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Effect of 3D magnetic perturbations on NBI ion confinement in the European DEMO

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Abstract. Fast ion losses due to 3D perturbations such as toroidal ripple can result in localized power loads on the first wall. Due to power plant and tritium breeding requirements, the allowable loads on the plasma facing components of the DEMO reactor will be a factor of 2-5 times lower than in ITER, while the NBI power will be 50 % higher. NBI simulations for the European EU DEMO1 2015 concept have been performed in a realistic 3D geometry using the Monte Carlo orbit-following code ASCOT. The 3D perturbations include the toroidal ripple and the ripple-mitigating ferritic inserts, calculated with COMSOL, while the NBI injectors were based on the latest 800 keV modular design. The beam ion confinement was found to be good, with NBI power losses remaining below 0.3% and wall loads below 20 kW/m^2 in all cases. The ferritic inserts effectively mitigated the toroidal ripple, reducing the losses nearly to the level of an axisymmetric field.

1. Introduction

The European DEMO design EU DEMO1 2015 [1] is planned to include up to 51 MW of external NBI heating. Good confinement of these particles is necessary not only for efficient heating and current drive, but also for machine protection.

Non-axisymmetric magnetic perturbations, such as toroidal ripple due to the finite number of toroidal field coils, increase fast particle transport and losses, which can result in localized heat loads on the plasma facing components [2, 3, 4]. Previous studies for ITER have shown that the power fluxes onto the wall can be substantial, reaching values greater than 100 kW/m^2[5]. Due to the tritium breeding blanket and power exhaust requirements, the peak power loads on the DEMO wall should not exceed 1 MW/m^2 [6], a factor of 2-5 lower than that for the ITER first wall. This includes heat loads not only due to fast ions, but also thermal particle and radiative heat fluxes. Thus detailed modelling of fast ion losses in a realistic geometry is vital to ensure that the design is consistent with these engineering requirements.

NBI ion confinement has previously been studied for an earlier iteration of the DEMO design using the orbit-following code ASCOT [7]. These simulations assumed an axisymmetric, simplified geometry and NBI injectors based on the 1 MeV ITER design. The EU DEMO 2015 features a lower-energy 800 keV injector, which has also previously been studied from the point of view of plasma performance in an axisymmetric case [8]. Thus it is important to study the NBI performance with a realistic geometry and injector design in support of the overall DEMO design effort.

In this contribution we use ASCOT to study the NBI ion losses during the flat-top phase in the European EU DEMO1 2015 design due to 3D magnetic perturbations, including the toroidal ripple and ferritic inserts, with the latest DEMO NBI injector design. The second section describes the models used for the plasma equilibrium, magnetic field geometry and first wall, contrasting these with the equivalent ITER parameters. The third section presents simulation results for the NBI ion confinement and wall loads. Finally, in the fourth section the implications of the results on the DEMO design are discussed.

2. DEMO model and simulation configuration

The NBI ion losses were simulated using the Monte Carlo orbit following code ASCOT[10]. The code follows markers representing a fast ion population in a realistic 3D magnetic field and geometry. The markers are followed until they slow down to 1.5 times the local plasma temperature, at which point they are considered thermalized, or until they impact the wall. Guiding center approximation is used until the particles approach within one Larmor radius of the wall, at which point full gyro orbits are simulated to precisely assess the point of impact on the wall.

