Central Fueling of Globus-M Plasma with the Help of Coaxial Plasma Gun

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Abstract. New experimental results on a plasma jet injection of an advanced plasma gun into Globus-M are presented. Local measurements have shown that already in 50 μs after the start of the plasma jet injection into the target plasma with the current of 0.2 MA and density of $(2\text{-}6)\times10^{19}\text{m}^{-3}$ the plasma density at the magnetic axis increased and the temperature dropped up to three times. The improved parameters of the jet generated by the two stage plasma gun are: density more than 2×10^{22} m^{-3}, total number of accelerated particles $(1\text{-}5)\times10^{19}$, the flow velocity more than 200 km/s and the pulse duration 10 μs. The source produces stable gas and plasma flow for many shots (>1000 pulses) due to modification of the gas and plasma generating stages. Kinetic energy of the jet was increased up to 200 J (by calorimetric measurements) by the higher discharge power at limited storage capacitor energy (2kJ). On test-bench experiments, the video and streak-cameras registered that the jet consists of different components with separate velocities from 100 to 250 km/s. Video frames of the jet injection into the tokamak plasma obtained with a fast video camera (4000 frames/s) visually demonstrated penetration to the central region. Temporal evolution of the electron temperature and density profiles obtained by means of multi-pulse Thomson scattering diagnostics during the first millisecond after the injection is analysed in the report. Varying the jet parameters, it was possible to control the jet penetration depth into the target plasma and the extent of its effect on the radial profiles of the plasma temperature and density. Under moderate modification of the density and temperature (up to 50 %) due to the jet injection, the plasma column kept MHD stability. Capability of the fast plasma jet penetration to the tokamak central region is proved by computations.

1. Introduction

One of the key problem of the tokamak-reactor control is fueling of it burning zone and peaked density profile formation. The fuel burnup is more intensive in the core of the plasma column, but refueling in conventional tokamak is due to the fuel diffusion from the cool periphery. Regular gas puffing is inefficient, because neutral atoms are ionized on the very periphery due to their low average free path, and only a small portion of them penetrates through the separatrix. As a result, the main part of the incoming fuel goes to the divertor, and the density profile formed at an intensive gas puffing is fare from the optimal one. Now, injection of frozen pellets of the hydrogen isotope mixture with speeds no more than 1-2 km/s is considered as the main method of the tokamak-reactor fueling. Also other methods are developed, the grate interest among them represent plasma accelerators providing much higher injection speed up to hundreds km/s .

The method of high speed, high density plasma jet injection is developed at the Ioffe Institute as a source of the tokamak fueling. Two stage plasma gun, with explosive method of gas feeding of a coaxial accelerator permits to combine necessary merit of the fuel injector – high density and speed of the jet with high purity of the substance. From the beginning of the experiments on the jet injection into Globus-M until now a cycle of experimental and modeling works have allowed us to increase the speed from 20-30 km/s and plasma density from 10^{21} m^{-3} by almost an order of magnitude. The probable mechanism of the jet penetration through magnetic field and plasma was suggested, and a possibility of deep penetration of the jet into the tokamak plasma was demonstrated. As result of the first experiments on the jet injection was a fast enhancement of the plasma column density in the absence of any visible distortion of the tokamak plasma. It was demonstrated also, that the plasma jet injected into a tokamak may be used as for fueling of the magnetic trap (tokamak), so for effective tokamak startup.

2. Plasma gun parameter improvement

Development of the gas and plasma stages of the gun, allowed us to get the plasma jet with the following parameters: maximum density more than 2×10^{22} m^{-3}, total number of accelerated particles $(1\text{-}5)\times10^{19}$ and a flow velocity more than 250 km/s. The improved construction of the gun [5] is shown in Fig.1.

