MHD STABILITY ISSUES IN A BURNING PLASMA

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GENERAL ATOMICS

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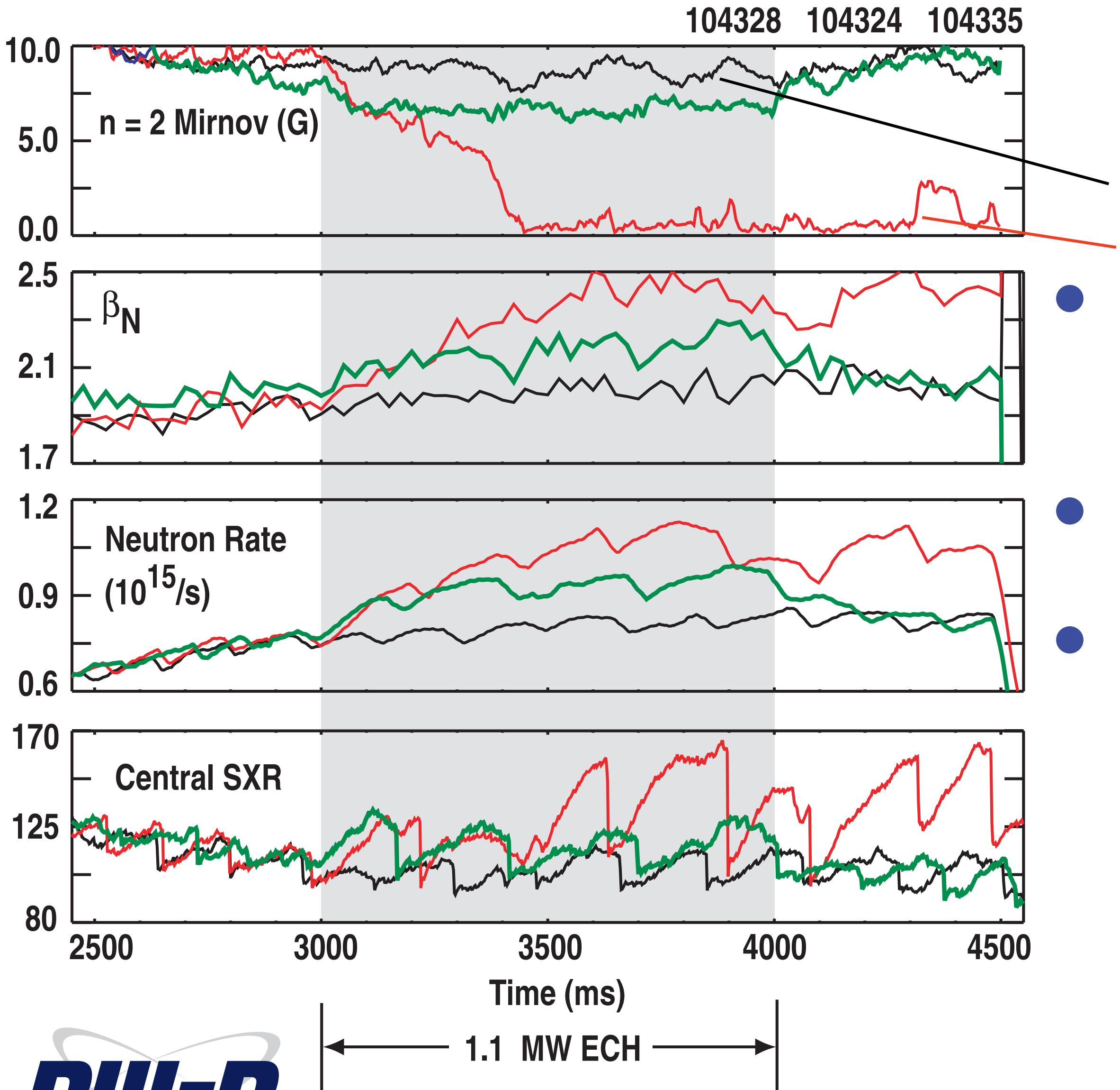
PRESENT UNDERSTANDING OF MHD STABILITY LIMITS IS SUFFICIENT TO DESIGN A BURNING PLASMA EXPERIMENT

- **Ideal MHD stability limits are well understood and predictable**
  - Upper limit to plasma stability
  - Credible foundation for design of next-step devices
- **Non-ideal effects introduce greater uncertainty**
  - Resistivity, finite Larmor radius, energetic ions, ...
- **Resistive instabilities are less predictable but may be avoidable**
  - Neoclassical tearing modes can be avoided transiently by profile modification
  - Recent experiments have suppressed NTMs with localized current drive
- **Steady operation very near stability limits has been demonstrated**
- **Burning plasma experiments go beyond present experience with MHD stability, and present new scientific challenges**

FULL STABILIZATION OF NTM OBTAINED WITH MODEST ECH POWER



- After reaching the seed size, the stabilization is rapid because the mode growth rate is negative
- β_N increases during stabilized phase
- Even in presence of large sawteeth the mode doesn't grow

