Rotation of Tokamak Halo Currents

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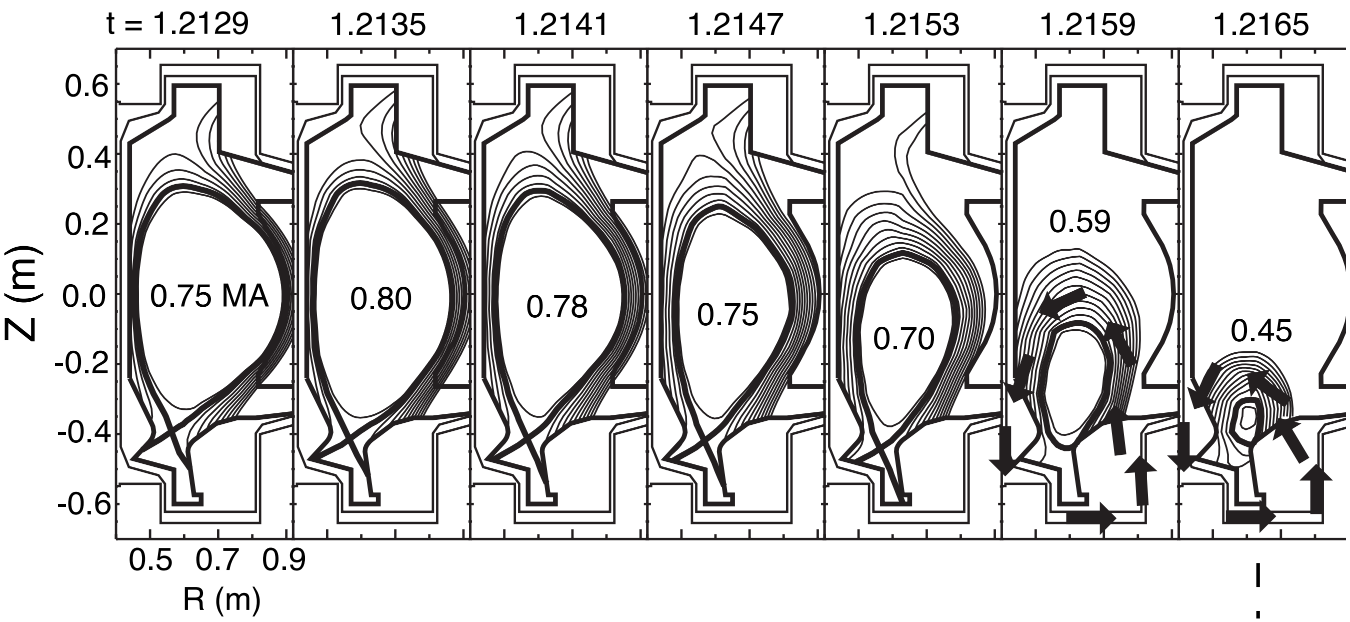
What are halo currents?



Vertical diplacement & halo currents on CMOD

The vertical position of a shaped tokamak plasma is unstable and requires feedback control.

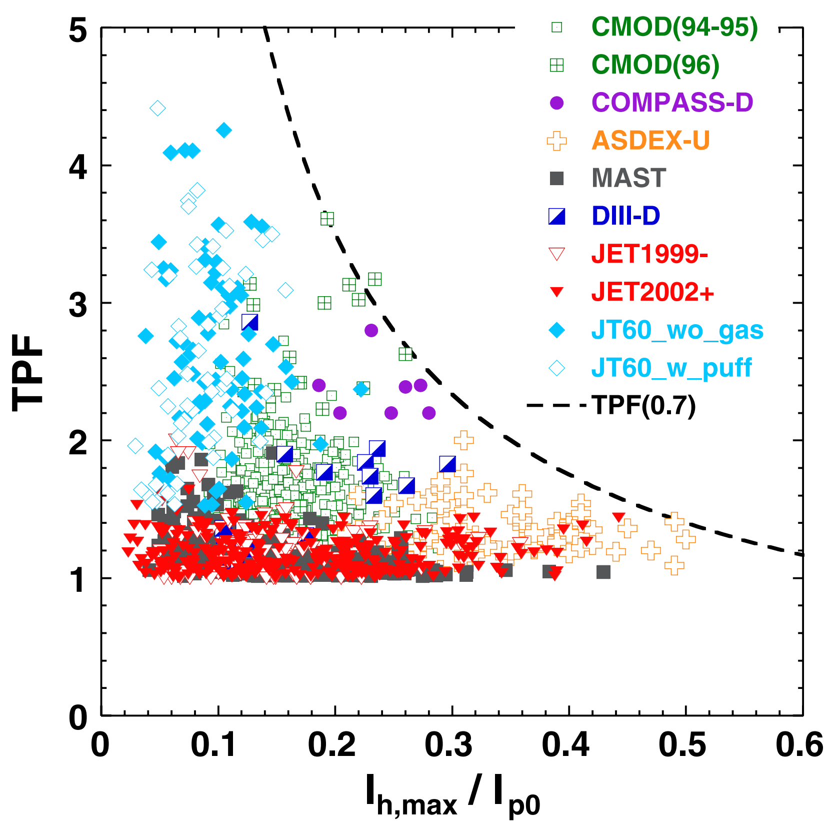
Loss of vertical control is called a vertical displacement event:

