NUKLEONIKA 2006;51(1):5–13

INVITED PAPER

Dense magnetized plasma and its applications: review of the 3-year activity of the IAEA Co-ordinated Research Programme

Vladimir A. Gribkov,
Artur Malaquias

Abstract A review of the results received in the course of fulfillment of the International Atomic Energy Agency Co-ordinated Research Project "Dense Magnetized Plasma" for the last 3 years is presented. Niche of the plasma type within the plasma physics field is outlined. Efforts of the CRP participants concentrated on design and operation of new Dense Magnetized Plasma devices are described. All of them designed for plasma heating and for other applications mainly based on the interaction of radiations generated by the devices with different objects. Materials exploitable, diagnostics of the interaction processes, as well as analytical equipment used by the participants to process the irradiated targets are described. Works developed in the frame of the CRP are covered thermonuclear fusion applications, fundamental plasma physics and material science issues, medicine, biology, and some other spheres. New data on the interaction of the radiations generated in this apparatus with various materials are given. E.g. it was found that the necessary dose producing activation/inactivation of enzymes can be much lower if used at a high-power flux density in comparison with those received with classical sources. All these experiments are discussed in the framework of pulsed radiation chemistry in its perfect sense thereto the criteria are formulated. New foreseen applications of DMP devices mainly based on neutron radiation are proposed and discussed.

Key words dense magnetized plasma • ion beams • plasma beams • neutron beams • X-ray beams • irradiation • high energy density • volumetric interaction

V. A. Gribkov✉
Institute of Plasma Physics and Laser Microfusion,
Department of Dense Magnetized Plasma,
23 Hery Str., 01-497 Warsaw, Poland,
Tel.: +48 22 683 9056, Fax: +48 22 666 8372,
E-mail: gribkovv@yahoo.com

A. Malaquias
International Atomic Energy Agency,
5 Wagramer Strasse, P. O. Box 100, A-1400 Vienna,
Austria

Received: 25 August 2005
Accepted: 17 February 2006

Introduction

Dense Magnetized Plasma (DMP) belongs to the class of high-temperature plasmas able to produce hard radiation including fusion neutrons. By its plasma density range among other fusion plasmas, it occupies a niche between those with magnetic confinement ($\leq 10^{14}$ cm^{-3}) and with the inertial ones (10^{23} cm^{-3} and above). By its temperature and fusion products yield it also lies in between of them being better than they are in the inertial fusion and lower than in the best present-day tokamaks. Historically, pulsed gas-discharge installations producing this plasma were the primary devices, with which scientists have attained first progress in fusion researches [9, 10]. But afterwards, DMP sphere was put out from this field and left mainly for fundamental plasma physics (because of simplicity of the devices) and for applications (due to their low cost). Main reasons for the barren competitiveness of DMP within the fusion field were as follows:

- there was no progress in scaling of fusion product yield with energy for decades of years,
- physics of these relatively simple devices appeared to be difficult and intricate, and its understanding was developed at a slack pace,
- plasma density, n_{pl}, is too high for the magnetic confinement schemes (e.g. it results in strong radiation losses), but too low for the inertial ones

(as the consequence of it the well-known Lawson parameter $n_{pl}\cdot\tau$, where τ is the plasma confinement time, is far below the necessary value 10^{14} cm^{-3} due to impossibility of generation of Giga-Gauss' magnetic fields for plasma confinement),

– moreover, it appears to be senseless to increase the plasma confinement time satisfying the above Lawson criterion in these devices because to hold up a plasma quasi-neutrality here one have to support the ion current component namely by fusionable ions (not by ions extracted, e.g., from electrode materials), which seemed to be a very difficult task in these 'electrodes' systems. Yet it should be mentioned also that even in those two above fields left for the DMP there were many problems with durability and effectiveness of the dense magnetized plasma generators.

However, it seems that a new high-current pulsed power technology appeared recently, as well as progress in understanding physics of the processes taking place in these devices, start to change the situation. In particular, this makes it possible to create very compact (even portable and transportable) and efficient DMP devices (Dense Plasma Focus – DPF – between them [1]) with reliable operation. Such devices may have a lifetime at a level of millions of shots and can work in a high repetition mode [4]. Main attributes intrinsic at present time to modern DMP devices are their compactness, high efficiency and reliable operation, but, in particular, the fact that many of them have a very high brightness of their hard radiations.

These radiations – plasma streams, fast electron and ion beams, X-rays (both soft and hard) and neutrons – have particle and photon energies much higher than the charging voltage making these devices ecologically attractive. The above-mentioned features open the possibilities for a number of important applications – in fusion programmes (i.e. in the inertial confinement scheme), in industry and in life sciences as well. Being very reach by different phenomena and various types of ionizing radiation, DMP devices give many opportunities in various teaching programmes covering plasma physics, optical and X-ray spectroscopy, nuclear and neutron physics, interaction of radiation with matter including radiation chemistry and biology, etc.

The paper is devoted to the description of new results received during the last 3 years within the frame of the International Atomic Energy Agency Coordinated Research Project (CRP) "Dense Magnetized Plasma". The works described were performed in Warsaw, Poland (Institute of Plasma Physics and Laser Microfusion – IPPLM), Moscow, Russia (Institute of Metallurgy and Material Sciences – IMMS, Moscow Physical Society – MPS, Moscow State University – MSU), Ferrara, Italy (Ferrara University – FU), Singapore (Nanyang Technological University – NTU), Beijing, China (Tsinghua University – TU), St. Petersburg, Russia (Physico-Technical Institute – PTI), Tallinn, Estonia (Tallinn Pedagogical University – TPU), Bucharest, Romania (University of Bucharest – UB), Yuseong, Daejeon, Republic of Korea (Korea Atomic Energy Research Institute – KAERI), i.e. in 8 countries, 9 cities, and 12 institutions in total.

