Introduction to Nuclear Fusion

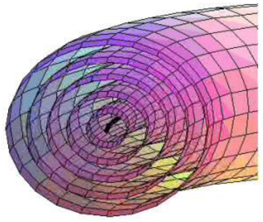
Prof. Dr. Yong-Su Na

Resistive MHD instabilities in a Tokamak

Tokamak Stability

- **Ideal MHD instabilities**

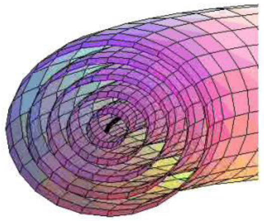
- current driven (kink) instabilities
  - internal modes
  - external modes
- pressure driven instabilities
  - interchange modes
  - ballooning modes
- current+pressure driven: Edge Localised Modes (ELMs)
- vertical instability



Flux conservation
Topology unchanged

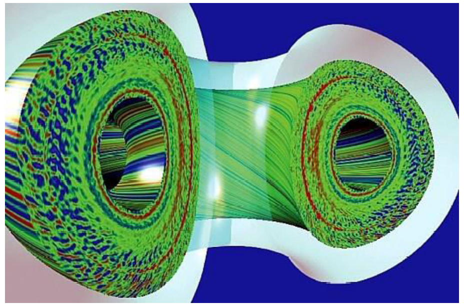
- **Resistive MHD instabilities**

- current driven instabilities
  - tearing modes
  - neoclassical tearing modes (NTMs)
- nonlinear modes
  - sawtooth
  - disruption



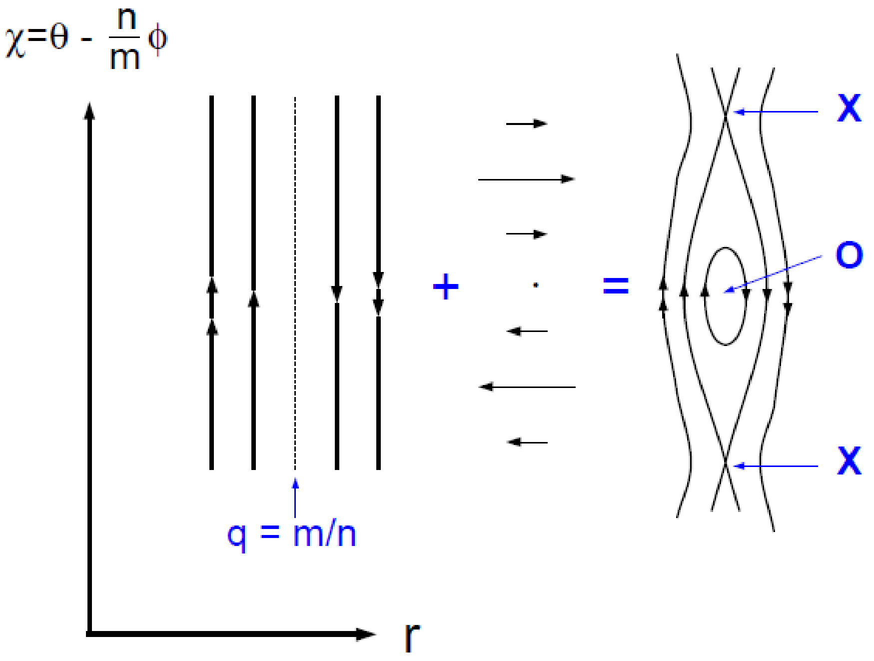
Reconnection of field lines
Topology changed

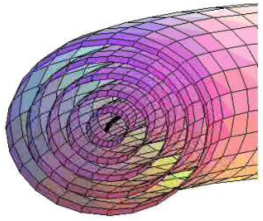
- **Microinstabilities - Turbulence**



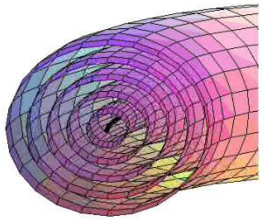
Resistive MHD Instabilities

- growing more slowly compared with the ideal instabilities (10^{-4}-10^{-2} s)
- resulting from the diffusion or tearing of the magnetic field lines relative to the plasma fluid
- destroying the nested topology of the magnetic flux surfaces





Flux conservation
Topology unchanged



Reconnection of field lines
Topology changed

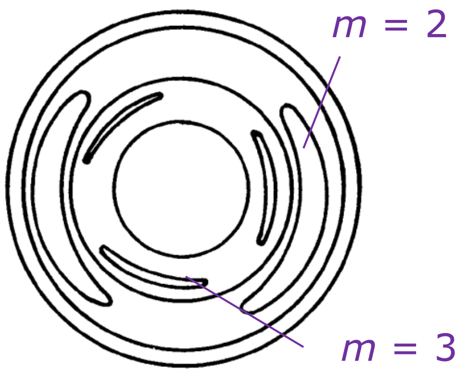
*H. P. Furth et al, "Finite-Resistivity Instabilities of a Sheet Pinch" Phys. Fluids **6** 459 (1963)*

Resistive MHD Instabilities

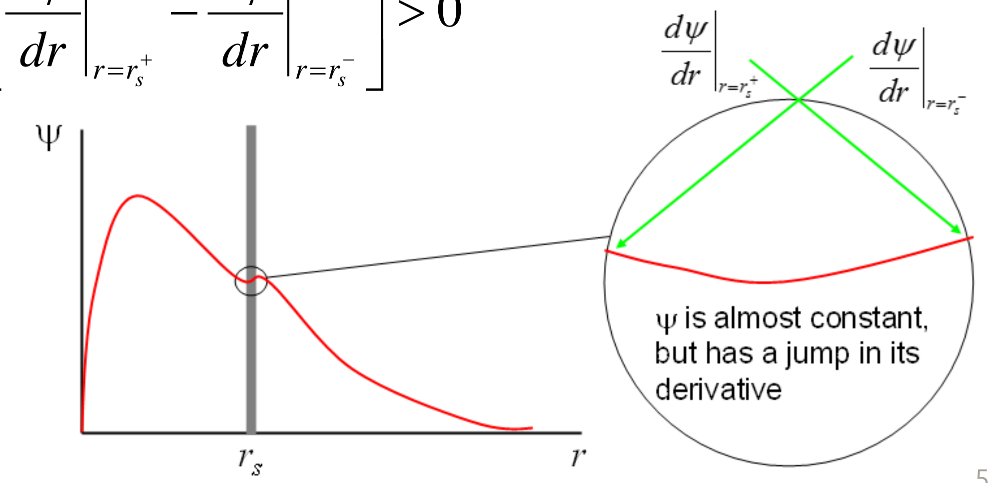
- **Tearing Modes**
  - resistive internal kink modes ($m \geq 2$)
  - driven by perturbed **B** induced by current layer (∇J) in plasmas
  - magnetic island formation
  - more tolerable and lower than ideal modes
  - unstable region reduced as sharpness of the current profile, closeness of the wall to the plasma, shear increases
  - stability condition: $q_0 > 3$

$$s(r) \equiv \frac{r}{q}\frac{dq}{dr}$$

$$\Delta' = \frac{1}{\psi}\left[\left.\frac{d\psi}{dr}\right|_{r=r_s^+} - \left.\frac{d\psi}{dr}\right|_{r=r_s^-}\right] > 0$$



$$\frac{dw}{dt} \propto \Delta'$$



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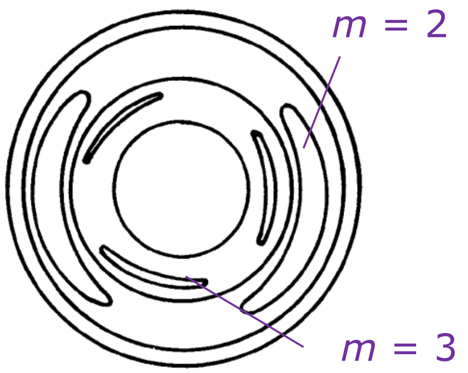

