Neoclassical Tearing Modes and Their Control

by R.J. La Haye

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GENERAL ATOMICS

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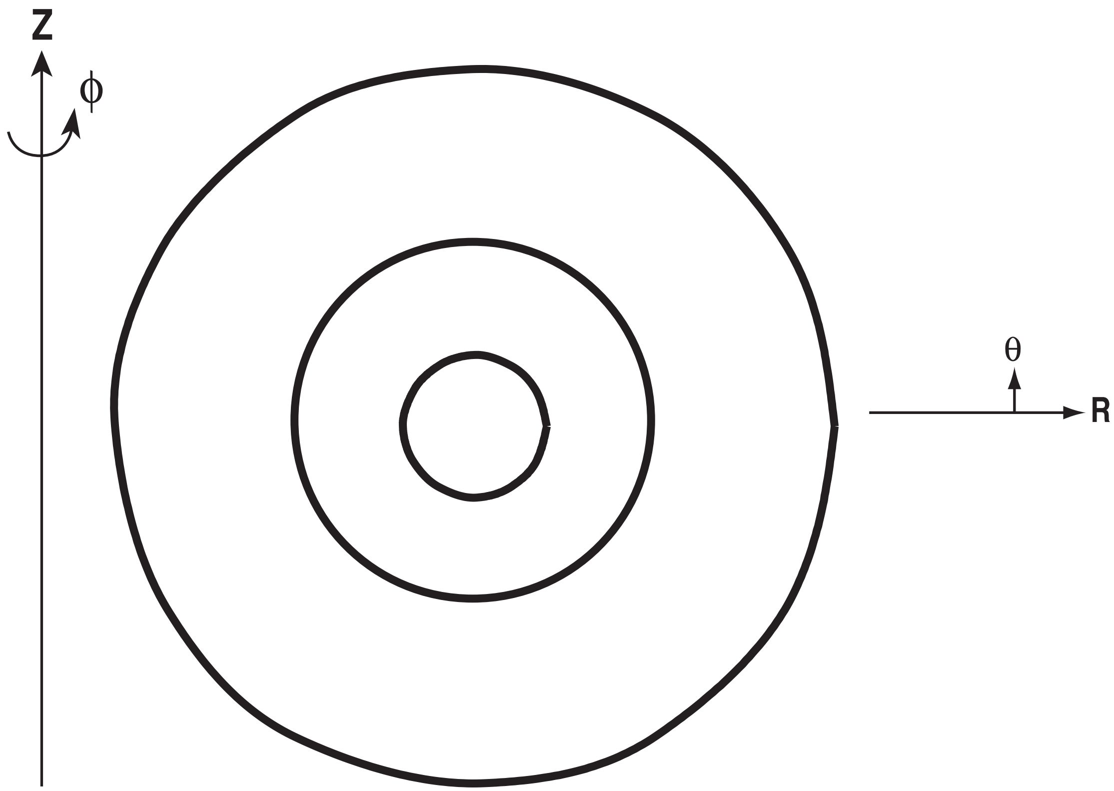
Physics of Neoclassical Tearing Modes

- **Theory for classical tearing modes is mature, well-understood and experimentally confirmed**
  - ★ perturbed helical currents at rational magnetic surfaces
    - – lower the magnetic energy of an unstable plasma current
- **Neoclassical tearing modes proposed theoretically 20 years ago experimentally validated only in the last 10 years**
  - ★ helically perturbed plasma pressure at a rational surface
    - – makes helical "bootstrap" currents that lower the magnetic energy . . . of a stable total plasma current
- **Both kinds of tearing mode islands**
  - ★ reduce plasma energy and rotation
    - – burning plasma experiments such as ITER . . . are of increased susceptibility to NTMs

Tearing Mode Magnetic Islands Deform Magnetic Surfaces

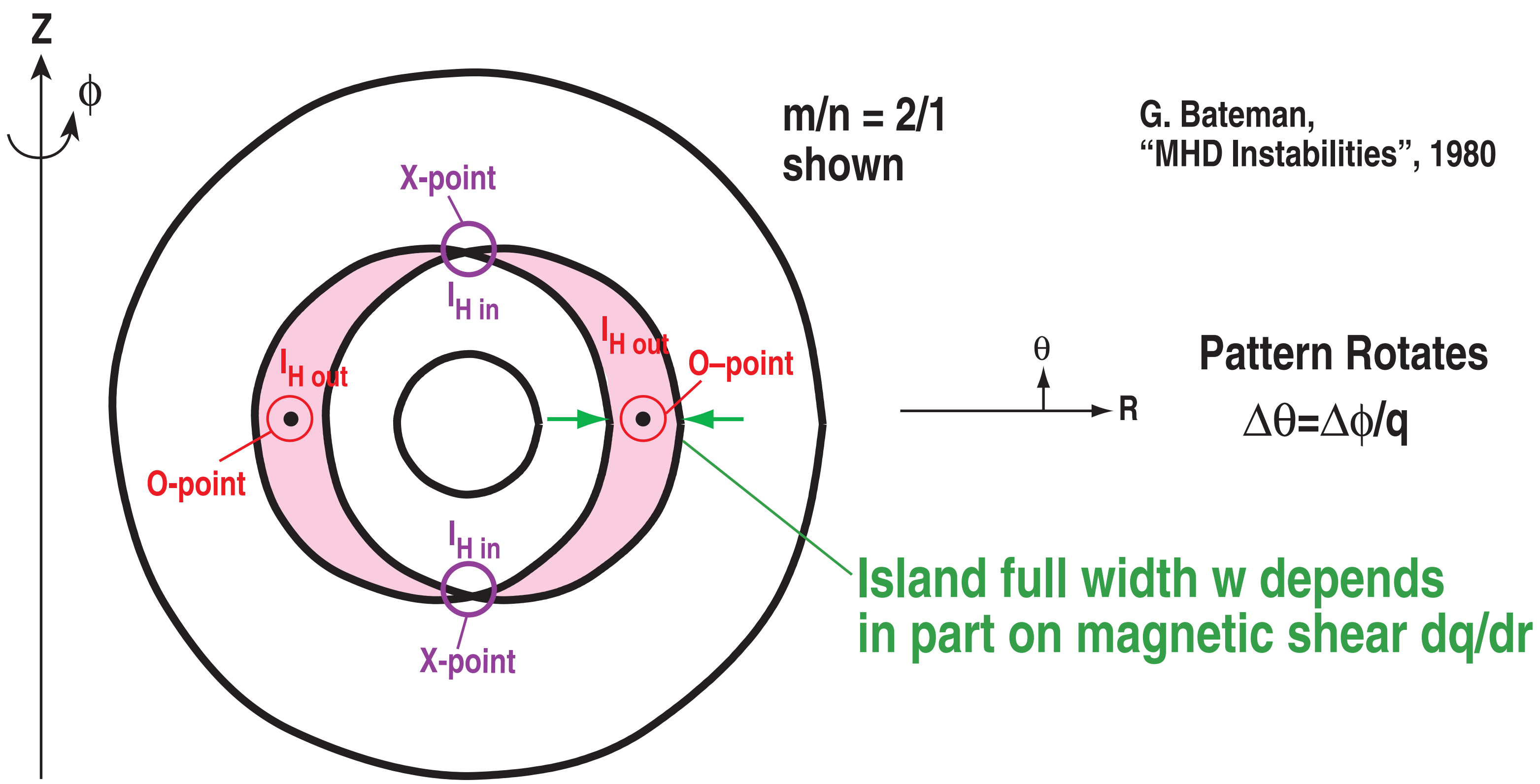
- **Finite plasma resistivity allows toroidally non-axisymmetric helical currents to break or tear magnetic field lines at rational surfaces q = m/n**
  - ★ original flux surfaces are toroidally axisymmetric



- **Safety factor q = dϕ/dθ gives path of magnetic field lines as they go around the torus**
  - ★ for m and n integers
    - – field line joins on itself
      . . . after m toroidal and n poloidal rotations

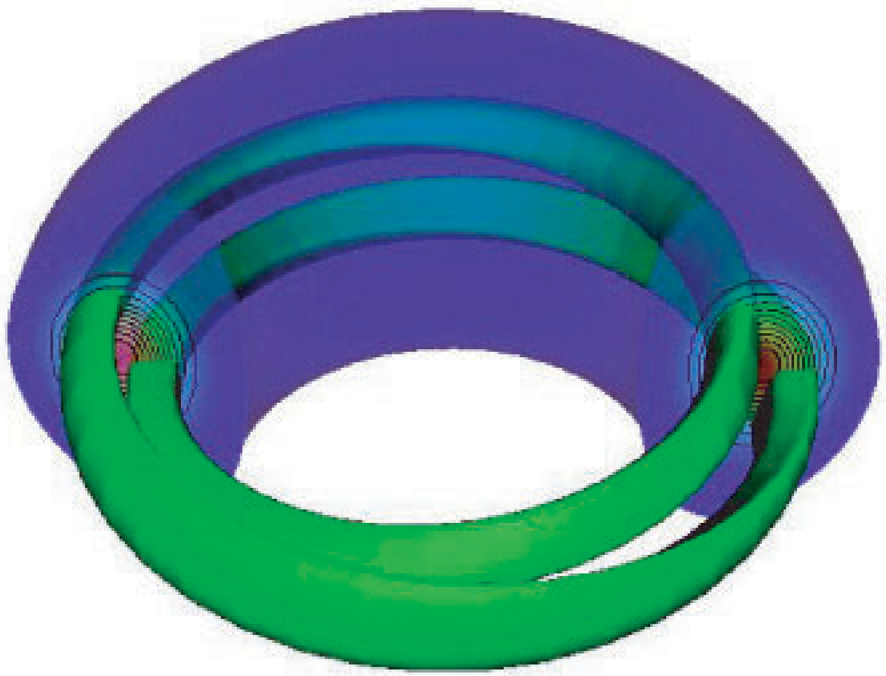
Tearing Mode Magnetic Islands Deform Magnetic Surfaces

- **Finite plasma resistivity allows toroidally <u>non-axisymmetric</u> helical currents to break or tear magnetic field lines at rational surfaces q = m/n**
  ★ reconnection of the magnetic field produces magnetic islands

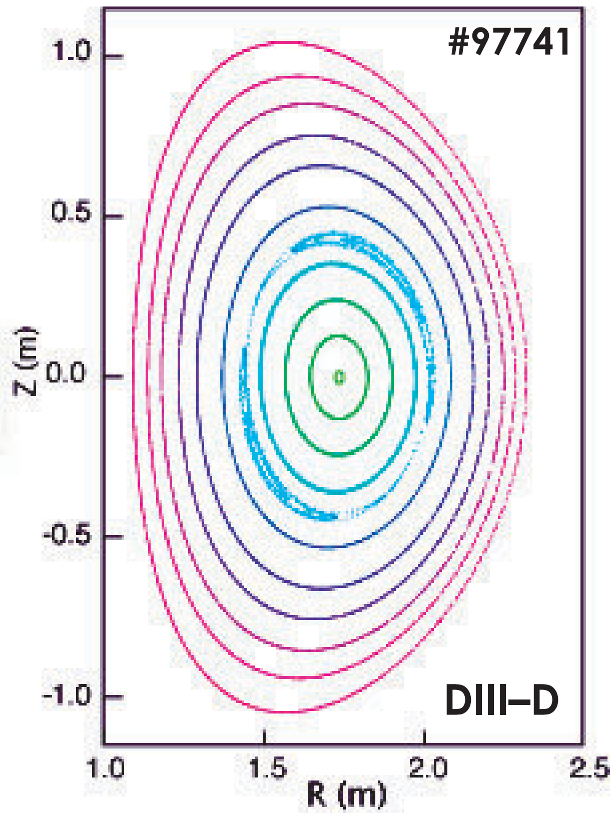


NIMROD Code Can Simulate Stability and Island Structure of an Unstable Tearing Mode

- **Here DIII–D geometry is simulated for an m/n=2/1 tearing mode**
  - ★ classically unstable



D.P. Brennan, et. al., 2004



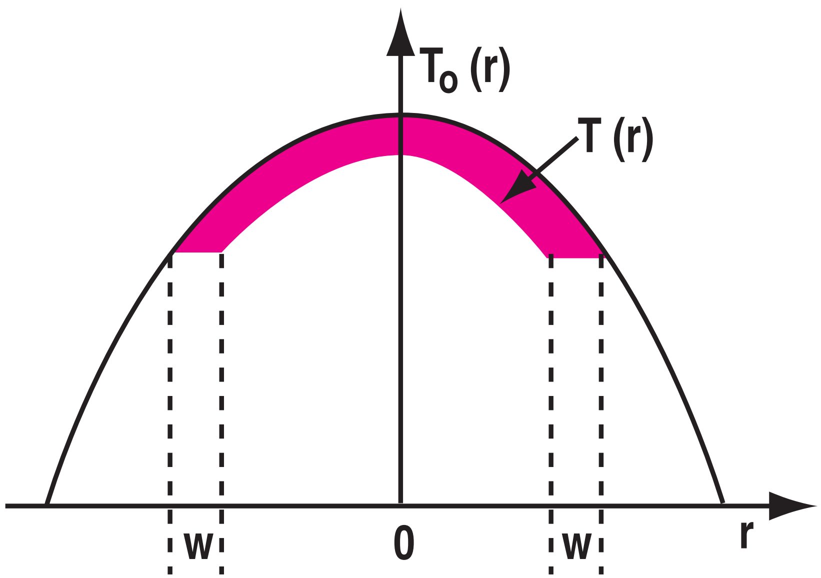
NIMROD
Non-Ideal MHD with Rotation
Open Discussion Project

CEMM

Tearing Modes Reduce Plasma Energy and Angular Momentum

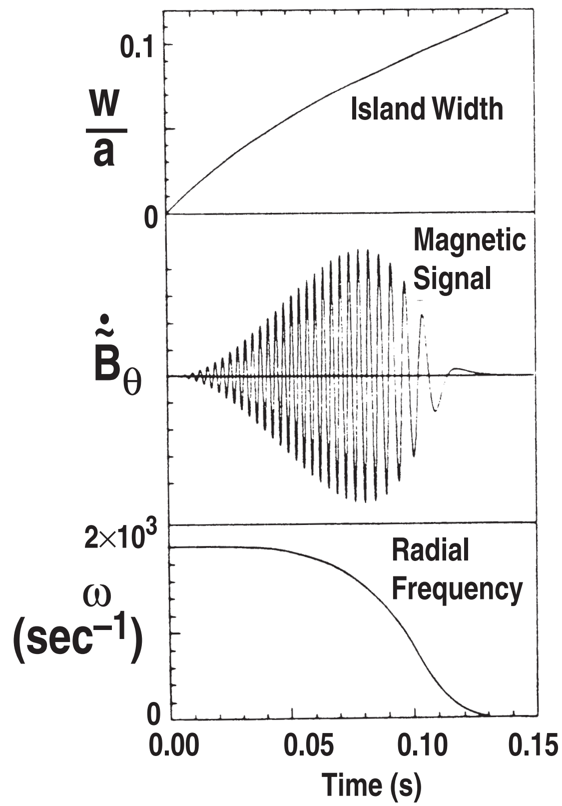
- **Islands "leak" energy radially**
  - ★ pressure gradient flattened in island
    - – energy lost in shaded region

