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0.2-kJ and 2-kJ high rep rate Dense Plasma *foci*: their design, technology, and applications

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Abstract The paper presents various designs of several medium and small size Dense Plasma Focus (DPF) chambers intended for numerous applications, a description of technologies used in these facilities, and some results reached with these devices by using a number of diagnostic techniques. In present experiments the DP *foci* have been used mainly as an X-ray source. We discuss here how it is possible to satisfy absolutely new and very strict demands on the construction and technology for the devices to be eventually applied in science and industry. Between these characteristics there are a high repetition rate (typically 1…15 Hz) and a long lifetime (over 1 million shots). Their switching elements, a collector and chambers must withstand a high quasi-continuous heat load (up to 100 kW). High energy density in the central part of the chamber anode and the necessity to provide a channel for radiation extraction demanded a special construction and specific materials implementation in this region. Their X-ray spectrum should be tuned. They have to operate with different working gases and preferably in a wide range of pressures. All these points are discussed in this report. Capabilities of the described techniques are illustrated by results of the recent experimental studies carried out with facilities located at the Nanyang Technological University (NX1) as well as at the Lebedev Physical Institute (PF-0.2).

Key words dense plasma focus • DPF installation • miniature focus chamber • soft and hard X-ray radiation

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Introduction

As it has been shown experimentally in [5] main parameters of a Dense Plasma Focus device scale with an increase of a current flowing through a pinch I_p are as follows: – pinch plasma density N_{pl} is constant; – pinch plasma temperature T_{pl} is constant; – current of medium energy ions responsible for neutron production $I_i \sim I_p$; – density of the magnetized medium energy ions around the pinch $N_i \sim I_p$; – current of fast electrons responsible for hard X-ray radiation $I_e \sim I_p$; – collective accelerating field in the plasma $E \sim I_p$; – plasma confinement time $\tau_{pl} \sim I_p$; – confinement time of the medium energy ions $\tau_i \sim I_p$; – dense plasma volume (pinch) $V_p \sim I_p^2$ thus producing overall scaling for the soft and hard X-ray output and neutron production, which are very well known from a literature. E.g. for neutron scaling we have:

$$N_n \sim N_{pl}\, N_i <\sigma v>T_{const}\, V\, \tau_{pl,i} \sim I_p^4 \tag{1}$$

This means that a perfect DPF operated at any feeding energy level (at least in the range 0.10 through 1,000.00 kJ) has the same energy density (contrary to e.g. tokamak devices) which makes the yield of various types of its radiation to be predictable. The radiation sources of DPF have a very short pulsed character (covering the range from ~1 through ~100 ns depending on dimensions of the device and the radiation type) and small size of radiating zones (from micrometers till centimeters). Radiation of each type has also a non-spherical angular distribution with certain preferential directions of its luminescence. All of these facts result in an extremely high brightness of the source making it very well fitted to different applications. The possibility to work with DPF on a low energy level as well as a relatively low cost of the related equipment (even modern one) produce unique opportunity for the various types of activity – scientific, educational, and applications as well.

In any of these branches, but in particular in applications, the devices should be reliable with a high repetition rate and long lifetime and should produce about the same dose in each run. These issues can be resolved now on the basis of new technologies and by using a special type of its operation. Our devices described in this paper were equipped with elements, which have been elaborated as the joint efforts of several research institutes.

In specific applications, intended for science (flash radiation biology, chemistry) and industry (pulsed defectoscopy, microlithography, micromachining) that have been explored by us, different constructions and special regimes of DPF operation are necessary. In particular, spectral range of X-rays generated by the device should be tuned. This can be done in DPF by various means including materials used for the construction of chamber and its filling gas.

The main principles, used as the basis for the devices of new generation, a list of the installation parameters as well as photographs of the DPF devices and DPF chambers have been published earlier [1, 2, 4, 6]. Here we concentrate our attention mainly on some specific features of chamber design and its manufacturing, and particularly on such chambers that have been used for the generation of soft and hard X-rays.

Apparatus

PF-0.2

During the last decade we have elaborated and used for different purposes two types of the DPF devices: the portable PF-0.2 (energy stored in a capacitor of about 0.2 kJ, current ~100 kA) and the transportable one (~2 kJ, 350 kA). Constructions of two types PF-0.2 chambers are presented in Fig. 1.

