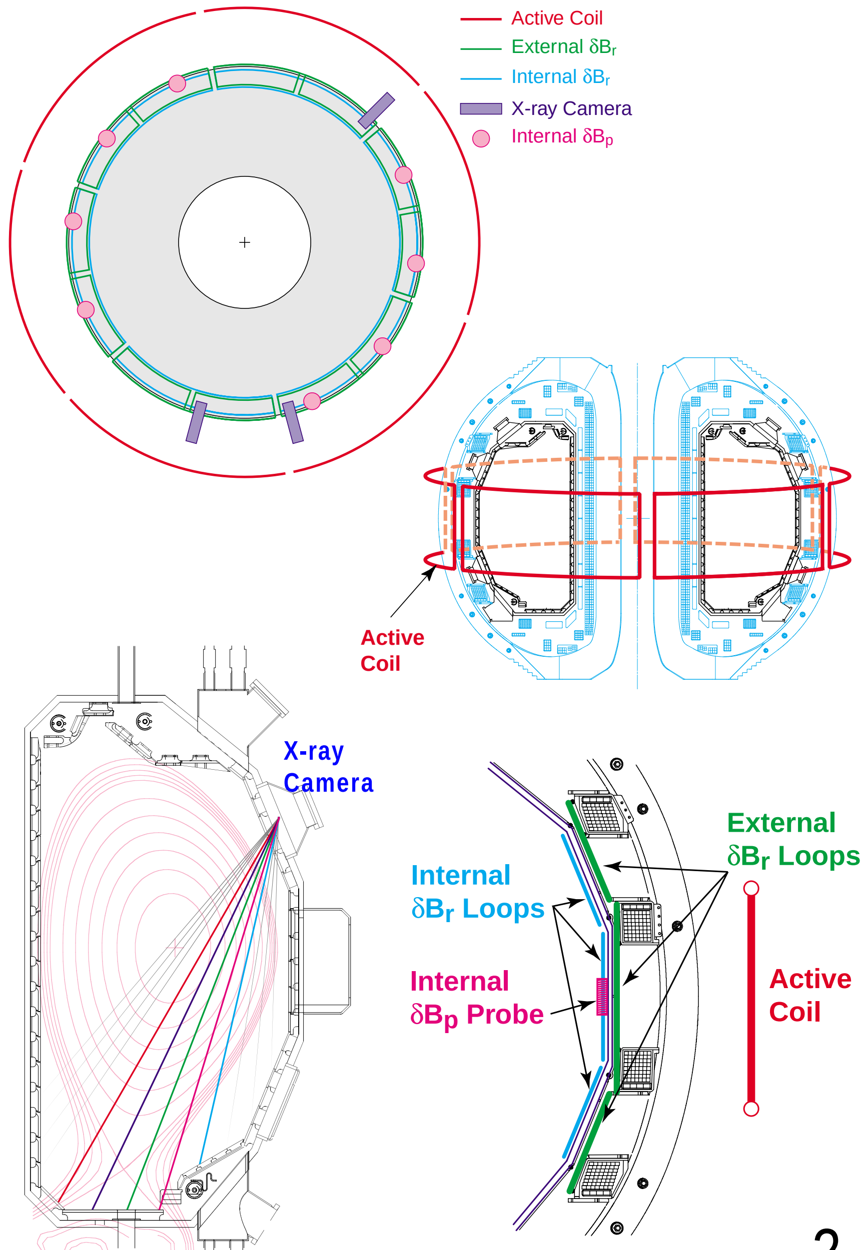
ABSTRACT

- Recent DIII-D experiments in plasmas with pressures at or above the no-wall ideal MHD stability limit have shown that rapid toroidal rotation can enhance the stabilizing effect of a surrounding conductive wall and delay the onset of resistive wall modes or, in some cases, prevent them altogether.
- When the braking arising from magnetic error fields is reduced, either by feedback or preprogrammed control of currents in correction coils, the plasma rotation can be sustained by torque applied by neutral beam heating.
- Stable operation has been achieved with pressures well above the no-wall limit for almost two seconds.
- These results are compared with cases where the input torque was reduced by using more nearly perpendicular beam injection or electron cyclotron heating.