      . . . $\Delta\tau_E/\tau_E \approx -4\, w\, r_s^3/a^4$



Z. Chang and J.D. Callen 1990
"Belt Model of an Island"

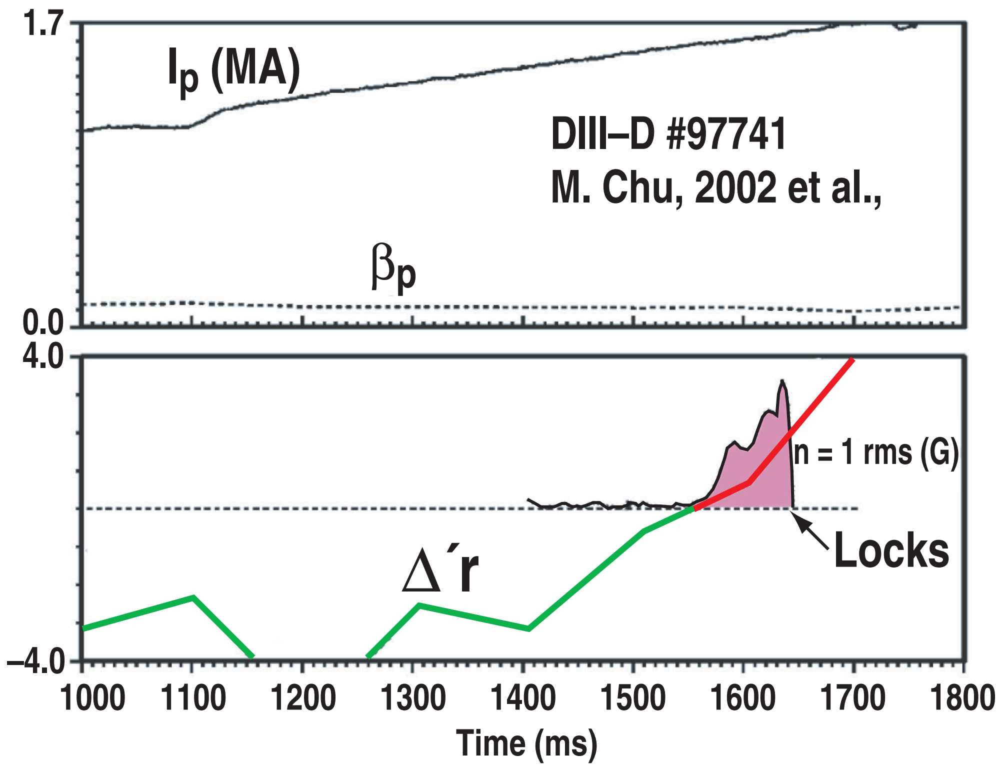
- **Eddy currents induced in vacumm vessel wall**
  - ★ exert drag at island surface
    - – can stop plasma rotation



M.F.F. Nave and J.A. Wesson 1990 Resistive Wall Theory

Classical Tearing is Made Unstable by an Unstable Plasma Current Profile

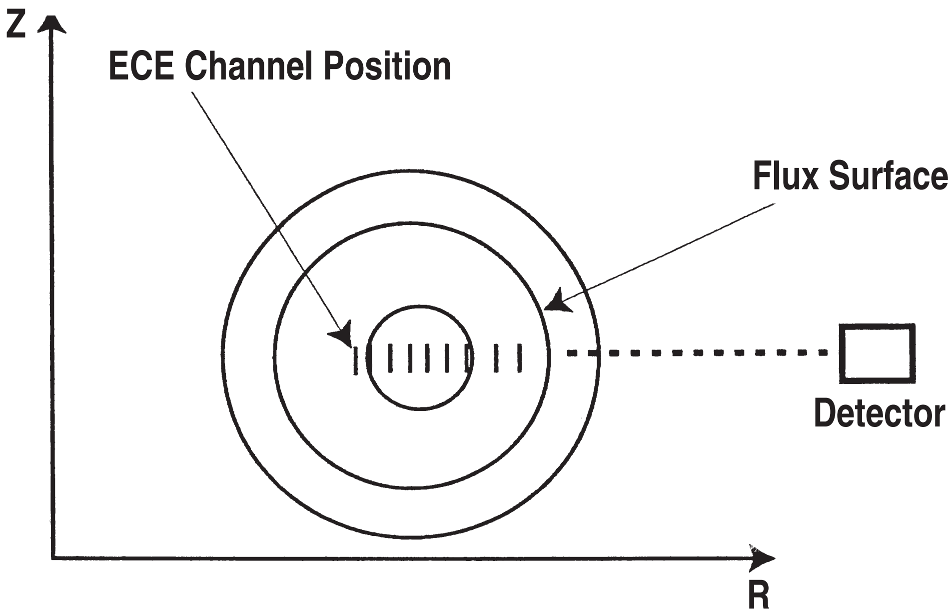
- **Rutherford Equation (P.H. Rutherford 1973)** $\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta'$, **the classical tearing index**
  - ★ τ_R is the plasma resistive time, r is the q = m/n minor radius
  - ★ for $\Delta' > 0$, the helically perturbed current has lower energy
    - – linearly unstable as the perturbed energy $\delta W_{mag} \approx -\frac{1}{4\mu_o}\left(\frac{r_s \tilde{B}_{rmn}}{m}\right)^2 \Delta' r_s < 0$



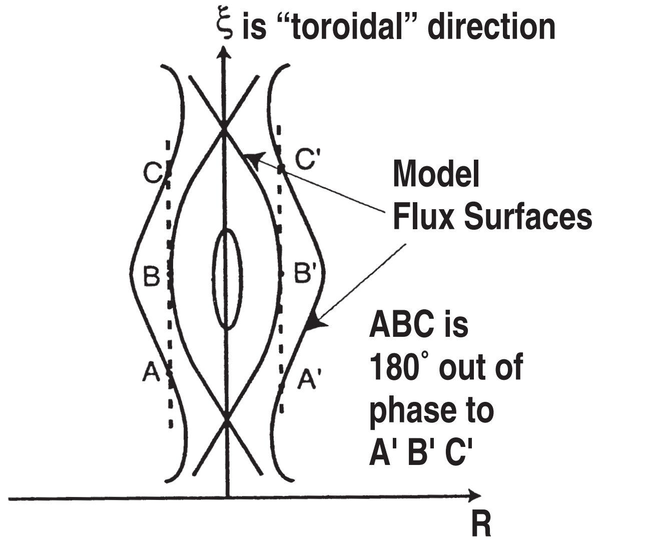
- **Linear theory confirmed by accurate equilibrium reconstruction to calculate Δ'**
  - ★ m/n=2/1 tearing grows when $\Delta' > 0$

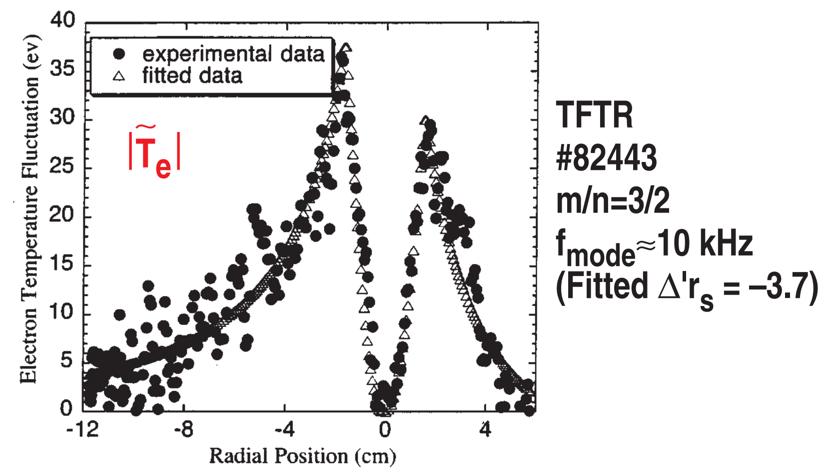
Island Structure Can be Measured by Electron Cyclotron Emission of T_e Fluctuation Radial Profile

- **Magnetic surface distortion**
  - ★ leads to T_e fluctuation



(Y. Nagayama et al., 1990)





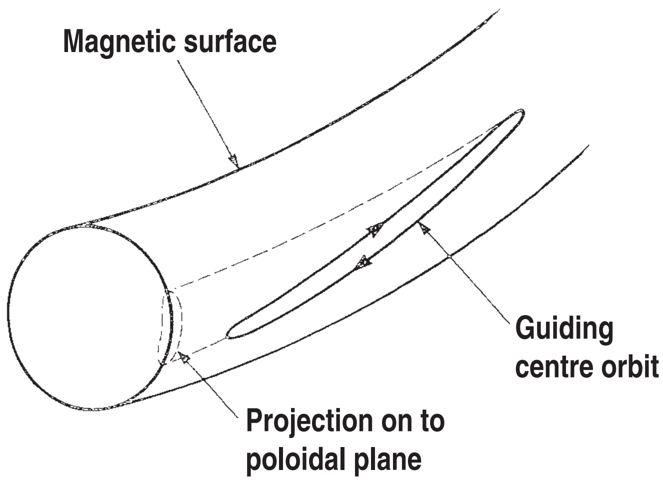
(C. Ren, et., 1998)

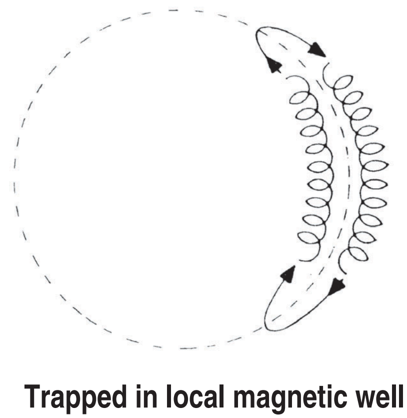
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

144-05/RJL/rs

Toroidal Effects Produce a Pressure Gradient Driven "Bootstrap" Current

- **Toroidal effects (finite ε=r/R) add <u>drift</u> to particle gyrations**
  - ★ **$\varepsilon^{1/2}$ of particles are trapped with "banana" width $w_b \approx \varepsilon^{1/2} \rho_\theta$**
    - – where ρ_θ is the poloidal gyroradius





Magnetic mirrors formed due to poloidal variation of magnetic field

J. Wesson, "Tokamaks", third edition, 2003

- **Bootstrap current carried by passing electrons** $j_{bootstrap} \sim -\frac{\varepsilon^{1/2}}{B_\theta}\frac{dp}{dr}$
  - ★ results from "friction" with trapped electrons and stationary ions
    - – exists independently of inductively driven and beam currents

Neoclassical Tearing Mode Destabilized by Helically Perturbed Bootstrap Currents

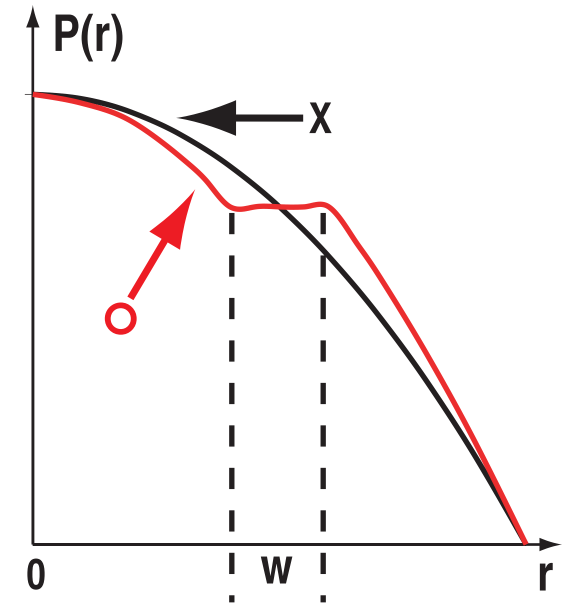
(neoclassical, adj. 1. belonging or pertaining to a revival or adaptation of a classic style. . ., Random House Dictionary of the English Language)

- **Linearly stable tearing mode ($\Delta' < 0$)**
- **"Seed" island at rational surface q=m/n**
- **Pressure is flattened at O–point, but not at X–point**

★ thus a helically perturbed bootstrap current

– reinforces the "seed" (for positive magnetic shear)

. . . a destabilizing effect that can lower the plasma magnetic energy



W.X. Qu and J.D. Callen 1985
R. Carrera, R.D. Hazeltine, M. Kotschenreuther 1986
J.D. Callen, W.X. Qu, K.D. Siebert, B.A. Carreras, K.S. Shaing and D.A. Spong 1987

Rutherford Equation is Modified for Helically Perturbed Bootstrap Current

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + 2\,\frac{j_{bootstrap}}{B_\theta}\,\frac{L_q}{w}$$

with $L_q = q/(dq/dr)$, the magnetic shear length

Δ': classical tearing index

$2\,\frac{j_{bootstrap}}{B_\theta}\,\frac{L_q}{w}$: destabilizing effect of perturbed bootstrap current

$$= \Delta' + \varepsilon^{1/2}\,\frac{L_q}{L_p}\,\beta_p\,\frac{1}{w}$$

with $L_p = -p/(dp/dr)$, the pressure gradient length

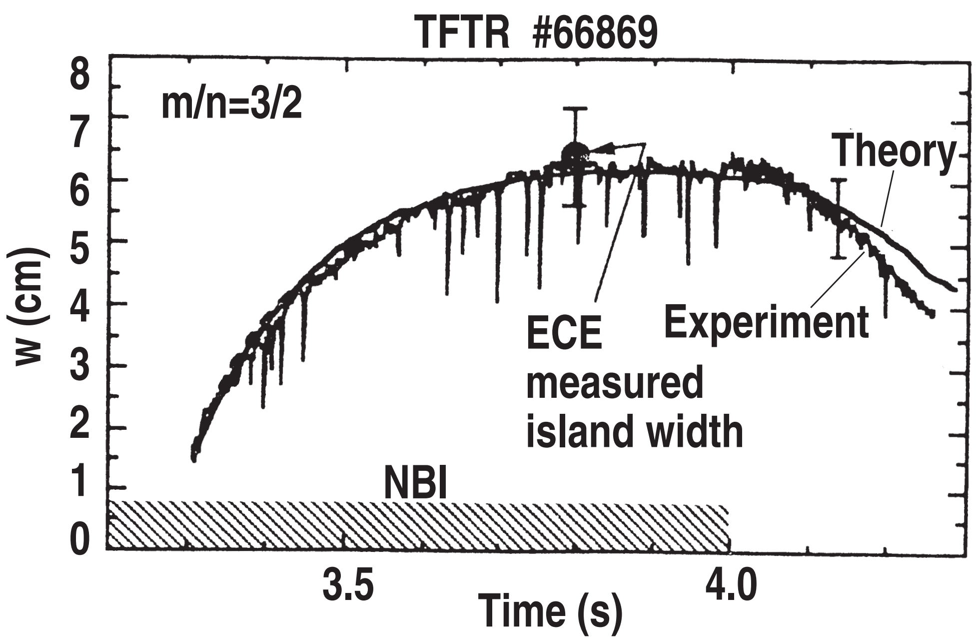
and $\beta_p = \frac{2\mu_o p}{B_\theta^2}$, the poloidal beta

- Destabilizing term increases with beta poloidal
  - ★ stabilizing for stellarators and advanced tokamaks with negative shear
- Saturated island $w_{sat} = \varepsilon^{1/2}\,(L_q/L_p)\,\beta_p\,/\,(-\Delta')$
  - ★ primitive theory suggests every island at q=m/n excited!
    - – in fact, islands are not pervasive

Neoclassical Tearing Mode Theory is in Good Agreement for Non-Linear Evolution of Islands in TFTR Supershots

(Z. Chang et al., 1995, first experimental identification of NTMs)

- **Small island initially with ∇p term dominant in mod. Rutherford Eqn.**
  - ★ $w \propto \sqrt{\beta_p (L_q/L_p) t} \sim t^{1/2}$
    - — in contrast to w~Δ´t for Rutherford linear growth
- **Saturated island**
  - ★ $w \propto \beta_p (L_q/L_p)/(-\Delta')$
    - — island shrinks with NBI off and fall in β_p



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Threshold Physics Makes an NTM Linearly Stable and Non-Linearly Unstable

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\frac{L_q}{L_p}\beta_p\left[\frac{w}{w^2+w_d^2} - \frac{w_{pol}^2}{w^3}\right]$$

transport threshold (w_d) — polarization threshold (w_{pol})

- **Transport threshold (R. Fitzpatrick 1995)**
  - ★ **transport along $\vec{B}$ in island is fast compared to perpendicular**
    - helical pressure perturbation washed out if perpendicular transport dominates

