https://doi.org/10.46813/2021-131-061

PARAMETERS OF HYDROGEN PLASMA STREAMS IN QSPA-M AND THEIR DEPENDENCE ON EXTERNAL MAGNETIC FIELD

M.S. Ladygina[1], Yu.V. Petrov[1], D.V. Yeliseev[1], V.A. Makhlai[1,2], N.V. Kulik[1], V.V. Staltsov[1,2]

[1]Institute of Plasma Physics,
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine;
[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine

E-mail: ladyginams@kipt.kharkov.ua

Present experimental studies are aimed at analysis of hydrogen plasma stream parameters in various working regimes of QSPA-M operation. Temporal distributions of plasma electron density are reconstructed with optical emission spectroscopy. The magnetic field influence on plasma streams parameters is analyzed. It is shown that in regimes with additional magnetic field the plasma electron density increases by an order of magnitude in comparison with a density value without magnetic field. The plasma velocity and energy density parameters as well as their temporal behaviors were estimatedin different operating regimes of QSPA-M facility. Features of plasma visible radiation were analyzed. This information is important for QSPA-M applications in experiments on interaction of powerful plasma streams with material surfaces.

PACS: 52.40.Hf; 52.70

INTRODUCTION

Quasi-stationary plasma accelerators (QSPAs), as powerful sources of supersonic plasma flows, are found their application insimulation experiments on reproduction of the ELMs and disruption impacts to the divertor targets in fusion reactor, studies of plasma-surface interaction (PSI) as well as material behavior and vapor shield effects in extreme conditions [1-6].

The QSPA-M plasma accelerator, as compare with other available QSPA devices, is equipped with magnetic coils creating the external longitudinal B-field up to 1T. Ability of QSPA-M to operate with additional external strong external magnetic field allows simulation of the divertor plasma flows along the B-field linesduring the transient events in ITER and DEMO reactors and predictive testing of candidate materials under powerful plasma exposures [7-9].

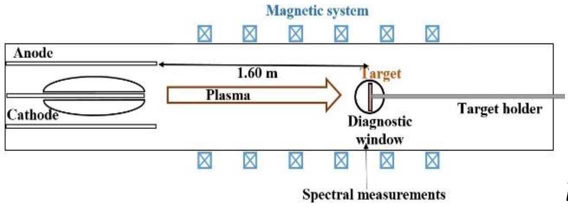
Present experiments were focused on the plasma parameters measurements in QSPA-M generated plasma streams in various operating regimes, which are important for simulation of plasma surface interaction in fusion relevant conditions.

1. EXPERIMENTAL SET-UP AND METHODS OF DIAGNOSTICS

The QSPA-M facility operated with follow working parameters: $I_{discharge}$ = 400 kA, $U_{discharge}$ = 2...10 kV, $T_{half\ period}$= 100 µs, B = 0.8 T, diameter of plasma stream of 10 cm, energy loads on the target surface Q = 0.1...0.5 MJ/m^2.The hydrogen (H) used as working gas. Integral gas supply of QSPA discharge was about 530 cm^3 H_2 at atmosphere pressure. The detailed description of facility and first experimental results are given in [7, 8].

Fig. 1 shows the QSPA-M plasma accelerator and the spectroscopic experimental arrangement. All spectroscopy measurements were carried out at the distance of 160 cm from the end of electrodes, where targets for plasma exposures are typically placed.

a



b

Fig. 1. General view of QSPA-M facility (a) and experimental arrangement scheme of QSPA-M (b)

Optical emission spectroscopy in visible wavelength range was used for determination of plasma electron density. Spectra of plasma emission were detected at different timepoints of the discharge were used for reconstruction of n_e temporal distributions. Broadening of H_β profile with wavelength 4861 Åvia the linear Stark effect was used for plasma density evaluation.

The intensity of plasma radiation in visible range of spectrum was monitored during the discharge using photodiodes.

Plasma stream velocity was measured by time-of-flightmethod between two photodiodes placed at different distances from accelerator output.

A set of miniature calorimeters was used for energy density measurements in the plasma stream [10-12].

