Advances in Understanding of Magneto-hydrodynamic Stability of Fusion Reactor Plasmas

E. Fredrickson
M. G. Bell, S. Bernabei, R. V. Budny, Z. Chang, D. Darrow, K. Hill,
F. Levinton, J. Manickam, E. Mazzucato, K. McGuire, R. Nazikian,
M. Okabayashi, W. Park, E. Synakowski, S. Zweben & the TFTR Group

Presented at

The APS Centenial Meeting,
Atlanta, Georgia, March 22, 1999

Diagnostic Capabilities on TFTR

Excellent equilibrium diagnostics:

Electron temperature and density profiles at high time resolution,
ion temperature, current density profiles, etc,
necessary for equilibrium reconstruction, input to MHD modeling codes.

Excellent MHD diagnostic set:

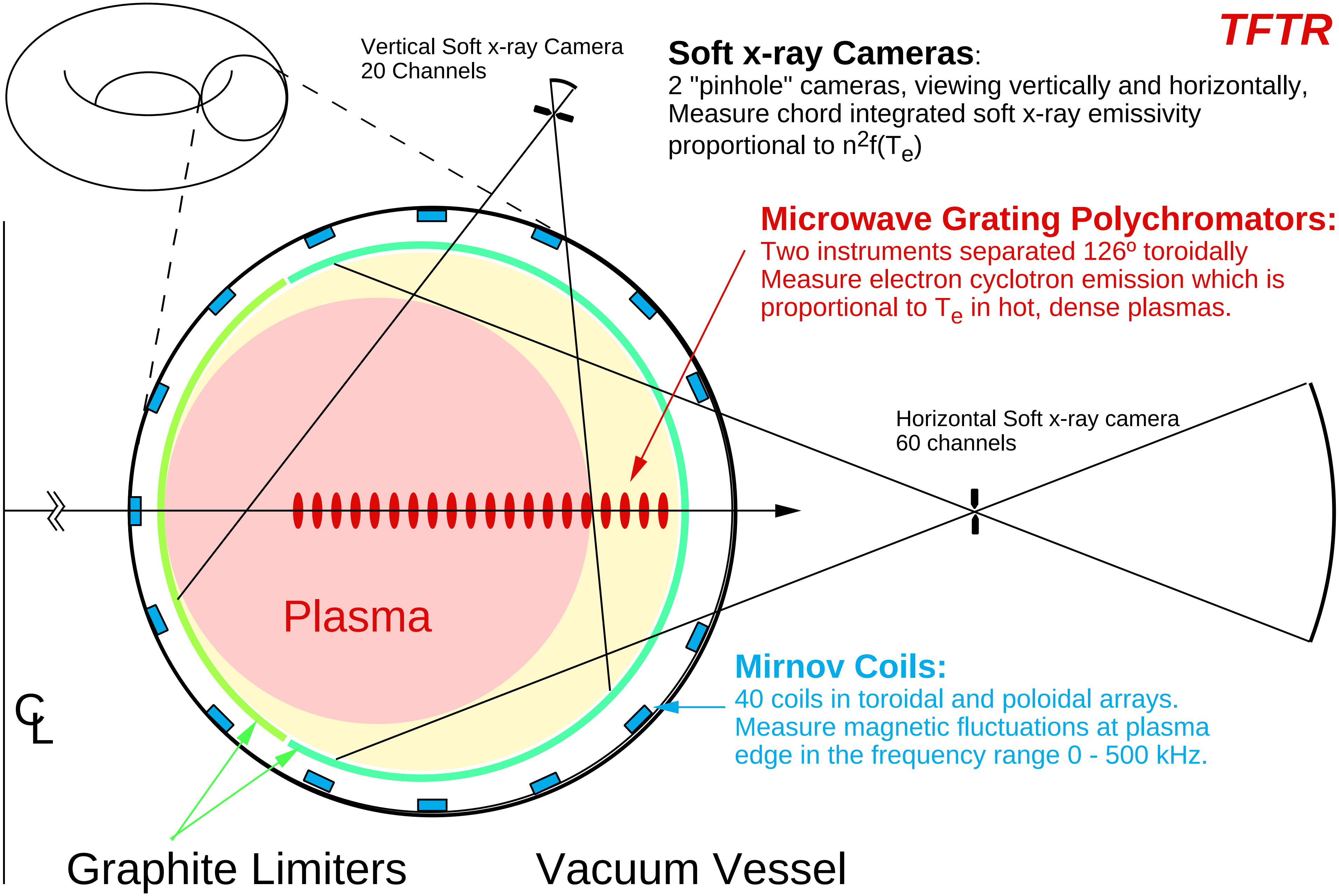
Mirnov Coil Array for poloidal and toroidal mode structure
[Fredrickson, et al., Rev. Sci. Instrum. 57 p2084 (1986)].

Soft x-ray pinhole cameras for measurements of internal MHD structure
[K. Hill, et al., Rev. Sci. Instrum. **56** p830 (1985), L. Johnson, et al., Rev. Sci. Instrum. **57** p2133 (1986)].

Grating Polychromators for measurements of internal MHD structure
[A. Cavallo, et al., Rev. Sci. Instrum. 59 p889 (1988)]

Diagnostics for the study of MHD on TFTR

TFTR



Soft x-ray Cameras:
2 "pinhole" cameras, viewing vertically and horizontally,
Measure chord integrated soft x-ray emissivity
proportional to $n^2 f(T_e)$

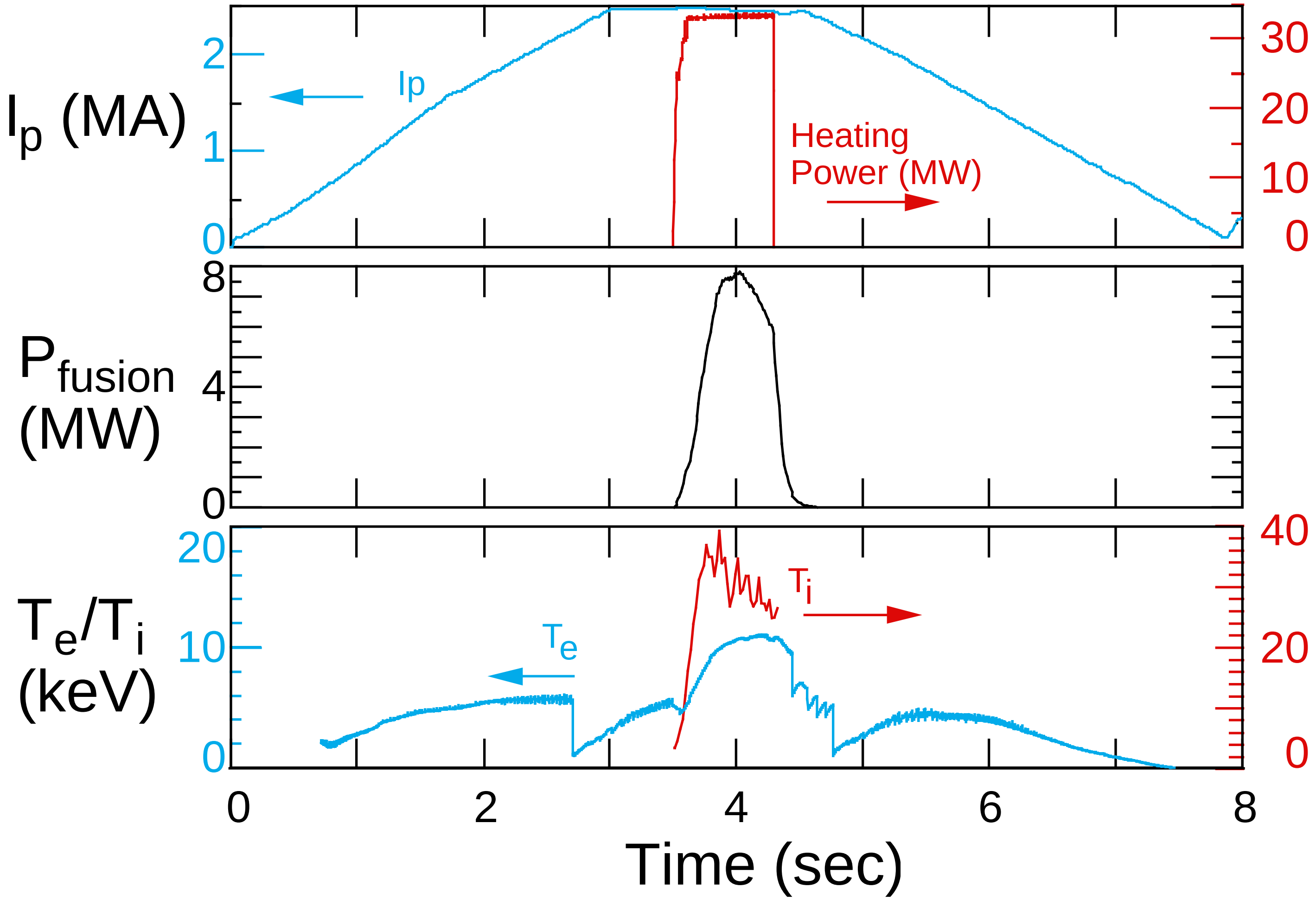
Microwave Grating Polychromators:
Two instruments separated 126º toroidally
Measure electron cyclotron emission which is
proportional to T_e in hot, dense plasmas.

