PROGRESS IN MHD STABILITY AND CURRENT DRIVE TOWARDS STEADY-STATE HIGH PERFORMANCE

by

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for

THE DIII–D TEAM

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GENERAL ATOMICS

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Progress in MHD Stability and Current Drive Towards Steady-State High Performance[1] T.S. TAYLOR, DIII-D TEAM, General Atomics — The DIII-D steady-state high performance scenario requires an elevated axial q with weak or negative central shear, which is favorable to local stability, high bootstrap fraction, and reduced transport. Two key research elements of this scenario are MHD stability at high β and off-axis current drive. Good progress has been made on stabilization of resistive wall modes (RWM) and neoclassical tearing modes (NTM), the main obstacles to sustaining high β. Identification of the error field amplification of a marginally stable RWM as the mechanism for the loss of rotation in high β plasmas has led to stabilization of the RWM by plasma rotation and an increase in β_N to approximately twice the free-boundary limit. In separate discharges, NTMs have been stabilized by feedback-localized electron cyclotron current drive (ECCD), and β was increased 20% above the NTM onset value. The efficiency of off-axis ECCD, which at low β suffers a reduction due to trapping effects, was found to increase with increasing β_e and recover near axial values at $\beta_e = 2\%$, as predicted by theory. Scenario modeling indicates the planned 3.5 MW of ECCD plus existing neutral beam heating can sustain these high bootstrap fraction, high performance scenarios.

[1] Work supported by the US DOE under Contract DE-AC03-99ER54463.

SUMMARY/OUTLINE

- High normalized beta $\beta_N = \beta_T/(I/aB)$ is required for steady-state high performance
- Stabilization of resistive wall mode by plasma rotation allows reproducible stable operation above β_{nowall}, up to ~ $\beta_{ideal\ wall}$
- Neoclassical tearing modes are stabilized by active feedback control of the deposition location of electron cyclotron current drive (ECCD)
- Modeling shows that 3.5 MW of off-axis electron cyclotron current drive (ECCD) can maintain favorable q-profile for advanced tokamak studies and avoidance of tearing modes

FOCUS OF DIII–D RESEARCH IS ON ADVANCED TOKAMAK PHYSICS

— Discovering the Ultimate Potential of the Tokamak —

- Innovative concept improvement of the tokamak concept toward
  - High power density
    - Improved stability, $\beta_T\uparrow$, $\beta_N\uparrow$
  - Compact (smaller)
    - Improved confinement, $\tau\uparrow$, $H\uparrow$
  - Steady state
    - High bootstrap fraction $\Rightarrow$ high β_N
    - Current drive and divertor optimization

Simultaneously integrated

- A self-consistent optimization of plasma physics through
  - Magnetic geometry (plasma shape and current profile)
  - Plasma profiles (current, pressure, density, rotation, radiation)
  - MHD feedback stabilization

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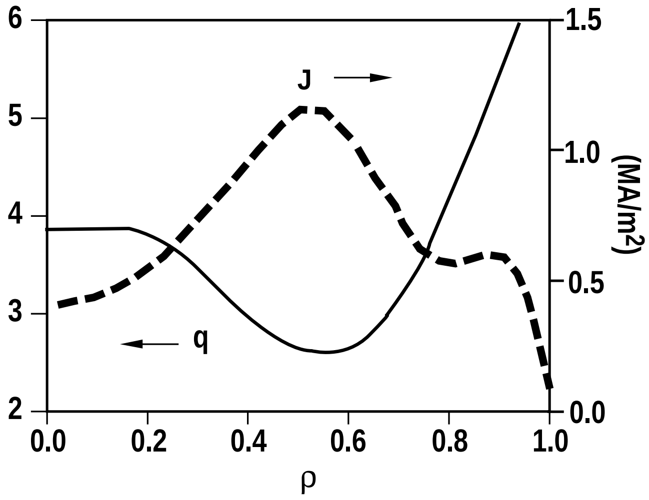
ULTIMATE POTENTIAL OF THE TOKAMAK
VISION: HIGH BOOTSTRAP FRACTION NCS SCENARIO



- Broad or hollow current profile and broad pressure profile
  - $q_{min} > 1 \rightarrow$ stability to central modes (ST, NTM, . . .)
  - q_0, $q_{min} > 1 \rightarrow$ high bootstrap fraction, f_{BS}
  - Low magnetic shear allows high core pressure gradients (ITBs) — second stable access
  - ITB gives good confinement
  - Strong coupling of external modes to wall → stabilization of resistive wall mode
  - Well-aligned bootstrap current, edge current (H–mode)

- Promise of exciting new physics in NCS regime, high q_0, q_{min}
  - Key is to maintain profile to investigate physics
  - High f_{BS} (β_N, β_p) needed for high q_0, q_{min}

- Building blocks for high performance plasmas represent important and rich scientific challenges
  - Density and impurity control
  - Current profile evolution and control ✓
  - Resistive wall mode stabilization ✓
  - Neoclassical tearing mode stabilization ✓
  - Transport barrier control
  - Pedestal optimization and control

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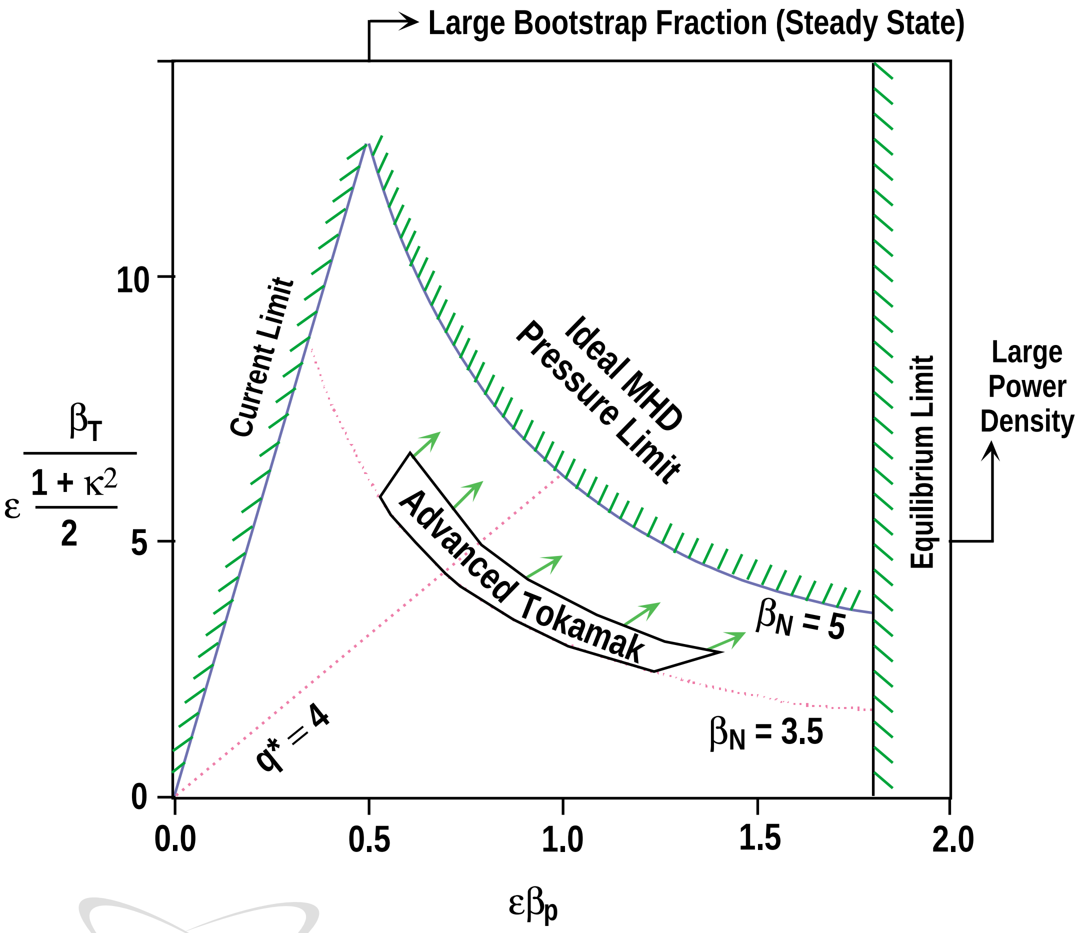
STEADY STATE HIGH PERFORMANCE REQUIRES OPERATION AT HIGH β_N

$$Q_{ss} = \frac{P_{fus}}{P_{CD}} \propto \frac{\gamma_{cur}}{nq} \quad \frac{\varepsilon_{eff} \quad \beta_N^2}{(1 - \xi \sqrt{A\, q\, \beta_N})} \quad B^3 a \kappa$$



- High power density $\Rightarrow$ high β_T
- Large bootstrap fraction $\Rightarrow$ high β_p
- Steady state $\Rightarrow$ high β_N

$$\beta_T\, \beta_p \propto \left(\frac{1 + \kappa^2}{2}\right) \beta_N^2$$

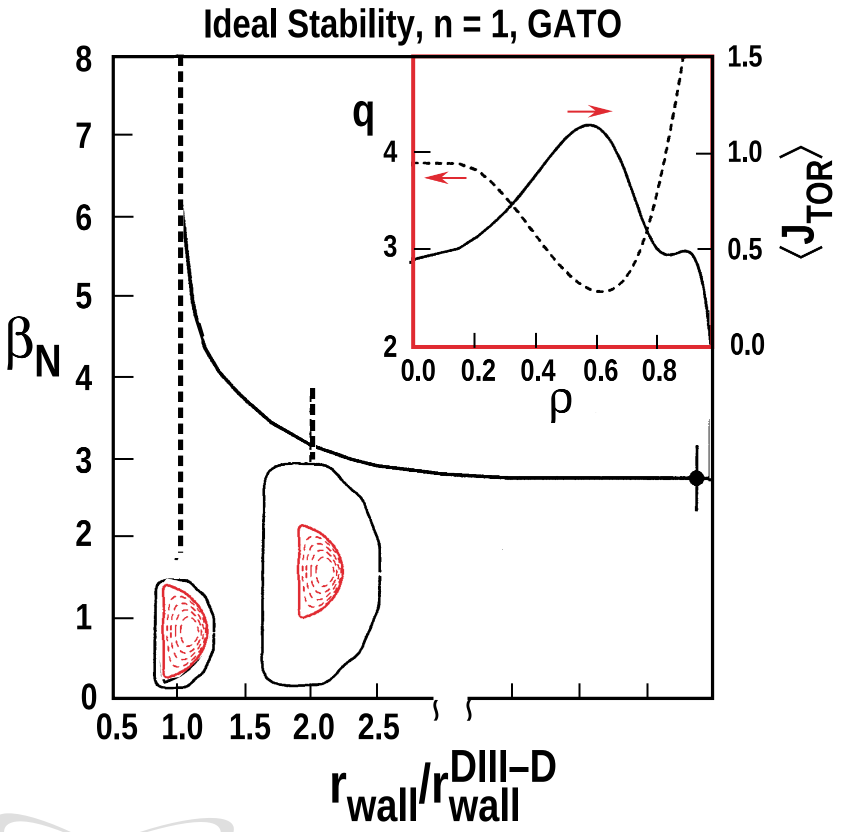
HIGH β_N OPERATION REQUIRES PLASMA SHAPING, BROAD PRESSURE PROFILES, AND WALL STABILIZATION

