RECENT RESULTS FROM DIII-D PERTAINING TO FIRE

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GENERAL ATOMICS

096–00/CCP/ci

OUTLINE

1. High density operation

2. Advanced tokamak regime

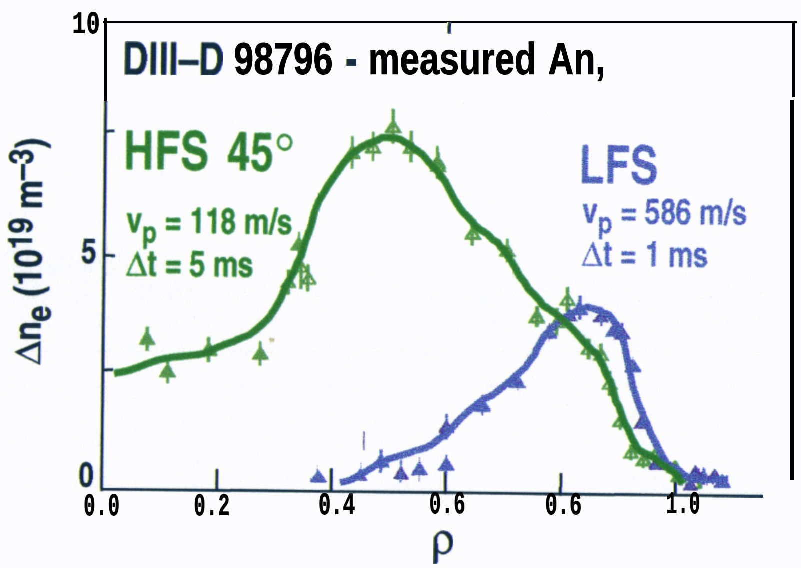
3. Beta limits

4. Normalized current

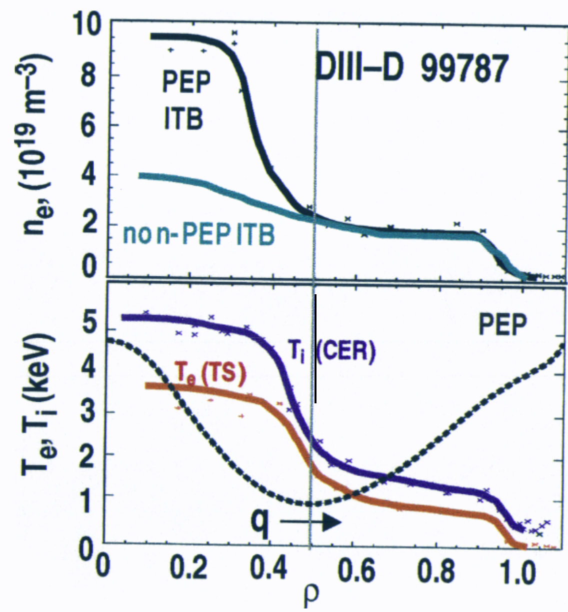
5. Summary

HIGH FIELD SIDE PELLET INJECTION ALLOWS EVALUATION OF INTERNAL TRANSPORT BARRIERS WITH $T_e \sim T_i$

2.7 mm Pellets - HFS 45° vs LFS

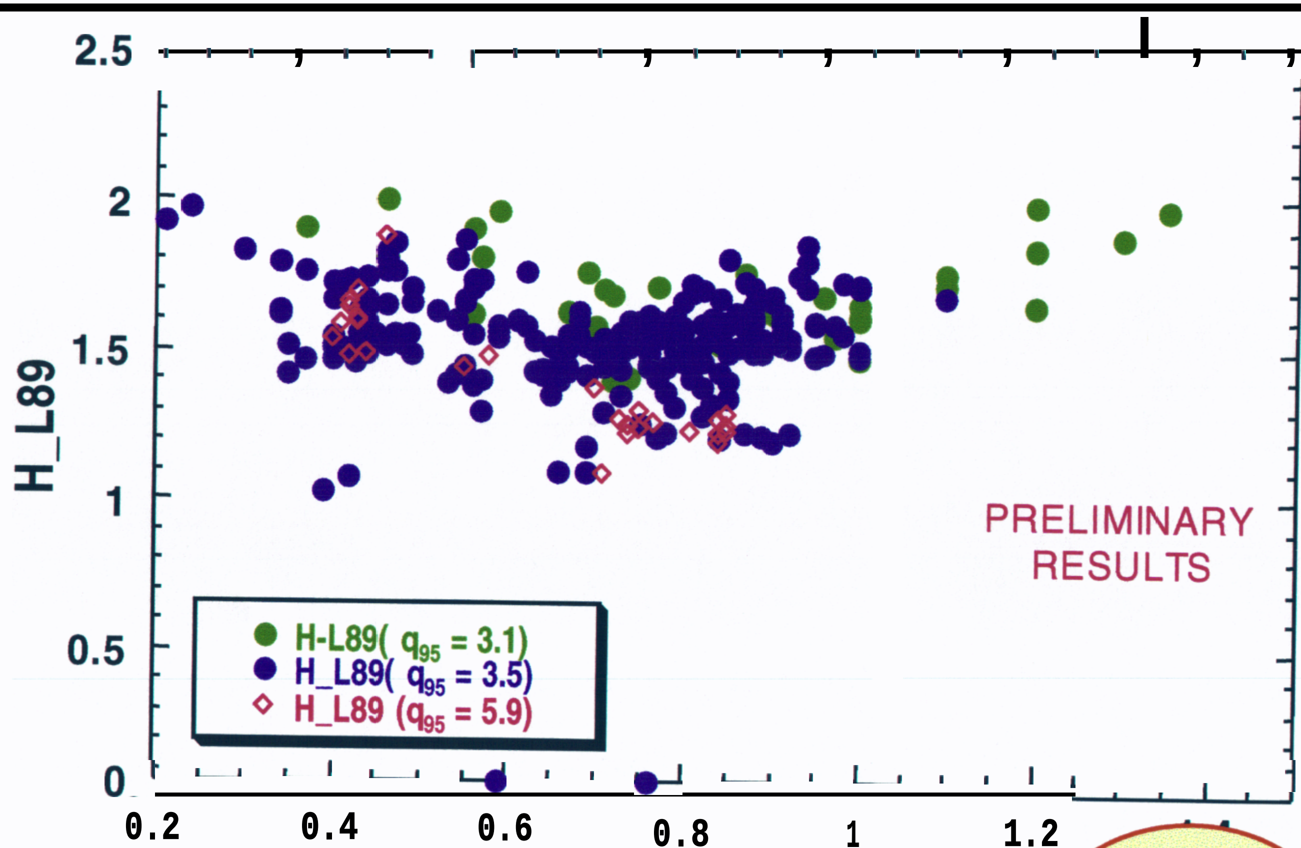


New capability in ITB control



- HFS pellet injection yields deeper particle deposition than LFS injection, consistant with theory
- Future work on ITB control and H-mode control with pellet

CONFINEMENT DOES NOT DEGRADE AT HIGH DENSITY IN LOW q_{95} PUMPED DISCHARGES



Mahdavi, Petrie

Summary and Conclusions of High Density Experiments

