Experimental study of electron component dynamics during injection of plasma jet and neutral beam into spherical tokamak Globus-M

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Introduction. A NBI auxiliary heating and a novel approach for plasma fuelling by a plasma gun is the backbone of research program on the Globus-M spherical tokamak. In early experiments and preliminary numerical modeling of jet penetration into the plasma we demonstrated that initial jet velocity ~200 km/s is sufficient to transport particles deep into relatively dense plasma. Previous experiments demonstrated an effective NBI heating of plasmas. The Thomson scattering (TS) diagnostics with a variable delay between probing pulses in the wide range [1] became the key instrument to perform the dynamic measurements of the electron temperature and density. The Nd-glass laser (the basic wavelength 1.054 μm) can generate up to twenty 2-4 J pulses with intervals 0.3 -1000 ms. During 2008-2009 the Thomson scattering (TS) diagnostics upgrade was made. The geometry of experiment is shown in Fig.1. A new observation point and high quality collection lens allowed to pick up the scattered radiation from inner to outer plasma border with minimal light losses. TS system was equipped with the novel 4-channel filter polychromators. It allowed us to improve the electron density limit down to $10^{18} m^{-3}$ owing to optical scheme optimization and the reduced noise amplifiers for APDs. A new magnet transporter can move the beam-marker (7 on Fig.1) along laser axis to align collection system and promptly spread the ten TS measurement points without vacuum violation. The filter polychromators and ADCs were moved to special thermo stabilized room. The optical connection was performed though the fiber lines with low losses.

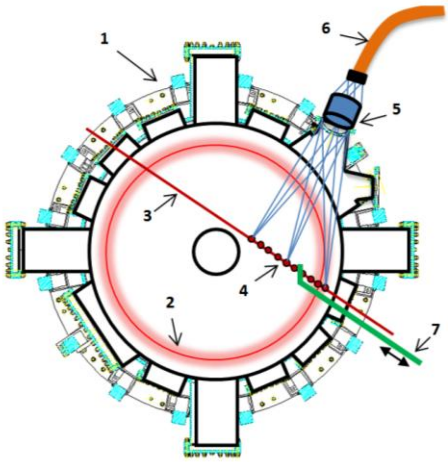

Fig.1. TS collection system. 1- Globus-M vacuum chamber, 2 – outer plasma boprder, 3- laser beam, 4 – TS measurement points, 5- collection lens, 6- fiber line, 7-magnet transporter

Experiment and modeling, L-H transitions

The TS diagnostics is capable to measure full n_e and T_e profile dynamics with high accuracy that gave a basis for modeling using the ASTRA transport code. The transport model consist of continuity equation for plasma density, ion and electron energy balance equations and an equation for poloidal flux solved together with the Grad-Shafranov equation in a real geometry of Globus-M. The boundary value condition for poloidal flux comes from the condition relation that the total plasma current should be equal to the measured value, and for conductivity used is neoclassical expression value calculated by NCLASS [2]. The last closed flux surface is set by its center R_0, half-width a_b, Shafranov shift Δ_b, elongation λ_b and triangularity δ_b. These boundary values are taken from equilibrium reconstruction performed with the help of the EFIT code. The transport coefficients were fitted in such a way that the density and temperature profiles and loop voltage agree with experimental data.

Ohmic discharge. The measurements were performed in conventional ohmic discharge with moderate initial density at the plasma current ~200kA. The gas puffing program provides the continuous growth of density similarly the discharges with auxiliary NBI heating. Figure 2 demonstrates electron density and temperature profiles for different moments during stationary plasma current. First profile (147 ms) corresponds to the L-H starting phase. Typical sign of transition to high confinement - D_α intensity drop is observed. As is seen, H-mode (161 ms) is attended by the strong n_e gradient on plasma periphery and valuable T_e growth. High density gradients agrees with Langmuir probe diagnostics data.