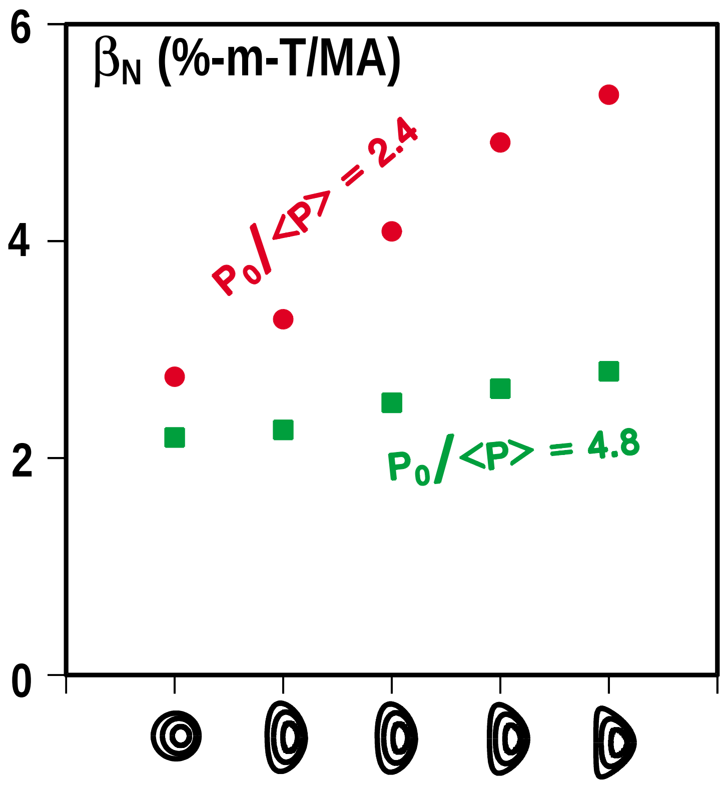
- $\beta_N \equiv \beta_T/(I/aB)$
- β_N ~ 6 with wall stabilization
- β_N ~ 3 without wall stabilization

- $\beta_T \; \beta_p = 25 \left(\frac{1+\kappa^2}{2}\right) \left(\frac{\beta_N}{100}\right)^2$

$\beta_p \rightarrow f_{BS} = C_{BS} \, \varepsilon^{1/2} \, \beta_p$

$\beta_T \rightarrow P_{FUS} \propto \beta_T^2 \, B_T^4$





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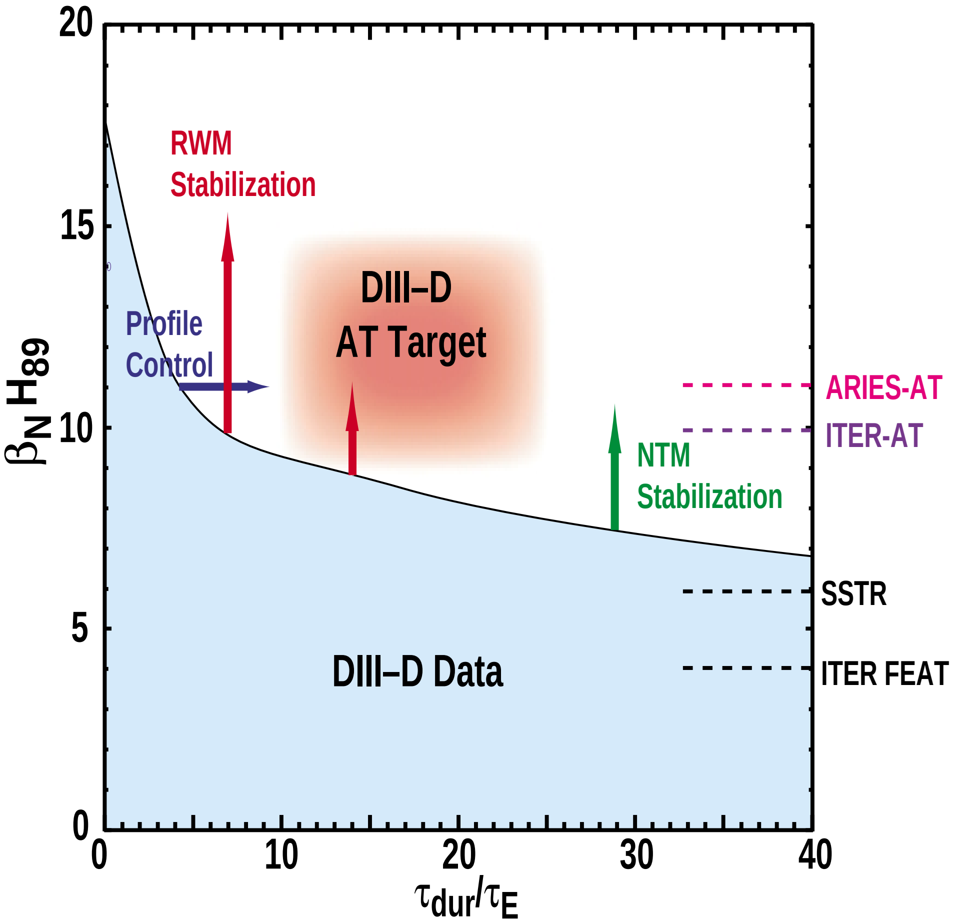
PROGRESS IN STEADY HIGH PERFORMANCE RELIES ON AVOIDANCE AND CONTROL OF MHD INSTABILITIES



- β_N limited by resistive wall modes
  — RWM stabilization

- $q_0 < 1.5$, β_N limited by neoclassical tearing modes
  — NTM stabilization

- Duration limited by current profile evolution
  — Profile control

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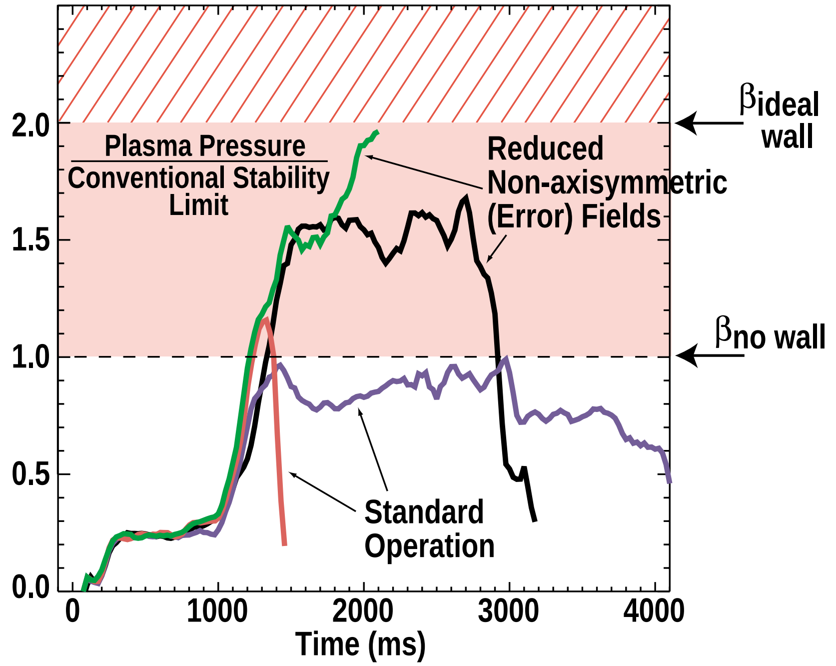
STABILIZATION OF THE RESISTIVE WALL MODE



KEY RESULT

- Plasma pressure is stably maintained above the conventional pressure limit; up to a factor of two above the conventional limit

KEY PHYSICS

- Resistive wall mode is stabilized by plasma rotation
- Identification of "error field amplification" as mechanism for loss of plasma rotation
- Reduction of non-axisymmetric error field → continued rotation → stable to high pressure

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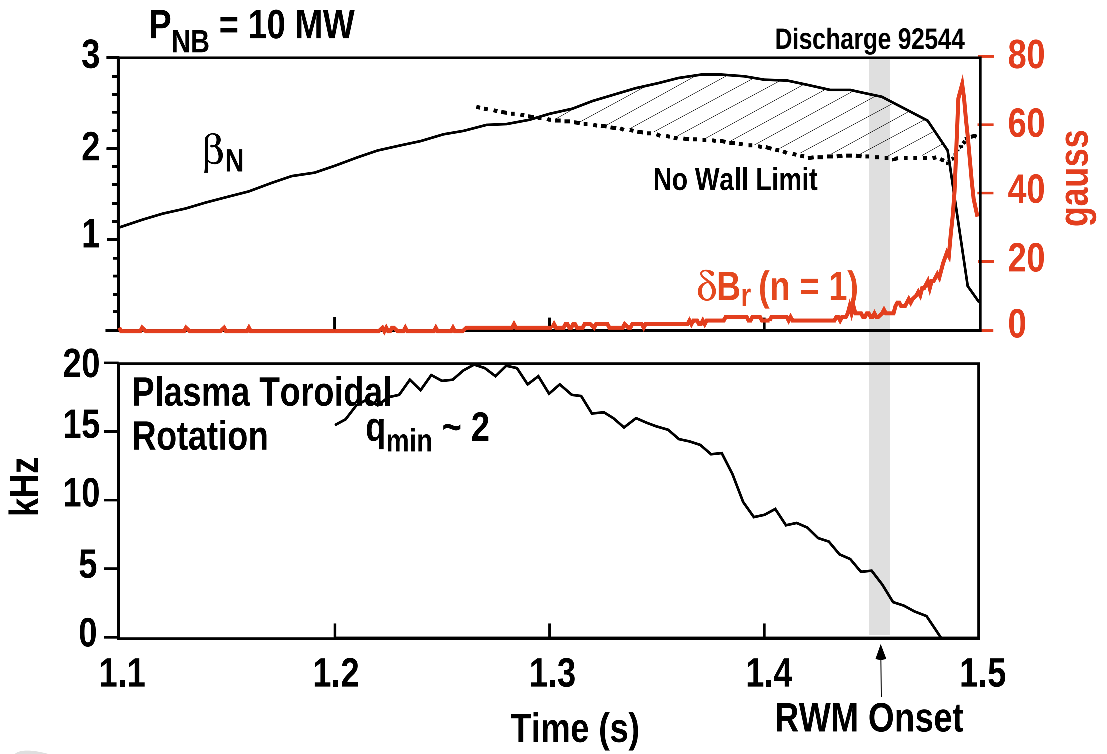
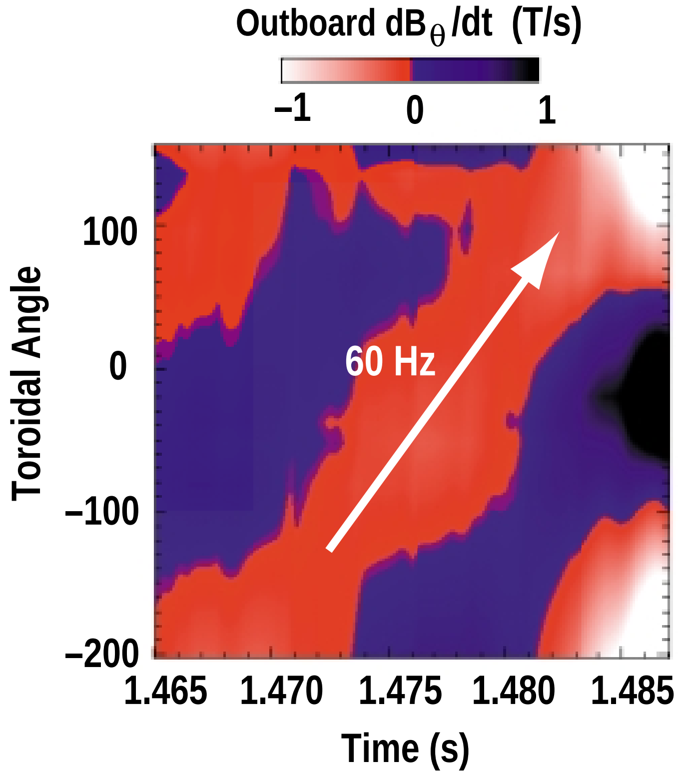
PREVIOUS EXPERIMENTS: DURATION OF HIGH BETA PHASE WITH $\beta_N > \beta_N^{\text{no-wall}}$ IS LIMITED BY SLOWING OF PLASMA ROTATION