The plasma is stripped of its outer surfaces by hitting the wall.
When q_{edge}~*3* to *2*, the *n=1* kink becomes highly unstable (*Manickam et al*).
Current flows along open field lines to preserve equilibrium (*Zakharov*).
Magnitude of this halo current is $I_h/I \sim \xi/a \sim 20\%$ (*Zakharov*).

Why are halo currents important?

Halo currents flow in part through the chamber walls, reach ~20% of original plasma current, and can exert large forces.

Halo currents can rotate and resonate with internal structures, which can increase the damage. *Rotation does spread heat load.*



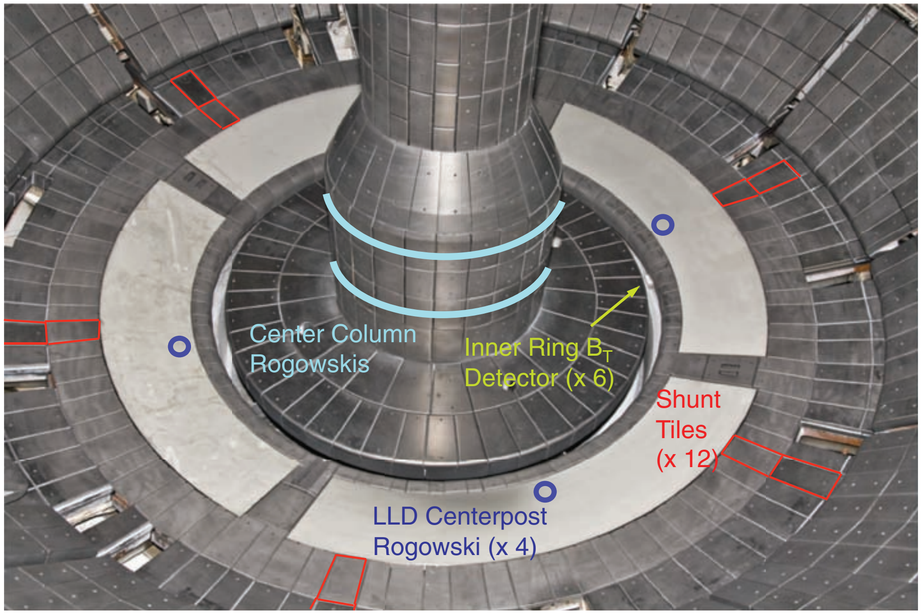
Halo current can be toroidally peaked concentrating force.

Peaking machine dependent

If measured in N_s toroidal segments,

$$TPF \equiv N_s \frac{\left|I_n^{(h)}\right|_{\max}}{\sum_n \left|I_n^{(h)}\right|}$$

Direct measurement of halo currents



In divertor region of NSTX

Certain "shunt" tiles mounted on resistive plates.

Makes total halo current into each shunt tile measureable.

