How will ITER deal with large magnetic islands?
— Some of the issues.

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2021 IAEA-PPPL Workshop on Theory and Simulation of Disruptions
July 23, 2021

*work supported by U.S. DOE contracts DE-AC02-09CH11466, DE-SC0016072, and DE-FG02-91ER54109.

How will ITER deal with large magnetic islands?

- 95% of disruptions in JET preceded by growth of large locked islands. (Gerasimov *et al*, 2018)
  - Suggests that great majority of disruptions in ITER will be preceded by growth of large islands.
- Data analysis suggests locked island $W/a \approx 30\%$ at disruption. (DeVries *et al*, 2016)
- Islands (rotating or locked) grow on a slow resistive time scale.
- What will ITER do while these islands are growing?
  - Retiring disruption issue on ITER will require minimizing mitigation events.
  - It will likely be advantageous to suppress these islands.
- ITER will have substantial electron cyclotron power (20 MW) for stabilizing islands, but
  - EC upper launcher in ITER optimized for stabilization of small islands produced by neoclassical tearing modes (NTMs) — toroidal launch angle fixed at 20°.
  - Available current will not always suffice for large, Δ' driven islands in colder L-mode plasmas.
  - This can be fixed.
  - Fix will also make nonlinear effects more prominent

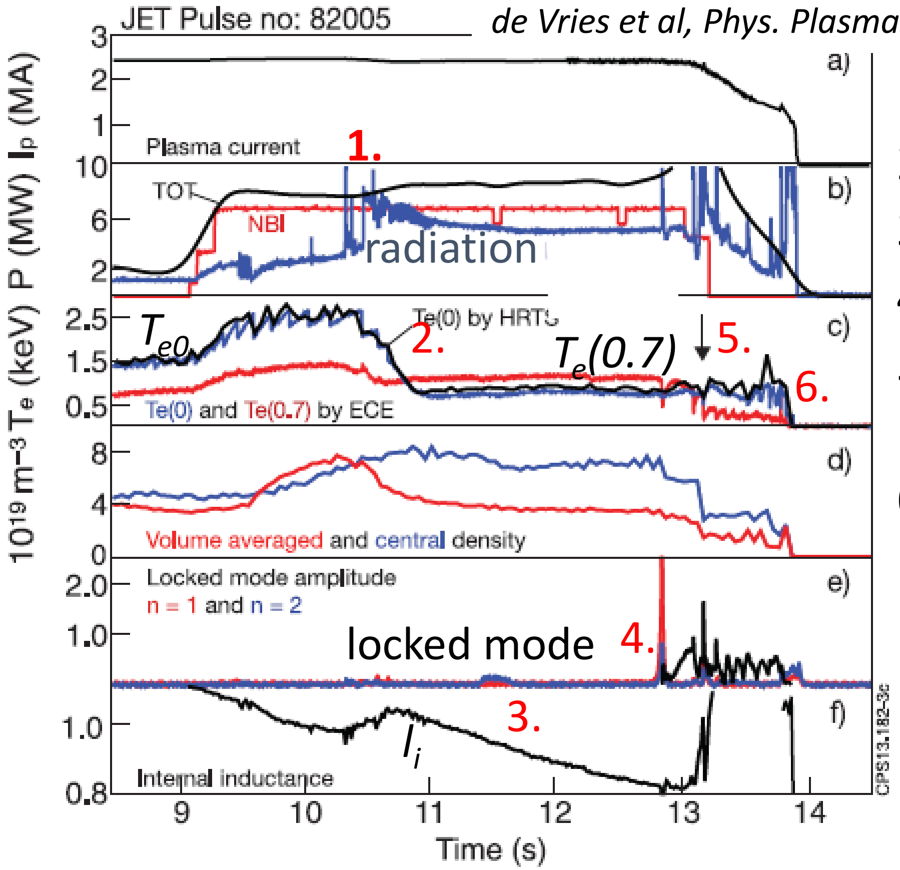
    — can be used to advantage, but must be accounted for in any case to aim rays properly.