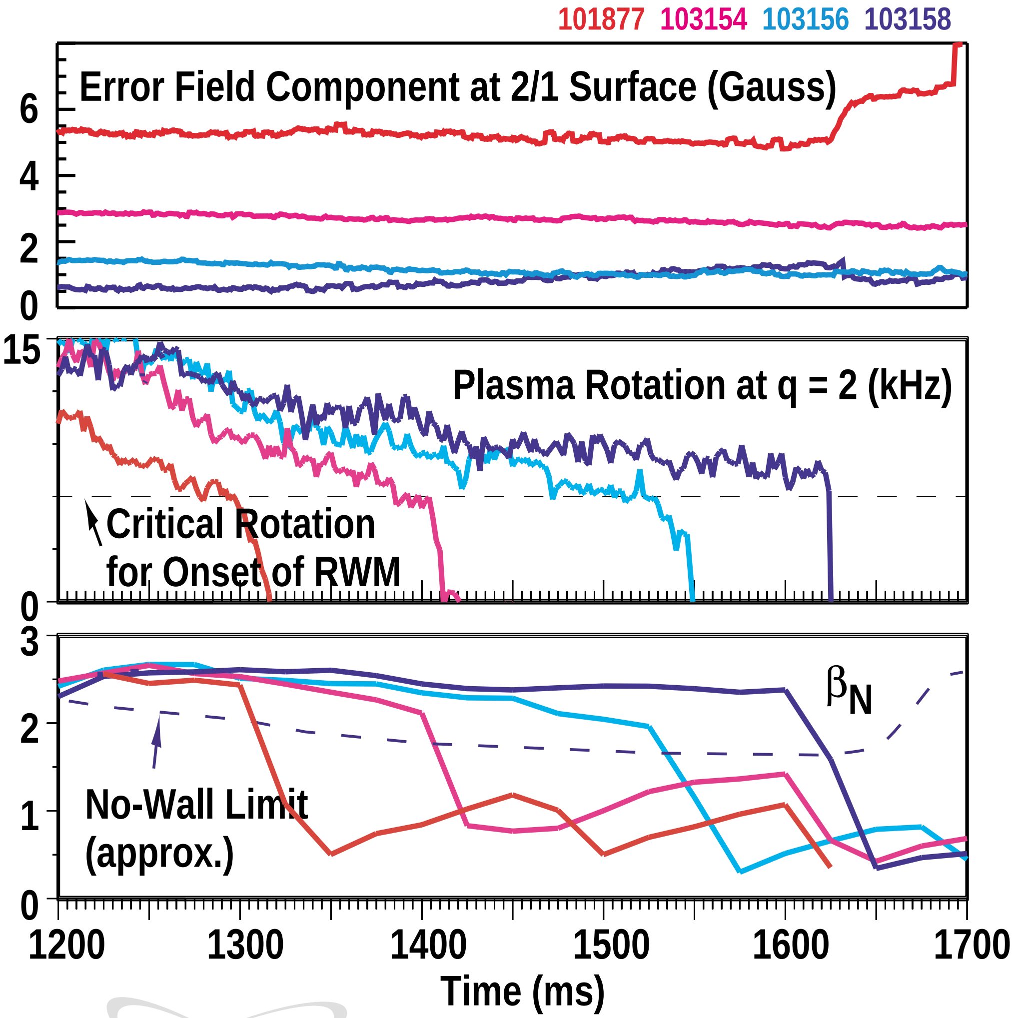
- Wall stabilization sustained with β_N up to $1.4 \times \beta_N^{\text{no-wall}}$
- Plasma rotation slows as β_N exceeds the no-wall limit
- Resistive wall mode grows when rotation drops below a critical value



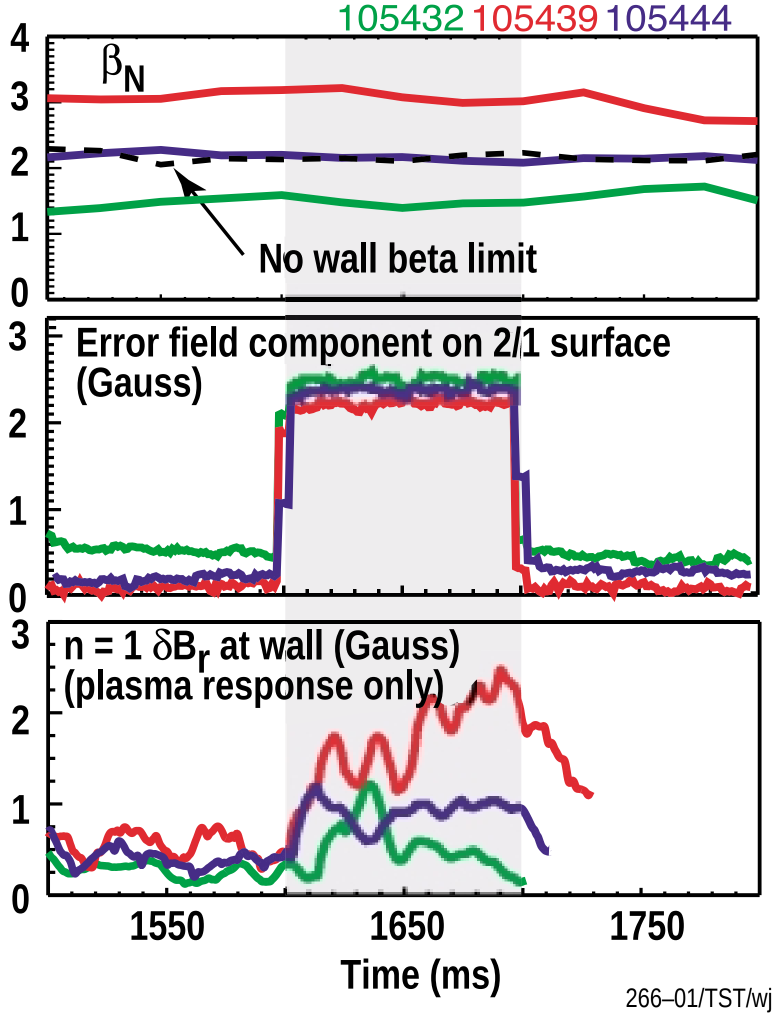


LOSS OF PLASMA ROTATION IS CAUSED BY AMPLIFICATON OF NON-AXISYMMETRIC ERROR FIELD WHEN β EXCEEDS $\beta_{\text{no wall}}$

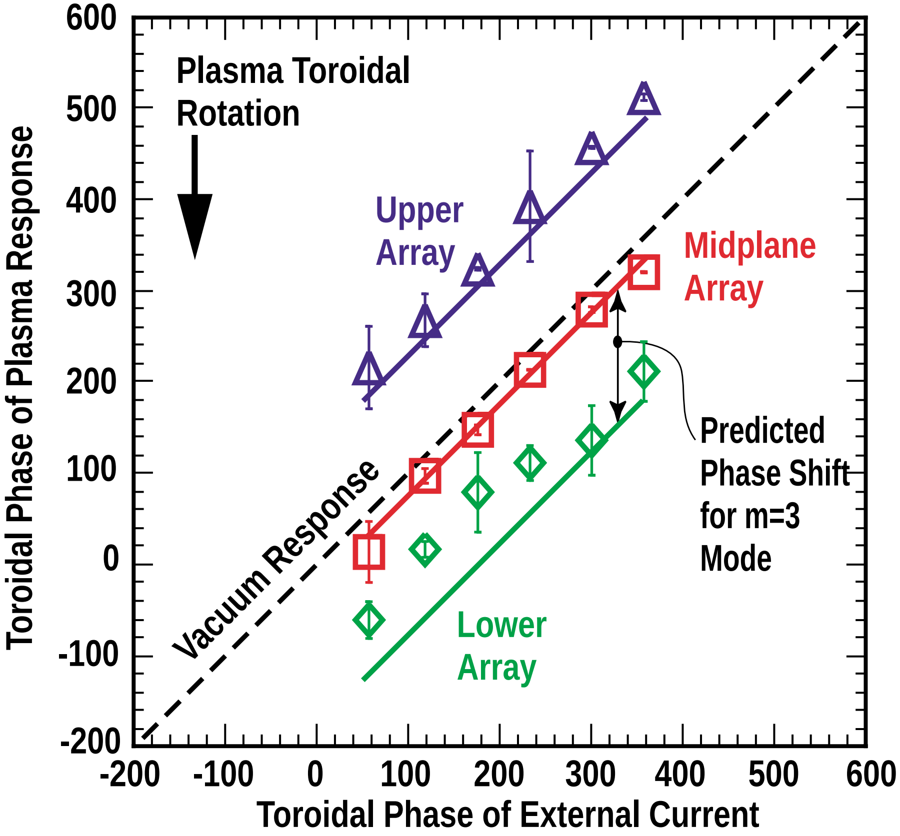
- Plasma rotation sustained longer with decreasing error field

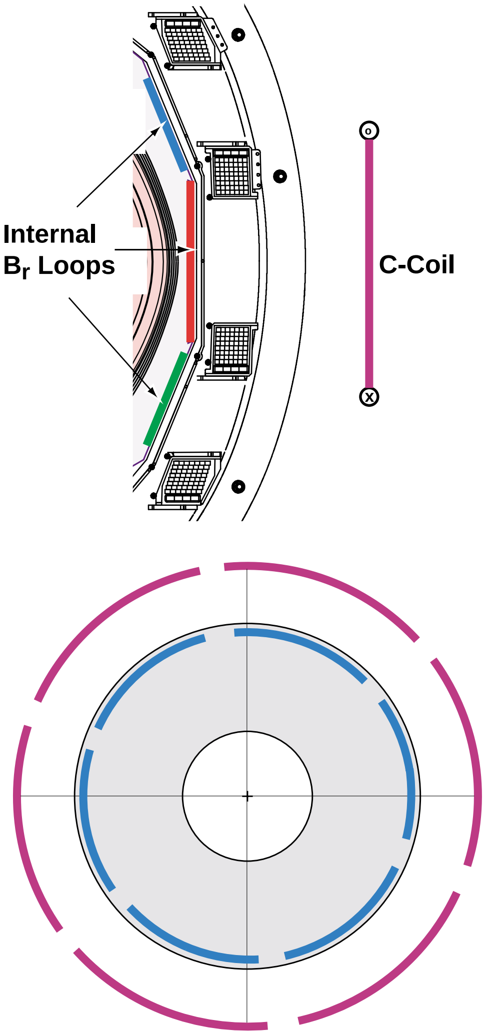


- Marginally stable RWM can be excited to finite amplitude by resonant, non-axisymmetric "error" field [A.H. Boozer, Phys. Rev. Lett. (2001)]



