THERMAL ENERGY CONFINEMENT AT THE GLOBUS-M SPHERICAL TOKAMAK.

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Abstract

The presentation is devoted to the overview of thermal energy confinement study at the compact spherical tokamak Globus-M. The regression fit of the database for the quasistationary H-mode plasma was performed. It indicates strong dependence on toroidal magnetic field \( B_t \) and density \( n_e \). The \( T_e \) dependence on plasma current \( I_p \) is weaker than conventional scaling IPB98(y,2) prediction. The \( B_t T_e \) dependence on \( v^4 \) is strong that is similar to NSTX and MAST results. The \( B_t T_e \) dependence on \( q \) an \( \beta \) cannot be quantified due to high correlation of the database, however the increase of both of them have strong stabilizing effect on thermal energy confinement. The energy and particle confinement exhibits different behavior in regimes with \( q_{	ext{min}}>1 \). These transient operational modes were investigated using NBI at the current ramp-up phase. Such scenario usually causes ITB formation for particle and/or for electron heat fluxes (e-ITB). For particle flux the internal diffusion barrier it is located in the region \( r/a \sim 0.5 \), the electron heat flux barrier (e-ITB) is located at \( r/a \sim 0.8 \). These advanced regimes are characterized with enhanced energy confinement relative to conventional H-mode.

1. INTRODUCTION

Thermal energy confinement in spherical tokamaks (ST) is one of the key points under investigation, because it differs from the confinement in conventional high aspect ratio tokamaks. Relatively low toroidal magnetic field in ST together with good confinement capabilities allows stable operation at significantly high \( \beta \) (the ratio of plasma pressure to magnetic field pressure). This fact, as well as large normalized ion gyroradius (\( \rho^* \)), high fraction of trapped particles, strong plasma shaping, etc. lead to significant difference in plasma turbulence that determine particle and heat fluxes. The results obtained on MAST[1] and NSTX[2] have shown that engineering scaling for energy confinement time (\( T_e \)) is different from the conventional IPB98(y,2)[3]. The main difference is a strong dependence of \( T_e \) on the toroidal magnetic field that is approximately negligible in IPB98(y,2). This result is connected with much stronger electron heat diffusivity dependence on collisionality. Further experiments and analysis have confirmed this statement [4][5].

The presentation is devoted to the overview of thermal energy confinement time behavior at the spherical tokamak Globus-M [6]. Experiments were performed in the plasma configuration with major radius \( R = 0.35 \) m and minor radius \( a = 0.21 \) m (\( R/a \sim 1.6 \)) and lower-null magnetic structure with moderate elongation \( k \sim 1.9 \) and triangularity \( \delta \sim 0.35 \). The device is very compact; there is only a few cm gap in equatorial plane between plasma and the vacuum chamber first wall. Special feature of the Globus-M tokamak is the extremely high input heating power density: \( \sim 0.6 \text{ MW/m}^3 \) in pure ohmic heating (OH) and \( \sim 2.5 \text{ MW/m}^3 \) under auxiliary heating by neutral beam injection (NBI).

This paper describes the confinement properties of the Globus-M plasma for two cases. The first case is the conventional steady-state H-mode at the quasistationary phase of the discharge. The other case is the scenario with early NBI at the current ramp-up phase when the \( q \) profile is non-monotonic. Such regimes usually causes formation of the stable ITB for particle and/or for electron heat fluxes (e-ITB) that sustain even when \( q \) profile becomes monotonic. The lifetime of the ITB regimes is limited with resonant surface \( q=1 \) appearance in plasma core. The paper is organized as follows. The second section is devoted to Globus-M database overview and to regression fit of the database, the third is concerned with dimensionless analysis and the last one describes the ITB features in Globus-M.
2. DIMENSIONAL ANALYSIS OF THE GLOBUS-M DATABASE

