RF Current Condensation and Suppression of Magnetic Islands

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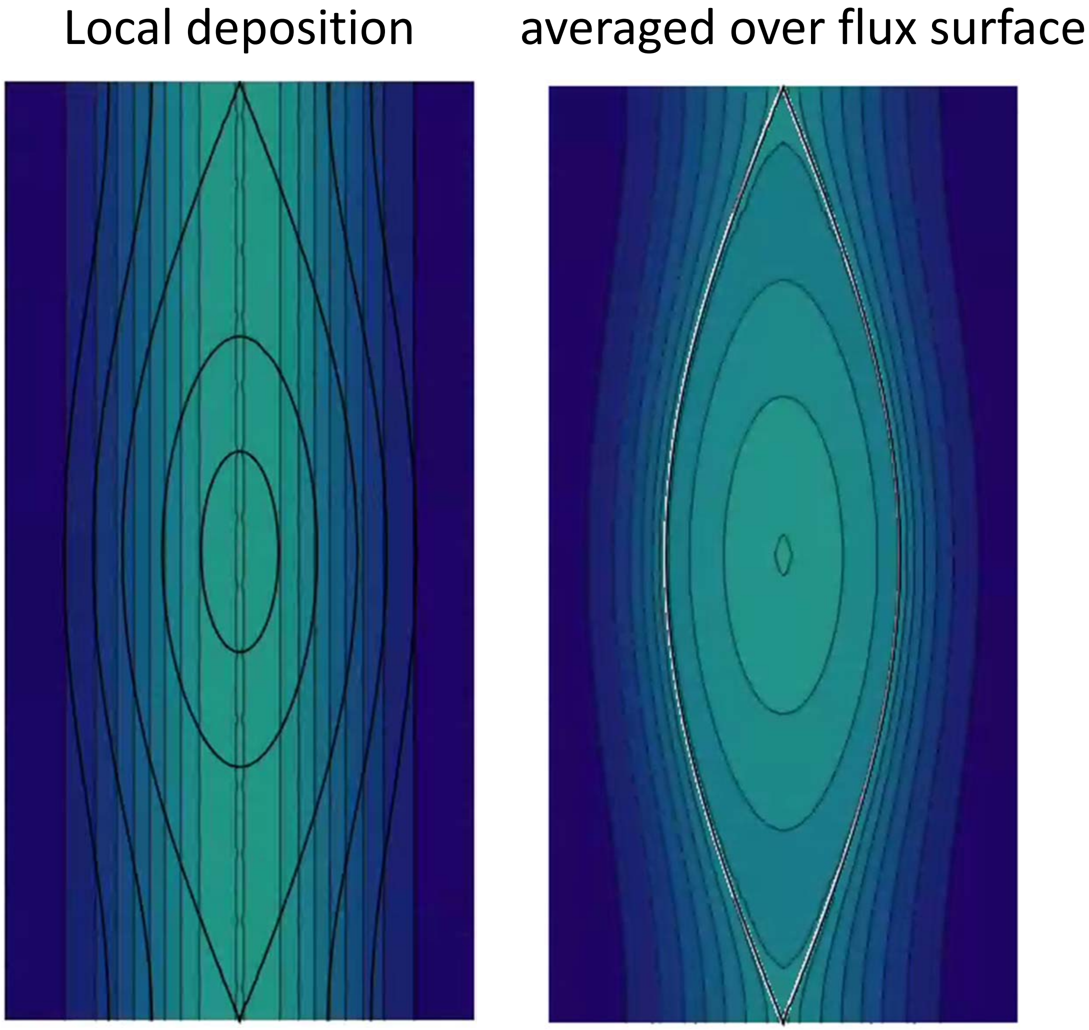
Neoclassical tearing modes (NTMs) identified as single most common root cause of disruptions on JET from 2000 to 2010.

- De Vries *et al* (Nucl. Fusion, 2011): 16% of total disruptions, or 38% of the disruptions with a physics root cause.
- In experiments with ITER-like wall, occurrence of disruptions triggered by NTMs was unchanged. (De Vries *et al,* Phys. Plasmas, 2014).
- ITER will have 20 MW of power capable of driving rf currents for NTM stabilization.

Conventional calculations of RF current drive in islands assume local acceleration of electrons unaffected by presence of island.