THE RWM HAS BEEN STUDIED ON DIII-D FOR SEVERAL YEARS

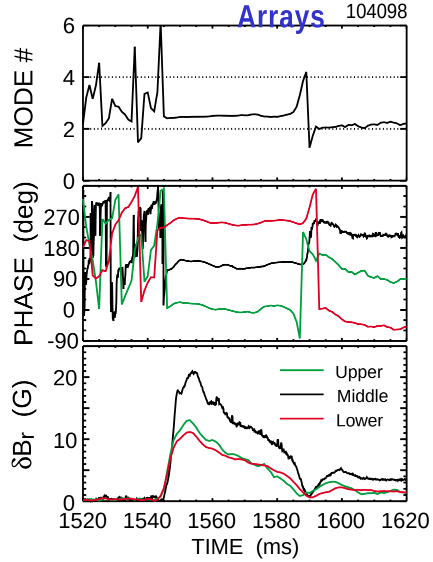
- **Extensive diagnostic sets characterize the Resistive Wall Mode (RWM).**
  - Thirty external δB_r loops and 18 internal δB_r loops measure radial perturbations.
  - Four pairs of diametrically opposed internal δB_p probes measure poloidal perturbations.
  - Identical x-ray cameras at three toroidal locations show RWM internal structure.
- **Six picture-frame coils allow pre-programmed or closed-loop feedback control of RWMs.**
  - Feedback stabilization commands are generated from magnetic sensor data, using a variety of algorithms, and sent to three power amplifiers.
  - Each amplifier energizes a pair of active coils with the proper current and phase for controlling growth of the mode.
  - The active coils are also used to correct magnetic error fields arising



RWM IS A GLOBAL KINK WITH $\gamma \sim \tau_W^{-1}$

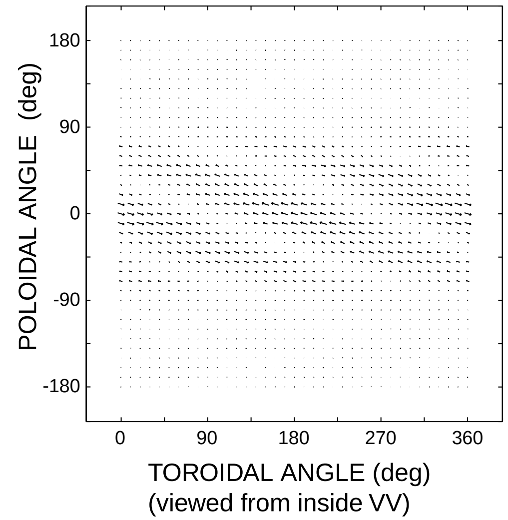
- **Magnetic probe and x-ray measurements confirm RWM global kink structure.**
- **Measured helical structure at the VV wall and internal radial displacements are in agreement with modeling results.**
- **Growth time is of order of the flux penetration time of the DIII-D VV wall, $\tau_W \sim 6$ ms.**