Mirnov Coils:
40 coils in toroidal and poloidal arrays.
Measure magnetic fluctuations at plasma
edge in the frequency range 0 - 500 kHz.

Evolution of a Typical Plasma Shot

TFTR

- Plasma shots are taken about every 15 minutes.
- Principle time of interest is during heating phase.



- Current ramp rates constrained by stabilty to current profile driven tearing modes.
- This was a plasma made using a mixture of Deuterium and Tritium; TFTR was only one of two tokamaks in the world capable of operation with Tritium.
- Sawteeth are visible before and after beam heating phase.
- In this shot, MHD during the heating phase are n=1 "fishbone-like" modes.

- Lithium Pellets Injected at 2.7, 4.7 sec to condition graphite limiters.

Sources of Free Energy to Drive MHD

Plasma Current Profile
  - Kink Modes
  - Tearing Modes
  - Sawteeth

Pressure Profile
  - Kink modes
  - Ballooning Modes

“Non-thermal” Ion Populations
  - Alfvénic Instabilities
  - Fast Ion Modes (Energetic Particle Modes)
  - “Fishbones”
  - Kinetic Ballooning Modes

Sawteeth:
Driven by pressure, current profile.

A resistive instability requiring change in Magnetic topology.

Precursor characteristics consistent with Kadomtsev’s model

Current profile measurements show no indication of reconnection [F. Levinton, et al., Phys. Fluids B **5**, 2554 (1993)].

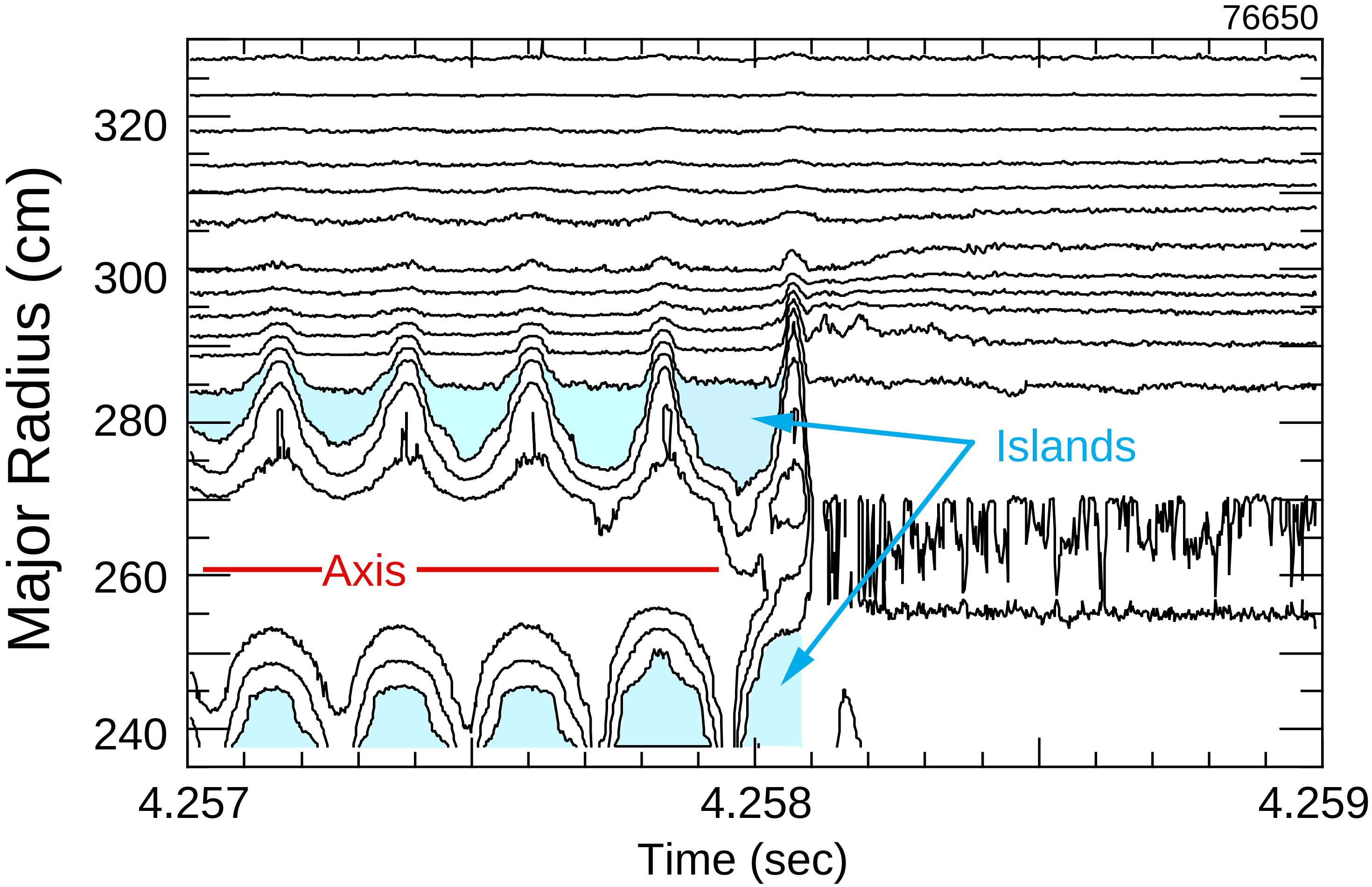
Soft x-ray tomography and ECE image reconstructions indicate growing m=1, n=1 magnetic island, much as predicted by Kadomtsev [Y. Nagayama, et al., Phys. Plasmas **3**, 1647 (1996)].

Many models for “partial reconnection” now exist - none are completely satisfactory.

Finite pressure modifies the (1/1) tearing mode, causing a bulge beyond q=1 radius

TFTR

- Island growth in this case is initially slow.



- This data and soft x-ray data can be used to reconstruct 2-D images of the island evolution.

Tearing Modes:

Classically driven by free energy in magnetic configuration

Located at rational surfaces, where helical field lines close on themselves.

Seldom seen on TFTR [H. P. Furth, P. H. Rutherford, H. Selberg, Phys. Fluids **16**, 1054 (1972).

Neo-classical tearing modes destabilized by pressure driven currents

First seen in 1985 on TFTR, observed to cause serious confinement degradation [McGuire, et al., Kyoto IAEA Vol. **I,** p421 (1986), E. Fredrickson, et al., Rev. Sci. Instrum., 59 1797 (1988), Z. Chang, et al., Nucl. Fus. **34**, p1309 (1994).

Positively identified as neo-classical [Z. Chang, et al., PRL **74**, p4663 (1995)].

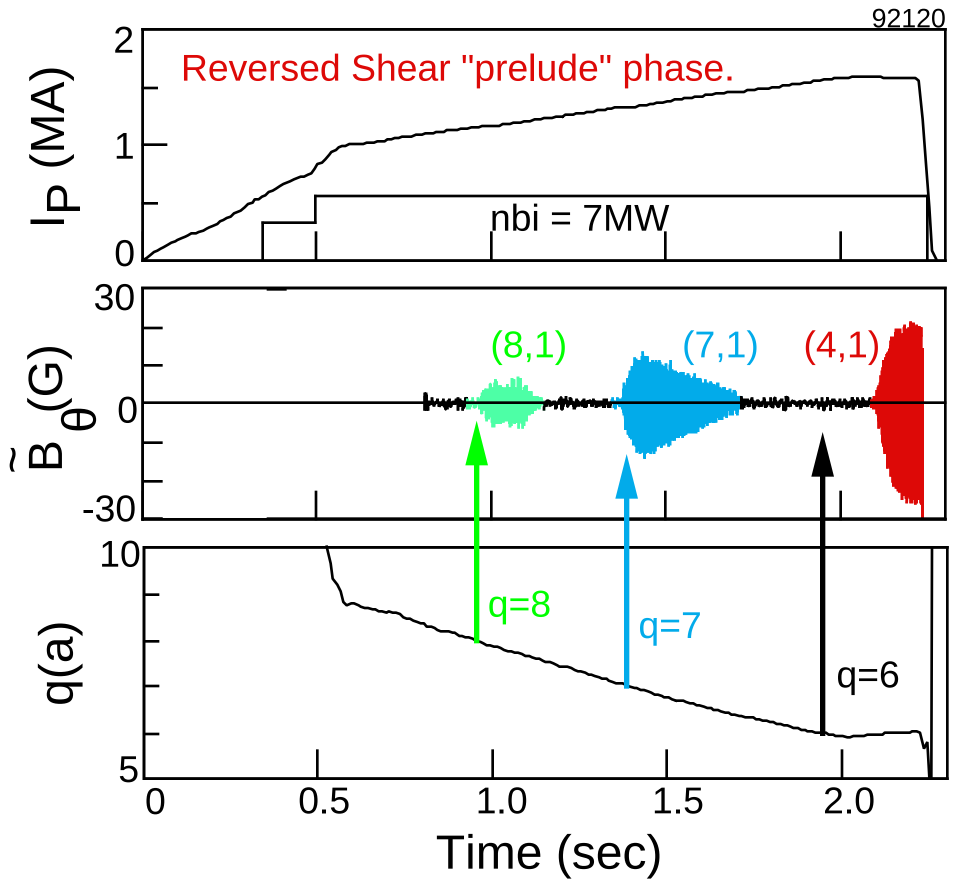
Threshold physics, scaling still not understood.

