RF Current Condensation and Suppression of Magnetic Islands

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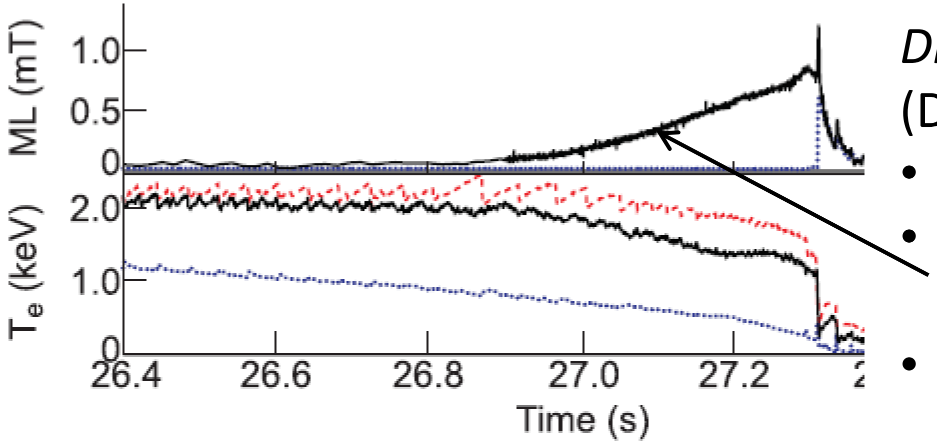
See also Phys. Rev. Lett. **121**, 225001 (2018),

and Rodriguez, Reiman, Fisch,
arXiv:1907.01612 (2019).

- “Operation of ITER will have to strongly focus on avoiding disruptions with a high success rate and on mitigating those in which avoidance techniques fail” – ITER Research Plan, Sept. 2018.
- Would like to avoid disruptions to the extent we can:
  - minimize loss of valuable machine time from cleaning up after mitigated disruptions;
  - keep cumulative damage to first wall at an acceptable level;
  - reduce risk.

- **Gerasimov et al (IAEA FEC 2018) report that 95% of disruptions in JET with ITER-like wall preceded by locked islands.**
  - In addition to triggering by NTMs, islands also arise in chains triggered by other off-normal events.
  - Once island forms, pressure flattens in interior, bootstrap current vanishes there, and neoclassical effect drives further growth.
    - Can we avoid disruptions by ECCD suppression of such islands?
    - Can we facilitate "soft landing" by ECCD suppression?
    - Need to do the experiments.
- **A nonlinear effect, "RF current condensation", can potentially facilitate the suppression of islands.**