Apparatus

Devices, which have been designed, constructed and used by participants, constitute 3 groups:

- plasma generators intended for plasma injection, e.g. into tokamak (PTI),
- plasma pinch devices used as sources of different types of hard radiation (IPPLM, IMMS, MPS, TU, NTU, FU) intended for various applications (e.g. in life sciences), and
- ion beam sources considered for ion beam injection into various targets (for plasma heating, for testing of radiation resistive materials, etc. – BU, KAERI, IPPLM).

Figure 1 presents the small devices of these groups, whereas in Fig. 2, two big facilities used are shown.

One team (PTI) works on the elaboration of a double-stage plasma source designed for plasma injection and on its testing with spherical tokamak Globus-M. As a result of the works, a novel type of plasma source for DMP clusters production and acceleration was developed and used in plasma fuelling experiments. After optimization procedures, plasma with minimal impurity contamination and a maximum flow velocity of 150 km/s was produced. Measurements of its parameters have shown that the source generates during the time interval of 50 μs a plasma jet having a density of 2×10^{22} m^{-3} and total number of accelerated particles $>10^{19}$. Deep jet penetration into plasma of the Globus-M tokamak and fast (< 0.5 ms) density rise of the last-named plasma from 0.65×10^{19} till 1×10^{19} m^{-3} (by 50%) did not lead to the plasma degradation.

Several groups between the CRP Project participants are joined around the biggest device in the world of the DPF type working with deuterium – PF-1000 (IPPLM). This facility has been modernized including driver system, supply of a number of new diagnostics as well as special tools and systems fitted to the material science experiments. It results in a formidable (by 1 order of magnitude) improvement of its neutron emission (however, not reached the scaling figure [1] yet) and in a strong increase of the yield of other hard radiations. For example, the implosion velocity of the current sheath was increased up to ca. 5×10^7 cm/s. Side by side with this work the groups construct new DMP devices. Being of much lower energy content they are based on modern high power technology (capacitors of KMK 30-7 type – 30 kV, 7 μF, 8 nH, 350 kA each, switches of pseudo-spark TDI1-150k/25 kind – 200 kA, $>10^{11}$ A/s, jitter 4 ns, etc.) and specially fitted to applications. First device in this row – PF-6 (IPPLM, ICDMP) – has a maximum energy storage of ca. 7 kJ. Quite similar one is the PF-10 device (MPS) having a bank energy of 13 kJ and placed at the Institute for Theoretical and Experimental Physics (ITEP, Moscow, Russia). The most important element of these devices is their discharge chambers [4]. They can be sealed up thus making, e.g. such a chamber filled with a deuterium-tritium mixture, a closed radiation source. For each application, depending on what kind of radiation will be used, these chambers have a specific design [2, 4]. It is described in papers presented by the participants from the IPPLM and MPS. One example of the internal

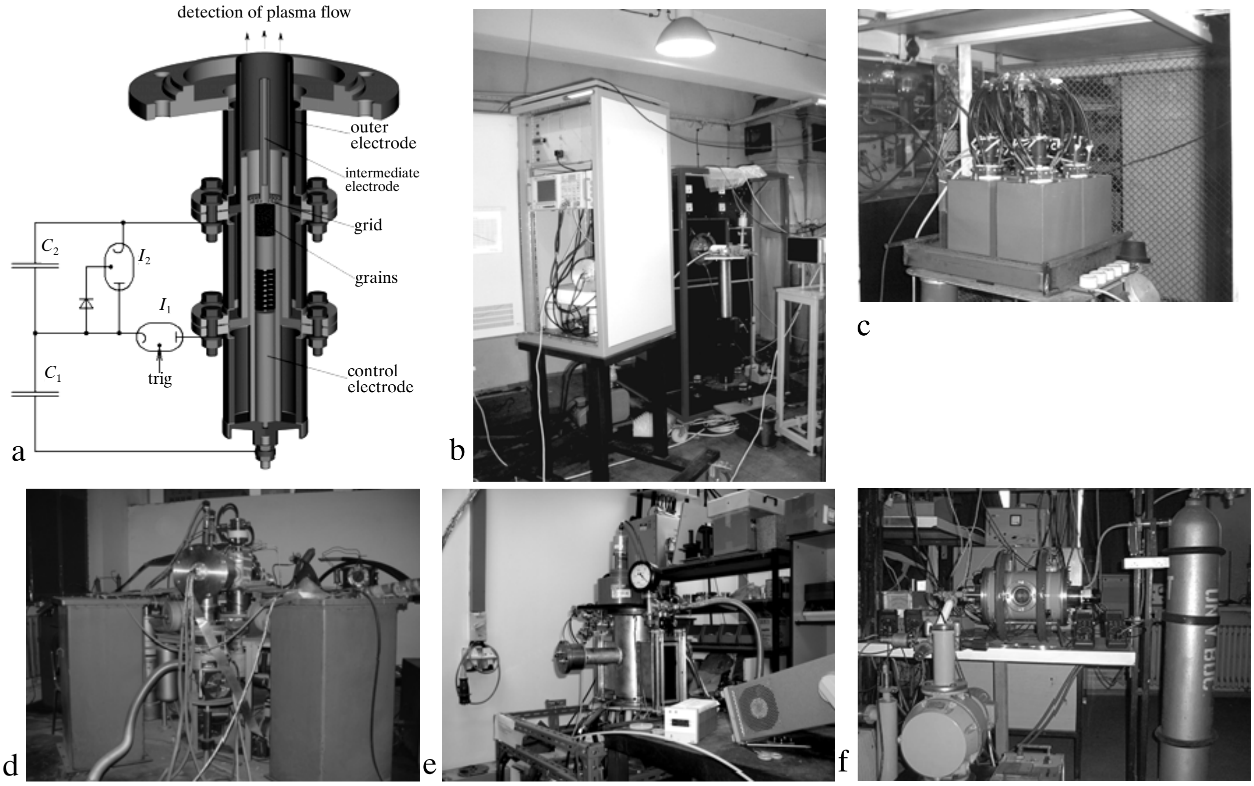

Fig. 1. Outward appearance of the DMP devices: a – double-stage plasma gun with granules – PTI; b – PF-6 device – IPPLM and ICDMP; c – PF-10 device – MPS and ITEP; d – gas-puff Z-Pinch – TU; e – 3-kJ DPF device – NTU; f – source of negative hydrogen ions – UB.

design of such a device optimized on a soft X-rays (SXR) emission is presented in Fig. 3. The PF-6 device has a maximum current of 750 kA reached at the quarter of its period ca. 1 μs.

