Wall Stabilized Operation and Active Feedback Physics Design in NSTX

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Workshop on Active Control of MHD Stability: Extension of Performance

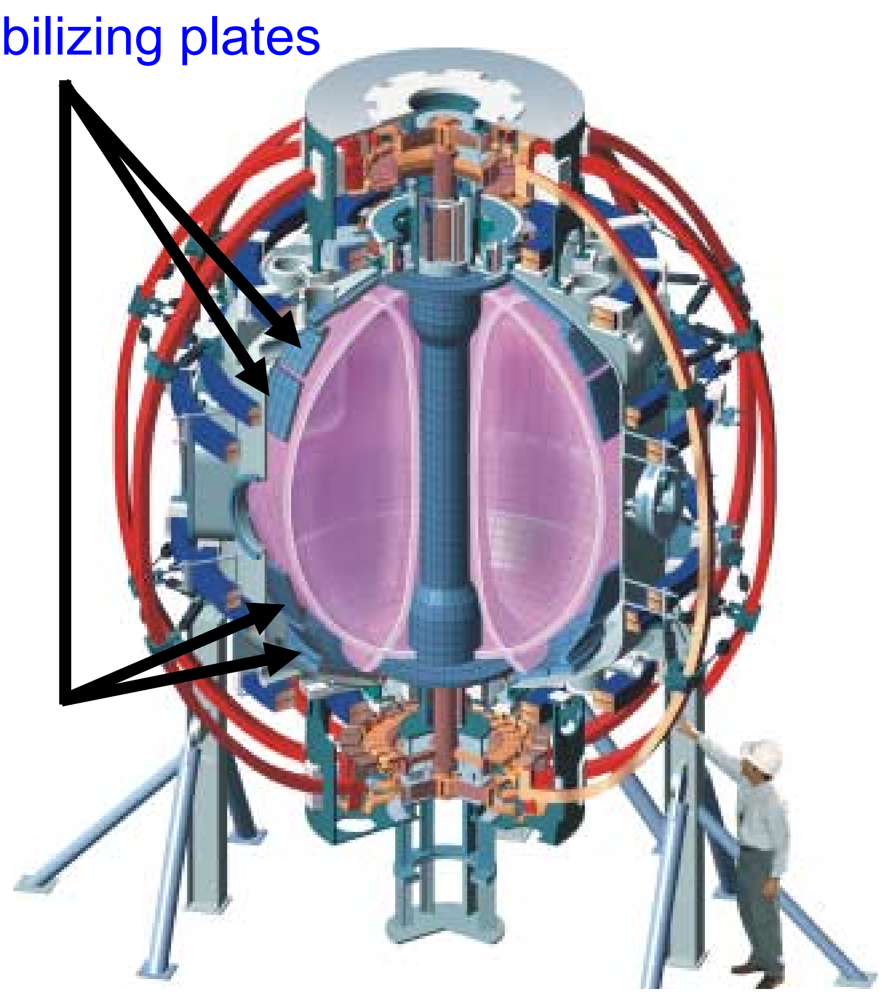
Columbia University - November 18th, 2002

NSTX is operating at sufficiently high beta to study passive wall stabilization

- **Motivation**
  - Conducting walls can stabilize global modes in a rotating plasma
  - Resistive wall mode (RWM) can heavily damp rotation
  - Examine sustained stabilization by active feedback (needed for reactors)

- **Outline**
  - Operation in wall-stabilized, high beta regime
  - Resistive wall mode and rotation damping
  - Physical mechanisms for higher β_N and longer pulse
  - Active feedback stabilization system physics design

NSTX is equipped to study passive stabilization



Machine

Aspect ratio	≥ 1.27
Elongation	≤ 2.5
Triangularity	≤ 0.8
Plasma Current	≤ 1.5 MA
Toroidal Field	≤ 0.6 T
NBI	≤ 7 MW

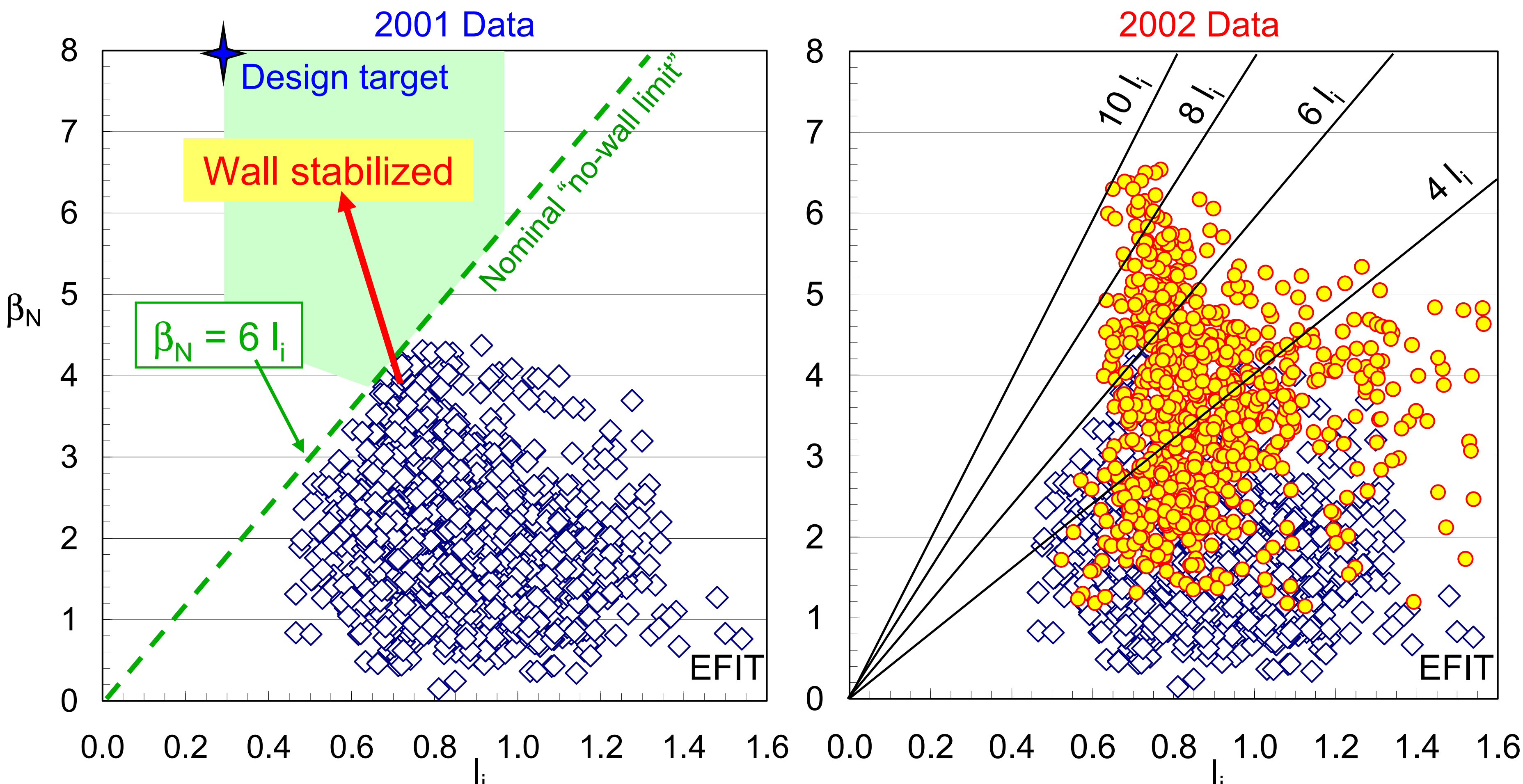
Analysis

EFIT – equilibrium reconstruction

DCON – ideal MHD stability (control room analysis)

VALEN – RWM growth rate

Plasma operation now in wall-stabilized space



- Normalized beta, $\beta_N = 6.5$, with $\beta_N / l_i = 9.5$; β_N up to 35% over $\beta_{N\ \text{no-wall}}$
- Toroidal beta has reached 35% ($\beta_t = 2\mu_0 \langle p \rangle / B_0^2$)

