Physics and control of Neoclassical Tearing Mode (NTM)

Valentin Igochine

Max-Planck Institut für Plasmaphysik
EURATOM-Association
D-85748 Garching bei München
Germany

Outline

- Magnetic islands
- Classical tearing mode: Rutherford equation
- Neoclassical tearing mode: Modified Rutherford Equation (MRE)
- Physics of NTM
- Control of NTM
- Conclusions

Basic classification of MHD instabilities

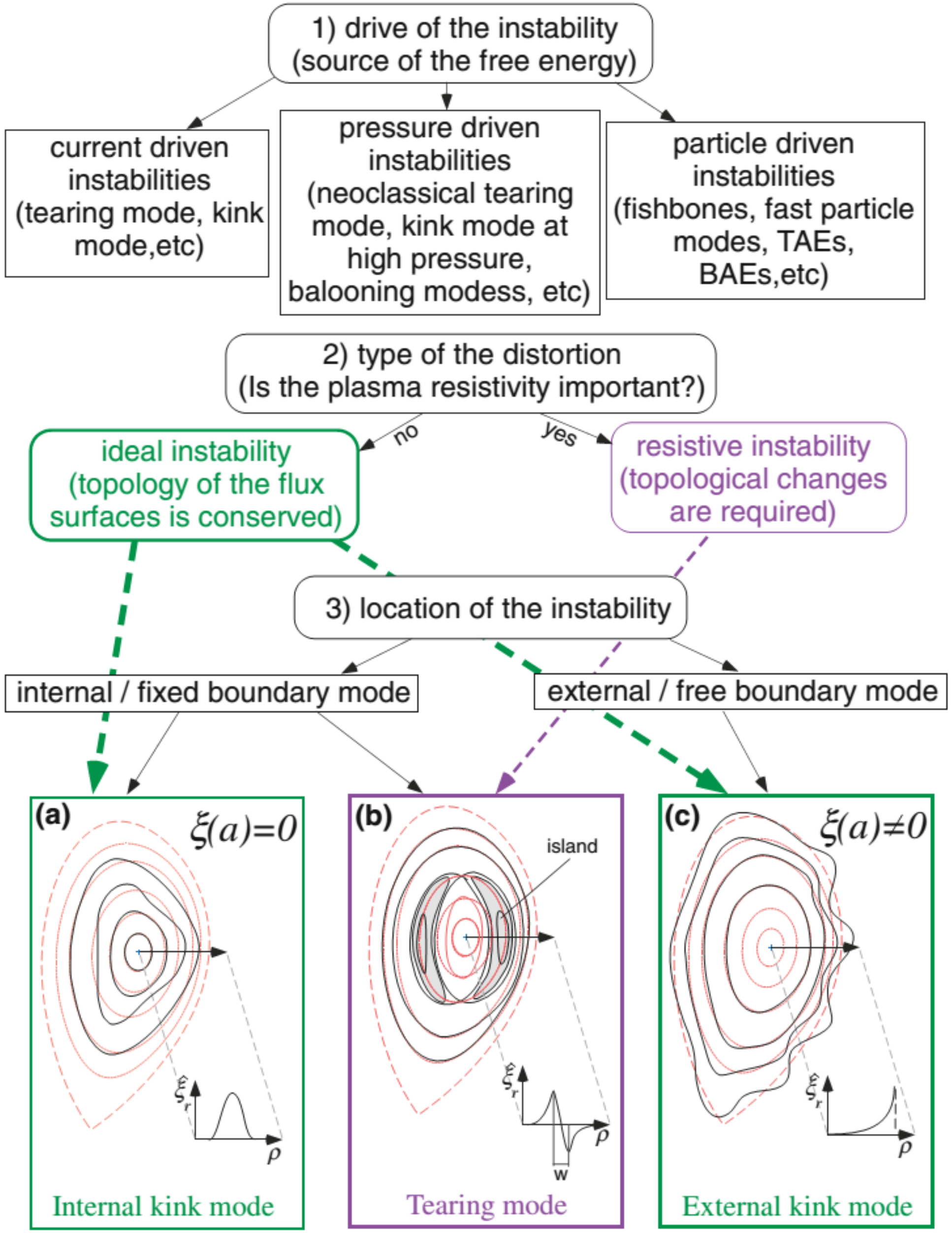
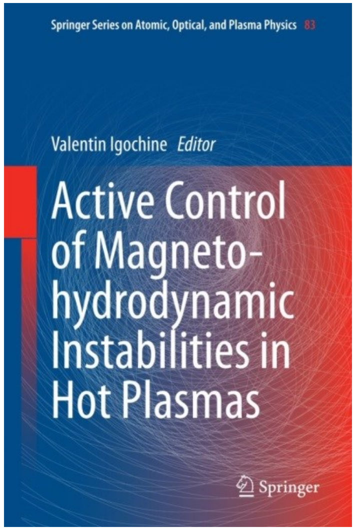


Fig. 2.8 The basic classification of MHD instabilities

from this book ☺



V. Igochine, "Active Control of Magneto-hydrodynamic Instabilities in Hot Plasmas", Springer Series on Atomic, Optical, and Plasma Physics, Vol. **83**, 2015 (Chapter 2)

The one fluid MHD equations

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

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

$$\vec{E} + \vec{v} \times \vec{B} = \eta\, \vec{j}$$ =0 if η=0 => frozen-in B lines — Ohm's law

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

plus Maxwell's equations for *E* und *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:

Advection (flux is frosen into magnetic field, no topological changes)

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

magnetic diffusion (changes topology)

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

Typical time scale of resistive MHD:

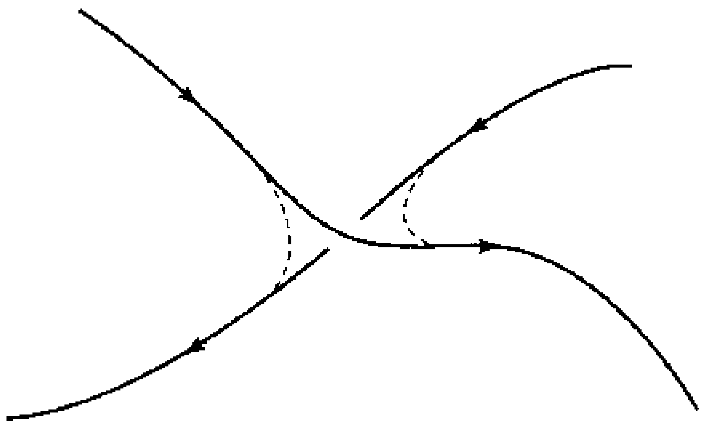
$$\tau_R = \mu_0 \sigma L^2$$

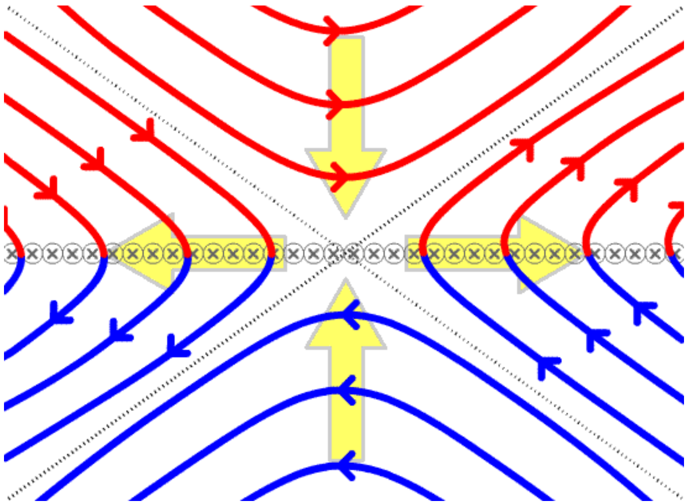
Since σ is large for a hot plasma, τ_R is slow (~ sec for 0.5 m) – irrelevant?

Reconnection in a hot fusion plasma

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

⇒ magnetic field lines and plasma move together

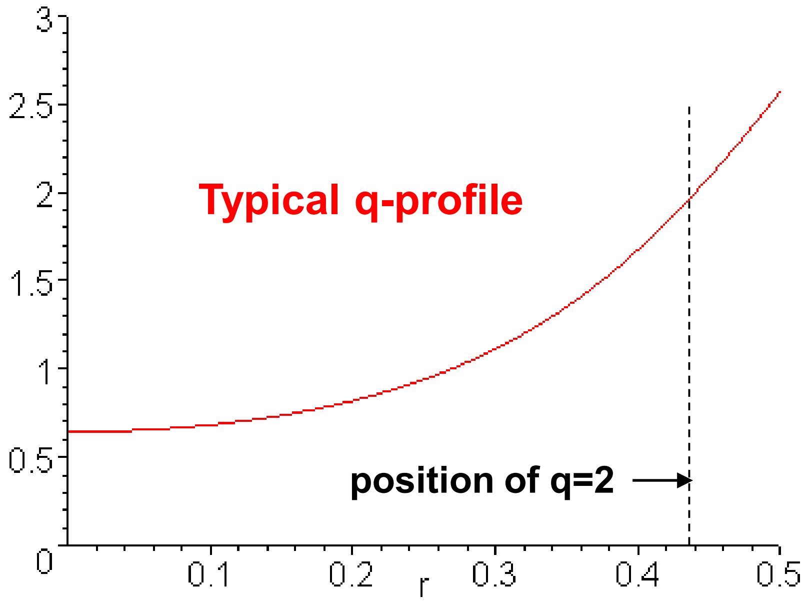


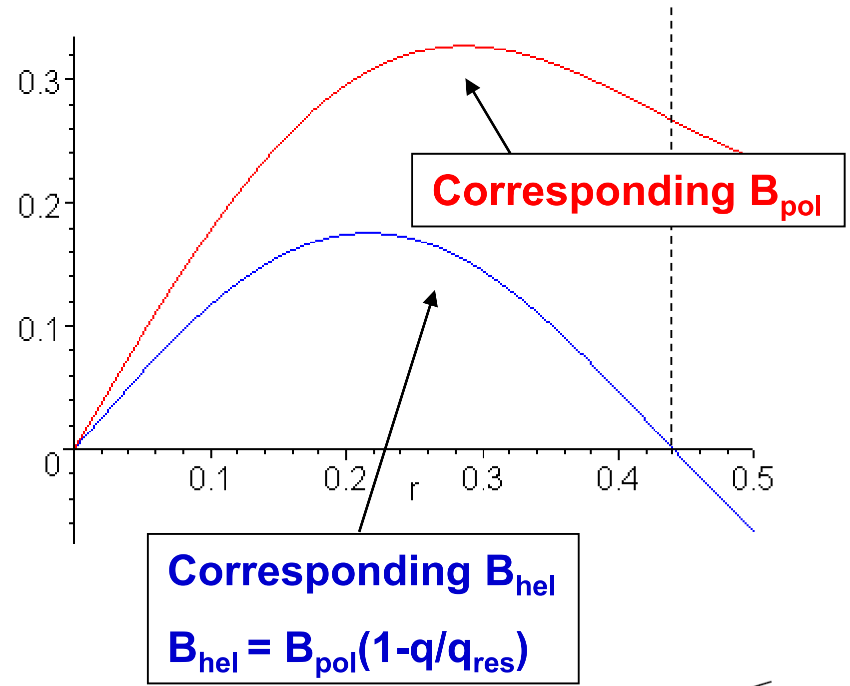


A change of magnetic topology is only possible through reconnection

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

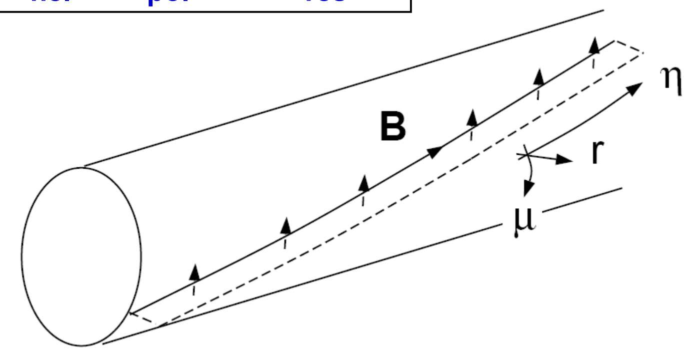
Reconnection on ‘rational’ magnetic surfaces





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

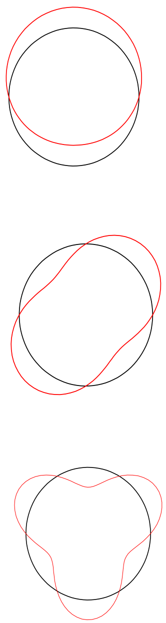
- reconnection of helical flux can form new topological objects - islands



Reconnection on ‘rational’ magnetic surfaces

Torus has double periodicity (toroidal + poloidal directions)

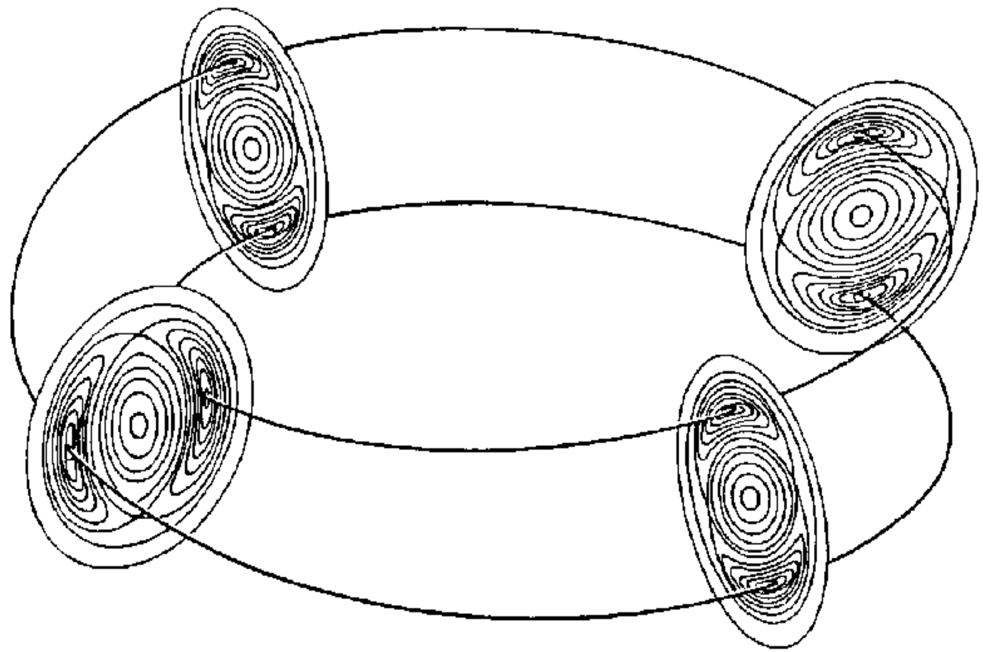
- instabilities with poloidal and toroidal 'quantum numbers'



m = 1

m = 2

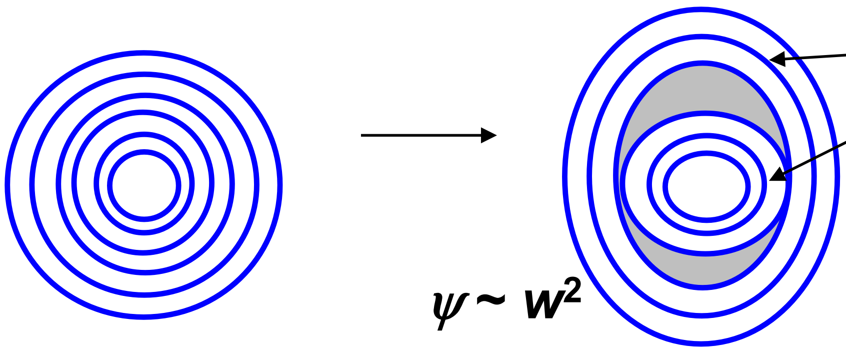
m = 3



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

MHD description of tearing mode formation

from force balance $\vec{j} \times B = -\nabla p$ using high aspect ratio approximation



tearing mode equation
(for outer region)

