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CURRENT STATUS OF THE MAGNETOPLASMA COMPRESSOR DEVICE IN BELGRADE – STUDY OF PLASMA FACING MATERIALS IMPORTANT FOR FUSION REACTORS

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ABSTRACT

The magnetoplasma compressor, a quasi stationary plasma accelerator, is a source of supersonic compression plasma flow. High plasma parameters of compression flow, large flow velocity and discharge duration enable their efficient usage for development of new plasma technologies, including material surface modification, creation of sub microstructures and nanostructures. In this paper spatial and temporal distribution of emissivity was studied using inverse Abel transform. This has been realized in LabVIEW environment. The plasma flow generated by quasi stationary plasma accelerators can be used for simulation of high energy plasma interaction with different materials of interest for fusion experiments. Surface phenomena are results of specific conditions during plasma flow interaction with target surface. As the next step in our research, spectral analysis of the plasma area around targets surface, after interaction between target and plasma, generated by magnetoplasma compressor, is planned. The first material which will be subjected to interaction with plasma will be a carbon fiber – material of big importance for divertor region in fusion devices.

KEY WORDS

magnetoplasma compressor, Abel inversion spectroscopy, materials of interest for fusion devices

CLASSIFICATION

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INTRODUCTION

The magnetoplasma compressor is a source of supersonic compression plasma flow (CPF) [1-4]. It represents a magnetoplasma analog of a Laval nozzle. This is a quasi stationary plasma accelerator with semitransparent electrode system which operates in an ion current transfer regime [3].

There are few advantages of the MPC as compared with the other types of accelerators: high stability of CPF generation, controllability of discharge composition (different gases and their mixtures), size (up to 6 cm in length and 1 cm in diameter) and plasma parameters (electron density up to $4 \cdot 10^{23}$ m^{-3} and temperature up to 20 000 K), as well as the discharge time duration sufficient for practical applications (up to 80 μs) [4]. It was found that CPF parameters predominantly depend on discharge current. The plasma parameters 'follow' the discharge current time evolution. This dependence is a measure of plasma flow stationarity [4]. High plasma parameters of compression flows (electron density and temperature close to 10^{23} m^{-3} and 20 000 K, respectively) together with large flow velocity (close to 100 kms^{-1} in hydrogen and 40 kms^{-1} in nitrogen) and discharge duration (stable CPF close to 50 μs) enable their efficient usage for development of new plasma technologies, including material surface modification [5, 6], creation of sub microstructures and nanostructures, etc. MPC is of great importance for the study of fundamental processes in plasma flows and their behavior in different configurations of electric and magnetic fields. Such systems and their plasma flows are also successfully used in different plasma technologies.

Plasma interaction with materials is important for fusion investigations. In fusion devices, the first wall and divertor plasma-facing components (PFC) must provide adequate protection of in-vessel structures, sufficient heat exhaust capability and be compatible with the requirements of plasma purity [6]. ITER will combine long pulse, high power operation with severe restrictions on permitted core impurity concentrations and, in addition, it will produce transient energy loads on a scale unattainable in today's devices. Intense thermal loads in ITER and other fusion devices which occur during ELMs (edge localized modes), plasma disruptions and VDEs (vertical displacement events), will result in macroscopic erosion associated with the formation of cracks, melting, droplets, evaporation or sublimation [7]. The main goals of plasma surface interaction investigation are simulation the expected ELM and disruption loads in ITER and other fusion devices. The plasma flow generated by quasi stationary plasma accelerators can be used for simulation of high energy plasma interaction with different materials of interest for fusion experiments.

Generally, our research program is devoted to the construction of two stage quasi-stationary high current plasma accelerator (QHPA), a combination of four MPC – compact geometry units [3]. QHPA will be used to produce fully ionized plasma at the entrance of the acceleration channel of QHPA. Such systems are the new generation quasi-stationary plasma accelerators. These accelerators are sources of quasi stationary compression plasma flows in which the duration of the compression stable state is much longer (∼100-1000 μs) than the flight time of the plasma in the acceleration channel of the one MPC-CG accelerator (1-5 μs).

This article contains an overview of the research activity on the Belgrade MPC device, some of our new experimental data as well as plans for future steps.