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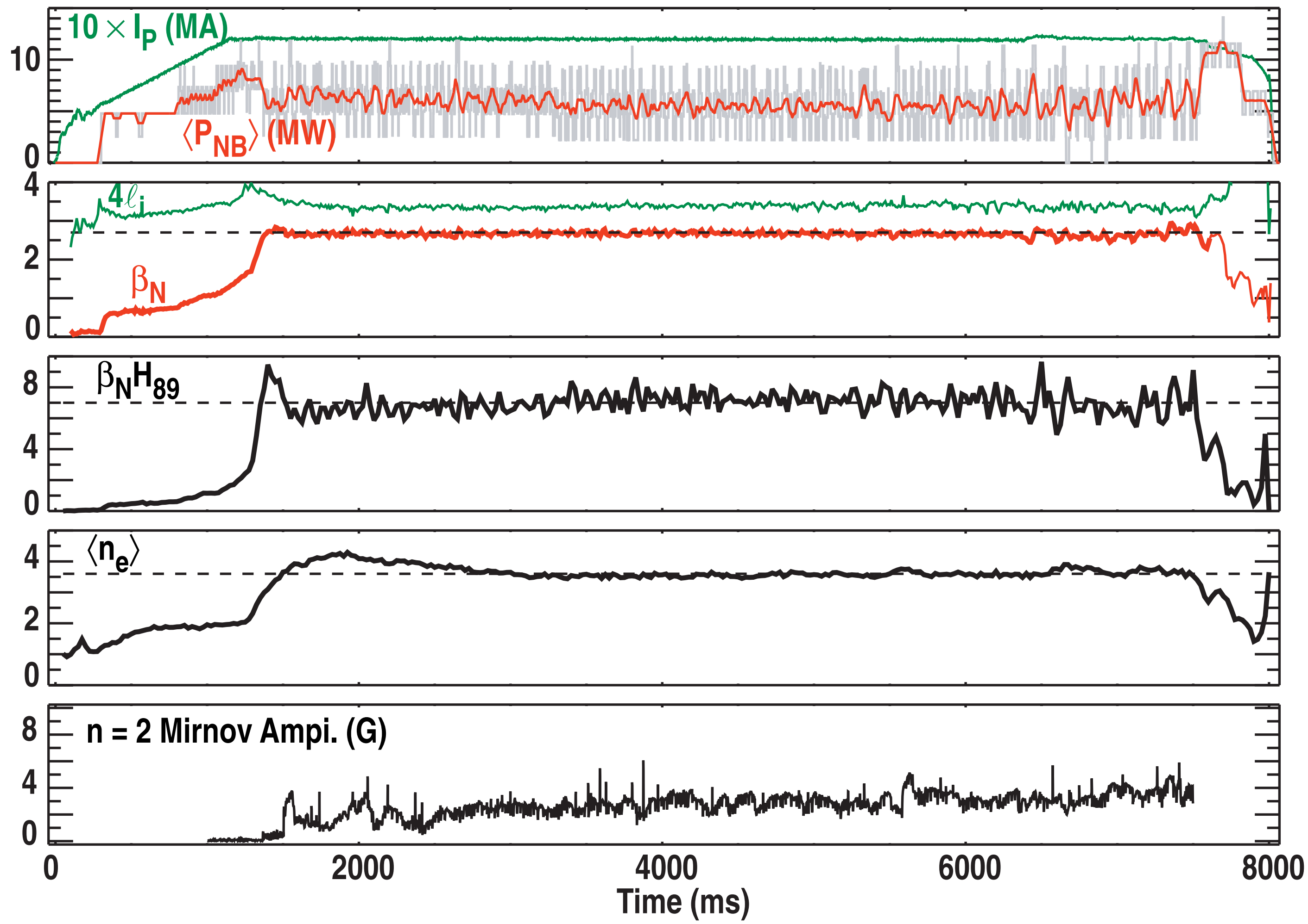
STEADY STATE HIGH PERFORMANCE DISCHARGES CAN BE ACHIEVED USING UNDERSTANDING OF STABILITY LIMITS AND DISCHARGE CONTROL

- β controlled to remain ~20% below predicted RWM limit
  - β also kept 5% below experimental 2/1 NTM β limit
- Discharge continued in steady state until beam termination
- No sawteeth
  - $q_0 \gtrsim 1$



