Macroscopic Plasma Modeling and its Application to Tokamak Disruptions

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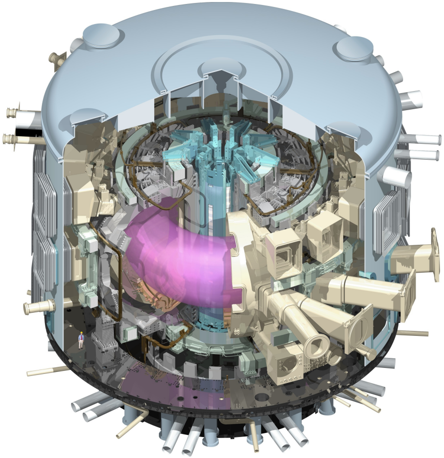
Outline

Disruptions and Runaway Electron Generation

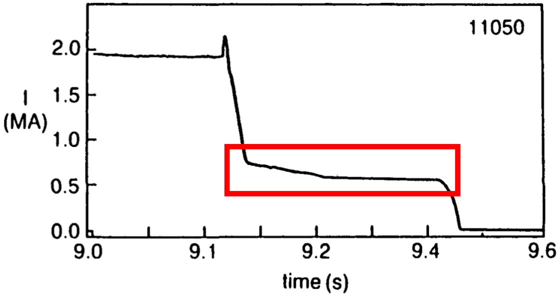
Disruptions pose risk to large scale magnetic fusion energy devices.

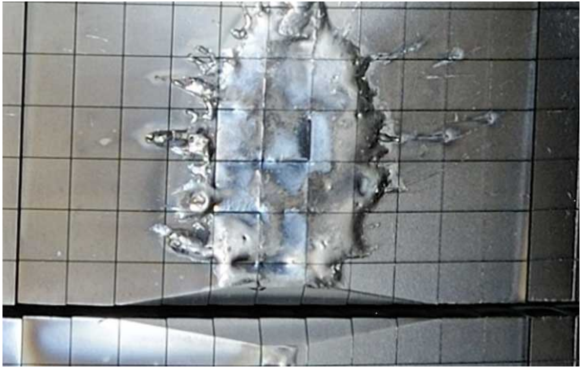


- ITER plasma will have >500 MJ combined stored thermal and magnetic energy, equivalent to 100 kg of dynamite.
- Thermal energy can be released on the 1s ms timescale.
- Magnetic energy can be released on the 10s ms timescale.

The ITER Tokamak, https://www.iter.org/album/Media/7%20-%20Technical (visited on 06/16/2020)

Rapid cooling of the plasma generates an electric field which accelerates the high-energy tail of electrons.



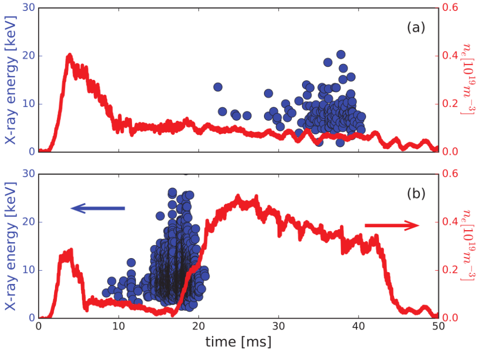


In plasma the highest energy portion of the velocity distribution is least collisional.

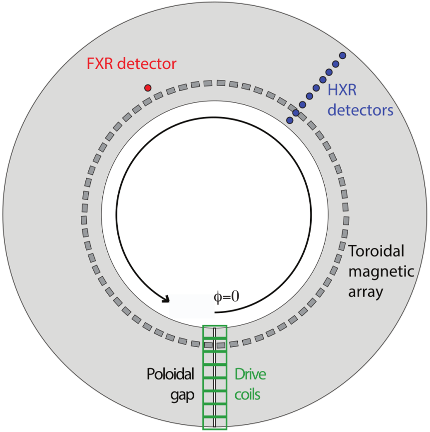
J. Wesson et al., "Disruptions in JET", Nuclear Fusion **29**, 641–666 (1989)
Generating runaway electrons in JET to benefit ITER, https://www.iter.org/newsline/-/2234 (visited on 06/18/2020)

Experimental Evidence for RE Suppression Using Resonant Magnetic Perturbations

The Madison Symmetric Torus can reproducibly generate runaway electron populations.