EXPERIMENTAL SETUP

The electrode system of the MPC [3] (shown in Figure 1) consists of a conically shaped copper central electrode (cathode) with radius 3 and 0,6 cm, length of 5 cm and with a divertor on the top. A cylindrical outer electrode (anode) is made of eight copper rods (0,8 cm in diameter and 14 cm in length), symmetrically positioned along the circle of 5 cm in diameter. A conically shaped cathode of the MPC defines a profile of the acceleration channel. The discharge device of the MPC-CG is situated in a 30×30×150 cm^{-3} vacuum chamber.

It has been found that the current cutoff, which limits the increase in the parameters in the case of classical plasma accelerators operating in the electron current transfer, can be avoided by switching to the ion current transfer [1]. Ion-drift acceleration of the magnetized plasma is realized using specially shaped accelerating channel [1]. The reduction of erosion of the electrodes is important task and because of that cathode of the MPC should not only be specially shaped, but also made of rods to be shielded by the self-magnetic field and therefore protected from the erosion.

Experimental setup consist of vacuum chamber within the MPC is positioned, optical system, Minutmen spectrometer, ICCD camera and PC, as well as of systems for voltage and current measurement. The most important part of experimental setup is schematically shown in Figure 1.

In the inter-electrode region the plasma is accelerated due to the Ampere force F_{Az}. Plasma flow is compressed due to the interaction between the longitudinal component of current I_z swept away from the discharge device, and the intrinsic azimuthal magnetic field $B_{\varphi z}$ as well as due to the dynamic pressure of the plasma flow converging to the system axis F_{Ar}. This is shown in Figure 2a.

There are four phases of the discharge development. In the first phase discharge breakdown takes place and plasma is accelerated along the cathode conical part. Second phase consist of radial plasma compression and relaxation of the accompanied plasma flow oscillations. Third phase is quasi-stationary state of compression plasma flow and in fourth part the compression plasma flow is in decay which is followed by after-glow effects. These four phases are shown in Figure 2b.

Figure 3 shows a part of time evaluation of discharge. These images have been made by using ICCD camera as detector and SpectraSuits software. SpectraSuite is a spectroscopy software program which can be used to capture and analyse spectral data from light sources with the use of a spectrometer. The width of spectral line is largest at the beginning of discharge (~ 10-20 μs) and after that the line width is narrower.

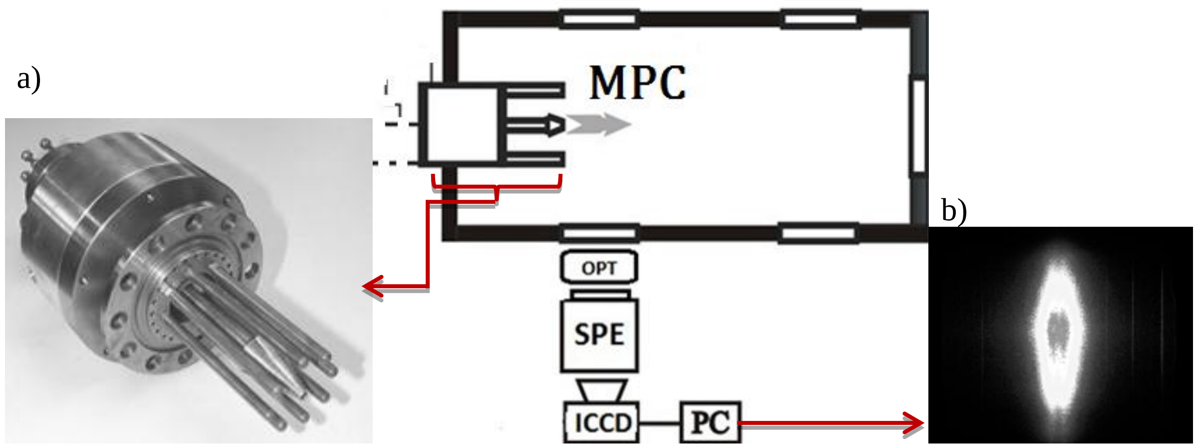
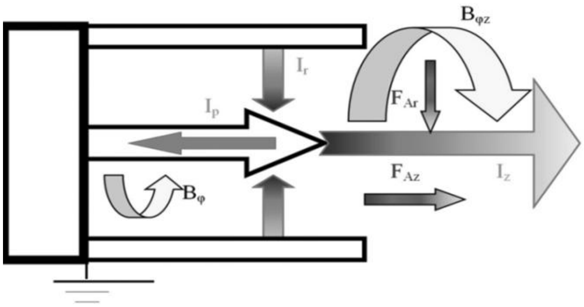


