Spatial distribution of ITER runaway electron wall loads in the presence of 3D magnetic perturbations

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Introduction Disruptions in large tokamaks can lead to the generation of a relativistic runaway electron beam that may cause serious damage to the first wall. The avalanching effect increases the number of runaways exponentially, reaching currents up to several megaamperes in a large tokamak. The uncontrolled loss of such a high energy electron beam is intolerable and therefore the issue of how to avoid or mitigate the beam generation is of prime importance for ITER. As a possible way to help suppressing the primary seed of runaway electrons the application of resonant magnetic perturbations (RMP) has been suggested. The ITER ELM mitigation coils can, in principle, be used for runaway mitigation purposes [1]. Earlier theoretical [2] and numerical [3] work suggested that runaway losses already in the early phase of the disruption are greatly enhanced in the regions where the normalized perturbation amplitude is higher than $\delta B/B \simeq 10^{-3}$. This applies to the region outside the radius corresponding to the normalised toroidal flux $\psi = 0.5$ in ITER [1]. Increasing the runaway losses at low energies is desirable, however, localised heat loads are better to be avoided. In this work we investigate the effect of RMP on the spatial distribution of the RE wall loads by simulating the RE drift orbits in magnetostatic perturbed fields and calculating the transport and orbit losses for various initial particle parameters and different magnetic perturbation configurations.

Modelling We solve the relativistic, gyro-averaged equations of motion for the runaway electrons including the effect of collisions, synchrotron- and Bremsstrahlung radiation with the ANTS code [3]. The simulations are based on the ITER scenario #2 (15 MA inductive burn) [4]. Inductive scenarios are expected to produce the largest and most energetic populations of runaway electrons. In the simulations a cold (10 eV [5]) post-disruption equilibrium is used, calculated with VMEC, based on plasma parameters obtained by simulations with the ASTRA code [4]. Since the complete 3D model of the first wall is currently unavailable, a particle is considered lost when it crosses the unperturbed equilibrium separatrix. The time-dependent electric field accelerating the runaways was modelled after an ITER-like disruption scenario taking into account the coupled dynamics of the evolution of the radial profile of the current density (including the runaways) and the resistive diffusion of the electric field [6]. We neglect the effect of shielding of magnetic field perturbations by plasma response currents. This approximation is expected to be valid in cold post-disruption plasmas. The perturbed magnetic field is obtained by superimposing the field from the perturbation coils on the field of the unperturbed VMEC solution. The ELM perturbation coil-set consists of 9×3 quasi-rectangular coils at the low field side, that allows for a wide variety of possible current configurations, out of which four $n=3$ were chosen for further investigation [1]. The configurations have identical perturbation strength, but due to the current flowing in different directions in the various coils, these can give rise to quite different magnetic structures, and hence, different loss enhancement. As an example, configuration "B" is shown in figure 1: black coils have clockwise-, red coils counter clockwise current.

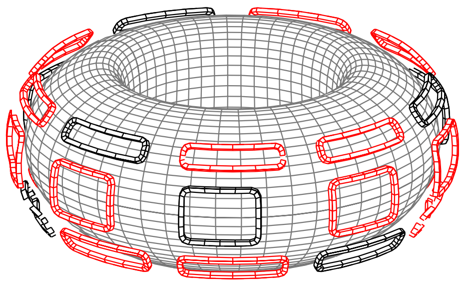

Figure 1: *Configuration $n=3$ "B".*

Transport in the perturbed field In the perturbed case the ergodic zone arising at the edge causes losses several orders of magnitude faster than in the unperturbed case. As shown in figure 2, losses start in the fraction of a μs, followed by an exponential "decay" of particles (without perturbation the first losses start after a couple ms [1]). Every step of radial length $\Delta\psi = 0.1$ leads to about an order of magnitude longer loss time. Black dots mark particles that are trapped inside of remnant island O-poins and therefore never get lost, not even after 100 ms and at an energy of 100 MeV. The 4/3 island chain at $\psi = 0.6$, that has the lowest poloidal mode number of the three, is completely stochastized without an O point in the transport domain. The exponential loss dynamics implies that most of the particles are lost during the very early phases of the disruption, which seems to be favourable from the avalanche generation point of view. This also means that the particles lost due to RMP will have low energies.

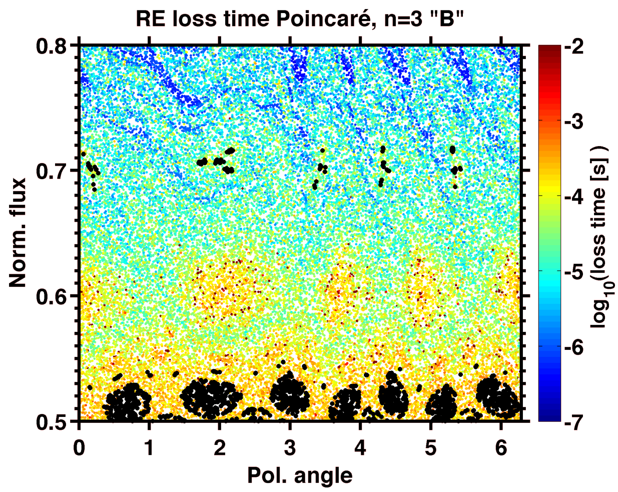

Figure 2: *Loss time of particles as a function of starting position (ψ,θ;$\varphi = 0$).*

Spatial distribution of losses Although losing the REs fast and at relatively low energies is beneficial, the RMP increases the localisation of wall loads. Without RMP, in an ideal case, the RE losses would be isotropic in the toroidal direction, and located at the low field side due to the energy gain related outward shift. In a given magnetic perturbation configuration (we will use the $n = 3$ "B" case as an example) the wall load pattern is only determined by the perturbation itself, and does not depend on initial particle parameters. Due to the stochastic magnetic fields and the complex nature of particle transport the starting position and the loss position of the particles are completely uncorrelated. The particle energy at the time when it is lost depends on the loss time. The loss time depends mainly on the starting position, which is independent of the particle loss coordinate. Therefore the loss pattern is also independent of energy. This is beneficial from a computational point of view, because future wall load studies will not necessarily have to follow a large amount of particles from the inner domains of the plasma.