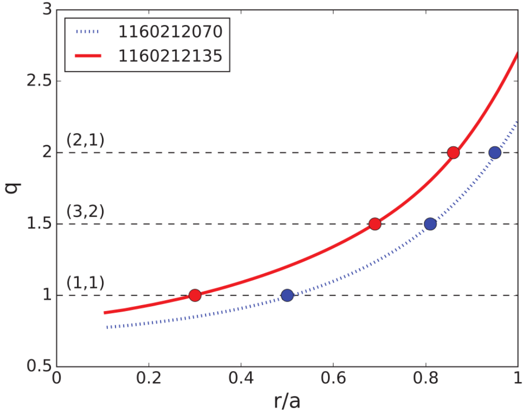


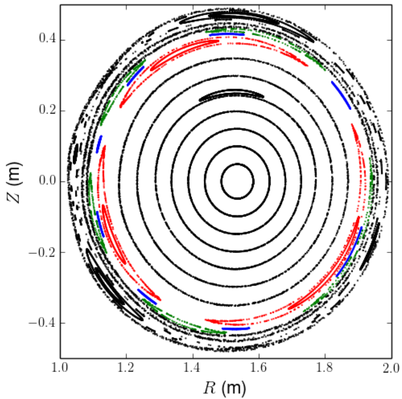
Below a critical threshold of plasma density for a given electric field runaway electrons can be generated.



S. Munaretto et al., "Generation and suppression of runaway electrons in MST tokamak plasmas", Nuclear Fusion **60**, 046024 (2020)

Resonant magnetic perturbations interact with rational surfaces of the plasma magnetic field.

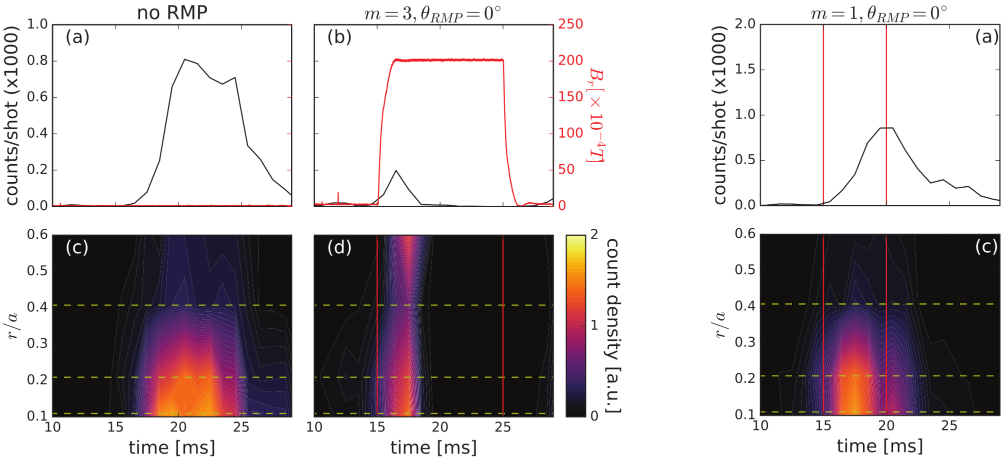




The $m = 3$ RMP induces $(3,3)$, $(3,2)$, $(8,5)$, $(5,3)$, $(4,2)$ island chains.

S. Munaretto et al., "Generation and suppression of runaway electrons in MST tokamak plasmas", Nuclear Fusion **60**, 046024 (2020)

Application of an $m = 3$ RMP suppresses runaway electrons while an $m = 1$ RMP produces to no suppression.



S. Munaretto et al., "Generation and suppression of runaway electrons in MST tokamak plasmas", Nuclear Fusion **60**, 046024 (2020)

Using Simulation as an Interpretive Tool for Experiments

A magnetohydrodynamics model without pressure was used to simulate these discharges.

These MST tokamak discharges have very low thermal energy compared to magnetic energy so pressure (P) is excluded from the MHD system. A uniform mass density (ρ) is also assumed.