- Densities up to $1.4 \times n_{GW}$, and H89p~1.9 are obtained with divertor pumping and gas fueling alone
  - ⇒ Pedestal densities up to 0.9 n_{GW} observed
  - ⇒ Pumping seems necessary for maintaining high confinement
  - ⇒ Best results obtained at low q and low power
- Good confinement is correlated with good fueling efficiency

Mahdavi,
Osborne,
Petrie

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Motivation for Improved Performance

- Magnetic fusion reactor
  maintain high fusion power density ($\propto \beta^2 B^4$)

- Steady-state $\Rightarrow f_{bs} \approx 1$ (in tokamak)
  increasing the bootstrap fraction means increasing q
  $\Rightarrow$ high q ($\propto f_{bs}^{1/2}$)

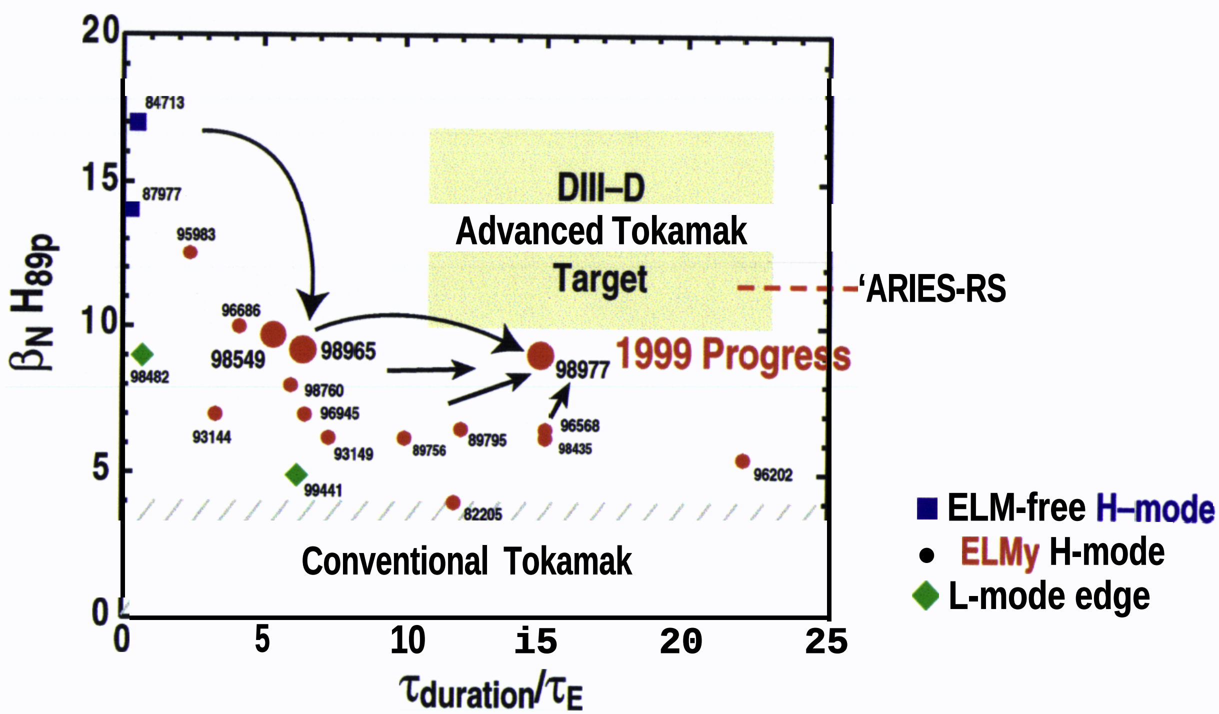
- Stability must be improved
  $\Rightarrow$ increase β_N ($\propto$ q)