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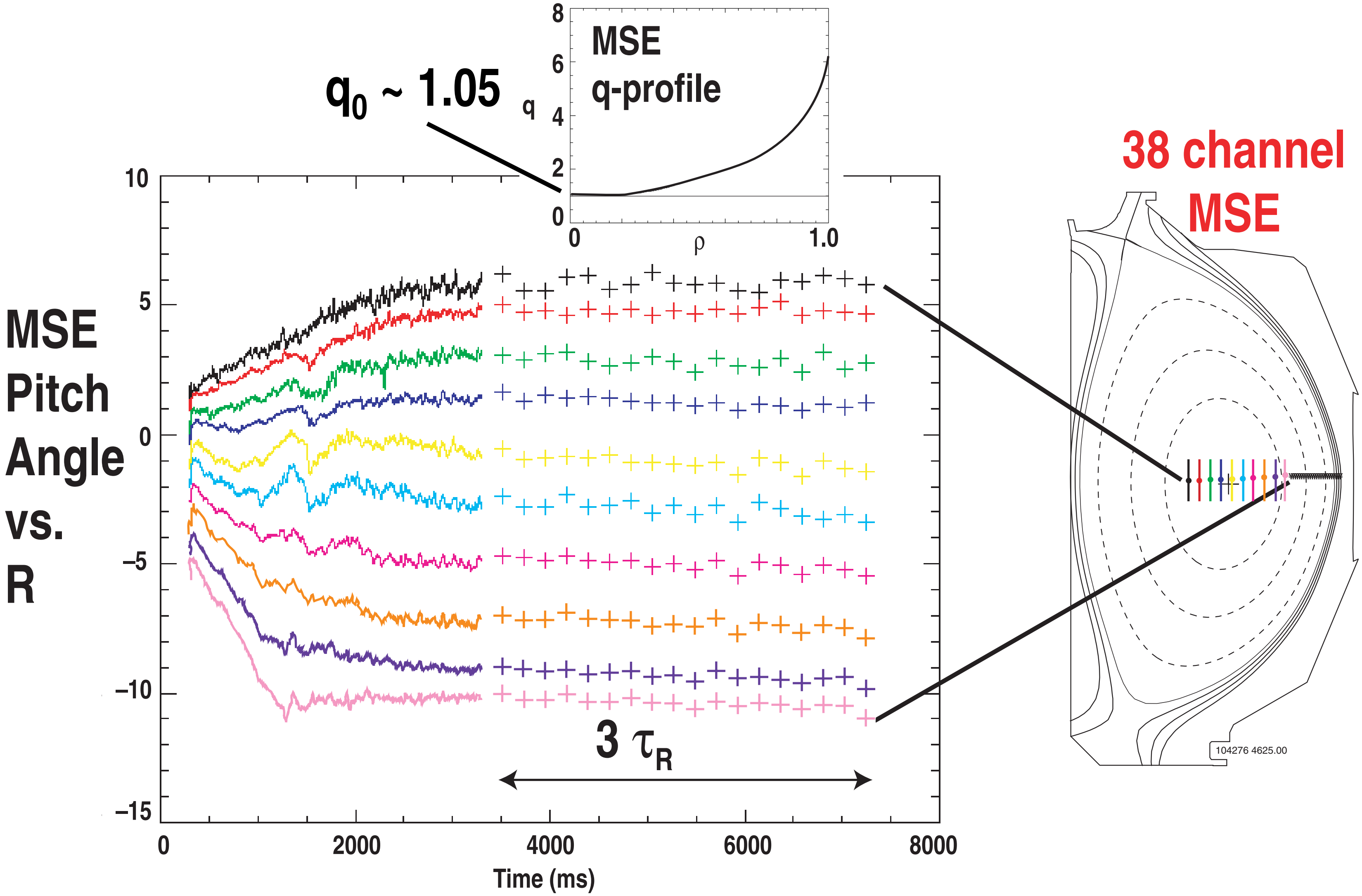
MSE shows J(r) profile has reached resistive equilibrium with q_0 ~1.05



WHAT DISTINGUISHES A BURNING PLASMA FROM EXISTING EXPERIMENTS?

- **Self-heating**
  - Less external control over profiles (p, j, Ω)
- **Energetic particle effects**
  - Large isotropic population of fast ions
- **New ranges of dimensionless parameters**
  - $\rho_i^* = \rho_i/a \sim T^{1/2}/aB$
  - $S = \tau_A/\tau_R \sim aBT^{3/2}/n^{1/2}Z_{eff}$
  - $\nu^* = \nu_i/\varepsilon\omega_{bi} \sim nqRZ_{eff}/\varepsilon^{3/2}T^2$