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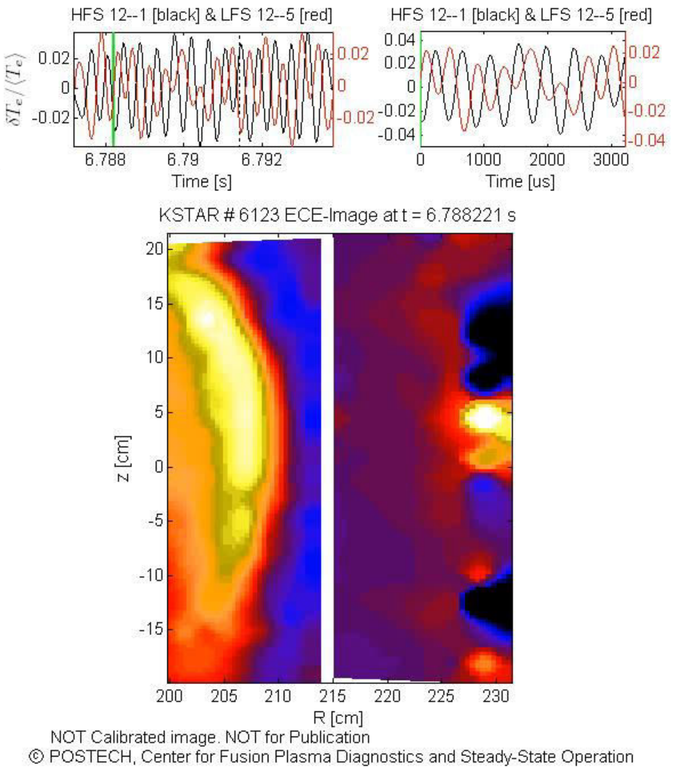
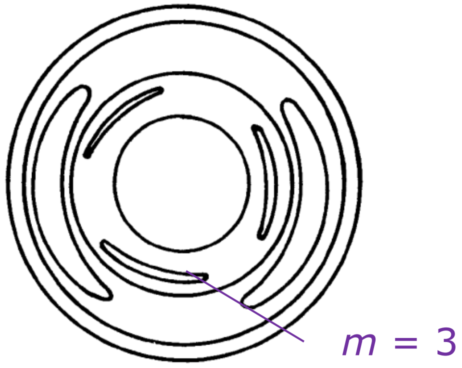
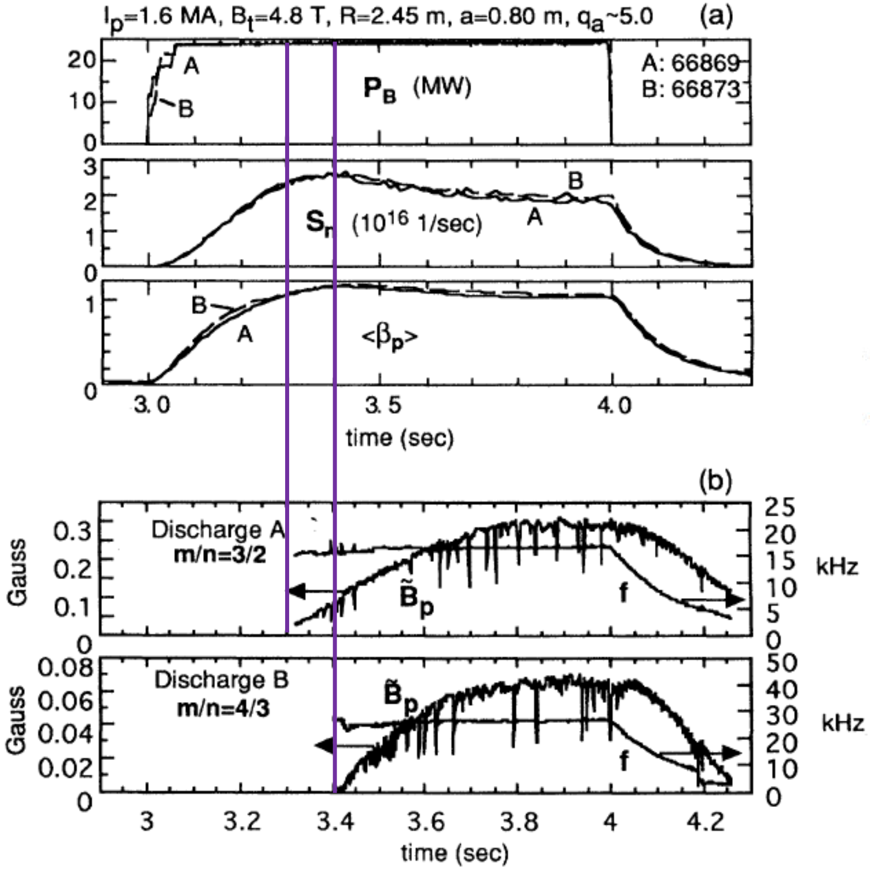


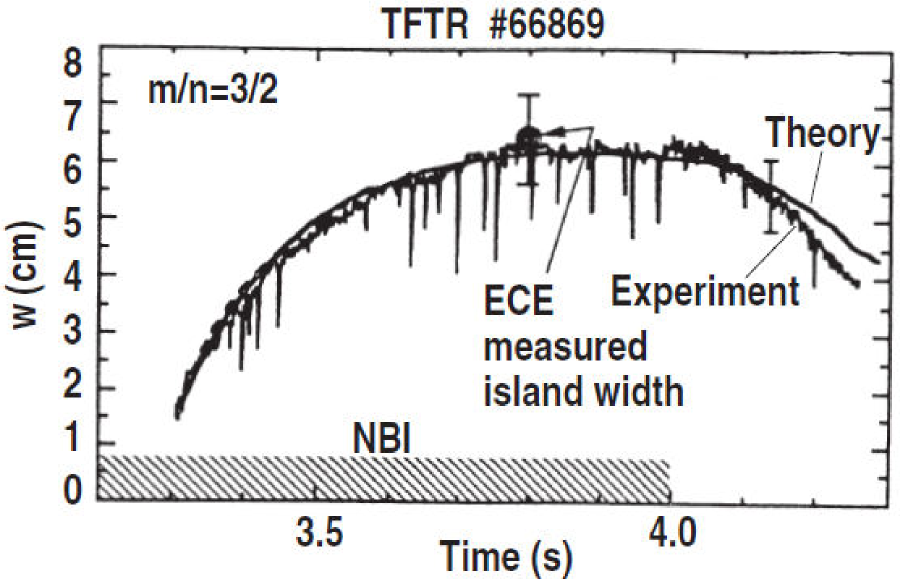
POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Resistive MHD Instabilities

- **Neoclassical Tearing Modes (NTMs)**
  - $\Delta' < 0$
  - Predicted theoretically first, observed experimentally in 1995







Resistive MHD Instabilities

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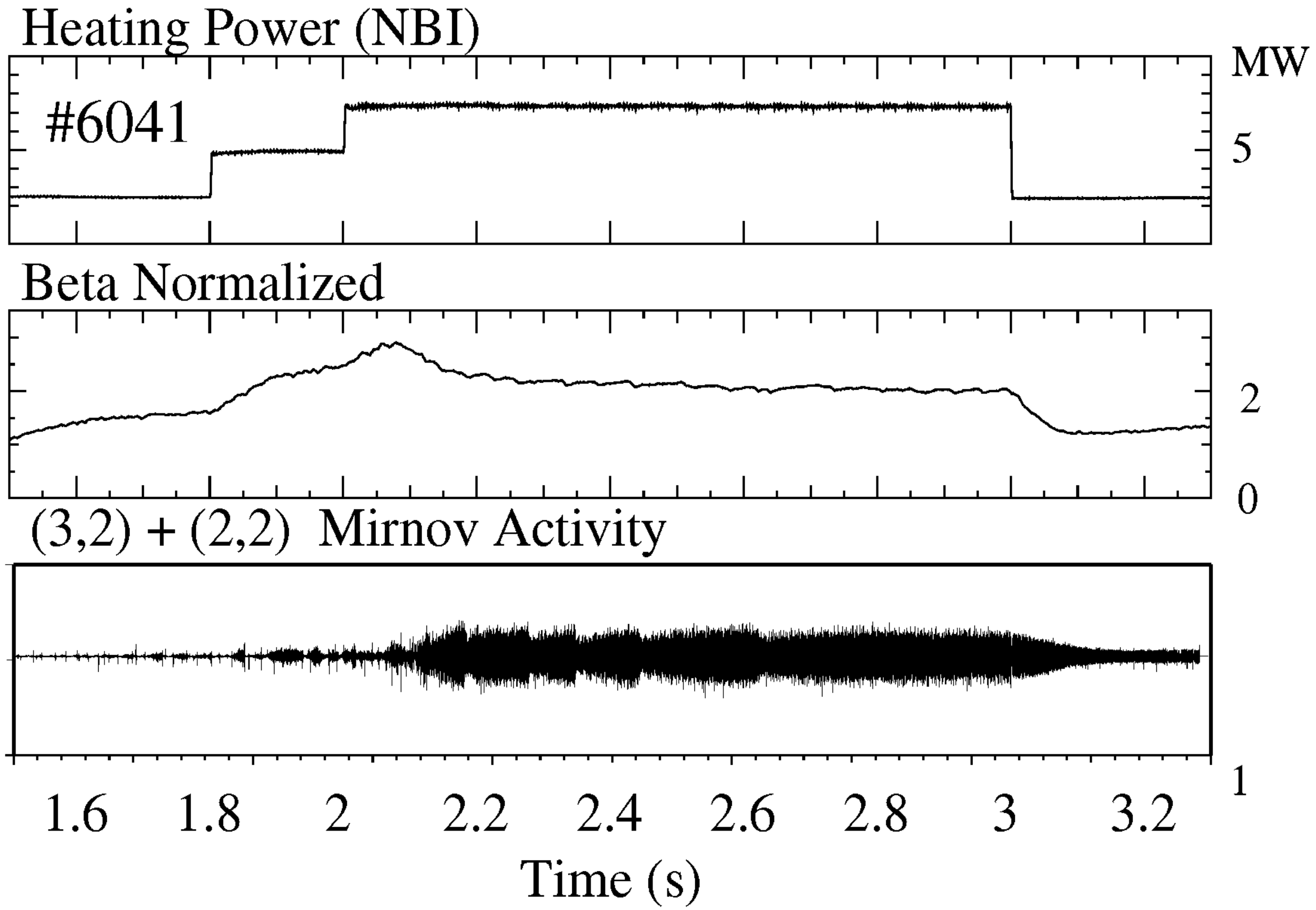
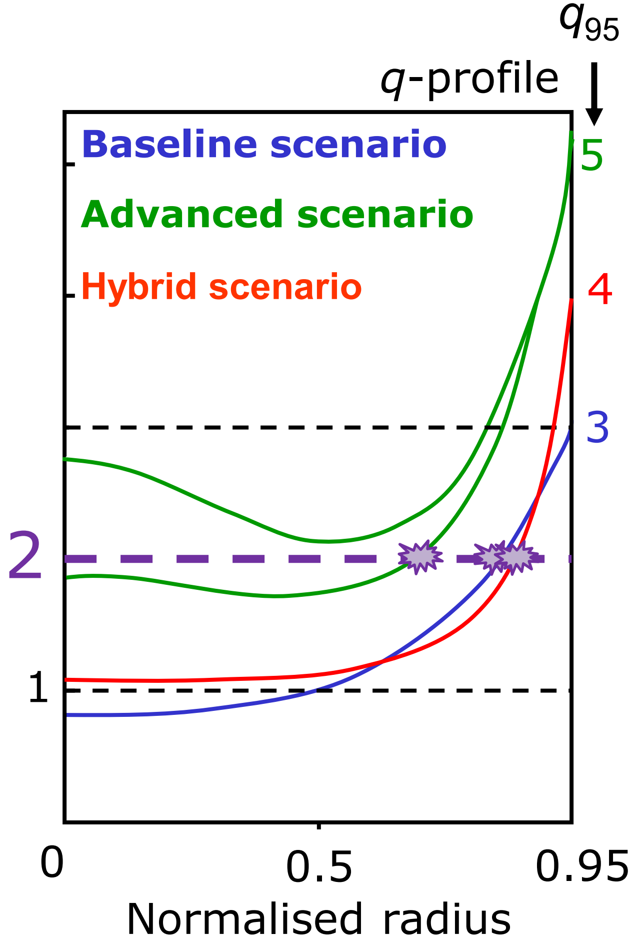


$$\beta_t = \frac{p}{B_t^2 / 2\mu_0} = \beta_N \frac{I_p}{aB_t}$$

Resistive MHD Instabilities

- **Neoclassical Tearing Modes (NTMs)**

$q = m/n = 2$ surface ($m = 2$, $n = 1$)