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

Deformation of flux surfaces opens up island of width W

- Tearing Mode equation ($\nabla p = j \times B$) singular at resonant surface:

  implies kink in magnetic flux ψ, jump in B

  $\Rightarrow$ current sheet on the resonant surface

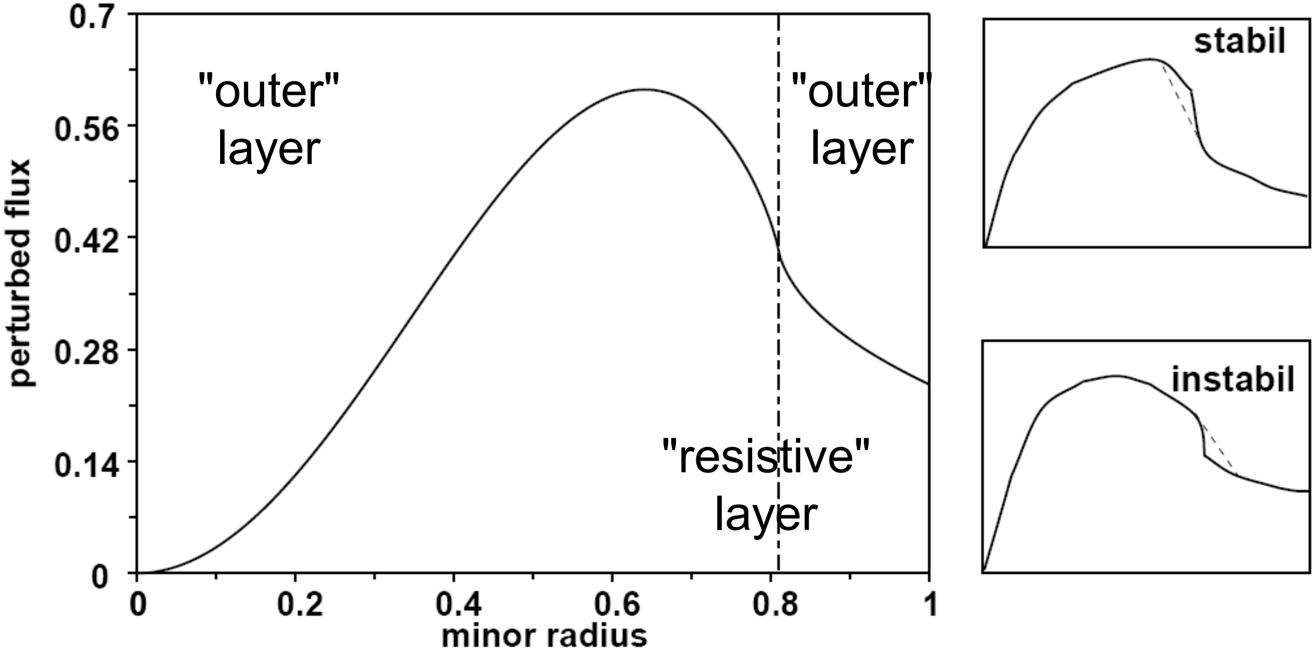
$\psi(r)$: helical magnetic flux

$j(r)$: current profile

$q(r)$: safety factor profile

m,n: mode numbers

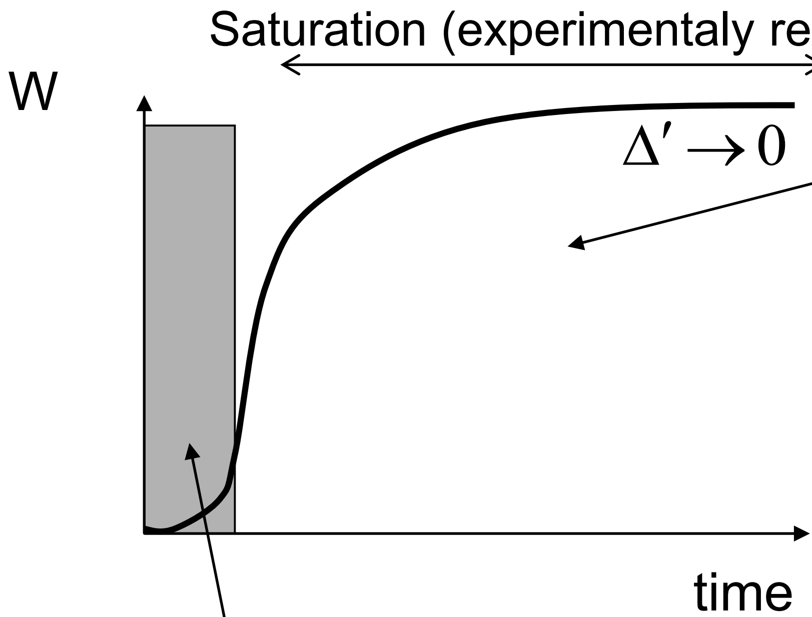
Classical tearing mode is a current driven instability



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 $\nabla j_{resonant\ surface}$

MHD description of "classical" tearing mode formation



Nonlinear phase,
Rutherford, 1973, Phys. Fluid

Linear phase, W □
Furth, 1963, 1973, Phys. Fluid

$$\gamma = \frac{0.55}{\tau_A^{2/5}\tau_R^{3/5}}\left(n\frac{a}{R}\frac{aq'}{q}\right)^{2/5}\left(a\Delta'\right)^{4/5}$$

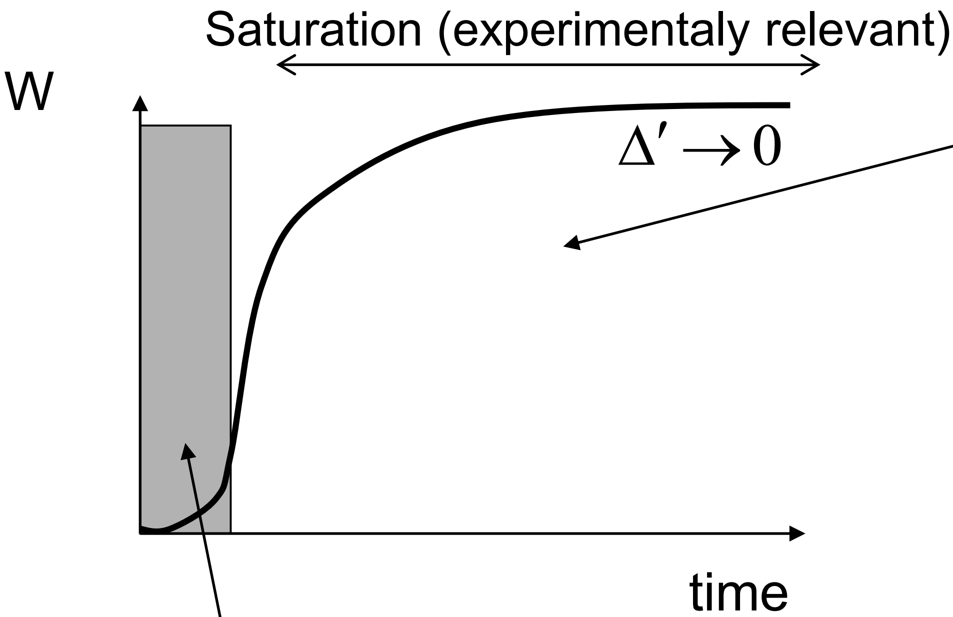
Aprox. 70ms for typical parameters

Rutherford equation

$$\frac{dW}{dt} = 1.66\frac{\eta}{\mu_0}\left(\Delta'(W) - \alpha W\right)$$

The island size has saturated value at

$$\Delta'(W_s) = \alpha W_s$$



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$$\Delta'(W_s) = \alpha W_s$$

Unfortunately, other effects play important roles and this equation should be extended

Two fluid 3D nonlinear MHD equations

IPP

The density equation,

$$\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{v} = S_n,$$

+Maxwell equations

The momentum equation,

$$\rho \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \equiv \rho[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v}] = \mathbf{j} curl \mathbf{B} - \nabla p - \nabla \cdot \Pi - \nu_\perp \rho \nabla^2 \mathbf{v}.$$

The pressure equation:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = -\frac{5}{3} p \nabla \cdot \mathbf{v} + \frac{2}{3}[\mathbf{Q} - \nabla \cdot \mathbf{q} - \Pi : \nabla \mathbf{v}].$$

The generalized Ohm's law

$$\underbrace{\mathbf{E} + \mathbf{v} \wedge \mathbf{B}}_{ideal\ MHD} = \underbrace{\eta \mathbf{j}}_{resistive\ MHD} + \underbrace{\frac{1}{\epsilon_0 \omega_{pe}^2 (1+\nu)}[\frac{\partial \mathbf{j}}{\partial t} + \nabla ...] +}_{electron\ inertia} \underbrace{\sum \frac{q_\alpha}{m_\alpha}(\nabla p_\alpha + \nabla \cdot \Pi_\alpha),}_{closures}$$

Ohm's law, neglecting inertia:

+ helic. Flux surf aver

$$\frac{\partial \psi}{\partial t} \sim \eta j_{||} B - \mathbf{B} \cdot \nabla(\Phi +) - \mathbf{B} \cdot \nabla \frac{q_\alpha}{m_\alpha} \Pi_\alpha,$$

→ Modif. Rutherford equ.

MRE

dw/dt ← $\partial \psi / \partial t$; Δ' ← $\eta j_{||} B$; Δ'_{bs} ← $\frac{q_\alpha}{m_\alpha}\Pi_\alpha$ term

Tearing Modes – nonlinear growth

Consider various helical currents on resonant surface...

$$B_\theta(r_s^{+}) - B_\theta(r_s^{-}) \propto \delta I = I_{Ohm} + I_{bs} + I_{extern}$$

$$I_{Ohm} \propto j_{Ohm} W \propto \sigma W \, d\psi / dt \propto \sigma W^2 \, dW / dt$$ inductive

$$I_{bs} \propto j_{bs} W \propto -\nabla p / B_\theta \, W$$ pressure driven

$$I_{extern}$$ externally driven

...leads to the so-called Modified Rutherford Equation (MRE)

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

where $\Delta' = (B_\theta(r_s^{+}) - B_\theta(r_s^{-})) / \psi$

Tearing Modes – nonlinear growth

Interpretation of the different terms

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

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

3D MHD simulations show that full non-linear NTM is more complicated

"Inner" layer much larger than expected

Outer and inner layers cannot be realy separated

Analysing 3D MHD saturated mode and MRE can lead to large differences

Modified Rutherford Equation (MRE)

Many terms can contribute to total // current within island

$$\frac{dw}{dt} = \frac{\rho_s}{\tau_R}\Big[\rho_s\Delta'(w) + \rho_s\Delta'_{bs} + \rho_s\Delta'_{GGJ} + \rho_s\Delta'_{pol} + \rho_s\Delta'_{cd} + \rho_s\Delta'_{\mu} + \rho_s\Delta'_{nc} + \rho_s\Delta'_{wall} + \rho_s\Delta'_{mncoupling} + \rho_s\Delta'_{new}\Big].$$

Main terms discussed and compared with experiment on 1st line

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

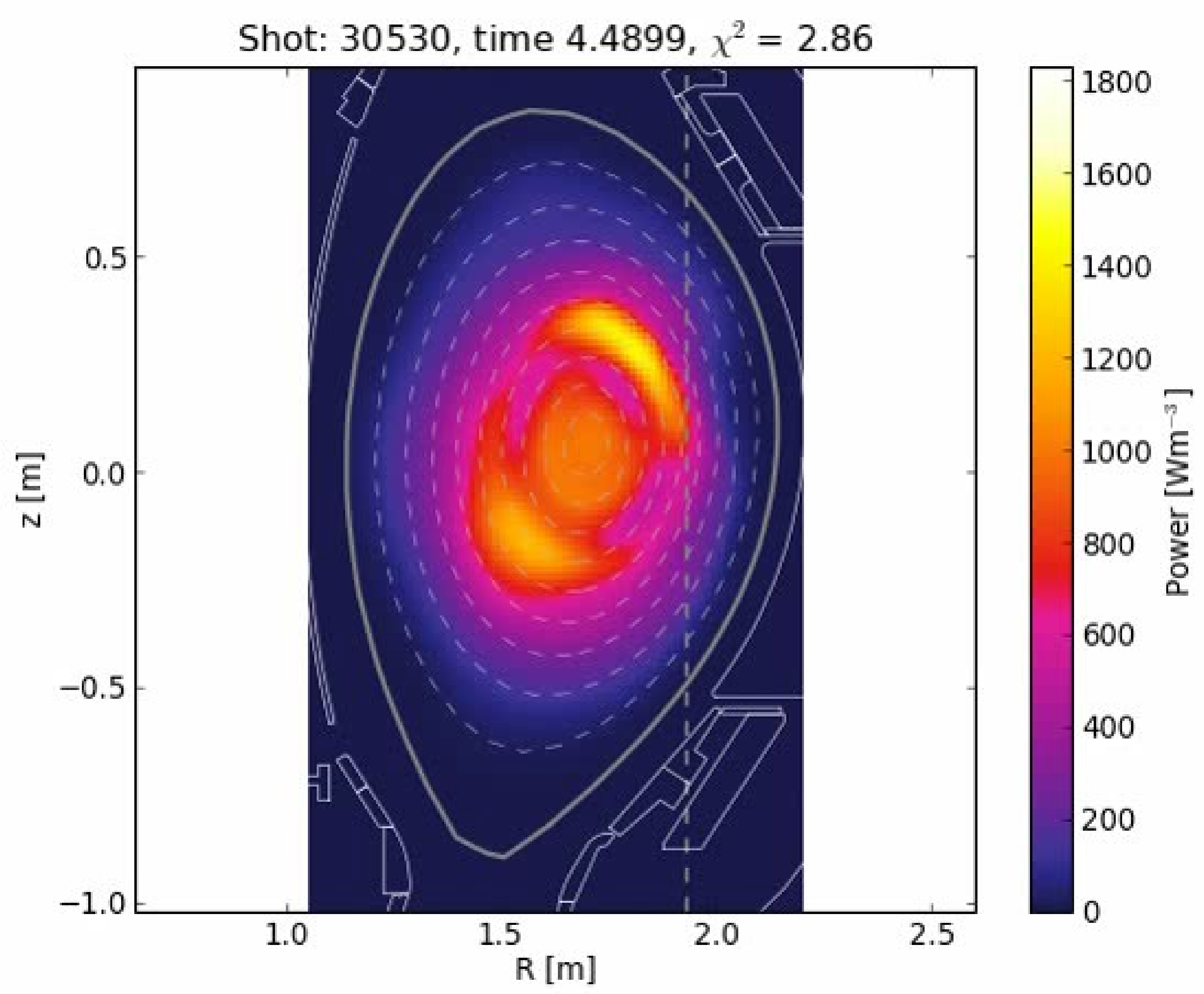
Glasser-Greene-Johnson

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

Unlocking and locking of NTM in ASDEX Upgrade



TM or NTM?

