ABSTRACT

The Effect of Error Fields on Resistive Wall Modes,* J.T. Scoville, E.J. Strait and R.J. La Haye, *General Atomics*, A.M. Garofalo, *Columbia University* — Experiments on the DIII-D tokamak have shown that the onset of the resistive wall mode (RWM) is correlated with an increase in normalized beta above the ideal resistive wall stability limit and a reduction in the rotation speed below a threshold value. The high beta RWM is also seen to become less stable as the fractional amount of error field correction is reduced. A reduction in the beta limit is observed in the presence of an error field and the RWM typically appears locked in phase to the error field. The intrinsic error field of the tokamak (typically about 10 G) may destabilize the RWM by reducing plasma rotation, by providing a seed perturbation, or by inhibiting the rotation of the RWM. Recently, the error field correction system on DIII-D was modified to also allow closed loop feedback control of the resistive wall mode. This joint role of the new RWM feedback control system and the relationship of error fields to the stability of the resistive wall mode will be discussed.

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INTRODUCTION

- The error field correction system on DIII-D has recently been modified to add the capability for active feedback control of the resistive wall mode (RWM).

  - new fast bipolar switching power amplifiers

  - new external saddle loop (ESL) detectors

- The level of error field correction is correlated with the onset of the RWM. Less error field correction leads to

  - reduced plasma rotation

  - lower β

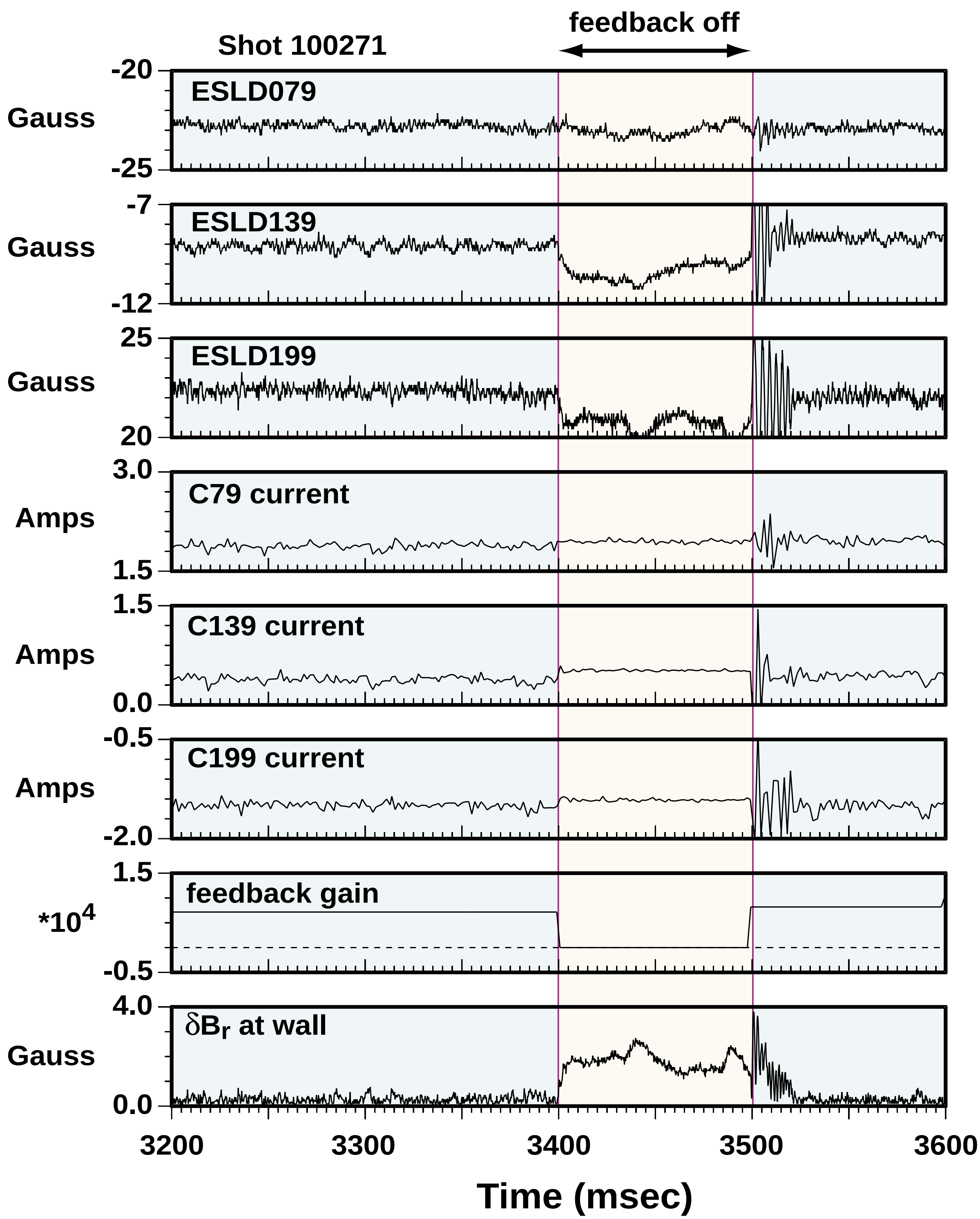
  - earlier RWM

- Initial experiments have had some success in stabilizing the RWM.

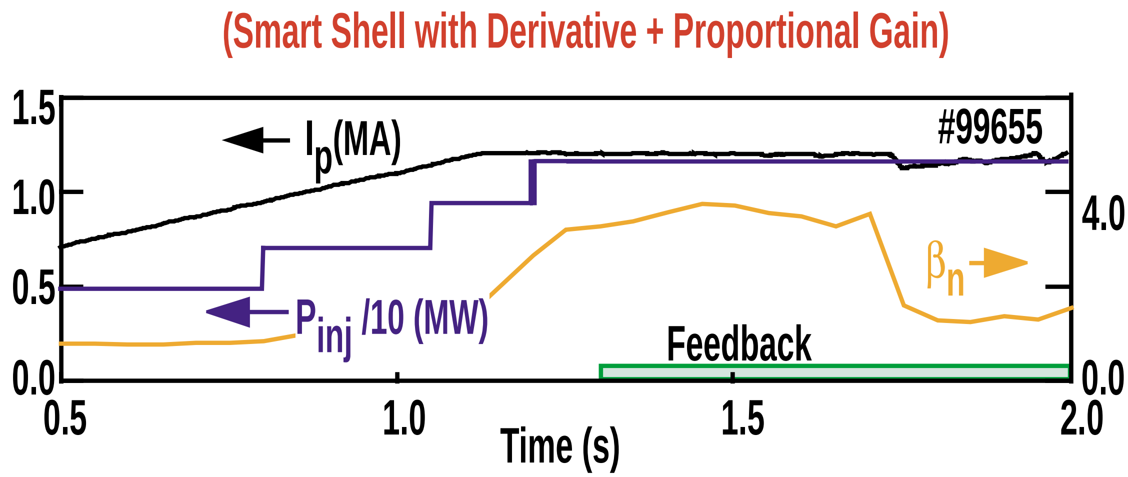
  - radial flux leakage of n=1 mode compensated

