Neoclassical Tearing Modes

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With contributions in particular from:

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Outline

- Magnetic islands
- Classical tearing mode -> Rutherford equation
- Neoclassical tearing mode: Modified Rutherford equation (MRE)
- **Metastable** properties (*large "hysteresis" between onset/offset*)
- Plasma performance and NTMs
- Strategies for NTM control in ITER:
  - Will there be more than one mode at the same time?
  - Stabilization
  - Preemption
  - Avoidance
  - Real-time control of NTMs:
    - Very complex yet simple
    - New "robust" control being tested in Europe
- Conclusions

Outline

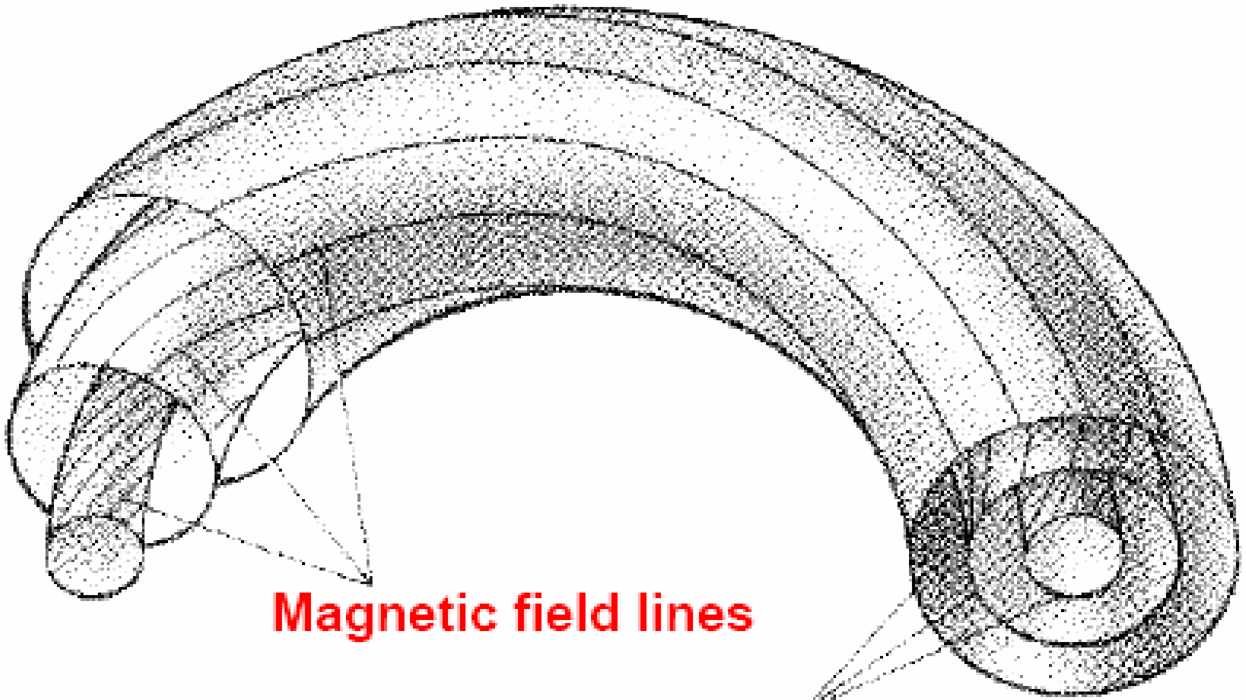
- Magnetic islands
- Classical tearing mode -> Rutherford equation
- Neoclassical tearing mode: Modified Rutherford equation (MRE)
- **M**
- P
- S

> - NTMS lead to a "soft" beta limit as opposed to "hard" beta limits leading to disruption
> - NTMs mainly lead to performance degradation
> - BUT if you push "too hard", NTMs can lead to disruption

  - ➢ Avoidance
  - ➢ Real-time control of NTMs:
    - ➢ Very complex yet simple
    - ➢ New "robust" control being tested in Europe
- Conclusions

Magnetic equilibrium in a tokamak

- Nested magnetic surfaces
- Axisymmetric structure
- Good radial confinement



- Rational surfaces: the field lines close on themselves after *m* toroidal turns and *n* poloidal turns (i.e. *m*/*n* toroidal revolutions needed to complete a poloidal turn following a field line)

The one fluid MHD equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (n\vec{v})$$ equation of continuity

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right) = -\nabla p + \vec{j} \times \vec{B} = 0$$ force equation

static equilibrium

$$\vec{E} + \vec{v} \times \vec{B} = \eta\ \vec{j}$$ =0 if η=0 Ohm's law

=> frozen-in B lines

$$\frac{d}{dt}\left(\frac{p}{\rho^{\gamma}}\right) = 0$$ equation of state

+ Maxwell's equations for *E* and *B*

MHD: consequences of Ohm's law

Consider equilibrium Ohm's law...

$$\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{\sigma}\vec{j}$$

...and analyse how magnetic field can change:

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \frac{1}{\mu_0 \sigma} \nabla \times \left(\nabla \times \vec{B}\right)$$

$$\Rightarrow \frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) + \frac{1}{\mu_0 \sigma} \Delta \vec{B}$$

Typical time scale of resistive MHD:

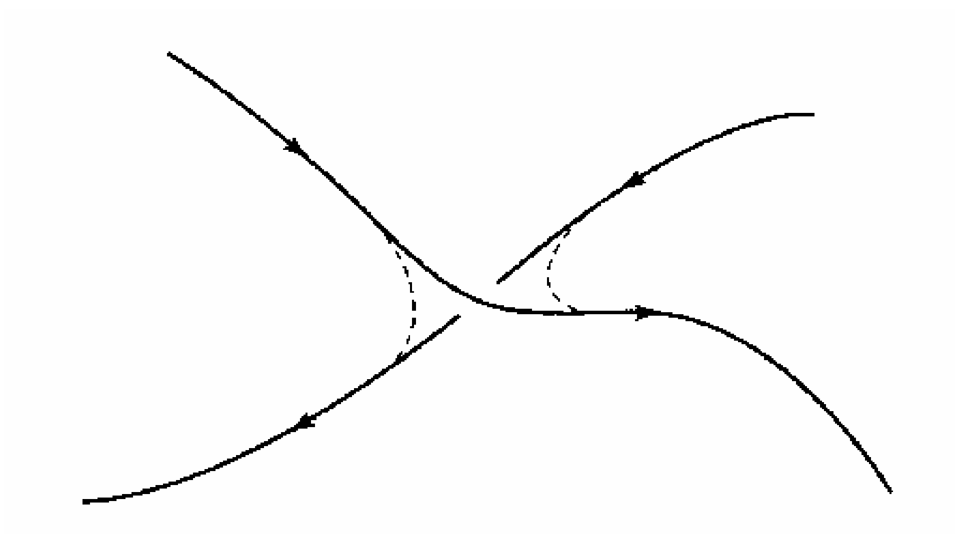
$$\tau_R = \mu_0 \sigma L^2$$

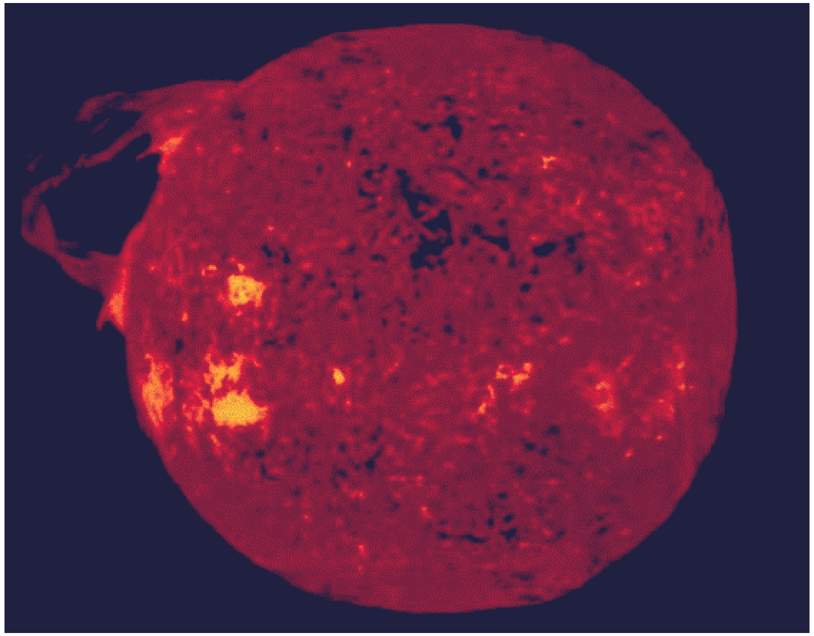
Since σ is large for a hot plasma, τ_R is slow (~ sec for 0.5 m) – irrelevant?

Reconnection in a hot fusion plasma

Due to high electrical conductivity, magnetic flux is frozen into plasma

⇒ magnetic field lines and plasma move together

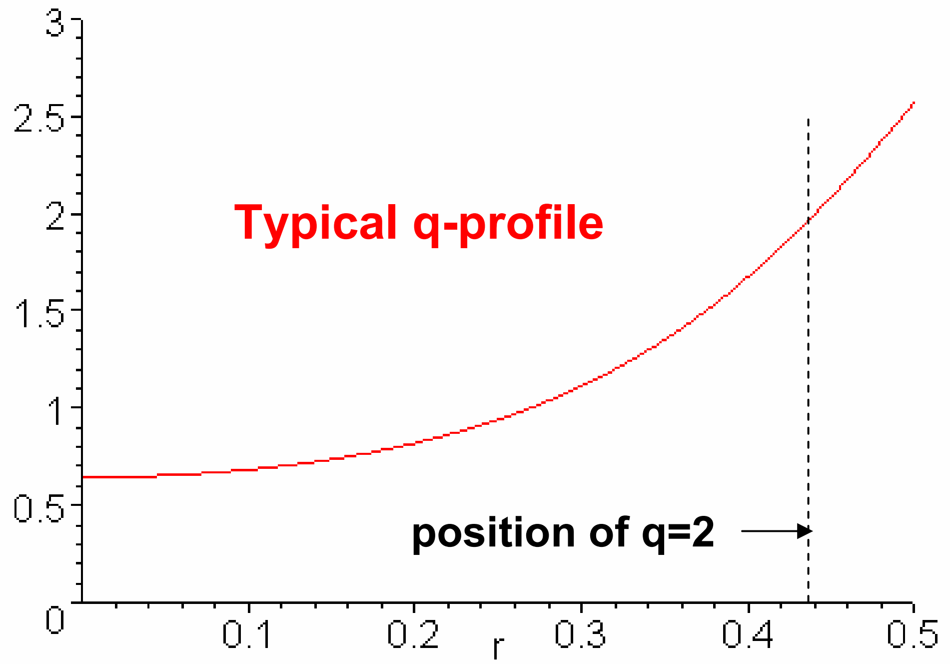


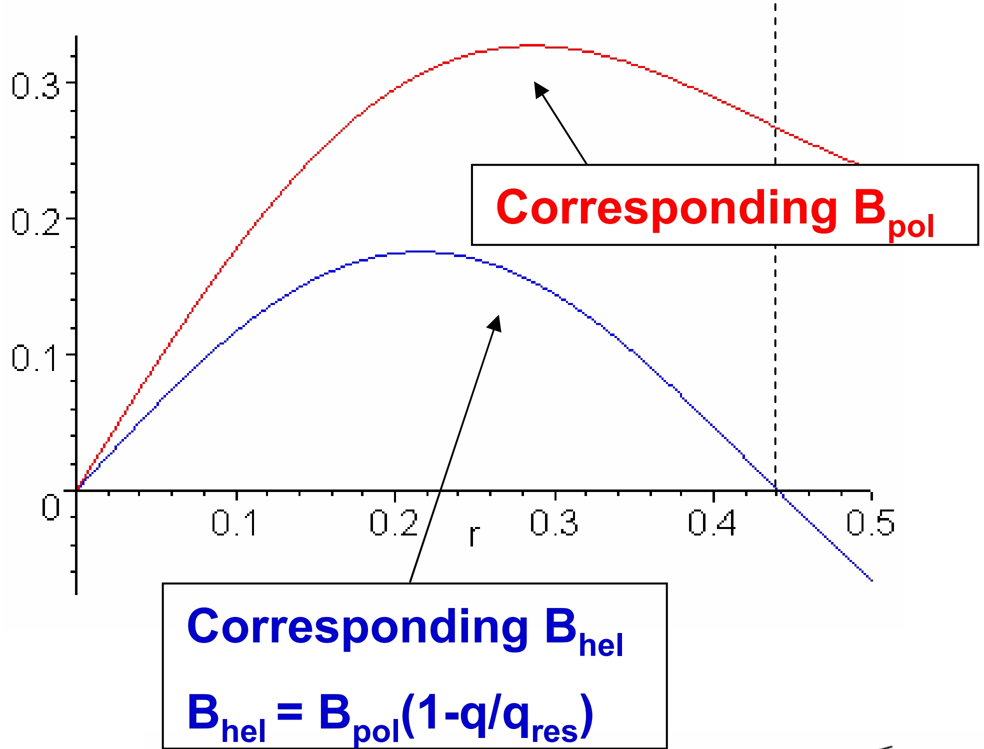


A change of magnetic topology is only possible through reconnection

- opposing field lines reconnect and form new topological objects
- requires finite resistivity in the reconnection region

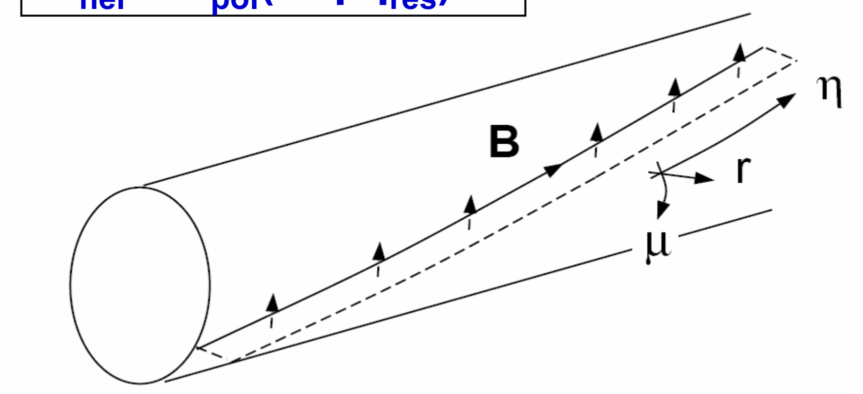
Reconnection on 'rational' magnetic surfaces





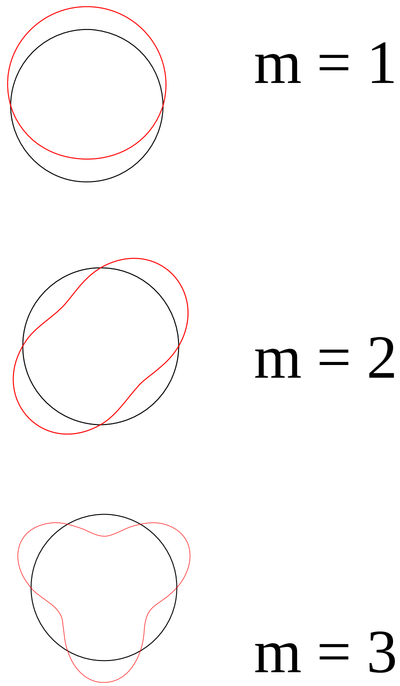
Helical field (i.e. ‚poloidal' field relative to resonant surface) changes sign:

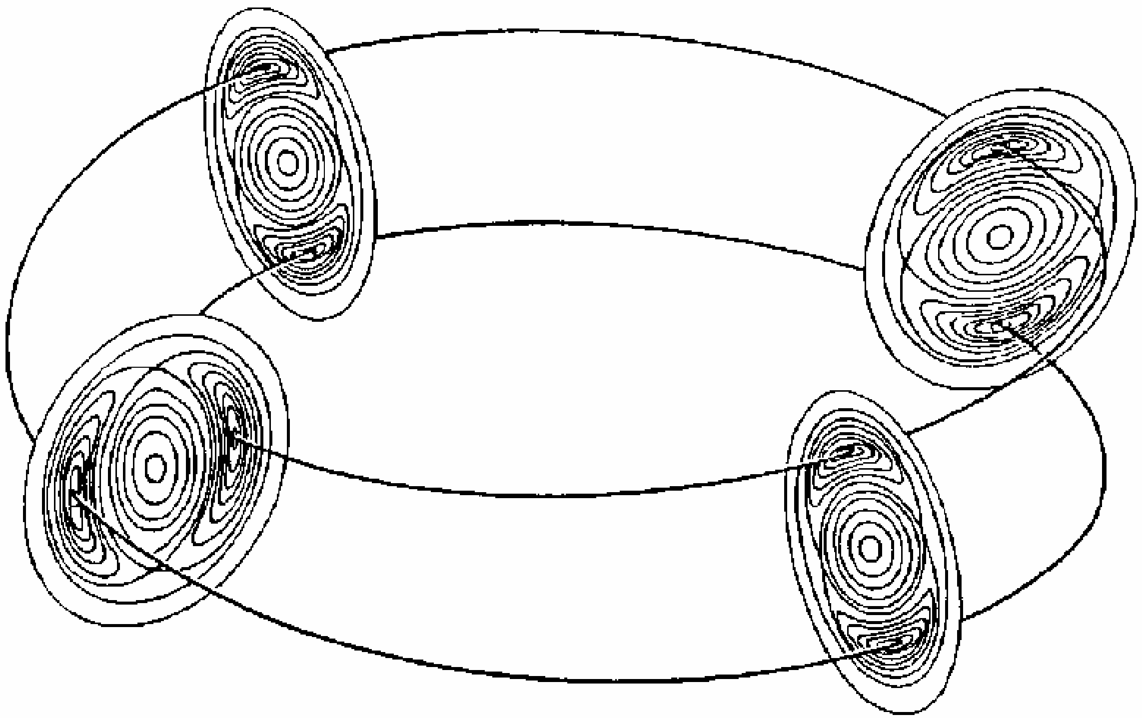
- reconnection of helical flux can form new topological objects - islands