The present study was performed in both OH and NBI heated H-mode deuterium plasma using deuterium beams with particle energy 26 keV and 28 keV. The NBI power was varied in range 0.35-0.75 MW. H-mode is the usual operational regime in Globus-M at moderate density range n_e>2.5·10^{19} m^{-3}. The typical waveforms for the basic plasma parameters during L-H transition one can find elsewhere [7][8][9]. Plasma total stored energy was estimated using both diamagnetic measurements and kinetic data analysis. The absorbed heating power was calculated by modified version of 3D fast ion tracking algorithm [10] and verified with the well-known NUBEAM code [11]. Fast ions losses in Globus-M are rather high, for the co-injection of the beam with energy 26 keV they are ~50% due to charge-exchange and bad orbit losses. The selected data corresponds to steady-state H-mode at the quasistationary phase of the discharges. The range of the major plasma parameters is as follows: I_p=0.12-0.25 MA, B_T=0.25-0.5 T, absorbed heating power P_{abs}=0.2-0.8 MW, averaged electron density n_e=1.8-5.5·10^{19} m^{-3}. The dependence of energy content W on I_p, B_T, P_{abs} and n_e is shown in Fig.1. Even from these figures one can see obvious W dependence on B_T and I_p. Plasma total stored energy W was obtained using diamagnetic measurements. The thermal energy contribution is 90-95% according to ASTRA modelling based on Thomson scattering and CXRS data. Fig. 2a, illustrates the comparison of the W with predictions of IPB98(y,2) scaling W_{IPB} \sim I_p^{0.95} B_T^{0.15} P_{abs}^{0.33} n_e^{0.41}. The H-factor is in the range 0.5-1.3, the bulk of the points corresponds to H-factor ~0.7. From the Fig. 2a one can see that scatter of experimental points is sufficiently large, therefore IPB98(y,2) functional dependence is poorly suited to describe the experiment. The regression fit was performed as follows W^{GLB}=C I_p^{\alpha I} B_T^{\alpha B} P_{abs}^{\alpha P} n_e^{\alpha n}. The result of the regression is presented in Fig. 2b, the ε=W/W_{IPB} distribution is close to normal. When fitting the following parameters were obtained C=9.07±0.95, αI=0.77±0.08, αB=1.3±0.06, αP=0.2±0.04, αn=0.67±0.04 while RMSE=25%. The absolute values of Pearson correlation coefficients are lower than 0.18 for all parameter combinations except, ρ(I_p,P_{abs})=-0.57 and ρ(I_p,B_T)= -0.33. The moderate interdependence of plasma current and absorbed power underlines the fact that fast ion losses depends mostly on plasma current under Globus-M conditions [10]. This fact indicates that τ_e dependence on I_p and P_{abs} is not clear, since higher [αP] solutions will satisfy for lower [αI] values. As for example for αP=0.31 (IPB98(y,2) like) one can find that the αI=0.66 and αB=1.28 with RMSE=26%. Assuming the τ_e dependence on power according to results presented in [7] τ_e=P_{abs}^{-0.28} RMS fitting yields αI=0.25 and αB=1.2 with RMSE=30%. However, there is no doubt that the dependence of the energy confinement time on B_T is very strong. This result corresponds well with previous experimental results obtained on larger ST machines with higher plasma current [1][2] and confirms the previous reports from Globus-M[12][13].

![Graphs](image)

**FIG. 1.** The dependence of energy content on major plasma parameters: a) W vs I_p, b) W vs B_T, c) W vs P_{abs}, d) W vs n_e.
FIG. 2. Comparison of the W with predictions using a) IPB98(y,2) scaling $W_{\text{IPB}} \sim I_p^{-0.93} B_T^{0.15} P_{\text{abs}}^{0.44} n_e^{0.41}$, b) $W_{\text{GLB}} \sim I_p^{0.77} B_T^{1.3} P_{\text{abs}}^{0.2} n_e^{0.67}$ regression fit.