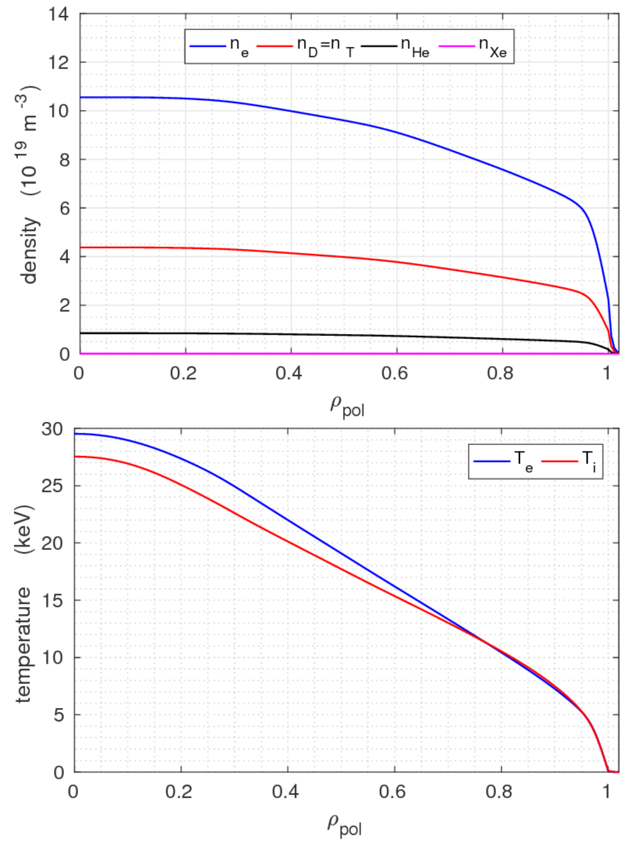

Figure 1. ASTRA-based plasma density (left) and temperature (right) profiles used in the simulations.

The plasma equilibrium and kinetic profiles (figure 1) are based on CRONOS and ASTRA[11] simulations, with a central density of 10.5·10^{19} m^{-3} and central electron and ion temperatures of 29.5 and 27.5 keV, respectively. The profiles assume a 50-50 mixture of deuterium and tritium, with approximately 8% helium ash and 0.02% Xenon impurity concentration. Extrapolated profiles in the scrape-off layer are included, corresponding to a SOL density e-folding length of 16 mm. The finite SOL density allows simulation of NBI particles ionized outside the last closed flux surface (LCFS), which can be rapidly lost due to the unconfined field lines and the proximity to the wall.

The NBI ions were initialized using the beamlet-based Monte Carlo neutral beam code BBNBI[12], which follows the ballistic trajectories of the injected neutral atoms from individual beamlets until they are ionized. The implemented injector geometry was based on the latest DEMO reference design, which consists of

20 modular negative ion sources in two columns with 60 beamlets each [13]. The injection energy is 800 keV and the total power is 16.8 MW per injector. Three injectors are located in adjacent toroidal sectors 20 degrees apart. Simulations were performed for a single NBI injector, and the results were toroidally cloned for the other injectors to represent the full geometry.

The EU DEMO1 2015 design features 18 superconducting toroidal field (TF) coils. A high-resolution TF ripple was calculated using the BioSaw code [14], which integrates the magnetic field using the Biot-Savart law based on a realistic coil geometry. The toroidal ripple reaches a value of 0.8 % near the outer midplane, falling to 0.01 % at the magnetic axis (figure 2). While the magnetic field and the TF coils are larger in DEMO compared to ITER, the ripple perturbations within the plasma volume are smaller than the corresponding ITER values of 1.1% and 0.015 %. This is due to the favourable plasma position on the high field side combined with a larger standoff to the coils themselves.

Ferritic inserts (FI), structures of ferritic material located near each TF coil on the low field side, are planned to be used for mitigating the ripple introduced by the finite number of TF coils. The magnetic perturbations due to the ferritic inserts were calculated using the finite-element solver COMSOL. This approach has previously been applied to similar studies in ITER [15, 5]. First, the magnetization of the FI's due to the toroidal field coils and plasma current were calculated. The magnetization was then used to calculate the 3D perturbations within the plasma volume, which was added to the axisymmetric equilibrium field and the TF ripple.

To assess the distribution of particle and energy fluxes on the first wall, a 3D wall mesh was implemented based on a CAD design of the DEMO wall structure. To improve resolution, each flat tile surface was divided into smaller segments, with the final wall model consisting of approximately 200 000 triangles in total. Due to the 18-fold symmetry of both the wall and the 3D magnetic field, the losses were remapped into a single 20 degree sector to improve the statistics for estimating the peak loads.

3. Fast ion losses

Fast ion loss simulations were performed for three cases: axisymmetric field, unmitigated ripple and ferritic insert configuration. The first case includes only an unperturbed equilibrium field. The second case adds the unmitigated TF ripple, while the ferritic insert configuration also includes the ripple-mitigating ferritic inserts.