A small gas-puff Z-Pinch Plasma Device has been constructed at TU. Its capacitor bank consists of four capacitors of 4 μF charged up to 23 kV. A hollow gas shell is produced by an injection of gas through a supersonic nozzle from a fast-acting electromagnetic valve. The mass of the gas shell can be varied using a different plenum pressure and changing the time delay between the start of gas injection and the initiation of the discharge. In these experiments, the peak discharge current is about 210 kA with its quarter period of 2.4 μs.

At the UB, in the last three years a reflex discharge plasma device as a potential source of negative ions has been created [17]. The study is motivated by the need for high-energy neutral particle beams for heating of plasma within controlled nuclear fusion machines. Experiments show that the optimum discharge conditions are obtained for pressure values around 1.0 Pa, the negative ion density is 8×10^{16} m^{-3}, the cold electron density and temperature are 4.2×10^{18} m^{-3} and 0.78 eV, correspondingly, the negative ion fraction increases from 1.4% to almost 2.2% within the pressure range 1–4 Pa, and the positive ion density scales with power.

At the KAERI, the large beam facility has been designed and constructed to test Neutral Beam Injection

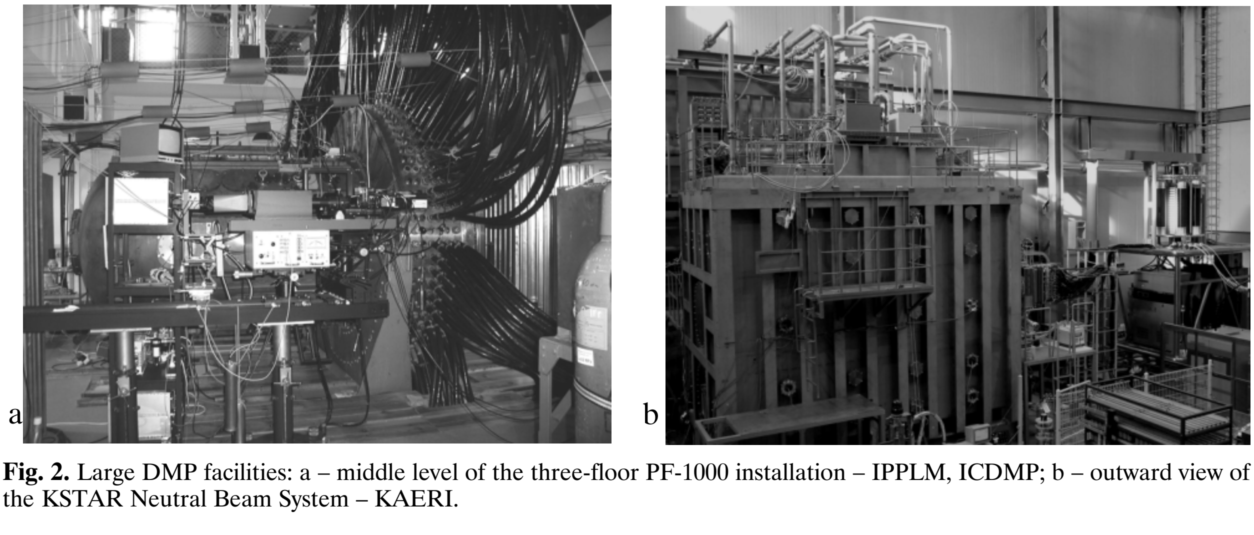

Fig. 2. Large DMP facilities: a – middle level of the three-floor PF-1000 installation – IPPLM, ICDMP; b – outward view of the KSTAR Neutral Beam System – KAERI.

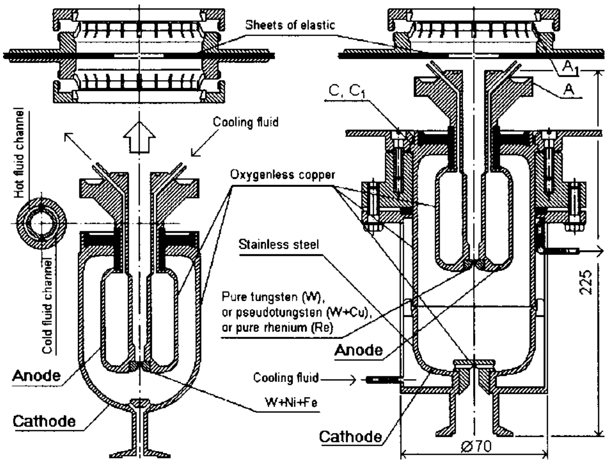

Fig. 3. Vertical section of the DPF chambers optimized for SXR production – MPS.

System for KSTAR tokamak. It is designed with the goals as follows: pressure profile and current density control, core fueling, plasma heating, and current drive. But it could also be applied to other areas such as fusion energy generation, material science, intensive heat flux source, and so on. The main parameters of the source: beam species – D, H (Test Phase), maximum beam energy (hydrogen) – 120 keV, pulse duration – 300 s, maximum beam power per a beam line – 8 MW (deuterium). The recent activities are concentrated on completion of the development of the large beam facility. Tests of the facility show that optimization of the device is still needed to reach the above figures. At present, problems of the team are: low beam currents compared with the designed value and high voltage insulation.