Most large islands in JET produced by off-normal events other than NTMs

Example: Disruptions triggered by tungsten impurity accumulation in core

- Analysis of JET shots with ITER-like wall run during 2011 – 2012 (de Vries *et al*, Phys. Plasmas, 2014):
  - 4.6% disrupted because of impurity accumulation and radiation in core.
  - 0.5% of shots disrupted because of NTMs;

Typical disruption from impurity accumulation in JET:



de Vries et al, Phys. Plasmas, 2014

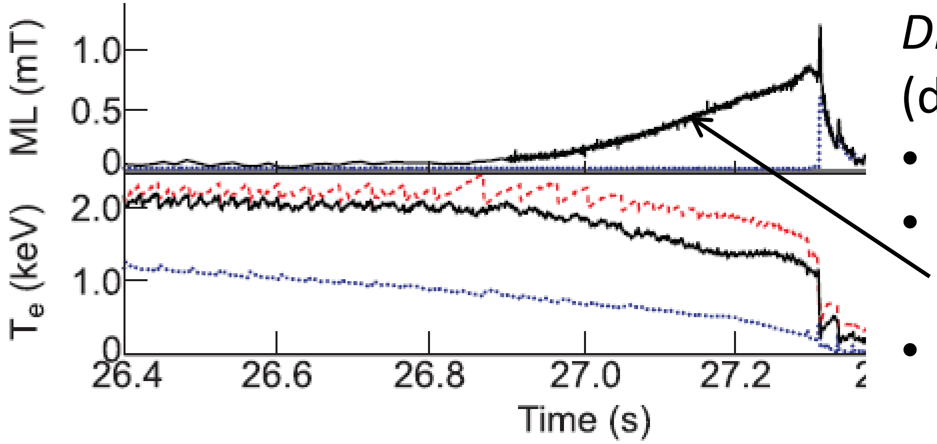
1. Rapid radiation increase at $t \approx 10.5$ sec.
2. Hollow temperature profile.
3. Current profile broadens. (l_i decreases.)
4. Rapid island growth and locking. (Δ' unstable?)
5. Thermal quench, but no disruption, 360 msec later. (Time scale will be much longer in ITER.)
6. Almost a second later: second thermal quench causes disruption.

Island directly triggers disruption.

What will ITER do when large islands appear?

What will ITER do when large islands appear?

- Ramp-down is on τ_R time scale, and can itself trigger disruption if too fast.



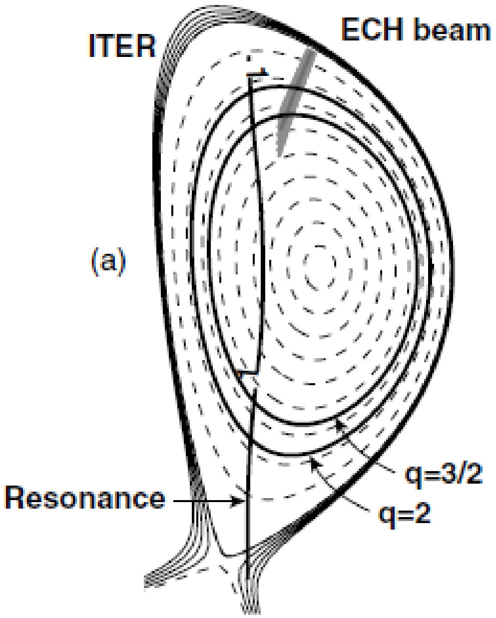
Disruption in JET shot 83601.

(de Vries *et al*, Nucl. Fusion 2016)

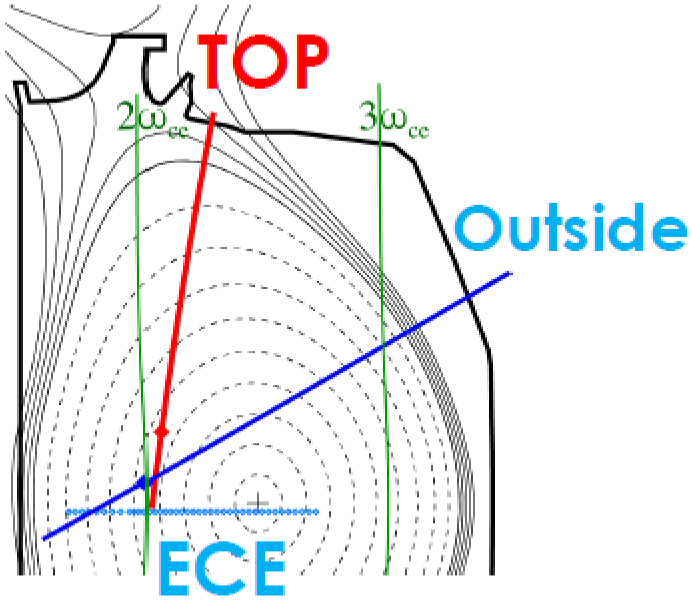
- 26.8 sec: locked mode appears
- 160 msec before thermal quench: discharge termination triggered
- 500 msec after mode onset: thermal quench

