Modelling of NBI fast ions and effect of the toroidal ripple in the COMPASS Upgrade tokamak

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Introduction

Fast particles are a key component of fusion reactors. In particular, their interaction with turbulent structures and MHD modes can significantly modify the behaviour of the background plasma. The COMPASS Upgrade tokamak [1] will be a tokamak of major radius R=0.894m with high-field (B>5T) and high-current (B>2MA). The machine should be completed by 2022. It will be located in Prague, Czech Republic.

Due to the high particle confinement – high fueling expected in H-mode in such a tokamak, we anticipate operation at densities of order 10¹⁹/m³. The scaling used to evaluate the H-mode pedestal density is:

\[ n_p = 0.7 \times 10^{19} \text{ cm}^{-3} \]

NBI has injection energy of 80keV (~58% of the beam). This will generate a large population of trapped fast particles in the edge region. We investigate the effect of magnetic (toroidal) ripple (TRF) in terms of fast ions losses and distribution in the pedestal and the SOL.

Transport modelling and equilibrium reconstruction

Detailed integrated transport modelling with the METIS code [3] yields density and temperature profiles during the flat-top with NBI of ECP and ECPM of ECP heating. The METIS code was developed at IPP of the Czech Academy of Science, Za Slovankou 3, CZ-182 00 Prague 8, Czech Republic. This work was supported by The Ministry of Education, Youth and Sports of the Czech Republic under project No. 16310101010003.

The FIESTA code [4] is used to reconstruct the equilibrium using the current distribution from the METIS code. We deliberately choose a large minor radius a=0.28m to study potential losses on PFCs.

NBI geometry and particle distributions

Each NBI wire will contain 2 units of 1MW each tilted with an angle i=+5° and 5° or +5° and -5°. Tangency radius is at most Rₗ=0.65m. We studied also a configuration with Rₗ=0.5m to consider a low momentum injection. The initial distribution of the birth points of the NBI particles is given by the BBNBI code [5]. EBBnbi go code [6] is then used to resolve the orbits.

Power given to the plasma and parallel velocity profiles

Assuming each NBI particle slows down to the thermal ion velocity, and neglecting radial transport, we can estimate the power deposited by the combined 2 beams with inclinations +5°. We compare the Rₗ=0.65m configuration with Rₗ=0.5m. The latter yields similar heating profiles (even slightly better in the core) with reduced momentum input.

Modelling of toroidal ripple using a Biot-Savart (BS) solver and Full-orbit Particle trajectories in static 3D-fields

The solution obtained from the Biot-Savart solver is compared with a more elaborate ANSYS calculation and yields similar results.

\[ B = \frac{\mu_0}{2\pi} \frac{L}{\rho} \left( \frac{R}{\rho} \right)^2 \]

The integrated evolution of the position of NBI D ions during 4ms in the 3D TRF field is done using a grid of size 560x104x19 in which the repeated RFF coils times. The relative error (R⁰/Rp) on the particle evolution remains below 0.1% for all markers. Each beam is represented by 3 millions markers.

Resonance patterns : N=16

Radial transport of trapped fast ions shows a strong correlation to the ratio of the bounce (n₁) and precession (n₂) frequencies. \[ n₁ = \frac{n}{n₂} \]

We calculated the caption of the figures the percentage of particles resonating with \[ n₁ \approx 1.162 \times 1/3 \times 6 \approx 1/3 \] for the 3 scenarios, in the more tangential and more perpendicular injection geometries.

Sensitivity of losses on the number of TF coils (scenario #1)

Although earlier studies hint at a possible negative impact of the TFR [8] on the overall quality of the confinement (density pump-out), we have assessed the impact of lowering the number of TF coils, since this would allow for better access to the torus for diagnostics and heating systems.

Population of NBI ions in pedestal and SOL

When we consider the extension of the orbits in the mid-plane, the effect of the TFR is clearly seen on the smaller Rₗ=0.25m injection geometry. Modified gradients of fast particles at the separatrix might change momentum and turbulence in the edge region.

Conclusions and outlook

A systematic integrated modelling approach (METIS+FIESTA-BBNBI EBBnbi go) was developed in order to simulate NBI-born particles in a tokamak. Power deposition and shape of momentum profiles were estimated. Since we neglected collisions, the values need to be further benchmarked against other codes. The calculations involving the ripple show small loss rate on the wall for Rₗ=0.65m (below 5kw/m²), during 4ms simulations. The configuration with low tangency radius scheme (Rₗ=0.5m) has the potential to deliver power to the plasma core (scen. #1 and #2) with low momentum input. However, a complex interaction appears between the ripple and deeply trapped ions. In the edge region, we anticipate non-negligible losses [scenario #1=1/20kW/m²] and possibly an interaction with the pedestal and SOL.

References


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