Fusion Reactor Technology 2
(459.761, 3 Credits)

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Non-linear Plasma Activity

- **Fishbone Instability**

Study of High-Beta Magnetohyd

K. McGuire, R. Goldston, M. Bell, M. Bitte
F. Dylla, H. Eubank, H. Fishman, R. Fonc

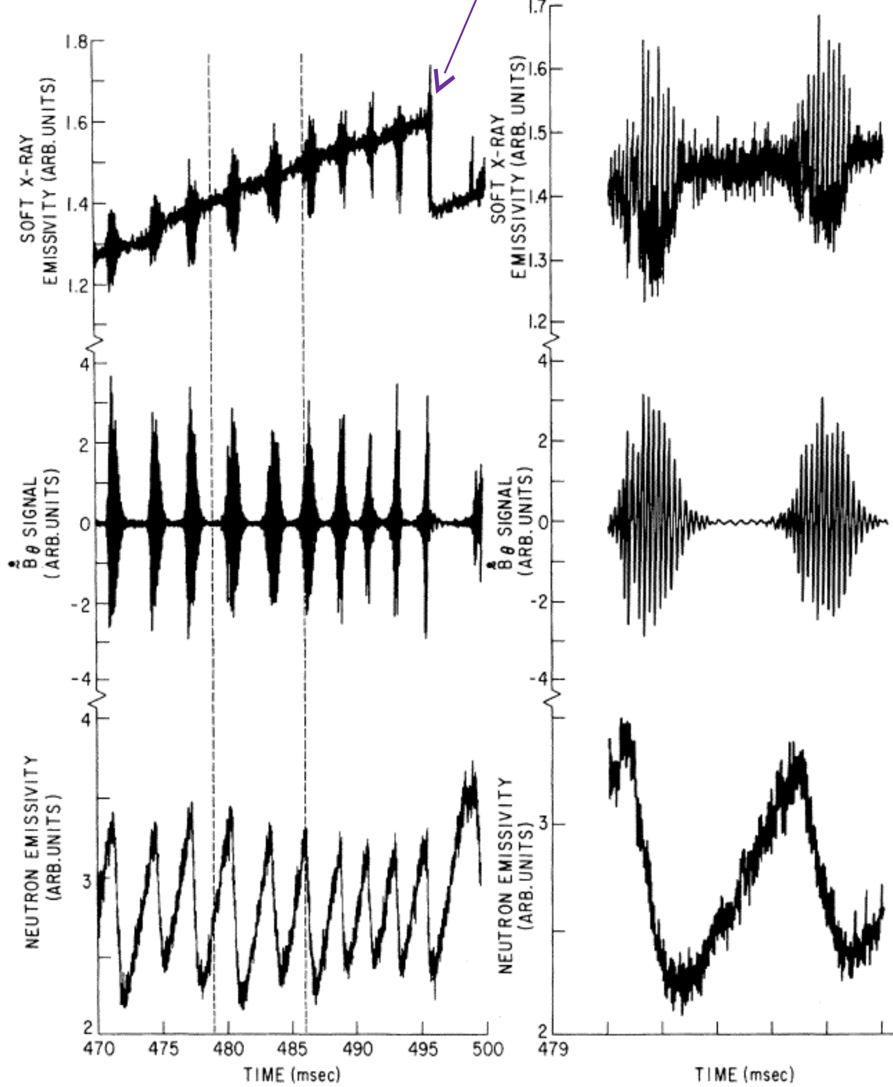
- Oscillation frequency (usually not high, ~ 10^4 Hz) in each burst decreases almost two-fold from the beginning of a burst to its end.
- The oscillations grow rather fast, then decay somewhat more slowly and plasma is stabilized until the next burst.

"fishbone instability" from its cha

PACS numbers: 52.55.Gb, 52.35.]

On the PDX tokamak, large-amplitude ma hydrodynamic (MHD) fluctuations have been served during plasma heating by injection o