Saddle Loop Arrays

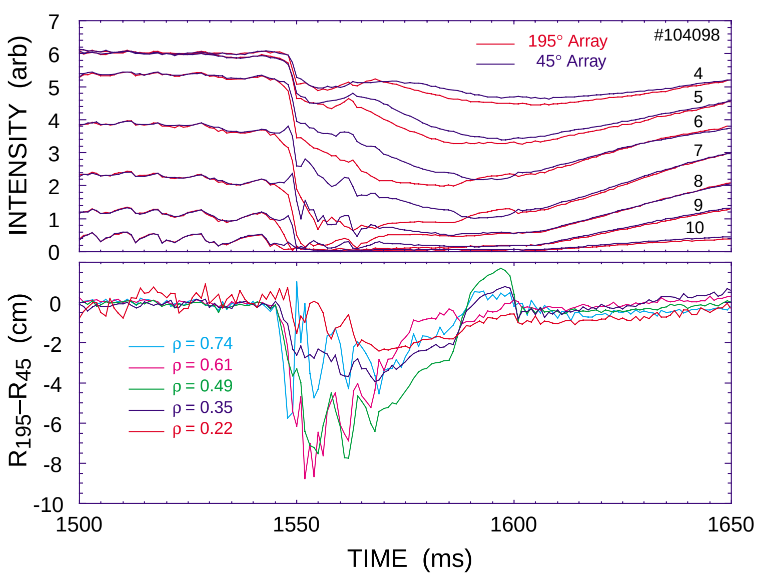


Currents at VV

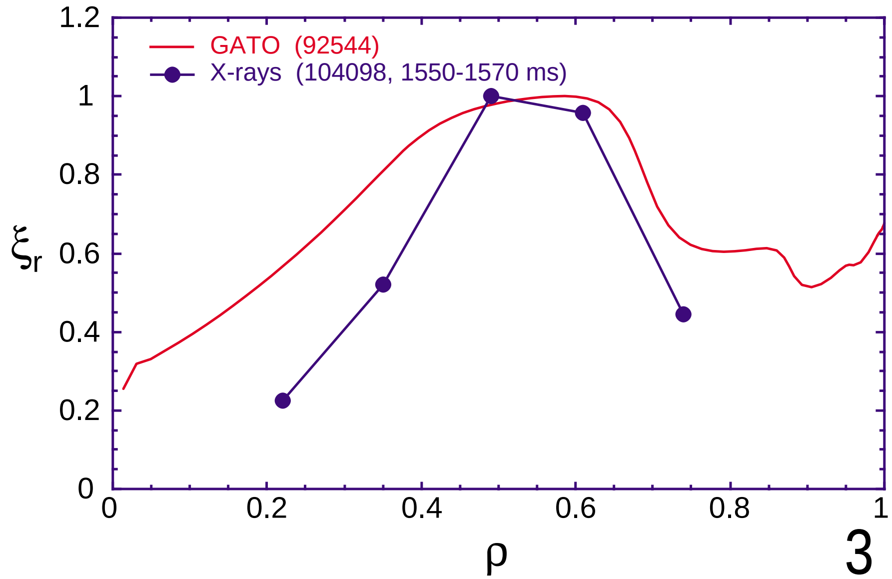
GATO-VACUUM



X-ray Arrays

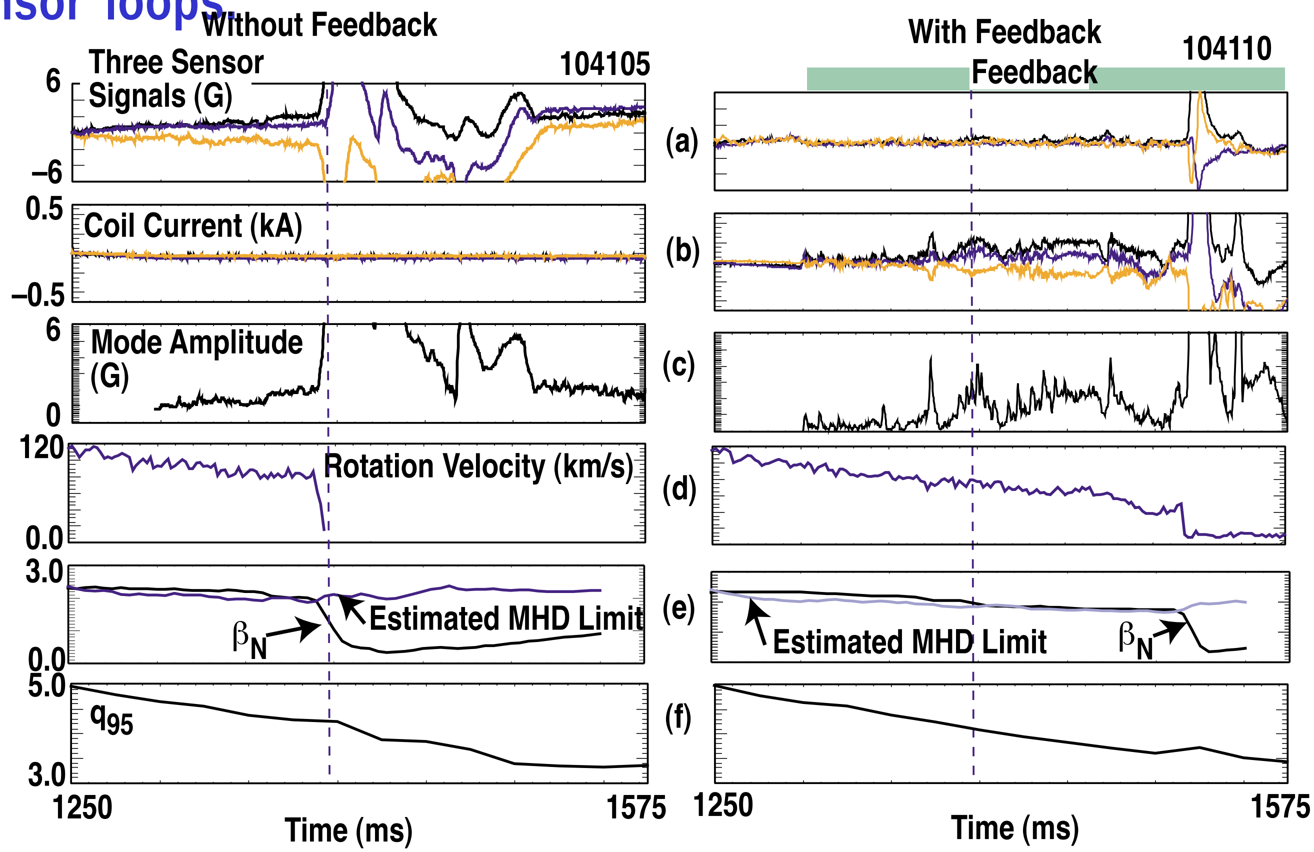


Radial Displacements



FEEDBACK EXPERIMENTS IN 2000 USED EXTERNAL δB_r SENSORS

- Most experiments in 2000 used <u>Smart Shell</u> logic, where the feedback system attempts to null the net radial flux through the sensor loops.



- Other experiments used <u>Explicit Mode Control</u> logic, where the feedback system attempts to suppress the residual flux from the mode after subtracting contributions from the active coils.

RWM KINK STRUCTURE IS RETAINED DURING ACTIVE FEEDBACK

- In this example of Smart Shell feedback using internal midplane δB_r loops, RWM mode amplitude is held at moderate level for ~ 20 τ_W.
- Internal radial displacement is well correlated with differences in δB_p from internal probes and phase-shifted δB_r from external midplane saddle loops.