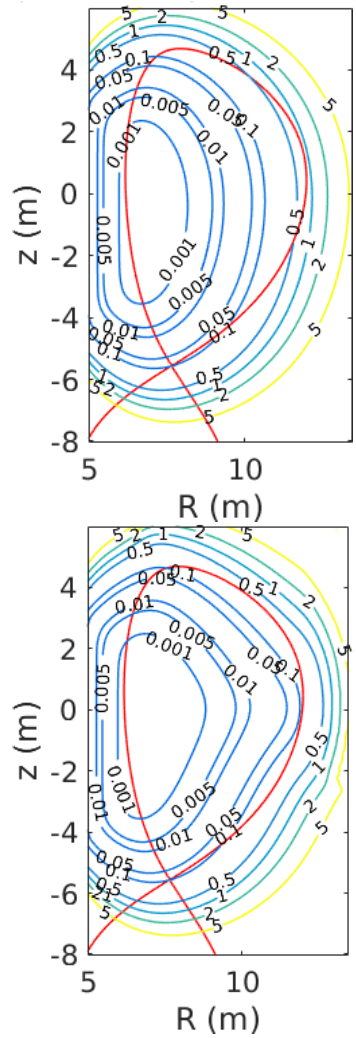

Figure 2. Average relative toroidal ripple $(\max B_\phi - \min B_\phi)/(\max B_\phi + \min B_\phi)$ contours in % for unmitigated ripple field (left) and with ferritic inserts (right).

3.1. NBI birth profiles

First, simulations were performed for all cases with 100 000 markers to evaluate the fast ion density and heating and current drive profiles. After this, larger simulations were performed to improve the statistics on the wall load estimates. In the earlier simulations, losses were observed only for particles originating outside normalized radial coordinate $\rho_{pol} > 0.6$. Thus for wall load simulations only approximately 500 000 markers born outside this surface were used. While the beam particles are able to penetrate to the magnetic axis and beyond, the number of ionized particles peaks near the edge of the plasma (figure 3). This is due to the high pedestal density combined with the 800 keV beam energy. However, the shine-through losses are negligible for the same reasons [8]. Particles ionized outside approximately $\rho pol > 0.73$, corresponding to

