Electron-cyclotron current drive (ECCD) stabilization of large islands could play an important role in reducing disruption frequency in ITER.

RF Current Condensation can facilitate this.*

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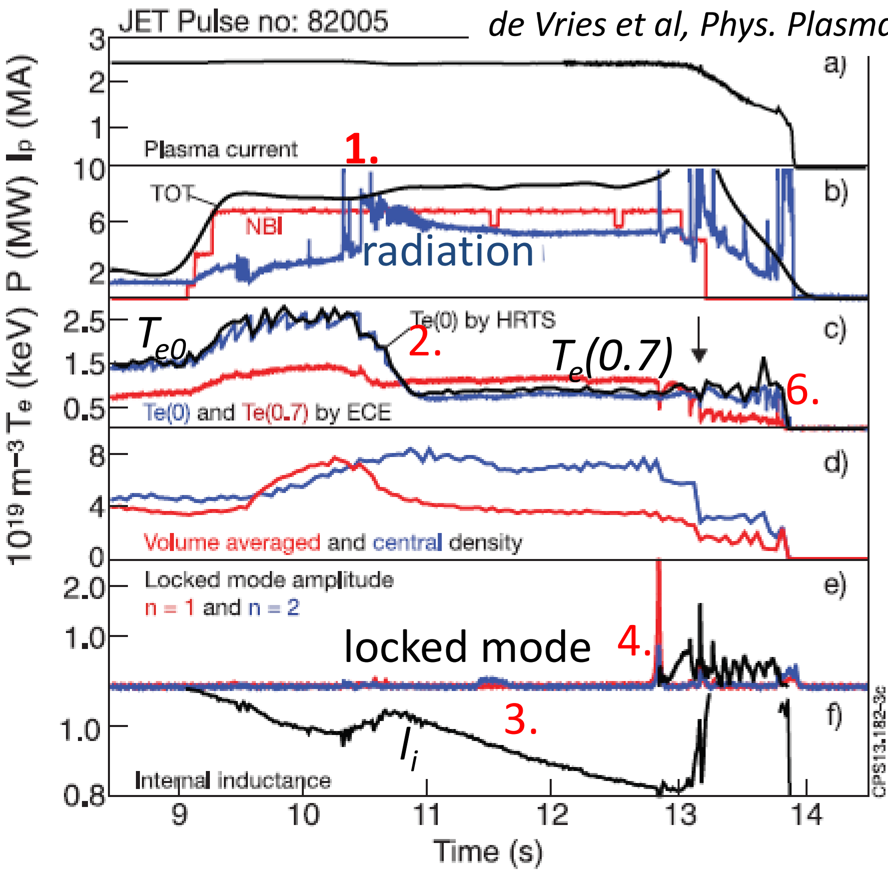
Can we reduce disruptivity by ECCD suppression of large islands produced by off-normal events?

- 95% of disruptions in JET with ITER-like wall preceded by locked islands (Gerasimov et al, IAEA FEC 2018) .
- Statistical analysis of 250 disruptions on JET finds distinct locked mode amplitude at which plasma disrupts (de Vries *et al*, Nucl. Fusion, 2016).
    - Further analysis concludes that $W/a \approx 0.3$ is threshold.
    - Suggests that islands are playing key role in triggering disruptions.

Most large islands that cause disruptions arise from off-normal events other than conventional neoclassical tearing modes (NTMs)

- Analysis of JET shots run during 2011 – 2012 (de Vries *et al*, Phys. Plasmas, 2014):
  - 0.5% of shots disrupted because of NTMs;
  - 4.6% disrupted because of impurity accumulation and radiation in core. (By far the major cause of disruptions in this period.)

de Vries et al, Phys. Plasmas, 2014



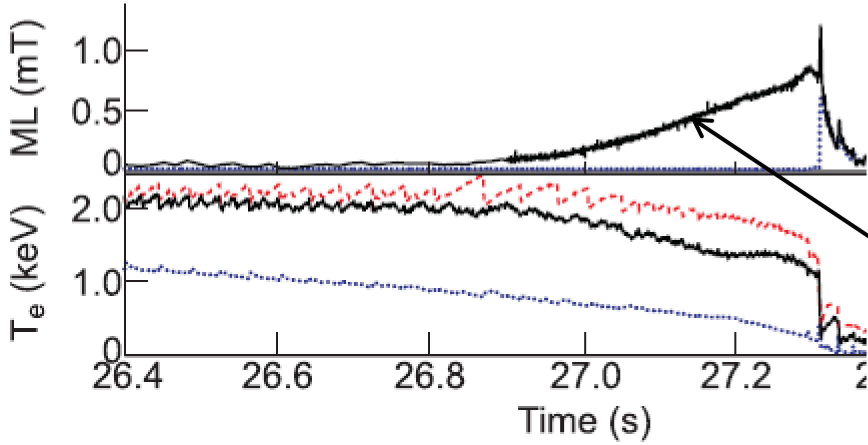
Typical disruption from impurity accumulation:

1. Rapid radiation increase at $t \approx 10.5$ sec.
2. Hollow temperature profile.
3. Current profile broadens. (l_i decreases.)
4. Rapid island growth and locking.
5. Thermal quench, but no disruption, 360 msec later.
6. Almost a second later: second thermal quench causes disruption.

Island plays key role in causing disruption.

What tools can intervene on needed time scale?

To avoid a disruption, the time scale associated with the actuator is critical.

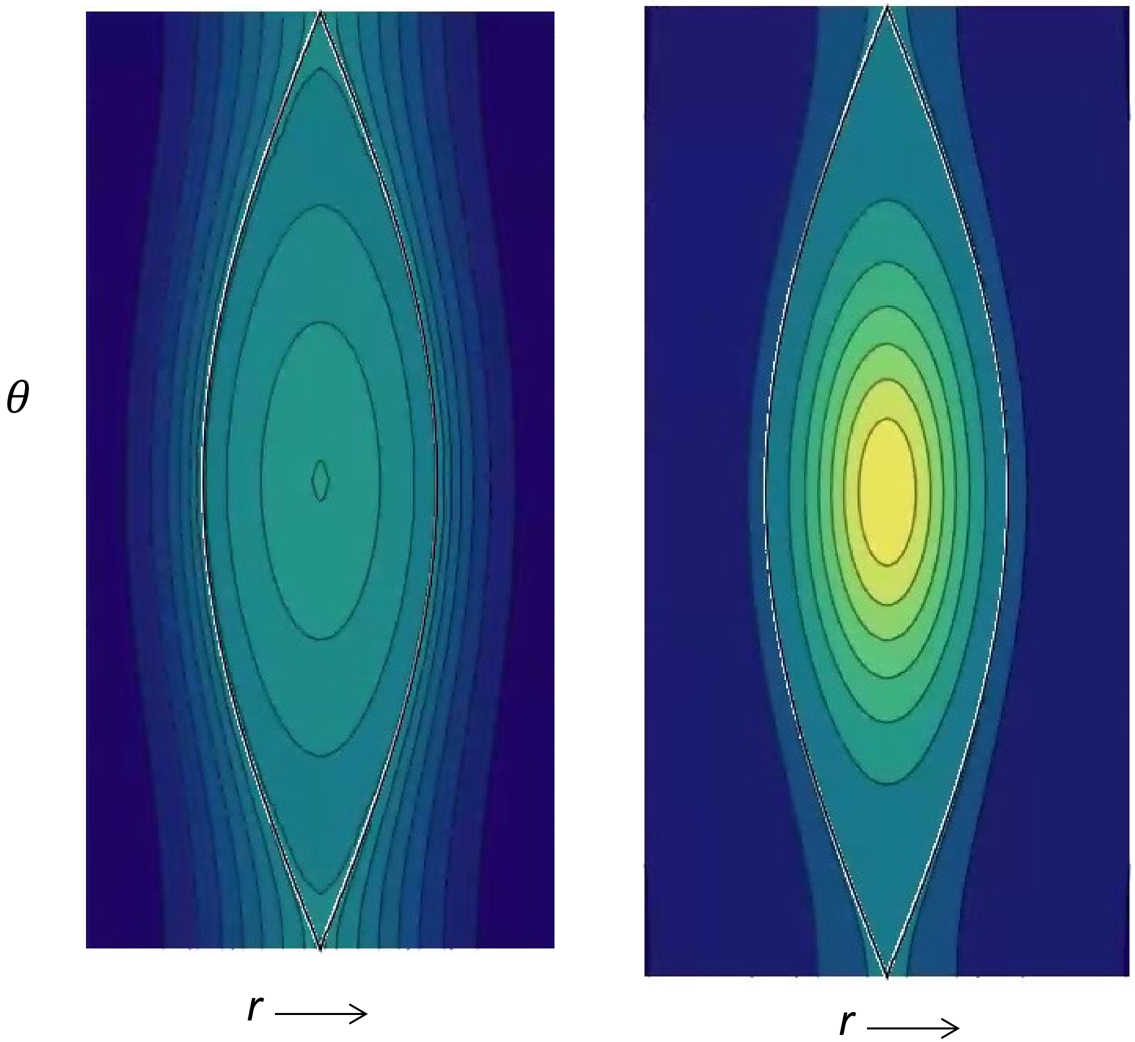


Disruption in JET shot 83601.
(Devries *et al*, Nucl. Fusion 2016)

