

Kinetic measurements of plasma electron component dynamics in the Globus-M tokamak during plasma gun injection experiment

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The design of efficient fuelling method is one of the key tasks for the tokamak-reactor. A new method based on high kinetic energy jet injection into tokamak plasma is under development and implementation at the Ioffe Institute. A two stage plasma gun generating the clean plasma jet of high velocity and density [1] and the set of different plasma diagnostics were used in investigation of jet-plasma interaction on spherical tokamak Globus-M.

Experiment. To improve jet penetration into the plasma core the significant plasma jet kinetic energy increase [2] was achieved. Velocity, measured in the test bench experiments by use of streak camera exceeded 200 km/s with total number of injected particle $\sim 10^{19}$ [2]. In the plasma experiments on Globus-M the fast videocamera RedLake MotionPro HS-3

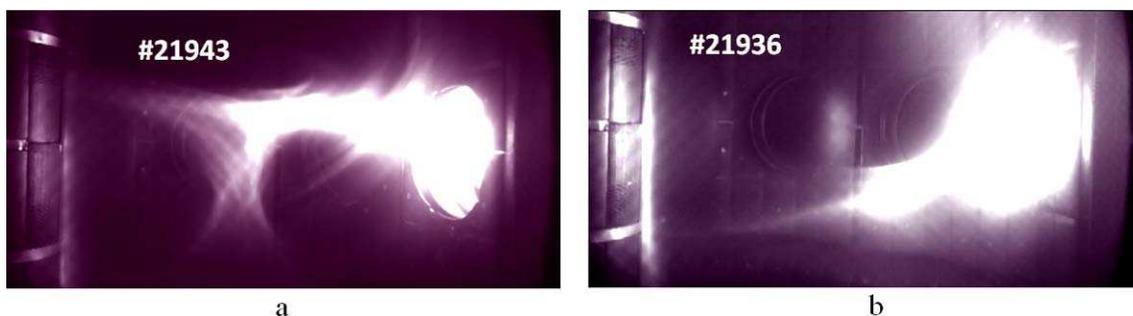


Fig.1. Gun jet shot into the ohmic discharge, a - moderate density $\langle n \rangle = 2 \cdot 10^{19} \text{ m}^{-3}$,
b - high density $\langle n \rangle = 4 \cdot 10^{19} \text{ m}^{-3}$

($t_{\text{frame}} = 250 \mu\text{s}$) has demonstrated deeper jet penetration into the plasma (see Fig.1, a, b) as compared with the previous experiments with jet velocity $< 100 \text{ km/s}$. The recording time was limited to a single frame with the exposure of $250 \mu\text{s}$, indicating small time of jet penetration. Parameters of the target plasma were $I = 200 \text{ kA}$, $B_1 = 0.4 \text{ T}$, $\langle n \rangle = 2-4 \cdot 10^{19} \text{ m}^{-3}$ in this experiment.

The conventional diagnostics such as plasma current, microwave interferometer, impurity spectroscopy have low temporal resolution and measure spatially averaged data which did not allow studying of the core parameter dynamic.

The Thomson scattering (TS) diagnostics with a variable delay between probing pulses in the wide range [3] became the key instrument to perform the dynamic measurements of the electron temperature and density during the jet injection. The Nd-glass laser (the basic

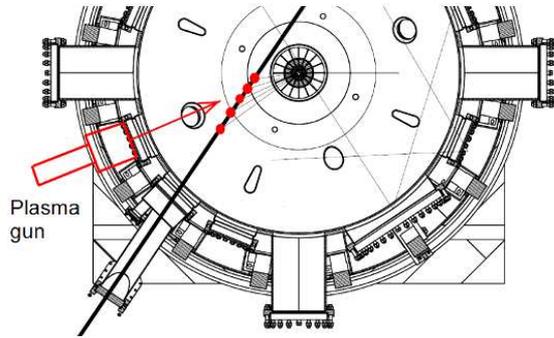


Fig.2. Top view of the Globus-M tokamak. Red circles are TS measurement points

wavelength 1.054 μm) can generate up to twenty 2-4 J pulses with intervals smaller than 500 μs . To perform the measurement close to the jet injection moment, the laser pulse train was synchronized to provide a gap of few tens microseconds between gun shot and third laser firing. The geometry of experiment is shown in Fig.2. The TS measurement points (resolution

$\sim 2\text{-}3\text{ cm}$) are placed along the major radius at $R=0.386, 0.306, 0.276, 0.211, 0.176\text{ m}$. The scattered signal is picked up by the set of five 4-channel filter polychromators equipped with APDs. Plasma jet injection was performed through equatorial port in the direction of tokamak major radius, shown by the arrow in Fig.2.

