Global energy confinement time of NBI-heated plasma on the COMPASS tokamak

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Introduction

The COMPASS tokamak (R = 0.56 m, a = 0.23 m, I < 400 kA) is equipped with two identical neutral beam injectors (NBI) manufactured by the Budker Institute of Nuclear Physics, Novosibirsk [1], [2]. Each of them produces the neutral beam with power up to 400 kW at energies of up to 40 keV. This contribution presents determination of beam power losses in the beam duct and of actually injected power into plasma for 40 keV NBI. Then, the global energy confinement time of ohmic and NBI heated discharges is determined and compared with previous results on the COMPASS-D tokamak in the Culham laboratory [3].

Really injected NBI power

Both NBIs on the COMPASS tokamak are installed in tangential orientation. Size of beam duct (d = 0.84 m) connecting NBI with tokamak chamber is limited by position of toroidal coils. This leads to beam clipping if the beam divergence is not optimal. The actually injected power of NBI into plasma P_{AUX} is crucial to determine for purpose of confinement time derivation. P_{NBI} is deposited at several places along beam trajectory.

$$P_{NBI} = 0.84 U_{acc} I_{beam} = P_{duct} + P_{AUX} \qquad\qquad P_{AUX} = P_{PL} + P_{abs}$$

Where U_{acc} is beam acceleration voltage and is 40 kV for all presented results. I_{beam} is current of extracted ions by the beam grids before their neutralization and factor 0.84 is the neutralization efficiency. P_{duct} represents lost beam power which heats narrow beam duct; P_{AUX} is actually injected power into plasma. P_{PL} are losses of the injected power in the plasma by shine through, charge-exchange and orbit losses. P_{abs} is absorbed beam power by plasma.

U_{acc} and I_{beam} are measured beam parameters. P_{aux} and P_{duct} are not measured directly. However, the phenomenon of the beam clipping is clearly observed on measured P_{abs} and the relation between P_{abs} and P_{NBI} is helpful for the purpose of verification of P_{duct} calculation.

The ion acceleration optics of the COMPASS tokamak NBIs consists from four circular grids with 887 circular holes. Each of these holes is a source of a beamlet whose divergence varies with beam parameters. Assuming that each beamlet is a Gaussian beam which is directed thanks to the grid geometry to the beam focus, we reconstruct the beam profile (see

Fig. 1). The dependence of duct losses P_{duct} on the beamlet divergence is derived using this simulation. Beamlet divergence and power of each beam energy component is calculated from the spectroscopic measurements of Doppler shifted emission lines emitted by NBI [4].

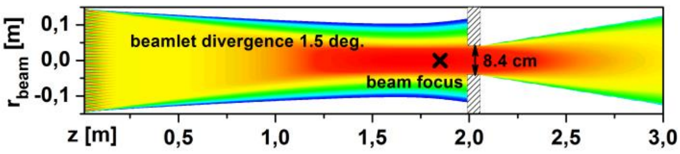

Fig. 1. Simulated beam profile in log scale. Individual beamlets are visible in proximity of last grid (z = 0 m).

Predicted P_{duct} based on the described calculation are compared with P_{abs}. If we assume that losses of injected power in the plasma P_{PL} are not strongly dependent on the injected power, P_{abs}/P_{NBI} should vary with P_{NBI} mostly due to the beam clipping. P_{abs} is derived using the following power balance equation:

$$P_{OH} + P_{abs} = P_{separatrix} + P_{radiation} + P_{position\ change} + P_{current\ change} + dW/dt$$

The experimental setup allows us to assume that the $P_{separatrix}$ is still unaffected by NBI heating soon after NBI start. Fig. 2 shows dependence of P_{abs}/P_{NBI} on the line average density n_e and also simulations done in FAFNER [5, 6] and RISK codes [7] for comparison.

