The Asymmetry between Magnetic Surface Breakup and Re-Formation

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1. Magnetic surface breakup and disruptions.
2. Cause of fast surface breakup.
3. Reason magnetic surfaces re-form.
4. How re-formation differs from breakup.
5. Why outside-in re-formation is dangerous.

1. Magnetic Surface Breakup and Disruptions

- Disruptions are a sudden loss of the plasma thermal energy, $\sim$ ms, followed by a fast decay of the plasma current.

- Can be caused by high-Z material falling into the plasma or by instabilities causing a breakup of the magnetic surfaces.

- The associated ***(a) power deposition on the walls, (b) forces on the walls, and (c) conversion of the plasma current into a current of relativistic electrons*** must be addressed within the ITER mission and are unacceptable in a power plant.

- Here we focus on the rapid breakup of magnetic surfaces and their re-formation.

2. *Cause of Fast Surface Breakup*

- Even an ideal evolution can cause an exponentially large variation in the separation between two magnetic surfaces. *Caused by magnetic field line chaos: an exponentially large variation in the separation of neighboring field lines while they remain within a finite region across the lines.*

- Where surfaces are close, η/μ_0 can interdiffuse field lines from different surfaces on a timescale $\tau_{ev}\ln\left(\tau_\eta/\tau_{ev}\right)$. τ_{ev} the evolution and $\tau_\eta=\mu_0 a^2/\eta$ the resistive time scale. $\tau_\eta/\tau_{ev}\sim 10^7$ in ITER.

- Faraday's Law plus Ohm's Law, $\vec{E}+\vec{v}\times\vec{B}=\eta\vec{j}$, give an advection diffusion equation $\frac{\partial\vec{B}}{\partial t}-\vec{\nabla}\times(\vec{v}\times\vec{B})=\frac{\eta}{\mu_0}\nabla^2\vec{B}$. *In 1984, Aref showed advection-diffusion equation gives mixing only logarithmically dependent on diffusivity* [1]. Requires $\vec{v}$ chaotic and three dimensions for $\vec{B}$.

- Effect noted by Boozer in [2] and confirmed by Jardin et al in [3].

3. Reason Magnetic Surfaces Re-form

- Disruptions are fast compared to the timescale for changes in the $\vec{B}\cdot\hat{n}$ penetrating the ITER walls, so magnetic boundary conditions remain essentially axisymmetric.

- The breakup of magnetic surfaces causes $\vec{\nabla}p$ to become small and $j_{||}/B$ to become constant across the plasma. The two drives in MHD for asymmetry $\vec{\nabla}p$ and $\vec{\nabla}(j_{||}/B)$ are removed.

- The minimum energy equilibrium with $p = 0$, $\vec{\nabla}(j_{||}/B) = 0$, fixed magnetic helicity, and axisymmetric boundary conditions is axisymmetric—*nested magnetic surfaces not chaotic magnetic field lines.*

4. How Re-formation Differs from Breakup

- The advection-diffusion equation implies an ideal flow can exponentially enhance mixing but not un-mixing.
  - Stirring a can of paint with separated colorant and carrier mixes the paint on a time scale only logarithmically dependent on the diffusion time. *But, further stirring hinders, not helps, separation of the colorant and carrier. Separation occurs because of gravity and their different densities.*
- The re-formation of magnetic surfaces when chaotic field lines are enclosed by an axisymmetric boundary-condition apparently requires resistivity.
- Although the re-formation of surfaces after a disruption has been observed in many simulations, how the reformation depends on resistivity and its profile are not clear.

5. Why Outside-In Re-formation is Dangerous

- Runaway electrons are a fundamental danger.

  Requires runaway confinement, and $T_e \lesssim 500$ eV.

- Runaways increase by a factor of ten per MA drop in plasma current—about a hundred per MA with impurities [4–7].

- Outside-in allows extremely localized deposition.

  Runaways in a chaotic core are confined by an annulus of magnetic surfaces.

- Inside-out re-formation puts runaways on magnetic surfaces, which makes localized deposition difficult.

- Possibility of extreme localization is what makes runways so dangerous.

  When the total plasma current is carried by runaways with 10 MeV energy, the total energy in runaways is $\sim 10\ \%$ of the pre-disruption thermal energy.

Outside-In Re-formation of Magnetic Surfaces

- Favored due to the high resistivity near the plasma edge.
- Runaways then fill a chaotic core, confined by an annulus.

  Can be counteracted by non-axisymmetric magnetic fields produced by disruption-induced wall currents.
- Annulus can be punctured by being pushed into the wall, a plasma kink striking the wall, or a resistive instability.
- The annulus breaks by a pair of magnetic flux tubes—one in and one out—carrying increasing flux extending between the reservoir and the wall. Called a turnstile. Runaways move only one way along $\vec{B}$, so only one of the tubes is important.
- The quicker the turnstile opens compared to the runaway transit time, the broader the spreading on the wall [8].

Experiments on Localization of Runaway Losses

- Damage from extreme localization of runaway losses is seen in many experiments, but not all.

- In highly unstable JET (PRL **126**, 175001 (2021)) and DIII-D (NF **61**, 116058 (2021)) plasmas, runaway spreading was sufficient to avoid problems.

- The fusion relevance of tokamaks requires the extreme damage of runaways be avoided.

- This defines the importance of determining why runaway loss is sometimes concentrated and sometimes not.
- Outside-in versus inside-out surface re-formation after disruptions a critical issue.

References

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