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DISSERTATIONS ON NATURAL SCIENCES

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MARIAN PADUCH

The Diagnostics Problems at Implementation of Plasma Focus Technique in Material and Environmental Sciences

Abstract

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Institute of Mathematics and Natural Sciences, Tallinn University, Estonia.

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Supervisor: Ülo Ugaste, Doctor Sci. (Physics and Mathematics), Professor emer. of the Institute of Mathematics and Natural Sciences at Tallinn University

Opponents: Matti Laan, Cand. Sci. (Physics and Mathematics), Docent of the Institute of Physics at Tartu University
Tõnu Laas, PhD, Senior researcher of the Institute of Mathematics and Natural Sciences at Tallinn University

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CONTENTS

LIST OF PUBLICATIONS

This thesis is based on the following papers, referred to in the thesis by their Roman numerials I–X.

I. A. Malinowska, A. Szydlowski, M. J. Sadowski, J. Zebrowski, M. Scholz, **M. Paduch,** M. Jaskola, A. Korman 2008. Measurements of fusion-produced protons by means of SSNTDs. – *Radiation Measurements*, 43, S295–S298.

II. V. A. Gribkov, A. Banaszak, B. Bienkowska, A. V. Dubrovsky, I. Ivanova-Stanik, L. Jakubowski, L. Karpinski, R. A. Miklaszewski, **M. Paduch,** M. J. Sadowski, M. Scholz, A. Szydlowski, K. Tomaszewski 2007. Plasma dynamics in the PF-1000 device under full-scale energy storage: II. Fast electron and ion characteristics versus neutron emission parameters and gun optimization perspectives. – *J. Phys. D: Appl. Phys.*, 40, 3592–3607.

III. V. A. Gribkov, B. Bienkowska, M. Borowiecki, A. V. Dubrovsky, I. Ivanova-Stanik, L. Karpinski, R. A. Miklaszewski, **M. Paduch,** M. Scholz, K. Tomaszewski 2007. Plasma dynamics in PF-1000 device under full-scale energy storage: I. Pinch dynamics, shock-wave diffraction, and inertial electrode. – *J. Phys. D: Appl. Phys.*, 40, 1977–1989.

IV. V. Gribkov, A. Dubrovsky, M. Scholz, S. Jednoróg, L. Karpinski, K. Tomaszewski, **M. Paduch**, R. Miklaszewski 2006. PF-6 – an effective plasma focus as a source of ionizing radiation and plasma streams for application in material technology, biology and medicine. – *Nukleonika*, 51(1), 55–62.

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VIII. A. Kasperczuk, R. Miklaszewski, **M. Paduch,** T. Pisarczyk, M. Scholz, K. Tomaszewski 2002. Final stages of the plasma column evolution in the plasma-focus PF-1000 device. – *IEEE Trans. Plasma Sci.*, 30(1), 56–57.

IX. A. Kasperczuk, R. Kumar, R. Miklaszewski, **M. Paduch**, T. Pisarczyk, M. Scholz, K. Tomaszewski 2002. Study of the plasma evolution in the PF-1000 device by means of optical diagnostics. – *Phys. Scripta*, 65, 96–102.

X. P. Kubes, J. Kravarik, **M. Paduch**, K. Tomaszewski, M. Scholz, L. Karpinski, A. Szydlowski, Y. L. Bakshaev, P. I. Blinov, A. S. Chernenko, E. M. Gordeev, S. A. Dan'ko, V. D. Korolev, A. Shashkov, V. I. Tumanov, V. Romanova, D. Klir 2001. Stabilizing of Z-pinch and Plasma Focus discharges due to thick wires. – *Nukleonika*, 46(1), 5–7.

AUTHOR'S CONTRIBUTION

Publication I: The author is responsible for diagnostics experiments, also participated in experiments and interpretation of the results.

Publication II: The author is responsible for measurements neutron emission, for drawing up the methodology of measuring system of the optical diagnostics and the synchronization circuit.

Publication III: The author is responsible for arrangement of the experiments and interpretation of the results of measurements.

Publication IV: The author is responsible for the measurements by high-speed photography and for analysis of experimental results.

Publication V: The author is responsible for high-speed photography observations and for contribution to soft x-ray investigation in plasma focus experiments.

Publication VI: The author is responsible for measurements by shadowgraphy and optical camera.

Publication VII: The author is responsible for contribution to soft x-ray investigation in plasma focus experiments.

Publication VIII: The author is responsible for high-speed photography observations.

Publication IX: The author is responsible for optical diagnostics experiments and for analysis of experimental results.

Publication X: The author is responsible for diagnostics experiments.

ABBREVIATIONS

DPF – Dense Plasma Focus
MHD – magnetohydrodynamic
PCS – plasma current sheath
SW – shock wave
CS – current sheath
DT – deuterium-tritium
CFC – carbon fiber composite
IFMIF – International Fusion Materials Irradiation Facility
ITER – international tokamak research/engineering project, originally was the International Thermonuclear Experimental Reactor
NIF – National Ignition Facility
FWHM – full-width half-maximum
CCD cameras – charge coupled device cameras
PC/AT – personal computer/advanced technology
SXR – soft X-Rays
SPD – scintillation-photomultiplier detector
MCP – microchannel plate
PIN-diode – diode with an intrinsic layer between the P and N-type regions

THE DIAGNOSTICS PROBLEMS AT IMPLEMENTATION OF PLASMA FOCUS TECHNIQUE IN MATERIAL AND ENVIRONMENTAL SCIENCES

Abstract

A new dense plasma focus (DPF) technique developed recently, as well as progress in the understanding of the physics of the processes taking place in DPF devices, have made it possible to create very compact and efficient devices, producing a variety of radiations of high brightness. These radiations – plasma streams, fast electrons and ion beams, X-rays and neutrons – have particle and photon energies much higher than the charging voltage, which makes these devices ecologically attractive. These features open up perspectives for a number of important applications of the DPF technique in several fields, particularly in material and environmental sciences.

At the same time special problems of diagnostics appear at the application of this technique in any definite field as usually the plasma bunches produced in DPF devices are nonlinear, non-stationary, and non-equilibrium objects of a non-reproducible character. For correct implementation of a DPF technique it is necessary to know what has happened during every shot produced by this device. To obtain data on the parameters of a DPF device 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 diagnostic tools have to be used both for the primary plasma torches (pinches) and for the secondary (irradiated target) ones. These features require application of a special diagnostic complex collecting a maximum of parameters in a single shot with the highest possible temporal, spatial, and spectral resolution.

The main goal of the presented studies was to elaborate a set of diagnostic tools able to measure the main parameters of non-steady state phenomena taking place in a DPF device and to clarify the particularity of the plasma and particles' beams dynamics of DPF devices in view of their special implementation in solving material and environmental science problems. As a result of the cycle of experiments described in this work a diagnostics set was created that has a nanosecond temporal and high spatial, angle and spectral resolution. Particularly, the tools worked out and tested include a multi-frames laser interferometer, photomultipliers plus scintillator probes for hard X-Ray and neutron diagnostics, a 4-frame visual camera, a 4-frame soft X-Ray camera and a PIN-diode array for soft and hard X-Ray monitoring.

This set is rather self-sufficient for characterizing all magneto-hydrodynamic and some kinetic phenomena taking place in non-steady state and non-equilibrium plasma produced by a DPF device. It can help in obtaining a large number of parameters of the plasma bunches as well as of fast particles and different types of radiation generated by this facility.

This set of diagnostics has already been successfully used in fundamental investigations in the field of Dense Magnetized Plasmas as well as in various other applications. Important results on plasma/beam dynamics as well as on mechanisms of producting radiation in DPF have been obtained with its help. Together with visible and SXR frame pictures, PIN diode data, and pin-hole camera pictures as well as interferometry can help to reconstruct temperature fields within plasma bunches with resolution in time and space. Being used with polarimetry this method can give information about the magnetic field distribution inside and on the boundary of the plasma column, which in turn can provide data on the distribution of current there.

These diagnostics are very important for monitoring the above radiations in a number of DPF applications, in particular in radiation material sciences and in environmental sciences. They may also be used in other fast plasma installations like exploding wires and laser produced plasma.

DIAGNOSTIKAPROBLEEMID PLASMAFOOKUSTEHNIKA RAKENDAMISEL MATERJALI- JA KESKKONNATEADUSES

Resümee

Uus ja üha suuremat kasutamist leidev tiheda plasma fookuse (TPF) tehnika ise ja edusammud plasmafookuskambrites aset leidvate füüsikaliste nähtuste seletamisel on teinud võimalikuks konstrueerida väga kompaktseid ja efektiivseid seadeldisi, mis suudavad tekitada suure “valgustugevusega” kiirgusi. Need kiirgused – plasma sambad, kiirete elektronide ja ioonide vood, röntgenkiirgus ja neutronid – sisaldavad osakesi ja footoneid, mille energia on palju suurem kui laengupingel, tehes neid kiirgusi emiteeriva seadeldise ka ökoloogiliselt atraktiivseks. Seadeldiste kompaktsus ja efektiivsus loovad võimaluse sellise tehnika rakendamiseks mitmesugustel teadusaladel, sealhulgas ka materjali- ja keskkonnateaduses. Samal ajal ilmnevad selle tehnika rakendamisel erinevatel aladel teatud diagnostikaprobleemid, kuna tavaliselt TPF-seadeldises tekkivad plasmasambad ja osakeste vood on mittereproduktiivse iseloomuga mittelineaarsed, mittestatsionaarsed ja mittetasakaalulised nähtused. Seega on TPF-tehnika korrektseks kasutamiseks vaja teada, mis toimub plasmafookuskambris iga laengulahenduse korral. Et omada andmeid nii TPF-seadeldise operatsiooniparameetrite kui ka kiirete elektronide/ioonide ning plasmavoogude, röntgenkiirguse ja neutronite sähvatuste kohta (nende dünaamika ja kiirus, nurkjaotused, spekter, võimsusvoo tihedus jne), tuleb kasutusele võtta terve hulk diagnostilisi vahendeid nii primaarse plasmasamba (pintš) kui ka sekundaarsete kiiritatud objektide jaoks. See nõuab spetsiaalsete diagnostiliste komplekside olemasolu, mis fikseeriksid iga üksiku laengulahenduse jaoks maksimaalse arvu parameetreid võimalikult kõrge ajalise, ruumilise ja spektraalse resolutsiooniga.

