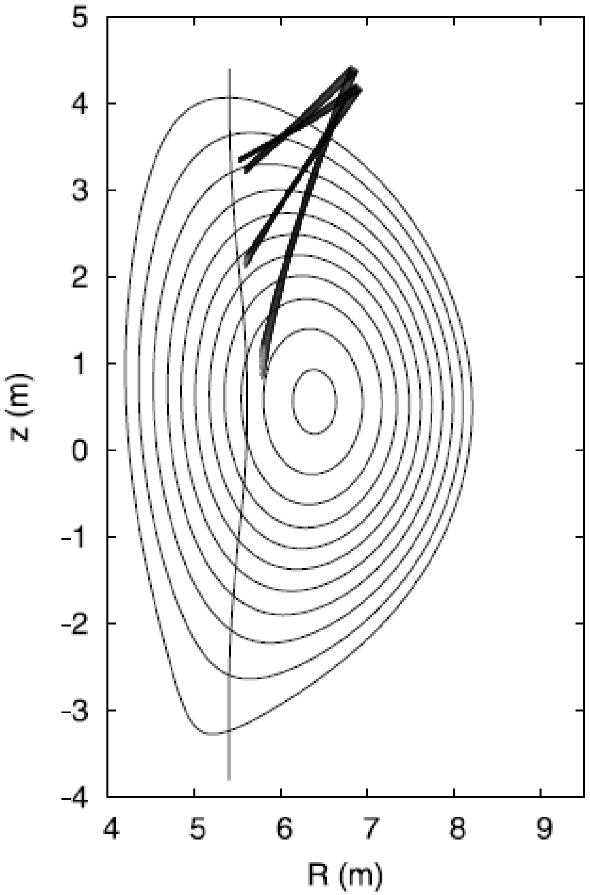
Stabilization of small islands produced by NTMs in ITER

A. Reiman, R. Nies, N. Fisch, PPPL

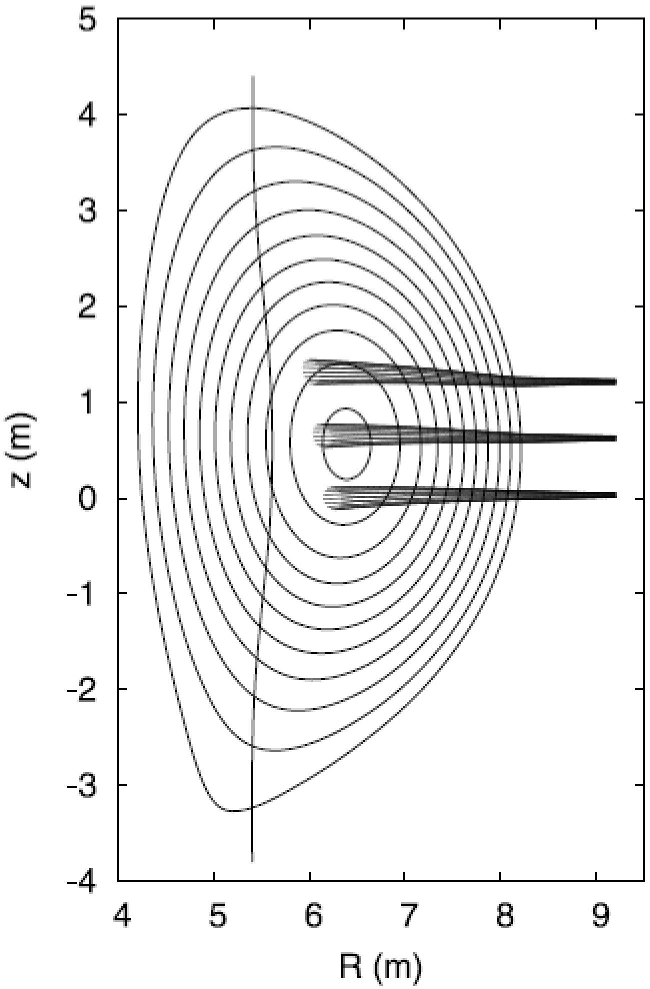
See Nies, Reiman and Fisch, Nucl. Fusion **62,** 086044 (2022)

Second IAEA Technical Meeting on Plasma Disruptions and their Mitigation, 19-22 July, 2022

ITER will have two sets of electron cyclotron wave launchers, upper and equatorial



- Upper launchers intended primarily for stabilization of neoclassical tearing modes (NTMs), which may arise routinely on ITER.
- Poloidal launch angle steerable, toroidal launch angle fixed.
- Toroidal launch angle chosen to be optimal for stabilization via continuouis RF.