2. EXPERIMENTAL RESULTS

2.1. ELECTRON DENSITY MEASUREMENTS FOR VARIED DISCHARGE VOLTAGE

First series of experiments was carried out with variation of the voltage at the condenser banks (that affects the energy density in plasma streams) to evaluate the range of plasma electron density values that could be reached in the QSPA-M facility both with and without additional B-field.

Fig. 2 illustrates the temporal behaviors of the electron density in regimes with B=0 and B=0.8 T accordingly.

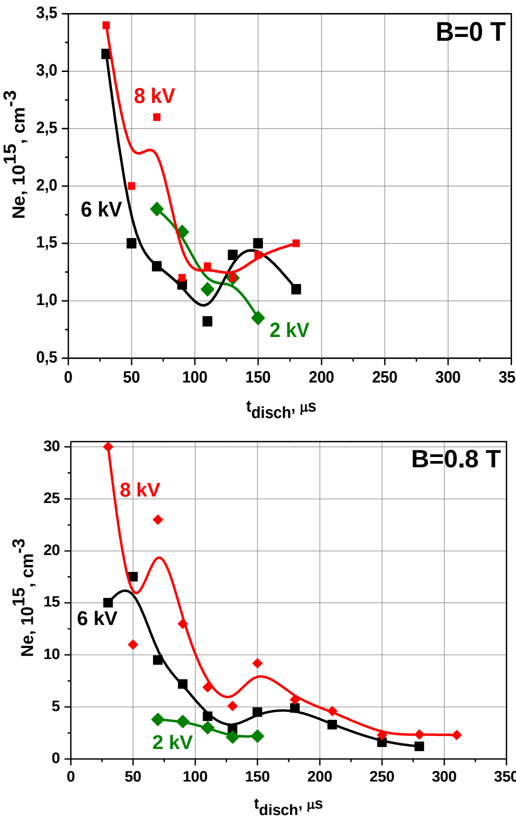


Fig. 2. Temporal behavior of plasma electron density in plasma streams for various working voltages, t_{exp} = 10 µs at B = 0 (a) and B = 0.8 T (b)

It should be mentioned that in regimes without magnetic field the electron density reaches the maximum $n_e = (1...3) \cdot 10^{15}$ cm^{-3} at 30...40 µs from the discharge ignition (working voltages $U_{discharge}$ = 2...8 kV). The values of density slightly increased with working voltage growth. After the 100-th µs the density kept on the level $n_e = (1...1.5) \cdot 10^{15}$ cm^{-3}.

Fig. 2,b shows that plasma in regimes with magnetic field the electron density is on level of $n_e = (3...4) \cdot 10^{15}$ cm^{-3} at $U_{discharge}$ = 2 kV during discharge time and it reaches the maximum $n_e = 3 \cdot 10^{16}$ cm^{-3}at 30...40 µs for $U_{discharge}$ = 8 kV. In the tail area the density still kept in the range of $n_e = (2...10) \cdot 10^{15}$ cm^{-3} in dependence of applying working voltage.

It should be noted that durations of H_β spectral line radiation can be also tracked using above-mentioned graphs. More intense andlonger duration of hydrogen spectral line that exceeds t = 300 µs is registered in regime with B = 0.8 T as compared with t = 200 µs for B = 0.

Abovementioned operation regimes with $U_{discharge}$ = 2...8 kV correspond to the energy loads range in plasma streams E = 0.1...0.55 MJ/m^2.

The magnetic pressure of longitudinal B-field compresses plasma stream. As consequence, higher plasma electron density is achieved in regimes with magnetic field. The average diameter of plasma stream under magnetic field influence decreased from 10...12 to 5...7 cm.

2.2. MAGNETIC FIELD INFLUENCE ON THE ELECTRON DENSITY IN PLASMA STREAM

The detailed measurements of plasma density were carried out at $U_{discharge}$ = 10 kV. This working voltage corresponds to maximal energy in the present experimental series and it is typically applied for exposures of tungsten targets in ELM simulation experiments [8].