Due to replacement of the grains in the discharge gap of the gas stage before each shot, the plasma gun is able to produce up to 1000 shots with satisfactory repeatability without recharge. The injected jet was studied in detail on a test bench. A picture of the jet made with a photo camera testifies its smaller divergence in comparison with the previous gun modification. The jet energy measured with a calorimeter was more than 200 J. The jet propagation speed was measured by means of radiation recorded with a streak-camera (Fig.2). In the figure on the horizontal axis is the time from the injection start and on the vertical axis is the distance from the gun muzzle age. The inclined stripes visible in the figure correspond to the separate fractions of the jet, and their slope defines the spread velocity of each fraction. The photos prove the fact that the plasma jet consists of several components, each of them propagating with its own speed from 100 to 250 km/s.The plasma jet purity is confirmed by absence of intensive impurity lines in its radiation spectrum measured by means of survey spectrometer in visible range.

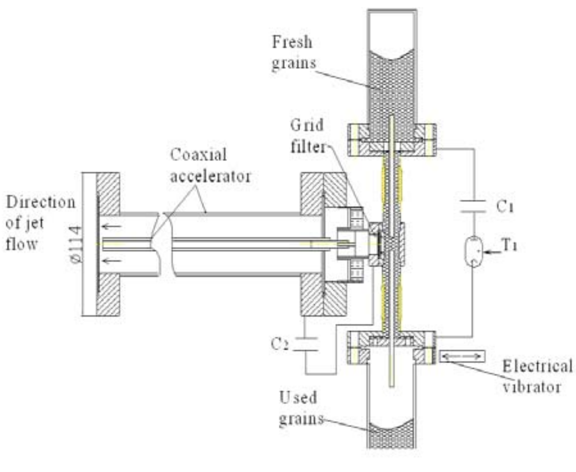

FIG.1 Two stage plasma gun, with explosive method of gas feeding a coaxial accelerator

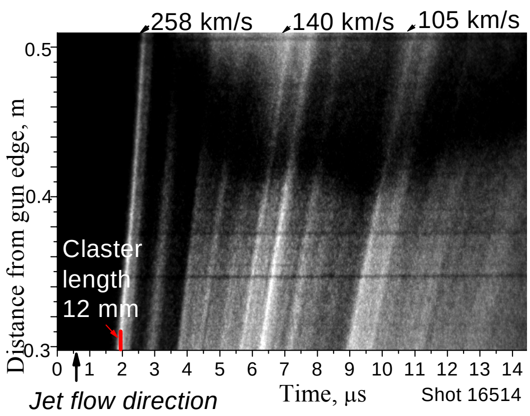

FIG.2 Jet radiation observed through a narrow slit with a streak camera; shot 13898 – perpendicular view

3. Plasma jet injection into the Globus-M tokamak

Experiments on the plasma jet injection into the Globus-M plasma by means of the advanced gun were carried out at two different gun positions shown in Fig.3. The Thomson laser beam with placed on it measuring spatial points, the video camera position and two positions of the plasma gun (1 and 2) are shown in the figure. The plasma jet was injected from the low field side in the major radius direction, through a port placed in the equatorial plane. Assumed better penetration ability of the plasma jet with advanced parameters has been proved in experiments on injection to the stationary phase of the Globus-M discharge. Visually, penetration of the jet into the tokamak plasma was demonstrated by means of a fast video camera RedLake MotionPro HS-3, providing record with frequency of 4000 frames/s. The video camera placed in the equatorial plane, with observation axis perpendicular to the jet spreading path. The target plasma parameters in these experiments were as follows: the plasma current, I_p=200 kA, the toroidal field, B_T=0.4 T, the average density, $\langle n \rangle=(2\text{-}4)\times10^{19}\ m^{-3}$. The video-frame of the jet injected to the target plasma with superimposed fragments of the magnetic lines corresponding q=1.5 and q=4 values is shown in Fig.4. The central column of the tokamak covered with graphite tales is seen at the left and the input port for the jet injection at the right. The bright region spreading along the major radius from the entrance port to the tokamak chamber center is the neutral hydrogen luminescence in the jet. One can see spreading the jet along the magnetic field lines (in more detail see section "Discussion"). As all process of the jet spreading is restricted by one frame, it gives us the upper estimate of the process duration – 250 µs. The observed picture, however, may raise doubts due to one angle observation, therefore we are planning to provide second angle in the nearest experiments. The second camera will be set on the upper dome port. At the same time, the video camera can give only qualitative picture of the plasma jet penetration. Therefore, our main efforts were focused on measurements of temperature and density evolution of the target plasma under plasma jet injection by means of the Thomson scattering diagnostic [6, 7]. Two series of the Thomson scattering experiments were carried out at two different gun positions (Fig.3). In the first case, the measurements were done in the points lying directly on the jet spreading axis or close to it. At that, local temperature and density measurements may be