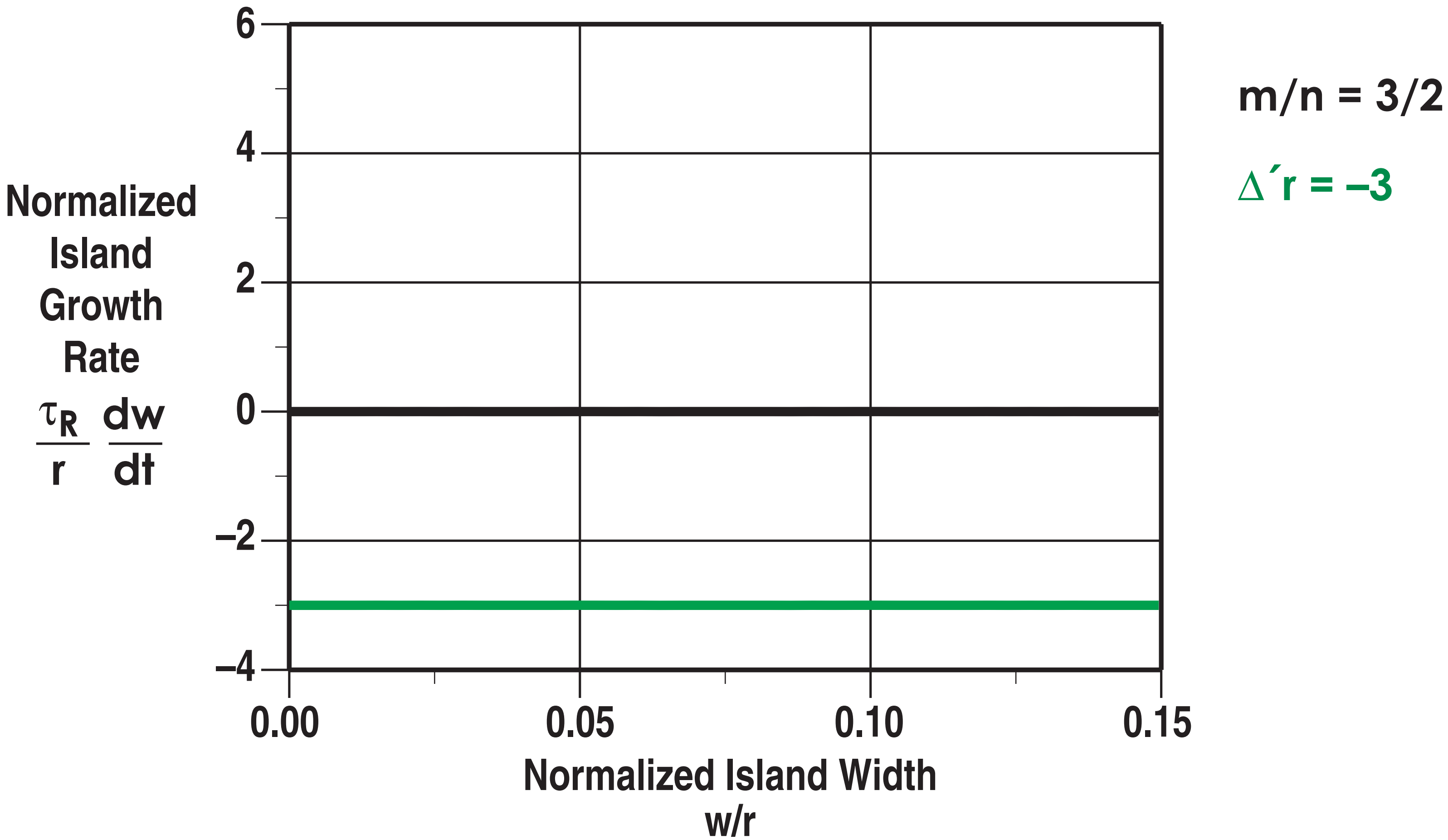
$$w_d \approx \left(\frac{L_s^2}{k_\theta^2}\frac{\chi_\perp}{\chi_{\parallel}}\right)^{1/4} \sim 1\ \text{cm}$$

- **Polarization threshold (H.R. Wilson et al., 1996)**
  - ★ **inertial effects are important in frame of E×B equilibrium flow**
    - polarization currents induced by island propagation are stabilizing for $\omega(\omega_{*i} - \omega) > 0$

$$w_{pol} \approx (L_q/L_p)^{1/2}\varepsilon^{1/2}\rho_{\theta i} \sim 1\ \text{cm}$$

Threshold Physics Makes an NTM Linearly Stable and Non-Linearly Unstable

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta'$$



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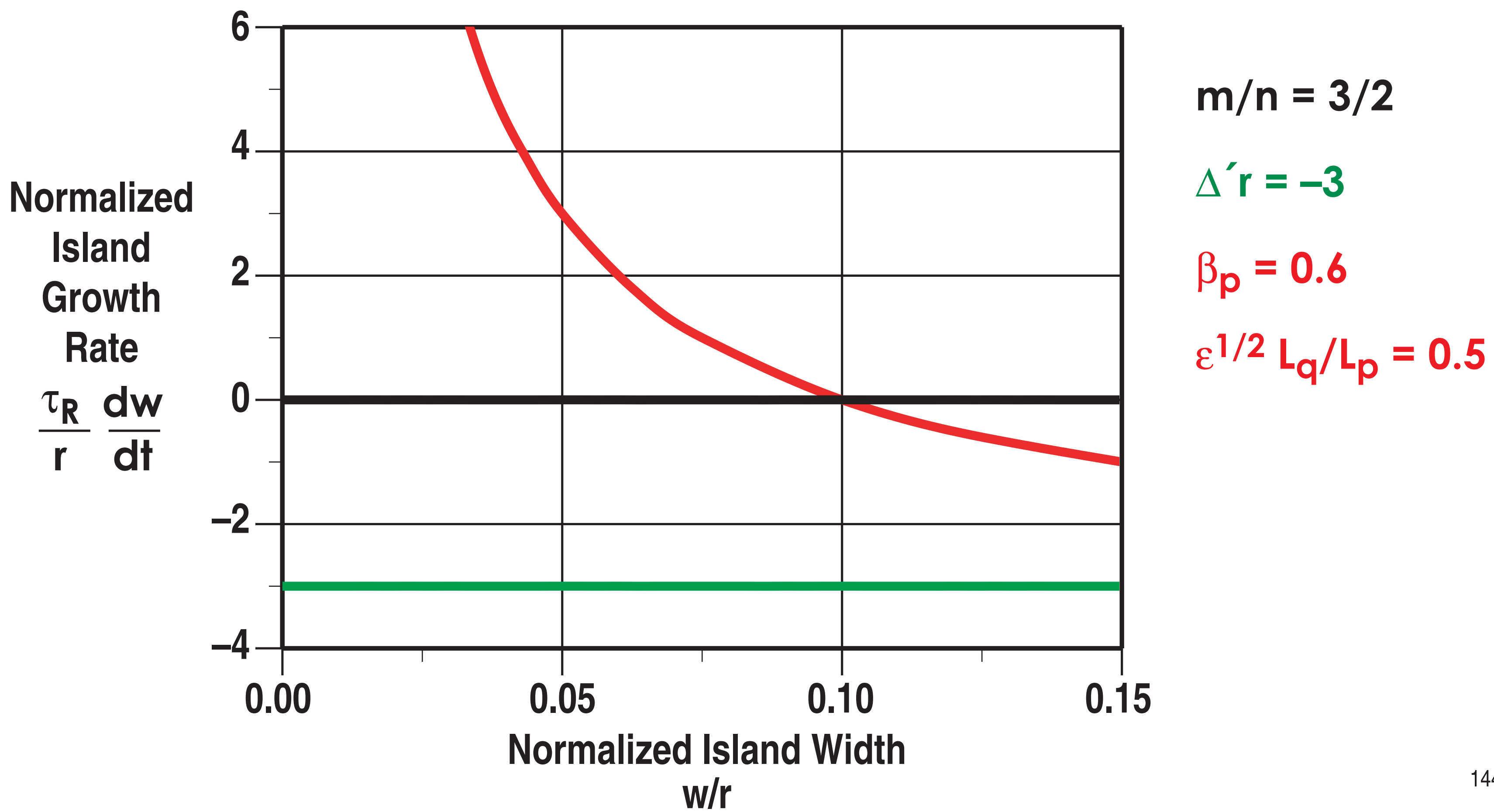
Threshold Physics Makes an NTM Linearly Stable and Non-Linearly Unstable

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\frac{L_q}{L_p}\beta_p\frac{1}{w}$$



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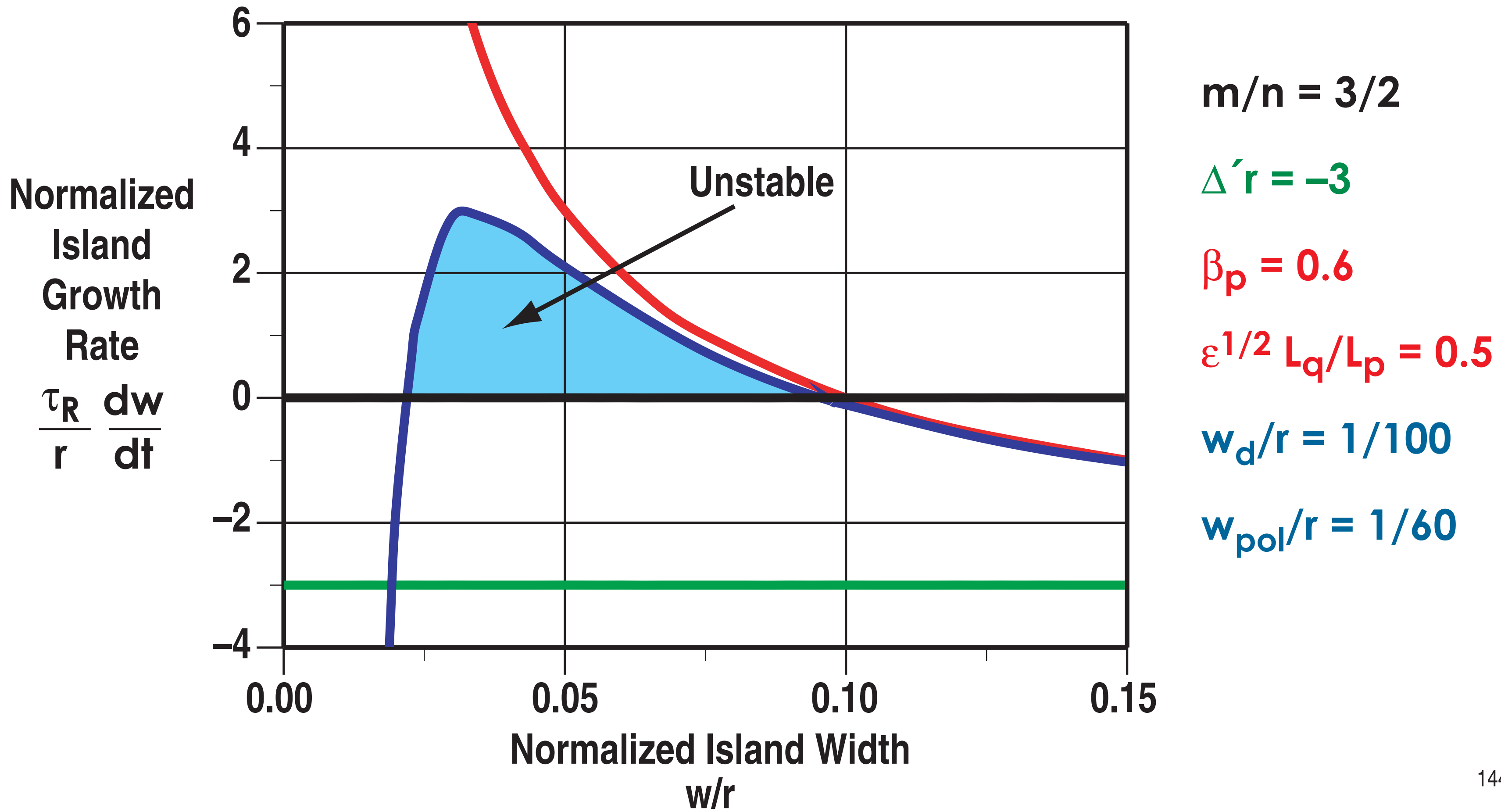
Threshold Physics Makes an NTM Linearly Stable and Non-Linearly Unstable

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\frac{L_q}{L_p}\beta_p\left[\frac{w}{w^2+w_d^2} - \frac{w_{pol}^2}{w^3}\right]$$

transport threshold (w_d^2)

polarization threshold (w_{pol}^2)



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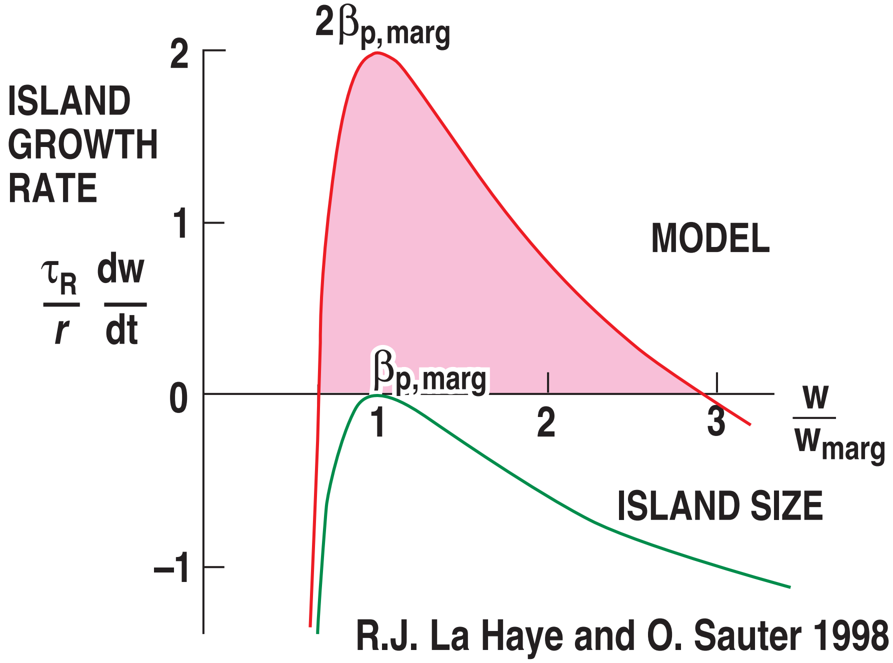
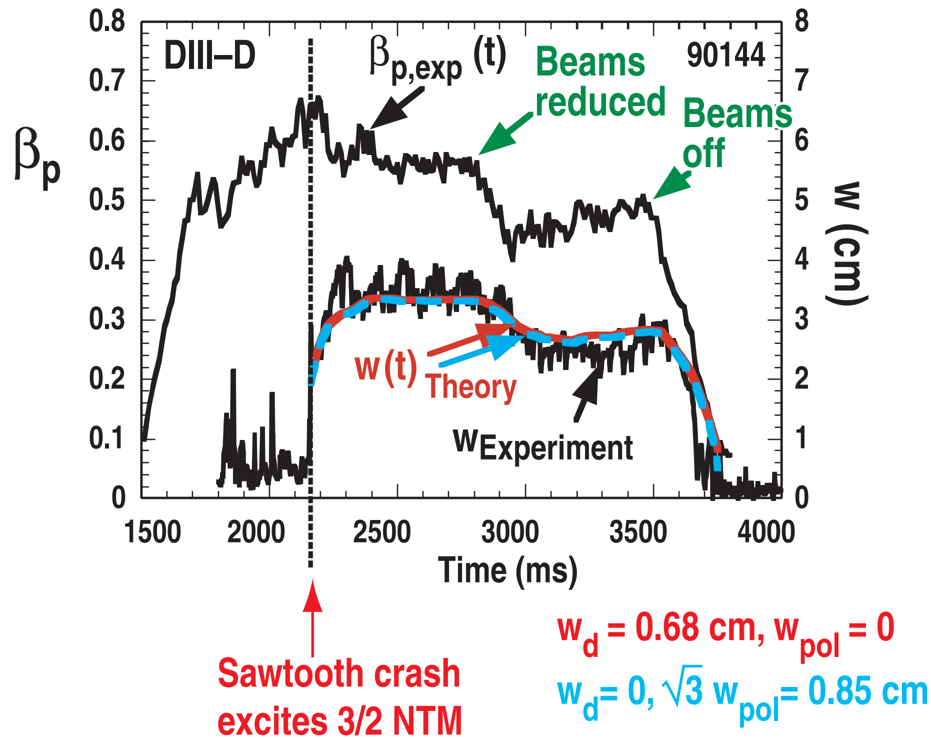
NTM Excitation Starts with a Metastable Condition

(metastable, adj. , . . . 2. Physics, Chem. pertaining to a body or system existing at an energy level above that of a more stable state and requiring the addition of a small amount of energy to induce a transition to the more stable state - Random House Dictionary of the English Language)

- **Analogy is a mountain snowpack**
  - ★ noise can trigger an avalanche
    - – to a lower energy state