Torus has double periodicity

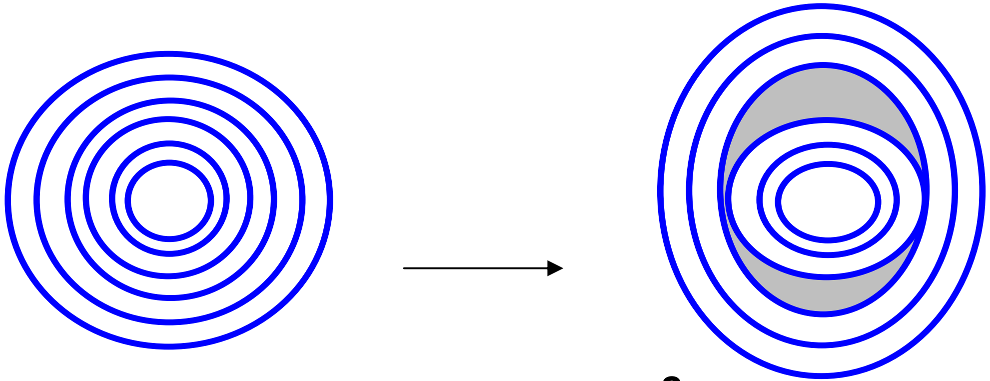
- instabilities with poloidal and toroidal 'quantum numbers'





‚Resonant surfaces‘ prone to instabilites with $q = m/n$

MHD description of tearing mode formation



$\psi \sim w^2$

$$\Delta\psi + \frac{\mu_0 \, {dj(r)}/{dr}}{B_\theta (1 - {n}/{m}\, q(r))}\psi = 0$$

j ~ q' => ψ ~ q"

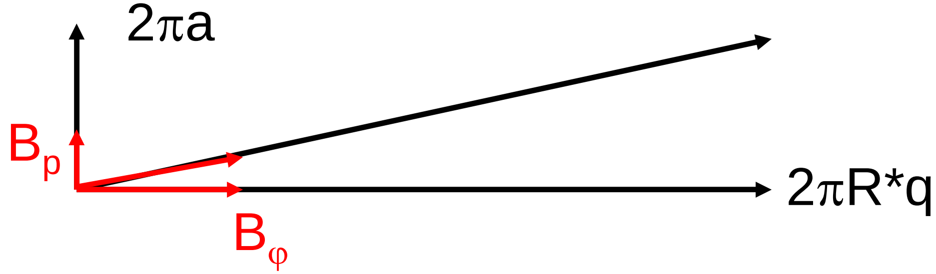
$$q'(\rho) \sim \int_0^\rho j_\varphi dS_\varphi + j_\varphi(\rho) \sim I_p(\rho) + j_\varphi(\rho)$$

Deformation of flux surfaces opens up island of width W

- Tearing Mode equation (*∇p = j x B)* singular at resonant surface:

  implies kink in magnetic flux ψ, jump in *B*

  ⇒ current sheet on the resonant surface



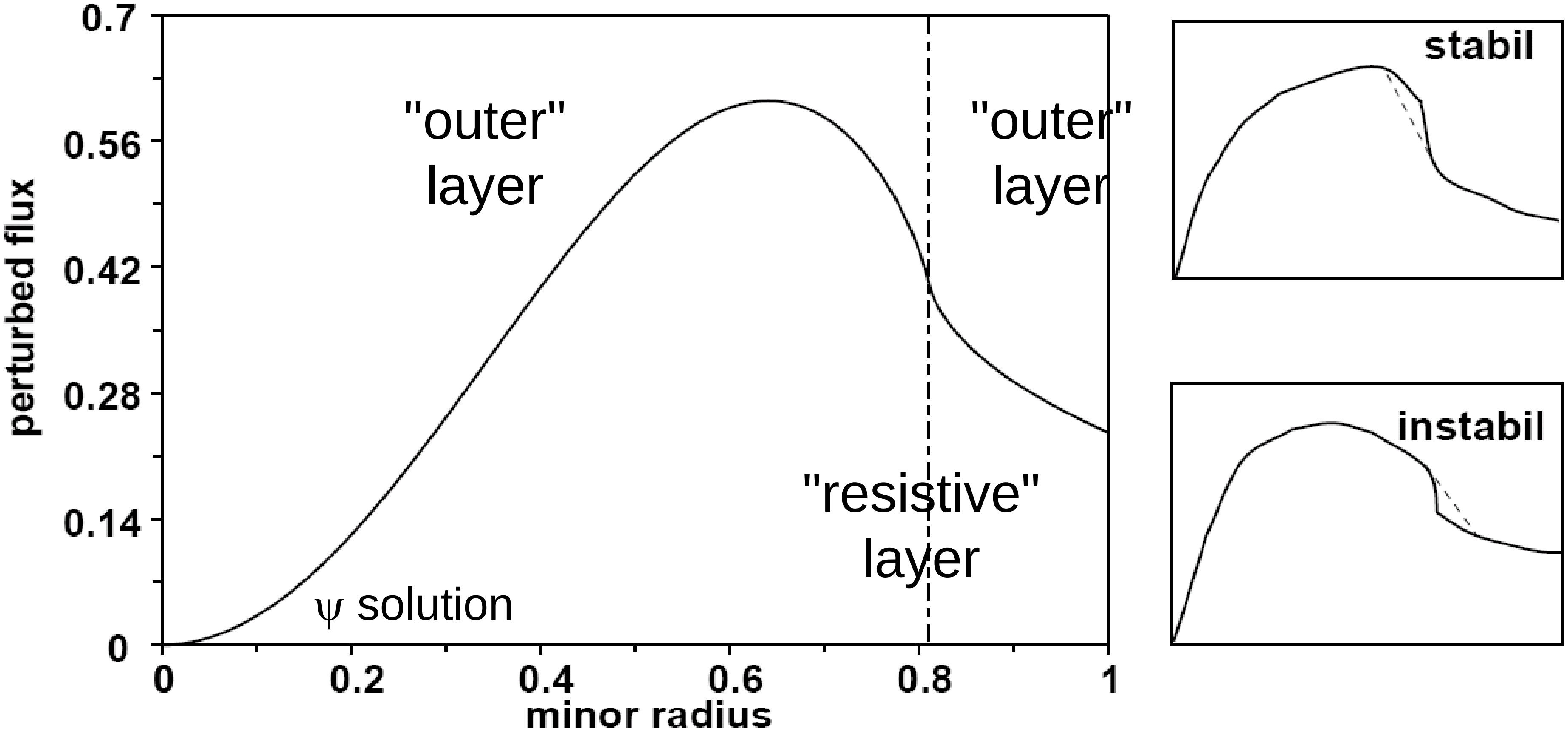
$\psi(r)$: **helical magnetic flux**

***j(r)*: current profile**

***q(r)*: field line helicity profile**

***m,n*: mode quantum numbers**

MHD description of "classical" tearing mode formation



Solution of tearing mode equation can be made continuous, but has a kink

- implied surface current will grow or decay depending on equilibrium j(r)
- the parameter defining stability is $\Delta' = ((d\psi/dr)_{right} - (d\psi/dr)_{left}) / \psi$
- if $\Delta' > 0$, tearing mode is linearly unstable – this is related to $\nabla j_{resonant\ surface}$

Tearing Modes – nonlinear growth

Equation for the growth rate of a finite size island of width w:

$$\tau_{res} \, {dW}/{dt} = a_1 \Delta' + a_2 \, {\nabla p}/{W} - a_3 \, {I_{extern}}/{W^2}$$

- for small ∇p, current gradient (Δ') dominates

  ⇒ 'classical Tearing Mode', current driven

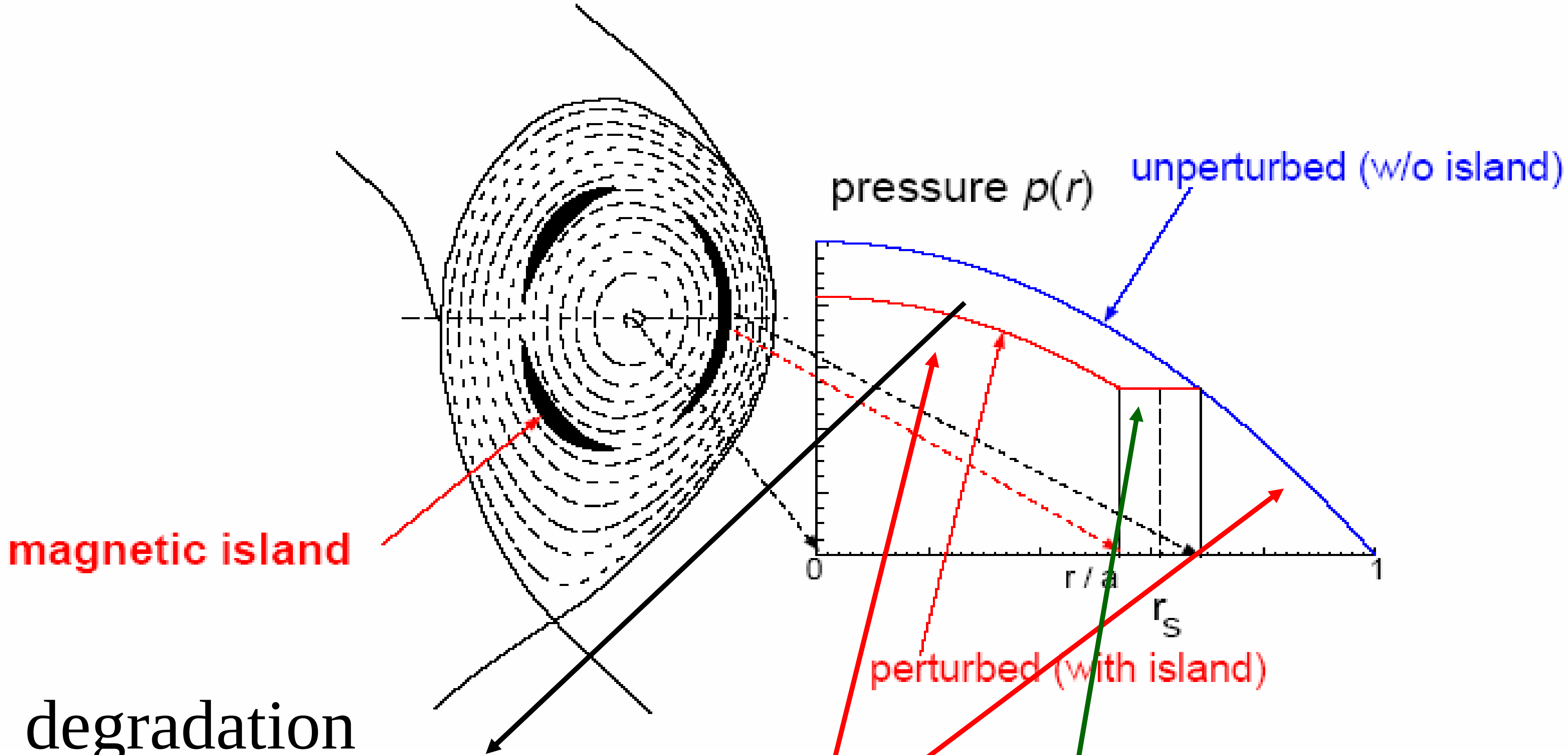
  (most of the time stable except if q profile is "tweaked", which is why resistive MHD was never a big thing up to end 1990s for tokamak interpretation)

- for larger ∇p, pressure gradient dominates:

  ⇒ 'Neoclassical Tearing Mode', pressure driven

- adding an externally driven helical current can stabilise

Magnetic islands deteriorate performances



degradation

$$\frac{\Delta\tau_E}{\tau_E} = 4\frac{w\rho_s^3}{a^4}$$

Chang et al, 1994, "belt-model"

Local transport stays same outside island
But "short-circuit" across island

Provides accurate simple measure of w_{sat}

Perturbed Bootstrap is driving term=>Neoclassical

- Evolution of the island connected with the parallel currents flowing near the resonant surface

- Current profile usually tearing-stable: $\Delta'<0$ in the Rutherford equation

$$\frac{dW}{dt} = c_1 \Delta'$$

[Furth et al., PoF 1963; Rutherford, PoF 1973]

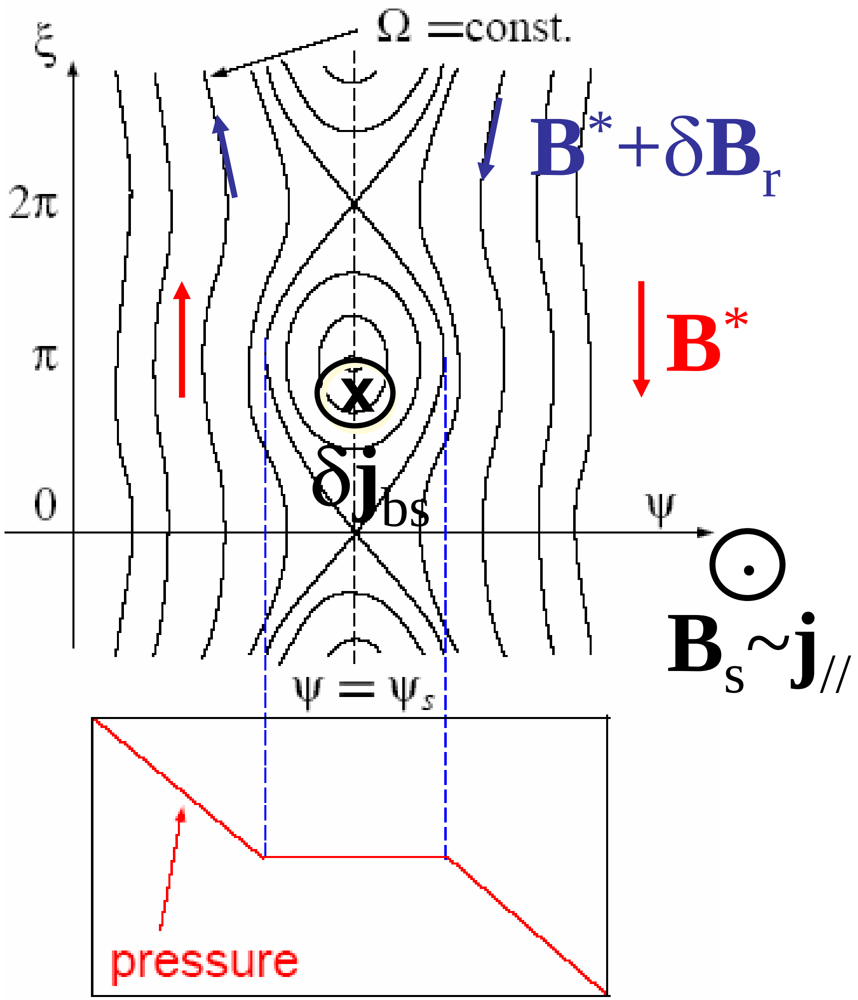
- Adding non-inductive current perturbation caused by the island itself

$$\frac{dW}{dt} = c_1 \Delta' + \frac{c_2}{W} \int_{-1}^{\infty} d\Omega \oint \frac{d\xi \cos\xi}{\sqrt{\cos\xi + \Omega}} \, j_{\parallel}^{n.i.}$$

Useful coordinates:

helical flux $\Omega \equiv 2(\psi - \psi_s)^2 / W_\psi^2 - \cos\xi$

helical angle $\xi \equiv m\theta - n\zeta$



$$B_\theta^* = B_\theta - B_{s\theta} \approx -\frac{q'_s}{q_s}(\rho - \rho_s) B_\theta$$