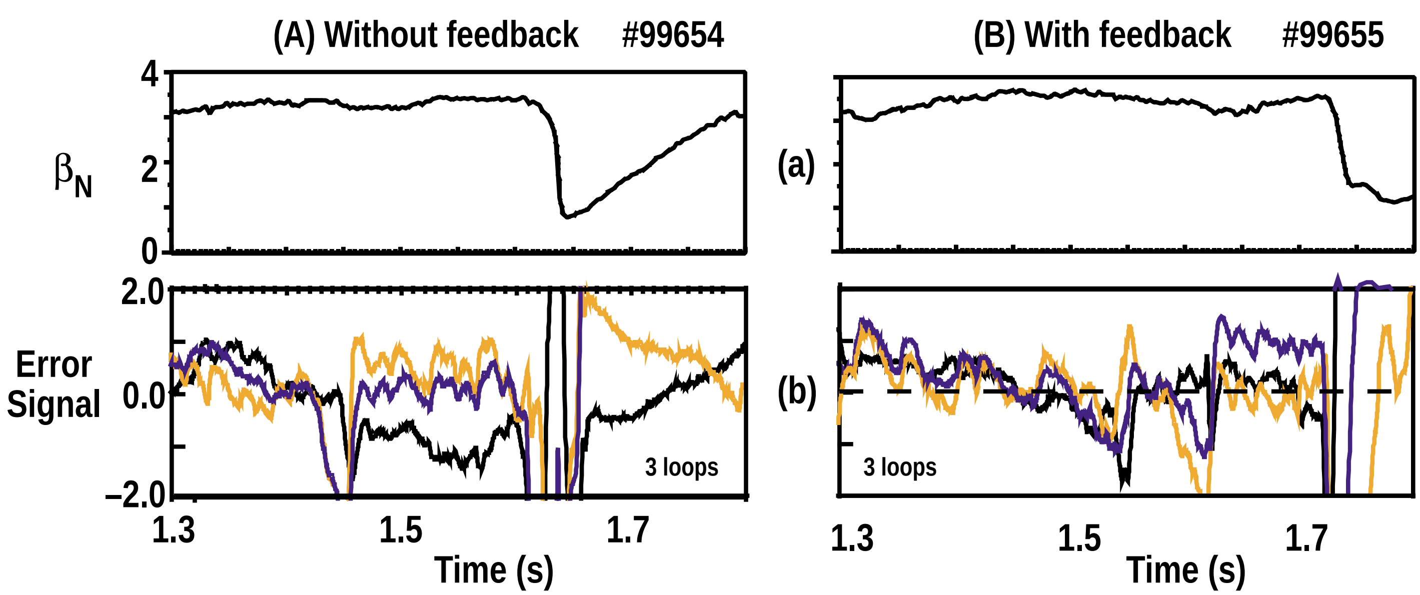
  - duration of high performance phase extended

