Novel Test-bed Facility for PSI Issues in Fusion Reactor Conditions on the Base of Next Generation QSPA Plasma Accelerator

I.E. Garkusha[1], V.V. Chebotarev[1], S.S. Herashchenko[1], V.A. Makhlaj[1], N.V. Kulik[1], M.S. Ladygina[1], A.K. Marchenko[1], Yu.V. Petrov[1], V.V. Staltsov[1], P.V.Shevchuk[1], D.G.Solyakov[1], D.V. Yelisyeyev[1]

[1] Institute of Plasma Physics, NSC "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine

E-mail contact of main author: garkusha@ipp.kharkov.ua

Abstract. In this report concept of new generation QSPA with external B-field up to 2 T has been discussed and novel test-bed facility, which recently constructed in Kharkov IPP NSC KIPT, has been described. It allows new level of plasma stream parameters and its wide variation in new QSPA-M device, as well as possible combination of steady state and pulsed plasma loads to the materials during the exposures. First plasma is recently obtained. Careful optimization of the operational regimes of the plasma accelerator's functional components and plasma dynamics in the magnetic system of QSPA-M device has been started approaching step by step the necessary level of plasma parameters and their effective variation. The relevant results on plasma stream characterization are presented. Energy density distributions in plasma stream have been measured with calorimetry. Spectroscopy and probe technique have been also applied for plasma parameters measurements. The obtained results demonstrate ability of QSPA-M to reproduce the ELM impacts in fusion reactor both in term of heat load and particle flux to the surface.

1. Introduction

Understanding of plasma-surface interaction (PSI) effects during the transient events (disruptions, VDEs, ELMs) in tokamak reactor requires dedicated R&D activity in plasma simulators used in close connection with material characterization facilities as well as with theory and modeling activities [1,2]. For such investigations various simulators of transient loads are now involved (quasistationary plasma accelerators QSPA, e-beams, pulsed plasma guns and, recently, PSI device), that are cost effective, flexible, able to provide faster results and important comparison of damage features from various machines [3-8].

In available experiments with QSPA-Be and QSPA-T facilities high-power plasma impacts to beryllium and tungsten samples are realized in absence of external magnetic field [4]. In simulation experiments with QSPA Kh-50 in Kharkov the plasma stream is able to be injected into the magnetic system with a longitudinal field of several kGs. However, during injection a significant part of plasma stream energy is unavoidable lost due to dissipation processes at the entrance of magnetic system [3,9]. The energy and plasma particles losses restrict further increase of B-field in QSPA Kh-50 device up to the ITER and DEMO relevant magnitudes. Other important issues that remain to be realized in simulation experiments are appropriate combination of a steady-state and transient plasma loads that intrinsic to a tokamak reactor operation and material surface exposures with helium containing plasma.

This paper presents concept of new generation QSPA as test-bed facility for fusion reactor materials as well as current status of the device maintenance. First results of experimental studies of plasma stream parameters, PSI issues in presence of external B-field as well as prospects for further experiments are briefly discussed also.

The strategic aim of these developments is putting into operation a new combined plasma device for studying the damage effects and the role of ELM´s simulated by means of this pulsed linear plasma. It will give better understanding and characterization of the fusion material behaviour under the plasma irradiation. This new device is suggested to be an appropriate combination of conventional QSPA with steady-state linear PSI device.

2. QSPA-M device

2.1. Experimental stand and QSPA plasma source

With these motivations, the concept of new generation QSPA plasma accelerator which is equipped with longitudinal B-field up to 2T has been developed to create novel powerful test-bed facility of compact geometry for adequate simulation of fusion reactor conditions, where plasma is transported to the divertor along the separatrix lines of magnetic configuration with B-field up to 5T and ELM peaks occur on the background of steady state energy and particle loads. General scheme of QSPA-M device that aimed at realization of this concept is presented in Fig. 1