- Must exceed ignition condition & maintain power balance during burn
  (maintain $P_{fusion}/P_{loss} \propto \beta\tau$)
  $\Rightarrow$ increase H ($\propto$ q)

- For example: if a tokamak reactor plasma has $q \approx 3$, $\beta_N H_{89p} \approx 5$, and fbs $\approx$ 40%, to reach $f_{bs} \approx 100\%$ at the same β would require $\beta_N H_{89p} \approx 12.5$ at $q \approx 4.7$.

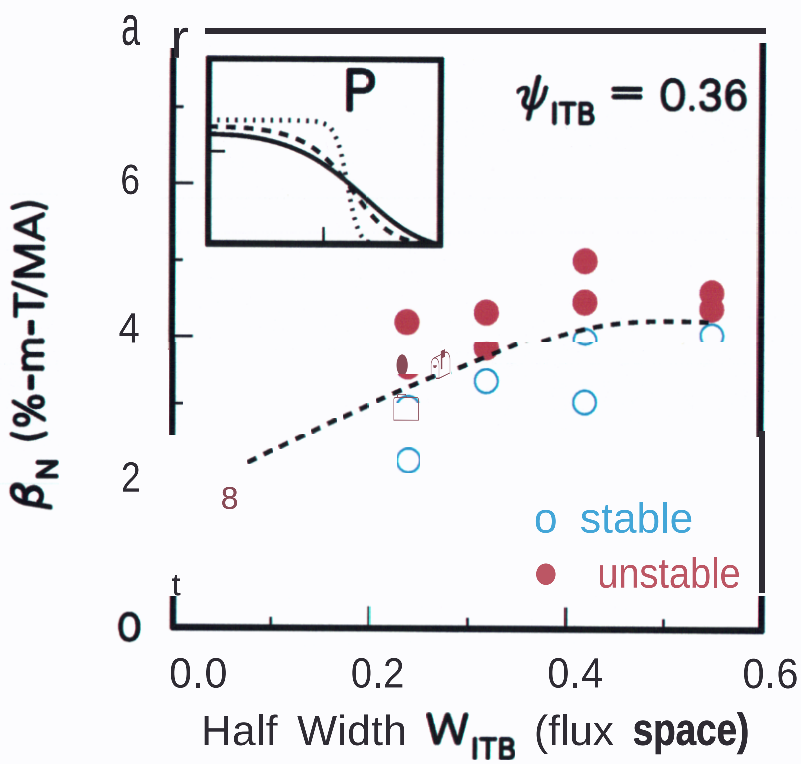
DIII–D Goal and Progress in 1999

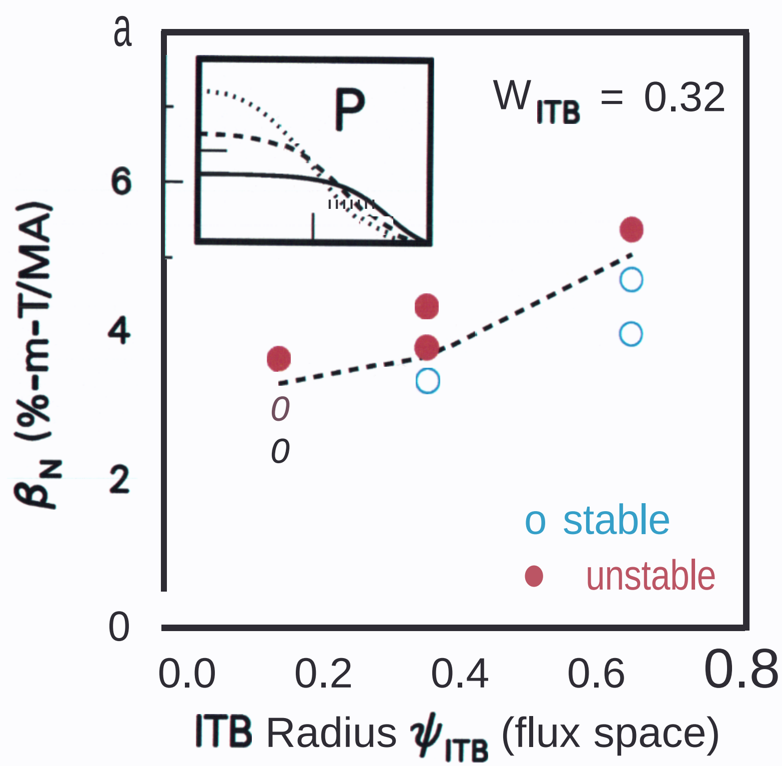
A principal near-term goal of the present DIII-D research program is a stationary plasma with $\beta_N H_{89p} \geq 10$, with no inductive current, a relaxed loop voltage profile, and > 50% bootstrap current.



