Halo and Runaway Currents

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July 9, 2014

Halo currents can unacceptably shorten time between major maintenance outages on ITER.

Potential for ITER damage from runaway currents is so great that they cannot be allowed to occur.

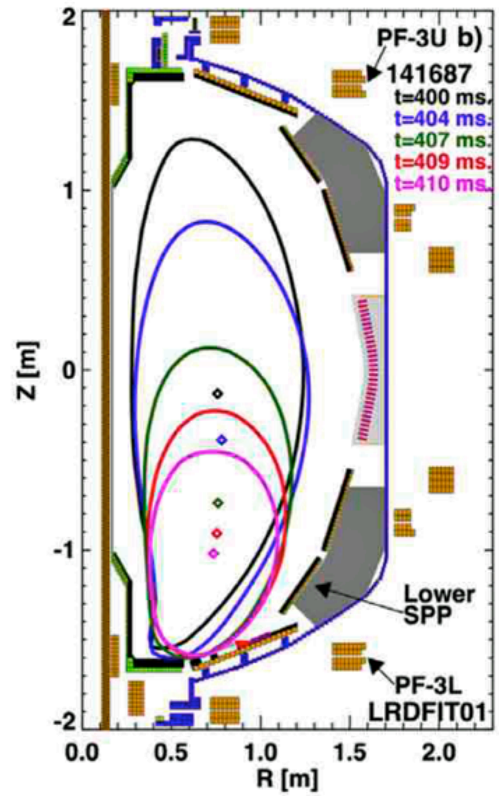
Mitigation methods for halo currents may unacceptably exacerbate the runaway problem.

*Halo theory: Boozer, PoP **20**, 082510 (2013)*
NSTX experiment: Gerhardt, Gerhardt, NF **53**, 023005 (2013))

Halo Currents

Flow along the magnetic field lines that intercept the walls just outside the main plasma body.

Arise whenever the plasma becomes too kink unstable for the chamber walls to slow the growth below an Alfvénic rate.



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Three important resistive decay times: $\tau_{plasma} >> \tau_{wall} >> \tau_{halo}$.

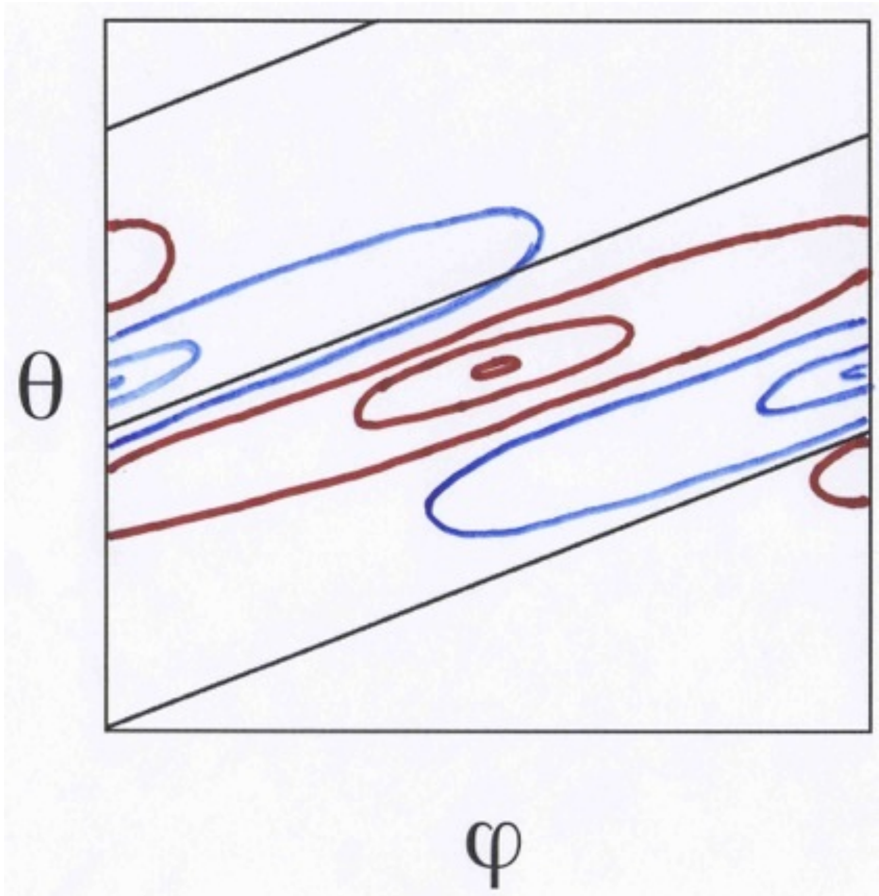
When position control is lost, plasma is pushed into wall on the time scale τ_{plasma} preserving its remaining q profile until q_{edge}~2 when an n=1 kink becomes highly unstable.