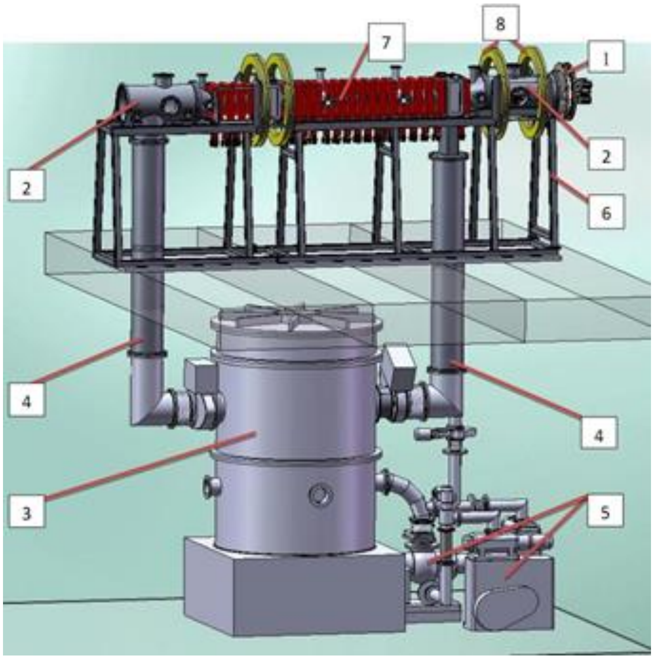

FIG.1. Scheme of QSPA-M test-bed facility: 1- QSPA plasma source; 2- chambers of QSPA and Hall-type steady-state plasma sources; 3- booster chamber; 4-pumping ports; 5- pumps; 6-support; 7- B-field coils; 8- Helmholtz coils.

The designed QSPA plasma source is shown in Fig.2.

There are three key issues [10-18], which provide QSPA operation for long pulse, help to avoid erosion of electrodes and plasma contamination, allow achievement of necessary plasma parameters (velocity and density). Also they are important for plasma transportation in external B field:

- input part, to provide ionization zone;
- anode part, to support electrical current between electrodes by ions;
- cathode part, to protect cathode elements from high energy ion bombardment;

A cathode unit of the new QSPA-M machine (see Fig. 2) consists of cylindrical and ellipsoidal parts. The ellipsoidal part is formed by 12 rods-lamellas. The maximal diameter of this part is 160 mm, and its length is 300 mm. The anode of the squirrel-cage type (of 250 mm in diameter and 730 mm in length) is composed of 24 rods, each of 10 mm in diameter.

Appropriate gas supply schemes of plasma accelerator were considered. Combination of end-type gas supply and gas injection from the cathode region was chosen. In order to supply the working gas into the acceleration channel the use is made of 4 axial gas-feed injectors (AGFI), which provide the plasma creation at the entrance section of the accelerator nozzle, and one additional radial gas-feed injector (RGFI) placed inside the cathode unit region. Separate supply units allow the gas injectors to deliver different combinations of gases and their mixtures into the accelerating channel.

The QSPA plasma accelerator is placed into the vacuum chamber with diameter of 340 mm and total length more than 3 m. Vacuum pumping system consists of the vacuum chamber and ports, the booster volume of 4.5 m^3, 2 forevacuum pumps and one turbomolecular pump providing the pumping speed 1500 l/s.

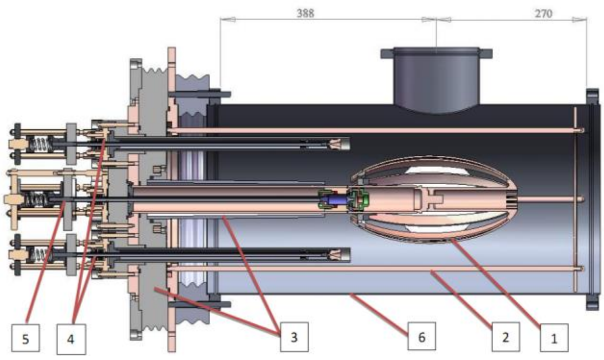

FIG. 2. QSPA plasma source. 1- cathode;2-anode; 3-insulators; 4- axial gas injectors; 5- radial gas injector.

Magnetic system of QSPA-M device consists of 21 base coils of longitudinal magnetic field and four Helmholtz coils in the regions of plasma accelerator and target chambers (Fig.1). Additional resistances were used for formation of magnetic field distribution along axis. The designed magnetic system serves to create B-field up to 2 T with variable distribution along the magnetic system for plasma magnetization and it further transportation to the target chamber (some chosen scenarios of increasing and plateau-like magnetic field are shown in Fig. 5).

