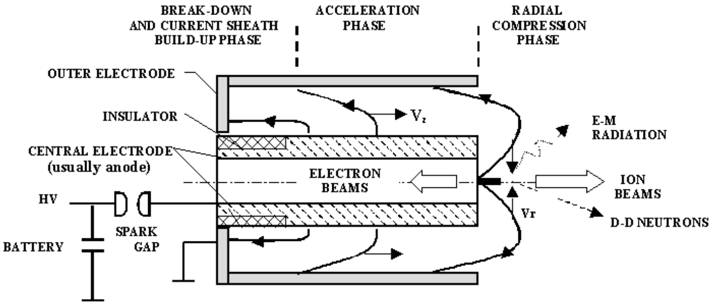

Fig. 1. Scheme of dense plasma-focus processes

produce about the same dose in each series of shots. These issues can be resolved now on a base of new technologies and by using a special type of operation of the devices.

During the last decade several types of the DPF devices have been elaborated on a base of the advance pulsed power technology [1] – [4]. At present, they already fulfill the above mentioned demands, but works on their improvement, refining, and in particular on their fitting to a specialized use are still in progress. Side by side with these modern facilities the traditional apparatus of a “laboratory type” are in exploitation in many centers where their potential opportunities in various fields are used for testing [5], [6]. Present status of DPF applications may be qualified as *experimental and verification stage*, even though in some cases this device has found already its niche in technological applications.

In this paper some possibilities to make use of Dense Plasma Focus for technical applications are presented.

2 Apparatus

The Dense Plasma Focus (DPF) facility belongs to a class of pinch formation discharges [1] (Fig. 1). During a fast electrical discharge of a capacitor battery a high electric current ($0.1 \div 4$ MA) produces plasma between two cylindrical electrodes: anode (called central electrode - CE) and cathode (outer electrode OE) placed inside a metallic chamber filled with a gas (usually hydrogen or deuterium) under the initial pressure of several hPa. The magnetic field generated by the high intensity current accelerates initially the plasma along electrodes (run-down phase) and than compresses towards the electrode axis (collapse phase). During the above mentioned process electrical energy stored in the condenser battery is converted to the magnetic field energy and is concentrated mainly in the vicinity of created and compressed plasma column (so-called “pinch”). After that, due to plasma instabilities a disruption of the pinch current occurs and a high electric voltage (about few hundreds keV) is induced. This voltage is much higher than the initial bank charging voltage ($\sim 20 \div 40$ kV). This field accelerates electrons to the anode face and ions in the opposite direction resulting (as secondary effects) in an intensive burst of hard X-rays and neutron radiation. (Fig. 1).

A Dense Plasma Focus facility consists of the following main units:

- the condenser bank and pulsed electrical power circuit with a collector and low-inductance cables,

- the mechanical vacuum and gas system which consist of the vacuum chamber, coaxial electrodes and gas handling system.

PF-1000 (operating in the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland) is the biggest DPF in the world. Its important features are as follows. The vacuum chamber, which surrounds the electrodes, has a large volume (1.4 m in diameter and 2.5 m in length). Two coaxial electrodes are shown on Fig. 1. The outer electrode (cathode) consists of 24 stainless steel rods with 32 mm in diameter. The outer electrode (OE) and copper center electrode (CE) radii are 0.2 and 0.1155 m respectively with the CE length of 0.6 m. The cylindrical alumina insulator sits on the CE and the main part of the insulator extends 0.113 m along the CE into the vacuum chamber. The insulator prescribes the shape of the initial current sheet between the CE and the back plate. The condenser bank of capacitance 1.332 F can be charged to voltage ranging between 20 – 40 kV, which corresponds to discharge energies ranging from 266 kJ to 1064 kJ.

Usually the number of “shots” between cleaning and repairing the elements in the laboratory-type device is 10^3 – 10^4. When a device is big and if it is intended to produce unique shots on the level of the highest energy density, the above figure – 10^3 – 10^4 shots is acceptable.

The situation differs strongly when we come to small devices fitted to low-scale applications. In these research normally one needs a high repetition rate ($\sim$ 10 Hz) and an acceptable lifetime (10^6 – 10^7 shots). Degradation of elements and systems of a DPF results from a high discharge current (0.1 – 1.0 MA) and radiation damage of the most sensitive parts of its construction (electrodes, rubber o-rings, diagnostic windows, construction elements inside a chamber, etc.).