MARGINALLY STABLE PLASMA MODE IS SHOWN BY RESONANT RESPONSE TO APPLIED n = 1 FIELD





- Vacuum response has no phase shift between arrays
- Toroidal phase shift agrees with phase shift predicted for m=3 mode

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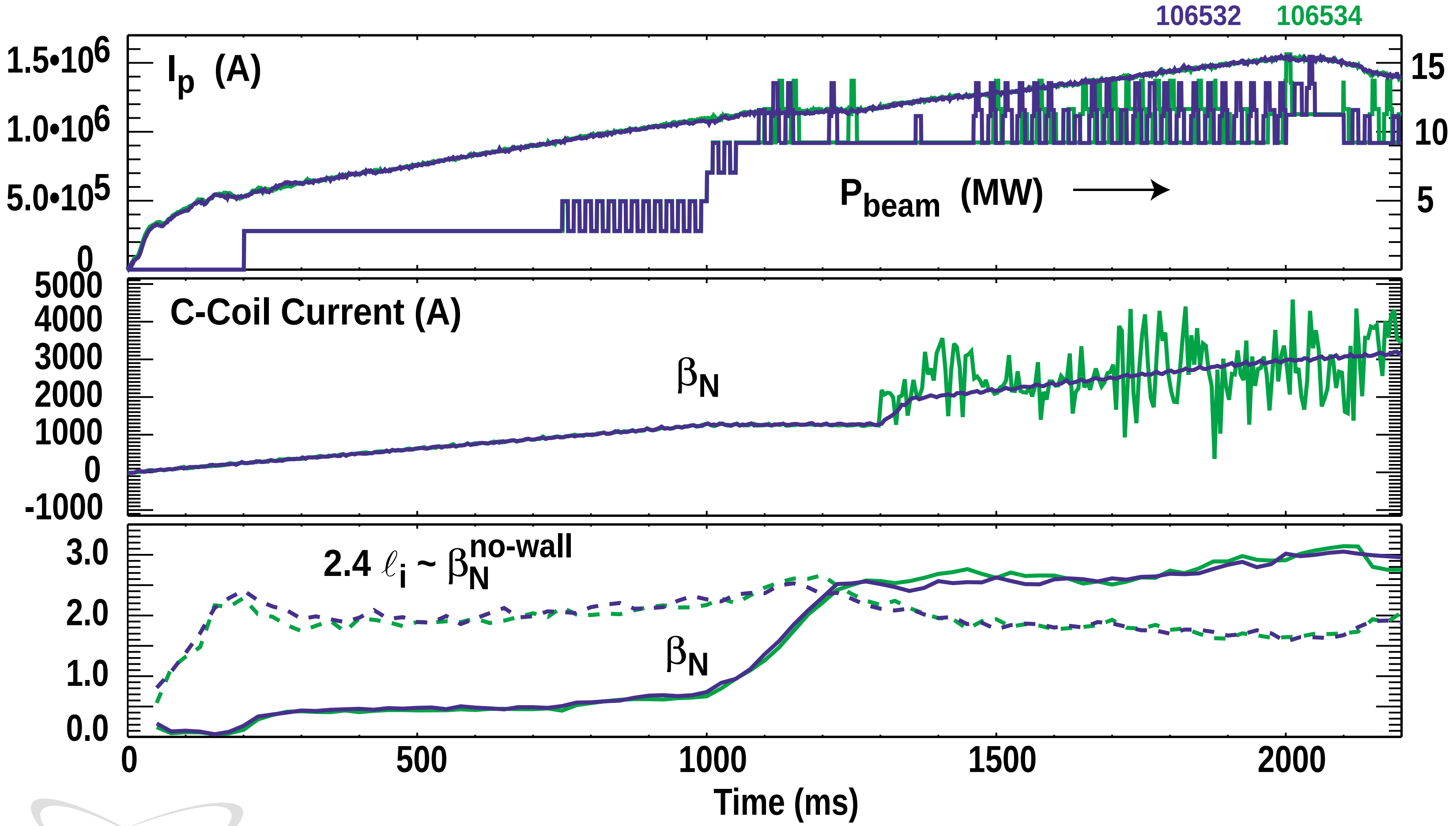
$\beta_N \sim 2x\ \beta_N^{\text{no wall}}$ IS OBTAINED WITH ACTIVE RWM FEEDBACK

- Optimized error field reduction found with high gain active feedback on RWM
- Same performance is obtained with preprogrammed error correction currents → stabilization is consequence of reduced error field and sustained plasma rotation



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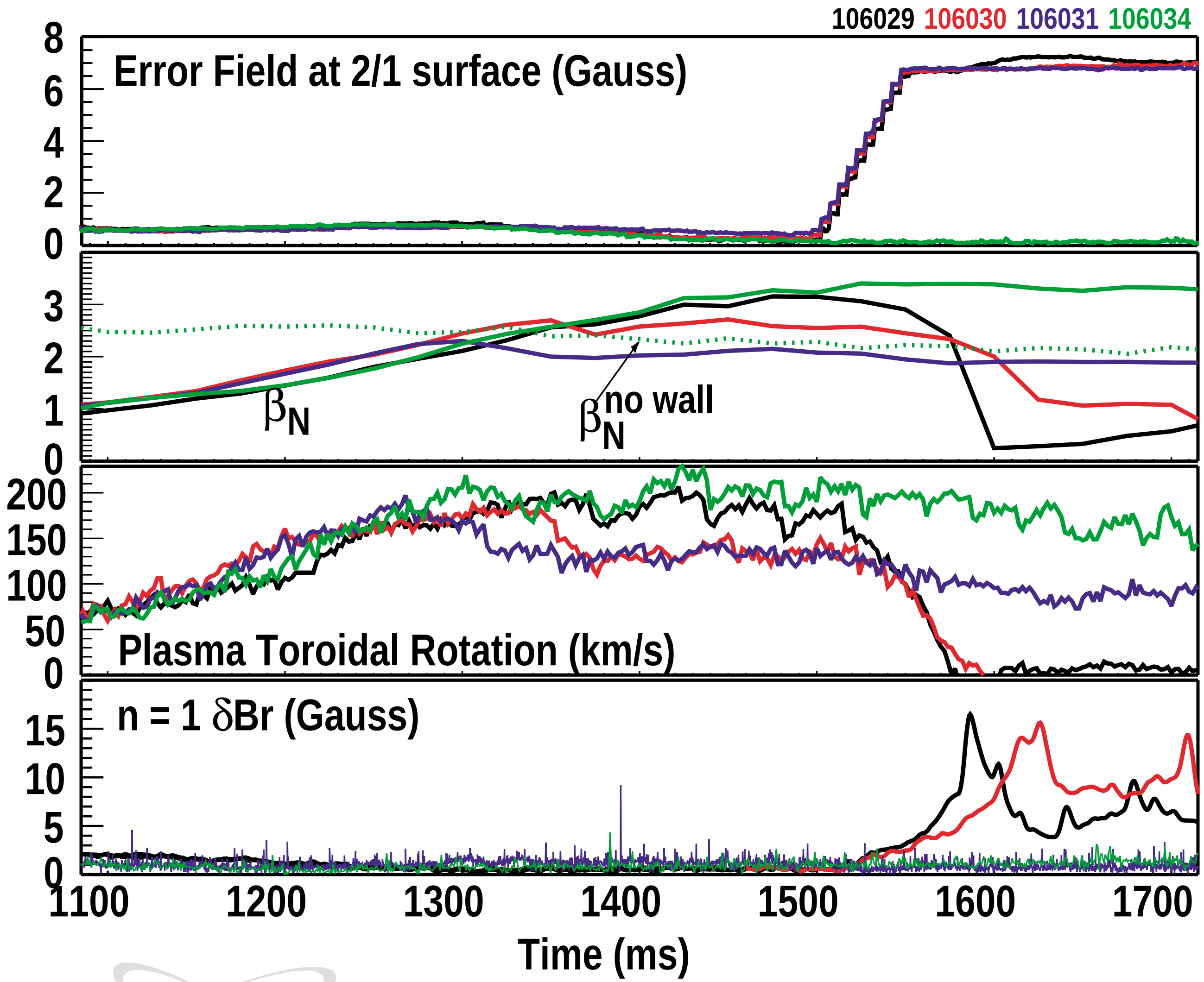
BRAKING EXPERIMENT AT DIFFERENT β VALUES GIVES EXPERIMENTAL BENCHMARKING OF CALCULATED NO-WALL LIMIT

- Increase error field during discharge



- $\beta_N \lesssim \beta_N^{no\ wall}$
  - RWM strongly damped
  - Rotation sustained
  - Stable plasma
- $\beta_N > \beta_N^{no\ wall}$
  - Large amplification of applied error field
  - Rotation decreases
  - Unstable RWM
- Independent confirmation of $\beta_N^{no\ wall}$
  - Agreement with ideal stability calculations (GATO)

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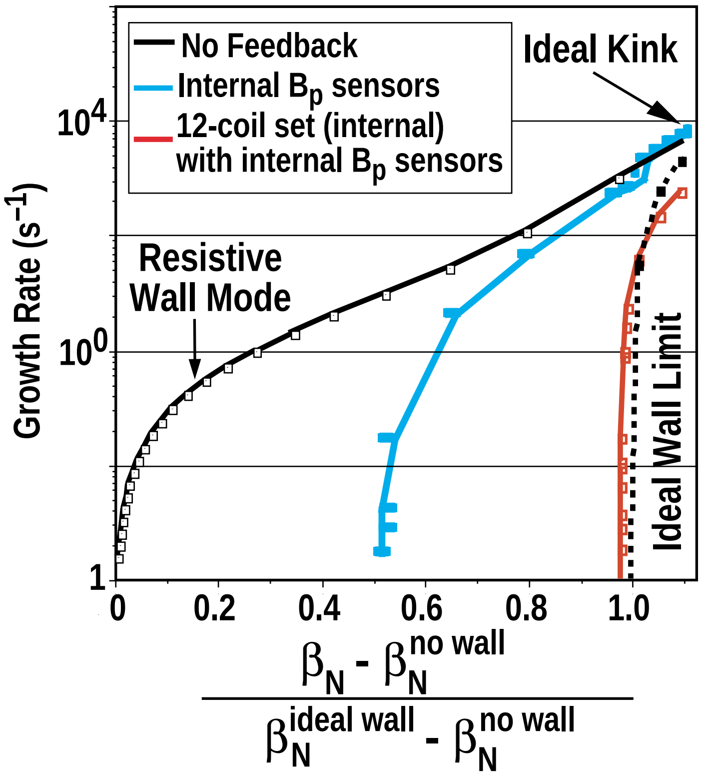
FUTURE DIRECTIONS FOR STABILIZATION OF THE RESISTIVE WALL MODE

- Stabization of the resistive wall mode by plasma rotation demonstrates stable operation at $\beta_N > \beta_N^{\text{no wall}}$ is feasible and validates theoretical models
- Active stabilization with non-axisymmetric coils is calculated to open this high beta regime to plasmas with no rotation