Application of small external magnetic field in the discharge area (Helmholtz coils engirding the plasma accelerator) was analyzed. It is concluded that longitudinal magnetic field of 0.1.B_{int} promotes plasma stream stability and plasma entrance to the external B-field of the vacuum chamber.

A power supply of the discharge in QSPA-M plasma accelerator comes from the capacitor battery with C=1770 μF, U_{max}=40 кV, and maximal stored energy W≈1,4 MJ with switching and synchronization equipment. Magnetic field system is supplied by battery with capacitance C=15120 μF and stored energy of W= 189 kJ for 5 kV maximum voltage at the banks. Battery of gas injectors has a capacitance C=1800 μF and maximum voltage of 5 kV.)

2.2. Analysis of plasma flow in QSPA accelerating channel

Plasma flow in chosen accelerator geometry was calculated on the base of MHD modeling in 2 different approximations.

Basic properties of plasma flow in accelerating channel were analysed based on Slow Changed Channel model (SCC) [10,11]. The main assumption for this model is that accelerating channel is changed very slowly along axis, that $\left(v_r / v_z \right)^2 << 1$. This model describes rather good the main central part of accelerating channel, excepting input area, where significant gradients of plasma stream velocity are observed and output region, where dissipative processes play important role. In SCC model the ion flux function can be written as: $\Psi_i(r,z) = \sqrt{2} a_*^2 n_{0*} C_{A0} \alpha(z) \sqrt{(1-\alpha(z))} \ln\left(\dfrac{r}{b(z)} \right)$

Where $\Psi_i(r,z)$ - ion flux function; a_* - average radius in the input part of accelerating channel; n_{0*} - plasma density in this point; C_{A0} - Alfven velocity in this point; $\alpha(z)$ - dependence of discharge current along channel axis; $b(z)$ - cathode radius (assume that anode is cylinder) and r - flux tube radius.

Ion flux functions were calculated for different dependencies of discharge current distributions along the axis and for varied accelerating channel profile. Then, on the base of SCC model the ratios of ion velocity v_i to local signal velocity $v_s = \sqrt{v_A^2 + v_{Ti}^2}$, were calculated. Taking into account that particle thermal energy is much less than kinetic energy, the local signal velocity practically corresponds to the local value of Alfven velocity $v_s \approx v_A$. Calculated ratios, plotted lines of equal values v_i / v_A for linear dependence of discharge current along axis are presented in Fig 3 for two considered channel profiles.

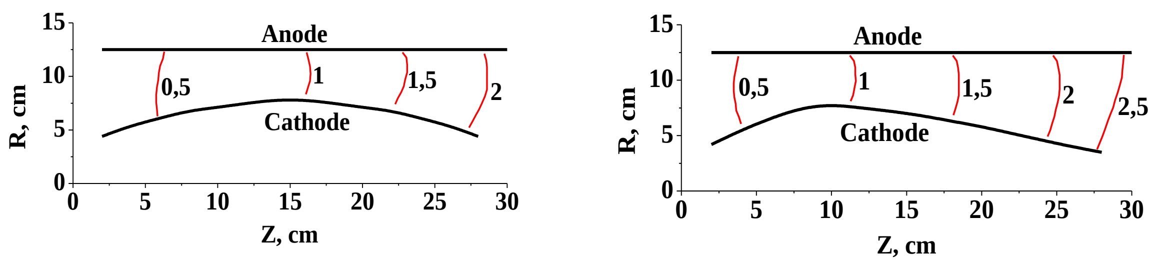

FIG.3. Lines of equal values of v_i / v_A.

As follows from these figures the plasma stream is accelerated along the QSPA-M channel and the achieved velocity is about (2-2.5) v_A at the accelerating channel output.