RF current drive stabilization operates on a fast time scale



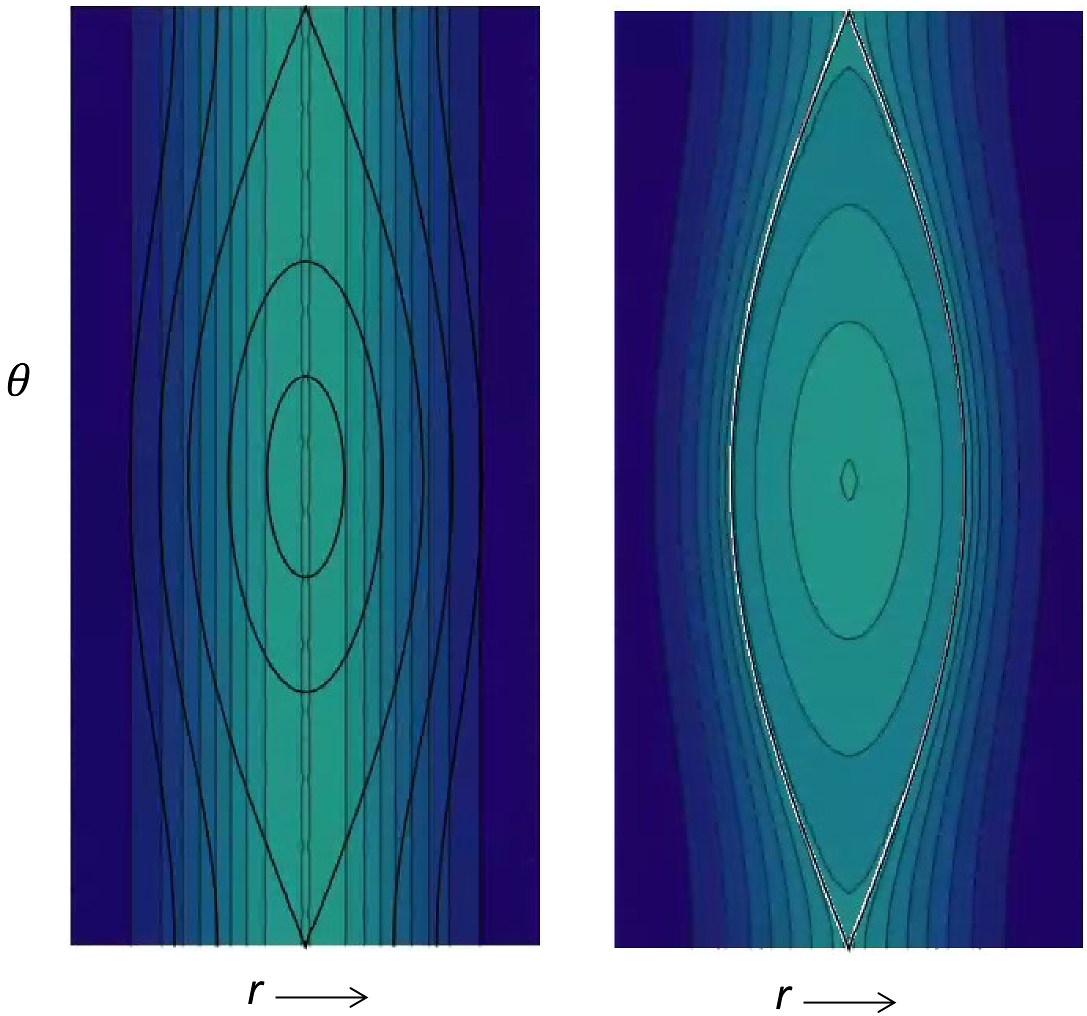
Disruption in JET shot 83601.
(Devries *et al*, Nucl. Fusion 2016)

- 26.8 sec: locked mode appears
- 160 msec before thermal quench: discharge termination triggered
- 500 msec after mode onset: thermal quench

- Island grows on time scale $\Delta' a \tau_R$, where τ_R is global resistive time scale.
  - Both rotating and locked.
- Fast ramp-downs can themselves trigger disruptions.
- ECCD: stabilizing electric field established on electron-ion collision time.
- Poli *et al*: Detection threshold and time to switch between mirrors on ITER combine to prevent feedback stabilization of 2/1 before locking (9 cm).
  - Suggest preemptive stabilization.
- Will 2/1 island lock earlier because of ELM RMP coils?