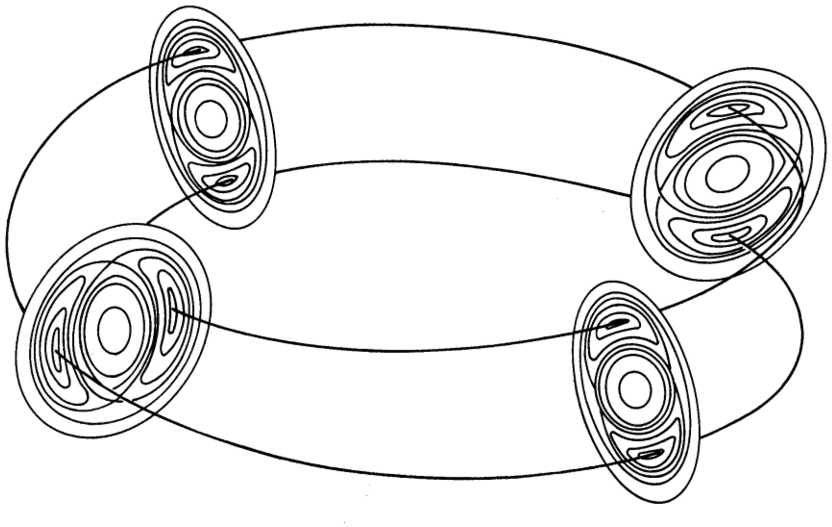


Tim Hender, "Neoclassical Tearing Modes in Tokamaks", KPS/DPP, Daejun, Korea, 24 April 2009

Resistive MHD Instabilities

- **Neoclassical Tearing Modes (NTMs)**

MAST
MEGA-AMPERE SPHERICAL TOKAMAK



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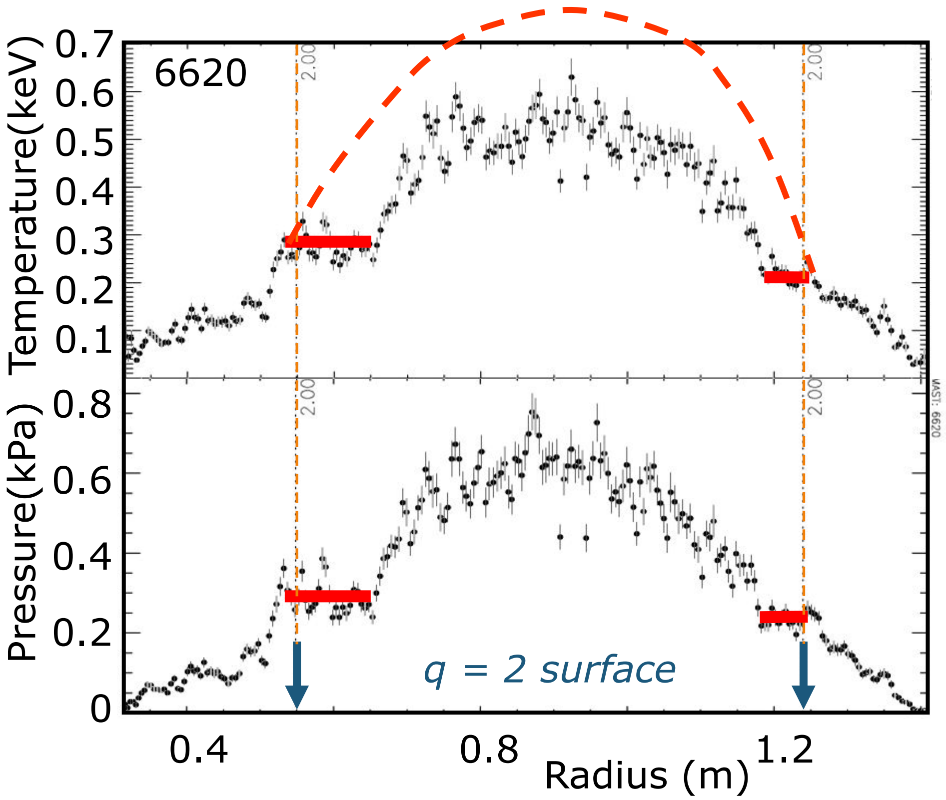


- Pressure flattening across magnetic islands due to large transport coefficients along magnetic field lines

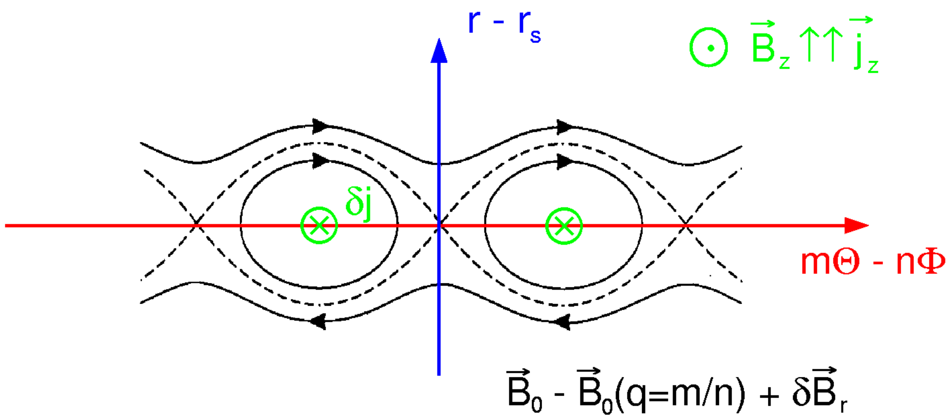
Tim Hender, "Neoclassical Tearing Modes in Tokamaks", KPS/DPP, Daejun, Korea, 24 April 2009

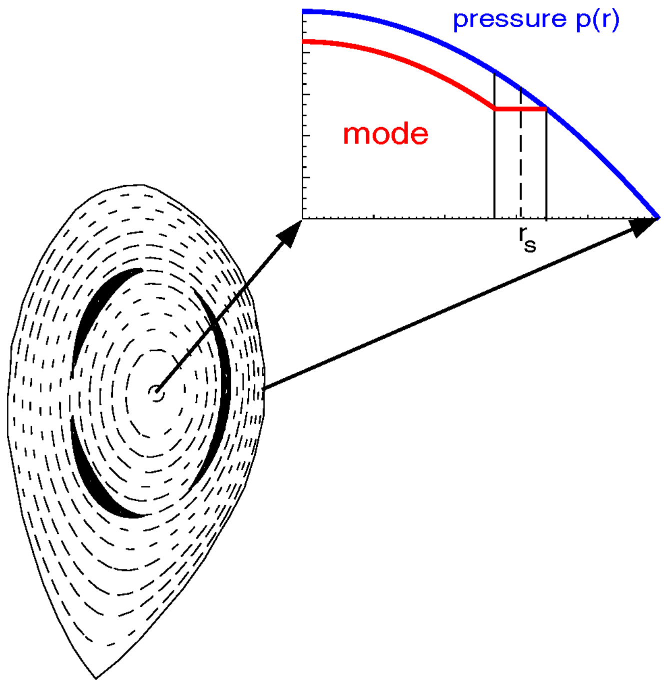
Resistive MHD Instabilities

- **Neoclassical Tearing Modes (NTMs)**
  - pressure gradient drives plasma current (self-generated Bootstrap current):

$$j_{BS} \propto \nabla p$$

  - inside islands ∇p flattened $\rightarrow$ j_{BS} vanished

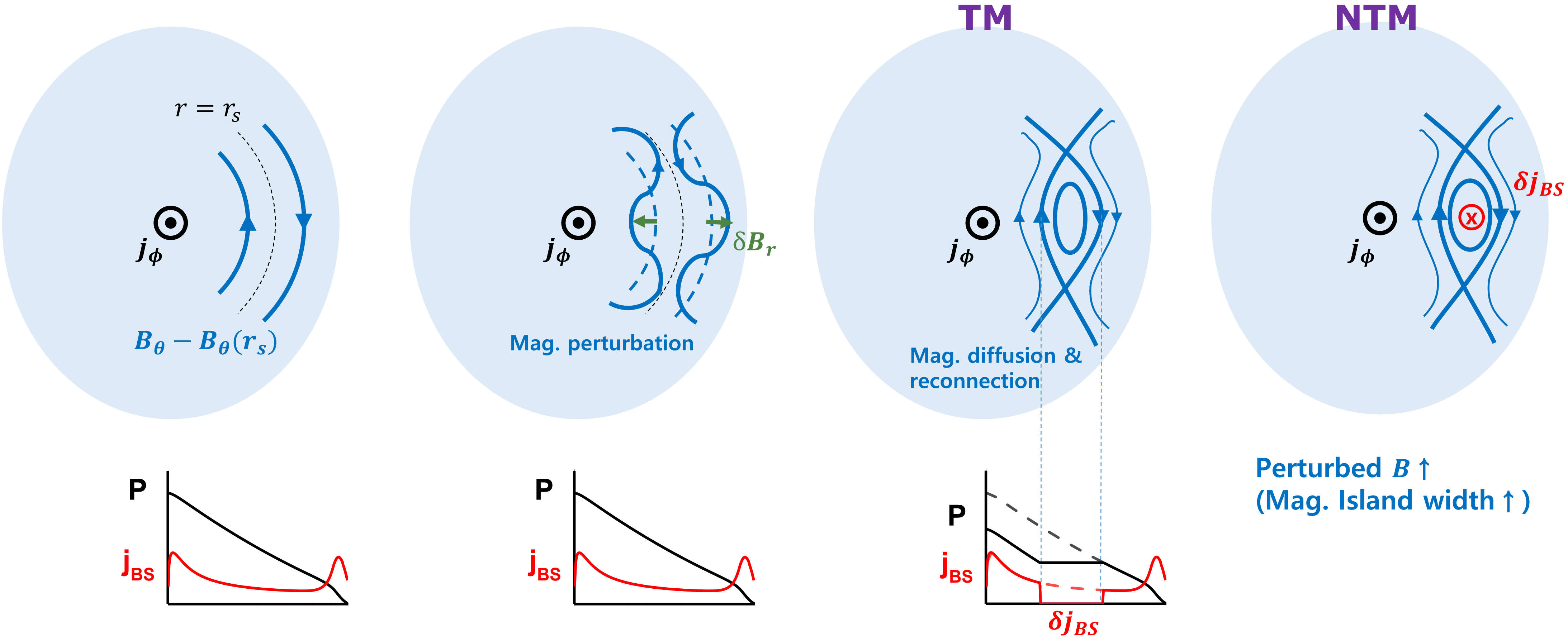




  - Loss of BS current inside magnetic islands acts as helical perturbation current driving the islands – so once seeded, island is sustained by lack of bootstrap current.