Based on SCC model the plasma density in the entrance of accelerating channel and it radial distributions were analysed assuming maximum value of discharge current in the acceleration channel of about 600 kA and exchange rate $\xi = 0.1$. Taking into account $\dot{N} = 2\pi\Psi_i^{max}$, the total mass flow rate could achieve $I_{\dot{m}} \approx 3.6\times10^{25} s^{-1}$ and Ψ_i^{max} will reach $\Psi_i^{max} = 6\times10^{24} s^{-1}$ respectively. Average radius at the entrance of accelerating channel $r = 10cm$. Thus, plasma density at $r = 10cm$ could be estimated as $n \approx 5\times10^{15} cm^{-3}$ and it radial distribution is shown in Fig.4.

In principle, there are two different ways to form such plasma density radial distribution. The first one is to inject neutral gas into accelerating channel from the cathode side in the entrance of accelerating channel. The second is to create electromagnetic force in the entrance part of accelerating channel that will push plasma to the cathode region. Both these ways can be applied in QSPA-M facility.

Maximum plasma stream velocity can be estimated based on calculated dated described above. So, for discharge current $I_d = 600kA$, plasma stream densities in the entrance cross-section $n = 5\times10^{15} cm^{-3}$, maximum velocity should be equal $v_{max} = 1.1\times10^{8} cm/s$. We have to stress that this value of plasma stream velocity can be achieved if discharge current between electrodes flows properly in radial direction.

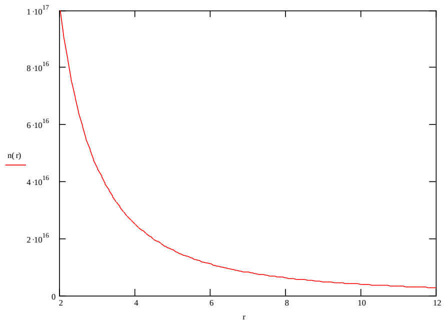

FIG. 4. Radial distribution of plasma stream density at the entrance of acceleration channel of QSPA-M.

3. First plasma experiments in QSPA-M

Photo of constructed and assembled new experimental device is shown in Fig.5. It should be mentioned that this new experimental stand creates possibility to apply simultaneously the QSPA-type and steady-state plasma sources which can be installed at the opposite ends of the vacuum chamber. It should here be stressed that plasma discharge in this new device is performed at the presence of the external magnetic field, which allows minimizing the particle and energy losses inherent to the entrance of a plasma stream into the magnetic field. As a result, it will allow us to investigate a wider range of plasma-stream parameters in the QSPA-M device, as well as to study possible combinations of steady-state and pulsed plasma-loads at the materials exposures. It provides possibility of an effective variation of the particle flux upon the target surface and the energy density in the generated plasma stream. In some cases it could be done independently by choosing different scenarios of the plasma discharge initiation and by applying various boundary conditions in the accelerating channel of the QSPA-M device.

Experiments with new QSPA-M test-bed facility have been already started. First plasma is recently obtained.

First experiments were launched at relatively low energy level of capacitor battery to adjust operational regimes of different QSPA units. Therefore, only part of QSPA power supply system was involved. Current-Voltage characteristics (CVC) were measured in QSPA mode of operation with pulsed gas injection from the cathode side, in both cases: without external magnetic field and applying longitudinal magnetic field of 400 Gs in the discharge area with further grow up to the maximum value of 3kGs at the distance of 270 cm from the accelerator output. Total gas supply of QSPA discharge was about 530 cm^3 H_2 at atmosphere pressure.

It was demonstrated that in presence of additional B-field the discharge in plasma accelerator became more stable. In addition, higher discharge voltage is achieved and the CVC curve is close to the theoretical expectations [10-12]. Measurements of plasma stream velocity by time of flight method between photodiodes situated at the distances of 1.5 and 2.0 m from the accelerator output also demonstrate possibility to achieve appropriate range of plasma stream parameters in presence of small longitudinal B-field in the discharge (FIG.6).