3. DIMENSIONLESS ANALYSIS OF THE GLOBUS-M DATABASE

3.1. Dimensionless analysis

The most important physical quantities that defines perpendicular energy transport are engineering safety factor $q_{\text{eng}} \sim B_T/I_p$, collisionality $\nu* \sim n_e/T^2$, normalized larmor radius $\rho* \sim T^{0.5}/B_T$ and plasma beta $\beta_T \sim W/B_T^2$. It was found that for conventional tokamaks thermal energy confinement exhibits strong degradation with $\beta_T$ and depends weakly on collisionality. ITER scaling predicts $B_T \tau_E \sim \beta_T^{-0.9} \nu^* - 0.01 q_{\text{eng}}^{-3}$ (1) [3], however different trend is observed for STs. The main feature of the thermal energy confinement in ST is strong $\tau_E$ dependence on collisionality [4][5]. For MAST tokamak $B_T \tau_E \sim q^{0.85 \pm 0.02} \nu^* \rho*^{0.1}$. For NSTX $B_T \tau_E \sim \nu^* \rho*^{0.79 \pm 0.1}$. Future fusion devices should operate in the range of sufficiently lower collisionality [14][15], while $q$ and $\beta_T$ values will be close to the parameters of the existing devices. In this connection the extrapolation of the experimental data to lower $\nu^*$ is the most interesting. The data from the larger STs corresponds for lower $\nu^*$ and $\rho^*$ range, therefore the Globus-M data may approve and underline the existing trend. The range of the dimensionless parameters for the Globus-M dataset used for dimensionless analysis is presented in Fig 3. The values of electron and ion temperatures are very close $\langle T_e \rangle = \langle T_i \rangle$ for Globus-M NBI plasma [13]. For dimensionless analysis we excluded OH shots in order to prevent disagreement in collisionality definitions, since in OH regimes $T_i$ is usually a few times lower than $T_e$. Formal regression fit in the form $B_T \tau_E \sim \rho*^{x_p} \nu^*^{x_q} q_{\text{eng}}^{x_q} q_{\text{eng}}^{x_q}$ yields $x_p = -2.7 \pm 1.2$, $x_q = 1.45 \pm 0.3$ $x_T = -0.45 \pm 0.01$, $x_q = 0.85 \pm 0.05$ with RMSE=10%. The absolute values of the Pearson correlation coefficients are

FIG. 3. Scatter plot for Globus-M data in the space of global dimensionless parameters.
in the range 0.5-0.66 that underlines moderate interdependence of the fitting parameters. Suggesting gyroBohm dependency ($x_p = -3$) it was found that $x_B = 1.49 \pm 0.02$, $x_{B\nu} = 0.47 \pm 0.01$, $x_q = 0.77 \pm 0.04$ (RMSE=10%), and Pearson correlations are as follows $\rho(x_q,x_B) = 0.51$, $\rho(x_q,x_{B\nu}) = -0.01$, $\rho(x_B,x_{B\nu}) = 0.21$. For Bohm case ($x_p = -2$) it appears that $x_B = 1.37 \pm 0.03$, $x_{B\nu} = 0.41 \pm 0.01$, $x_q = 1.04 \pm 0.04$, (RMSE=11%), and Pearson correlations are as follows $\rho(x_q,x_B) = 0.49$, $\rho(x_q,x_{B\nu}) = 0.16$, $\rho(x_B,x_{B\nu}) = 0.08$. The confinement time dependence on collisionality can be bounded like $B_T \tau_E \sim \nu^{-0.47,-0.41}$. Unfortunately, the $B_T$ dependence on $q$ and $\beta$ cannot be quantified using this approach due to high $\rho(x_q,x_B)$ values. Nevertheless it should be noted that increasing both of them have strong stabilizing effect on thermal energy confinement.

![Graphs](Image)

**FIG. 4.** Scatter plot for Globus-M RMS fit in the space of global dimensionless parameters. a) $B_T \tau_E \sim \rho^{2.71} \beta^{1.43} \nu^{0.47} q_{cm}^{0.77}$ b) gyroBohm case $B_T \tau_E \sim \rho^{0.71} \beta^{1.43} \nu^{0.47} q_{cm}^{0.77}$ c) Bohm case $B_T \tau_E \sim \rho^{2.37} \beta^{2.13} \nu^{0.41} q_{cm}^{1.04}$