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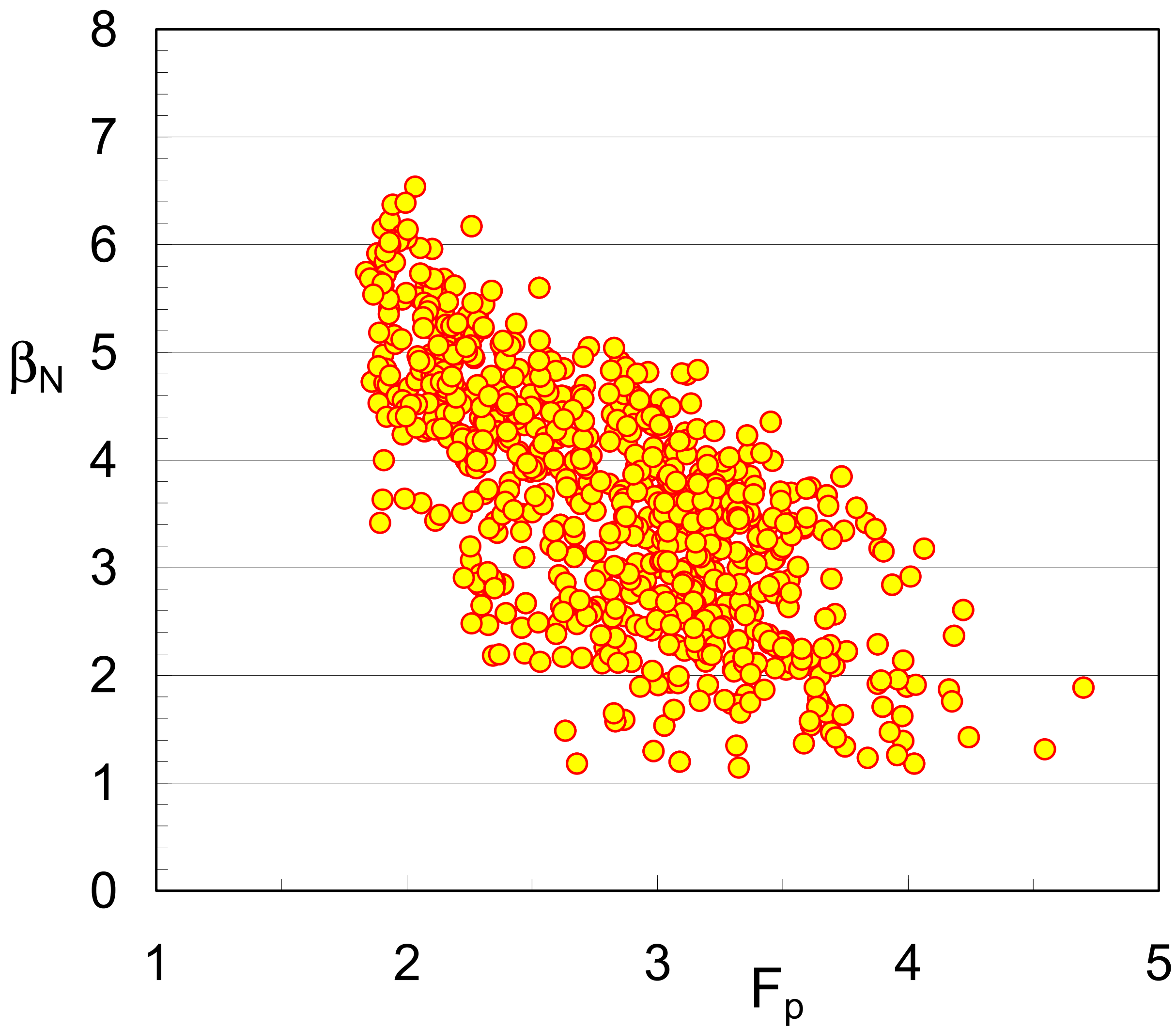
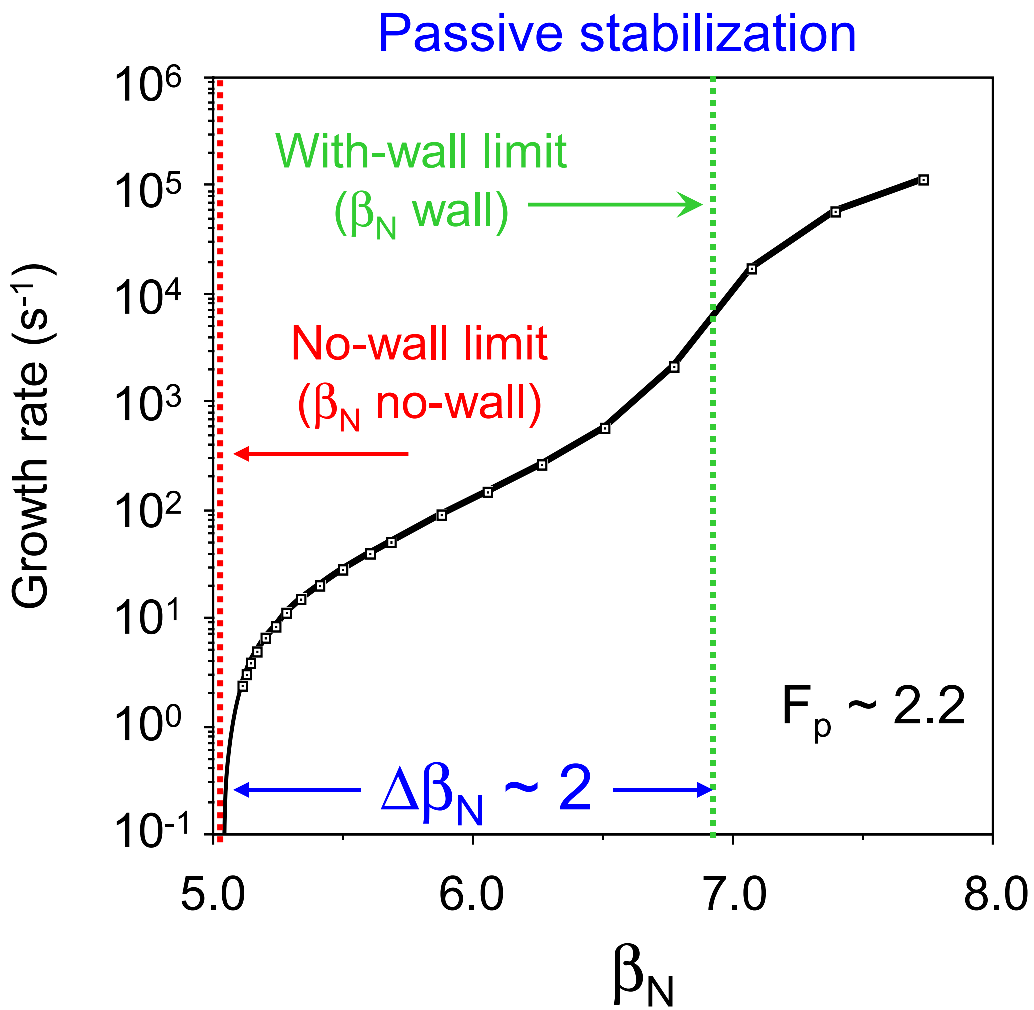
Maximum β_N strongly depends on pressure peaking



- $F_p = p(0) / \langle p \rangle$
- P profile from EFIT using P_e, diamagnetic loop, magnetics
- Time-dependent calculations required to evaluate stability limits and mode structure

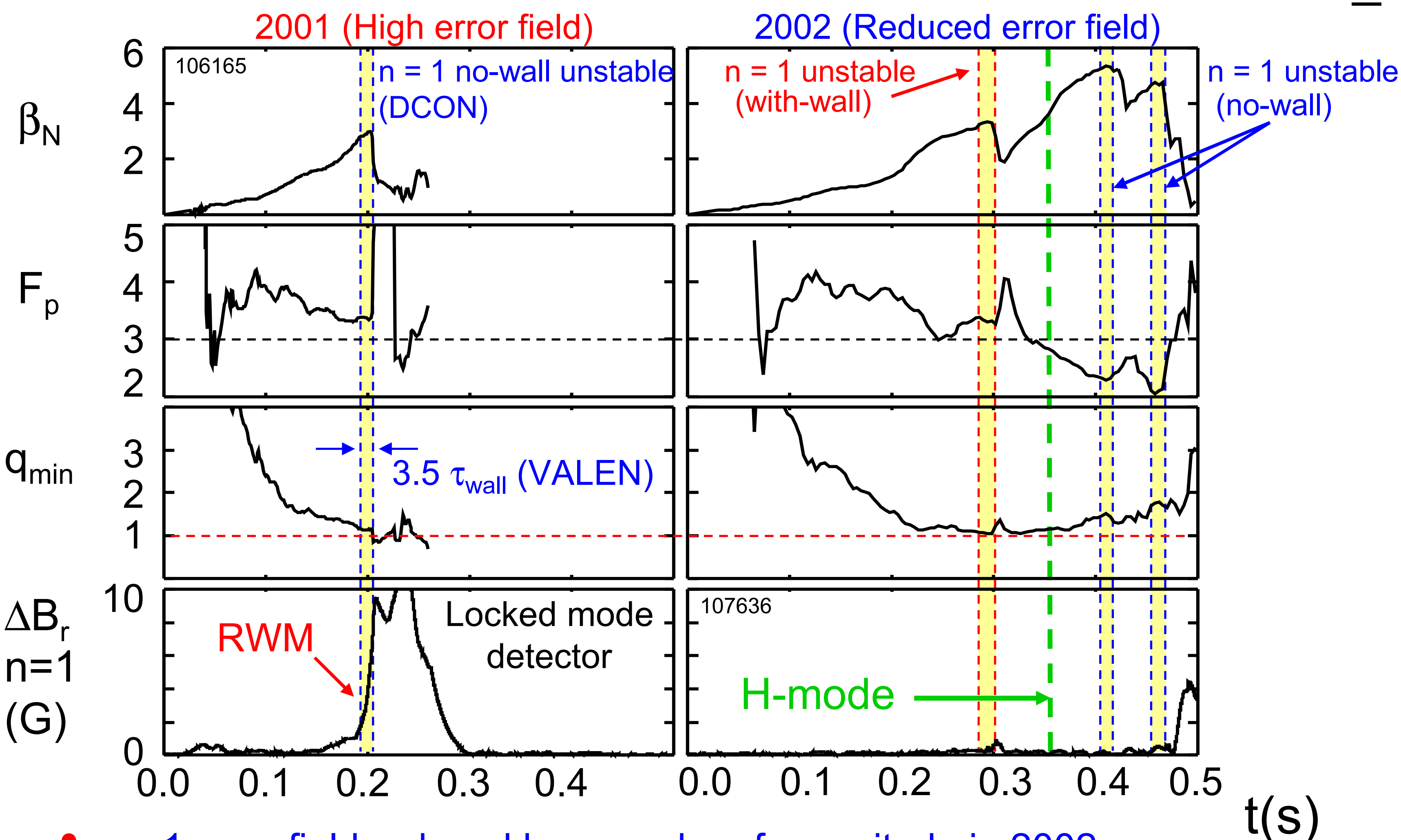
Theoretical RWM growth rate depends on β_N



- Growth rate depends on mode structure and ∇p drive
  - Mode structure depends on equilibrium parameters
- Quantitative agreement between theory and experiment
  - Growth rates, passively stabilized β_N range agree well
  - based on DCON input from plasma 106165

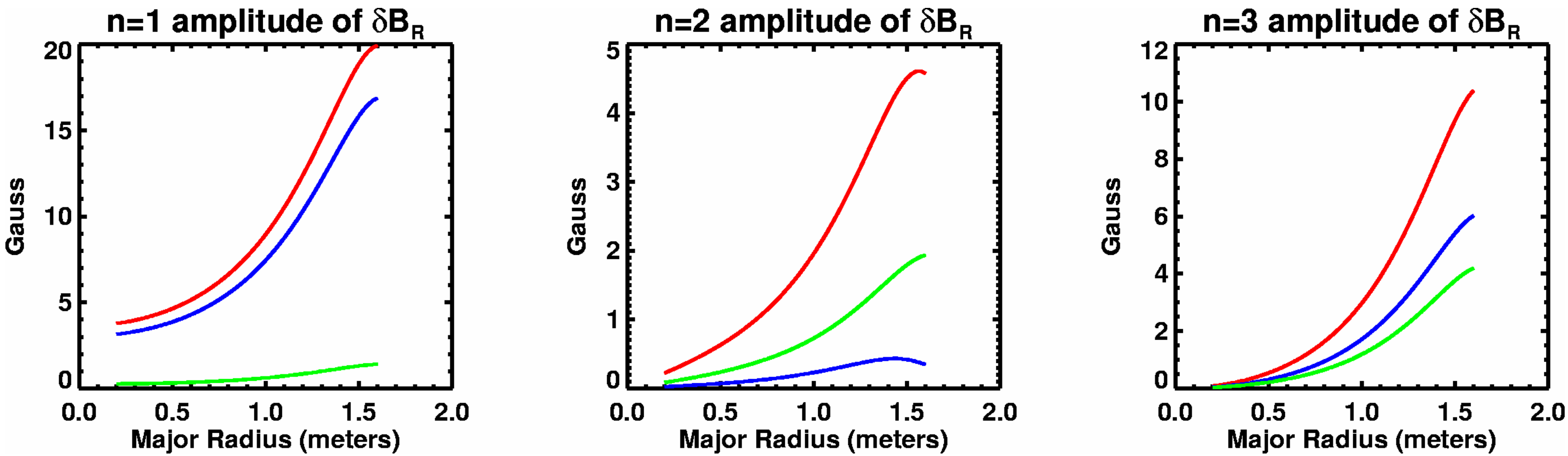
VALEN: J. Bialek

Operational improvements yield higher, sustained β_N



- n=1 error field reduced by an order of magnitude in 2002
- H-mode pressure profile broadening raises β_N limit
- q_{min} > 1 maintained (EFIT q_{min} without MSE)