INITIAL RESULTS - RWM APPEARS WHEN THE FEEDBACK IS TURNED OFF

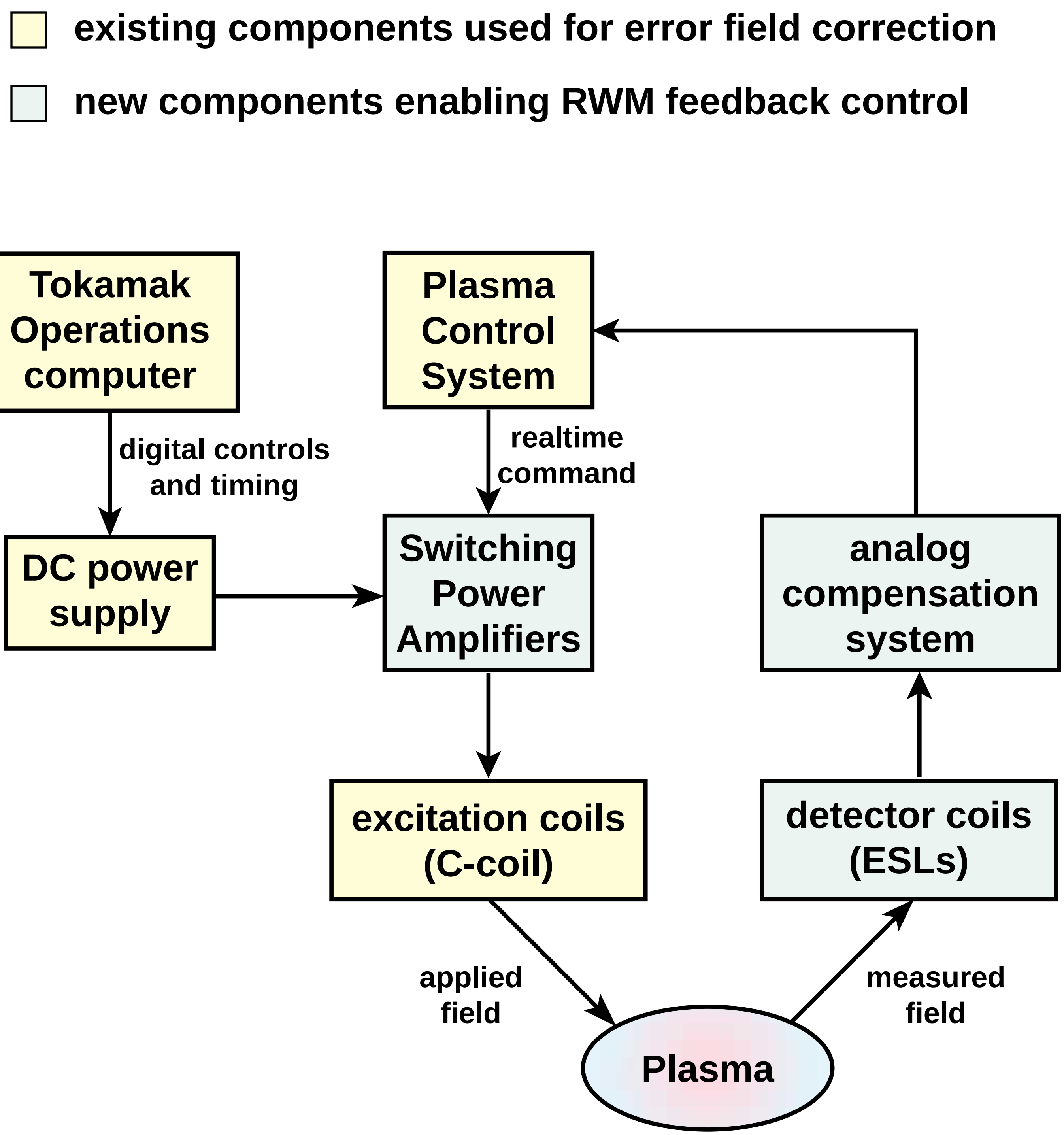


RWM FEEDBACK EXTENDS DURATION OF HIGH PERFORMANCE PHASE



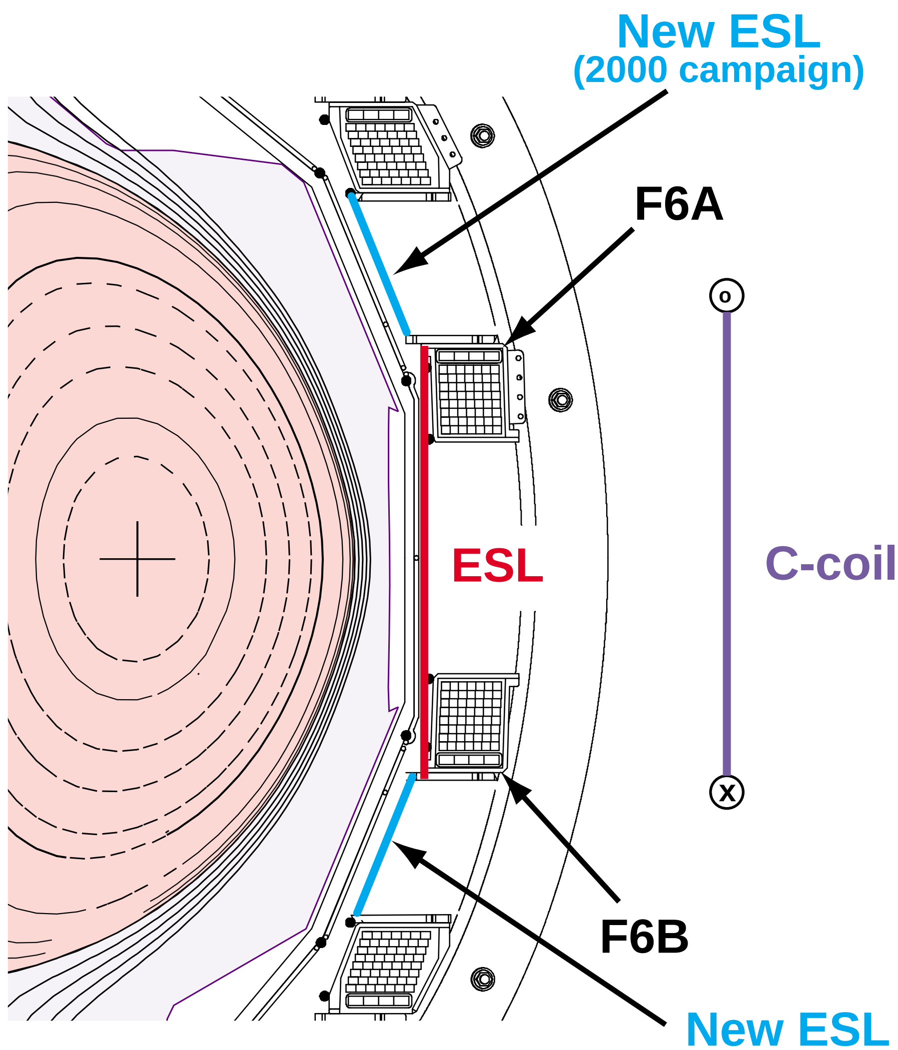


RWM CLOSED LOOP FEEDBACK CONTROL SYSTEM BLOCK DIAGRAM



EXTERNAL SADDLE COILS (ESLs) HAVE BEEN INSTALLED CLOSE TO THE VESSEL WALL FOR DETECTION OF RESISTIVE WALL MODE

- Radial magnetic field measurements < 1 Gauss
- Six sections, concentric to C-coil sections



TWO FUNCTIONS PERFORMED BY SAME SYSTEM: ERROR FIELD MINIMIZATION AND RESISTIVE WALL MODE CONTROL

• Error field reduction:

Input		Algorithm		Output
error field sources: (TF coil and field shaping coil currents)	→	calculate C-coil currents that minimize error field	→	commands to control C-coil currents

- Cycle time approximately 1 msec.

• RWM control:

Input		Algorithm		Output
saddle loop measurements of mode amplitude	→	Fourier coefficients used to cancel flux or rotate the mode	→	commands to control C-coil currents

- Cycle time approximately 100 μsec.

- two components of command:

  * cosine term - command in phase to cancel measured flux - "smart wall"

  * sine term - 90^{o} phase shift applied to drive the mode - "soft rotor"

INCOMPLETE ERROR FIELD CORRECTION REDUCES RWM STABILITY

- **Theory predicts RWM can be stable with enough plasma fluid rotation.**
  - $f_{q=3} > f_{crit}$ **(Strait CP1.75)**

- **AT discharges with negative central shear (NCS), $q_{min} > 1.5$, may have less shear at q=2 and q=3**
  - **less negative Δ_o' $\Rightarrow$ more torque from error fields (Fitzpatrick, et. al.)**

- **Routine error field correction assumes the field penetrating to q=2 is of the form**

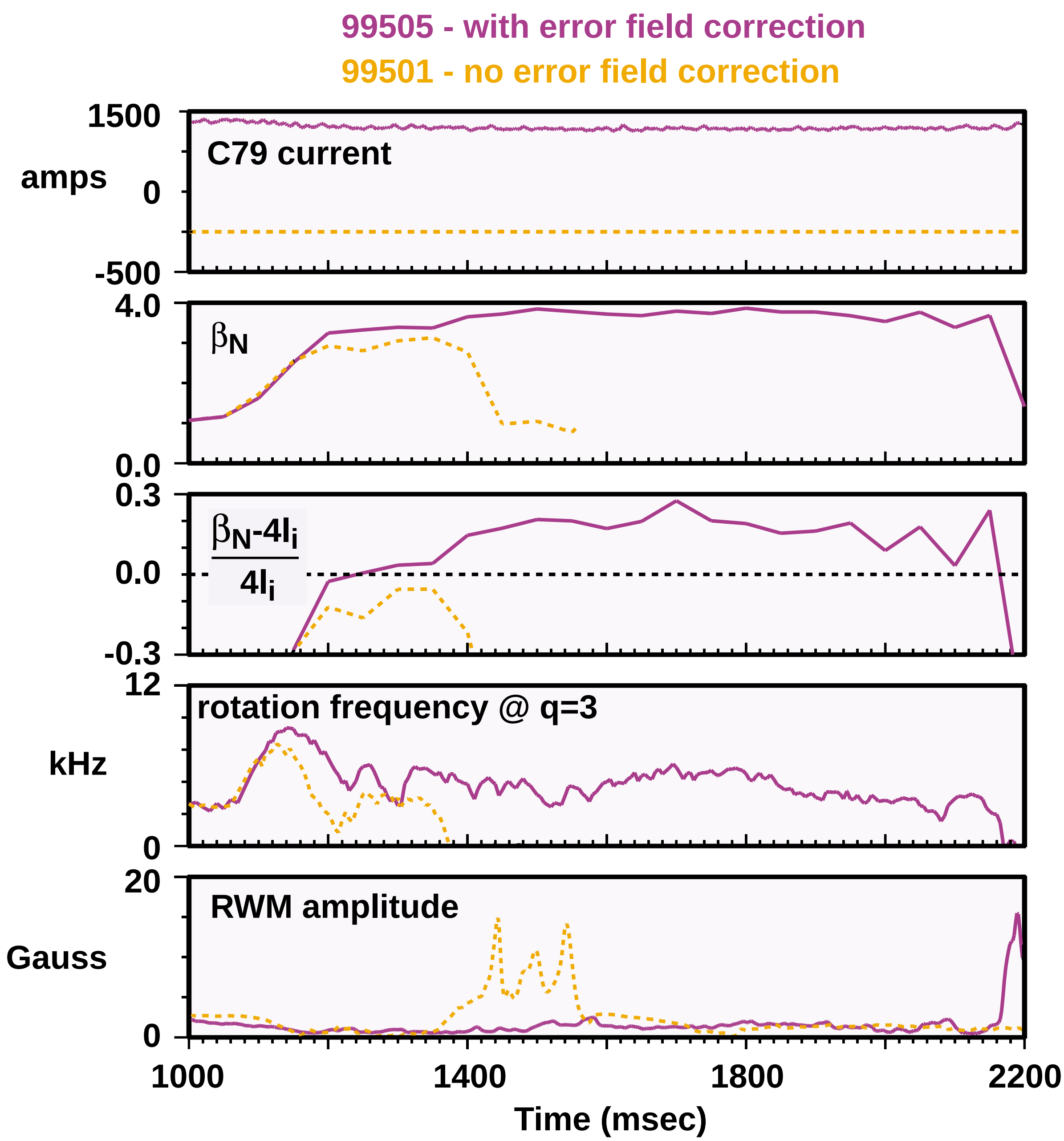
  $$B_{pen}^2 = \alpha B_{11}^2 + \beta B_{21}^2 + \gamma B_{31}^2 \ ,$$

  but for AT plasmas near RWM threshold
  - **q=1 no longer within plasma (α=0)**
  - **m=3 to m=2 coupling (β, γ) may be different**

