

The effect of resonant magnetic perturbations on runaway electrons

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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 runaway beam the application of resonant magnetic perturbations (RMP) has been suggested. The ITER ELM mitigation coils can, in principle, be used for runaway mitigation purposes. Earlier theoretical [1] and numerical [2] work suggested that runaway losses 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 [3]. In this work we investigate the effect of RMP on the confinement of runaway electrons by simulating their drift orbits in magnetostatic perturbed fields and calculating the transport and orbit losses for various initial energies and different magnetic perturbation configurations.

Modelling

We solve the relativistic, gyro-averaged equations of motion for the runaway electrons including the effect of synchrotron and Bremsstrahlung radiation with the ANTS (plasma simulatioN with driftT and collisionS) code [2]. This code calculates the drift motion of particles in 3D fields and takes into account collisions with background (Maxwellian) particle distributions, using a full-f Monte Carlo approach with a collision operator that is valid for both non-relativistic and relativistic energies. The simulations have been carried out for 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. This was calculated with VMEC, based on plasma parameters obtained by simulations with the ASTRA code [4]. The time-dependent electric field accelerating the runaways was modelled after an ITER-like disruption scenario using a model for 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]. Particles can reach energies in excess of 100 MeV, although as soon as avalanching starts, the runaway distribution will be dominated by $\mathcal{O}(10)$ MeV particles. 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, nevertheless, our results should be interpreted as an upper limit on the actual losses. 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 [3]. Two $n = 3$ current configurations, marked with “B” and “C”, are presented in this paper. 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.

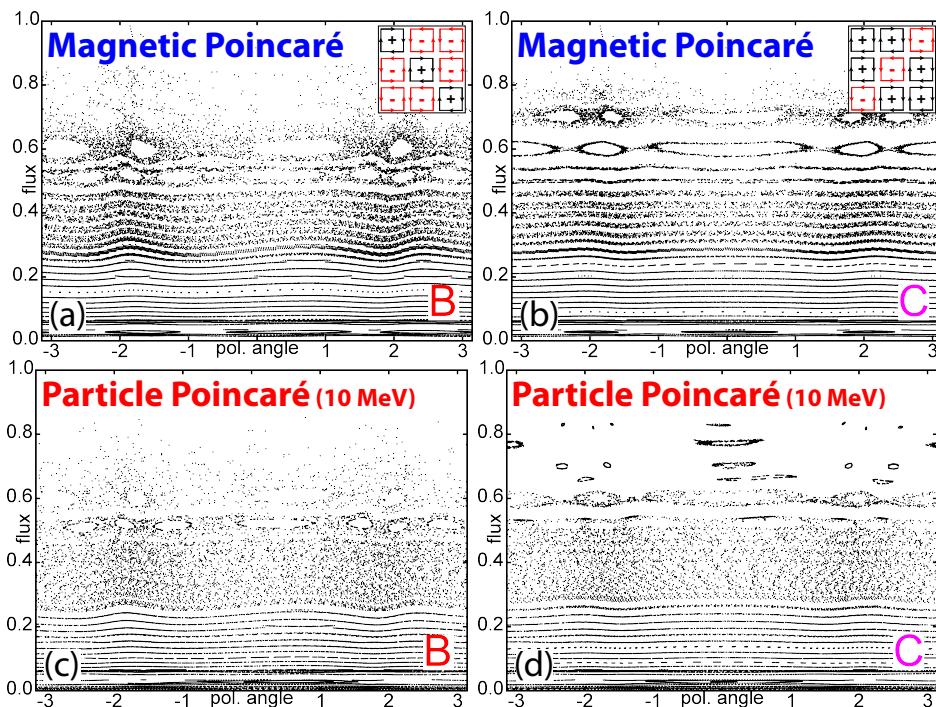


Figure 1: Magnetic (a-b) and particle (c-d) Poincaré plots visualize the difference between configurations “B” and “C”. Sketch of the current configuration is shown in the corners of (a-b).

Figure 1 shows magnetic- and particle Poincaré plots to visualize the different effect of the most successful “B” and the least successful “C” configuration. In the case of “B”, a wide ergodic zone forms at the edge of the plasma starting at $\psi \simeq 0.5$, that enhances radial transport of particles. In the case of “C”, edge islands trap and confine the particles for longer times, leading to only a slight transport increase.

