Ohmic and NBI Heating in the TUMAN-3M with Increased Toroidal Magnetic Field

S.V. Lebedev 1), L.G. Askinazi 1), A.G. Barsukov 2), F.V. Chernyshev 1), V.A. Kornev 1), S.V. Krikunov 1), A.D. Melnik 1), A.A. Panasenkov 2), D.V. Razumenko 1), V.V. Rozhdestvensky 1), G.N. Tilinin 2), A.S. Tukachinsky 1), M.I. Vildjunas 1), N.A. Zhubr 1)

1) Ioffe Institute, RAS, 194021, St. Petersburg, Russian Federation
2) RRC "Kurchatov institute", Moscow, Russian Federation

E-mail of main author: sergei.lebedev@mail.ioffe.ru

Abstract. Paper reports results of the study of toroidal magnetic field influence on *H*-mode energy confinement and on Neutral Beam Injection efficiency in low Bt tokamak TUMAN-3M. The study was performed in toroidal field range of 0.68-1.0 T. Presented data indicate strong dependence of the energy confinement time on toroidal field: $\tau_E \sim Bt^{(0.75\text{-}0.8)}$. Observed strong dependence is in line with earlier observations on tight aspect ratio tokamaks NSTX and MAST and differs from IPB98(y,2) scaling (τ_E(IPB98) $\sim Bt^{0.15}$). The conclusion might be important for the designing of small aspect ratio devices, in which toroidal field is usually small due to technical limitations. With the increase of Bt from 0.68 to 1.0 T the portion of captured NBI produced fast ions and their confinement were found to enhance. Increased fast ion population lead to 2-fold rise in the neutron rate and 50% enhancement in NBI efficiency.

1. Introduction

Anomalous electron transport is one of the main issues in physics of plasma heating in MCF devices. Importance of electron transport studies comes from the fact that fusion alphas will transfer significant portion of their energy to electrons. Additional reason to study the problem appears in view of recently growing interest to small aspect ratio tokamaks, in which the role of electron transport is essentially important. Earlier studies revealed essential influence of toroidal magnetic field B_t on energy confinement in the low B_t operational domain [1,2]. In this paper we report results of a study of toroidal magnetic field effect on energy confinement and on electron transport in the TUMAN-3M tokamak [3].

Recent upgrade of the power supply in the TUMAN-3M allowed to increase maximum toroidal magnetic field B_t in the NBI phase from 0.68 to 1.0 T. In these conditions a study of B_t influence on the energy confinement time and on the electron temperature in the both ohmically and NBI heated plasmas was performed. With the increased toroidal field a range of achievable plasma currents was extended from 140 to 190 kA. Thus, the effect of plasma current I_p on energy confinement was explored as well.

Besides the fundamental interest a motivation of the study is an intention to increase efficiency of Neutral Beam heating in the TUMAN-3M. The increase in the NBI efficiency with B_t was expected, firstly, because of enhanced capture of fast particles and, secondly, due to enhancement of power portion transferred to bulk ions with possible T_e growth.

2. Experimental setup

TUMAN-3M toroidal field (TF) coils power supply was designed to produce relatively fast increase in the B_t in the start-up phase of the plasma discharge and slow decay of the field