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

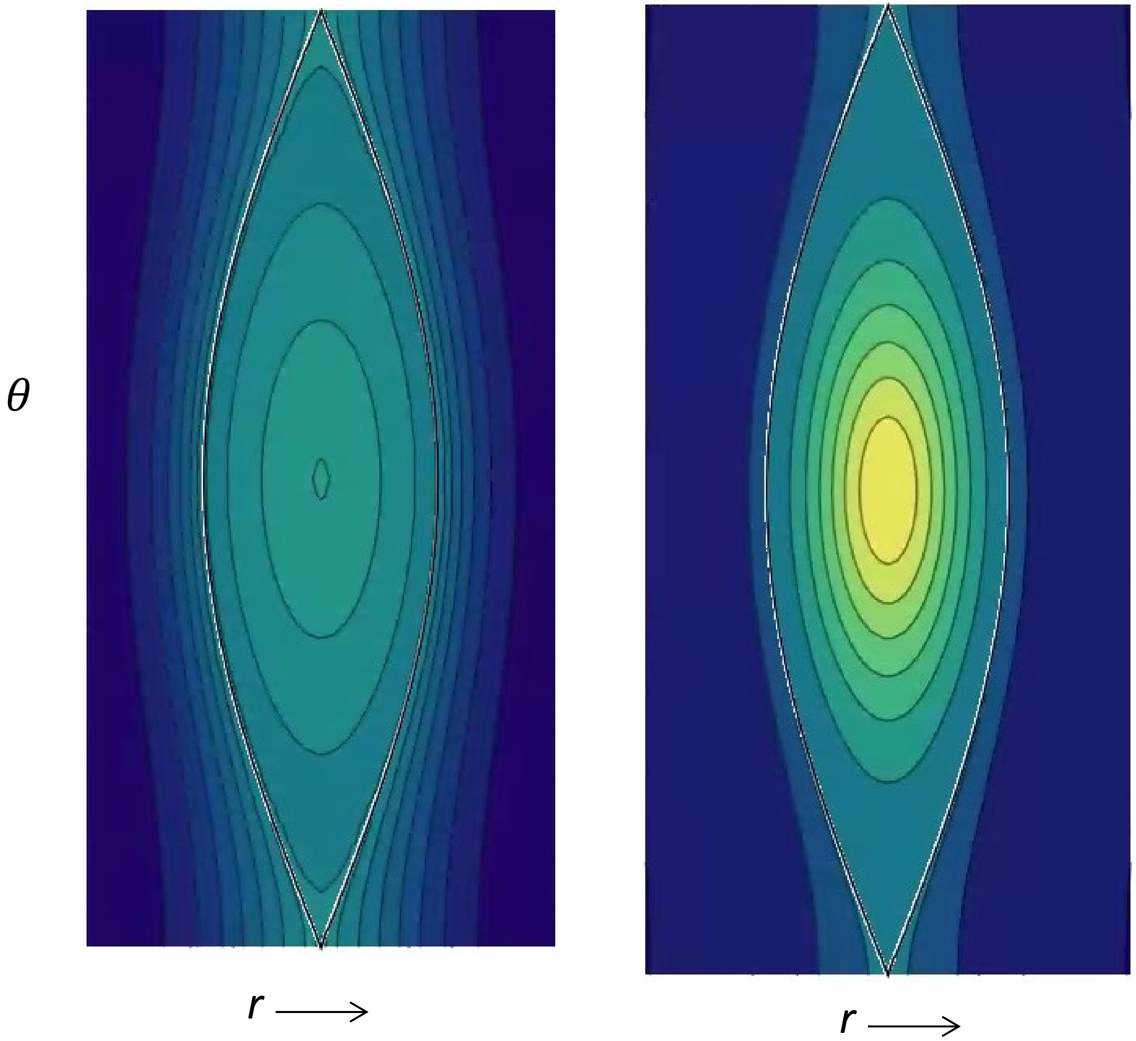
Local deposition Averaged over flux surface



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.

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



- Current concentrates near center of island.
- Larger resonant component gives more efficient stabilization of larger islands that can cause disruptions.

In electron-cyclotron current drive (ECCD) and lower hybrid current drive (LHCD), energy deposited on electron tail → deposition sensitive to temperature.

- Number of resonant electrons and therefore power deposition

$$\propto \exp\left(-V_p^2/V_T^2\right),$$

  where V_T is thermal velocity, V_p phase velocity.

- Let $T = T_0 + \tilde{T}$, where T_0 is unperturbed temperature, and let $w \equiv V_p/V_T$. Then