Drives:

TM (current driven)

NTM (pressure driven)
Power ramp down experiments help to distinguish NTM from TM.

NTM does not grow below marginal β value independent of its size

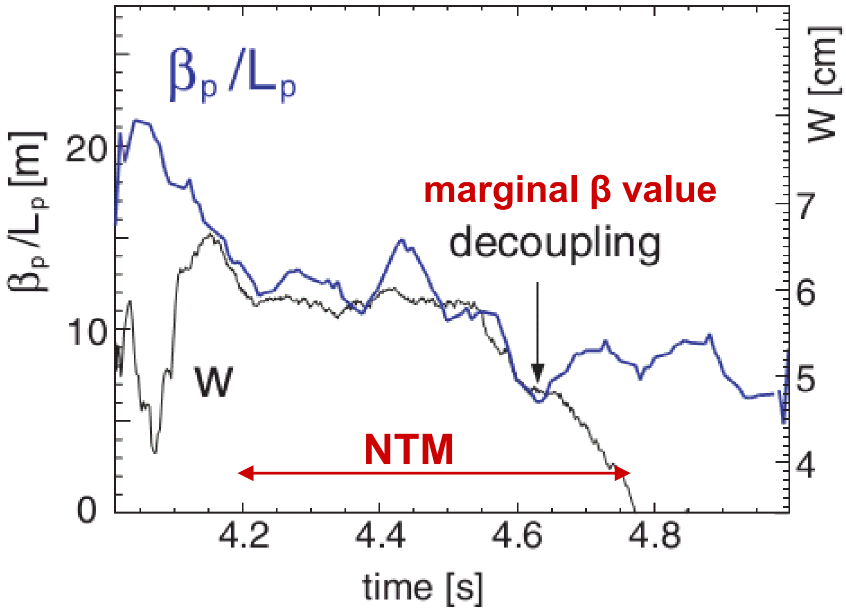


Figure 1. $\beta_p/L_p(2T\nabla n + n\nabla T)/\nabla p$ at the island's rational surface as a measure of the bootstrap current density fraction and (3, 2) island size in power ramp down experiments. The pressure gradient length has been corrected here to account for the different influence of temperature and density gradients on the bootstrap current density. The arrow indicates the time after which the island size is not correlated to the bootstrap current density any more.

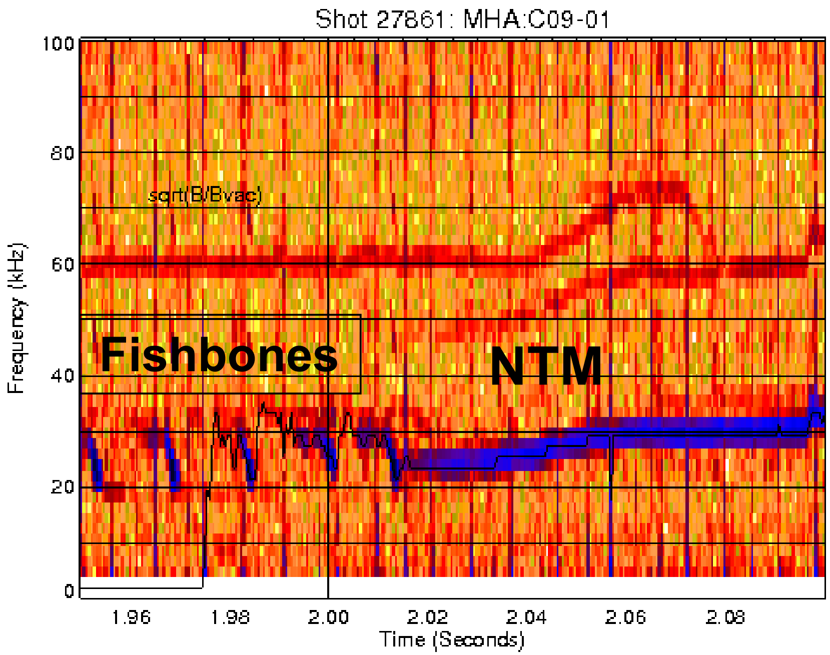
S. Günter *et al* Nucl. Fusion **43** (2003) 161–167

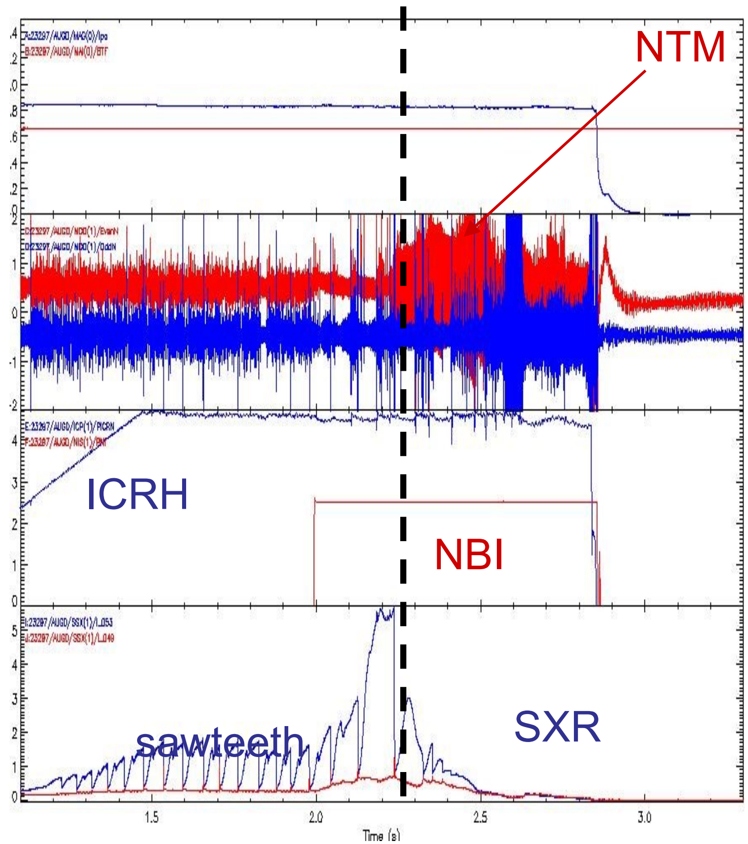
Onset of NTM

Typically triggers come from other events. Examples are from ASDEX Upgrade

Sawtooth

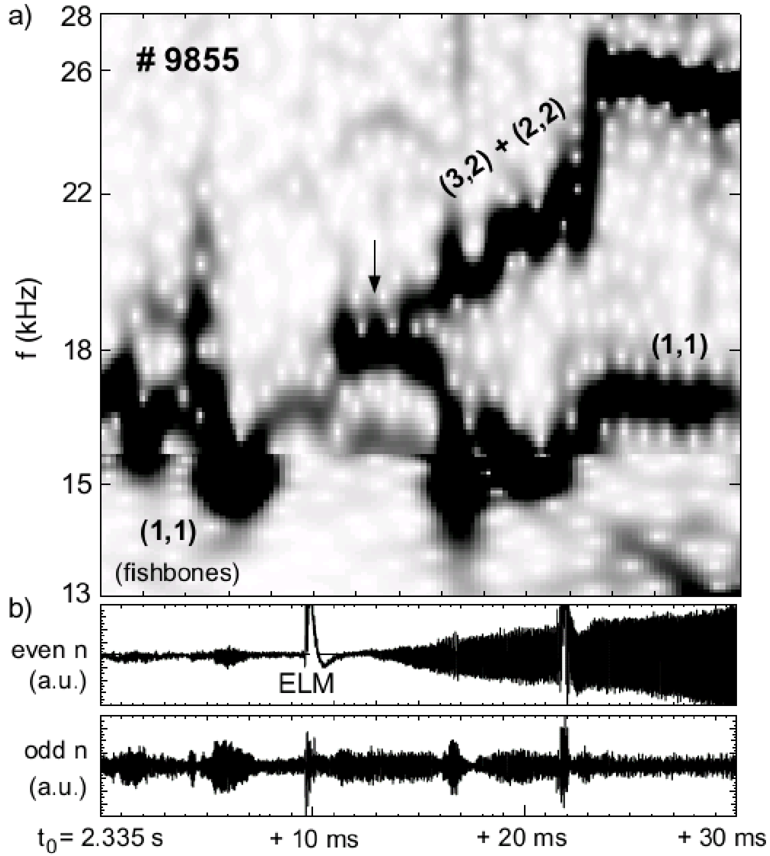
Fishbones





Triggers on NSTX tokamak: fast particle modes and ELMs

But there are also cases when the mode grows almost from noise!



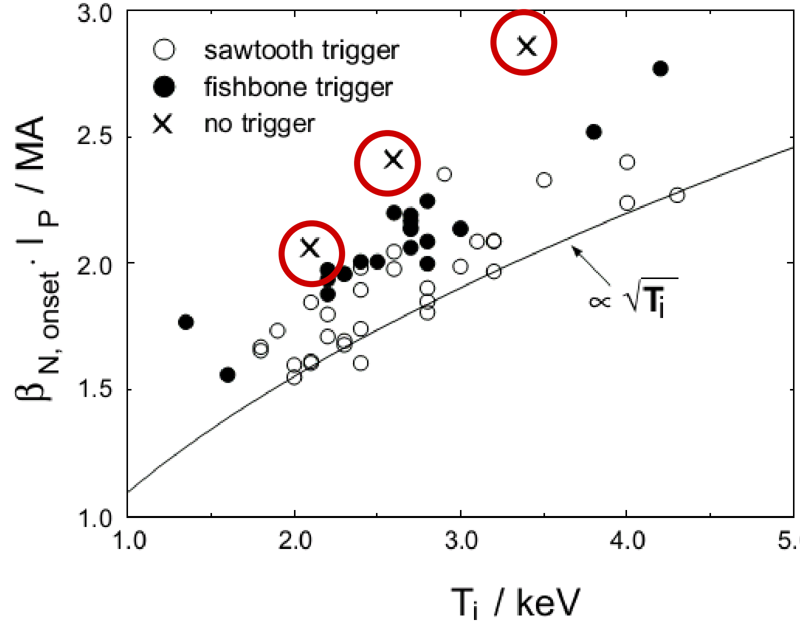
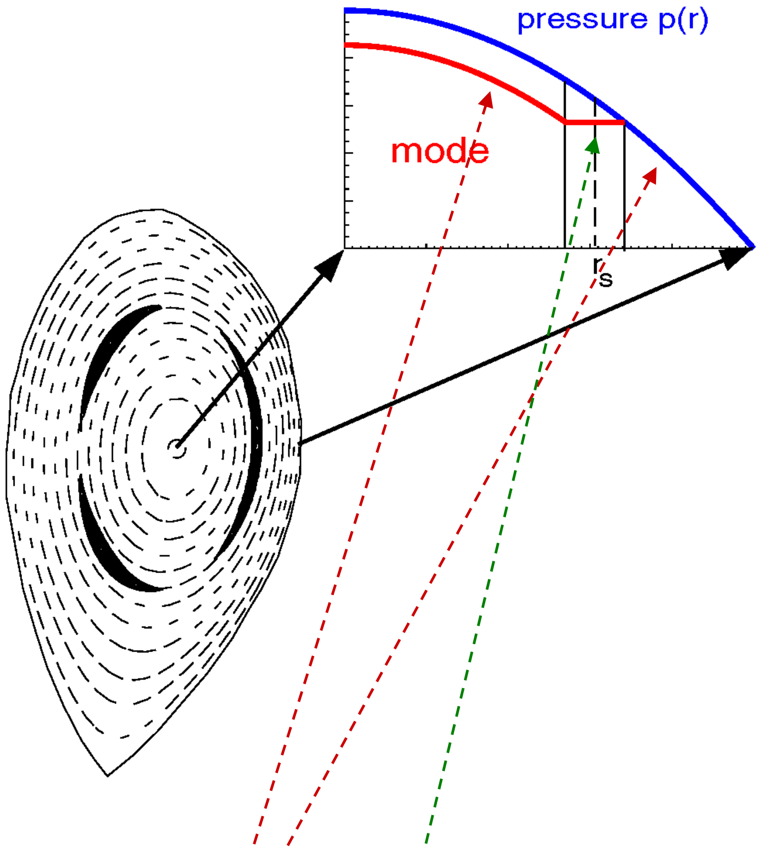


Figure 7. $\beta_{N,onset} I_p$ versus the ion temperature at the rational surface of the (3,2) mode, T_i, for $q_{95} = 4 \ldots 4.5$. Additionally the scaling, $\beta_{N,onset} I_p \propto \sqrt{T_i}$, is shown.