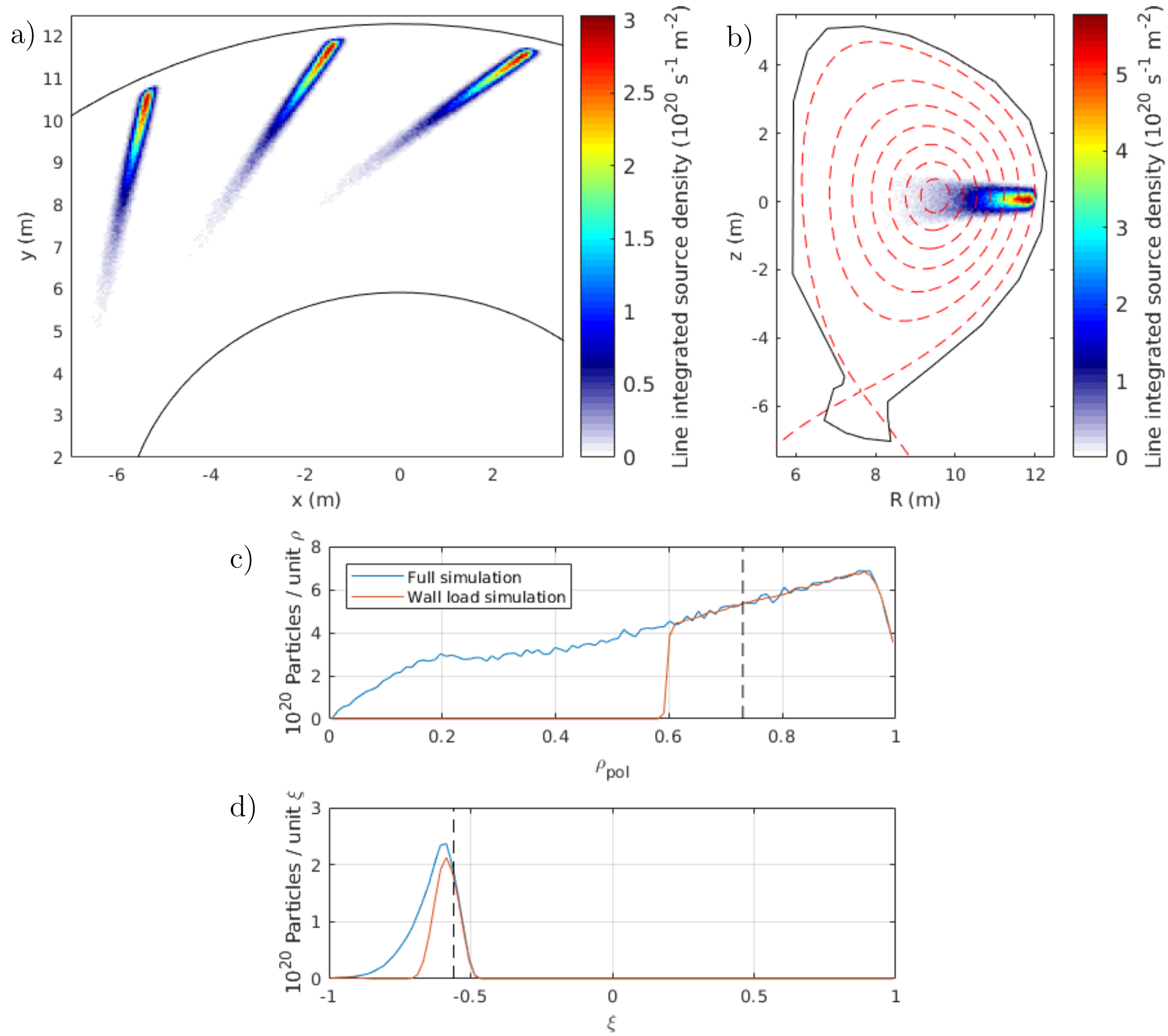

Figure 3. Integrated NBI source density in (a) top-down view, depicting the locations of the injectors, and (b) in the poloidal plane, illustrating the beam penetration. The density as a function of (a) radial coodinate $\rho_{pol} = \sqrt{(\psi - \psi_0)/(\psi_{sep} - \psi_0)}$ and (b) initial pitch $\xi = v_{\parallel}/v$ (bottom). Approximate boundary between passing and trapped particles is indicated with the dashed line. Particles born outboard of this line are born on trapped orbits.

Table 1. NBI ion losses for the axisymmetric 2D equilibrium, unmitigated ripple and ferritic insert configurations.

	NBI losses
2D equilibrium	< 1 kW
Unmitigated ripple	49 kW
Ripple + ferritic inserts	1 kW

$|\xi| < 0.56$, become trapped on banana orbits, while particles deeper inside are born on passing orbits.

3.2. Overall confinement

The confinement of the NBI ions was found to be excellent in all cases, with losses of less than 0.3% of total injected power even in the unmitigated ripple configuration (table 1). Including the ferritic inserts further reduces the losses to 2 kW, nearly to the level of the unperturbed axisymmetric case.

The losses have negligible effect on the fast ion density, power deposition and beam driven current (figure 4). Total current driven by the 3 beams is approximately 0.96 MA, while the total torque is approximately 75.5 Nm. A drop in torque is observed at the edge of the plasma in the unmitigated ripple due to the $j \times B$ torque caused by the lost particles. With the ferritic inserts, the torque at the edge is restored, but additionally the total torque is slightly increased. This is due to the poloidally asymmetric FI perturbations, which has the effect of slightly increasing the mean poloidal magnetic field, and thus