Figure 1. Experimental setup: OPT – optical system, SPE – Minutemen spectrometer, a) magnetoplasma compressor of compact geometry, b) image of plasma on a computer.

a)



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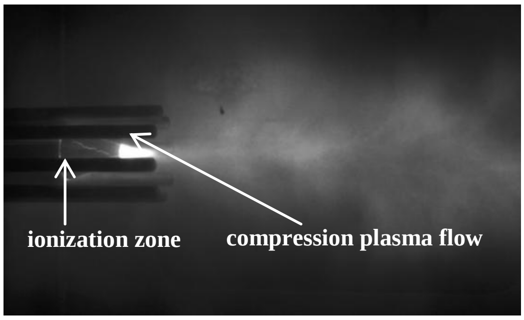

Figure 2. a) compression of plasma flow, b) image of plasma flow photographed with camera using the violet filter.

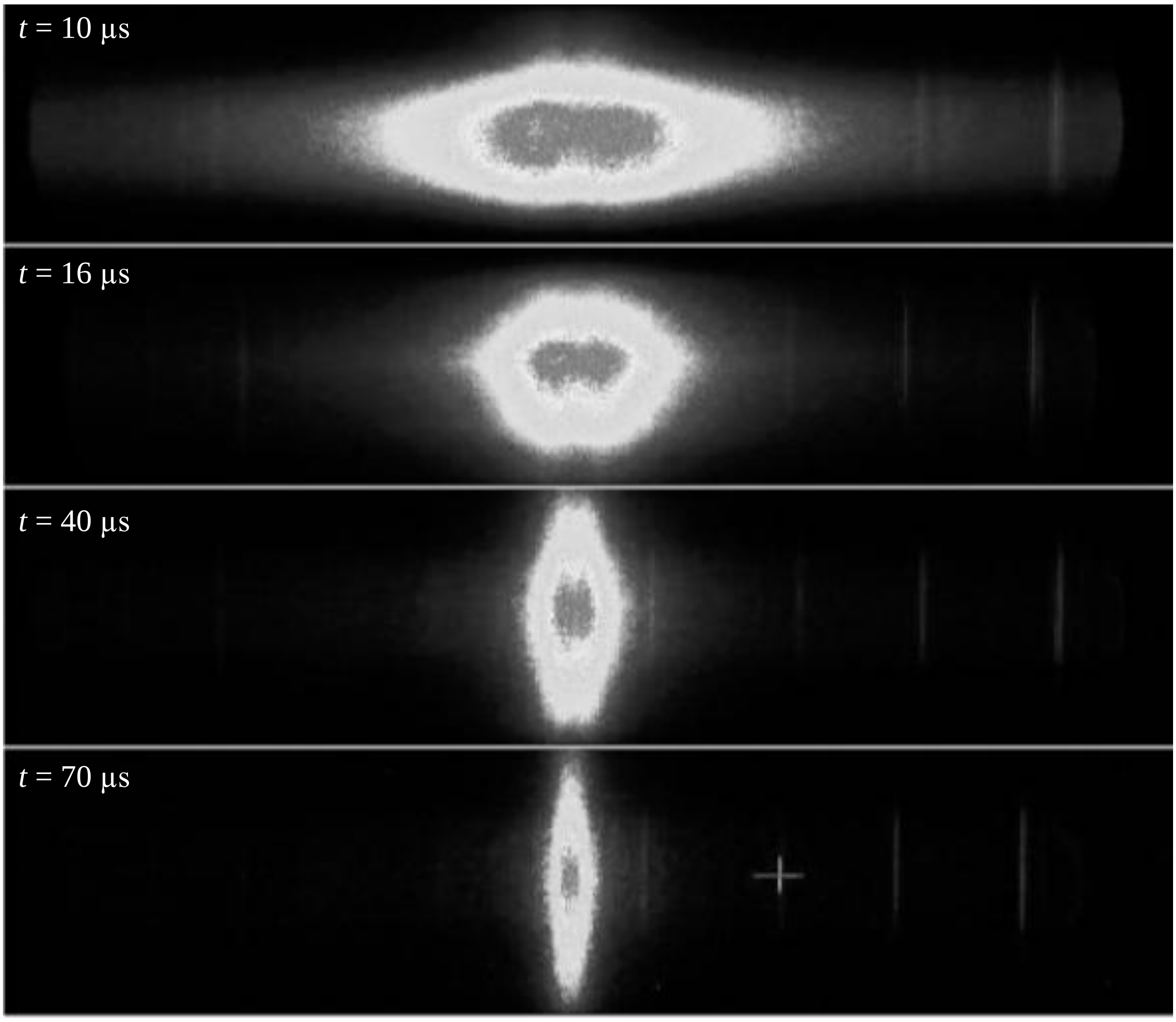

Figure 3. H_β (486,1 nm) recorded by ICCD camera, shown in SpectraSuit program.

RECENT EXPERIMENTAL RESULTS

Several papers were devoted to the study of different MPC characteristics. The electric and thermodynamic parameters of the discharge and the plasma flow created in different gases and their mixtures (hydrogen, nitrogen, argon and Ar with 3 % of H_2) have been measured to optimize the working conditions within the 100-3000 Pa pressure range for input energy up to 6,4 kJ [3, 4, 7].

Recent research activities are related with possibility of MPC usage for investigation of high energy plasma interaction with different materials of interest for fusion experiments.

RADIAL DISTRIBUTION OF EMISIVITY

During experimental determination of radial distribution of emissivity, working gas was hydrogen (100 %) at pressure p = 10 mbar and temperature $T \approx$ 40 000 K.

According to well-known correlation between local emissivity and measured intensity,