Resistive MHD Instabilities

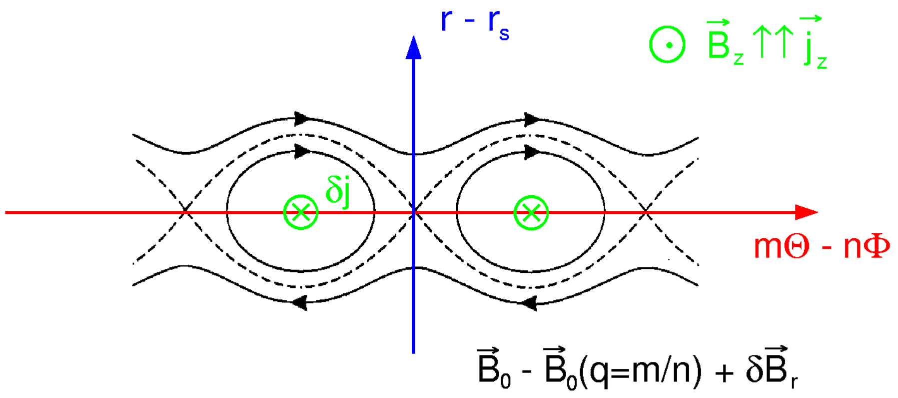
- **Neoclassical Tearing Modes (NTMs)**



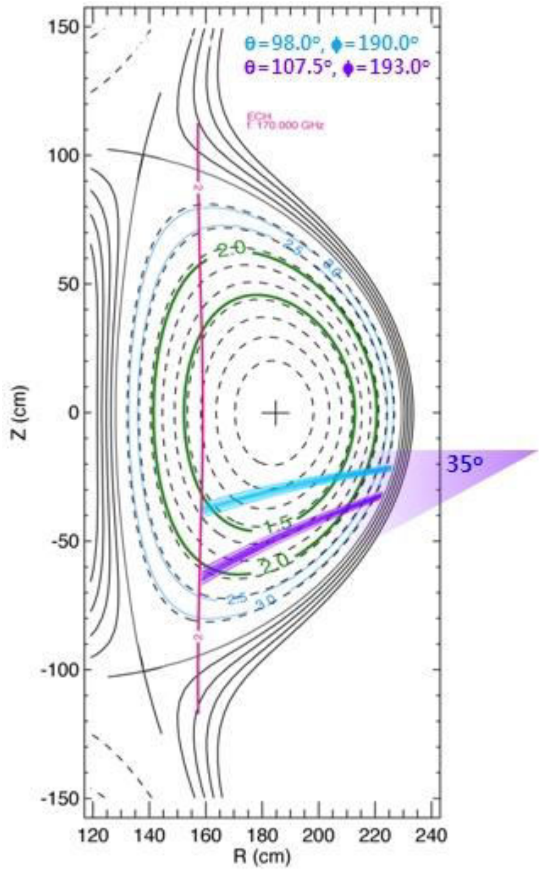
Perturbed B ↑
(Mag. Island width ↑)

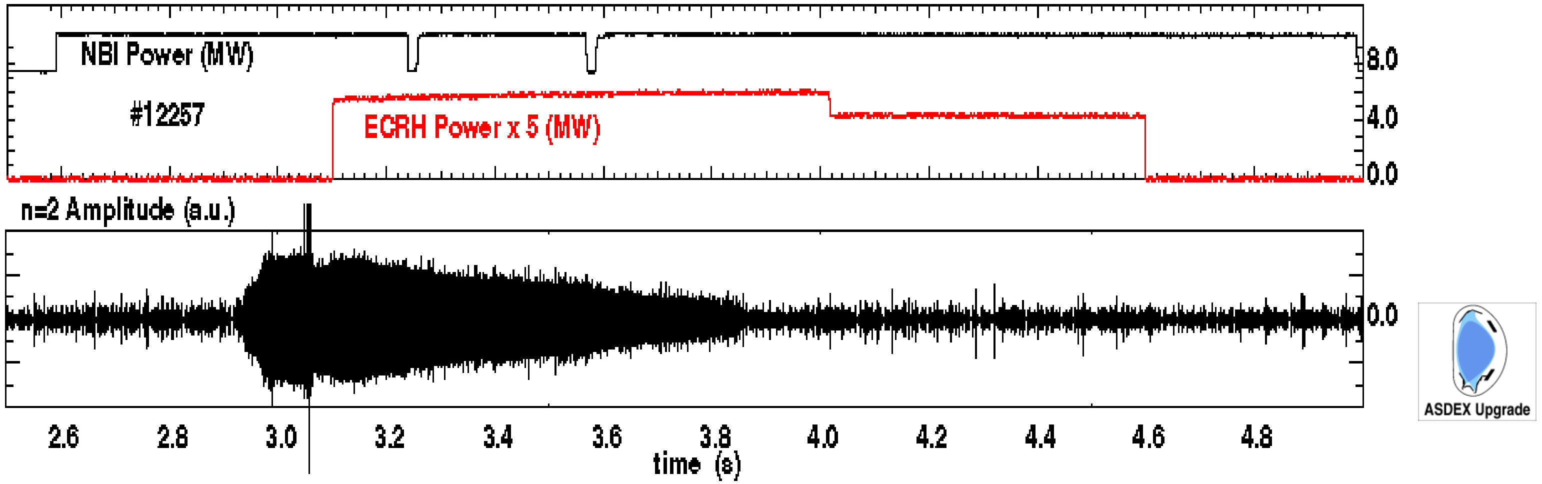
Resistive MHD Instabilities

- **Neoclassical Tearing Modes (NTMs)**



- Missing bootstrap current inside island can be replaced by localised external current drive.

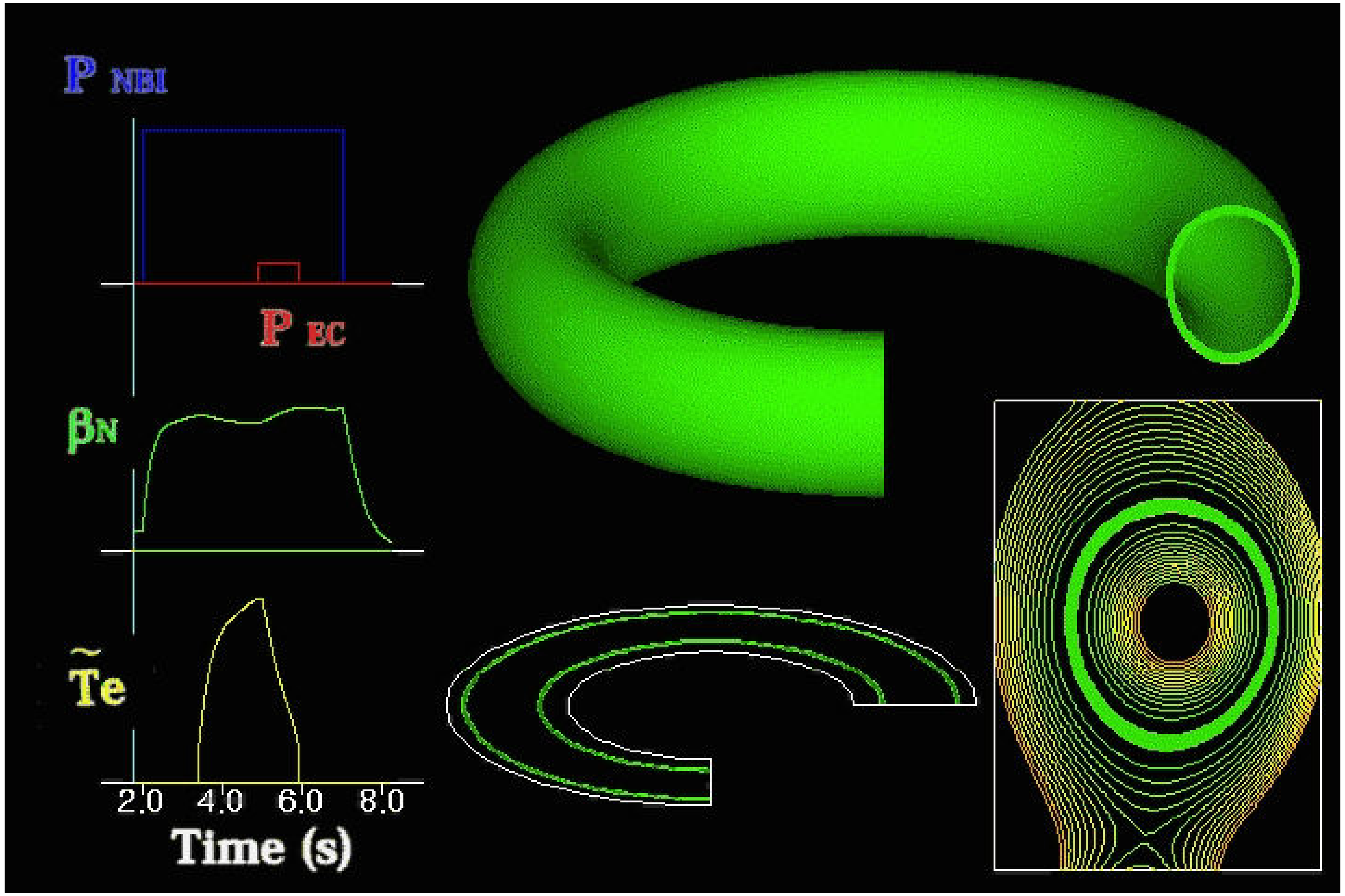




- complete stabilisation in quantitative agreement with theory.