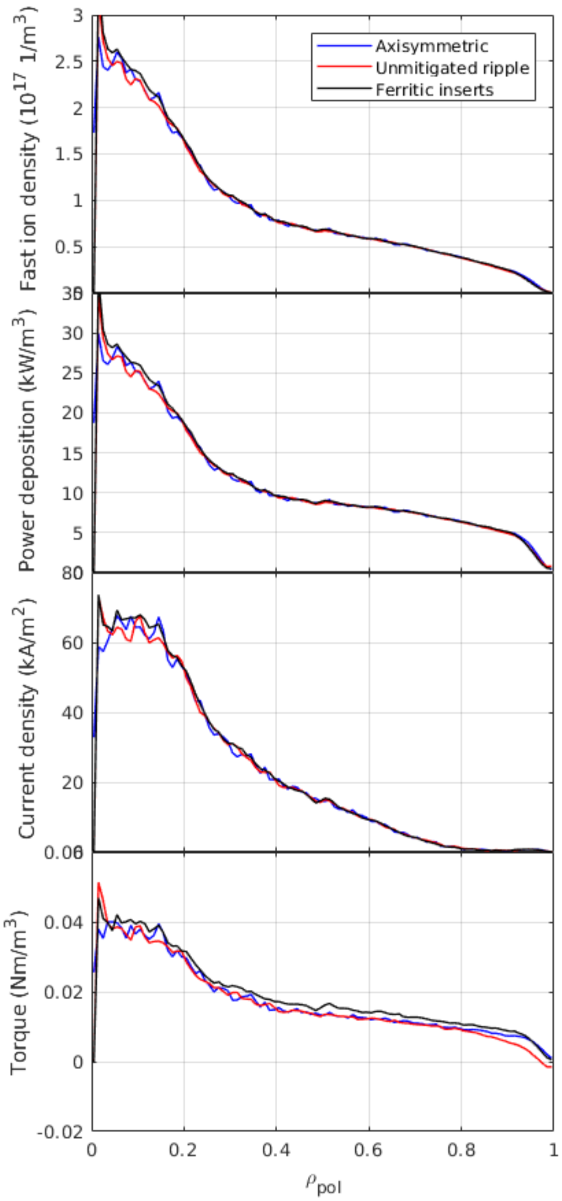

Figure 4. NBI ion slowing down density, current density, power deposition and torque with axisymmetric, unmitigated ripple and ferritic insert configurations for a single injector.

the $j \times B$ torque, along part of the particle orbit (figure 5).

3.3. Loss mechanisms and wall loads

In the unmitigated ripple case, the NBI ion losses are primarily concentrated on the outer midplane and the divertor (figure 6). Additionally, some particles impact the wall near the top of the machine, while some are lost to the baffle at divertor entrance. The losses on the main chamber wall correspond to locations where the distance between the LCFS and the wall are smallest. The losses at the outer midplane are

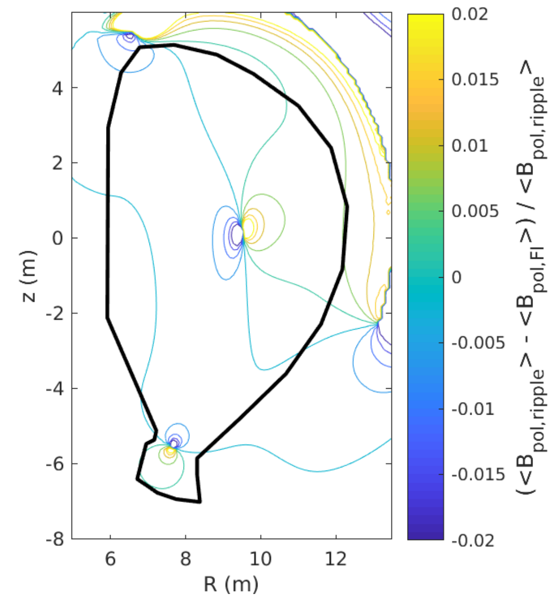

Figure 5. Relative difference in poloidal magnetic field between the unmitigated ripple and ferritic insert cases. The mean poloidal field is increased with FIs in a significant fraction of the plasma volume.

eliminated with the inclusion of FI's. The peak wall loads remain below 20 kW/m^2 even in the unmitigated ripple configuration.

The majority of NBI ions are born close to the edge of the plasma due to the 800 keV injection energy and high density. However, first orbit losses are nearly non-existent: all lost particles have already slowed down considerably (figure 7) and take a minimum of 10^{-3} s to reach the wall. The losses at the top of the machine and the two tiles at and above the outer midplane have similar pitch distribution, peaking around $\xi = -0.2$. These are ripple-enhanced diffusive losses of deeply trapped banana orbits.