The profiles of the electron temperature and density just before the gun shot and 55 μs later are shown in Fig.3. The jet was injected into the target plasma with density in the centre $\sim 3 \cdot 10^{19}\text{ m}^{-3}$. The measurements have

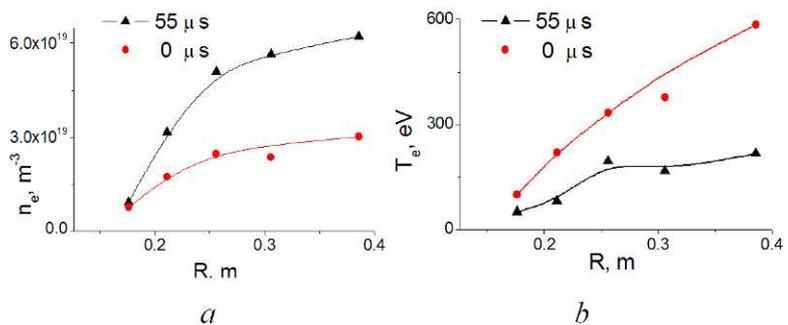


Fig.3. Electron density and temperature profiles variation within 55 μs after the gun shot, #21660.

demonstrated very fast and severe variation of density and temperature profiles. No valuable drop in plasma current, change of impurity contamination, MHD activity were recorded. The

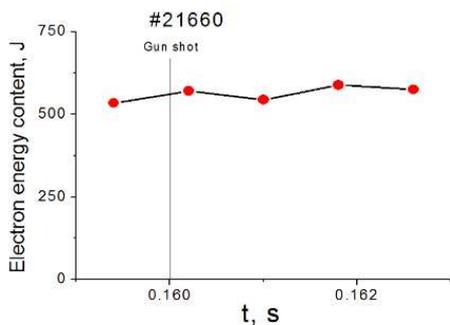


Fig.4. Electron energy content, #21660. Vertical line marks the gun shot.

electron energy content was calculated on the basis of TS and EFIT reconstruction data. As is seen in Fig.4, the jet injection does not influence also the electron energy content of the plasma column. Relative stability of the tokamak discharge for the strong disturbance of plasma by a high density low temperature jet is observed.

The electron parameter evolution within 8 ms time interval for different target plasma density prior and after the gun shot is presented in Fig.5.

Plasma jet is injected at the stationary discharge phase. The hollow points on the dashed line (gun shot moment marker)