VALEN Calculations



Coils Being Installed in DIII–D

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NEOCLASSICAL TEARING MODE STABILIZATION

KEY RESULTS

- m/n = 3/2 neoclassical tearing mode stabilized by active feedback control of the location of electron cyclotron current drive (ECCD)
  - ECCD replaces missing bootstrap current in the island
  - Accurate positioning of EC deposition with respect to the island is required; ~1 cm
  - Rigid plasma shift (or small change in B_T) under active feedback control aligns the EC deposition with the island location
  - β is increased after NTM stabilization, by approximately 60%

CO-ECCD RADIALLY LOCALIZED AT ISLAND CAN REPLACE THE “MISSING” BOOTSTRAP CURRENT AND COMPLETELY STABILIZE THE NEOCLASSICAL TEARING MODE

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \varepsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{rw}{w^2+w_d^2} - \frac{rw_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2 w^2}\left(\frac{\eta\, \overset{\overset{\text{rf}}{\Downarrow}}{j_{ec}}}{j_{bs}}\right)\right],$$

$$\eta = \eta_0 e^{-\overset{\overset{\text{positioning}}{\Downarrow}}{[5\Delta R/3\delta_{ec}]^2}} / \,(1+2\overset{\overset{\text{width}}{\Downarrow}}{\delta_{ec}^2} / w^2)$$

$m/n = 3/2$

$\beta_\theta = 0.9$

$\Delta' r = -3$

$r = 0.36$ m

$\varepsilon^{1/2} = 0.5$

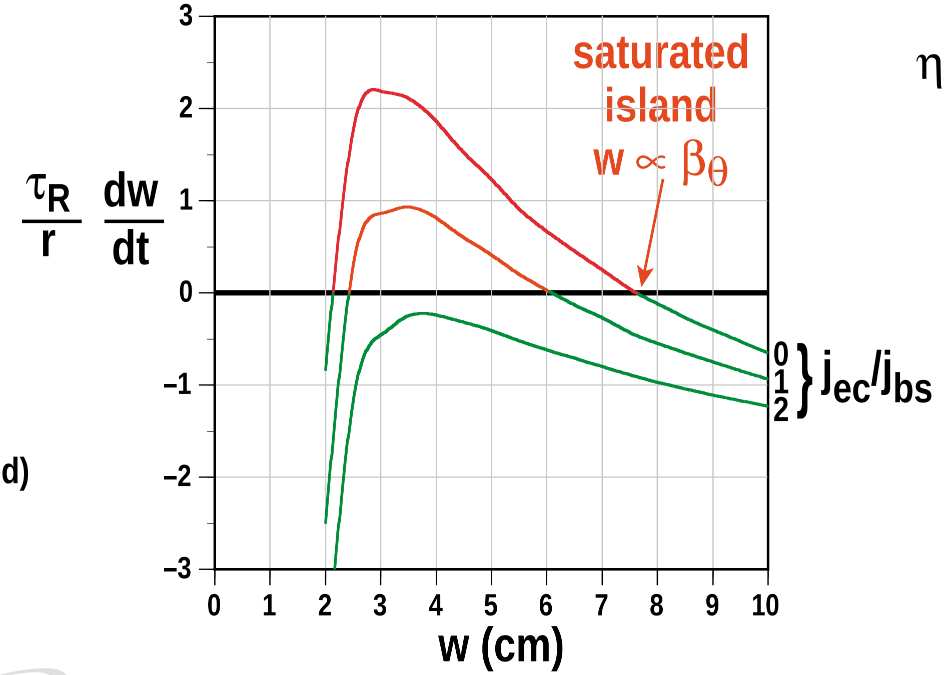
$L_q/L_p = 1.5$

$w_{pol}/r = 0.05$

$\delta_{ec}/r = 0.08$

$\eta_0 = 0.4$ (no mod)

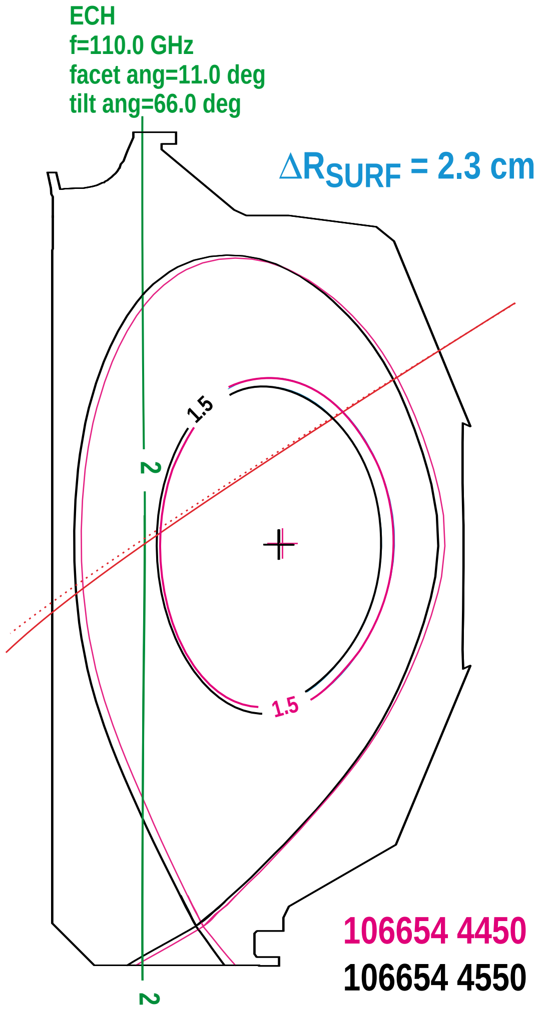
$\Delta R/\delta_{ec} = 0$



- NTM amenable to complete suppression because $\dot{w} < 0$ for $w \lesssim w_{pol}$
- ECCD must be within island
  - no effect for $\Delta R > \delta_{ec}$

PLASMA CONTROL SYSTEM REAL-TIME FEEDBACK NTM CONTROL VARIES MAJOR RADIUS IN RESPONSE TO MODE AMPLITUDE

- Execute ΔR "Blind Search" pattern when mode (3/2 island) amplitude exceeds threshold
- Move plasma major radius (and island) "rigidly" (ΔR_{step} = 1 cm)
- Detect alignment of ECCD current deposition with island ("sweet spot") by sufficient change in mode amplitude over the specified "dwell" time (100 ms)
- If mode decays at > threshold rate, continue to dwell. If not, continue search (or "jitter" . . .)



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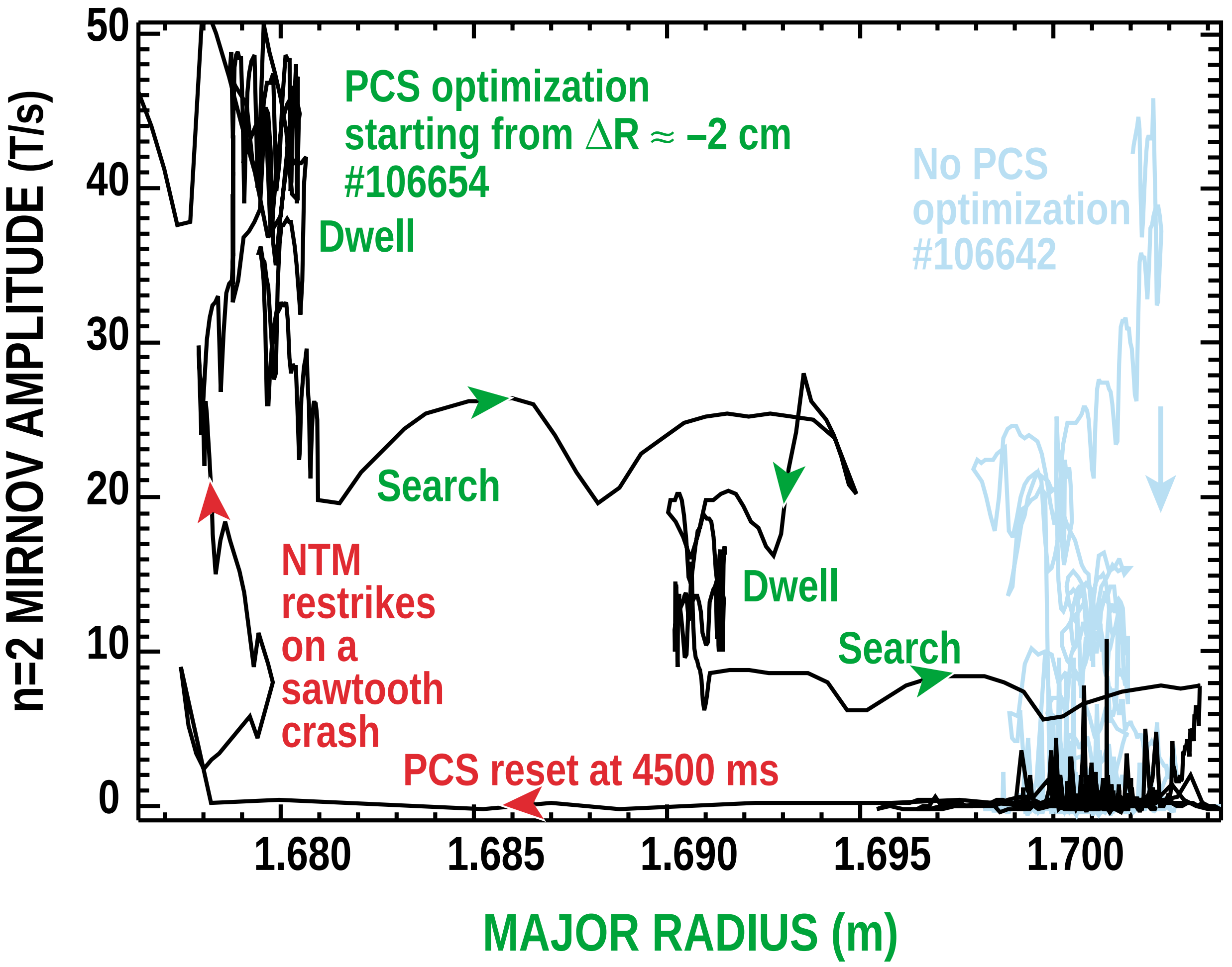
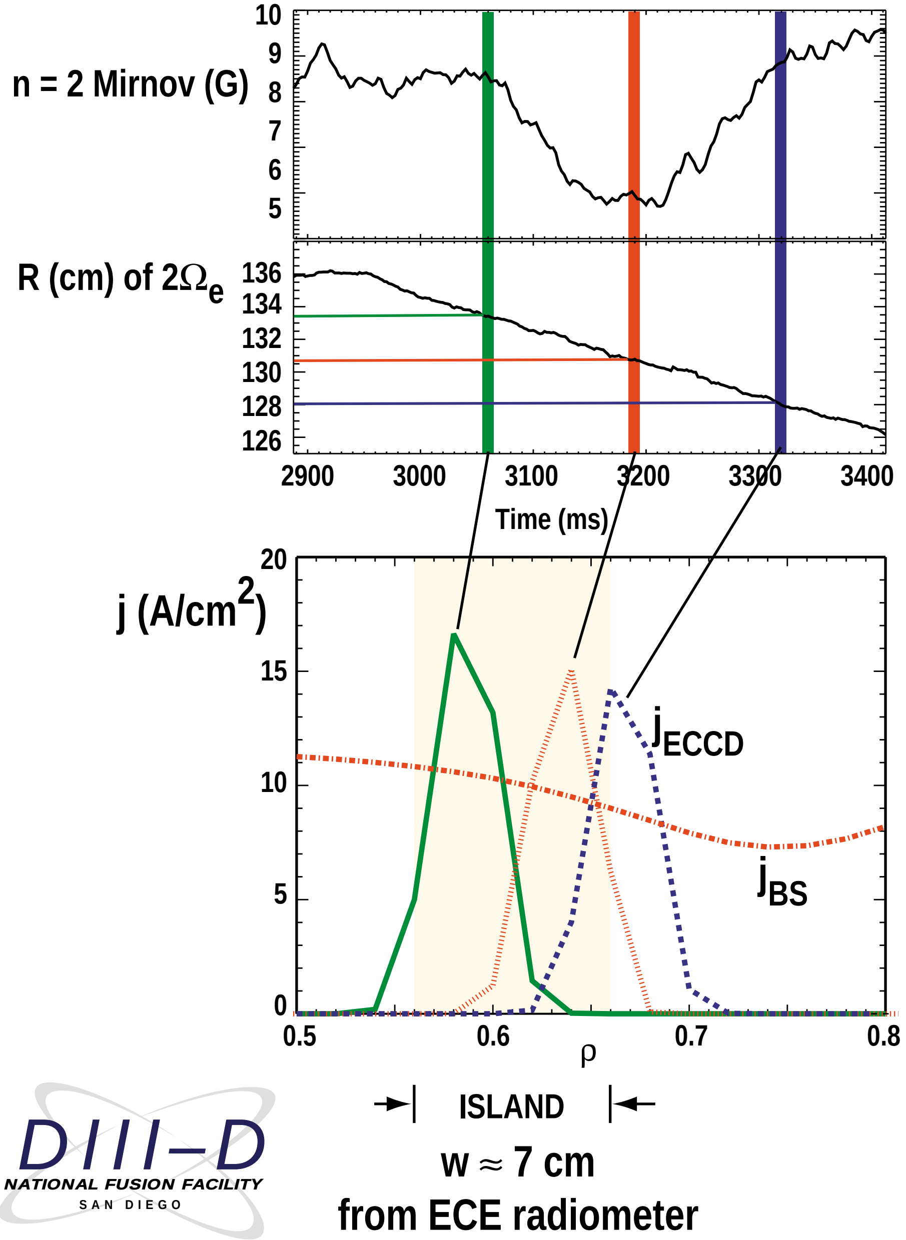
REAL-TIME CONTROL OF MAJOR RADIUS FOR ECCD SUPPRESSION (m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms)