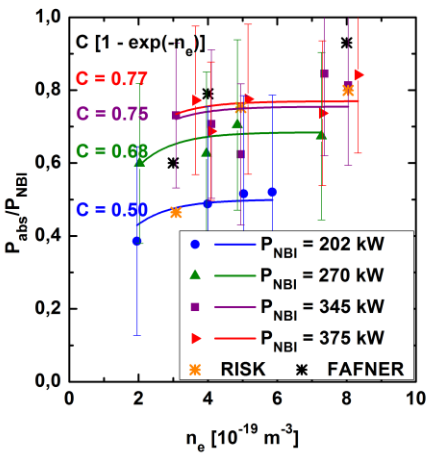

Fig. 2. P_{abs}/P_{NBI} versus the line average density n_e for several P_{NBI} is shown. Results of RISK and FAFNER simulations are for P_{NBI} = 300 kW without including clipping losses in the beam duct. The increase of the exponential limit C with P_{NBI} is mostly result of beam clipping in the beam duct.

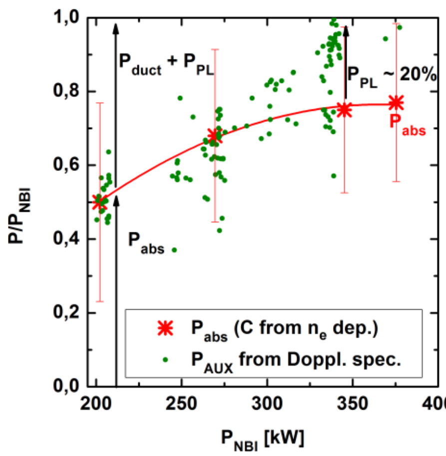

Fig. 3. Deposited and absorbed power fractions of P_{NBI} in respect to produced power P_{NBI}. The red stars are maximum ratios P_{abs}/P_{NBI} C derived from n_e dependence (fig 2). Green dots show P_{AUX}/P_{NBI} derived from a combination of spectroscopic beam diagnostic results and the beam clipping model.

We see lower P_{abs}/P_{NBI} for lower n_e, which is probably due to higher shine through losses, however it is not such as significant as the simulations predict. There is also clearly visible that P_{abs}/P_{NBI} increases with applied power, which is a consequence of a reduced beamlet divergence and thus smaller beam clipping.

Fig. 3 shows calculated auxiliary heating power P_{AUX} and absorbed power in the plasma P_{abs} in respect to P_{NBI} are presented. We see that the NBI losses in the plasma P_{PL} are up to 20% when we compare calculated P_{AUX} and P_{abs}. P_{PL} for higher densities from the simulation results shown in Fig. 2 are similar. Result of these studies is that we can use our model for including duct clipping to obtain more precise estimation of P_{AUX}. Also derived dependency of P_{abs} on n_e and P_{NBI} is useful for derivation of power losses across the separatrix $P_{separatrix}$. However the error of P_{abs} shown in Fig. 2 and also in case of P_{AUX} (beamlet divergence is has error about 50%) is high and method how to reduce it has to be improved. All of these results are for NBI with maximal nominal beam energy 40 keV.

Global energy confinement time

The global energy confinement time τ_{E_EXP} is derived from experimental data as a ratio of plasma energy (EFIT reconstruction [8]) and total heating power (P_{OH} + P_{AUX}). To exclude the term of plasma energy time derivation, we analyse the steady state phase of a discharge. Radiated power losses are not subtracted from total heating power because we are comparing it with scaling laws [9] which were derived from data determined also without radiation losses subtraction. The global energy confinement time τ_{E_EXP} of various discharges with steady state phase realized during 2016 on COMPASS in respect to n_e are shown in Fig. 4.

