Simulating beam ion charge exchange in MAST-U

P. Ollus[1], J. Varje[1]*, D. Keeling[2], R. Akers[2], R. Sharma[2], A. Snicker[1],
T. Kurki-Suonio[1], the MAST Upgrade Team and the EUROfusion WPTE Team
[1] *Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland*
[2] *Culham Centre for Fusion Energy, Abingdon, UK*
* Current affiliation: *Tokamak Energy Ltd., 173 Brook Dr, Milton Park, Abingdon, UK*

Abstract

Atomic processes were implemented in the orbit-following code ASCOT for simulating fast-ion charge exchange (CX) in magnetically confined fusion plasmas. The model was verified by reaction mean free path estimation and agrees with TRANSP to within 20% on CX losses. ASCOT predicts that 22% of beam power is lost due to CX in a MAST-U target scenario. While plasma heating and current drive are decreased towards the edge, CX is predicted to increase current drive closer to the core. Peak wall power loads of 60–90 kWm^{-2} are estimated on the central poloidal field coils and the vacuum vessel between them.

Introduction

Charge-exchange (CX) reactions with background atoms caused significant beam-ion losses in MAST, and the same is expected in MAST-U [1, 2]. In addition to the loss of heating power and current drive, the escaping fast particles can damage sensitive plasma-facing components and cause impurity sputtering and wall erosion.

To enable simulation of fast-ion CX, the orbit-following code ASCOT [3] was equipped with a model for atomic processes [4]. The near-optimal scaling of ASCOT on supercomputers combined with its full gyro-orbit following capabilities allows for high-fidelity simulation of fast-ion populations in high-∇B geometries such as the spherical MAST-U tokamak. As markers, charged or neutral, are followed all the way to an arbitrarily detailed 3D wall representation, global and localized wall power loads can be estimated.

Implementation and verification of the atomic processes model

An atomic processes model for fast ions was implemented in the orbit-following code ASCOT. Neutralization of hydrogenic fast ions by CX with background atoms is modelled based on fundamental cross-section data from the ADAS database [5]. Upon their neutralization, markers are followed ballistically until they are reionized or hit the wall. Reionization is modelled using effective beam-stopping coefficients from ADAS. If the fast-particle energy or plasma or atomic density or temperature are outside the domain of the atomic data, linear extrapolation is used.

The atomic processes model was verified by estimation of reaction mean free paths. The CX neutralization of fast deuterons and the ionization of fast deuterium atoms were simulated in a pure deuterium plasma, with Coulomb collisions turned off to conserve particle energy and constant plasma and atomic density and temperature profiles. Each mean free path was estimated using 100 000 simulated markers and compared to the analytical mean free path, $d_{MFP} = u/\mathscr{R} = u/(\langle\sigma v\rangle n)$, where u is the fast-particle speed, $\mathscr{R}$ the reaction rate, $\langle\sigma v\rangle$ the rate coefficient and n the bulk density. All estimates matched the analytical mean free paths across a range of fusion-relevant fast-particle energies and bulk-particle densities and temperatures.

Simulating beam ion charge exchange in a MAST-U target scenario

ASCOT was used to simulate beam ions slowing down in the MAST-U high-density target scenario A.1, with a 1.0 MA plasma current and on- and off-axis beams with a combined power of 5.0 MW [6]. Scenario data was extracted from simulation number 99999I38 with the transport code TRANSP [7], at the steady-state time point 5.7 s. Due to current limitations of ASCOT, a pure deuterium atomic background at the ion temperature was assumed. The atomic density used was the sum of the deuterium and hydrogen densities that constitute the atomic background in TRANSP. The atomic density ranges from $1.5 \cdot 10^{13}$ to $5.0 \cdot 10^{17}$ m^{-3}. The highest density is reached at the separatrix and extrapolated constantly to the scrape-off layer. A considerable caveat in this analysis is that the atomic background is assumed poloidally uniform.

ASCOT reproduced the beam-ion behaviour that TRANSP predicted, as shown in Fig. 1, which compares the simulated beam-ion slowing-down distributions as functions of the normalized poloidal flux ρ_{pol}. Between $\rho_{\mathrm{pol}} = 0.1$ and 0.8, the ASCOT prediction for the beam-ion density is within 5% of that of TRANSP. Outwards, the ASCOT prediction is up to 30% lower. However, the absolute density is low and the impact of CX high close to the edge. Since ASCOT and TRANSP agree on the general behaviour of the beam ion ensemble in the plasma, comparison specific to the effects of CX is possible. ASCOT and TRANSP agree to within 20% on the CX-induced loss of beam power.

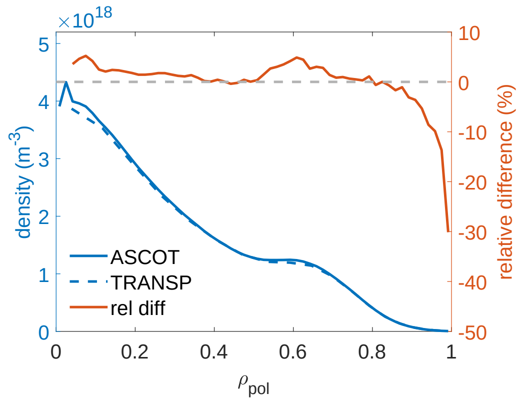

Figure 1: *Simulated slowing-down profiles of beam ions in MAST-U.*

ASCOT predicts that 1.1 MW, or 22% of the captured beam power is lost due to CX. Since the CX process is sensitive to the background atomic density, the simulation was repeated with varied densities to gauge how uncertainty in the assumed density cascades into uncertainty in the impact of CX. The dependence of the simulated CX-induced beam power loss on the atomic density is shown in Tab. 1.