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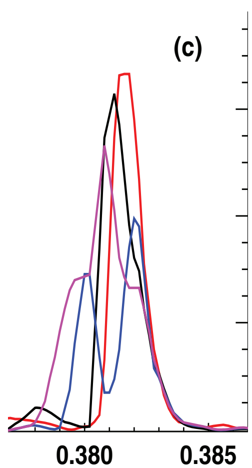
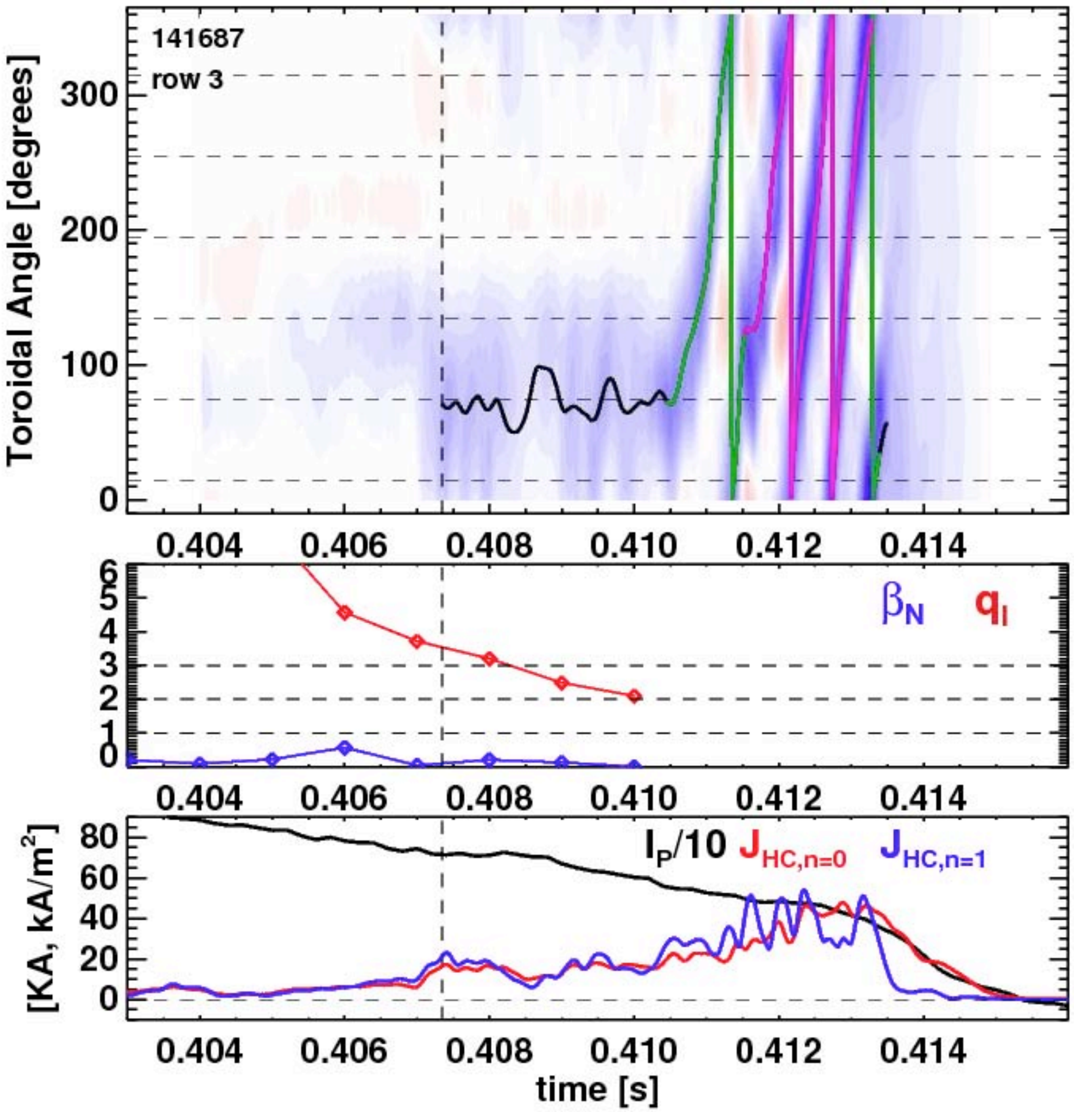


Halo current versus time flowing into four individual shunt tiles located at
φ = 45°, 135°, 225°, and 315°.

Halo current formation and rotation

S. Gerhardt and NSTX group



Why do halo currents rotate?

1. Ambipolarity in the non-axisymmetric magnetic field of the *n=1* kink, $\delta B/B \sim \xi/R_0$, locks the toroidal plasma rotation to that of the kink but with an offset velocity $v_a(r)$ between them.