	DIII–D	C-MOD	JT-60U	JET	FIRE	IGNITOR	ARIES-RS	ITER-FEAT	ITER-FDR
aB (m-T)	1.3	1.7	3.5	4.3	5.3	6.1	10	11	16

EXISTING EXPERIMENTS ARE SUFFICIENT TO INVESTIGATE MANY ISSUES OF MHD STABILITY

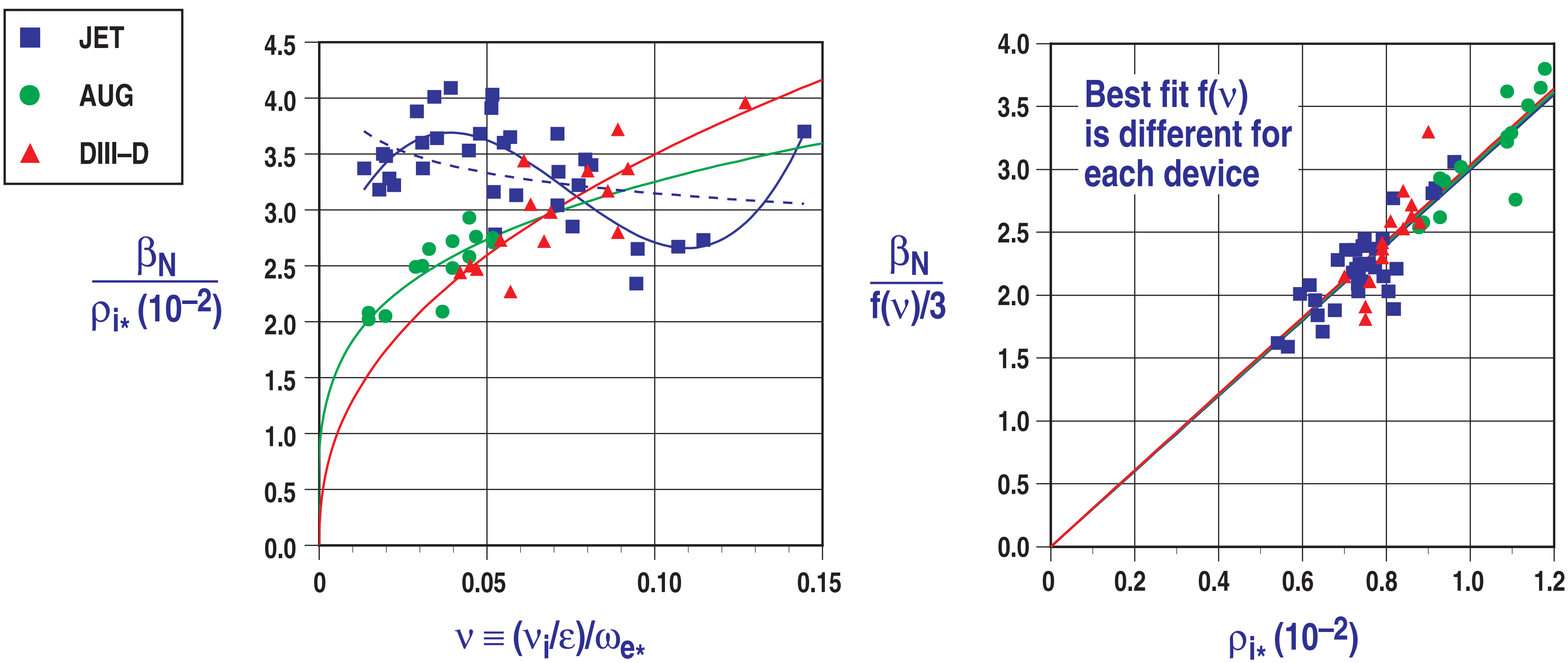
- Ideal MHD stability limits
  - Profile dependence
  - Shape dependence
  - Aspect ratio dependence
- Feedback stabilization of RWM
- ECCD stabilization of NTM
- Edge-driven instabilities
  - Identification of instability
  - Dependence on bootstrap current
- Stability with non-inductively driven current profiles

BURNING PLASMA-SIZE EXPERIMENTS (WITHOUT ALPHA HEATING) ARE REQUIRED TO INVESTIGATE SCALING OF MHD STABILITY PHYSICS

- **NTM beta limit scaling**
  - Threshold island size decreases with decreasing ρ_i^*
  - Seed island size decreases with increasing S
- **Edge-driven instabilities**
  - Edge gradients determine stability limit
  - Pedestal width determines coupling to core
  - Scaling of edge parameters is not well understood
- **Resistive wall mode stability**
  - Rotation frequency required for stabilization may increase with S ($\Omega\ \tau_A$ ~ 0.05)
- **Runaway avalanche during disruption**
  - Number of e-foldings increases with plasma current
  - Runaway electron current multiplication
    - ★ $\gtrsim 10^2$ at I_p = 2 MA
    - ★ $\gtrsim 10^6$ at I_p = 5 MA

NTM THRESHOLD SCALES LINEARLY WITH NORMALIZED ION LARMOR RADIUS

- But scaling of β_N/ρ_i^* with collisionality is not consistent between machines
  - Possible additional dependence on ρ_i^* or S
- $\beta_N \propto \rho_{i*} f(\nu)$ is consistent with polarization/inertial model of Wilson et al.