Gude, NF, 1999

NTM control

Magnetic islands deteriorate performances



Influence of different NTMs on plasma confinement

(3,2) NTM loss up to 20%

(2,1) NTM loss up to 30-40% (ultimately could lead to disruption)

This situation is unacceptable. We can not live with big NTMs!

Local transport stays same outside island

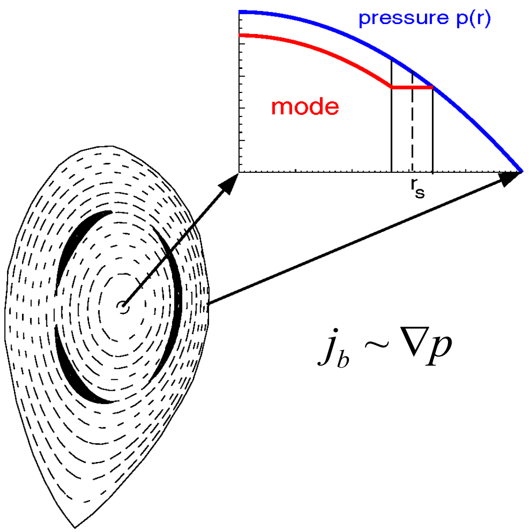
But "short-circuit" across island

What to do with NTM? Possible strategies.

Main problem: Neoclassical Tearing Mode flattens pressure and temperature profile → smaller β_N (Fusion power ~ β_N^2)

Possible approaches:

- keep the mode at small level (small influence on the plasma confinement)
- replace the missing bootstrap current in the island
- modify density and(or) temperature profile, reduce the probability of the NTM excitation
- avoid triggers for NTMs
- completely avoid dangerous resonant surfaces (3,2) and (2,1)



No bootstap current in the island

↓

Current hole in the island

↓

Mode grows

Could we live with NTM in principle?

Frequently interrupted regime of neoclassical tearing mode (FIR-NTM)

A new regime was discovered in ASDEX Upgrade in 2001. The confinement degradation is strongly reduced in this regime. [A. Gude et. al., NF, 2001, S.Günter et. al. PRL, 2001]

Neoclassical tearing mode never reach its saturated size in this regime. Fast drops of NTM amplitudes appear periodically.

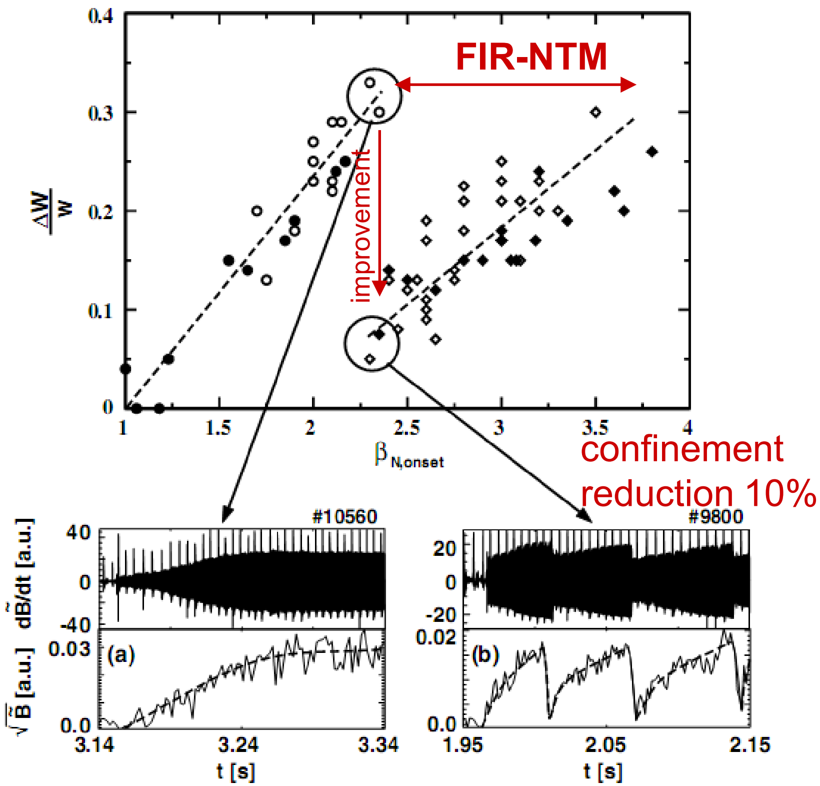


Figure 9. Comparison of reduction in energy confinement ($\Delta W/W$) due to (3,2) NTMs on ASDEX Upgrade (open symbols) and JET (full symbols). Very good agreement is seen, both in the relative confinement degradation as well as in the β_N value above which FIR-NTMs cause less energy losses. The lower figure shows the NTM behaviour for two ASDEX Upgrade discharges at about $\beta_N = 2.3$. The time-averaged amplitude for the FIR-NTM is significantly smaller (b) than the saturated amplitude of the smoothly growing mode (a). [T. Hender et. al. NF, 2007]

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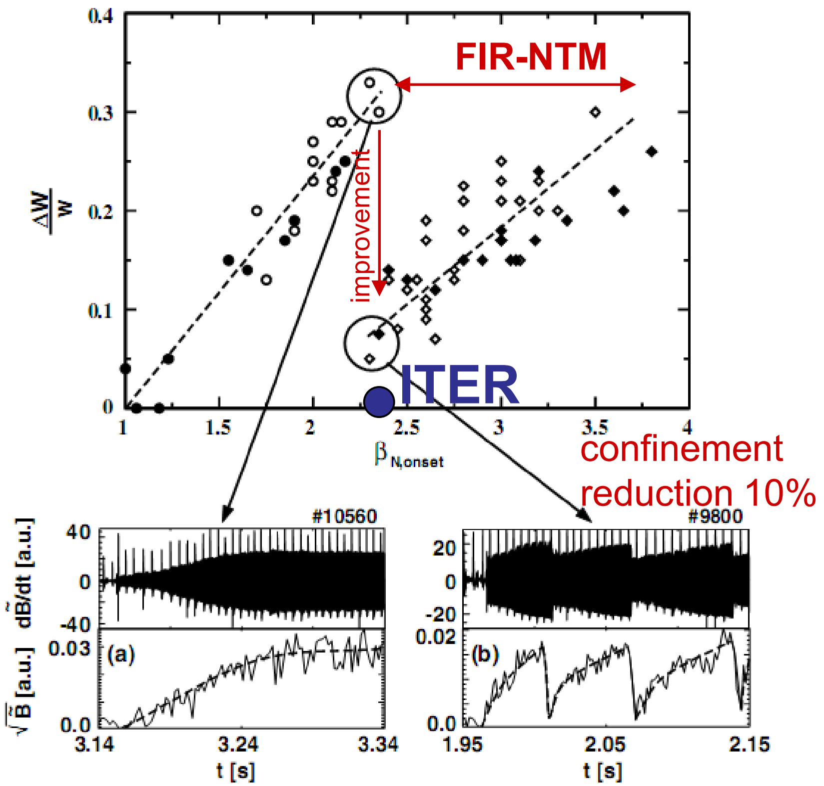
Transition to this regime may be an option for ITER.



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It was found that the reason for this fast periodic drop is interaction of the (3,2) neoclassical tearing mode with (1,1) and (4,3) ideal modes. Such interaction leads to stochastization of the outer island region and reduces its size. (The field lines are stochastic only during the drop phase.)

(3,2) only

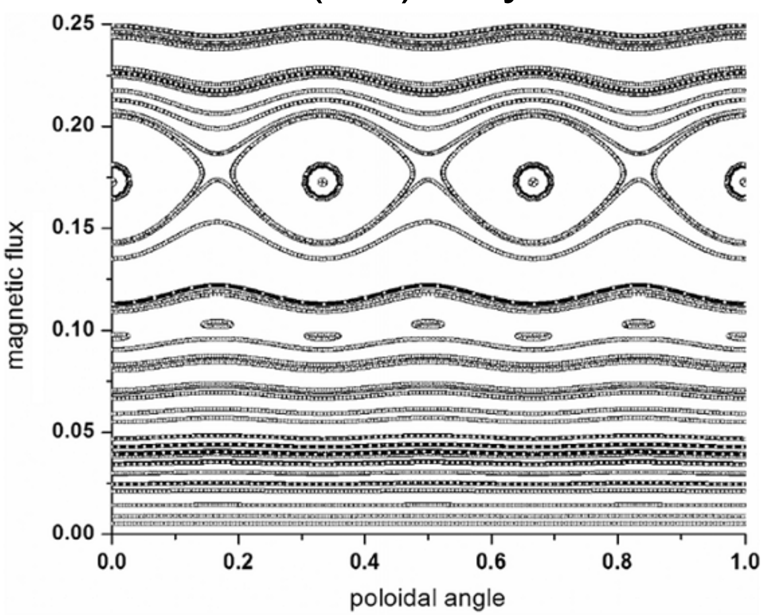


Figure 3. The (3, 2) mode is used as a perturbation. Shape of the perturbation is shown in figure 2. The ASDEX Upgrade discharge No #11681, $t = 2.98$ s.

(3,2) + (1,1) + (4,3)

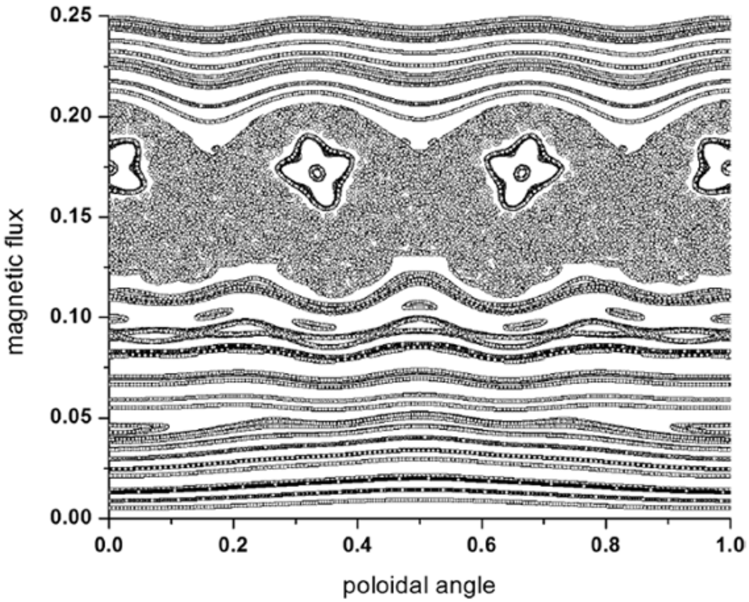
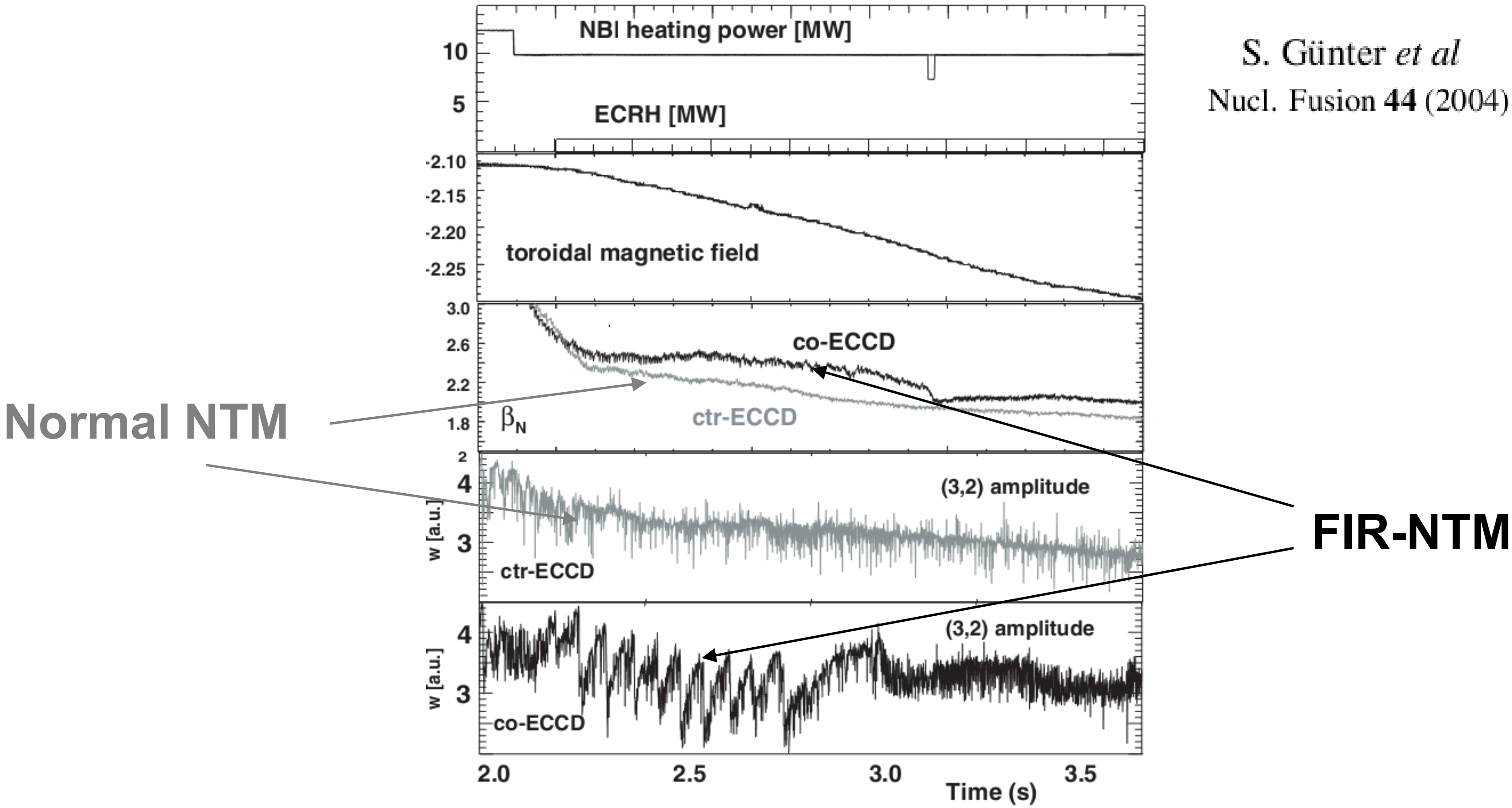


Figure 5. The (1, 1), (3, 2) and (4, 3) modes are used as perturbations. Shapes of the perturbations are shown in figure 2. The ASDEX Upgrade discharge No 11681, $t = 2.98$ s.