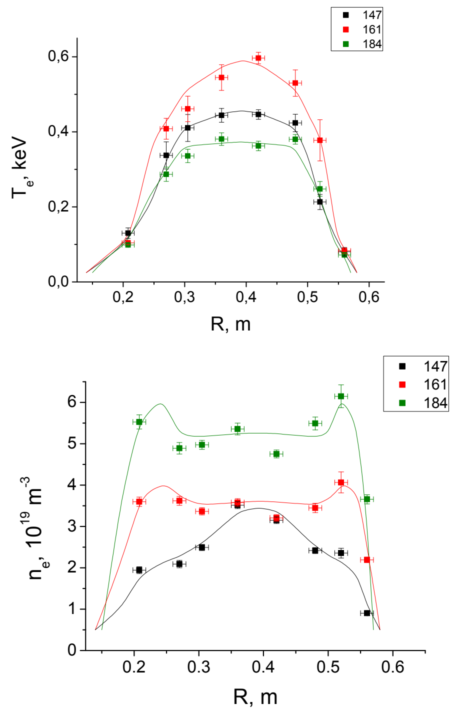

Fig.2. TS profiles, ohmic discharge #26505. Points- TS experiment, lines –ASTRA fitting

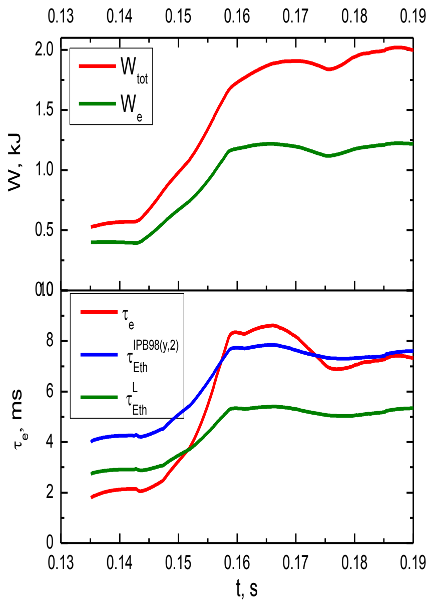

Fig.3. a) Energy content, red –total, green-electron, b) energy confinement time, red- calculated, green /blue – ITER scaling for L / H modes.

The probe is placed in horizontal plane outside the separatrix in the point R=0.6 m (~3-4 cm outside separatrix). At the same time, the energy content (Fig.3a) remains practically constant from L-H transition till the end of discharge. The ASTRA simulation demonstrates strong increasing of the energy confinement time just during the L-H transition from 2 ms to 8 ms that is consistent with the ITER scaling for L- and H-modes (Fig.3b) [3].

NBI discharges. The main scenarios of this discharge is similar to the OH one. The $n_e(t)$ variation resulted from both gas puffing and neutral beam injection, which were triggered sequentially. Main parameters of the NB are the following: E=26 keV, P~0.8 MW. The behavior of plasma after L-H transition is also similar to the ohmic discharge. The density profiles and temperature became wider and take on the table-like form. On the initial stage of H mode, n_e,&T_e grow simultaneously. During the H-modes the temperature begins to fall and is changed inversely to the density, so the total plasma energy content is kept practically unchanged (see Fig.5a). Unlike ohmic discharge the energy confinement time is changed modestly ~1.5 times, but that is consistent with the ITER scaling for L and H-modes [3]. It worth to note, that H-mode during NBI is characterized by wider temperature profiles than for the ohmic discharges and density is not “ear-shaped”. The reason is the different nature of particle intake – for OH discharge it is periphery gas puffing, NBI one has internal particle source.