Plasma diagnostics

To have data on parameters of the devices operation as well as on the fast ion/electron beams and plasma streams, X-ray and neutron flashes (dynamics and velocity, angular distribution, spectrum, power flux density, etc.) a number of diagnostics was used both for the primary plasma torches (e.g. pinches) and for the secondary (irradiated target) ones by teams at the CRP. Between them:

– classical electro-technical probes (Rogowski coil, magnetic loops, voltage dividers, etc.),
– nuclear track detectors for fast ion registration (energy and space distribution),
– Cerenkov radiation detectors based on rutile crystals for fast electron investigation,
– optical and soft/hard X-ray spectroscopy, OMA Data analysis,
– soft and hard X-ray detectors plus Ross filters,
– neutron counters and fast photomultiplier + scintillator probes,
– movable probe (based on piezoceramics) for measurement of the pressure profile and total kinetic energy of jets,
– PM-355 Detector Sandwich to simultaneously record 16-MeV ^{3}HeD protons and 3-MeV DD protons,

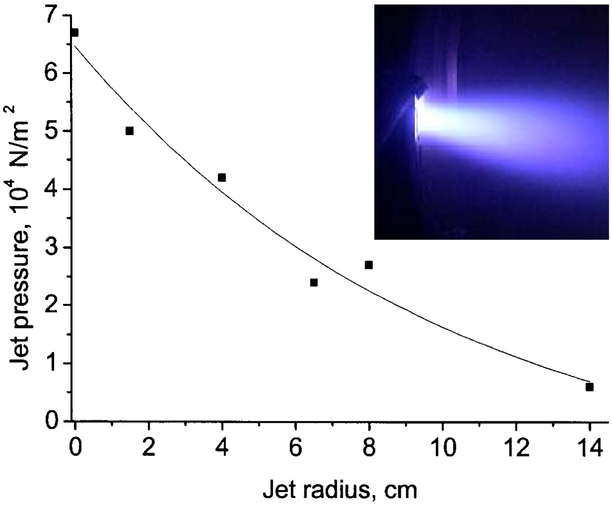

Fig. 4. Parameters of the jet injecting into Globus-M tokamak and its frame picture – PTI.

– proton camera to have images of spatial distribution of PF fusion protons using polymer nuclear track detectors: PM-355 (super-grade CR-39),
– bolometers and calorimeters registering radiation losses and particle energy release,
– photographing plasma dynamics by the frame optical and X-ray cameras with 1-ns time resolution,
– laser interferometry,
– Thomson scattering, etc.

Several examples of the plasma diagnostics result obtained on the above-mentioned devices are presented in Figs. 4–7. All these diagnostics have temporal and spatial resolution, which can characterize magneto-hydrodynamic (MHD) plasma behavior (best figures here are down to 1 ns and 10 μm). Certainly, an urgent need in much faster and more precise technique is existed to investigate processes on kinetic level (demanding much higher rate of financing of the research works).

Materials and analytical equipment

Success in experiments on radiation physics and chemistry in many respects depends on quality of the

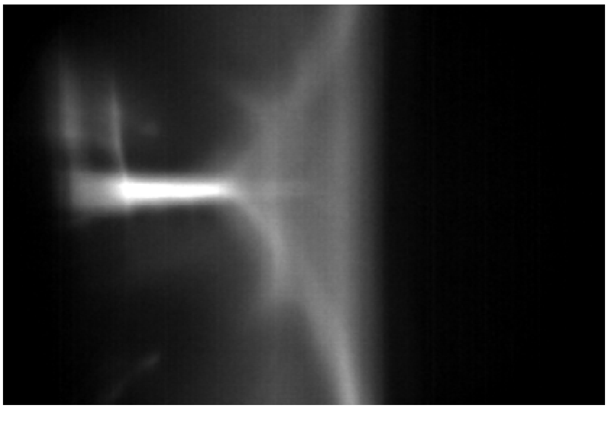

Fig. 5. Frame ns self-luminosity photography of pinch plasma – IPPLM.

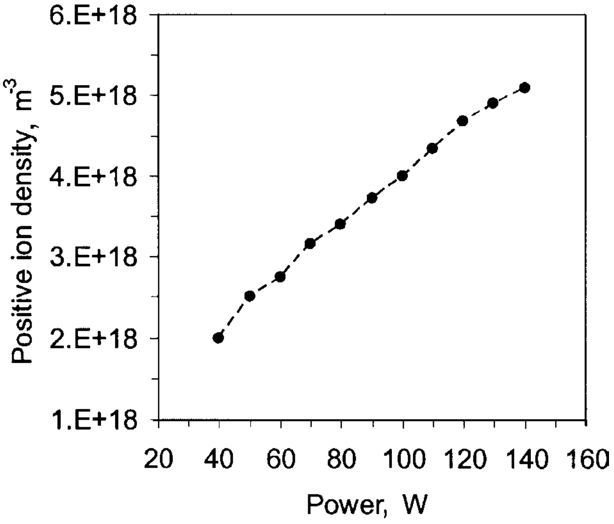

Fig. 6. Positive ion density vs. power – BU.

materials used and on the analytical equipment in operation a posteriori.

In radiation enzymology, the participants use electrophoretically homogeneous angiotensin-converting enzyme and native horseradish peroxidase purchased from Biozyme Company (MSU, IPPLM). In experiments on radiation material sciences, last versions of the "Eurofer" alloy and SiC composite materials designed especially for the use in ITER tokamak were investigated side by side with low-activated austenitic steel, tungsten, aluminum alloy, and some other materials.