Käesoleva uurimistöö peaeesmärgiks oli välja töötada diagnostiliste vahendite kogum, mis oleks võimeline fikseerima TPF-seadeldises tekkivate mittestatsionaarsete nähtuste peamisi parameetreid ning välja selgitama neis evolutsioneerivate plasma ja osakeste voogude dünaamika iseärasusi, pidades silmas nende seadeldiste kasutamisperspektiive materjali- ja keskkonnateaduses. Diagnostikavahendite väljatöötamiseks läbiviidud eksperimentide tulemusena on loodud vahendite kompleks nanosekundilise ajalise ning nõutava kõrge ruumilise, nurgalise ja spektraalse resolutsiooniga. On välja töötatud ja testitud mitmekaadriline laser-interferomeeter, spetsiaalne stsintillaator-fotokordisti jäiga röntgenkiirguse ja neutronite diagnostikaks, 4-kaadriline visuaalkaamera, 4-kaadriline pehme röntgenkiirguse kaamera ja PIN-dioodide seadis pehme ja jäiga röntgenkiirguse monitooringuks. See kompleks on piisav TPF-seadeldise mittestatsionaarses ja mittetasakaalulises plasmas esinevate kõikide magnetohüdrodünaamiliste ja mõningate kineetiliste nähtuste iseloomustamiseks. Kompleks võib aidata saada suure hulga parameetreid iseloomustamaks nii seadeldise kambris tekkivaid plasmasambaid kui ka kiireid osakesi ja erinevaid kiirgusi.

Väljatöötatud diagnostikavahendite kogumit on juba edukalt kasutatud nii tiheda magnetiseeritud plasma fundamentaalsetes uuringutes kui ka mitmesugustes TPF-seadeldiste praktilistes rakendustes. Nende vahendite abil on saadud olulisi tulemusi nii plasmavoogude dünaamika kui ka kiirguse mehhanismi kohta TPF-is. Koos nähtava valguse ja pehme röntgenkiirguse piltidega võivad PIN-dioodide andmed ja auk-kaamera pildid ning interferomeetria aidata rekonstrueerida plasmasamba temperatuurivälja piisava ajalise ja ruumilise resolutsiooniga. Kui seda süsteemi kasutada koos polarimeetriga, siis võimaldab see meetod anda informatsiooni ka magnetvälja kohta nii plasmasamba sees kui ka äärealadel, mis omakorda aitab luua paremat ettekujutust voolu jaotumise kohta plasmavoos. Loodud diagnostikavahendite kompleks on oluline TPF-tehnika rakendamisel materjali- ja keskkonnateaduses.

PREFACE

Dense Plasma-Focus (DPF) is a gas-discharge installation producing X-Ray and neutron pulses with the quite high total yield being on the level of the best contemporary neutron pulsed sources but having pulses of nanosecond duration – contrary to the classical neutron generators, which produce pulses in the microsecond range. The modern DPF is characterized by several outstanding features such as operation with vacuum-tight chambers with life-time of the device on the order of 10^6 “shots”, having relatively low size and weight, comparatively low cost, possibility to work with a high repetition rate, etc. At the same time for the correct using this DPF technique in several applications it is necessary to have diagnostic tools to measure main parameters of the above radiation types forming in DPF device.

The aim of the studies presented in the thesis was to elaborate a set of diagnostic tools able to measure main parameters of these non-steady state phenomena and to clarify a specificity of plasma and beams dynamics of DPF devices of various scales, especially taking into account implementation of these devices in material and environmental sciences.

In this study several examples of data collected with elaborated diagnostic technique are presented. It is shown that the elaborated set of diagnostic tools is rather self-sufficient for characterization of all magneto-hydrodynamic and some kinetic phenomena taking place in non-steady state and non-equilibrium plasma produced by Dense Plasma Focus device. The presence of such diagnostic tools allows implementation of plasma focus technique in the wide spectra of problems in the field of environmental and material sciences.

The present thesis consists of two major parts. The first presents the summary of papers I–X, where the main results of the studies are drawn out and discussed. In the second part the reprints of the papers are presented.

1. INTRODUCTION

Dense Plasma-Focus (DPF) (Bernard et al. 1998) is a gas-discharge installation producing neutron pulses with the quite high total yield being on the level of the best contemporary neutron pulsed sources but having pulses of nanosecond duration – contrary to the classical neutron generators, which produce pulses in the microsecond range. It may also provide powerful streams of soft and hard X-Rays, hot plasma streams, as well as beams of fast electrons (10 keV…1.0 MeV) and ions (10 keV…100 MeV).

This DPF-based neutron source is *ecologically more acceptable* compared with others because it produces a neutron radiation only "on demand" for a few nanoseconds (a so-called "push-button device"), it doesn't require a special storage, and it uses charging voltage of about 10 kV only (instead of several MV as in the case of classical accelerators of the Van de Graaf type). This modern DPF is characterized by several outstanding features such as operation with vacuum-tight (welded) chambers (so it can be treated as "closed, or sealed radiation source" even when using the radioactive deuterium-tritium mixture as a working gas) with life-time of the device on the order of 10^6 "shots", having relatively low size and weight (0.5…1.0-m^2 footprint and 100–400 kg thus it is a transportable device), comparatively low cost, possibility to work with a high repetition rate, etc.

1.1. The apparatus construction and operational modes

The device belongs to the Z-pinch class. The DPF construction comprises two cylinder metallic coaxial electrodes and operates with a cylindrical insulator positioned at the lower part of the internal electrode (anode). Initial pressure of the working gas is equal to a few Torr. Temporal evolution of the discharge undergoes as a rule the following several phases.

The first stage is a gas breakdown developing along the exterior of a cylindrical insulator. This surface discharge (Borisov, Khistoforov 2000) takes from a few through a hundred ns and bears non-equilibrium kinetic (K) character (acceleration of initial charged particles, streamers, avalanche, etc. (Pejovic et al. 2002)).

The second one is of a magneto-hydrodynamic (MHD) nature. It is an inverse pinch, when the plasma sheath expands from the insulator to the cathode bars, being stable all the time.

The third one, being relatively long (several microseconds for medium- and large-scale facilities), is also mainly of an MHD nature (Filippov et al. 1971). It starts after the second stage with supersonic plasma acceleration by an azimuth magnetic field of the discharge current and matures with implosion of the plasma onto the Z-axis of the chamber. There are two types of electrodes systems of DPF – the Filippov's configuration, where plasma accelerates to the chamber's Z-axis radially along flat anode immediately after the second stage, and the Mather's one where plasma accelerates first next to the anode tube elongated up to Z-axis and only after this stage it turns around the edge of the tube and implodes radially. The speeding up plasma (plasma-current sheath – PCS) is contained during its movement to the chamber's axis between a shock wave (SW) in front of it and a current sheath (CS) behind the SW. The discharge current at this time is subdivided inside the DPF chamber into four non-equal parts (Gribkov et al. 1990; Gribkov et al. 1976; Gribkov 1976):

1) Current flowing along the front of the SW.
2) Skin-layer current at the back side of the PCS (constituting the main part of the current, which is established in this device during the so-called "working regime of DPF operation" after passing through a set of conditioning shots); it pushes PCS to the chamber axis.
3) Residual current flowing behind the PCS throughout low-density plasma, which has been non-completely captured by the PCS; this current turbulizes the residual plasma and produces the "third type of insulation" – isolation of the main part of current flowing within the PCS and later on through a *pinch* (dense plasma column) from the surrounding residual plasma.
4) Remnant current on the insulator surface (which is not present in some DPF devices).

However this phase also bears an evidence of some kinetic phenomena (Gribkov et al. 1976; Gribkov 1976), viz. micro-turbulence within the skin-layer of PCS, making the sheath more rigid in relation to the flute instability from the side of short wavelengths, runaway electrons accelerated both at the front of the converging quasi-cylindrical shock wave and within the PCS, and turbulence of residual plasma.

This stage is completed first by a convergence of the SW on Z-axis (singularity line for the azimuth magnetic field) accompanied (in the case when deuterium is used as a working gas) by runaway of its part of the current. These fast runaway electrons ("runaways") form a thin filament near Z-axis (of a diameter equal to circa SW front) and produce medium-energy X-Rays (with energy of photons about 30…50-keV) (see e.g. Gribkov et al. 1976; Gribkov 2000). Then, some tens of ns later, this phase finishes by the maximum plasma compression on the chamber axis Z, with confinement of this *pinch* plasma during circa 100 ns. This phase is accompanied with plasma cooling due to radiant and electron conductivity. Soft X-Ray radiation (of about 1-keV photon energy) is produced during this process. It is clear that during this period, known in literature as a so-called "first compression" stage, three "pinches" in fact exist (Gribkov 2000):

1) "Current pinch" occupying the biggest diameter (~ 10 cm) and including in itself almost total discharge current (seen by magnetic probes and due to Faraday rotation measurements)
2) "Dense plasma pinch" (~ 1 cm) containing dense plasma imploded about the chamber axis (seen by interferometry) and carrying circa 70% of the discharge current; and
3) "Bright plasma pinch" (a few mm of diameter), which is positioned about the Z-axis and usually related to current/plasma filamentation (runaways) taking place near this line of the magnetic field singularity and seen by soft X-Ray pin-hole camera.