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} - \eta \vec{J} \right)$$

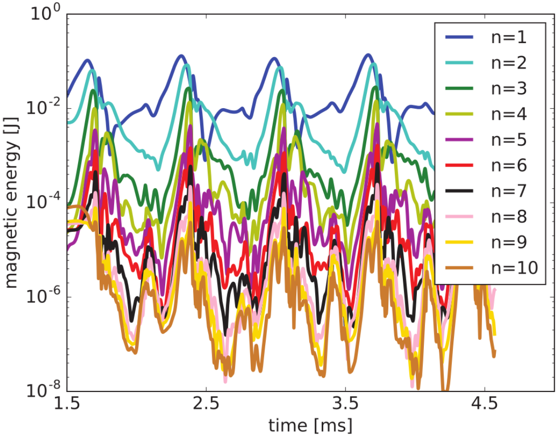
$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \vec{\nabla} \vec{v} \right) = \vec{J} \times \vec{B} + \vec{\nabla} \cdot \rho \nu \left[\vec{\nabla} \vec{v} + \left(\vec{\nabla} \vec{v} \right)^T - \frac{2}{3} \left(\vec{\nabla} \cdot \vec{v} \right) \underline{\underline{I}} \right]$$

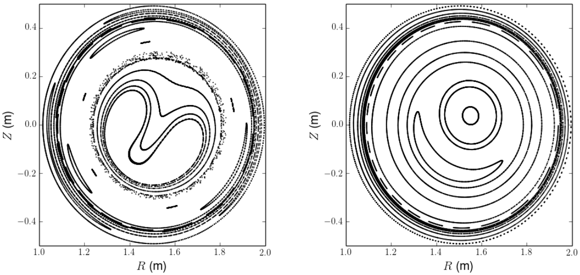
$$\mu_0 \vec{J} = \vec{\nabla} \times \vec{B}$$

$$0 \approx \left(\vec{\nabla} \cdot \vec{B} \right)_{\text{numerical}}$$

The electrical resistivity (η) and viscous diffusivity (ν) are taken to be constants comparable to within the experiment.

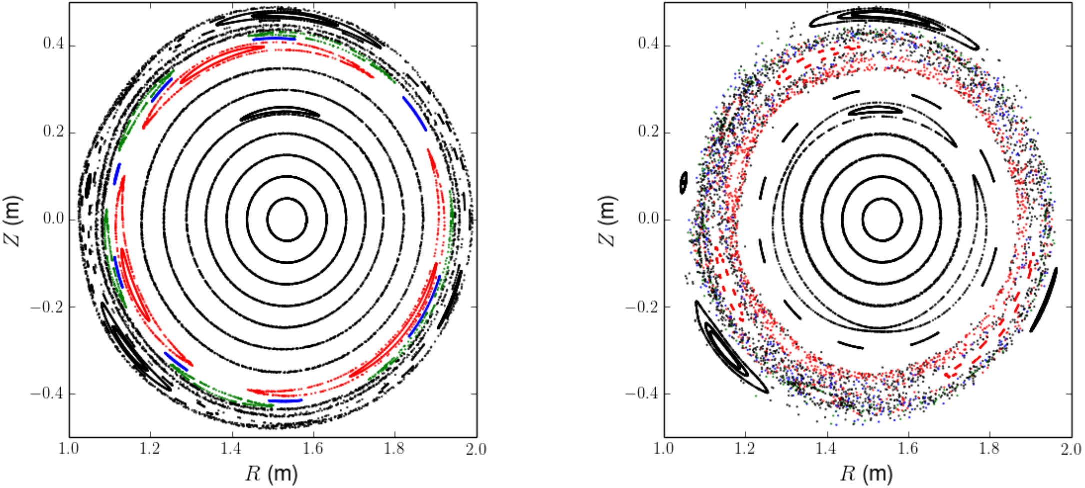
Simulations indicate that these discharges contain sawtoothing.