$$\varepsilon(r) = -\frac{1}{\pi}\int_r^R \frac{dI(y)}{dy}\frac{dy}{\sqrt{y^2 - r^2}}, \quad (1)$$

radiation profile can be found at any position along the radius of plasma if inverse Abel transformation is done. This was performed using a LabVIEW program for determining confidence intervals of Abel-inverted radial emission profiles [8]. This program works with random noise generation. One additional program has been written for data organizing and processing.

For finally analysing of data it is important to know from which point of y-axis the radiation comes. Because of that, it was necessary to calibrate the system. That has been done by using a small source of radiation: PEN-light which is Hg source, heights h = 3,8 cm and λ = 435 nm as line of interests (Figure 4).

Value of one pixel in nm can be found by:

$$n = \frac{3.8 \text{ cm (y axis)}}{190 \text{ piksel}} = 0.02 \frac{\text{cm (y axis)}}{\text{piksel}} \quad (2)$$

Figure 5 shows integral profile and radiation profile at one selected position along the radius of plasma.

Time evolution of emissivity at one chosen position is shown in Figure 6.

These radiation profiles have been used for determination of spatial and temporal distribution of electron concentration. One of the obtained profiles, electron concentration dependence on radius at t = 30 μs, is shown in Figure 7.

a) b)