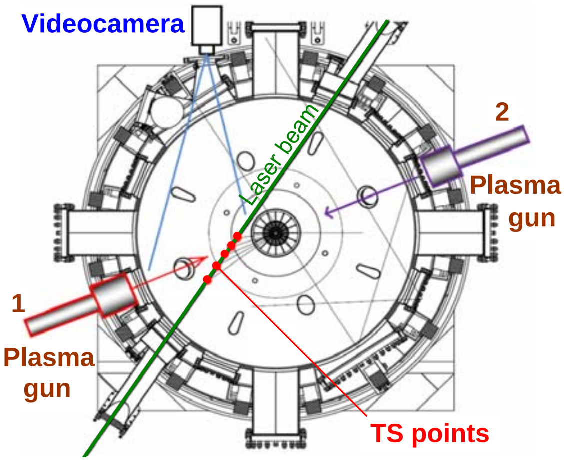

FIG. 3 Top view of Globus-M.
Red circles are TS measurement points

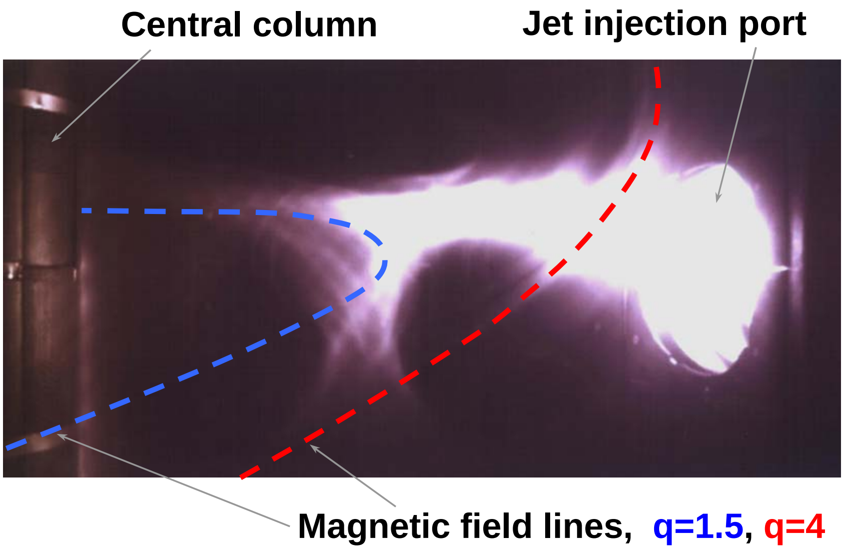

FIG. 4 Plasma jet penetration to the target plasma: video frame of the plasma jet and magnetic field line for q=4 and q=1.5, calculated with EFIT

