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Simulation of a Mixed Plasma-Conductor Instability and Tokamak Halo Current Asymmetry

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Introduction

Control of the vertical position of a tokamak plasma can be lost, due to a disruption or control system failure due to other MHD. The plasma then undergoes a Vertical Displacement Event (VDE) [1], and comes into contact with the surrounding wall. When this happens, 'halo' currents can flow between the outer open field line plasma and the wall. Halo currents can have harmful effects on the wall, such as localized arcing, thermal loads and electromagnetic forces [2, 3, 4]. Simple scaling arguments based on force-balance show that larger tokamaks such as ITER [5] may be more vulnerable. Furthermore, halo currents commonly develop toroidal asymmetry [3, 4, 6] which intensifies the problem. We propose that the asymmetry may be related to a new 'mixed-circuit' instability. This arises because the halo-wall circuit can readily develop asymmetric current paths while the adjoining outer core plasma cannot.

The mixed circuit mechanism

The mechanism depends on the observation that the composite toroidal annulus surrounding the plasma core, consisting of the halo plasma and part of the vessel, can, in some sense, act as a rational magnetic surface at the plasma edge.

The halo plasma can accept perturbation current along its magnetic field at any value of the local safety factor or mode number. This is a consequence of the magnetic surfaces being open, so that a current circuit is completed between inboard and outboard field-wall contacts, via some of the surrounding conductors. These are isotropic and thus do not impose a constraint on the normal current density perturbation.

In contrast, the plasma core enclosed by this mixed circuit has closed and generally irrational magnetic surfaces, which prevents a mirroring flow of current along its field. Potentials induced by a current perturbation evolving in the adjacent halo and wall are electrostatically eliminated along the core field, reappearing across the field as radial $\mathbf{E} \times \mathbf{B}$ drifts which bring core plasma into the halo region. This locally increases halo conductivity, further increasing the halo perturbation current, and closing a feedback cycle. The contrast is that between an ohmic mixed-circuit and an ideal magnetized plasma, and is analogous to that between the ideal regions and the resistive resonant magnetic surface of a tearing mode.

Simple analytic model

The intrinsic heterogeneity of this system makes analysis difficult, as no simple coordinate system fits. For illustration however, we may consider a simple slab version.

A diverted discharge is approximated in periodic slab geometry, where the halo mixed circuit occupies a thin layer placed on top of a semi-infinite slab representing the plasma core, as in Fig. 1. We consider zero pressure and a large equilibrium field, so that perpendicular and parallel components of Ohm's law can be applied along fixed directions.