The losses below the outer midplane and at the divertor baffle are concentrated around pitch $\xi = 0$, suggesting the losses in this region are due to local ripple well trapping. However, the particles have already slowed down to energies below 400 keV before becoming trapped and rapidly transported downwards to the wall by the ∇B drift.

Finally, the losses in the divertor region are concentrated near thermal energies, indicating these are primarily diffusive losses from deeper inside the plasma.

4. Summary and discussion

Despite the increased power and stricter engineering constraints for first wall power loads in the European DEMO design compared to ITER, NBI ion losses are not expected to pose a concern to the integrity of

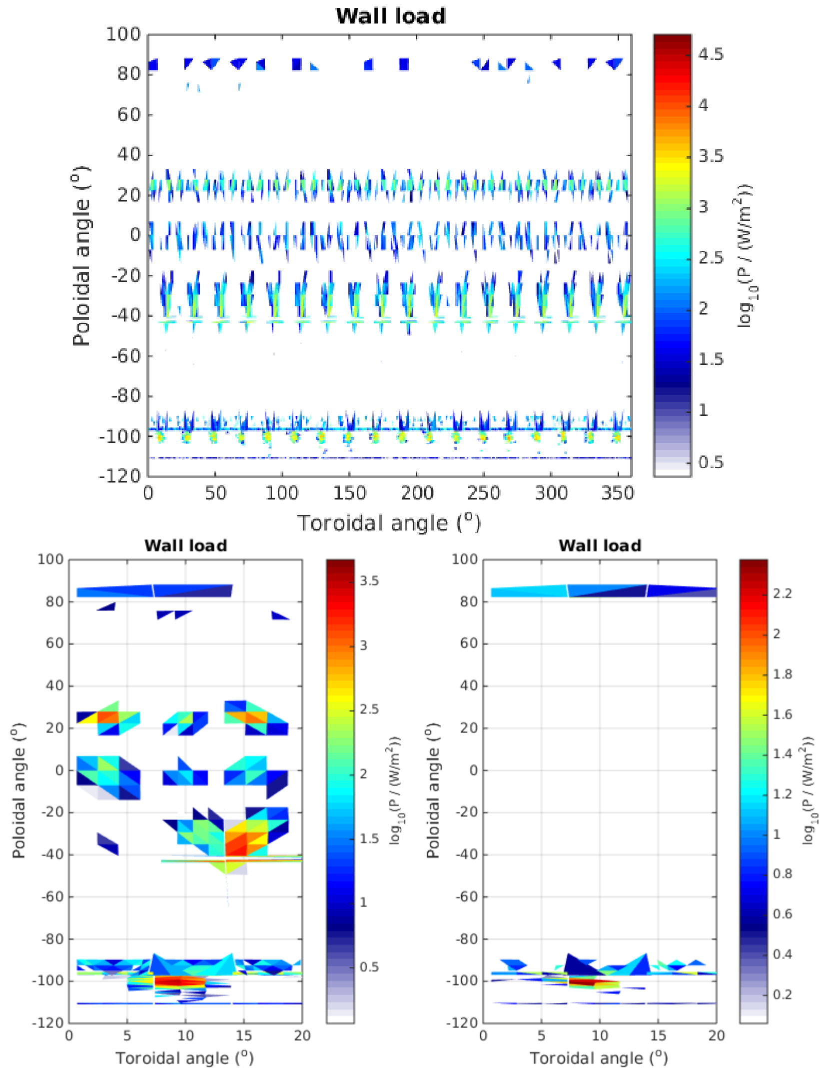

Figure 6. Wall power loads in the unmitigated ripple case (top), remapped into a single 20^o sector to improve statistics (bottom left) and the wall loads in the ferritic insert case (bottom right).

the plasma facing components. Based on 3D ASCOT simulations, total losses remain below 0.3% of the injected power of 50 MW, and peak wall loads do not exceed 20 kW/m^2 even with unmitigated toroidal field ripple perturbations. This is well below the engineering limits of 1 MW/m^2. The ripple-mitigating ferritic inserts reduce the losses nearly to the level of unperturbed axisymmetric field. Heating and current drive efficiency was not found to suffer from the perturbations.