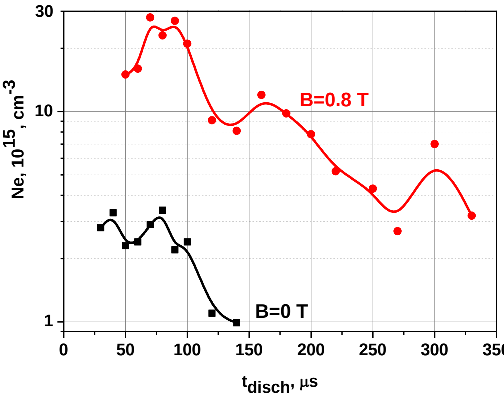


Fig. 3. Temporal behavior of plasma electron density at working voltage $U_{discharge}$ = 10 kV in free plasma stream with B = 0 and B = 0.8 T, t_{exp} = 10 µs

Fig. 3 shows the difference between values of densities and its temporal behavior when the magnetic field was either switched on or off. The plasma electron density in regimes with magnetic field increased by one order of magnitude in comparison with its values without magnetic field.

2.3. PLASMA DISCHARGE RADIATION

The obtained results of behaviour of plasma density were supplemented with photodiode data of the plasma radiation monitoring. Fig. 4 shows the intensities of radiation from plasma stream together with discharge current curve. Both the amplitude of signal and its duration became essentially higher when external magnetic field is applied.

Besides that, it is clearly seen the similarity between temporal behaviour of plasma density and plasma radiation (see Figs. 3, 4). In regime with magnetic field, the distinct peak is observed at 60...80 µs in both figs. Behaviours of density and plasma radiation without magnetic field are rather similar also.

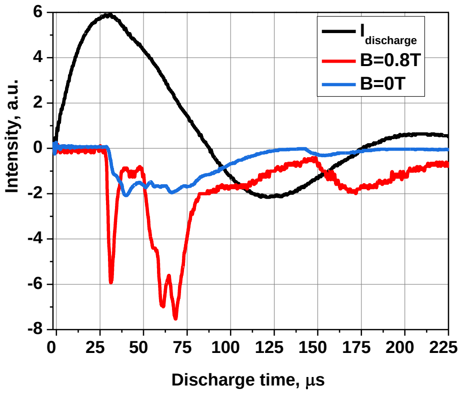


Fig. 4. The radiation of plasma stream versus discharge time, $U_{discharge}$ = 10 kV, B = 0 and B = 0.8 T

2.4. MEASUREMENTS OF PLASMA STREAM VELOCITY

The average plasma stream velocity was measured at the distances between 90 and 160 cm from the end of electrodes. Fig. 5 illustrates the growth of plasma velocity with increasing discharge current and magnetic field influence on the velocity values.

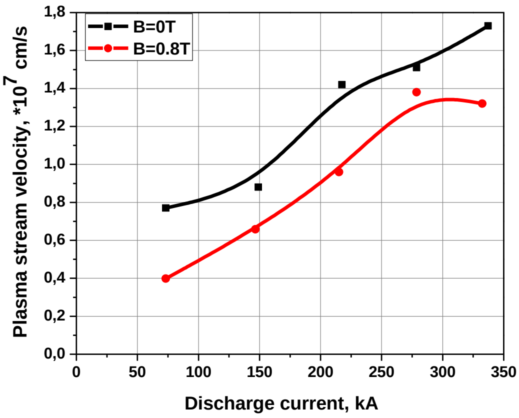


Fig. 5. The behavior of plasma velocity at discharge current increase with B = 0 and B = 0.8 T

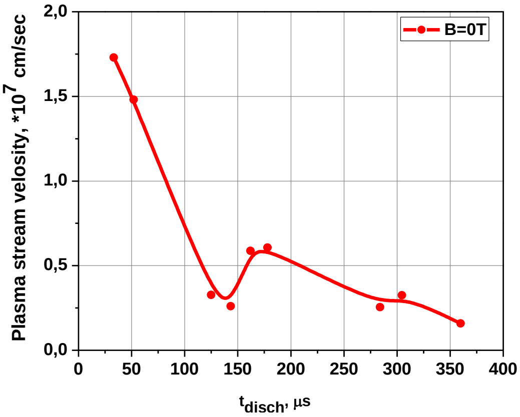


Fig. 6. Temporal behavior of plasma velocity in plasma stream at B = 0

Plasma velocity reach v = 1.3·10^7 cm/s in external magnetic field. Fig. 6 shows the behavior of plasma velocity during discharge time. The plasma stream has a fast head part with a high velocity up to 1.7·10^7 cm/s in regime B = 0 T. The velocity of plasma stream dropped after 100 µs to v = 0.25·10^7 cm/s.