N=1 error field greatly reduced by EF coil correction



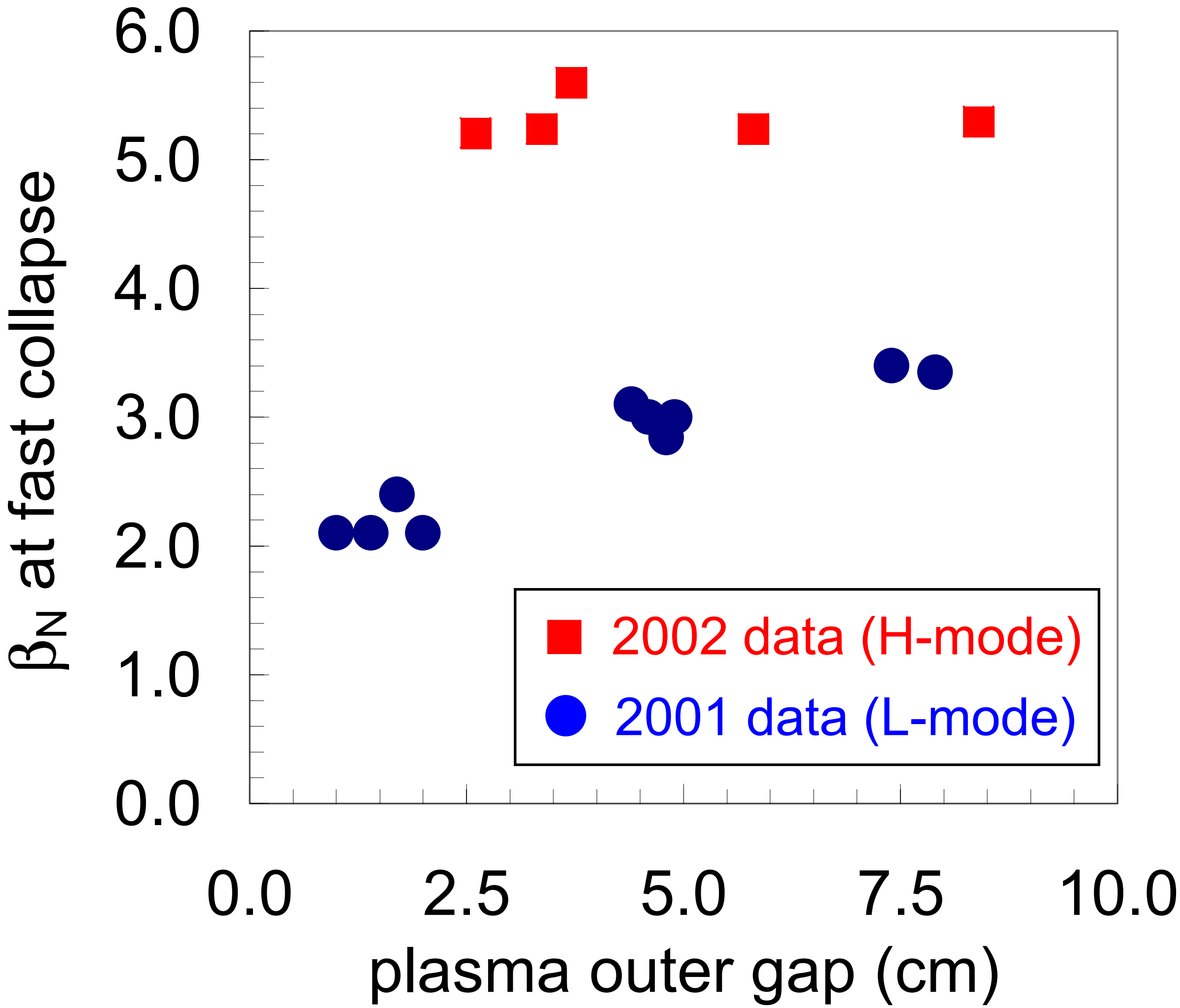
- **n=1 amplitude reduced by factor of 12**
- n=2 amplitude increased slightly
  - Still only 2 Gauss at plasma edge
- n=3 is largest predicted amplitude
  - 4 Gauss at plasma boundary
  - Localized effect from coil feeds

- **RED** = magnetic measurements **before correction**
- **BLUE** = using measured coil radius, **before correction**
- **GREEN** = using measured coil radius, **after correction**

Calculations assume I_{PF5}=10kA

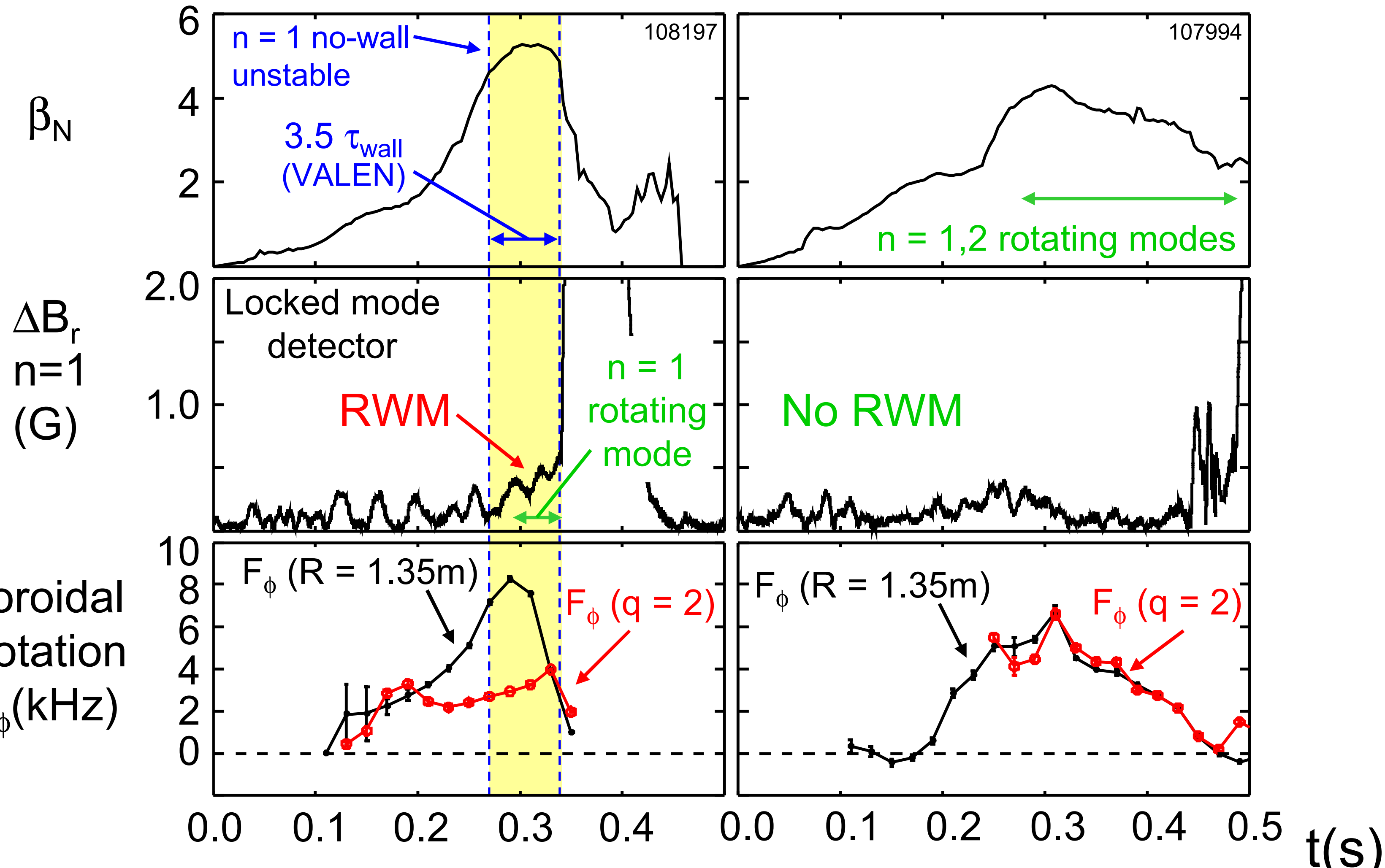
J. Menard

β_N limit now insensitive to plasma proximity to wall



- At high β_N ~ 5, external modes are well-coupled to passive stabilizing plates, independent of gap
  - Confirmed by ideal MHD stability calculations
- Higher error field (2001 data) may have also lowered β limit for smaller outer gap

Rotation damping rate larger when $\beta_N > \beta_{N\ no\text{-}wall}$



- Rotation damping rate is ~ 6 times larger when $\beta_N > \beta_{N\ no\text{-}wall}$

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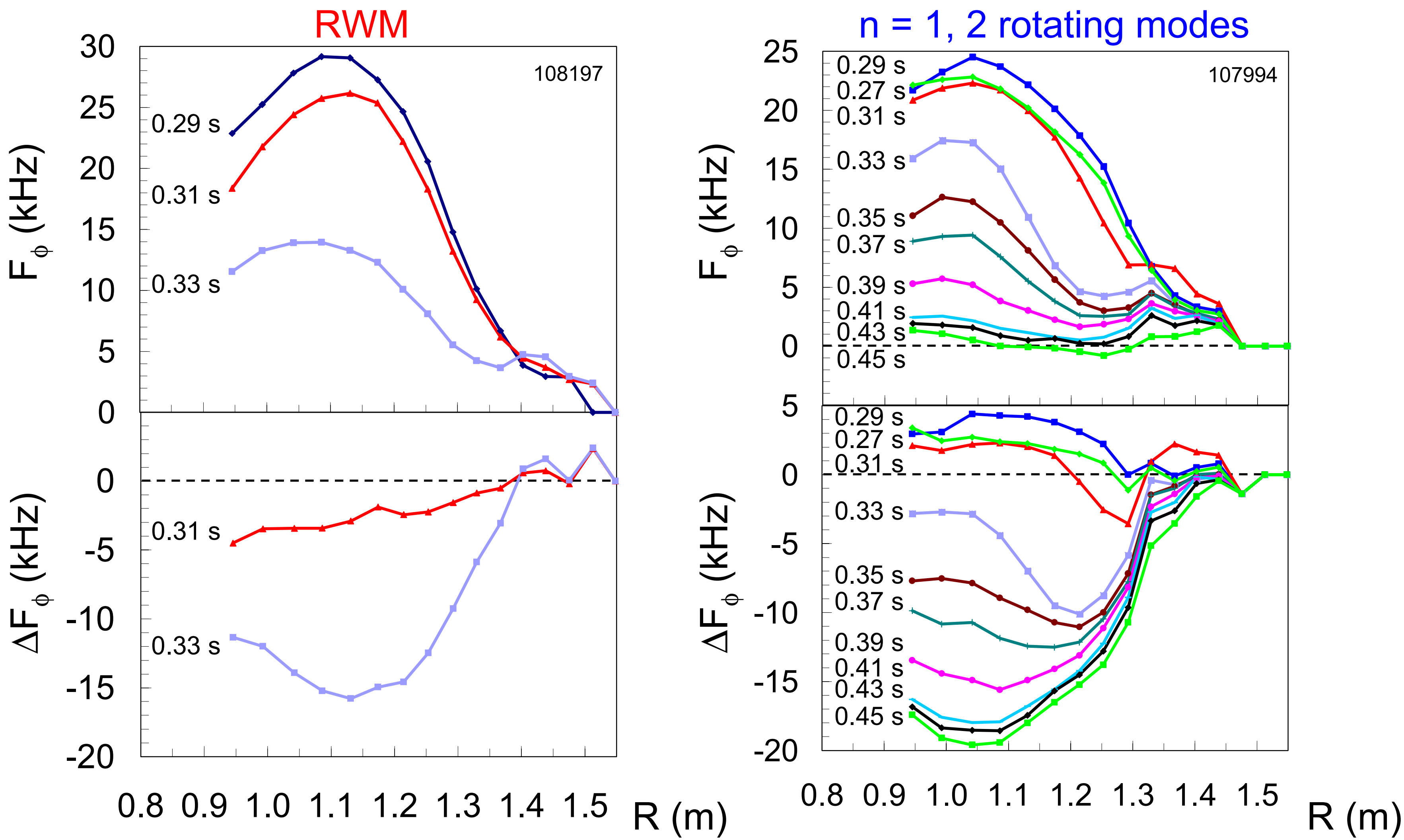
Two stages of rotation damping during RWM

