Influence of the reversed safety factor profile on the transport in the Globus-M spherical tokamak

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Introduction

At the Globus-M [1] spherical tokamak it is possible to study regime with reversed shear (so-call AT-like q-profile) when the neutral beam injection (NBI) starts at the plasma current ramp-up phase. The reversed safety factor q profile entails the appearance of the negative magnetic shear at the plasma column center that leads to the formation of an internal transport barrier (ITB) and a peaked electron density profile. These cause the bootstrap current and the normalized beta ($\beta_N = aB_T\beta_T/I_p$, a – minor radius, B_T – toroidal magnetic field, β_T – toroidal beta, I_p – plasma current) increase. When β_N approaches the Troyon limit the so-called AT-mode is realized [2]. This regime is the main scenario for the DEMO-FNS [3] and one of the promising regime of ITER operation [4].

Experiment

The experiments at the Globus-M were carried out in the deuterium plasma (the toroidal magnetic field $B_T=0.5\ T$ and the plasma current $I_p=200\ kA$) with the deuterium NBI (beam energy $E_b=28\ keV$, beam power $P_b=0.75\ MW$). Figure 1 demonstrates the main parameters of the discharge which was chosen for modeling. As can be seen from the figure, the NBI is started during current ramp-up (t=130 ms) when $I_P=140\ kA$. It's about 70% of the maximum plasma current at the discharge. At t=143 ms (marked by grey dash line) the transition to I-phase occurred. It is characterized by the appearance of low-frequency (5-9 kHz) oscillations the so-called limit cycle oscillations (LCO) in the signals of Dα light emission and Doppler backscattering diagnostic. Detailed analysis of I-phase in this discharge was carried out in [5]. At t=160 ms, the I-phase end is

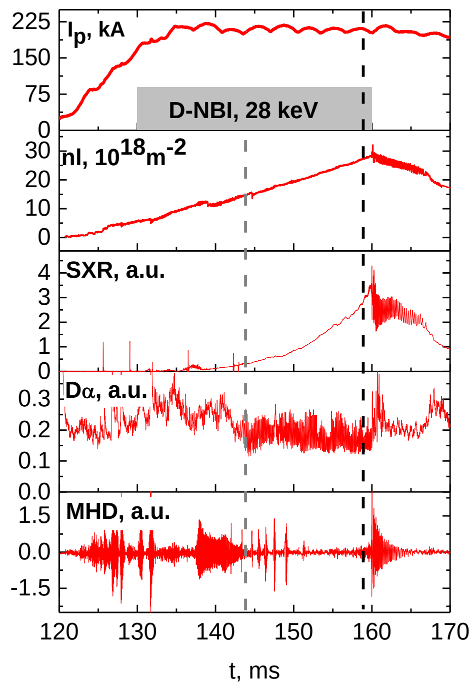

Figure 1. *Evolution of plasma parameters: plasma current, averaged plasma density, SXR signal, Dα emission, MHD-signals. (shot #37000)*

accompanied by a decrease of SXR-signal and the Dα signal increase and the intensive MHD instability and reconnection developement.

Modeling and Discussion

The dynamic modeling of the discharge was carried out using the ASTRA code. The Z_{eff} value was determined comparing the estimate loop voltage and the experimental one ($Z_{eff} \approx 2.5$). The magnetic configuration was restored by solving the Grad-Shafranov equation using the EFIT data. The neutral particles density profiles were calculated by DOUBLE on the base of the neutral particles analyzer (NPA) measurements. Calculation of the absorbed beam power profiles was carried out using the NUBEAM code. Additional corrections were made for absorbed power in order to take into account first orbits losses of fast particles, which were determined using a three-dimensional modeling algorithm and Boltzmann equation solution [6]. The input data for the calculation were the profiles of the electron temperature and density (shown in figs. 2 a,b) measured by Thomson scattering diagnostics.

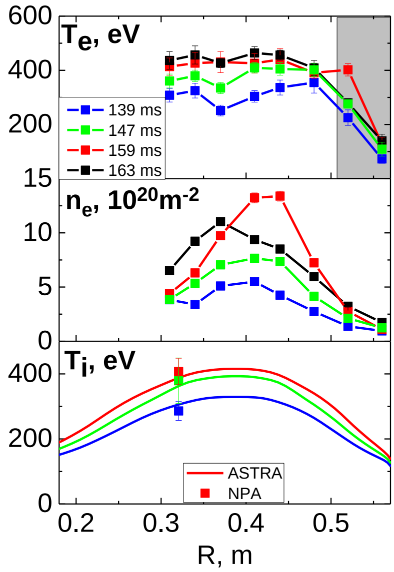

***Figure 2**. Evolution of the electron temperature (a), density (b) and ion temperature(c) profiles*

The q profile dynamic modeling (fig. 3) confirmed that the NBI started with reversed q profile. The current diffusion leads to a monotonic q profile formation. At 159 ms the q=1 surface appeared. This calculation result was consistent with the experimental measurements. MHD mode m=1/n=1 was observed by the Mirnov probes as well as by the SPD linear array. The instability was identified as the "snake" [7]. Before MHD instability appearance bootstrap current reaches the maximum value for the discharge (fig. 4) up to 25% (50 kA). However the current drive is only 7% (up to 15 kA) because of the low absorbed beam power and the low electron temperature.