- **Routine error field correction is not optimized for AT plasmas near RWM threshold.**
  - **Incomplete error field correction reduces plasma rotation and the stabilizing effect of flow on the RWM.**

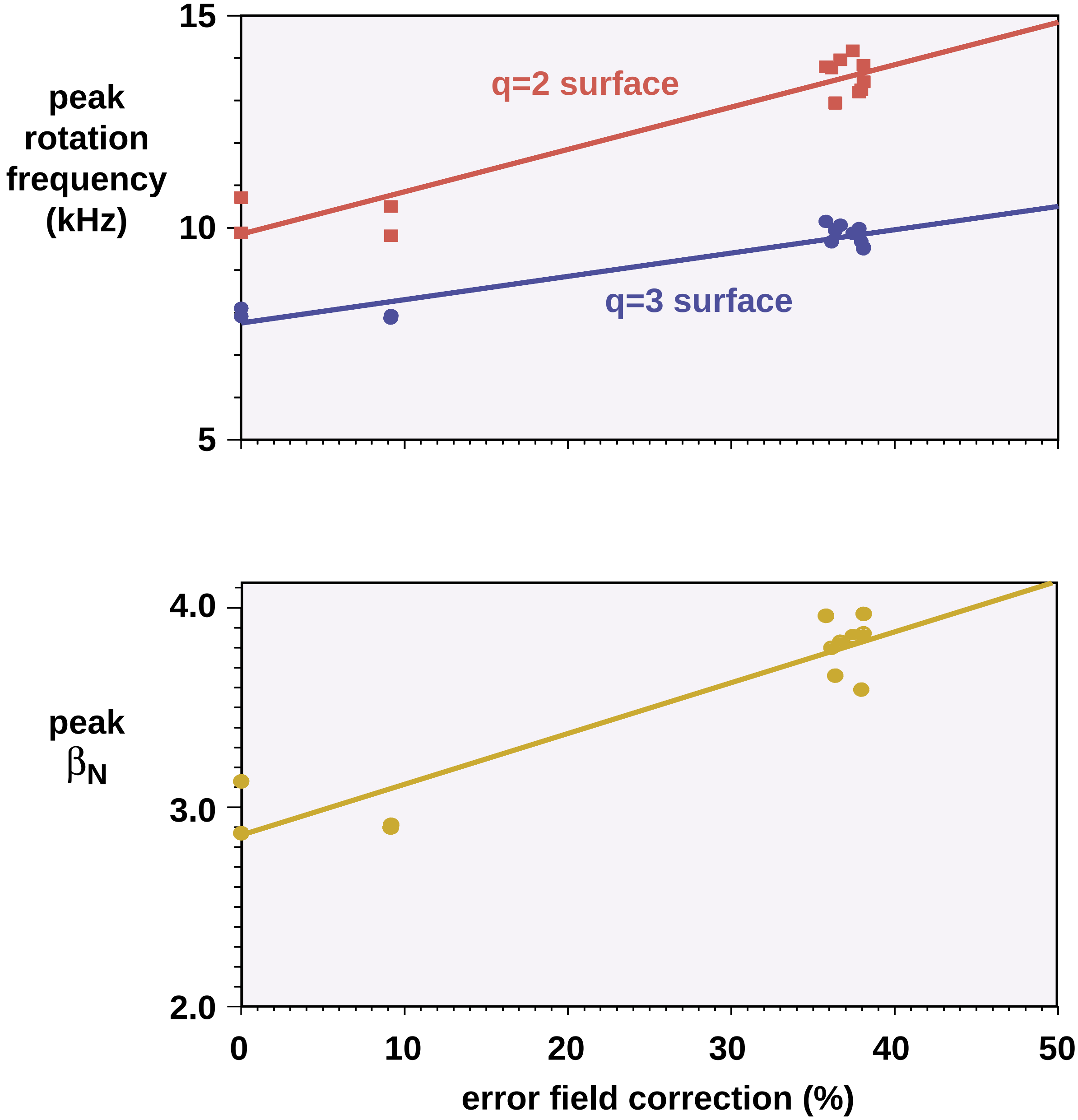
PARTIAL ERROR FIELD CORRECTION RESULTS IN HIGHER PEAK ROTATION AND A DELAY IN ONSET OF THE RWM

- **Identical discharges except for error field correction**



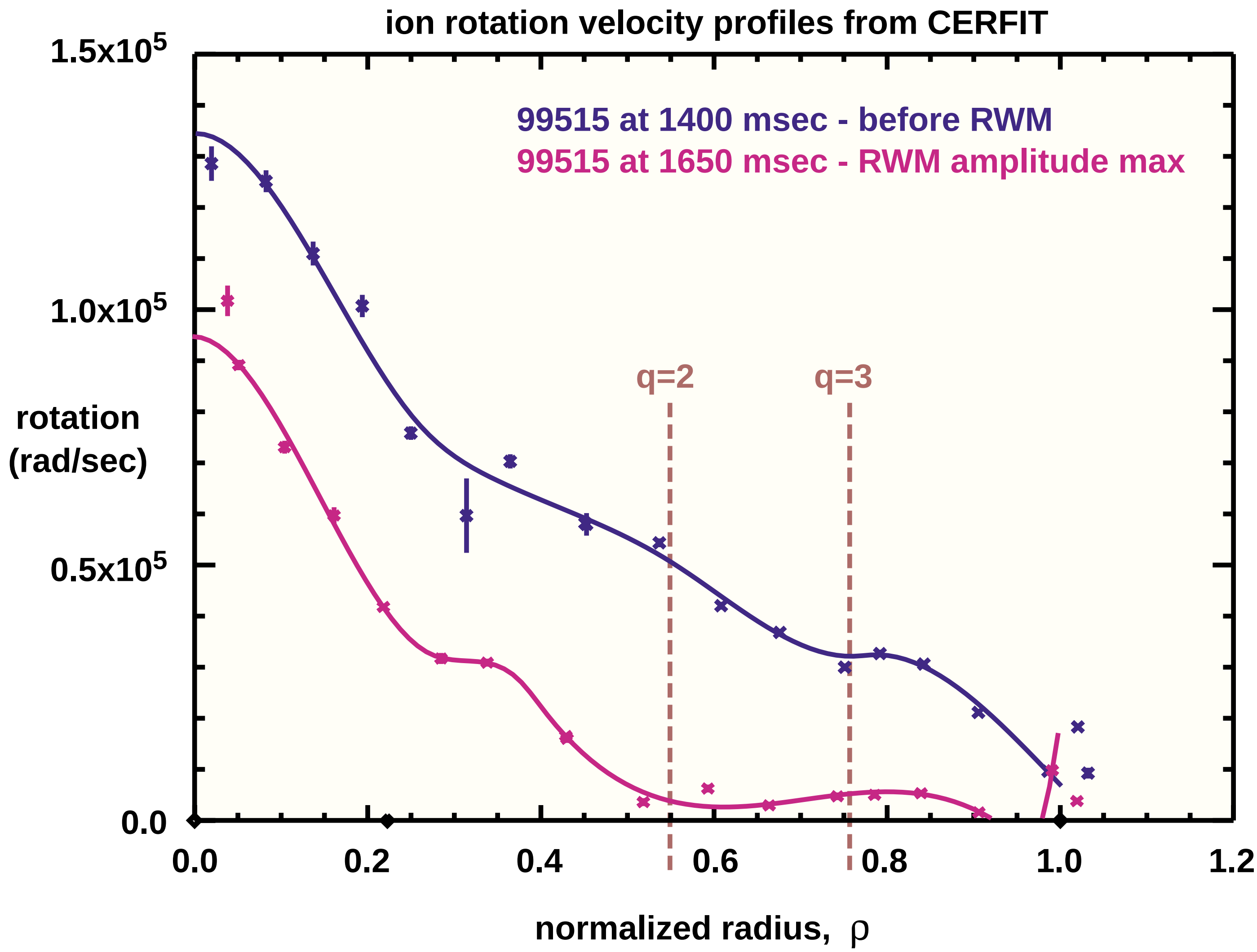
PEAK ROTATION FREQUENCY AND PEAK NORMALIZED β INCREASE AS THE ERROR FIELD IS CORRECTED