Equatorial launchers to be used for other purposes.

Design of upper launcher guided by series of increasingly detailed calculations from late 2000's to mid 2010's

Some of the papers:

- Ramponi *et al*, Fusion Science and Technology, 52:2, 193-201 (2006).
- Henderson *et al*, Nucl. Fusion 48 054013 (2008).
- La Haye et al 2009 Nucl. Fusion 49 045005
- Bertelli *et al*, Nucl. Fusion 51 (2011) 103007.
- van den Brand *et al* 2012 *Plasma Phys. Control. Fusion* **54** 094003.
- Moro *et al*, AIP Conference Proceedings 1580, 550 (2014).
- Figini *et al*, Plasma Phys. Control. Fusion 57, 054015 (2015).

.

More recent work calls into question some key assumptions made in these calculations.

- Rapidity of locking.
- Deposition profile predicted by ray tracing codes.

There is a potential problem, and a possible solution.

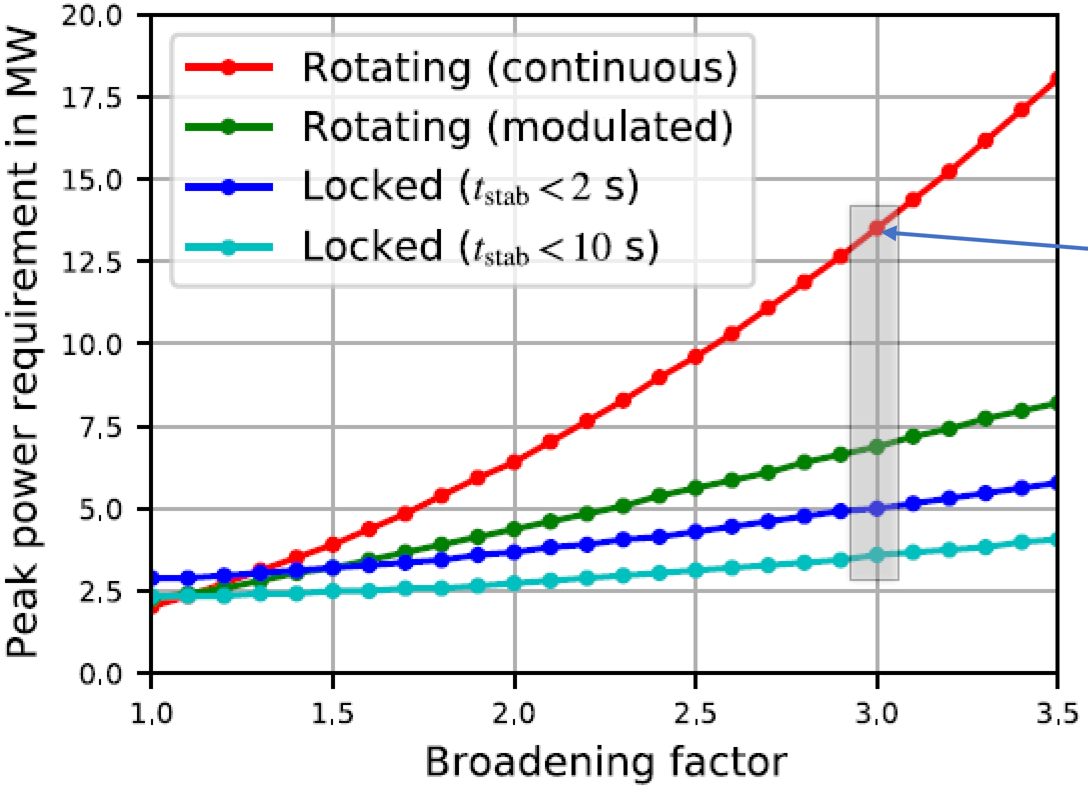
More recent developments:
1. Island locks more quickly and at smaller width than previously realized.

- Time to lock governed by thick blanket modules rather than inner vessel wall (La Haye *et al*, Nucl. Fusion **57** 014004 (2017)).
  - Island predicted to lock in 2.4 sec
  - Predicted width at locking 9 cm (4.5%)
- 3 seconds will be required to switch power from equatorial launchers to upper launcher.
  - Implies that sufficient power to stabilize NTM must be reserved to the upper launcher, and will not be available to equatorial launcher.

