

Thermal energy confinement time scaling with I_p and B_T in the Globus-M H-mode.

E.O. Kiselev, M.I. Patrov, G.S. Kurskiev, N.N. Bakharev, V.K. Gusev, A.Yu. Telnova, N A Khromov, I.V. Miroshnikov, Yu.V. Petrov, N.V. Sakharov, V.B. Minaev, A D Sladkomedova, P.B. Shchegolev, V.V. Solokha, V A Tokarev, S.Yu. Tolstyakov

Ioffe Institute, St. Petersburg, 194201, Russia

Introduction

Recent research conducted in spherical tokamaks (ST) have shown that dependence of energy confinement time τ_E on collisionality, in the H-mode differs from the ITER scaling [1] for conventional large aspect ratio tokamaks. It was found that $B\tau_E \sim \nu_e^{-0.82}$ for MAST [2]. A similar dependence was achieved on NSTX $B\tau_E \sim \nu_e^{-0.97}$ [3]. However, the ITER scaling represents a weaker dependence $B\tau_E \sim \nu_e^{-0.01}$ [1]. This work is devoted to a study of thermal energy confinement dependence on collisionality in Globus-M [4].

Globus-M is a small aspect ratio tokamak with the major radius $R_0=0.36$ m, minor radius $a=0.24$ m, aspect ratio $R/a \sim 1.6$ and vertical elongation $k \sim 1.8-2$. The experiments described below were performed in deuterium plasma in lower null magnetic configuration with the toroidal magnetic field range $B_T=0.32-0.5$ T, plasma current range $I_p=0.15-0.25$ MA and density $\langle n_e \rangle = 3-5 \cdot 10^{19} \text{ m}^{-3}$. Additional heating was performed with the neutral beam injector with power of 0.76 MW and deuterium beam energy $E_b=26$ keV.

Scaling in physical dimensionless variables

The energy confinement time scaling in physical variables is defined as

$B_T \tau_E \sim \rho_*^{x\rho_*} \nu_*^{x\nu_*} \beta^{x\beta} q^{xq}$, where: toroidal beta $\beta = 2\mu_0 n_e T / B^2 \sim n_e T / B^2$, normalized Larmor

radius $\rho_* = \frac{\rho_i}{a} = \frac{V_T}{a\omega_{ci}} \sim \frac{\sqrt{T}}{B}$, engineering safety factor $q_{eng} = \frac{2\pi a^2 B}{R\mu_0 I_p} \sim \frac{B}{I_p}$ and normalized

collisionality $\nu_* = \nu_{ii} q R / V_i^{1/2} \epsilon^{3/2} \sim \langle n_e \rangle R / T^2$. Temperature is defined as volume averaged

$T = W_{th} / (3V \langle n_e \rangle)$, to exclude difference between ion and electron temperature. The exponent

$x\nu_*$ in scaling can be determined from a set of plasmas which differ in collisionality but with

the other dimensionless parameters kept constant $\rho^*, \beta, q = \text{Const}$. From the requirement that

$\rho_* \sim \sqrt{T}/B = \text{Const}$, $\beta \sim n_e T / B^2 = \text{Const}$, $q \sim B/I_p = \text{Const}$ one finds that the range of

the scan is controlled by the span of the toroidal magnetic field [2]. For this purpose we have selected discharges with $B_T=0.32, 0.4, 0.5$ T and $I_p=0.15, 0.2, 0.25$ MA.

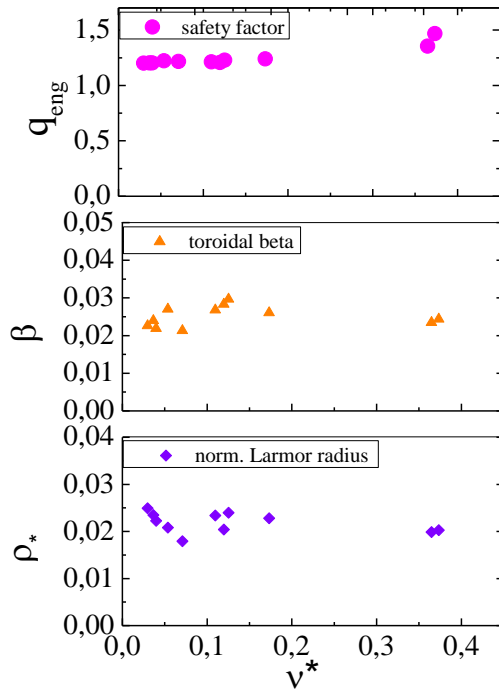


Figure 1. Engineering safety factor, beta and normalized Larmor radius scattering in scan.