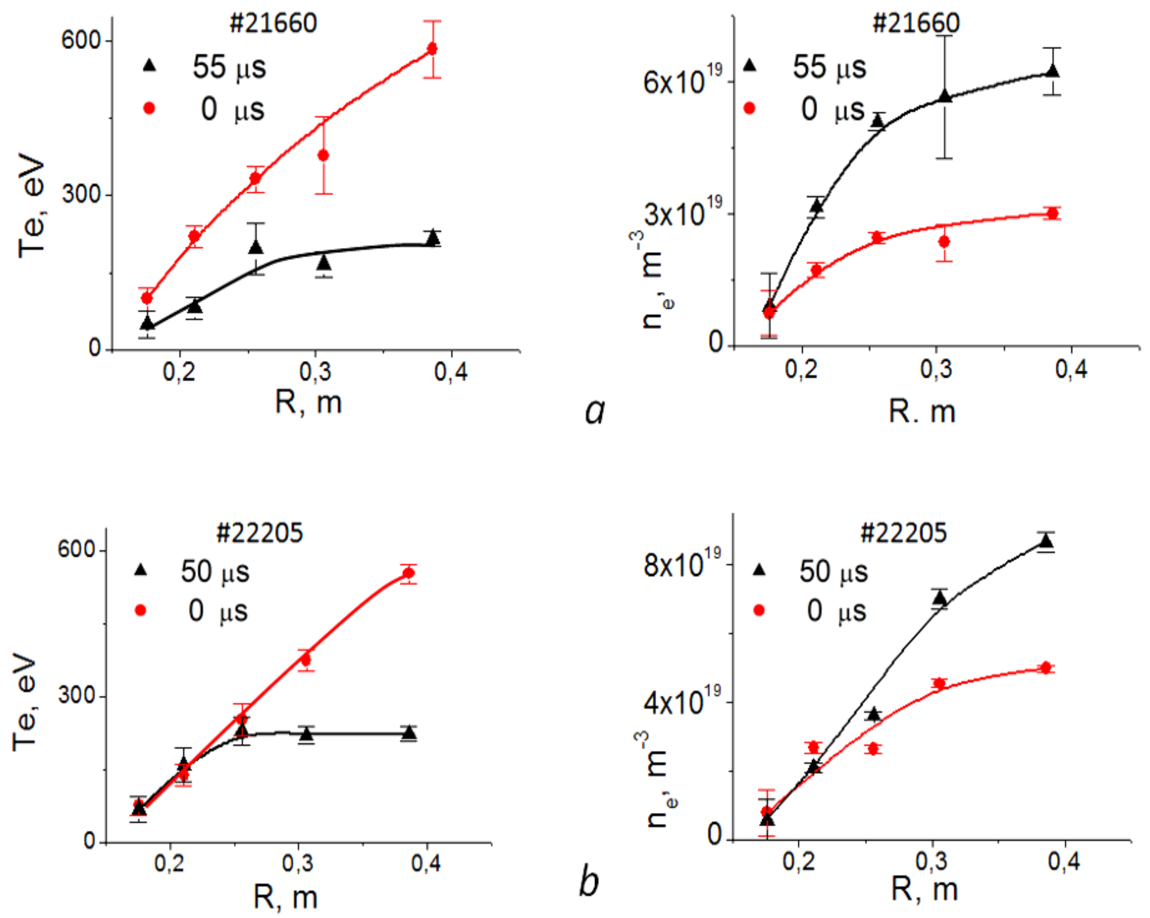

FIG. 5 Electron density and temperature profiles measured before and after the jet injection, in cross section near the gun (upper pictures, shot #21660) and in remote cross section (lower pictures, shot #22205).

different from the magnetic surface averaged values at the delay times from the gun shot less than the characteristic averaging-out time. In the second case, the measurement points were removed from the gun by 180^o in toroidal direction. In that case, the magnetic surface averaged values are measured. The gun shot was synchronized with the laser pulse train in such a way to provide the delay of several tens microseconds to the third laser pulse. Varying the delay from shot to shot, we have got the possibility to observe evolution of the temperature and density profiles during very short times. Unfortunately, pickups in the Thomson scattering apparatus initiated by the gun prevented to get close to the gun shot. The closest in time, reliable profile measurements were carried out at the delay of 50 µs, and only individual measurements were carried out at delay of 35 µs. The temperature and density profiles just before the gun shot and in 50 µs after it, for the measuring points lying directly on the jet spreading axis are shown in Fig.5a (upper plots) and in the remote in toroidal direction by 180^o cross section – in Fig.5b (lower plots). It is seen from the figure that already in 50-55 µs after the gun shot the electron density increases and temperature drops approximately twice in both cases. Measurements with delay from 50 to 200 µs made in other shots for the close target plasma and jet parameters gave simple results. Also, the experiments were made on the jet injection into the target plasma of different density. The evolution of the plasma density and temperature is shown in Fig.6, in the points corresponding to the major radius values R=38.6, 30.6 and 25.6 cm, at the jet injection into the target plasma density $n_e(0)=5\times10^{19}$ m^{-3} (Fig.6a) and 8×10^{19} m^{-3} (Fig.6b). It is seen from