- RF current drive establishes stabilizing electric field on electron-ion collision time. (Reiman, Phys. Plasmas 1983)
  - Fast relative to other actuators.
- False positives not an issue.
- ECCD stabilization of large islands would be desirable.
  - Can we return to desired operating point?
  - Can we at least buy time for a safe shutdown?

ITER has potentially advantageous EC top launch



Ray trajectory in ITER (figure from Prater et al 2008)



Compare with conventional outside launch in contemporary tokamaks. (figure from X. Chen et al, IAEA 2021)

Top launch can provide more efficient current drive:

- Longer residence in absorption zone can allow deposition in more energetic electrons, which give more efficient current drive.
- Efficiency increases with increasing toroidal launch angle until trapped particle effects encountered.
  - Top launch deposits power farther from resonance (& trapped-passing boundary).
  - Deposition on low field side of plasma reduces trapped particle effects
    — but outside launch for 2nd harmonic X-mode then has 3rd harmonic deposition.

Benefits of top launch are lost at low toroidal launch angle.

- Recently implemented top launch in DIII-D demonstrated current drive efficiency twice that of outside launch for toroidal launch angle of 58°.
- Higher ECCD efficiency at larger angle impacts power required for stabilization, allowing stabilization of larger islands.
  - Effect particularly significant in ITER when l_i or plasma current reduced and rational surface moves radially inward.
- ITER upper EC launcher will initially have fixed toroidal launch angle of 20°
  - Relativistic effects limit deposition to narrow region for low toroidal launch angle.
  - 20° launch angle gives higher peak current density, advantageous for small islands

    — but lower total current drive efficiency disadvantageous when islands get larger.
  - Could change toroidal launch angle of one of the two UL mirrors.
    - Each capable of handling 13.5 MW of total available 20 MW.
  - Making ITER mirrors toroidally steerable would be better.

    —Many contemporary ECH installations started with fixed mirrors, later made steerable.

Power will be an issue for stabilizing large islands in ITER.
— Efficiency of current drive and stabilization will matter.

- Simplified version of the modified Rutherford equation has been used by a number of papers to estimate requirements for stabilization

$$\frac{dW}{dt} \propto r_s \Delta' + c\left(j_{bs}\frac{1}{W} - 5\, j_{ECCD}\eta_{CD}W_{cd}\frac{1}{W^2}\right),$$

where W is island width, j_{bs} bootstrap current, W_{cd} deposition width, and η_{CD} is ECCD stabilization efficiency (≈0.4 for $W_{cd} \ll W$ in rotating islands). (See e.g. E. Poli *et al*, Nucl. Fusion (2015))

- Analyses for ITER have focused on NTMs in Scenario 2 equilibrium, with stabilizing Δ' such that island saturates at $W_{sat} \approx 32$ cm in the absence of ECCD
  — automatically stabilizing at large *W*.
- If Δ' = 0 need increasingly high power to stabilize at large *W*.
- Power required for stabilization increases further if Δ' > 0.
- Current drive efficiency decreases with T_e e.g. when plasma falls into L-mode.

Broadening of deposition profile at large toroidal launch angle can be compensated by nonlinear “RF condensation”.

- Higher toroidal launch angle further broadens deposition profile.
  - Already significantly broadened by scattering off density fluctuations at plasma edge.

- Nonlinear effects increasingly prominent at large toroidal angle.

(See e.g. Reiman and Fisch, PRL (2018); Reiman, Bertelli, Fisch, Frank, Jin, Nies, Rodriguez, Phys. Plasmas (2021)).