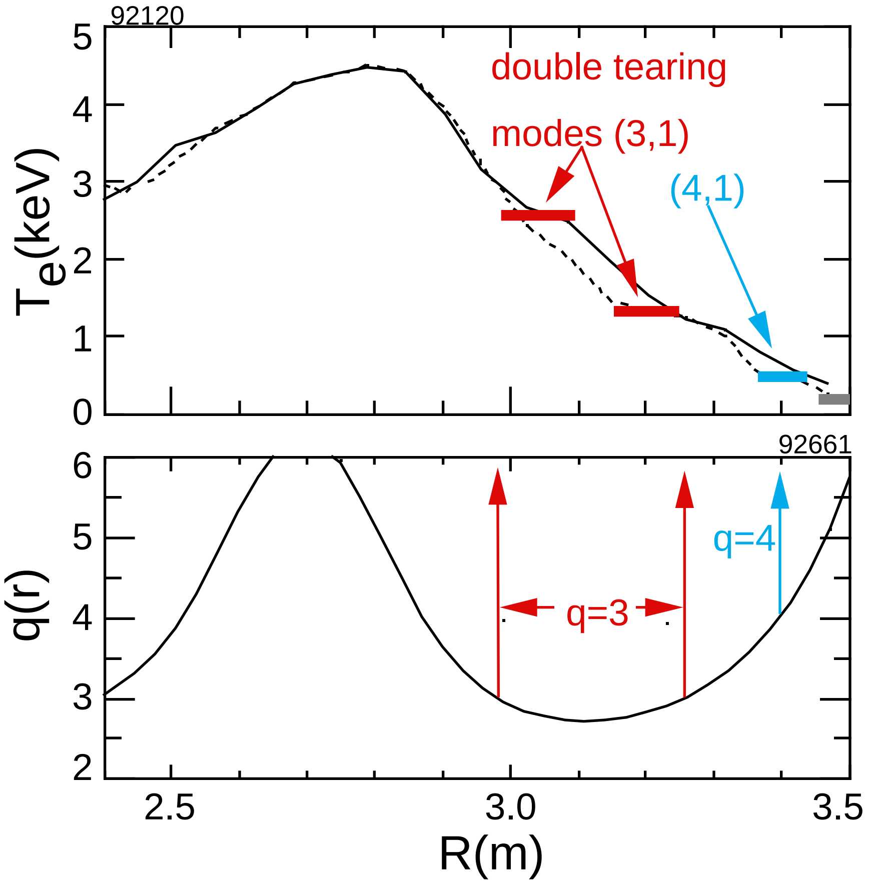
Predictions for reactors not reliable

Active feedback control is a possible solution.

In the presence of two rational surfaces, two tearing modes can exist

TFTR





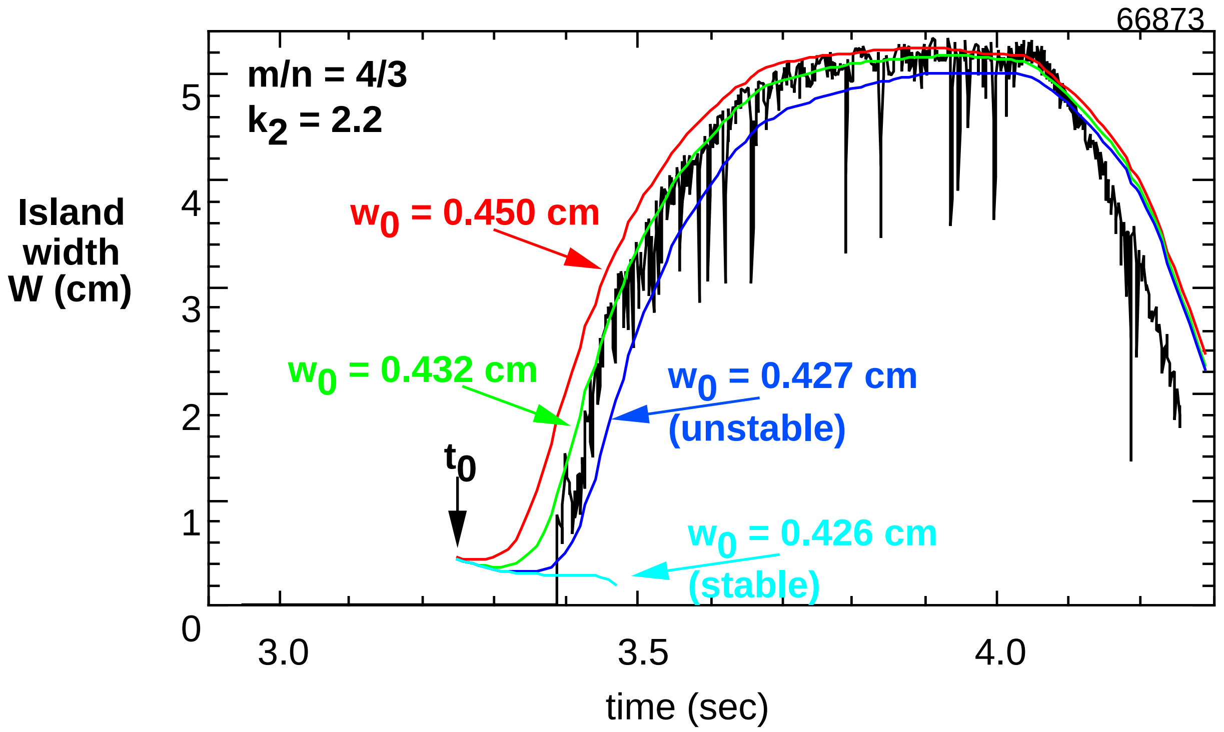
- The double tearing mode is more unstable than a single mode; it also couples to higher m's and can lead to disruptions.

"Neo-classical" Tearing Modes

TFTR

- Even with current profiles stable to tearing modes, currents driven by pressure gradients in the helical, toroidal geometry of tokamaks can make modes non-linearly unstable.
- Mode evolution is qualitatively predicted by the equation:

$$\frac{dw}{dt} = 1.22\frac{\eta_{nc}}{\mu_0}\left(\Delta' + k_2\Delta_b\frac{w}{w^2 + w_d^2}\right)$$



W. X. Qu and J. D. Callen, Univ. of Wisconsin Report No. UWPR-85-5 (1985)

Z. Chang, et al PRL **74** 4663 (1995)

Z. Chang, et al, NF **34** 1309 (1994)

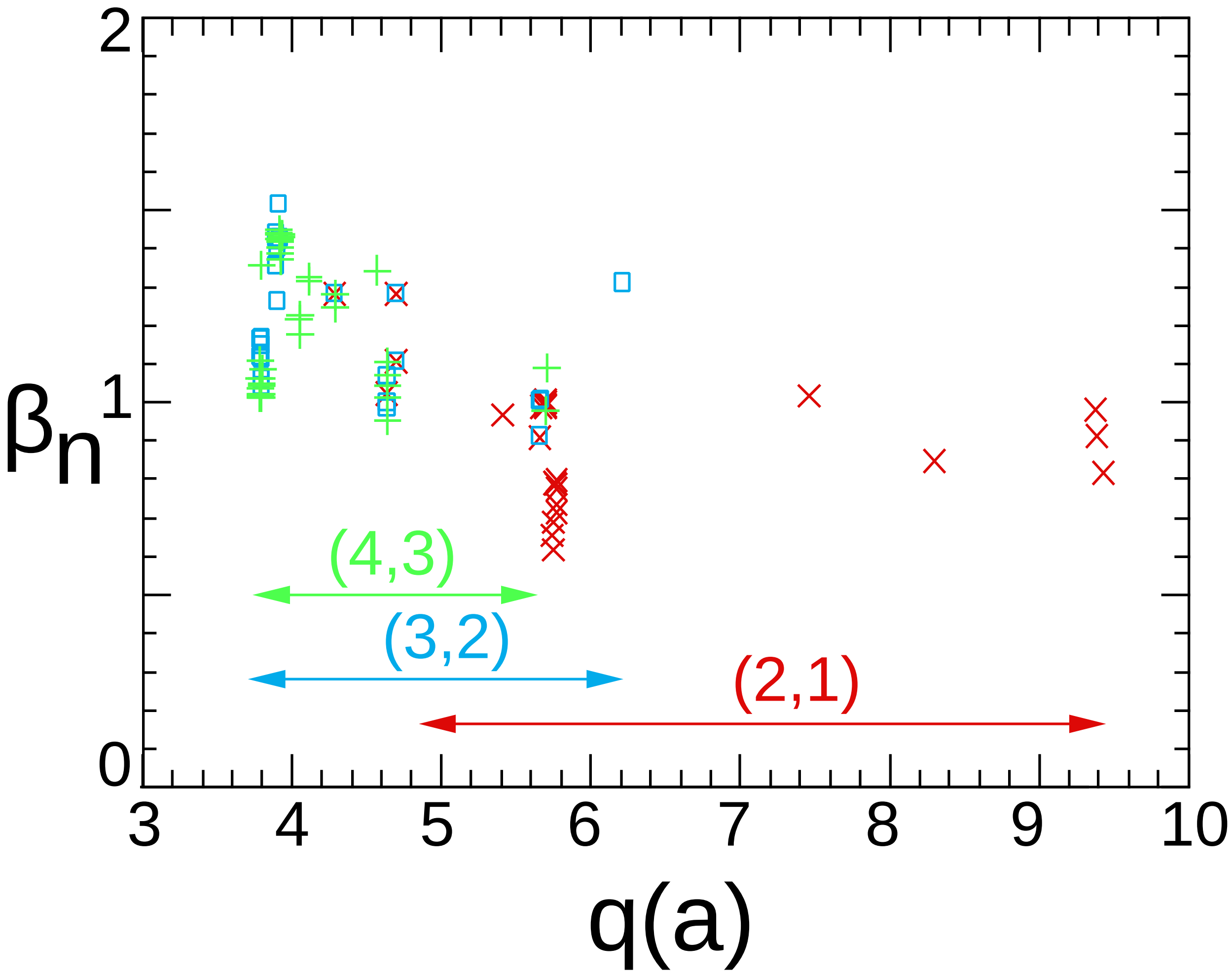
N. N. Gorelenkov, et al, Phys. Plasmas **3** 3379 (1996)

Z. Chang, et al, Phys. Plasmas **5** 1076 (1998)

Neoclassical tearing modes have less impact at higher plasma current

TFTR

- The mode structure tends to be higher n, m at lower q(a).