[V. Igochine et. al. NF, 2006]

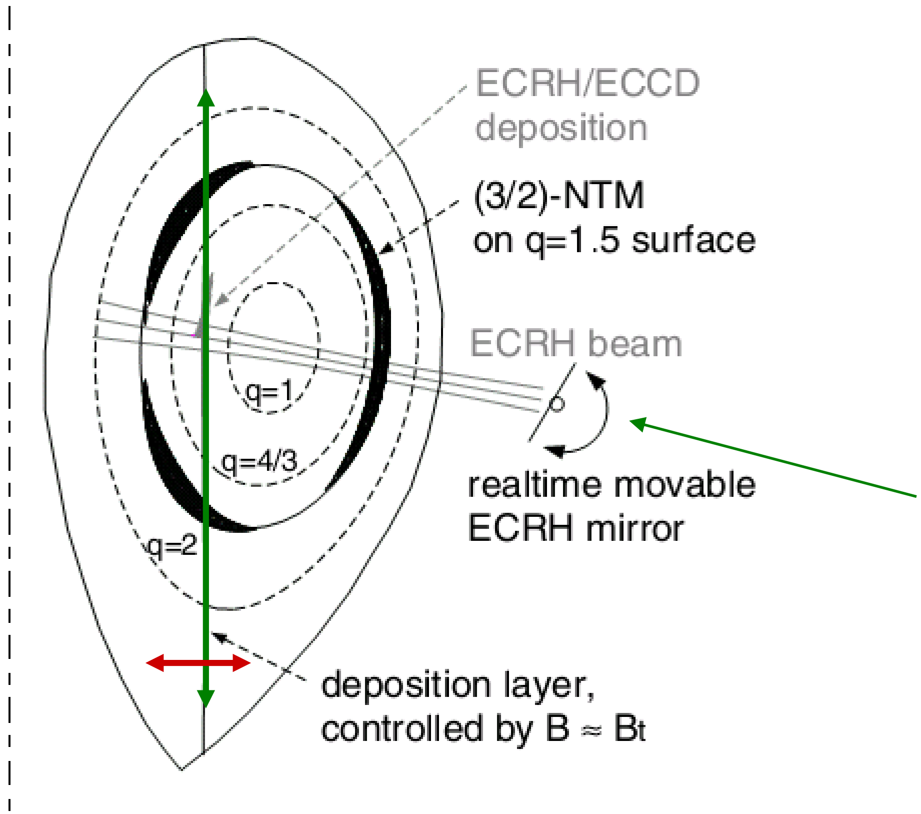
Could we go to this FIR-NTM regime?

Yes, we can if we act on the (4,3) resonant surface with current drive (ECCD)



S. Günter *et al*
Nucl. Fusion **44** (2004) 524–532

triggering of ideal pressure driven (4/3) mode by q-flattening with ECCD



Changes of the resonant layer position with B_{tor}

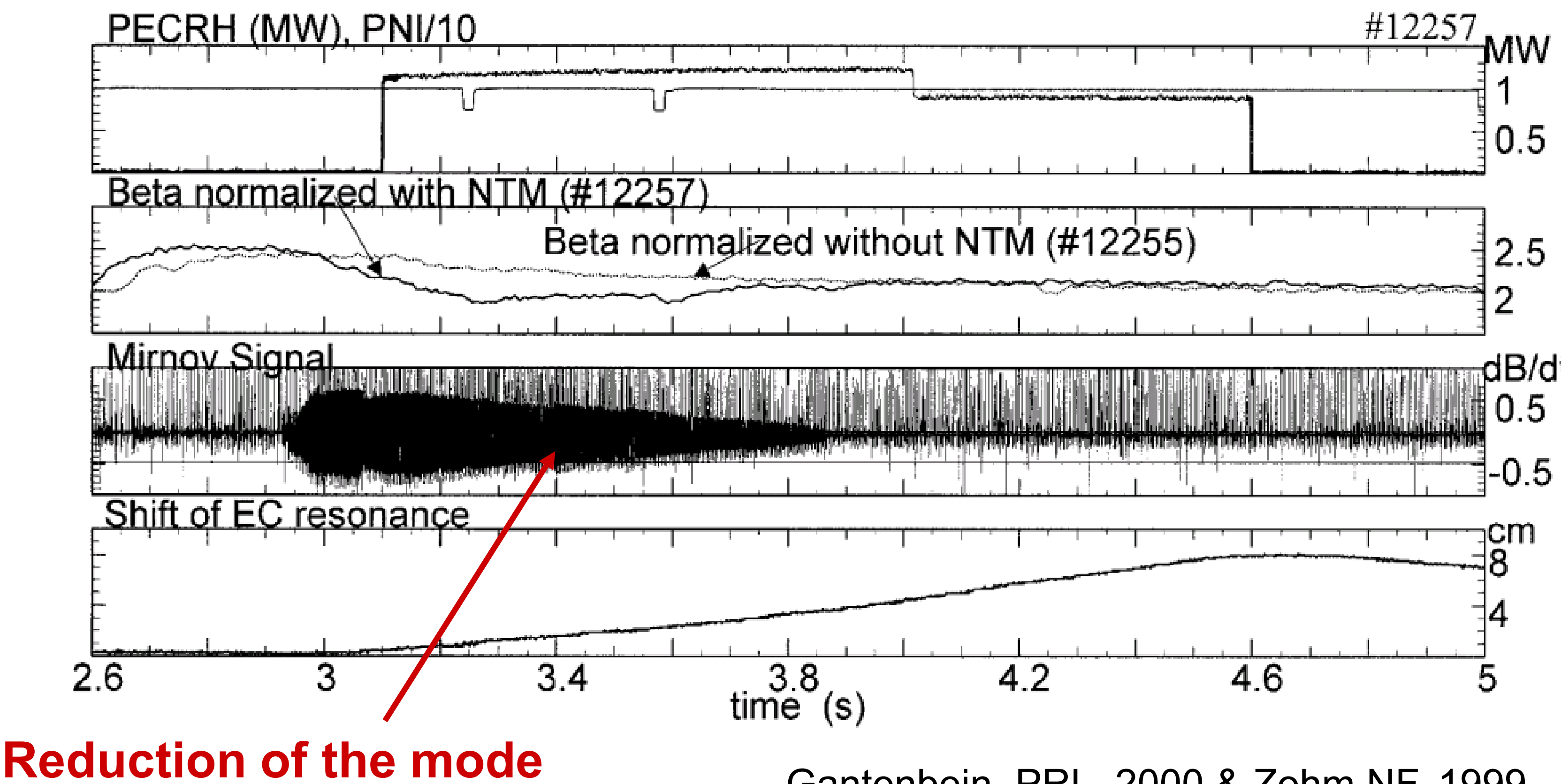
Aim: fill the current hole in the island

Rem.: deposition outside the island give negative effect.

Changes up and down along the resonance is possible with mirror

NTM was stabilized for the first time in ASDEX Upgrade

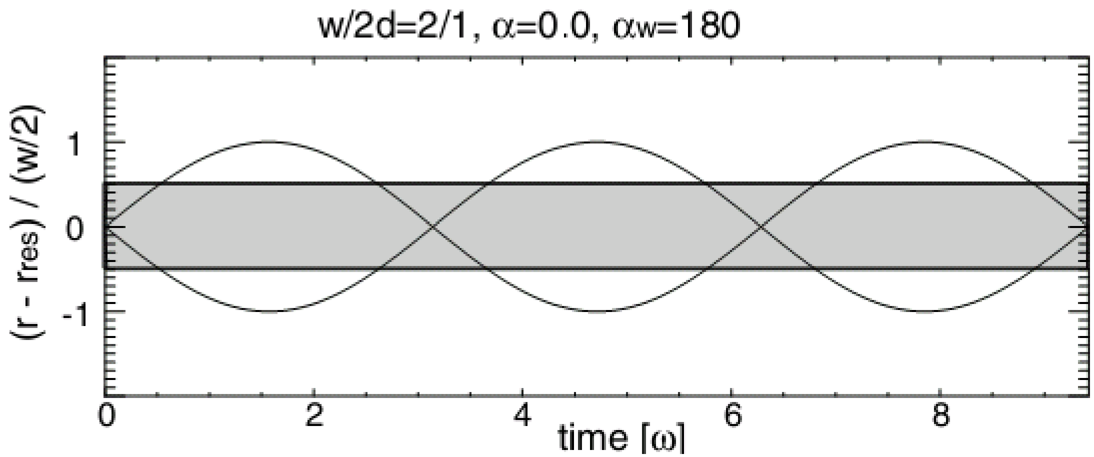
Scan of the resonance position was done by changing B_{tor}



Gantenbein, PRL, 2000 & Zohm NF, 1999

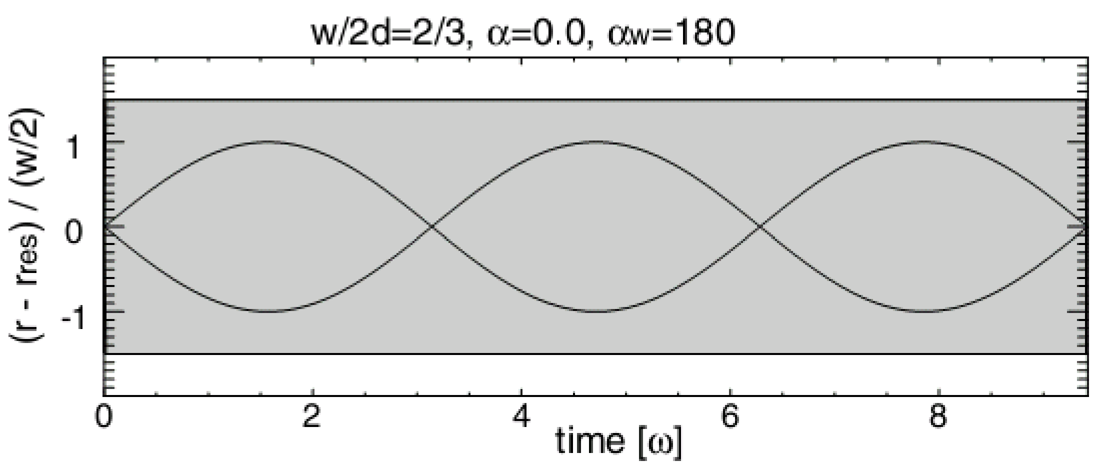
Problem with deposition width of the ECCD

Early experiments,
narrow deposition,
Almost all current
is inside the island



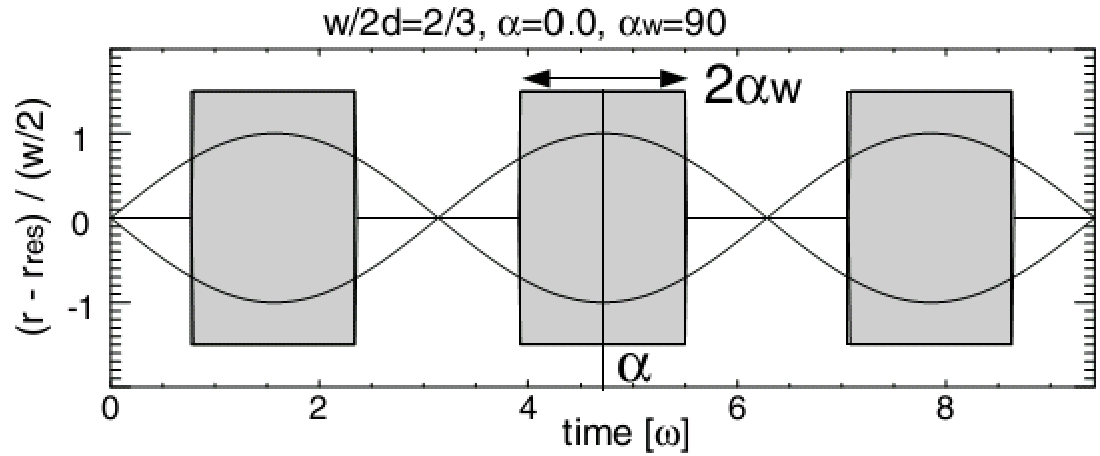
ITER case
broad deposition due
to geometry of the
heating system.

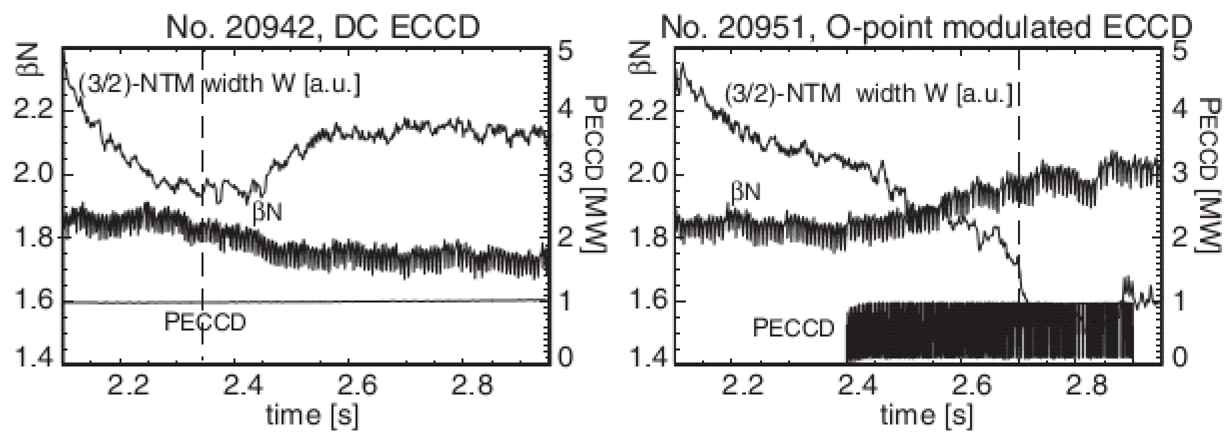
A lot of current
outside the island
(destabilizing effect)