- **Above marginal beta, a "seed" can start the NTM to grow**

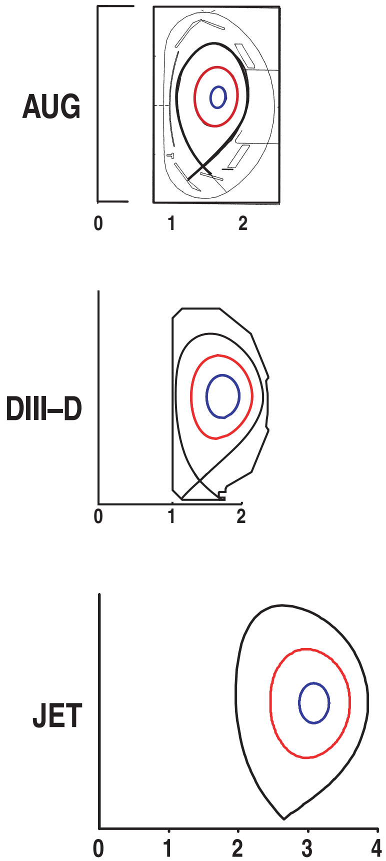


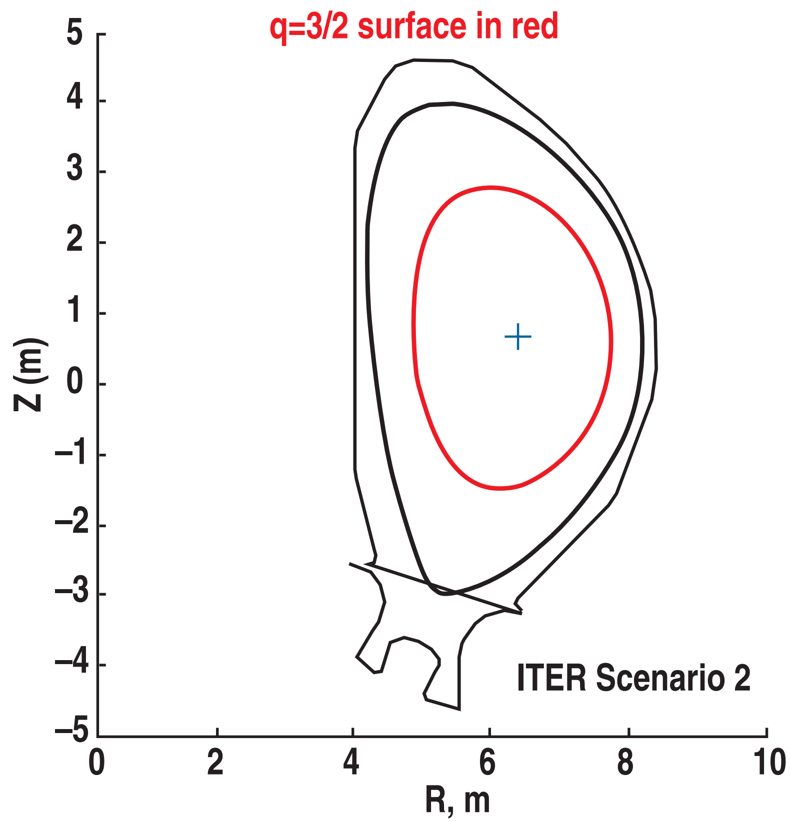
Other MHD Events Needed to Seed an NTM

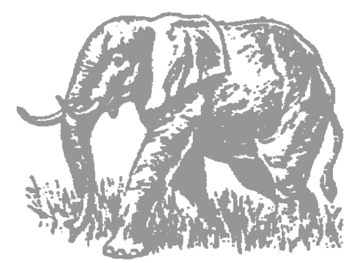
- **SAWTEETH**
  - ★ **current density peaking on axis**
    - — drives reconnection at q=1
- **FISHBONES**
  - ★ **periodic fast particle instabilities**
- **ELMs (edge localized modes)**
  - ★ **driven by dp/dr and j at edge**
    - — periodic intermediate n modes
- **RMPs (resonant magnetic perturbations)**
  - ★ **controlled seeding**
- **Spontaneous or seedless NTMs**
  - ★ **current-diffusive ballooning micromodes?**
- **Initial $\Delta' > 0$ leading to $\Delta' < 0$ NTMs**
  - ★ **unstable total current profile**
  - ★ **pole in Δ' near an ideal kink limit**

“Wind Tunnel” Scaling of Critical Beta for NTMs

- **Assume physics is similar and scale invariant**
  - ★ **extend the range of scaling with multiple devices**
    - — ELMy H–mode with sawteeth and $q_{95} \gtrsim 3$







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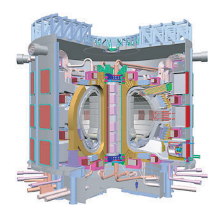

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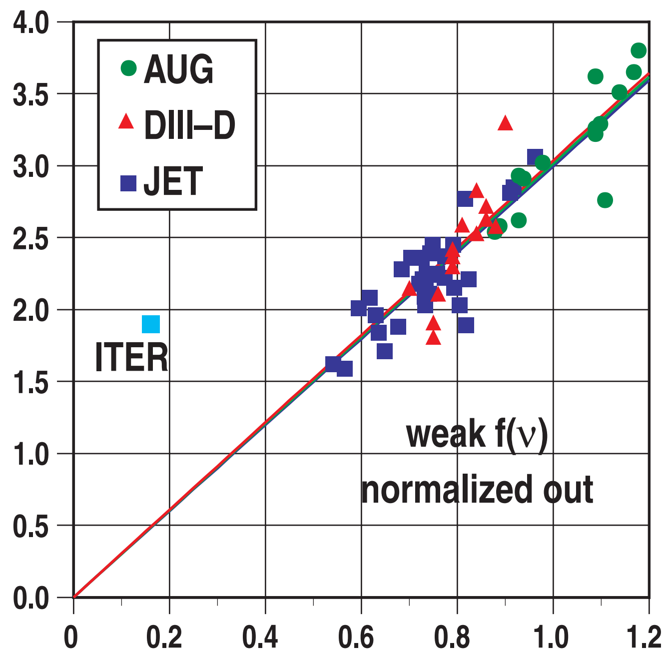
Critical Beta for m/n=3/2 NTM Increases with Normalized Ion Gyroradius

- Scales towards increased susceptibility in ITER
  - ★ relatively smaller ion Larmor radius
  - ★ relatively similar collisionality
    - — $\nu \equiv (\nu_{ii}/\varepsilon)/\omega_{e*}$

Sawtooth Excited
Onset of m/n = 3/2 NTM

$\beta_N \equiv \dfrac{\beta\ (\%)}{I_p\ (\mathrm{MA})/aB_T}$



Normalized Ion Larmor Radius $\rho_{i*} \equiv \rho_i/a\ (10^{-2})$

R.J. La Haye et. al., 2000

- Critical beta mixes scaling of marginal and seed islands
  - ★ $\dfrac{\beta_{p,crit}}{\beta_{p,marg}} = \dfrac{(w_{seed}/w_{marg})}{\left[\dfrac{3}{2} - \dfrac{1}{2}\left(\dfrac{w_{marg}}{w_{seed}}\right)^2\right]}$
    - — w_{marg} from threshold physics
      - . . . $w_{marg} \approx \sqrt{3}\,(w_d^2 + w_{pol}^2)^{1/2}$
    - — w_{seed} from other MHD events
      - . . . issue is reconnection
    - — $\beta_{p,crit} \Rightarrow \infty$ for $w_{seed} \lesssim w_{marg}/\sqrt{3}$
      - . . . cannot excite the NTM

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Threshold Physics Can Be Studied Separately by Beta Rampdown Experiments to Remove the Neoclassical Tearing Mode

- Reducing beta eventually removes the m/n=3/2 NTM

(Experiment)

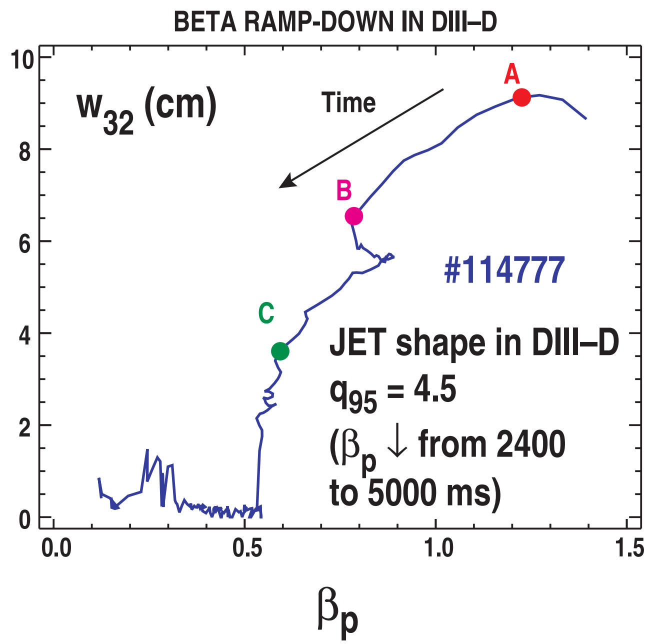
- Reducing beta eventually removes the m/n=3/2 NTM

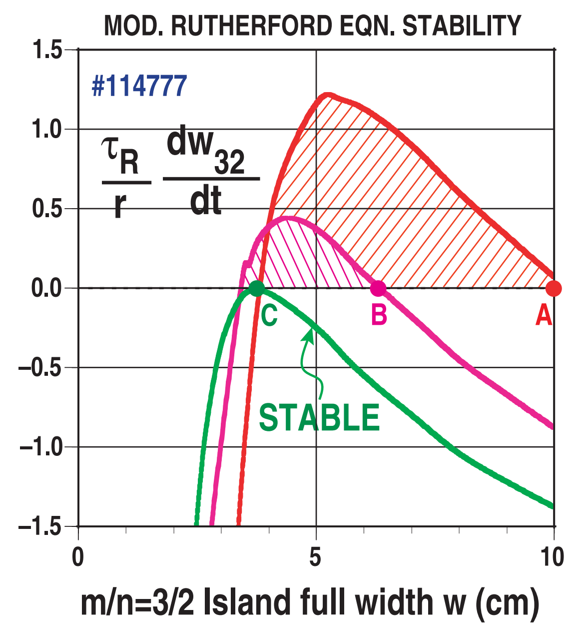
(Modeling)

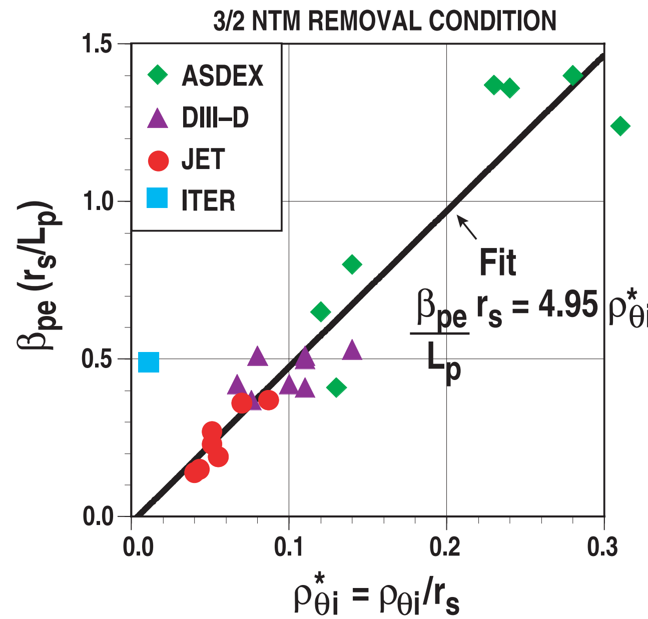
- Unstable space removed at "marginal" beta and island width

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

R.J. Buttery et. al., 2004







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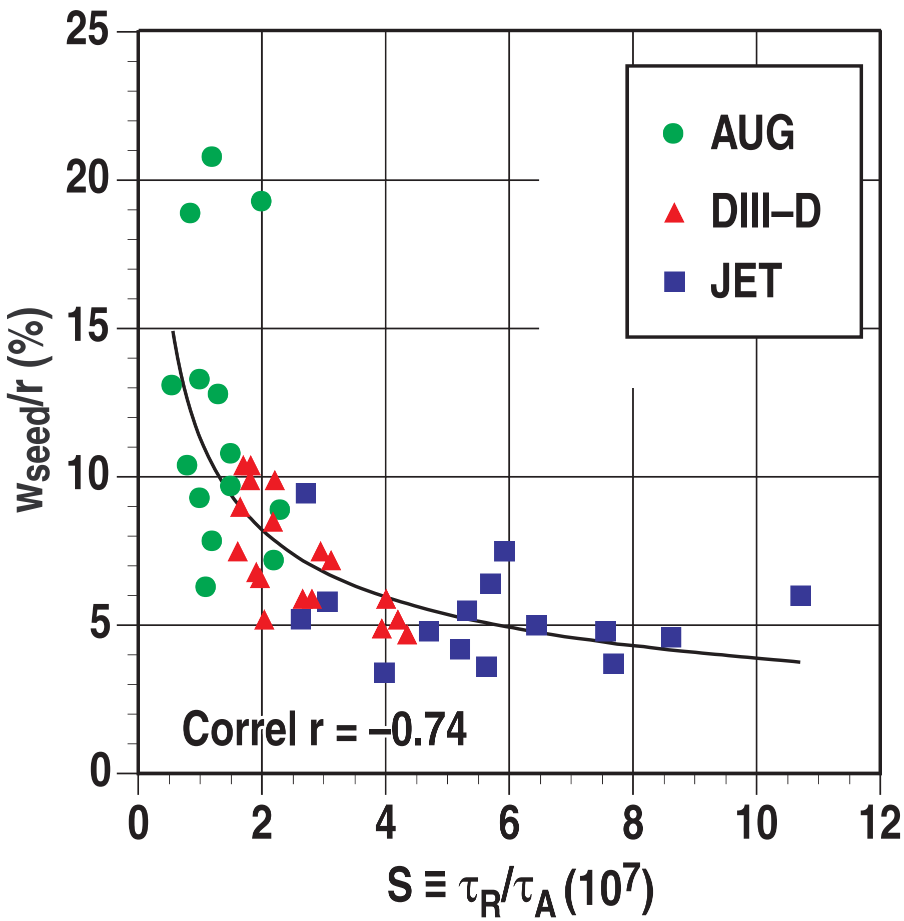
Relative Seed Island from Sawteeth Decreases with Increasing Magnetic Reynolds Number as Reconnection Inhibited

- **Periodic sawteeth seed 3/2 NTM**
  - ★ theory suggests driven reconnection inhibited in larger, hotter, higher field plasmas
    - – high magnetic Reynolds number . . . $S = \tau_R/\tau_A$
- **$w_{seed}/r \propto S^{-0.46\pm0.05}$ (R. La Haye et al, 2000) consistent with dynamical coupling model of C.C. Hegna et. al., 1998**
  - ★ favorable scaling for ITER at high S (≈3×10^9) and low ρ_{i*} (<0.002)?
    - – seed too small to excite mode? . . . being studied in NIMROD code



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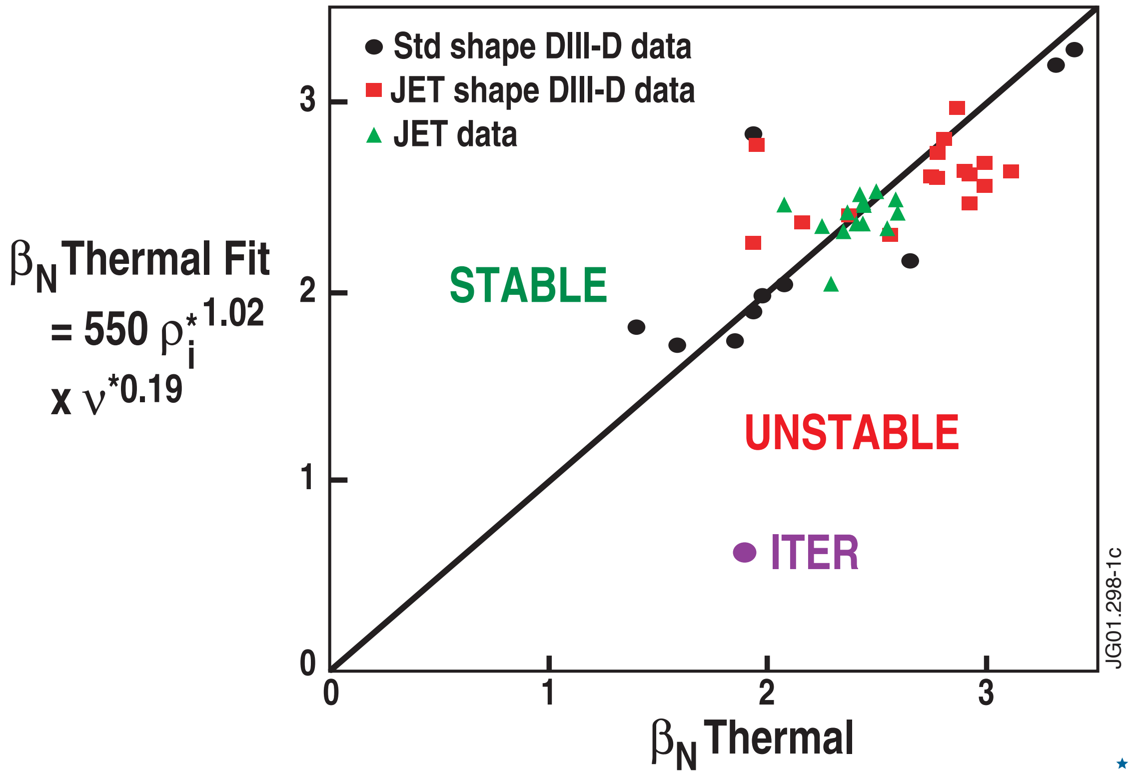
Critical Beta for m/n=2/1 NTM Also Scales with ρ_{i*}