The higher n modes have less impact on confinement - they are smaller islands closer to the core.

Disruptions:
A *potential* problem for Fusion Reactors

Disruption Effects:

Mechanical Stress

High Transient Heat Loads - melting, ablation, thermal stress

Damage from energetic (MeV) electrons.

Disruption Causes:

Human error

Hardware/software faults/”things falling in”

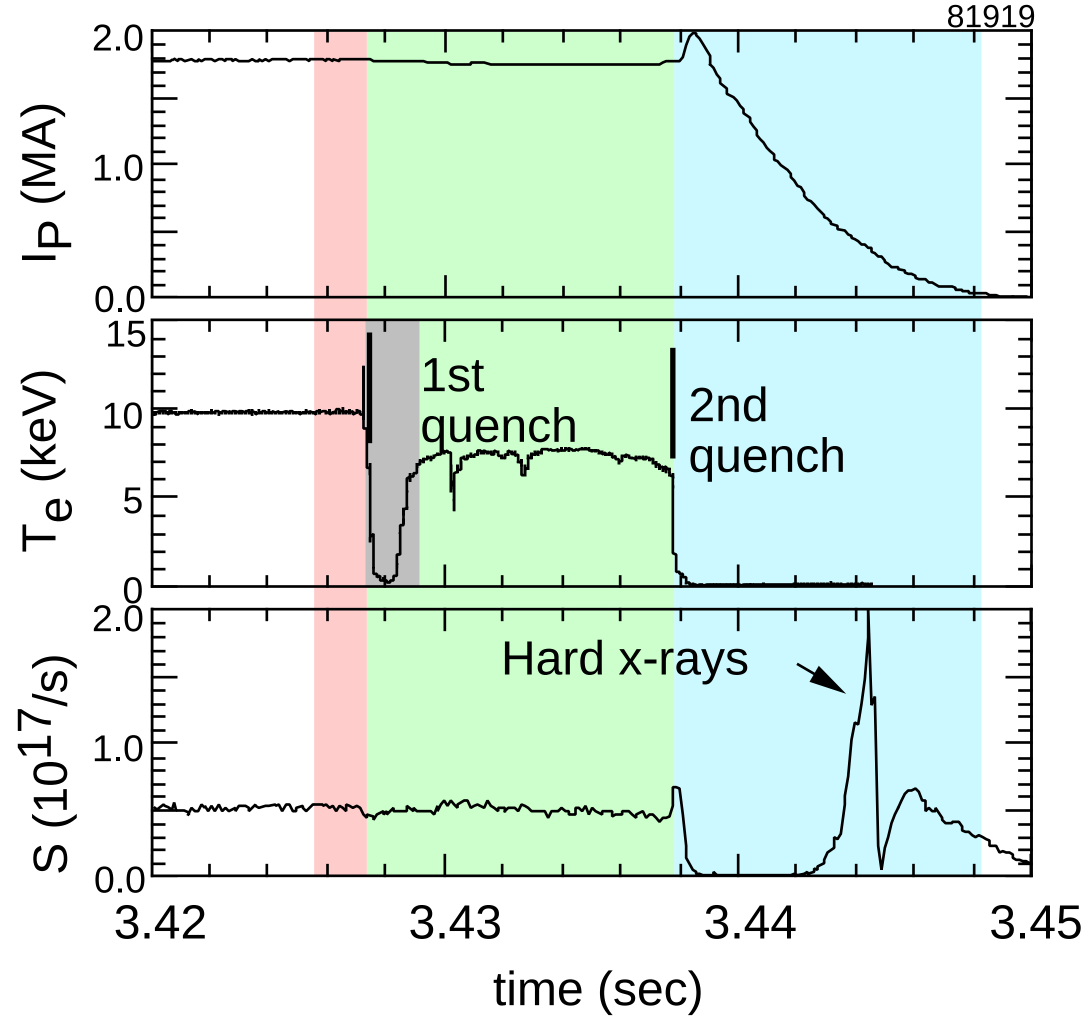
Unpredicted plasma response (transition to improved confinement)

Disruption Frequency

The disruption frequency was < 1% during high performance operation of TFTR.

β-limit Disruptions have 3 phases

TFTR



Precursor growth phase:

Pressure driven modes grow exponentially.

Ends in partial thermal quench, triggering impurity influx, more MHD activity.

Thermal collapse phase.

Impurities, radiation, MHD cause thermal collapse.

Ends in (1,1) driven flux reconnection

Current quench phase:

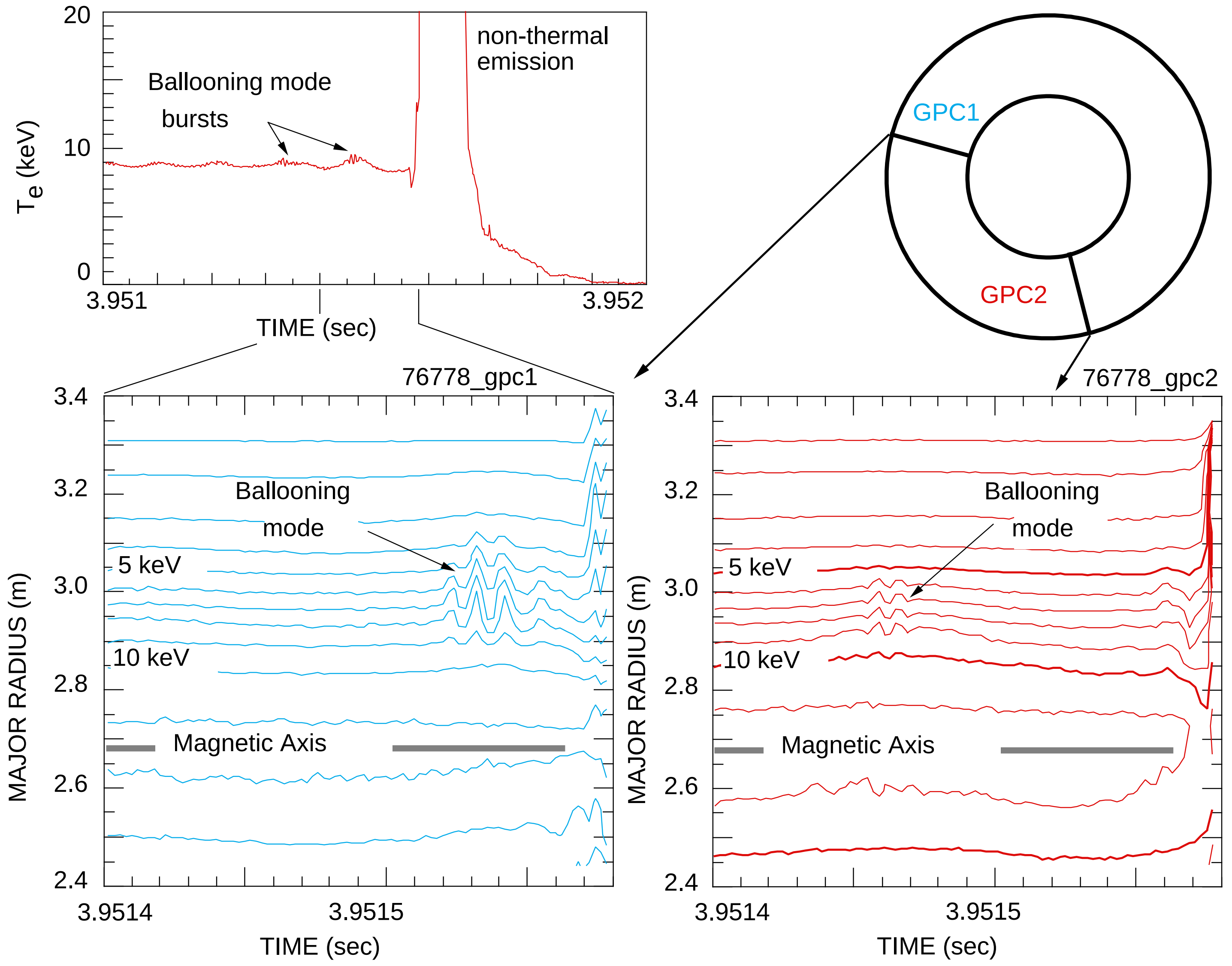
If resistivity is too high, runaway electrons are generated.

