Neutral beam injection modelling in JT-60SA axisymmetric equilibria

M. Vallar[1,2], T. Bolzonella[1], R. Coelho[3], J. Garcia[4], T. Kurki-Suonio[5], L. Pigatto[1], K. Sarkimaki[5], J. Varje[5], M. Romanelli[6]

1. *Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy*
2. *Università degli studi di Padova, Via VIII febbraio, 35122 Padova, Italy*
3. *Instituto Superior Técnico, Univ. De Lisboa, Portugal*
4. *CEA, IRFM, 13108 Saint-Paul-lez-Durance, France*
5. *Aalto University, P.O. Box 14100, FI-00076 AALTO, Finland*
6. *CCFE, Culham Science Centre, Abingdon, Oxford, OX14 3DB, UK*

Introduction - The superconducting tokamak JT-60SA, under construction in Naka (Japan), is a device which will study advanced plasma conditions, such as Steady State scenarios and break-even equivalent plasmas [1,2,3]. The additional heating system relies on a flexible combination of Electron Cyclotron and Neutral Beams (NBs). The beam injection system is composed of 12 neutral beam units with positive ion sources (P-NB) and two beams with negative ion sources (N-NB) for a total power of 34 MW. P-NBs have a wide variety of injection geometries (perpendicular, tangential co- and counter-current) and, due to their energy (85 keV), these beams deposit most of the power on ions. The N-NBs are both tangential and co-current: this helps to control the current profiles since at the energy of 500 keV, particles couple mostly with electrons. In Figure 1 the poloidal projection of beam trajectories is shown.

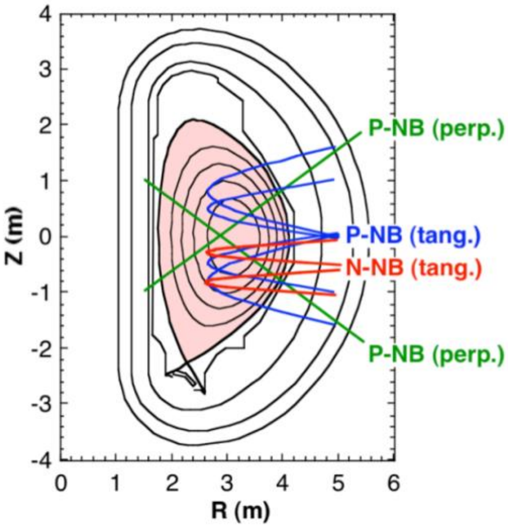

Figure 1 *Beam trajectories on poloidal section*

Modelling tools - NBI simulations are carried out using BBNBI (Beamlet-Based NBI-model) [4] and ASCOT (Accelerated Simulation of Charged Particle Orbits in a Tokamak) [5]. BBNBI is a Monte Carlo code to simulate the ionisation of fast particles injected through NBs. It uses the full description of the beamlet geometries and, given the NB output power and energy, it generates a set of markers representing a constant particle flux which get ionised. For the present work, 10^5 markers have been used. The fast ion birth profile and the shine-through (un-ionised fraction of injected particles) can be calculated using BBNBI. ADAS cross-sections are used for ionisation collision [6]. ASCOT is a hybrid solver of the Fokker-Plank equation which combines guiding centre and full particle gyro-motion. Given the ionised particles' initial position and velocity, the code

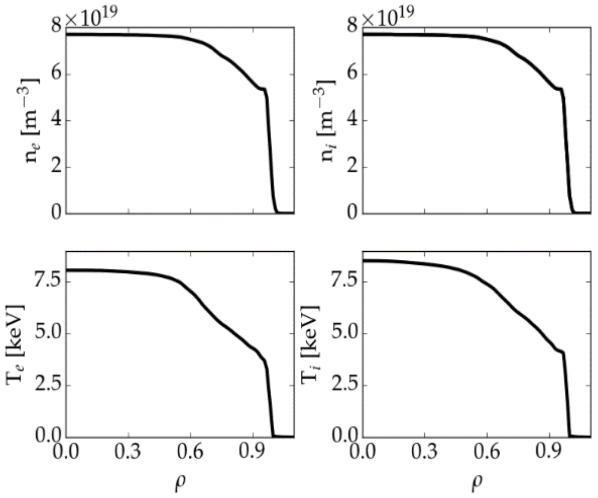

Figure 2 *Plasma profiles for the simulation.*

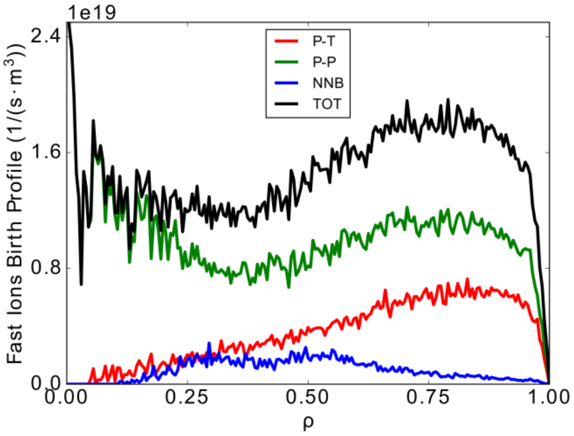

Figure 3 *Fast ion birth profile. P-P labels the perpendicular PNBs, and P-T the tangential PNBs. NNB labels the negative beams. TOT is their sum.*