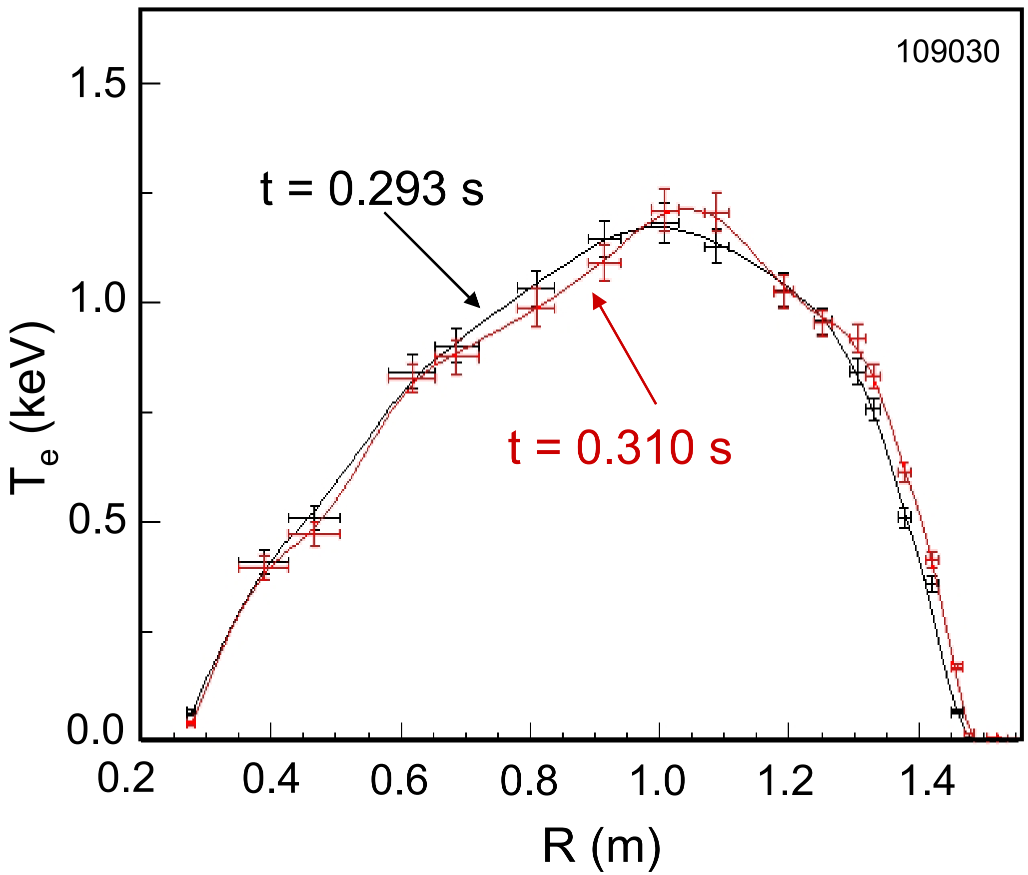
- Initial stage: Global, non-resonant rotation damping
- Final stage: Local rotation damping at resonant surfaces appears as rotation slows
- Analogous to rotation dynamics in induced error field experiments
  - E. Lazzaro, *et al.*, Physics of Plasmas **9** (2002) 3906. (JET)

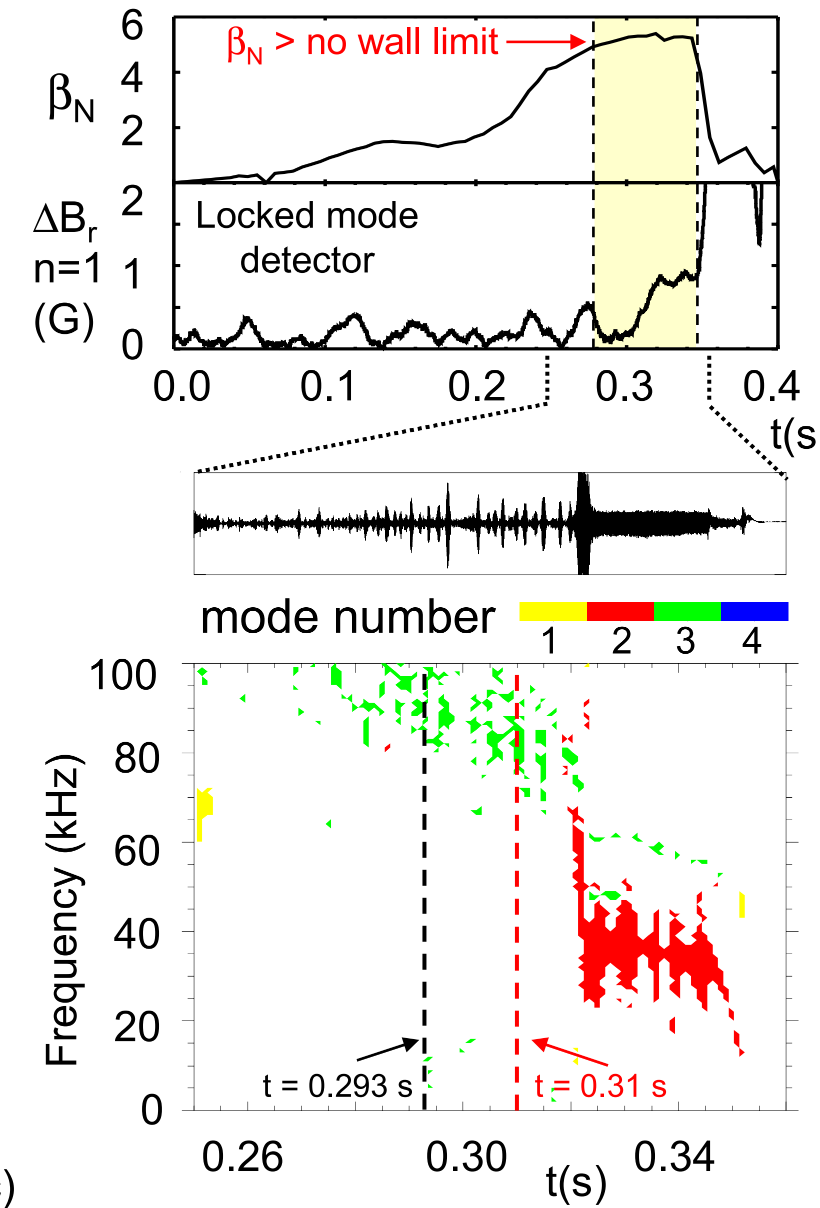
Rotation damping during RWM is rapid and global