- Sawtooth-induced 3/2 NTM, ELMing H–mode

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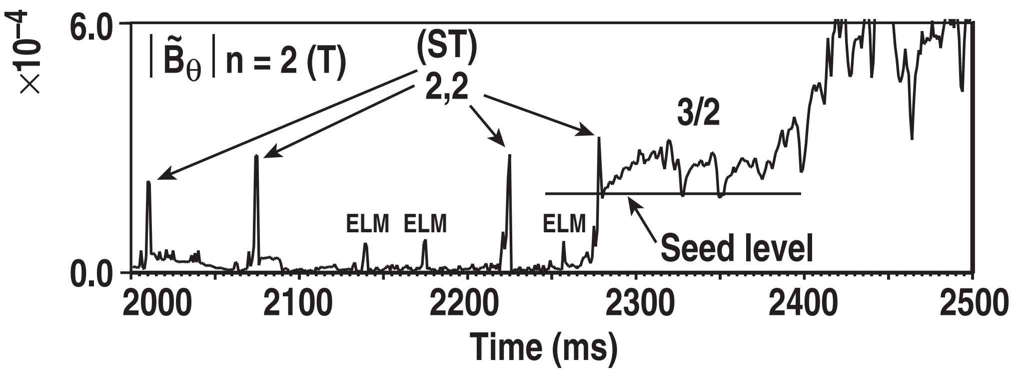
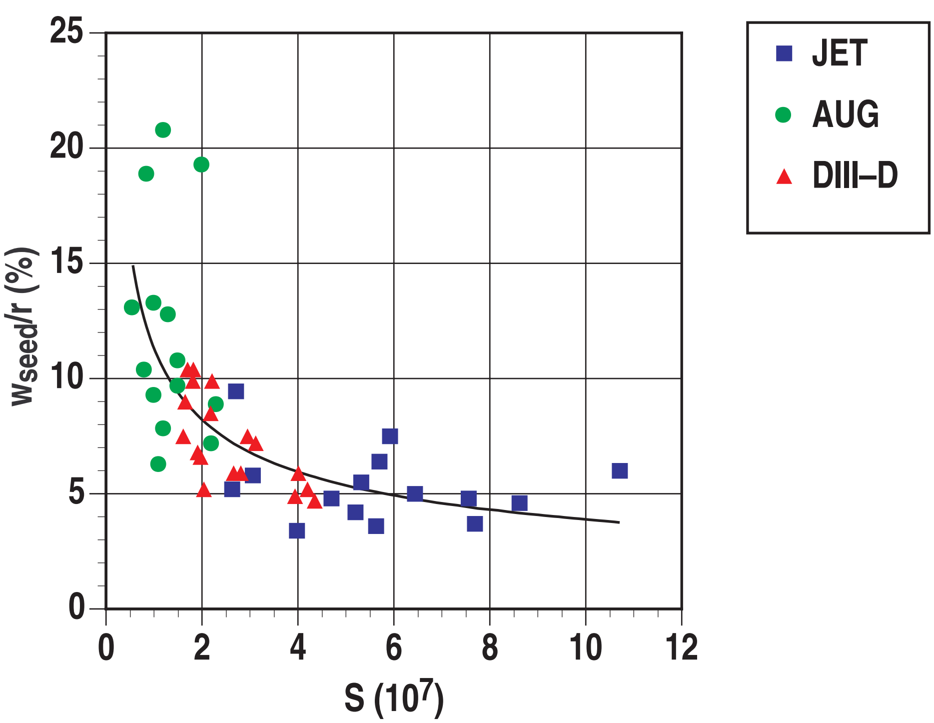
SAWTOOTH INDUCED SEED ISLANDS SCALE INVERSELY WITH MAGNETIC REYNOLD'S NUMBER

- Seed islands estimated from m/n = 3/2 Mirnov level upon excitation

★ $w_s \approx \left(\frac{16rR\,|\tilde{B}_r|}{3s\,B_T}\right)^{1/2}$ with $|\tilde{B}_r| \approx \frac{1}{2}\left(\frac{b}{r}\right)^4 |\tilde{B}_\theta|_{wall}$



- Best fit has $w_{seed}/r \propto S^{-0.46\pm0.05}$, correl r = −0.74 consistent with dynamical coupling model of Hegna et al.



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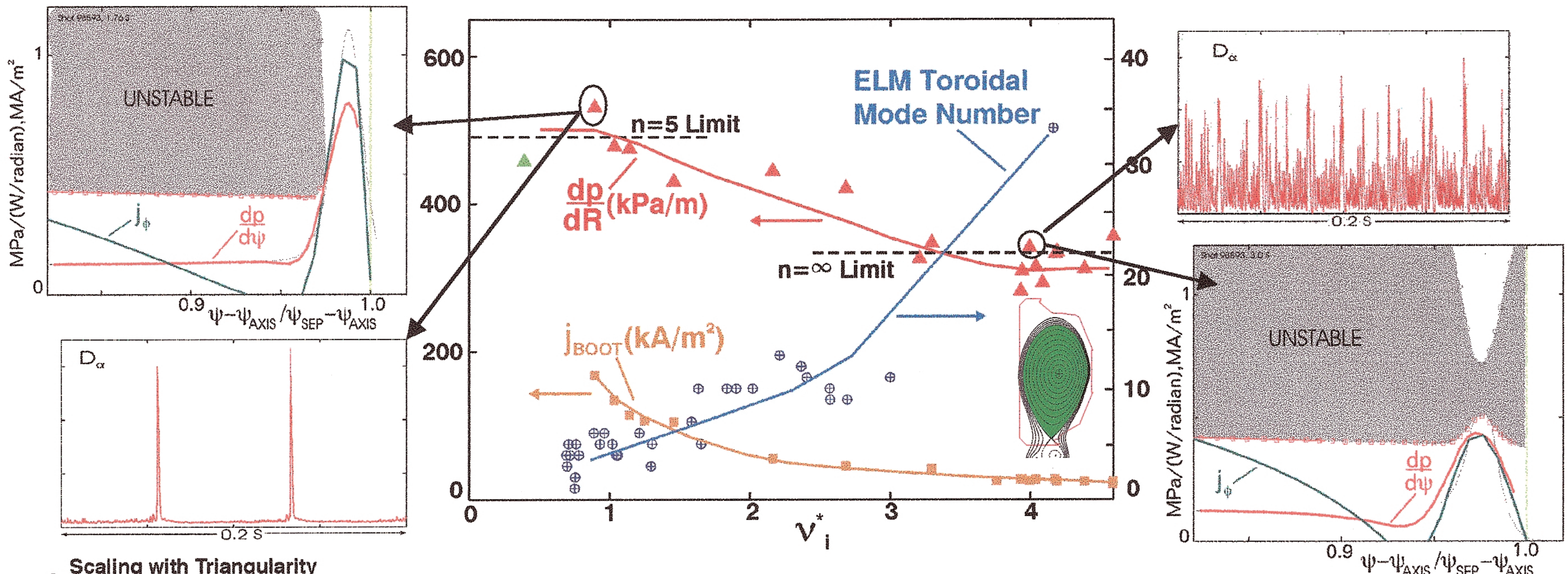
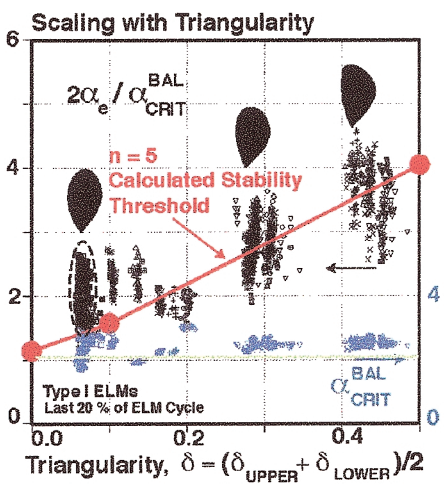
EDGE STABILITY AND ELM CHARACTER DEPEND CRITICALLY ON COLLISIONALITY