sawtooth collapse



Non-linear Plasma Activity

- **Fishbone Instability**

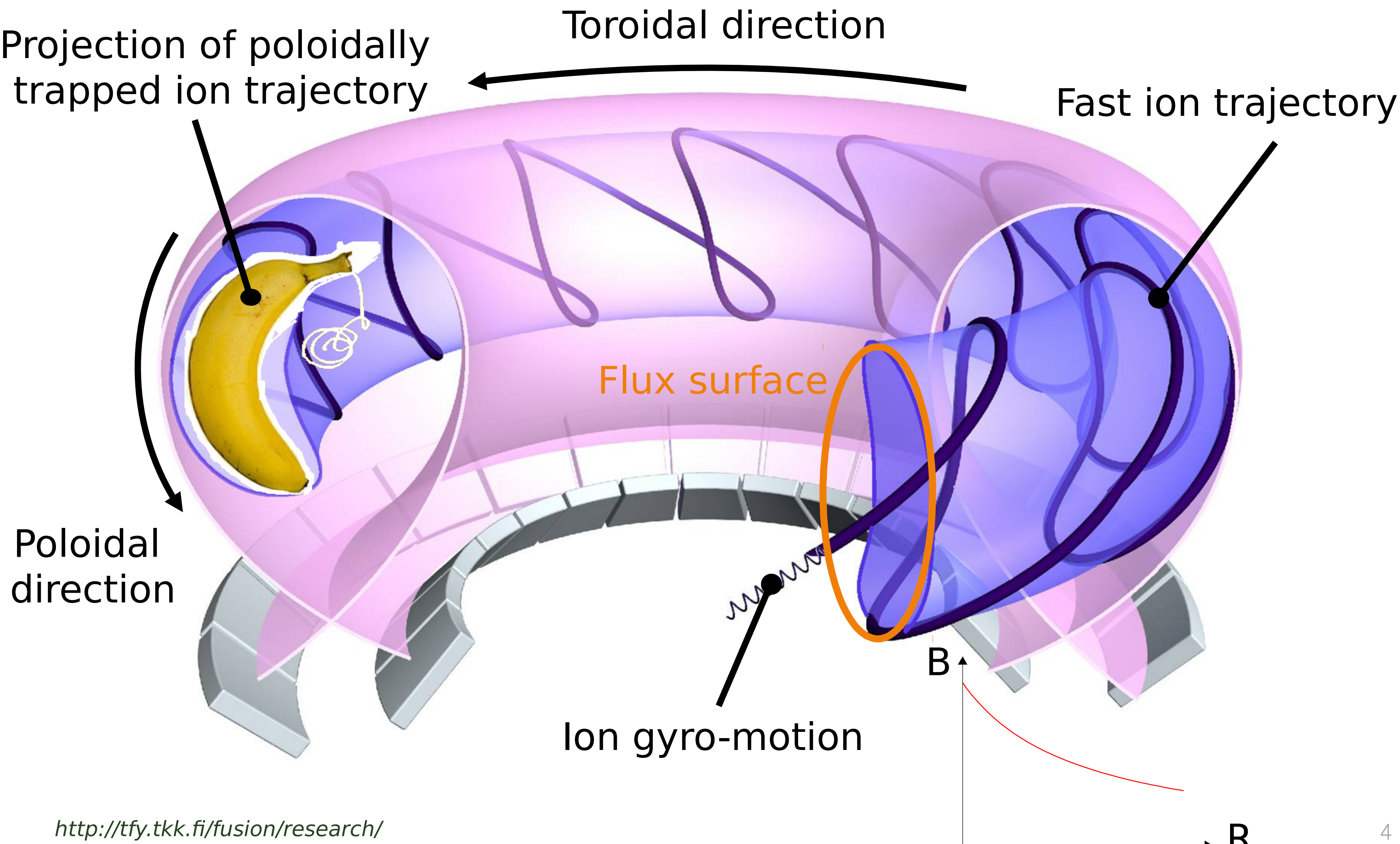
- Occurring under certain conditions when a high energy neutral beam is injected to heat the plasma.
- Driven by $\partial f/\partial r$, the radial gradient in the fast particle distribution function: kinetic excitation of the internal helical mode by fast ions
- Due to an interaction between the injected particle and an $m = 1$, $n = 1$ MHD perturbation.

  Interaction of the resonance type characterized by Landau damping, but here causing growth

  Resonance between the toroidal wave velocity of the instability and the toroidal drift experienced by trapped energetic particles from the injected beam

  Cf. Fishbones would not occur for injection parallel to **B**.
- Oscillations dropping when the energy of resonant particles is exhausted until the next spike of fishbone activity.