- Damping from rotating modes alone is localized and diffusive

T_e perturbation measured during RWM

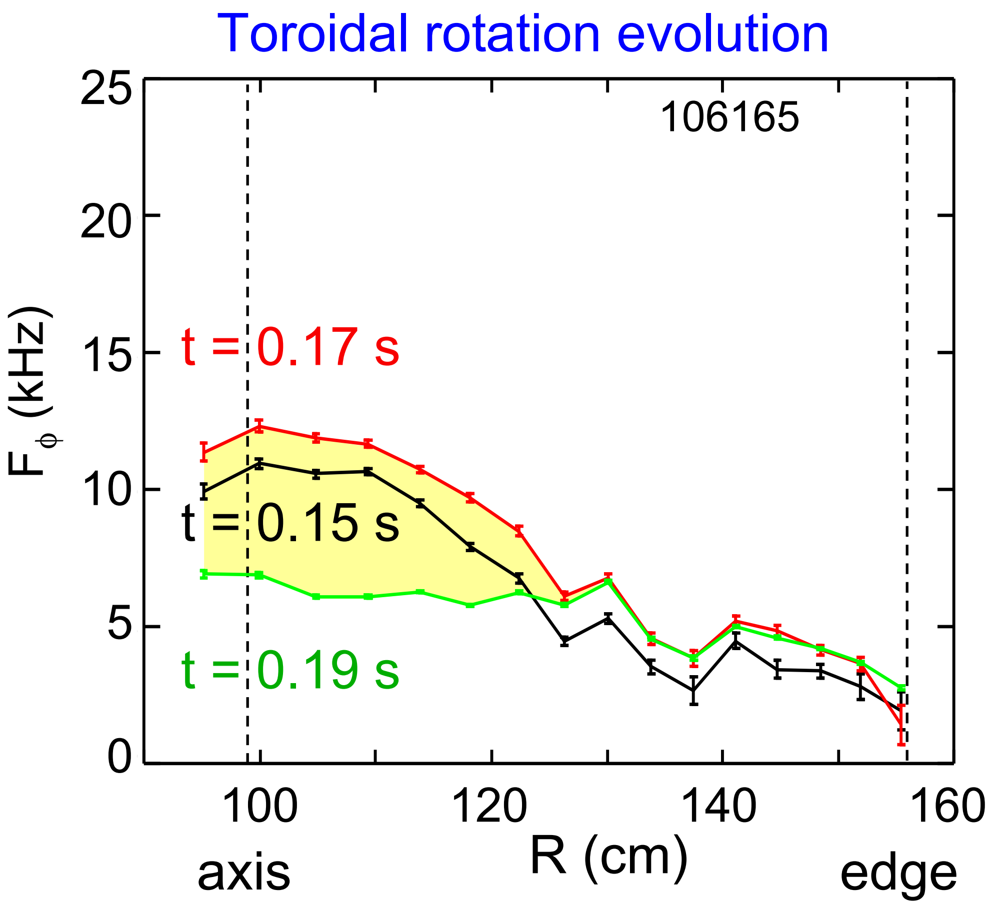


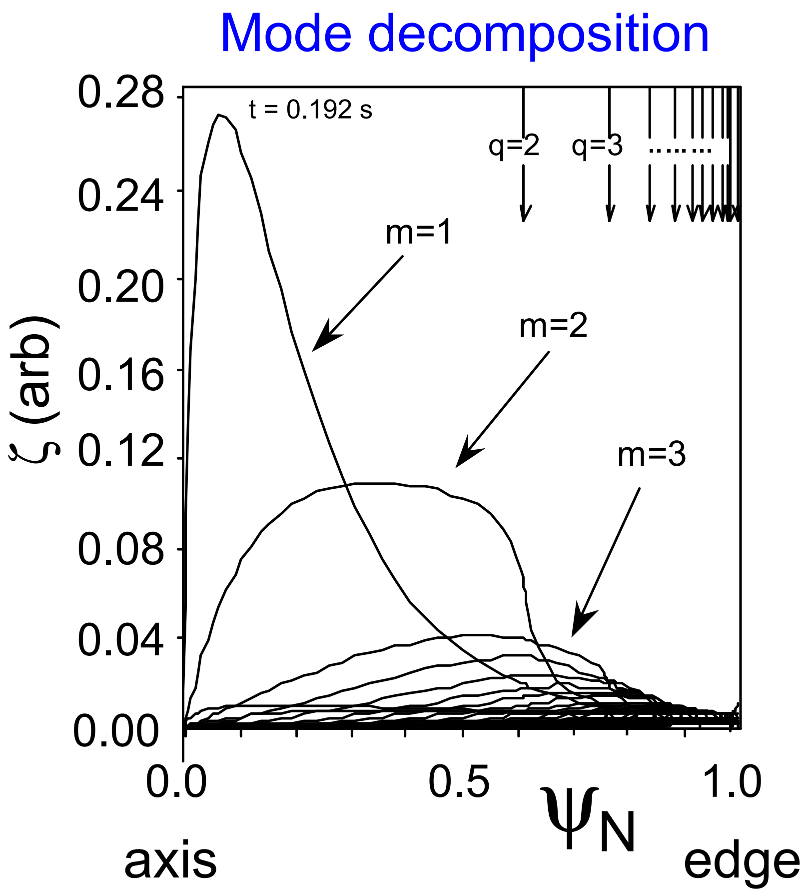


- No low frequency (< 80 kHz) rotating modes observed during measured δT_e
- δT_e displacement precedes n=2 rotating mode

Thomson scattering (LeBlanc)

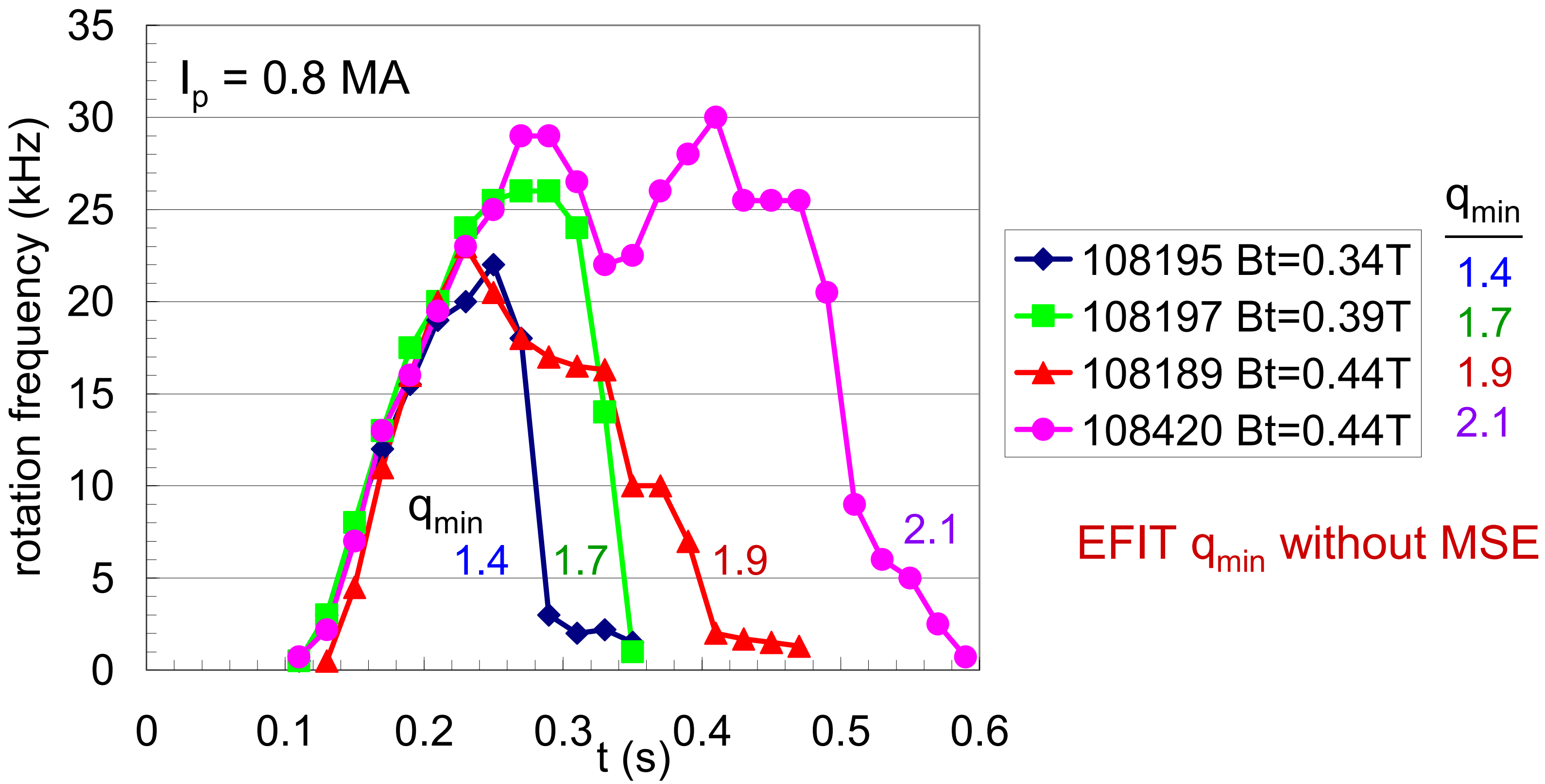
Rotation damping strongest where mode amplitude largest





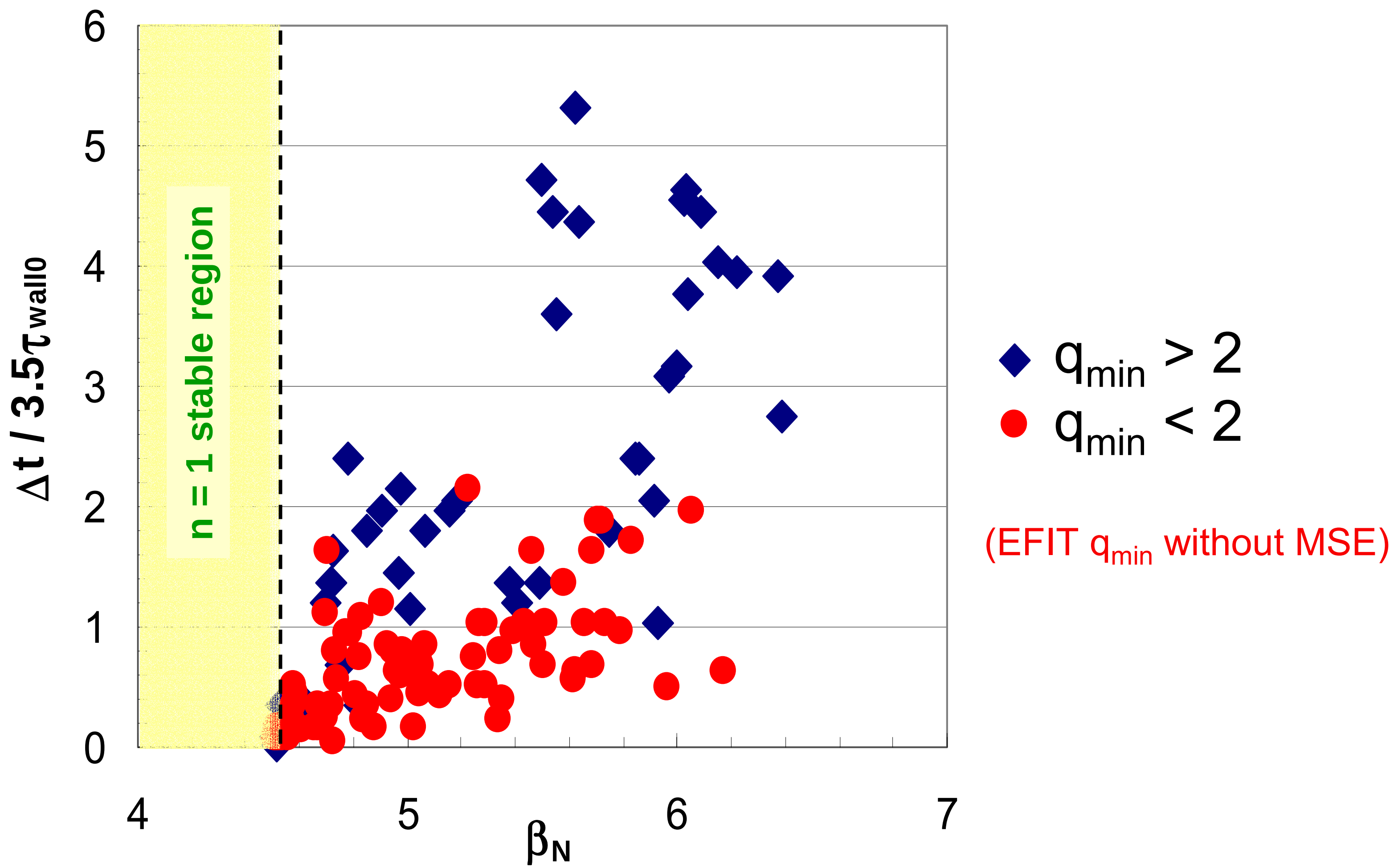
- Field ripple damping by neoclassical parallel viscosity ~ $\delta Br^2 T_i^{0.5}$ possible candidate for observed damping profile

