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

J. Varje[1], P. Agostinetti[3], T. Kurki-Suonio[1], A. Snicker[2], P. Sonato[3], K. Särkimäki[1],
F. Villone[4], P. Vincenzi[3]

[1] *Department of Applied Physics, Aalto University, FI-00076 AALTO, Finland*

[2] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

[3] *Consorzio RFX Corso Stati Uniti 4 - 35127 Padova, Italy*

[4] *Università di Cassino, Viale dell'Università, 03043 Cassino, Italy*

The current European DEMO design, with a fusion power of 1.8 GW and up to 51 MW of external NBI heating, will produce copious amounts of energetic particles both in 3.5 MeV fusion-born alphas as well as 800 keV NBI ions. Good confinement of these particles is necessary not only for efficient heating and current drive, but also for machine protection. Losses introduced by 3D magnetic perturbations such as the toroidal ripple can result in localized heat loads on the first wall. However, due to the tritium breeding blanket and power exhaust requirements, the peak loads on the DEMO wall should not exceed 1 MW/m^2 [1]. Thus detailed modelling of fast ion losses in a realistic geometry is required to ensure that the design is consistent with these engineering requirements.

The European DEMO design features 18 superconducting toroidal field (TF) coils. Additionally, ferritic inserts (FI) will be used to mitigate the ripple introduced by the finite number of coils. A high-resolution TF coil ripple field was calculated using the BioSaw code [2], which integrates the Biot-Savart law based on a realistic coil geometry. The perturbations due to the ferritic inserts were calculated using the finite-element solver COMSOL. 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 (Figure 2). This approach has previously been applied to similar studies in ITER [3]. In addition to the full FI model, also cases with reduced FI mass were calculated to assess the effectiveness of the ripple mitigation.

The fast ion losses were simulated using the Monte Carlo orbit following code ASCOT, which follows test particles representing the fast ions until they are thermalized or are lost. The guiding center approximation is used until the particles approach close to the wall, at which point the full gyro orbits are simulated to precisely assess the point of impact on the wall.

The fusion alpha test particles were initialized using the ASCOT Fusion Source Integrator AFSI [4], which calculates the thermonuclear fusion alpha production based on the Bosch-Hale parametrisation. The NBI ion test particles were initialized using the beamlet-based Monte

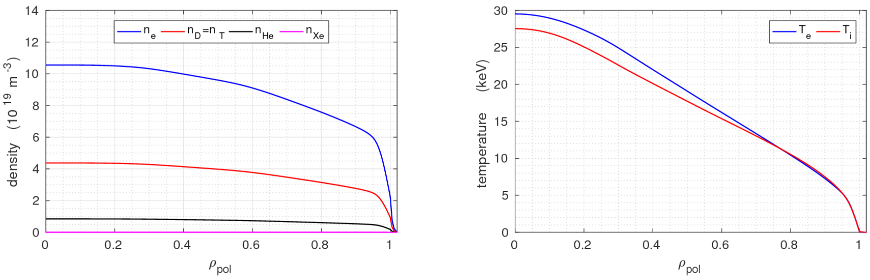


Figure 1: Predicted plasma density (left) and temperature (right) profiles used in the simulations.

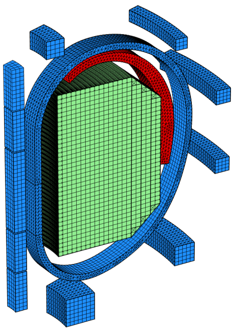
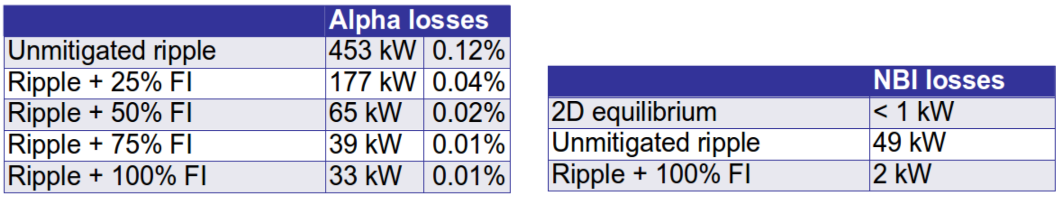


Figure 2: COMSOL mesh for magnetic field calculations with coils (blue), ferritic inserts (red) and plasma volume (green).

Carlo neutral beam code BBNBI[6]. The NBI model was implemented based on the latest DEMO reference design, with an injection energy of 800 keV and power of 16.8 MW per injector [7]. The geometry consists of 20 injector modules in two columns with 60 beamlets each. The fusion alpha losses were simulated with an ensemble of 400 000 test particles, while 100 000 test particles were used to simulate the losses from a single NBI injector.

To assess the loads on the first wall, a 3D wall mesh was implemented based on a CAD design of the DEMO wall structure. To improve resolution, each wall tile was divided into smaller segments, with the 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.



	Alpha losses	
Unmitigated ripple	453 kW	0.12%
Ripple + 25% FI	177 kW	0.04%
Ripple + 50% FI	65 kW	0.02%
Ripple + 75% FI	39 kW	0.01%
Ripple + 100% FI	33 kW	0.01%

	NBI losses
2D equilibrium	< 1 kW
Unmitigated ripple	49 kW
Ripple + 100% FI	2 kW

Figure 3: Fusion alpha losses (left) and NBI ion losses for a single 16.8 MW injector (right) in different magnetic field configurations.