- Density or Radiation limit disruptions skip phase I.

E. Fredrickson, et al., Phys. Plasmas **4**, 1589 (1997)
S. Mirnov, I. Semenov, et al., Phys. Plasmas **5**, 3950 (1998).

High β disruptions are triggered by an n=1 kink coupled with toroidally localized ballooning modes.

TFTR

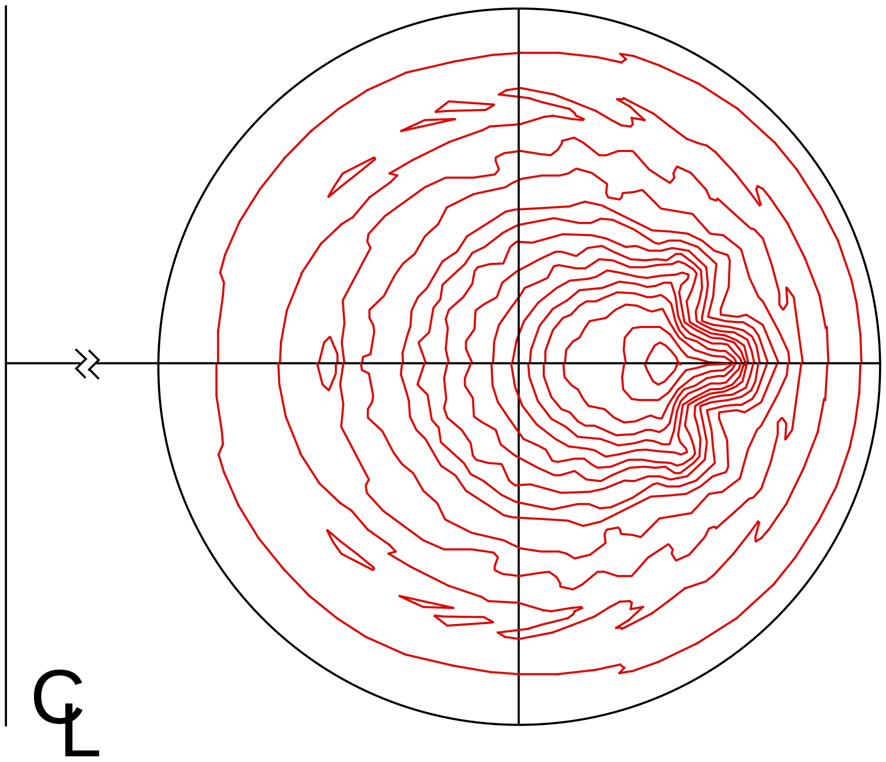


E. Fredrickson, et al., Phys. Fluids **3**, 2620 (1996) and W. Park, et al., Phys. Rev. Lett. **75**, 1763 (1995).

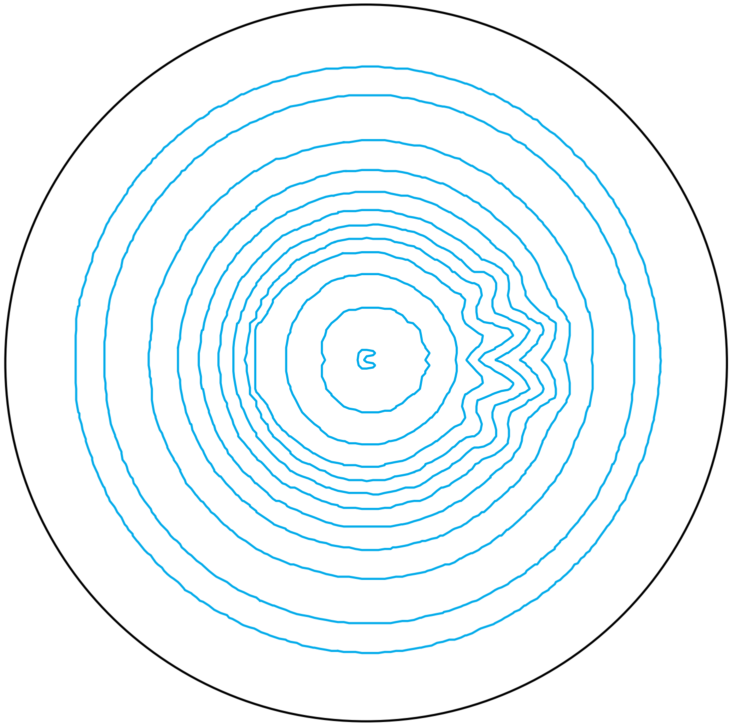
Simulations with MH3D by W. Park have predicted a coupling between global MHD and Ballooning modes.

TFTR

MH3D Simulation



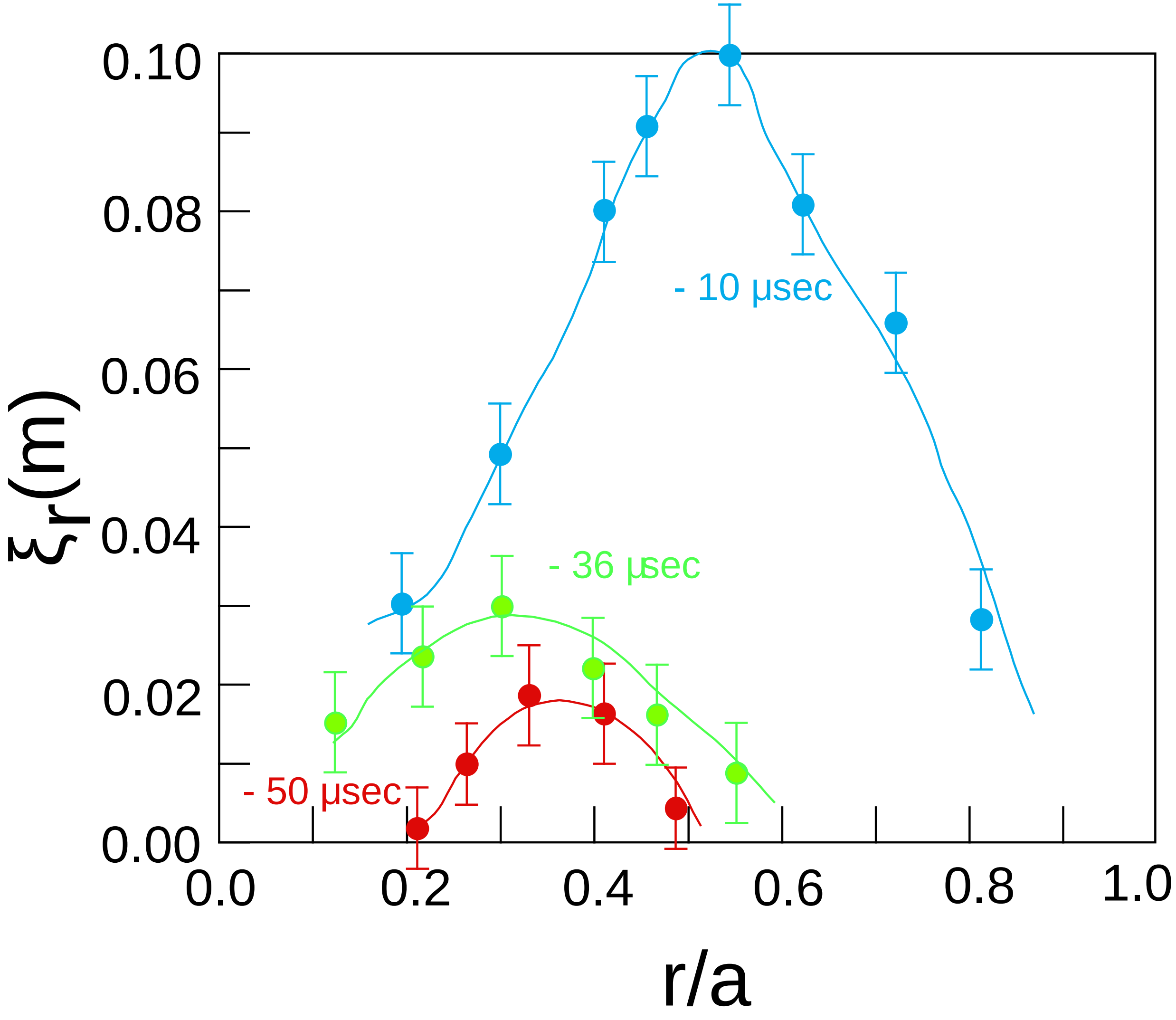
TFTR Reconstructed Data



W. Park, E. D. Fredrickson, A. Janos, J. Manickam, and W. M .Tang, Phys Rev. Lett. **75** 1763 (1995).
E. D. Fredrickson, K. M. McGuire, Z. Chang, et al., Phys. Plasmas **3** 2620 (1996).

As predicted in Park's simulations, the ballooning modes move outward as they grow.

TFTR



The ballooning modes are toroidally localized by the symmetry-breaking global mode.