Toroidal Precession



http://tfy.tkk.fi/fusion/research/

Non-linear Plasma Activity

- **Fishbone Instability**

- Leading to intensive loss of fast ions trapped in plasma

  → worsens the efficiency of additional heating

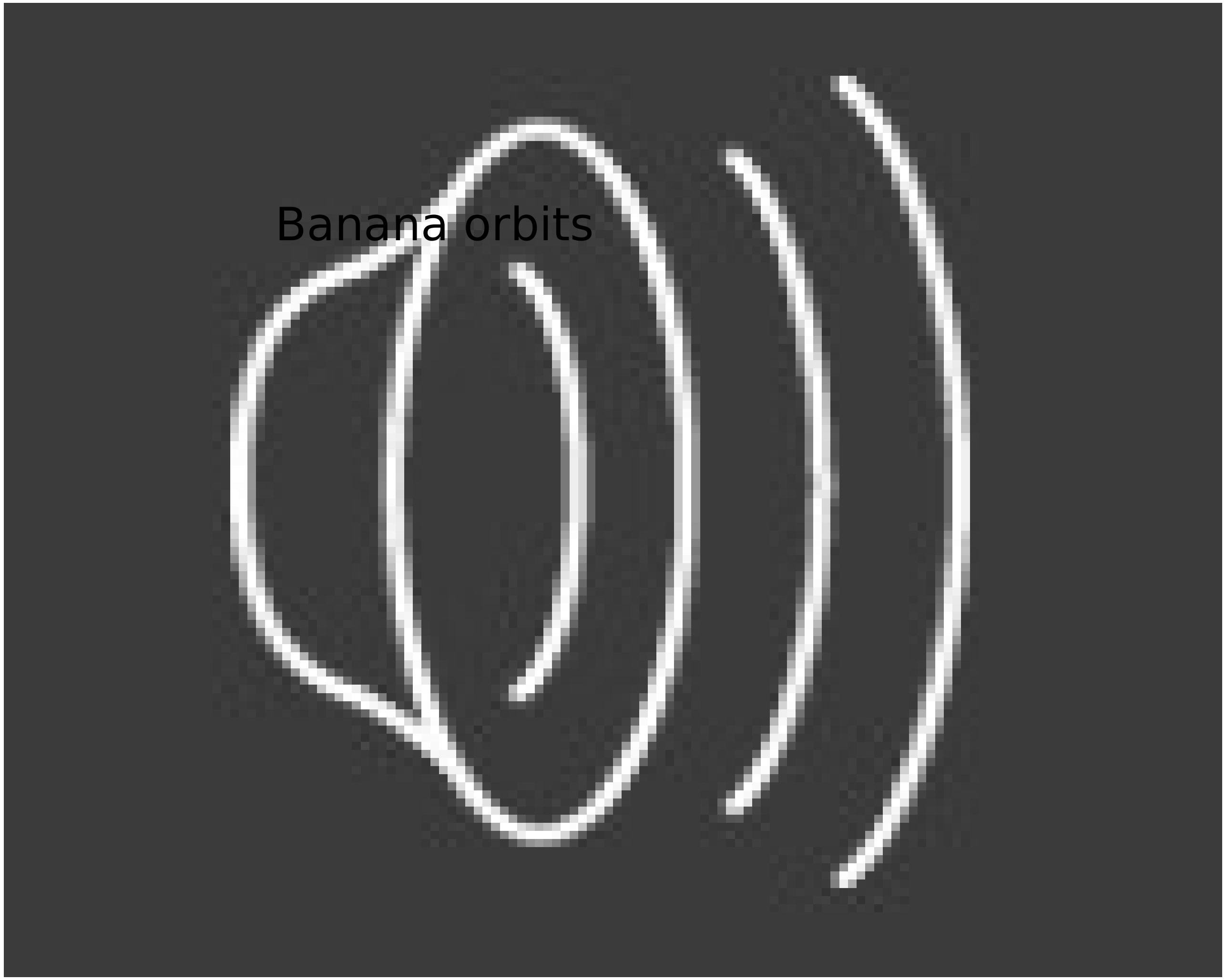
- Dangerous in fusion reactors:

  helical-mode destabilization may be excited by α-particle produced in the D-T reaction.

Why is fishbone frequency is constant?

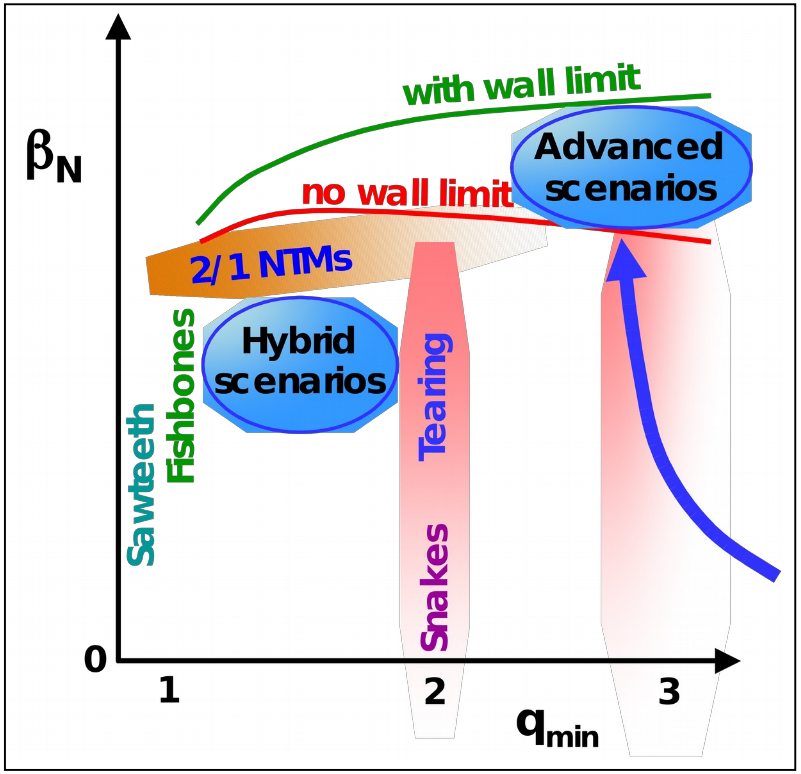
Non-linear Plasma Activity

- **Fishbone Instability**



MHD Instability

- **Instabilities limiting beta**



R. Buttery, EFPW 05

Resistive Wall Mode (RWM)