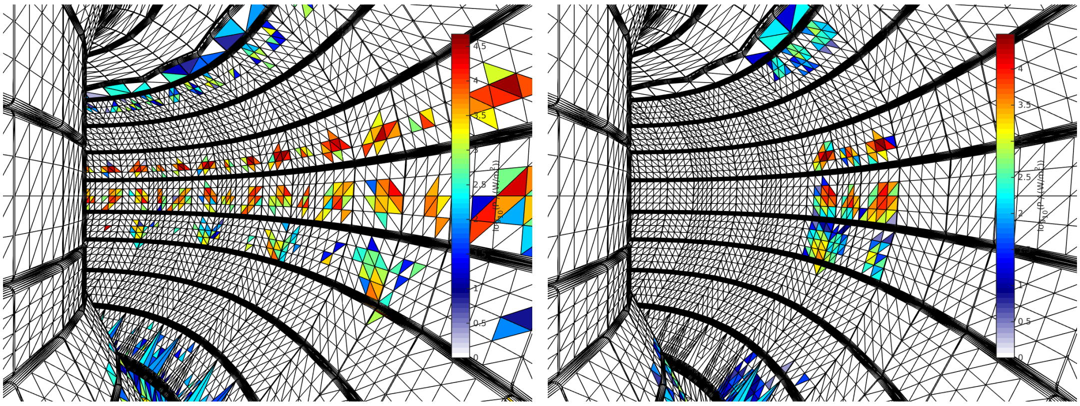


Figure 4: Wall loads in the unmitigated ripple case (left) and with the wall strikes remapped into a single 30^o sector to improve statistics (right).

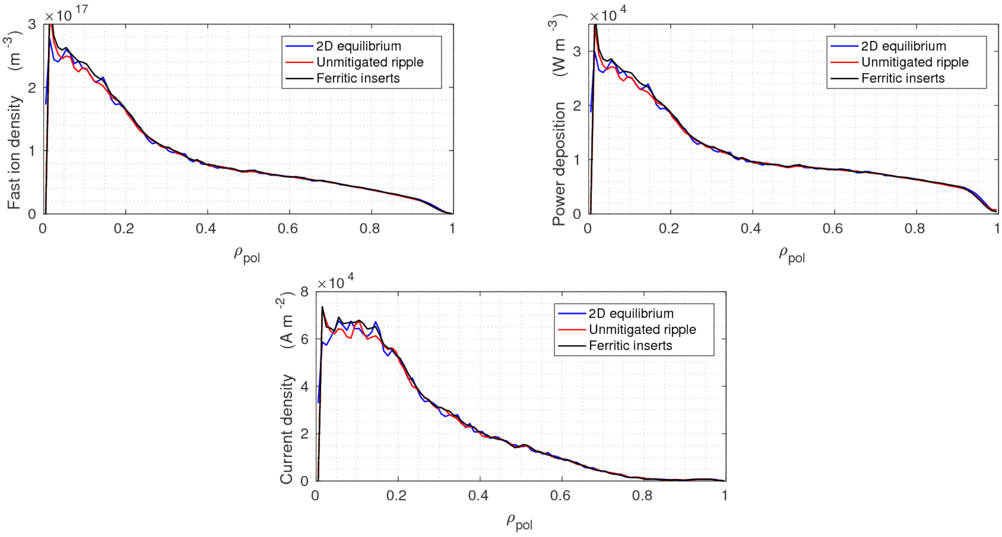


Figure 5: NBI ion density (left), current density (right) and power deposition with axisymmetric, unmitigated ripple and 100% ferritic insert mass configurations for a single injector.

Fusion alpha confinement was found to be good in all cases (Figure 3, left). Even with the unmitigated ripple, losses remained below 0.12% of total alpha power. Introducing the ferritic inserts reduces the losses by an order of magnitude, and already at 50% of the FI mass the losses are reduced by more than 80%. The fusion alpha losses are concentrated on the outer midplane of the wall, with peak loads remaining below 100 kW/m^2 even in the unmitigated ripple configuration.

The confinement of the NBI ions was likewise found to be good, with losses less than 0.3% in the unmitigated ripple configuration (Figure 3, right). Including the ferritic inserts further reduces the losses nearly to the level of unperturbed axisymmetric field. The losses have negligible effect on the fast ion density or the power deposition and current drive (Figure 5).

Based on the simulations, the fast ion losses in the European DEMO do not present a threat to the first wall. Additionally, ferritic inserts even with 50% reduced mass were found to reduce the losses by nearly an order of magnitude. However, the simulations assume only perturbations due to the toroidal ripple and ferritic inserts in the vacuum approximation. Inclusion of further perturbations such as resonant magnetic perturbations using ELM control coils can dramatically increase the losses, requiring further studies that also include the effect of the plasma response [8].

Acknowledgements

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. This work was carried out using the HELIOS supercomputer system at International Fusion Energy Research Centre, Aomori, Japan, under the Broader Approach collaboration between Euratom and Japan, implemented by Fusion for Energy and JAEA. The supercomputing resources of CSC - IT centre for science were utilized in the studies. Some of the calculations were performed using computer resources within the Aalto University School of Science 'Science-IT' project.

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