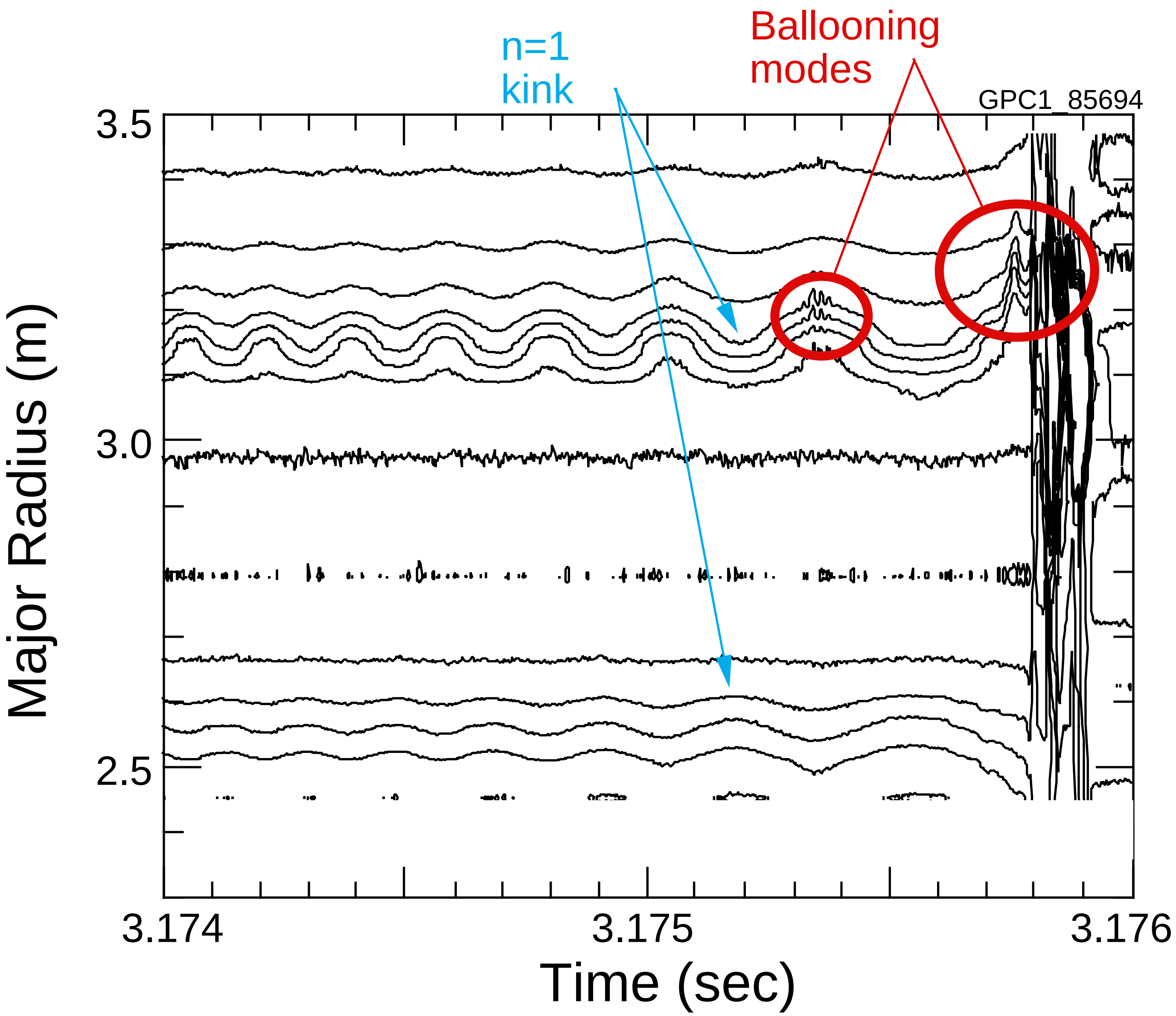
The strong gradients from the modes probably drive local reconnection of the magnetic field lines.

This reconnection allows a "weak" thermal quench, of order 10 - 30% of the stored energy.

- The ballooning mode growth rate is of order 20 μsec.

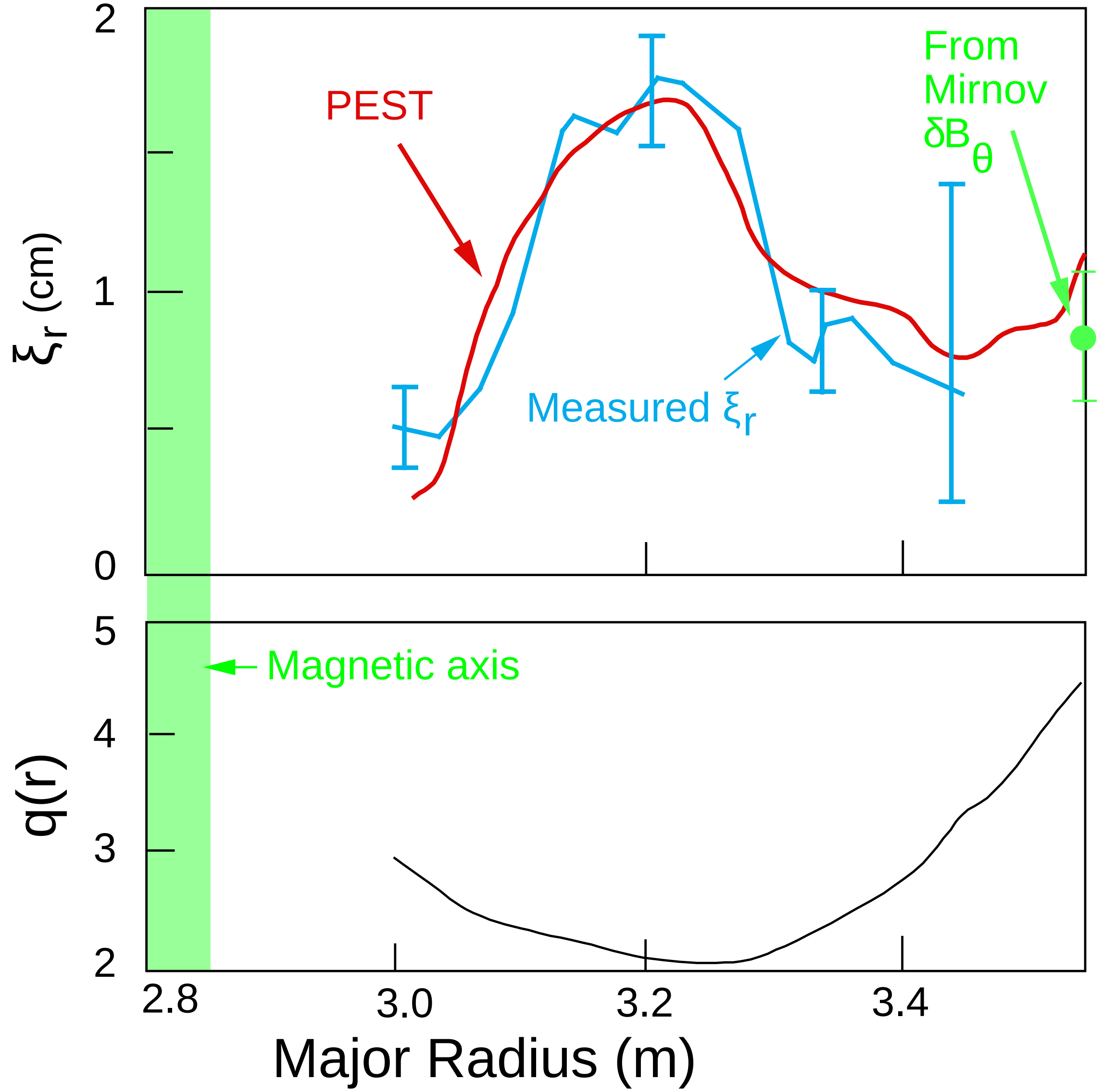
Ballooning modes have also been seen in disruptions of "Reversed Shear" plasmas