  - Can be used to narrow deposition profile in island and increase stabilization efficiency, further reducing power requirement.
  - In reactor, could be used with LHCD to provide passive, automatic stabilization, with no need for feedback control.
  - Can lead to premature power absorption and decreased stabilization if not considered in aiming of ray trajectory.

Nonlinear effects arise from sensitivity of driven current and power deposition to the temperature perturbation in the island.

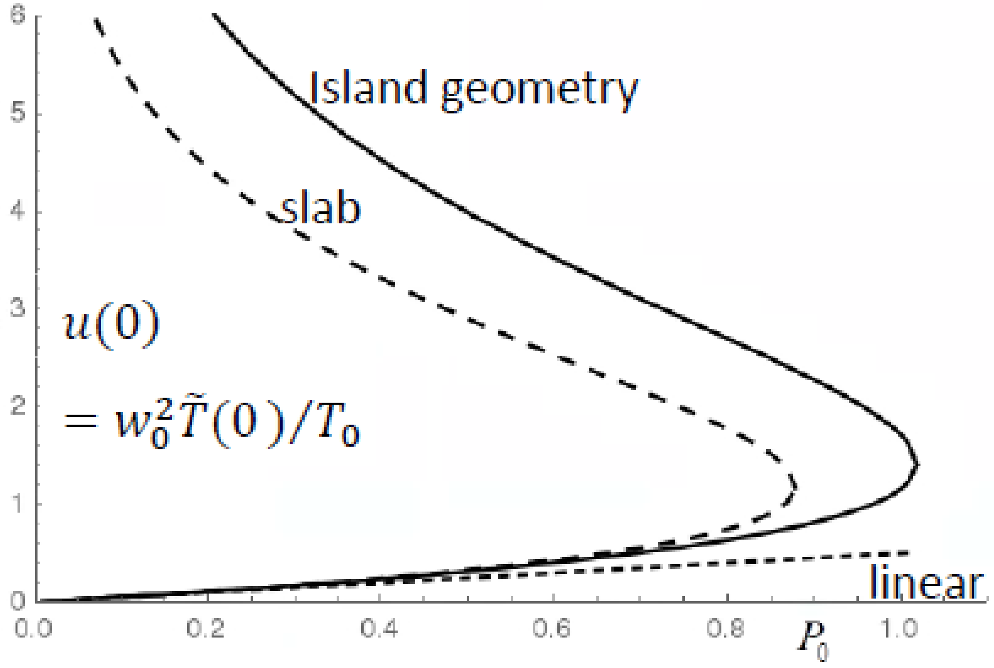
Number of electrons locally resonant with wave Maxwellian $\propto \exp\left(-V_p^2/V_T^2\right)$,

with V_T thermal velocity, V_p phase velocity.

Let $T = T_0 + \tilde{T}$, with T_0 unperturbed temperature, and

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

w_0 becomes larger at large toroidal angle, increasing temperature sensitivity and ECCD efficiency