In Fig. 1a) one can see a device optimized for neutron production, whereas the DPF chamber, which is marked as b) in this Figure, is designed as a hard X-ray generator. Central part of its anode in the last case is realized as an insert made of a high-melting W-Ni-Fe alloy in order to prolong a working life of the chamber. It also enlarges the hard X-ray radiation yield due to the utilization of tungsten as a component of the above alloy having a high Z value.

We noted earlier [4] this characteristic property of the DPF hard X-ray spectrum as a strong enrichment of its long-wave part. The main reason for this is the overlapping of bremsstrahlung by a high-energy part of thermal plasma radiation. This strongly differs DPF from conventional X-ray tubes. This may be important for some applications, e.g. for visualization or irradiation of soft tissues at X-ray examination or treatment of an object.

However, it should be noted that in the case of using a certain chemical element for the anode insert, it is possible to increase X-ray intensity locally in a particular spectral range by means of excitation of K-series lines of the element. E.g. for Cu $E_\gamma \approx 8–9$ keV for K-series (K_α = 8.048 keV). The efficiency of electron energy transformation into X-ray at this mechanism is much higher than at normal bremsstrahlung process, so great part of DPF medium energy X-rays radiates just at these K-lines. Furthermore, in the case of using the same chemical element for a foil material, positioned as an outlet channel filter, such a filter will be predominantly transparent for these lines. This is because the absorption curve of the filter has a "window of transparency" starting from a K-edge (in the case of copper it is 8.993 keV and some below). It is also possible to find regimes of a DPF operation where the portion of more energetic quanta is negligible in comparison with the line radiation. Thus, such a DPF device one can consider as a powerful pulse generator of a quasi-monochromatic X-ray radiation. The efficiency of energy transformation from a bank to X-ray radiation by this mechanism exceeds 0.1% at the device. We have used such a generator of Cu K_α-line radiation for our radiobiological research [7]. This type of spectrum formation may be used in the range from about 1 keV (Al insert) till 112 keV (for uranium).

The tuning within a soft part of X-ray spectrum generated by DPF can be executed by a thermal plasma radiation. Side by side with neon also pure deuterium, argon, krypton and mixtures of these gases were tested as working media in chambers of the type. These gases can give us the possibility to cover a spectral range within the interval from a few hundred eV till above 1 keV.

Current-contact surfaces of both electrodes are made of pure oxygen-free copper. The chamber hull (cathode) is realized by means of a rolling technology, not by turning. Special types of technology are also used during the assembly of the chamber. Between them there are:

- welding of metallic parts of the chambers by electron and laser beams,
- use of special metals for firm joining of the parts in the weld formation,
- spray application of a metallic layer onto the ceramic surface, so as to make it suitable for subsequent vacuum welding with metallic components,

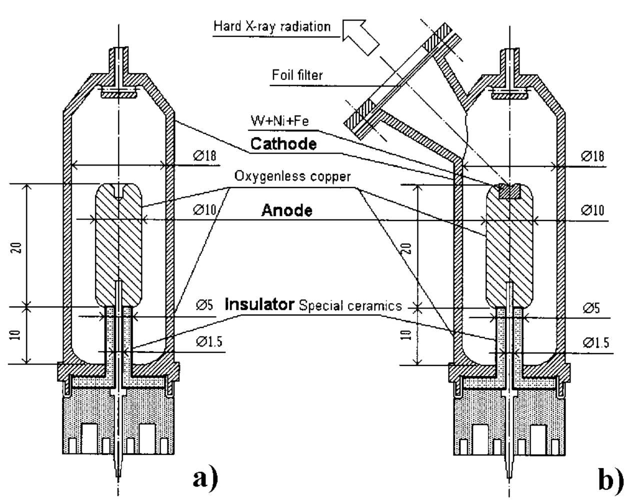

Fig. 1. Schematic picture of two PF-0.2 chambers: a) neutron DPF chamber, b) hard X-ray DPF chamber.