The most important system of a DPF to be discussed in this connection is its power generator (energy storage plus switch). Usually in laboratory devices they are based on cheap capacitors and high pressure or vacuum spark gaps having relatively low lifetime. To increase their durability to the level acceptable here, in principal, there are three possibilities discussed in literature: ferromagnetic pulse compressors based on metglass, underloaded capacitors with pseudosparks [2], and a full solid state technology [1]. The ultimate values for their lifetime and repetition rate at the moment are on the level of 10^7 shots and 10 – 20 Hz. All the above mentioned possibilities have their own advantages and drawbacks as well, but detailed discussion of these problems exceeds a scope of the paper.

In our works on a relatively small energy Dense Plasma Foci we made a choice in favor of the second type of its design [2]. We have developed two types of DPF – with energy storage of 200 J (PF-0.2), and 2 – 3 kJ (PF-2 and NX1) respectively. The first one appears to be the best for applications, where a *portable* source of different types of radiation (its weight is about 15 kg) is needed for exploitation in single-shot operational regime. The second one, *transportable* device has high rep rate, long lifetime, and high efficiency. This design is based on the following principles [2]:

1. Capacitors designed for much higher maximum voltage than the charging one are used.

2. Pseudo-sparks switches with several hundred kA of switching current, more than 10^6 operations per its lifetime, and switching time/jitter of a few ns, are implemented.

3. Careful chambers design with special attention paid to surfaces quality and elimination of any rubber o-rings (modern laser and e-beam welding technology was used). Different inserts in the anode have been used to withstand the flashes of hard radiation.

4. Efficient water cooling system allows the device to work with a high rep rate (several tens of kW of average electric power inside several cm dimensions).

The chamber design and the electrode geometry should be properly modified for different applications. To put a device into operation after the change of a gas, electrode material, its geometry, or after exposing them to the atmosphere, a set of conditioning "shots" is needed [7]. Electrodes are saturated with a working gas and an insulator surface is modified in a special manner during this period. A search for a proper combination of charging voltage and initial gas pressure is executed at the same time.

3 Fundamental research and education.

Let us discuss here some results on DPF applications, already explored experimentally or discussed hypothetically, which might be of interest for scientists and engineers working in this field.

The most natural use of DPF in science is its application for research in the field of basic plasma physics. With this device, relatively simple and cheap in comparison with the modern nuclear fusion devices like NIF, NX or JET, many phenomena of dense magnetized plasma dynamics, plasma transport properties, turbulence, etc., may be investigated. Let us present here just as an example our latest new results in this field.

The biggest devices of this type (MJ device, e.g. [4]) have current on the level of several MA and pulsed magnetic fields of about several megagauss (some publications insist on figure at least an order of magnitude higher). Self-focusing relativistic electron beams carry the energy up to hundreds kJ and produce at the anode surface a power flux density of more than 10^{17} W/m^2. All these features result in corresponding pressures on a megabar level, which is far beyond of the strength of materials [8]. These facts make large DPF devices a tool for investigation of a matter under extreme conditions, e.g. to deduce its state equation.

Another problem for MJ device is a scaling law for neutron yield as DPF is a very intense neutron source. Scaling laws for the neutron yield formulated at the beginning of the plasma focus investigations were very promising for these devices. Later investigations however, carried out on bigger devices suggested that there is a certain energy limit above which scaling laws saturates. Hence, the essential problem to be resolved in PF research has always been to discover the physics, which dominates the configuration, a question closely related to the neutron production mechanism and plasma dynamics.

Recently, because of demands implied by nanostructure manufacturing applications, namely to reach good X-ray yield in the spectral region of X-rays near 4 Å, we use the device NX2 [3] with Argon filling. It is attainable if a plasma electron temperature can reach $T_e \geq 1$ keV at the pinching or another phases where it has a high enough density.