Resistive MHD Instabilities

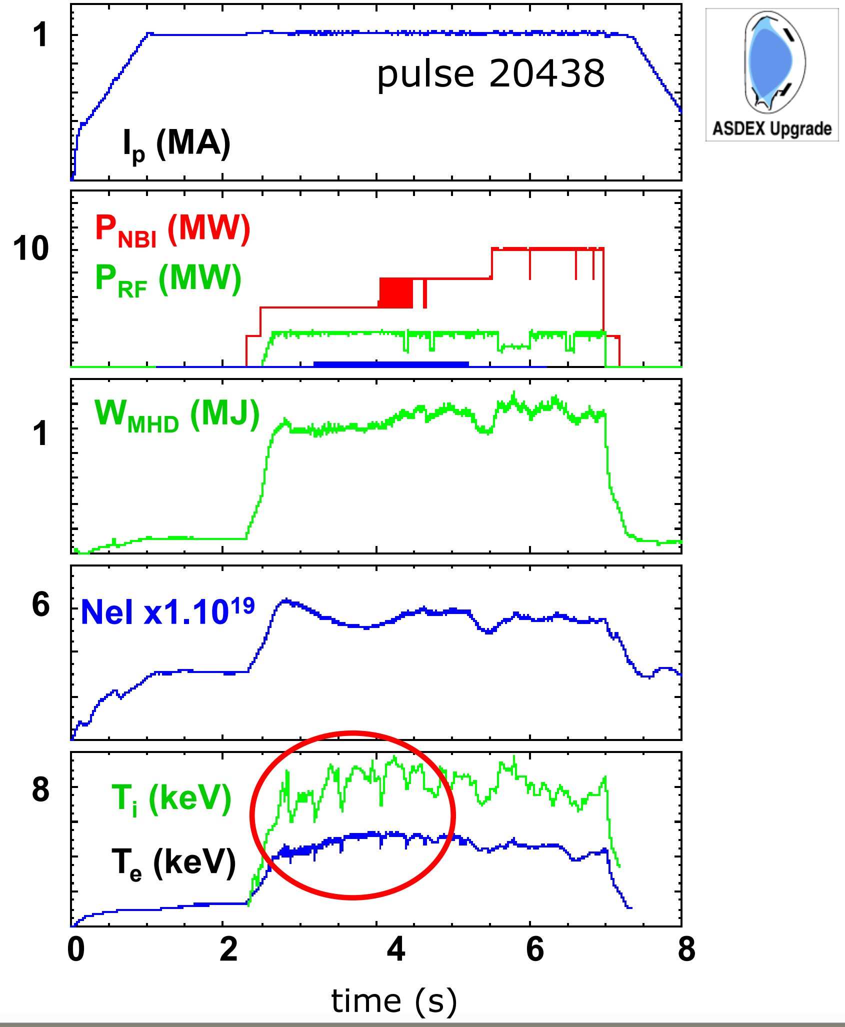
- **Neoclassical Tearing Modes (NTMs)**

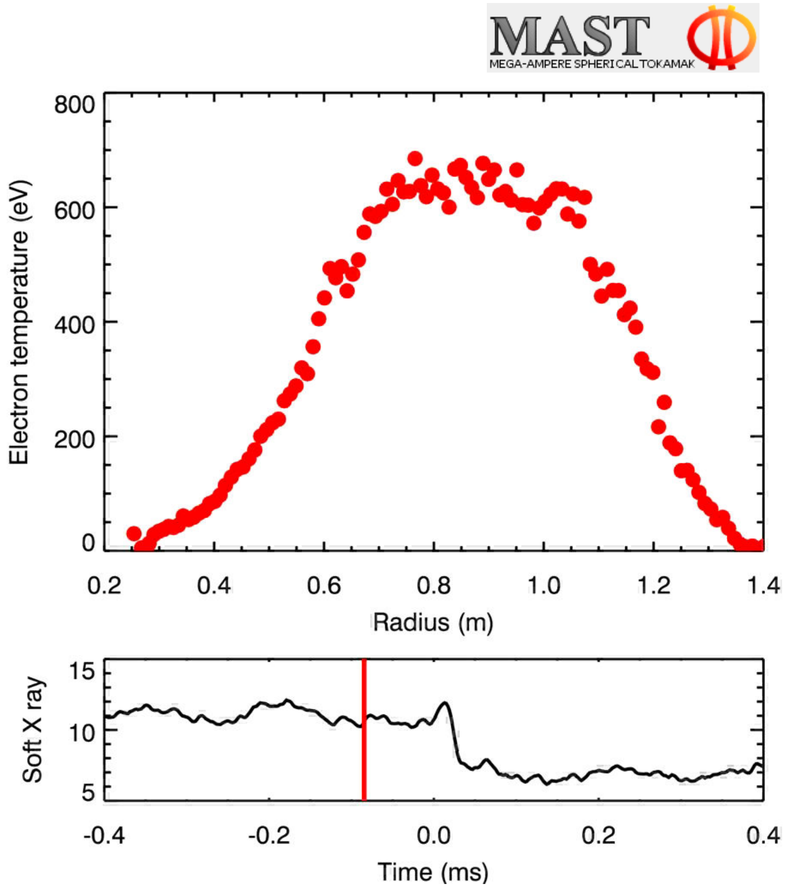


Complex non-linear instabilities in a Tokamak

Non-linear MHD Instabilities

- **Nonlinear low-*n* internal modes: Sawtooth**





I. T. Chapman et al, PRL (2010)

Non-linear MHD Instabilities

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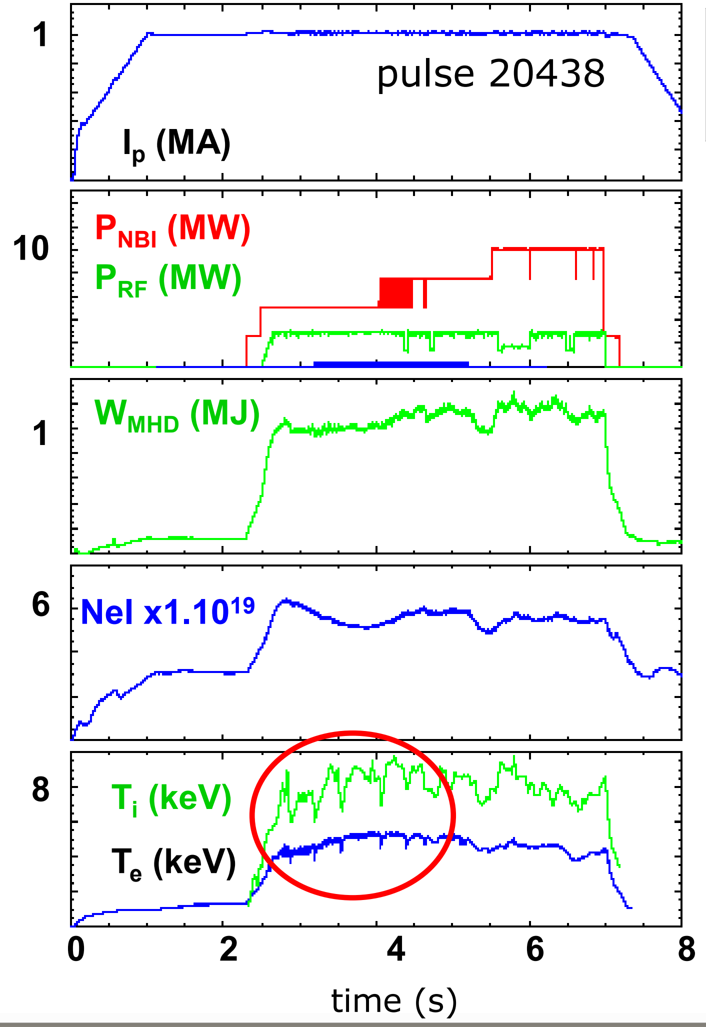