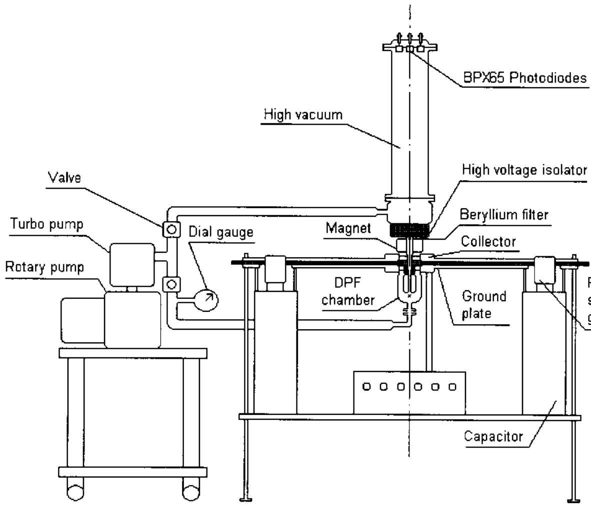

Fig. 2. The scheme of soft X-ray installation NX1.

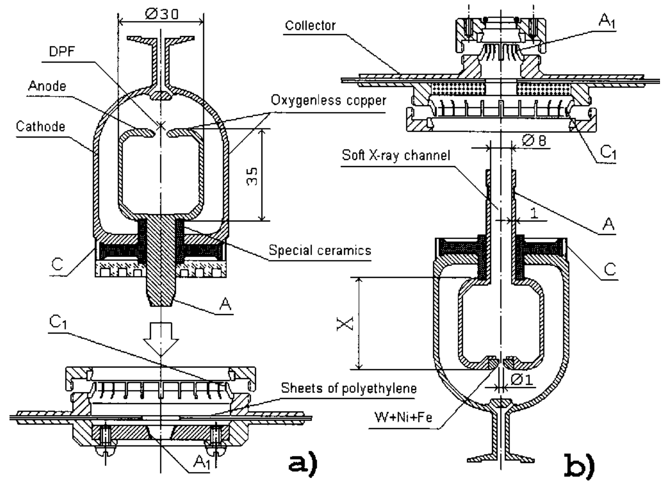

Fig. 3. Schematic picture of two PF-2.0 chambers: a) neutron DPF chamber, b) soft X-ray DPF chamber, first generation.

- chemical treatment of parts before and after certain operations.

Very important distinguishing properties of the chambers are the absence in its construction of any rubber o-rings for vacuum seal as well as matching of the joining materials by their coefficients of thermal expansion. The noted properties are inherent to all the DPF chambers in this report. Now we shall describe the construction of five successive generations of the DPF chambers of a bigger device – PF-2 (in the Nanyang Technological University the device based on this module has the name NX1), that has been elaborated for microlithography and micromachining [1, 6].

PF-2

The scheme of NX1 (PF-2) installation designed for this branch of investigations is presented in Fig. 2. For an optimizing procedure as well as for the subsequent activity of various kinds, the following diagnostics were in use (for specific tasks we use only part of them): 1. Rogowski coil, 2. Voltage divider, 3. Multi-channel soft X-ray spectrometer, based on PIN diodes, folded by different foils, 4. Pin-hole chamber with a CCD matrix, 5. Soft X-ray crystal spectrometer, 6. Neutron activation counters, 7. Multi-channel nitrogen laser with 1 ns pulse duration for frame shadow plasma visualization, 8. Fast ion spectrometer.

Fig. 3 a) presents the construction of DPF chamber, which was designed at the All-Russian Institute of Automatics for neutron production. The working gas used was deuterium. This facility was the basis from which we have started our present study.

Our construction of the soft X-ray DPF chamber of first generation is shown in Fig. 3 b). In order to satisfy demands of the chamber for X-ray microlithography, it was necessary to change the construction of its inner electrode. We make a choice in favor of the construction that could provide the output of a soft X-ray radiation through the anode directly to the target to be irradiated. Our angular aperture was 5 degrees. In order to increase the intensity of the radiation extracted from the plasma focus chamber at the soft X-ray wavelengths (9–14 Å) required for microlithography, we used neon as the working gas (Ne-IX and Ne-X lines). Substitution of deuterium by neon required some changes in the chamber construction to ensure the electrical and dynamical parameters of the discharge to be consistent. In particular, we varied the length of the inner electrode X (Fig. 3 b)) in the range from 35 to 54 mm. The optimal anode length proved to be 43.5 mm. For each electrode length we selected initial pressure of the working gas filling the chamber as well as the charging voltage. Our selection criteria were that the time of formation of the plasma focus should coincide with the beginning of slowing down of the discharge current curve, and also that a "singularity" in the current oscilloscope trace should be deep. The described DPF chamber was operating well at an installation energy store level of about 1 kJ (with a single high voltage capacitor, 8 μF, 10 nH, 150 kA).