, E. Poli

Modified Rutherford Equation (MRE)

Many terms can contribute to total // current within island

$$\frac{dw}{dt} = \frac{\rho_s}{\tau_R}\left[\rho_s \Delta'(w) + \rho_s \Delta_{bs}'(w) + \rho_s \Delta_{GGJ}'(w) + \rho_s \Delta_{cd}'(w) + \right.$$

$$\left. \rho_s \Delta_{pol}'(w,\omega) + \rho_s \Delta_{ech}'(w) + \rho_s \Delta_{wall}'(w,\omega) + \rho_s \Delta_{mn}'(w,\omega) + \ldots \right]$$

Main terms discussed and compared with experiment on 1st line

"classical" + bootstrap + curvature + polarisation + (EC)CD

Glasser-Greene-Johnson

wall and mode coupling can also be important

→ in particular, efficient locking of 2/1 mode

Despite limits of MRE, method/coeff. described in Sauter et al PoP 1997 and PPCF 2002 + Ramponi PoP 1999 for Δ'_{wall} describes essentially all exp. Results+prediction

Considering main contributions

$$\mathbf{MRE} \times \frac{1}{\rho_s|\Delta'|}: \quad \frac{dw}{dt} \sim \tilde{f}(w) = -1 + f_{\tau mn} \frac{w_{sat\infty}\, w}{w^2 + w_{marg}^2} - 1.1\, f_{\tau mn} \frac{w_{sat\infty}}{w_{cd}} \frac{j_{cd}}{j_{bs}}\, \underbrace{4\eta_{aux}\left(\frac{w}{w_{cd}}\right)}_{\sim 1 \text{ (for } w_{cd} \sim w)}.$$

$$f_{\tau mn} = (1 - \Delta_{\tau mn} w)$$

$$\Delta_{\tau mn} = 4\frac{\rho_s^3}{a^4},$$

$$\frac{\Delta\tau}{\tau} = -\Delta_{\tau mn} w_{sat},$$

$$w_{sat\infty} = \rho_s\, \beta_{p0}\, \frac{a_{bs} - a_{GGJ}}{\rho_s|\Delta'|}$$

To obtain self-consistent solution with confinement degradation

$$w_{sat} = \frac{w_{sat\infty}}{1 + \Delta_{\tau mn}\, w_{sat\infty}}$$

$$\beta_{psat} = \frac{\beta_{p0}}{1 + \Delta_{\tau mn}\, w_{sat\infty}}$$

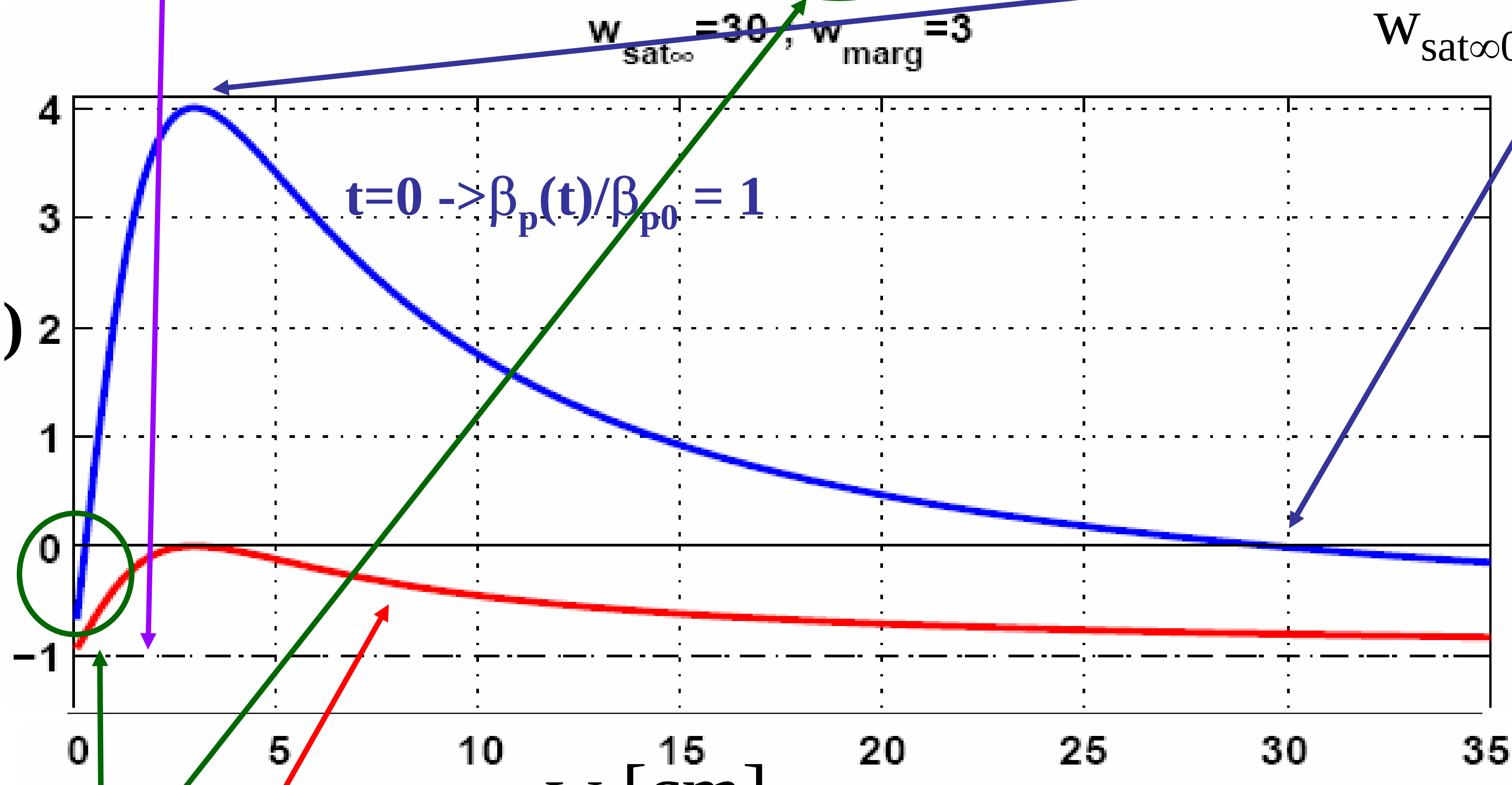
w structure of steady-state MRE (no CD)

$$\tilde{f}(w) = -1 + \frac{\beta_p(t)}{\beta_{p0}} w_{sat\infty,0} \frac{w}{w^2 + w_{marg}^2}$$

ITER expected 2/1 parameters

w_{marg}=3cm

$w_{sat\infty0}$=30cm



$\tilde{f}(w)$

w [cm]

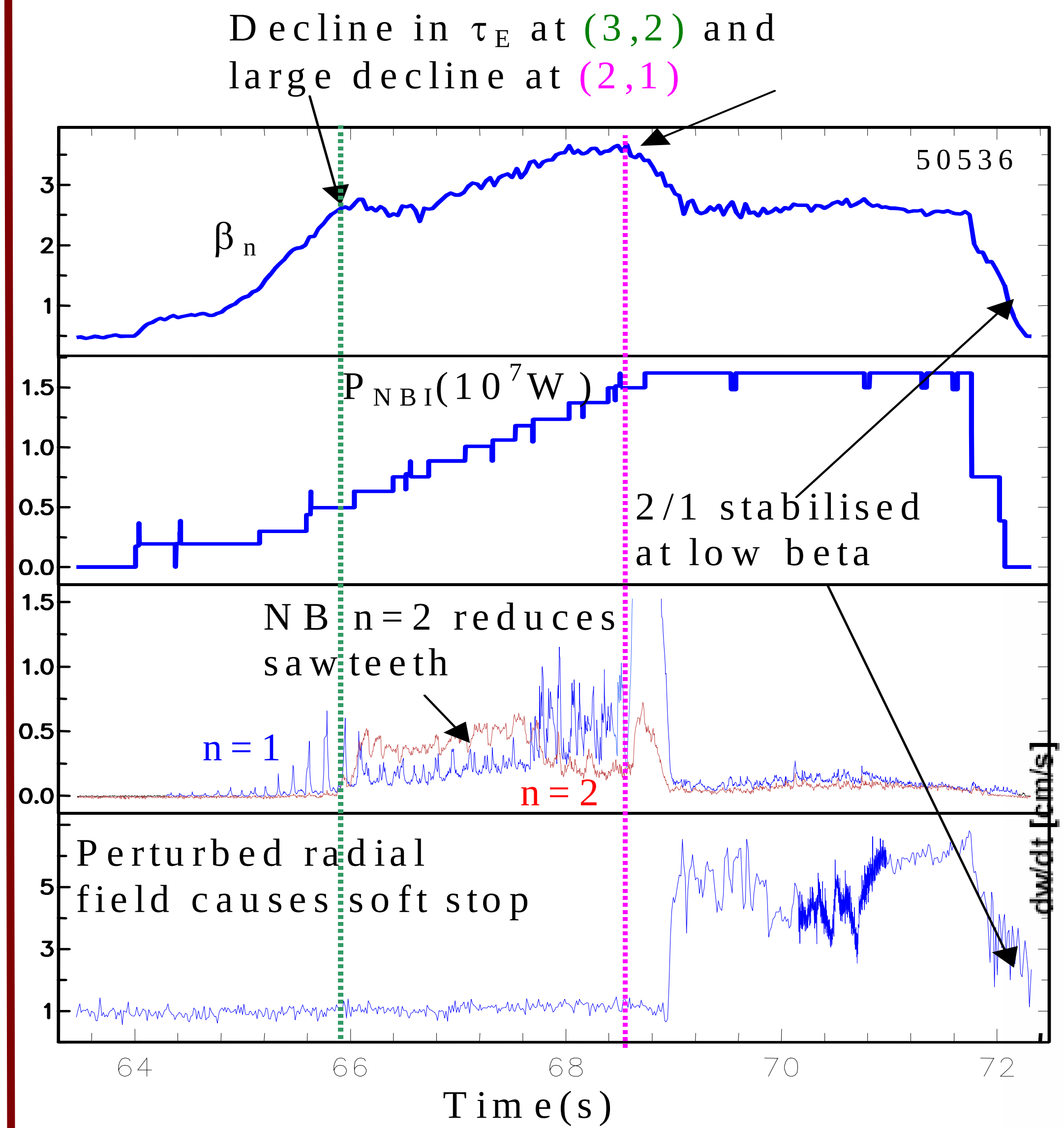
t=0 -> $\beta_p(t)/\beta_{p0}$ = 1

$\beta_p(t)/\beta_{p0}=2w_{marg}/w_{sat\infty0}$ (=0.2 in this case)

$$\beta_{p,marg} = 2\frac{w_{marg}}{w_{sat\infty,0}}\beta_{p,0}$$

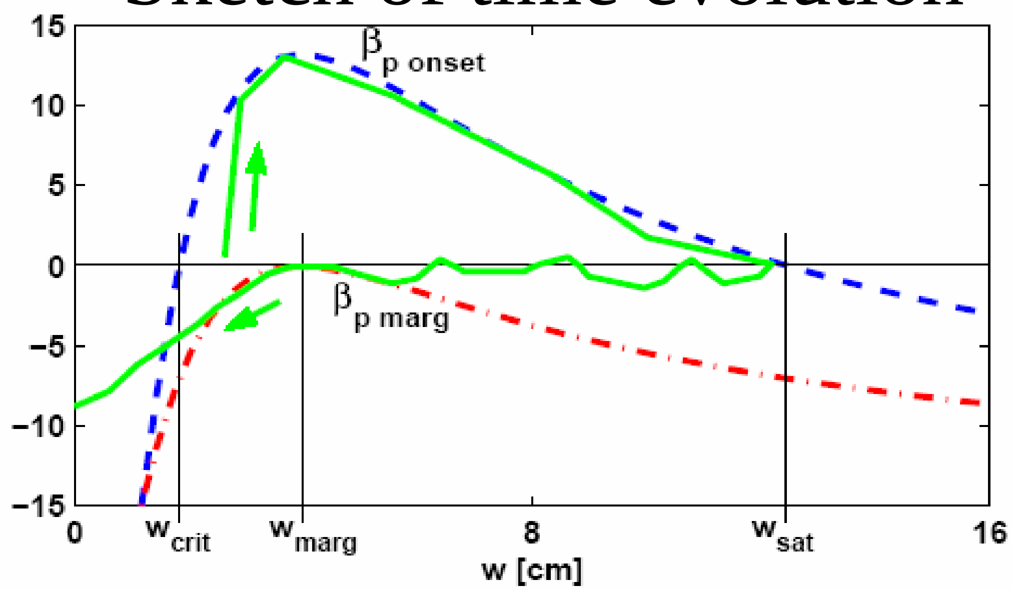
NTMs are metastable: require seed island

Typical effects of NTMs



- **3/2 NTMs lead to 10-20% losses**
- **2/1 NTMs lead to greater losses and to disruptions**