OPTIMUM LOCATION OF ECCD IS FOUND BY SWEEPING TOROIDAL FIELD



w ≈ 7 cm
from ECE radiometer

- Toroidal field was ramped down to scan ECCD past the island
- Alignment within ±1 cm is required
- $j_{ECCD} > j_{BS}$ is satisfied (TORAY-GA)

★ 2 gyrotrons for ≈ 1 MW injected

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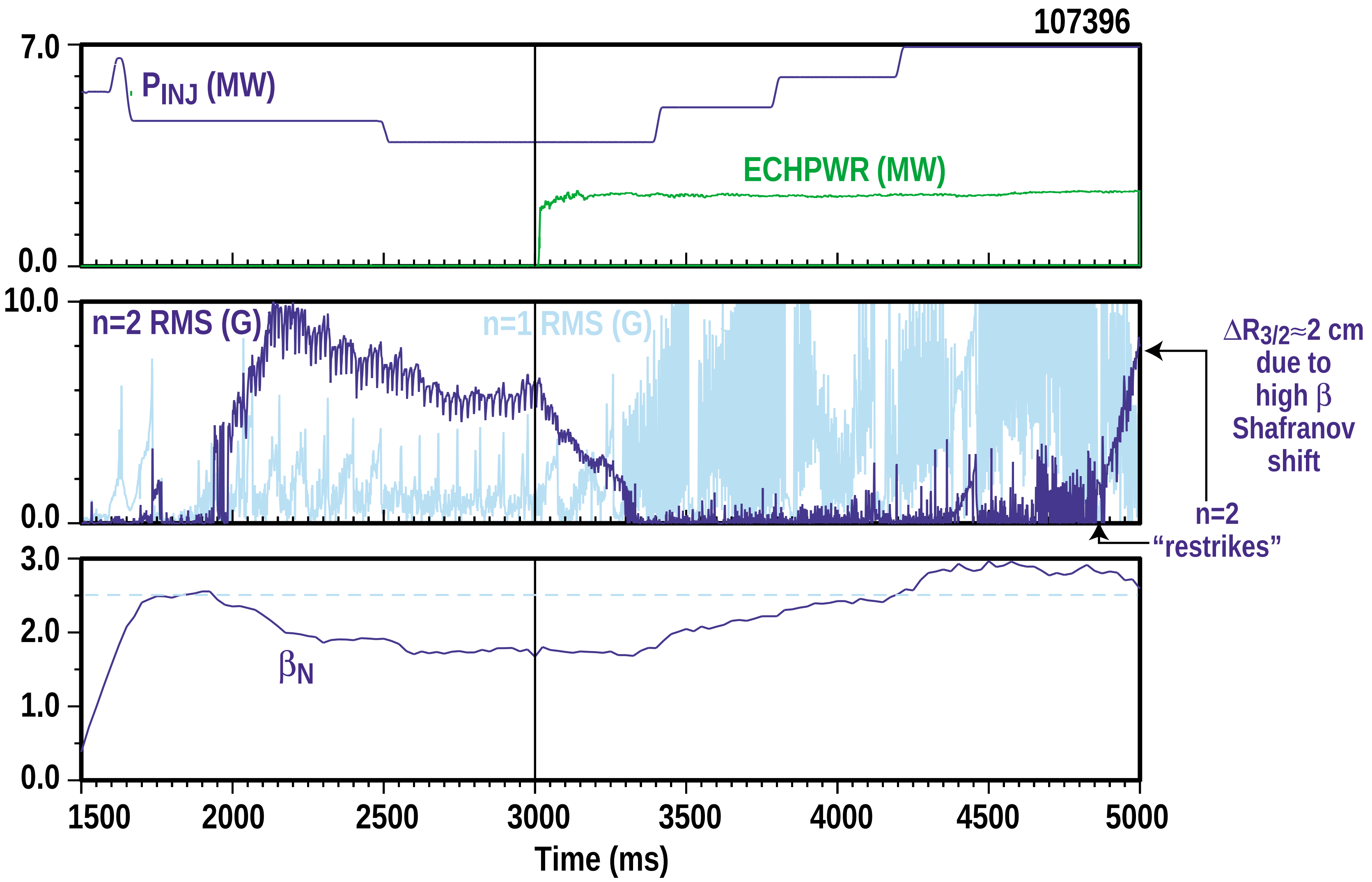
β_N IS INCREASED ~60% FOLLOWING SUPPRESSION OF m/n = 3/2 NTM WITH ECCD



CURRENT PROFILE CONTROL: MAINTAIN $q_{min} > 1.5$ TO AVOID NTM AND EXTEND HIGH PERFORMANCE DURATION

- High performance discharges near DIII–D AT target obtained
  - Duration limited by growth of m/n = 2/1 tearing mode
  - Experimental observable: mode grows as q_{min} approaches 1.5
- m/n = 2/1 island appears when Δ' approaches a pole, near ideal stability limit
- ECCD current drive will be used to maintain q-profile
  - ECCD physics model validated; normalized CD efficiency increases with β_e
  - Modeling indicates 3.5 MW ECCD can keep $q_{min} > 1.5$ and extend duration of AT discharge

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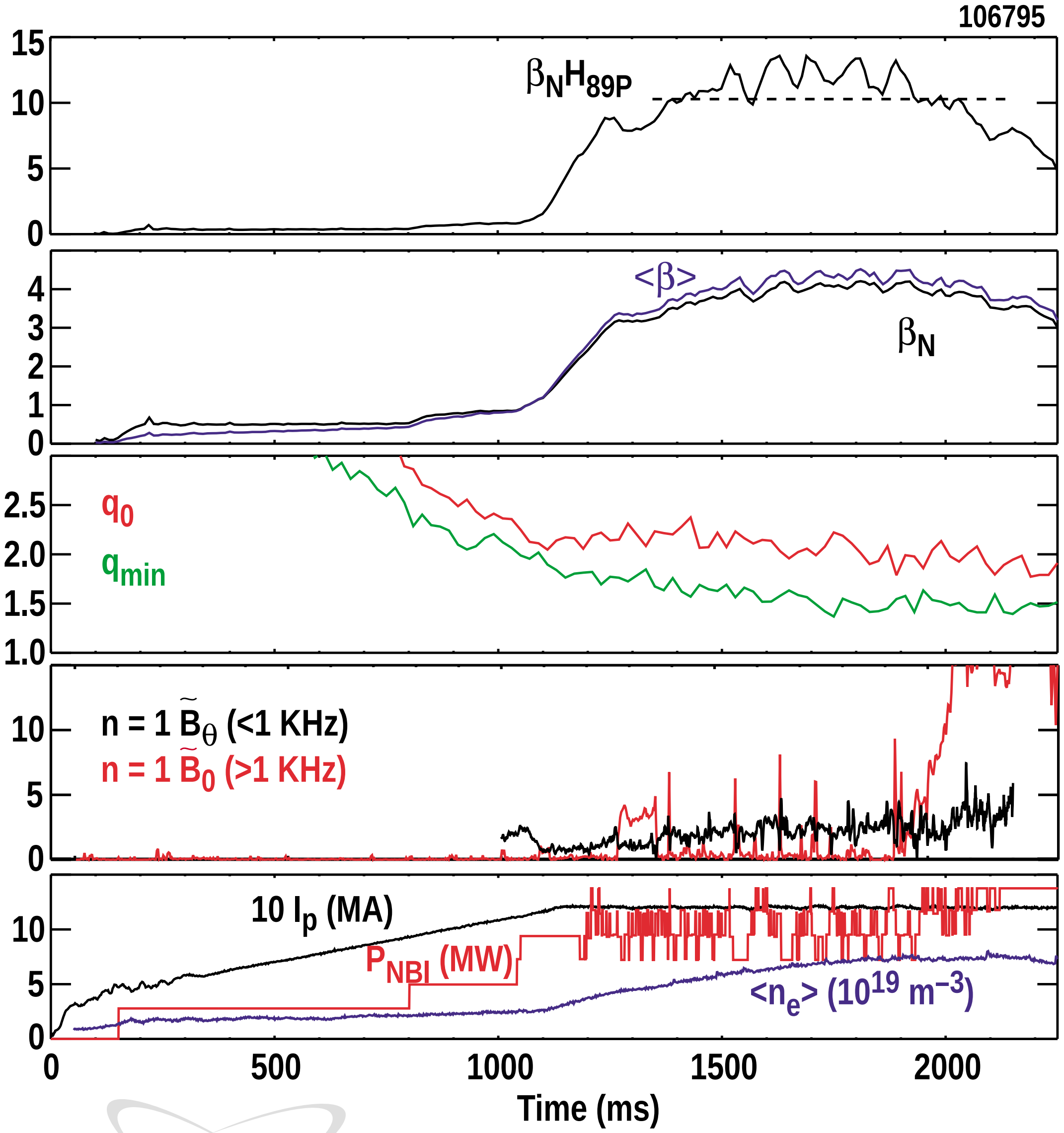
HIGH PERFORMANCE ($\beta_N H > 10$), HIGH BOOTSTRAP FRACTION ($f_{BS} > 60\%$) SUSTAINED FOR ~10 τ_E