Core rotation damping decreases with increasing q



- Largest rotation damping (dF_ϕ/dt = -600 kHz/s) at B_t < 0.4T, q_{min} < 2
  - Factor of 8 times larger than damping from n=2 island
- When q_{min} ~ 2, rotation damping rate is reduced and F_ϕ is maintained longer
- Consistent with theory linking rotation damping to low order rational surfaces

High β_N plasmas with q_{min} > 2 have longer pulse length



- Typically (15 ms < τ_{wall} < 25 ms), τ_{wall0} ≡ 20 ms
- (1.8 < F_p < 2.3); n=1 mode typically computed stable for β_N< 4.5

W. Zhu

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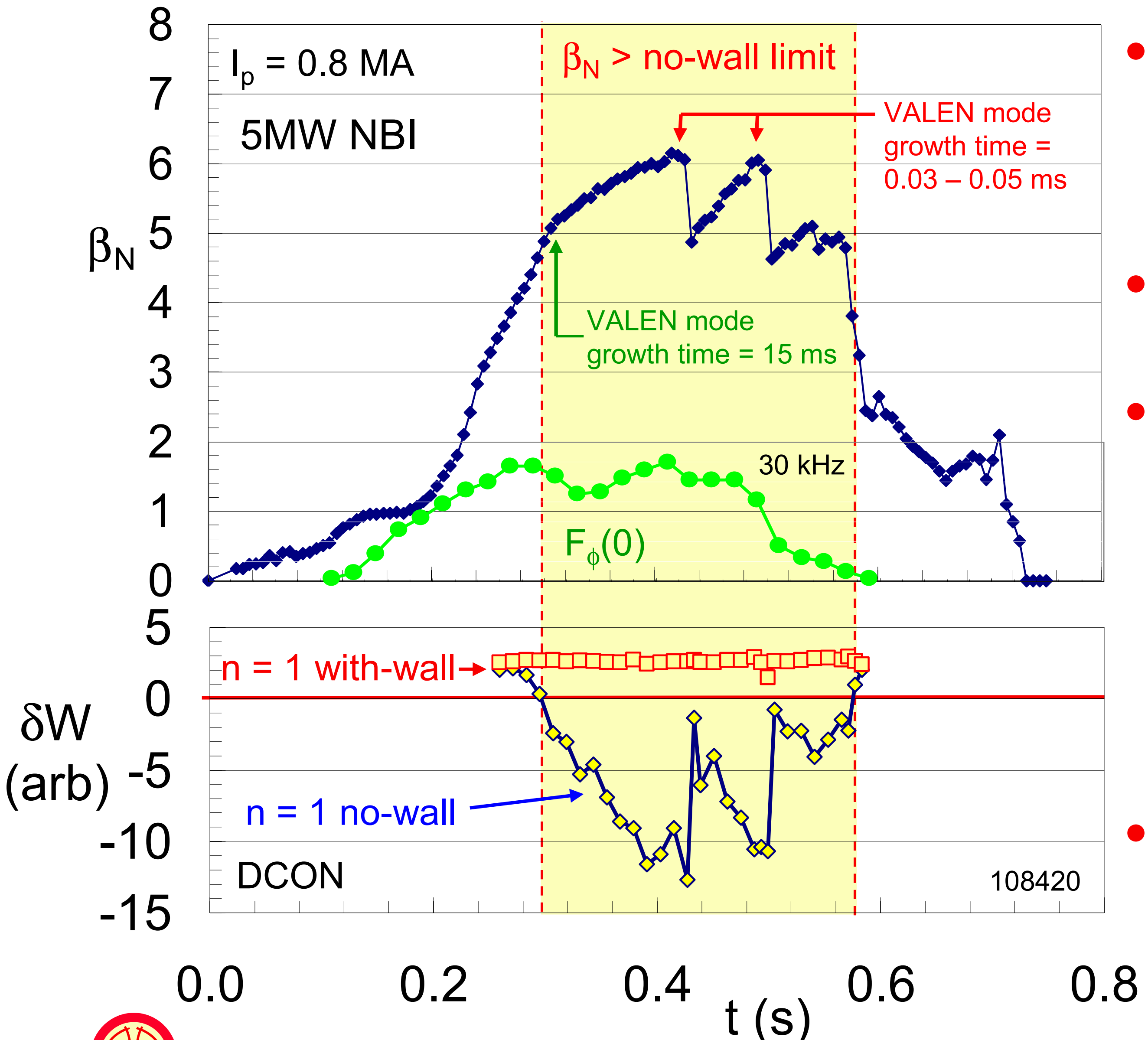
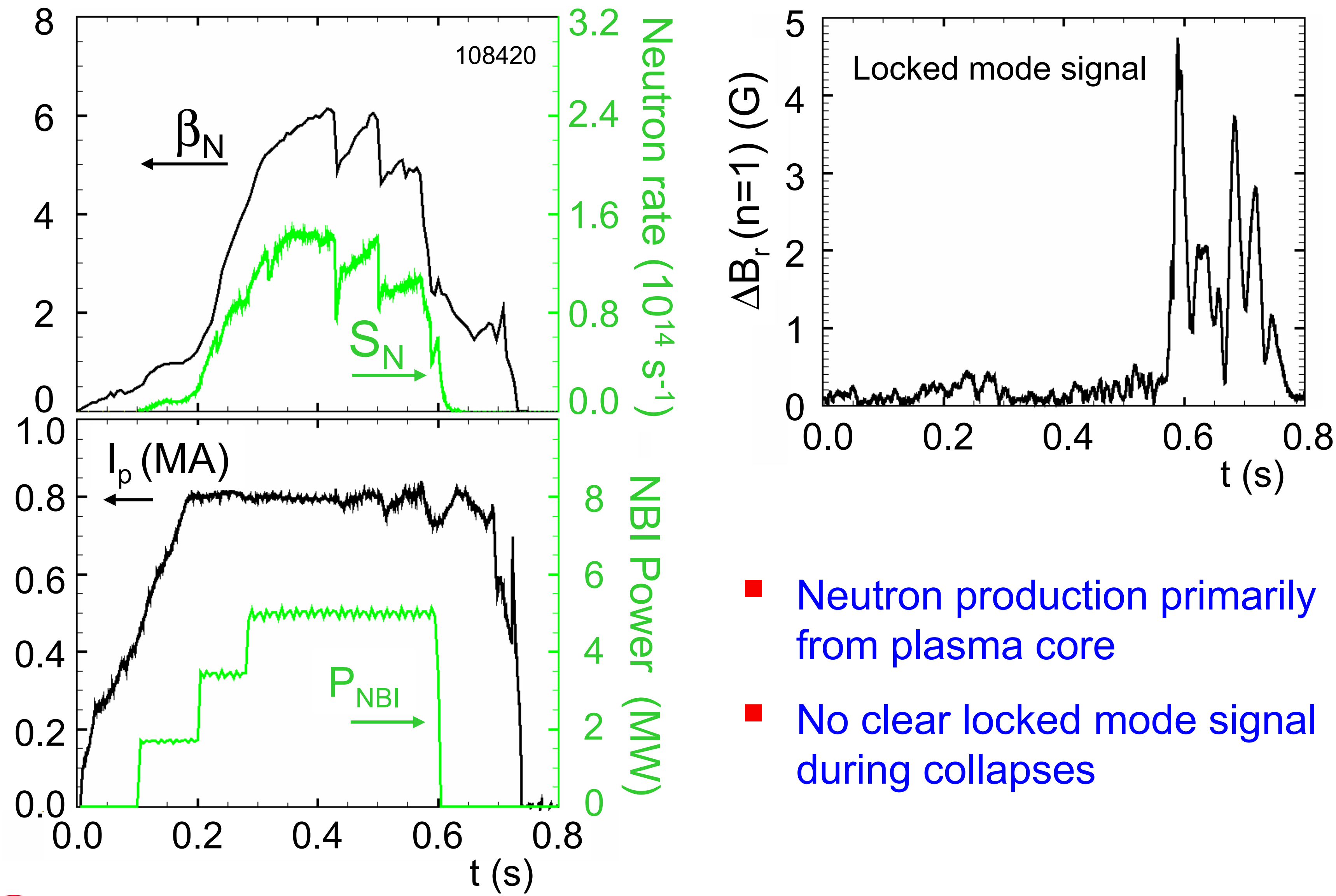
Plasma stabilized above no-wall β_N limit for 18 τ_{wall}



- Plasma approaches with-wall β_N limit
  - VALEN growth rate becoming Alfvénic
- $F_\phi(0)$ increases as β_N >> β_N no-wall
- Passive stabilizer loses effectiveness at maximum β_N
  - Neutrons collapse with β_N - suggests internal mode
  - Larger ∇p drive, mode shape change
- TRANSP indicates higher F_p
  - Computed β_N limits conservative

Neutron collapses at highest β_N suggest internal mode



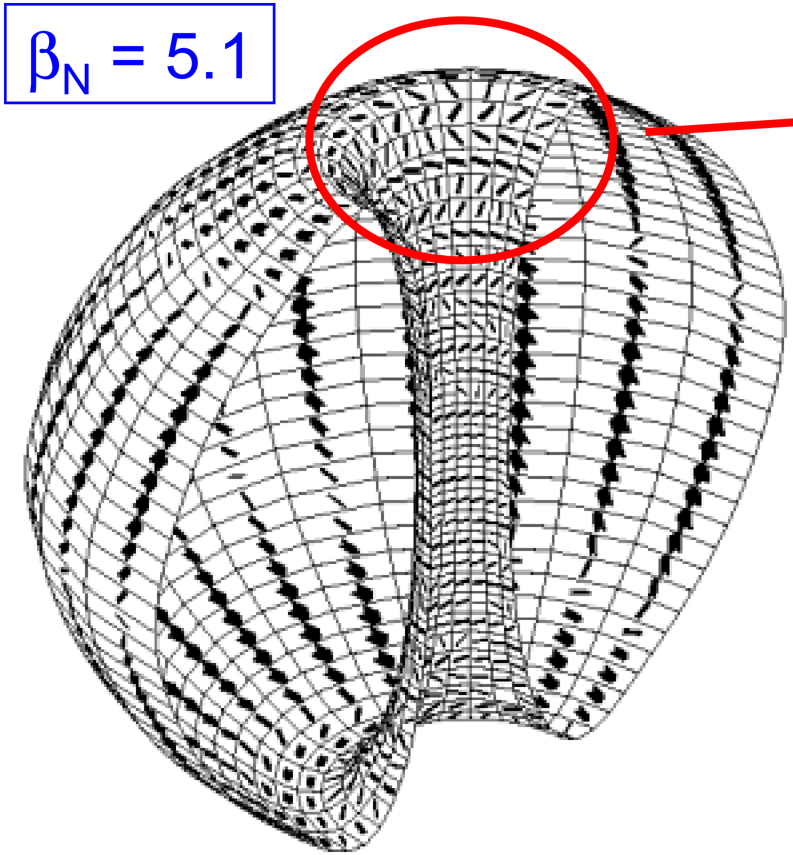
- Neutron production primarily from plasma core
- No clear locked mode signal during collapses

