TRANSPORTATION OF QSPA PLASMA STREAMS IN LONGITUDINAL MAGNETIC FIELD

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INTRODUCTION

Plasma stream-magnetic field interaction is one of the fundamental problems of plasma dynamics, which is of importance for hot plasma injection into magnetic traps of different kinds. At the same time powerful magnetized plasma streams are widely used now for investigations of hot plasma interaction with solid surfaces simulating power load conditions in future fusion devices [1-4].

The main aim of this work is analysis of efficiency of QSPA powerful plasma streams transportation in longitudinal magnetic field in dependence on operational mode of accelerator and plasma stream parameters.

EXPERIMENTAL DEVICE

Experiments were carried out in the QSPA Kh-50 device. The full-block powerful quasi-steady-state plasma accelerator consists of two stages. The first one is used for plasma production and pre-acceleration. The second stage (main accelerating channel) is a coaxial system of shaped active electrodes-transformers with magnetically screened elements (those elements are current supplied either from independent power sources or branching partly the discharge current in self-consistent regime of operation). The geometry of QSPA accelerating channel is formed mainly by profile of the cathode. Two types of cathodes were used in these experiments. The first one is semi-active cathode of 62 cm in length and with maximum diameter of 36 cm described in details in [1]. The second one is new cathode transformer with the length of profiled part 63 cm and maximum diameter of 40 cm. It profiled surface is formed with 20 solid strips of 20 mm in width and 5 mm in thickness. Thus the distance between cathode and anode in critical section of main accelerating channel is reduced (Fig.1). Also the distance between the nozzles of the input ionization chambers and profiled part of the cathode transformer is essentially reduced in experiments with new cathode transformer.

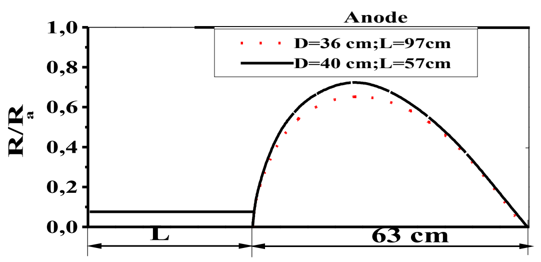

Fig.1. Scheme of QSPA main accelerating channel with the cathodes of different diameters (D). L -distance between the nozzles of the input ionization chambers and profiled part of the cathode; R_a=27,5 см- radius of anode collector.

The working gas is hydrogen. The power supply of all accelerator units comes from the capacitor banks. The main results were obtained with capacitor voltage of the main discharge up to 12 kV (total energy about 0.5 MJ).

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 consisting of 4 separate magnetic coils. The first magnetic coil was placed at the distance of Z_S = 1.2 m from accelerator output. The currents in each coil were specially selected to provide plasma streams propagation in slowly increasing magnetic field (Fig. 2). The maximum value of magnetic field B_0=0.54 T was achieved in diagnostic chamber (in the region between 3 and 4 magnetic coils) [4,5].

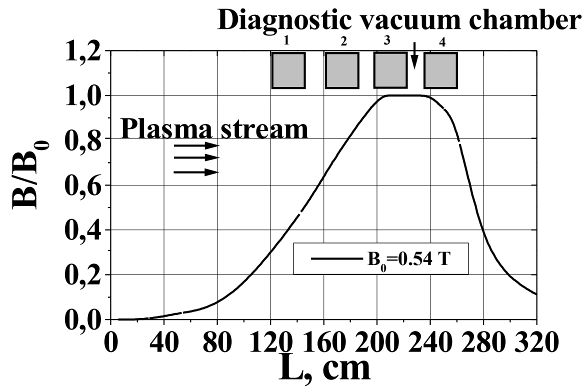

Fig. 2. Dependence of normalized vacuum magnetic field, on the distance from the accelerator output.