The next stage is a short-lasting event of a kinetic (K) character (a few tens/hundreds nanoseconds) (Gribkov et al. 1976; Gribkov 1976; Gribkov 2000; Gribkov et al. 1990; Gribkov 1993). It starts from the so-called "current abruption" phenomenon when the pinch is disturbed by Rayleigh-Taylor instability provoking in turn various micro-instabilities. These non-linearly coupled instabilities, practically instant (during time period much less than 1 ns), substitute the classical collisional current within the pinch by the collisionless stream of fast electrons having characteristic energy of several hundred keV. The latter *fast electron beam* generates hard X-Ray radiation on the anode (Filippov et al. 1971; Gribkov 1976; Gribkov 2000; Petrov et al. 1958; Mather 1965). Then these fast electrons are magnetized, and the whole current is carried mainly by fast ions (Gribkov et al. 1987) having spectrum extended to several MeV.

The first MHD phase forms a "target" – hot ($\leq$ 1 keV) compressed ($\leq 10^{19}$ cm^{-3}) plasma, whereas during the second one (K) the powerful beams of fast electrons and ions are generated and start to interact with plasma and electrodes. A noticeable part of the fast ion stream composed of "medium" energy particles (usually in the range 50…150 keV) is captured by a magnetic field of the pinch and confined within the plasma "target" for a period of about 10 drift times of them (Krompholz et al. 1977; Jäger, Herold 1987). Interactions of these ions – both Coulomb and direct fusion ones – with the above-mentioned plasma target (at the operation of DPF with deuterium or deuterium-tritium – DT – mixture as a working gas) results in neutron emission (Krompholz et al. 1977; Jäger, Herold 1987; Bogolyubov et al. 1998). Energy E_c, released from capacitors to the discharge, is in the range from just a few Joules to circa 1 Mega Joule (MJ).

1.2. Spheres of DPF applications

At the present time there is a rapidly increasing field, which includes various applications of *small-* and *medium-size* DPF installations. The new high-current technology (Bogolyubov et al. 1998) introduced in these devices provides an opportunity for their reliable exploitation with a high repetition rate (up to tens cps) and ensures their long life-time (circa 10^7 discharges) (Lee et al. 1998). According to our experience at least 3 modern elements have to be introduced in any new DPF device of a small or large scale: capacitors of the assembly similar to KMK type, pseudo-sparks as a main switches, and DPF chambers manufactured by means of e-beam or laser welding having no any rubber o-rings (Bogolyubov et al. 1998; Lee et al. 1998).

Such a device may be used as a source of radiation of various types for goals of semiconductor industry (projection and proximity X-Ray lithography, micromachining), biology and medicine, but in particular in *material sciences*, and for resolving a number of *ecological problems* (Lee et al. 1998; Tartari et al. 2004; Scholz et al. 2002a; Sadiq et al. 2006; Rawat et al. 2003; Gribkov 1993).

In *radiation material sciences* it may be applied for researches of such problems like testing of materials intended for use in nuclear fission and fusion reactors. These tests are provided by the irradiation of specimens of these materials (tungsten, CFC, beryllium, low-activated stainless steels, ceramics of various types, etc.) with powerful streams of hot plasma, fast electron and ion beams, neutrons and X-Rays generated by DPF. The device may be also used in this filed for modification of surfaces of the above materials with aims of increasing their radiation, corrosion and tribology resistance. It was shown that the device can form different nanostructures on the sample's surfaces by their plasma/ion beam irradiation.

In *environmental sciences* Dense Plasma Focus devices may be utilized in the *express Neutron Activation Analysis* for characterization of different (supposing poison or dangerous) materials. For this aim a single-shot Nanosecond Impulse Neutron Investigation Systems (Gribkov, Miklaszewski 2005) might be applied. It would also be interesting to investigate DPF applications for pulsed low-dose water sterilization, in different medical and biological works, etc.

As to the fame of the *big* DPF facilities, it is based on the fact that the large-scale DPF might be a very intense and efficient neutron-producing device. The main interest to the installation on its highest energy level operation is connected with a favorable scaling law for neutron production yield – $Y_n \sim E_c^2$ or $Y_n \cong 10^{10} I_p^4$ (sometimes $Y_n \sim I^5$ (Bernard et al. 1998), in particular for the same device (Gribkov 2000). The scaling type is valid for deuterium as a working gas, where I is a discharge current, and I_p is the part of a total current, which *flows through the dense plasma pinch*, measured in MA. The transition to the operation of a DPF with the deuterium-tritium mixture produced an increase in the neutron yield by a factor of circa 100 (Bernard et al. 1998) compared with pure deuterium-operated devices. This means that on the level of a 10-MA current a DPF might produce the same neutron yield as modern pulsed fission reactors differing from them however by much shorter neutron pulse duration – few hundreds of ns – and by almost monochromatic spectrum centered near 14 MeV. This would open opportunities for many applications in science (e.g. in neutron spectrometry due to a very high "quality" of the source, $q \geq 10^{37}$ [neutrons per second^{-3}]) and technology (e.g. in radiation material sciences). It looked in the middle of 70's of the previous century as a very promising opportunity for the efficiency of neutron production namely of large facilities having a high value of E_c. However, later on the investigations carried out with the biggest devices of that time revealed that a certain limit existed for bank energy, above which the scaling law with those installations was not fulfilled (Herold et al. 1989). Apart from the failure of fusion perspectives, even now this experimental fact is a serious preclusion for a particular use of a big DPF. We mean their possible exploitation as a powerful source namely of *fusion* neutrons for material sciences, viz. as the source for testing of materials perspective for the first wall components and construction elements in the magnetic confinement fusion and, especially, in the inertial confinement fusion reactors (where the neutron interaction with materials will be of the "explosive-like" type – the same as within a DPF).

Indeed, the present day expectations in this field related to the IFMIF facility (http://www.frascati.enea.it/ifmif/) are based on a powerful high energy deuteron accelerator (about 40 MeV, 0.5 A). It is thought that it will be able to ensure, during a one-year irradiation term, the neutron fluence on the levels from 0.01 till 50 displacements per atom (dpa) in various zones positioned near a target having the area 5×20 cm^2. The value of 1 dpa corresponds to the irradiation e.g. of iron-based specimens (counted as the perspective ones for a fusion reactor (Gribkov et al. 2003) with the *mean* neutron flux $4.5 \cdot 10^{16}$ n/m^{2}s during a year. 1 dpa is approximately equal to a total fluence of 10^{21} neutrons per sm^2 for Be- and C-based materials. The total cost of the IFMIF is estimated to be above the level of 10^9 US$ with the operating cost of circa $6 \cdot 10^7$ US$ per year. Projected construction time of this notable facility is about 10 years.

However the above new run-up operational DPF technology might be fit for a construction of an effective 0.5-1.0 MJ DPF facility (thus on the level of present-day devices) working on DT mixture with a current of the order of 5.5…6 MA and in a high repetition mode. The cylindrical shape of the plasma neutron source in this device will be characterized by a diameter of 1 cm with a length of 10 cm. 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 above-mentioned. And what's more this kind of facility can be constructed and put into operation in a 3-year period of time. Thus this device might easily fill the niche between *fission* reactors (having no proper neutron spectrum), used at the moment for the above purpose, and IFMIF. But to reach this aim the neutron yield of the DPF of a few hundred kJ must follow the above scaling law $Y_n = 10^{10} I_p{}^4$ for deuterium as a working gas (where I_p is the current *flowing through the pinch*, measured in MA).

It means that if in the facility of the PF-1000 type (Scholz et al. 2000) the pinch current would be about 6 MA its neutron yield will exceed 10^{13} of 2.5-MeV neutrons/pulse. It will give $>10^{15}$ for the 14-MeV neutrons at the operation of the DPF with the deuterium-tritium mixture as a working gas. Taking into consideration a possible geometry of the near-pinch anode part of the DPF of this energy level it is easy to estimate that 1 dpa can be succeeded during an operational year in a volume of about 1 liter with the irradiation area ~ 0.1 m^2. For all that a PF must work with a repetition rate of 3-4 cps with the irradiating zone positioned 0.1 m apart from specimens. During a one-year run main parts of the device (capacitors and switches) will be changed 10–20 times. These figures for a facility, designed with the use of the above-mentioned new technology, look feasible since for several years we have already DPF devices working with a repetition rate 3-16 cps (Lee et al. 1998) whereas with our recent PF-6 device (Gribkov, Miklaszewski 2005) we reached current circa 760 kA and neutron yield Y_n about 10^9 neutrons per pulse with deuterium as a working gas with 4 capacitors having the overall energy bank E_c = 7 kJ only. According to our experience in scaling law for bank parameters the above-mentioned figures might be expected for the same type of DPF-based neutron test facility on the level of a few hundred kJ.

2. OBJECTIVES

As for the above-mentioned saturation of the DPF neutron yield several phenomena, responsible for the effect, were found during the last two decades. To our meaning it is possible to get over these difficulties.

But there is something more in this sphere. This project in the field of radiation physics and chemistry of material science (in the case of a success in the above scaling) could be aimed to develop a new field within the area. Namely, it might ensure radiation tests at *heightened* conditions thus *shortening* the test periods of candidate radiation resistive materials (e.g. beryllium, tungsten, ceramic composites, austenitic and ferritic steels, lithium, etc.), being designed to meet the needs of fission and fusion power engineering, space industry and accelerator technology.

In fact, in the field of radiation tests of materials there is a unique opportunity to shorten period of testing session. Indeed such a device enables to ensure a *peak* power flux density of neutron radiation in the range 10^{23} n/cm^{2}s (or its energy density up to 10^{10} J/cm^3). It is even much higher for *e*- and *i*-beams as well as for plasma streams generated by DPF. Thus it seems to be tempting in such experiments to produce, just during a few shots, a whole number of the same effects as under exploitation of classical radiation devices *for years* when operated at the much lower working power flux density. And what's more, many major problems can be investigated here – atoms displacements, blistering, erosion, redeposition and material migration, fuel recycling and retention, etc., possibly during a very short period of time. It seems that it would also generate material-specific activation and radiological property data, and support the analysis of materials for use in safety, maintenance, recycling, decommissioning, and waste disposal operations.