- **Series of identical RWM threshold discharges with varying error field correction levels**



RESISTIVE WALL MODE RESULTS IN LOSS OF PLASMA ROTATION

- comparison of discharge before RWM onset and at peak RWM amplitude
- error field correction stepped down early in discharge (at 1200 msec)



TORQUE BALANCE MODEL: ERROR FIELD SLOWS ROTATION

- **In equilibrium, the driving torque, T_D, (from beams, *etc.*) is balanced by the viscous torque and the torque from the error field:**

$$T_D - T_{visc} - T_{ef} = 0$$

- viscosity:

$$T_{visc} \approx R\,(\bar{n}\, m_i\, 2\pi R\, \pi a^2)\left(\frac{\upsilon_\perp}{a^2}\,\frac{\omega_\phi R}{2}\right)$$

- error field:

$$T_{ef} \propto -R\left(\frac{r_{mn}}{qR}\right)\left(\frac{2m}{-\Delta'_o r_m}\right)\left(\frac{B^2_{rmn}}{\mu_o}\right)\left(\frac{1}{\omega\tau_{rec}}\right)$$

- **If no error field, a "natural" frequency exists:**

$$T_{ef} = 0 \Rightarrow \omega_o \equiv \frac{T_D}{\bar{n} m_i \pi^2 R^3 \upsilon_\perp}$$

- **Complete torque balance with error field at the q=2 surface is:**

$$T_D = \bar{n} m_i \pi^2 R^3 \nu_\perp \omega_\phi + C_{21}\left(\frac{B^2_{r21}}{\omega_\phi \tau^{rec}_{21}}\right)$$

- **Solving this quadratic for frequency gives:**

$$\boxed{\frac{\omega_\phi}{\omega_o} = \frac{1}{2} + \frac{1}{2}\sqrt{1 - kB_{pen}^2}}$$

where B_{pen} is the error field penetrating to the 2,1 surface and k is a constant characteristic of that surface.

- **The peak rotation frequency data at q=2 and q=3 for a set of RWM discharges was fit to curves of this form. The $\omega \rightarrow \omega_o / 2$ model predicts increased rotation if error fields are eliminated:**

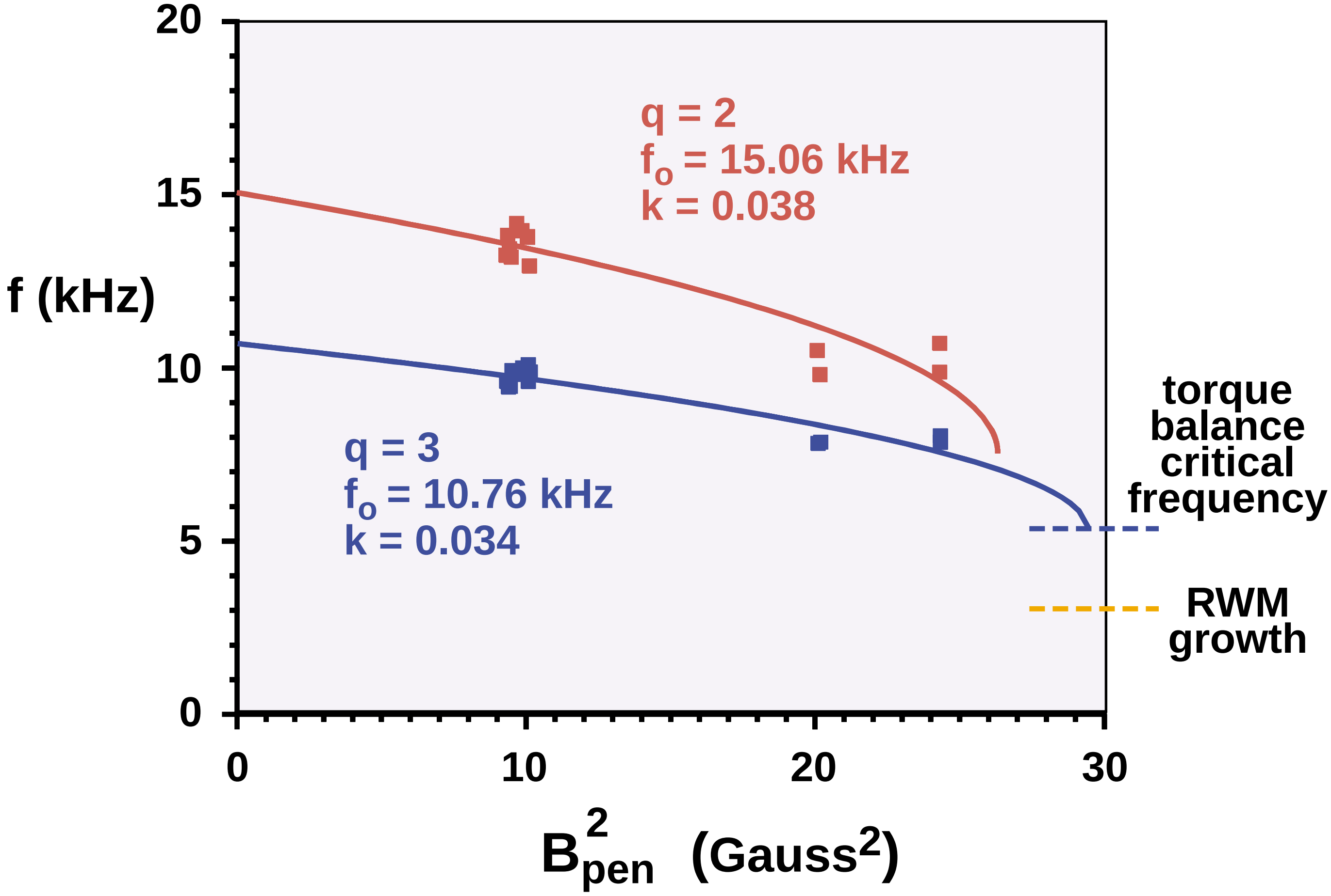
q=2, ω_o = 15.06 kHz
q=3, ω_o = 10.76 kHz