- **With increasing edge density or $\nu^* \propto n/T^2$.**
  - Calculated j_{BOOT} decreases ⇒ edge magnetic shear increases, $S \approx S_0 - 2\left\langle j_{TOR}^{EDGE} \right\rangle / \bar{j}_{TOR}$, ⇒ SS access lost
  - ELM modes increase in n.
  - Pressure gradient is reduced from calculated limit for n=5 edge localized ideal kink/ballooning (GATO) to ideal nigh n ballooning mode limit (BALOO).

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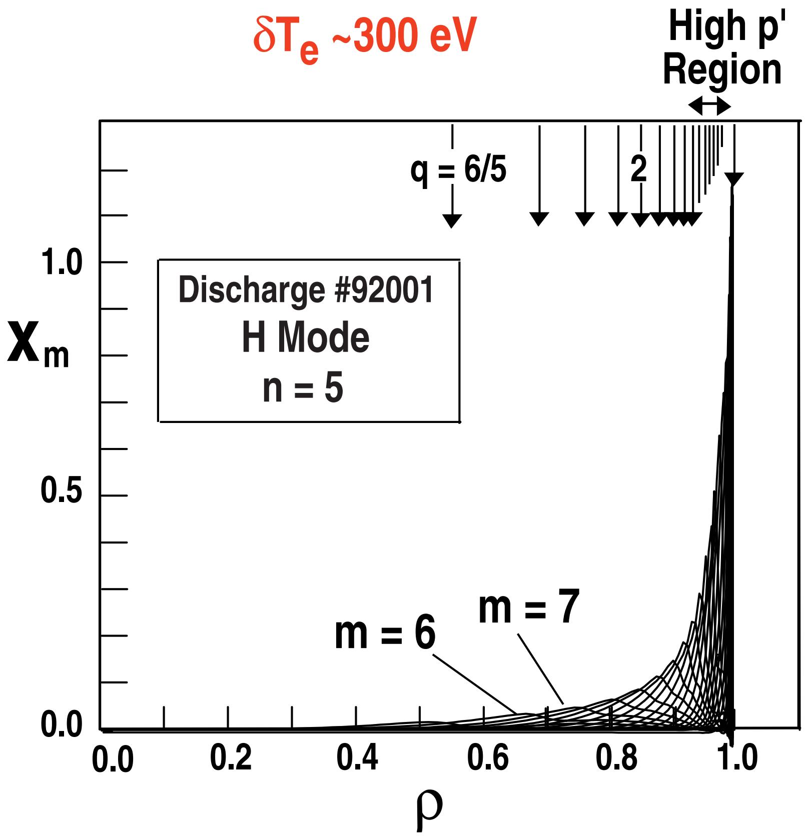
ELM SIZE CORRELATES WITH RADIAL WIDTH OF PREDICTED UNSTABLE INTERMEDIATE n KINK MODE

