Innovative Powerful Pulsed Technique, Based on a Plasma Accelerator, for Simulation of Radiation Damage and Testing of Materials for Nuclear Systems

V.N. Pimenov[1], A.V. Dubrovsky[1,2], E.V. Demina[1,2], V.A. Gribkov[1,2,3], S.V. Latyshev[1], S.A. Maslyaev[1,2], I.P. Sasinovskaya[1], M. Scholz[3]

[1] A.A. Baikov Institute of Metallurgy and Material Sciences (IMET), Moscow, Russian Federation
[2] Moscow Physical Society, Moscow (MPS), Russian Federation
[3] Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland

Email contact of main author: pimval@mail.ru

Abstract. Innovative technology of a plasma accelerator of the Dense Plasma Focus (DPF) type based on modern elements of high-current nanosecond electronics is presented. This technology ensures operation of the devices having capacitor bank energy 1 through 10 kJ with a high repetition rate (up to tens cps) and a long life-time (on the level of 10^6 "shots"). These devices can operate with different gases, including deuterium-tritium mixture. They may produce plasma streams having velocity 1…5×10^7 cm/s and density about 10^{18} cm^{-3}, fast ion and electron beams with particle's energy about 100 keV, soft and hard X-Rays, and 2.5 and 14.0 MeV neutrons during 0.1…1.0 μs pulse durations. DPF phenomenon been discovered in 50's is the most well diagnosed observable fact. It is usually characterized by a number of diagnostics with nanosecond temporal, micrometer spatial and very high spectral resolution. The same statement can be applied to the secondary plasma parameters' measurements as well as to the transient events appeared on the surface and inside the specimens' bulk under tests. A number of such diagnostics used in the simulation and test experiments together with the results received will be described. Power flux density of plasma and fast ion/electron streams on the sample's surface during the experiments simulating conditions on plasma-facing components inside thermonuclear fusion reactors may reach as much as 10^{10} W/cm^2. It is about those expected in the reactors with the inertial (IPC) plasma confinement and much higher than those with the magnetic plasma confinement (MPC).
Pulse durations of *primary* irradiating streams are in the limits from 10^{-7} s up to a few microseconds. It is quite similar to those expected in the IPC reactors. Discussion of a so-called "damage factor" will be presented in the connection with MPC reactors. However the life-time of secondary plasmas produced by the above streams on the sample's surface and by current flowing during 4-5 cycles of the oscillating discharge is 30…100 μs, which simulate heat loads appeared in tokamaks during transient events (ELMs, disruption instability, etc.) in a perfect way also by the pulse's durations.

1. Introduction

Dense Plasma Focus (DPF) phenomenon been discovered in 50's is the most well diagnosed observable fact [1]. It belongs to the plasma accelerator class of devices of the "Z-pinch" type. Installations based on this principle have two modifications of electrodes named by their authors: Filippov and Mather geometries. We shall discuss in this paper namely the second type of DPF (see Fig. 1 *a*).

DPF is a powerful source of nanosecond pulses of hot (~1 keV) fast (~ 10^7 cm/s) plasma streams, high-energy electron (up to 1 MeV) and ion (up to 100 MeV) beams, soft and hard X-Rays (SXR & HXR), and 2.5- and 14.0-MeV fusion neutrons of a very narrow spectrum (ΔE/E ~ 1-3%). Mechanisms of production of these radiation types have been discussed in many papers (see e.g. [2]). Their parameters are usually characterized by a number of diagnostics with nanosecond temporal, micrometer spatial and very high spectral resolution. Scheme of generation, localization and transportation directions of these streams inside the DPF chamber are shown in Fig. 1 *b*.