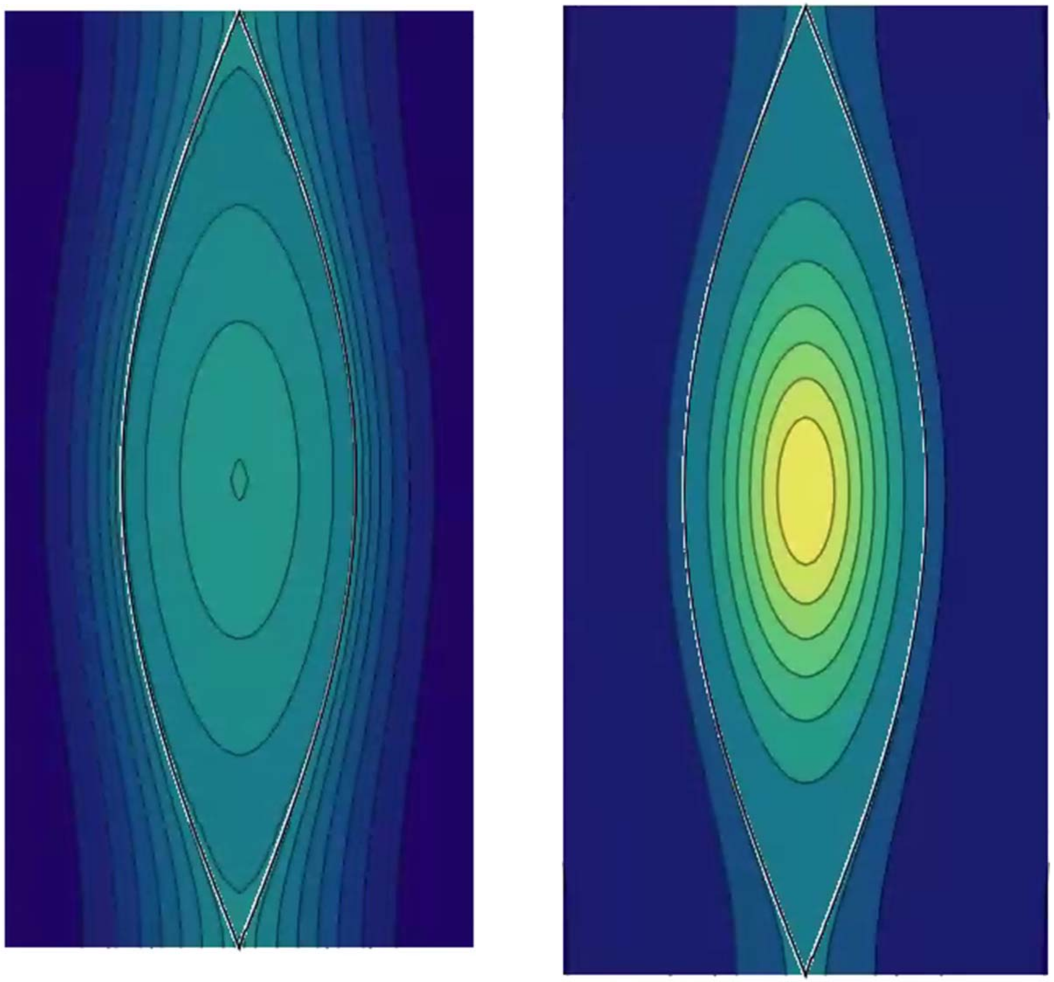


Rapid motion of electrons along field lines gives $\mathbf{B}\cdot\nabla(j_{\parallel}/B)=0.$

Geometry gives higher $j_{\parallel}$ near center -> stabilizing resonant component of field.

Sensitive to radial alignment: Destabilization for $\Delta r > 0.5\max(W_i, W_d)$.

Sensitivity of current drive and power deposition to small changes in temperature can give rise to “current condensation”.



- RF heats island, with T peaked at center.
- Larger resonant component gives efficient stabilization of larger islands that can cause disruptions.
- Reduces sensitivity to precise radial alignment of RF ray trajectories.

Electron-cyclotron and lower-hybrid waves deposit their energy on electron tail → deposition sensitive to temperature.

- Dissipated power

$$P_{RF} \propto \exp(-V_{p1}^2/V_T^2),$$

V_T is thermal velocity, V_{p1} phase velocity at lower end of wave spectrum.