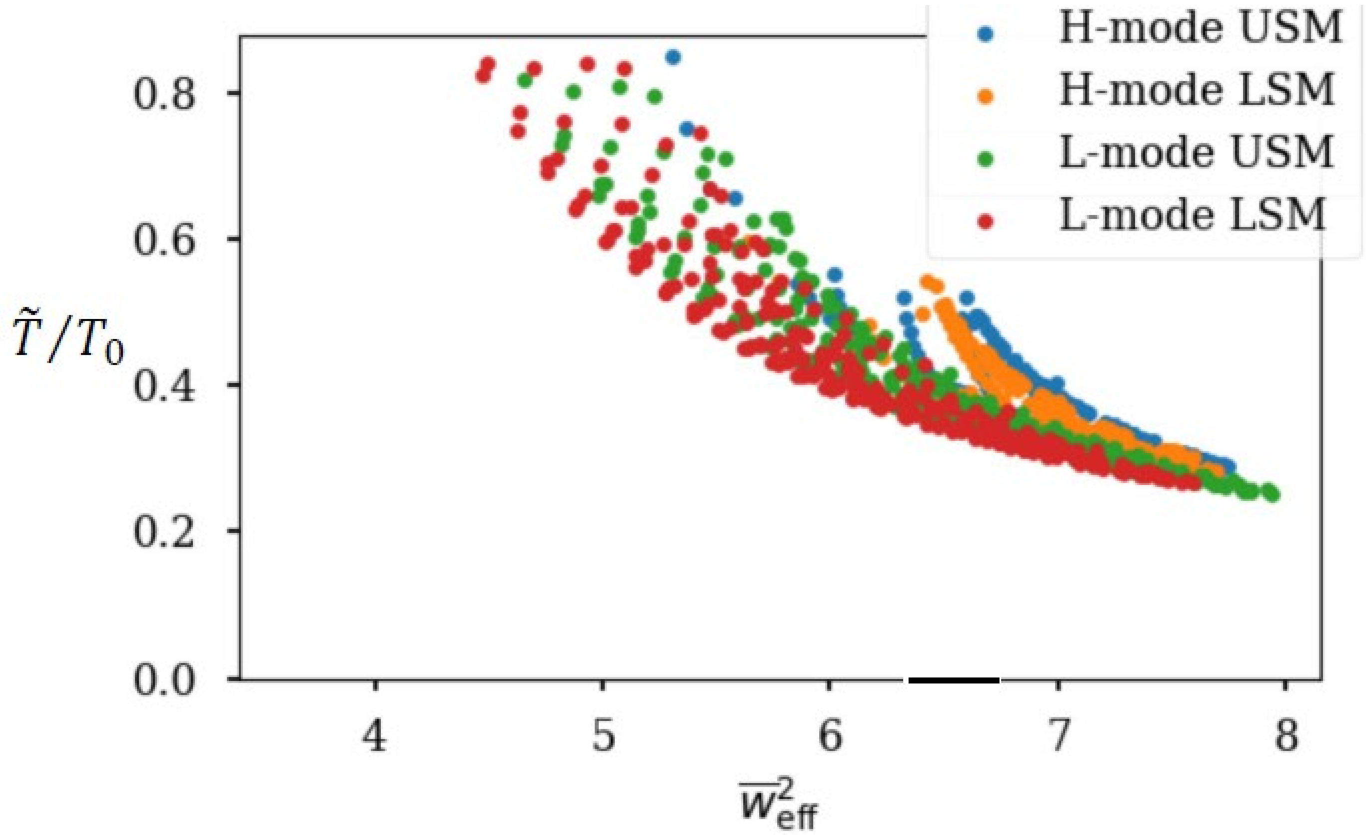
Nonlinear feedback increases $\tilde{T}$.

- Significant increase in $\tilde{T}$ when $w_0^2\,\tilde{T}/T_0 \geq 0.5$.
- Bifurcation for $w_0^2\,\tilde{T}/T_0 > 1.5$.
- Above bifurcation threshold, $\tilde{T}$ increases until additional physics comes in (energy depletion in wave, profile stiffness).

In combination with sensitivity of RF current drive to $\tilde{T}$, gives RF current condensation.

- Can be used to concentrate RF driven current near island O-point, increasing stabilization efficiency.

A new simulation capability (OCCAMI code) couples the GENRAY ray tracing code to the solution of the thermal diffusion equation in a magnetic island.