Constraints on Halo Currents

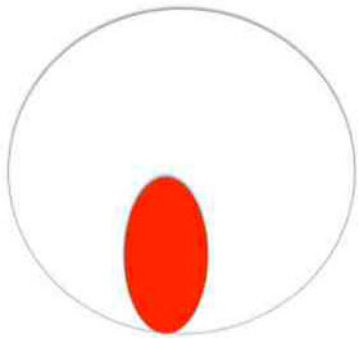
1. Halo current must produce the same external magnetic field distribution that would be produced by currents in a resistive shell located at the plasma surface.

2. Halo current in plasma must be force fee—must flow along $\vec{B}$.

3. Halo current channel on plasma surface must have a width at least comparable to the amplitude of the kink.

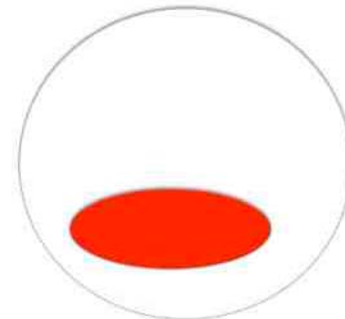


Localization of Halo Currents on Wall



A helical distortion pushes the plasma towards the wall at some φ and pulls the plasma from the wall at other φ.

Increasing toroidal angle $\varphi \rightarrow$



For a simple wall, the halo current enters and leaves the wall in an elongated elliptical region after $N(\varphi_0)$ poloidal and $M(\varphi_0)$ toroidal circuits along a field line $\theta = q_h(\varphi - \varphi_0)$.

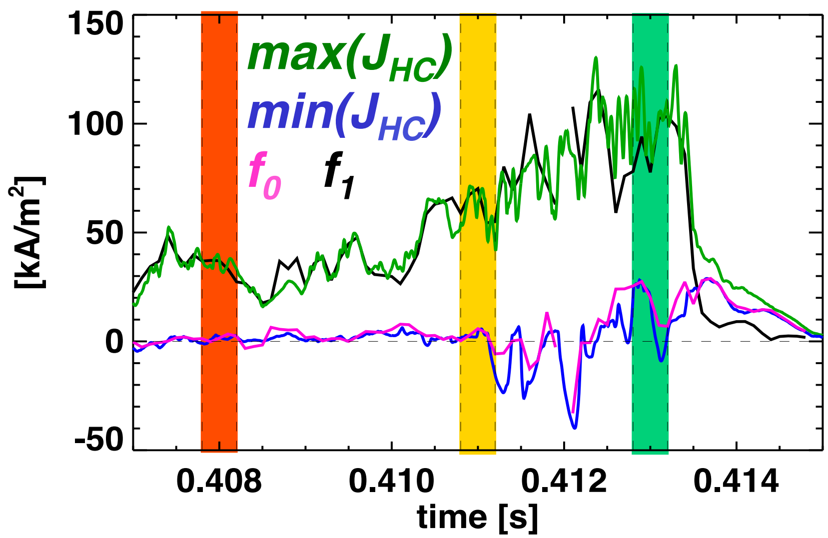
$\delta_\theta \sim \sqrt{2\Delta_h / a} << 1$ and $\delta_\varphi \sim \sqrt{2\Delta_h / \Delta_k}$