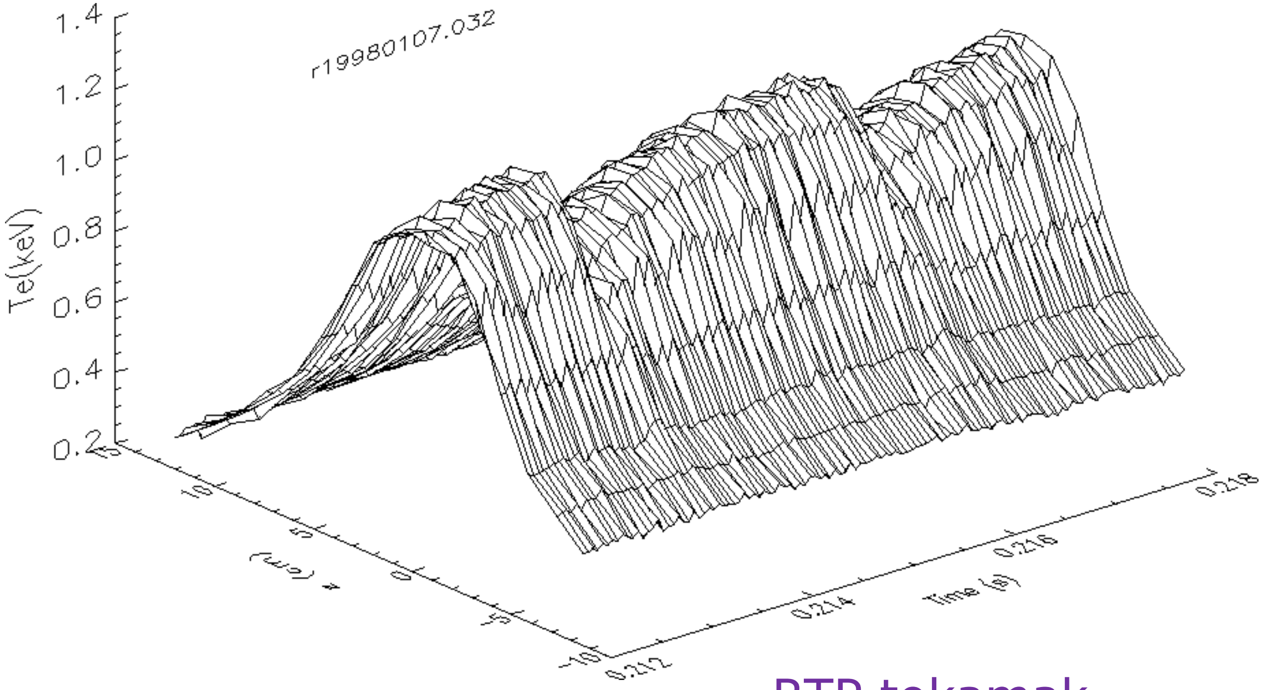

RTP tokamak

Non-linear MHD Instabilities

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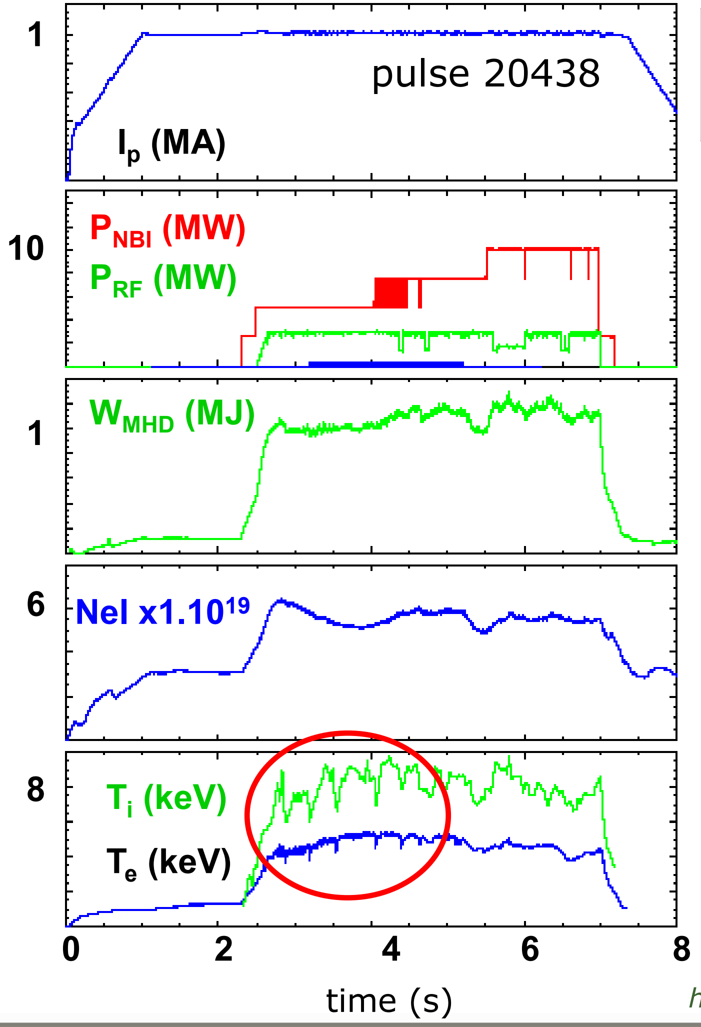
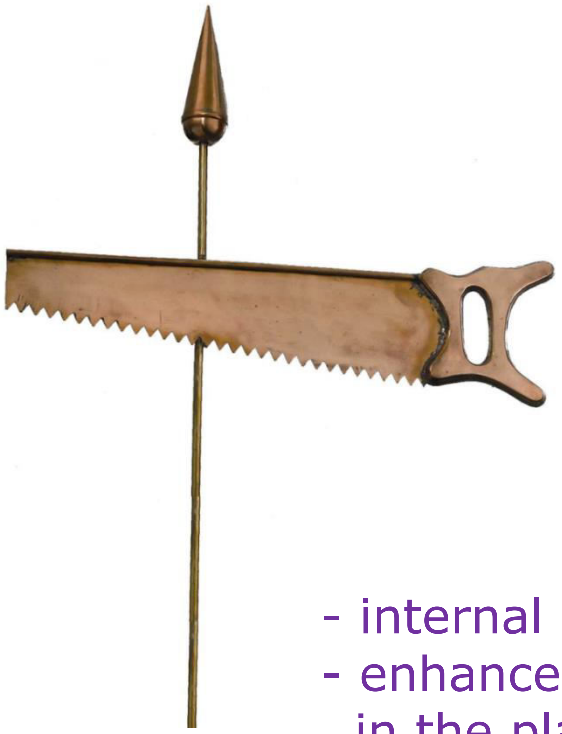


ASDEX Upgrade

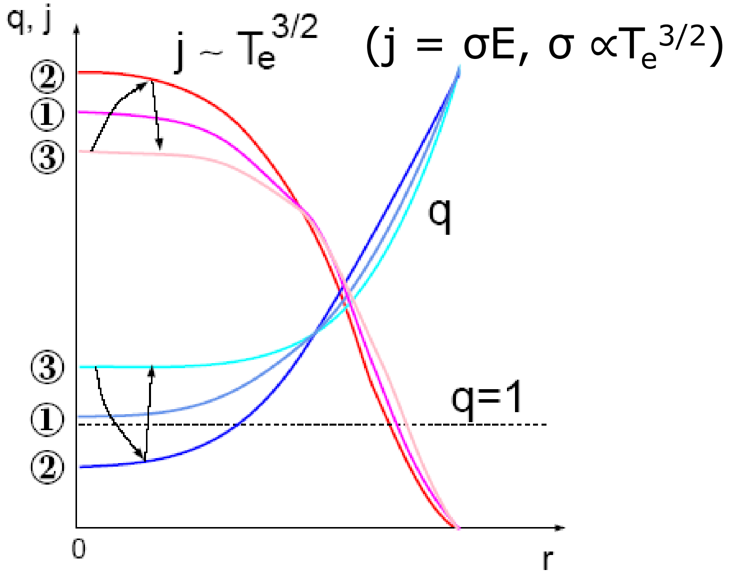


- internal (minor) disruption
- enhanced energy transport in the plasma centre

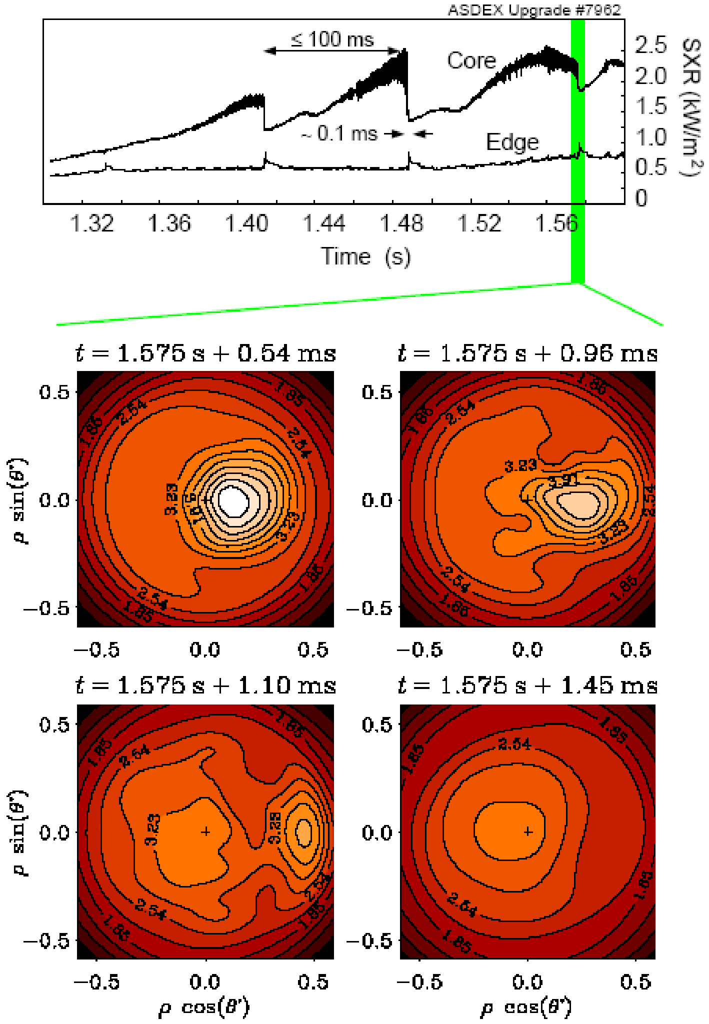
http://www.weathervanesofmaine.com/weathervanes/weathervanes-catalog/special-interest-weathervanes

Non-linear MHD Instabilities

- **Nonlinear low-*n* internal modes: Sawtooth**



1. $T(0)$ and $j(0)$ rise
2. $q(0)$ falls below 1
   → kink instability grows
3. Fast reconnection event:
   T, n flattened inside $q = 1$ surface
   $q(0)$ rises slightly above 1
   kink stable



W. Suttrop "Experimental Results from Tokamaks", IPP Summer School, IPP Garching, September (2001)

Non-linear MHD Instabilities

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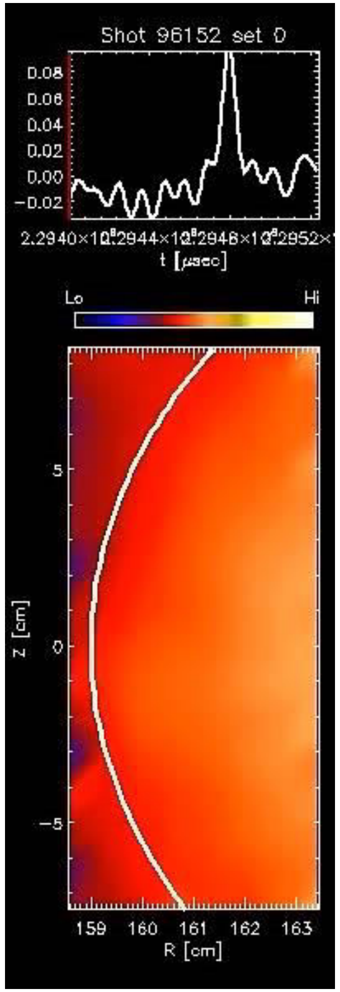