Modelling technique

The calculation was performed in two stages.

First, with the help of a 0-dimensional model [5] we can quickly, automatically calculate and select useful discharges and time points for good statistics. This model allows us to calculate basic integrated variables: the electron and ion energy content, ohmical heating power, averaged density and temperature, beta, Larmor radius, collisionality, etc without complex modelling. The input data are the electron temperature and density profiles, measured by the Thomson scattering diagnostic, EFIT equilibrium, and central ion temperature measured with NPA. Second stage is more accurate and complex 1.5 dimensional modeling with the ASTRA code [7]. For calculation of fast particle behavior, we use NUBEAM [6]. This is Monte-Carlo code, which is used to calculate

on the base of the ASTRA output data the absorbed power and loss power. This data is used in ASTRA code to calculate the energy confinement time and heat conductivity. We calculate neutral density profiles with DOUBLE code [8] on the base of the NPA data.

Fast particle behavior

In the Globus-M tokamak fast particle losses are large, and have two main loss channels: first orbit losses and charge-exchange losses. The main reasons for this are the low toroidal magnetic field and relatively small size of the machine. Significant charge-exchange losses are caused by a relatively small distance between wall and plasma and hence high neutral density. As you can see from Table 1, in all discharges with low toroidal field, plasma current and high collisionality main loss channel is first orbit losses, and CX losses are lower. In the next two groups of discharges with lower collisionality and higher toroidal field and plasma current, higher losses occurred due to CX mechanism, and bad orbit losses significantly lower.

In all discharges the power absorbed by electrons is almost constant, but power absorbed by ions increases with increasing toroidal field and plasma current. The explanation for this fact is as follows. On the one hand, if the initial fast ion energy is increased, more power should be transferred to the electron component, because at high energies collisions with electrons predominate. On the other hand, the increase in plasma temperature

Table 1

v_e	B_T, T	I_p, MA	charge-exchange, kW	first orbit loss, kW	shine-through, kW	P_e, kW	P_i, kW	P_{full}, kW	P_{inj}, kW
high	0,3	0,15	193,7	399,4	3,3	108,9	45,3	154,2	760
median	0,4	0,2	427,5	125,8	22,2	108,1	88,3	196,4	760
low	0,5	0,25	420,9	79,9	20,3	90,2	120,4	200,6	760

leads to the growth of the so-called critical energy above which the energy of a fast ion is primarily transferred to plasma electrons and below which it is primarily transferred to plasma ions, $E_{crit} \sim (m_f/m_i^{2/3}) \cdot T_e$ [8], where m_f is fast ion mass, m_i is the average mass of the bulk ions and T_e is electron temperature). Both of these effects compensate each other.

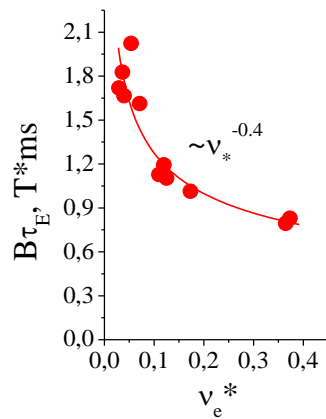


Figure 2. Energy confinement time dependence on collisionality.

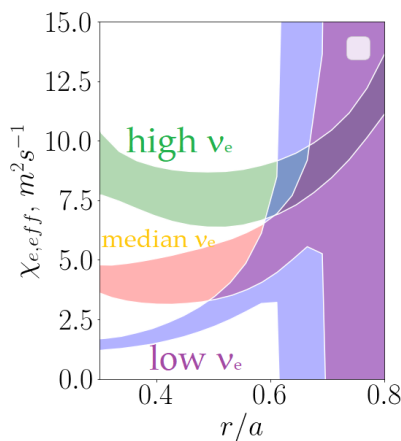


Figure 3. Changing of electron heat conductivity in collisionality scan.