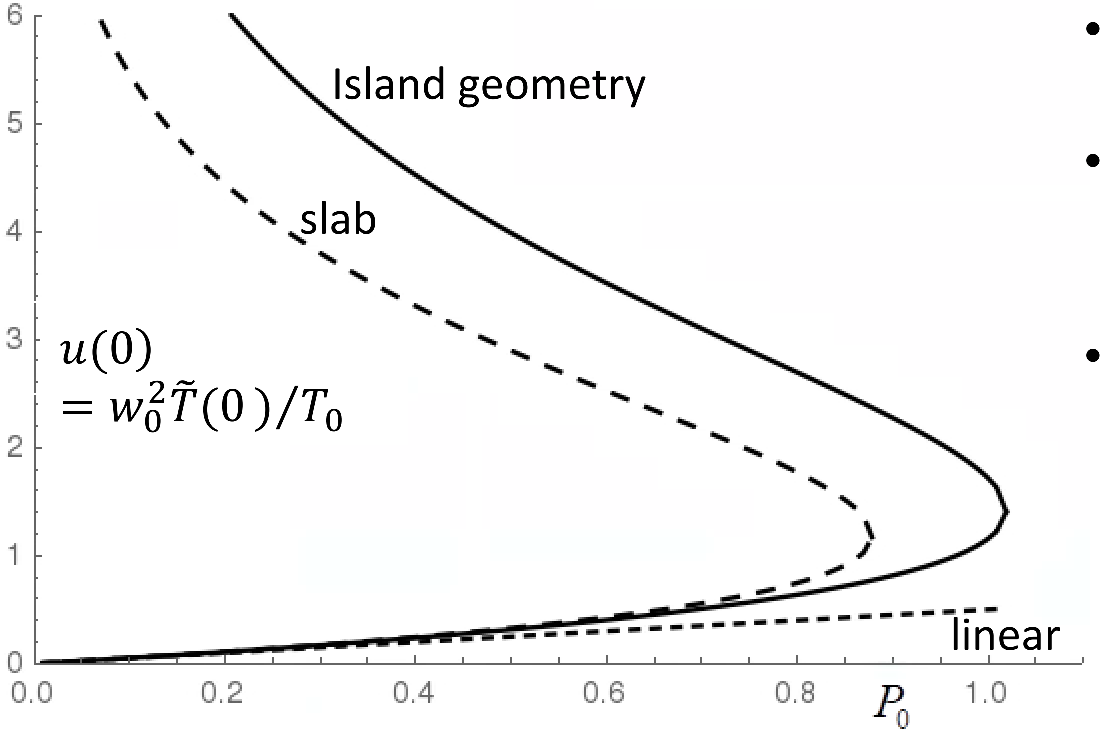
$$P_{RF} \propto \exp(-w^2) = \exp(-w_0^2)\exp\left(w_0^2\,\tilde{T}/T_0\right),$$

  where w_0 is unperturbed w.

- Can have $w_0^2 \approx 10$ for ECCD, and $w_0^2 \approx 20$ for LHCD, so small change in $\tilde{T}/T_0$ can produce large change in P_{RF}.

Both the power deposition and the RF driven current (Reiman, Phys. Fluids (1983)) **are sensitive to the temperature perturbation.**

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



- $P_{RF} \propto \exp\left(w_0^2\,\tilde{T}/T_0\right)$ for small $\tilde{T}$.
- No steady-state solution for small $\tilde{T}$ above the bifurcation point.
- $\tilde{T}$ grows until additional physics comes in.

$$\boxed{P_0 \propto P_{RF0} W_{\mathrm{i}}^2}$$

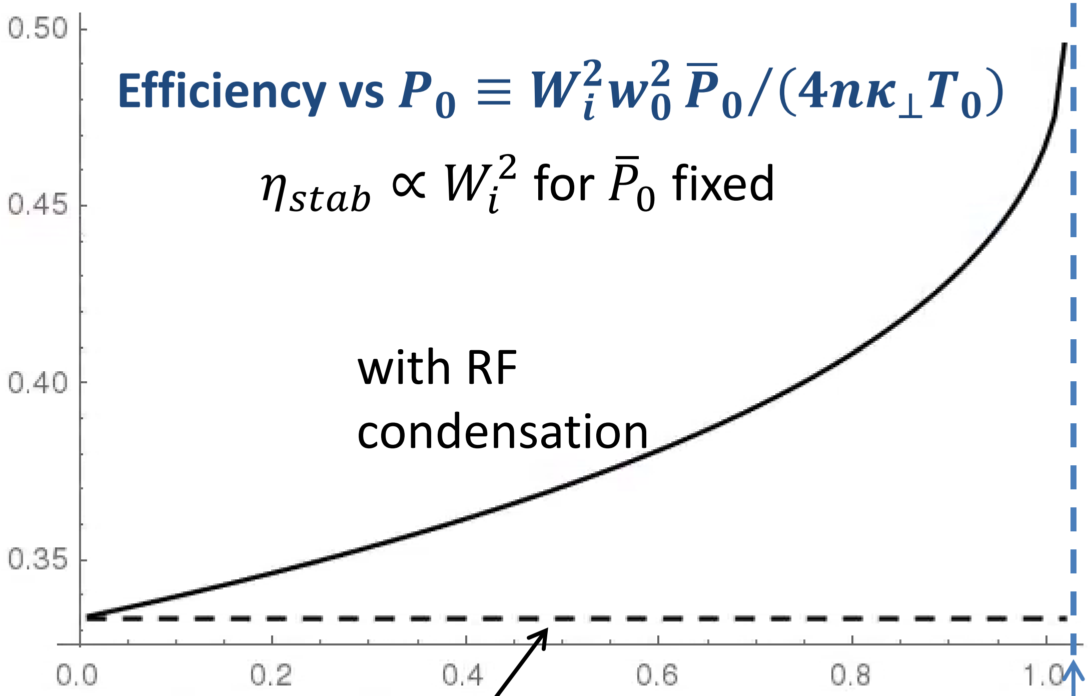
slab geometry: $\partial^2 u/\partial x^2 = -P_0 \exp(u)$