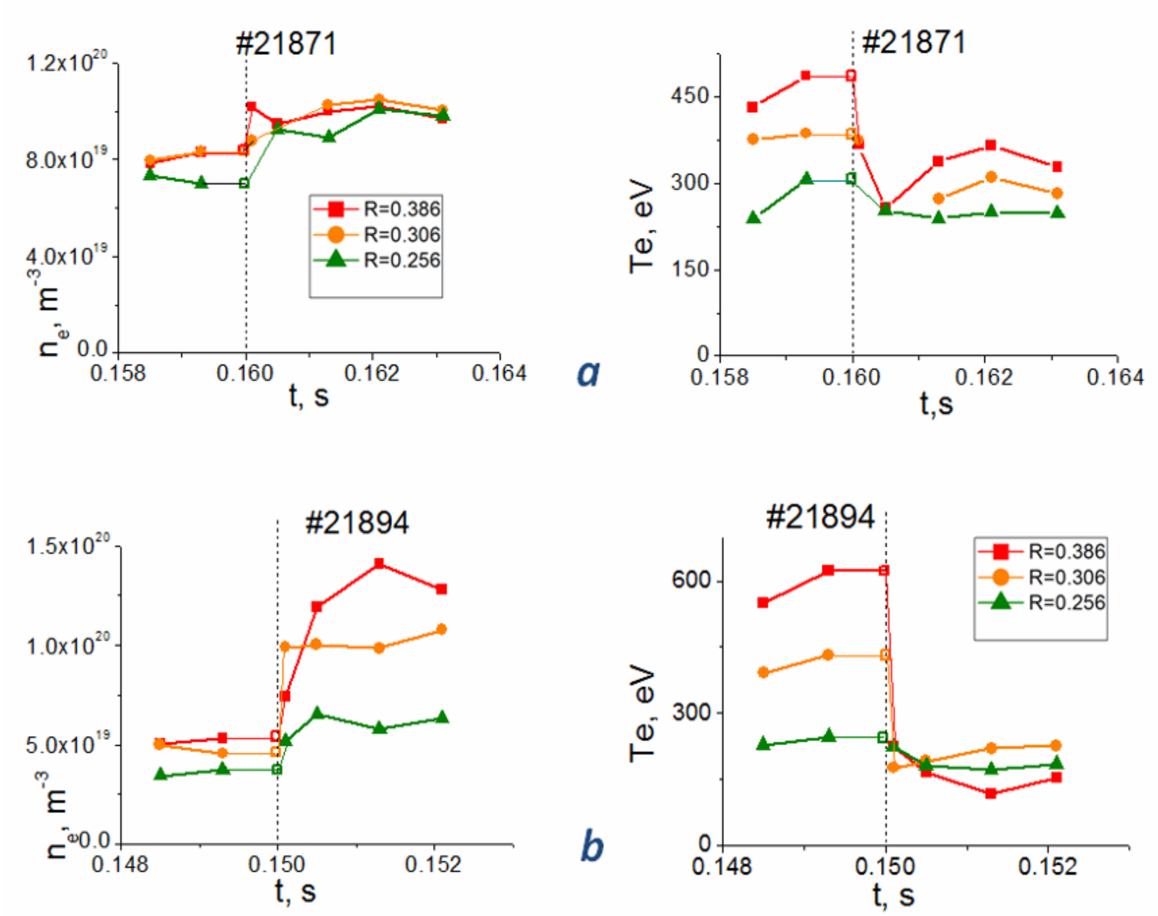

FIG. 6 Electron density and temperature evolution in shots with plasma jet injection at different spatial points and different central density.

the figure that the jet better penetrates to the target plasma with lower density. So in shot #21894 with the base density of $n_e(0)=5\times10^{19}$ m^{-3} the temperature drop and density grow in the central points (R=38.6, 30.6 cm) is more than twice, while in shot #21871 with the base density of $n_e(0)=8\times10^{19}$ m^{-3} the change is by 20-30 % only.