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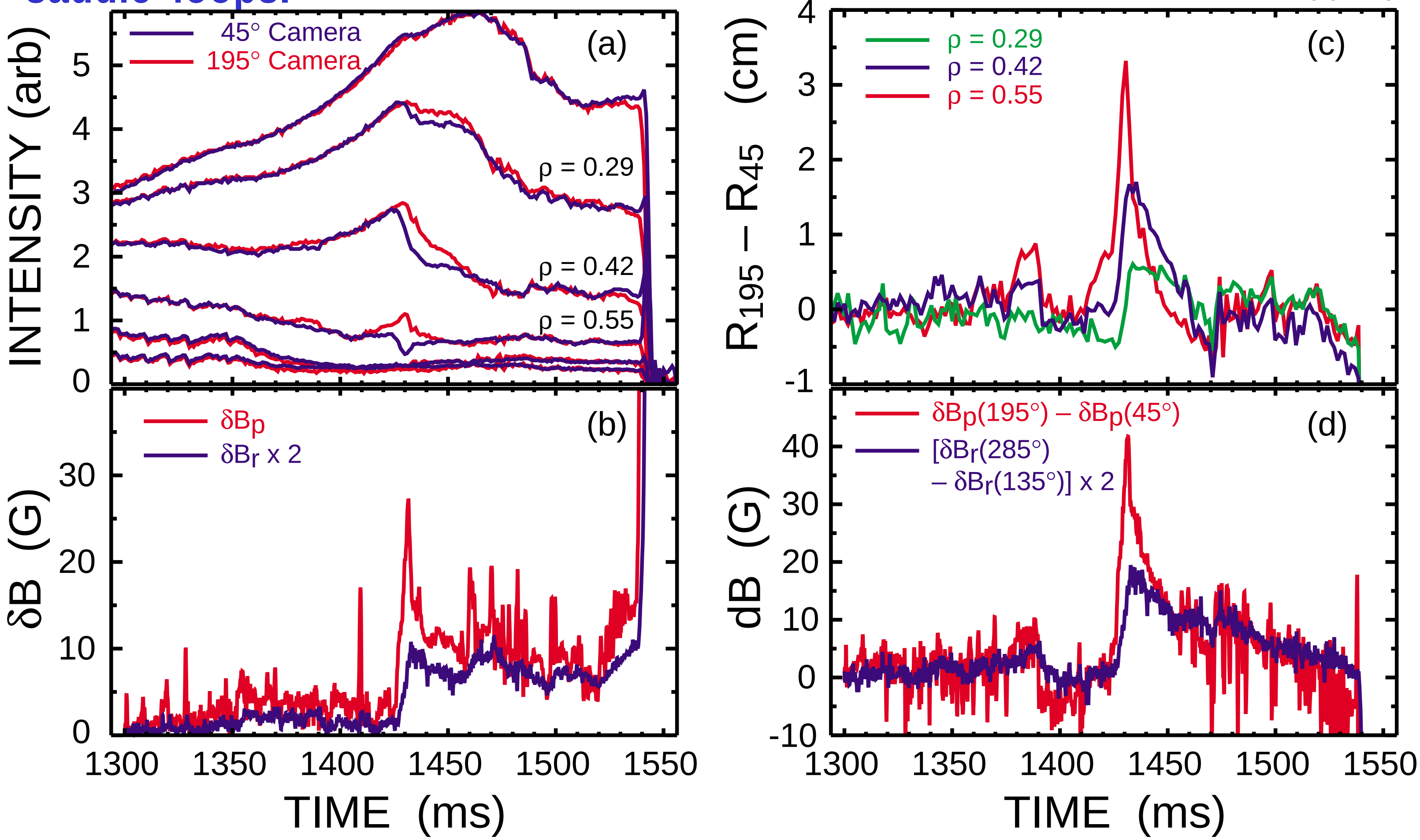
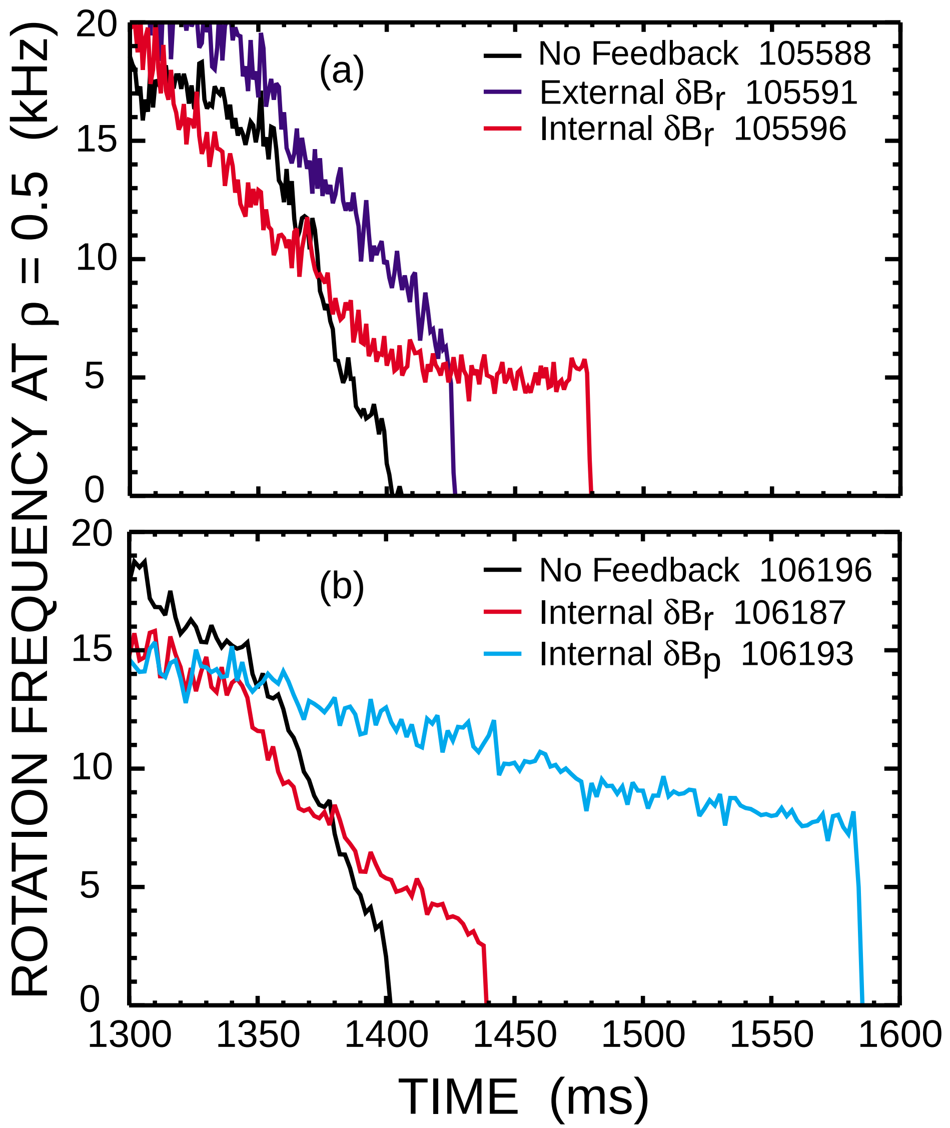