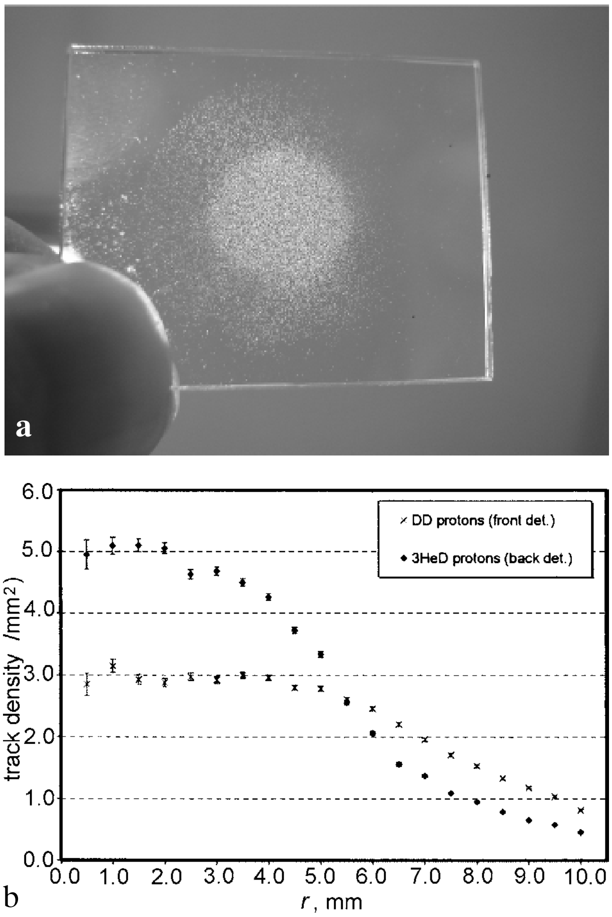

Fig. 7. Exposed and etched PM-355 detector (a) and radial distribution of tracks inside the ion beams of DD protons and ^{3}HeD protons (b) – NTU.

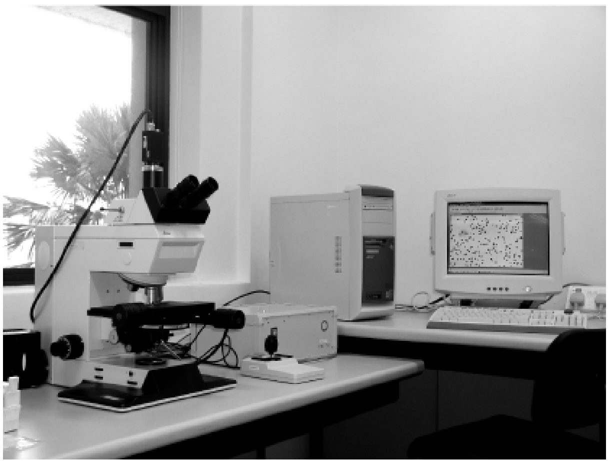

Fig. 8. Automatic track detector system – NTU.

Analysis of the irradiated sample was made as follows:

- in the case of radiation enzymology, the measurements of enzyme activity was performed with a Shimadzu UV 120-02 spectrophotometer,
- activation of carbon target irradiated by a beam of high energy ions in the case of short-lived isotope production was measured by a high-purity germanium detector (effectiveness 18%) connected with a multichannel analyzer having a resolution of 2.04 keV near 1.0 MeV,
- in material science experiments, the morphology of the irradiated sample surfaces was investigated by optical, electron and atomic force microscopes; X-ray microanalysis and structural analysis, tribological and micro-hardness measurements side by side with the concentration distribution (Elastic Recoil Detection Analysis) were made also here,
- in X-ray nanolithography, the irradiated resists were scanned by electron microscopy,
- automatic scanning system was used in a track-detector measuring technique (Fig. 8).

Results on fundamental plasma physics

Dense magnetized plasmas are complicated objects. Because of temperatures and densities intrinsic to them, typical MHD temporal and spatial scales (e.g. evolution of plasma boundaries) lie in the ns and sub-millimeter ranges, whereas the corresponding events of the kinetic phenomena (e.g. turbulence index) are in the range of picoseconds and submicrometers. Moreover, usually the plasma bunches produced in DMP devices are nonlinear, nonstationary, and nonequilibrium objects, bearing non-reproducible character. These features dictate (as it was mentioned in Section: 'Plasma diagnostics') the usage of a diagnostic complex collecting maximal parameters in a single shot with the highest possible temporal, spatial, and spectral resolution. In spite of the fact that the complexes now available in the DMP groups are quite far from perfection, important data were collected and new models more adequate to the investigated phenomena were elaborated. Let us present a few examples on this point.

At the PF-1000 device, the mutual application of multi-frame cameras (visual and soft X-rays), Cerenkov detectors, nuclear track detectors, and PM tubes with scintillators for a neutron emission monitoring gave the possibility to check a model of fast electron/ion beams generation processes based on a plasma diode concept and its correlation with the Gyrating Particle Model of neutron production mechanism [1].

At the same device, plasma dynamics under the shock wave/plasma current sheath interaction with an obstacle at the anode edge was investigated. Explanation of a double-pinch dynamics based on a shock wave bifurcation was developed.

It should be mentioned here that side by side with the present IAEA CRP, the field of researches in the Dense Magnetized Plasma sphere become wider and wider for the last decade. Fundamentals of the DMP physics are under deep investigations. As we have mentioned in the introduction, it is connected mainly with the new technology, improvement of the phenomena understanding, and with very perspective applications including a number of fusion programmes (see e.g. [15]). A comprehensive survey of the contemporary results on basic researches in this field can be found, e.g. in the Proceedings of International Conference on Dense Z-Pinches and Applications [3].