More recent developments:
2. Broadening of EC beam power deposition profile reduces stabilization efficiency.

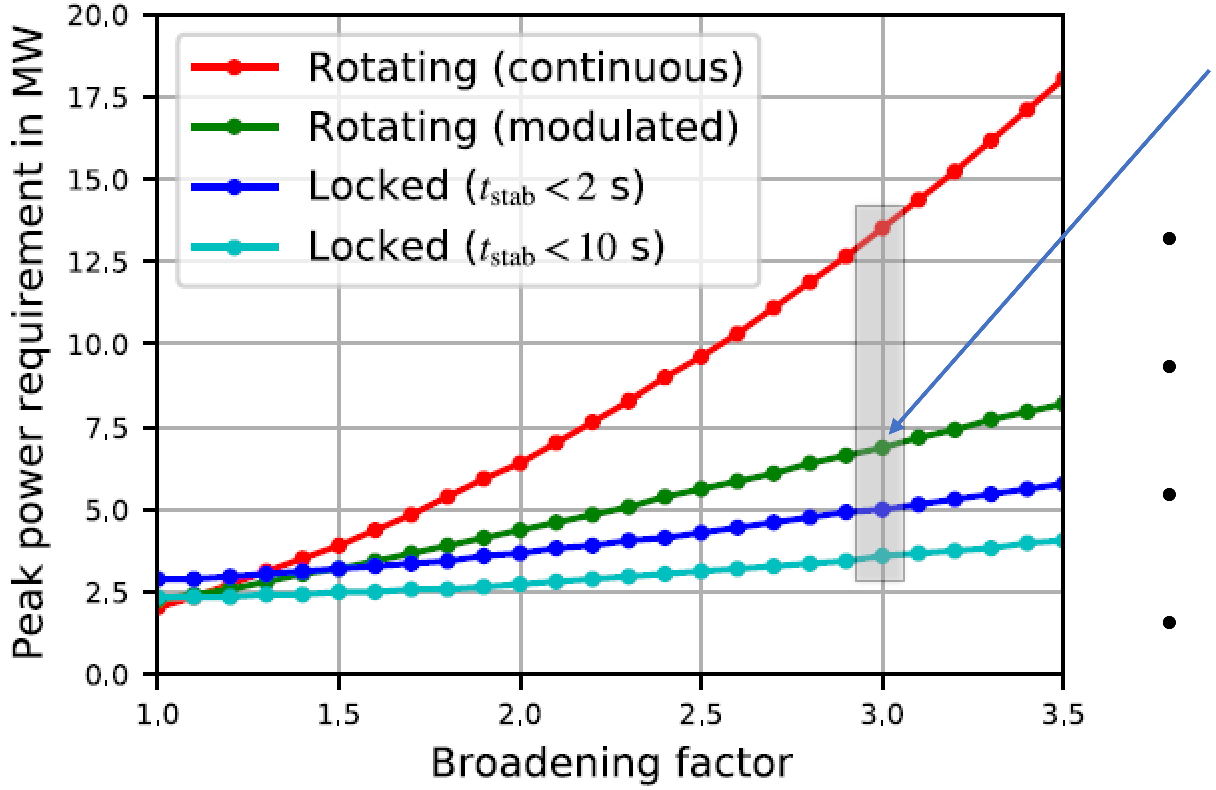
- A number of papers have now reported experimental observations of broadening:
  - Brookman *et al*, EPJ Web Conf. 147 03001 (2017).
  - Chellaï *et al*, Phys. Rev. Lett. 120 105001 (2018).
  - Chellaï *et al*, Plasma Phys. Control. Fusion 61 014001 (2019).
  - Brookman *et al*, Phys. Plasmas 28 042507 (2021).
- It is now expected that the EC beam in ITER will broaden significantly, relative to predictions of ray tracing codes, by scattering off density fluctuations at the plasma edge.
- Theoretical calculations predict that the EC beam power deposition profile in ITER will be broadened by a factor of 2.5 to 3.5 (Snicker *et al*, Nucl. Fusion 58 016002 (2018)).

Deposition broadening will have a severe impact on the power required to stabilize NTMs via continuous RF.