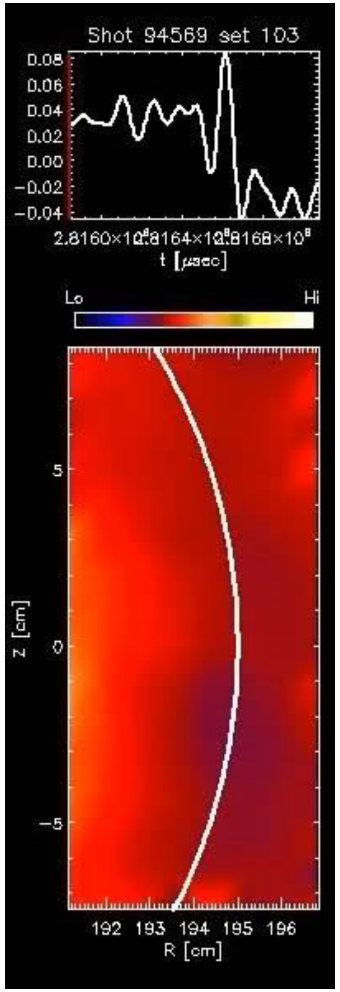

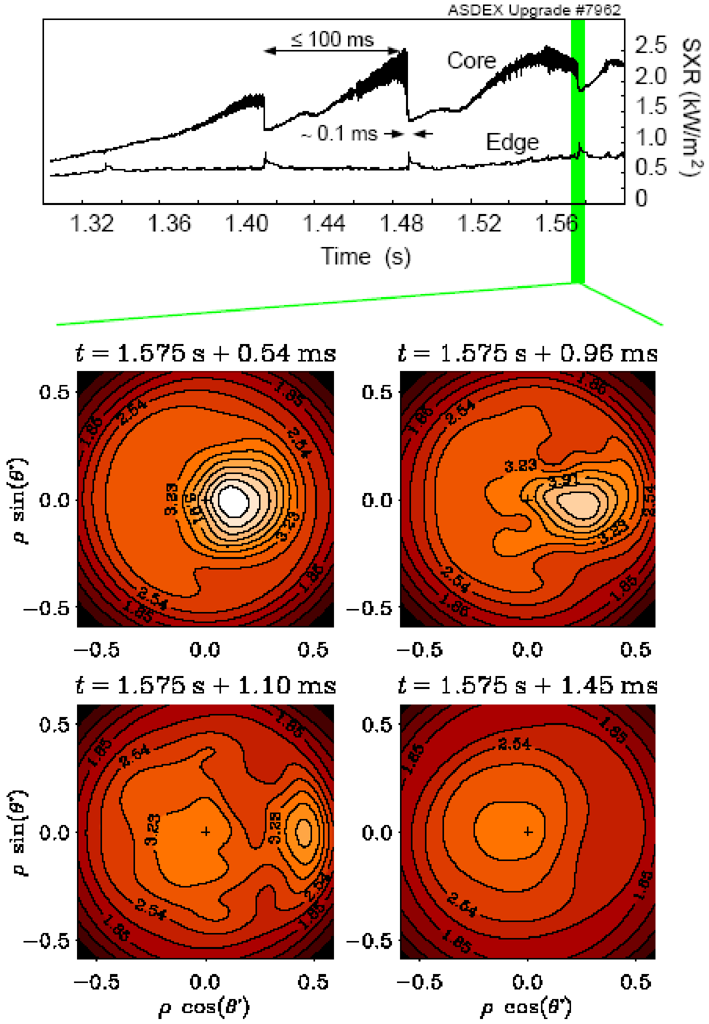

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Courtesy of H.K. Park (UNIST)

Non-linear MHD Instabilities

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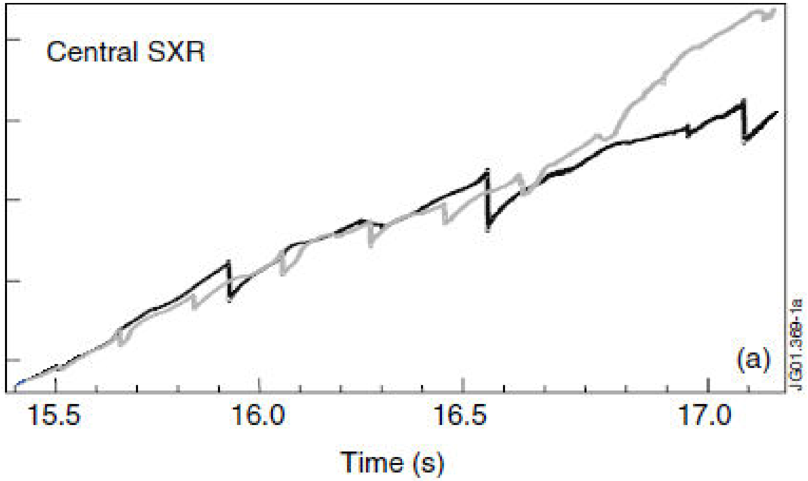
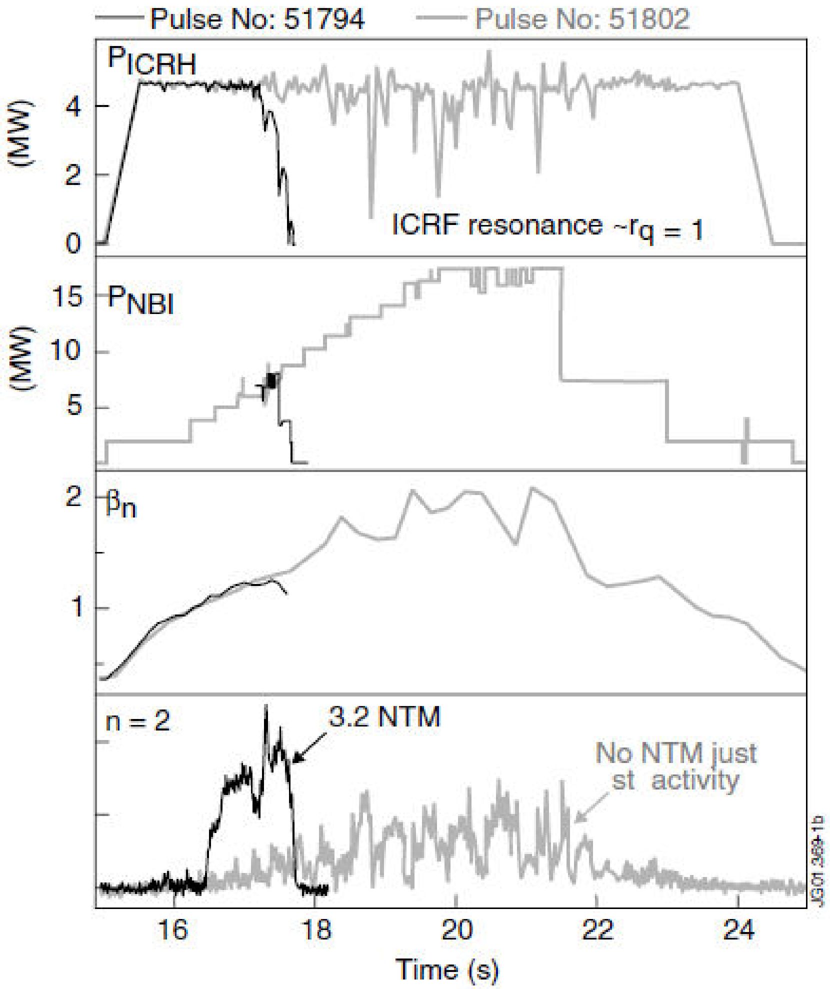
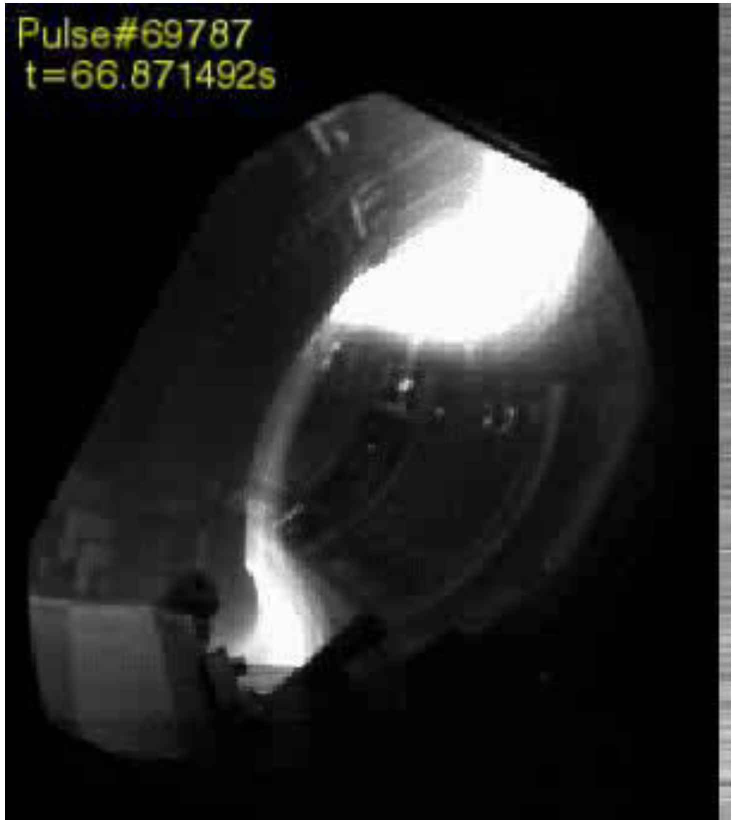




- Increased sawtooth period due to stabilisation by fast ions produced by ICRH leads to the triggering of n = 2 NTM activity which causes a termination of the discharge.