2. Kink could rotate freely if wall were (i) axisymmetric, (ii) a perfect conductor, and (iii) no penetrating non-axisymmetric B-field.
   Otherwise, kink can lock or rotate with a rate set by wall resistivity.

3. When kink can rotate freely enough, its velocity set by the plasma velocity, which is determined by either:

   a. one of two near edge effects
      i. interaction with neutrals or
      ii. E_r in the halo required for quasi-neutrality on open B-lines.

   b. interaction of deep interior plasma with an error magnetic field.

Characteristic Rates Clarify Physics

Rotation relaxation to offset velocity $\frac{d}{dt}\mathrm{v}_{pl} = -\nu_{drag}\left(\mathrm{v}_{pl} - \mathrm{v}_a(r)\right)$

$$\nu_{drag} \approx \frac{1}{\nu_*}\left(\frac{\delta B}{B}\right)^2 \frac{C_s}{R_0}$$

Cross-field (gyro-Bohm) viscosity negligible $\frac{\nu_{drag}}{\nu_{vis}} \approx \frac{1}{\nu_*}\left(\frac{\delta B}{B}\frac{a}{\rho_s}\right)^2$

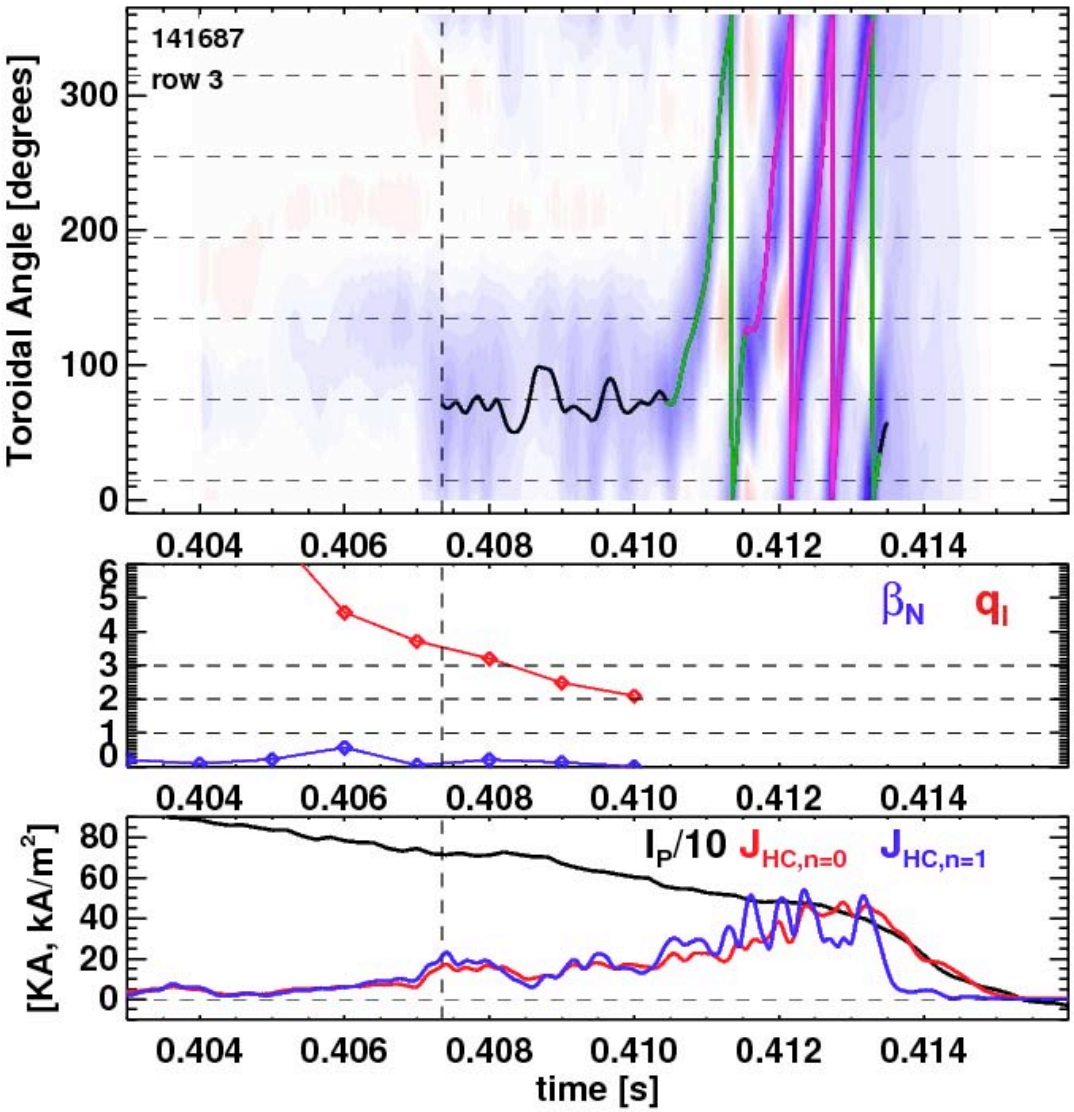
Implies $\mathrm{v}_{pl}(r) = \mathrm{v}_a(r) + \mathrm{v}_{kink}$.