Development of applications

Radiation material science

Results on applications in the field of radiation material science look as follows:

1. DPF of several types as well as IBIS plasma accelerator working with different gases and in various (however very powerful) modes, were used for irradiation of some metallic and optical materials by pulsed ion and high temperature plasma streams thus modeling the conditions in fusion reactors with magnetic and inertial plasma confinement. Different austenitic and ferritic steels, carbon based materials, tungsten, vanadium, copper and aluminum alloys as well as sapphire, quarts and topaz were tested. Three typical regimes of the influence of the streams upon the target positioned at the cathode part of PF device were found: “implantation regime” of the interaction ($q \approx 10^5$–10^7 W/cm^2); “detachment mode” of irradiation, i.e. with screening of the sample surface from plasma jet action by a secondary plasma cloud ($q \approx 10^7$–10^8 W/cm^2); and “explosive, or broken implantation” type of irradiation ($q \approx 10^8$–10^{10} W/cm^2) [7].
2. It was shown that the action of ion beams and plasma streams upon a target in Plasma Focus devices can be separated in time and reorganized in their time sequence, whereas their partial energy contribution into the target material damage can be varied and controlled.
3. Comparative damage characteristics were investigated. Among the results received we have:
   - data organization on typical morphological changes produced by radiation – blisters, craters, pores, cracks, ridges, etc., as well as on material phase transformations (see e.g., Fig. 9),
   - detection of higher radiation resistance of quartz in comparison with sapphire and topaz among the optical materials under investigation,
   - disclosure of redistribution of the components at the surface layer of austenitic chromium-manganese steels,
   - finding of absence of blisters, craters and pores on the irradiated non-polished surface of tungsten samples exposed in the same conditions as steels, but appearance of many cracks on it,
   - discovery of low damaging of carbon-based composites (e.g. of SiC type) – contrary to pure carbon, which has been destroyed just in a single shot by shock wave knocking the sample;
   - correlation between the fluence (more specifically surface flux density, expressed in particles per cm^2) of high energy ion stream and the surface density of the structural defects;
   - the advantages of Plasma Focus device application to modify the surface layer in hard-to-reach parts of the treated details, such as internal surfaces of tubes, were demonstrated.

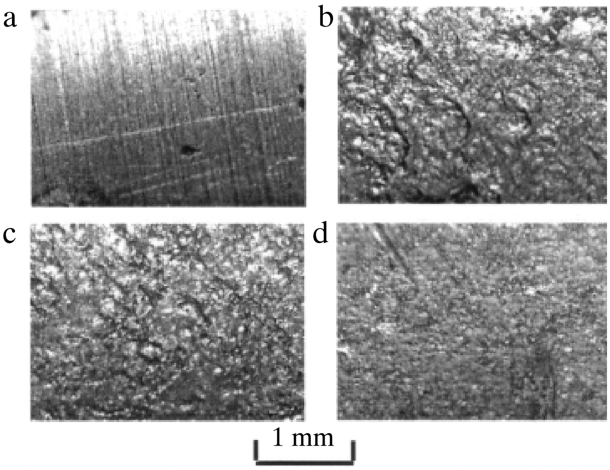

Fig. 9. Topography of the duraluminum surface in the initial state (a) and after 13 ‘shots’ of deuterium plasma pulses: b – specimen #1 (“hot” part), c – specimen #3 (“middle” part), d – specimen #5 (“cold” part) – IMMS.

Positron emission tomography

Positron emission tomography (PET) is one of several methods currently exploiting nuclear physics principles for health – so-called nuclear medicine (NM). PET consists of three elements: production of positron-emitting short-lived isotopes, synthesis of biological molecules labeled with the above positron emitters, and scanning of human body. Experiments have been provided on the first problem [14]. The most commonly used at present time as PET tracers are the isotopes ^{11}C, ^{13}N, ^{15}O and ^{18}F, because they can be introduced into biological molecules without altering the composition of these molecules.

DPF, in which ions are accelerated by collective effects, can be attractive as alternative to cyclotrons for the production of these isotopes, in particular because of its potentially lower cost and lower level of system complexity. Experiments on production of the ^{13}N isotope were made using a reaction: $C^{12}(d,n)N^{13}$. The main objective of the work was to determine the activity induced by fast deuterons impinging into the target and thus to calculate the production with the DPF help of positron emitting isotope ^{13}N. The activity induced in a carbon target after its irradiation was measured. It gives a quantity of MeV ions ejected from PF-150 (20-kJ energy bank): $N \approx 10^{13}$. This result has shown that such a DPF working with a frequency of 10 Hz can produce for the time period of 100 s (1/6 of the half-lifetime of ^{13}N) an amount of this isotope having an activity ca. of 30 MBq. Note that for the tomographic diagnostics of human head with the help of this method the necessary quantity of the isotope determined by its activity is 10 MBq.

X-ray lithography

X-ray lithography in the semiconductor industry may use DPF as a source of soft X-rays (SXR) having a high efficiency (ca. 10%) and a very small size of its radiation zone (200 μm down to 2–3 mm) [8]. It was demonstrated [5] that this source can produce the necessary exposure of the resist with chemical amplification SU-8 for several hundred shots (~500) only at its operation with a repetition rate of 3.5 Hz. This is several times less than the dose necessary for the same aim at the usage of a conventional X-ray tube.

Radiation enzymology

In the experiments on radiation enzymology, different enzymes were irradiated by medium and hard X-rays *in vitro* with various doses, dose power and spectral range of the radiation. In this set of experiments [6], we have confirmed our previous results on a tremendous difference in enzyme activation/inactivation after its irradiation by X-rays from DPF and from a conventional isotope source (γ-source ^{137}Cs). It appears that we have about the same phenomena in both cases but with DPF the effects appear at doses 4 orders(!) of magnitude less, whereas the dose power difference in these irradiation experiments was about 7–8 orders of magnitude.