EXPERIMENTAL RESULTS

The main parameters of plasma streams (density, velocity, electron temperature) were measured in the vicinity of maximum value of a magnetic field for different operation regimes of plasma accelerator. The plasma stream velocity was measured by the time-of-flight of the plasma stream between two magnetic probes, the electron density in the plasma stream was evaluated on the basis of Stark broadening of the H_β spectral line, radial distributions of the plasma stream energy density were measured with a movable copper calorimeter, the power density was calculated on the basis of measurements of the time dependencies of the plasma stream density and its velocity. Plasma pressure was measured by piezoelectric detectors. Electron temperature was evaluated on the base of measurements of the ratio of CIII and CII spectral lines intensities.

Time behaviour of some plasma parameters in diagnostic chamber, obtained with magnetic field B_0 = 0.54 T, for both profiles of accelerating channel are shown in Figs. 3 and 4. The plasma stream parameters for regime with cathode of 36 cm in diameter were as follows: the electron density (2-3)$\times10^{16}$ cm^{-3}, maximum proton energy 200 eV, maximum power density up to 20 MW/cm^2, the duration of plasma generation (half-height width of power density curve) achieved (0.15-0.17) ms.

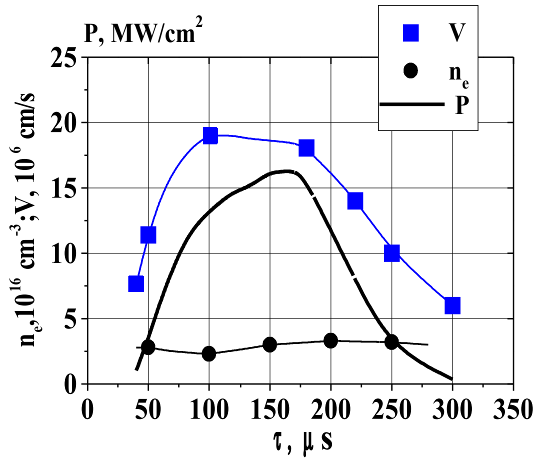

Fig.3. Time dependencies of plasma stream parameters: velocity (v), electron density (n) and power density (P); regime of QSPA operation with 36 cm cathode.

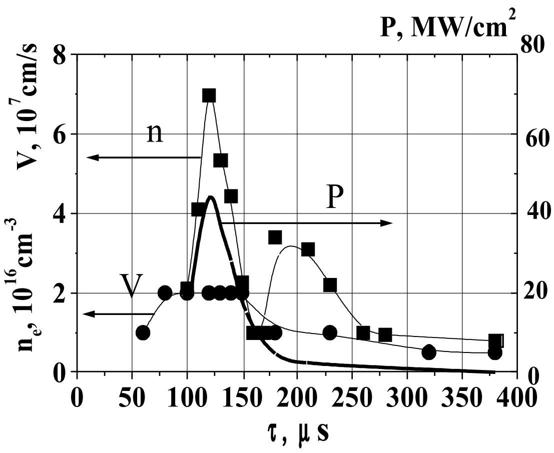

Fig.4. Time dependencies of plasma stream parameters: velocity (v), electron density (n) and power density (P); regime of QSPA operation with new geometry of accelerating channel

Variation of the accelerating channel profile and distance between accelerator stages results to difference in temporal evolution of plasma density. Average density ((2-4)$\times10^{16}$$cm^{-3}$) is not changed, but maximum value is increased up to 7$\times10^{16}$ cm^{-3}. While the maximum value (about 2$\times10^7$ cm/s) and time dependence of plasma stream velocity remains unchanged.

The peak power density of plasma stream increased up to 45 MW/cm^2. The total energy content in the plasma stream passing through the magnetic field increased from 56 kJ to 100 kJ.

The plasma stream pressure in magnetic field increased also. Typical signal of the plasma stream pressure for new geometry of accelerating channel is shown in Fig.5. The plasma pressure in near axis region in achieves P≈16 Bar and has peaked character. The plasma pressure time behavior correlates with temporal evolution of plasma density. It is necessary to note that the maximal pressure of the plasma stream, generated by QSPA with cathode of 36 cm in diameter, was not more than 3 Bar.