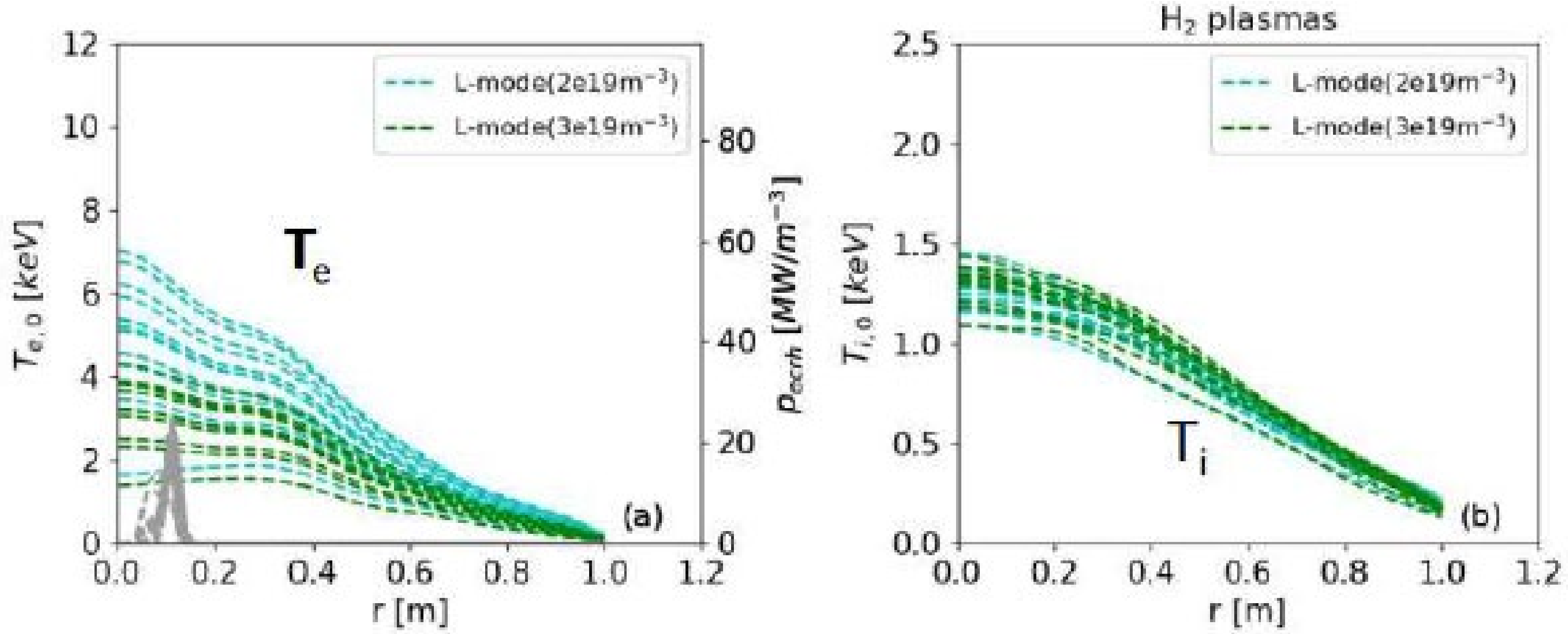
Scan looks at bifurcation threshold as a function of poloidal and toroidal launch angles for EC power up to the 20 MW available on ITER. (25% island.)

- Bifurcations will be accessible under some circumstances.
- Nonlinear effects significant at $\tilde{T}$ a factor of 3 lower and will be present under a range of conditions.

Further investigation will address issue of profile stiffness.

Issue of stiffness is complicated by flattening of density profile in island.

- In absence of density source in island, diffusion flattens density profile in large islands.
- Flat density stabilizes TEM modes.
- ITG expected to limit $\tilde{T}_{\text{ion}}$ when $\tilde{T}_{\text{ion}}/T_0 > W_{island}/a$ — primarily affects ions.
- Electron energy lost through collisional coupling to ions – complicated function of island width, location of power deposition.



AUG ECH power scan

- Beurskens et al, IAEA 2021

T_{i0} pinned below 1.5 keV by ITG, T_{e0} rises to 7 keV.

Conclusions

- Experience on JET suggests that the great majority of disruptions on ITER will be preceded by growth of large islands.
- Islands (rotating and locked) grow on resistive time scale, and generally trigger disruptions only when they reach large size.
- Desirable to suppress islands to minimize number of mitigation events.
- ITER ECCD top launch scheme potentially beneficial for stabilizing large islands

— but benefits lost at initial fixed 20° toroidal launch angle, chosen for optimal stabilization of small islands produced by NTMs.

- Can be addressed by changing angle of one UL mirror or, preferably, by making UL mirrors steerable in toroidal angle.
- At larger toroidal launch angle, nonlinear effects will become more pronounced:
  - Can be used to improve stabilization efficiency.
  - Must be accounted for in any case to aim ray trajectories properly.
- Retiring disruption issue on ITER will require minimizing number of mitigation events.
  - ECCD stabilization of large islands could be critical component of that.
  - Should be addressing this now in experiments and theory.

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