The kink can either lock to or rotate through a fixed external error field. The force between an error field δB_{er} and the field due to the kink δB_{kink} depends on relative toroidal phase $\delta\varphi$:

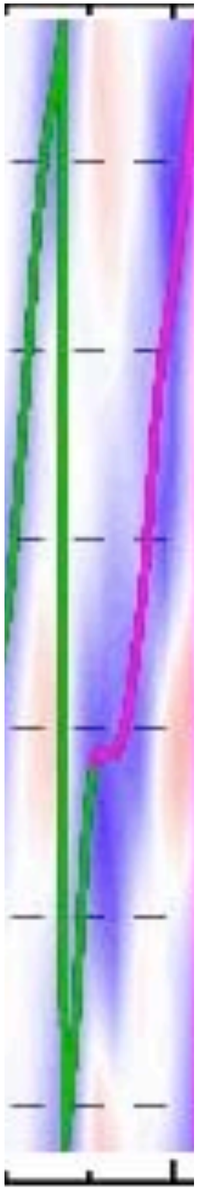
$$f_\varphi = \frac{\delta B_{kink}\delta B_{er}}{\mu_0}\sin(\delta\varphi).$$

Halo current rotation

S. Gerhardt and NSTX group



Why is halo current rotation intermittent?



Although the magnitude of the *n=1* component of halo current is set by force balance, the halo current can vary in a more complicated way from tile to tile.

Such variations would obviously occur if some tiles hit by the halo were perfect resisters.

An n=1 current would still flow as long as a sufficient number of tiles were conductors.

In this case the halo current associated with a smoothly rotating *n=1* kink would appear to lock and unlock as it jumped from one set of conducting tiles to another.

Kink itself is expected to rotate smoothly.

What could additional theory contribute?

1. No force-balance code exists that can calculate non-axisymmetric equlibria with a large fraction of the current in the halo, ~20%.

   Such a code is certainly feasible

   Would clarify many issues, such as

   - intermittant rotation
   - machine dependence of halo toroidal peaking factor (TPF)

2. Comparisons with theory for

   - locked and rotating halo currents.
   - rotation rates from edge and central models for velocity.

3. Studies of how poloidally concentrated the halo current can be. Naively, each open magnetic field line can have a current density independent of its neighbors. Natural current width, $\Delta_{nh} = \sqrt{2\pi R_0 \rho_s}$.

4. Studies of radial width of halo current: cross-field transport, limitation on current density due to ion saturation current, etc.

What do I hope you've learned?

1. Loss of vertical control in a tokamak naturally leads to a kink with a strong halo current with its *n=1* component set by force balance.

Otherwise evolution would be Alfvénic with ~10^6 volts along open magnetic field lines—drives whatever current is needed to restore equilibrium (Zakharov).

2. Halo current, *~20% I*, is primary responsible for destructive forces due to disruptions:

can be more toroidally localized than n=1, and localization makes the halo current more destructive.

3. Ambipolarity locks toroidal rotation of plasma and kink with an offset velocity $v_a(r)$ between them. Plasma flow can be determined by various effects either at the edge or error fields penetrating the core.

4. Although overall kink is expected to either lock or rotate smoothly, halo current can rotate intermittantly when wall structures have a variable electrical properties.