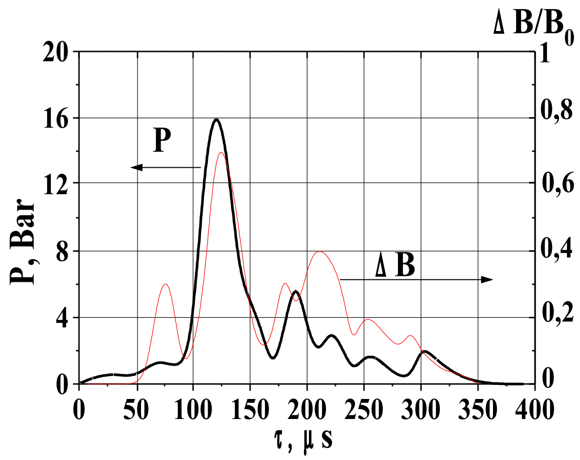

Fig.5. Time dependencies of plasma pressure (P) and displaced magnetic field (ΔB), normalized by the value of vacuum magnetic field (B_0=0.54 T), in diagnostic vacuum chamber.

Injection of powerful plasma streams into magnetic field is accompanied by magnetic field displacement out of plasma. The magnetic field displaced by plasma ΔB was measured by magnetic probes located in different cross- sections along the magnetic system. The value of a magnetic field in plasma B_{pl} was found as a difference B_0 - ΔB, where B_0 is vacuum a magnetic field

The B_{pl} value in incoming plasma stream depends on the distance from input of magnetic system. For example, in the region between first and second magnetic coils (Z=1.55 m from a accelerator output) the full displacement of magnetic field by incoming plasma stream was observed for plasma stream with the power density of 45 MW/cm^2. While the value of displaced magnetic field in diagnostic cross-section is of order Δ B/B_0~ 0.7 (for time moment corresponding to maximum of power density). The signal of magnetic probe which is located at the region of homogeneous magnetic field (Z=2.3 m from a accelerator output) was shown in the Fig.(5). The temporal behavior of the signal of displaced magnetic field is not differs from the temporal dependence of the plasma pressure.

For a detailed investigation of plasma stream magnetization the radial distributions of magnetic field in plasma stream were measured at the different distances from accelerator. The radial profiles of relative values of magnetic field in plasma (B_{pl}/B_0=(B_0 - ΔB)/ B_0)) for both regimes of QSPA operation are shown in Figs.6 and 7.

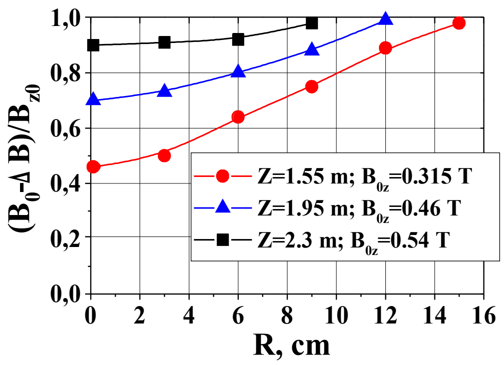

Fig.6. Radial distributions of magnetic field in plasma stream normalized by vacuum magnetic field value (B_0) at the different distances (Z) from accelerator output, in moment of time corresponding to maximum of power density; regime of QSPA operation with 36 cm cathode

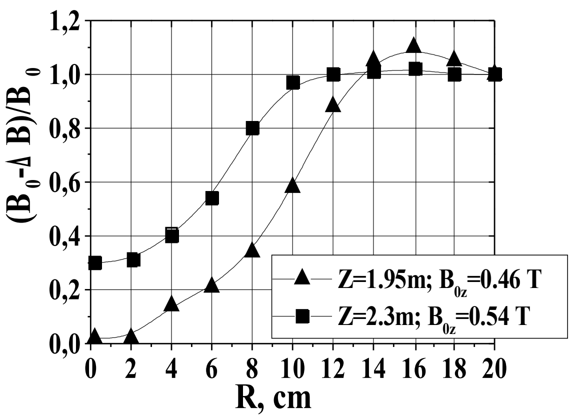

Fig.7. Radial distributions of magnetic field in plasma stream normalized by vacuum magnetic field value (B_0) at the different distances (Z) from accelerator output. Regime of QSPA operation with new cathode.