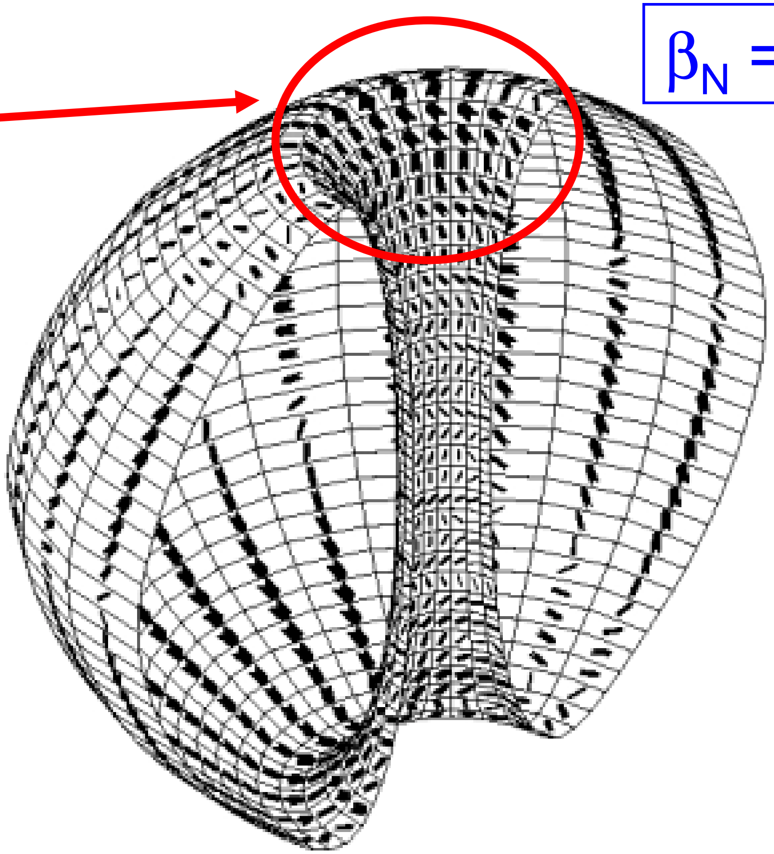
Mode intensifies in divertor region at highest β_N

VALEN / DCON computed *n* = 1 external mode currents

$\beta_N = 5.1$

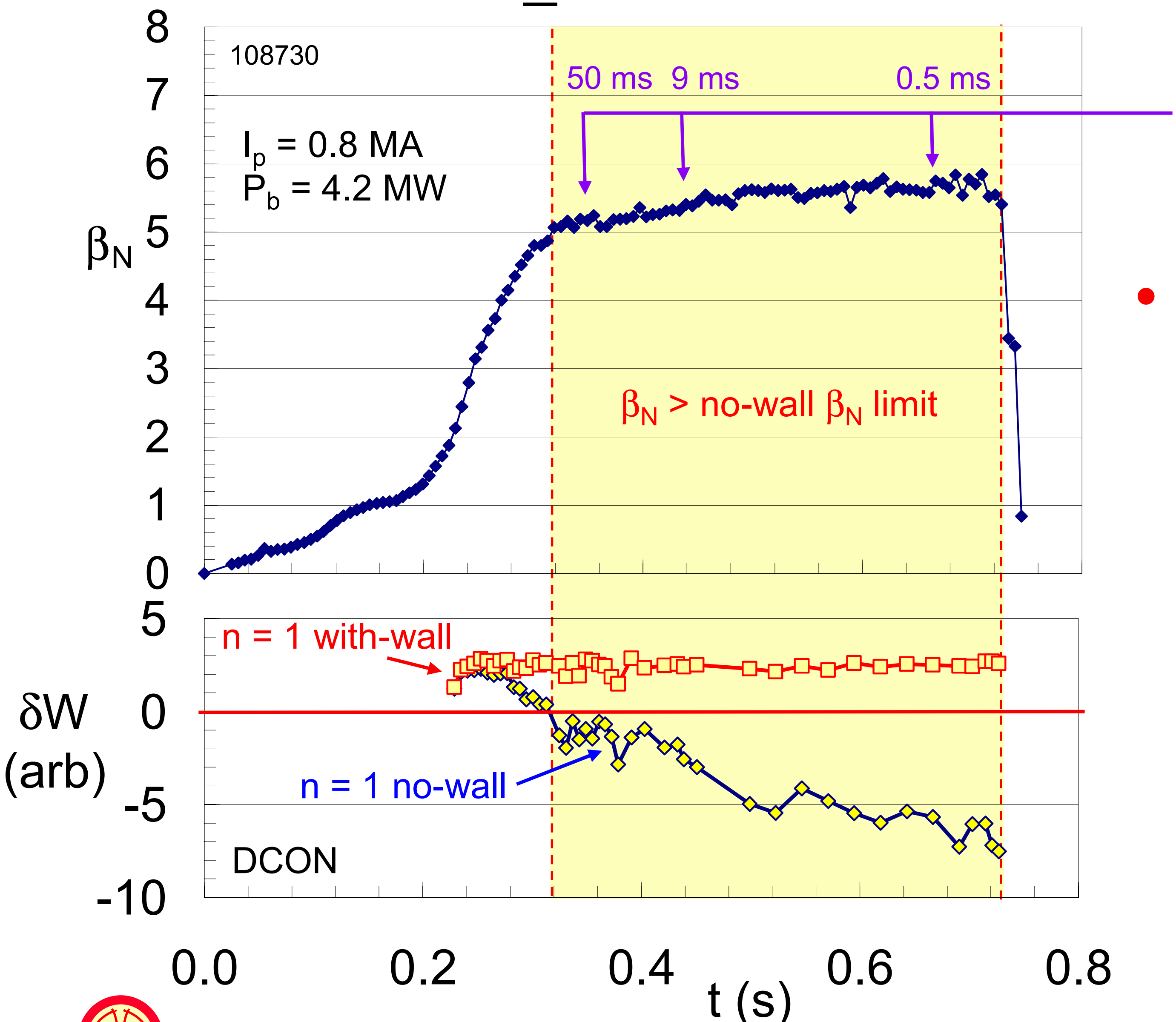
$\beta_N = 7.1$





- Increased ∇p drive more significant in producing higher growth rate

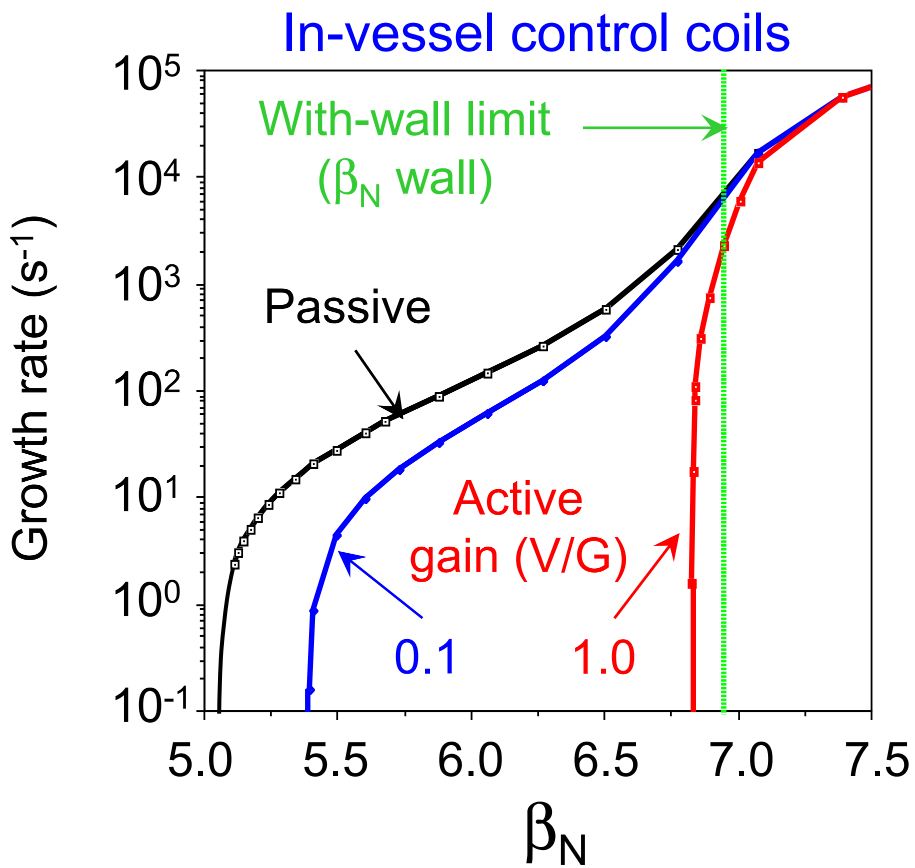
Ideal no-wall β_N limit exceeded and maintained



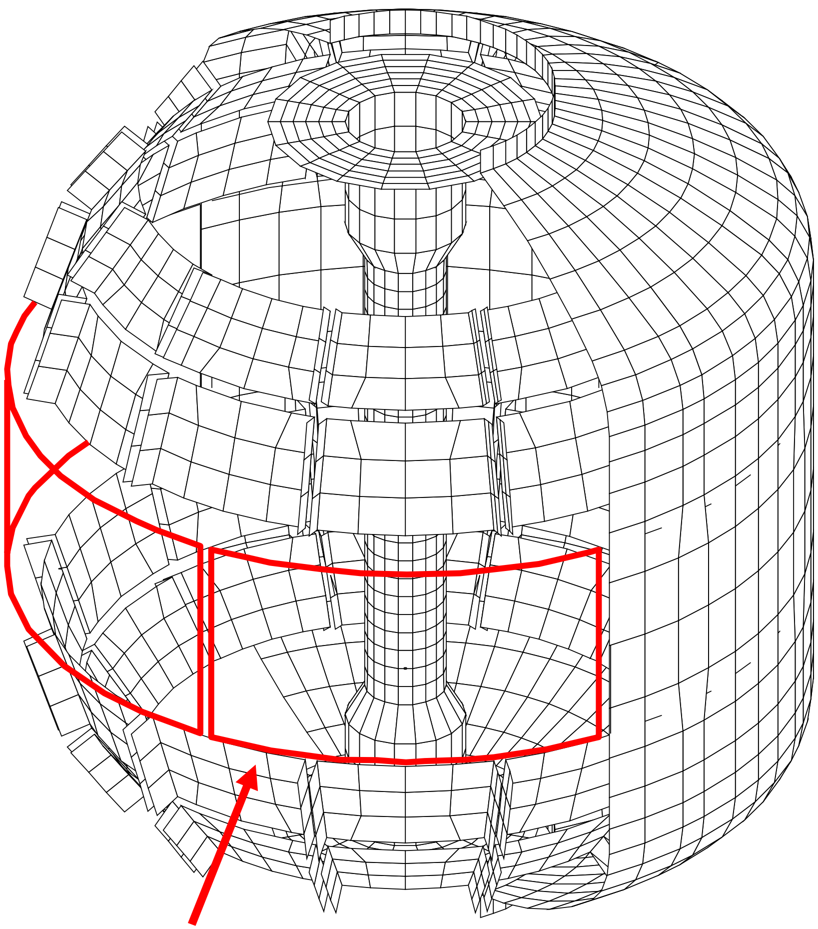
- Ideal no-wall limit violated for 400 ms
  - $t_{pulse} \sim 8\ \tau_E$
  - Computed τ_{wall} for n = 1 mode decreases by factor of 100
  - Average of computed τ_{wall} gives pulse length > 20 τ_{wall}