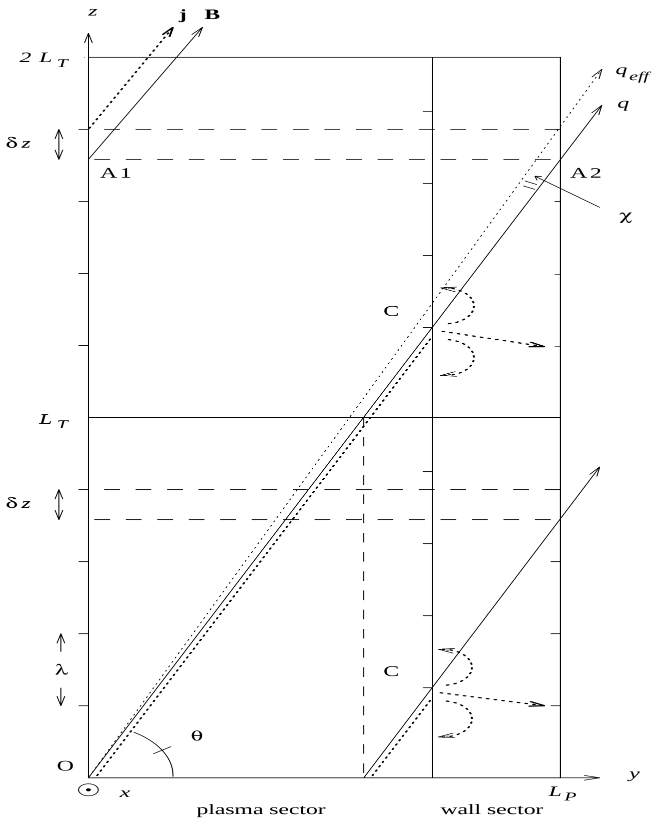

Fig. 1 *Slab version of the plasma-wall circuit. Two 'toroidal' periods are shown, with z the toroidal coordinate. Solid lines represent the equilibrium magnetic field B, thick dotted lines the perturbation current j, and a thin dotted line the direction of q_{eff}. y is the 'poloidal' coordinate.*
For $x > 0$ (out of the page, in the radial direction), the wall sector is occupied by the conducting wall, and the plasma sector is occupied by the halo plasma. For $x < 0$, both sectors are occupied by the core plasma.
λ is the toroidal wavelength of a perturbation. $\tan\theta = qA$, where A is the aspect ratio. In this diagram $q \sim 1.7$. The angle χ quantifies the discrepancy between q and q_{eff}.

We neglect the effect of eddy currents in the wall. The only role of the wall is to enable the rationalization of the halo current.
Since halo perturbation current flows along the magnetic field, its toroidal phase remains constant following a field line in the halo. In the wall, the current does not follow the field, flowing instead partly to the same or opposite-side field-wall contact. As shown in Fig. 1, this means that after a complete poloidal transit the phase of the perturbation slips relative to a magnetic field line. If the slip is small, it can be treated as continuous over many poloidal transits, and it may be assumed that the halo current flows in the direction of q_{eff}, an average rational effective q, different from the irrational q of the core. The angle χ between q and q_{eff} determines the amplitude of the resulting radial drifts. Solving in the different layers, it is not difficult to show that the matching between the core and the halo can be quantified by a Δ', analogous to that of a resonant layer. Assuming that the core radial displacement causes a convective modification to the halo conductivity, we may derive a dispersion relation

$$\gamma \simeq \zeta - \omega_{kw} \,, \tag{1}$$

where growth corresponds to a positive γ. ω_{kw} is the resistive penetration rate of the halo layer, of radial width w, by a mode of wavelength k. In this simple model the halo would behave like a passive resistive shell, but for the presence of a conductivity gain ζ. If ζ is sufficiently large and positive, resistive decay gives way to instability. ζ depends on the gradient of conductivity (σ) at the core-halo interface and for small χ is given by

$$\zeta \equiv \frac{\hat{\mathbf{r}} \cdot \nabla\sigma}{\sigma} \frac{E_{\|}}{B\chi} \qquad \text{where} \qquad \chi \simeq \frac{f(n)}{nq^2 A} \qquad \text{and} \qquad f(n) \equiv (nq - 0.5 \bmod 1) - 0.5 \,. \tag{2}$$

Case	loop voltage	I_p (MA)	q_{edge}	z (m)	a (m)	growth rate (kHz)
1	150.	3.0	3.25	0.63	1.00	stable
2	270.	2.8	2.18	0.98	0.88	stable
3	280.	2.6	1.68	1.15	0.77	$\sim$ 3.
4	260.	2.3	1.15	1.35	0.62	stable
5	210.	2.3	0.93	1.41	0.59	$\sim$ 9.

Table 1 *Equilibrium parameters during a JET simulation, the cases corresponding to successive times during a VDE. For each case examined the simulation predicted a growth rate.*

The unusual dependence of the geometric factor f on a 'mod' operation, implies that unstable wavenumbers can always exist. Divergent growth rates are predicted whenever $\chi \to 0^-$ (the model breaks down). Assuming $\nabla \sim w_{halo}^{-1}$ (radial) and $B_{tor} \gg B_{pol}$, it is straightforward to rewrite a necessary condition for instability ($|\zeta| > \omega_{kw}$) as

$$q R \sigma V_T > 2|f(n)|\, I_{TF} \,, \tag{3}$$

where V_T is the toroidal 'loop' voltage around the halo and I_{TF} the current in the toroidal field coils. According to this relation, an increase in toroidal voltage and halo conductivity (as during a VDE) is destabilizing, and the resonance is rather broad.