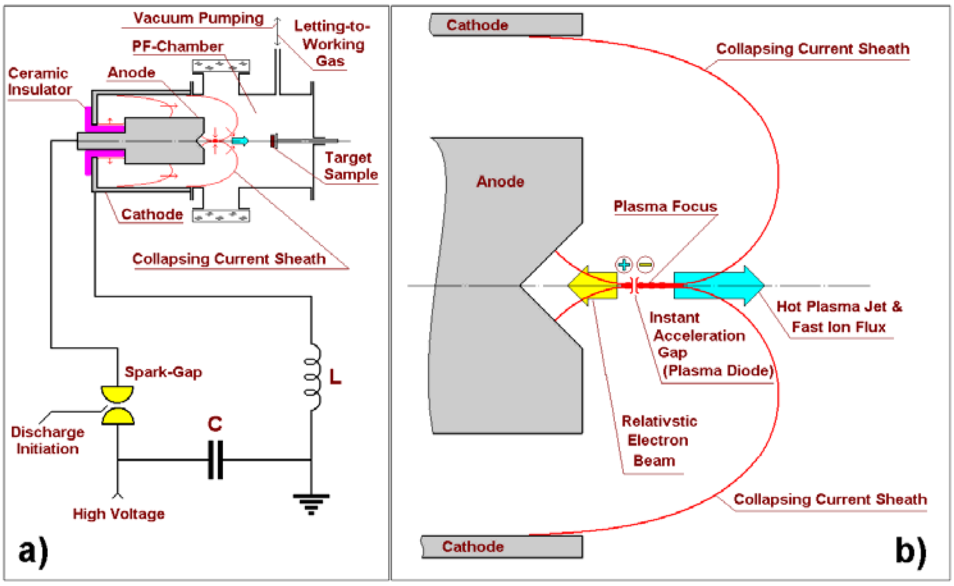

FIG. 1. The diagram of PF device (a); scheme illustrating particle acceleration mechanisms inside a DPF chamber (b)

DPF devices at present time are used in many applications such as radiation material sciences, radiation biology and medicine, dynamic quality control, neutron activation analysis including the disclosure of hidden illegal objects, etc. [3, 4]. It became possible because of recent progress in high-current nanosecond electronics, which gave an opportunity to manufacture DPF devices having high reliability, long life-time (~ 10^6 shots before replacing its most sensitive components), high repetition rate (up to 50 cps), etc.

2. Apparatus

During last several years using cooperation in the frame of the IAEA CRP with our colleagues form Poland and Italy we have put into operation several DPF devices of "medium" energy (2…10 kJ) stored in their capacitors. Between them PF-5M (A.A. Baikov Institute of Metallurgy and Material Sciences, Moscow, RF – IMET), PF-6 (Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland – IPPLM), PF-10 (A.I. Alikhanov Institute for Theoretical and Experimental Physics, Moscow, RF – ITEP), and DPF recently been manufactured at the Abdus Salam International Centre for Theoretical Physics (ICTP, Trieste, Italy). These devices are presented in Fig. 2. Some experiments were made with the use of the PF-1000 facility (1.2 MJ bank).

Typical set of diagnostics comprises the following instruments having nanosecond temporal resolution, micrometer spatial resolution, high spectral and angular selectivity: Rogowski coil, magnetic probes and voltage divider; PMT plus scintillator; activation counters; trek detectors; Thomson-parabola mass-spectrometers for e- and i-beams; micro-wave, infra-red, visible, vacuum ultra-violet, soft and hard X-Ray spectrometers; Čerenkov detectors; fast frame and streak cameras working in visible and soft X-Ray ranges; laser interferometry, etc. One of the most important applications of DPF in radiation material sciences is testing of samples of materials, which are counted as the candidate ones for use in plasma facing and construction elements of nuclear fusion reactors of both types – with magnetic (MPC) and inertial (IPC) plasma confinement. Let's examine how DPF devices of medium and large bank energy may help in these experiments.