STABILITY LIMIT IMPROVES WITH INTERNAL TRANSPORT BARRIER WIDTH AND RADIUS

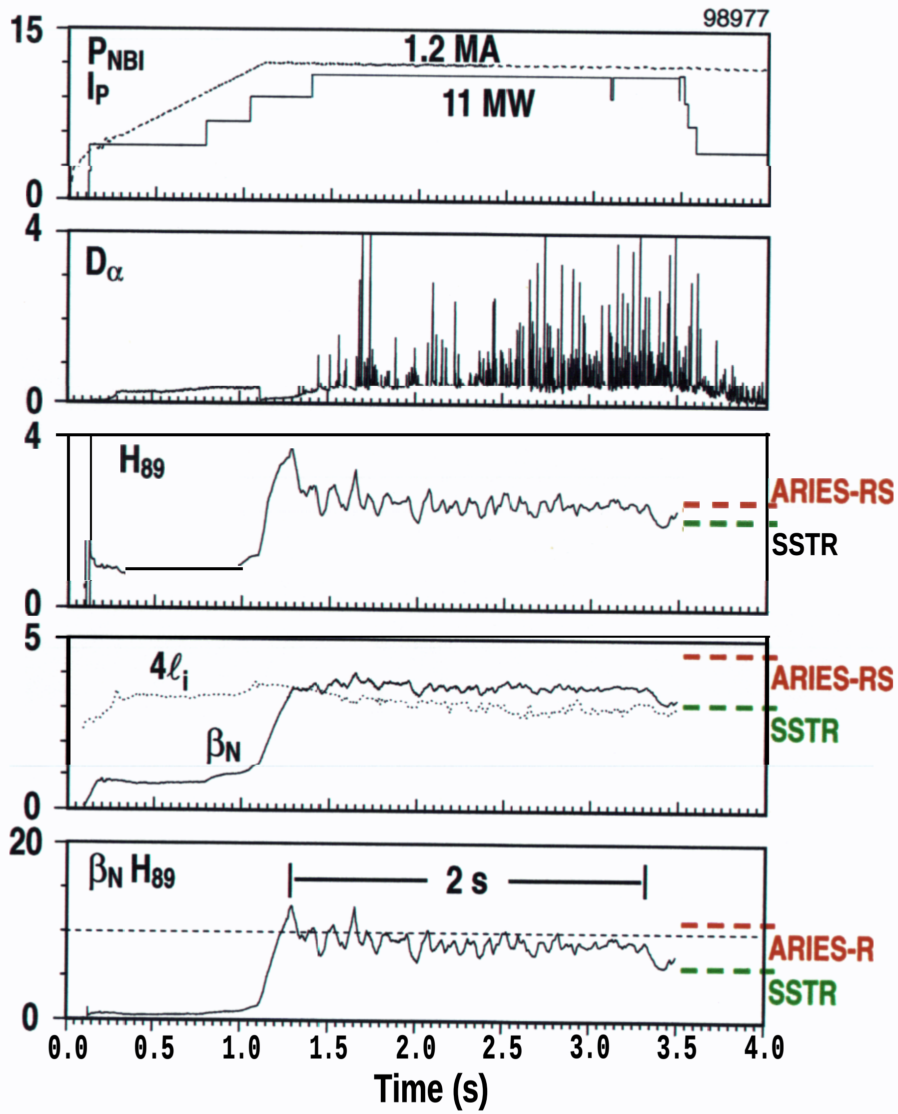
- Fixed shape, DND, q_{95} □ 5.1, q_0 □ 3.2, q_{min} □ 2.2 based on a DIII-D discharge
- Hyperbolic tangent pressure representation
- Ideal n = 1, wall at 1.5a