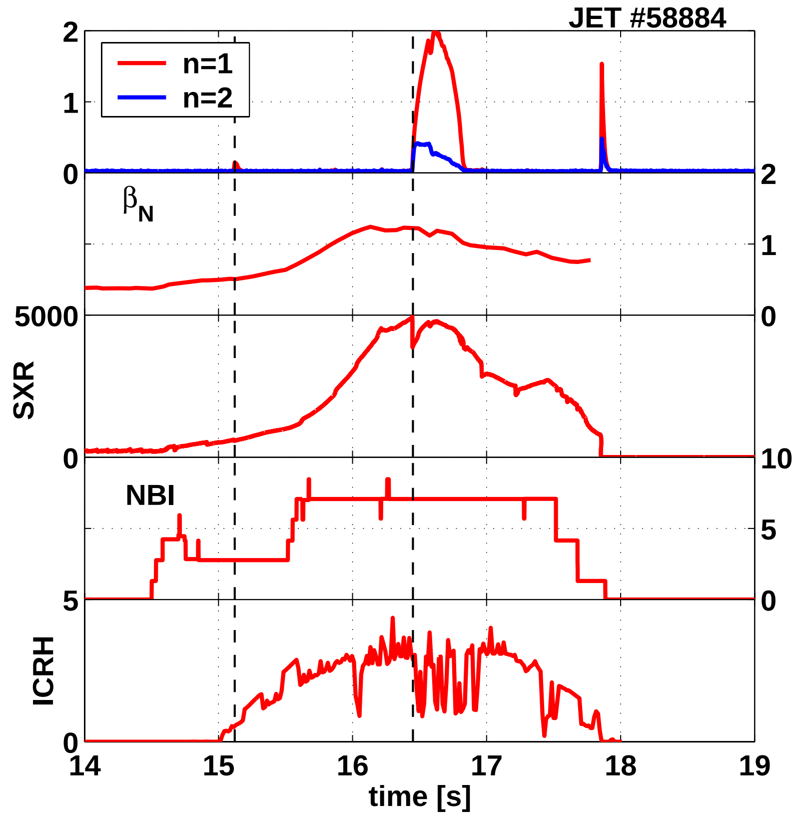
Sketch of time evolution

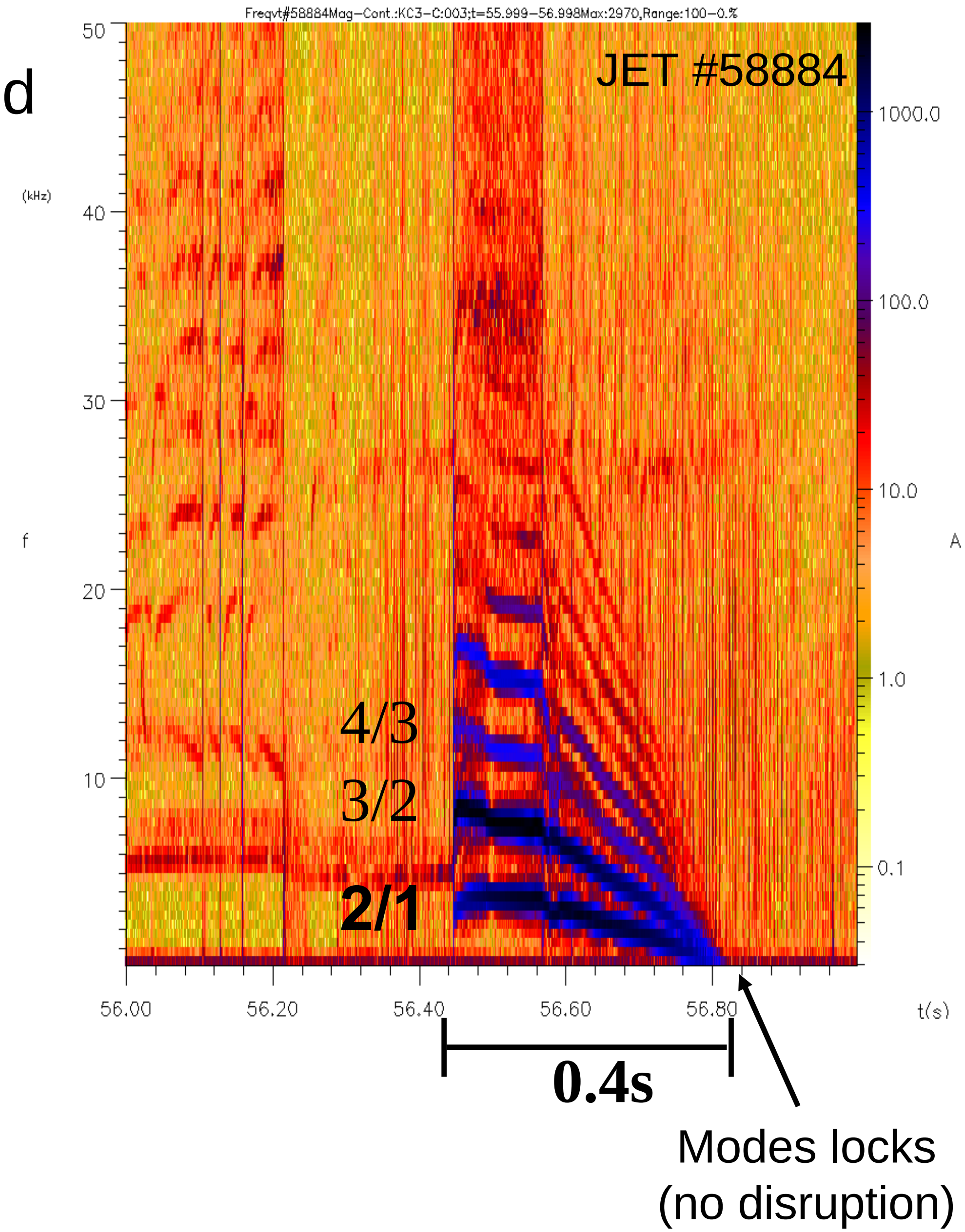


Hender, chap 3, NF 2007

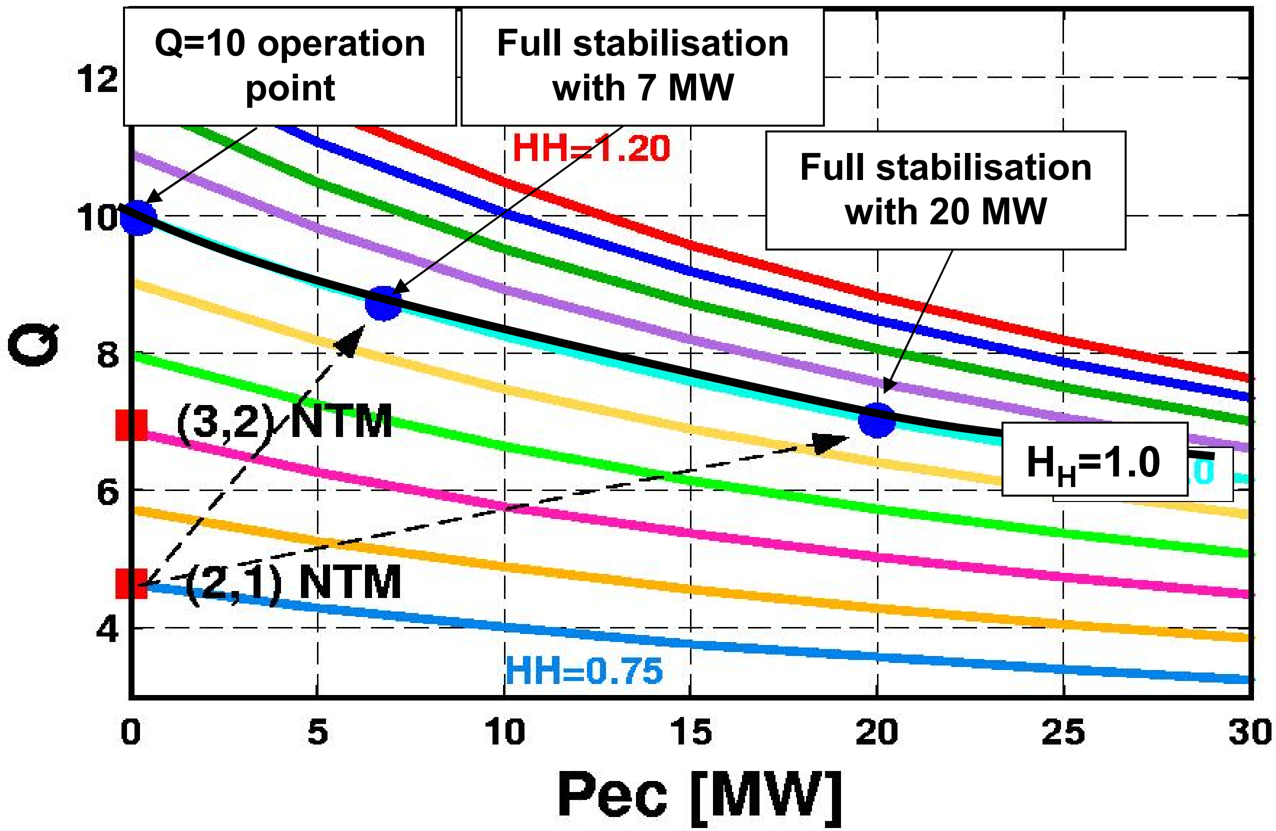
Standard Scenario: Sawteeth and Mode Locking

- As discussed in ST session, crashes after long sawtooth period can trigger several modes
- Modes can lock rapidly (within 0.4s in this JET case)





NTMs in ITER – predictions for Q=10 scenario



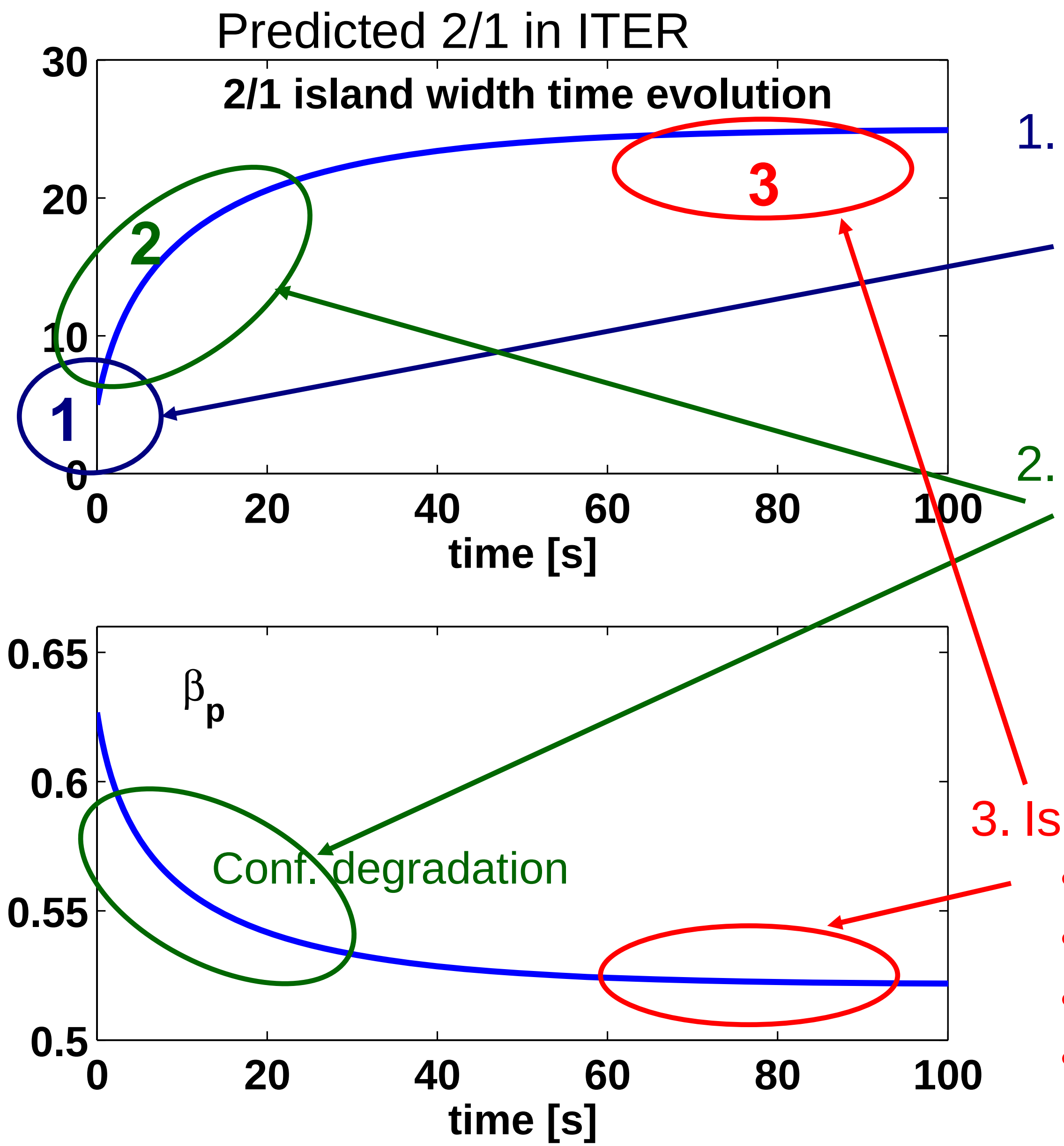
ITER burn curves in the presence of ECCD
at q=3/2 and q=2

(O. Sauter and H. Zohm, EPS 2005, also Plasma Phys. Contr. Fusion 52 (2010))

Impact on Q in case of continuous stabilisation (worst case):

- Q drops from 10 to 5 for a (2,1) NTM and from 10 to 7 for (3,2) NTM
- with 20 MW needed for stabilisation, Q recovers to 7, with 10 MW to Q > 8
- note: if NTMs occur only occasionally, impact of ECCD on Q is small

What are we controlling?



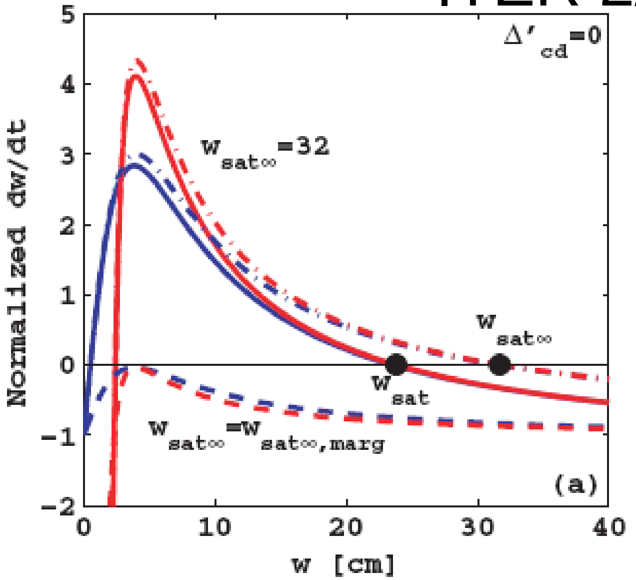
1. Island starts
   - At large w_{seed} from ST trigger
   - At small w_{seed}
   - Without trigger from q profile (Δ'>0)

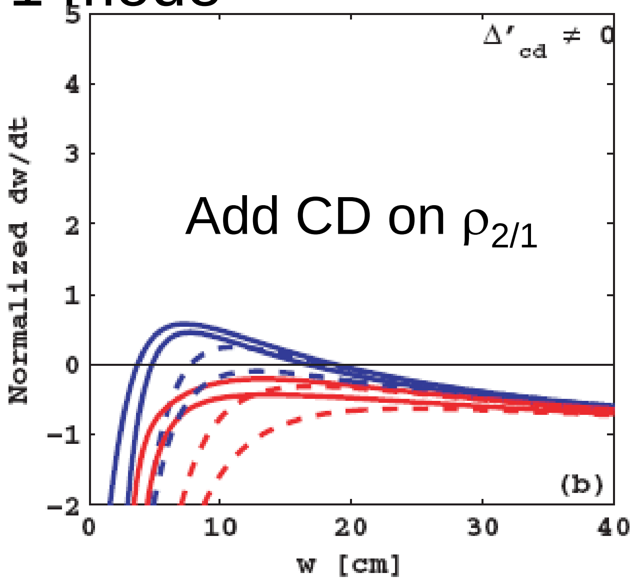
2. Island grows and rotates or locks
   - Growth rate depends on beta
   - Beta drop depends on ρ_{res}, w
   - Locking depends on β, q_{95}, and error field

3. Island saturates or plasma disrupts
   - Depends on island size
   - On proximity to beta limit
   - On w versus a-ρ_{res} (on q_{95})
   - On island overlap

How are we controlling?

ITER 2/1 mode





Criteria for ITER:

$w_{cd} \leq 5$cm

AND

$\eta_{NTM} w_{cd} \geq 5$cm

($\eta_{NTM}=j_{cd}/j_{bs} \geq 1$)

Compute P required for various models:

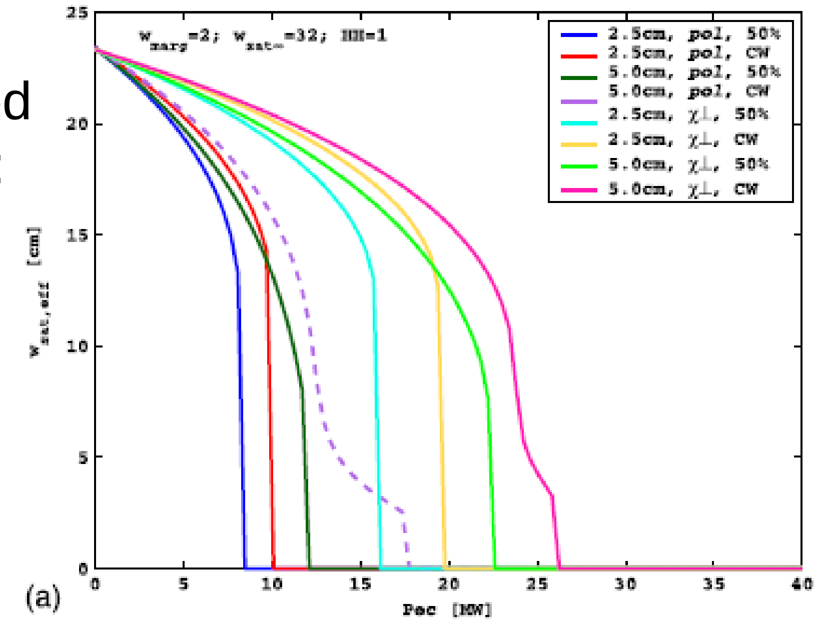
w_{cd}

w_{marg}

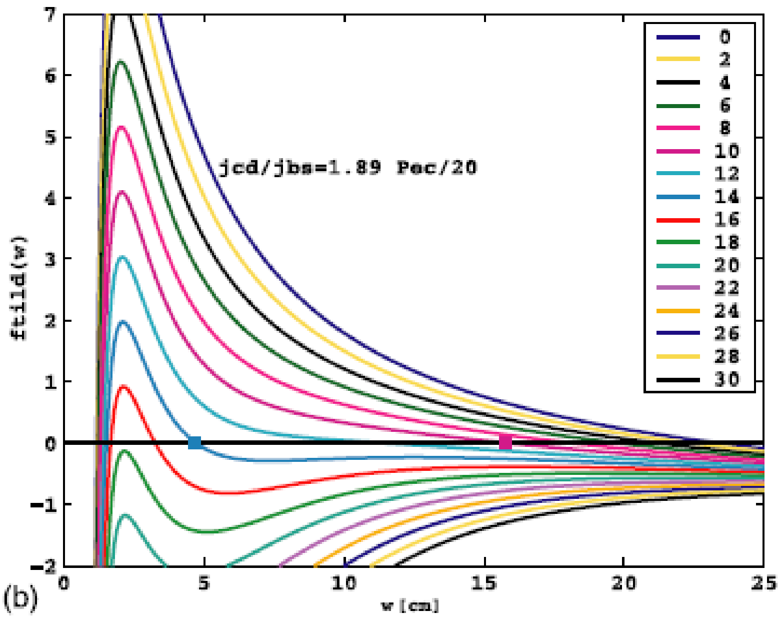
pol type

$\chi_{\perp}$ type

CW or 50%



(a)