The duration of this decay correlates with the half-period of the discharge current. Considering the behavior of the density and velocity of plasma stream with several coinciding peaks with a characteristic time of about 100 µs, it can be assumed that the plasma stream has several successive bunches.

2.5. ENERGY DENSITY MEASUREMENTS IN PLASMA STREAM

The calorimetric measurements were performed on the axis of plasma stream (Fig. 7).

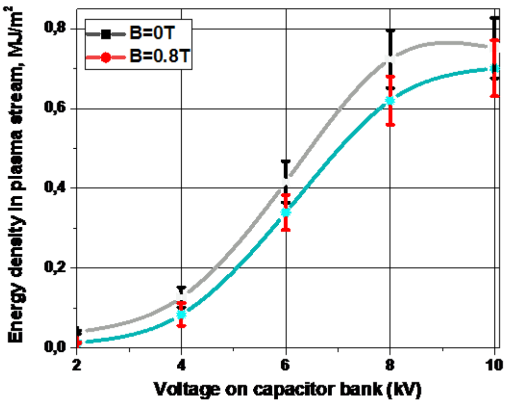


Fig. 7. Energy density in plasma stream at B = 0 T and B = 0.8 T versus discharge voltage

It has not been observed substantial difference between the values of energy density as well as it behavior in regimes with and without magnetic field. The maximal energy density is over than Q = 0.75 MJ/m^2 and it reached at $U_{discharge}$ = 10 kV. The interaction of plasma with the target surfaces and the energy transfer from the plasma stream to the target surface are discussed in [8].

CONCLUSIONS

Detailed measurements of plasma stream parameters in QSPA-M facility have beenperformed.

The maximal values of plasma electron density and its temporal behavior in dependence of discharge voltage have been analyzed. It was found that plasma electron density reach in maximum n_e = 1...3·10^{15} cm^{-3} in regimes without magnetic field and up to n_e = 3·10^{16} cm^{-3} in regimes with magnetic field. Thus, external magnetic field compresses the plasma stream that leads to decreasing plasma stream diameter and essential growth of plasma density. As consequence, intensity of plasma radiation signal with magnetic field exceeds the signal amplitude without magnetic field by several times.

The results of plasma stream velocity measurements show that head part of the plasma stream propagates with v = 1.7·10^7 cm/s in regimes without magnetic field and a little bit less velocity $v = 1.3\cdot10^7$ cm/s is attributed to the regimes with applied magnetic field.

The maximal energy density of the plasma stream is over $E = 0.75$ MJ/m^2 at $U_{discharge} = 10$ kV. There is no substantial difference between values of energy densities as well as its behavior in regimes with and without magnetic field. Taking into account that the energy density could be estimated as $E \sim nvtmv^2/2 = m_i ntv^3/2$, we can conclude that it might be kept on the same level in both regimes with and without an additional B-field due to self-consistent variation of plasma stream density and its velocity.

ACKNOWLEDGEMENTS

This work has been supported by National Academy Science of Ukraine within the projects X-2-11-10/2020, П-2/24-2020 and № П- 9/24-2020.