Lao et al 1999

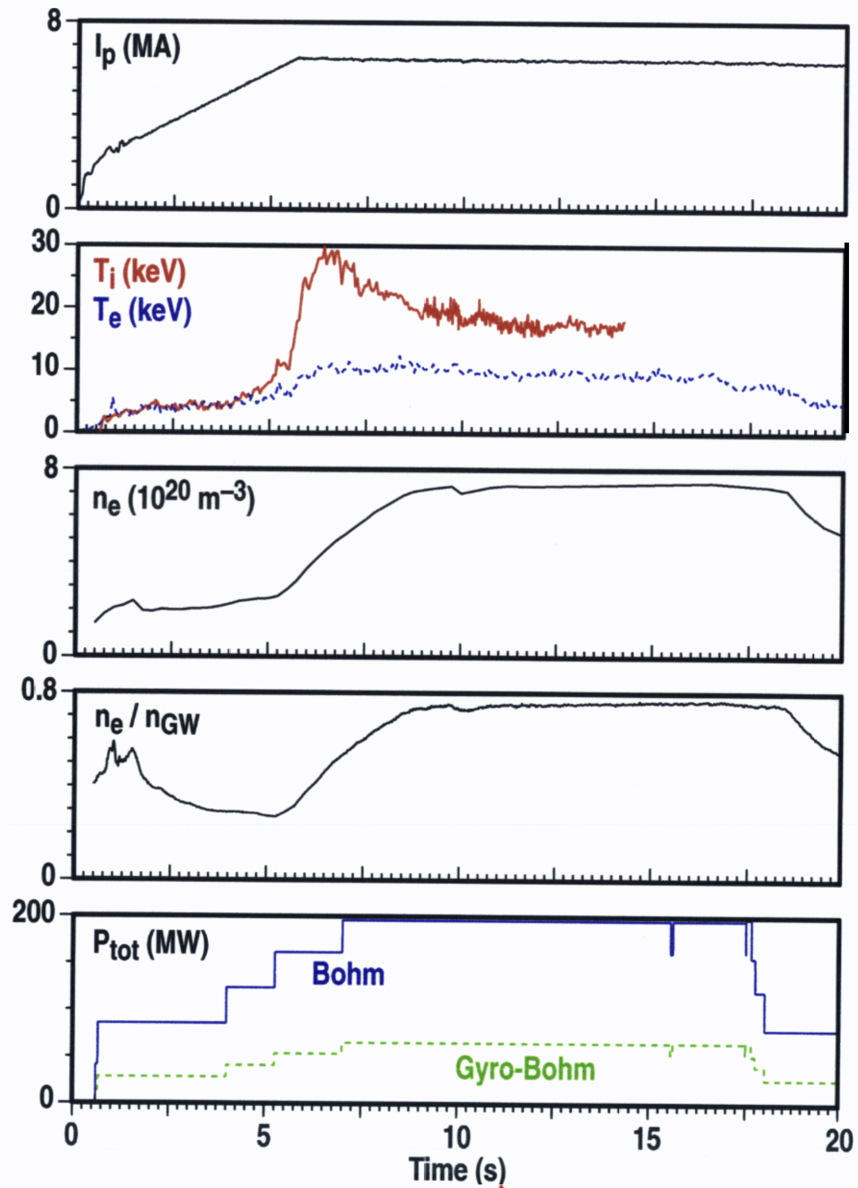
$\beta_N H_{89p} \geq 9$ for 2 sec (16 τ_E & ~1 τ_R)



- Discharge preparation to produce hot core with hollow current profile
- Confinement meets reactor requirements
- β exceeds no-wall limit
  – no reduction when ELMs start
- Flat-top β limited by a combination of high frequency modes, RWMs, and ELMs
- Duration is many τ_E
  – comparable to current relaxation time

ADVANCED TOKAMAK DISCHARGE ON DIII-D SCALED TO FIRE AT FIXED β, ν AND B_p/B_T BUT SMALLER ρ_*

- FIRE has higher aspect ratio than DIII-D and thus will have lower safety factor and bootstrap fraction
- If current is reduced to increase bootstrap fraction, then density will exceed the density limit



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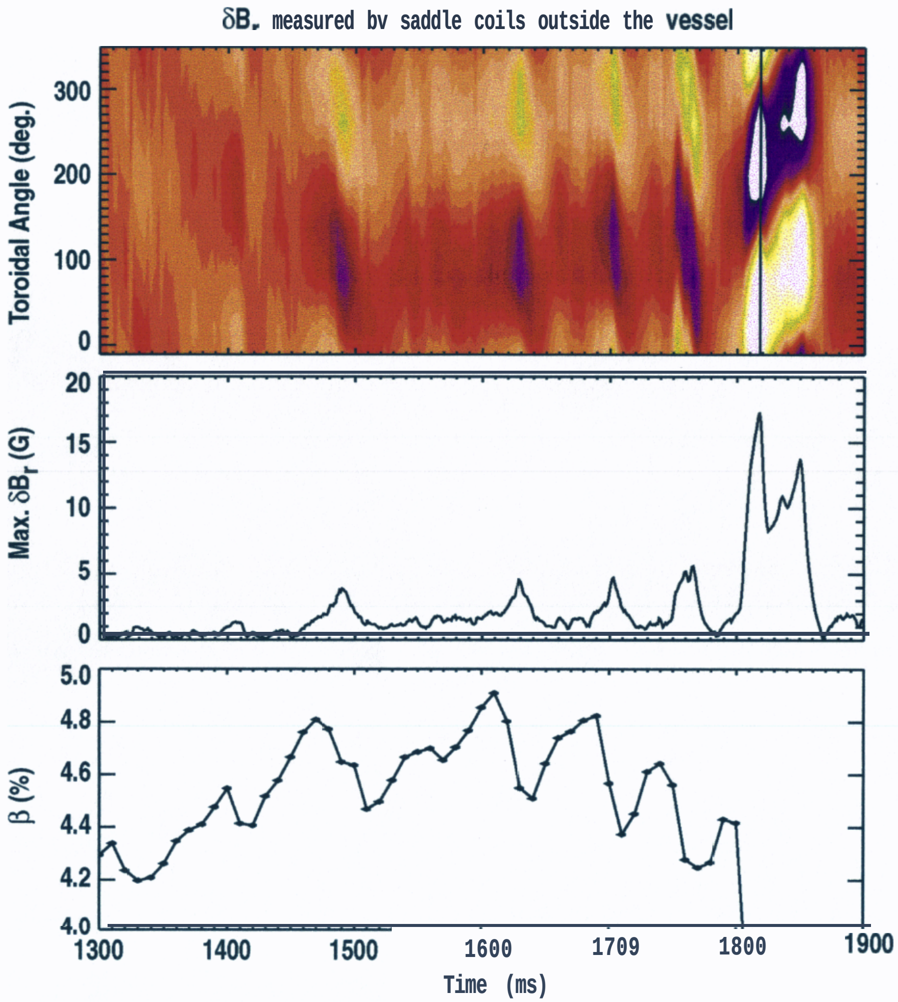
BETA IS LIMITED IN MAGNITUDE AND DURATION BY RESISTIVE WALL MODES