Features aiding the NBI confinement in DEMO include a favourable coil geometry, where the plasma is located on the high field side of the coils, reducing the maximum TF ripple within the plasma volume to 0.8% compared to ITER values of 1.1%. Additionally, the shallow pedestal density profile allows deeper beam penetration despite the reduced NBI energy of 800 keV compared to ITER injection energy of 1 MeV. Combined with a larger standoff distance between the last closed flux surface and the first wall, this minimizes prompt high-energy losses. Instead, the losses are due to ripple-enhanced diffusion, with the strike locations in some cases affected by local ripple well trapping.

Based on the simulation results, NBI ion losses in the European DEMO are not a concern for machine protection or plasma performance during flat-top operation. The good confinement with unmitigated ripple suggests that the ferritic inserts may not even be needed from the point of view of NBI ion confinement. However, these simulations assume only perturbations due to the toroidal field ripple and ferritic inserts in the vacuum approximation. Other perturbations, such as mitigation of edge localized modes with resonant magnetic perturbations imposed with external ELM control coils (ECC) can dramatically increase the losses. In previous simulations for ITER the losses

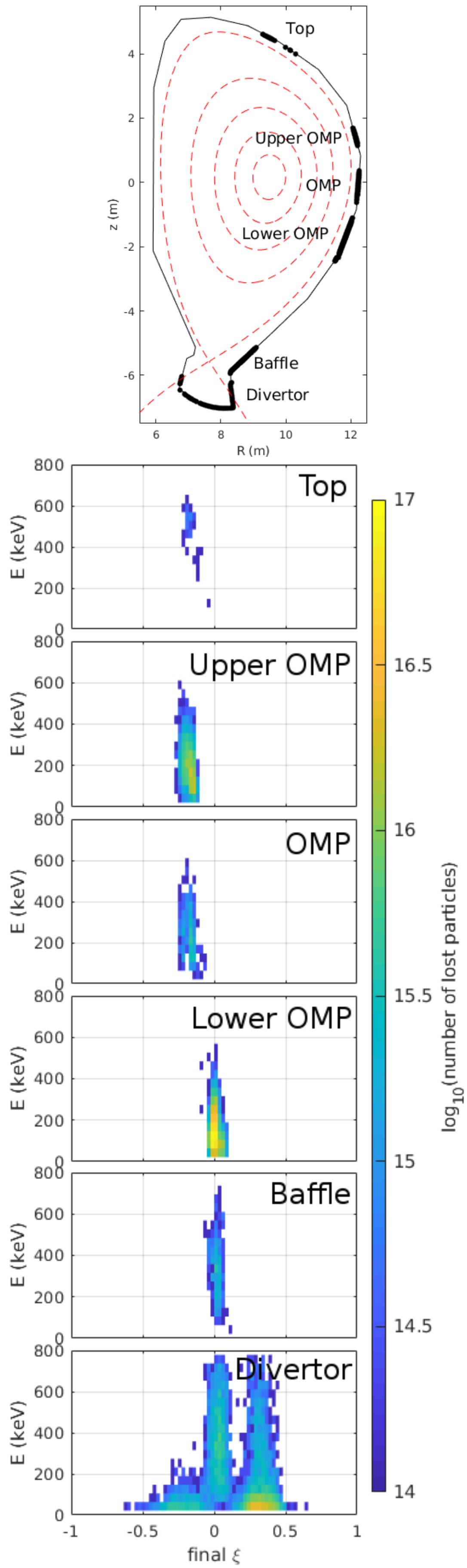

Figure 7. Pitch-energy distribution of the lost particles in each loss domain, corresponding to the strike points depicted in the poloidal plane (top). Flux surfaces and separatrix are depicted with dashed red lines.

have been observed to reach up to 4% of the injected power. Furthermore, the response of the plasma to the external perturbations can change and redistribute the losses [16]. These simulations can be performed for DEMO once a conceptual design of the ECCs is available.

Finally, the simulations assume only neoclassical transport in a quiescent plasma with no sawtooth, NTM, TAE or other fast particle instabilities. While the plasma performance required in DEMO does not allow for significant instabilities, these can redistribute the fast ions and possibly increase the losses. Simulations with these perturbations will follow once the DEMO design is converged and detailed plasma simulations become relevant.

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