Thus potentially it can give an opportunity to sustain a rate of the materials' investigation and their selection (e.g. for space vehicles and fusion devices like ITER, NIF or Z-machine) in a proper time regime in relation to fusion program development. But of course for this aim a so-called "*damage factor*" should be established: $F \sim qt^{1/2}$ (where q is power flux density and t – pulse duration of radiation), i.e. a dependence of both damage degree and its nature (side by side with other interaction effects) on power flux density, i.e. on energy and pulse duration of penetrating radiation. A dependence of the damage factor on elemental contents of materials should also be investigated as well.

As one may see from the above-mentioned fields of scientific activity connected with the Dense Plasma Focus facilities, there is a room for investigation of different transient events taking place during a discharge cycle both in DPF plasma and at the surfaces of targets illuminated by different types of radiation generated by the device. Such researches might help both in promoting of the small- and middle-size DPF applications in various fields as well as in supporting of improvements of the present-day large facilities and in the development of new generation of DPF with higher energies.

The main aim of the present work was to elaborate a set of diagnostic tools able to measure main parameters of these non-steady state phenomena and to clarify a specificity of *plasma and beams dynamics* of DPF devices of various scales.

This set of diagnostic tools includes the following elements:
1. multi-frames laser interferometry,
2. photomultipliers plus scintillators probes for hard X-Ray and neutron diagnostics,
3. 4-frames visual camera,
4. 4-frames soft X-Ray camera,
5. PIN-diode array for soft and hard X-Rays monitoring.

All these diagnostics have about 1-ns temporal and high angle and spectrum resolution, which is very important for characterization of fast transient physical phenomena taking place in DPF plasma.

3. STUDY AREAS

3.1. DPF devices

In our experiments we use mainly two Dense Plasma Foci – the PF-6 device and the PF-1000 facility (see Fig.1 a) and b) respectively). In some experiments the PF-150 device (operated in the energy range of its bank from 20 to 60 kJ) was exploited.

The PF-6 device (Gribkov, Miklaszewski 2005) has a capacitor bank with energy content up to 7 kJ, and its maximal current reaches the value 760 kA. This set-up can produce up to 10^9 2.45-MeV neutrons per shot. The repetition rate of the device is up to 1 cps.

The PF-1000 facility (Scholz et al. 2000), manufactured on the base of the corresponding technology of 70-s of the previous century, has nevertheless one the largest bank in the world (operating on the energy level about 1 MJ) with the discharge chamber exploiting deuterium as a working gas.

It consists of the following main units:

- vacuum and gas assembly which includes vacuum chamber (right-hand side of Fig. 1) with coaxial electrodes and vacuum/gas handling systems
- condenser bank positioned on two other levels of the building ($E_c \cong 1.056$ MJ at initial charging voltage up to $U_0 = 40$ kV) and pulsed electrical power circuit with high-pressure spark-gaps, low-inductance coaxial cables, a collector (left-hand side of Fig. 1 b) and a control room.

a) b)

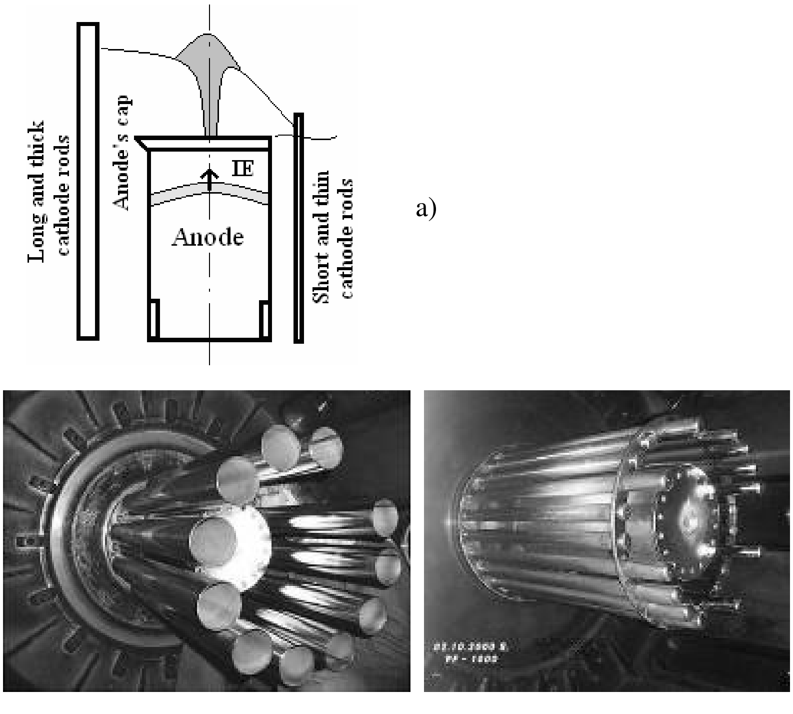
Figure 1. The PF-6 (a) device and the discharge chamber of the PF-1000 (b) facility

After the engaging of the spark-gaps, energy, which has been stored in the bank, is transferred by means of coaxial cables through the collector to electrodes of DPF chamber. The vacuum chamber, which contains the electrodes, has a large volume (1400 mm in diameter and 2500 mm in length).

Two families of electrode geometries differing essentially by their inter-electrode gaps, lengths and shape were used in this set of experiments. The copper *anode* has a diameter 230 mm with a length of 600 mm. This anode had on the top of it a cap, which in two dissimilar types of experiments had a diameter equal to or slightly larger than the anode tube itself (Fig. 2*a*). In the second case the protrusion of the cap outside of the anode tube was manufactured as a circular hat-shaped “tooth” on its end (in fact the anode cap was of a radius 1 cm larger than the anode cylinder itself). Its primary destination was to grasp excessive metallic debris possibly produced and entrained by the current sheath from the anode on its way to the Z-axis of the DPF chamber. But it constitutes a small obstacle for a shock wave (SW) pushed by a magnetic field of a current sheath (CS). This SW stumbles on the obstacle when arriving to the edge of the anode.

Fig. 2*b* is an example of the first type of the *cathode* electrode system. It is made as a squirrel cage which consists of 12 stainless-steel rods each of 40 mm in diameter and of an 800-mm in length, distributed around a 400 mm diameter circumference. In Fig. 2*c* we show a second type of a squirrel cage cathode – 24 stainless steel rods 32 mm in diameter and with a length of 600 mm. They were distributed also around a 400 mm diameter perimeter with the same anode and insulator. As it may be seen from Fig. *2a* (left side), *b* the cathode rods in the first case are much longer than the anode. In the second configuration (Fig. 2*a* – right side, *c*) some of them are equal to the anode's length with the others being slightly longer (by a value of 2 times less than the pinch's length). The cylindrical alumina insulator sits on the lower part of the anode. The main part of the insulator extends 113 mm along the anode into the vacuum chamber. The condenser bank of capacitance 1320 μF (264 capacitors having 5 μF capacitance and 40 nH inductance each) was charged in these experiments to the voltage U_0 varying between 20 to 40 kV, which corresponded to discharge energies E_c ranging from 264 kJ to 1056 kJ. Usually the bank was exploited on the level of 810 kJ and 35 kV, respectively.

In our last set of experiments with PF-1000 compared with previous researches (Rager 1981; Herold et al. 1988; Scholz et al. 2002b; Schmidt et al. 2002) the energy increase was made by the bank *capacitance* increase (*not* by a voltage rise as was made previously with those devices). And, as circuit/chamber matching demands, the electrodes dimensions were increased in relation to the previous ones in an attempt of harmonizing external and internal inductances of the gun and equalizing the current quarter of the period with the plasma collapse time. This device operates with a rate not higher than 1 "shot" per 10 minutes.



a)

b)

c)

Figure 2. Electrodes set up (*a* – scheme of two variants – left and right – of cathode roads and a cap of the anode, and their pictures – *b* and *c*)

3.2. Experimental diagnostics arrangement

Scheme of the optical diagnostics set-up installed at the PF-1000 facility is shown in Fig. 3. To study the MHD evolution of plasma, a three/four frame optical camera with exposure time of about 1 ns was employed (see Fig. 4). The delay between the subsequent frames is in the range of 10–20 ns. An interference filter (λ_{max} = 593 nm, FWHM = 6 nm) recording only continuum radiation far from spectral lines was put into the optical path of the passive optical diagnostic subsystem.