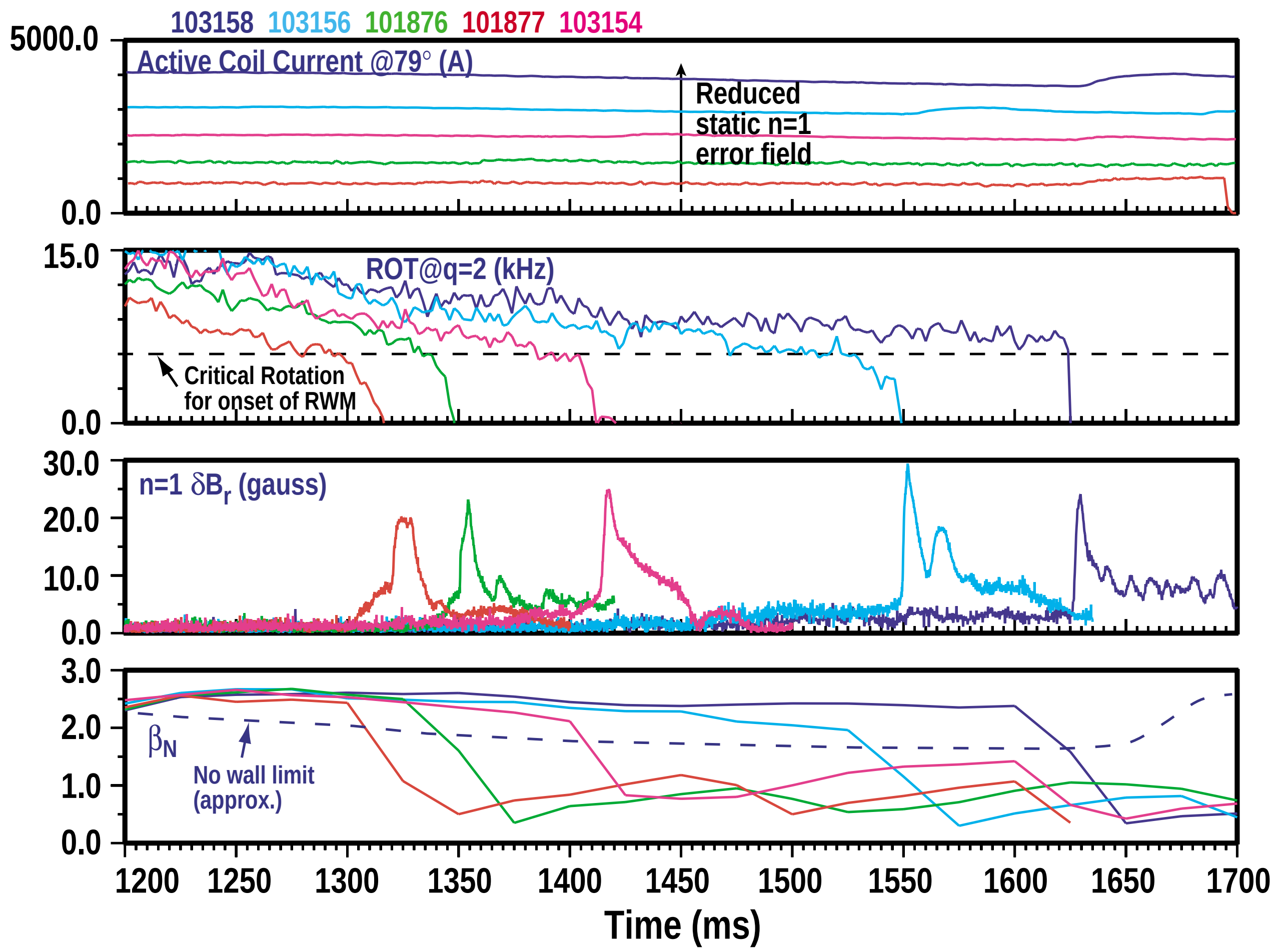
INTERNAL SENSORS ENABLE IMPROVED FEEDBACK CONTROL

- This figure shows toroidal plasma rotation data for experiments using a rapid I_p ramp to reliably trigger an RWM at ~1400 ms in the absence of closed-loop feedback. (Toroidal rotation is a sensitive indicator of the presence of an RWM.)
- With Smart Shell feedback, internal δB_r loops are more effective than external loops in controlling the RWM.
- Internal δB_p probes with Explicit Mode Control feedback are far more effective than either internal or external δB_r loops and Smart Shell feedback.