magnetic island geometry:

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

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:



Efficiency vs $P_0 \equiv W_i^2 w_0^2 \bar{P}_0/(4n\kappa_\perp T_0)$

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

without RF condensation (Hegna & Callen)

solution bifurcates

Get combined effects from

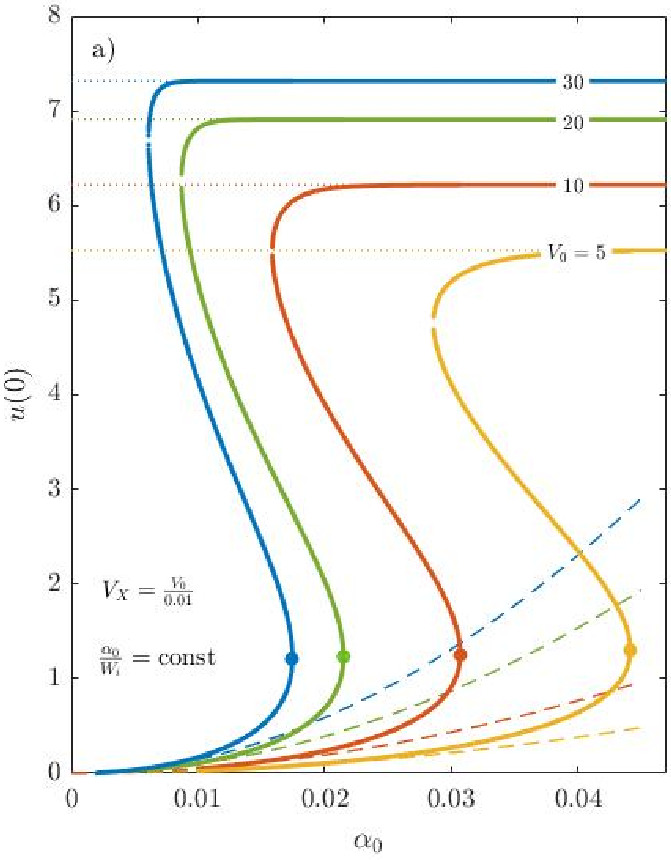
$$\frac{J_{RF}}{J_{RF0}} = \exp\left(\frac{w_0^2\tilde{T}}{T_0}\right)$$

and

$$\frac{P_{RF}}{P_{RF0}} = \exp\left(\frac{w_0^2\tilde{T}}{T_0}\right).$$

Inclusion of wave energy depletion adds a third branch to the solution.

(See poster by Rodriguez *et al*.)