- **The Effect of a Resistive Wall**

- A perfectly conducting wall, placed in close proximity to the plasma can have a strong stabilizing effect on external kink modes.
- In actual experiments, the metallic vacuum chamber surrounding the plasma is a good approximation to a perfectly conducting wall.
- However, its conductivity is not infinite but is finite.
- In fact we do not want the conductivity too high and/or, too thick because it would take too long externally applied feedback fields to penetrate the shell and interact with the plasma.
- Also, higher resistivity, smaller currents are induced in the chamber during transients, alleviating power supply requirements.
- The question raised here concerns the effect of finite resistivity of the wall on external kink stability.

Resistive Wall Mode (RWM)

- **The Effect of a Resistive Wall**

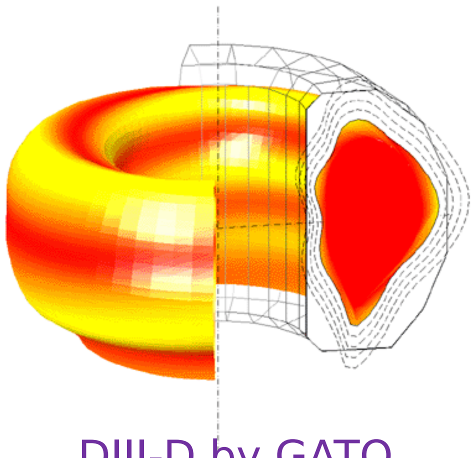
- There are three possible situations and only one is really interesting.
- In the first case the plasma is stable to external kinks with the wall at ∞. Here, since the plasma is already stable, a wall, either ideal or resistive does not affect stability. This case is uninteresting.
- In the second case, the plasma is unstable with the wall at ∞ and with the wall at its actual position, assuming the wall is perfectly conducting. Since the plasma is unstable with a perfectly conducting wall as $r = b$, making the wall resistive does not help. This case is also uninteresting.
- The interesting case is when the plasma is unstable with the wall at ∞, but stable with a perfectly conducting wall at $r = b$. Does the resistivity of the wall destroy wall stabilization?

Resistive Wall Mode (RWM)

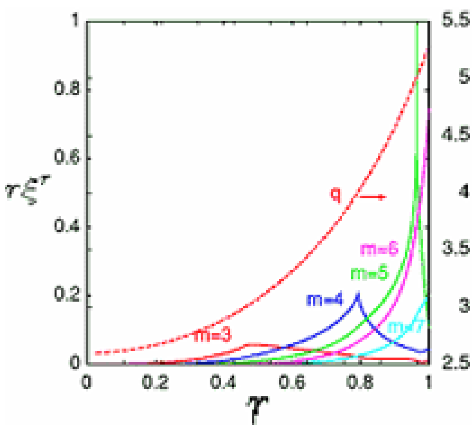
- **Physics of the resistive wall destabilisation**

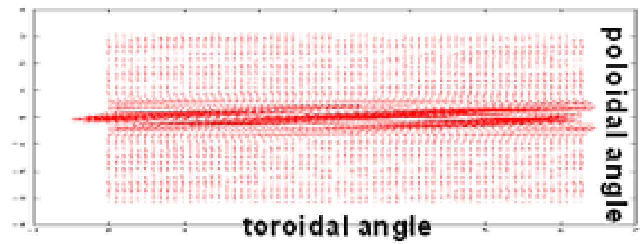
- As the plasma moves under the action of a potentially unstable perturbation, currents are induced in the conducting wall.
- Generally, these currents flow in a direction to oppose the plasma motion and thus provide stabilisation.
- For a perfectly conducting wall these current can exist *ad infinitum*.
- For a resistive wall the currents will decay on a diffusion time scale (τ_D).
- Since the characteristic time of a stable ideal MHD oscillation is much shorter than τ_D the rapidly oscillating wall stabilised mode is only slightly affected by the presence of a resistive wall.
- If, however, the plasma develops an unstable perturbation on the slower τ_D time scale, then stabilising wall currents are not able to develop and the disturbance continues to grow.