follows charge particle orbits in toroidal geometry considering interaction with background plasma via Monte Carlo collision operators. The simulation assumes a steady-state background and the particles are followed up to a thermalisation/loss condition is reached. For the present simulations, the thermalisation condition is $E_{part}=2T_e$ and the loss condition is $\rho_{part}=\rho_{wall}$. For all the figures in this paper, ρ is the poloidal normalised flux. An additional condition when particles are no more considered energetic is used, i.e. when $E_{part}<10$ keV.

Plasma scenario - An inductive H-mode scenario at low Greenwald fraction ($f_{Gr}=0.5$) (also called Scenario 2 [3, 7]) has been chosen to study the fast-ions behaviour on JT-60SA. The ion species in the plasma and the injected neutrals are deuterium. The kinetic profiles of the simulations are shown in Figure 2.

Beam ion birth profile -At first, it is needed to compute the fast ion generation profiles. In Figure 3 the fast ions birth profile can be seen, subdivided in the main beam categories: the negative neutral beam, the positive perpendicular and the positive tangential beams. The positive beams energy is such that most of the particles are ionised in the outer half of the plasma. For the perpendicular beams, an increase near the core is visible due to their trajectory (closer to the core). For the negative beams, the majority of the particles is generated at ρ~0.25 and ρ~0.6 due to the off-axis injection geometry. The shine-through is small in the case of study (less than 0.05%) and, for the positive tangential beams, it goes to zero.

Slowing-down profiles - Given the NB ionisation profiles, the power deposition to the background plasma, current drive and deposition of toroidal angular momentum are investigated. The critical energy (where stopping by ions and electrons are equal) in this plasma is around 100 keV. This implies that P-NBs (85 keV energy) deposit around 85% of their energy to ions, while N-NBs (500 keV energy) deposit around 65 % of their energy to

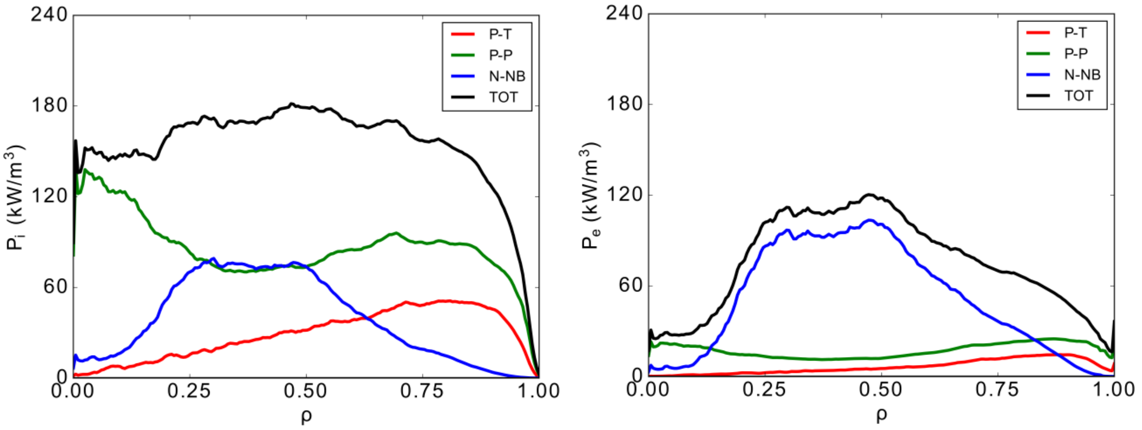

Figure 4 *Power deposition profiles for ions (left) and electrons (right)*

electrons. In Figure 4 the power deposition profiles confirm the theoretical estimate: N-NBs have the same order of magnitude for the two species, whereas P-NBs heat mainly ions. The total power deposited after the slowing-down is around 29 MW: 85% of the injected power. Figure 5(a) shows the contribution to the current given by the tangential P-NBs: it sums to zero except at the edge. The net zero contribution is due to the symmetry in their injection geometries: two are co-current while two are counter-current. The edge increase is given by the trapped-passing orbits boundary for beam particles and it can be seen also in the total current density, shown in Figure 5(b). Most of the current is given by the N-NBs, as expected given the beam energies. Considering the torque from the tangential P-NBs (Figure 5(c)), their contribution sums to zero but at the edge the counter-injected particles cause the high