TFTR



Ideal Codes Predict kink mode structure for q>1

TFTR

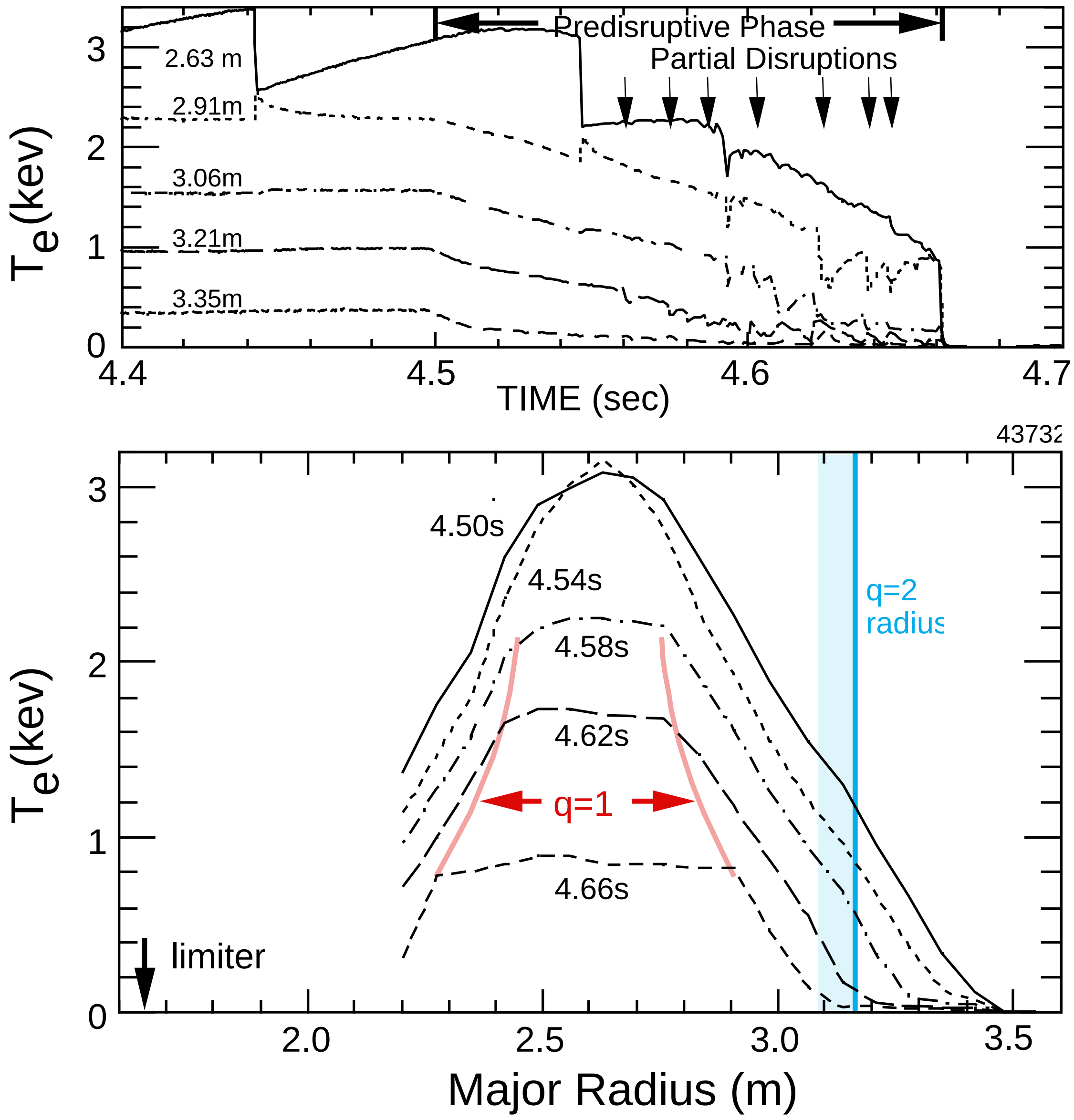


- Poloidal coupling agrees with PEST Infernal eigenmode structure.
- Mode is localized in weak shear region
- Role of ballooning modes is uncertain - they have been observed, but not in all disruptions.
- Mode structure measured with the two Grating Poly-chromators.

M. Okabayashi, et al., Nucl. Fus. **38** 1149 (1998)
J. Manickam, et al., IAEA Montreal Vol. I, 453 (1997)

Phase II - Thermal Collapse from edge

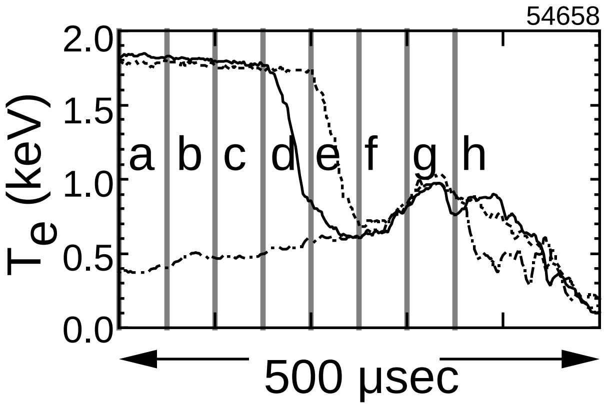
TFTR

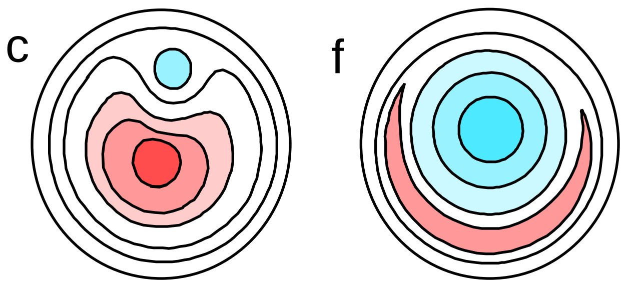


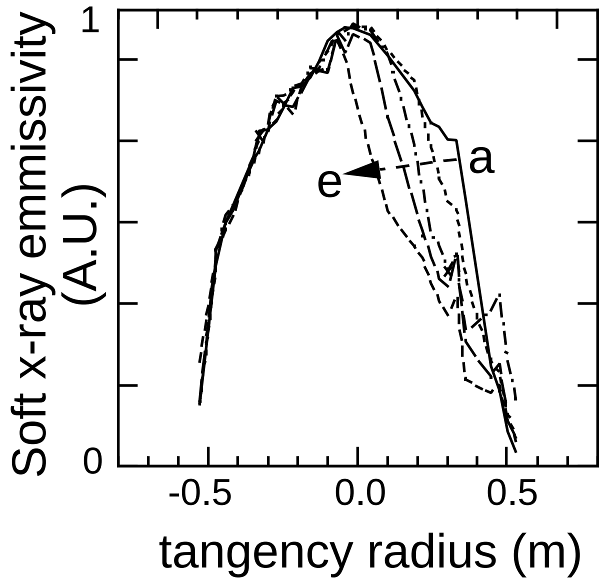
- Cold Mantle grows from plasma edge.
- Confinement still good between mantle and core.
- Confinement inside q=1 is poor; flat T_e implies low shear.
- Final quench occurs when mantle extends inside q=2 surface.

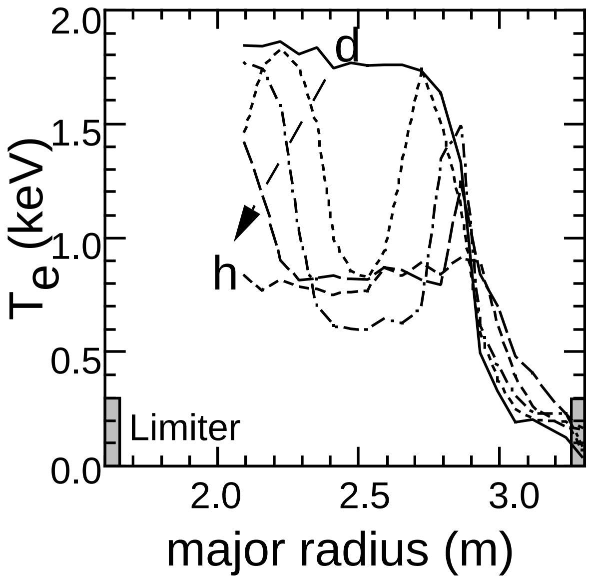
2nd Quench (1st in Density Limit) in Disruptions due to (1,1) Kink Mode

TFTR









- The kinks can have a "cold bubble" structure, probably due to low shear.
- The final growth of the kink leads to reconnection of the magnetic flux.
- The reconnection leads to a thermal quench and influx of impurities.

E. Fredrickson, et al., Nucl. Fusion **33**, 141 (1993).

Kinetic Instabilities: Important for Reactor with large β_α

Toroidal Alfvén Eigenmodes first observed on TFTR:

Beam Driven [K. Wong, PRL **66**, 1874 (1991)] and ICRF-generated tail-ion driven modes [J. R. Wilson, et al.,] were both first observed on TFTR.

Significant enhancements in fast ion losses were directly measured [D. Darrow, et al., Nucl. Fusion **37**, 939 (1997)]

Energetic Particle Modes (Fast Ion Modes):

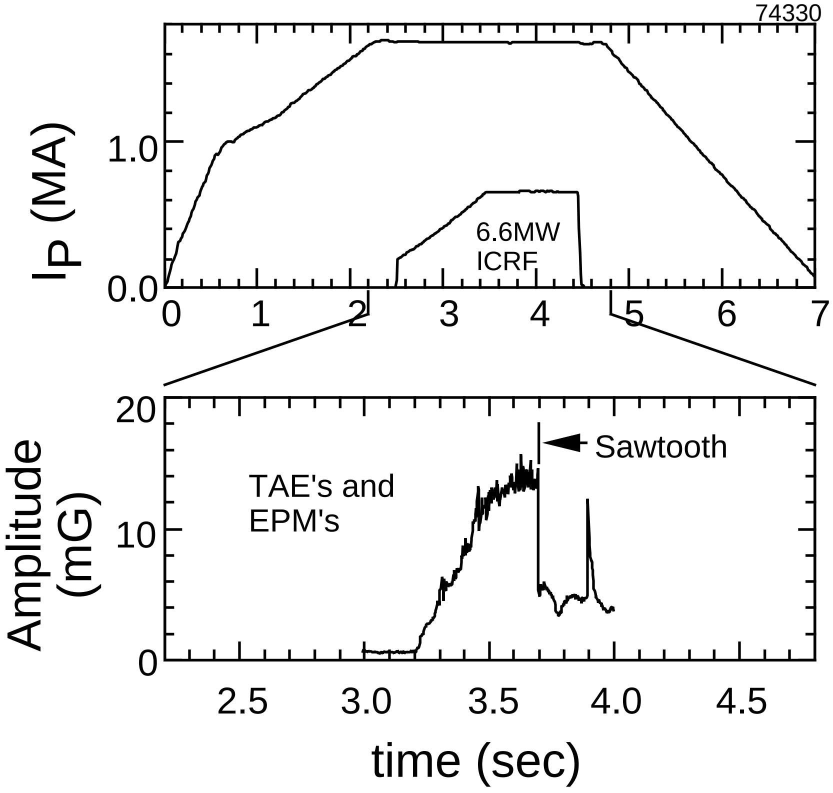
With very large fast ion beta, purely kinetic modes can be driven [E. Fredrickson, et al., Nucl. Fusion **35**, 1457 (1995), S. Bernabei, et al., Submitted to Phys. of Plasmas]