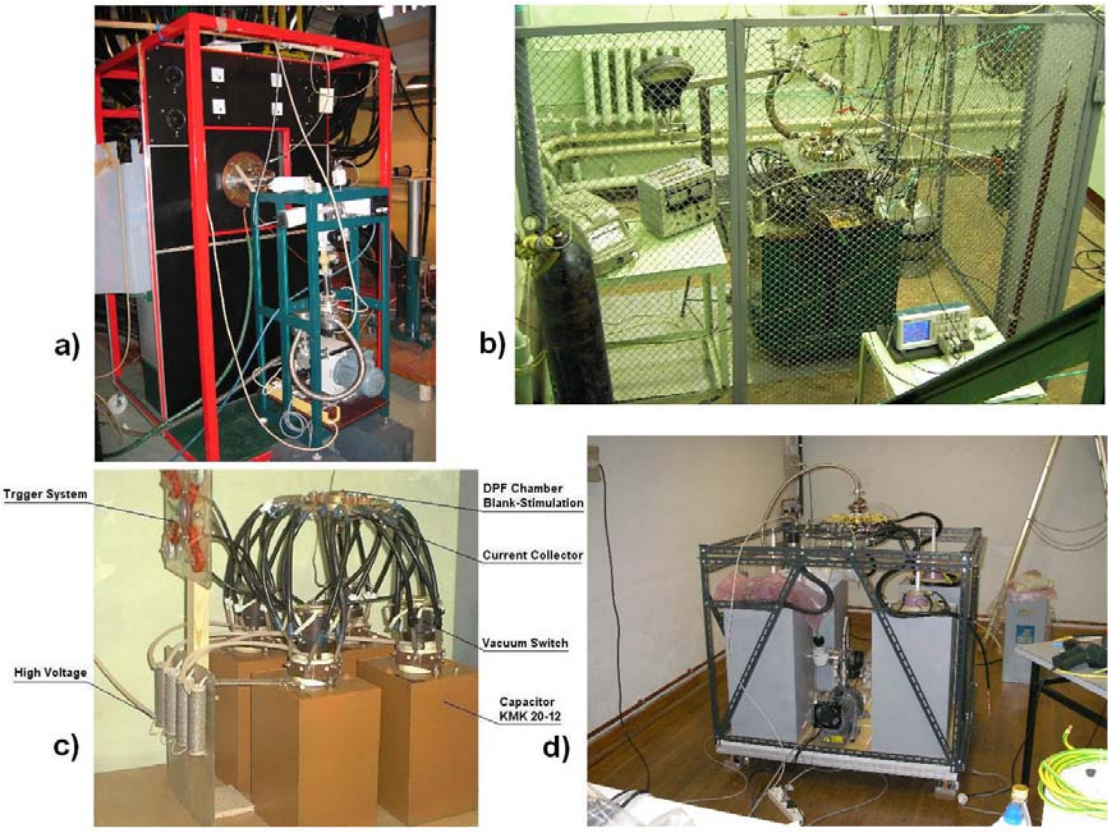

FIG. 2. Experimental DPF devices of medium bank energy: PF-6 (IPPLM) (a), PF-5M (IMET) (b), PF-10 (ITEP) (c), and the DPF device of ICTP (d)

3. Experiments

During numerous tests of different candidate materials we use as samples: 1) various kinds of steel (of austenitic, ferritic, and Eurofer types), 2) tungsten, aluminium, copper, and some other metals, 3) ceramics (CFC, SiC, alumina, etc.). We placed our samples in the central part of the anode of the DPF chamber thus acting on it by fast electrons, hot plasma and soft/hard X-Rays. But our main part of experiments was provided with samples positioned in the cathode part of the chamber at different distances from the anode. In this case the most important types of radiation producing damage effects are hot plasma streams and fast ion beams (see Fig. 3). These damage defects produced in the samples are discussed in a separate paper presented at this conference by Dr. E. Demina. Their origin is connected with thermal loading of the targets and shock waves produced in the samples by powerful beam of fast ions.