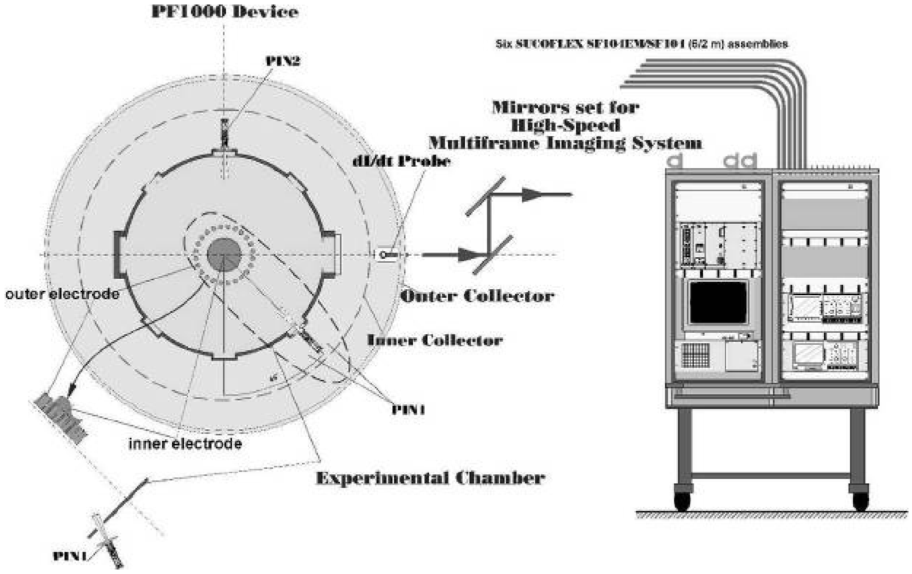


Figure 3. Scheme of the experimental set-up

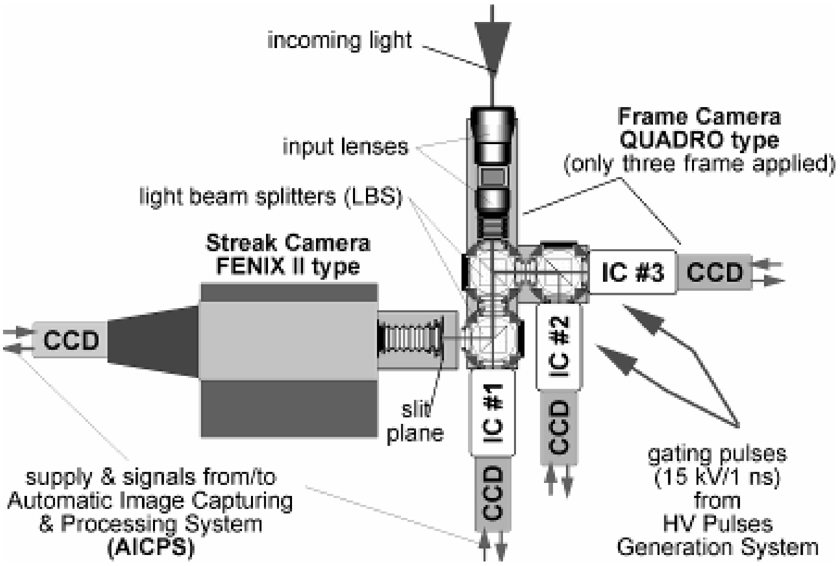


Figure 4. General layout of the passive optical diagnostics subsystem

In addition to this diagnostics visible streak camera was also used. In this camera its slit was positioned perpendicular to Z-axis of the chamber. It ensures measurements of the radial plasma CS and SW speeds and gives information on the implosion symmetry.

Side by side with these passive optical diagnostics we have elaborated an active method based on laser interferometry. Scheme of the system where we have applied this active laser probe is presented in Fig. 5.

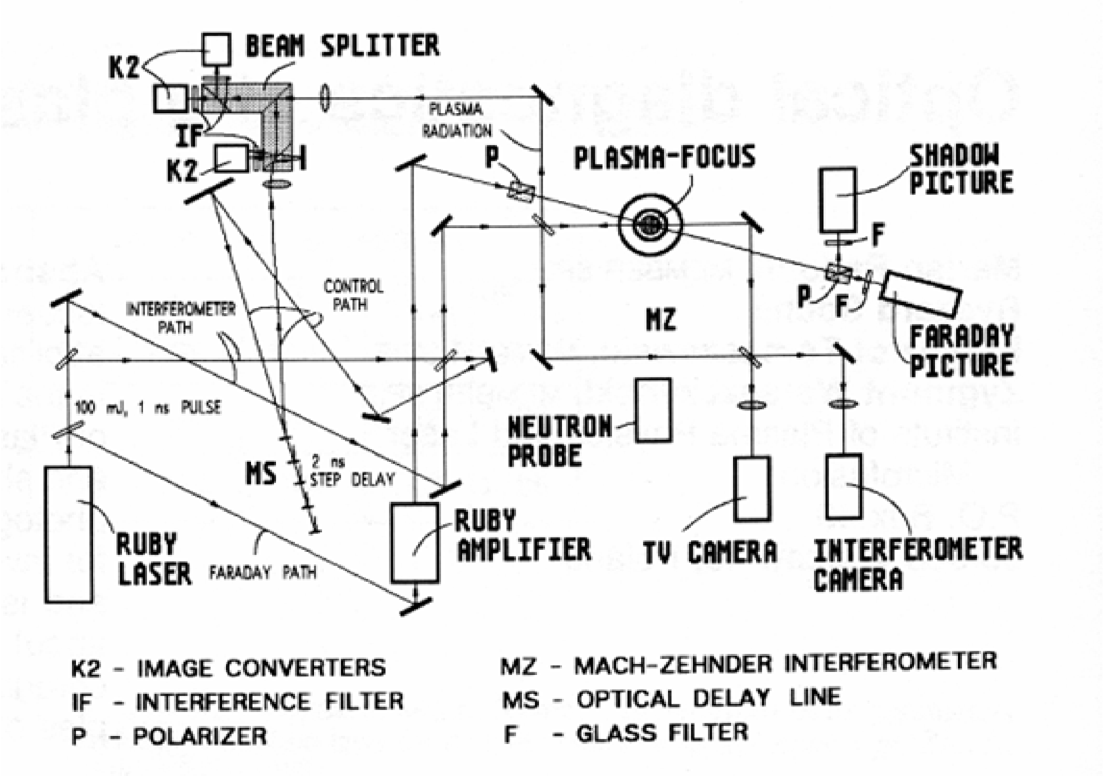


Figure 5. The system of optical diagnostics with the laser probe

We used a pulsed ruby laser with pulse duration about 1 ns and the Mach-Zehnder interferometer. A multi-frame system uses a special optical delay line to separate each frame both spatially and temporally. The inter-frame pause was varied 5 to 20 ns, and up to 4 interferograms can be registered in a single DPF shot. The same laser source was also used for multi-frame shadowgraphy and, with a polarizer, for the Faraday rotation measurements.

All diagnostic methods described above give images as their output. The essential information existing in such a two-dimensional image must be extracted using an image-processing technique. In the past, the images were registered on the photographic film and then they were processed using various methods. The resulting data for final computations of the desired plasma parameter contained errors enhanced by manual or semi-automatic handling. Both error minimization and a general simplification of the measurements become possible due to an automatic image capture and processing system developed by us. Together with the enhanced version of the image convertor cameras as well as of the interferometer and the polarimeter, the system can operate in a fully automatic way with 10 independently settled channels.

The whole active optical system shown in Fig. 5 consists of the following parts:

1) A pulsed ruby laser of 100 mJ energy and 1 ns pulse duration, applied here as the light source for interferometer and polarimeter, and also for triggering the spark gaps in the synchronization system
2) An optical system for expending and shaping the laser beam for the interferometer and polarimeter
3) A Mach-Zehnder interferometer of aperture 100 mm, which ensures the registration of both interferometric and shadow photos
4) A polarimeter for measuring the Faraday rotation angle
5) An electro-optical frame camera with three independently triggered and exposed image convertor tubes
6) A 10-channel image capturing and processing system, containing CCD cameras, multiplexed frame grabbers, and a PC/AT compatible controller
7) A synchronization system enabling proper time relations between all diagnostics and the DPF discharge.

Since all images obtained in the system are captured in an automatic way, all outputs of the diagnostics have their own CCD cameras connected to a single channel of the image acquisition system. This is the main difference between contemporary systems and systems applied in the past. This solution is described below in more detail.

Image acquisition is base on a TV signal that is not as fast as the changes in the images being registered. It can be used for imaging only 25 frames per second (CCIR standard). To enable use of the TV signal in high-speed photography, we applied a special synchronization and gating circuit, together with single-image-converter cameras used as the primary image sensors in the image acquisition system. The general scheme of the automatic system for image capture is shown in Fig. 6. Specialized and expensive cameras can be used in such systems, but we used simple CCD cameras of high sensitivity (MINTRON MTV-1801CB). They operate in continuous mode, are synchronized from a common source, and look on screens of electro-optical frame modules. The images appearing on the screens in the short time interval are digitized, each in its own frame grabber (VISIONETICS VFG-512-8BC). The frame grabber digitizes images with a resolution of 512×512 pixels, of 256 intensity levels, and are connected to the common 10-channel multiplexer (named MULTIGRAB and developed by us). The multiplexer is controlled by a PC/AT compatible microcomputer and operates as the part of the synchronization scheme. Each frame grabber has its own video memory, enabling capture of the full image in real time.

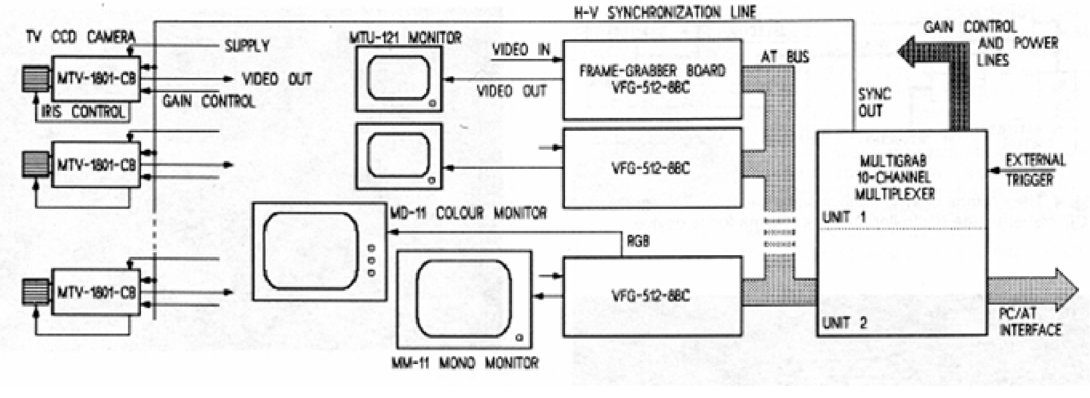


Figure 6. Scheme of the 10-channel automatic image capturing and processing system

Synchronization between all diagnostics and the DPF phenomena with an accuracy of about 1 ns or better is not a simple task. The non-repeatable nature of all processes under study does not allow use of a series of successive shots to observe temporal evolution of a phenomenon with good accuracy, which is why the synchronization is so important here. We developed the scheme shown in Fig. 7, which fulfills all the demands mentioned above.