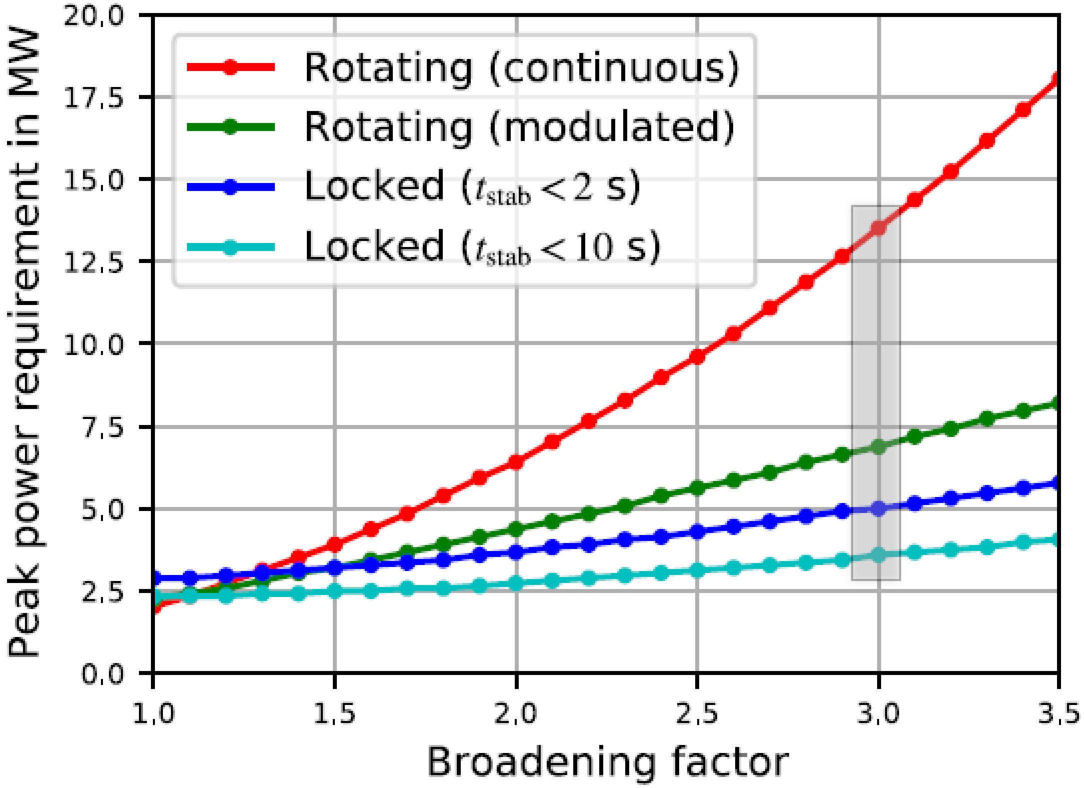
- Broadening predicted to be in range 2.5 to 3.5.
- For a broadening factor of 3, required power for continuous RF rises from ≈2 MW to ≈13 MW.
- Power must be reserved by upper launcher.
- ITER will initially have 20 MW total EC.

Modulated RF will require less peak power, but must remain on indefinitely.



- For broad deposition, island can be stabilized more efficiently if RF is modulated so that it is off when X-line in front of EC launcher.
- Requires knowledge of location of X-point and O-point.
- There is a threshold island width below which island cannot be detected.
- Modulated RF cannot shrink island below that width.
- It is believed that the threshold will be larger than the width below which island is stabilized.
- Modulated power must remain on indefinitely – impacting fusion gain, *Q*.

Stabilization of a locked island is less affected by broadening, as long as O-point is in front of EC launcher.



- Island can be shrunk below threshold width for NTM growth, and can then be turned off.
- Required peak power can be reduced if island width reduced more slowly, but maintenance of H-mode may require suppression on momentum confinement time scale.
- **The issue: It has been widely thought that locking of island is dangerous and must be avoided.**

It has been widely thought that island locking must be avoided at all cost.

- Widespread belief that locking poses risk of imminent disruption.
- Locking can accelerate island growth.
- Locking can lead to loss of H-mode.
- Concern that magnitude of nonaxisymmetric field required for locking at desired phase would be prohibitive.