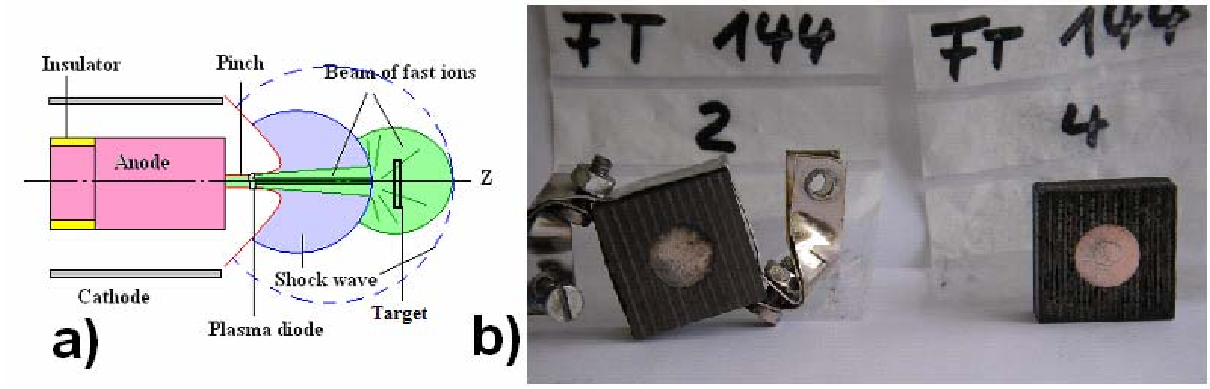

FIG. 3. Schematic view of propagation of plasma stream (Shock Wave) and fast ion beam (a) and a sample CFC+W irradiated by hot plasma stream and fast ion beam (b)

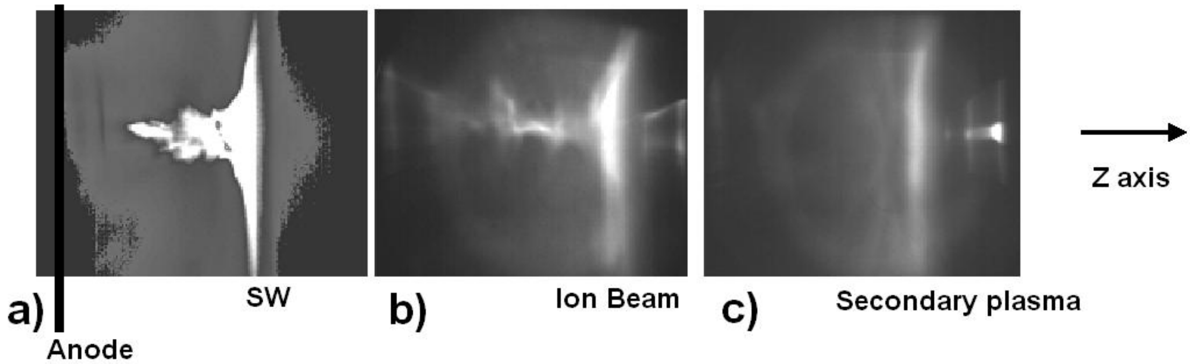

FIG. 4. Plasma shock wave (a), beam of fast ions (b), and secondary plasma (c)

Our diagnostics applied for investigation of secondary plasma plum has the same features as previously described for the primary plasma. In Fig. 4 we present 3 successive frames of plasma and target taken in visible light with the exposure of 1 ns. The primary plasma stream (shock wave – SW), fast ion beam propagating from the anode to the target (from left to right), and secondary plasma flying out from the target in opposite direction are clearly seen. Our previous spectroscopic investigations [5] where the recording equipment (containing a collimator and quartz light-pipe coupled to the MECHELLE®900 spectrometer) has shown (see Fig. 5) that the duration of the existence of secondary plasma is 20-50 times longer compared with the duration of the plasma/beam action upon the target (100 ns…1 μs). That system had the spatial resolution of about 10 mm and the exposition time was 0.5 μs. It makes possible observations of the temporal evolution of the investigated spectra, because a triggering system of the spectrometer was synchronized with plasma discharges, and the beginning of the exposition was varied (within the range of 0-100 μs).