Active stabilization might sustain 94% of with-wall β limit

In-vessel control coils



VALEN model of NSTX
(cutaway view)

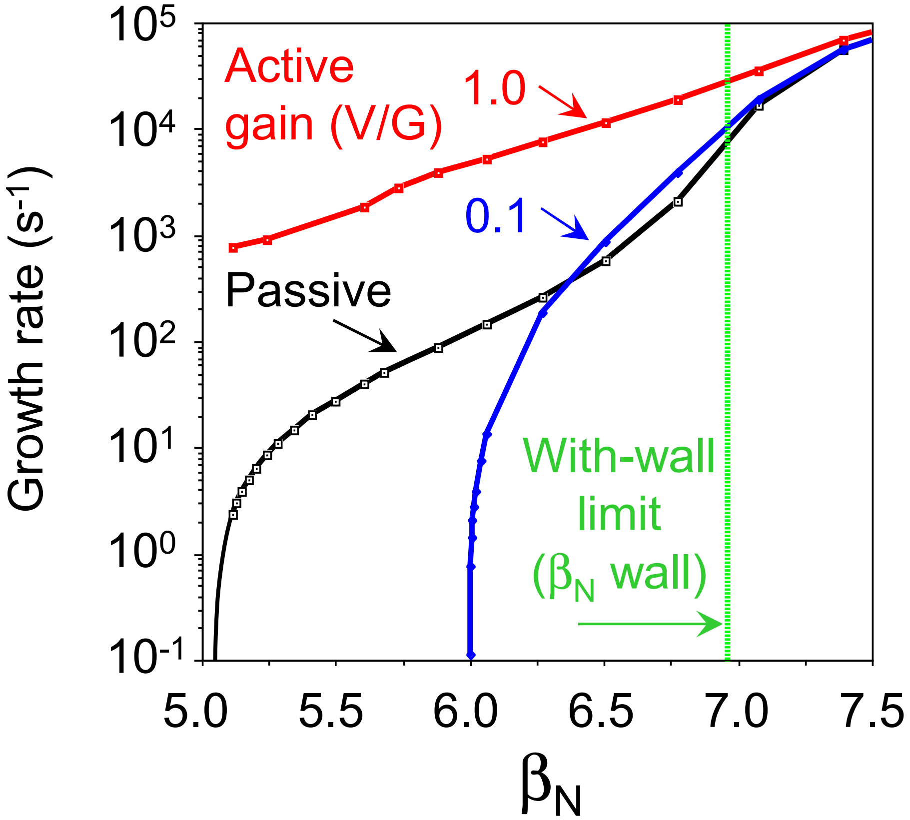


Modeled active feedback coils

- System with ex-vessel control coils reaches 72% of $\beta_{N\ wall}$

VALEN: J. Bialek

Control coils among plates reach only 50% of $\beta_{N\ wall}$



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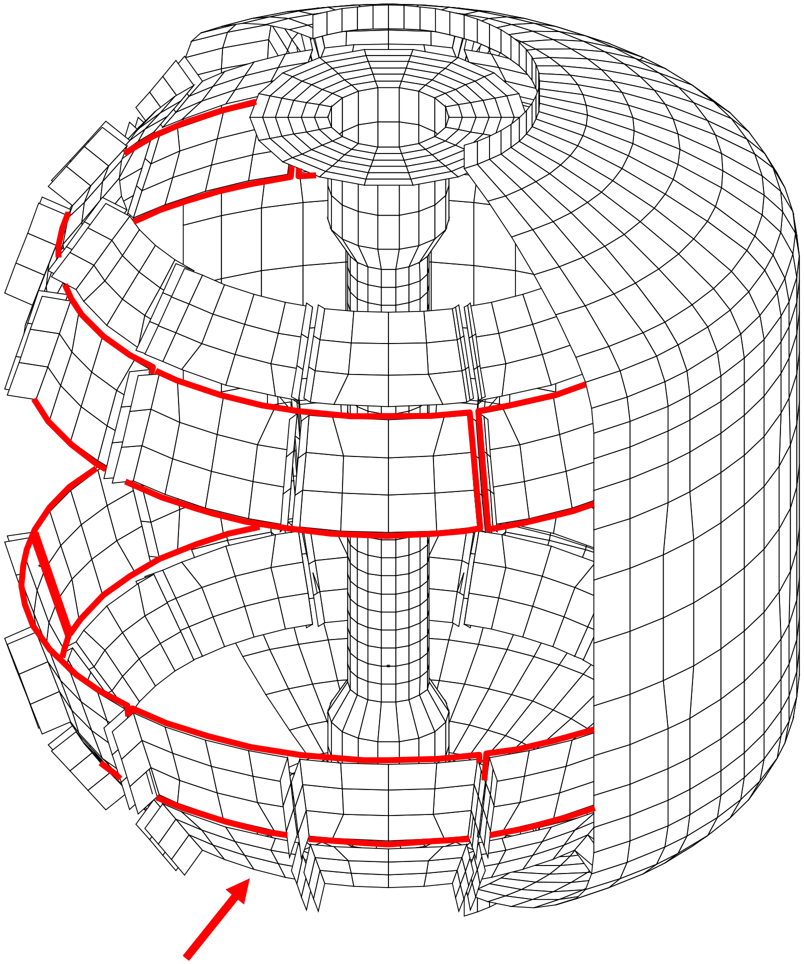
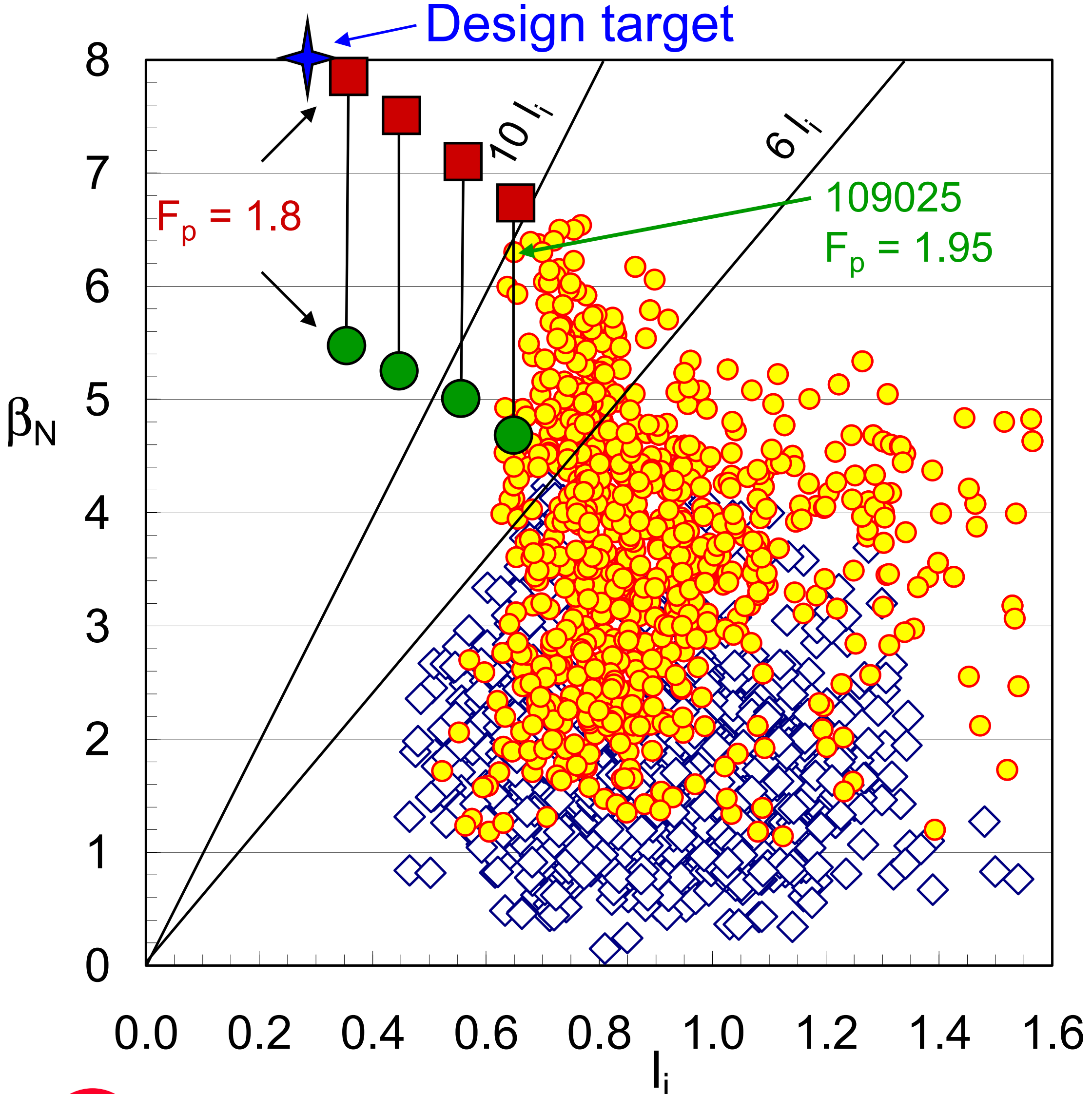


Modeled active feedback coils

VALEN: J. Bialek

Access to β_N = 8 conceptual design target exists



- Pressure peaking factor close to existing EFIT experimental reconstructed value
- Need to maintain elevated q as I_p is increased to sustain plasma

F. Paoletti

Research on passive stabilization and high β_N rotation damping physics has begun

- Passive stabilization above ideal no-wall β_N limit by up to 35%
  - Improvement in plasmas with highest β_N up to 6.5; $\beta_N/l_i = 9.5$
- The β_N limit increases with decreasing pressure profile peaking
- Stability limit insensitive to plasma proximity to passive plates in high β_N plasmas with reduced error field
- Global T_e perturbation measured during RWM
- Rotation damping at $\beta_N > \beta_{N\ no\text{-}wall}$ has two stages
  - Global, non-resonant damping
  - Local, resonant field damping during final stage
- Rotation damping rate substantially decreases as q increases
- Passive stabilizers may become ineffective at highest β_N due to increased ∇p drive and altered mode structure
- Active feedback design shows sustained $\beta_N/\beta_{N\ wall} = 94\%$ possible