- 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.
  - Resistive time scale will be much longer on ITER.
- Ramp-down is on τ_R scale, and can trigger disruption if too fast.
- RF current drive establishes stabilizing electric field on electron-ion collision time. (Reiman, Phys. Plasmas 1983)
- **Need to be investigating use of ECCD as a tool to stabilize large islands produced by off-normal events.** (ECCD island stabilization studies for ITER have focused on stabilization of small islands produced by NTMs.)
- **Nonlinear effects can facilitate ECCD suppression of large islands.**

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 can provide more efficient stabilization of large islands that can cause disruptions.

A. Reiman and N. Fisch, Phys. Rev. Lett. **121**, 225001 (2018).

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

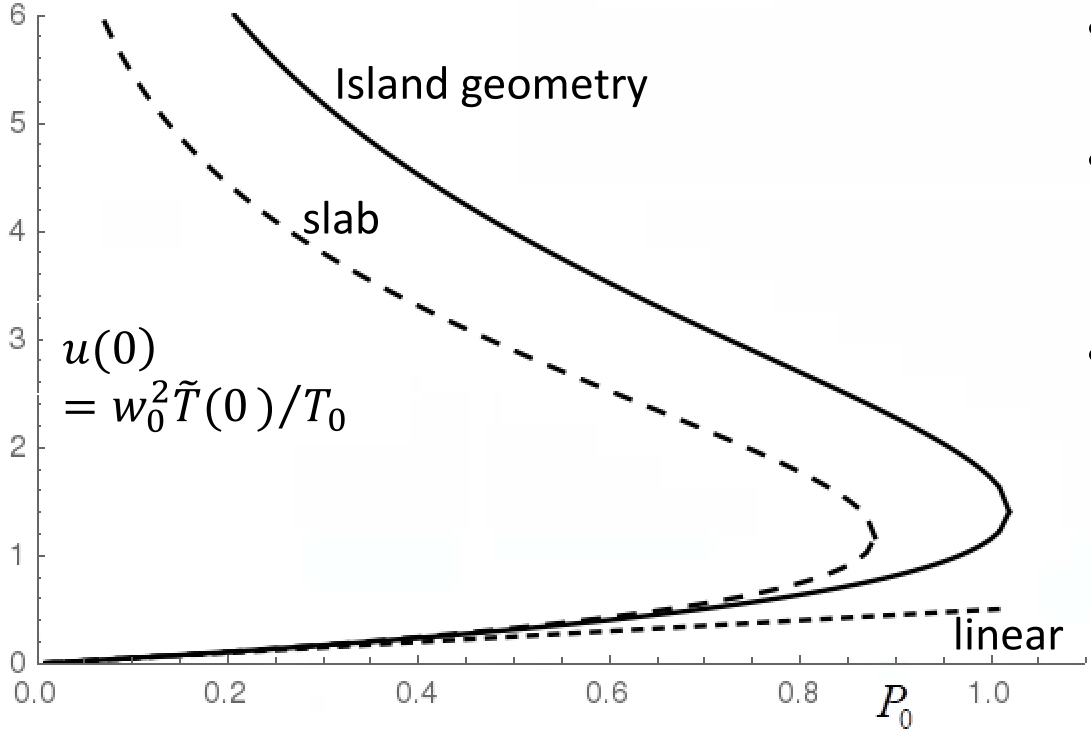
- Number of resonant electrons and therefore power deposition Maxwellian

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

  with V_T thermal velocity, V_p phase velocity.

  Let $w \equiv V_p/V_T$. (Island width will be denoted W_i.)
- Let $T = T_0 + \tilde{T}$, with T_0 unperturbed temperature, and. $P_{RF} \propto \exp(-w^2) = \exp(-w_0^2)\exp\left(w_0^2\,\tilde{T}/T_0\right)$, w_0 unperturbed w.
- Typically $w_0^2 \geq 4$ for ECCD, larger for LHCD.
- Significant nonlinear effect on power deposition and driven current when $\tilde{T}/T_0 \approx 0.5/w_0^2$, an experimentally relevant regime.
- Increased power deposition with increasing temperature feeds back on itself to give nonlinearly enhanced 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.