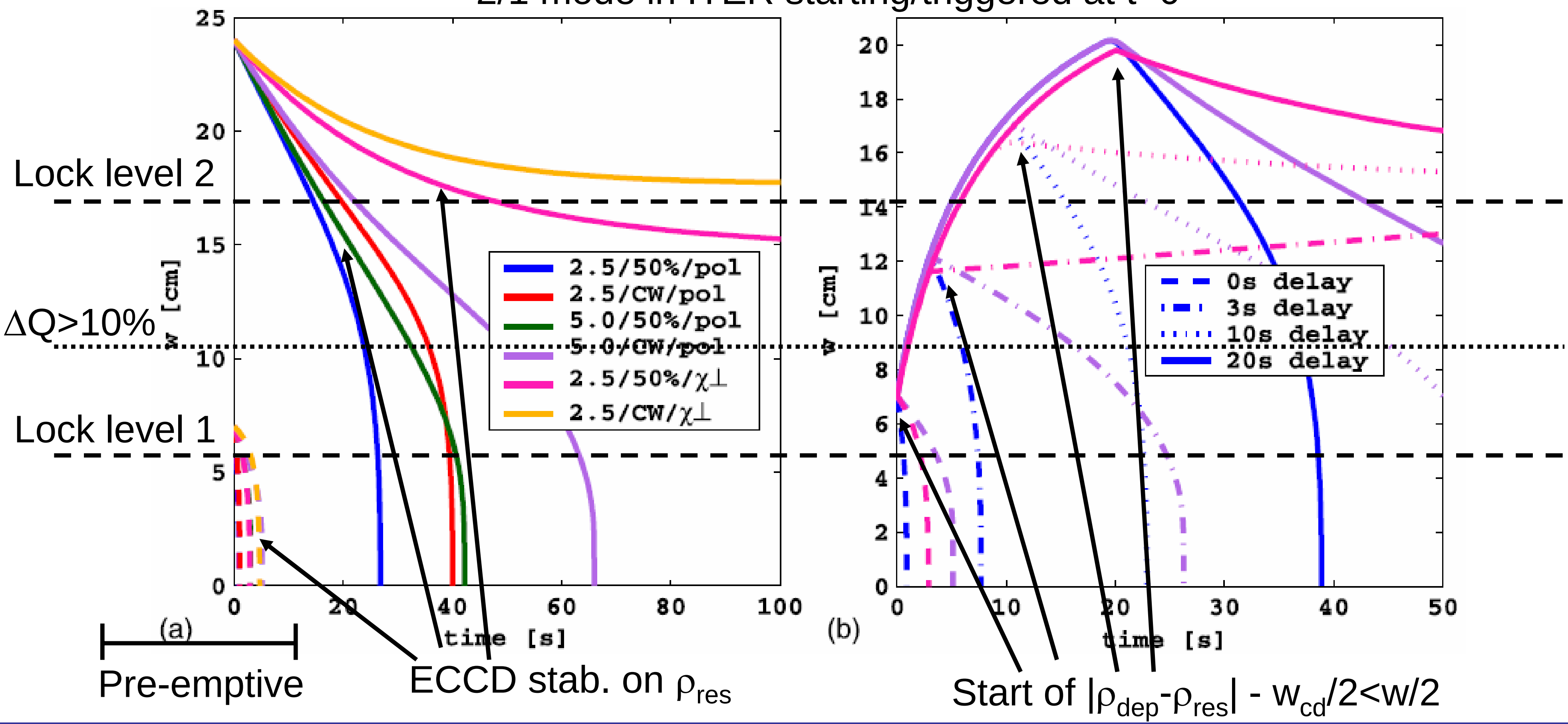


(b)

Sauter, PPCF 2010

Why and when do we intervene?

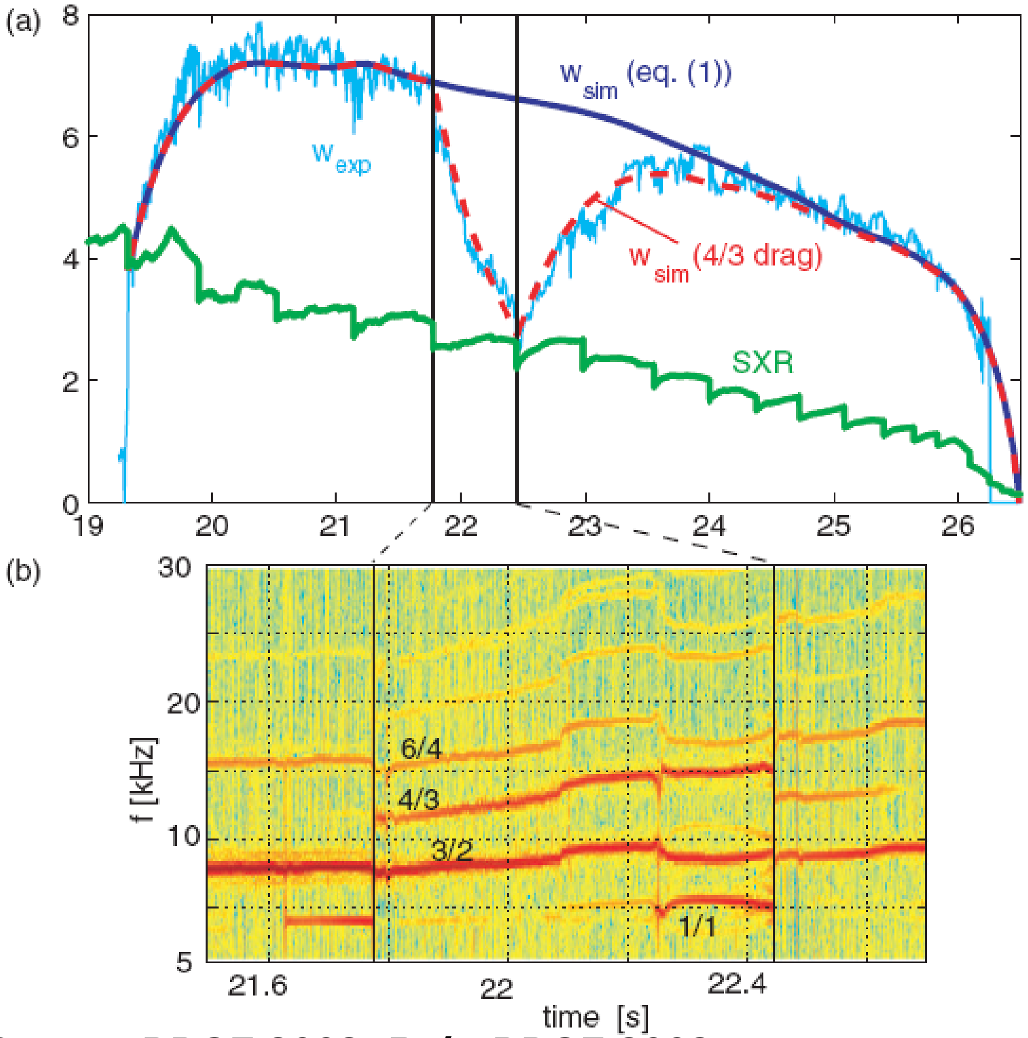
2/1 mode in ITER starting/triggered at t=0

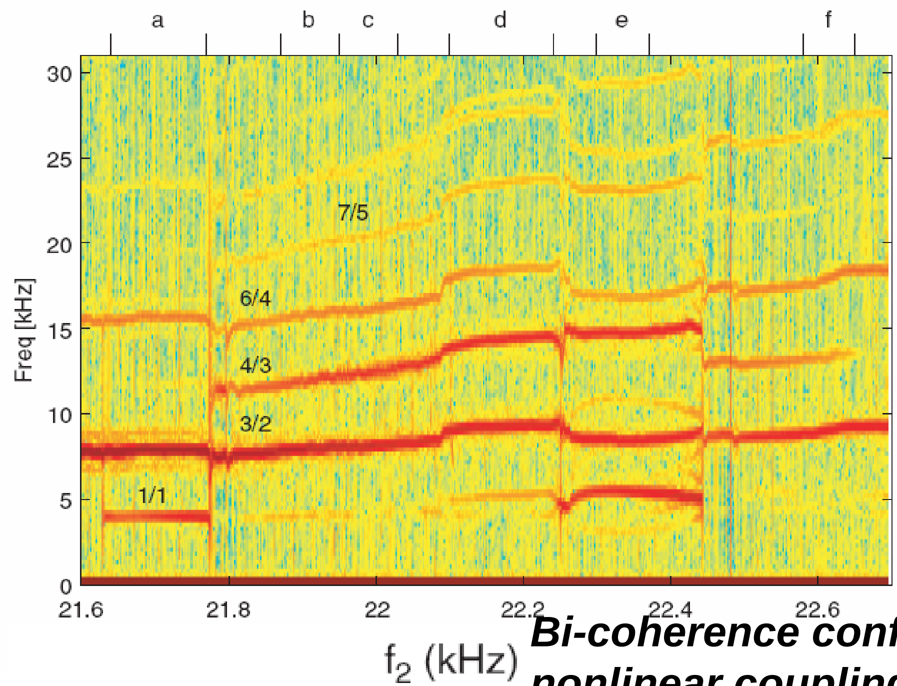


- Lots of "conditions" and constraints to take into account
- Extra plots are to be added:
  - Proximity to disruption, mode freq. vs time (fast diagn. used to predict locked mode)
  - Confinement degradation/proximity to H-L transition, etc
- Using real-time control+simulation, these will also be known predictively
  - Calculations within few ms and prediction for next 10-20s => opens new "control space"

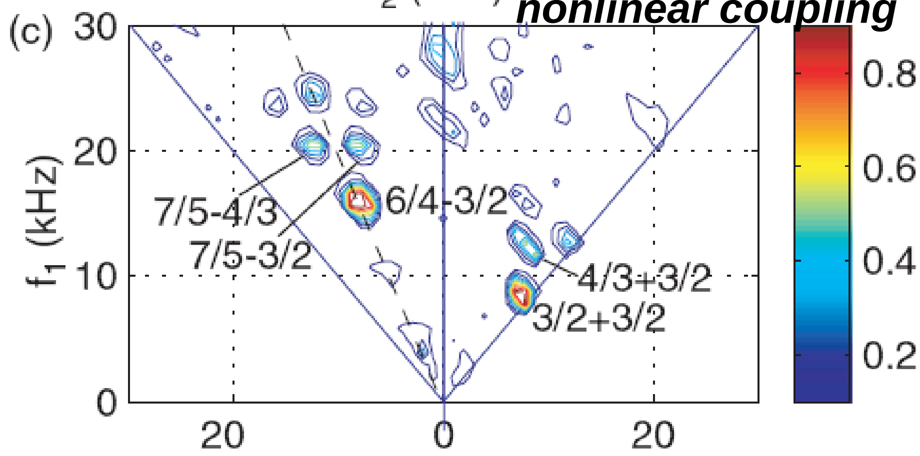
Mode coupling: usually favourable

- 4/3 mode triggered by sawtooth crash is seen to stabilize 3/2 mode observed in JET and TCV, similar to FIR-NTMs seen on AUG and with XTOR





Bi-coherence confirm nonlinear coupling



Sauter, PPCF 2002; Raju PPCF 2003

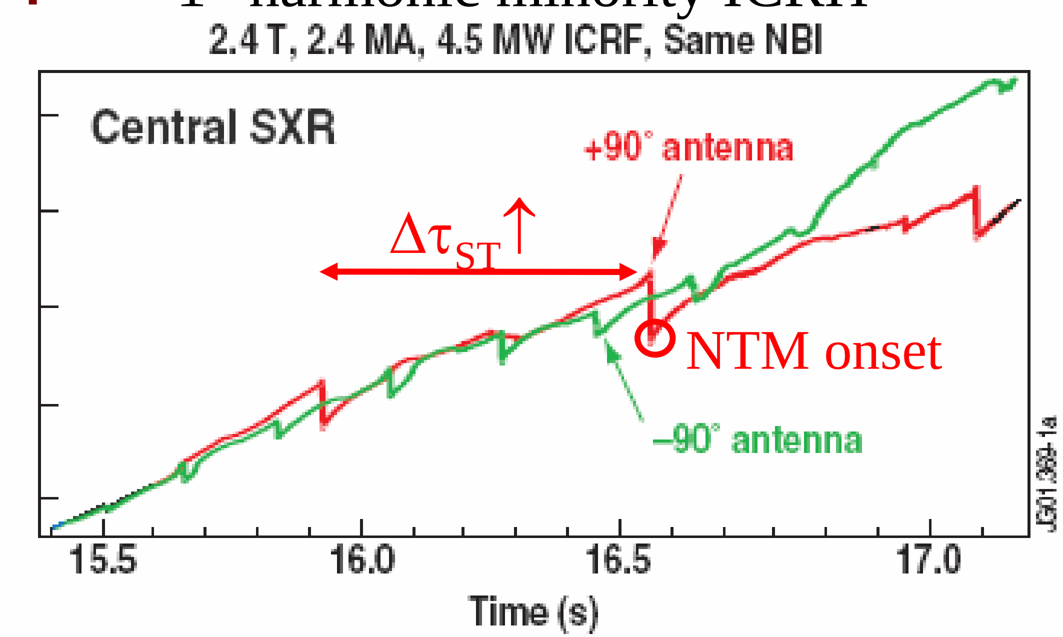
Scalings for predictions for ITER

- Scalings of $\beta_{p,onset}$ hard to use as prediction since
  - Couples seed island and bootstrap drive
  - Needs similar trigger mechanisms
  - Very hard to predict triggered island size
- Use ramp-down experiments to perform scalings of:
  - $w_{sat}(\beta_{p,max})$ (allows test of bootstrap drive and Δ')
  - $\beta_{p,marg}$ (includes also effects of stabilising terms)
  - w_{marg} (stab. terms and provides info size of trigger)
- Then can test the physics against these scalings
- $\beta_{p,marg}$ scaling: ITER metastable to both 3/2 and 2/1 modes