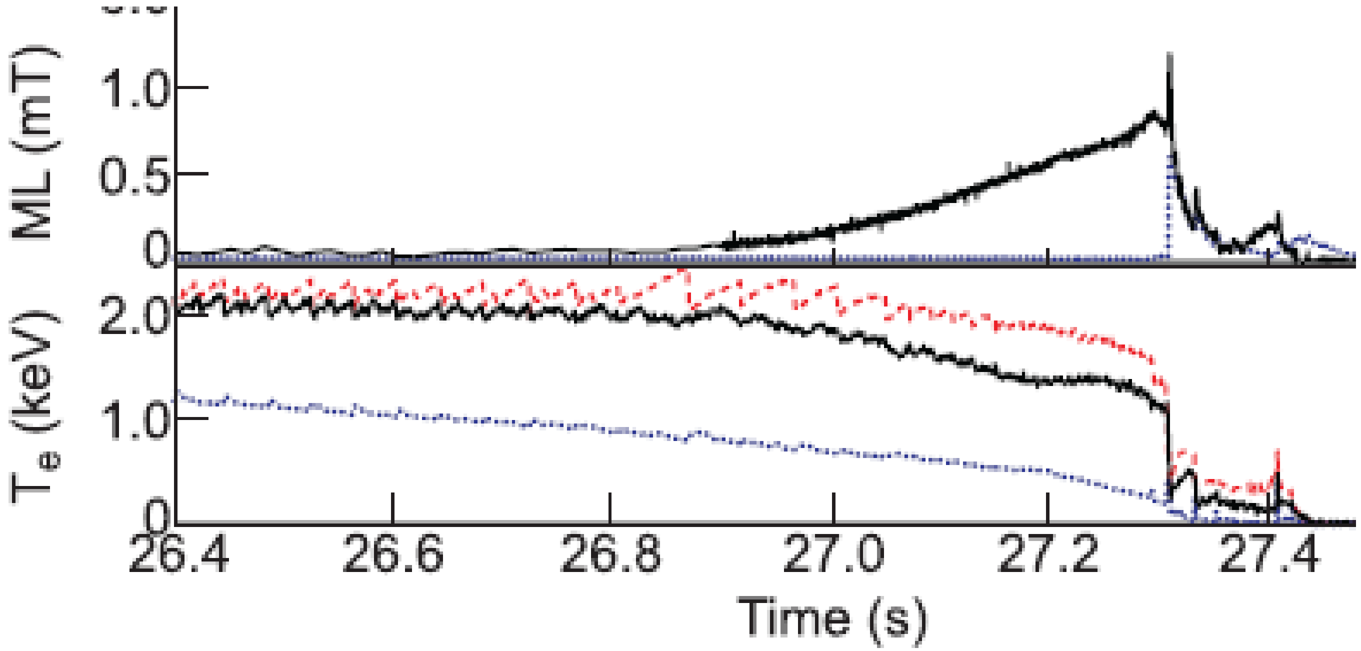
It is widely thought that locking poses danger of imminent disruption.

- Disruptions in present day tokamaks often preceded by mode locking.
- 95% of disruptions in JET preceded by locked islands (Gerasimov *et al,* Nucl. Fusion **60** (2020))

But:

- Study of JET disruptions found that disruptions generally triggered when locked islands reached width ≈ 30% (de Vries *et al,* Nucl. Fusion 56026007 (2016))
- 2/1 NTM in ITER predicted to lock at ≈ 4.5%
- Magnetic islands grow on resistive time scale, providing significant margin in ITER between locking and disruption events.
- Islands (locked or rotating) grow on a resistive time scale, and generally do not (never?) trigger disruptions when they are small.

Do locked islands pose an imminent threat of disruption? (continued): An example from JET (de Vries *et al*, Nucl. Fusion 2016)



Born locked mode in JET shot 83601.