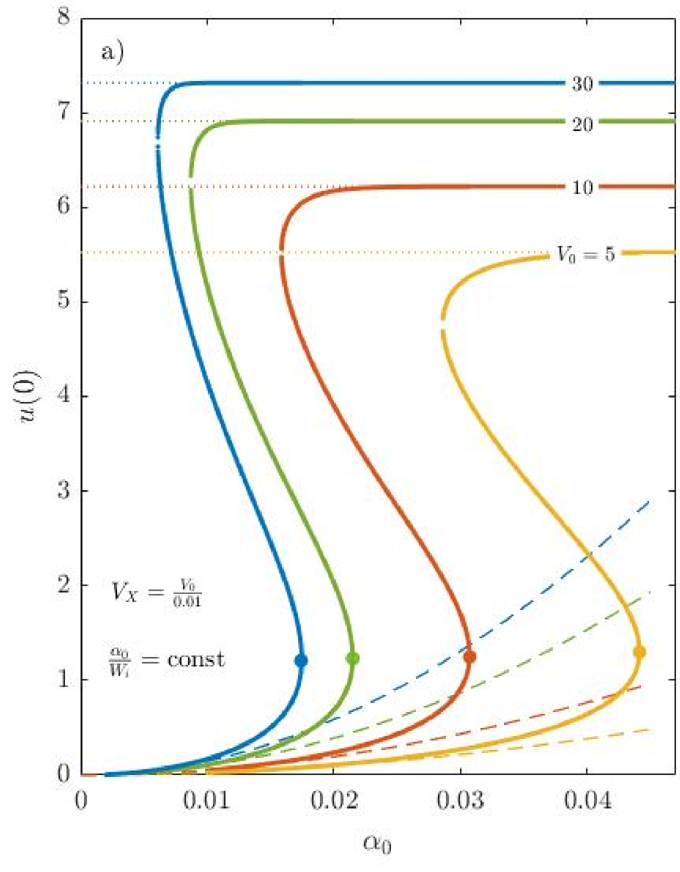
$P_0 \propto P_{RF0} W_{\mathrm{i}}^2$

magnetic island geometry:

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

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

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



Central island temperature vs. island width, using slab model of island interior.
Calculation by Eduardo Rodriguez.

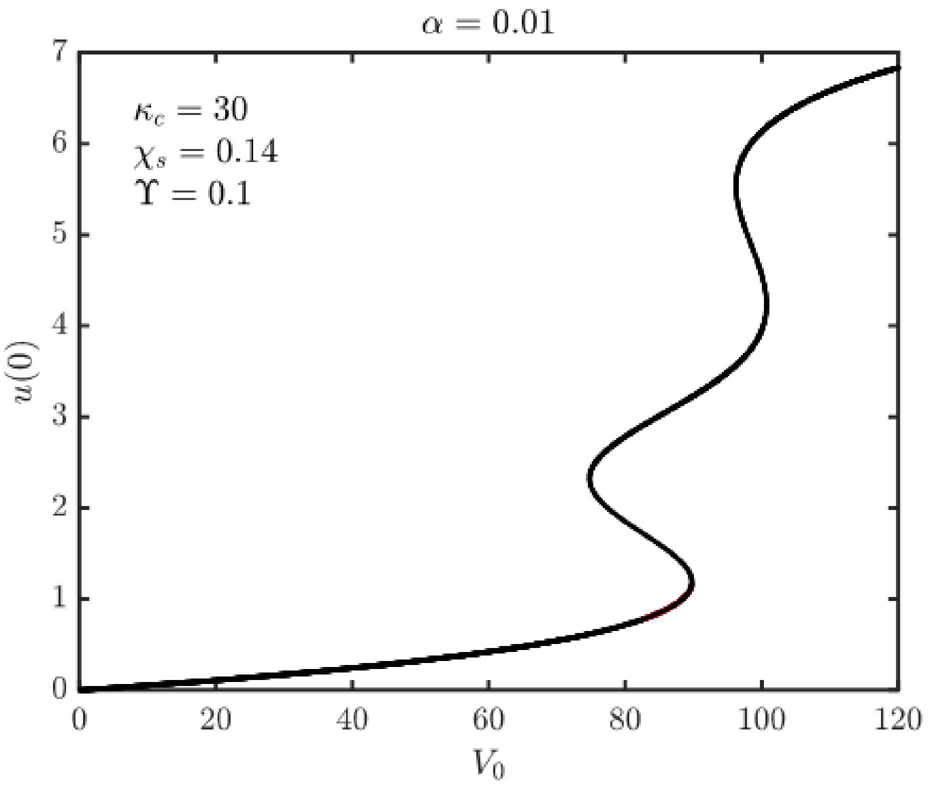
- Discontinuous jump in temperature with increasing Power.
- Increase in temperature terminated by depletion of wave energy.
- Hysteresis: As ECCD shrinks island, it remains on third branch.