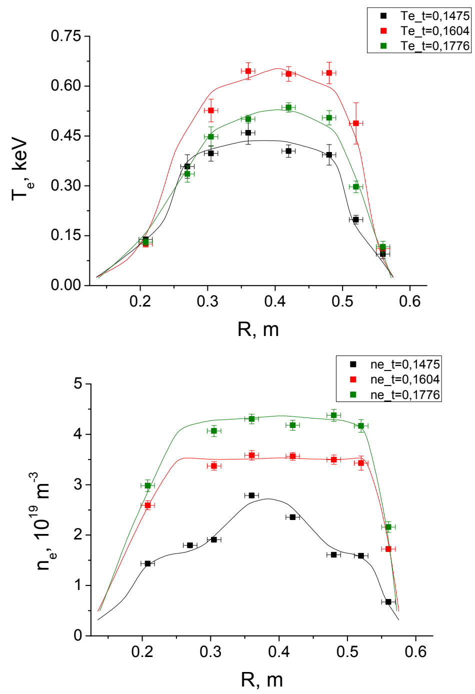

Fig.4. TS profiles, NBI, shot#26238. Points- TS experiment, lines –ASTRA fitting

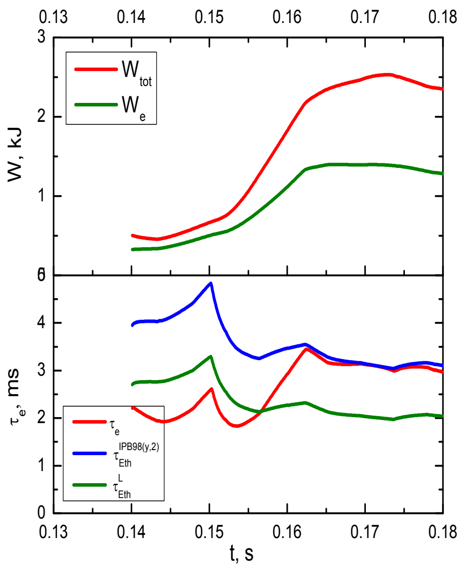

Fig.5. a) Energy content, red –total, green-electron, b) energy confinement time, red- calculated, green /blue – ITER scaling for L&H-modes.

Plasma gun injection. The design of an efficient fuelling method is a high priority task for the tokamak-reactor. A new method based on high kinetic energy jet injection into tokamak plasma is under development and implementation at Globus-M tokamak. The improved gun produces fully ionized clean hydrogen jet with density up to 3×10^{22} m^{-3}, kinetic proton energy up to 300 eV and number of particles within 5×10^{18} - 5×10^{19} [4]. As it was demonstrated the jet may penetrate into central region of the plasma column without discharge degradation. The only way to study this local and fast disturbance is to measure dynamic of n_e and T_e profiles using TS diagnostics. Figure 6 presents profiles measured 460 mks before gun shot (black), and 60 mks (red) after. This discharge was NBI heated with beam initiated H-mode before the gun-shot. The result of plasma jet penetration into the plasma core is recorded shortly after injection (60 mks) like an n_e rise and T_e drop near the plasma column axis. The temperature fall is not valuable, apart from our early experiments with the successive strong plasma cooling [5].

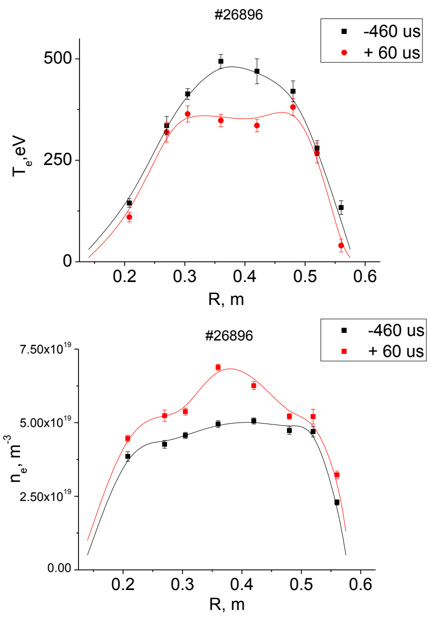

Fig.6. TS measurements, gun, shot#26896

Conclusions.

The TS upgrade provided measurements of full n_e and T_e profile dynamics on the Globus-M tokamak. Confident basis for transport simulation is created and possibility of very fast profile variation measurements were demonstrated. ASTRA transport code simulations demonstrated an agreement of the energy confinement time with ITER scalings in regimes with moderate energy content, but there are still open questions concerning more pronounced agreement for high energy content regimes.

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