### 3.2. Collisionality scan

Dedicated analysis was performed using a set of plasma discharges with different collisionality values while the other dimensionless parameters were kept as constant as possible $\rho^*, \beta_T, q = \text{const}$. From these conditions one can find that the range of the scan is controlled by the span of the toroidal magnetic field [1]. For this purpose we have selected discharges with $B_T = 0.32, 0.4, 0.5$ T and $I_T = 0.15, 0.2, 0.25$ MA. The range of the dimensionless parameters in this dataset is presented in Fig. 5. Fig. 6. illustrates the dependence of thermal stored energy and normalized confinement time on collisionality. One can see that both of them are strong, especially for the low $\nu^*$ values. The exponent indexes calculation was performed by log-linear regression yielding $B_T \tau_E \sim \nu^{-0.4 \pm 0.2}$. Errors are caused by the input data uncertainty and scattering of the constant variables $\rho^*$, $\beta$, $q$. The largest uncertainty is connected with scattering of the Larmor radius. The scaling as a function of $\nu^*$ are even stronger when the variation of $p^*$ is taken into account through the Bohm and gyro Bohm assumptions, with the normalized confinement going as $\rho^{2}B_T \tau_E \sim \nu^{-0.45}$ and $\rho^{2}B_T \tau_E \sim \nu^{-0.52}$, respectively. The main reason for confinement improvement is the decrease of the electron heat conductivity. Fig. 7a. represents electron heat conductivity in three cases: low ($\nu^* = 0.05$), medium ($\nu^* = 0.1$) and high collisionality ($\nu^* = 0.4$). With the fixed minor radius $r/a = 0.5$, we calculated $B_T \chi_e$ dependence on collisionality, $B_T \chi_e \sim B_T \theta$. The indexes changed along minor radius from $B_T \chi_e \sim \nu^{-0.2}$ to $B_T \chi_e \sim \nu^{-0.6}$. The result is in consistence with the obtained energy confinement time dependence on collisionality. Ion heat transport is close to neoclassical level. However, the presence of anomalous contribution is observed at low collisionality. Fig. 7b illustrates the dependence of the $T_\theta^{\text{CRS}}/T_\theta^{\text{neo}}$ on collisionality. Here $T_\theta^{\text{CRS}}$ is the ion temperature measured in the plasma core using charge-exchange spectroscopy and $T_\theta^{\text{neo}}$ is the ion temperature at the plasma center calculated assuming neoclassical ion heat diffusivity. This obtained result is consistent with regression analysis of the database. However the dependence is weaker than the data from NSTX $B_T \tau_E \sim \nu^{-0.79}$ [5] and MAST $B_T \tau_E \sim \nu^{-0.82}$ [1] but stronger than in ITER scaling [3]. This difference between the Globus-M tokamak and other spherical tokamak results (NSTX and MAST) in exponent indexes indicates the difference in mechanisms that drives heat transport. The range of $\nu^*$ and $q_{cm}$ are very similar for Globus-M and larger ST. However $\beta_T$ values on MAST and NSTX are twice larger than at the Globus-M, while $\rho^*$ is twice lower.
FIG. 5. Variation of engineering safety factor, beta and normalized Larmor radius for collisionality scan.

FIG. 6. The dependence of thermal stored energy a) and normalized confinement time on collisionality.

FIG. 7. a) Electron heat conductivity vs collisionality with fixed $\rho^*$, $\beta$, $q$. High collisionality $\nu^* = 0.4$ (0.3 T and 0.15 MA), medium $\nu^* = 0.1$ (0.4 T and 0.2 MA) and low $\nu^* = 0.05$ (0.5 T and 0.25 MA). b) The dependence of the $T_{\text{CXR}}/T_{\text{neo}}$ on collisionality.
4. CONFINEMENT BEHAVIOR OF THE GLOBUS-M PLASMA IN AT-LIKE REGIMES