Importance of trigger mechanism

Controlling sawteeth changes significantly β_{onset}

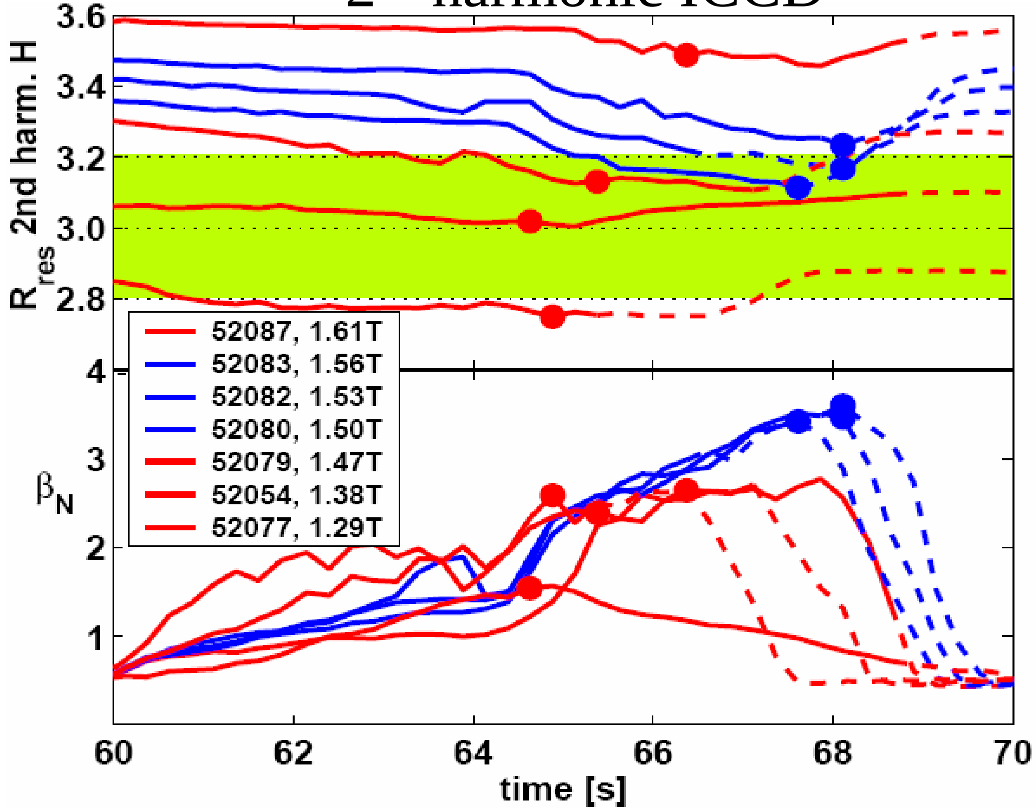
1st harmonic minority ICRH



+90: phase: $\beta_{N,onset}\approx 1$

-90: No NTM with β_N up to 2

2nd harmonic ICCD

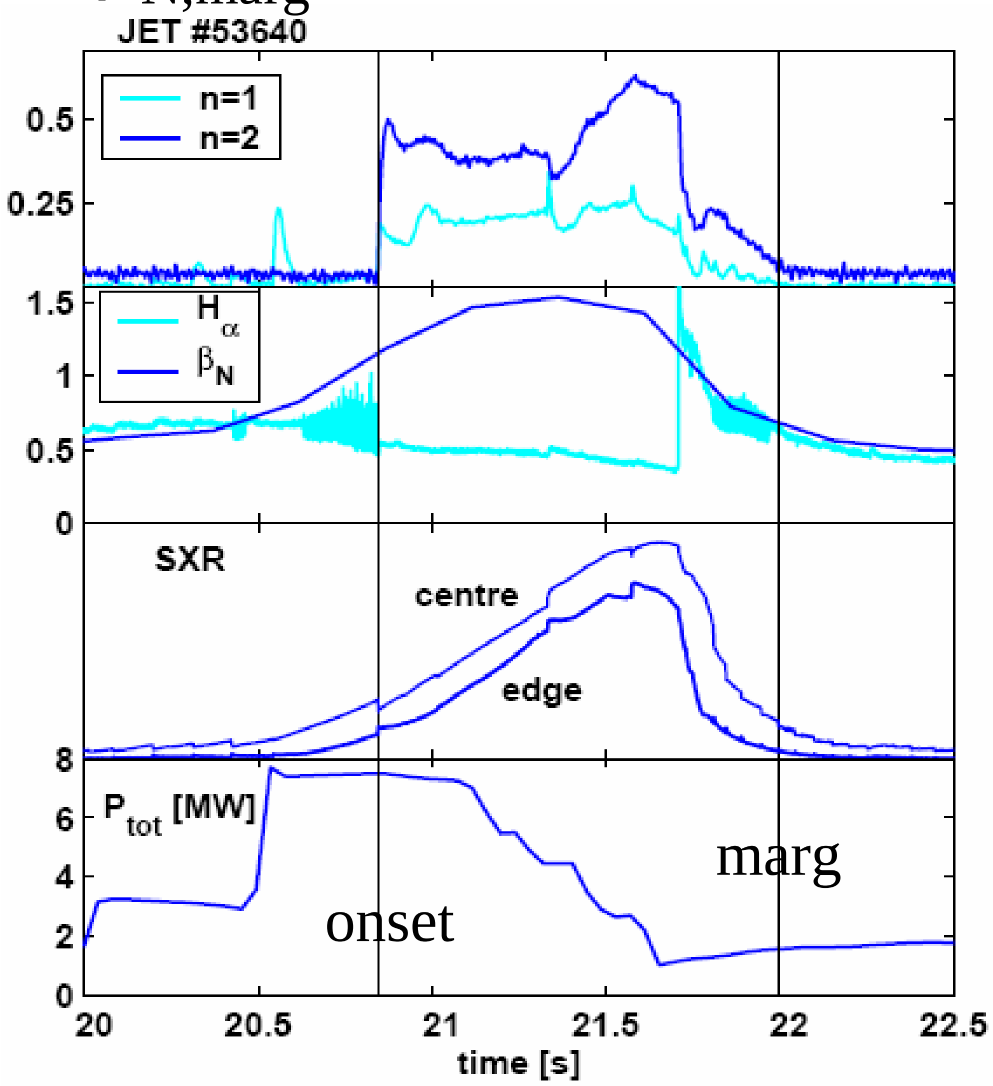


Sauter et al, PRL 2002

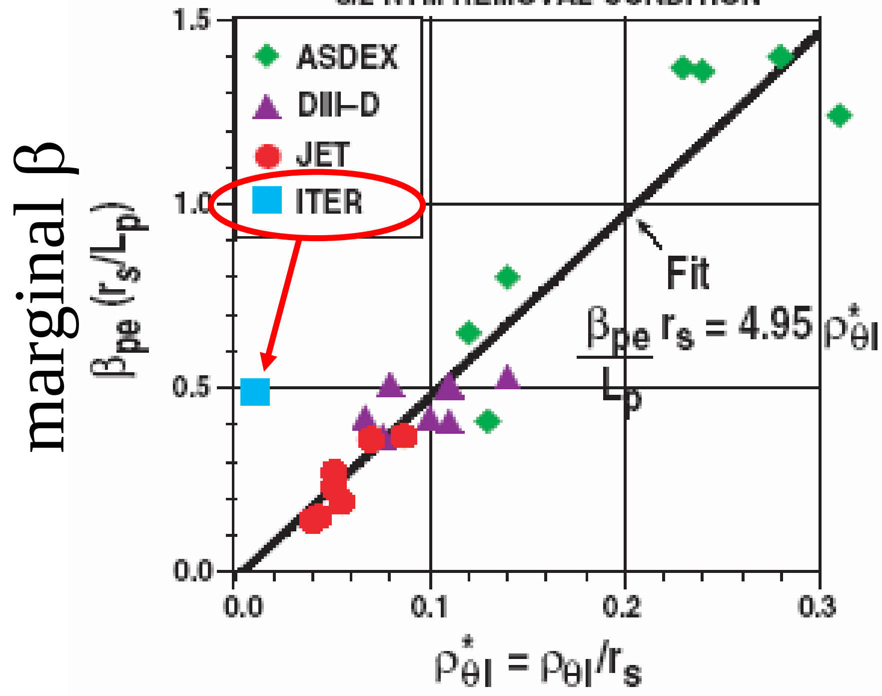
Power ramp-down studies

q_{95}=2.54 case does not disrupt even with 2/1 mode

$\beta_{N,marg}$ < L-H threshold

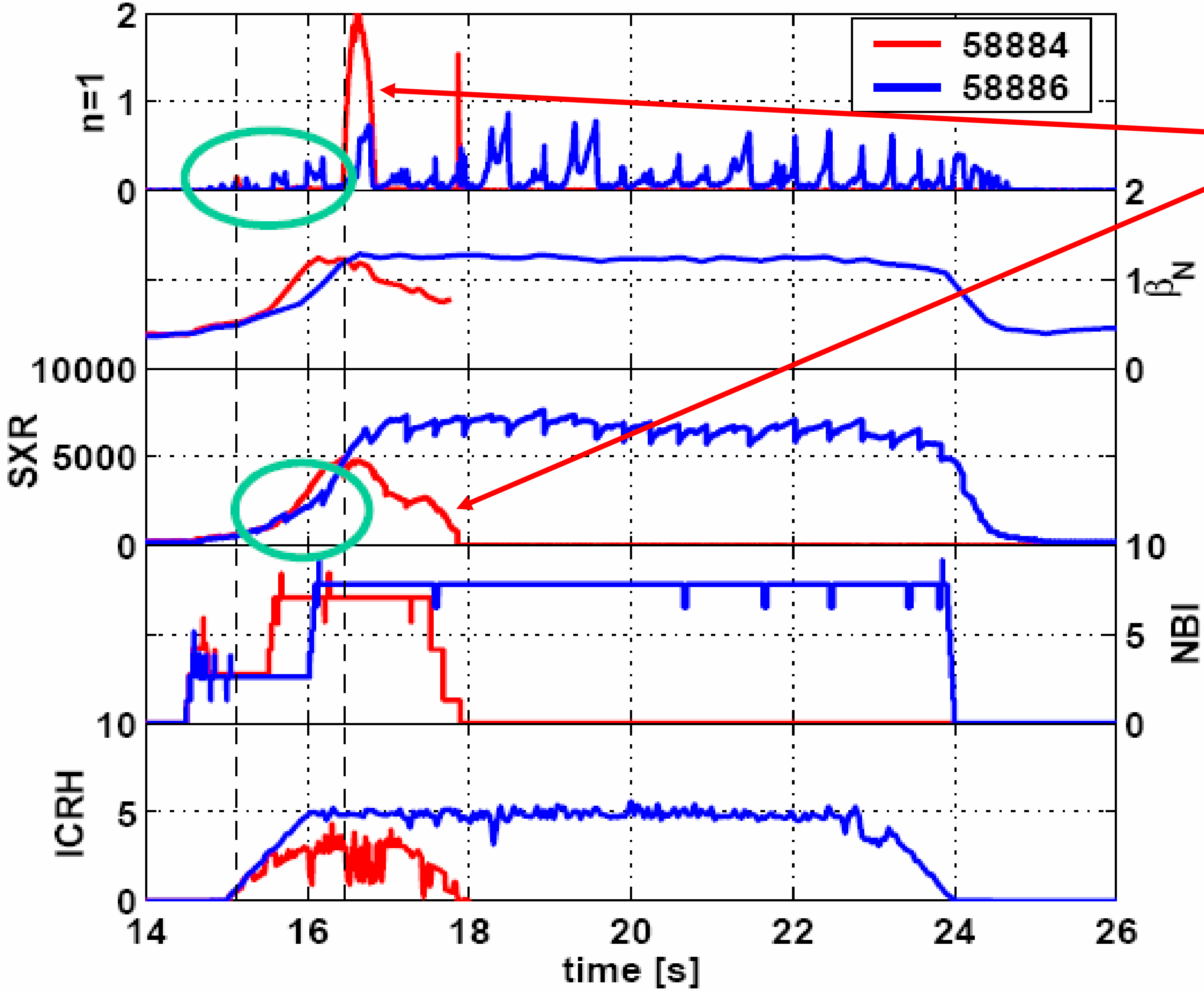


★ $w_{marg} \approx 2\, \varepsilon^{1/2}\, \rho_{\theta i}$
(twice ion banana width)



DIII-D NATIONAL FUSION FACILITY SAN DIEGO
EFDA JET
ASDEX Upgrade

NTMs Avoidance technique required in JET high performance: control of 1st sawteeth



2/1 NTM triggered leads to end of shot (soft-stop)

Lack of sawtooth control actuators is a difficulty for these scenarios (high current and shape)

"Ultimate" control of NTMs: ECCD

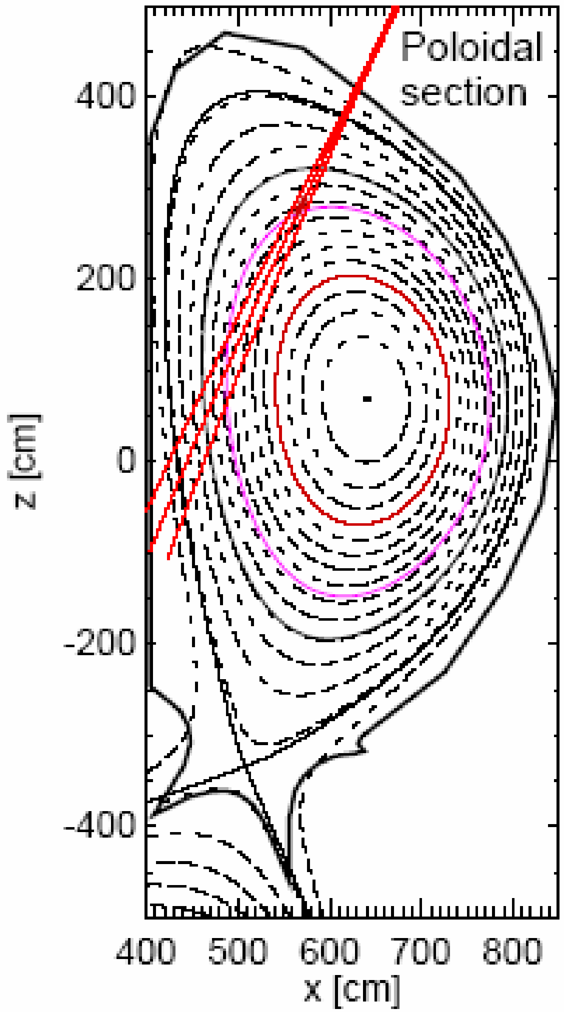
Why ECCD in ITER? (4 ports dedicated to NTM stab.)

- ECCD can drive localised current
- Deposition location is well defined and depends essentially on launching mirrors
- Mirrors can be oriented in real-time to control NTMs

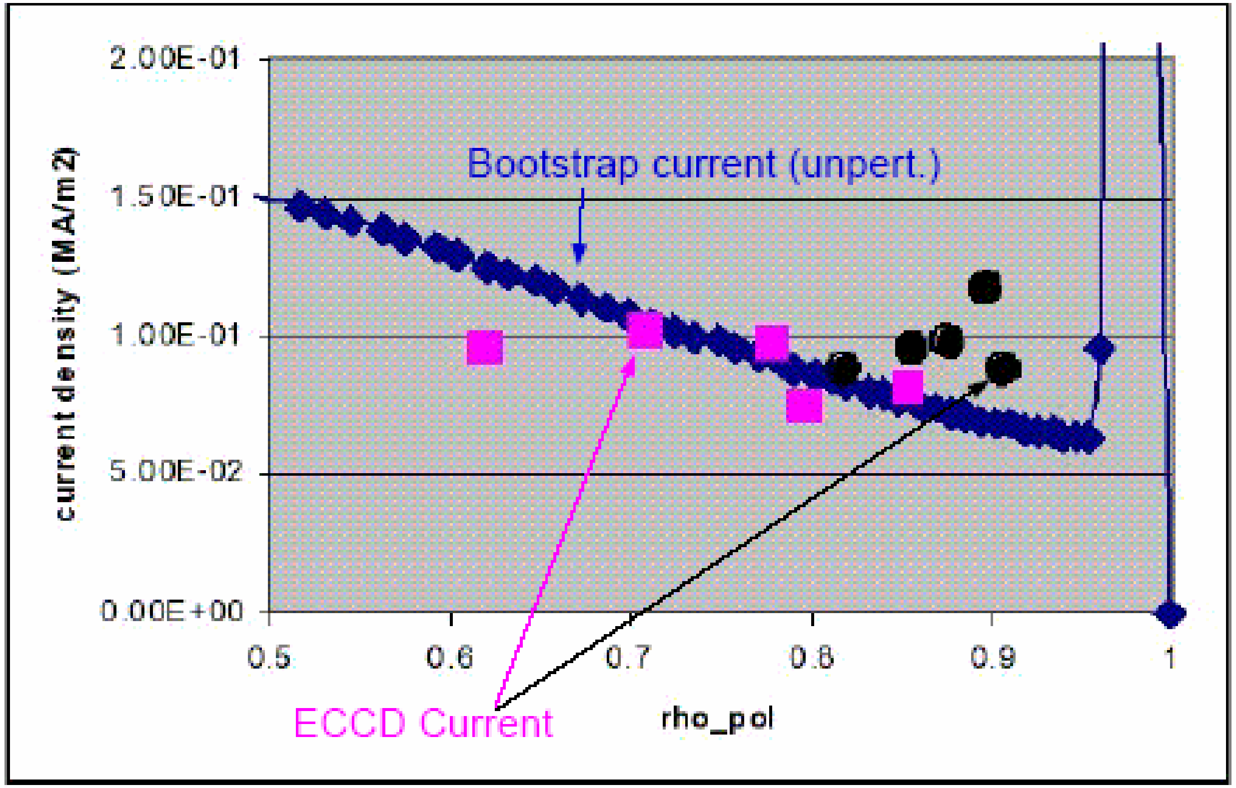
- Aim:
  - Replace missing bootstrap current by driving j_{CD} in O-point of island
  - (Modify j_{tot} to decrease further Δ') (*in theory*)

Active NTM stabilisation in ITER

- Upper ECRH system for active stabilisation of (3,2) and (2,1) islands under development
- Current deposition calculated by means of the TORBEAM code [Poli et al., CPC 1999]



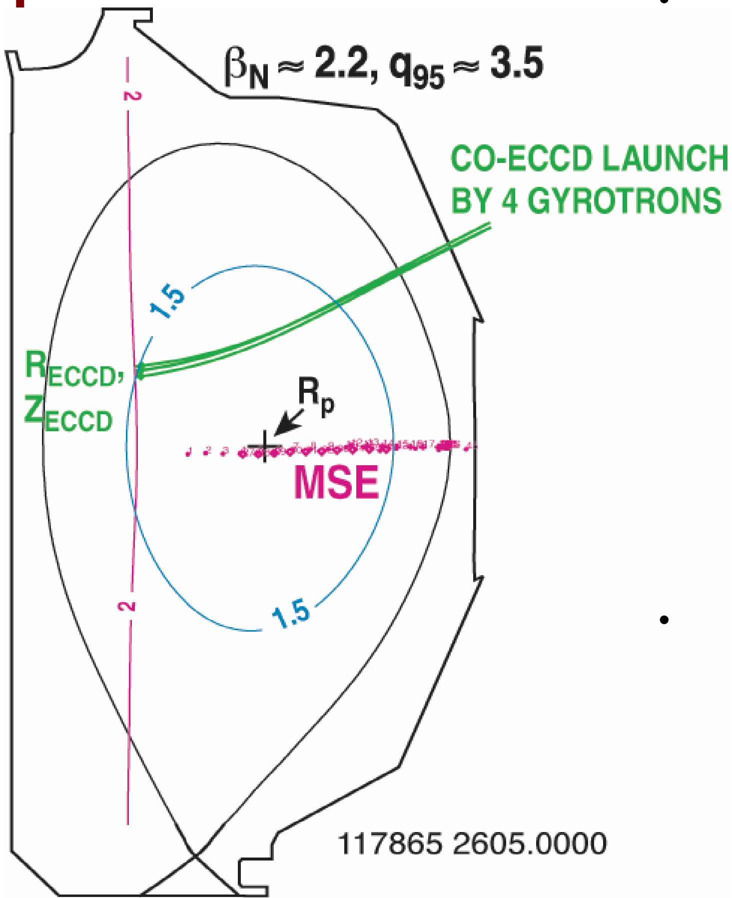
- Driven current smaller than the missing bootstrap current for the present design