Runaway loss enhancement

Even in the unperturbed case, the confinement volume shrinks as the particle population is shifted towards the Low Field Side (LFS) with increasing energy. Confinement volume shrinkage for 10 MeV particles is visualized in figure 2 for cases with and without RMP. As expected, at lower energies such as 10 MeV, the particles are mostly confined in the unperturbed case, and in the least effective configuration “C”. In the case of “B”, the confinement volume shrinkage is largely increased, up to 50%. Therefore, in the following we will study the losses caused by the “B” perturbation configuration. For higher energies, such as 100 MeV, RMP is less effective. Confinement volume shrinkage can be up to 50% without perturbation, further increased until 60% in case “B”.

If we launch 1 MeV particles on a flux surface that is within the confinement zone but will be outside it at large energies e.g. $\psi = 0.7$, we will observe particle losses even without perturbation. This is caused solely by the high energy that the particles reach during the disruption. Without the RMP, particle losses from $\psi = 0.7$ start around 10 ms and finish by 11 ms.

In the perturbed case the ergodic zone arising at the edge will cause losses several orders of magnitude faster than in the unperturbed case. As shown on figure 3, particles launched at $\psi = 0.7$ start to get lost already after 1 μ s, and losses continue with logarithmic temporal dependence until ~ 0.1 ms (note the logarithmic time axis on the figure). At around 0.1 ms already 95% of the particles are lost, but the remaining 5% takes up to 2-3 ms to

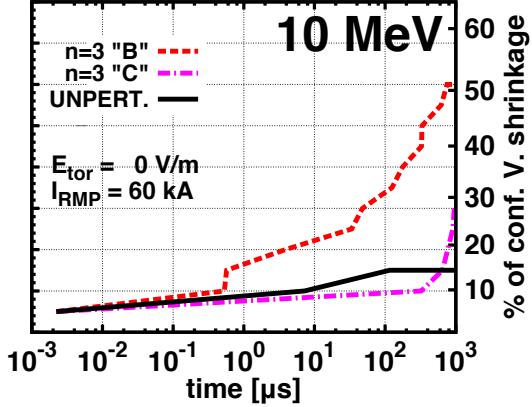


Figure 2: Confinement volume shrinkage for two different $n = 3$ perturbations for 10 MeV particles.

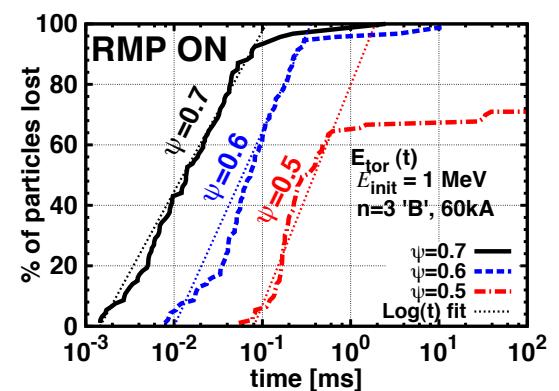


Figure 3: Particles losses with RMP.

get lost. Similar dynamics is observable if the particles are launched at the flux-surface $\psi = 0.6$. The particle losses start an order of magnitude later at 10 μ s, and dynamics of the losses is the same: logarithmic losses up to ~ 0.2 ms, where around 95% of the particles are lost, followed by a longer period during what the remaining particles are also lost within 10 ms. If we go one more $\Delta\psi = 0.1$ step further in, the losses start again 10 times later at 100 μ s, and the logarithmic dependence will be the same. In this case not all the particles will be lost, since the high energy LCFS is in the vicinity of the $\psi = 0.5$ surface. Particles launched further in, e.g. at $\psi \lesssim 0.5$ will not get lost even with strong RMP.

The logarithmic loss dynamics show that most of the particles are lost during the early phases of the losses, which seems to be favourable from the avalanche generation point of view. Also, the particles lost due to RMP will have low energy, while the losses caused by the shrinkage of the confinement zone result in lost particles in the 100 MeV energy range. Thus, RMP not only increases the amount of the particles lost outside $\psi=0.5$, it might also significantly weaken the avalanche generation in that region and result in lost particles at several orders of magnitude lower energies. All of these results seem to be beneficial from the runaway electron suppression point of view. However, losing fast electrons from the edge may lead to a larger inductive field in the centre of the plasma, making the avalanche stronger there. Therefore, quantitative conclusions about the magnitude of the total runaway current can only be drawn from simulations where both the evolution of the electric field and losses due to RMP are included self-consistently. This could be achieved e.g. by the ARENA code [7], using the results presented in this paper as inputs, possibly in a form of radial transport coefficients and/or time-dependent losses at the edge.

Acknowledgments

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