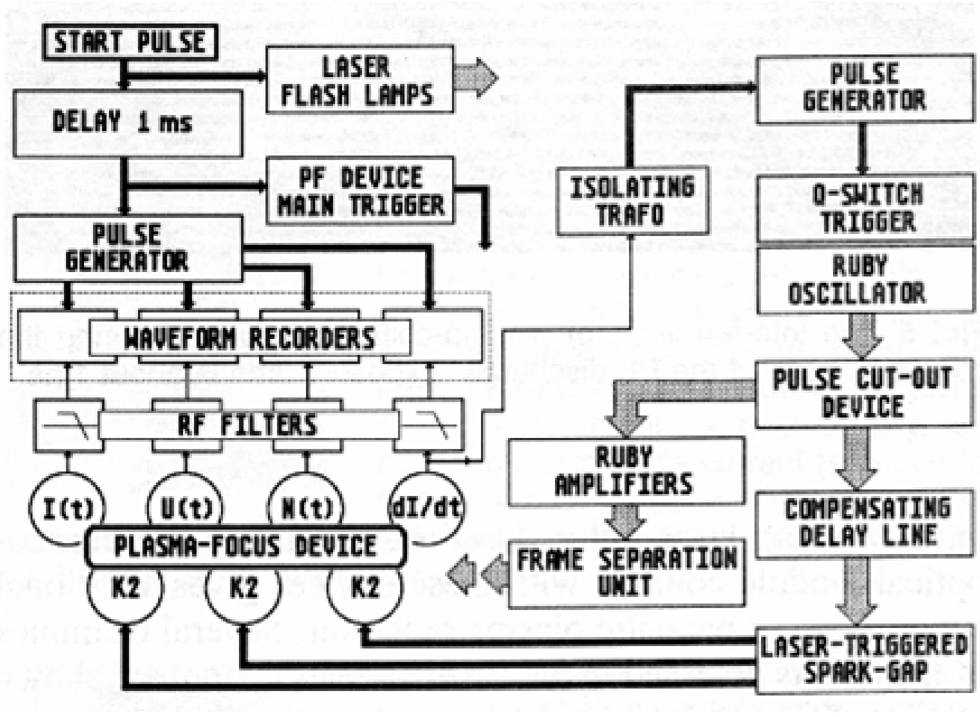


Figure 7. Synchronization circuit used in the investigation of DPF diagnostics systems by means of optical diagnostics

Two main parts can be distinguished in the synchronization system: the first one is used for rough synchronization and the second – for fine adjusting of the time relations between the operations of each diagnostics device. The rough synchronization is achieved in the classical way – by means of a high-voltage electronic delay lines and triggers connected to the DPF operating systems. It operates with accuracy not more than 10 ns. To enhance this accuracy and to obtain the proper timing of the whole arrangement, the electro-optical and pure optical devices are used in the system, i.e., the laser-triggered spark gaps and optical delay lines. They ensure, for example, that the moment when the diagnostic beam of the interferometer is passing through plasma is the same as the moment of opening of the electro-optical frame camera (with sub-nanosecond precision). Timing is verified by an additional optical delay line, which is coupled with one of the electro-optical modules. The part of the diagnostic beam passing through the line generates a number of light spots on the image. Both the position of the spots and their quantity determine the temporal relation between the interferograms and the plasma image, which is so essential in temperature measurements (Kasperszuk et al. 1989). The measurements carried out using the system described here has shown that about 80% of shots are synchronized perfectly and about 50% of them can be used in a subsequent data processing procedure.

To synchronize the slow TV signal with the DPF phenomenon and with the controller the additional synchronization circuit was developed. It is shown in Fig. 8.

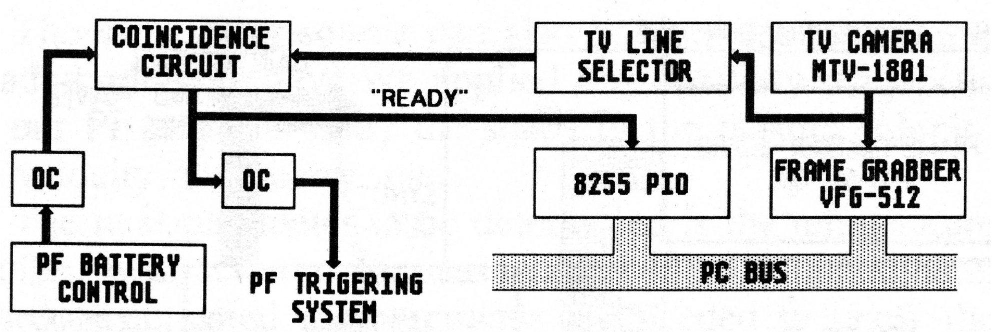


Figure 8. Scheme of synchronization between the TV signals from CCD cameras, the controller, and the DPF device

The triggering signals are electrically separated from the DPF device by means of opto-couplers. The TV line selector is the main part of this synchronization sub-system. The program in the controller sequentially checks the presence of the "READY" signal on the parallel input/output board input. When this signal appears, the program instructs all frame grabbers through the multiplexer to capture the first incoming TV frame. Such an operation allows the short-time image to be captured within the wide time interval even within the TV field. The electro-optical camera acts here as a high-speed shutter with its exposure time controlled by its own circuit. For the interferometer or the polarimeter, this exposure time is determined by the laser pulse duration. At the same time use of the electro-optical module coupled with these devices gives additional suppression of parasitic plasma radiation.

The special data processing system was elaborated to acquire images from CCD cameras and to extract from the images all necessary data. The imaging system is controlled by MULTIX, the software package designed by us to interface with the operator and to acquire images from all CCD cameras used in the measuring system. The MULTIX is also used for preliminary image processing during the experiment and for advanced post-processing of image files stored on the system disc. The package has a user-friendly interface based on screen windows, pull-down menus, and graphics.

The preliminary image processing includes main operations on image memory in the frame of grabbers, buffering the image files in the controller memory, filtering the images when a lack of one of the TV-fields appears in the captured image (caused by the nature of the readout of the CCD chip used in the camera), and storing the images to disc.

The advanced image processing includes more sophisticated filtering of image's noise (median filters and averaging low-pass filters or other filters based on Fourier transform). After filtering, the image can be processed in the way required by a particular diagnostics method. The images are registered in the side-on direction to the Z-axis of the device (plasma column), hence the Abel transform must be applied to the image's data (Kasperszuk et al. 1978). E.g. in the case of interferograms, the image data are first used to obtain the phase shift of the entire field of view and then to solve Abel transform. In such a case, the Fourier transform can be used to derive a distribution of the phase shifts immediately from the interference pattern (Takeda et al. 1982). Side by side with the optical diagnostics described a number of methods for investigation of hard ionizing radiation produced by DPF were developed. In particular, a very careful investigation of X-Rays generated by DPF was undertaken.

Two types of the *four-frame soft X-Ray* (SXR) cameras have been applied in order to obtain plasma images in soft X-Ray range – one based on an open microchannel plate (MCP) device

(Fig. 9) and another just a time-integrated pin-hole camera with an X-Ray film registration. Regardless of construction details the first camera has an MCP and phosphor screen, divided into four electrically independent sectors. The screen is attached to a fiber optics plane-plate separating the vacuum inside the camera from the atmospheric pressure outside. Each sector is gated by a single (positive) electrical pulse with amplitude of 5-6 kV applied between a phosphor screen and the input side of MCP, which is connected to a common ground. Its activation is produced for a time interval 1 ns with a delay of 10…20 ns with regard to others.

The MCP is charged automatically through capacitor divider formed by a gap between MCP and MCP-screen. After applying a voltage pulse to any sector, SXR radiation is converted into an electron flow, which is amplified inside MCP and converted by a phosphor screen into visible light outgoing from a fiber optic plate. Both SXR cameras were used *side-on* to Z-axis.

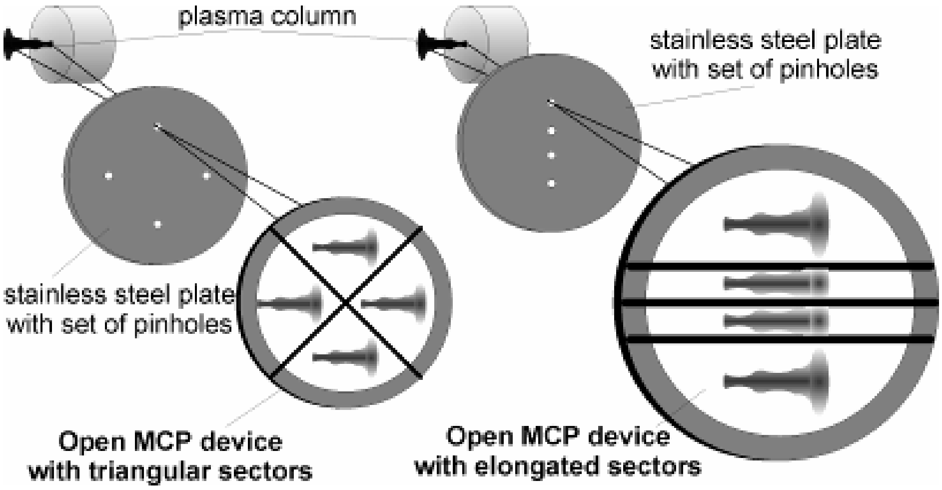


Figure 9. Schematic diagram of the set up of the four-frame soft X-Ray camera

Time-resolved measurements of soft X-Ray (SXR) radiation was also made by means of PIN diodes covered with different filters. E.g. one of them was blocked by a 10-μm Be foil, therefore the diode sensitivity covered the range 0.8…10.0 keV. Their temporal resolution is about 1 ns. One of these signals from a PIN diode was used for synchronization purposes and for the determination of temporal relation between the SXR radiation of the plasma and the frame images recorded by means of optical and X-Ray diagnostics.

For investigation of soft X-Rays side by side with the above four-frame camera and PIN diodes we elaborated time-integrated pin-hole cameras and X-Ray spectrometer. This spectrometer can register time-integrated emission spectra of highly charged ions using a focusing spherical technique with two-dimensional spatial resolution and with different magnification of images.