4.1. Early NBI at the current ramp-up phase.

Regimes with $q_{min} > 1$ are the promising regimes for the fusion reactor or fusion neutron source (FNS) due to high fraction of the non-inductive currents and absence of sawtooth oscillations. Investigation of such operational modes was performed in high aspect ratio tokamaks[18] as well as in STs[17][18]. The reversed $q$ profile entails the appearance of the negative magnetic shear at the plasma core that is favourable to the formation of an internal transport barriers (ITB). The maximum of the bootstrap current is achieved in these modes, and when the normalized beta $\beta_n$ approaches the Troyon limit, the so-called AT-mode is realized [19]. This mode is the main scenario for the DEMO-FNS neutron source [20] and one of the promising modes for ITER operation[21]. At the spherical tokamak Globus-M such regimes can be investigated when the neutral beam injection (NBI) beginning at the current ramp-up phase. 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). Typical plasma parameters evolution in the regime with early NBI is presented in Fig. 8a. The NBI started at the current ramp-up (130 ms) when $I_p=140$ kA that is about 70% of the flat-top value. At the 143 ms one can see the sign of the L-H transition - the D$_\alpha$ line intensity drops against the background ongoing density rise. However, the edge density measured with Thomson scattering is twice lower than the edge density in H-mode regimes with the same average density. Careful analysis performed using data of the Doppler backscattering diagnostic indicates the limit cycle oscillations (LCO) phase till the 160 ms [5]. The density and SXR signal rise till 160 ms also, until the intensive MHD activity and reconnection caused the mixing of the plasma center. After that D$_\alpha$ increases and the plasma density increase ceases and a serpentine track can be observed on SXR signal [22] that corresponds to “snake” instability [23]. As the LCO starts formation of steep gradients on electron temperature and density is observed, Fig 8b. Density gradient is located in the plasma core $r/a<0.5$, while temperature profile is flat in this region. Temperature gradient is located at $r/a=0.8$. This phenomenon is very similar to the previous experiments at the Globus-M when $B_T$ was as low as to 0.4 T. At that experiments ITB formation was observed in $B_T=0.4$ T discharges for $n_e$ and $T_e$ located at $r/a=0.4$ and $r/a=0.7$ correspondently [24]. The q-profile dynamic was calculated using ASTRA code, see Fig. 9a. It indicates that NBI starts when the q-profile is reversed and the negative magnetic shear region exists in plasma core where the density gradient forms. At the current flat-top phase q-profile becomes monotonous due to current profile relaxation, however the peaked density and flat temperature profiles survive till the mixing of the plasma core due to MHD. Towards 159 ms, the value of the stability margin decreases to 1 and the mode $n/n=1/1$ appears that causes to reconnection (fig.1).

The maximum value of the bootstrap current reaches 50 kA (Fig. 9b) (25% of the total plasma current). The current generated by the atomic beam is only 15 kA (about 7% of the total plasma current) because of the low fraction of the absorbed beam power and the relatively low electron temperature. The simulation of the discharge dynamic was carried out using the ASTRA code [26] and calculation of the absorbed beam power profiles was performed using the NUBEAM code [11]. The plasma thermal energy $W_\text{th}$ was calculated on the basis of kinetic data measurements, during the discharge simulation using the ASTRA code, and verified on the basis of diamagnetic measurements. The results of calculations and measurements are shown in Fig. 10a. The contribution of the fast particles pressure to plasma total stored energy is within 10% that is in line with previous Globus-M experiments [13]. The confinement time increases with increasing density and the H-factor reaches unity starting from 150 ms of discharge Fig. 10b. This indicates some improvement in energy confinement in comparison with similar discharges ($I_p=0.2$MA, $B_T=0.5$ T) with beam injection at current flat-top phase [13], where H-factor didn’t exceed 0.8. Fig. 11 represents the simulated transport coefficients for shot #37000. The thermal diffusivity of ions (fig. 6 - red) was considered neoclassical and calculated by the NCLASS code [27], the calculated ion temperature agrees with NPA measurements. The peaked density profile is a consequence of the decrease in the diffusion of particles in the plasma core $r/a < 0.6$ down to the level of the neoclassical values. The toroidal beta is as high as 4.5% that corresponds to the normalized beta 2.7. This value is twice lower than the simple estimate of Troyon limit for Globus-M parameters [25]. The degradation of the discharge is concerned with $q=1$ resonant surface appearance in plasma and following MHD instability of $m=1/n=1$ structure. It leads to internal reconnection that collapses the pressure profile. The other reason that limits the $\beta_n$ value in Globus-M is the insufficient auxiliary plasma heating power. For the Globus-M2 parameters the additional input heating power should be as high as 2 MW in order to reach Troyon limit. Such conditions can be realized with the use of the additional 1 MW beam that will be installed at the tokamak nearest year.
FIG. 8. Shot #37000 a) Evolution of the main plasma parameters: plasma current, averaged plasma density, SXR signal, \( \text{D}\alpha \) emission, MHD-signals. Electron temperature (c) and density (d) profiles dynamics #37000

FIG 9. a) - evolution of the safety factor and b) - dynamic of the non-inductive currents fraction

FIG. 10. Shot #37000. Total stored plasma energy (a) and the energy confinement time in comparison with IPB98(y,2) scaling (b):
FIG. 11. Thermal diffusivity for electrons and ions, the diffusion coefficient for electrons, and the neoclassical diffusion coefficient estimated for shot #37000.

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