# DIAGNOSTICS OF PLASMA STREAMS AND PLASMA-SURFACE INTERACTION OF ESSENTIALLY DIFFERENT DURATION OF PLASMA PULSES

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Studies of main characteristics of the plasma streams generated by magneto-plasma compressor (MPC) and quasi-stationary plasma accelerator QSPA Kh-50 have been performed. Main features of Plasma Surface Interaction (PSI) have been researched in dependence on plasma heat loads, plasma density and pulses duration. QSPA Kh-50 creates long pulse plasma streams (pulse length of 0.25 ms) with heat load on exposed surfaces of (0.45…0.75) MJ/m$^2$. The MPC generates short (duration of 10…20 μs) compressed plasma streams with plasma density up to $10^{18}$ cm$^{-3}$, and plasma energy density of (0.05…0.5) MJ/m$^2$. Performed studies of plasma-surface interaction include measurements of plasma energy deposited to the material surface as a function of the impacting energy and kind of targets. Temporal and spatial dependencies of electron density and temperature have been found. Special attention was paid to the dynamics of the spectral lines near surfaces of exposed targets.

PACS: 52.40.Hf; 52.70

## INTRODUCTION

Analysis of features of processes accompanied of plasma surface interaction (PSI) and material damages under plasma impacts of different duration is extremely important for plasma technologies, fusion science and engineering [1-3]. The studies of parameters in different plasma facilities (for instance, quasi-stationary plasma accelerator (QSPA) and magneto plasma compressor (MPC)) make it possible to optimize the modes of operation for different application. The electron density *Ne* and energy density *Q* together with pulses duration are most important parameters characterized a PSI. Using of facilities generate plasma streams of essentially different pulses duration allows to identify the main features of processes of plasma surface interaction.

## 1. EXPERIMENTAL DEVICES

Spectroscopic measurements together with evaluation of the surface heat load during the plasma-surface interaction were performed in quasi-stationary plasma accelerator QSPA Kh-50 and the magnetoplasma compressor (MPC) (Fig. 1).

QSPA Kh–50 is the largest and most powerful device of its kind. Plasma streams, generated by QSPA Kh–50 were injected into magnetic system of 1.6 m in length and 0.44 m in inner diameter to provide its magnetization in longitudinal magnetic field up to $B_0$ = 0.54 T [1, 4]. The plasma parameters were varied both by changing the dynamics and the amount of gas filling the accelerator channel and by adjusting of the operating voltage of the capacitor bank powering the discharge.

The experiments were performed with repetitive pulses of the duration of 0.25 ms and the heat loads on exposed surfaces in the range of 0.45…0.75 MJ/m$^2$, which simulate the ELMs impact in ITER. The plasma stream diameter is 18 cm, the ion energy is about 0.4 keV, and maximum plasma pressure achieves 0.32 MPa.

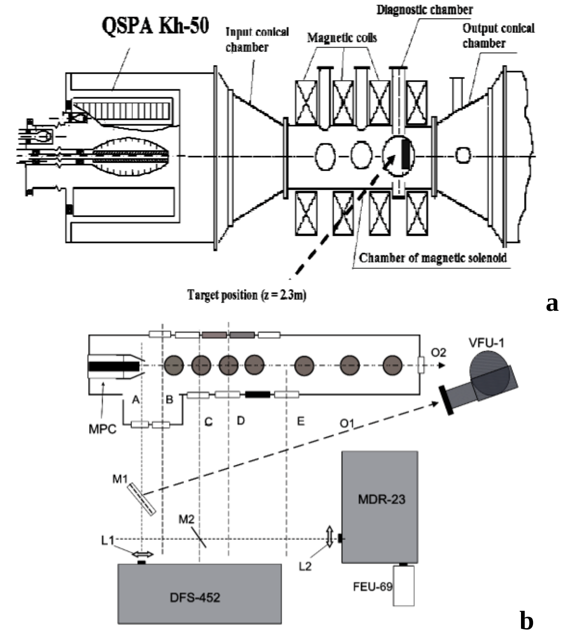

*Fig. 1. Experimental devices: Quasi-stationary plasma accelerator QSPA Kh-50 (a); Magnetoplasma compressor MPC (b)*