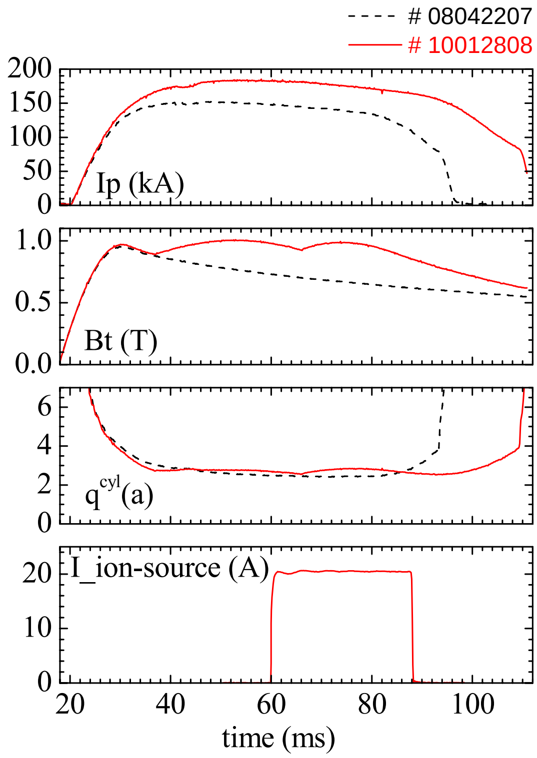


FIG.1. Plasma current Ip, toroidal magnetic field Bt, safety factor q^{cyl} and NBI ion source current (indicative of NBI application period) in the shots before (# 08042207) and after (# 10012808) power supply modification.

during I_p flattop, see dashed curves on FIG.1. Characteristic time of B_t decay is 160 ms. Drawbacks of this scenario are low B_t in the NBI phase – 0.68 T and necessity to reduce plasma current to keep constant edge safety factor $q^{cyl}(a)$ through a discharge. Recently modification of the power supply was performed. The modified supply provides compensation of the resistive losses in the TF coils and thus allows to maintain approximately constant (with 10% accuracy) B_t for 80 ms, see solid curves in FIG.1. With the modified power supply B_t in the NBI heating phase was increased up to 1.0 T and I_p was increased up to 190 kA.

Extended device capabilities allowed study of electron confinement dependence on B_t and on I_p. The study was performed in two operational scenarios – ohmic *H*-mode [4] and Neutral Beam heated *H*-mode [5]. Plasma parameters in the described experiments were as follows: R_0/a_l =0.53/0.22 m, B_t=0.68-1.0 T, I_p=140-190 kA, $\bar{n}_e$=(2-5)$\cdot10^{19}$ m^{-3}, $T_e(0)$=0.4-0.9 keV, $T_i(0)$=0.18-0.4 keV. For study of NBI efficiency the tangential co-current NB injection with impact parameter of 0.42 m was utilized. Input NBI power was up to 0.4 MW, deuterium beam energy – E_0<25 keV.

Electron temperature has been measured using array of SXR detectors equipped with a set of beryllium foils. Ion temperature was obtained from NPA spectra. Fast ion behavior was monitored by neutron flux detectors. Stored energy was derived from diamagnetic measurements.

3. Energy Confinement in the Ohmic *H*-Mode

In the ohmic *H*-mode electron temperature was measured in three regimes characterized by different toroidal fields and plasma currents: 1) B_t=0.7 T, I_p=140 kA, 2) B_t=1.0 T, I_p=140 kA, 3) B_t=1.0 T, I_p=170 kA. $\bar{n}_e$ evolution was similar in these regimes. FIGURE 2 presents waveforms of some plasma parameters in the representative shots. Central T_e is shown in fourth frame. Dotted (black) and dashed (blue) curves present T_e evolution in similar shots with only one different 'engineering' parameter: B_t. Observed increase in the electron temperature, from 400-500 to 550-600 eV, could be explained assuming τ_E increases substantially in the shot # 09111221 with higher toroidal field. Dependence of τ_E on toroidal field, which fits T_e measurements, is $B_t^{0.75}$. Noteworthy this dependence is much stronger than scaling IPB98(y,2) [6] predicts: $\tau_E \propto B_t^{0.15}$.

Two scenarios with same B_t and varied I_p allowed to study τ_E dependence on plasma current. Example of shots with B_t=1 T and I_p=140 and 170 kA is given on FIG.2, # 09112420 & # 09111221, respectively. Plasma current increase from 140 kA to 170 kA with constant B_t resulted in the further growth of T_e from 550-600 eV up to 650-750 eV as shown in fourth frame in FIG.2 by solid (red) curves – shot # 09112420. The growth is in a good agreement with IPB98(y,2) prediction: $\tau_E \propto I_p^{0.93}$.