4. Modeling

Jet penetration depth was estimated on the basis of the analytical model described earlier [4]. According to the model jet polarization, which is responsible for its motion across a magnetic field, is reduced due to, first, currents in the Alfven wave emitted into the ambient plasma, and, second, by vertical grad B - induced currents. For the experimental parameters the jet can penetrate up to 24 cm from the separatrix, before the first mechanism will decelerate the jet significantly. The backward shift due to grad B effects is estimated as 10 cm. In reality both processes are going simultaneously and a rigorous consideration is rather complex, however one can expect that significant part of injected particles should be deposited in the core in accordance with observations. The numerical simulation was performed with the code described in [8] for the following jet parameters: temperature 5 eV, diameter 9 cm, total number of injected particles 1.5×10^{19}, density 10^{21} m^{-3}, velocity V=200 km/s. It is demonstrated that at t=0.9 μs, when jet reaches the plasma centre the drop in the electron temperature is immense, see Fig.7. While the electron temperature is dropped almost immediately, the density homogenization over the flux surface is much slower and is determined by the sound speed with the jet temperature. The jet temperature at t=0.9 µs does not exceed 50 eV and the velocity of jet expansion along B is of the order 10 – 20 km/s, estimated time for the density homogenization is less than 100 µs.

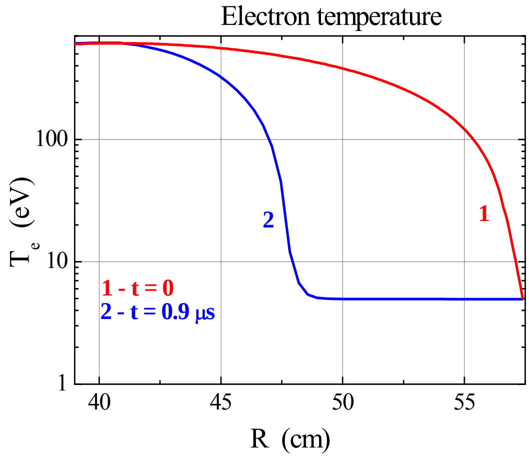

FIG.7 Simulated electron temperature profile evolution during the time interval to the time of jet flight to the plasma center

5. Discussion

In accordance with measurements made on the test bench, the plasma jet in the most successful shots has the speed of 200 km/s, the directed motion energy of 200 J, the density of 2×10^{22} m^{-3} and the total number of jet particles $(1\text{-}5)\times10^{19}$. The jet parameters can be varied in dependence of voltage on capacitors of the first and second stages. Besides, there exist slow degradation during the time and dispersion from shot to shot. In test bench experiments, all jet parameters are measured in each shot, while in tokamak experiment it is impossible. Therefore, we attribute to the jet parameters obtained on the test bench at the same capacitor voltage.

At jet injection to the tokamak, the total number of particles in the plasma column increased from 20 to 100 %, that corresponded to $(2\text{-}10)\times10^{18}$ particles in absolute value. The ratio of this quantity to the total number of particles in the jet was 20 – 30 % that proves higher efficiency as compared with conventional gas puffing, where this ratio does not exceed 10 %. Consequences of the plasma jet effect strongly depend on its parameters. The penetration depth to the tokamak plasma grows with increase of the jet velocity and particle density, and degree of the target plasma density and temperature changing also depends on total jet particle number. Unfortunately, it is impossible to vary independently the speed and total particle number in this gun construction (they grow simultaneously). The range of the jet parameters was restricted by the discharge stability to the jet effect in the tokamak experiments.

In described experiments we made an effort to get the jets with maximum velocity. Too high particle number led to sharp rise of the target plasma density (up to three times) accompanied by yet stronger temperature drop that led in the end to the discharge disruption. At a moderate number of particles, the density increase up to two times was observed, accompanied by corresponding temperature drop. Arising at that MHD instabilities had restricted amplitude and only sometimes led to disruption as a result of locked mode development (usually m=2/n=1) through a sufficiently large time after injection (more than 3 ms). At a small jet particle number, when the density increased no more than by 50 % and the temperature dropped no more than twice, no essential grow of the plasma column MHD distortion was observed. In all described cases, the plasma jet penetrated to the tokamak center that is proved by Thomson measurements and video camera observations. At injection of the jets with lower velocities, as in our previous experiments [4], the smaller depth penetration took place. From all aforesaid one can draw a conclusion that at a right fit the jet parameters it is possible not only to grow the column particle number, but to control the density profile in a discharge, realizing the main particle contribution to the central or peripheral zone.