There are at least three possible ways to get the above temperature. One is to use a mixture of light gas (ultimately deuterium) with argon to produce hot spots by plasma necking ruled by flute instability. The second one is to increase a current sheath (CS) velocity in pure argon, which will result in a corresponding temperature rise. The third way is to use a mixture of heavy gas (e.g. krypton) with argon to produce separation of gases at the shock wave front of a DPF current sheath and subsequently to compress argon by a “heavy shell”.

Using a pinhole equipped with a CCD matrix and a pair of pin diodes folded by different foils in all three methods we have successfully measured a reasonable yield inside the above-mentioned spectral range. Within these modes of the DPF operation it was possible to find clear distinction between three characteristic regimes: a hot spot regime, a pinch regime and a runaway regime. It is just the compression by a heavy shell, which demonstrated a remarkable difference with the previous two modes. In this case we have received a pulse shape of X-rays with a very sharp rise-time (just equal to the temporal resolution of our oscilloscope – less than 1 ns). The absolute yield was about an order of magnitude higher than in cases of the DPF operation with pure argon or a D_2+Ar mixture.

DPF is also an excellent device for training students in various disciplines of general physics education. Since it produces high temperature plasma and different types of ionizing radiation it can be used in a modern laboratory for studies of thermodynamics, electromagnetism, atomic physics, optics and spectroscopy, nuclear physics, etc. Special advantage of this apparatus as an equipment for modern physics laboratory in University is that it is ecologically clean in comparison with isotopes. It becomes a radiation source only for a few ns during the discharge through gas.

It can also be used for training in specialized disciplines like plasma physics, plasma diagnostics, nuclear methods, material sciences, etc., for graduating students. Postgraduates and PhDs can explore this facility for scientific investigations and industrial applications using many different types of radiation emitted from this pulsed powerful source.

4 Industrial applications

One of the most dynamic spheres of modern industry is nanotechnology. It encompasses precision engineering as well as electronics, electromechanical systems (such as the development of ’lab-on-a-chip’ devices), biochips and other tools for gene engineering, drug manufacturing and delivery, sensors, diagnostics and analytical devices, etc. Between them X-ray microlithography is one of the most promising applications.

4.1 X-ray microlithography (Ne-operational DPF)

In semiconductor manufacturing, microlithography is used to transfer the pattern of circuitry from a mask (a plate containing the “master copy” of circuitry) to a wafer (a thin slice of semiconductor material on which chips are made). Lasers, presently in use in semiconductor industry, cannot fulfill the up-to-day demands for manufacturing of chips with feature size less than 0.2 micrometer. To overcome a diffraction limit X-rays must be implemented instead. In comparison with its main competitor, namely the synchrotron source, DPF is much cheaper, can be used with the beam inclined in any direction, and safer in case of emergency. Usually it is used here with Ne gas filling. Touted as “likely the world’s first application of ‘next-generation’ lithography for revenue semiconductor production” by *WaferNews* and *SAL’s One Step Ahead (2000)*, the SAL company bases its source of soft X-rays [1] on DPF of the type similar to our NX2. It has been already installed a year ago at the Microwave Electronics Center of Sanders, A Lockheed Martin Company. The company uses it for exposures of their 150 nm-generation of high frequency GaAs integrated circuits on 150-mm GaAs wafers and reports excellent uniformity as well as device performance across a wide range of products including advanced microprocessors and DRAM. There are several other groups in the world, which have explored the DPF as a powerful X-ray source for development of proximity lithography for many years (see e.g. [9]). We also have made experiments in this field [2] showing resolution better than 100 nm.

4.2 X-ray micromachining (Ar-operational DPF)

One evident goal of transition to shorter wavelength in comparison with previously used Ne gas filling is to increase spatial resolution of the method. But besides of the resolution the 4 ÅAr radiation can be implemented in micromachining. This technology (consisting of LIGA - *lithographie galvanoformung abformung (German),* M^4 – *Micro/Meso Mechanical Manufacturing,* and MEMS – *Micro Electro-Mechanical Systems*) is making small mechanical designs that put function in a small package a reality. Application in this field will be possible, if Ar -filled DPF emits enough hard X-rays, allowing a deeper penetration of the radiation into a resist to make production of a 3D structures possible.