The MPC device consists of two copper coaxial electrodes a pulsed gas supply system [5-7]. The MPC facility is powered by condenser battery with the stored energy of 28 kJ (at 25 kV). The working regimes could be varied by the selected value of the discharge voltage and choosing the quantity of gas, supplying the MPC compressor Variation of residual gas pressure (initial concentration) and sort of working gas (He, Xe, N, Ar and their mixtures) has been also applied. The amplitude of a discharge current achieves 500 kA, and the discharge half-period is ~ 10…20 μs. The MPC generates compression plasma streams with plasma density up to $10^{18}$ cm$^{-3}$, and plasma energy density varied in the range of (0.05…0.6) MJ/m$^2$.

Spectroscopy, piezo-detectors, electric and magnetic probes, and other diagnostics were applied for measurements of plasma streams parameters. The diagnostics are described in more details elsewhere [4-13]. Observations of plasma interactions with exposed surfaces and droplets monitoring were performed with high-speed CMOS camera PCO AG [9-13].

## 2. EXPERIMENTAL RESULTS

### 2.1. ELECTRON DENSITY OF FREE PLASMA STREAMS

### 2.1.1 Long plasma streams (QSPA Kh-50)

Spectroscopy studies of electron density ($N_e$) have been realized by means of monochromator associated with an electro-optical converter (EOC). Main attention was paid to the spectral range of 478.6…493.6 nm. This region contains hydrogen spectral line ($H_\beta$) and some lines of impurity elements (CuI, II). It should be mentioned, that lines of impurities appears only at a large exposition (about 0.15 ms). That indicates on appearing of impurities at the end of PSI. Experimental spectrum obtained with exposition of 150 μs is shown in Fig. 2. In our previous experimental series [14] some impurity copper spectral lines (491.0, 493.1, 495.3 nm) were used for $N_e$ determination by quadratic Stark broadening. However its intensities and half-widths could not be applied due to very weak intensity as compared with $H_\beta$ intensity.

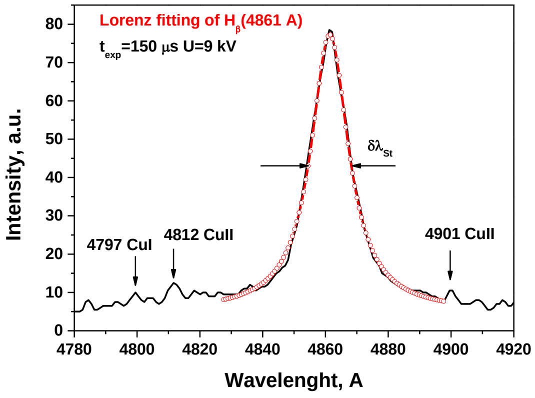

*Fig. 2. Typical waveform and fitting result (Lorentz component) of $H_\beta$ (4861 A) in a free plasma stream*

Fitting procedure (circle line) and linear Stark broadening with the prevailing Lorentzian contour of $H_\beta$ profile give us the possibility to estimate electron density. Temporal dependence of $N_e$ has been obtained in a free plasma stream with exposition time 10 μs (Fig. 3). Plasma comes after 70…80 μs from the discharge beginning. The maximal electron density was found to be $0.5\times10^{16}$ cm$^{-3}$ and corresponds to half period of discharge current.

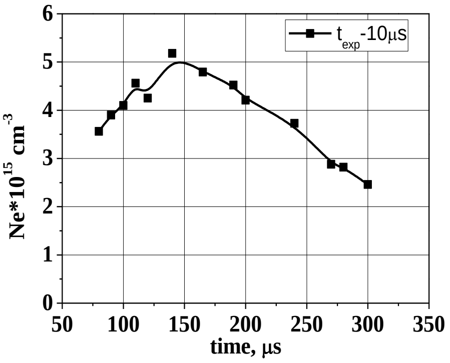

*Fig. 3. Temporal behavior of chord averaged $N_e$ in a free plasma stream in regime with heat load to surface of 0.45 MJ/m$^2$*

### 2.1.2. MPC

Spatial distributions of electron density ($N_e$) have been obtained in a free plasma stream and in front of stainless steel target in MPC (Fig. 4). In free plasma stream the maximum value of the density Ne ≈ $7\times10^{17}$ cm$^{-3}$ was measured at a distance of 8…10 cm from the electrode ends.