- Highly localized instability computed from GATO

  ⇒ Type I ELM has little effect

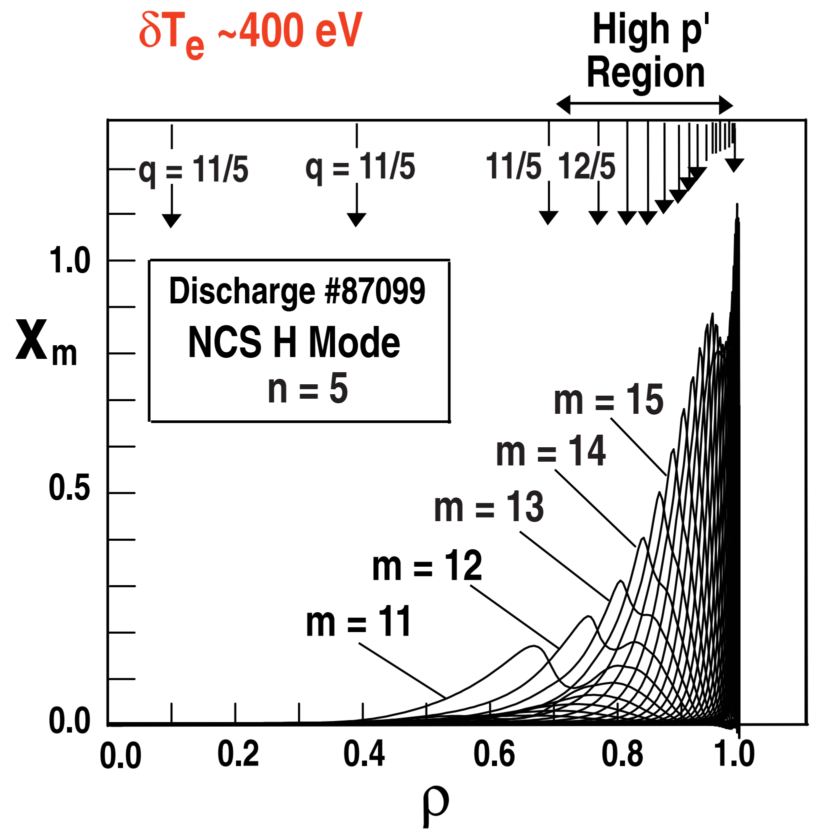
  δT_e ~300 eV



- Predicted instability computed from GATO code penetrates into core

  ⇒ High performance is lost

  δT_e ~400 eV



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A BURNING PLASMA (STRONG ALPHA HEATING) IS NEEDED TO INVESTIGATE KEY ISSUES OF MHD STABILITY

- Energetic particle interactions with MHD modes (sawteeth, fishbones, TAE, ballooning modes, etc.)
  - Stabilization or destabilization of MHD modes by alphas
  - Enhanced transport of alphas by MHD modes
- Self-heating ($P_\alpha >> P_{external} \Rightarrow Q \geq 10$)
  - Stability limits with pressure profiles determined by alpha heating
  - Plasma rotation with little or no external momentum input (RWM stability, mode locking, error field sensitivity)

$$\Omega \sim \omega^* \sim T/a^2B \quad ?$$

- Steady-state operation ($\tau > \tau_{CR} \sim a^2T^{3/2}/Z_{eff}$)
  - Stability limits with self-consistent current density and pressure profiles

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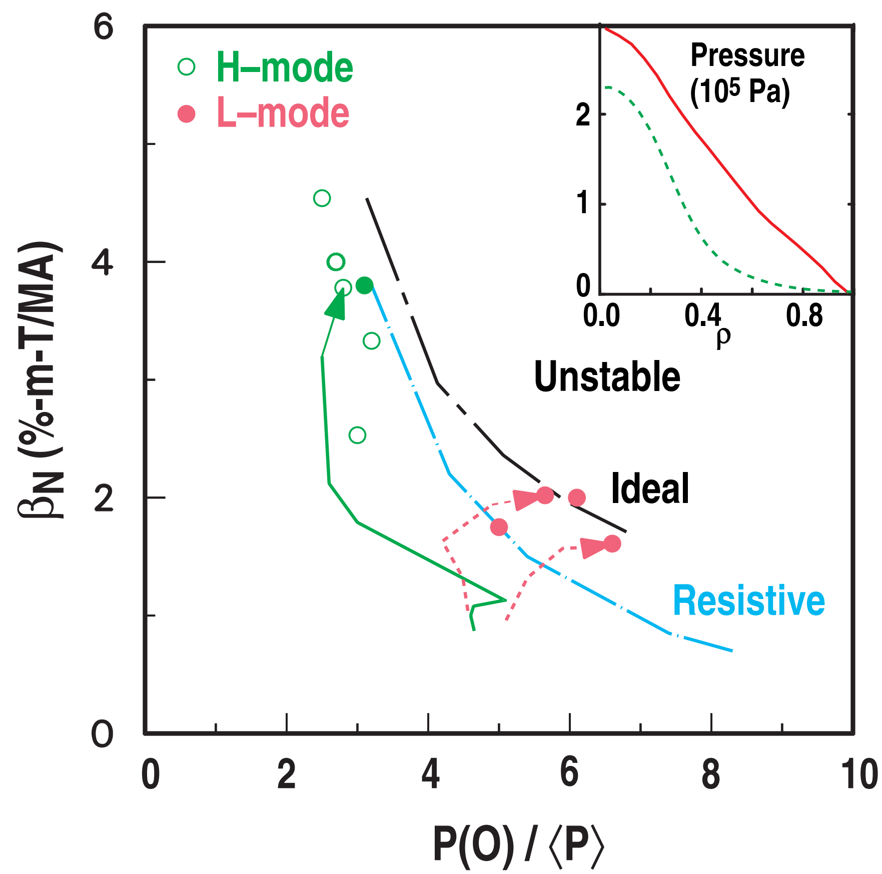
STABILITY LIMIT DEPENDS STRONGLY ON THE FORM OF THE PRESSURE PROFILE