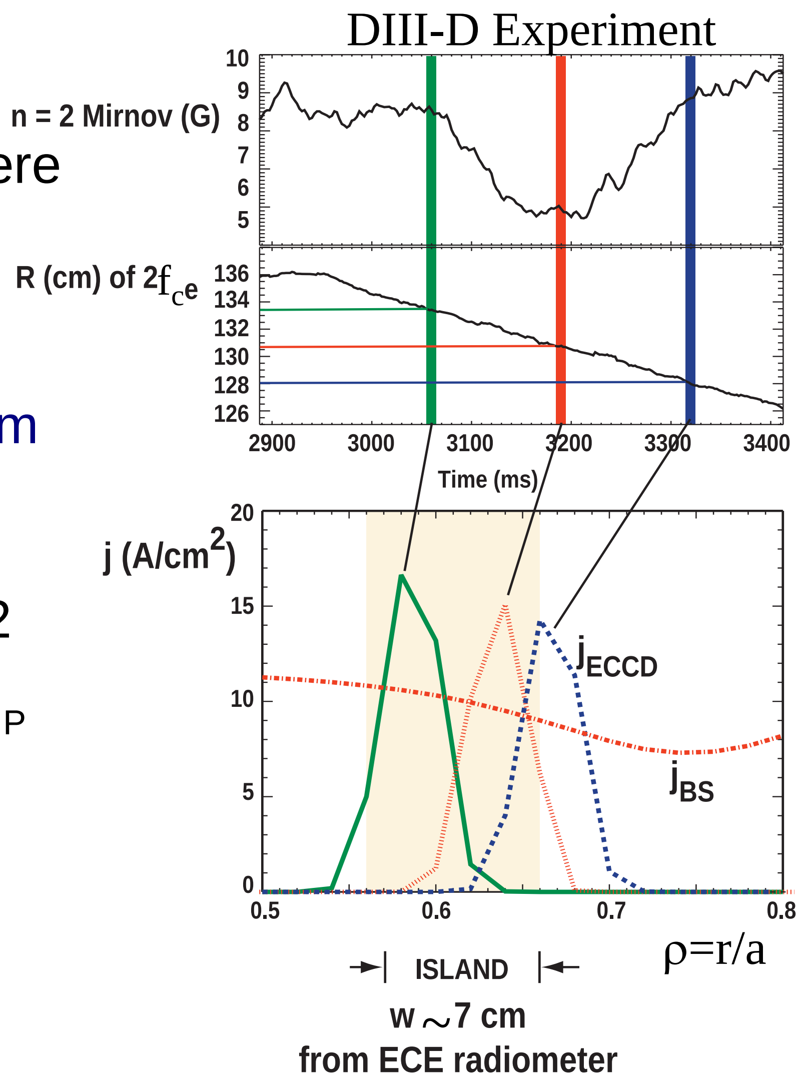
[Zohm, Poli et al., EC13 (2004)]

IPP Kolloquium, E. Poli

ECCD Localized at Islands Can Replace Missing Bootstrap Current and Stabilize NTM



- ECCD deposition must be accurately positioned at q=m/n rational surface where NTM island forms
  - Alignment accuracy required in DIII-D ~ 1 cm
- EC total current drive (for 2 MW injected) ~30 kA ~2%I_P
- NTM control achieved at ASDEX-U, JT-60U, DIII-D, FT-U



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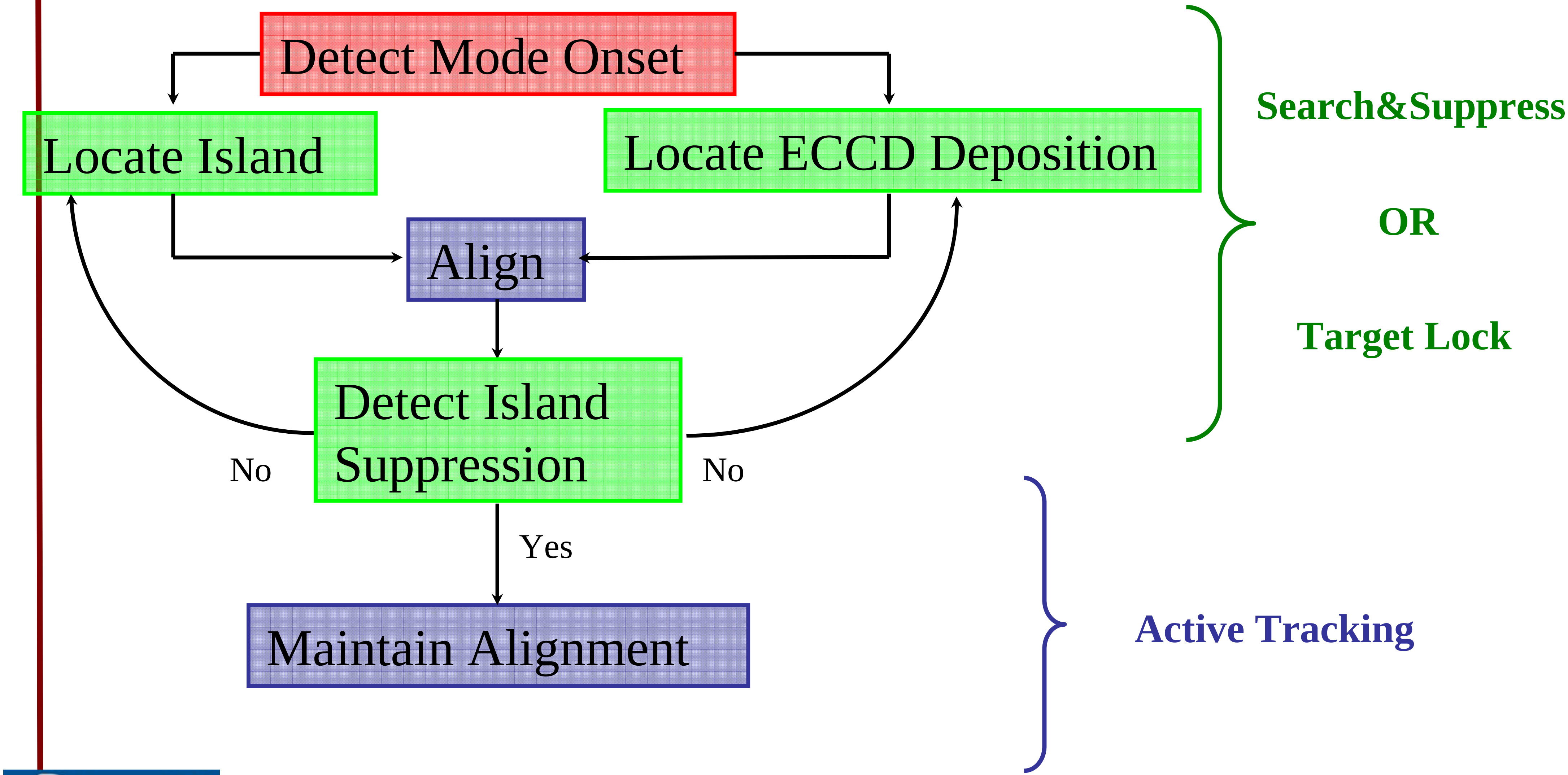
NTM Control Requires Achieving and Sustaining Dynamic Island/ECCD Alignment



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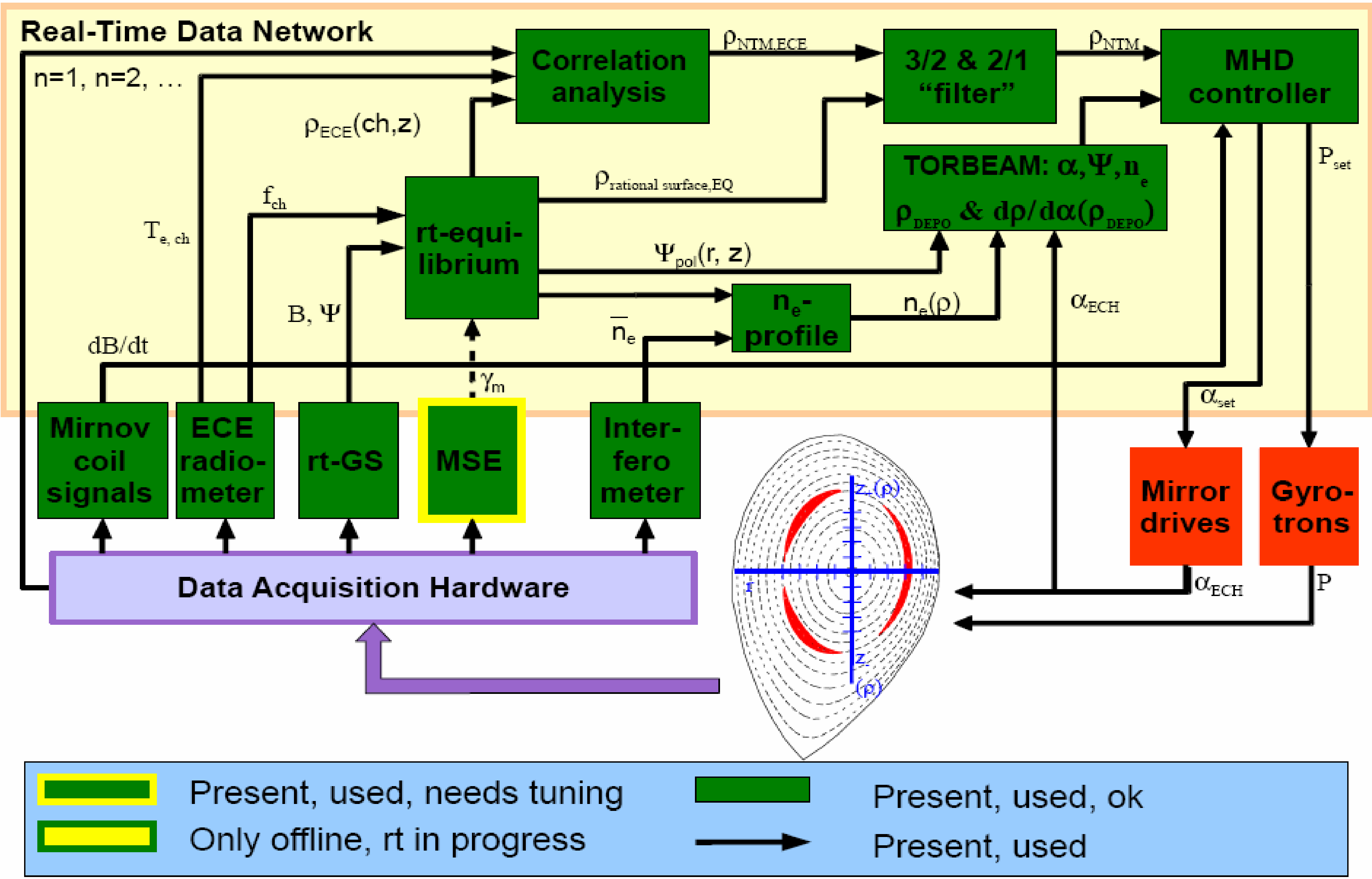
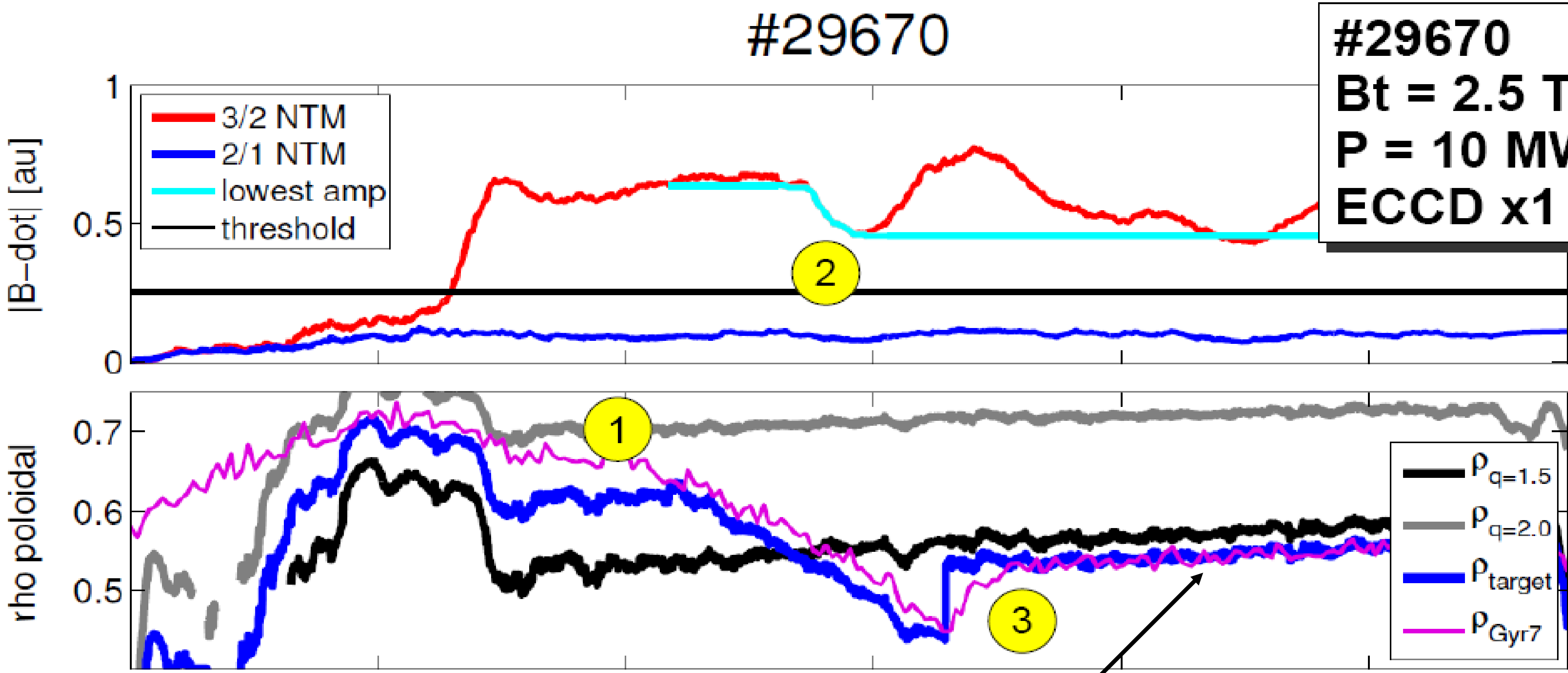
NTM stabilization at ASDEX Upgrade



NTM stabilization – *sweep and suppress*

(similar to DIII-D "target-lock" technique)



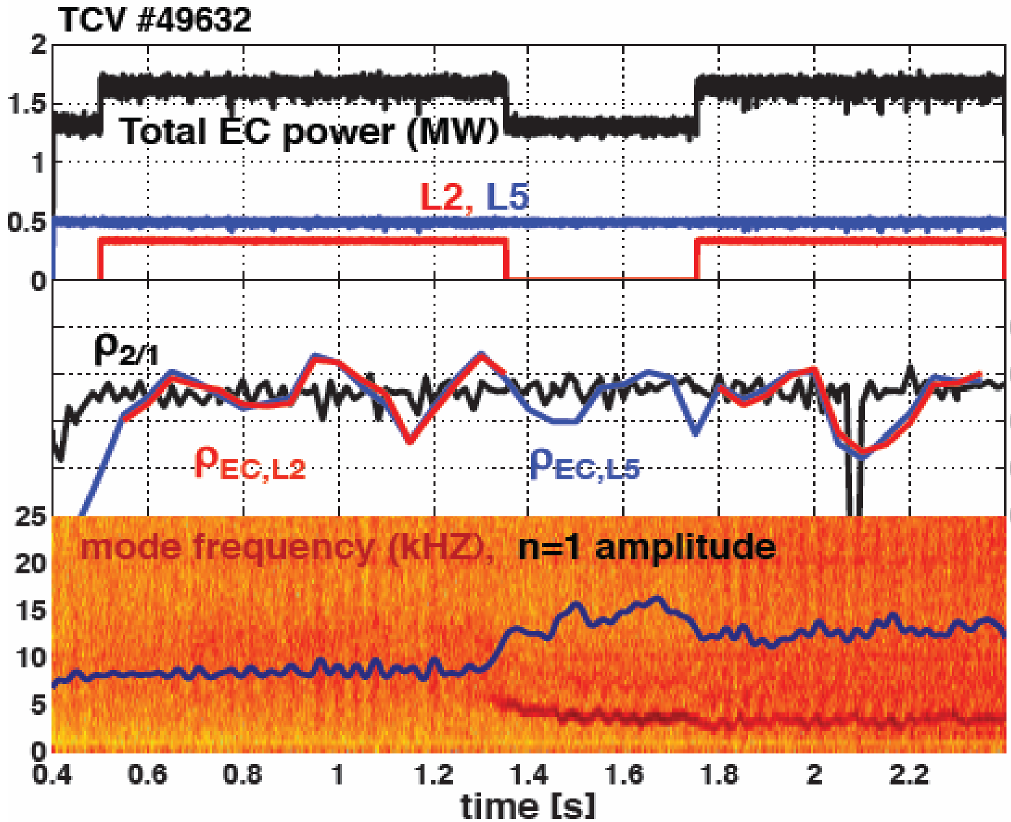
#29670
Bt = 2.5 T
P = 10 MW
ECCD x1

Main problem: there is always some mismatch between $\rho_{ec,dep}$ and $\rho_{m/n}$ due to equilibrium reconstruction, launcher inaccuracies, changes in density profiles, etc

