INVESTIGATION OF HIGH POWER QUASI-STEADY-STATE PLASMA STREAMS FLOW IN MAGNETIC FIELD AND THERMAL QUENCH DISRUPTION SIMULATIONS

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1. Introduction

Plasma stream-magnetic field interaction is one of the fundamental problems of plasma physics, which is of importance for hot plasma injection into mirror magnetic traps of different kinds. The main aim of this work is analysis of interaction of high-power quasi-steady-state plasma streams with magnetic field, their magnetization in uniform longitudinal magnetic field and modelling experiments on magnetized plasma-divertor plates interaction under thermal quench disruption.

2. Experimental device

Experiments were carried out in the QSPA Kh-50 device [1]. The full-block powerful quasi-steady-state plasma accelerator was used as a plasma streams source. It consists of two stages. The first one is for plasma production and pre-acceleration. The second stage (main accelerating channel) is coaxial system of shaped active electrodes-transformers with magnetically screened elements. We call active transformers in the case of their elements are current supplied for their magnetic screening by the independent controlled power sources and ions (from anode side) or electrons (from cathode side) are supplying the discharge by individual particle sources. The working gas is hydrogen.

The main discharge was normally supplied by condenser bank of about 0.9 MJ stored energy (C = 7200 μF, U_C < 16 kV) and discharge current duration achieved 300 μs – regime 1 (see Fig. 1). To increase the discharge duration and, therefore, to increase the quasi-stationary phase of acceleration, the main condenser bank was separated by 6 sections switched on with some delay one to another - regime 2. As the result, the pulse of discharge current (and the plasma potential) was increased up to 500 μs (Fig. 1).

The magnetic solenoid of 1.6 m in length and 0.42 m in inner diameter consists of 4 separate magnetic coils. Coils current supplying provides creation of magnetic field with magnetic field strength increasing with the length. The maximum value of magnetic field at the vicinity of diagnostic chamber (between 3^{d} and 4^{th} coils) achieved 1 T. Set of magnetic coils was placed either at the distance of z = 1.25 m from accelerator output (closer to the compression region of plasma stream) or at z = 2.45 m, where incident plasma stream is diverging. Thus, solenoid position defines the efficiency of plasma penetration into magnetic field and efficiency of it’s magnetizing.

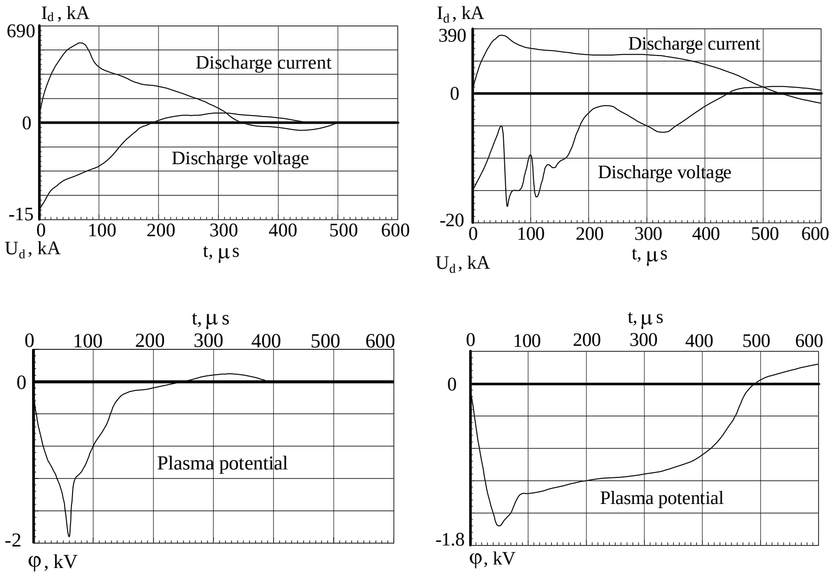

Fig. 1. Signals of discharge current and voltage and plasma potential: left hand – switching on whole condenser bank; right hand – programming switching on separate sections of condenser bank.