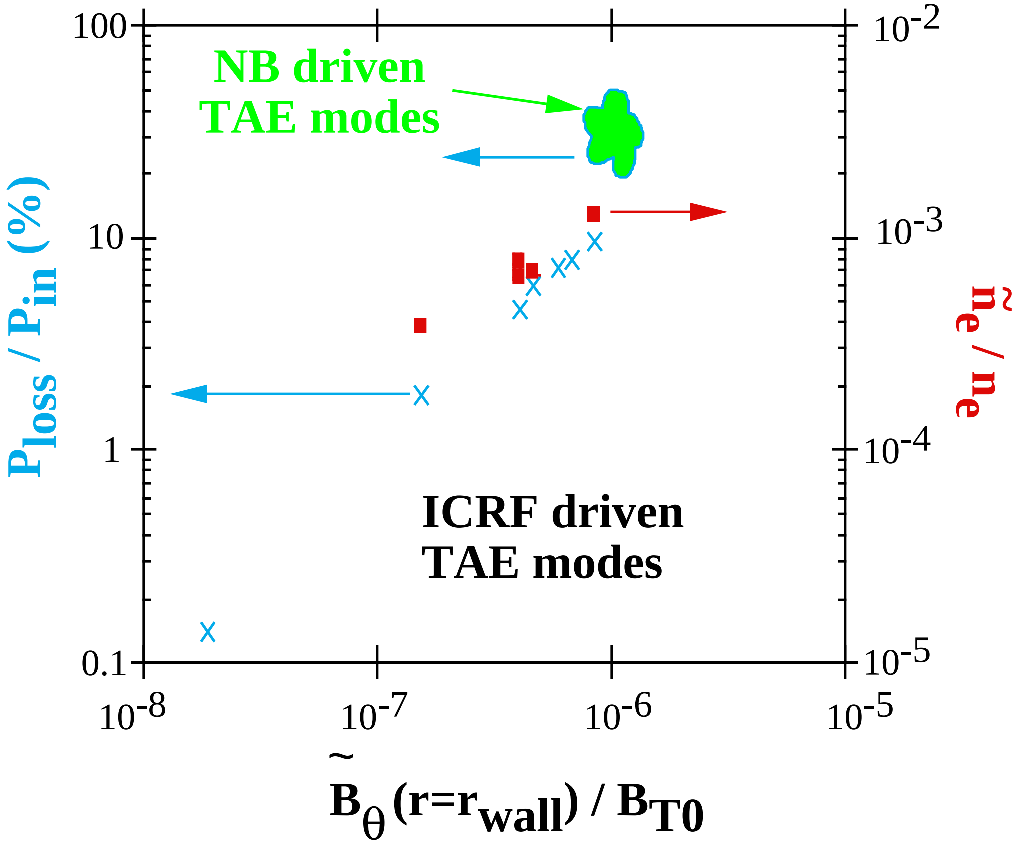
Kinetic Ballooning Modes:

Beam driven modes were observed to cause fusion alpha losses in high performance plasmas [Z. Chang, et al., PRL **76**, 1071 (1996)]

Alfvén Range of Frequency modes cause fast ion losses at P_{ich} > 2-3 MW

TFTR



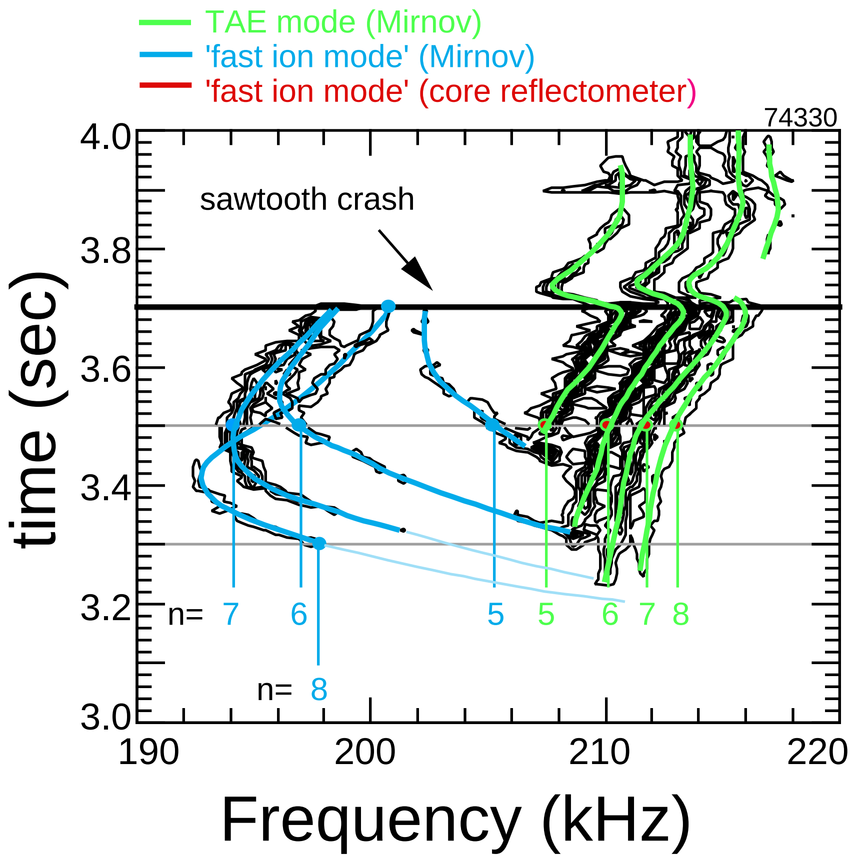


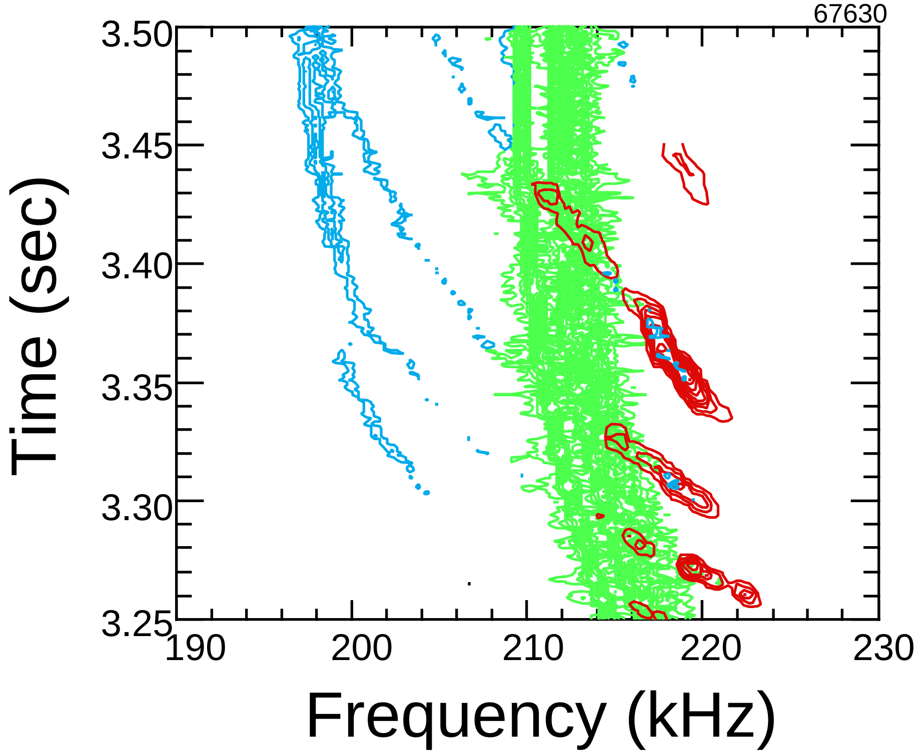
- Losses are estimated at up to 10% of input RF power, larger losses were seen for beam driven modes.

D. Darrow, et al., Nucl. Fusion **37**, 939 (1997)

Two Branches of Alfvén Eigenmodes are typically seen in low q, ICRF heated plasmas

TFTR





- The upper branch are Toroidal Alfvén Eigenmode (TAEs).
- The lower branch are Energetic Particle Modes (EPMs).

E. Fredrickson, et al., Nucl. Fusion 37, 939 (1997)
S. Bernabei, et al., submitted to Phys. of Plasmas

Summary

Excellent equilibrium diagnostics and MHD diagnostics are necessary for detailed comparisons to theoretical simulations.

TFTR had a unique capability for internal measurements of MHD mode structure with the two Grating Polychromators.

The high temperature, reactor grade plasmas facillitated these measurements as well as made them valuable for extrapolations to future reactor concepts.

The MHD studies on TFTR both helped to direct theoretical efforts as well as test and benchmark theoretical predictions.