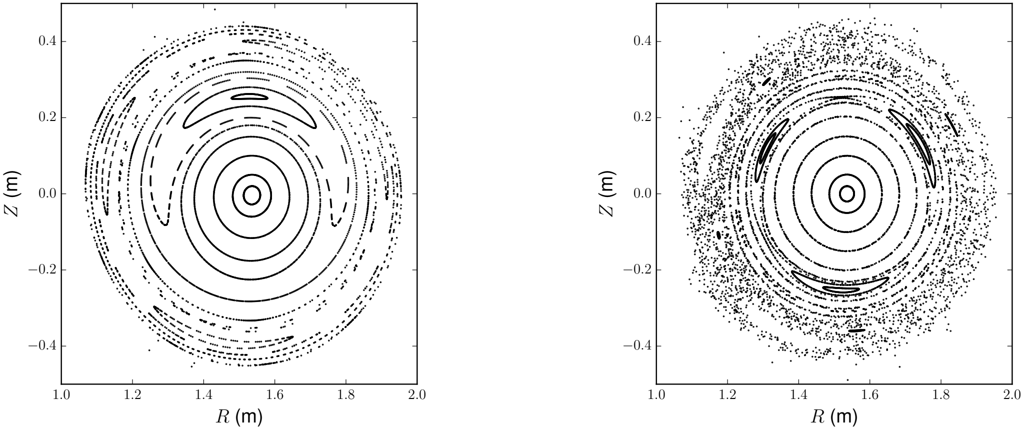


Magnetic field topology during the high energy (left) and low energy (right) phases.

An RMP induces magnetic islands which can overlap to produce a stochastic magnetic field region.



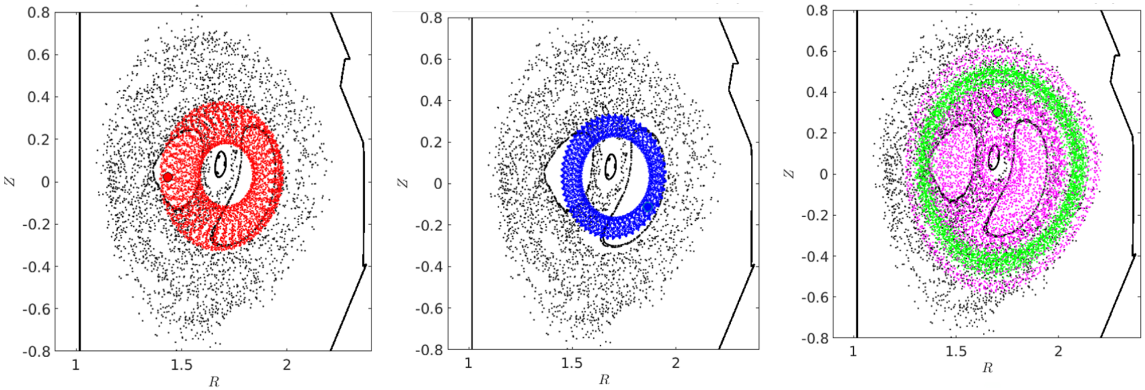
The $m = 3$ (right) RMP produces a substantial stochastic region whereas the $m = 1$ (left) RMP has a weaker effect.



The magnetic reorganization from the sawtoothing behavior may be important for transporting seed runaway electrons from the core to the stochastic edge.

New Opportunities for Continued Modeling Efforts

Relativistic electrons do not strictly follow magnetic field lines.



Full orbit tracing using the KORC code from Oak Ridge National Laboratory shows the deviation of runaway electron paths from the magnetic surfaces.

D. Del-Castillo-Negrete et al., "Numerical simulation of runaway electrons: 3-D effects on synchrotron radiation and impurity-based runaway current dissipation", Physics of Plasmas **25**, 056104 (2018)

Close collaboration with experiments and complementary computational tools can be rewarding.

- Suppression of runaway electron populations is an important component of disruption mitigation techniques for magnetic fusion energy experiments.
- There is experimental evidence that RMPs of the appropriate helicity can suppress runaway electrons.
- Our modeling has led to a plausible explanation for the different behavior of runaway electron suppression via RMP in MST tokamak discharges.
- Further modeling will provide additional information to develop a more complete understanding of these results.

Acknowledgments

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