- **Long wavelength, large minor radius m/n=2/1 tearing mode is most deleterious**
  - ★ can "lock" plasma rotation and lead to disruption
- **Joint experiments on JET and DIII–D show very similar instability behavior**
  - ★ linear scaling of global beta onset with normalized ion gyro-radius

(T.C. Hender, et al., 2004)



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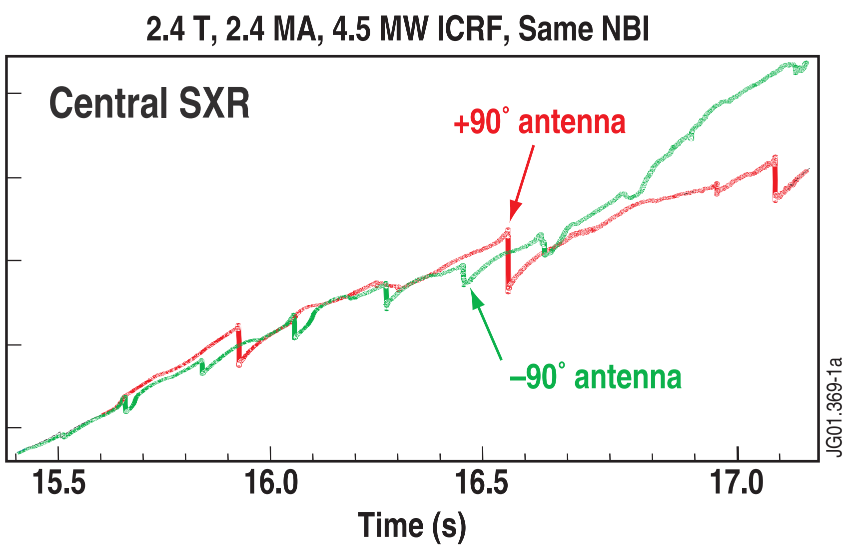
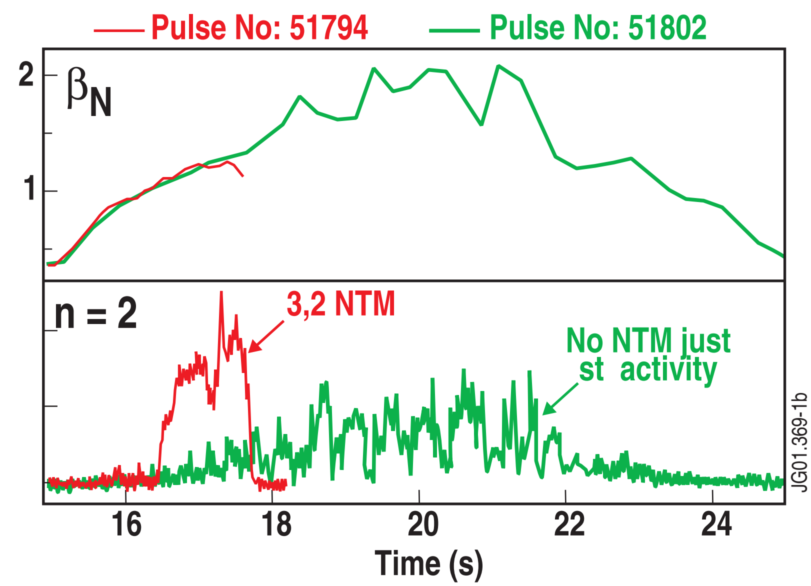
Control of Neoclassical Tearing Modes

- **"Quieter" plasma to reduce seeds**
  - ★ sawteeth avoidance (transiently in DIII–D)
  - ★ sawteeth control (ion cyclotron current drive in JET, electron cyclotron current drive in ASDEX Upgrade)
- **Inhibiting the resonant perturbed bootstrap current**
  - ★ with a non-resonant helical field
    - — FIR-NTM (Frequently Interrupted Regime in ASDEX Upgrade and JET)
    - — applied field from an external coil (DIII–D)
- **Microwave power co-current drive from resonant absorption**
  - ★ make a more stable total plasma current
    - — Δ' more negative
  - ★ replace the "missing" bootstrap current in the island

Sawteeth Control for Reduced Seeding

- **Transiently removing sawteeth (and fishbones) by keeping q(0) > 1 in DIII-D**
  - ★ raised the beta limit to m/n=3/2 NTMs
    (R.J. La Haye, B.W. Rice and E.J. Strait, 2000)
- **Sawteeth control by ion cyclotron current drive in JET**
  (O. Sauter et. al., 2002)
  - ★ destabilized sawteeth are frequent, small amplitude, reduced seeds
    — NTM triggered in #51794 at first crash when $\beta_N > \beta_{Ncrit}$





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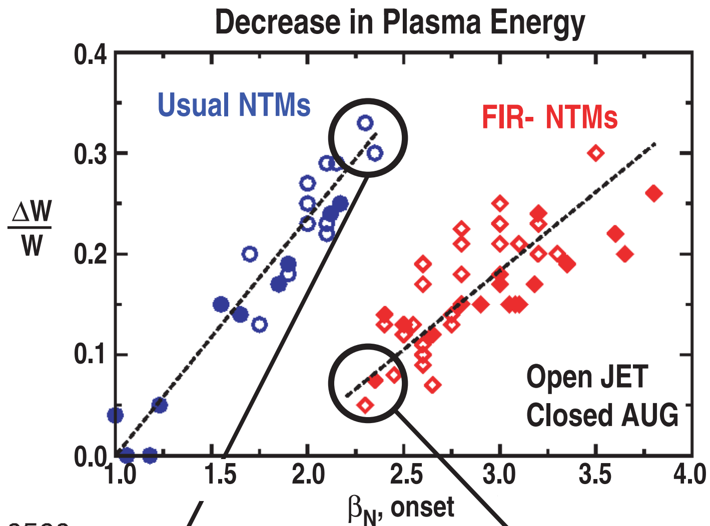
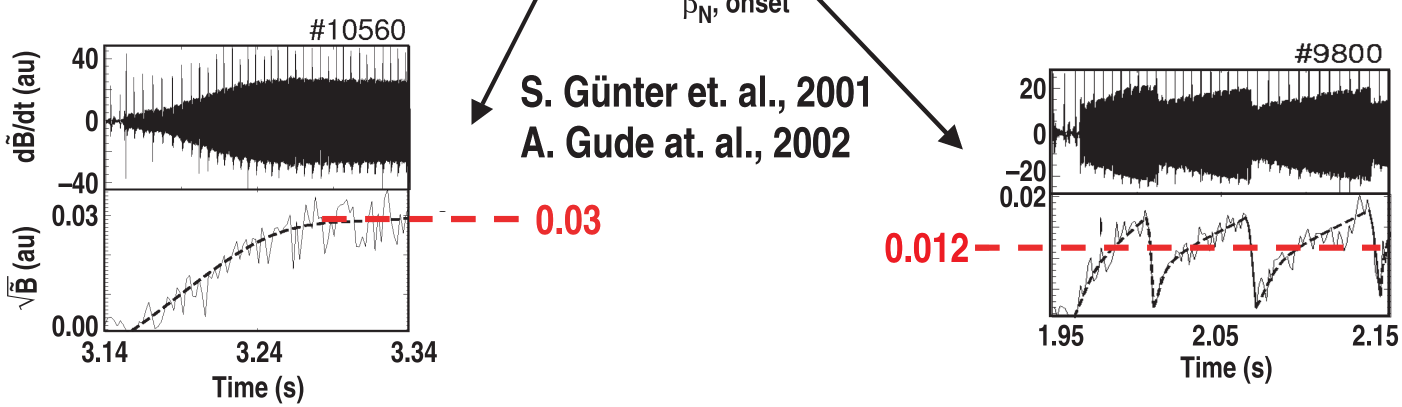
FIR (Frequently Interrupted Regime) – NTMs

- **Only benign confinement degradation by 3/2 NTM**
  ★ amplitude drops caused by non-linear coupling to (4,3) and (1,1) modes

- **Example of a stabilizing effect of a non-resonant helical perturbation on an NTM (Q. Yu et al., 2000)**





- **Active triggering possible by ECCD at q ≈ 4/3 (M. Maraschek et al., 2005)**

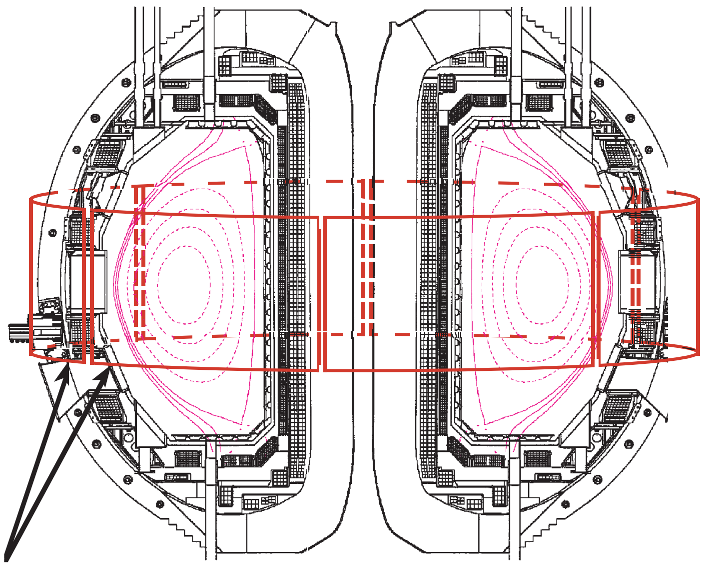
ASDEX Upgrade

EFDA JET

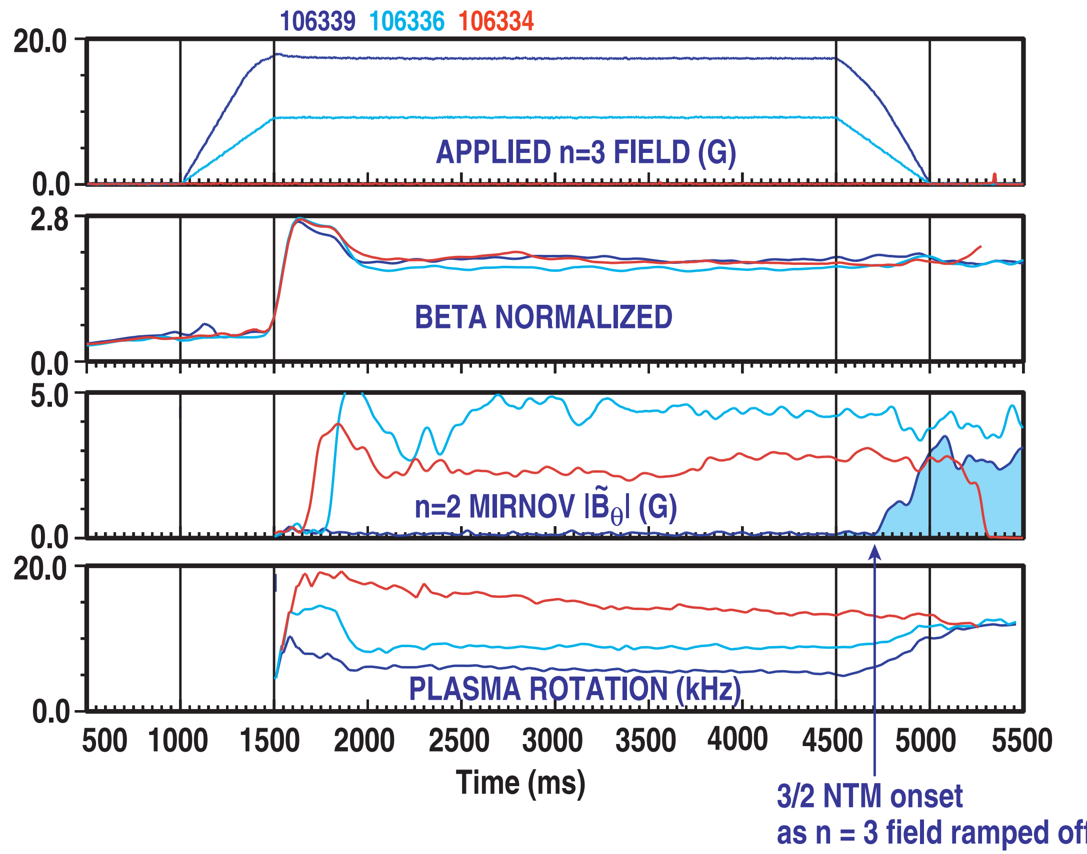
144-05/RJL/rs

Applied Helical Field of Different Helicity Can Weaken the NTM Perturbed Bootstrap Current, Stabilizing It

- **DIII–D 6 – section C-coil**
  - ★ **n = 3 helical field is predominantly non-resonant**



- **Successful in inhibiting the 3/2 NTM (R.J. La Haye, S. Günter et al., 2002)**
  - ★ **but plasma rotation reduced**
    — an issue for ITER



A Major Line of Research on NTM Stabilization at High Beta is Use of Microwave Power Co–Current Drive at a Rational Surface

- **Two stabilizing mechanisms predicted**

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta_0' r + \delta\Delta' r + a_2 \frac{j_{bs}}{j_{||}} \frac{L_q}{w}\left[1 - \frac{w_{marg}^2}{3\,w^2} - K_1 \frac{j_{cd}}{j_{bs}}\right]$$ mod. Rutherford Eqn