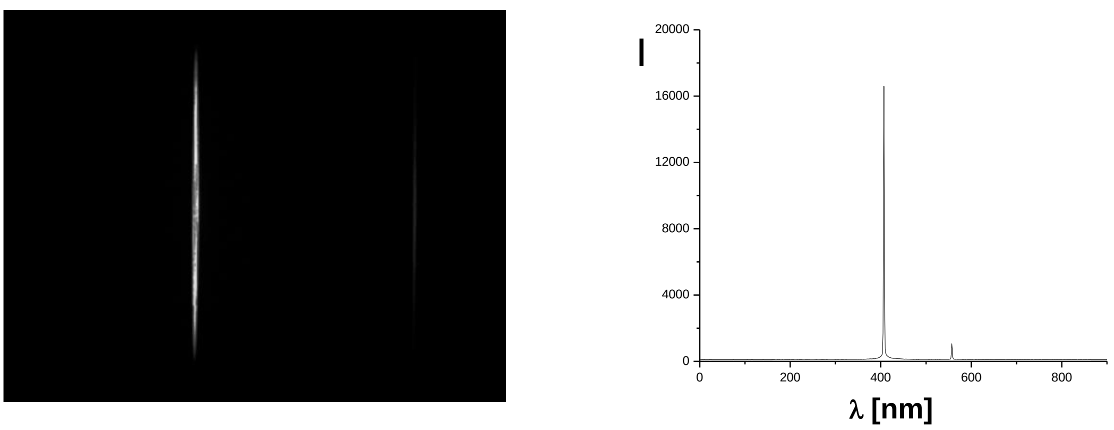

Figure 4. PEN – light, Hg I, 435 nm, ICCD camera, a. integral profile - picture from program SpectraSuits, b. Integral profile – after data processing in Origin.

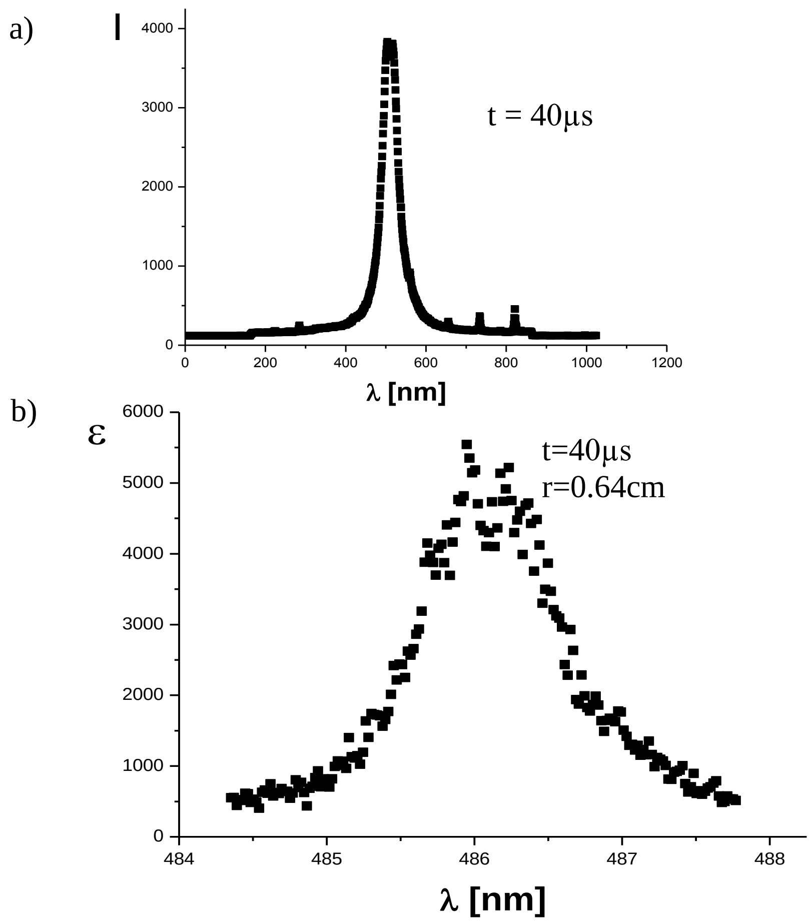

Figure 5. H_β ICCD, t = 50 μs, a) integral profile, b) radiation profile at one selected position along the radius of plasma r = 1,43 cm.