REFERENCES

1. I.E. Garkusha et al. Tungsten melt losses under QSPA Kh-50 plasma exposures simulating ITER ELMS and disruptions // *Fusion Science and Technology*. 2014, v. 65(2), p. 186-193.
2. A.A. Shoshin et al. Plasma-surface interaction during ITER type iELMs: Comparison of Simulation with QSPA Kh-50 and the GOL-3 Facilities // *Fusion Science and Technology***.** 2011, v. 59(1 T), p. 57-60.
3. V.A. Makhlai et al. Residual stresses in tungsten under exposures with ITER ELM-like plasma loads// *Physica Scripta T.* 2009, v. T138, p. 1406.
4. S. Pestchanyi et al. Simulation of residual thermo-stress in tungsten after repetitive ELM-like heat loads // *Fusion Engineering and Design*. 2011, v. 86(9-11), p. 1681-1684.
5. V.A. Makhlaj et al. Tungsten damage and melt losses under plasma accelerator exposure with ITER ELM relevant conditions // *Physica Scripta*. 2014, v. T159, p. 014024.
6. S.S. Herashchenko et al. Effect of sequential steady-state and pulsed hydrogen plasma loads on structure of textured tungsten samples // *Nuclear Inst. and Methods in Physics Research.* 2019, v. B 440, p. 82-87.
7. I.E. Garkusha et al. Novel test-bed facility for PSI issues in fusion reactor conditions on the base of next generation QSPA plasma accelerator // *Nuclear Fusion*. 2017, v. 57, p. 116011.
8. I.E. Garkusha et al. Influence of a magnetic field on plasmaenergy transfer to materialsurfaces in edge-localized mode simulation experiments with QSPA-M // *Nuclear Fusion.* 2019, v. 59, p. 086023.
9. I.E. Garkusha et al. Simulation of plasma–surface interactions in a fusion reactor by means of QSPA plasma streams: recent results and prospects // *Physica. Scripta.* 2016, v. 91, p. 094001.
10. A.K. Marchenko et al. Diagnostics of plasma streams and plasma-surface interaction of essentially different duration of plasma pulses // *Problems of Atomic Science and Technology. Series «Plasma Physics» (106).* 2016, № 6, p. 125-128.
11. V.V. Chebotarev et al. Characteristics of the transient plasma layers produced by irradiation of graphite targets by high power quasi-stationary plasma streams under the disruption simulation experiments // *Journal of Nuclear Materials*. 1996, v. 233-237, p. 736-740.
12. I.E. Garkusha et al. Experimental study of plasma energy transfer and material erosion under ELM like heat loads // *Journal of Nuclear Materials*. 2009, v. 390-391, p. 814-817.

Article received 10.01.2021

ПАРАМЕТРЫ ПОТОКОВ ВОДОРОДНОЙ ПЛАЗМЫ В КСПУ-М И ИХ ЗАВИСИМОСТЬ ОТ ВНЕШНЕГО МАГНИТНОГО ПОЛЯ

М.С. Ладыгина, Ю.В. Петров, Д.В. Елисеев, В.А. Махлай, Н.В. Кулик, В.В. Стальцов

Проведенные экспериментальные исследования направлены на анализ параметров водородной плазмы в свободном потоке для различных рабочих режимов работы КСПУ-М. С помощью оптической эмиссионной спектроскопии восстановлены временные распределения плазменной электронной плотности. Проанализировано влияние магнитного поля на параметры плазменных потоков, и показано, что плотность при работе в дополнительном магнитном поле возрастает на порядок величины по сравнению с плотностью, измеренной без магнитного поля. Оценены параметры скорости и густоты энергии плазмы, а также их временное поведение в различных режимах работы установки КСПУ-М. Проанализированы особенности излучения плазмы. Данная информация очень важна для применения КСПУ-М в экспериментах по взаимодействию мощных плазменных потоков с поверхностями материалов.

ПАРАМЕТРИ ПОТОКІВ ВОДНЕВОЇ ПЛАЗМИ В КСПП-М ТА ЇХ ЗАЛЕЖНІСТЬ ВІД ЗОВНІШНЬОГО МАГНІТНОГО ПОЛЯ

М.С. Ладигіна, Ю.В. Петров, Д.В. Єлісєєв, В.О. Махлай, М.В. Кулик, В.В. Стальцов

Проведені експериментальні дослідження спрямовані на аналіз параметрів водневої плазми у вільному потоці для різних робочих режимів роботи КСПП-М. За допомогою оптичної емісійної спектроскопії реконструйовано часові розподіли електронної густини плазми. Проаналізовано вплив магнітного поля на параметри плазмових потоків та показано, що густина плазми при роботі з додатковим магнітним полем зростає на порядок величини в порівнянні з густиною, виміряною без магнітного поля. Оцінено параметри швидкості та густини енергії плазми, а також їх поведінку під час розряду в різних режимах роботи установки КСПП-М. Проаналізовано особливості випромінювання плазми. Ця інформація дуже важлива для застосування КСПП-М у експериментах по взаємодії потужних плазмових потоків з поверхнями матеріалів.