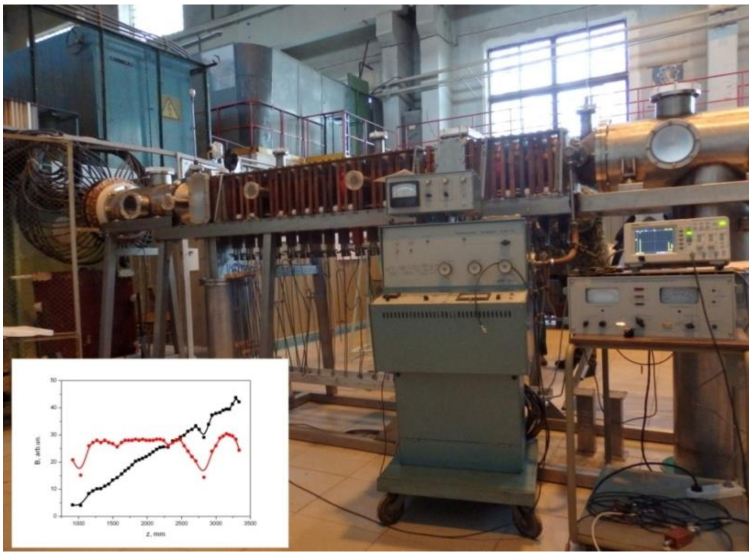

FIG. 5. Assembled QSPA-M device and 2scenarios of B-field distributions for plasma transportation in the magnetic system.

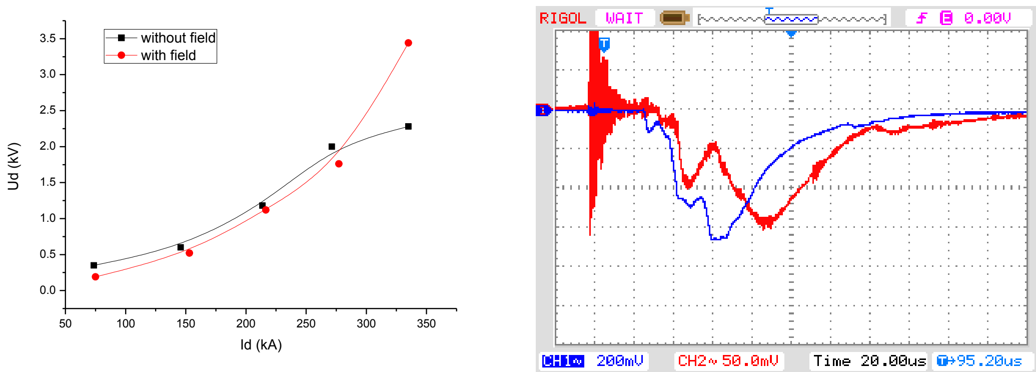

FIG.6. Current-voltage characteristics of QSPA-M discharge with and without external magnetic field (a) and signals of photodiodes from the generated plasma stream.

Energy density distributions in plasma stream have been measured with calorimetry. Results of first experiments are presented in Fig. 7. These measurements were performed at rather far distance L=165 cm from the accelerator output to analyze the plasma stream transportation in vacuum chamber of QSPA-M device. In presence of external magnetic field the energy density in plasma stream at large distances from the accelerator is found to be smaller, but difference between energy characteristics with and without B-field essentially decreases with growing value of discharge current in plasma accelerator. It indicates necessity of experimental studies on plasma stream dynamics aiming at optimization of plasma stream transportation in magnetic system of QSPA-M device

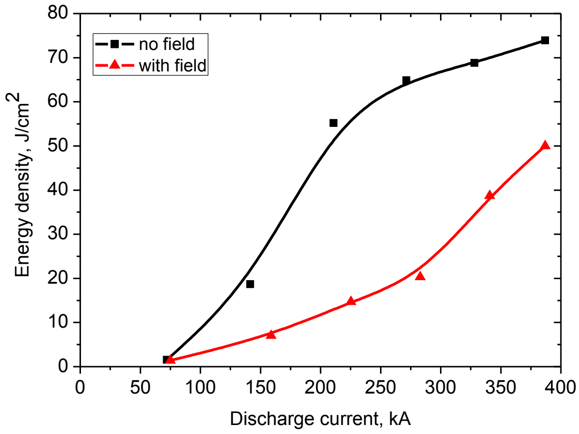

FIG.7. Energy density in plasma stream measured with calorimetry at the distance of 1.65 m from the accelerator output

Spectroscopy and probe technique have been also applied for plasma parameters measurements. Optimization of the operational regimes of the plasma accelerator's functional components and plasma dynamics in the magnetic system of QSPA-M device has been performed approaching step by step the necessary level of plasma parameters and their effective variation. Plasma stream density was measured by Stark broadening of H_{β} spectral line without temporal resolution at the distance of 35 cm from accelerator output. The chord averaged electron density in plasma stream propagating in external longitudinal B-field was about (0.8-2).10^{16} cm^{-3}.