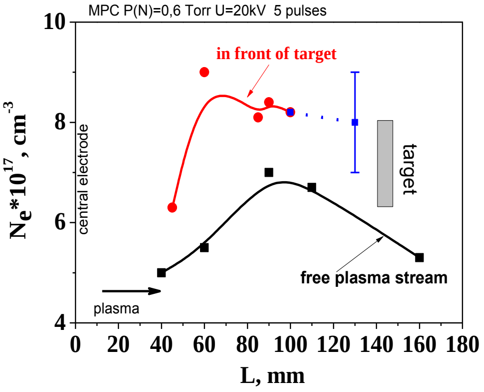

*Fig. 4. Spatial distributions of electron density ($N_e$) in free plasma stream and in front of stainless steel target in MPC*

### 2.2. RESULTS ON PLASMA-TARGET INTERACTION

### 2.2.1. Long pulse plasma streams (QSPA Kh-50)

Electron density measurements have been performed near W-target located on the distance of 2.3 m from QSPA accelerator and placed perpendicularly to the plasma stream. Observation zone is determined by the width of spectrometer enter slit. Size of such zone is 0.3 cm in vicinity to the target surface. Two spatial distributions of $N_e$ near target surface are presented in Fig. 5 for magnetized plasma streams and without magnetic field. The plasma density near target surface in magnetic field is more than one order of magnitude higher in comparison with that in the impacting plasma stream. The shielding layer thickness grows with the increasing magnetic field value.

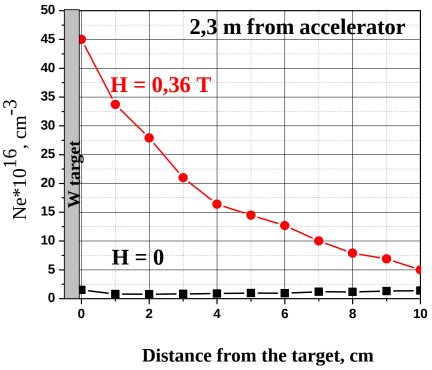

*Fig. 5. Spatial dependence of $N_e$ near W-target with and without magnetic field in QSPA facility*

Droplets splashing from melt layer of W target also have been obtained using high-speed CMOS camera PCO AG. The irradiation of tungsten surface with QSPA Kh-50 plasma heat load below the cracking threshold (0.3 MJ/m$^2$) does not trigger the generation of erosion products. At the heat load above the cracking threshold but below melting threshold only several dust particles traces have been registered. Increase of heat load leads to the surface melting and results in splashing of eroded material. Number of ejected particles rises with increasing heat load due to growing thickness of melted layer. Example of droplet erosion of W target is presented in Fig. 6. Quantity of particles ejected from irradiated surface increases more than twice as a consequence of heat load elevation from 0.6 to 0.75 MJ/m$^2$ only [9-11].

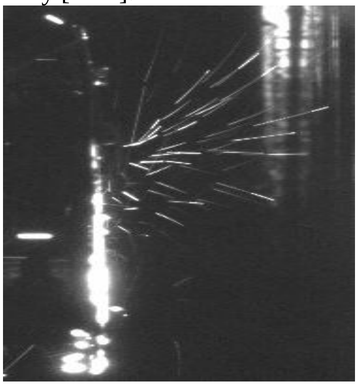

*Fig. 6. Splashing droplet during plasma impact on W target, $t_{exp}$=2 ms*

### 2.2.2. Short plasma streams

The main difference from the experiment described above is a short duration of plasma-target interaction (10…20 μs). Stainless steel sample (4.3x6.5x0.2 cm) was placed in a vacuum chamber under residual pressure of nitrogen 0.6 Torr at the distance of 14 cm from electrodes.