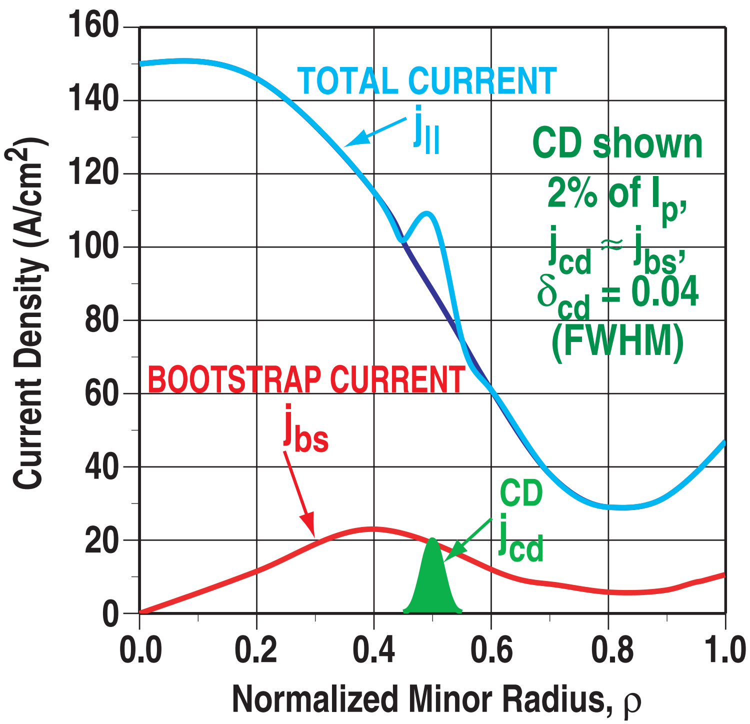
CD makes Δ' more negative

CD replaces "missing" bootstrap current

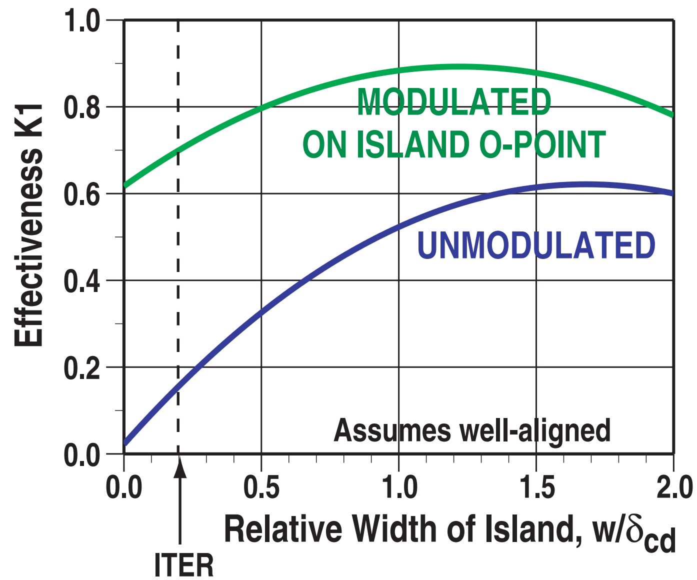
E. Westerhof 1990,
A. Pletzer and
F.W. Perkins, 1999

$$\delta\Delta' r \propto \frac{-L_q}{\delta_{cd}} * \frac{j_{cd}}{j_{||}}$$

if well-aligned

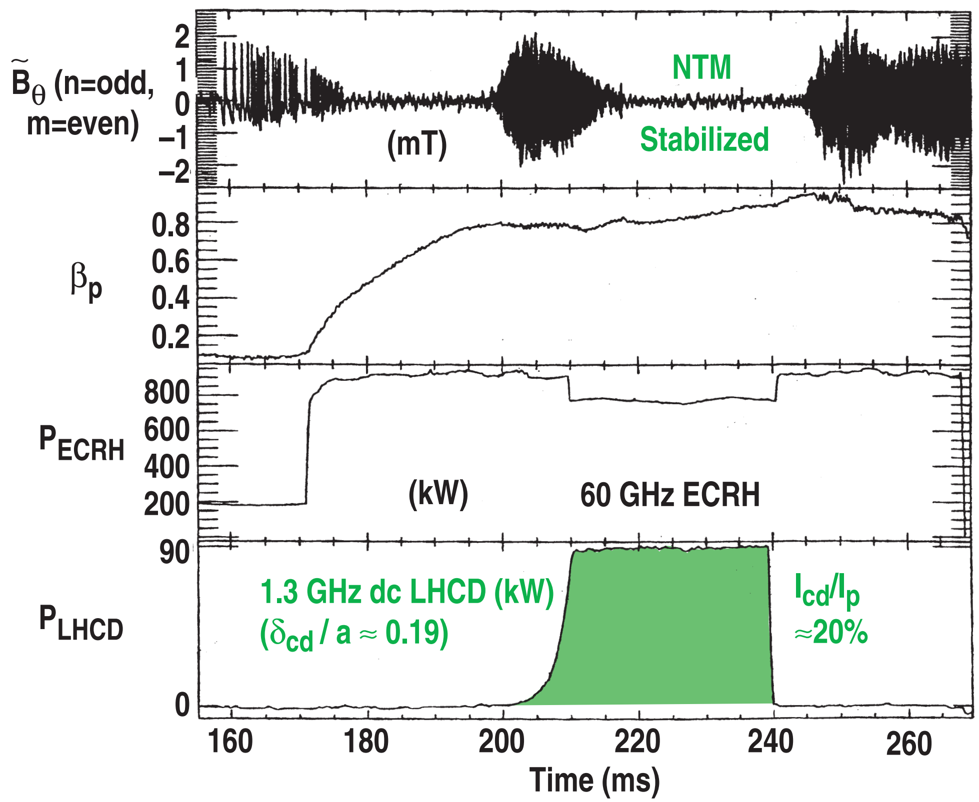


C.C. Hegna and J.D. Callen 1997,
H. Zohm 1997, F.W. Perkins et al., 1997



Lower Hybrid Current Drive Shown to Stabilize m/n = 2/1 NTM in COMPASS-D

- LHCD is an alternate NTM control for ITER (G. Giruzzi, et. al., 1999)
  - ★ but microwave power sources, broad CD and aiming are issues
- COMPASS-D (C.D. Warrick, et. al., 2000) consistent with reduction in stability index Δ´



- 2/1 NTM stabilized by LHCD as long as LHCD is on
- Beta "recovers"
- Balance EC for <u>no</u> ECCD
- LHCD relatively broad and large current

UKAEA Fusion Working with Europe

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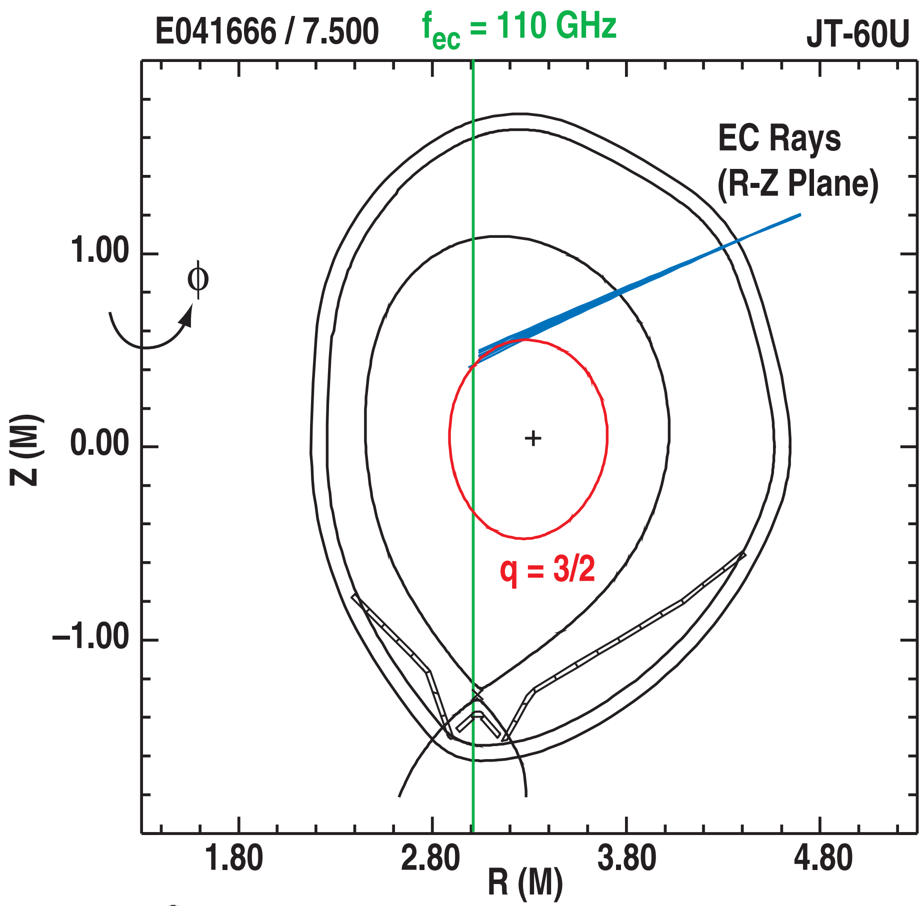
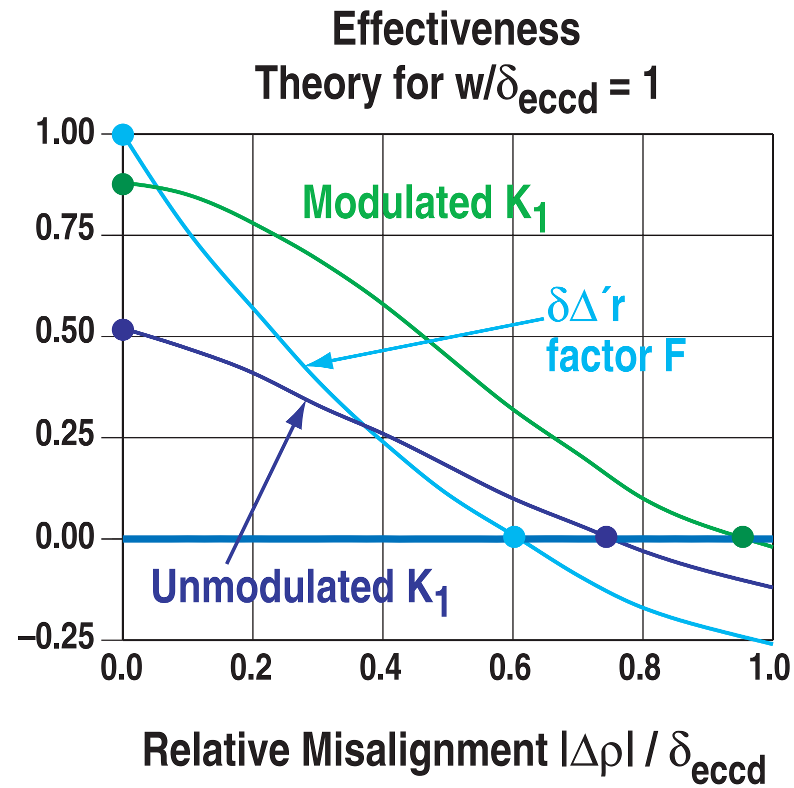
Electron Cyclotron Current Drive Stabilization of NTMs is Proving Effective Across the World

- **Successful on ASDEX Upgrade, DIII–D and JT-60U without using modulation**
  - ★ advantage of ECCD is narrow current drive
    - — but alignment on mode rational surface must be "precise"





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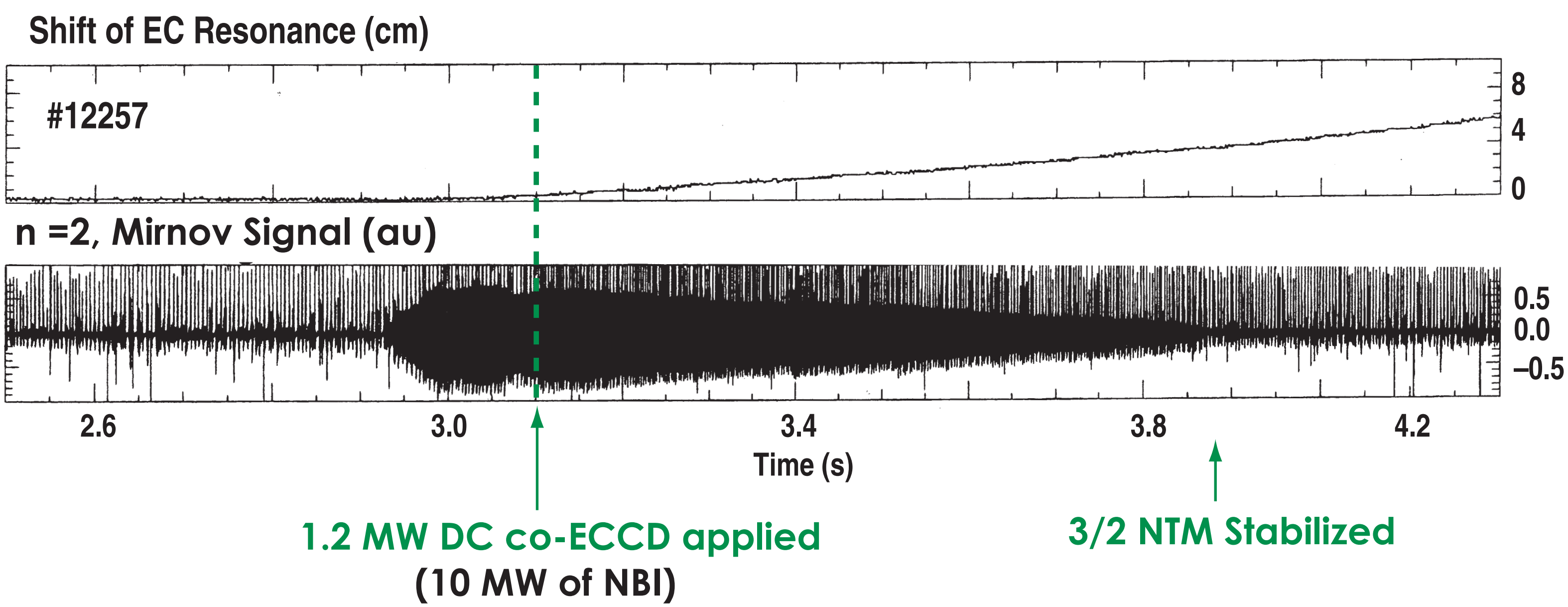
ASDEX Upgrade Uses a Slow Toroidal Field Scan to Match the ECCD to the Rational Surface

(G. Gantenbein et. al., 2000, H. Zohm et. al., 2001, F. Leuterer, et. al., 2003)

- **First device to completely stabilize an NTM with ECCD**
  - ★ complete stabilization of m/n = 3/2 NTM
    - — $I_{ECCD}/I_P \approx 1.4$ %



ASDEX Upgrade

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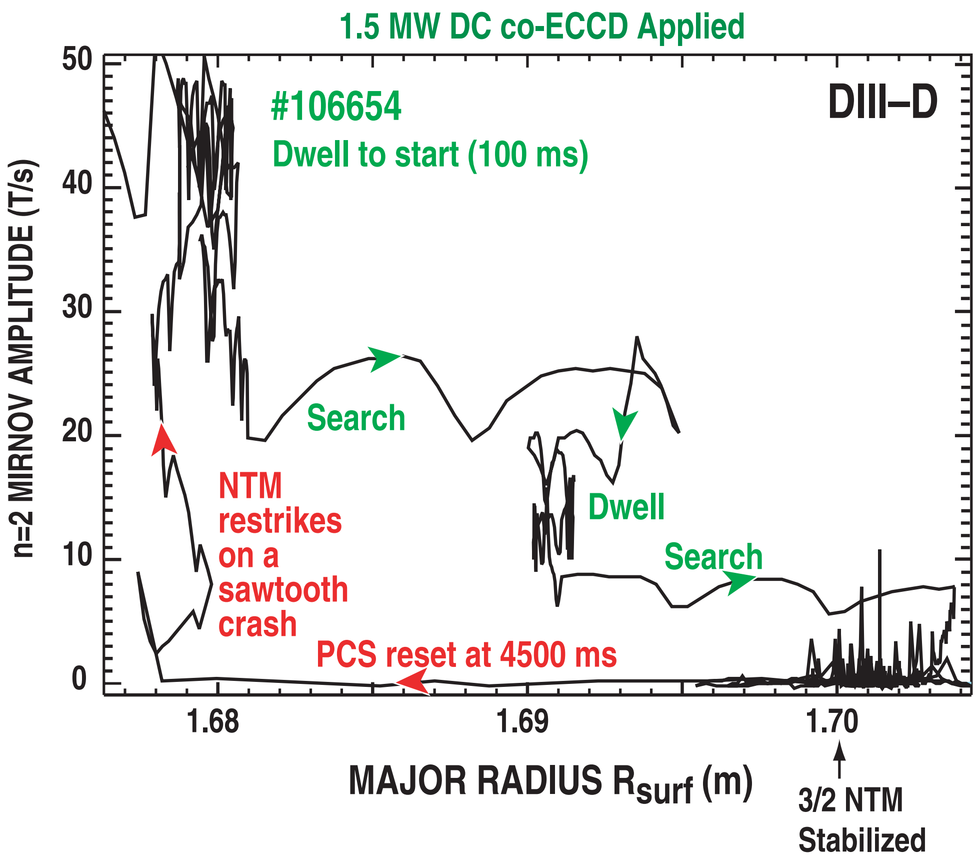
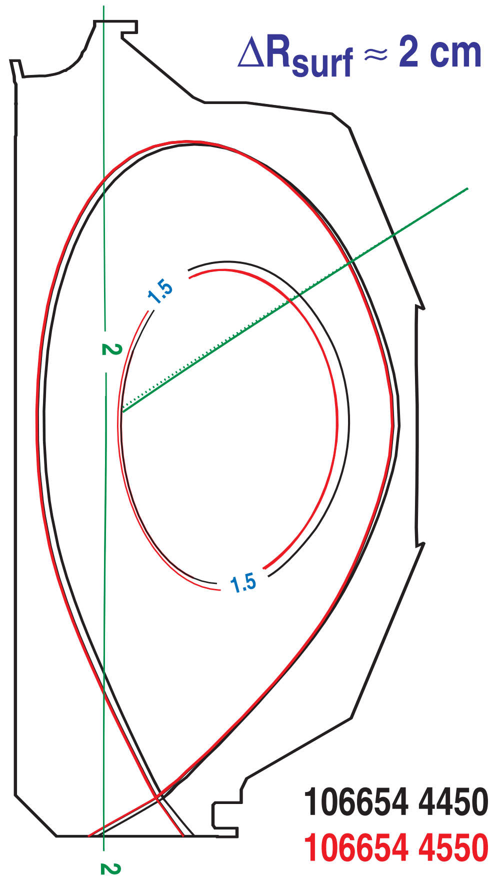
DIII-D Uses Real-Time Feedback of Plasma Major Radius to Put the Rational Surface on the ECCD