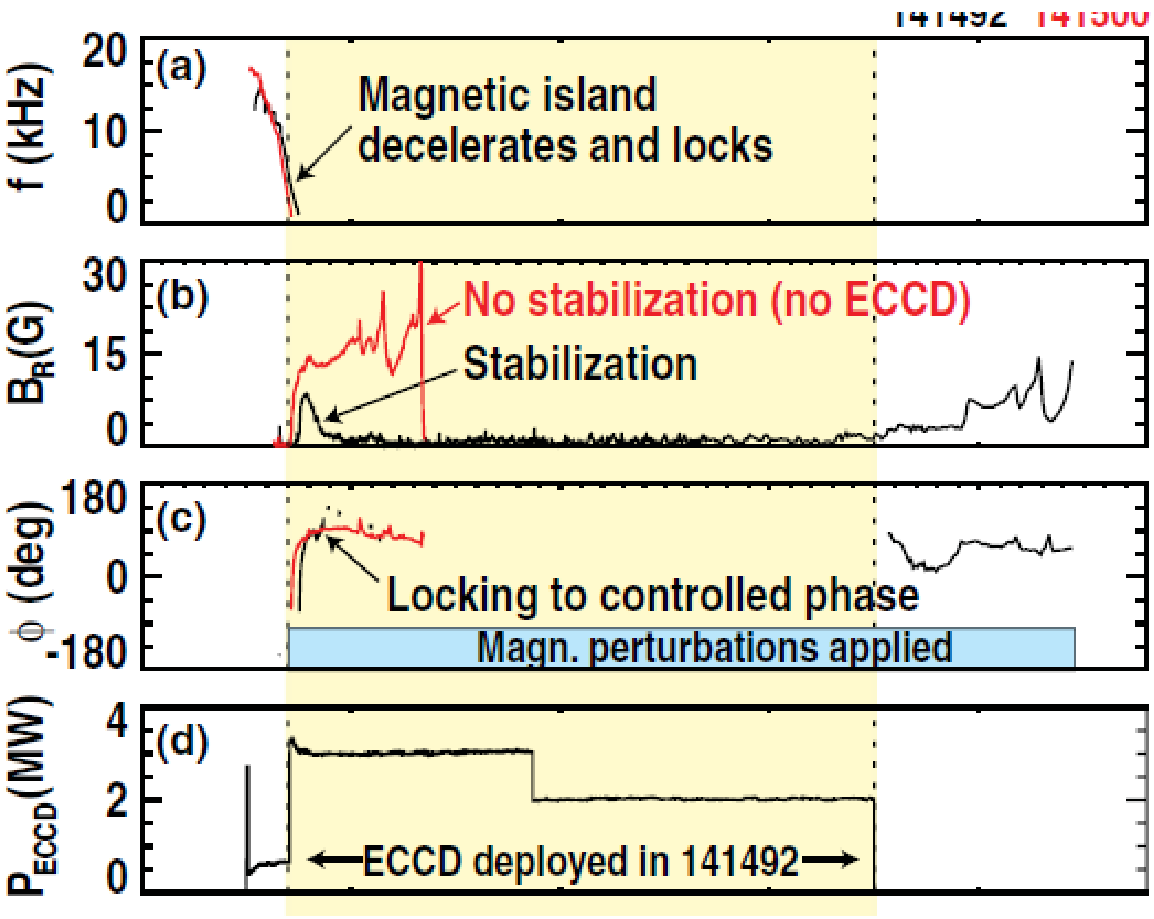
- 26.8 sec: locked mode appears
- 500 msec after mode onset: thermal quench

- 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.

Concern about acceleration of growth rate when island locks

- Growth of island may accelerate after locking:
  - Resistive wall boundary condition is stabilizing for rotating islands, but not for locked islands;
  - Resonant component of field error stabilizing for rotating islands, destabilizing for locked islands.
- These effects generally small, except for large, saturated, rotating islands.
  - Loss of wall stabilization after locking may lead to island growth and to disruption.
- Although island may grow more rapidly after locking, it grows on slow, resistive time scale
  - significant margin between locking of small island and disruption.

Concern about acceleration of growth rate when island locks (continued): An example from DIII-D (Volpe *et al*, PRL **115**, 175002 (2015))



2 shots nearly identical, except that in one case ECCD stabilization applied when island locks.

- Resonant magnetic perturbation applied at 1700 ms in both cases to lock islands.
- Island with ECCD rapidly suppressed, without losing H-mode.
- Island without ECCD continues to grow for about another 650 ms, until it triggers disruption when it reaches width of about 30% of minor radius.

Concern about loss of H-mode after island locks

- H-mode often lost after locking.
- Sequence of experiments on DIII-D where large RMP used to lock relatively large islands found that H-mode preserved if mode stabilized by ECCD promptly after locking.
  - Relevant time scale appeared to be momentum confinement time scale.
- Paucity of data on islands ≈ 4.5% of minor radius.
- RMPs for ELM stabilization believed to produce locked islands ≈ 2% - 3% of minor radius.

Concern that magnitude of RMP required for control of island phase would be prohibitive.