- **As error field increases, $kB_{pen}^2 \rightarrow 1$ and rotation decreases. Rapid reduction in rotation speed as $\omega \rightarrow \omega_o / 2$.**

  - reduced rotation leads to growth of RWM

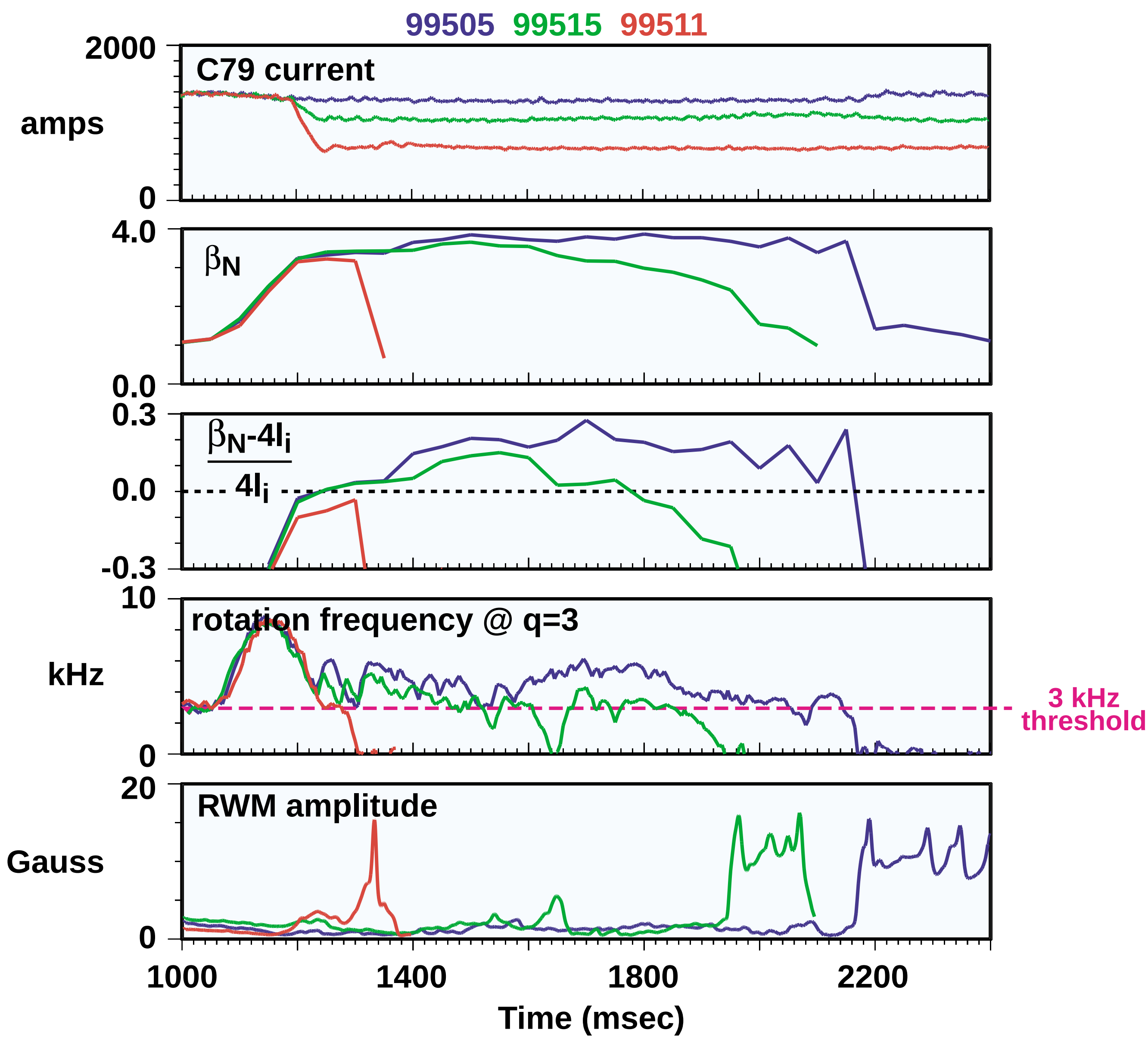
DATA AND MODEL SHOW REDUCTION OF ROTATION AS ERROR FIELD INCREASES

- Rotation data at q=2 and q=3 surfaces is fit to the torque balance model.
- Below a critical frequency, model predicts rapid cessation of rotation.
  - RWM observed when $f_{q=3}$ < 3 kHz



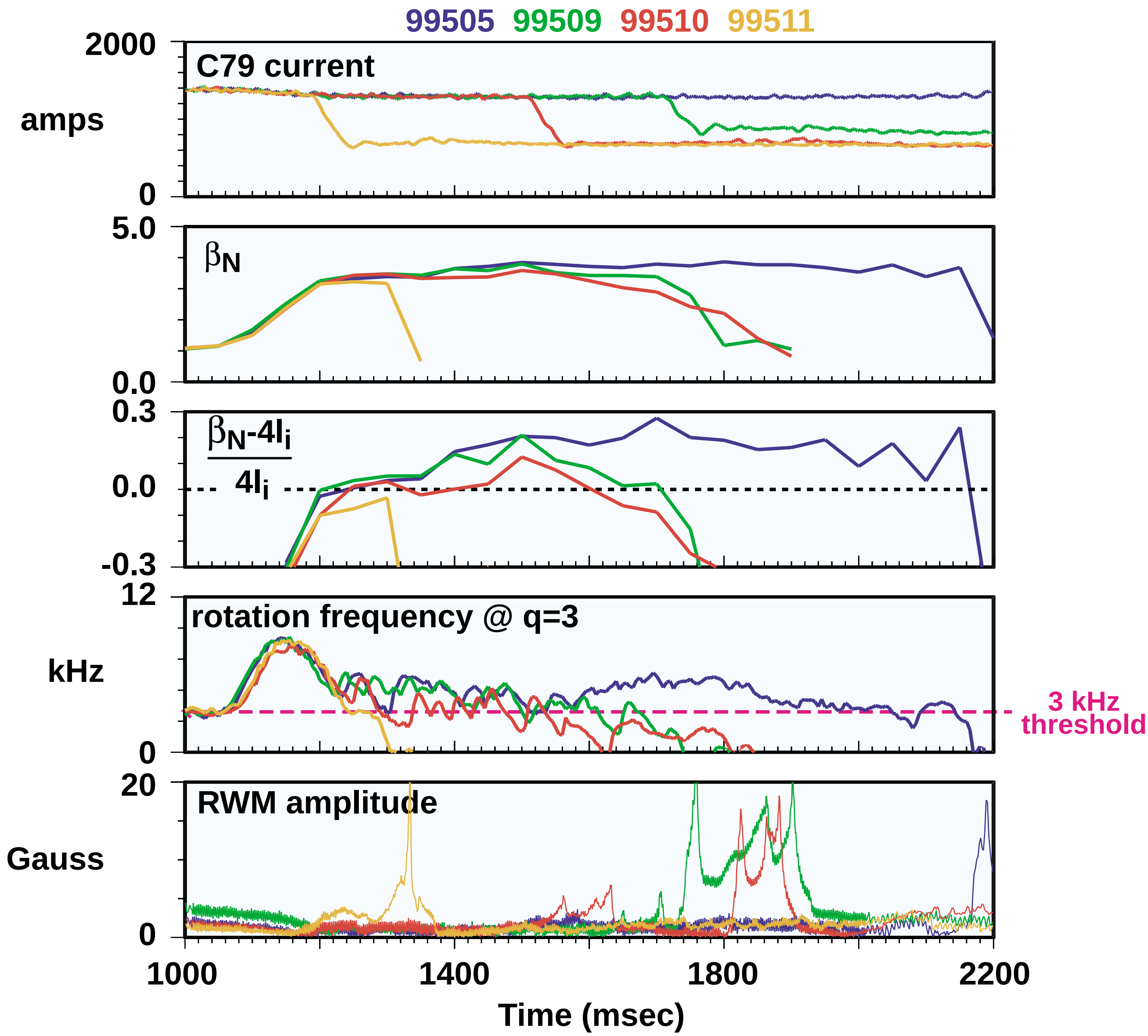
ONSET OF RWM ADVANCES AS ERROR FIELD CORRECTION IS STEPPED DOWN TO DIFFERENT LEVELS