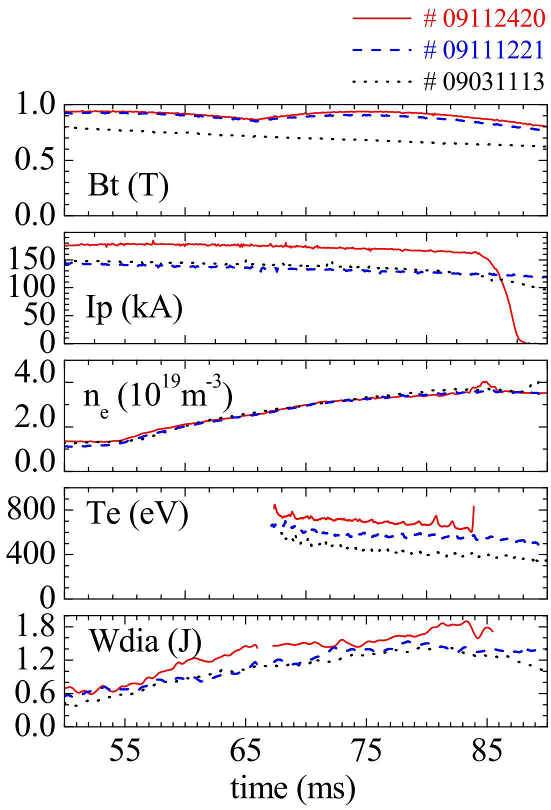


FIG.2. Magnetic field Bt, plasma current Ip, average density n_e, central Te and diamagnetic energy in the shots with different Bt (# 09111221 & # 09031113) and Ip (# 09112420 & # 09111221)

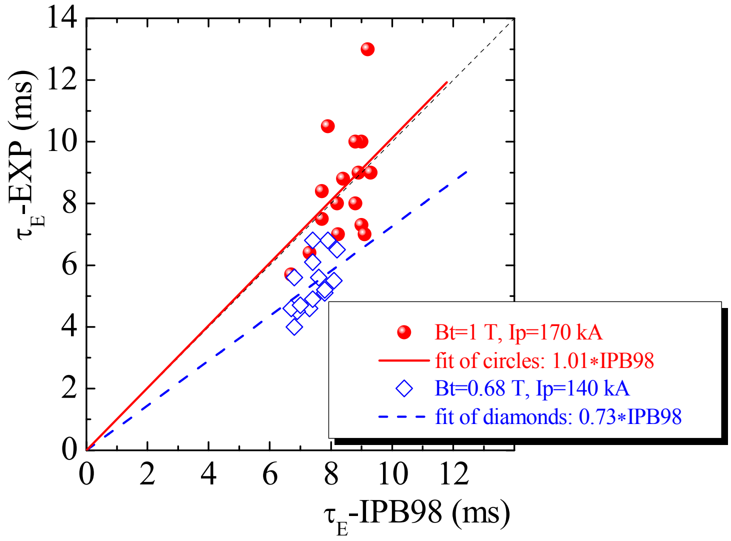


FIG.3. Experimental τ_E vs IPB98(y,2) scaling in the ohmic H-mode: blue ◊ – Bt=0.68 T, Ip=140 kA (linear fit – blue dashed line); red • – Bt=1.0 T, Ip=170 kA (linear fit – red solid line).

Diamagnetic measurements showed clear growth of the stored energy with increased toroidal magnetic field and plasma current. Results of the measurements are shown in bottom frame in FIG.2. Using the diamagnetic data τ_E was calculated. Derived τ_E is presented in FIG.3 as a function of IPB98(y,2) scaling predictions. The figure suggests good agreement between measured and IPB98(y,2) confinement times at high B_t and I_p. Data obtained at low B_t and I_p indicate distinctive τ_E-EXP deviation from IPB98(y,2) scaling. The deviation could be explained by the influence of B_t on τ_E. The difference suggests $\tau_E \propto B_t^{0.8}$, what is close to the dependence derived from T_e measurements with varying B_t: $\left(\tau_E \propto B_t^{0.75}\right)$ and considerably stronger than in IPB98(y,2).