- Limiting modes have the characteristics of resistive wall modes: $\gamma \sim 1/\tau_W$
- Rotational stabilization is difficult to maintain
  - Theoretical understanding of drag mechanism needed

⇒ Active feedback stabilization is required

- RWM stabilization is a key issue for RFP, ST, and spheromak (FESAC goal #2)

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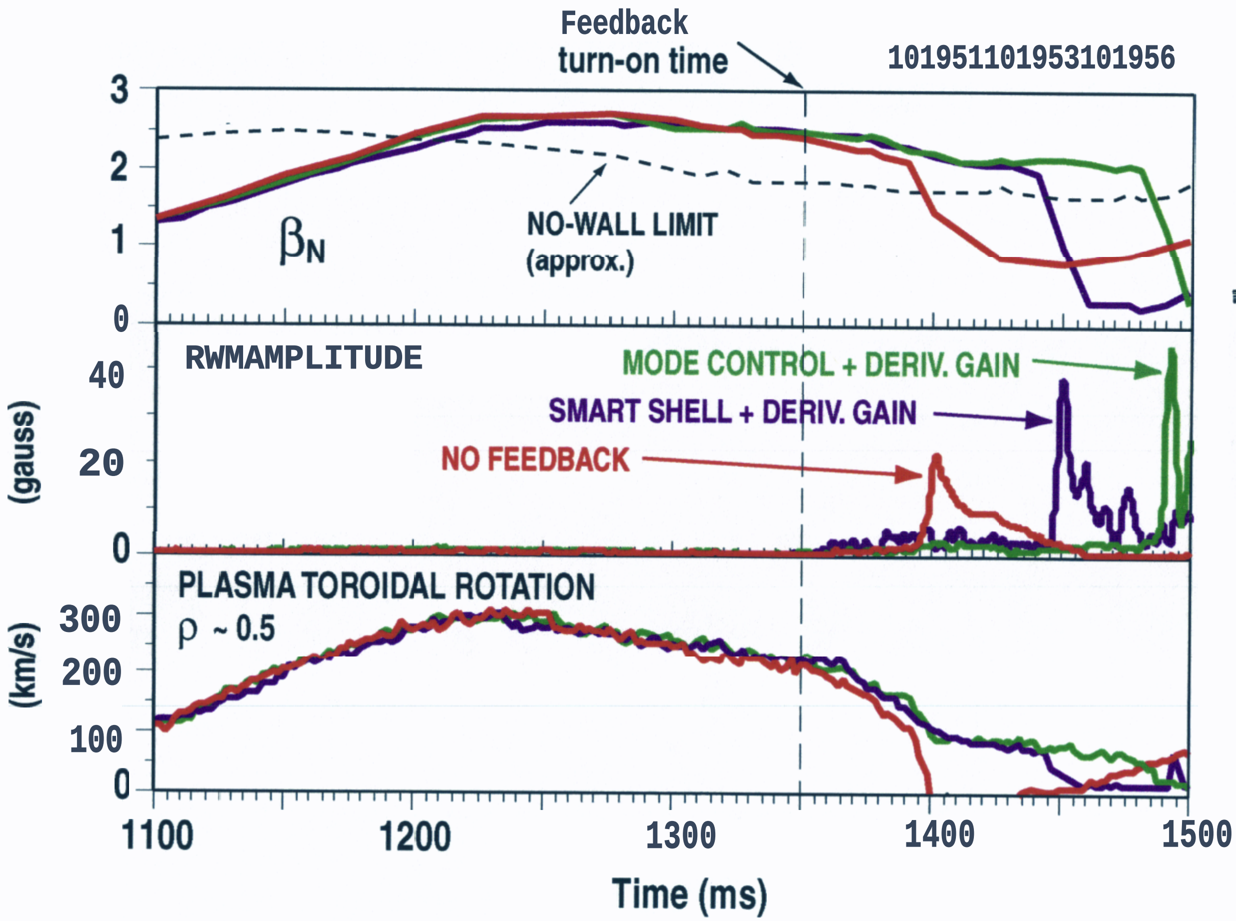
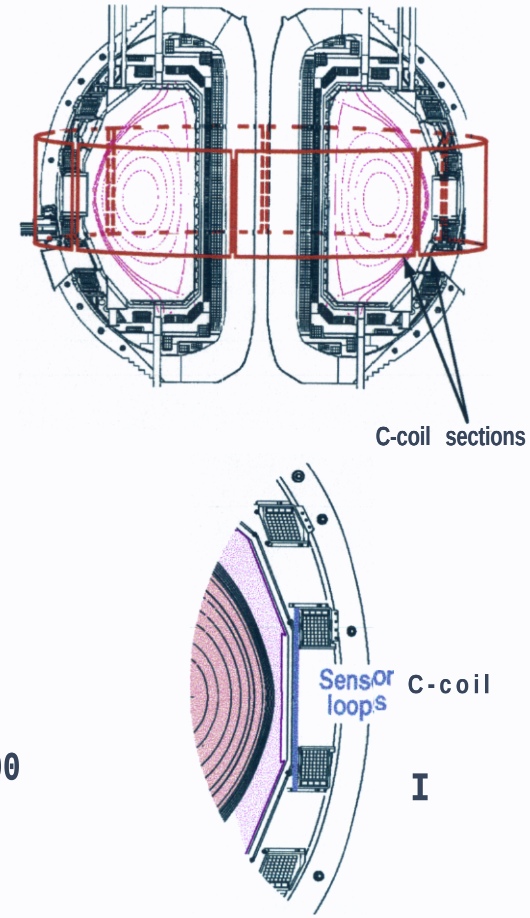
ACTIVE FEEDBACK STABILIZATION EXTENDS HIGH β DURATION