(R.J. La Haye et. al., 2002, R. Prater, et. al., 2003, R.J. La Haye et. al., 2005)

- "Search and Suppress" locks onto optimum alignment
  - ★ island is placed on current drive
  - — by moving plasma slightly

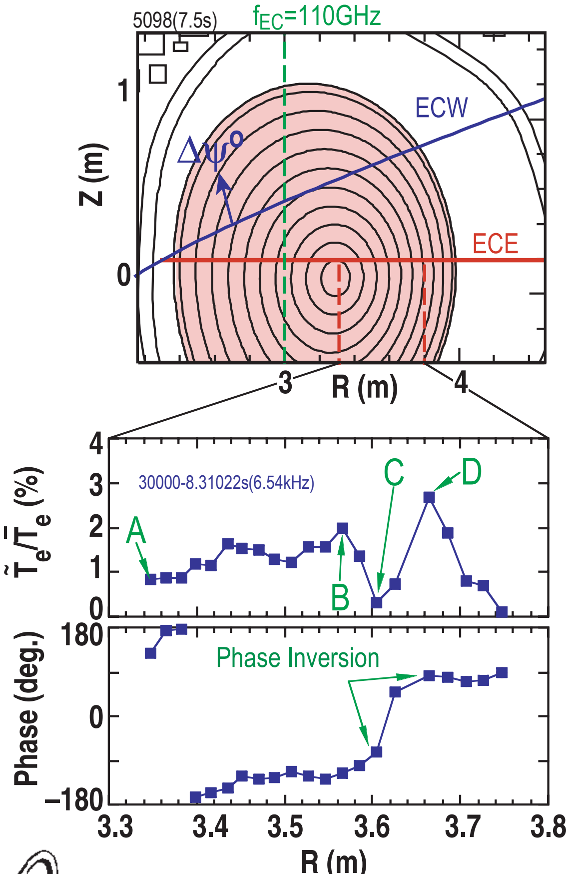


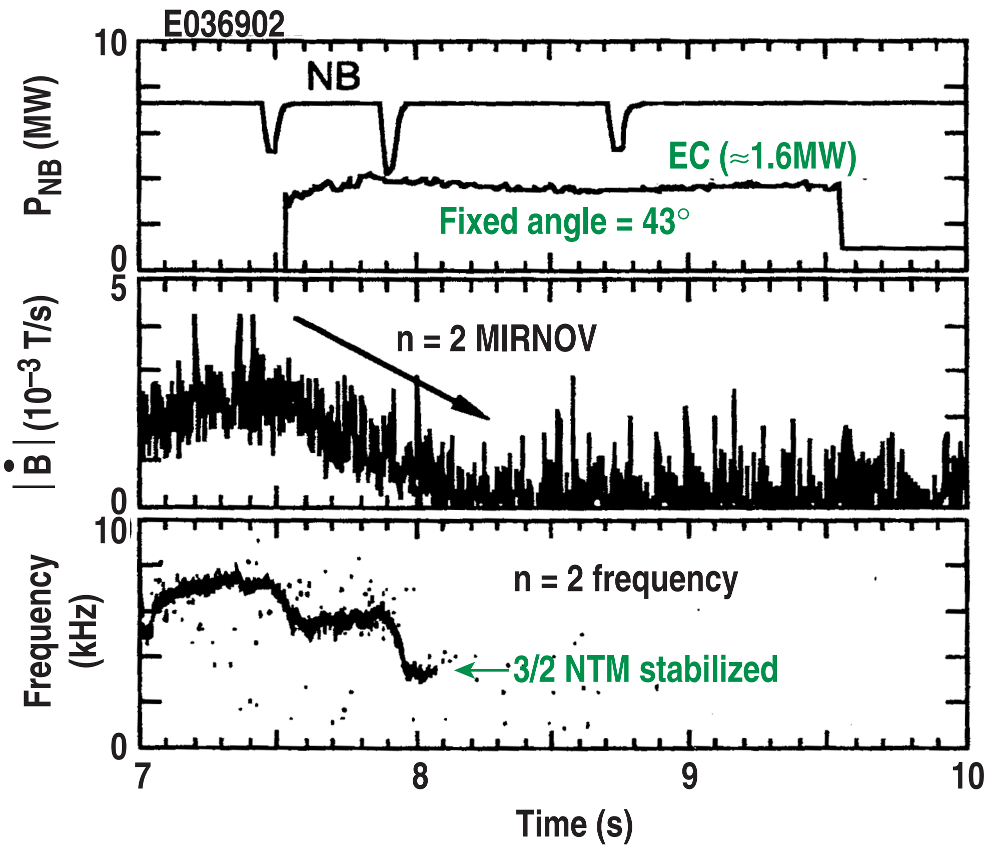


JT-60U Changes the Launcher Mirror Angle to Put the ECCD on the Island Rational Surface

(A. Isayama et al., 2000, K. Nagasaki et al., 2003, N. Hayashi et al., 2004)

- Complete stabilization of m/n = 3/2 mode using 1.6 MW DC ECCD, $I_{ec}/I_p \approx 2\%$
- Optimum injection angle also determined by heterodyne radiometer





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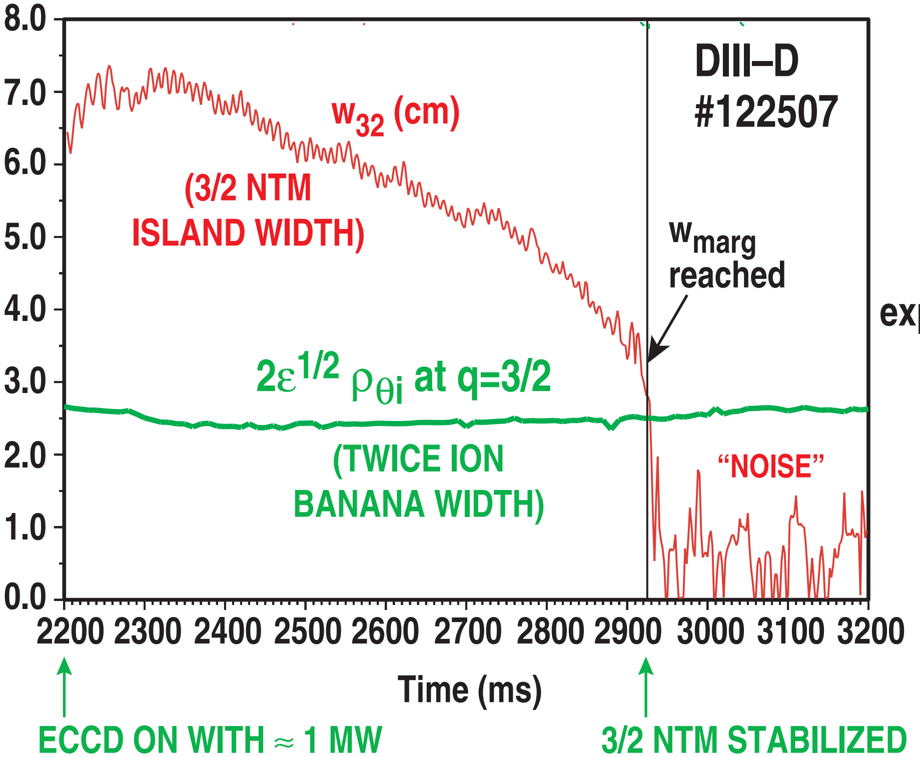
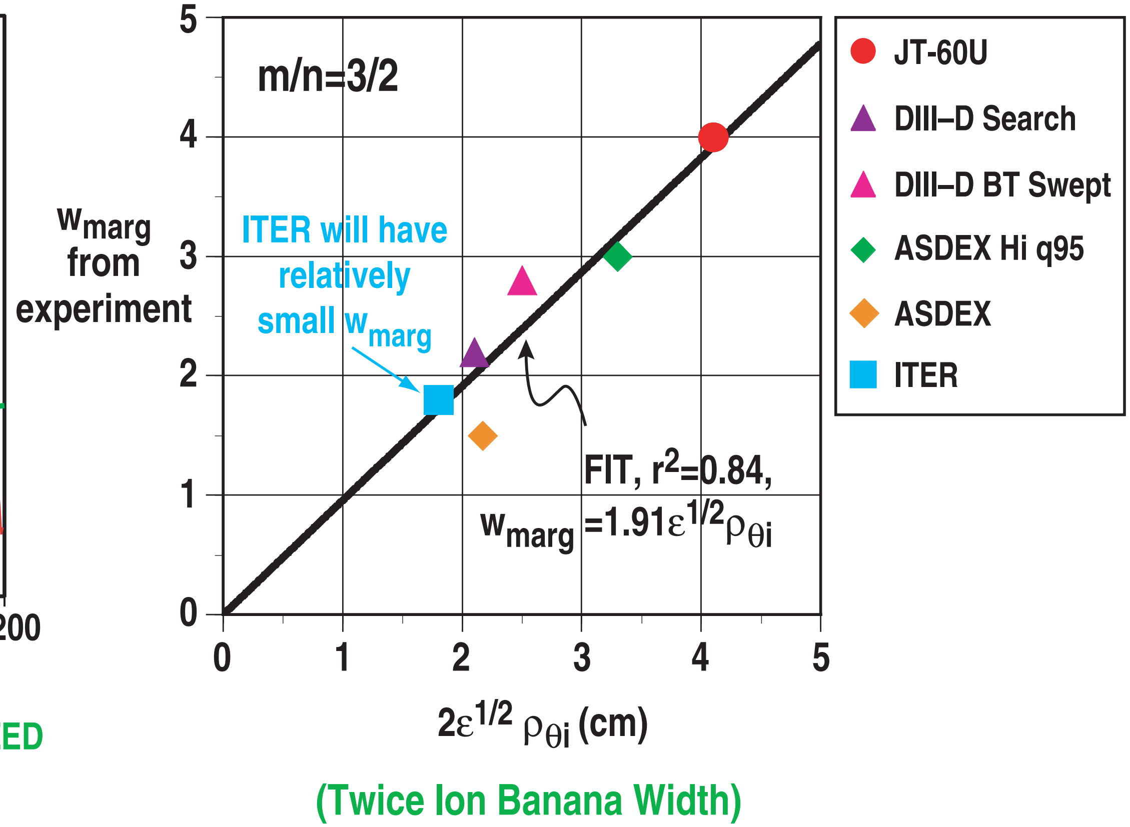
Comparison of Case Studies of ECCD Stabilization of m/n = 3/2 NTM Show Similar Phenomenology

(R. La Haye, et al., 2005)

- **All "suddenly" stabilize when $w \approx 2\varepsilon^{1/2} \rho_{\theta i}$, twice the ion banana width**
  - ★ consistent with the beta rampdown results





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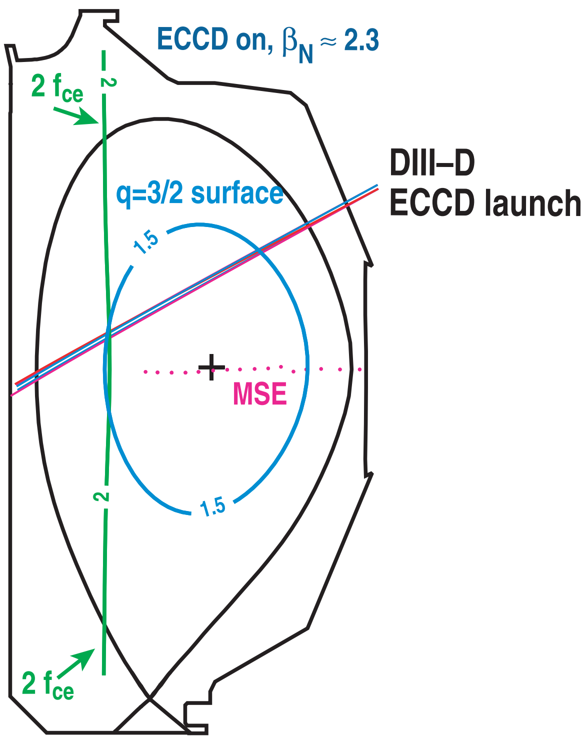
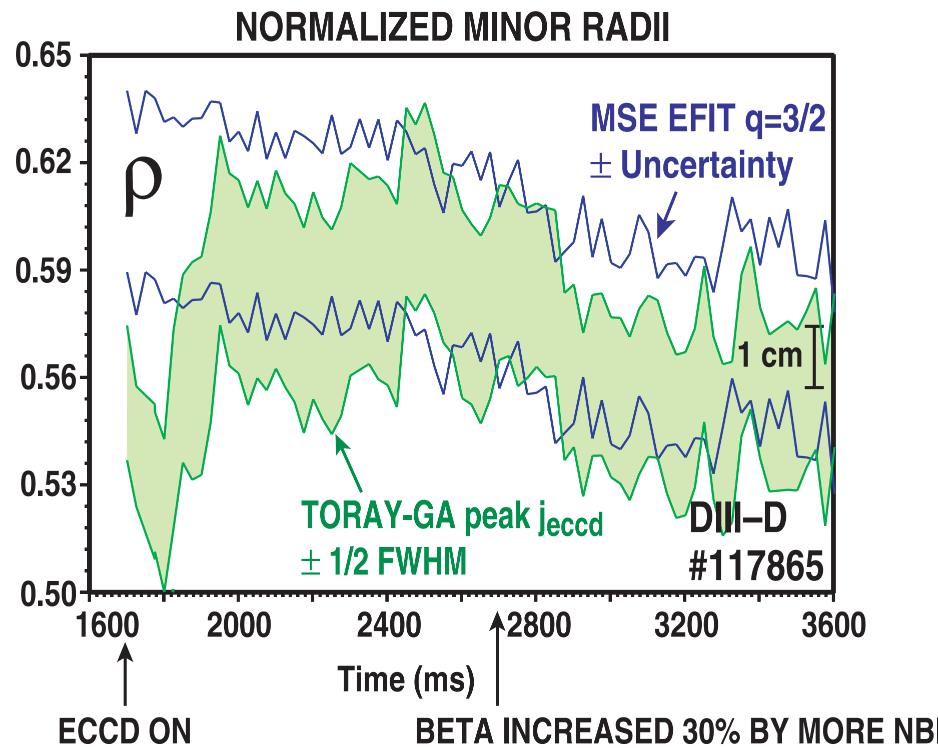
Preemptive ECCD Can Avoid NTM Occurring

- **JT-60U has applied "early ECCD" with best estimate of alignment fixed**
  - ★ 3/2 NTM avoided with EC on and beta constant (K. Nagasaki, et al., 2003)
- **DIII–D uses early ECCD with real-time equilibrium reconstruction for alignment**
- **Motional Stark Effect diagnostic of plasma poloidal field profile**
  - ★ accurate location of rational sufaces (B.W. Rice, et al., 1997)

