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.

\[ P_{NBI} = 0.84U_{acc}I_{beam} = P_{duct} + P_{AUX} \]

\[ P_{AUX} = P_{PL} + P_{abs} \]

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 $P_{\text{duct}}$ 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].

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

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

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

We see lower $P_{\text{abs}}/P_{\text{NBI}}$ 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 $P_{\text{abs}}/P_{\text{NBI}}$ 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 $\tau_{E,\text{EXP}}$ 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 $\tau_{E,\text{EXP}}$ of various discharges with steady state phase realized during 2016 on COMPASS in respect to $n_e$ are shown in Fig. 4.

![Graph showing $\tau_{E,\text{EXP}}$ for NBI heating and only OH discharges in L-mode (left) and H-mode (right)](image)

*Fig. 4. $\tau_{E,\text{EXP}}$ 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 $\tau_{E\_\text{EXP}}$. 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 $\tau_{E\_\text{EXP}}$ calculated from experimental data with predicted values $\tau_{E\_\text{calc}}$ 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 ITER92 and IPB98 is not so significant.

**Conclusion**

The way how to calculate the power losses in the beam duct $P_{\text{duct}}$ and the really injected NBI power $P_{\text{AUX}}$ was found. $P_{\text{duct}}$ is negligible for maximal power of NBI. Calculated $P_{\text{AUX}}$ fits well with independent measurement of absorbed NBI power $P_{\text{abs}}$ in the plasma which is reduced by NBI losses in the plasma $P_{\text{PL}}$. Observed and simulated losses by FAFNER and RISK $P_{\text{PL}}$ are both up to $\sim20\%$ for densities higher than $4\times10^{19}\text{m}^{-3}$. For lower $n_e$ the simulation results are significantly below experimental ones.

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

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