Rodriguez, Reiman, Fisch, Phys. Plasmas, 26, 092511 (2019).

- But: If aiming of ray trajectory does not take into account nonlinear effect, can get "shadowing":
  - **Power can be depleted before reaching O-point.**

Profile Stiffness: Transport coefficient increases at ITG threshold.

- For island with initially flattened temperature profile, experimental and computational evidence suggests that thermal diffusion coefficient relatively small relative to that outside island.
- ITG turbulence can saturate temperature increase above bifurcation threshold, giving third root and hysteresis.
- Second bifurcation can appear at still higher power.



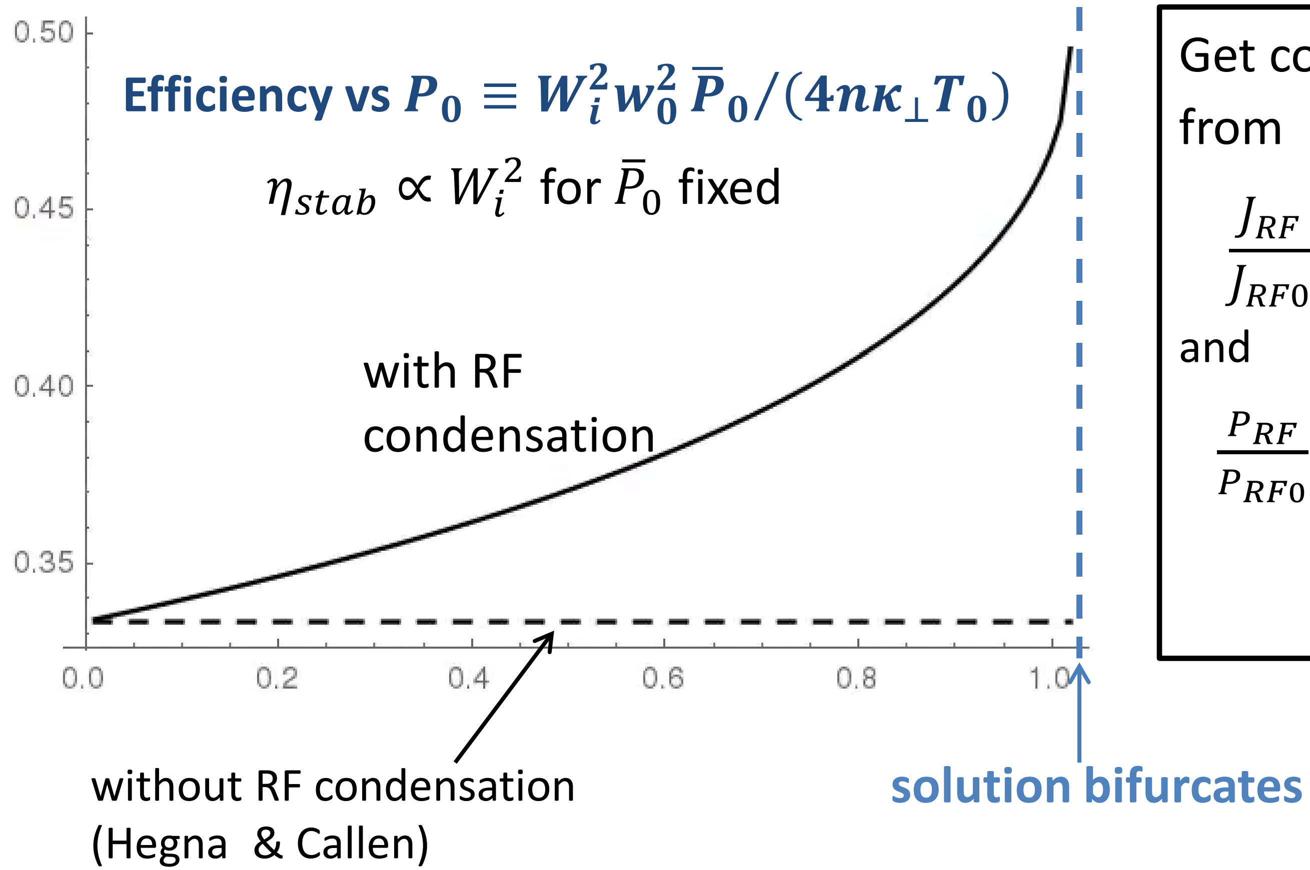
Normalized central temperature vs. power.