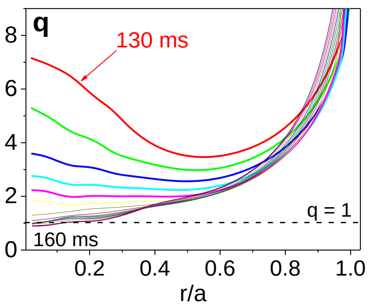

***Figure 3**. Evolution of the safety factor*

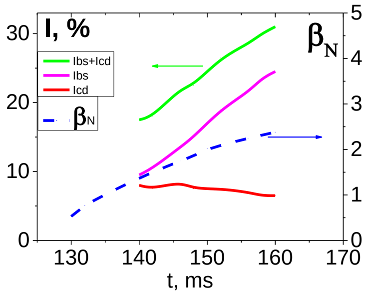

***Figure 4** Evolution of the non-inductive currents and β_N*

The evolution of β_N is shown in fig. 4. β_N increases during the shot and reaches the maximum ≈ 2.5 (for Globus-M Troyon limit is about ≈ 6 [8]). Low β_N calculated in the discharge can be explained by insufficient auxiliary heating

The energy confinement time ratio of the experimental to calculated by the IPB98(y, 2) scaling can exceed unity in the AT-mode (H-factor ≈ 1.1-1.3). To estimate the energy confinement time during the simulation, the total stored plasma energy *W* was calculated. The calculated values of *W* were compared with the results of diamagnetic measurements. The results are shown in fig. 5a. The 10% difference can be explained by the perpendicular fast particle pressure [9].

The calculated energy confinement time calculated was compared with the IPB98(y, 2) scaling, the fig. 5b. The figure demonstrate that the energy confinement time increased with increasing density and the H-factor reached unity starting from t=150 ms of the discharge. This indicates an improvement in energy confinement in comparison with discharges without the reversed shear [9], where in the H-mode H-factor was up to 0.8.

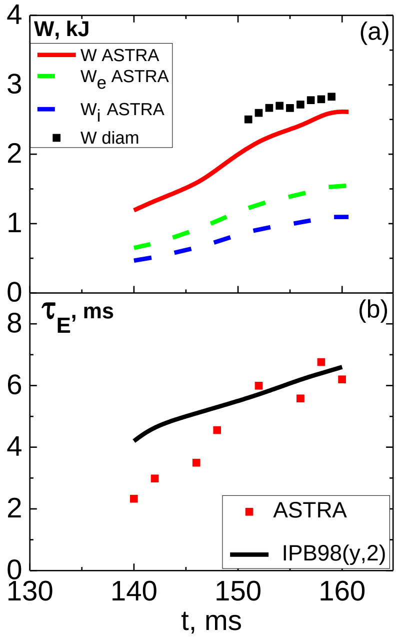

Figure 5. *The total stored plasma energy (a) and the energy confinement time (b).*

Calculations of the transport coefficients were performed for t = 159 ms discharge, when the maximum β_N was reached. At the first stage of modeling, the inverse problem was solved for calculating the electron thermal diffusivity coefficients. Since in the central region of the plasma there was practically no electron temperature gradient (fig. 2a), the calculation was performed only for the region r/a>0.6. The results of the calculation are shown in fig. 6. In this region, the electronic thermal diffusivity varied in the range 1-5 m^2s^{-1}. The thermal diffusivity of the ions (fig. 6) was assumed to be neoclassical [10] and was calculated using the NCLASS code.

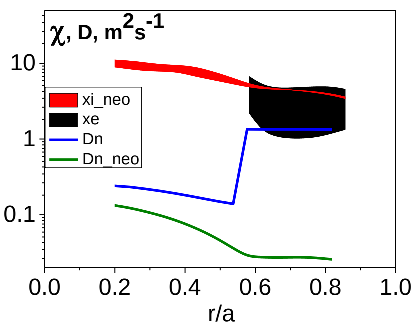

Figure 6. *The coefficients of thermal diffusivity for electrons and ions, the diffusion coefficient for electrons, and the neoclassical diffusion coefficient*

It was determined that the ion temperature, calculated with neoclassical transport coefficients, is consistent with the ion temperature measured by NPA (fig. 2c).

The second stage of the simulation was a solution of the direct problem for the particle balance equation. The electron diffusion coefficient was a free parameter. The pinch velocity was assumed to be neoclassical and was calculated according to the Wayer convection. The profile of the diffusion coefficient was chosen according to the electron density profile. The diffusion coefficient corresponding to the best similarity between the calculated and experimental electron density profiles is shown in fig. 6. The density profile peaks due to a decrease in the diffusion of particles in the entire central region of the plasma $r/a <0.6$ to the level of neoclassical values.

The performed analysis demonstrates that in this discharge a significant fraction of non-inductive currents is realized, more than 30% of the plasma current. However, under conditions with a peaked density profile, the Troyon limit was not reached, in addition, the discharge was accompanied by a significant level of impurities in the plasma and high radiation losses [7]. One way to solve this problem is to search for modes with ITB at the electron temperature. Such discharge scenarios were realized in earlier experimental campaigns on the Globus-M tokamak in the ohmic regime. In experiments with early injection on the Globus-M tokamak at a value of $B_T = 0.4\ T$ [11], a decrease in diffusion was observed only in the region $r/a = 0.4$. Consequently, an increase of only 25% in the toroidal magnetic field made it possible to expand the region with suppression of anomalous particle transport. A further increase in B_T and experiments with two neutral beams on the Globus-M2 tokamak [12] probably will make it possible to approach the Troyon limit and obtain the AT mode. The experiments on Globus-M2 has been started operating recently.

Acknowledgment

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