Δ_h halo width; Δ_k kink amplitude; a plasma radius;

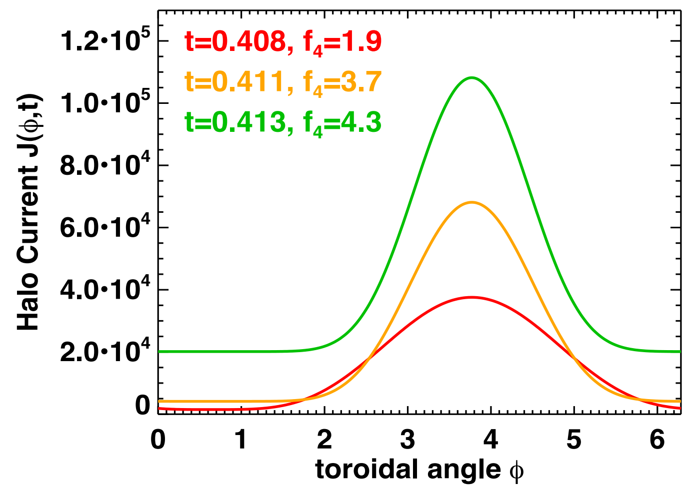
$\vec{B}$ lines exit in top half of ellipse and enter in bottom.

Halo Current Channel Width in Plasma

A narrow toroidal extent of halo current channel implies strong coupling of different toroidal modes, but only n=1 is unstable. Coupling can make halo-current drive energetically impossible.



$$f(t,\phi) = f_0 + f_1 \cos^{2f_4}\left(\left(\phi - f_2 - f_3 t\right)/2\right)$$



Lobe understandable if halo width $\Delta_h \sim \Delta_k$ kink amplitude.

Axisymmetry at end understandable if $\vec{B}\cdot\hat{n}_{wall} \sim$ axisymmetric.

Linear I_h growth understandable if $\gamma_h \propto 1/\Delta_h$ and $\Delta_h / a \approx I_h / I_p$.

Halo Forces Given by Path Through Wall

In the plasma edge, the halo current flows along a line of $\vec{B}$, entering the wall in one tile and exiting the wall from another.

In the wall, while going from one tile to the other, the halo current follows the minimum impedance path.

Measurable in existing machines;
Calculable using existing codes (Bialek).

The minimum impedance path depends on

a. the design of the wall and structures.
b. $\gamma_h \tau_w$, the halo growth rate times the wall time.

When $\gamma_h \tau_w >> 1$, path inductive—not resistive—possible arcing.
Halo current rotation makes path more inductive.

Current path can be manipulated by resistors and shunts.

Halo current rotation affected by φ–symmetry of wall impedance.

Runaway Current

A relativistic electron colliding with background electrons feels a drag force that can be written as eE_c, which depends only on the background electron density, $E_c \sim 0.075\ n_b$. Units of n_b are $10^{20}/\mathrm{m}^3$. At lower energy, drag is greater.

Only when parallel electric field $E_{//} > E_c$ is runaway possible.

Runaway electrons knock background electrons to a sufficient energy to runway, so

$$\frac{dn_r}{dt} = n_r \frac{E_{\parallel} - E_c}{E_c \tau_r}\ \text{, where }\ \tau_r \sim \frac{0.85\mathrm{s}}{n_b}$$

when pitch-angle scattering is ignored.

Importance of Pitch-Angle Scattering

Ratio to acceleration is $z_r \equiv \dfrac{(1+Z_r)E_c}{E_{\|}-E_c}$. Note, $Z_{nuc} \geq Z_r \geq Z_{eff}$.

Runaways can penetrate to any nucleus but $\ln\Lambda$ *reduced.*

Fredrik Ansdersson's 1998 Chalmers thesis on p.20 implies poloidal flux consumption to produce a given number of e-folds is $\Psi(z_r)/\Psi(0) = \sqrt{\frac{2\pi}{3}}\, z_r$ when $z_r >> 1$.