Table 1: *CX-induced beam power loss for various proportional atomic density profiles. Change relative to the target scenario in parenthesis.*

atomic density	60%	80%	100%	120%	140%
beam power loss	20.0% (-11%)	21.7% (-2.6%)	22.3%	23.8% (+6.5%)	24.2% (+8.6%)

The reduction in heating, i.e., deposition of power from beam ions to bulk electrons and ions, is estimated to be less than 10% inside $\rho_{\text{pol}} = 0.6$. Outwards, the reductions in both heating and current drive grow rapidly, reaching maxima of 80% at the separatrix. However, inside $\rho_{\text{pol}} = 0.6$, CX is predicted to increase the current drive, with a maximum increase of 20% at $\rho_{\text{pol}} = 0.5$, as shown in Fig. 2. This increase is explained to result from beam particles that are CX-neutralized close to the separatrix and transported inwards. If these CX atoms are reionized on the low-field side, the strong ∇B drift enables contribution to current drive even deeper in the plasma on the high-field side. The total current drive is estimated to be 130 kA, 13% lower than it would be in the absence of CX.

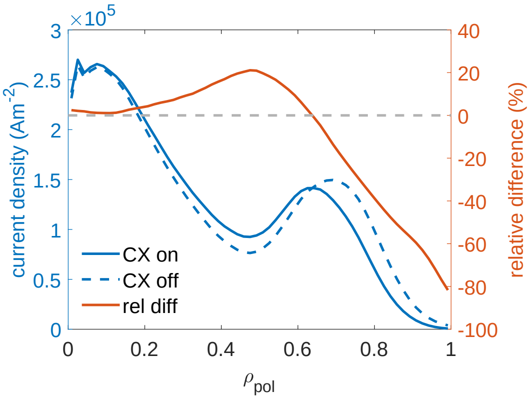

Figure 2: *Electron-shielded beam-ion current drive simulated by ASCOT in MAST-U.*

To estimate the power loads on the MAST-U wall from beam particles lost due to CX, a detailed 3D wall representation consisting of 7 million triangles was used. To match the marker ensemble to the resolution of the wall, each marker was split into 30 identical markers, increasing the number of markers from 19 536 to 586 080. While charged particles escaping the plasma are channeled to the divertor, CX atoms penetrate the magnetic field and reach other wall regions. The deposition of CX atoms on the wall depends on their birth distribution. Due to the strong ∇B drift, the large Larmor radii in the weak outboard field and the peaked atomic density, the birth rate of CX atoms is concentrated in the outer scrape-off layer, peaked around the midplane. This birth distribution is reflected in the power deposition on the wall, partially visible in Fig. 3, which shows the wall power loads on a sector of the simulated 3D wall. The wall deposition is concentrated on the central poloidal field coils and the vacuum vessel between them. The estimated peak power loads on the upper central poloidal field coil, the vacuum vessel between the central coils and the lower coil are 70, 60 and 90 kWm^{-2}, respectively. Above the upper coil and below the lower coil, the power loads on the vacuum vessel are less than 4 and less than 7 kWm^{-2}, respectively. There is more deposition on the bottom half of the tokamak, explained by the orientation of the particle orbits and the plasma shape.

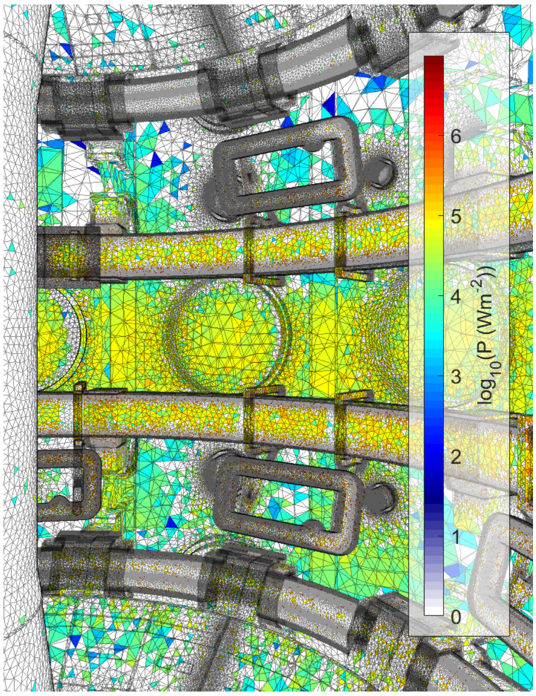

Figure 3: *Beam-ion power loads estimated by ASCOT on a sector of the MAST-U wall.*

Summary and future work

To enable the simulation of fast-ion CX in ASCOT, an atomic processes model was implemented and verified by estimating reaction mean free paths. ASCOT was used to simulate beam ions slowing down in a MAST-U target scenario. The CX-induced loss of beam power was estimated at 22%, which was in agreement with TRANSP to within 20%. Due to CX, plasma heating and current drive were decreased by up to 80% towards the edge. However, the current drive was increased by up to 20% closer to the core, leaving the reduction in total current drive at 13%. The simulated wall deposition was concentrated around the outer midplane, with peak power loads of 60–90 kWm^{-2} on the central poloidal field coils and the vacuum vessel between them.

Next, the transition will be made to 2D atomic background data. The ASCOT CX model will be validated using the FIDASIM [8] code to compare predictions of the beam-ion distribution function to fast-ion deuterium-α spectroscopy measurements in MAST-U.

References

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