4. Influence of Toroidal Magnetic Field on NBI Efficiency

Enhancement in the ohmic plasma parameters had improved noticeably the conditions for the NBI heating. Firstly, the increases in the toroidal field and plasma current lead to improvement of fast NBI particles capture. This effect is illustrated on FIG.4 showing calculated fraction of captured fast ions (FI) versus neutral beam energy for two scenarios differing by toroidal field and plasma current. The figure allows to conclude 30-40 % growth of captured FI fraction with increasing B_t from 0.68 to 1.0 T. Secondly, as reported in previous section, electron temperature is substantially increased at B_t=1 T. The T_e increase is expected to result in longer FI slowing down time τ_{SE} and thus enhancements in their amount and in power fraction transferred to thermal ions.

Electron temperature in the NBI phase in the regime with B_t=1 T is found to be 620-670 eV. The value is higher than at B_t=0.68 T (420-460 eV) as shown in third frame in FIG.5. The result confirms observation of favorable effect of B_t on T_e made in the ohmic *H*-mode.

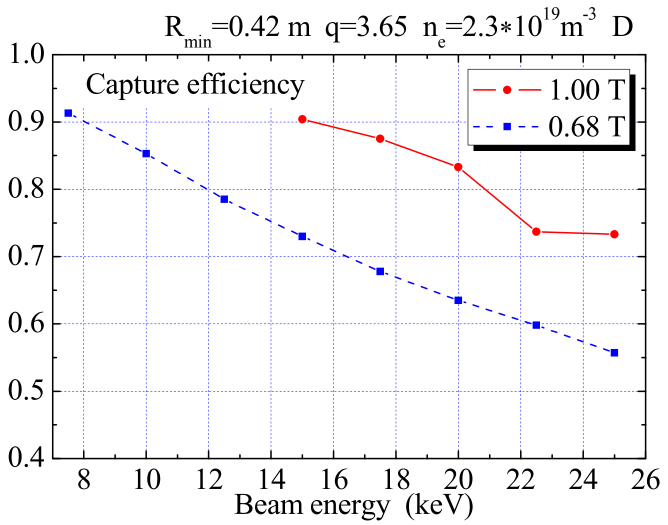
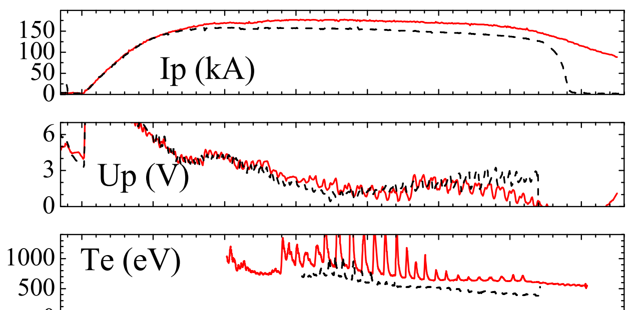


FIG.4. Fraction of captured fast ions vs NB energy in two scenarios: small Bt&Ip – blue dashed curve; high Bt&Ip – red solid curve

In the conditions of improved FI capture and increased electron temperature an amount of fast ions accumulated in plasma is noticeably increased. That is evidenced by measurement of 2.45 MeV D-D neutron rate. FIGURE 6 shows the temporal evolution of the fluxes measured in both regimes. Since temperature of thermal ions is low in the TUMAN-3M the neutron rate is proportional to amount of FI capable to produce fusion reaction with bulk ions. Thus observed 2-fold increase in the neutron rate reflects corresponding rise of FI population.

Improved capture and confinement of fast particles resulted in clear enhancement of ion heating. On FIG.7 evolution of T_i in scenarios with low $B_t \& I_p$ (lower curve) and high $B_t \& I_p$ (upper curve) is compared. Absence of ion temperature saturation during NBI pulse in latter case should be mentioned. Observed increase in the T_i is about 50% larger than at low $B_t \& I_p$. Calculations had shown the improvement in FI capture is mainly due to 2-3 fold

FIG.5. Plasma current, loop voltage, electron temperature and ion source current in NBI unit in two scenarios: small Bt&Ip – black dashed traces; high Bt&Ip – red solid traces