Resistive Wall Mode (RWM)

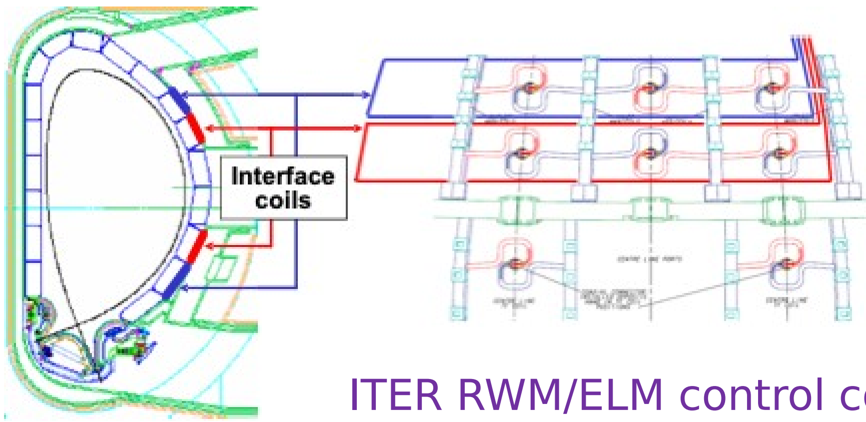


DIII-D by GATO





Unstable RWM eigenfunction inside the plasma and eddy current on the resistive wall calculated by RWMaC.



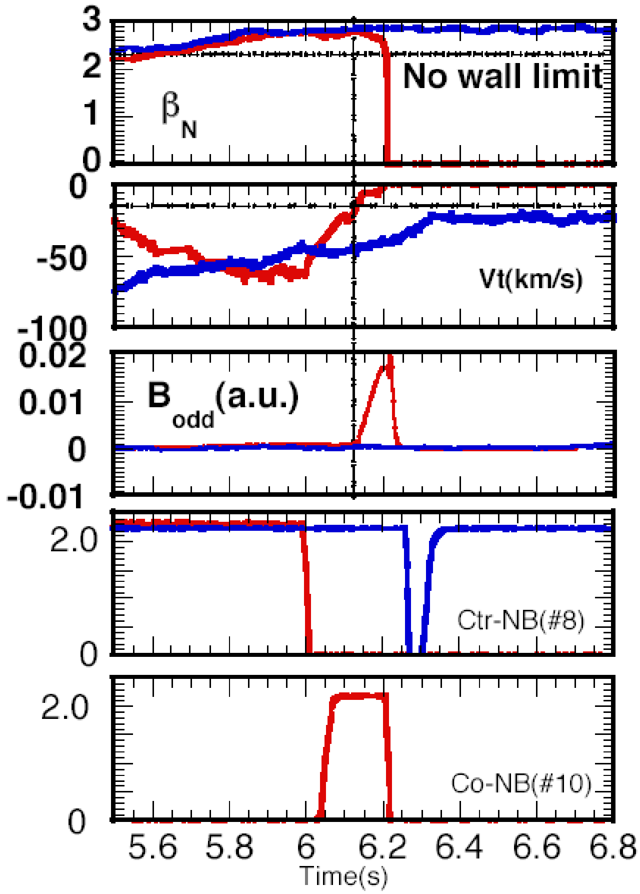
ITER RWM/ELM control coils

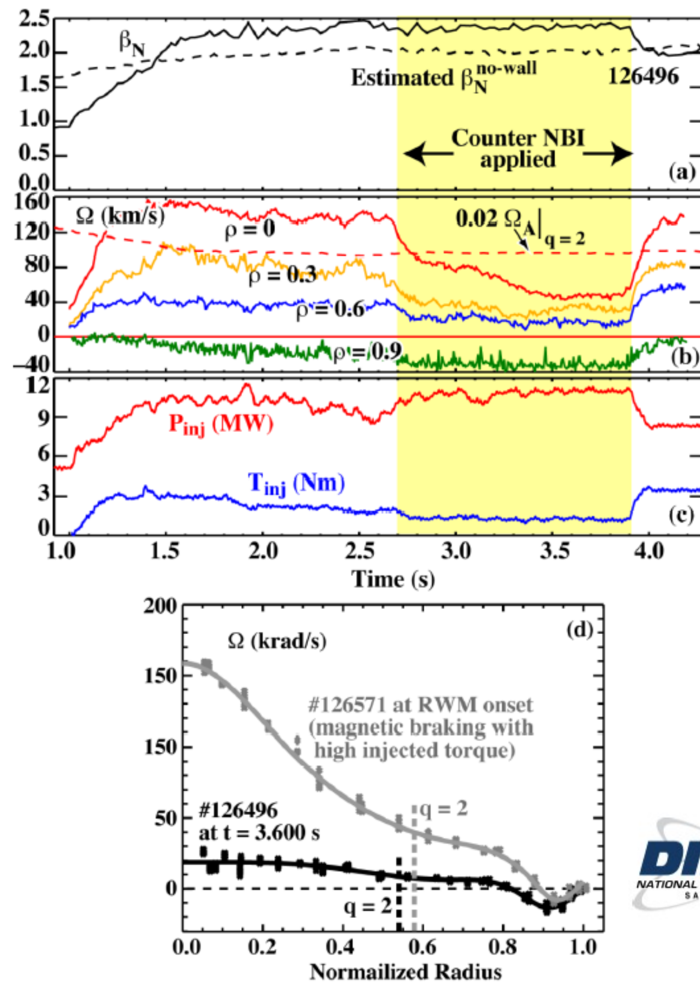
Resistive Wall Mode (RWM)