For investigation the neutron production process by measuring its time evolution, the anisotropy and the absolute neutron yield we elaborated a kit of diagnostics tools on the basis of both time-integrated methods and time-resolved registration of neutron pulses. It may be applied at different angles to the electrode axis. The total neutron yield (Y_{tot}), i.e. the number of neutrons produced during a single discharge (“shot”) and emitted in various directions, was measured taking into consideration the data received by means of five silver-activation counters (SC) placed on equal distances at different angles around the PF-1000 experimental chamber.

Five scintillation-photomultiplier detectors (SPD), located at different angles to the Z-axis of the DPF chamber – head-on (0°), side-on (90°), and back-on (180°) – all of them placed at different distances from the electrode outlet – were used to perform time-resolved measurements of the hard X-Ray radiation and neutron emission, pulses of which were separated on the oscilloscope traces due to the corresponding time of flight. Their time resolution was 5 ns. Special electrical and optical synchronization arrangements allowed the synchronizing of all diagnostics with the PF phenomenon with a temporal precision of 5 ns.

The above systems being used simultaneously in a single shot of a DPF device can give important information on macroscopic dynamics of plasma and beams, as well as on parameters of plasma blobs, soft and hard X-Ray radiation, neutron flux, the fast electron and ion beams generated by the device with high temporal, spatial and spectral resolution.

4. RESULTS AND DISCUSSION

4.1. Some examples of data collected with the diagnostics technique

In this chapter some examples of data collected with the above described diagnostics technique are presented (Ref. I–X). In Fig. 10 one may see a sequence of the several four-frame images of pinch plasma taken each in a single shot in a visible range and collected by time delay. Such picture can give a macroscopic behavior of plasma evolution during the discharge as well as dimensions and shapes of plasma bunch in various moments of time (i.e. “plasma confinement time”). By these pictures it is possible to deduce various Magneto-Hydrodynamic (MHD) Instabilities, e.g. the Raleigh-Tailor instability (see 2nd and 3rd rows) with its increment, typical wavelength sizes, etc. The enlarged pictures (Fig. 10 d) and in particular displayed in pseudo-colors (Fig. 11) can give some additional information on distribution of brightness throughout the plasma blob as well as small details related to a certain kinetic phenomena taking place during the final stage of plasma development.

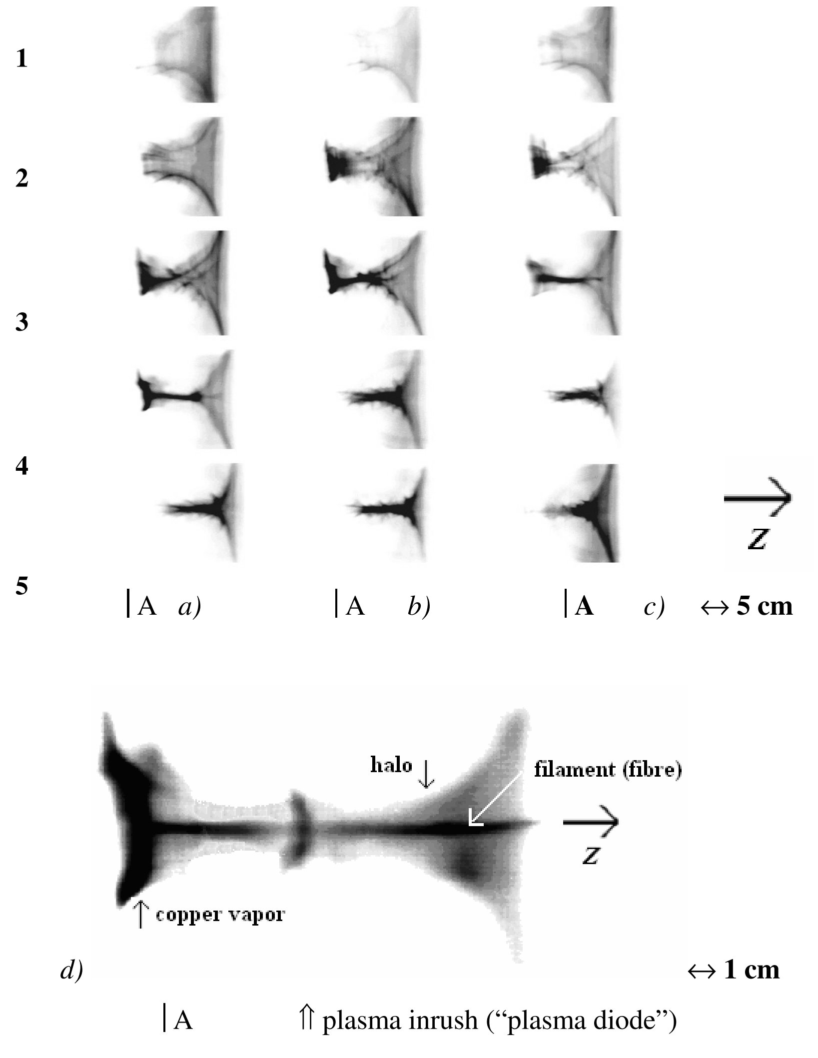


Figure 10. A set of visible frame camera pictures of pinching dynamics (time sequence develops from the left to the right: *a), b), c)* and from the top to the bottom of the picture 1 through 5 with “A” – anode position) and *d)* – an enlarged example of the pinch with “filament”, “halo”, “plasma diode” and copper vapors at the anode surface; PF-1000 facility

Such 1-ns time exposure pictures can also give important information on beams generated inside the DPF and on their interaction with targets placed on the way of the beams for various applications (Fig. 12 – the radiation material experiment devoted to radiation tests of specimens designed for future nuclear fusion reactors). In these picture one may see shape of the plasma streams (semi-spherical) and fast ions beams (conical one), their internal structures (central stem of the above beam and horizontal moving striations). It is possible to measure a speed of these striations. One may also investigate a secondary plasma plum produced on the surface of the specimens by these plasma and fast ion streams.

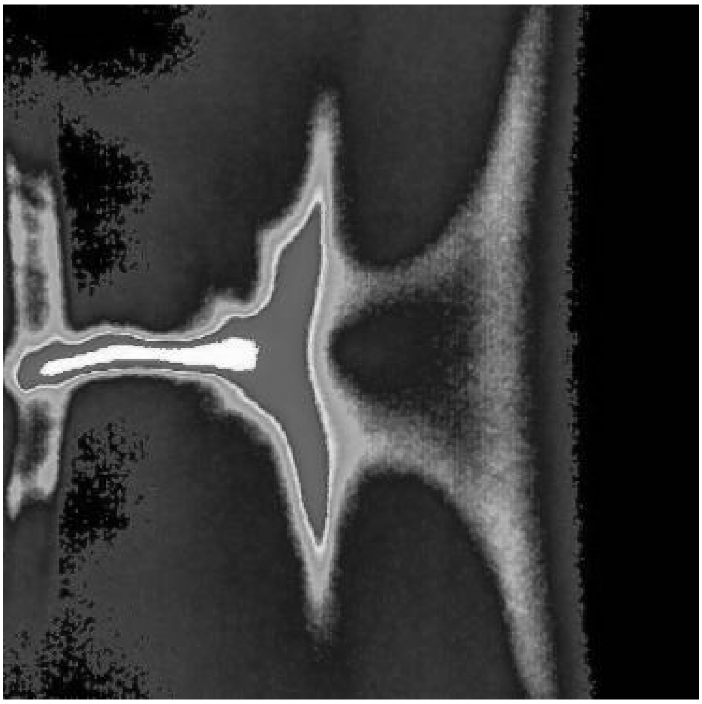
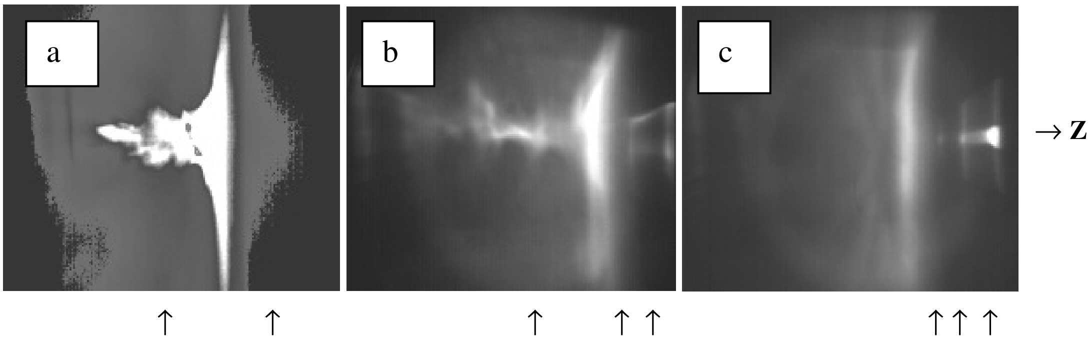


Figure 11. Pinch at its maximum compression presented in pseudo-colors



Pinch Hemispherical shock wave
a)

Plasma diode Ion beam with 2 “discs” (striations)
b)

Ion beam with 3 “discs”
c)

Figure 12. 1-ns frame pictures taken in visible range for 3 different shots and demonstrating a shock wave produced by a cumulative stream during the plasma pinching *(a)* and an ion beam structure as it appears after the current abruption phenomenon *(b)* and *(c)*

Interferometry can deliver information on electron density distribution and on its evolution in plasma during the DPF discharge (see Fig. 13).

Figure 13. Typical interferogram taken at the moment close to maximal plasma compression

The 3- or 4-frame pictures taken in the soft X-Ray range can provide information on zones occupied by hot plasma as well as on their evolution in time (Fig. 9 and 14).