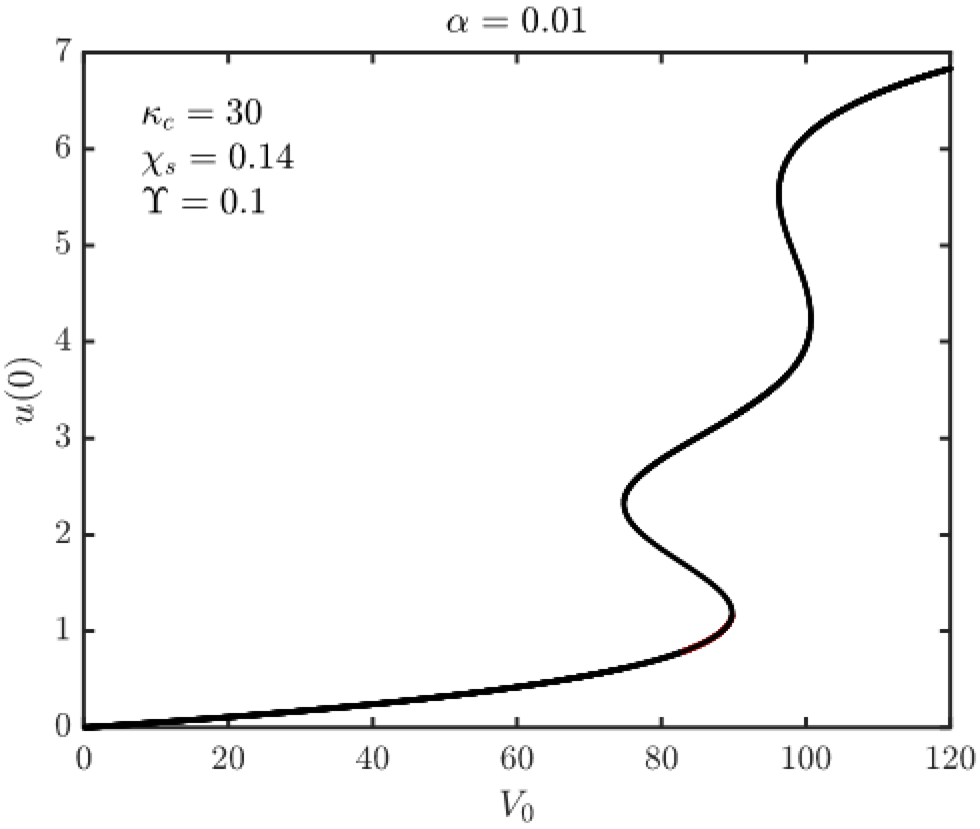
- Increase in temperature terminated by depletion of wave energy.
- Discontinuity in solution to steady-state thermal diffusion equation in island.
- Hysteresis: As ECCD shrinks island, it remains on third branch until it shrinks below 2nd bifurcation point.

Central island temperature vs. island width for a set of constant incident wave energy densities, using slab model of island interior.
Calculation by Eduardo Rodriguez.

Taking account of stiffness, can get two bifurcations.

Stiffness: Transport increases above microstability threshold.

