Runaway electron losses enhanced by resonant magnetic perturbations

G. Papp$^{1,2}$, M. Drevlak$^3$, T. Fülöp$^1$, P. Helander$^3$, G. I. Pokol$^2$

1) Chalmers University of Technology, Göteborg, Sweden
2) Budapest University of Technology and Economics, Budapest, Hungary
3) Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
Introduction

• Runaway electrons generated in disruptions pose a serious threat on large devices
• Resonant magnetic perturbations (RMP) significantly alter the magnetic structure and transport of tokamaks
• The undesired population of high energy runaway electrons can be lowered by RMP in experiments

- RMP can influence the low-energy edge runaways
- Large amount of runaways can be removed in ITER
- An effective RMP configuration was identified

G. Papp et al, Nuclear Fusion 51 043004, 2011.
G. Papp et al, PPCF 53 095004, 2011.
Modelling of RMP

- **Resonant Magnetic Perturbation (RMP)** is a possible method to reduce the number of runaway electrons.
- Promising, but inconclusive experimental results\(^1,2\).
- **Theory** suggests that \(dB/B=0.1\%\) is enough to suppress the avalanche generation\(^3\).
- Runaway transport in perturbed fields is very complex. ➡️ 3D numerical modelling is required.
- Solving the complete kinetic problem requires tremendous computational power.
- **Approximation**: test particles in predefined 3D fields.

---

\(^{1}\) M. Lehnen *et al*, *PRL* 100 255003, 2008.
\(^{2}\) V. Riccardo *et al*, *PPCF* 52 124018, 2010.
\(^{3}\) P. Helander *et al*, *PoP* 7 4106, 2000.
Modelling of RMP

- Relativistic drift equations to follow the particle propagation in 3D EM fields
- Extended version of the ANTS (plasma simulation with drift and collisions) code\(^4\)
  - Collisions with background plasma are calculated with an MC collision operator valid for arbitrary energies\(^5\)
  - Synchrotron and Bremsstrahlung radiation losses
  - Cartesian coordinate system for the highest flexibility and accurate treatment of arbitrary magnetic fields

Modelling for TEXTOR

- TEXTOR-like plasma + Dynamic Ergodic Divertor (DED) system
  - \( n=2 \) DC configuration superposed on the VMEC equilibrium field
  - \( dB/B=0.1\% \) up to \( \psi=0.8 \) @6kA
  - Edge ergodic zone at \( \psi > 0.8 \)

![Magnetic Poincaré, \( I_{DED} = 6 \text{ kA} \)](image)

![F.-Average dB/B](image)

![Ergodic Islands](image)
• Increasing energy $\Rightarrow$ runaway population is shifted towards the LFS $\Rightarrow$ causes significant losses regardless of the DED
• Effect of RMP decreases with increasing particle energy

Drift topology $\neq$ magnetic topology!

Core is intact...
Loss enhancement

- Low energy (~1 MeV) particles closer to the edge ($\psi > 0.7$) are affected
  - Particle losses initiate sooner, similar loss dynamics
  - At higher energies the difference is negligible
  - Runaway current damping rate is the same order as in experiments

- Simulations did not explain the loss of core- and high energy electrons
- It may be explained by MHD instabilities onset by the disruption\textsuperscript{6} - in small tokamaks

Runaway losses in ITER

- ITER inductive scenario #2, $I_P=15$ MA
  - RMP with the ELM perturbation coil system (9 X 3 coils)
  - $n=3$ and $n=9$ perturbations with $dB/B=0.1\%$ up to $\psi=0.5$
- $n=3$ creates broader islands, hence, is more effective - 4 configs. tested

![Averaged dB/B vs Radial position (normalized flux)](chart)

- $I_{\text{RMP}}: 60$ kA
2 out of the 4 configurations is shown.

Magnetic Poincaré

Alignement

Particle Poincaré (10 MeV)

Stochasticity

B

Non-alignement

Particle Poincaré (10 MeV)

Islands

B

C

C

G. PAPP  IAEA Meeting on Energetic particles  2011-09-10
Confinement volume shrinkage

- Losses due to energy gain
- Up to 50% shrinkage for 10 MeV particles (10% without RMP)
- Up to 60% for 100 MeV >50% without RMP
  - RMP is less effective for high energies
  - Not many particles reach up to 100 MeV
- “B” is the best configuration

Time-dependent electric field

- Taken from simulations of the evolution of the radial profile of the current density and the diffusion of the electric field \cite{Smith2009}.

\[ H. M. \text{ Smith et al, } \text{PPCF 51 124008, 2009.} \]
Loss enhancement

- ~ 11 ms until 100% loss for particles launched at $\psi_0=0.7$
- With RMP, losses start at 1µs, 100% loss by 0.1 ms
  - Logarithmic loss dependence on time: $N_{\text{lost}} \sim \log(t)$
  - Loss initiation depends exponentially on $\psi_0$
  - Particles within $\psi<0.5$ are practically untouched
Conclusions

• Identified a possible RMP configuration for runaway suppression in ITER
  ➔ RMP enhances the edge ($\psi>0.5$) particle transport that significantly increases particle losses
  ➔ Particles get lost while still at low energies
• Can be applied along with other mitigation methods (e.g. pellet or gas injection)
• Fast losses reduce the seed population for avalanche
  *but might increase the electric field*
• Self-consistent calculation of the runaway dynamics is feasible with the ARENA+ code in the near future

G. Papp et al, Nuclear Fusion 51 043004, 2011.
G. Papp et al, PPCF 53 095004, 2011.