As follows from these pictures, propagation of plasma stream along the magnetic system is accompanied by magnetization of plasma. The efficiency of magnetic field penetration into plasma is in dependence on incident plasma parameters. For instance, for plasma stream with power density equal to 20 MW/cm^2 about 90 % of external magnetic field penetrates into the plasma stream. Meanwhile, with increase of a power density of incoming plasma stream up to 45 MW/cm^2 about 30% of external magnetic field penetrates into plasma stream.

At the same time a decrease of plasma stream diameter with the distance along magnetic system was observed. Plasma stream radius was defined as the radius of plasma boundary where $\Delta B_z = 0$. Despite of sufficiently different plasma parameters for two regimes of operation, one can see from Figs.6 and 7 that plasma stream radii are more or less comparable and equal to 8-10 cm at the position of diagnostic chamber.

An ordinary pressure balance equation on the plasma boundary was used for estimation of the transversal plasma pressure. It was found that in the case of high level of plasma magnetization the average plasma pressure $\langle P \rangle = \langle n \times (T_e + T_i) \rangle$ was equal (1.4-1,6)x10^{17} eV/cм$^{-3}$ while for low magnetization ‹P›=(2-5)×10^{17} eV/cм^3. Average β value, calculated on the basis of plasma pressure and vacuum magnetic field $\beta = 8\pi P/B_0^2$ is about 0.4-0.6 for plasma stream with higher peak density, and 0.1-0.2 for the regime with lower plasma density. This indicates more effective plasma magnetisation in the latter case.

Electron temperature was calculated from the ratio of intensities of impurity lines (CII and C III) and from time of magnetic field diffusion into plasma $\tau_D=4\pi R^2\sigma_0/c^2(1+(\omega_{Be}\tau_{ei})^2)$. Here R-radius of plasma, σ_0- Spitzer conductivity of plasma, c- velocity of light, $\omega_{Be}\tau_{ei}$- the Hall parameter. Obtained values of T_e= (2-4) eV by both methods are in satisfactory agreement with each other. Temperature of ions T_i was determined from the Doppler broadening of lines CII and NII. The ion temperature value was at the level of T_i= (10-20) eV. This result is in good agreement with plasma temperature estimation from the pressure balance equation.

CONCLUSIONS

Variation of the accelerating channel profile leads to difference in temporal evolution of plasma stream density. Maximum value of plasma density is increased up to 7× 10^{16} cm^{-3}. The peak power density of plasma stream achieved 45 MW/cm^2. The efficiency of transportation of plasma streams in magnetic field is also essentially improved. The pressure of plasma stream propagating in magnetic field is increased up to 16-18 Bar. Average β is at the level of (0.4-0.6).

It is important to note that for providing comparison of accelerator operation for both profiles of accelerating channel the working regime parameters of first stage of accelerator remain unchanged. Since accelerating rate for new geometry of main accelerating channel is higher, some mismatch of accelerator stages is occurred. As result half-height width of power density curve is decreased. Nevertheless total energy content in the plasma stream passing through the magnetic field exceeded 100 kJ even in these nonoptimal conditions.

Thus modernization of a plasma accelerator allowed to increase at least in twice the plasma stream power density as well as the total energy content in the plasma stream being magnetized in longitudinal magnetic field. Further optimization of first stage of accelerator is necessary to achieve compatible plasma inflow to the main accelerating channel.

REFERENCES:

[1] V.I.Tereshin, Plasma Phys. Control. Fusion 37, 1995 p.177

[2] N. Arkhipov, V. Bakhtin et al. // Fusion technology, vol. 32, 1997, p. 45-74.

[3] S.I. Ananin, V.M. Astashynski et al. Proc. of 29th EPS Conf. On Plasma Physics and Controlled Fusion. ECA Vol. 26 B, P-5.049 (2002)

[4] V.I.Tereshin, V.V.Chebotarev et al, Transactions of fusion technology, v.35 No 1T, 1999, p.248-252.

[5] V.I.Tereshin, V.V.Chebotarev et al., Brazilian Journal of Physics, v.32, No1, 2002. p165-171.