Radiation medicine

Medium and hard X-rays from DPF were used in radiation medicine. As it is well known, a relativistic electron beam (REB) generated by DPF as a pulse of a bell-like shape in time and having the current much higher than the Lawson limit may be transported inside a tube for a long distances due to back-current generation within the surrounding plasma and in the tube wall. These electrons may be extracted directly from the DPF at the end of the tube through a thin foil. A target made from the material of high Z, when positioned at the end of the tube, will irradiate hard X-rays (HXR) due to its bombardment by the electrons. This HXR radiation as well as the beam itself may be used for the interstitial radio surgery (interstitial brachytherapy).

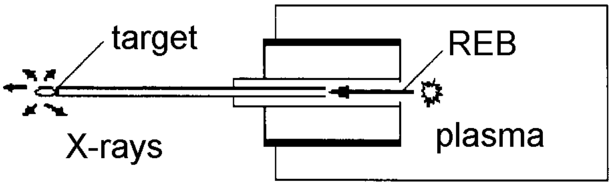

Fig. 10. Experimental scheme of interstitial surgery – FU.

In these experiments, DPF has a pipe attached to the inner part of the anode and having several collimations, which define a target spot of about 5 mm when the target is positioned at 20 cm far from the pinch region (Fig. 10). Experimental results [16] with a tungsten target show that the photons energy spectrum consists mainly of characteristic *L*-shell of energy around 10 keV superimposed by a low intensity bremsstrahlung. A selective *K*-shell ionization performed by using target made of Fe to Cd indicates that the mean energy of the REB is in the range 35–40 keV in this device. The dose delivered in a LiF dosimeter at 10 mm from the X-ray source was estimated around 1 Gy/shot. The dose power greater than 10^8 Gy/s obtained shows that in the usage of the DPF devices with relatively high repetition rate this proposal can be suitable.

Theory and numerical simulations

Computational works as well as analytical theories are the necessary elements of the up-to-day experiments in all stages of the researches – design of installations, optimization of their working regimes, but, in particular, in applications. Examples of activity in this field are presented below.

By numerical simulations the PTI team has analysed the acceleration process of compact mass without losses in a coaxial electrode configuration of the accelerator with a variable capacity battery and muzzle length. Optimized parameters of the accelerator have been chosen. These calculations have been verified in the experiments, which gave a possibility to improve the injector of plasma to a great extent.

The TPU team (Tallinn, Estonia) concentrated mainly their efforts on theoretical stochastic problems including diffusion of the implanted ions within the irradiated samples. To solve this problem, a new method for treatment of the stochastic dissipation rates in the diffusion zone at the superposition of thin material layers was worked out with a dedicated computer simulation program. As a result, it was shown that some interesting phenomena take place in simple onedimensional systems, arising as a consequence of interplay between a nonequilibrium noise, thermal noise, and deterministic force. On this basis, it was found a number of collective effects displayed in these conditions when an "instant" pulse of ions is injected into the bulk of material during a period short compared with the characteristic diffusion time:

1. A resonant behavior of absolute negative mobility at certain values of repetition rate.
2. The existence of a negative differential resistance.
3. For large values of the repetition rate and at low temperatures, the flux is very sensitive to small variation of an external force F – a phenomenon of "hypersensitive differential response".
4. For some parameters, there is a finite interval of the tilting force F where the current is very small compared to that in the surroundings (the effect of "disjunct windows"). It is a new anomalous transport phenomenon for Brownian particles.
5. For the nonstationary cases when a duration of the fast ion pulse is short compared with the diffusion process, it was shown that the distribution of the implanted ions within an irradiated material must peaked inside the bulk of a specimen due to subsequent diffusion of the ions in both directions – inside the sample and outside it through the free surface. It was supported by a subsequent analysis of the irradiated specimens [7].

One of the important conclusions has been made on the basis of analytical examination of an unexpected result received in material science. Experiment provided at a high power flux density irradiation ($\sim 10^9$ W/cm^2) has shown that the higher the number of irradiation "shots" the lower the concentration of the implanted ions inside the examined specimen. This paradoxical result has found its explanation on the basis of a strong damage of the irradiated samples, which convert 2-D sample surface into the 3-D structure. This process increases an effective area of the free surface thus increasing the rate of gas outlet from the sample.

Discussion

Many of the results presented above have found its interpretation on the basis of formulated in the frame of these works pulsed radiation physics and chemistry [11–13] in its perfect sense [6]. By these researches, physics of high energy density was spread out from the surface effects (laser physics) onto the volumetric ones (powerful hard radiation sources). Two conditions must be fulfilled in this case: effective interaction micro-volumes of irradiating particles or of secondary particles (e.g. spurs at water electrolysis) must be overlapped, and this overlapping have to proceed during time interval short compared with the reciprocal process (e.g. diffusion). In this case the interaction will have a nonstationary and nonequilibrium character. In this connection, one particular question arises – whether the nanosecond flashes of X-ray radiation can be used for the low-dose X-ray diagnostics of patients or just contrary to the low-dose X-ray therapy of them? Direct experiments with various bio-materials must be done to solve this problem. One of them is the presented works made in the field of pulsed radioenzymology.

As it is seen from the above materials, the new technology introduced into the DMP field really improves the situation in this field. New devices of "industrial" character of operation are available now. But it is clear that one of the most important features of DPF – high neutron yield produced during nanosecond pulses – is not used yet. One application for this DPF parameter – the easiest one – is the neutron activation analysis. For example, use of elastic and inelastic neutron scattering measured by the time-of-flight method may be applied to the problem of hidden objects search (e.g. at airports). Another challenge is connected with the spread of this source of neutrons and X-rays directly to the fusion field.