Samples of different materials to be irradiated by plasma in magnetic field were placed through the sluice chamber at the diagnostic chamber.

3. Results of experiments and discussion

The magnetic field displacement by plasma stream, total plasma energy and other plasma parameters were measured for plasma streams propagating along the magnetic field. Plasma parameters measured for the regime 1 at the end of solenoid with magnetic field strength of 0.74 T (Z = 1.25 m) were as follows: plasma stream density was up to (3-5).10^{16} cm^{-3}, proton energy achieved 200-250 eV, maximum power density was up to 20 MW/cm^2, electron temperature 2-3 eV, the duration of quasi-stationary phase of acceleration achieved 0.15-0.2 ms, total energy containment in plasma stream was about 0.2 MJ. The time behaviour of some plasma stream parameters, measured for the regime 2 at the same other conditions, are shown in Fig. 2. Plasma density was deduced from H_β spectral line Stark broadening measurements, plasma velocity – by time of flight plasma between two photodiodes, and plasma power was calculated on the base of those measurements. It is follows from this picture that the power pulse is sufficiently longer for this regime of operation, as compare with the regime 1, and it’s duration achieves 0.3-0.35 ms.

Plasma injection into magnetic field was accompanied by strong magnetic field displacement out of plasma at the input to magnetic solenoid. Than, with plasma propagation along the solenoid, magnetic field step by step penetrates into plasma. The efficiency of penetration is in dependence of incident plasma parameters and magnetic solenoid position.

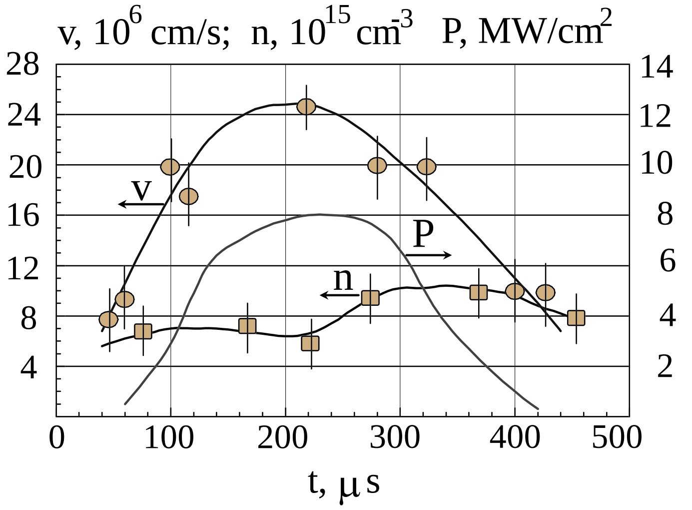

Fig. 2. Time dependencies of plasma stream parameters in magnetic field for the regime 2 of QSPA operation: velocity (v), electron density (n) and power (P)

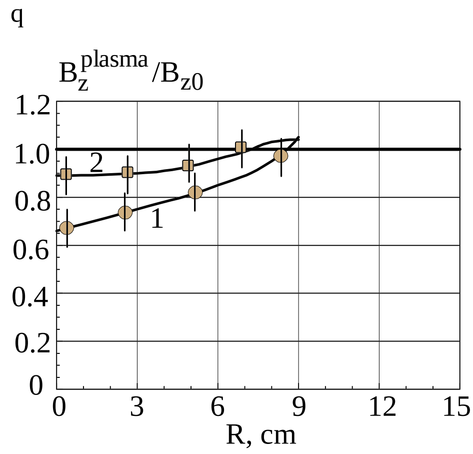

Fig. 3. Radial distribution of magnetic field in plasma stream normalized by vacuum magnetic field value:
1 – regime 1; 2 – regime 2

Radial profiles of relative values of magnetic field in plasma, measured at the position of diagnostic chamber for two regimes of QSPA operation, are shown in Fig. 3. Despite sufficiently different plasma parameters for these regimes of operation, one can see from this picture that plasma stream radii, defined as a plasma boundary where $B_{pl} = B_{0,}$ are more or less comparable and equal 6-8 cm. As to the β value ($\beta = 8\pi nkT/B_{pl}^2$), it is about 50-60 % for the operation regime 1, with sufficiently higher level of density, and 10-20 % for regime 2, indicating more effective plasma magnetization in the latter case.