(March 2000)





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PLASMA CURRENT IS WHAT MAKES TOKAMAKS GREAT

- Normalized current $\frac{I}{aB_T} = \frac{B_P}{B_T}\left(\frac{2\pi}{\mu_o}\right)$ is relevant quantity

- Beta increases with normalized current regardless of beta limit

$$\beta = \left(\frac{\beta_N}{100}\right)\left(\frac{I}{aB_T}\right)$$

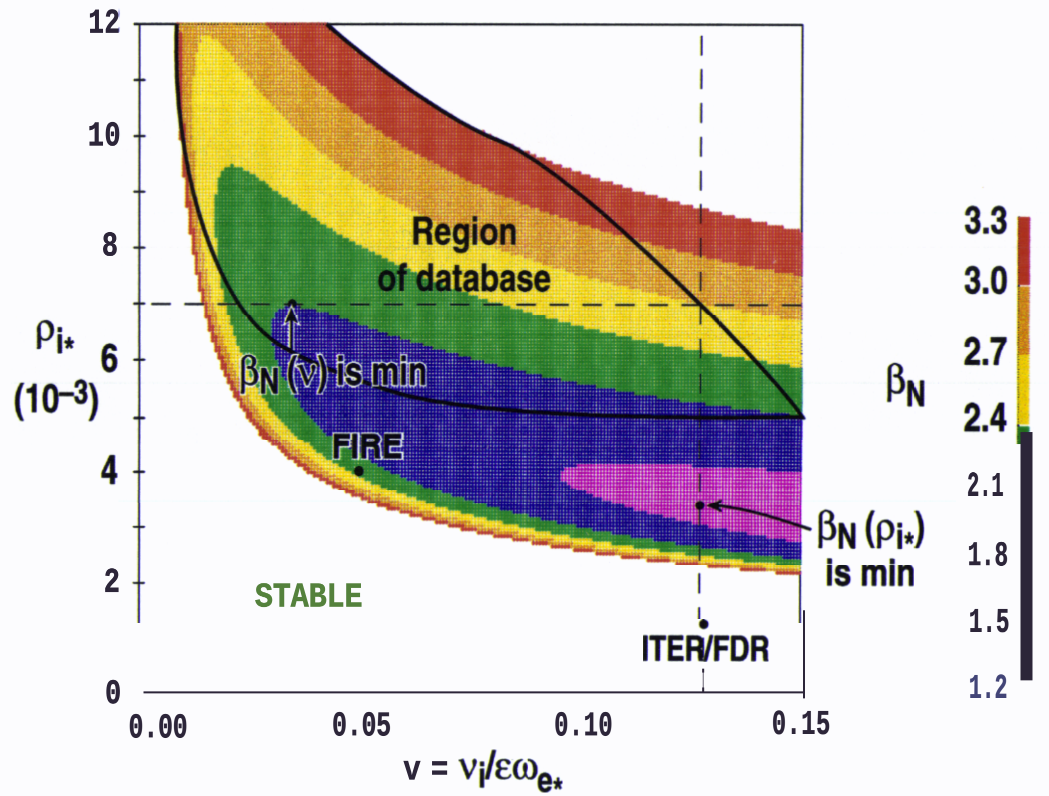
- Confinement increases with normalized current

$$B_T\,\tau_{th} \propto \rho_*^{-3.1}\,\beta^{o}\,\nu^{-0.4}\left(\frac{I}{aB_T}\right)^{1.4}$$ for DIII-D H-modes

- Thus, the ignition criteria Q is a strongly increasing function of normalized current