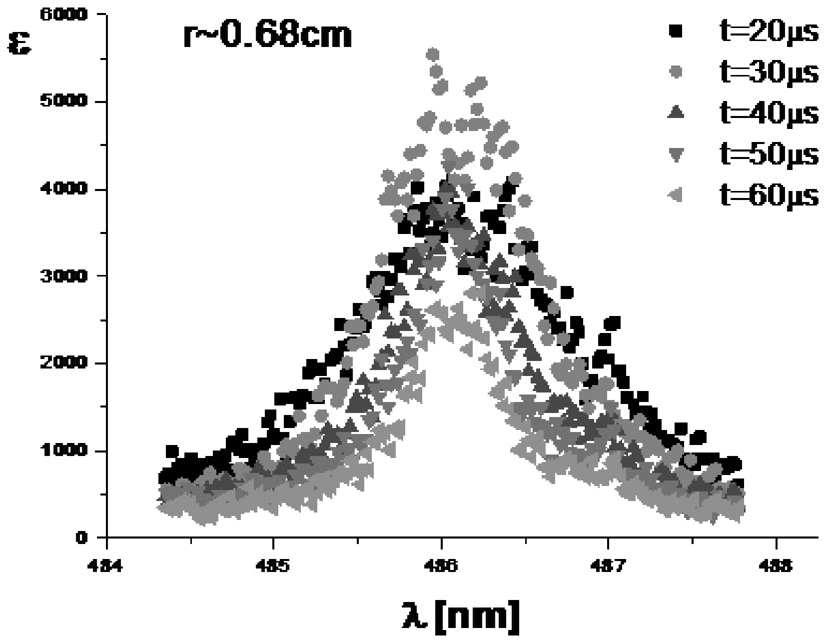

Figure 6. Radiation profiles at one position along the radius of plasma at different times.

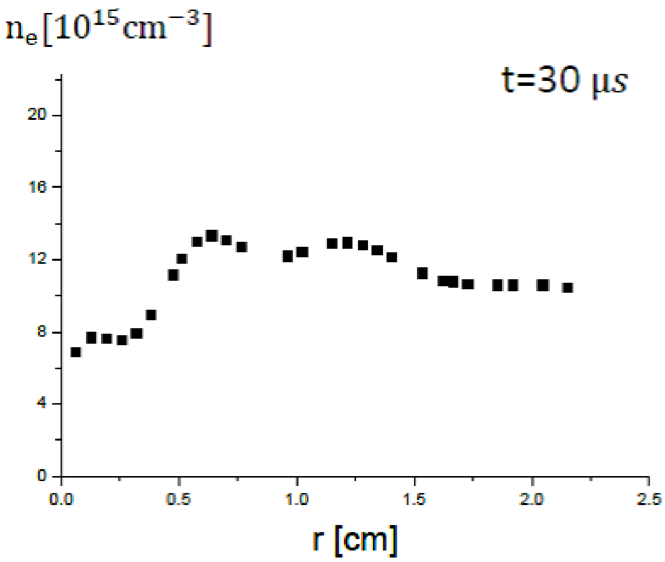

Figure 7. Electron concentration dependence on radius at t = 30 μs.

PLASMA FLOW INTERACTION WITH ITER DIVERTOR RELATED SURFACES

As it has been mentioned in the Introduction, the plasma flow generated by MPC can be used for simulation of high energy plasma interaction with different materials of interest for fusion experiments. Processes such as ELMs (edge localized modes), plasma disruptions and VDEs (vertical displacement events) can be studied and analysed through experiments using plasma guns. Modification of different targets, like tungsten, molybdenum, carbon fiber components (CFC) and silicon single crystal surface by the action of hydrogen and nitrogen quasi stationary compression plasma flow (CPF) generated by MPC has been studied [7]. MPC plasma flow with standard parameters (1 MJ/m2 in 0.1 ms) was used for simulation of transient peak thermal loads during Type I ELMs and disruptions. Analysis of the targets erosion, brittle destruction, melting processes, and dust formation has been performed [8].

The next step is spectral analysis of the plasma area around targets surfaces generated by MPC. After the interaction between MPC plasma flow and target, phenomena as a targets erosion, destruction, melting and dust formation can be observed. Surface phenomena are results of specific conditions during plasma flow interaction with target surface. The idea is to completely analyse processes in plasma around target after interaction with plasma as it has been done in [9], but with different device (MPC) and under different conditions (source voltage, temperature, pressure). This will be a spectral analysing. The first material which will be subjected to interaction with plasma will be a carbon fiber. This type of materials, according to newest agreement, is of big importance for divertor region in fusion devices. Experimental setup is schematically shown in Figure 8.

Data analysing will include analysing of radial distribution of emissivity and spatial and temporal distribution of electron concentration. Procedure for reaching these distributions is explained in previous section.