- Let $T = T_s + \tilde{T}$ in island, where T_s is temperature on separatrix, and let $w_1 \equiv V_{p1}/V_T$. Then

$$P_{RF} \propto \exp(-w_1^2) = \exp(-w_{1s}^2)\exp\left(w_{1s}^2\,\tilde{T}/T\right),$$

where w_{1s} is w_1 evaluated at separatrix.

- Typically $w_{1s}^2 \approx 10$ for ECCD, and $w_{1s}^2 \approx 20$ for LHCD, so small change in $\tilde{T}/T_s$ produces large change in P_{RF}.

There are two pieces to the RF condensation effect:

1. Increase of driven current with increasing temperature;
2. Increased power deposition with increasing temperature feeds back on itself.

Both ohmic and rf currents are affected by temperature.

- Low diffusivity in island enhances both effects.
- Increase of ohmic current extensively studied,
  - believed to have provided significant stabilizing effect in a number of experiments:
  - $\Delta J_{Sp}/J_{Sp} = \Delta\, \sigma_{Sp}/\sigma_{Sp} = (3/2)\, \tilde{T}/T_s$
- Increase of rf current with temperature goes like:

$$\Delta J_{RF}/J_{RF} = \exp\left(w_{1s}^2\, \tilde{T}/T_s\right) - 1 > w_{1s}^2\, \tilde{T}/T_s$$

- When bootstrap current comparable to ohmic, required RF current comparable to ohmic, and $\Delta J_{RF} \gg \Delta J_{Sp}$.
- Effect pointed out in: Reiman, Phys. Fluids **26**, 1338 (1983).
  - First paper to propose use of RF driven currents to stabilize magnetic islands, and to show that it is practical.
  - Calculations applicable to ECCD as well as LHCD.

Increase of P_{RF} with T gives nonlinear self-reinforcement of heating in island.

- Transport time scale fast, so can consider steady-state heat diffusion.
- For simplicity, initially consider slab:

$$n\kappa_\perp \partial^2 \tilde{T}/\partial x^2 = -\bar{P}_0 \exp\left(w_{1s}^2 \tilde{T}/T_s\right),$$

with n, $\kappa_\perp$, $\bar{P}_0$ assumed constant in island, $x \equiv (r - r_s)/W_i$.

- When $\tilde{T}$ small, but $w_{1s}^2 \tilde{T}/T_s$ not small, dependence of P_{RF} on $\tilde{T}$ comes only through exponential: $P_{RF} = \bar{P}_0 \exp\left(w_{1s}^2 \tilde{T}/T_s\right)$.
- Write as $\partial^2 u/\partial x^2 = -P_0 \exp(u)$,

where W_i is island width, $u \equiv w_{1s}^2 \tilde{T}/T_s$, $P_0 \equiv W_i^2 w_{1s}^2 \bar{P}_0/(4n\kappa_\perp T_s)$.

- Can solve analytically:

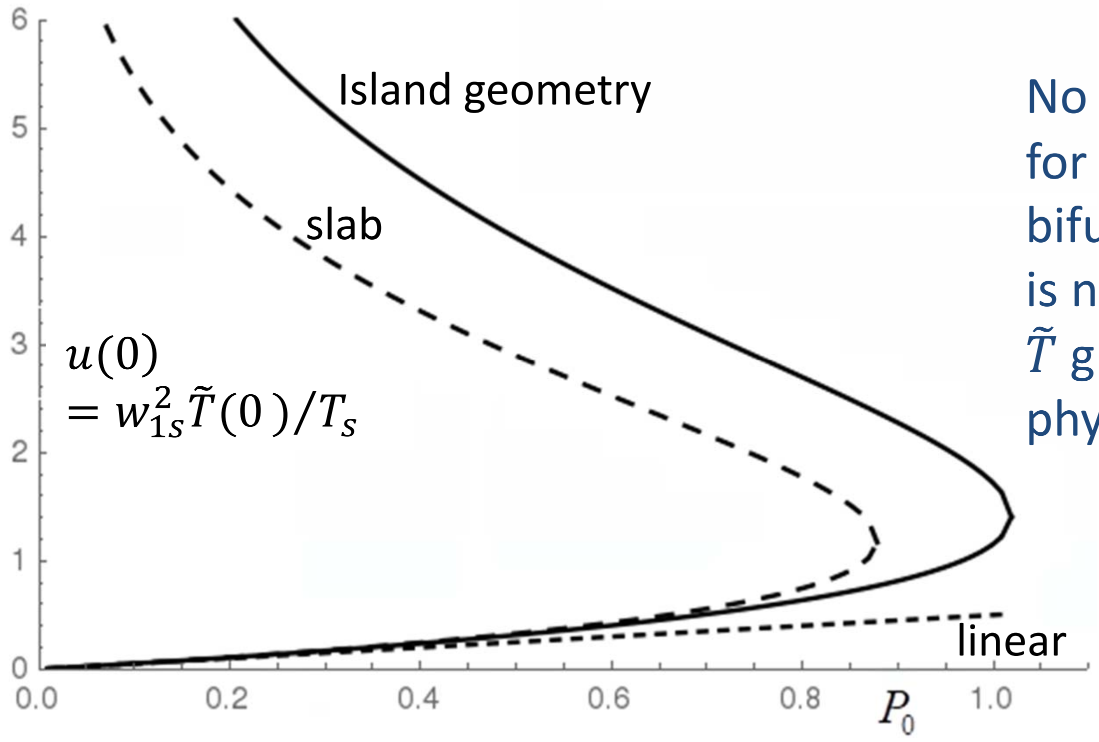
$$u(x) = \ln(\lambda_1/2\,P_0) - 2\ln\left\{\cosh\left[\sqrt{\lambda_1}\,(x-\lambda_2)/2\right]\right\}.$$