Thus, the obtained results demonstrate attractiveness of QSPA-M as test-bed facility for fusion materials studies and ability of QSPA-M to reproduce the ELM impacts in fusion reactor both in term of heat load and particle flux to the surface.

4. Conclusions

QSPA with external B-field up to 2 T has been developed and novel test-bed facility has been constructed. It allows new level of plasma stream parameters and its wide variation in new QSPA-M device, as well as possible combination of steady state and pulsed plasma loads to the materials during the exposures.

First plasma is recently obtained. Careful optimization of the operational regimes of the plasma accelerator's functional components and plasma dynamics in the magnetic system of QSPA-M device has been performed approaching step by step the necessary level of plasma parameters and their effective variation.

The obtained results demonstrate ability of QSPA-M to reproduce the ELM impacts in fusion reactor both in term of heat load and particle flux to the surface.

Acknowledges

This work has been performed in part within IAEA CRP F1.30.13 and partially supported by STCU-NASU project 6057and the Targeted Program of NAS of Ukraine on Plasma Physics

References

[1] ROTH, J. et al. J. Nucl. Mater. 390–391(2009) 1

[2] LANDMAN I. et al. Phys. Scr. T111 (2004) 206 doi: 10.1238/Physica.Topical.111a00206

[3] TERESHIN, V.I. et.al. Plasma Physics and Controlled Fusion 49, (2007) A231–A239

[4] KLIMOV, N.S. et al. Fusion Science and Technology 66, 1 (2014) 118-124

[5] Integrated Approach to Dense Magnetized Plasmas Applications in Nuclear Fusion Technology, Report of a Coordinated Research Project 2007–2011, IAEA TECDOC No. 1708., ISBN:978-92-0-142810-3), 231 pp. (2013).

[6] GARKUSHA, I.E., AKSENOV, N.N., CHUVILO, et al., Transient Plasma Loads to the ITER Divertor Surfaces: Simulation Experiments with QSPA Kh-50, Nukleonika 57(2) (2012) 167-170.

[7] SHIROKOVA, V., et al., “Comparison of damages in tungsten and tungsten doped with lanthanum-oxide exposed to dense deuterium plasma shots”, Journal of Nuclear Materials 135 (1-3) (2013) 181-188.

[8] LOEWENHOFF, Th., et al, “Tungsten and CFC degradation under combined high cycle transient and steady state heat loads”, Fusion Engineering and Design 87 (2012) 1201-1205.

[9] TERESHIN V.I. Quasi-stationary Plasma Accelerators (QSPA) and their Applications // Plasma Physics and Controlled Fusion.-1995.- Vol. 37.- P. A177-A190.,

[10] MOROZOV A.I.. Plasma dynamics, in Encyclopedia of Low Temperature Plasma, V3. ed. V.Fortov(in Russian);

[11] MOROZOV A.I. Introduction to Plasmadynamics. Moscow. FIZMATLIT. 2006, 576 p (in Russian).

[12] MOROZOV A.I. Sov. J. Plas. Phys 1990, v.16, N2.

[13] TERESHIN V. I. et al., Brazilian Journal of Physics 32, № 1, 165-171 (2002).

[14] TERESHIN V. I. et al., Plasma Phys. Control. Fusion 49 (2007) A231

[15] MOROZOV A.I., SHCHUROV O. A., PAVLICHENKO O.S. et. al. QSPA Kh-50 full-sale high-power quasistationary plasma accelerator // Plasma devices and operations. - 1992. - Vol.2, № 2. - P. 155-165

[16] VOLKOV Ya. F. et al, Sov. J. Plas. Phys. 1992, V.18, N. 9, p. 1138.

[17] VOLKOV Ya. et al. Sov. J. Plas. Phys. 1992, V. 18, 4, p.456

[18] VOLKOV Ya. F., GARKUSHA I.E et al. Sov. J. Plas. Phys. 1994. V.20, 1, p.77