CONCLUSIONS

Current researches on MPC device in Belgrade are related to the fundamental aspects of high energy plasma flow interaction with materials of interest for fusion. One of the purposes is investigation of plasma interaction with first wall and divertor component materials related to

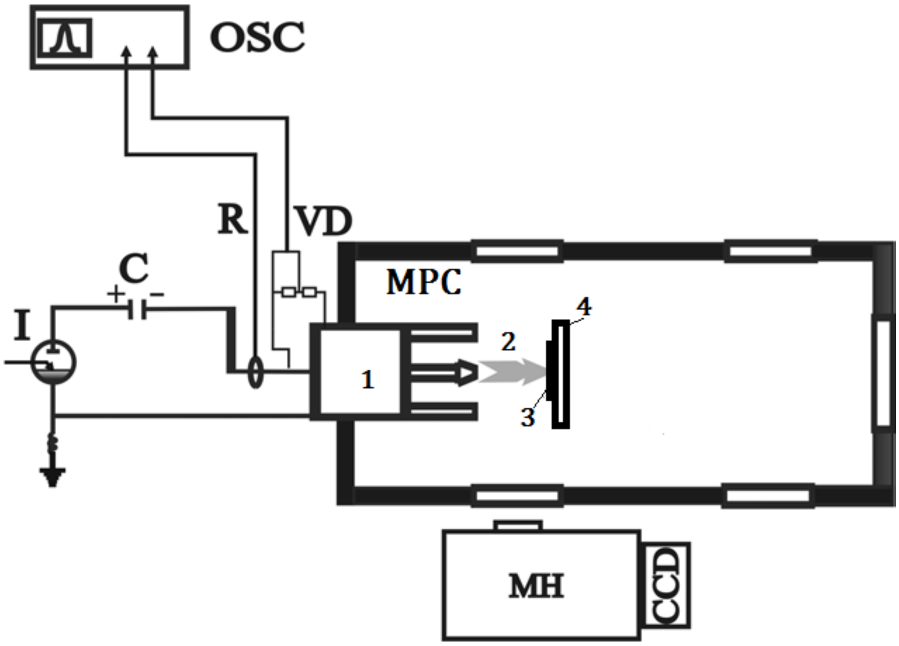

Figure 8. Scheme of experimental setup: (1) Magnetoplasma compressor (MPC), source of quasistationary compression plasma flow, (2) compression plasma flow, (3) sample, (4) sample brass holder.

the ITER experiment. The performance of fusion devices and of a future fusion power plant critically depends on the plasma facing materials and components. Resistances to local heat and particle loads, thermo-mechanical properties, as well as the response to neutron damage of the selected materials are critical parameters which need to be understood and tailored from atomistic to component levels. Plasma flow generated by MPC is used for investigation of high energy plasma interaction with different materials of interest for fusion experiments and every result is useful for a more complete picture of the plasma facing materials problem in fusion reactors.

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SADAŠNJE STANJE KOMPRESORA MAGNETOPLAZME U BEOGRADU – PROUČAVANJE MATERIJALA U KONTAKTU S PLAZMOM, BITNIH ZA FUZIJSKE REAKTORE

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SAŽETAK

Kompresor magnetoplazme, kvazistacionarni akcelerator plazme, izvor je toka plazme nadzvučne brzine. Relativno visoki parametri kompresijskog toka, znatne brzine toka i znatna trajanja izboja omogućuju njegovo učinkovito korištenje za razvoj novih tehnologija plazme, uključujući i razvoj površinskih modifikacija materijala, stvaranja submikroskopske- i nano-strukture. U ovom radu razmatrana je prostorna i vremenska distribucija emisivnosti pomoću inverzne Abelove transformacije. To je ostvareno programskim okruženjem LabVIEW. Tok plazme generiran kvazistacionarnim ackeleratorom plazme može se koristiti za simulaciju visokoenergetskog međudjelovanja plazme i različitih materijala bitnih za fuzijske eksperimente. Površinske pojave rezultat su posebnih uvjeta tijekom međudjelovanja toka plazme i površine mete. Kao sljedeći korak u istraživanjima, planirana je spektralna analiza područja plazme oko površine mete, nakon međudjelovanja između mete i plazme. Prvi materijal podvrgnut međudjelovanju s plazmom bit će ugljična vlakna, materijal značajan za divertore fuzijskih reaktora.

KLJUČNE RIJEČI

kompresor magnetoplazme, Abelova inverzna spektroskopija, materijali fuzijskih reaktora