- With boundary conditions, get nonlinear eigenvalue equation:

$$\lambda_1 = 2P_0 \cosh^2\left(\sqrt{\lambda_1}/2\right).$$

- 2 solutions below a critical value of P_0, none above.

Steady-state solution for small $\tilde{T}$ exhibits fold bifurcation ("fold catastrophe" in catastrophe theory).



No steady-state solution for small $\tilde{T}$ above the bifurcation point if wave is not depleted.
$\tilde{T}$ grows until additional physics comes in.

A heating effect: does not require current drive.

slab geometry: $\partial^2 u/\partial x^2 = -P_0 \exp(u)$

magnetic island geometry:

$$\frac{d}{d\rho}\left(\frac{1}{\rho}[E(\rho)-(1-\rho^2)K(\rho)]\frac{d}{d\rho}u(\rho)\right) = -P_0 \rho K(\rho) e^u$$

Estimated thresholds for nonlinear heating enhancement are in an experimentally relevant regime.

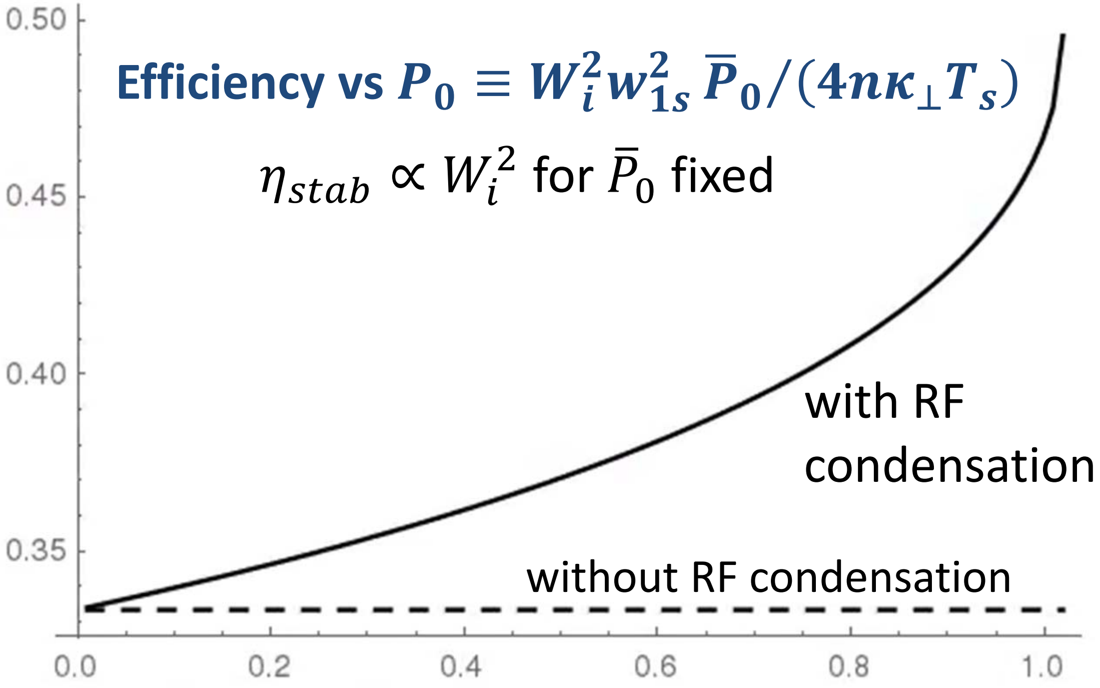
- Solution of diffusion equation provides threshold estimates:
  - significant nonlinear heating enhancement when $\tilde{T}_{\max}/T_s \geq 5\%$;
  - bifurcation threshold of $\tilde{T}_{\max}/T_s \approx 15\%$.
- TEXTOR experiments measured $\tilde{T}_{\max}/T_s \approx 20\%$.
  - Hysteresis effect above bifurcation threshold expected to shrink islands to smaller widths.
  - Experiment observed suppression to island widths well below calculated widths of power deposition profiles.
  - Further analysis of TEXTOR experiments could provide useful information.