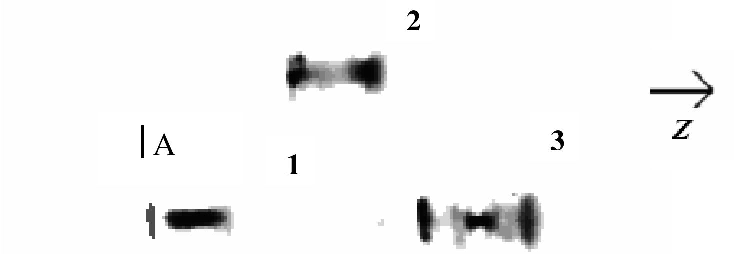
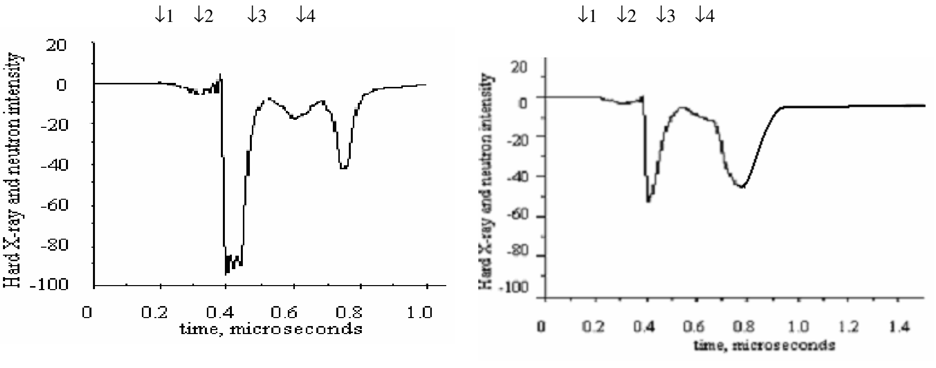


Figure 14. 3-frame picture of evolution of the plasma zone irradiating in the soft X-Ray range (1-ns time exposure)

Oscilloscope traces taken by the help of photomultipliers with scintillators (see Fig. 15) can provide data on duration of neutron and X-Ray pulses as well as on their intensity, spatial and spectral distribution, etc.



a) b)

Figure 15. Hard X-Ray (1st and 2nd pulses) and neutron signals (3rd and 4th pulses) being taken by SPD positioned at 0°, i.e. for neutron emission propagating along the direction of Z-axis (head-on – *a*) and at 90° (side-on – *b*) to Z-axis accordingly.

In combination with oscilloscope traces taken by other detectors (electrical probes – Rogowski coil, voltage divider, magnetic probes, Cerenkov detectors, PIN diodes, etc.) the can help to deduce a temporal sequence of transient events taking place in DPF during time interval of generation of its main radiations (Fig. 16).

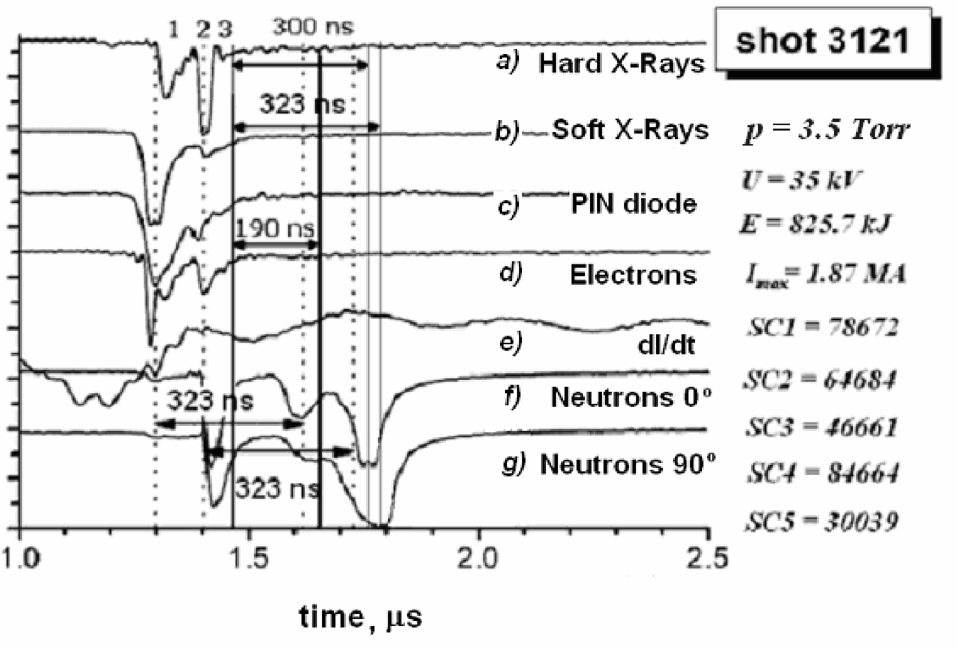


Figure 16. Typical set of registered signals illustrating correlation of various signals versus temporal evolution of neutron emission with its anisotropy data

4.2. Information on plasma and radiation obtained with the diagnostics systems

Processing procedure applied to data of the types demonstrated in the previous chapter can provide a very wide set of data on plasma and beams' parameter with resolution in time, space and wavelengths necessary for interpretation of quite complicated and non-stationary and non-equilibrium phenomena taking place in Dense Plasma Focus devices (published mainly in Ref. III, IV, IX & X) .

E.g. the Abel transform used (as it was mentioned above) in the case of interferometric pictures may help to obtain a two-dimensional distribution of the electron density in plasma bunches. Together with the visible and SXR frame pictures, PIN diode data, and pin-hole camera pictures as well the interferometry can help to reconstruct temperature fields within the plasma bunches with resolution in time and space. Being used with polarimetry this method can give information of magnetic field distribution inside and on the boundary of plasma column, which in its turn can provide data on current distribution there.

Information received with the help of SPD and neutron activation counters, being used in collection with data on plasma density and temperature, as well as with data on dynamics of plasma and beams of fast ions can help in reconstruction of mechanisms of neutron generation in DPF. In particular to make a choice in favor of one of two mechanisms currently under discussion: "moving boiler" and "beam-target".

In the experiments with wires (exploding wires, liner compression, etc.) these diagnostics can help to investigate symmetry of the target compression, stability of plasma produced, etc.

It is hard to overestimate the role of these diagnostics in *monitoring* main parameters of plasma, beams of fast particles and radiations (X-Rays and neutrons) in works where DPF is used for industrial, ecological, and bio-medical application. Exact data on the parameters of the above radiations are necessary not only for characterization of effects under investigation but also for forecasts the effects, which can be expected at higher energies and in different conditions.

CONCLUSIONS

As a results of the cycle of experiments provided in this work on elaboration of diagnostic systems a set of diagnostics was created having nanosecond temporal and high spatial, angle and spectral resolution. Particularly, it was worked out and tested multi-frames laser interferometer, photomultipliers plus scintillators probes for hard X-Ray and neutron diagnostics, 4-frames visual camera, 4-frames soft X-Ray camera and PIN-diode array for soft and hard X-Rays monitoring.

This set is rather self-sufficient for characterization of all magneto-hydrodynamic and some kinetic phenomena taking place in non-steady state and non-equilibrium plasma produced by Dense Plasma Focus device. It can help in obtaining a large number of parameters of the plasma bunches as well as of fast particles and different types of radiation generated by this facility.

These diagnostics are very important for monitoring of the above radiations in works devoted to a number of DPF application, in particular in radiation material sciences and in environmental sciences. They may be used in other fast plasma installations like exploding wires and laser produced plasma.

This set of diagnostics has been already successfully used as in fundamental investigations in the field of Dense Magnetized Plasmas so in various application. Important results on plasma/ beam dynamics as well as on mechanisms of radiations production in DPF have been obtained with its help.

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DIAGNOSTIKAPROBLEEMID PLASMAFOOKUSTEHNIKA RAKENDAMISEL MATERJALI- JA KESKKONNATEADUSES

Kokkuvõte

Tiheda plasma fookuse (TPF) seade kujutab endast gaaslahendus-installatsiooni, mis on nii röntgenkiirguse kui ka mitmesuguste osakeste (sealhulgas neutronite) impulss-allikaks. Seejuures näiteks neutronite koguväljund on samas suurusjärgus nagu parimatel nüüdisaegsetel neutronallikatel, kuid erineb viimastest selle poolest, et impulsside kestus on mõõdetav nanosekundites tavaliste mikrosekundi pikkuste impulssidega võrreldes. Nüüdisaegsetel TPF-seadmetel on mitu eelisomadust. Nende vaakumkambritega opereerivate installatsioonide “eluiga” on võrdne suurusjärgus 10^6 “lasku”, mille suurus, kaal ja hind on suhteliselt väikesed. Samal ajal on TPF-tehnika korrektseks kasutamiseks vajalik kasutada diagnostikariistu mõõtmaks TPF-seadmes formeeruvate kiirguste peamisi parameetreid, kusjuures iga rakendusala puhul peavad need vahendid olema erinevad.

Käesolevas töös läbi viidud uurimuste eesmärgiks oli välja töötada ja testida diagnostilisi vahendeid, mis võimaldaksid mõõta TPF-seadmetes esinevate mittestatsionaarsete protsesside põhilisi parameetreid ning välja selgitada plasma ja kiirguse dünaamika eripära mitmesuguse suurusega installatsioonides, võttes arvesse eelkõige nende seadmete kasutamisvõimalusi materjali- ja keskkonnateadustes.

Diagnostikasüsteemide väljatöötamise eesmärgil läbi viidud eksperimentide tulemusena on loodud kõrge ruumilise, nurgalise ja spektraalse ning nanosekundilise ajalise resolutsiooniga diagnostikavahendite kompleks. See kompleks on piisav iseloomustamaks kõiki magnethüdrodünaamilisi ja mõningaid kineetilisi nähtusi, mis leiavad aset TPF-seadmes tekkivas mittestatsionaarses ja mittetasakaalulises plasmas ning ta võimaldab mõõta suurt hulka nii fokuseeritud plasma enda kui ka TPF-seadme genereeritud kiirete osakeste ning mitut tüüpi kiirguse parameetreid.

Selline diagnostika on äärmiselt vajalik mainitud kiirguse monitooringul mitmesuguste TPF-tehnika rakenduste juures, eriti materjaliteaduses ning keskkonnauuringutega seotud eksperimentides.

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