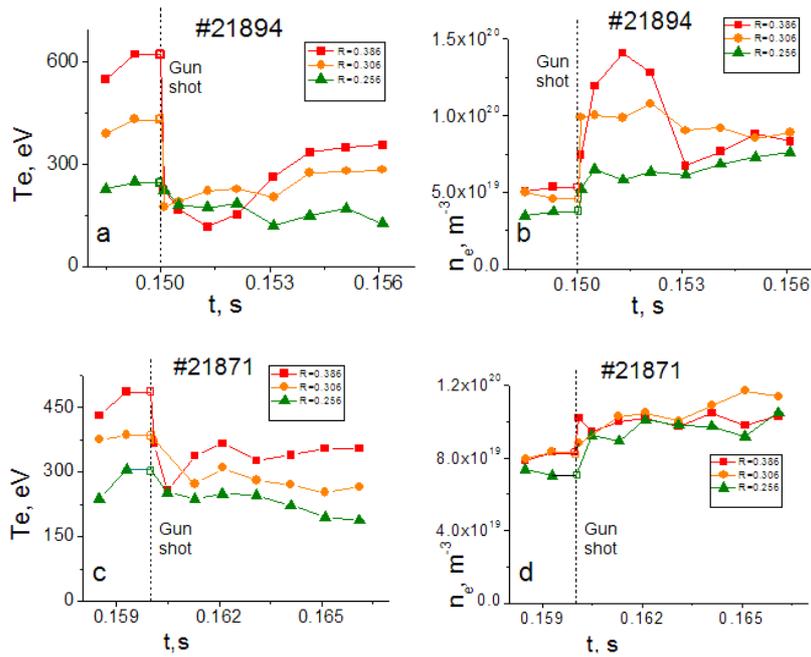


Fig.5. Electron temperature and density temporal evolution prior and after the gun shot at different spatial points, $R=0.386$ m - squares, 0.306 m - circles, 0.256 m - triangles. Vertical line marks the gun ejection. a, b – moderate central density $5 \cdot 10^{19} m^{-3}$, c, d – high central density $8 \cdot 10^{19} m^{-3}$.

(gun shot moment marker) are extrapolated values of temperature and density equal to the previous values before the gun shot. The first temporal point after injection has the delay relative to the gun shot $\sim 100 \mu s$ in shot #21894 and $\sim 15 \mu s$ in shot #21871. As it seen from Fig.5 a, b, the density grows faster in the point $R=0.306$ m than $R=0.386$ m, placed more

close to the gun. It may be connected with the geometry of the experiment, see Fig.2. The temperature measurements demonstrate significant cooling of the plasma centre – temperature drop is down to 6 times. Despite huge plasma disturbance the discharge successfully survived, returning to the stationary phase in a time interval of ~ 4 ms. For the higher target density $n_e(0.386 \text{ m}) \sim 8 \cdot 10^{19} m^{-3}$ (Fig.5 c, d) and nearly the same gun parameters the jet also penetrates into the plasma column centre ($R=0.386$ m) but with smaller density growth. At moderate target densities the density rise in the plasma column center is resulted in the density profile peaking lasting for 2.5 ms.

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 Alfvén wave emitted into the ambient plasma, and, second, by vertical grad B - induced currents. For the

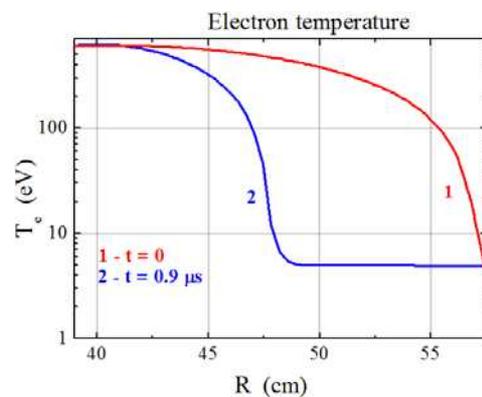


Fig.6. Simulated electron temperature profile evolution during the time interval equal to time of jet flight to the plasma center

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 [5] for the following jet parameters: temperature 5 eV, diameter 9 cm, total number of injected particles $1.5 \cdot 10^{19}$, density 10^{21} m^{-3} , velocity $V=200 \text{ km/s}$. It is demonstrated that at $t=0.9 \text{ } \mu\text{s}$, when jet reaches the plasma centre the drop in the electron temperature is immense, see Fig.6. 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 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 .

Conclusions. First experiments and preliminary numerical modeling of jet penetration into the plasma has demonstrated that initial jet velocity $\sim 200 \text{ km/s}$ is sufficient to transport particles deep into relatively dense plasma. The response of density profile, measured experimentally on plasma inboard side is no more than 55 μs , that testifies the straightforward jet penetration across magnetic surfaces. Also very fast (simulation) and fast (experiment) temperature drop in the plasma core is evident. Plasma cooling effect during plasma jet injection may have much in common with cooling processes during fuel injection in cryogenic pellet except different time scales. Fast and deep jet penetration without the discharge damping, provide enough reasons to use the plasma gun as the prototype for future tokamak-reactor fuelling. Future plans include modification of experiment geometry and simulation model improvement.

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REFERENCES

- [1] Gusev V.K., Chernyshev F.V., Golant V.E., et al., Nuclear Fusion, 46 (2006) 1–8
- [2] Voronin A.V., this conference P2.104
- [3] S.Yu. Tolstyakov, V.K. Gusev, M.M. Kochergin, et al, Technical Physics , Volume 51, Number 7, 846 – 852, July 2006
- [4] V. Rozhansky et al 33rd EPS conf. on Plasma Phys., Rome 2006, P4107
- [5] V. Rozhansky et al Nuclear Fusion 46 (2006) 367