Calculation by Eduardo Rodriguez.

Rodriguez, Reiman, Fisch, Phys. Plasmas **27**, 042306 (2020).

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:



Get combined effects from

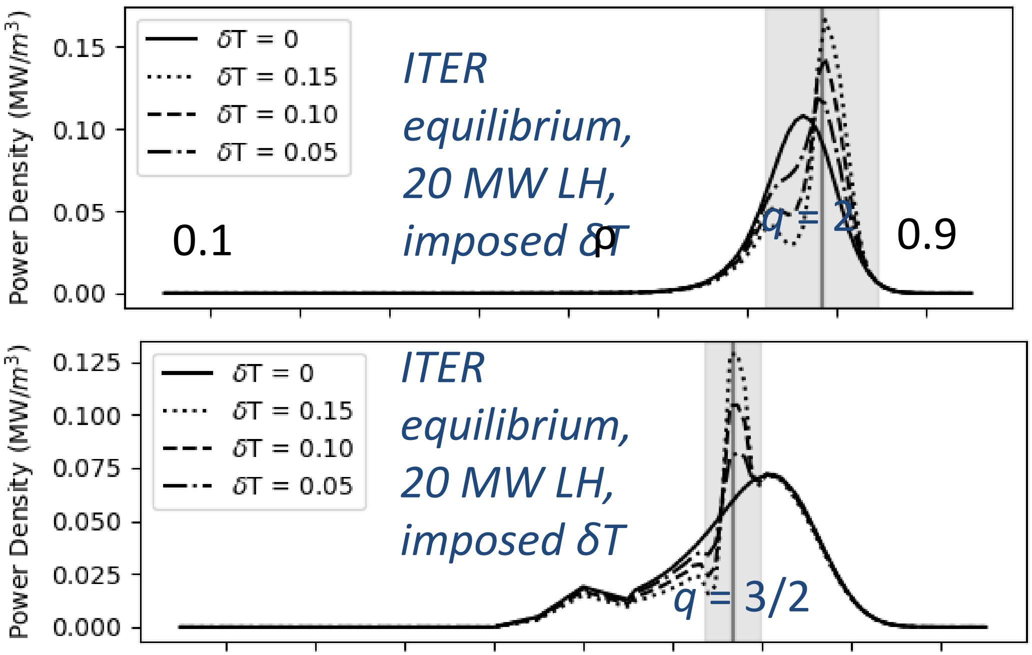
$$\frac{J_{RF}}{J_{RF0}} = \exp\left(\frac{w_0^2 \tilde{T}}{T_0}\right)$$

and

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

RF current condensation motivates reevaluation of lower hybrid current drive (LHCD) for stabilizing islands

Raytracing-Fokker Planck calculations (Sam Frank, Paul Bonoli, MIT)
S. Frank, A. Reiman, N.Fisch and P. Bonoli, Nucl. Fusion, to appear.