- **The Ever Evolving Requirements for RWM Stability**

- Ideal MHD kink mode cannot be stabilized by a resistive wall: resistive wall mode (Pfirsch & Tasso, NF 1971)
- Experiments suggest RWM stability above no-wall beta limit (Okabayashi, IAEA 1986)
- Rapid plasma flow and some dissipation alters linear stability and can stabilize RWM (Bondeson and Ward, PRL 1994)
- Kinetic effects can stabilize RWM without plasma flow (Hu & Betti, PRL 2004)
- DIII-D experiments with near-balanced NBI and optimized error field correction show RWM stable at very slow rotation (Reimerdes, PRL 2007)
- Fast ions contribution essential for RWM stability at low rotation (Reimerdes, PRL 2011)
- Recent tokamak experiments at RFX-mod show that the RWM can be stable at *q*-edge below 2 in ohmic plasmas.

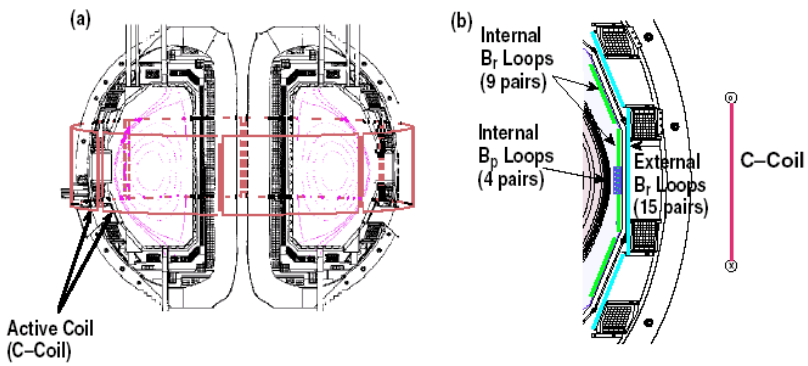
Resistive Wall Mode (RWM)

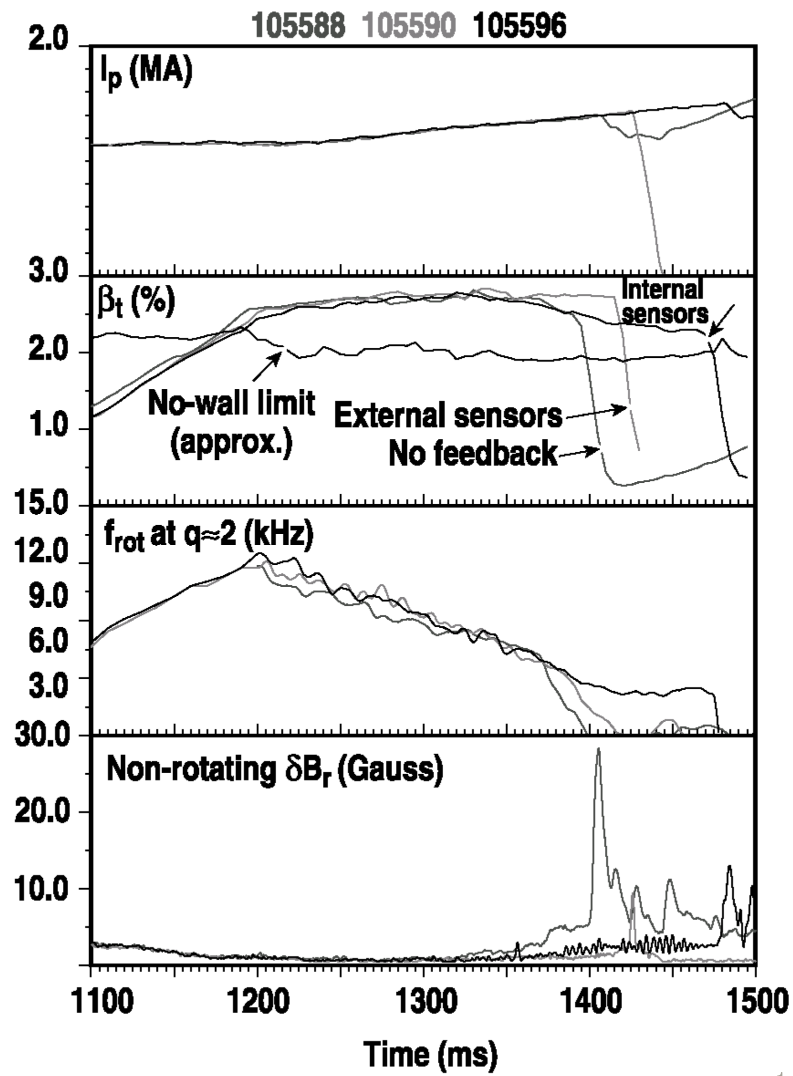




- (Positive) surprises as we go to lower net momentum input.
- The rotation threshold may be very sensitive to ambient error field.
- But physics not yet clear (e.g. role of n_i as highlighted by NSTX)