- Duration limited by growth of m/n = 2/1 NTM

- m/n = 2/1 growth experimentally correlated with q_{min} ~ 1.5

- ECCD will be used to sustain favorable current profile ($q_{min} > 1.5$)

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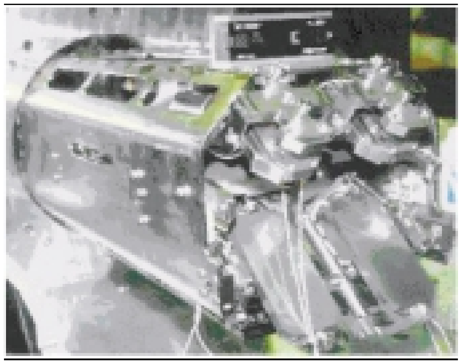
ELECTRON CYCLOTRON CURRENT DRIVE PROVIDES LOCALIZED CURRENT WITH GOOD CONTROL

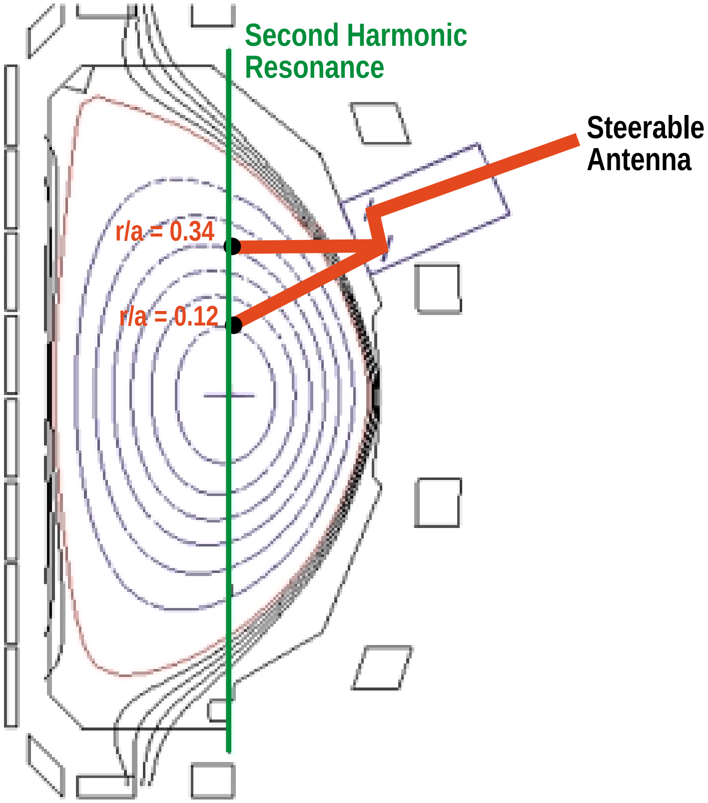
— Excellent Tool for Profile Control —

CPI Diamond Window Gyrotron



PPPL Launcher

- Four 1 MW class gyrotrons available for 2001
- Six gyrotrons planned for 2002
- Radial deposition is controlled by poloidal launch angle and resonance location (B_T)



- Independent control of toroidal and poloidal launch angle facilitates science (independent $n_{||}$ and ρ scans)
  - For 2 gyrotrons in 2001
  - For 4 gyrotrons in 2002
  - Two gyrotrons fixed toroidal, variable poloidal (2001 and 2002)

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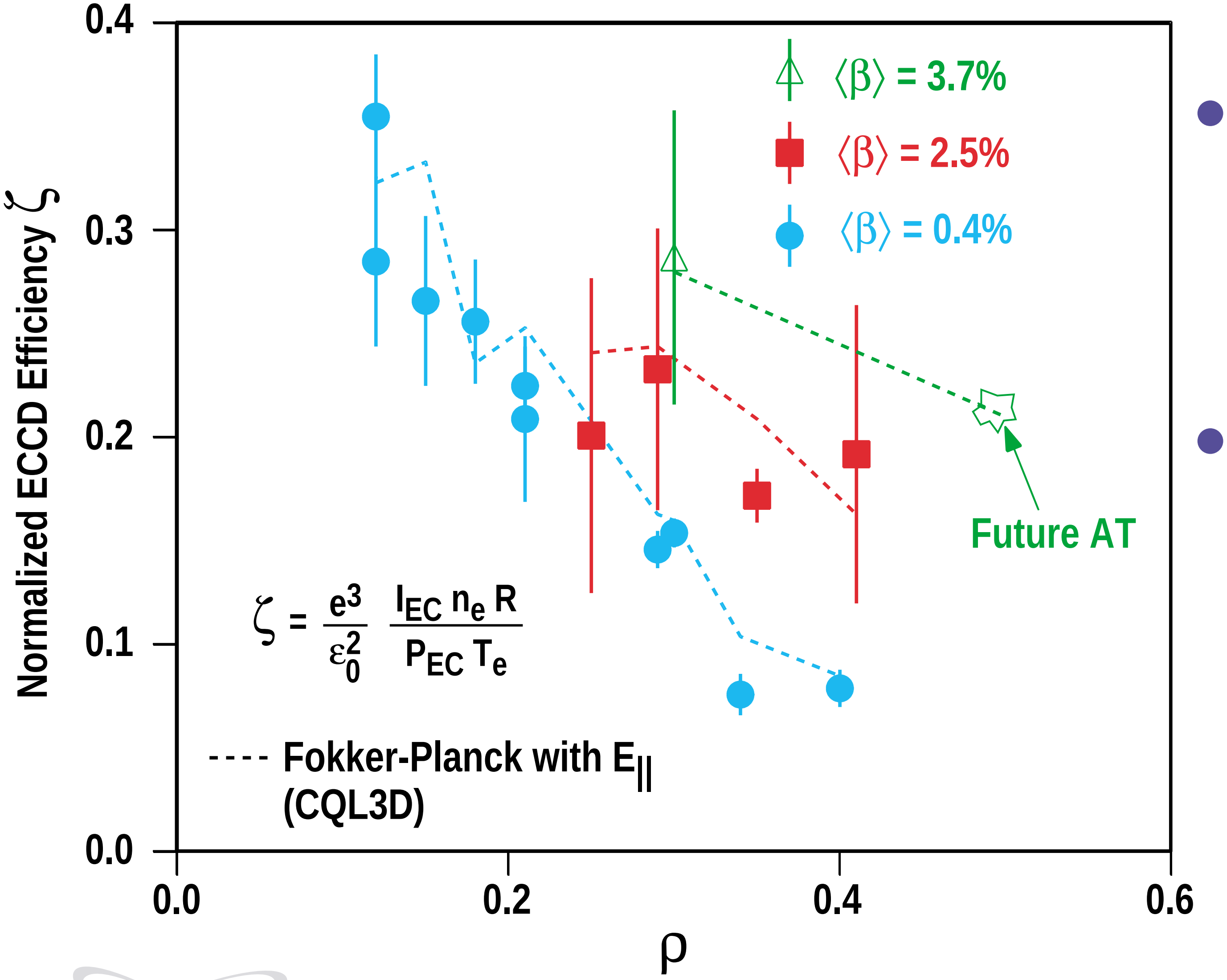
OFF-AXIS ELECTRON CYCLOTRON CURRENT DRIVE EFFICIENCY INCREASES IN HIGH β PLASMAS



- Good agreement between measured efficiency and theory

- Measured efficiency consistent with AT target scenario requirements

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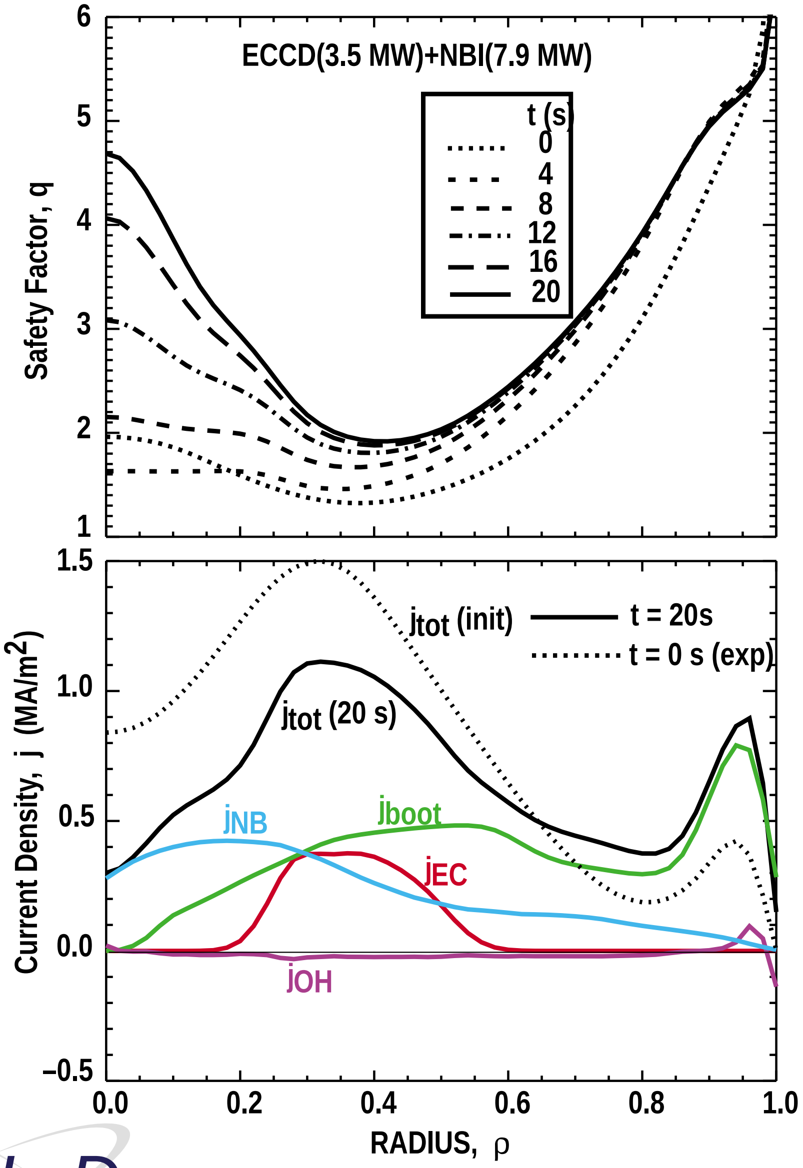
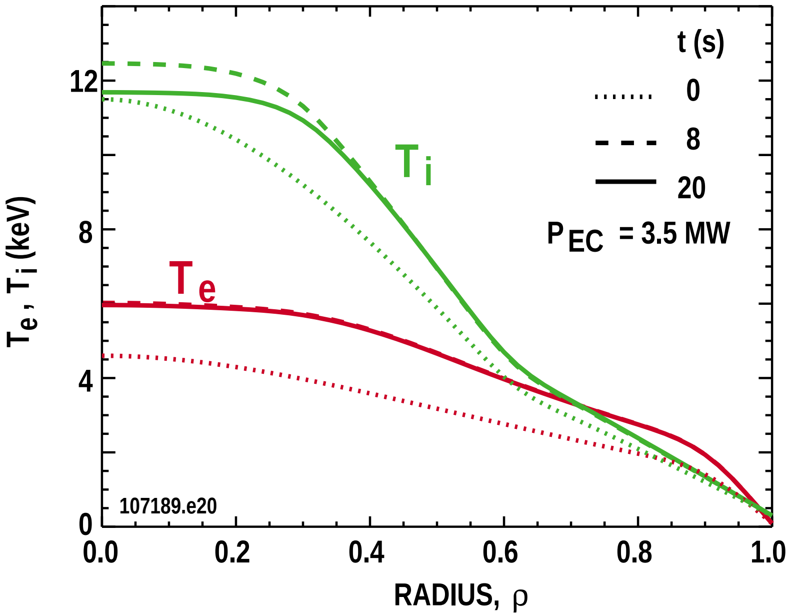
MODELING PREDICTS DISTRIBUTED 3.5-MW ECCD CAN SUSTAIN β_N =4, H_{89P}=3.1 WITH f_{BS}= 65% FOR MORE THAN 10 s