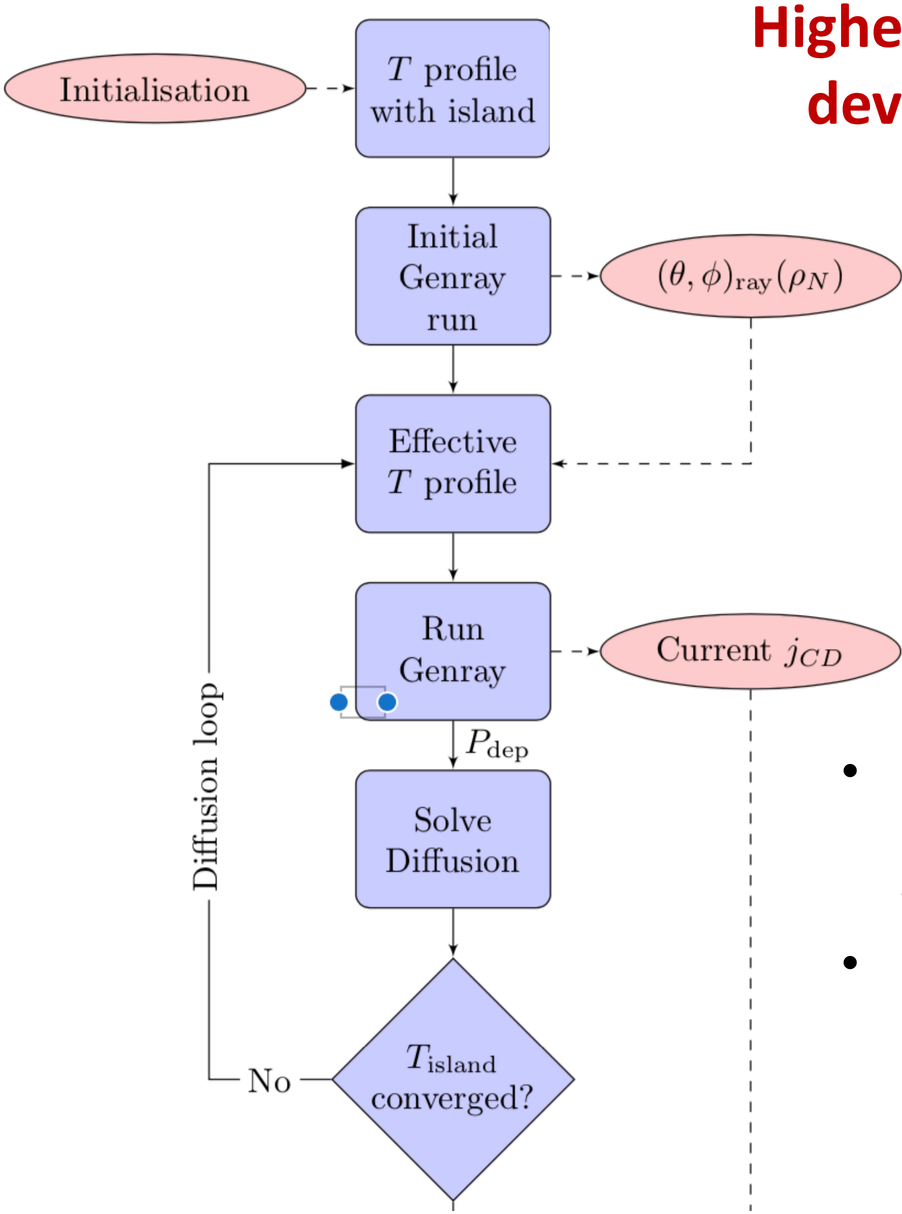


- Broad deposition provides little stabilization in conventional model, but can be localized by condensation effect.
- LH very sensitive to δT (large w).

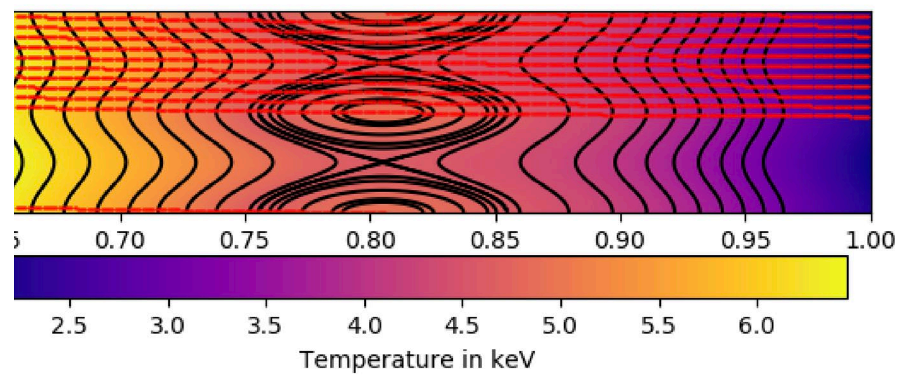
- Further improvement with pulsing investigated by Suying Jin.