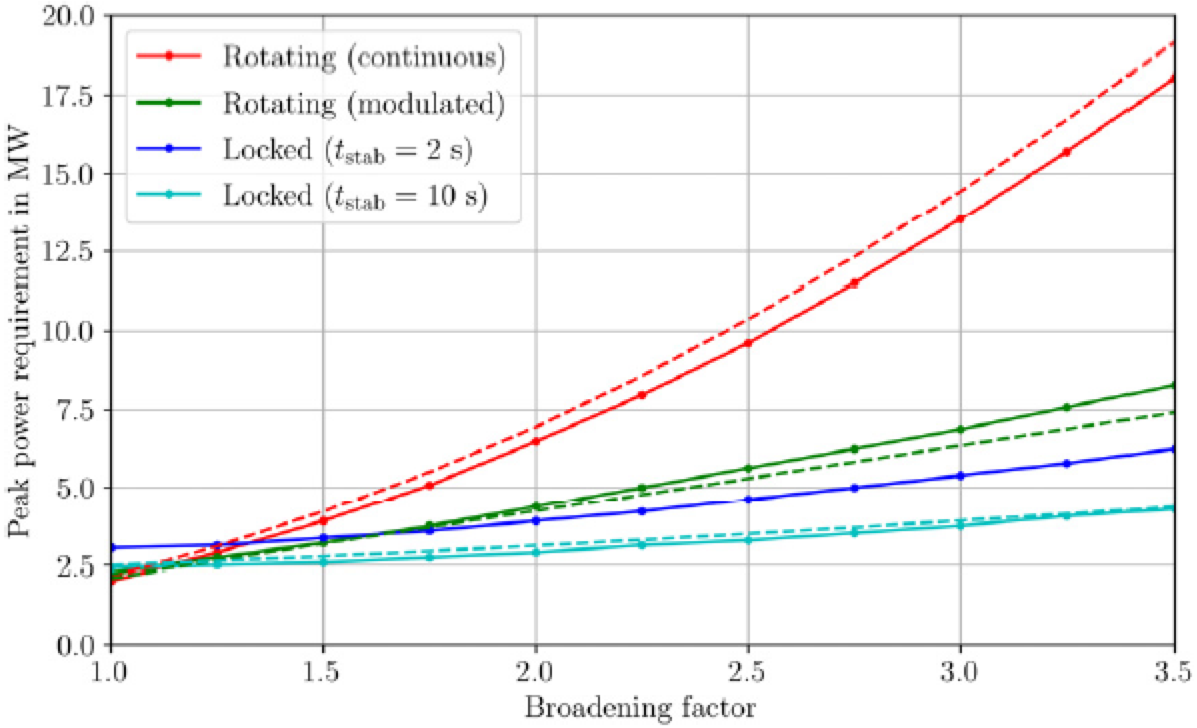
ITER will have nonaxisymmetric error field correction coils.
(See e.g. Amoskov *et al,* Phys. Part. Nucl. Lett. **12** 375–9 (2015).)

- Intended to compensate *n* =1 field errors.
- Expected to reduce field error by factor ≈ 4.
- 2/1 NTM islands will slow and lock to residual field error.
- Will need to adjust field from compensation coils such that O-point locks in front of EC launcher.
- Will not need separate coils to control phase, and associated magnitude of field modification likely to be quite small.

If island phase not controlled in this way, then when 4.5% island does lock, will not be able to use ECCD to suppress it as it grows and eventually triggers disruption mitigation system.

Approximate analytical solutions confirm that results retain validity for range of parameters.

- Numerical calculations done for ITER scenario 2 parameters.
- Analytical solutions approximately reproduce numerical results and have been applied to a range of parameters. (Nucl Fusion, 2022)



Solid lines show numerical results. Dashed lines show predictions of approximate analytical formulae. (See Nucl. Fusion paper.)

Conclusions

- A number of papers have presented detailed, careful calculations using ray tracing codes to help guide the design of the upper EC launcher on ITER.
- It is now believed that the predictions of those ray tracing codes with regard to the width of the power deposition profile are significantly inaccurate, perhaps by a factor of 3.
- The predicted broadening of the EC beam would have a severe impact on the power required for the favored stabilization strategy using continuous RF, limiting the EC power available for other purposes.
- Stabilization via modulated RF would have a lower peak power requirement, but the EC power would need to remain on throughout the shot, severely affecting Q (fusion gain).
- Calculations suggest that a strategy of waiting until the islands lock before stabilizing them may provide an attractive alternate strategy.
- Concerns about negative impacts of locking are likely unwarranted for small locked islands.
- Experimental tests of the locked island stabilization strategy would be desirable.