	Sim.	(Exp.)			
P_{EC} (MW)	3.5	(0)	β_T (%)	4.2	
P_{NBI} (MW)	7.9	(7.9)	β_N	4.0	(3.1)
B_T (T)	1.85		H_{89P}	3.1	(3.0)
I_p (MA)	1.21		$n(10^{20} m^{-3})$	0.41	
I_{Boot} (MA)	0.77		n/n_G	0.40	
I_{ECCD} (MA)	0.16		T_i (0) (keV)	11.7	(11.5)
I_{NB} (MA)	0.31		T_e (0) (keV)	6.0	(4.6)
I_{OH} (MA)	–0.02				

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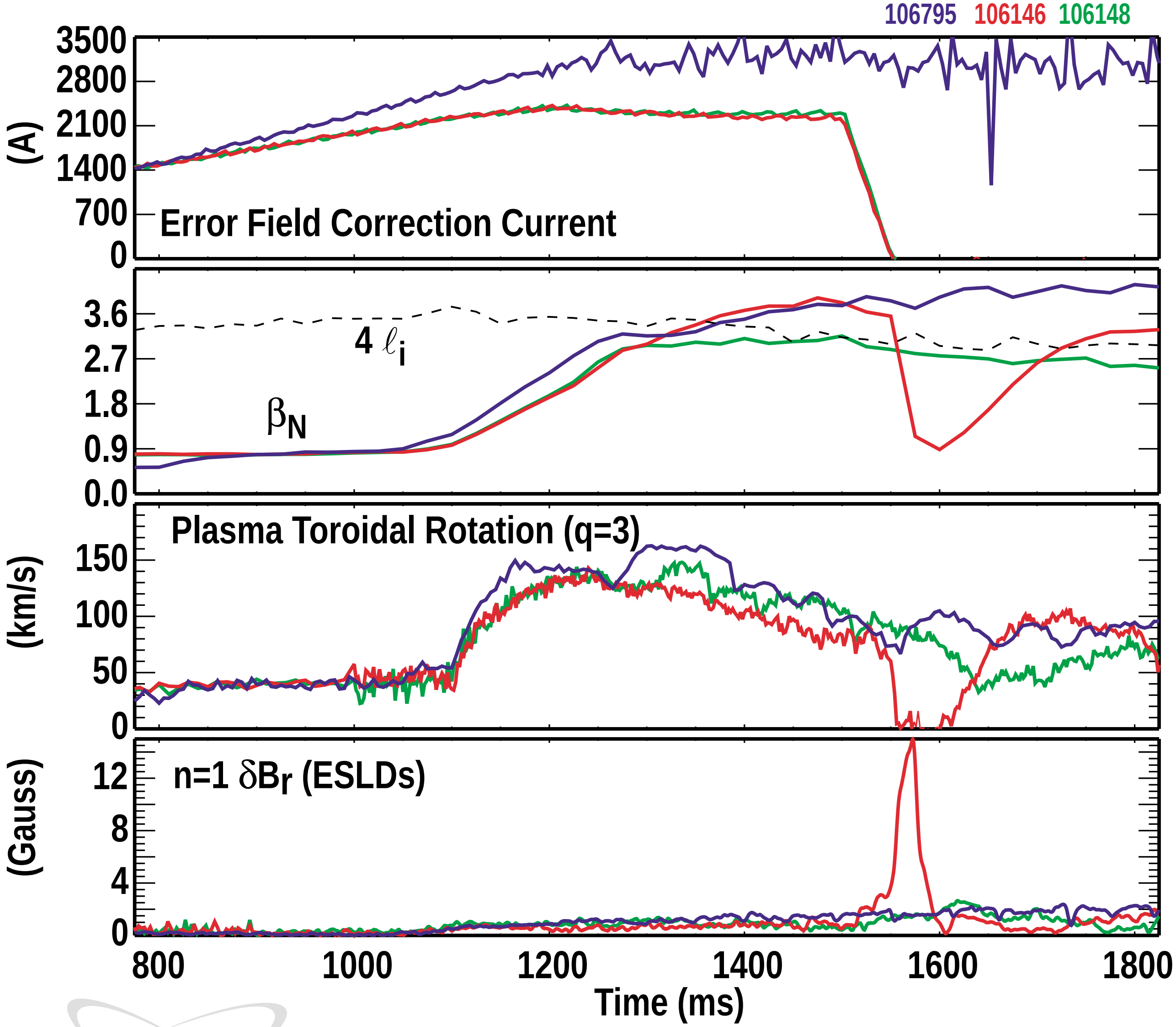
SUMMARY/OUTLINE

- High normalized beta $\beta_N = \beta_T/(I/aB)$ is required for steady-state high performance
- Stabilization of resistive wall mode by plasma rotation allows reproducible stable operation above β_{nowall}, up to ~ $\beta_{ideal\ wall}$
- Neoclassical tearing modes are stabilized by active feedback control of the deposition location of electron cyclotron current drive (ECCD)
- Modeling shows that 3.5 MW of off-axis electron cyclotron current drive (ECCD) can maintain favorable q-profile for advanced tokamak studies and avoidance of tearing modes

SAME PHYSICS OF ERROR FIELD-RWM INTERACTION OBSERVED FOR PLASMAS WITH $\beta_N^{\text{no wall}}$ ~4 ℓ_i OR ~2.4 ℓ_i



- Error field amplification at $\beta_N > 4\ \ell_i$ enhances efficiency of magnetic braking of plasma rotation, leading quickly to RWM-induced beta collapse

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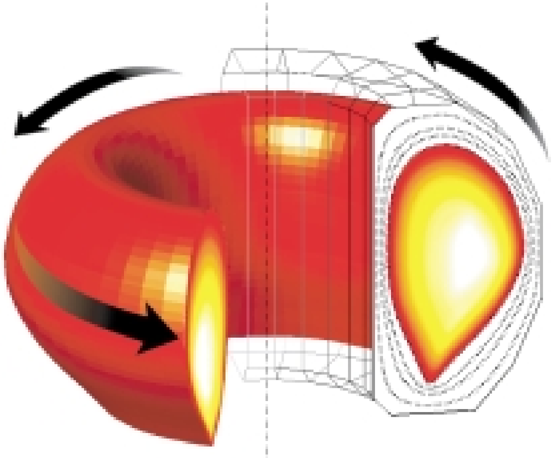
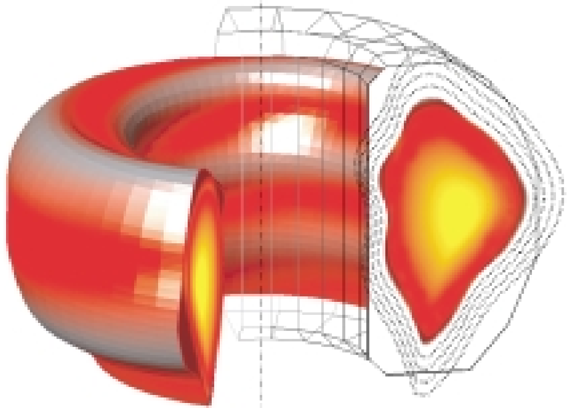
AT HIGH PRESSSURE (β), THE PLASMA BECOMES UNSTABLE TO A GLOBAL KINK MODE DEFORMING THE PLASMA SURFACE



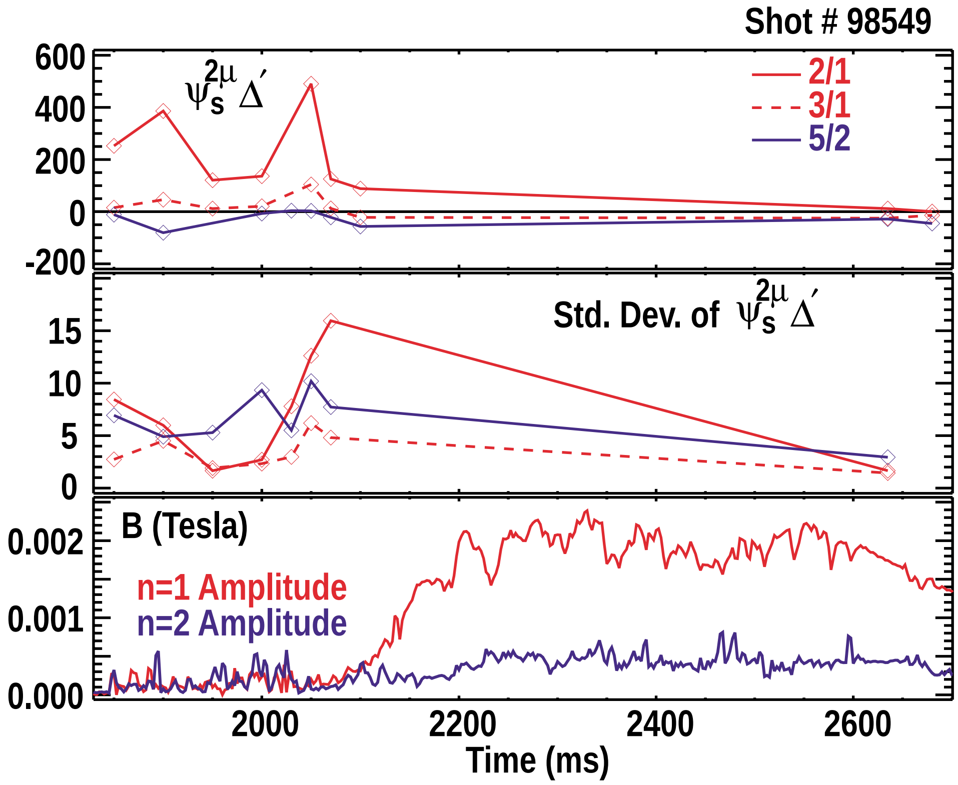
- Stable plasma with axisymmetric surface
  - Plasma rotation in the presence of a conducting wall



- Unstable plasma with helical surface deformation
  - Deformation is exaggerated about 10 times

APPROACH TO AN IDEAL STABILITY BOUNDARY (POLE IN Δ') MAY BE AN ONSET MECHANISM FOR NEOCLASSICAL TEARING MODES

- No seed island evident
- Δ' becomes large prior to onset on m/n = 2/1 mode
- Large standard deviation of $\psi_s^{2\mu}\Delta'$ indicates pole



Ideal Pole May Cause Tearing Mode Onset