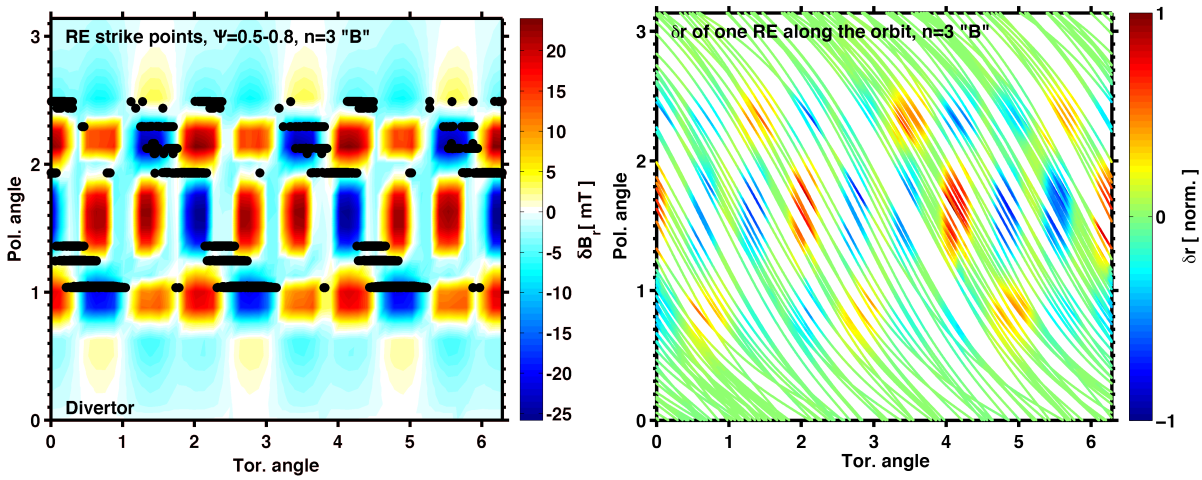

Figure 3: *(a) Particle loss positions (black dots) overlaid on the radial perturbation strength δB_r. Particles get lost where the field perturbation component points inwards. (b) Normalized δr of the particle along the axis, note the similarity with (a).*

The loss pattern for case $n = 3$ "B" is shown in figure 3(a). Black dots mark the particle loss positions. Every dot stands for one particle, and possible overlaps hide the angle distribution of the hot spots. The hot spots are localised between the RMP coils in the regions where the magnetic field perturbation component points inwards. To understand this behaviour, figure 3(b) shows a plot for just one particle along the orbit (for easier understanding), and colors show the δr change in the radial position of the particle at the given spots. The correlation between these radial steps and the local radial magnetic field is above 90% for every investigated case. Note the similarity between plots 3(a)-(b), *but* with a different sign. The ITER scenario #2 is a co-current scenario, however, runaway electrons move antiparallel to the current, therefore antiparallel to the magnetic field ($v_\|$ is negative for REs). In other words, the particles follow the bent field lines backwards, hence if a field line is bent inwards, REs move outwards. With this in mind we can understand figures 2 and 3(a). Particles along their orbit are constantly shifted inwards or outwards every time they pass in front of the RMP coils. However, these steps bring the particles to a region with a different q, hence in the next round the angle of approach to the RMP pattern is different. This leads to a chaotic random walk with a random step size both along the orbit and in the radial direction. Those particles that are born in a region where these steps lead to a sudden loss will get lost first, those particles for which the perturbation is averaged out along the orbit are the ones become trapped in the remnant O-points. All the rest follows a random walk, which leads to a diffusive process that explains the exponential dependence of the cumulative losses on time.

The most probable spot to get lost is close to the end of the region with outwards shift, that is along the negative B_r fields. In this picture the particles move from the top left corner to the bottom right corner, therefore losses should be more pronounced at the lower coils. This is indeed the case, the lower "blue" RMP coils experience 6-7 times as much RE loads than the upper ones.

The results show that the wall load pattern is closely related to the δB_r component on the edge, therefore to determine the most probable RE hot spots under the effect of RMP this is the key factor. This also means that RMP scenarios with low n remove particles faster, but the heat loads will be more localized. The exact loss pattern depends on the complete 3D model of the first wall, which is currently unavailable. As a general rule of thumb RMP coils with clockwise currents has to be placed far from delicate machine parts such as heating antennas and alike.

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References

[1] G. Papp et al. Plasma Physics and Controlled Fusion, **53**(9):095004, 2011.
[2] P. Helander et al. Physics of Plasmas, **7**(10):4106, 2000.
[3] G. Papp et al. Nuclear Fusion, **51**(4):043004, 2011.
[4] A. Polevoi. Tech. Rep. 22KZK3, ITER Documentation System (IDM), 2002.
[5] T. Hender et al. Nuclear Fusion, **47**(6):S128, 2007.
[6] H. M. Smith et al. Plasma Physics and Controlled Fusion, **51**(12):124008, 2009.