Rotate mirror located before spectrometer enter slit was used for registration of optical spectra of near-surface plasma. Example of spectrum after 5 impulses is presented on Fig. 7. A lot of NII, III spectral lines were identified. Some of them, particularly NIII of 410.3 nm and 409.7 nm, have been used for $N_e$ estimations using quadratic Stark broadening.

The maximal value of $N_e$, i.e. compression zone, is moved on 3 m towards electrodes in comparison with the case of a free plasma stream (see Fig. 4). The target presence has influence on the electron density dynamics. Nevertheless the values of $N_e$ are almost the same for both cases and is equal to 7×10$^{17}$ cm$^{-3}$ in a free plasma stream, (8…8.5)×10$^{-17}$ cm$^{-3}$ near the target.

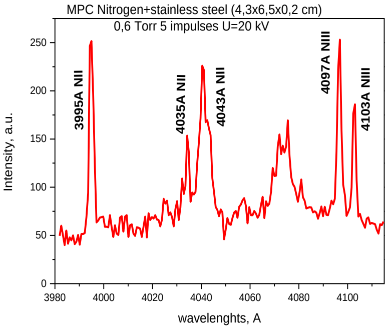

*Fig. 7. Example of integral spectrum within MPC facility after 5 shots, P= 0.6 Torr of N, U=20 kV*

All spectral investigations were carried out simultaneously with the measurements of energy density in free plasma stream and heat load to exposed surface (Fig. 8). Calorimeter 0.5 cm in diameter was inserted into stainless steel target. Thus we were able to measure the heat load on irradiated surface. It has been found that MPC facility can generate powerful pulsed plasma streams with energy density up to 0.5 MJ/m$^2$. Heat loads linearly rose with increasing energy density of impact plasma. Maximal heat load to target surface exposed to plasma achieved 0.45 MJ/m$^2$.

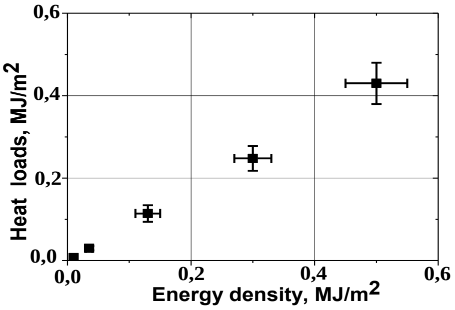

*Fig. 8. Heat load to the target (stainless steel) surfaces vs. the energy density of impacting nitrogen plasma stream*

## CONCLUSIONS

1. Experimental studies of plasma streams impact on tungsten and stainless steel samples have been fulfilled with QSPA Kh-50 (long pulse) and MPC (short pulse) facilities.
2. Temporal and spatial dependencies of plasma electron density $N_e$ have been performed in a free plasma stream and with a target using spectral diagnostics methods.
3. Shielding layers of cold plasma created near irradiated surfaces by long duration plasma streams

(250 μs) protect target surface from the damaging effects of plasma impact. Formation of such layer led to

reduction of the energy density delivered to target surfaces. Interactions of short plasma streams with surface do not result in appearance of clearly shielding effect. Energy density of plasma stream and heat load to surface are weakly different.

5. The obtained results can be used for validation of predictive numerical models for ITER and DEMO developed for estimations and lifetime of divertor armour materials.

## ACKNOWLEDGEMENTS

This work has been performed in part within joint projects supported by National Academy of Sciences of Ukraine (NASU) and National Academy of Sciences of Belarus the project № 11-02-16 and the Targeted Program of NASU on Plasma Physics.