Non-linear MHD Instabilities

- **Major Disruption**

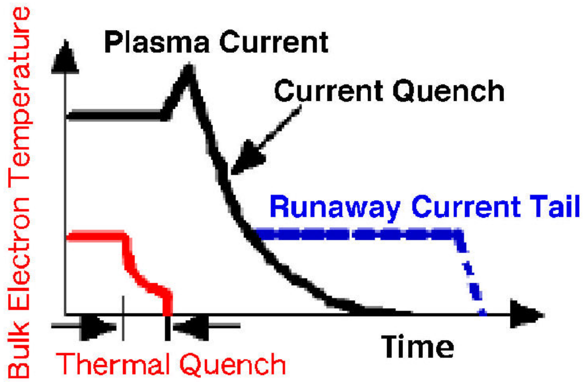


Non-linear MHD Instabilities

- **Major Disruption**

  - Disruptions are fast (~1 ms) global instabilities that my arise in magnetic confinement fusion devices that use plasma current for confinement such as tokamak.
  - Termination of confinement, uncontrolled loss of thermal and magnetic energy

    - shift of the plasma column
    - heat load damage to plasma facing components (PFCs)
    - large mechanical stresses from **J**x**B** forces during current quench
    - rapid cooling of the plasma → increase of resistivity
    - increase of loop voltage → runaway electrons (0.1-10 MeV) through avalanche amplification, resulting in a > 5 MA of relativistic electron beam
      → deep penetration of materials (~cm)



Non-linear MHD Instabilities

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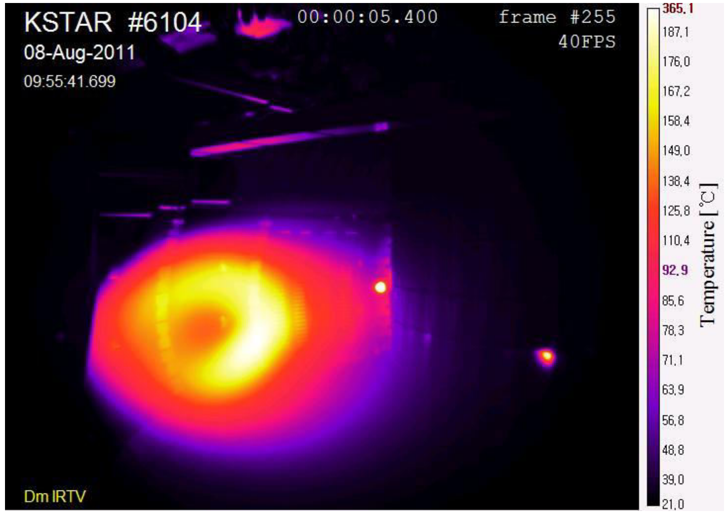


- Synchrotron radiation

IR images (left): electrons of ~ 25 - 35 MeV

Visible light images (right): electrons of > 60 MeV

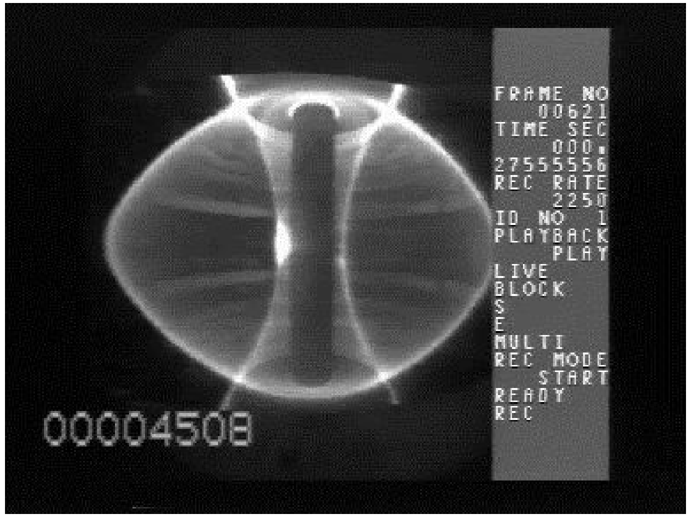
Junghee Kim et al, "Runaway electron suppression in KSTAR", KPS/DPP, Daejeon, Korea, 26 April 2013

Non-linear MHD Instabilities

- **Major Disruption**

  - Several classes of "triggering" instabilities lead to this "final" ideal instability

    - Beta / pressure limits
    - Radiative limits
    - Vertical position instability (Vertical Displacement Event (VDE))



MAST
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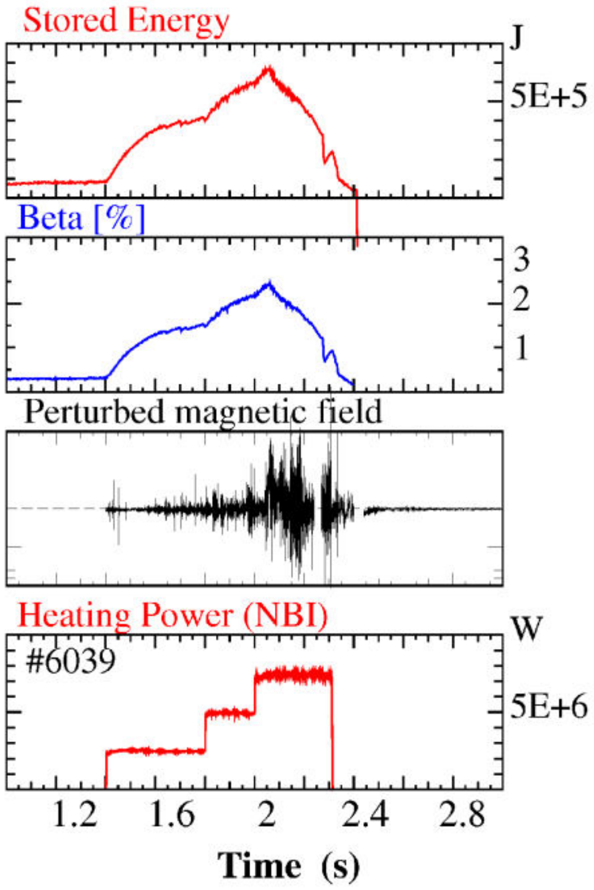

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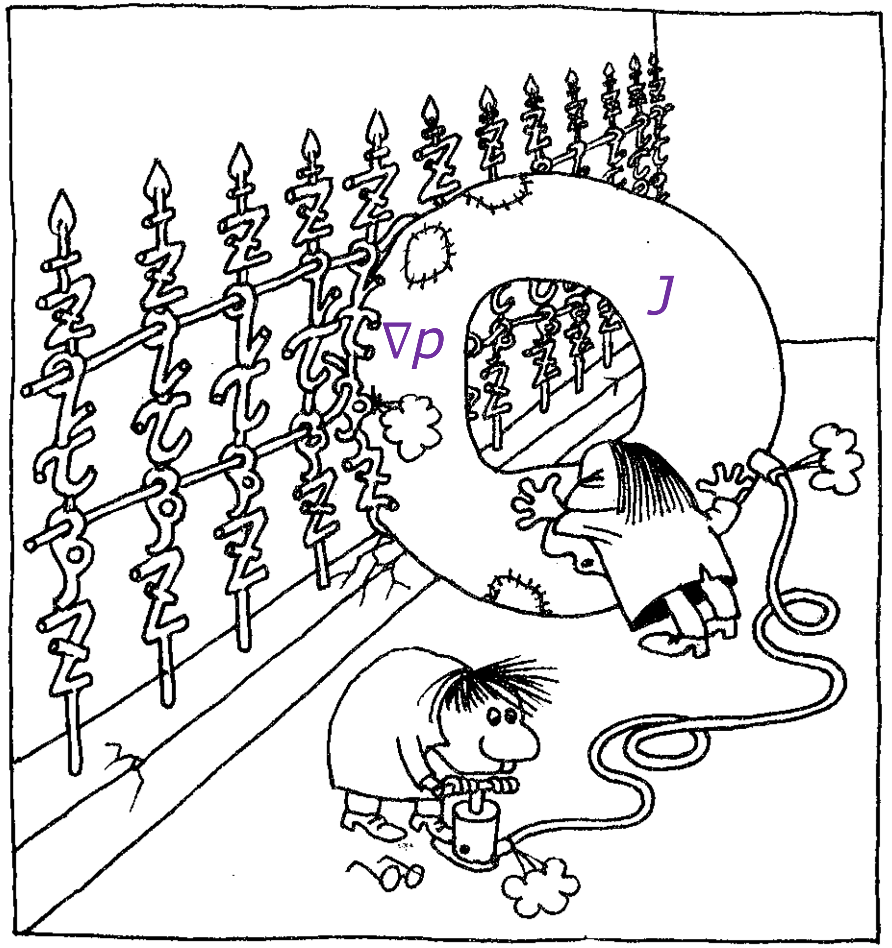
Non-linear MHD Instabilities

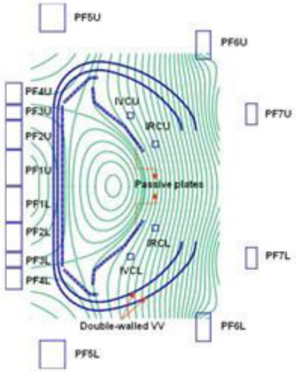
- **Disruption Mitigation**
  - Killer pellet injection: fast conversion of thermal energy to the radiation energy
  - MGI (Massive Gas Injection): H, He, Ne, Ar, Kr, Xe, etc.
  - RMP (Resonant Magnetic Perturbation) to reduce runaway electrons

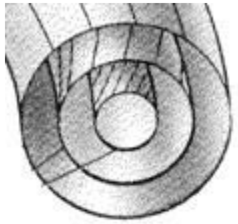
Non-mitigated VDE

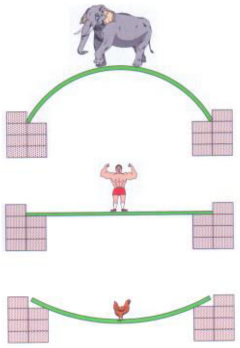
Neon gas jet injection triggered by control system

Tokamak Instabilities and Their Control

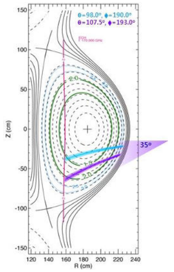


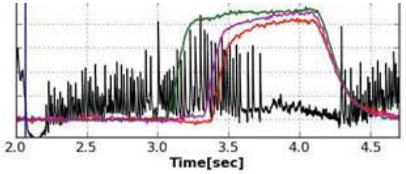






- conducting wall
- magnetic shear
- minimum-**B** configuration
- profile optimisation
- dynamic stabilisation
  by feedback control
- …





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