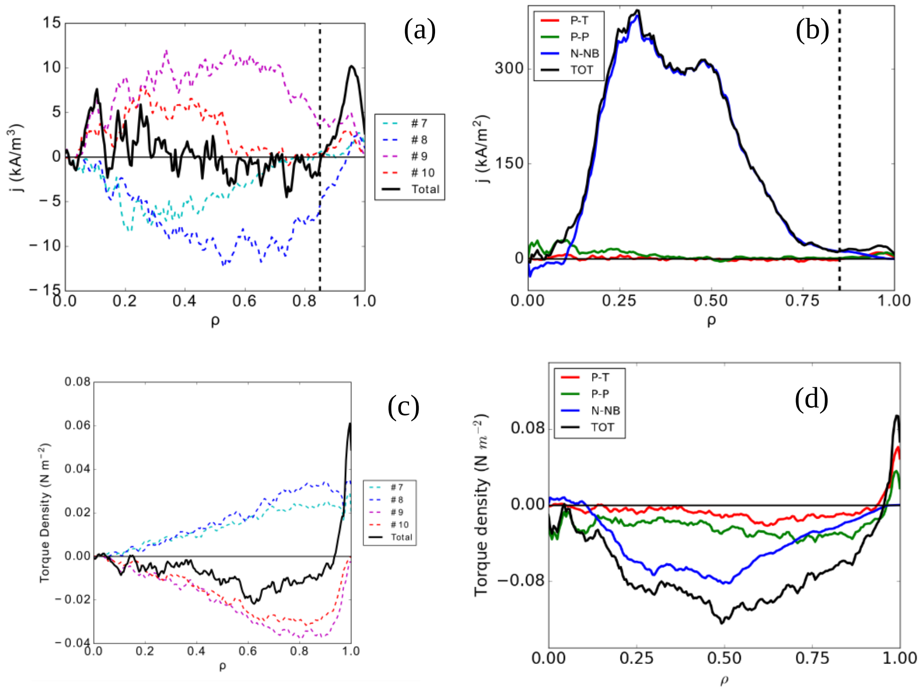

Figure 5 *(a) current density from tangential P-NBs (b) total induced current density (c) torque density from tangential P-NBs (d) total torque density*

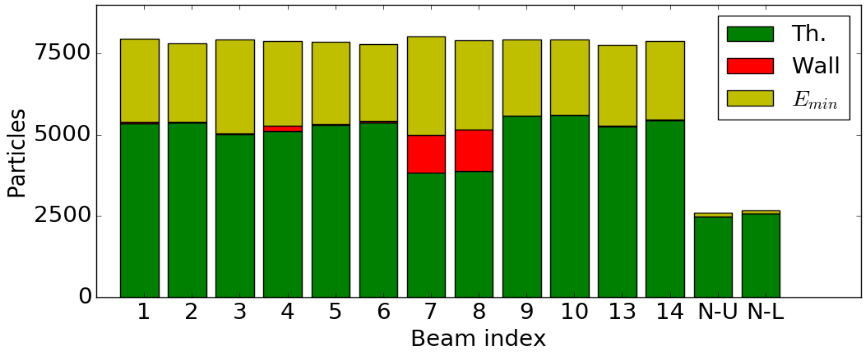

Figure 6 *Histogram of particles ending status for each beam.* Th. *Labels the thermalized particles,* Wall *the particles lost to the wall,* E_{min} *the particles no more considered fast but neither thermalised*

increase in the torque contribution. This edge effect is non-negligible neither in the total torque density, as Figure 5(d) shows. The final status of the particles is shown in Figure 6: most of wall losses are generated from beams #7 and #8, the counter-current tangential beams, as expected. The overall losses to the wall reach 3% of the injected particles.

Conclusions and outlook - In this work, axisymmetric NBI simulations have been carried out for JT-60 SA inductive H-mode scenario at low Greenwald density fraction. The fast ions birth profile has shown to be peaked to the edge for P-NBs and peaked around ρ~0.25 and ρ~0.6 for N-NBs. The shine-through has resulted negligible. For slowing-down simulations, the ions heating is given mostly from P-NBs while for electrons the N-NBs contribute the most. The energies used are such that the N-NBs induce the majority of the current in the plasma. The P-NBs contribution both to current and to torque is compensated because of the injection geometry. Trapped-passing orbits boundary effects and particle losses are mostly given from counter-injected P-NBs (as expected) and the overall losses are around 3%. The foreseen work includes analysing the fast ion distribution function to study the stability of MHD modes in presence of fast particles. In addition, cases with carbon impurities and beam energy modulation will be carried out.

Acknowledgment This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] Y. Kamada et al., Nucl. Fusion **51** (2011) 073011

[2] H. Shirai et al., Fusion Eng. Des. 109–111 (2016) 1701.

[3] JT-60SA Research Plan, http://www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf, v3.3, Mar. 2016.

[4] O. Asunta et al., Comput. Phys. Commun. **188** (2015) 33-46

[5] E. Hirvijoki et al., Comput. Phys. Commun. **185** (2014) 1310 –1321

[6] ADAS, Atomic data and analysis software, http://www.adas.ac.uk/

[7] J. Garcia et al, Nucl. Fusion **54** (2014) 093010