NEOCLASSICAL TEARING MODE BETA LIMIT

- Model for onset β_N fitted to database for m/n □ 3/2 NTM induced by sawteeth
  - ★ DIII–D, JET, and ASDEX-Upgrade (ELMy H, q95 ≳ 3, LSND)
  - ★ Seed island decreases faster with ρ_{i*} than threshold
    - — Stabilizes at very low ρ_{i*}, high S, i.e. w_{seed}/w_{thresh} c 1
  - ★ FIRE is predicted to be unstable at $\beta_N \simeq$ 2.1-2.4



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JET
ASDEX Upgrade
UKAEA
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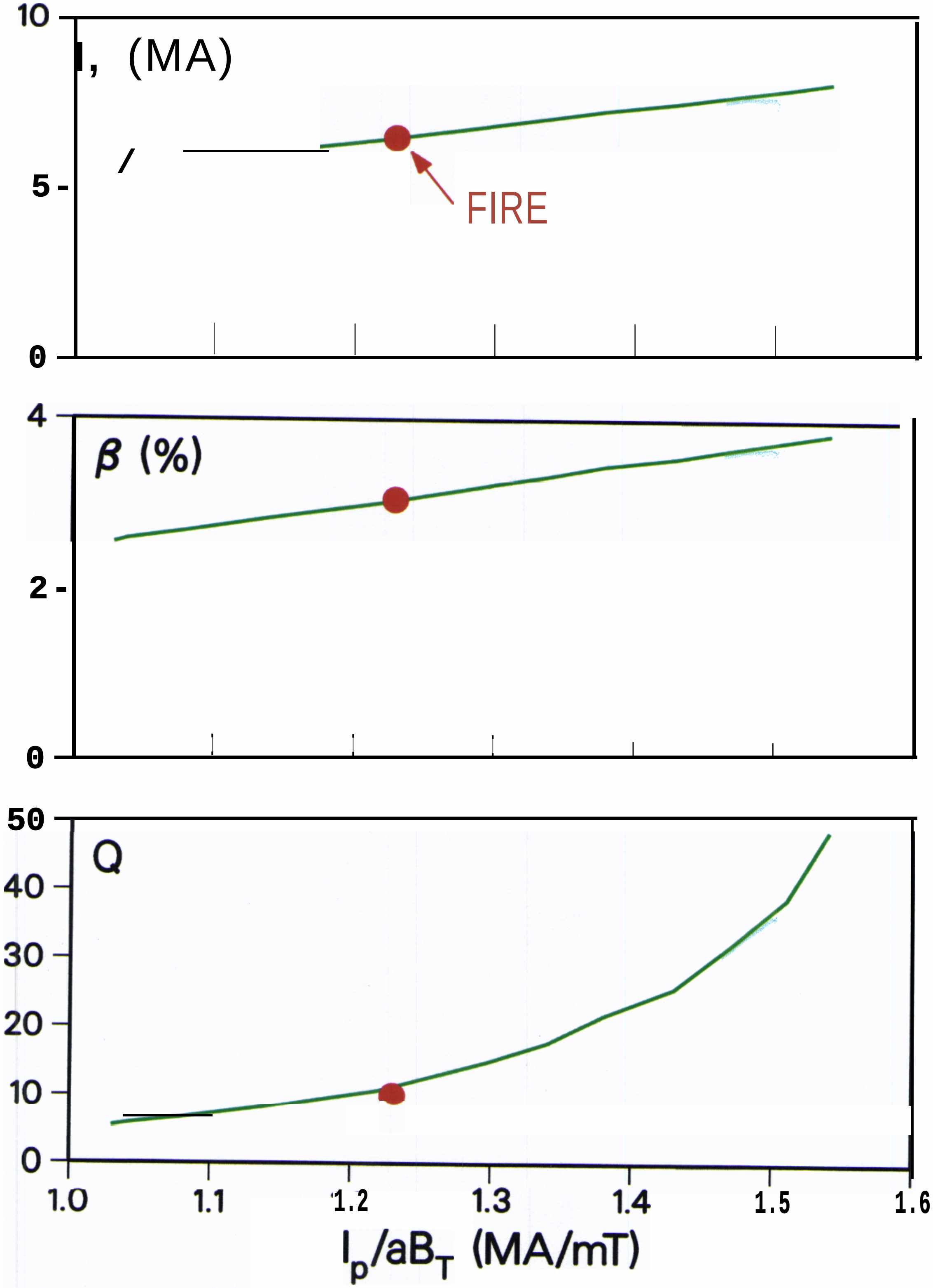
THE IGNITION CRITERIA Q RAPIDLY INCREASES WITH NORMALIZED CURRENT (R, B_T AND β_N FIXED TO FIRE VALUES)



GENERAL ATOMICS

SUMMARY

- Good confinement at high density is correlated with good fueling efficiency
  - Best results obtained at low beta
- Long duration AT regime ($\beta_N H = 9$) has broad pressure profile and beta only ≈ 10% above ideal no wall limit
  - Obtained in hot-ion mode with rapid rotation
- Neoclassical tearing mode predicted to be unstable for sawtoothing plasmas in FIRE around $\beta_N = 2.1–2.4$