Analogy may be done between the plasma jet and pellet injection. In both cases, the penetration ability depends on speed and density of the injected object, and the influence degree to the target plasma is defined by total number of injected particles. At that, decreasing of the particle density in the plasma jet (10^{21}-10^{22} m^{-3}) by one-two orders of magnitude in comparison with the particle density in the cloud surrounding the pellet (10^{23}-10^{24} m^{-3}) [9], is compensated by the corresponding velocity increase. As in pellet case spreading of the gas cloud alone the magnetic field take place leading to a similar picture of the injected object propagation [9]. The gas cloud spreading along the magnetic field lines is well seen in Fig.4. The most clearly one can see coincidence of the shape of protuberances spreading along the field with the slope and curvature of the magnetic field lines close to outer wall (q=4) and in the central region (q=1.5). That put forward a possibility to measure q profile at the use of double angle observation of the injected jet luminescence.

The essential question is the injected plasma purity. At injection of the hydrogen plasma jet to the test bench and to the tokamak (without plasma and magnetic field), its purity was confirmed by absence of the intensive impurity lines in the luminosity spectrum, measured by means of a survey spectrometer in visible region. However, observations of the same spectrum at the plasma jet injection to the tokamak discharge showed small radiation increase of the impurity lines CIII, FeI и CrI. Apparently, in this case, the impurity coming in is due to contact of the jet deviated by magnetic field with walls of the port through that the injection is produced. The contact with the walls is confirmed by the video frame, Fig.4. In the figure, the bright luminescence of the port walls is seen, that is absent at the jet injection without magnetic field. This contact can be avoided widening the port and placed the gun closer to plasma. At the same time, the impurity coming in did not affect the global characteristics of the tokamak discharge such as plasma current and loop voltage.

The next essential question is the speed of the plasma jet propagation in the tokamak plasma. In our experiments it was estimated by evolution of the electron temperature and density profiles after the jet injection. As was said above, the reliable, reproducible profile measurements were made at delay from the gun shot of 50-55 μs. At that, the measurements as in the injection cross section, so in the remote by 180^o in toroidal direction one, showed the jet penetration to the tokamak center (central temperature drop and density increase more than twice, see Fig.5). On the base of these measurements, one can contend that the jet penetration process to the center and homogenization of the density and temperature along the magnetic surfaces is going during the time no more than 50 μs that does not contradict the theoretical estimate. Measurements at shorter temporal delay will require additional efforts.

Visible discrepancy between behavior of the calculated (Fig.7) and experimental (Fig.5) temperature profiles require some explanation. The calculated profile demonstrates stronger cooling of the periphery in comparison with the central region, while the experimental profiles denote the stronger effect in the column center. It should be noticed that the model considers only the beginning of the process (1 μs from the injection start), and calculates the local temperature on the jet path. At the same time, the Thomson measurements show us what is going on with the temperature profiles for the later period, after homogenization along the magnetic surfaces. Perhaps, it is possible to get better fit with modeling, measuring the profiles in the injection cross section with shorter delays after the gun shot. And also the model should be improved to calculate later processes of the jet propagation.

6. Conclusion

Penetration into the central zone in accordance with modeling was demonstrated in experiments on injection of the plasma jet with the speed more than 200 km/s to the target plasma of the Globus-M tokamak. The penetration fact is confirmed by the video camera frames. It is proved by means of the Thomson measurements that the density rise in the center accompanied by the temperature drop occurred in the time less than 50 μs. It is shown that it is possible to affect the penetration depth and the degree of influence on the electron density and temperature profiles varying the jet parameters. Moderate affect on the target plasma (the central density rise by 30-50 %) does not result in essential discharge distortion. Some impurity coming in observed by a survey spectrometer is apparently due to contact of the jet with the entrance port walls, and can be avoided.

The achieved results make the plasma gun a perspective instrument for tokamak fueling and density profile control, and also, the possible diagnostic method for q profile measurements.

Further efforts will be done on more accurate definition of the characteristic times of the plasma jet propagation and the temperature and density homogenization on the magnetic surfaces. For this goal, we are planning measurements of the temperature and density profiles with delays less than 50 μs from the injection moment.

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