- Reduced error field correction results in reduced rotation frequency
- RWM onset correlated with a threshold frequency of approximately 3 kHz at q=3



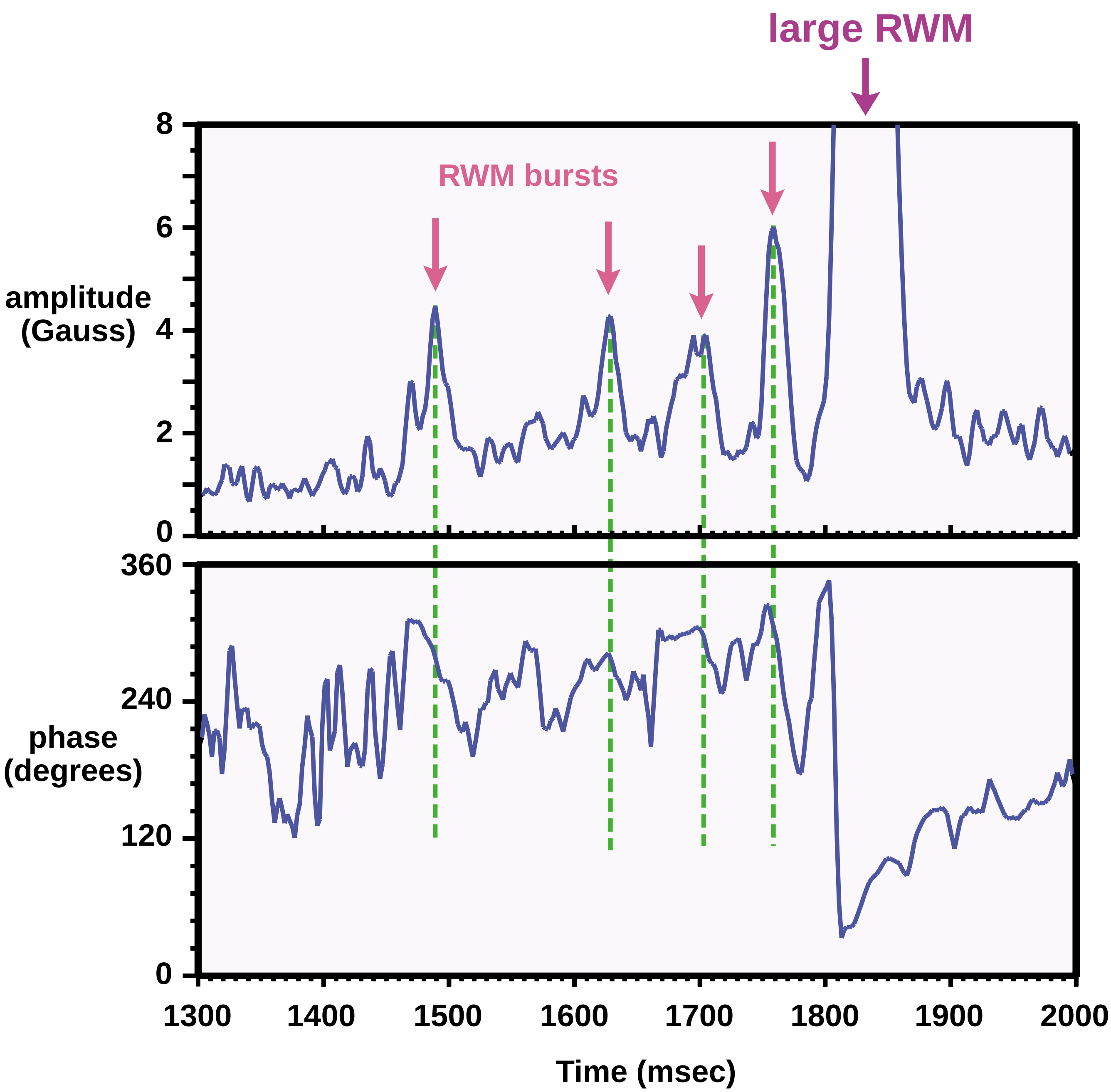
ONSET OF RWM FOLLOWS TIMING OF STEP DOWN IN ERROR FIELD CORRECTION

- Error field correction stepped down by fixed level at different times
- Onset of RWM delayed as stepdown is delayed