4. Discussion

Our device is a gas-discharge installation where capacitors release their energy into a load ("plasma pinch") having mainly an inductive nature. So the overall discharge has several (usually 3-5) damping oscillations (see Fig. 6, where an oscilloscope trace of current derivative recorded at the discharge of the device PF-5M (IMET) is presented). One may see that periods of these oscillations are not changed in time. It means that the main part of the currents is flowing through the same characteristic size of the DPF plasma having about the same inductance as in the first have a cycle.

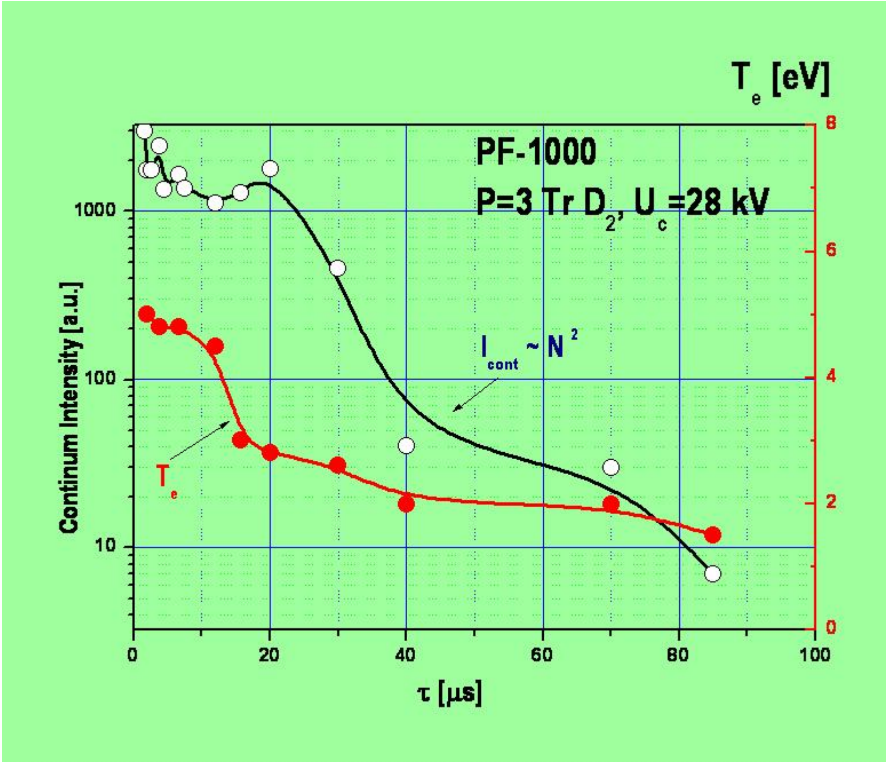

FIG. 5. Time evolution of the main parameters of secondary plasma obtained by means of spectroscopy with temporal and spatial resolution

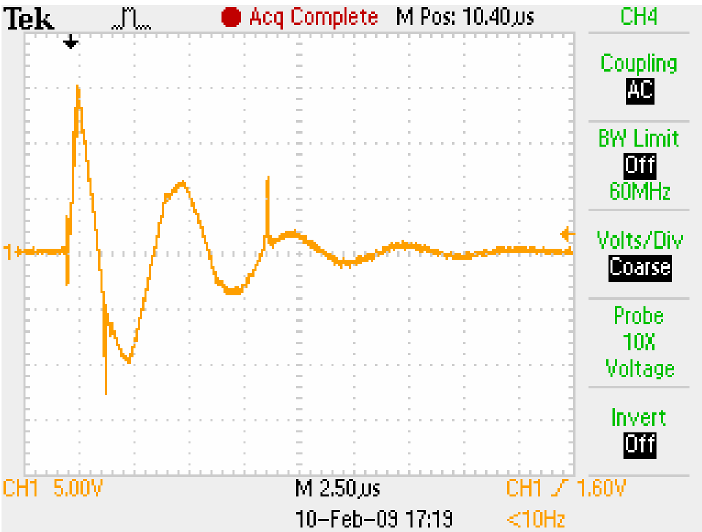

FIG. 6. Current derivative taken by Rogowski coil during the discharge at the PF-5M device