In our research with Ar filling of the NX2 chamber (see above) we have received an X-ray output in the range of 1 – 10 J. At this yield several hundred shots are necessary for resist irradiation. From one side it means that to preserve a reproducibility of the total dose from chip to chip not worse than 1% we have to make namely not less than 100 shots. But at the same time with a rep rate of 15 Hz and with a possibility to interrupt the exposure of a resist at any moment by simply tracing dosimeter readings it is possible to satisfy the demands of a microlithography or micromachining.

4.3 Electron beam lithography

Because DPF is an efficient source of e-beam it can be also used for the e-beam lithography [10]. Preliminary experiments have shown that the efficiency here is much higher whereas additional work is needed to fulfill the demands on irradiation uniformity.

4.4 Application for material sciences

In this field DPF has found quite wide spectrum of applications like: ion implantation, surface modification, plasma-wall interaction, as it can produce power flux density and efficiency incomparable with other sources [8], [11], [12]. At low ion flux density deposition of various materials on the substrate takes place [13]. Interaction with material surface of powerful high temperature (~ 1 keV) deuterium plasma jets (velocities up to $5 \cdot 10^5$ m/s) and fast ion beams (50 – 150 keV) generated in DPF device produce another effects [11]. We investigated low-activated austenitic steels (e.g. 25Cr12Mn20W) and ferrite steels (10Cr9W), which are counted to be perspective ones for the most loaded parts of fusion facilities. The specimens were positioned in cathode part of DPF and irradiated with 3 to 10 shots. The recoil nucleus method [14] together with Rutherford Universal Manipulation Program [15] was used in order to trace the deuterium atoms within the irradiated specimens.

It was found that at power flux density of about $10^{1}0$ – $10^{1}2$ W/m^2 normal ion implantation into the irradiating material surface layer is observed. When the power flux density increases above $10^{1}3$ W/m^2, the so-called “broken-implantation” takes place. An ion diffusion velocity of the implanted deuterium through both interfaces – “layer-bulk material” and “layer-gas phase” – for Fe-based alloys has been estimated theoretically [16].

DPF can be used also for simultaneous neutron-X-rays dynamic quality control of mechanisms in course of its operation (turbines, tyres, etc.) [17].

In *oil industry* neutron activation analysis is already implemented for more than 10 years with vacuum and gas-filled neutron generators. It is evident that DPF can find a niche where a very short and powerful pulse of neutrons is needed. In this case “time-of-flight” method of investigation can be used. Between problems to decide there is determination of a leakage rate of oil along the well tube, estimation of an oil percentage within a pulp pumping from the wells, etc. In a *coal industry* an important problem is to determine a degree of water, as well as the ash contents within the coal. As for *gold* [6] it is a remarkable fact that a nuclear activation analysis (NAA) is probably the only possibility to check the gold in ingots and namely DPF can be good because of short pulse duration (short time-of-flight base) and high cross-section for almost monochromatic 2.45 MeV neutrons of D_2-operated DPF.

4.5 Pulsed radiation biology and medicine

Our experiments with enzymes have shown as follows. We illuminated [18] three types of enzymes (horseradish peroxidase, APF and angiotensine) by X-rays from isotopes and from our DPF. The DPF radiation was concentrated mainly (by filter technique) near 9 keV. It appears that the DPF produces the same effects (both activation and inactivation of the enzymes) as usual isotope source but at doses 4 orders (!) of magnitude lower. At present time we examine several reasons possibly responsible for this effect. Between them are power flux density (8 orders of magnitude higher with DPF than with isotope), selective (by spectrum) excitation of Zn atom positioned in the nuclei of the enzymes, and a problem of so called “resonance doses”, i.e. doses within the limits of comic level and one medically allowed.

4.6 Positron Emission Tomography (PET)

PET is one of several diagnostics methods currently explored in nuclear medicine. Two antiparallel quanta of energy 0.511 MeV emitted in a radioactive decay within the human body can be detected in coincidence. Belonging to diagnostics, this method mainly yields functional and physiological data on human organs and systems under study. The most commonly used as PET tracers are isotopes ^{11}C, ^{13}N, ^{15}O and ^{18}F. DPF can generate streams of fast ions necessary for production of isotopes [19]. It makes the device ecologically much more acceptable and cheap in comparison with accelerators of classical types.

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