- DIII–D high $p_o/\langle p\rangle$ ~ 6.0 (L–mode): $\beta_N \lesssim 2.5$
  - Limited by fast n = 1 disruption
- TFTR high $p_o/\langle p\rangle$ ~ 6.0 (ERS–mode): $\beta_N \lesssim 2$
  - Limited by fast n = 1 disruption
- DIII–D low $p_o/\langle p\rangle$ ~ 2.5 (H–mode): $\beta_N \lesssim 4$
  - No disruption
    limited by ELM-like activity from finite edge pressure gradients



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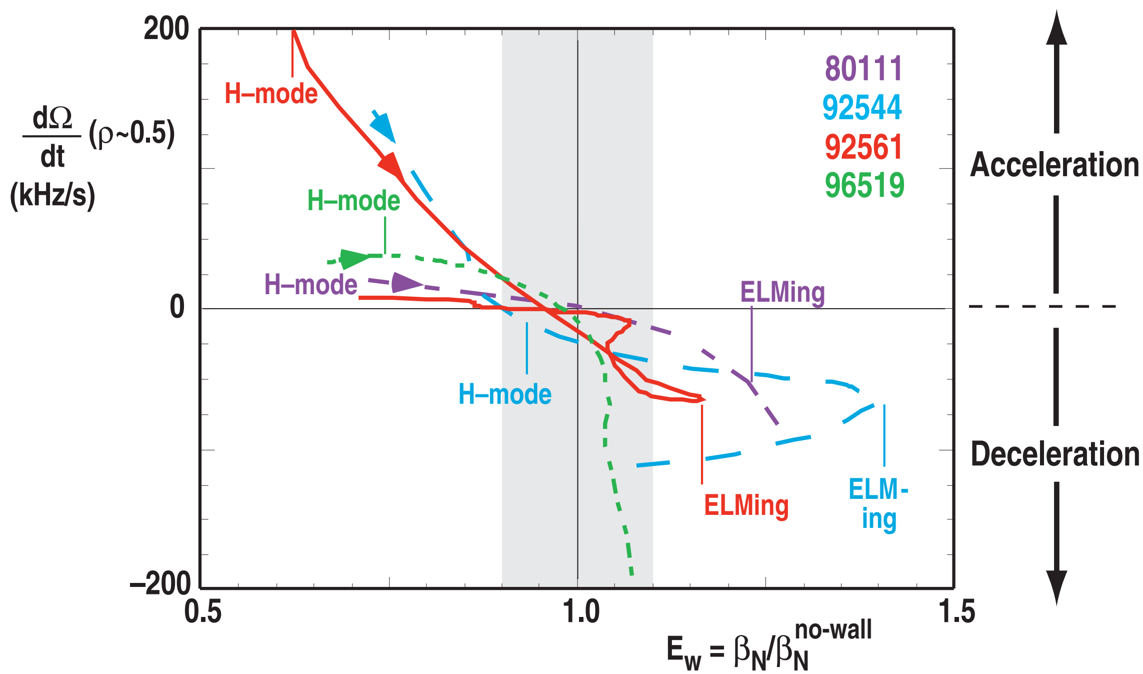
ROTATION DECELERATES ABOVE THE NO-WALL β LIMIT (EVEN WITH LARGE TORQUE)



- Two competing models are being investigated
  - Gimblett and Hastie torque balance model with marginally unstable RWM predicts qualitative behavior
  - New data is consistent with resonant amplification of static error fields by marginally stable RWM

CONCLUSIONS

- Some issues of MHD stability require burning-plasma parameters to investigate
  - NTM beta limit scaling
  - Edge-driven instabilities
  - Resistive wall stabilization
  - Disruption scaling (runaway avalanche)
- Some key issues of MHD stability can only be addressed with strong alpha heating
  - Energetic alpha interactions with MHD modes
  - Stability with profiles determined by self-heating ($t \gg \tau_E$)
  - Stability with self-heating and relaxed current density profile ($t \gg \tau_{CR}$)
- Many of the issues requiring a burning plasma are not purely MHD stability issues but issues of integration (transport, profile control, burn control, etc.)

INTEGRATION OF SEPARATE ELEMENTS MAY BE THE MOST IMPORTANT MISSION FOR A BURNING PLASMA EXPERIMENT

- Strong coupling of transport, heating, and stability leads to a more "self-organized" plasma than in a short-pulse, externally heated tokamak

  - Pressure profile → Fusion rate → Alpha heat deposition → Thermal transport → Pressure profile
  - Pressure profile → Bootstrap current → Current profile → Thermal transport → Pressure profile

- MHD instabilities can intervene in these loops:

  - Pressure, current density, and fast ion profiles → Instabilities → Modification of profiles

- Investigation of such a complex, non-linear system represents a scientific challenge, and may yield some surprises

RECOMMENDATION: A "next step" burning plasma experiment is needed as the only way to address this challenge