Resistive Wall Mode (RWM)





- Saddle coils for direct stabilisation

- Different feedback schemes exist
- First results look promising
- New experiments with in-vessel coils under way on DIII-D

RWM Control

- RWM feedback allows stable operation above no-wall beta Limit

- High beta plasmas with no feedback and standard EFC suffer RWM and beta collapse.
- Low beta discharges OK without RWM feedback

- Stability also obtained with feedback off and appropriately programmed *n* = 1 currents

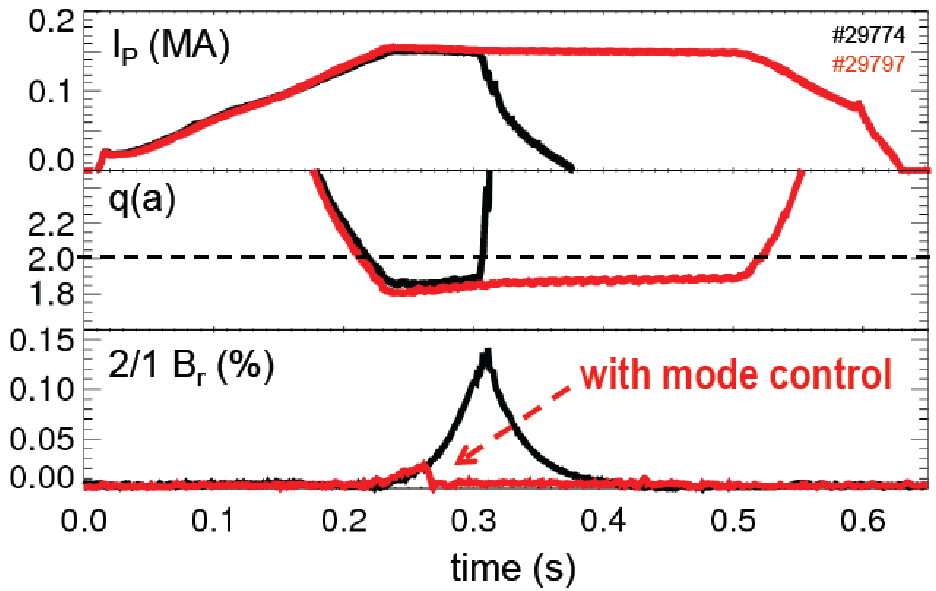
- Pre-programmed error correction currents “suggested” by feedback reproduce active feedback results
- Standard EFC (determined from low density LM onset) is not adequate.
- Feedback senses change in error field amplification as beta increases, drives currents to correct intrinsic error.

A.M. Garofalo et al, PoP (2002)

Resistive Wall Mode (RWM)

- Low-*q* operation has long been limited to $q_a > 2$ by a strong current-driven $n = 1$ kink (Strait IAEA 1988, Wesson NF 1989, Lazzaro NF 1990, Kamada NF 1993)
- RFX-mod operating as an ohmic tokamak demonstrated robust $q_a < 2$ operation via magnetic feedback control of the $n = 1$ RWM (Zanca PPCF 2012)

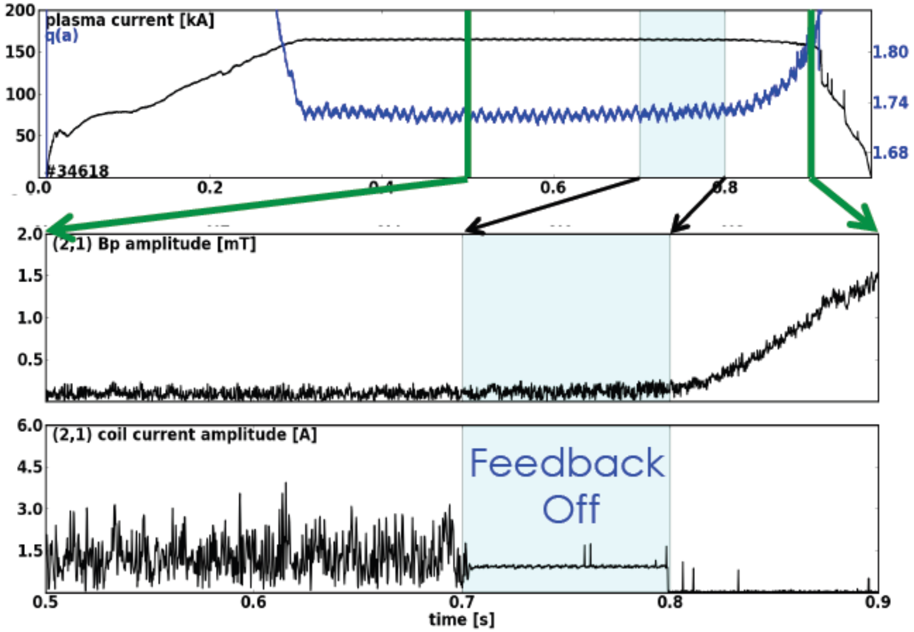
CONSORZIO RFX
Ricerca Formazione Innovazione