The simulation model

A computer code was developed which solves an improved version of the above slab model, conducted in realistic toroidal geometries and incorporating wall currents. The magnetic surfaces of the halo and the plasma core are represented as rigid, anisotropically conducting toroidal shells. As mixed-circuit currents flow, stability will be determined by the exact placement of the induced $\mathbf{E} \times \mathbf{B}$ drifts relative to the halo regions where current is increasing or decreasing. Drifts that move the core plasma towards the halo are assumed to change halo conductivity via gain coefficients. The model omits the contribution of free energy that may be available in the core profiles. However, at this stage the aim is to simply establish the viability of the proposed mechanism in realistic geometries.

The code solves for the linear evolution of a toroidal mode number n. Perturbation fields are generated from perturbation currents semi-analytically, using the Biot-Savart law. Grids are not fixed, but follow the poloidal cross-sections of the vessel and the magnetic surfaces of the halo and the core plasma. The cross-sections were imported from a Grad-Shafranov equilibrium solver. The equilibrium can then be examined for stability, and some scalar parameters varied (eg voltage, conductivities).

Preliminary results

At this level we can only examine trends, and to do this we have made a preliminary scan of JET-like equilibria imported to the code from a simulation of a JET VDE, during which an asymmetry developed, considering a time sequence of 5 equilibria during its progress. In each case we test for instability, to compare against the known time of asymmetry onset. Based on this single study we can make the following observations:

The physical mechanism initially proposed remains viable in the toroidal case, with the halo currents and core drifts occasionally locking together in a positive feedback. The

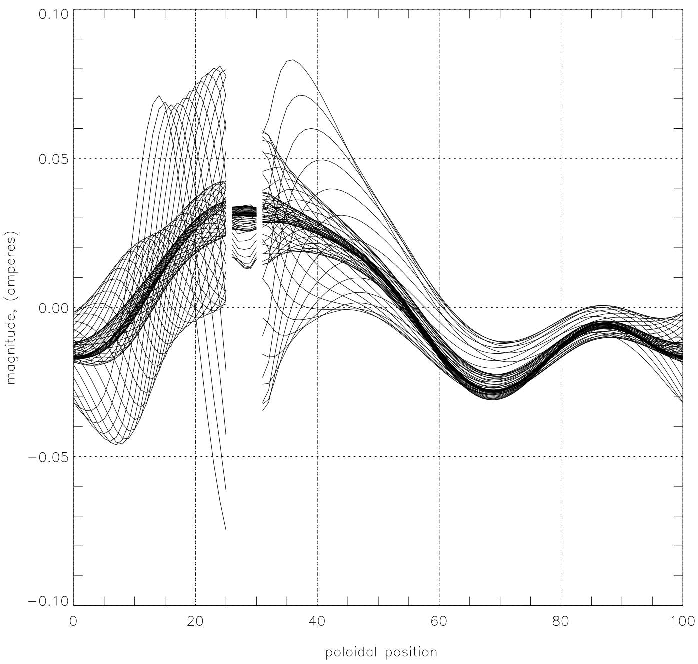

Fig. 2 *Evolution of an unstable $n = 1$ mode from an initial perturbation. Shown is the current streamfunction of the vessel. The discontinuities correspond to halo current leaving or entering the plasma at the open surface contact points, where it links up with wall eddy currents.*

simulation is consistent with the previous slab-geometry analysis. A high toroidal voltage increases the growth rate, provided instability is possible. This is consistent with the appearance of the asymmetry near the peak of the voltage surge. The onset of an $n = 1$ resonance is predicted at the time when it was observed, which is encouraging (see also Table 1). This was at a q well above 1, while an ideal kink model gives instability at q less than 1. $n = 1$ is dominant, as observed experimentally. However, in some equilibria the $n = 2$ is also predicted at a lower growth rate. Higher n modes do not seem to play a role.

These findings are consistent with experiment although more examples, and dependencies on other quantites such as wall path length, aspect ratio, and shape, are required.

Summary

A mixed-circuit instability is proposed, depending on the halo-vessel circuit acting as a rational surface, which may be responsible for the observed asymmetry of halo currents during VDEs. We have illustrated this idea by a simple slab-geometry analysis and a toroidal-geometry simulation employing simplified physics. The 'Δ'' of the mixed-circuit should interfere with the evolution of any other MHD instability in the plasma core, generating a jump condition to be considered alongside those due to conducting shells, or rational surfaces. Numerical modelling of the mechanism shows it is a viable interpretation of experimental observations.

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