Thermal energy confinement study in the Globus-M spherical tokamak

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Introduction

The presentation is devoted to the thermal energy confinement study at the Globus-M spherical tokamak. Globus-M [1] is a small aspect ratio machine. The experiments described below were carried out in deuterium plasma with major radius R = 0.35 m, minor radius a = 0.21 m, R/a ~ 1.6, vertical elongation k ~ 1.8, lower null magnetic configuration with fixed toroidal magnetic field B_T=0.4 T, plasma current in the range I_p=0.12-0.24 MA. This paper is organized as follows: the first section describes data processing technique and results carried out for I_p=0.2 MA ohmic heated (OH) plasma for a density $<n_e> \sim 2\text{-}6\ 10^{19}\ m^{-3}$; the second section is focused on the plasma current influence on confinement time; the third one is devoted to impact of the additional heating by neutral beam on plasma thermal insulation.

Confinement in OH I_p=0.2MA plasma

Total stored thermal energy was calculated by the volume averaging of the kinetic data: $W = \int_V (n_e T_e + n_i T_i) dV$. The plasma volume and shape was estimated using EFIT reconstruction, electron temperature and density profiles were measured by the Thomson scattering diagnostics. For analysis we used steady-state phase of the discharge where $T_e(R)$, $n_e(R)$ and loop voltage (U_{loop}) don't change in time. At the figure (Figure **1** a,b) one can see an example of electron component profiles for different plasma densities. Figure **1**c represents electron and ion temperature dependence vs line average density. Each point corresponds to a different discharge. To estimate ion temperature profile we used ASTRA modelling assuming ion thermal conductivity as neoclassical (using NCLASS), the comparison of T_i measured by NPA in the plasma center with calculated one are shown in figure (Figure **1** d). To calculate ion concentration we assume carbon as the main impurity. Effective plasma charge values were achieved by fitting the calculated loop voltage to the measured one, assuming neoclassical plasma conductivity. In figure (Figure **1**e) one can see obtained Z_{eff} and heating power for electrons and ions. Ohmic heating power P_{OH}~0.3 MW and doesn't change significantly in the considered dataset while ion heat power rises with density. It should be noted that OH power density in Globus-M is rather high ~0.6 MW/m^3 that is twice higher than in MAST(<0.3 MW/m^3)[2] and similar to NSTX(<0.6 MW/m^3)[3]

experiments with additional heating. Radiation losses in the Globus-M OH plasma are at the range of 0.02-0.06 MW and play significant role in the energy balance for high density. For the density lower than $2.5*10^{19}$ m^{-3} the plasma total stored energy is mostly determined by the electrons (see Figure **1**f). For the higher density the ion heating is rather high and $W_i/W_{tot}\approx 0.3$. The confinement time exhibit linear dependence on density for $n_e<2.5*10^{19}$ m^{-3} and the main power loss is due to electron channel, for higher density power the losses through the ion channel rise significantly and saturation of ohmic confinement regime is observed (Figure **2**). For LOC $\tau_E \approx 1{,}7\cdot \tau_E^{neoalcator}$, for SOC H-factor is rather low $H^{IPB98(y,2)}$ $\approx$0.65-0.7.

Confinement time dependence on I_p at fixed density

To study confinement time dependence on plasma current we used a scan for the fixed average density $<n_e>\approx 3*10^{19}$ m^{-3}. From the figure (Figure 3 a,b) one can see that as the plasma current rises the density profile becomes flatter. Electron temperature increases as well as the ion temperature (Figure 3 c) and plasma total stored energy rises too (Figure **4** a). For the considered shots heating power remains constant $P_{OH}\approx 0.3$ MW and effective plasma charge varies from 2.4 at 0.12 MA to 1.5 at 0.24 MA. The confinement time linearly depends on plasma current (Figure **4** b). This fact corresponds well with predictions of ITER H-mode scaling $\tau_E\sim I_p^{0.93}$[4] and contradicts results of MAST $\tau_E\sim I_p^{0.59}$[2] and NSTX $\tau_E\sim I_p^{0.57}$[3]. The electron heat diffusivity was found to decrease with plasma current, the ion heat diffusivity remains neoclassical.

Impact of NBI on confinement time.

Fast ion confinement in Globus-M that determine heating efficiency by NBI are well described in [5]. For this study we used hydrogen beam with particle energy of 26 keV. The beam power was changed between 0.75 MW and 0.5 MW. The electron heating is well observed for $<n_e> > 3*10^{19}$ m^{-3} (Figure **5** a). NPA measurements indicate that ion temperature in the plasma center is twice higher than in OH discharges T_i~0.5-0.4 keV. Modelling by fast ion tracking algorithm [5] shows that fast ion losses in the described discharges for $<n_e>\approx 4*10^{19}$ m^{-3} are the following: ~20% particles are lost due to shine through and first orbit losses, ~30% particles due to charge exchange during thermalization process. For lower density the losses are higher. As a result only a half of the injected power is absorbed. Effective plasma charge obtained with ASTRA modelling rises from 1.5 in OH phase to 2.5-3 during NBI and the radiation losses rises as well reaching 0.1 MW level. Taking into account the accuracy of the absorbed power estimation it can be concluded that the double increase of the absorbed power leads to W_{tot} increase by a factor of 1.5 mostly due to electron heating (see Figure **5** b). Confinement time decreases from 5 ms in OH regime to 4 ms in the case of 0.75 MW beam. It results in rather week dependence on absorbed power $\tau_E \sim P^{-0.3}$ that is similar to performance of L-mode plasma on NSTX[3] $\tau_E \sim P^{-0.37}$. Electron heat diffusivity is estimated to be 2 times higher than for the OH case, while χ_i remains neoclassical (see Figure **5**b).