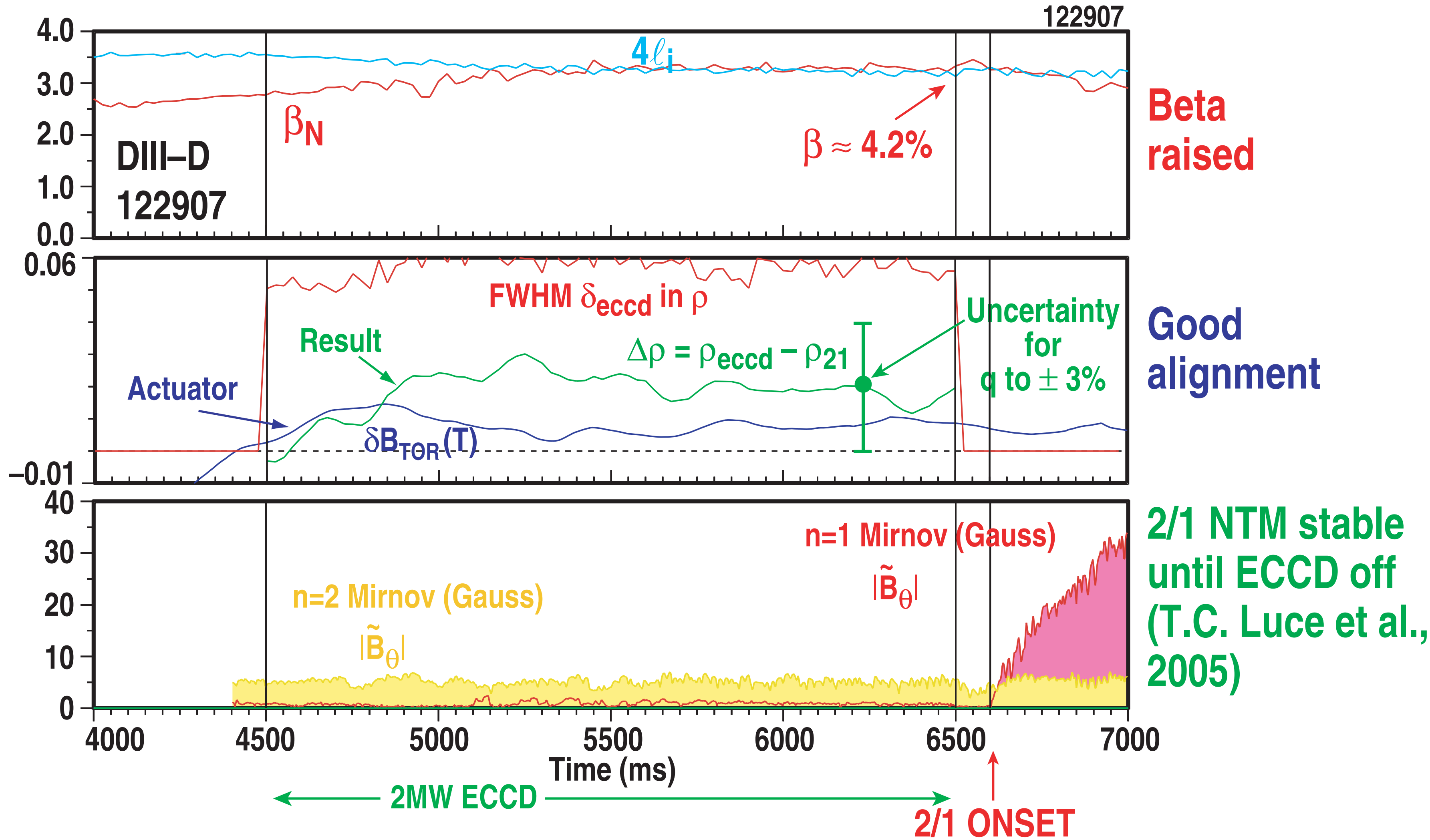


- **Real-time MSE equilibria (J.R. Ferron et al., 1998)**
  - ★ allow alignment to be maintained
  - — NO m/n = 3/2 NTM ever appears



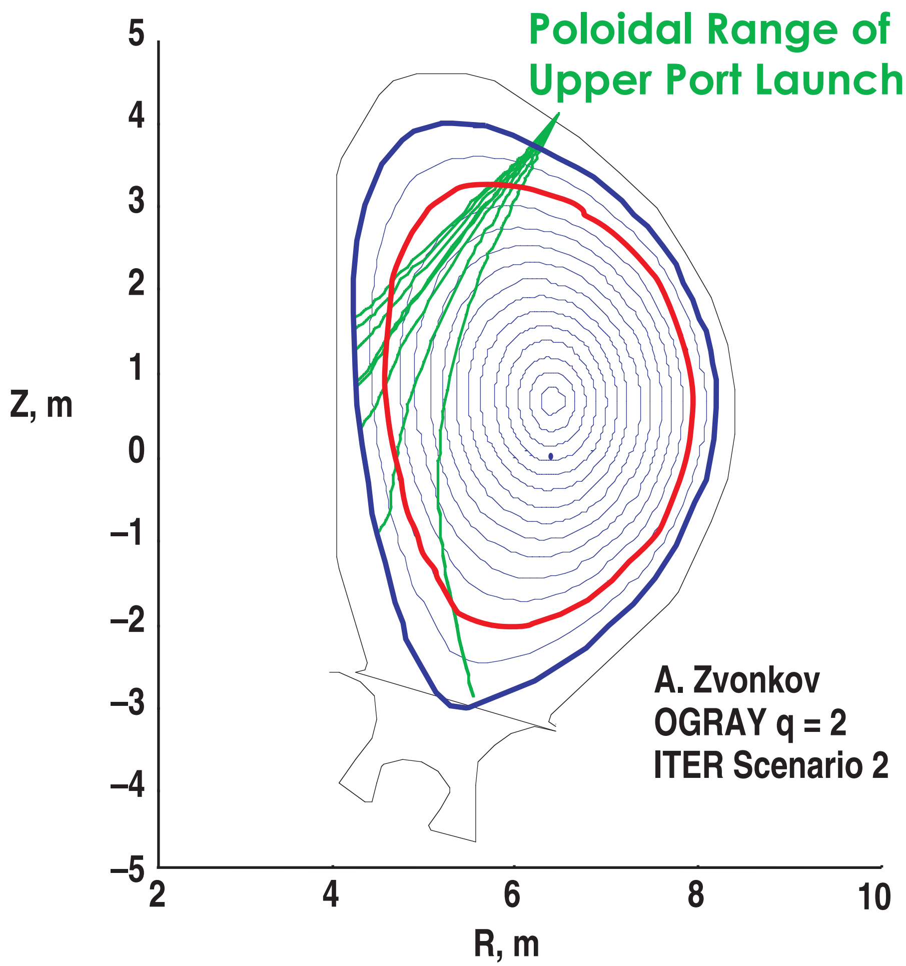
Preemptive ECCD Avoids m/n=2/1 NTM at n=1 Free Boundary Beta Limit in DIII–D

- **Hybrid scenario with m/n=3/2 NTM keeping q(0)≈1**
  - ★ Toroidal field adjusted by **real-time MSE EFIT** to keep peak j_{eccd} on q = 2



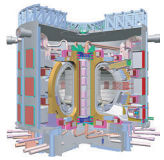
ECCD is the Primary Tool for NTM Control in ITER

(ITER Physics Basis Editors 1999 and Tokamak Physics Basis Editors 2005, Nucl. Fusion)



20-170 GHz CW Gyrotrons (20 MW injected)

- **Relatively wide ECCD**
  - ★ $\delta_{eccd} \approx 7.5$ cm
    - — $2\varepsilon^{1/2} \rho_{\theta i}/\delta_{eccd} \approx 1/5 << 1$
      ... favors using modulation



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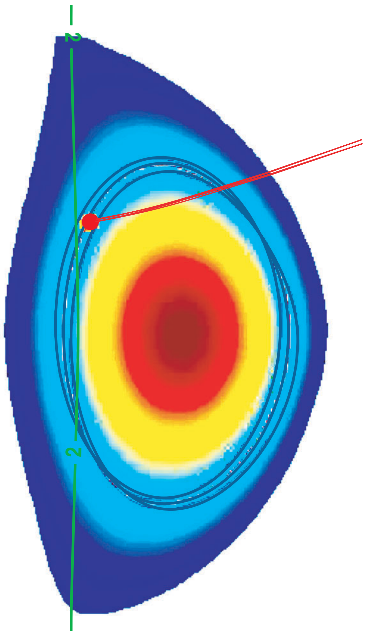
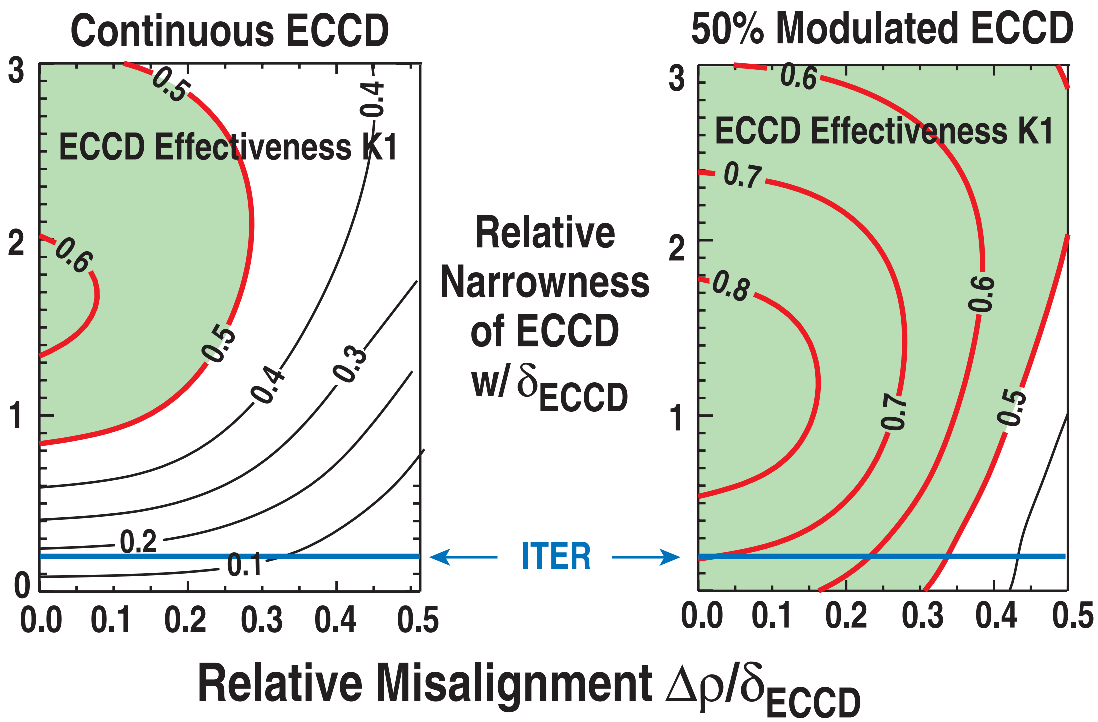
Modulation of ECCD in Phase with Island O-point Could be More Effective in ITER

(F.W. Perkins, R.W. Harvey, M. Makowski, M.N. Rosenbluth, 1997)

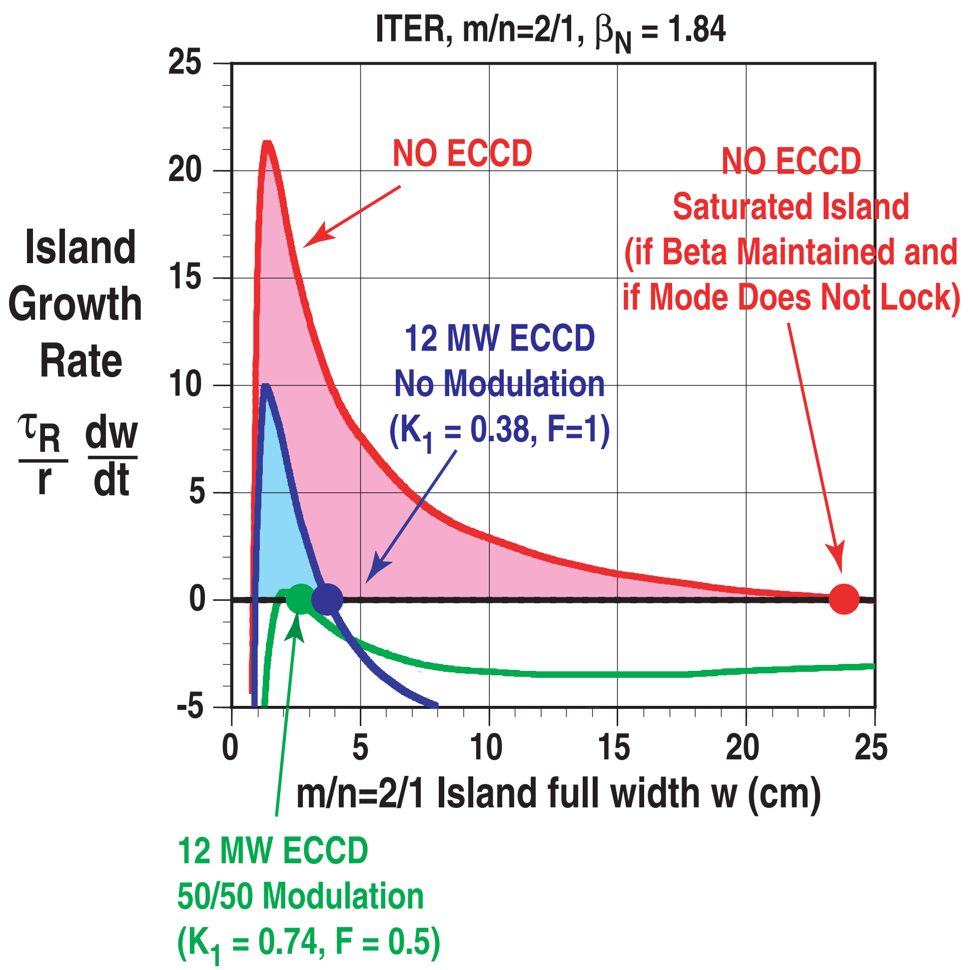




- **Disadvantages: (1) modulation, (2) $\delta\Delta'$r halved (3) need island to modulate**
  - ★ issues of plasma dynamical response to modulation (G. Giruzzi et al., 1999)
- **Present experiments have w/δ_{ECCD} ~1, so no big advantage**
  - ★ ASDEX Upgrade has tested the effect of phasing co-ECCD (H. Zohm et al., 1999)
    — stabilizing on O-point, destabilizing on X-point

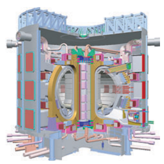
ECCD in ITER Can Control the m/n=2/1 Mode

- **No ECCD**
  - ★ large saturated island
    - — mode locking and disruption



- **with ECCD**
  - ★ **adjust modulated j_{ec} for $w \gtrsim 2\varepsilon^{1/2}\rho_{\theta i}$**
    - – a stationary operating point at 12 MW
  - ★ **unmodulated 12 MW less effective**
    - – but should avoid locking and disruption

(Benchmarking NTM physics and ECCD to ASDEX Upgrade, DIII–D, JET and JT–60U, R.J. La Haye, R. Prater, R.J. Buttery, N. Hayashi, A. Isayama, M.E. Maraschek, L. Urso and H. Zohm, 2005)



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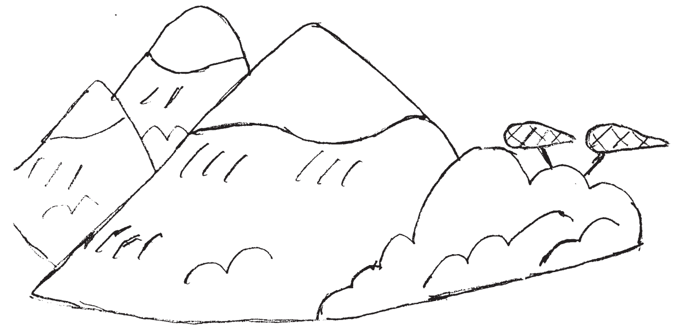
Lots of Progress in Understanding and Control of NTMs

- **The NTM is linearly stable and nonlinearly unstable**
  - ★ metastable state must be "seeded" for an island to grow
    - – island destabilized by helically perturbed bootstrap current

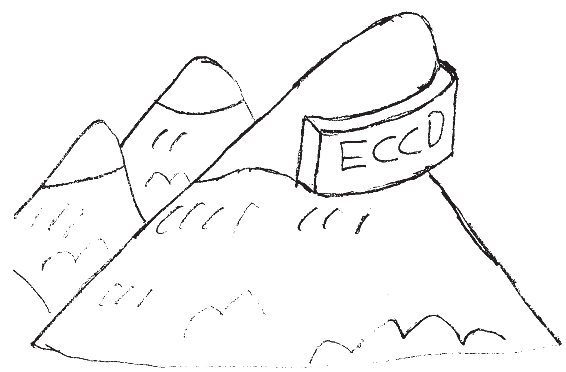
      . . . high beta instability

- **Scaling of critical beta with normailzed ion gyroradius**
  - ★ extrapolates to increased susceptibility in ITER
    - – unless high Magnetic Reynolds number

      inhibits reconnection and seeding



- **ECCD in ITER is an essential element for controlling m/n = 2/1 tearing modes which otherwise lock and disrupt**
  - ★ existing devices need to confirm the advantage of ECCD modulation

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