Analysis of energy containment in plasma streams passing through the magnetic solenoid had shown that it's absolute value is in strong dependence on magnetic solenoid position. Being equal of an order 40-60% of incident plasma stream energy for closer position of solenoid, it falls down to about 20 % for z = 2.45 m. This is due to the higher plasma stream divergence just at the input to solenoid and, therefore, more strong plasma reflection by the mirror in the latter case.

Magnetized plasma streams were utilized in experiments modelling situation on the divertor plate surfaces under the thermal quench disruption [2]. There was shown in our experiments that maximum graphite (MPG-7) erosion depth is in strict dependence of magnetic field presence. The maximum erosion coefficient for normal plasma irradiation (averaged by 10 shots) was of an order 2-3 µm per 1 kJ/cm^2 of incident plasma energy (P = 20

MW/cm^2, pulse of power duration 0.17-0.2 ms). The value of this coefficient (0.3-0.4 μm per 1 kJ/cm^2) was sufficiently lower for irradiation in magnetic field of 0.72 T. It was increased at least by 1.5-2 times for inclined target irradiation in magnetic field.

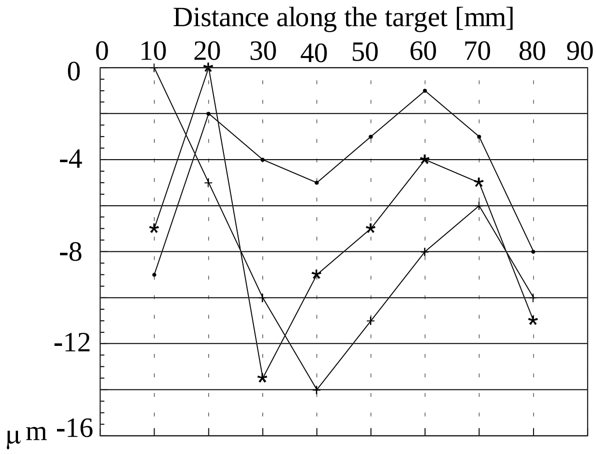

Fig. 4. Erosion profiles of quartz surface (90 x 90 mm) for different cross-sections. Inclined incidence of plasma.

The quartz material was chosen for analysis of fine structure of surface irradiated by powerful plasma streams. All pictures were obtained under irradiation during one plasma pulse of power density 20 MW/cm^2 and pulse duration 0.15-0.17 ms. The main experiments were carried out with non-polished quartz (it has higher erosion depth as compared to a polished quartz). The plates of 9x9 cm in size were irradiated by plasma stream both normally to the surface and under the angle of inclination 20^0 with respect to the plasma stream axis. The erosion profiles for inclined irradiation are shown in Fig. 4. The profiles are plotted for three sample cross-sections: median cross-section and 20 mm right and left on it. The maximum values of erosion depth are comparable for both cases. Nevertheless, for inclined irradiation the erosion profiles have more complicated structure along the surface. They have periodical structure with periodicity of an order 5-6 cm. This result is in agreement with numerical simulation carried out in [3], where was shown that erosion modulation can be occurred due to modulation of shielding layer.

4. Conclusions

Investigation of plasma streams (with power density 2-20 MW and time of generation up to 0.35 ms) interaction with magnetic field was carried out. There were found conditions of plasma magnetising when propagating along the magnetic solenoid. Some effects of plasma stream- surface interaction were analysed too.

References

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