Fig. 6 gives also the following information. Current peculiarity seen after the current maximum (*∂I/∂t=0*) during the first half a period is repeated one more time during the second period but at the negative current half-wave (positive derivative). It means that we have second pinching process taking place at the opposite polarity of the electrodes. So according to these data generally speaking the whole process looks as follows:

1) During the first half-wave we have plasma pinching, abruption of current, formation of e- and i-beams [2] acting upon the target in a very harsh manner;

2) Then after the pinch plasma disruption a plasma cloud is formed in the close vicinity to the anode. This cloud cannot be increased too much in its size (increasing its inductance) as it is seen from the discharge successive period. The same is true for the fast ion beam which must be closed electrically on the cathode;
3) Total current continues to flow through this cloud producing a sort of plasma confinement in this region. Sometimes this confinement may result in second (third…) pinching of this residual plasma.
However this secondary residual plasma has to have low temperature and power flux density compared with the pinch's plasma and beams generated during the first half-wave.

Thus the target after strong action of high-power streams in the first period will be subjected to the influence of the residual low-temperature plasma cloud existing and confined during the whole discharge oscillations.

Because our information on plasma dynamics during the subsequent discharge periods is rather poor we undertake a numerical modelling of the processes.

5. Numerical simulations

In our simulations we use a model previously elaborated for laser produced plasma [6]. According to this paper plasma is modeled by "large particles" presented by thin discs. Under the action of gas-kinetic forces of pressure the discs may move perpendicular to the target's surface and change their radius. Transverse widening of the discs was examined in automodel approximation. It means that radial velocities of different internal parts of the disc were connected with the radial speed of the disc's border by the law: $V_r(r)=V_R\,(r/R)$, where r – radius of the internal point of the disc, R and V_R – radius and radial speed of the disc's border. Thus this quasi-two-dimensional model presents something in between pure one-dimensional model and 2-domensional cylindrically symmetrical model.

This work presents a new advanced quasi-two-dimensional hydrodynamic model, makes it possible to calculate critical parameters of parietal plasma originating from its interaction of plasma as well as ion streams generated by the devices of Plasma Focus (PF) type with solid-state target. Typical plasma and ion energy flux densities used at the material science experiment are of the value $q \sim 10^6 - 10^{11}$ W/cm^2, the typical influence time durations are within $\tau \sim 100 - 1000$ ns.

The energy absorption of plasma and ion streams moving from the PF takes place within a thin surface layer of the target. It's typical thickness is differs by high energy ions with the average energy of about 100 keV. The track of hydrogen ion H^+ of that energy is near 0.1…1.0 μm in different metals [6]. It is 1-2 order of magnitude less then typical thickness of the target layer, which is evaporated or weld penetrated. On account of this the full energy-release takes place just within the first disk, which thickness is chosen approximately equal to the trace of the most representative (on energy) high-energy ions. The influence of $P_0=n_0(1+Z_0)kT_0$ pressure and the thermal radiation of warm gas σT_0^4 onto the surface of parietal plasma are take into account at the model.

The Fe parietal plasma temperature dependence on time after the cease-influence of powerful energy fluxes from plasma "pinch" with and without action of warm working gas is presented in Fig. 7. The operation factors of the energy flux originating from the "pinch" were taken as the next: $q = 10^9$ W/cm^2, t = 1 μs, the temperature of warm working gas surrounding the target $T_0 = 2$ eV. The effect of warm working gas influence becomes apparent while the temperature of parietal plasma is reduced to the value of working gas temperature. This effect results in stabilization of the spread parietal plasma temperature around the value of the working gas temperature. Thus the spread process of parietal plasma on its latest stages transforms from the adiabatic form into an isotherm one. Such a phenomenon was obtained by us at the next installations: PF-1000 (1 MJ, $T_{discharge}$ = 28 μs) and PF-6 (6 kJ, $T_{discharge}$ = 8 μs) – see Fig. 5. At that the isotherm stage duration was about 100 μs for PF-1000 device and about 30 μs for PF-6.