Collisionality scan

Collisionality scan (Figure 2) was performed with almost constant normalized Larmor radius, safety factor and beta $\rho^*, \beta, q = \text{Const}$ (Figure 1). But the points are scattered, that caused error in calculation of the exponent indexes. Points were divided into three groups: high collisionality (0,3 T and 0,15 MA), median (0,4 T and 0,2 MA) and low collisionality (0,5 T and 0,25 MA). The difference of the energy content (Figure 4) and confinement time (Figure 2) between two groups with high and median collisionality is small, but the difference between two groups with low and median collisionality is large, the energy content and the energy confinement time is doubled. The exponent indexes calculation was performed by log-linear regression. The dependence is linear in the logarithmic scale, and exponent indexes represent the slope of the line. The result is $B\tau_E \sim v_e^{-0.4 \pm 0.2}$, that differ from the data from NSTX $B\tau_E \sim v_e^{-0.97}$ and MAST $B\tau_E \sim v_e^{-0.82}$ but stronger than in ITER scaling. This difference between the Globus-M tokamak and other spherical tokamak results

(NSTX and MAST) in exponent indexes is caused probably by changing in heating power at the scan (Figure 2). Errors is caused by error in the input data and in the scattering of the

constant variables ρ^* , β , q . The biggest uncertainty is connected with scattering of the Larmor radius. The scaling as a function of v_e are even stronger when the variation of ρ^* is taken into account through the Bohm and gyro Bohm assumptions, with the normalized confinement going as $\rho_*^2 B \tau_E \sim v_e^{-0.45}$ and $\rho_*^3 B \tau_E \sim v_e^{-0.52}$, respectively. Similar result was obtained on NSTX [3]. This uncertainty is taken into account into the calculation of exponent index error.

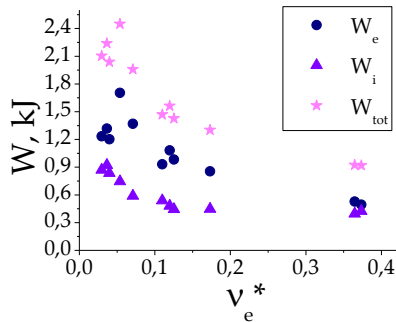


Figure 4. Total, electron and ion energy content in the scan.

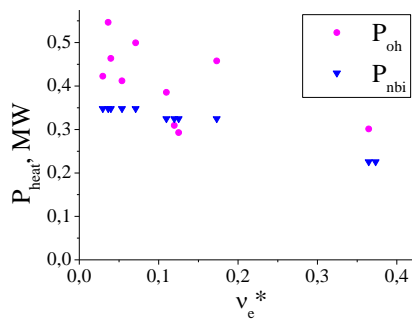


Figure 5. Changing of absorbed NBI and ohmic power in collisionality scan.

Figure 3 represents electron heat conductivity in three cases: low, median and high collisionality. With the fixed minor radius, we calculated B/χ_e dependence on collisionality, $B/\chi_e \sim B \tau_E$. The indexes changed along minor radius from $B/\chi_e \sim v_e^{-0.2}$ to $\sim v_e^{-0.6}$. The result is in consistent with the obtained energy confinement time dependence on collisionality.

Conclusion

The strong dependence of energy confinement time on collisionality is obtained $B \tau_E \sim v_e^{-0.4 \pm 0.2}$ and it is weaker than the results from other spherical tokamaks: NSTX ($B \tau_E \sim v_e^{-0.97}$) and MAST ($B \tau_E \sim v_e^{-0.82}$). But dependence is stronger than in ITER scaling ($B \tau_E \sim v_e^{-0.01}$). A more accurate dependence can be obtained by changing the parameters within a wider range of parameters and at a higher beta.

Acknowledgement

Thermal energy confinement study was supported by RFBR, research project № 16-32-60114 mol_a_dk.

Experiments were conducted with support of Presidium Program of RAS.

References:

- [1] ITER Physics Basis 1999 Nuclear Fusion 39 217
- [2] Valovic M. et al 2009 Nuclear Fusion 49 075016
- [3] Kay S.M. et.al. 2006 Nuclear Fusion 46 848-857
- [4] Gusev V.K et al 2013 Nuclear Fusion 53. 093013
- [5] G. S. Kurskiev *et al* 2017 Physics of Atomic Nuclei 80 1313
- [6] A. Pankin et al 2004, Comp. Phys. Comm. 159 157. – 55043023.
- [7] Pereverzev G.V., Yushmanov P.N. 2002. Max-Planck IPP report. P. 5-98.
- [8] Bakharev N.N. et al 2015 Nucl. Fusion. – T. 55 – 55043023.