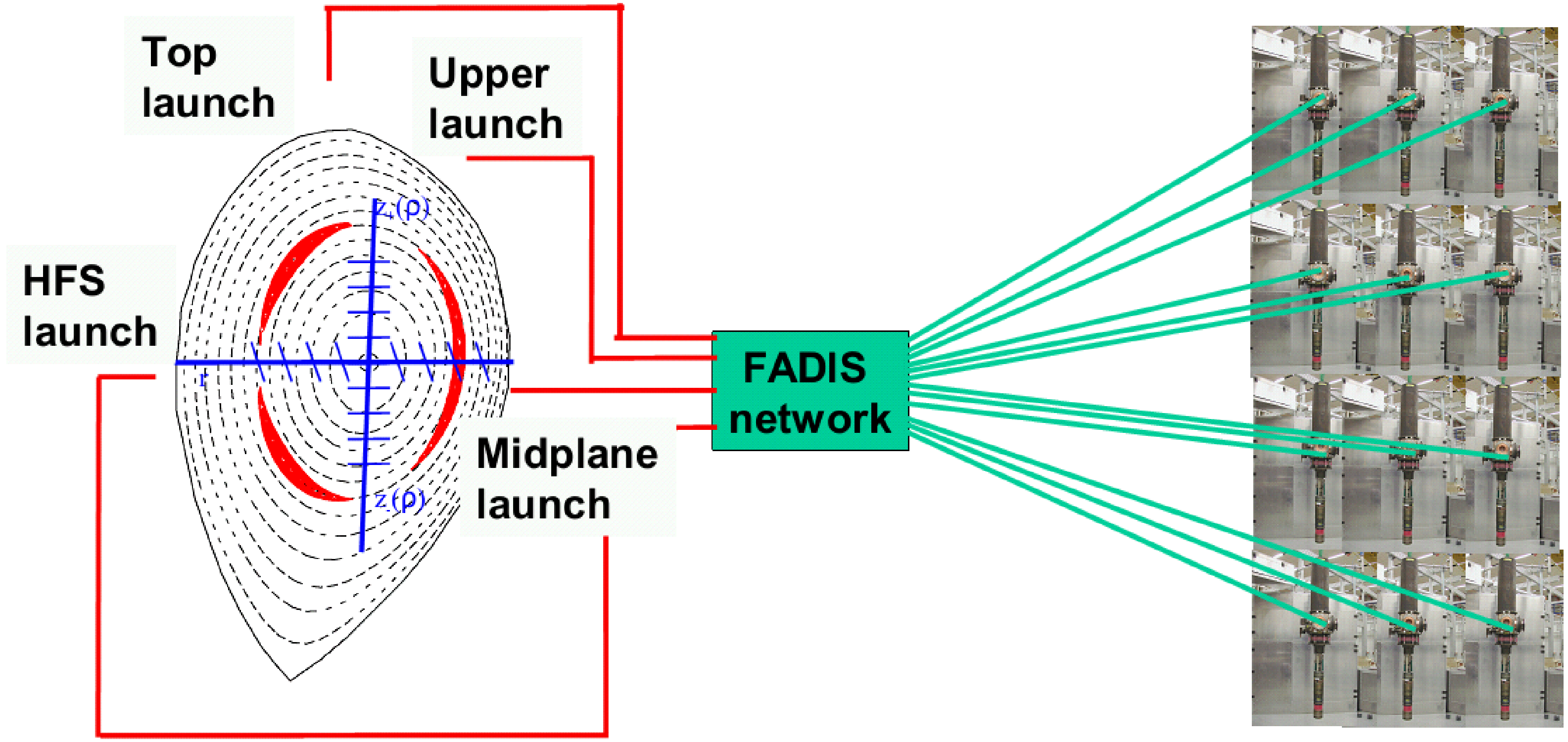
Modulated ECCD is more effective compare to constant ECCD in case of broad deposition.

…but we loose the half of the power from gyrotrons…



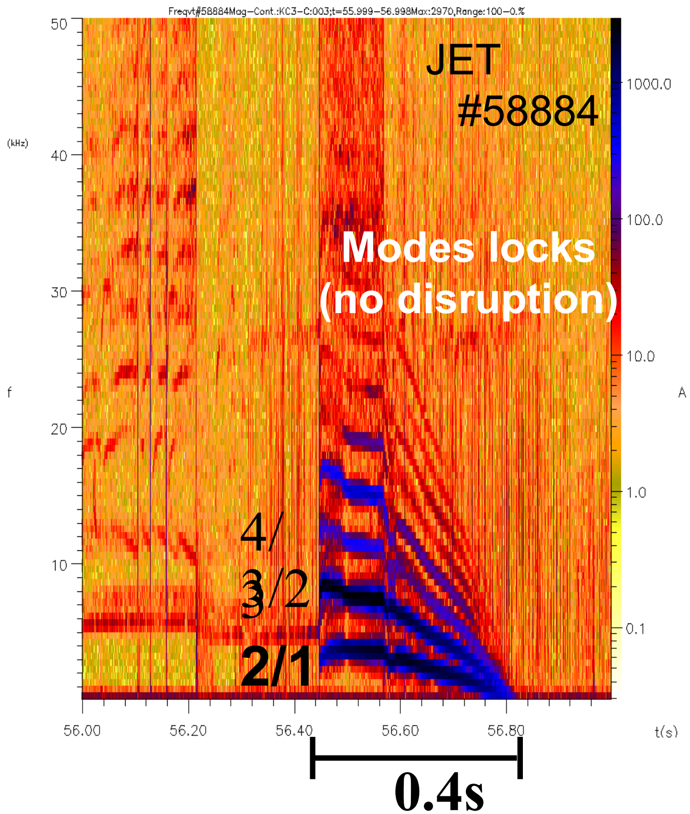


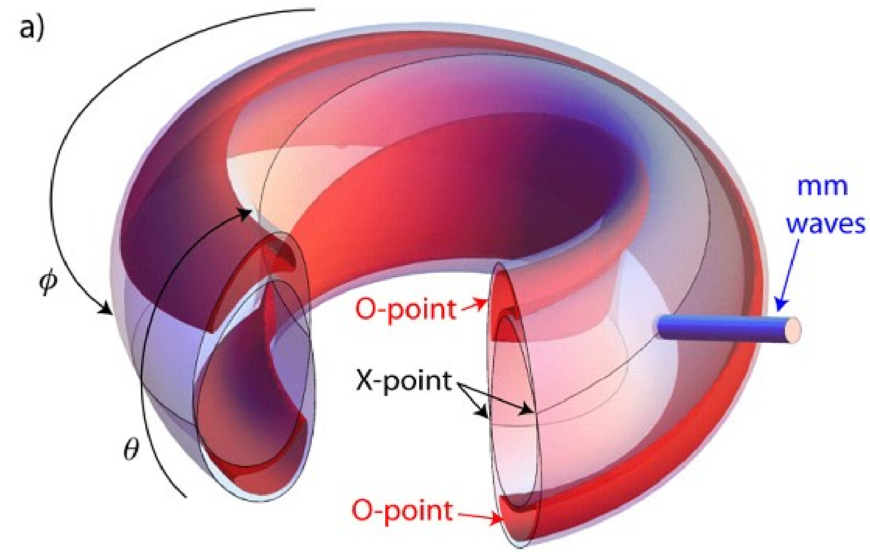
Maraschek, PRL, 2007



- ECCD in O-point only is more efficient than DC operation ⇒ 50% duty cycle
- gyrotrons with small frequency variations can be combined and switched to different transmission lines via a FADIS (FAst DIrection Switch) ⇒ follow O-point in 3d with ideally 100% duty cycle

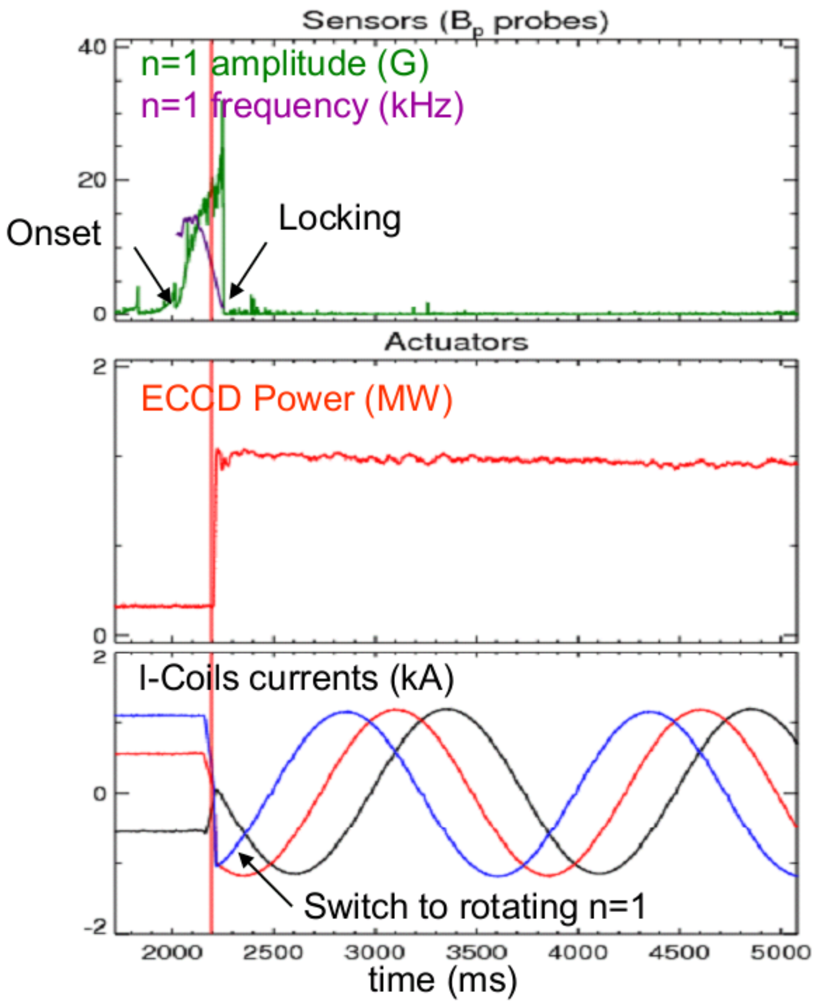
- **As discussed in ST session, crashes after long sawtooth period can trigger several modes**
- **Modes can lock rapidly (within 0.4s in this JET case)**

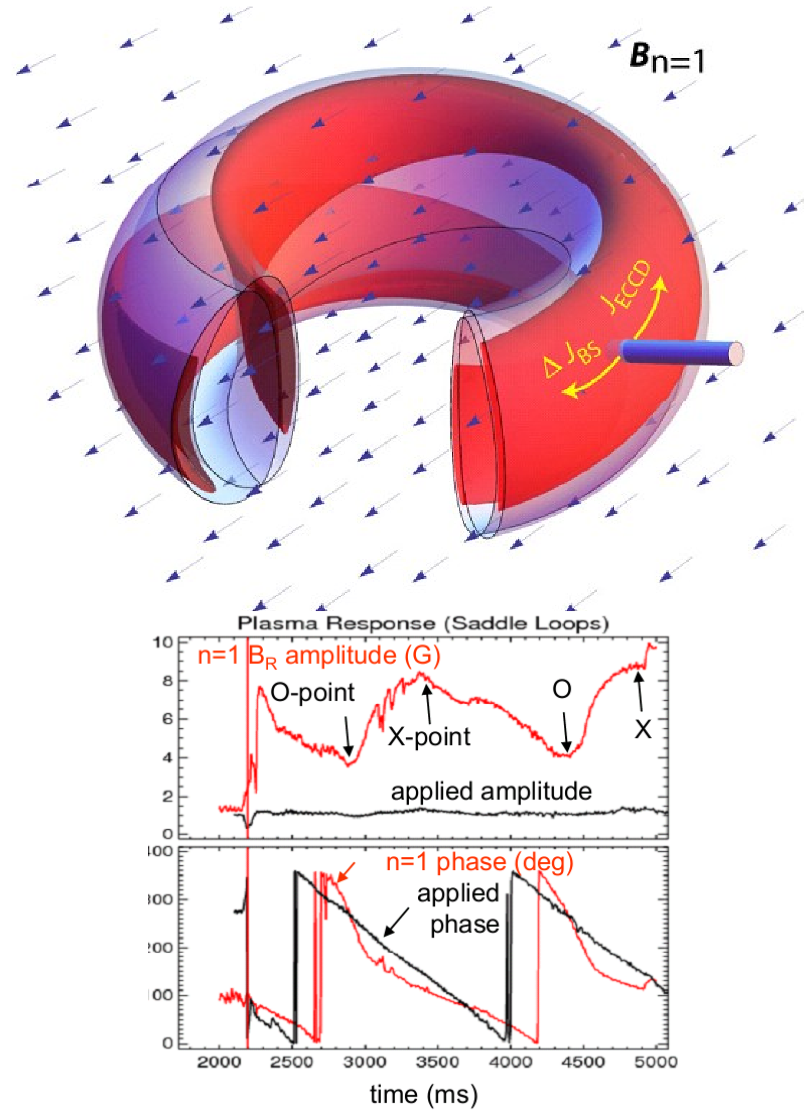




In this case O/point of the island could be inaccessible for ECCD!

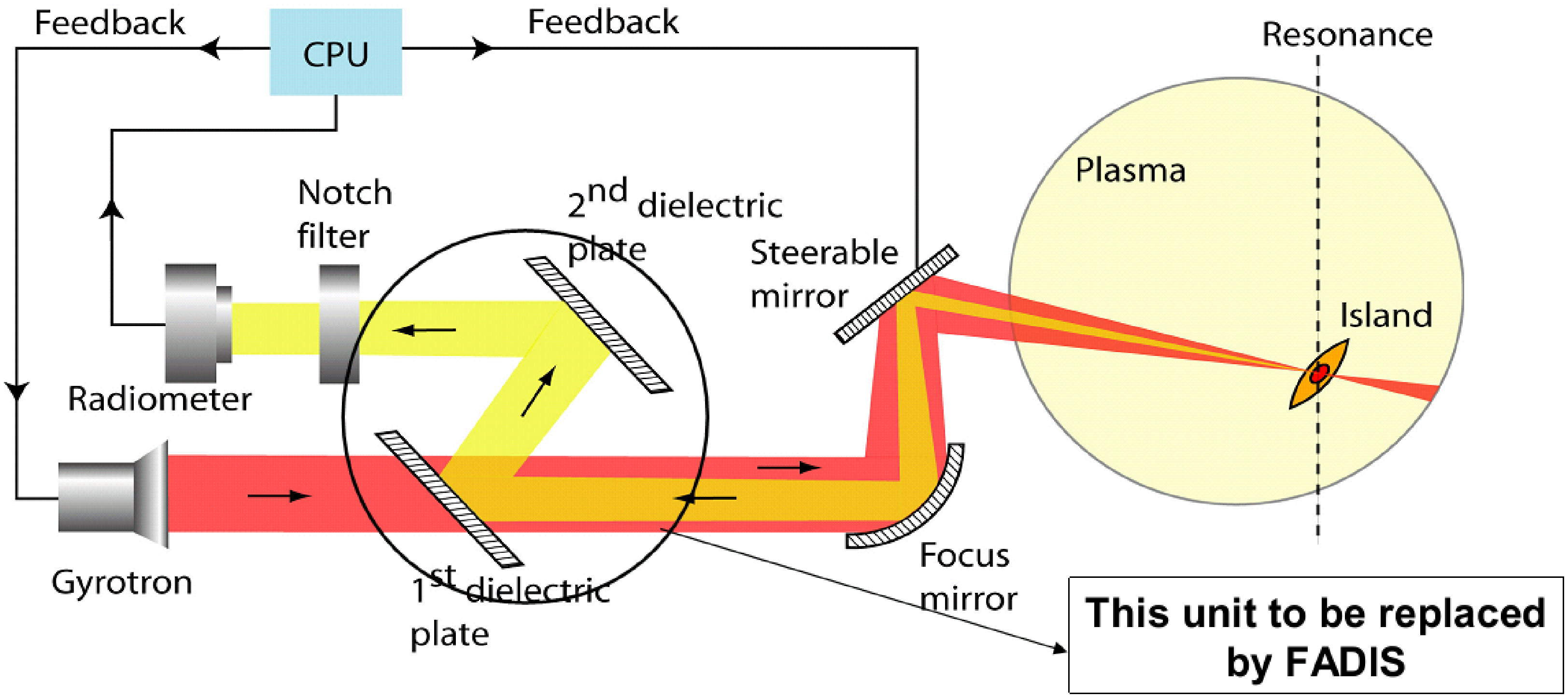
Additional actions are required!