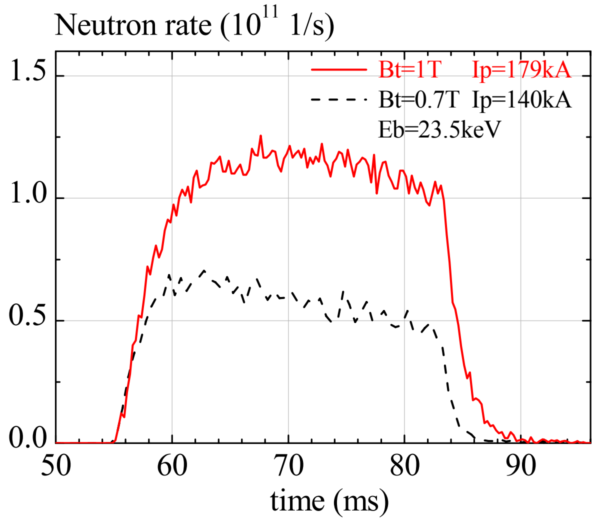


FIG.6. Neutron rate in the regimes with low Bt&Ip – black dashed curve and high Bt&Ip – red solid curve

reduction of the first orbit losses. In the conditions of diminished wall bombardment lesser plasma dilution by impurity influx was observed. Estimations had shown factor of 1.5 decrease of Z_{eff} (down to 1.2) with increasing B_t and I_p .

5. Conclusions

Study of electron energy confinement in the ohmic *H*-modes with low toroidal field has revealed strong effect of B_t on electron temperature. Observations indicate $\tau_E \propto B_t^{0.75\div 0,8}$ which is considerably stronger than the dependence predicted by scaling IPB98(y,2). Noteworthy strong τ_E dependence on B_t was observed in other experiments with low toroidal magnetic fields [1,2]. The conclusion might be important for the designing of small aspect ratio devices, in which toroidal field is usually small due to technical limitations.

Due to increased electron temperature and improved fast ion capture and confinement at high

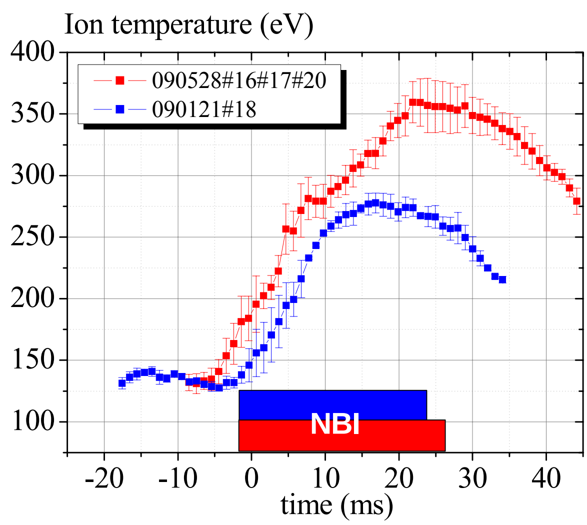


FIG.7. Ion temperature in the regimes with low Bt&Ip – blue symbols (lower curve) and high Bt&Ip – red symbols (upper curve)

B_t and I_p the NBI efficiency was substantially increased: ΔT_i is 50% larger than at low field, 2 fold increase in the neutron rate indicate increasing population of fast ions at high B_t

Acknowledgement. The work was funded by the Russian Academy of Sciences (Programme # 30), Federal Agency for Science and Innovations (Contract # 02.518.11.7112) and Russian Foundation for Basic Researches (Grant # 10-02-01414-a).

References:

[1] KAYE S.M. et al, Nucl. Fusion 46(2006) 848
[2] VALOVIC M. et al, Nucl. Fusion 49(2009) 075016
[3] VOROBIEV G.M. et al, Sov. J. Plasma Phys. (Fisika Plazmy), **9**(1983), p.65
[4] LEBEDEV S.V. et al, PPCF, **38**(1996), p.1103
[5] LEBEDEV S.V. et al, in Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) (Vienna: IAEA) CD-ROM file EX/P3-15
[6] ITER Phys. Expert Groups on Conf. and Transp. and Conf. Mod. and Database, ITER Physics Basis Editors, Nucl. Fusion, **39**(1999), p.2175