Remarkably little has been published on pitch-angle scattering. Effect not included in many empirical studies. Instabilities could enhance, but no clear candidates known.

Importance of Runaway Isotropy

The number density and parallel current density of electrons with kinetic energy > $(\gamma - 1)m_e c^2$ are

$$n_r(\gamma) \equiv \int_\gamma^\infty f d^3p \quad \text{and} \quad j_r(\gamma) \equiv -e\int_\gamma^\infty \mathrm{v}_{\|} f d^3p.$$

Anisotropy of runaways $\varepsilon_a(\gamma) \equiv \dfrac{j_r(\gamma)}{en_r(\gamma)c}$, where $1 > \varepsilon_a(\gamma) > 0$.

Runaways loose power by drag and gain power from $E_{||}$.
To be energetically possible need $j_r(\gamma)E_{\|} > en_r(\gamma)cE_c$.

$E_{||}$ required for runaway is $E_{\|} > \dfrac{E_c}{\varepsilon_a(\gamma)}$. Expect $\varepsilon_a(\gamma) \propto \dfrac{1}{z_r}$.

Runaway Current Representation

Particle simulation can efficiently determine runaway current. Need only $\left\langle j_{\|} / B \right\rangle$ averaged along $\vec{B}$ and the runaway pressure,

$$\overleftrightarrow{P}(\vec{x}) \equiv \int \gamma m_e \vec{\mathrm{v}}\vec{\mathrm{v}} f d^3 p, \qquad \text{and} \qquad \vec{j}_\perp = \frac{\vec{B} \times \vec{\nabla} \cdot \overleftrightarrow{P}}{B^2}. \qquad \text{Also } \vec{\nabla} \cdot \vec{j}_r = 0.$$

$$\vec{j}_r = (K_{net} + K_{ps}) \frac{\vec{B}}{\mu_0} + \vec{j}_\perp, \quad \text{so} \quad \frac{\partial K_{ps}}{\partial \ell} = \frac{\mu_0}{B} \vec{\nabla} \cdot \vec{j}_\perp$$

$$\left\langle \vec{\nabla} \cdot \vec{j}_\perp \right\rangle \equiv \lim_{L \to \infty} \frac{\int \vec{\nabla} \cdot \vec{j}_\perp \, d\ell / B}{\int d\ell / B} = 0 \qquad \text{and} \quad K_{net} = \left\langle \frac{\mu_0 \vec{j} \cdot \vec{B}}{B^2} \right\rangle$$

$$\left| \frac{j_\perp}{j_r} \right| \approx \left| \frac{\gamma m_e n_r c^2 / aB}{e n_r c} \right| \approx \frac{\rho_r}{a} \approx \frac{1.7 \times 10^{-3} \gamma}{Ba} \mathrm{Tesla} \cdot \mathrm{m} \sim 10^{-2}.$$

Unimportance of Synchrotron Radiation

Power loss through synchrotron radiation is usually small compared to power loss to background electrons.

$$\frac{\nu_{syn}}{\nu_{drag}} = \frac{2}{3}\left(\frac{\omega_p}{\omega_c}\right)_0^2 \frac{\gamma^2 \sin^2\vartheta}{\ln\Lambda} \qquad \text{where} \qquad \left(\frac{\omega_p}{\omega_c}\right)_0^2 = \frac{0.0974B^2}{n_e}$$

Pitch angle of runaways to $\vec{B}$ is ϑ.

Summary

Before ITER operates at ~10 MA assurance will be required that the probability that a large fraction of that current can be converted into 10 MeV runaways is essentially zero—otherwise the danger to ITER is too great.

Runaway avoidance and mitigation techniques cannot be demonstrated empirically—when operating in the required regimes; the danger to the machine is too great.

Theory is required—but is not being developed.

The forces and arcing caused by halo currents can be mitigated by rapidly cooling the plasma, but this may give unacceptable runaway production.