Acknowledgments

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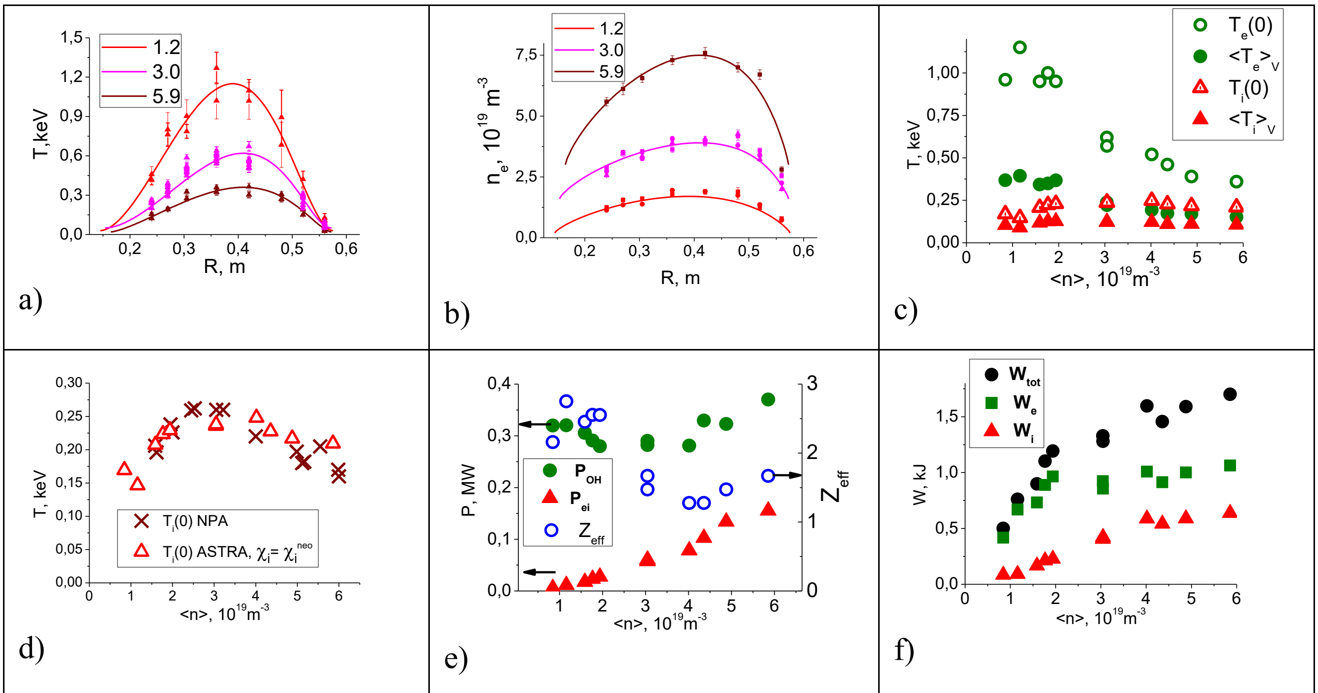

Figure 1. *Electron temperature a) and density profiles b) for density scan at 0.2MA, the correspondent density are shown in units $10^{19}m^{-3}$; c) temperature dependence on density T_e – experimental, T_i – modelling; d) comparison of measured and calculated ion temperature; e) OH power and power transferred from electrons to ions – left axis, blue open dots – estimated Z_{eff}; f) thermal energy content*

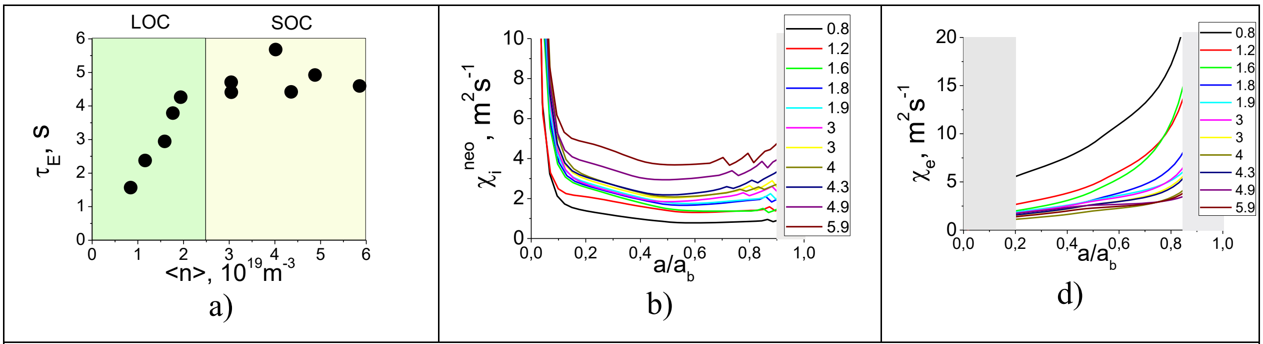

Figure 2. *a) Confinement time dependence on density; b) and c) – ion and electron heat diffusivity, the correspondent density is shown in legend in units* 10^{19} m^{-3}.