Combined, enhanced heating and current drive lead to “RF current condensation” that increases stabilization efficiency.

Widely used measure of efficiency of RF current drive stabilization is ratio of resonant Fourier component of current to total RF driven current:

$$\eta_{stab} = \int_{-\infty}^{\infty} d\,x \oint d\,\zeta j_d(x,\zeta) cos(m\zeta\,)/\int_{-\infty}^{\infty} d\,x \oint d\,\zeta j_d(x,\zeta).$$

where $\zeta = m\theta - n\phi$.



Efficiency vs $P_0 \equiv W_i^2 w_{1s}^2 \bar{P}_0/(4n\kappa_\perp T_s)$

$\eta_{stab} \propto W_i^2$ for $\bar{P}_0$ fixed

Get combined effects from

$$\frac{J_{RF}}{J_{RF0}} = \exp\left(\frac{w_{1s}^2 \tilde{T}}{T_s}\right)$$

and

$$\frac{P_{RF}}{P_{RF0}} = \exp\left(\frac{w_{1s}^2 \tilde{T}}{T_s}\right).$$

The effects will be relevant for larger islands on ITER.

- Low locking threshold and desire for minimal power usage have led to ITER studies for stabilizing islands at small width and modest power deposition – below threshold for these effects.
- Will not be 100% successful – flakes fall into plasma, etc.
  - Will want to stabilize larger islands to prevent disruptions, using available power.
- Locked modes can be stabilized by rf with field error overcompensation.
  - After compensating for field errors, add small field to control phase of locked modes. (See F. A. Volpe, *et al*, Phys. Rev. Lett. **115** (2015).)

Transport calculations by Westerhof *et al* suggest that RF current condensation effect will be seen in ITER

- ASTRA transport simulations for ITER 2/1 magnetic island (Westerhof *et al*, Nucl. Fusion **47,** 85 (2007)) considered a 24 cm island.
  - With 20 MW of heating power and $\chi_e = 0.1 \ m^2/sec$, found $\tilde{T}_{\max}/T_s \approx 25\%$.
- Threshold for significant nonlinear effect is $w_{1s}^2 \, \tilde{T}_{\max}/T_s \approx 0.5$, or $\tilde{T}_{\max}/T_s \approx 5\%$.
- $\tilde{T}_{\max}/T_s$ scales as $W_i P_{tot}$, where P_{tot} is total power deposition in island.
  - Threshold island width for 20 MW about 5 cm.
  - Threshold island width for 10 MW about 10 cm.

Summary and Discussion

- $J_{RF}, P_{RF} \propto \exp\left(w_{1s}^2 \tilde{T}/T_s\right)$ in island.
- Nonlinear feedback on P_{RF} increases $\tilde{T}/T_s$, and can lead to bifurcation.
- Combined effect gives "RF current condensation" in island:
    - Efficiency of current drive stabilization greatly increases as power deposition or island width increases.
- The effect also reduces sensitivity of stabilization to radial misalignment of ray trajectories with island O-point.
- Nonlinear threshold for effect is in regime that has been encountered in experiments, and will likely be encountered in ITER.
    - Will allow stabilization of larger islands in ITER that would otherwise lead to disruptions.
- With 20MW ECCD, ITER may be able to get NTM disruptions to low level.
- Would be valuable for existing tokamaks to test strategies for doing that.
    - Could piggyback on existing experiments.
- Design of strategies will need to take into account RF condensation effect.