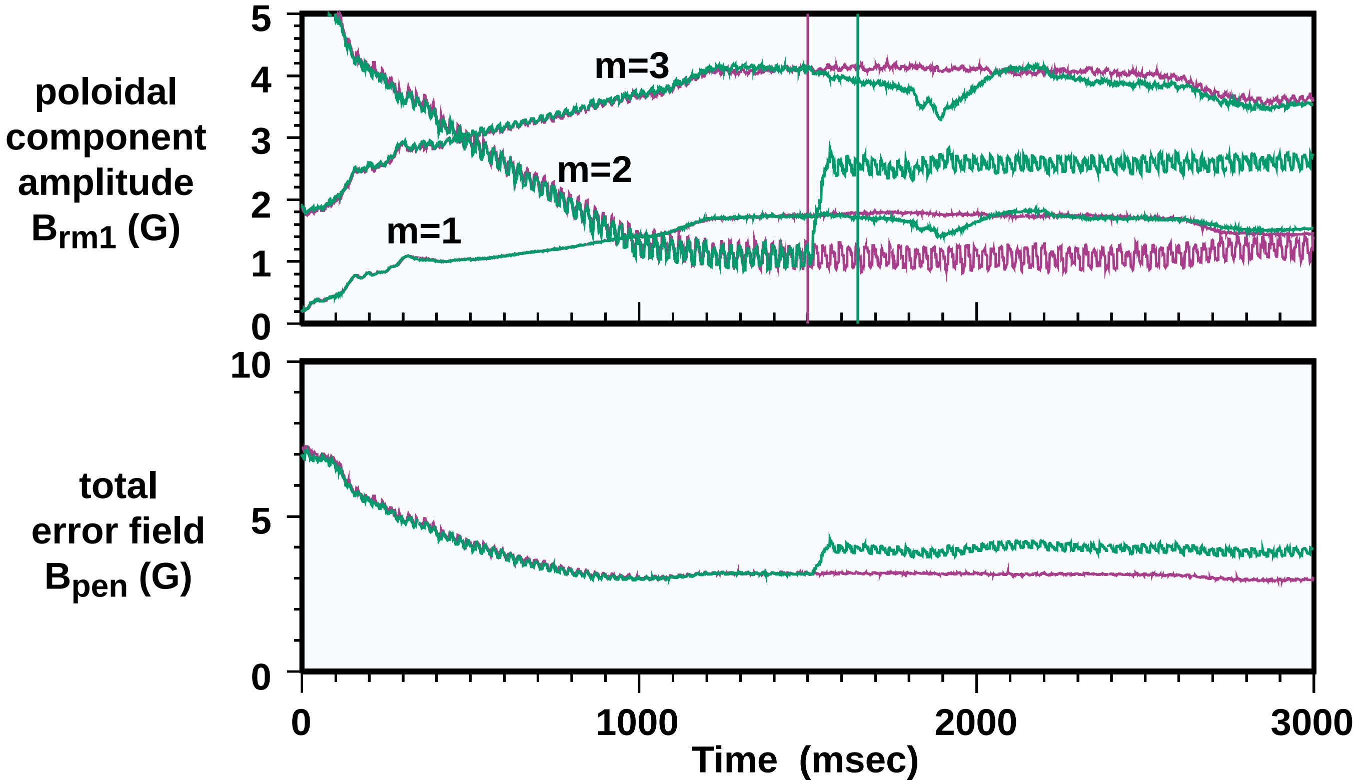
"BURSTING" RWM APPEARS WITH A CONSTANT PHASE, SUGGESTING IT IS LOCKED TO THE ERROR FIELD

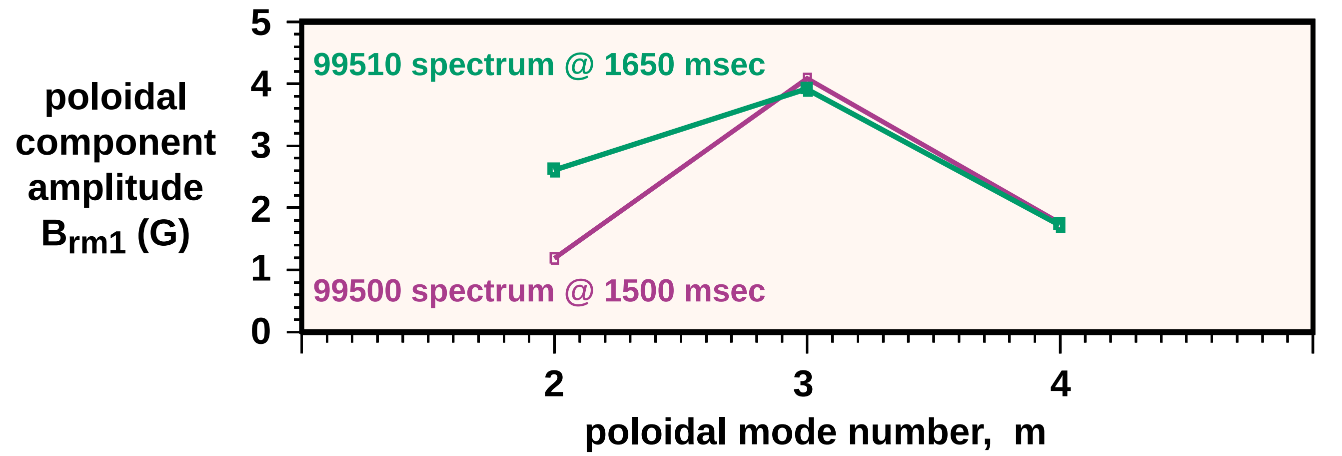
- **Small RWMs "spin up" in direction of decreasing toroidal angle. Large RWM goes the other direction.**



SMALL CHANGES IN THE ERROR FIELD POLOIDAL COMPONENT SPECTRUM AFFECT THE RWM STABILITY

- 99500 has no RWM. 99510 has stepdown in error field correction and develops RWM.





CONCLUSIONS

- Error fields are observed to play a role in the stability of the resistive wall mode, possibly through deceleration of the plasma rotation.

- Preliminary experiments show that the onset of the RWM can be correlated with a decrease in the plasma rotation velocity to a threshold level.

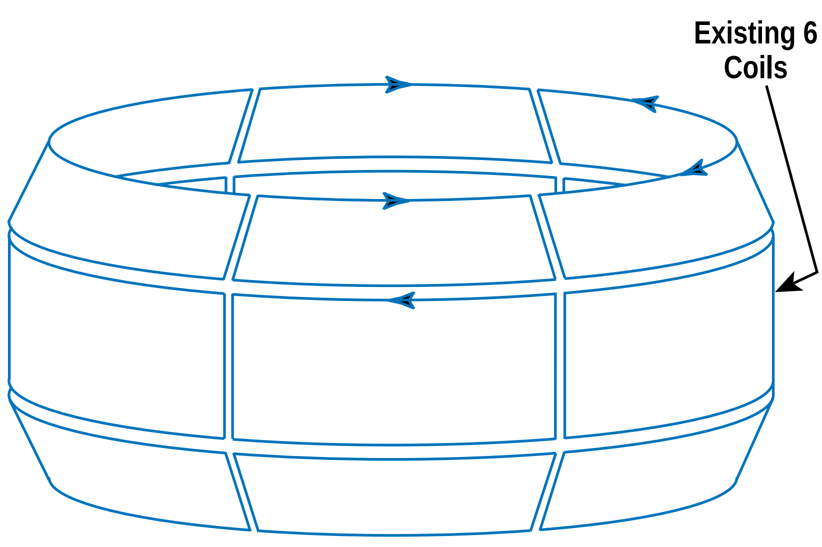
- Improved error field correction may lead to improved performance by delaying or avoiding the resistive wall mode.

FUTURE WORK

- Optimize error field correction for AT plasma discharges (RWM targets).

- Optimize RWM control algorithm to allow feedback stabilized operation above RWM threshold for extended durations. (See CP1.79)

- Expand to 18 coil set - add 6 above midplane and 6 below midplane
  - Better match to poloidal mode structure
  - Model predicts significant increase in β limit



RELATED PAPERS AT THIS CONFERENCE

This poster session:

CP1.75 **Stabilization of Resistive Wall Modes by Plama Rotation**

CP1.76 **Internal Structure of Resistive Wall Modes in DIII-D**

CP1.77 **Beta-Collapse Events in AT Regime on DIII-D**

CP1.79 **Feedback Stabilization of the Resistive Wall Mode (RWM) in DIII-D**

CP1.80 **Active Feedback on Locked Modes in DIII-D**

CP1.81 **Optimization of Feedback Control Coils for Resistive Wall Mode Stabilization in DIII-D**

Tomorrow's oral session:

GO2.14 **Stability of the Resistive Wall Mode in Advanced Tokamak Plasmas**

GO2.15 **Initial Results of the Resistive Wall Mode Feedback Stabilization Experiment on DIII-D**