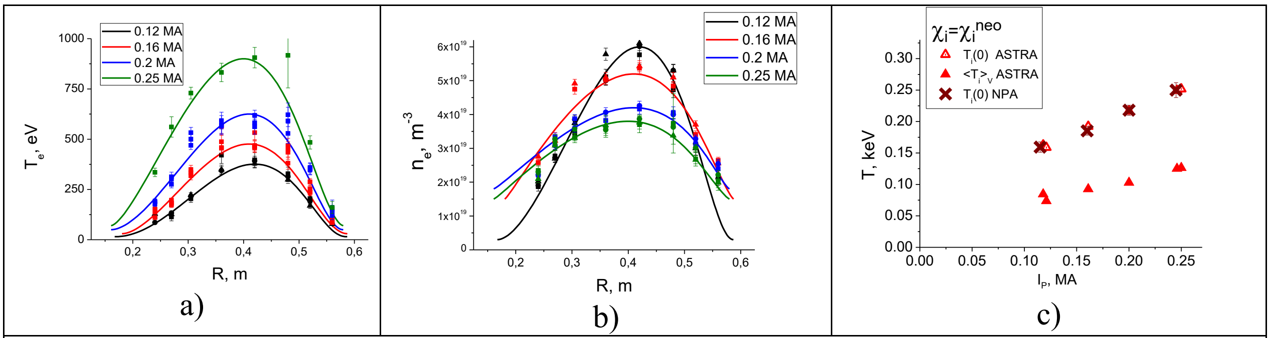

Figure 3 *a) and b) Electron end temperature profile for current scan; c) comparison of calculated ion temperature with NPA data.*

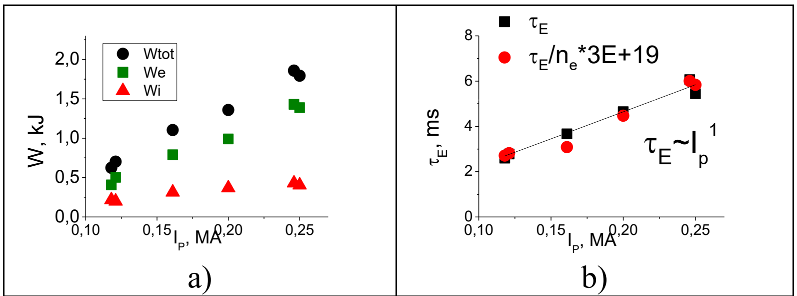

Figure 4 *Thermal energy content a) and confinement time vs plasma current b) for density* $<n_e>=3*10^{19}m^{-3}$

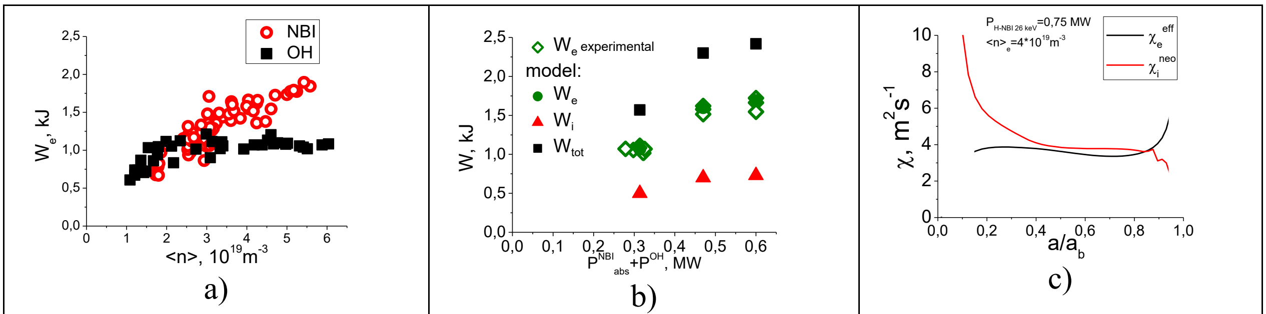

Figure 5 *a) Thermal energy stored in electrons for NBI and OH cases, open dot corresponds to NBI power of 0.5 and 0.75 MW vs density; b) thermal energy against absorbed power for* $<n_e>=4*10^{19}m^{-3}$*; c) electron and ion heat diffusivity for* $P_{NBI}=0.75$ *MW.*