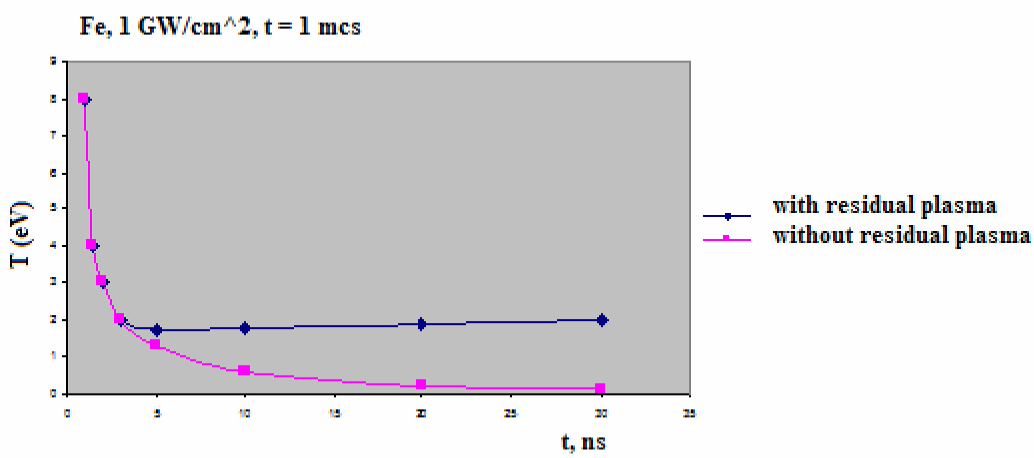

FIG. 7. The dependences of Fe-target parietal plasma temperature after the cease-influence of powerful energy fluxes from plasma "pinch" with and without action of warm working gas

6. Conclusion

By this work we have shown that DPF can be used for modeling of short powerful action of radiation typical for nuclear fusion reactors with IPC during the first half-wave of the device and for simulation of short-lasting events of the ELM's and disruption types taking place in fusion reactors with MPC using DPF with the full oscillating cycle of its discharge.

To refine experiments of the first type (i.e. to exclude influence of low-temperature residual plasma) we can use one of the schemes of DPF bank switching presented in Fig. 8.

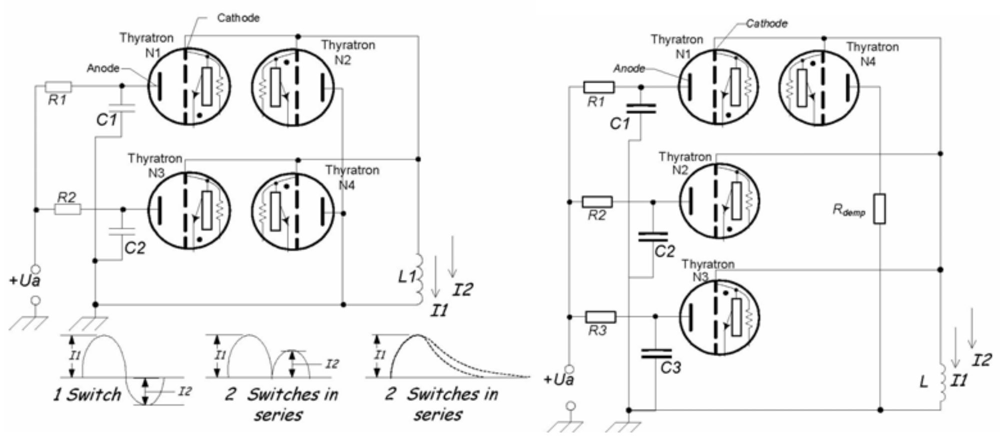

FIG. 8. Two possible variants of switching the bank onto the DPF chamber

7. Acknowledgements

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