Transition to a full-scale experiment with four capacitors required a substantial increase in the mechanical strength of X-ray output channel, since the magnetic field corresponding to an increased current for this case proved to be so large that its pressure crushed the channel after 30–50 DPF shots. We were able to eliminate this deficiency by filling the inner electrode with a double-part output channel, the external copper tube and the internal stainless steel tube were welded at the outlet part of the chamber. Two versions of this new chamber construction are shown in Fig. 4. The DPF chamber construction changes led to the principal changes in the construction of a current collector. The main idea was to exclude the contact of any sparkling and to ensure good insulation. Therefore, a corresponding collector sketch accompanies each chamber version, which is presented in Figs. 3–5. Different versions of electric contacts of the split terminal type were tested. In the presented Figures the most important reciprocal electrical parts, in respect of extra high current, are marked as A, A_1, and C, C_1 for chamber-anode, collector-anode, and chamber-cathode, collector-cathode contacts, correspondingly. The final construction proved to be very reliable.

Each chamber shown in Fig. 3 b), Figs. 4, and 5 a) has an insert made of a high-melting W-Ni-Fe alloy with an opening of a diameter 1 mm, which makes it possible to use differential vacuum pumping. Use of the latter is necessary for

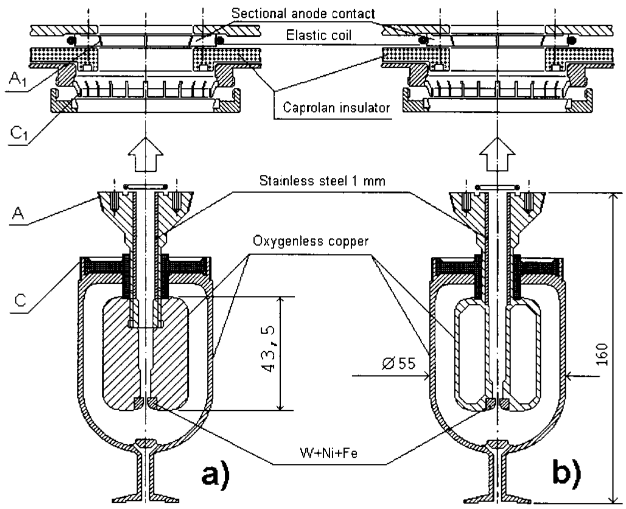

Fig. 4. Schematic picture of two soft X-ray PF-2.0 chambers: a) with a block-structured anode, b) with an anode having a single-component copper part.

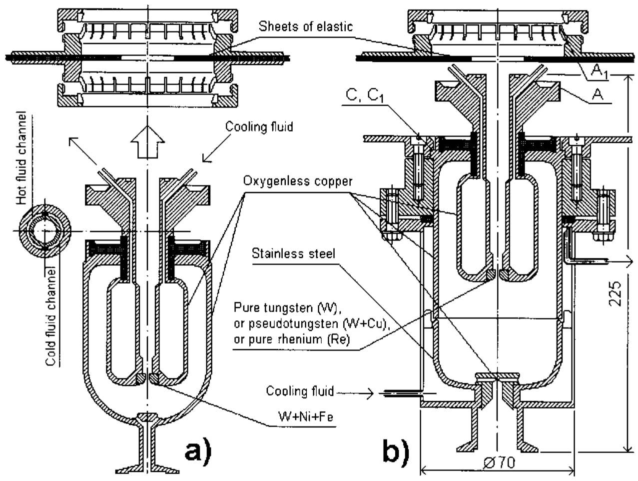

Fig. 5. Schematic picture of two PF-2.0 chambers: a) with cooling anode, b) with complete chamber cooling.

both the volume of DPF chamber itself and separately for the X-ray lithography chamber if one has to decrease the radiation loss along the beam optical path to the mask. This is, in addition, also used to increase longevity of the chamber. This is really very important in view of the large absorption coefficient of gaseous neon in the wavelength range used for X-ray lithography.

To put the new device into operation in a certain regime, after changing the electrode material or its geometry, a set of conditioning "shots" is needed. During this period the electrodes are saturated with the working gas and the insulator surface is modified in a special manner. At the time of this run the search for both – the proper charging voltage and the initial gas pressure – is executed. In the fall of set (about 100 shots) the device is ready to work. Thus, the conditioning and optimization procedures appear to be a very important part of the work. It is interesting to note that transition to the repetition mode of operational regime with cooling of the DPF chambers (see below) had given us an opportunity to really appreciate ability of the regime for optimization procedures at least.