Resistive Wall Mode (RWM)

- More recently, RFX-mod has shown that the RWM can be stable without feedback at $q_a < 2$
  - Feedback needed to find optimal error field correction
  - With optimal EFC, feedback can be turned off (freezing)
  - Analogous to dynamic error field correction in high beta DIII-D experiments

- Passive RWM stability in ohmic, $q_a < 2$ plasma with slow rotation, weak kinetic effects, no fast ions is a new challenge for RWM theory
  - “Plasma rotation and kinetic effects cannot stabilize the current driven RWM” (Wang, PoP 2012)



RWM Control

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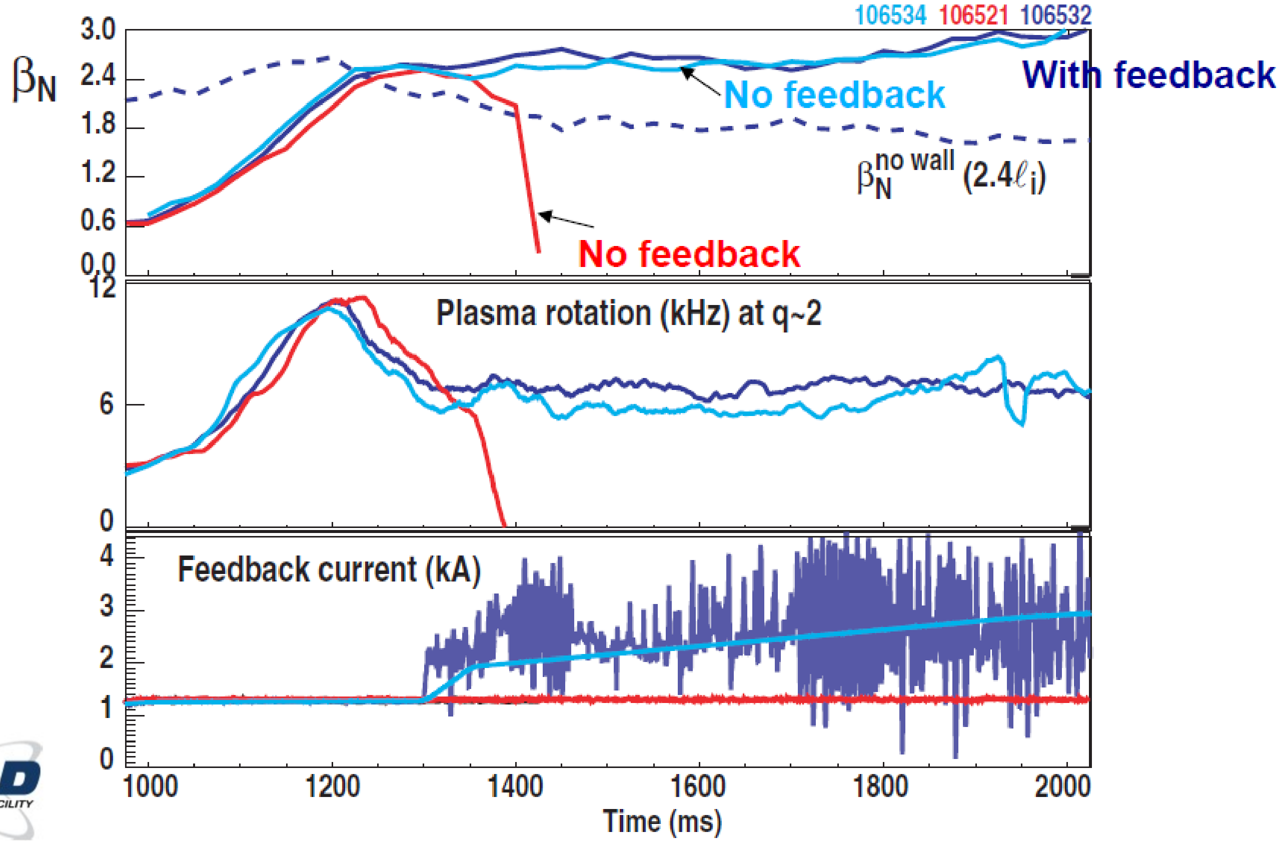

A.M. Garofalo et al, PoP (2002)

References

- *A. M. Garofalo, P. Piovesan, C. Piron, “An Emerging Interpretation of q<2 Stabilization Experiments”, ITPA MHD TG Meeting, October 8-11, 2013, Hefei, China*