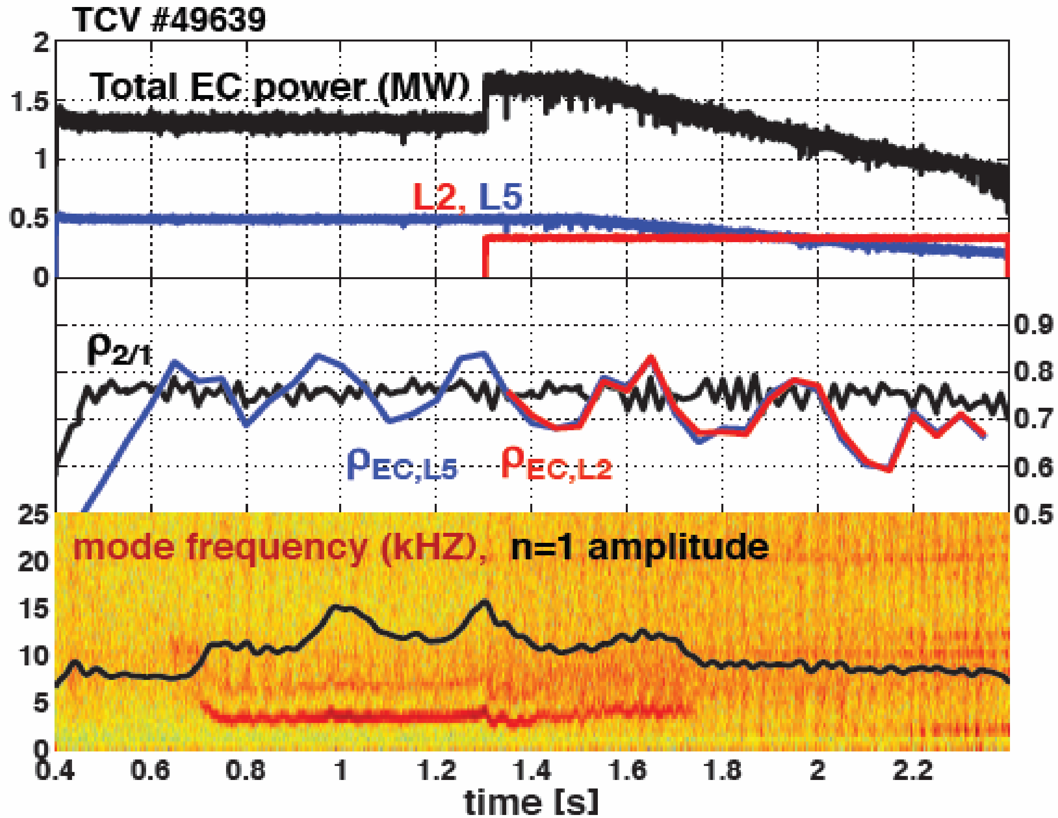
New control strategy developed on TCV

•Add a systematic sweep around target position
•Limits systematic errors, use slow growth of tearing modes (*resistive timescale*)

2/1 mode pre-emption with robust contol

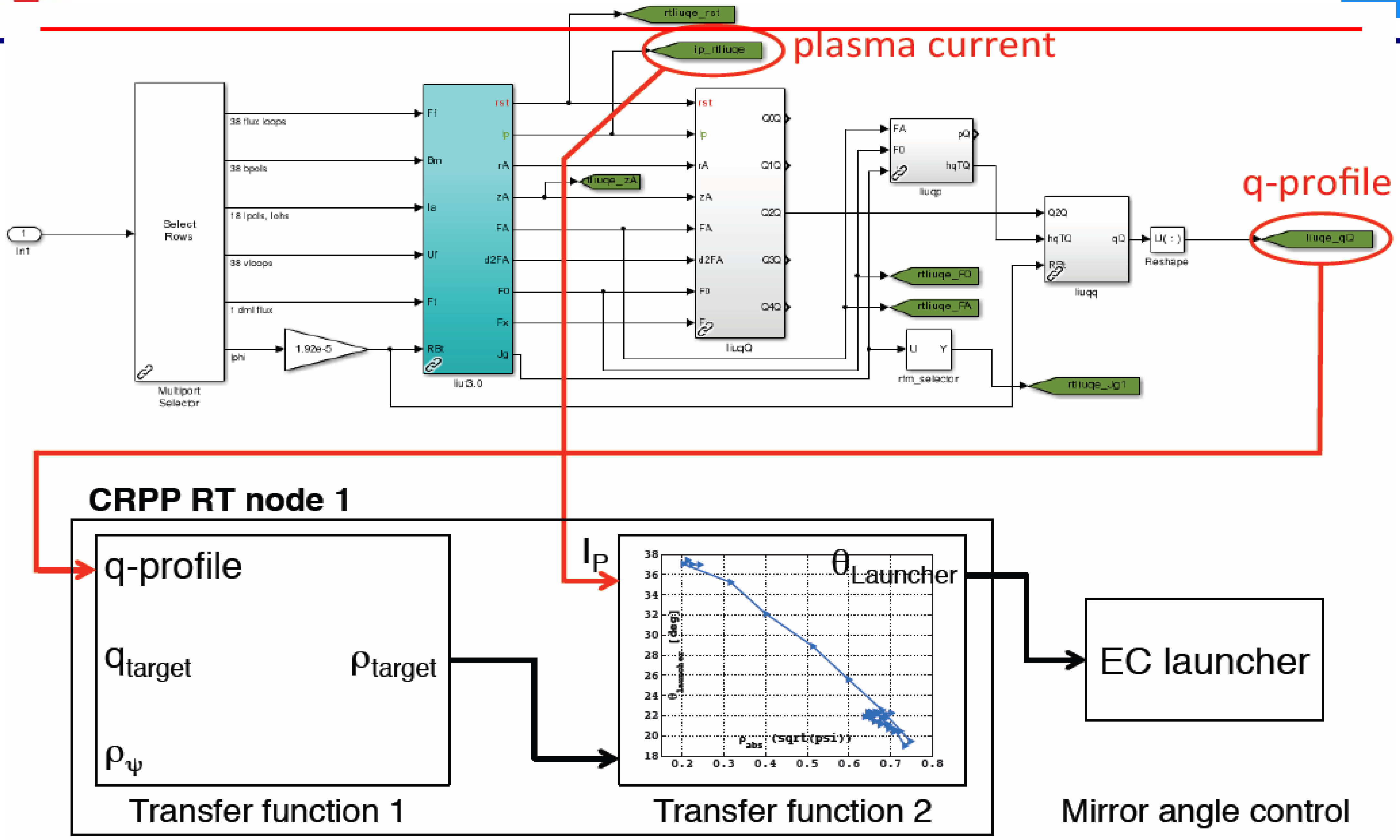


2/1 stabilization with robust control

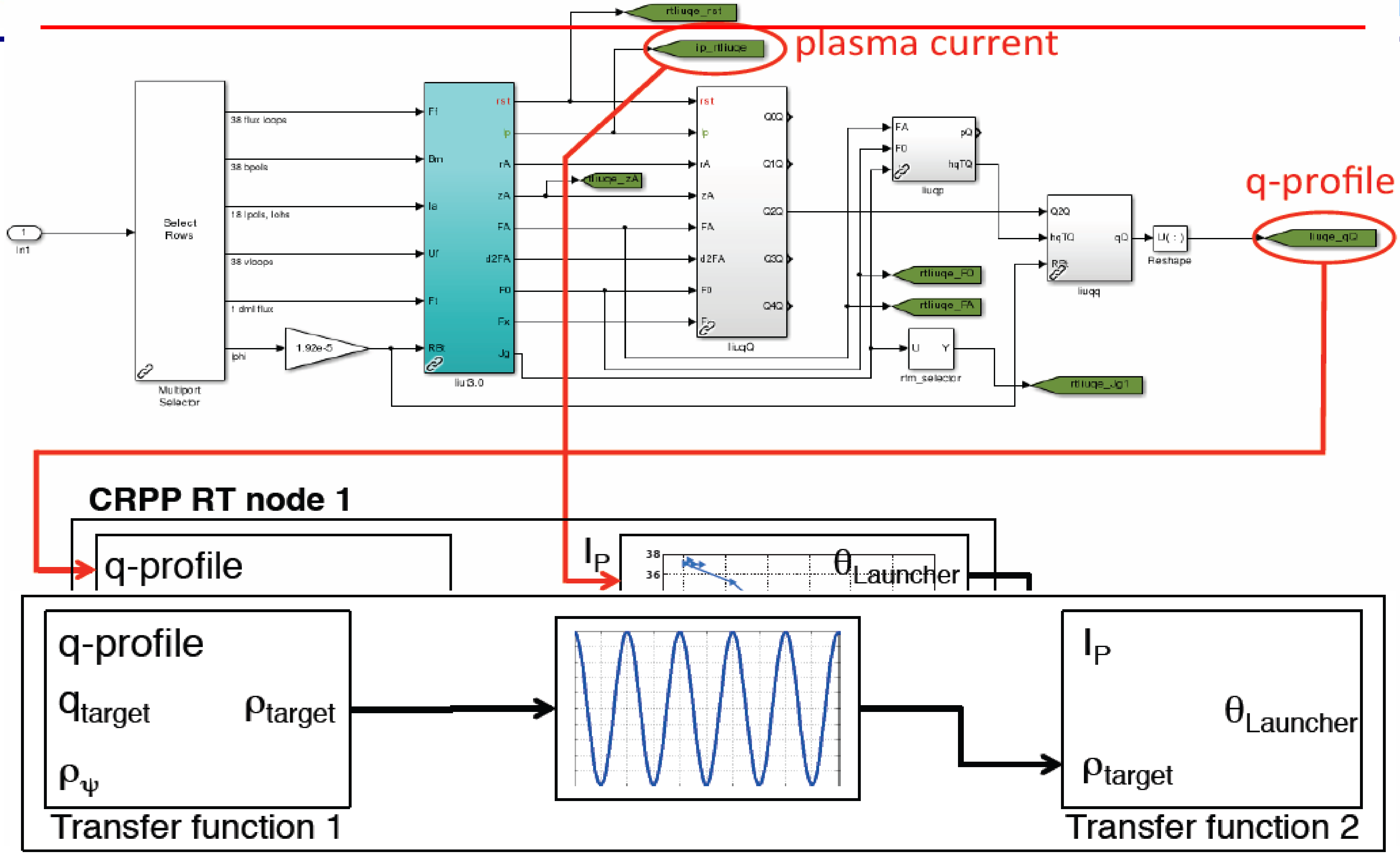


•Works for both preemption and stabilization, scales for ITER
•Allows more precise physics studies => better prediction for ITER

Simple to add to present feedback control

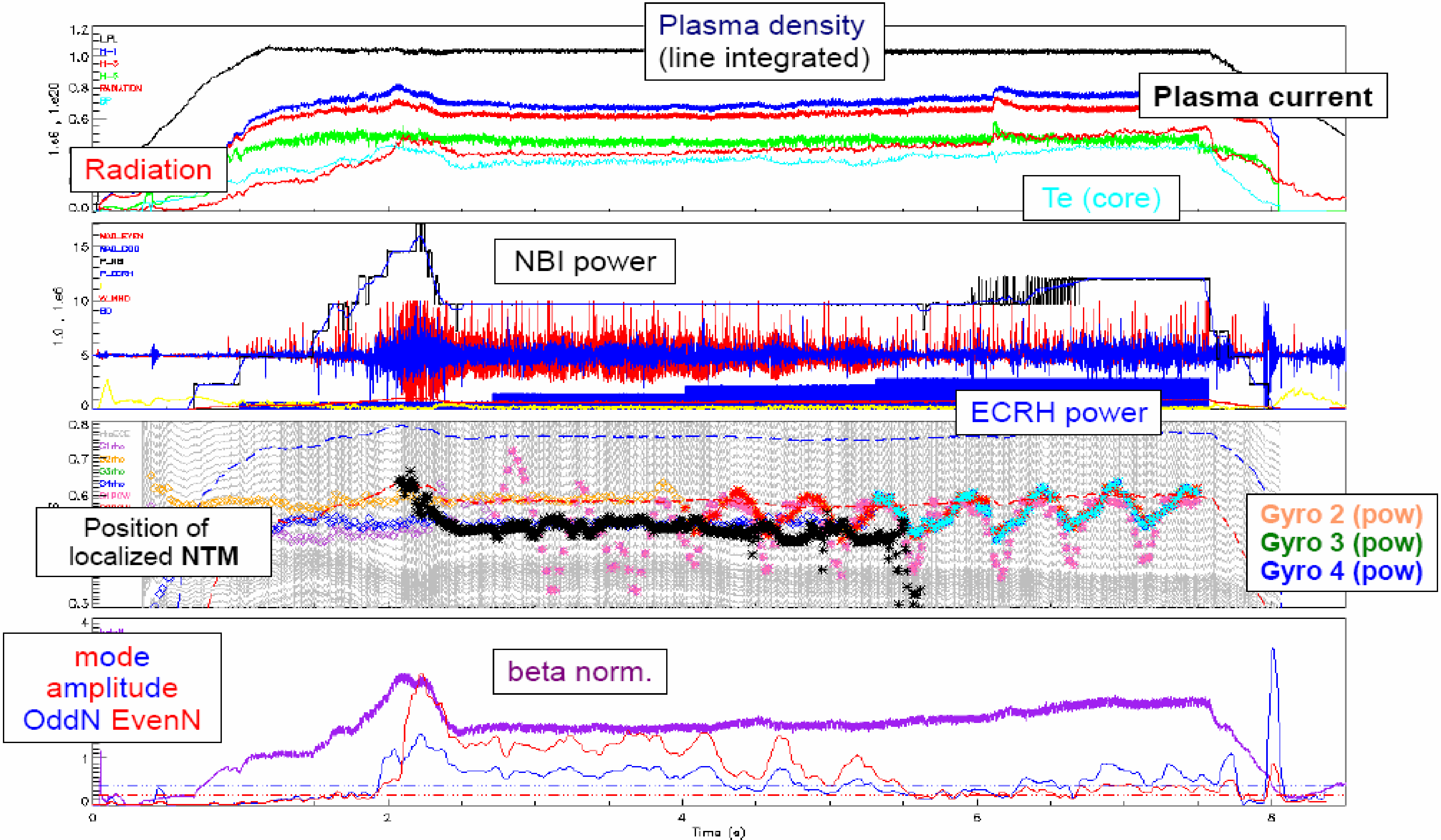


Simple to add to present feedback control



NTM stabilization needs > 2 MW ECCD

(at 10 MW NBI)



ITER scenarios and NTMs

- Standard scenario:
  - Monotonic q profile, medium to high shear:
    -> quite stable in shaped plasmas
  - In H-mode, quite "meta"-stable
  - Sawteeth stabilized by fast particles:
    -> large seed islands can be triggered at ST crashes
  - Should control sawteeth
- Hybrid and advanced scenarios
  - Flat or reversed q profile:
    -> quite unstable to classical tearing
    (no need for seed islands)
  - bN quite large -> more "meta-stable"
    -> need NTM preemption and stabilization
- ITER plasma rotation is small -> quite prone to mode locking

Conclusions

- Basic physics of NTMs well understood
- Modified Rutherford Equation allows us to understand main physics mechanisms
- Detailed "first principles" calculations should not rely on MRE but on 3D MHD codes coupled to kinetic codes
- Nevertheless "fitted" MRE can be used for predictive calculations
- In burning plasmas, performance will decide best strategy for NTM control. *Note small modes can have large effect on neutron rate*.
- Best strategy depends on scenario, mode onset and available actuators
- 2/1 mode is clearly main mode to avoid/control
- Detrimental effect of multiple modes not expected
- Apart from 2/1 locking, one has time to control NTMs
- Sawtooth control for standard scenario and preemptive ECCD for hybrid and advanced scenarios seem best at present
- New robust NTM control strategy can do the job on ITER