Volpe, MHD workshop, 2010

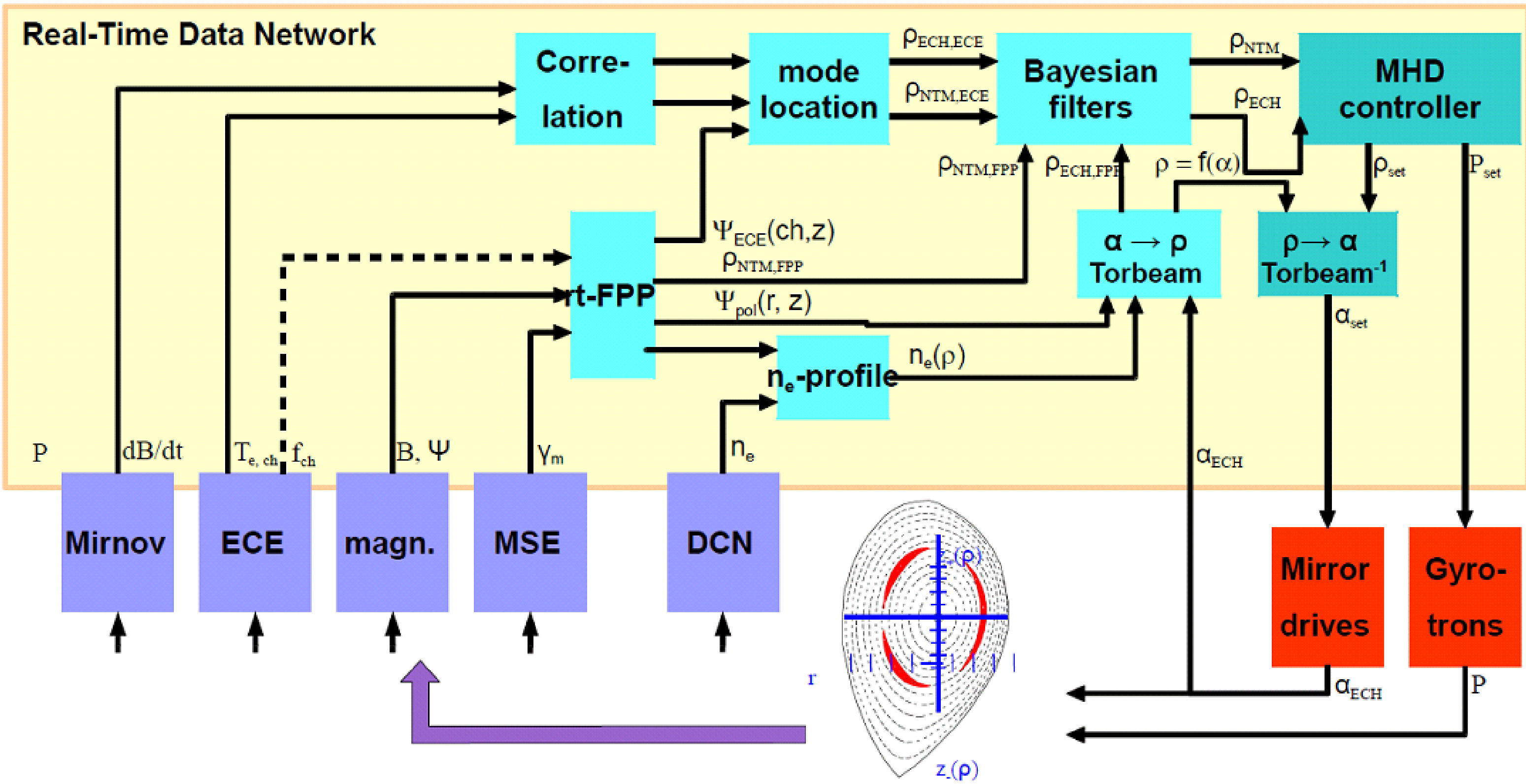
In line ECE for island control in case of locked mode



- plasma emission measured directly near deposition
- main mirror will be FADIS system (transparent for ECRH and reflecting for ECE emission, f-dependence!)
- good initial guess required, no realtime equilibrium needed

E.Westerhof, 13th Workshop on ECE and ECRH, 2004
J.W. Oosterbeek, FEaD 82 (2007) 1117; M.R. de Baar, IAEA2008, EX-P9-12

Realtime-loop for (N)TM- control at ASDEX Upgrade



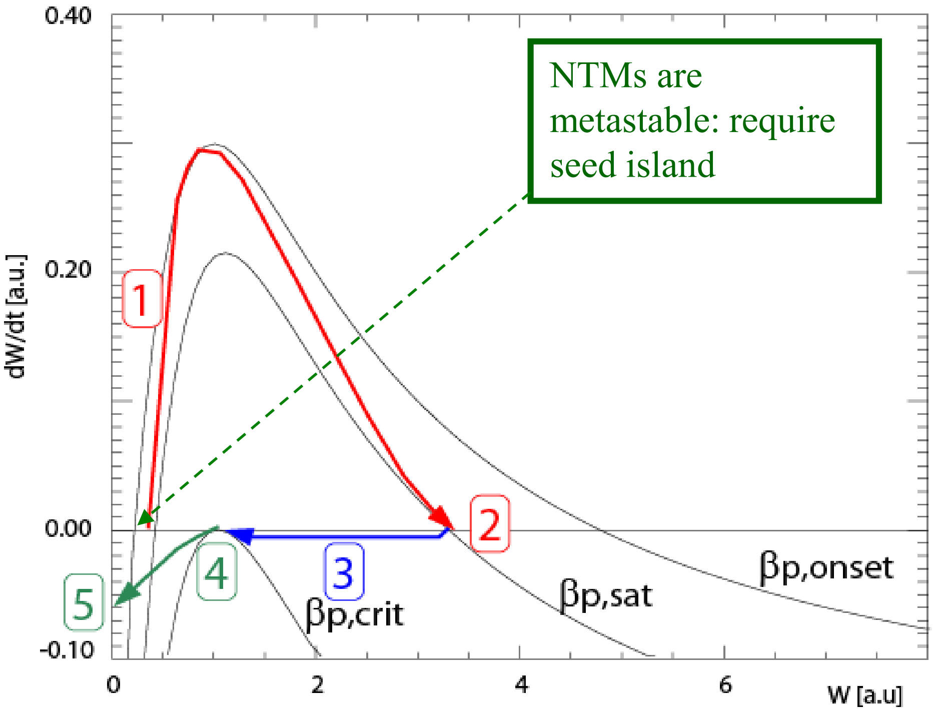
- magnetics provide rt equilibrium and expected $\rho_{(N)TM}$'s $\Rightarrow \rho_{(N)TM,Eq}$
- ECE/SXR/… detects mode location, if still possible $\Rightarrow \rho_{(N)TM,ECE}$, W
- Mirnov diagnostic provides mode numbers, W and LM $\Rightarrow$ m,n, W, LM
- rt - raytracing code (TORBEAM) provides ρ_{ECCD} $\Rightarrow \rho_{ECCD}$

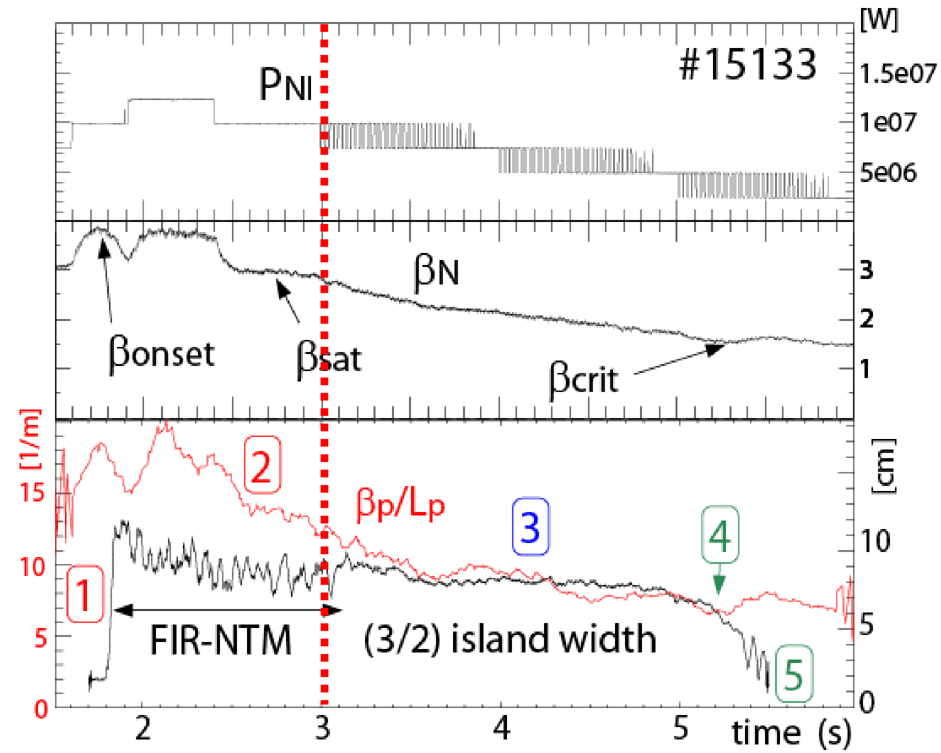
Conclusions

- 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 fast 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
- 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

Backup slides (for these who are interested in the details ☺)

Typical behaviour of an NTM





1: onset at $\beta_{p,onset} > \beta_{p,crit}$, + seed-island

2: saturated size $W_{sat} \sim \beta_{p,sat} \leftrightarrow$ FIR-NTM

$\rightarrow$ ECCD stabilization requirement

3: reduction of β_p (P_{NBI} ramp) until $\beta_{p,crit}$ is reached

4: $\beta_p \leq \beta_{p,crit}$, mode decouples from β_p

5: $\beta_p < \beta_{p,crit}$ for all times $\Rightarrow$ mode decays away

$W_{sat} \sim \beta_p$

$\langle W(FIR) \rangle < W_{sat}$

$W_{sat}(ECCD) \ll W_{sat}$

$P_{fusion} \sim \beta^2$

Other current drive techniques for NTM control

ICRH: current deposition is too broad → not possible to control NTM

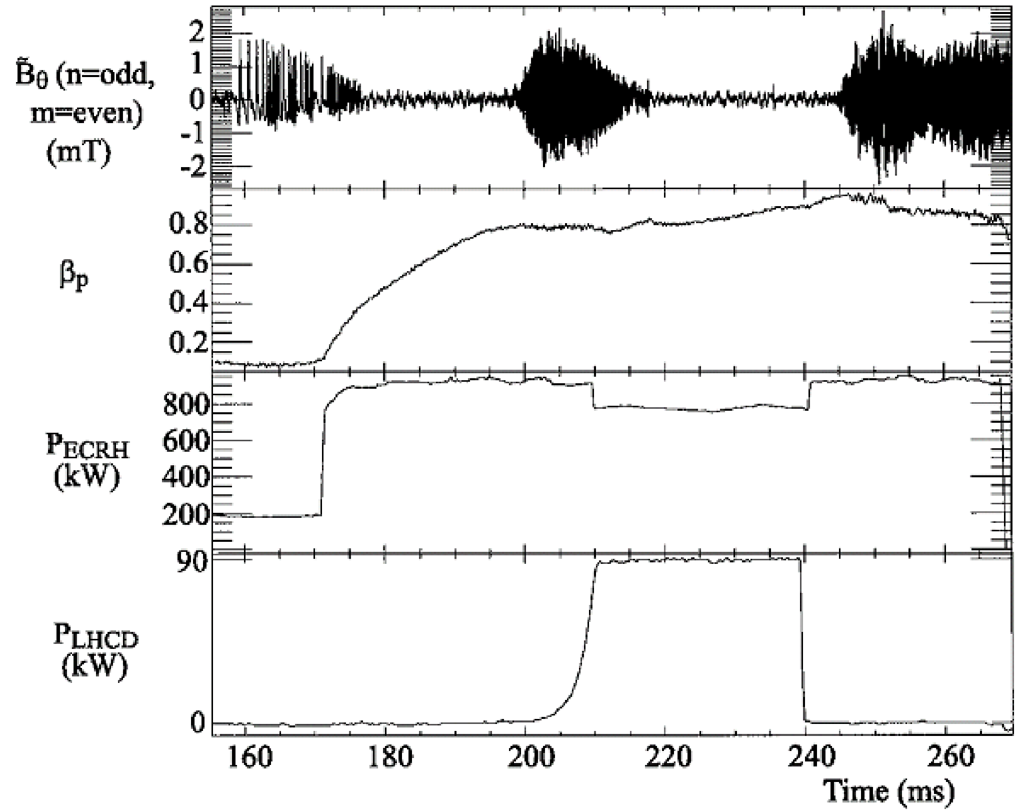
…but this system can be used for profiles control and avoidance

LHCD: Stabilization is possible … but due to local changes in current profile and further reduction of the classical TM term

$$\frac{dw}{dt} = \left(\frac{1.22\,\eta_{nc}}{\mu_0}\right)\left[\Delta' + a_1 \varepsilon^{1/2}\beta_p\left(\frac{w}{w^2 + w_c^2}\right) - a_2\left(\frac{\rho_{\theta i}^2 \beta_p g(\varepsilon, \nu_i)}{w^3}\right)\right],$$