S. Jin, N. Fisch, and A. Reiman, Phys. Plasmas 27, 062508 (2020).

Higher fidelity simulation code developed by Richard Nies



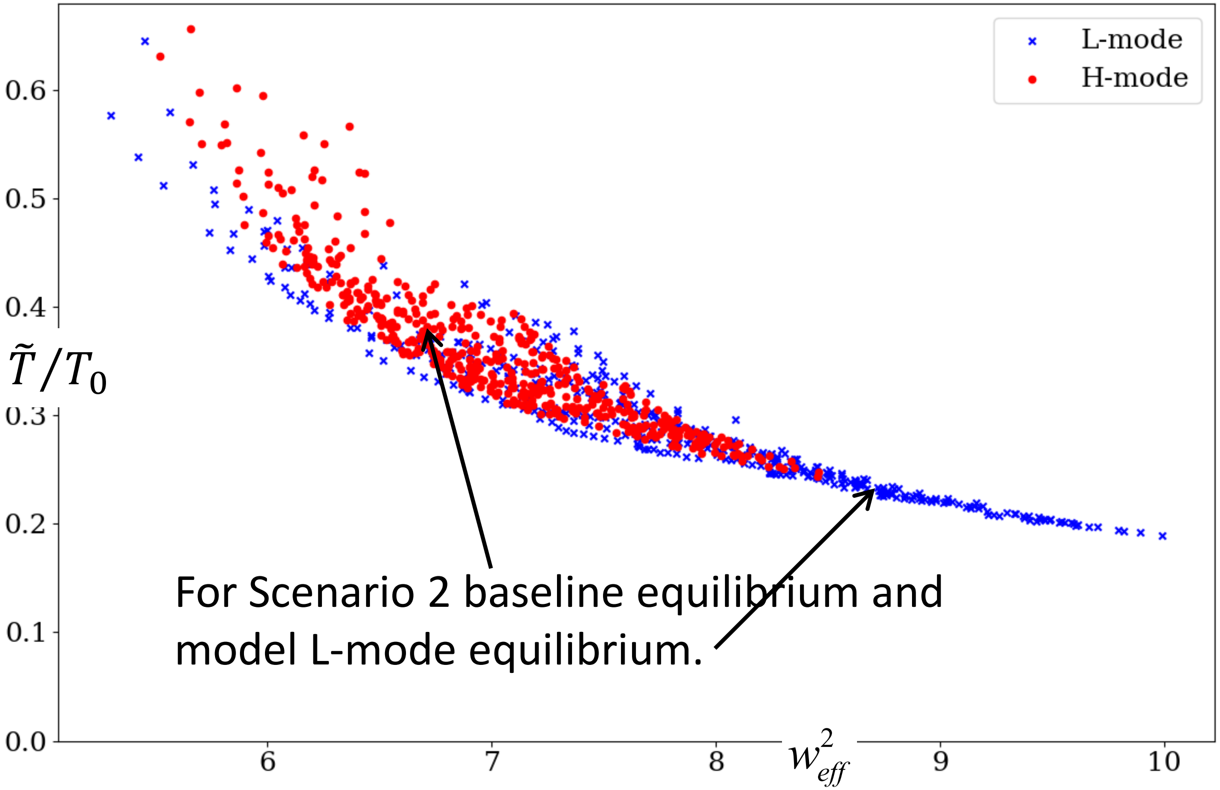
R. Nies, A. Reiman, E. Rodriguez, N. Bertelli, N. Fisch, http://arxiv.org/abs/2005.05997



- Couple to GENRAY to calculate EC power deposition and driven current along ray trajectories (with help of Nicola Bertelli).
- Solve thermal diffusion equation in magnetic island with calculated power deposition.

The bifurcation threshold will be accessible in ITER plasmas

(but not at initial preset toroidal launch angle of 20°).



Result of 20,000 calculations looking at bifurcation threshold for ITER equilibria as a function of poloidal and toroidal launch angles and launch position. Calculations by Richard Nies.

20% island, EC power limited to max 20 MW.

- Constant diffusion coefficient assumed in island, without stiffness effect at ITG threshold.
  - Bifurcation achievable below ITG threshold;
  - Stiffness effect to be studied.

Conclusions

- ECCD island stabilization studies for ITER have been focused on stabilization of small islands produced by NTMs, using as little power as possible.
- 95% of disruptions in JET preceded by appearance of large locked islands – mostly produced by off-normal events other than NTMs.
- We are investigating potential use of ECCD to stabilize large islands produced by off-normal events before they cause disruptions.
    - Will be desirable to use full 20 MW of available power for stabilization, if necessary.
- For large islands and high power, sensitivity to temperature perturbation gives rise to RF current condensation effect – can facilitate stabilization of large islands.
- Need experimental studies:
    - Dedicated experiments to validate physics;
    - Piggyback experiments on disruption avoidance via ECCD stabilization of locked islands.

References

A. H. Reiman and N. J. Fisch, Phys. Rev. Lett. **121**, 225001 (2018).

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E. Rodriguez, A. Reiman, N. Fisch, Phys. Plasmas 27, 042306 (2020).

S. Frank, A. Reiman, N. Fisch, P. Bonoli, Nucl. Fusion, to appear.

S. Jin, N. Fisch, and A. Reiman, Phys. Plasmas 27, 062508 (2020).

R. Nies, A. Reiman, E. Rodriguez, N. Bertelli, N. Fisch, http://arxiv.org/abs/2005.05997.