## REFERENCES

1. I.E. Garkusha et. al. // *Phys. Scr.* 2016, v. 91, p. 094001.
2. V.M. Astashinskii et al. *// J. Eng. Phys. Therm.* 2011. v. 84 1102.
3. V.F. Ermolovich et al. // *Tech. Physics.* 2000, v. 45, p1241-125.
4. V.I. Tereshin et al. // *Brazil J. Phys.* 2002, v. 32, p. 165-171.
5. A.K. Marchenko et al. // *Acta Tech*. 2011, v. 56, p. T113-122.
6. D.G. Solyakov et al. // *Plasma Phys. Rep*. 2013, v. 39, № (12), p. 986-992.
7. A.K. Marchenko et al. // *Prob. At. Sci. Techn*. 2014, № 6(94), p. 83-86.
8. A. Chuvilo et al. // *Nucleonika*. 2012, № 57(1), p. 49-53.
9. V.A. Makhlaj et al. // *Acta Politech*. 2013, № 53(2), p. 193-196.
10. I.E. Garkusha et al. // *Nucleonika*. 2012, v. 57, № 2, p. 167-170.
11. I.E. Garkusha et al. // *Journal of Nuclear Materials*. 2009, v. 390-391, p. 814-817.
12. V.A. Makhlaj // *Prob. At. Sci. Techn*. 2013, № 1(83), p. 73-75.
13. S.S. Herashchenko et al. // *Ukr. J. of Physics.* 2016, v. 61, № 7, p. 578-582.
14. A.V. Tsarenko et al. // *Nucleonika.* 2001, v. 46(1), p. 37-40.

*Article received 10.11.2016*

## ДИАГНОСТИКА ПЛАЗМЕННЫХ ПОТОКОВ И ВЗАИМОДЕЙСТВИЯ ПЛАЗМА-ПОВЕРХНОСТЬ СО ЗНАЧИТЕЛЬНО РАЗНЫМИ ДЛИТЕЛЬНОСТЯМИ ПЛАЗМЕННЫХ ИМПУЛЬСОВ

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Изучены основные характеристики плазменных потоков, генерируемых магнитоплазменным компрессором (МПК) и квазистационарным плазменным ускорителем КСПУ Х-50. Исследованы основные особенности плазмоповерхностного взаимодействия в зависимости от тепловой плазменной нагрузки, плотности и длительности импульса. КСПУ Х-50 генерирует длинноимпульсные плазменные потоки (длительность импульса 0,25 мс) с тепловой нагрузкой на облучаемую мишень (0,45…0,75) МДж/м$^2$. МПК генерирует короткие (длительность 10...20 мкс) компрессионные плазменные потоки плотностью плазмы до $10^{18}$ см$^{-3}$ и плотностью энергии в диапазоне (0,05…0,5) МДж/м$^2$. Представленные исследования плазмо-поверхностного взаимодействия включали измерения энергии, достигающей поверхность материала, как функцию энергии плазмы и сорта материала. Получены временные и пространственные распределения электронной плотности плазмы. Особое внимание уделялось динамике спектральных линий около поверхности облучённых мишеней.

## ДІАГНОСТИКА ПЛАЗМОВИХ ПОТОКІВ ТА ВЗАЄМОДІЇ ПЛАЗМА-ПОВЕРХНЯ З ІСТОТНО РІЗНИМИ ТРИВАЛОСТЯМИ ПЛАЗМОВИХ ІМПУЛЬСІВ

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Вивчені основні характеристики плазмових потоків, що генеруються магнітоплазмовим компресором (МПК) та квазістаціонарним плазмовим прискорювачем КСПП Х-50. Досліджено основні особливості плазмовоповерхневої взаємодії в залежності від теплового навантаження, густини та тривалості імпульсу. КСПП Х-50 генерує довгоімпульсні плазмові потоки (довжина імпульсу 0,25 мс) з тепловим навантаженням на опромінену мішень (0,45…0,75) МДж/м$^2$. МПК генерує короткі (тривалість 10...20 мкс) компресійні плазмові потоки з густиною плазми, що сягає $10^{18}$ см$^{-3}$, та густиною енергії в діапазоні (0,05…0,5) МДж/м$^2$. Представлені дослідження плазмовоповерхневої взаємодії включали вимірювання енергії плазми, що досягає поверхні матеріалу, як функція енергії плазмі та сорту матеріалу. Отримано часові та просторові розподіли електронної густини плазми. Особлива увага приділялась динаміці спектральних ліній біля поверхні опромінених мішеней.