Warrick C.D.et al 2001 Phys. Rev. Lett. 85574

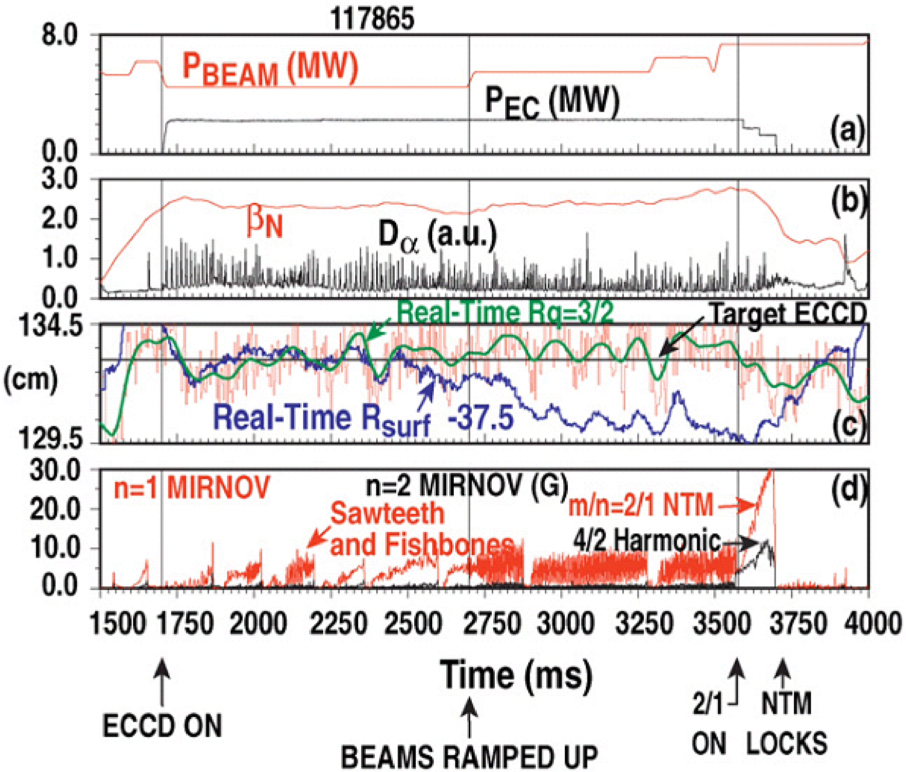
COMPASS-D



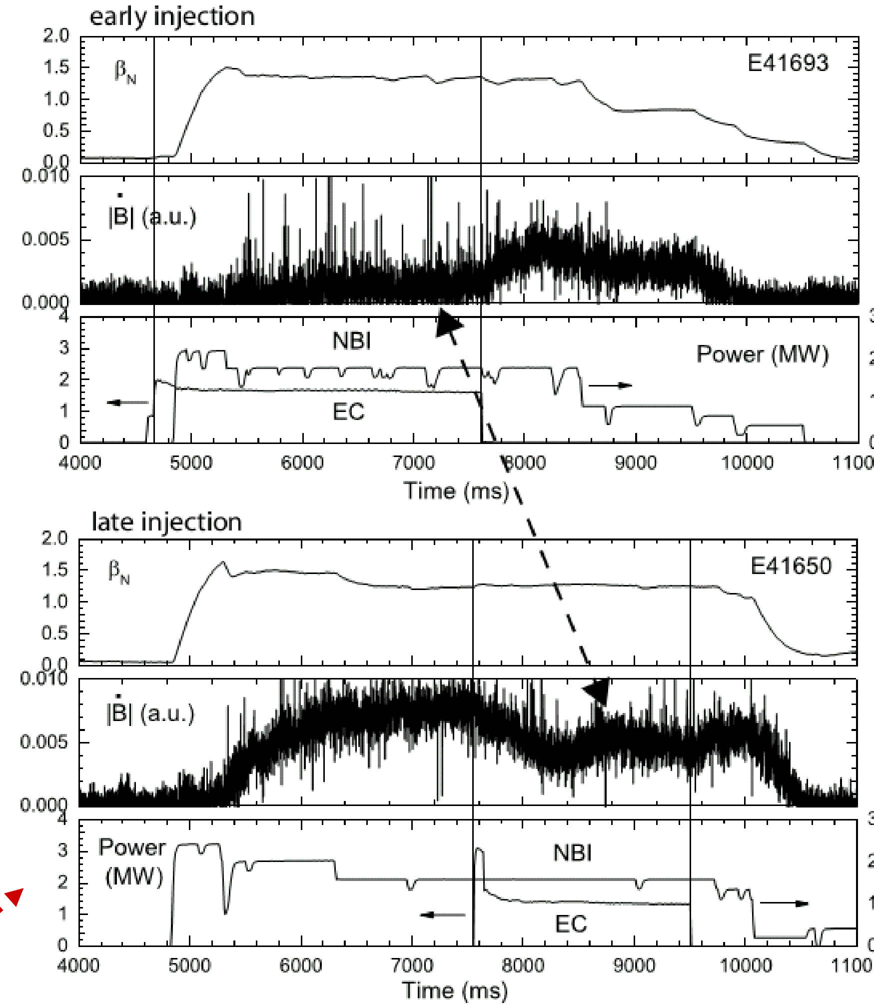
JET: no success

JT-60: possible

1) Preemptive ECCD at resonant surface

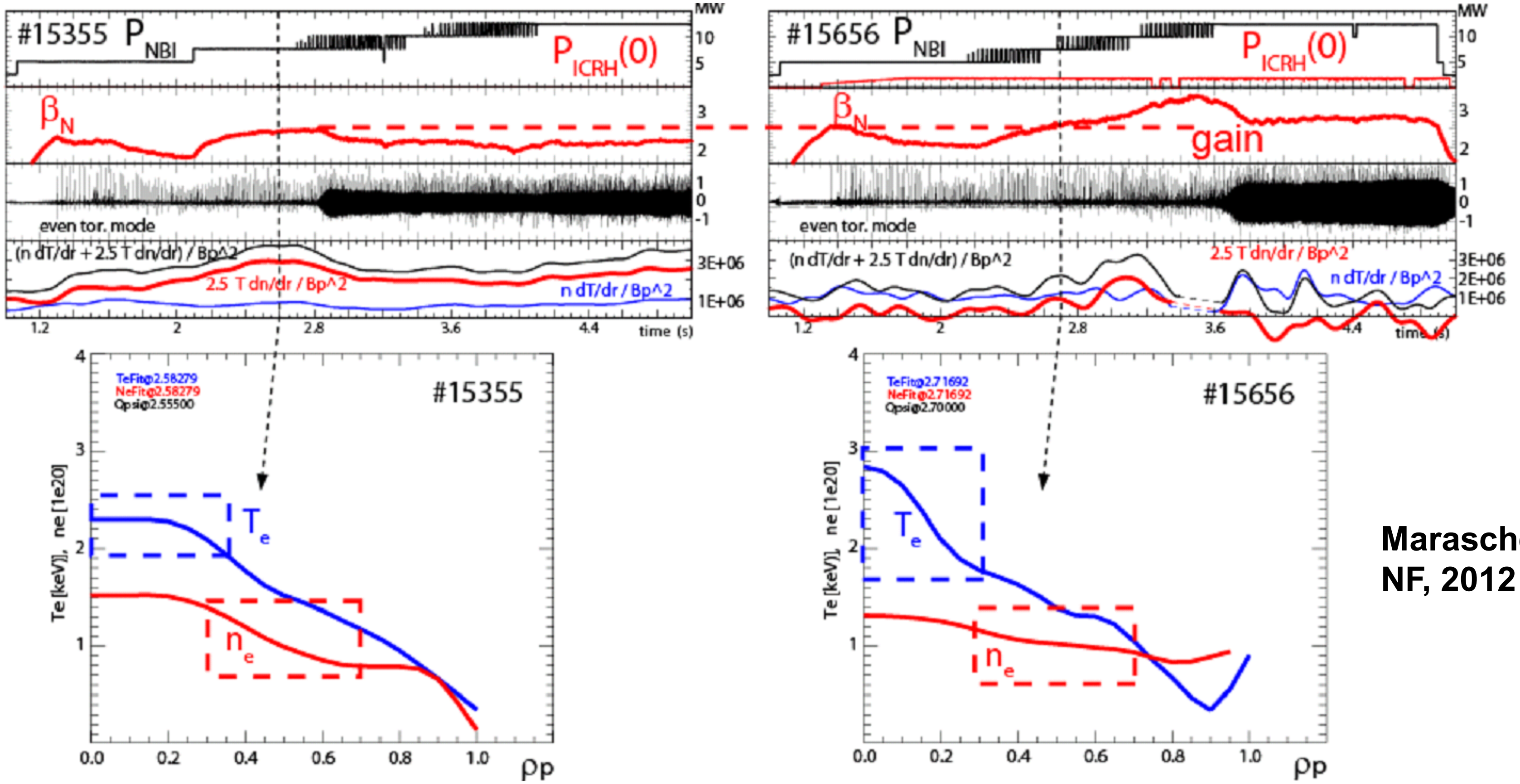


DIII-D, LaHaye, NF, 2005



With early ECCD (before the onset of the modes) the saturated island size never becomes as large as in the late ECCD case. (JT-60U, Nagasaki K.et al 2003 Nucl. Fusion43L7)

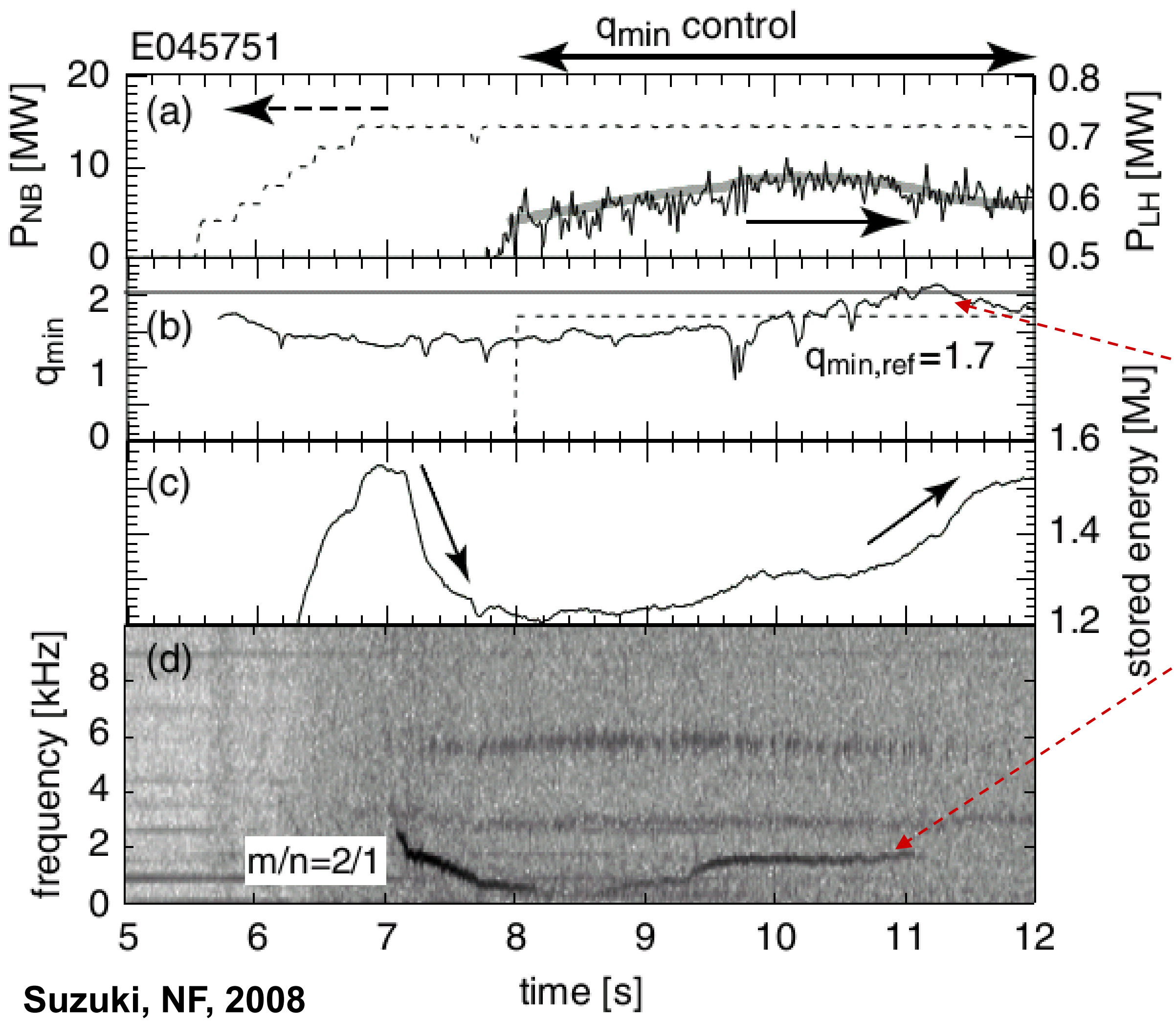
2) Profile tailoring with wave heating (reduction of the pressure gradient→ small bootstrap current → small changes in MRE)



Maraschek, NF, 2012

Figure 14. Two otherwise identical discharges without (left) and with central (right) electron heating via ICRH are compared. From top to bottom the applied heating power, the achieved β_N, the even magnetic amplitude $dB_{pol}(n = 2)/dt$, the total corrected pressure gradient and its parts from ∇n_e and ∇T_e are shown. At the bottom the n_e and T_e profiles at the indicated time points are shown for the two cases.

3) Change of the current profile with LHCD to remove resonant surface



Suzuki, NF, 2008

$q_{\min} > 2$

and (2,1) mode disappears

Different schemes to avoid:

- Sawteeth,
- Fishbones,
- ELMs,
- strong fast particle modes

It is important to remember that:

$$\beta_{onset}(Sawtooth) < \beta_{onset}(fishbone) < \beta_{onset}(ELM) < \beta_{onset}(trigger-less)$$

Gude, NF, 99

Thus, some triggers are more dangerous then the others!

Good review about NTM control

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SPECIAL TOPIC

Control of neoclassical tearing modes

M. Maraschek

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, D-85748 Garching, Germany

E-mail: Maraschek@ipp.mpg.de

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