First possibility of this kind is related to the neutron tests in radiation material science. Indeed, the above new run-up operational DPF technology might be fitted for a construction of a 0.5–1.0 MJ DPF facility working with a DT mixture in a high repetition mode. In this case, such a device could ensure during the one-year run an overall fluence of the order of 0.1–1.0 dpa with its total and operational costs two orders of magnitude less compared with the IFMIF facility. And what is more such a kind of facility can be constructed in a 3-year period of time. Taking into consideration a possible geometry, it is easy to estimate that 1 dpa can be succeeded during an operational year in a volume of about 1 liter. For this goal, the DPF must work at the level of its well-known scaling [1] with a repetition rate 3–4 cps with the neutron-irradiating zone positioned 0.1 m apart from specimens and having the irradiation area ~ 0.1 m^2.

Second opportunity, which might be explored in this frame, is connected with a very high efficiency of soft X-ray generation in DPF. Indeed, this efficiency reaches in the best devices values of about 10%. And what is more, no any limits or saturation of this yield has been found yet (quite the opposite to the neutron yield). This opens perspectives on the DPF use in inertial confinement fusion for the hohlraum schemes. It seems that it will be interesting to investigate this opportunity at a high level of energy stored in DPF banks because the best present-day pulsed generators of soft X-rays ("Z-machine", Sandia, USA) cannot work in a repetitive mode.

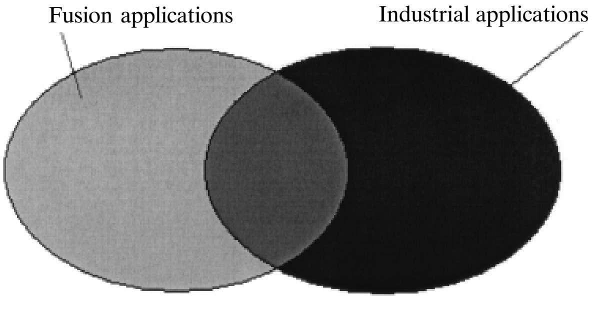

Fig. 11. Actual (black) and possible (light grey) fields of DPF-based neutron/X-ray source use in industrial and fusion applications.

Conclusions

The present-day DMP devices based on the modern high-power pulsed technology can operate reliably with high-power flux density of penetrating radiation. Their applications in fusion programme as well as in pulsed radiation physics and chemistry, been overlapped (Fig. 11), give promising results. Neutron sources based on these devices look attractive and must be tested in applications in the future.

Acknowledgments These works were supported in part during the last three years by grants of the International Atomic Energy Agency, Vienna, Austria, in the framework of the Co-ordinated Research Project "Dense Magnetized Plasma".

References

1. Bernard A, Bruzzone H, Choi P *et al.* (1998) Scientific status of Dense Plasma Focus Research. J Moscow Phys Society 8:1–93
2. Bogolubov EP, Gribkov VA, Dubrovsky AV *et al.* (2005) Use of installations of a Dense Plasma Focus type for material sciences. In: Proc of Inter-Branch Sci-Tech Conf: Portable neutron generators and technologies on its base, 26–30 May 2004, VNIIA, Moscow, pp 81–97
3. Dense Z-pinches (2005) 6th Int Conf on Dense Z-Pinches and Applications, Oxford, UK. AIP Conference Proceedings, vol. 808
4. Dubrovsky AV, Gribkov VA (2000) Installations based on high efficiency high rep rate miniature DPF chambers for material science. Nukleonika 45;3:159–162
5. Gribkov VA (2005) Plasma-focus based radiation sources for nanotechnology. In: Emerging applications of radiation in nanotechnology. IAEA, Vienna. IAEA-TECDOC-1438, pp 233–237
6. Gribkov VA, Orlova MA (2004) On various possibilities in pulsed radiation biochemistry and chemistry. Radiat Environ Biophys 43:303–309
7. Gribkov VA, Pimenov VN, Ivanov LI *et al.* (2003) Interaction of high temperature deuterium plasma streams and fast ion beams with stainless steels in Dense Plasma Focus device. J Phys D 36:1817–1825
8. Lee S, Lee P, Zhang G *et al.* (1998) High rep rate high performance plasma focus as a powerful radiation source. IEEE Trans Plasma Sci 26;4:1119–1126
9. Mather JW (1964) Investigation of the high-energy acceleration mode in the coaxial gun. Phys Fluids 7;Suppl:28–32
10. Petrov DP, Filippov NV, Filippova TI, Khrabrov VA (1958) Powerful pulsed gas discharge in chambers with conductive walls. In: Plasma physics and a problem of controlled thermonuclear fusion reactions. Academy of Sciences of the USSR, Moscow. Vol. 4, pp 170–181 (in Russian)
11. Pikaev AK (1985) Sovremennaya radiacionnaya khimiya. Vol. 1. Osnovnye polozheniya eksperimental'naya tekhnika. Nauka, Moscow
12. Pikaev AK (1986) Sovremennaya radiacionnaya khimiya. Vol. 2. Radioliz gazov i zhidkostej. Nauka, Moscow
13. Pikaev AK (1988) Sovremennaya radiacionnaya khimiya. Vol. 3. Tverdoe telo i polimery, prikladnye aspekty. Nauka, Moscow
14. Scholz M, Bieńkowska B, Gribkov VA (2002) Dense Plasma Focus for applications in positron emission tomography. Czechoslovak J Phys 52;Suppl D:D85–D92
15. Stygar WA, Cuneo ME, Vesey RA *et al.* (2005) Theroretical z-pinch scaling relations for thermonuclear-fusion experiments. Phys Rev E 72:026404
16. Tartari A, Da Re A, Mezzetti F, Angeli E, De Chiara P (2004) Feasibility of X-ray interstitial radiosurgery based on plasma focus device. Nucl Instrum Meth Phys Res B 213:607–610
17. Toader EI, Covlea V, Graham WG, Steen P (2004) High density and low temperature direct current reflex plasma source. Rev Sci Instrum 75:382–386