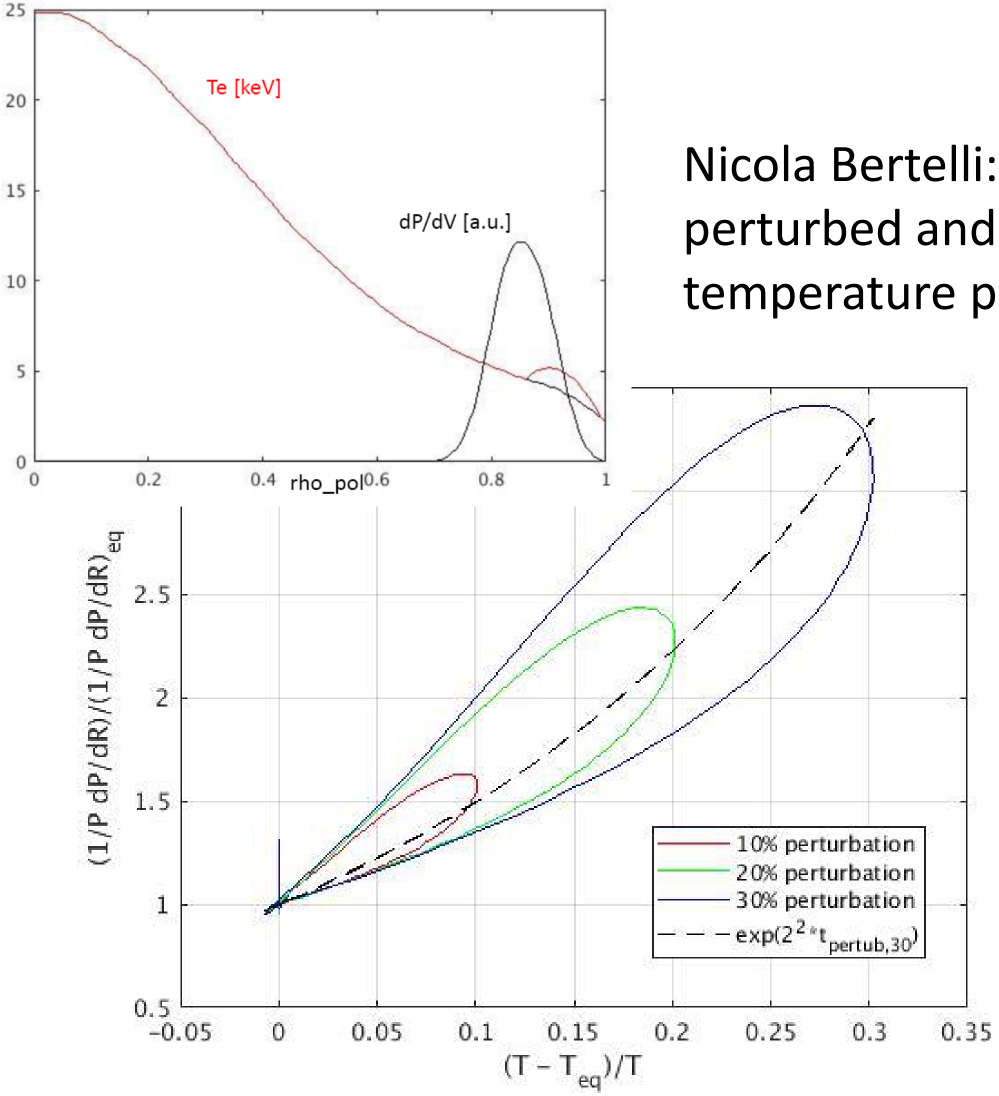
$$\kappa = \kappa_0\left[1+\frac{\kappa_s}{\kappa_0}\left(\frac{-R\partial_r T}{T}-k_c\right)H\left(\frac{-R\partial_r T}{T}-k_c\right)\right]$$



Normalized central temperature vs. power.

Calculation by Eduardo Rodriguez.

Ray tracing calculations of EC power deposition sensitivity to temperature perturbation



Nicola Bertelli: Ray tracing calculation for perturbed and unperturbed ITER temperature profiles at *q*=2 surface.

Ratio of fractional power deposition with and without perturbation vs. temperature perturbation.

Mike Brookman doing similar calculations for DIII-D.

Estimated thresholds for nonlinear enhancement are in an experimentally relevant, and ITER relevant, regime.

- Threshold estimates for $w = V_p/V_T$ = 3:
    - significant nonlinear current drive enhancement at O-point when $\tilde{T}_{\max}/T_s \geq 5\%$;
    - bifurcation threshold of $\tilde{T}_{\max}/T_s \approx 15\%$.
    - Compares with experimental observation of $\tilde{T}_{\max}/T_s \approx 20\%$.
- ASTRA transport simulations for ITER 2/1 magnetic island (Westerhof *et al*, Nucl. Fusion **47,** 85 (2007)) can be used to estimate threshold for seeing nonlinear effect in ITER:
    - ITER threshold island width for 20 MW (total available ECCD power) about 5 cm (.025 *a*).
    - Threshold island width for 10 MW about 10 cm.
    - Will want to use all available ECCD power for suppression when island width poses threat.
    - Aiming of ray trajectories will need to take into account nonlinear effect.

Discussion

- Nonlinear effects can significantly facilitate rf current drive stabilization of magnetic islands.
  - Experiments and theory now finding substantial turbulent spreading of EC beams, making condensation even more important.
- Gerasimov et al (IAEA FEC 2018) report that 95% of disruptions in JET with ITER-like wall preceded by locked islands.
  - Can arise during chain triggered by off-normal event other than NTM.
  - Can target islands with full available ECCD power at lower threshold than would trigger discharge termination.
  - Can suppression have a significant impact on the disruption frequency? Experimental campaigns needed to determine this.
  - Need adequate EC power on present day experiments to explore this.
- Need dedicated experiments to improve understanding of nonlinear effects in ECCD stabilization of islands.
- **We should be making a serious effort to eliminate disruptions, not just mitigate them, and ECCD should be one component of that effort.**