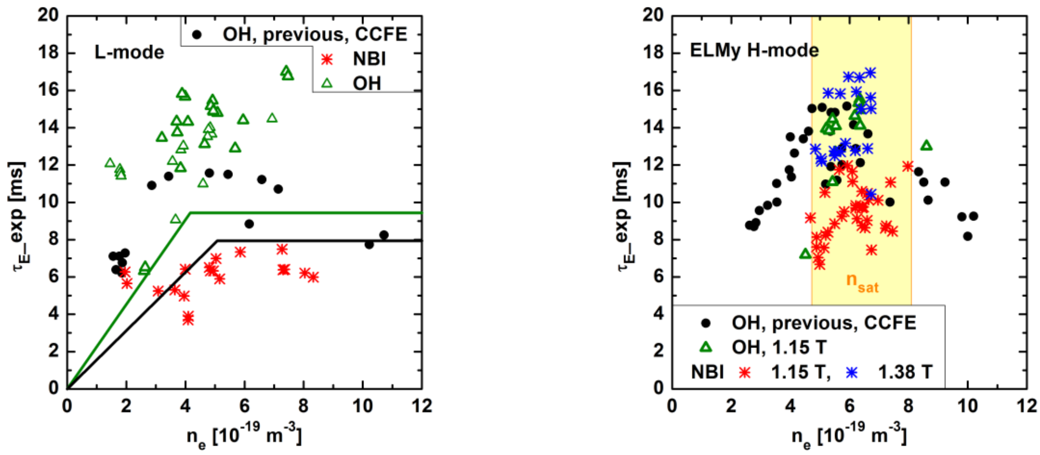

Fig. 4. τ_{E_EXP} for steady state phase of NBI heating and only OH discharges in L-mode (left) and H-mode (right) are compared with data measured on COMPASS-D at UK. Lines on the left graph represent neo-Alcator scaling for average discharge settings for previous data, CCFE (black) and current data (green). The range of n_{sat} of neo-Alcator scaling for minimum and maximum parameters of discharges is shown at right graph by orange rectangle.

It is seen that majority of experimental data are significantly higher than the prediction of neo-Alcator scaling (plotted by the full lines in Fig. 4). Similar observation of this phenomenon was also seen in COMPASS-D during its operation at UK. NBI heating significantly degrades τ_{E_EXP}. It is interesting to note that most of the recent H-mode discharges with steady state phase of discharge parameters were realized in the range of neo-Alcator saturation densities. Fig. 5 compares τ_{E_EXP} calculated from experimental data with predicted values τ_{E_calc} by two different scaling laws for L-mode discharges. In this case the L,th scaling law is visibly better. For H-mode discharges the difference between the scaling laws ITERH92 and IPB98 is not so significant.

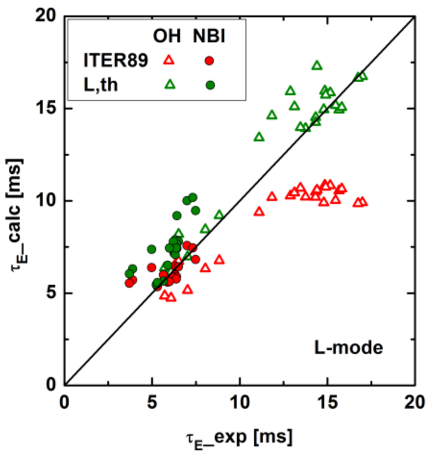

Fig. 5. Experimentally obtained global energy confinement times are compared with two different scaling laws. L,th fits better than ITER89.

Conclusion

The way how to calculate the power losses in the beam duct P_{duct} and the really injected NBI power P_{AUX} was found. P_{duct} is negligible for maximal power of NBI. Calculated P_{AUX} fits well with independent measurement of absorbed NBI power P_{abs} in the plasma which is reduced by NBI losses in the plasma P_{PL}. Observed and simulated losses by FAFNER and RISK P_{PL} are both up to ~20% for densities higher than $4\times10^{19}m^{-3}$. For lower n_e the simulation results are significantly below experimental ones.

The global energy confinement time τ_{E_EXP} was derived for a wide range of discharges using the formula for P_{AUX}. It is in general in a good agreement with data measured on COMPASS-D during its operation in the UK. In both cases measured τ_{E_EXP} is higher than neo-Alcator scaling predictions.

Acknowledgements and references

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[1] R. Panek et al., PPCF (2016)
[2] P. Deichuli et al., RSI 83, 02B114 (2012)
[3] P. G. Carolan et al., PPCF 36, A111 (1994)
[4] K. Mitosinkova et al., Nukleonika 61, 419 (2016)
[5] J. Urban et al., Czech. J. Phys. 56, B176 (2006)
[6] J. Urban et al, 35th ECA 32, P-2.098(2008)
[7] A. Seman, dipl. thes., CTU (2016)
[8] J. Halicek et al., Proc. of Con. Pap., 234 (2007)
[9] J. Wesson (2004)