The next versions of two chamber modification deal with the realization of chamber cooling system (Fig. 5). A cooling of the DPF electrodes by de-ionized water is undertaken in order to increase the frequency of repetition mode of the device operation as well as to prolong the duration time of each experimental series. The experiment with the DPF chamber version Fig. 5 a) is being carried out at present time. The installation is able to operate in the rep rate regime with a frequency of 3.5 Hz for time intervals of 2 min. However, it is important to accentuate that the noted figures do not define the frequency operation ability of the construction. In fact, we are restricted now by the scope of the high voltage charger used. Only when a higher powerful bank charger is applied we will be able to determine limitations of our chamber cooling system. The same one can say concerning the construction Fig. 5 b) with a complete cooling, which is ready to operate at present time, but is not yet tested. It is note that we intend to put for testing three new refractory materials as a realization of the anode insert in the final chamber generation. The motivation for this is as follows.

As a matter of fact, the earlier used W-Ni-Fe alloy proves to be subject to the effect of a strong electron beam, which takes place in the DPF discharge. As a result of several thousands of DPF shots such an effect is realized either in some widening of the anode insert hole diameter, initially equal to 1 mm, or just opposite to it in its blocking. The last one demands a cleaning procedure. Widening of working diameter does not lead to a chamber spoiling as a powerful soft X-ray source. Yet it will certainly result in an additional complexity in the future application of differential vacuum pumping.

Some experimental results

Our study of the described DPF device, tested by means of a pinhole technique in combination with a CCD matrix, has demonstrated that there are two regimes of its operation [3]. In the first one – at high pressures (8 through 16 mbar) – a size of the soft X-ray (in the region 0.8…1.2 nm) source is about 300 μm. At low pressures (2–8 mbar) it is less than 10 μm. BPX65 PIN diode detectors fix an average X-ray yield of 70 to 100 J in the full space angle per one DPF shot. (The

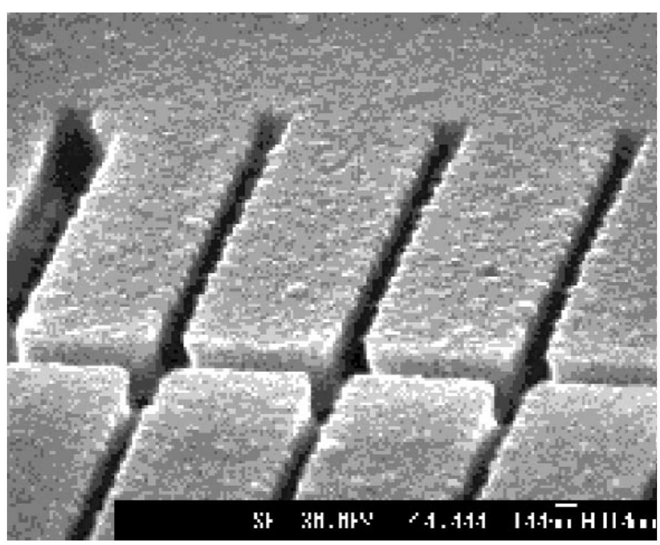

Fig. 6. Photo of the resist structure obtained with NX1 device during about 1.000 shots.

record value is about 200 J per one shot). Fig. 6 is an example of the resist structure obtained with our devices during about 1000 shots made at high-pressure mode of the DPF operation. It was shown that it is possible to produce structures with characteristic dimensions of about 50 nm. The number of shots can be dramatically decreased by implementing the differential pumping of working gas and by the use of resists with chemical amplification. Those regimes of this facility give an opportunity to make a successful exposure of resists with a 100-nm structure for about a hundred shots. There is no need to de-crease this value. Such a large number of shots are necess-ary because of the relatively big difference in the X-ray output of the device. But it is not dangerous. This means that to preserve a reproducibility of the total dose from chip to chip not larger than 1% we have to namely not less than 100 shots. But at the same time with a rep rate of 15 Hz and with the possibility to interrupt the exposure of a resist at any moment just following the dosimeter readings, it is possible to satisfy the demands of microlithography or micromachining processing.

Conclusion

The construction of some generations of small chambers for the dense plasma focus device is described here in detail for the first time in the scientific literature. Special attention is given to the selection of structural materials as well as to some design features of the device.

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