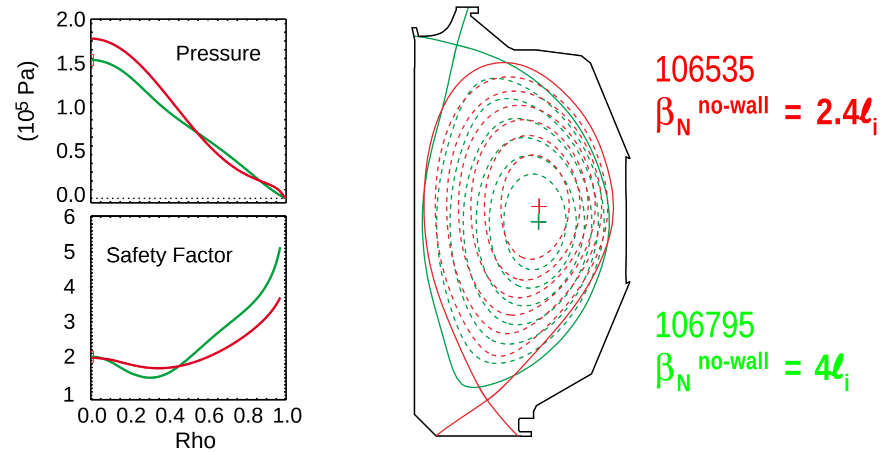
OPTIMIZING ERROR FIELD CORRECTION IMPROVES STABILITY

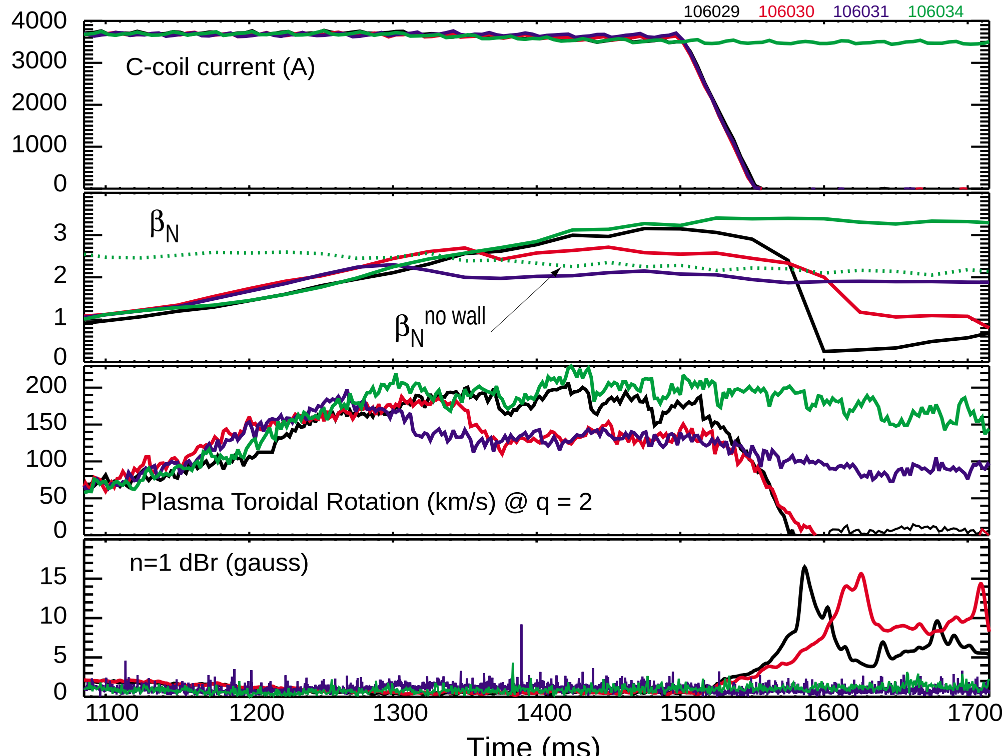
- By shot-to-shot optimization of currents in the active coils, static n=1 error fields can be minimized.
- With optimized error field correction, plasma rotation is sustained for a longer period and onset of RWM is delayed.



EXPERIMENTS VALIDATE CALCULATED β_N NO-WALL LIMIT

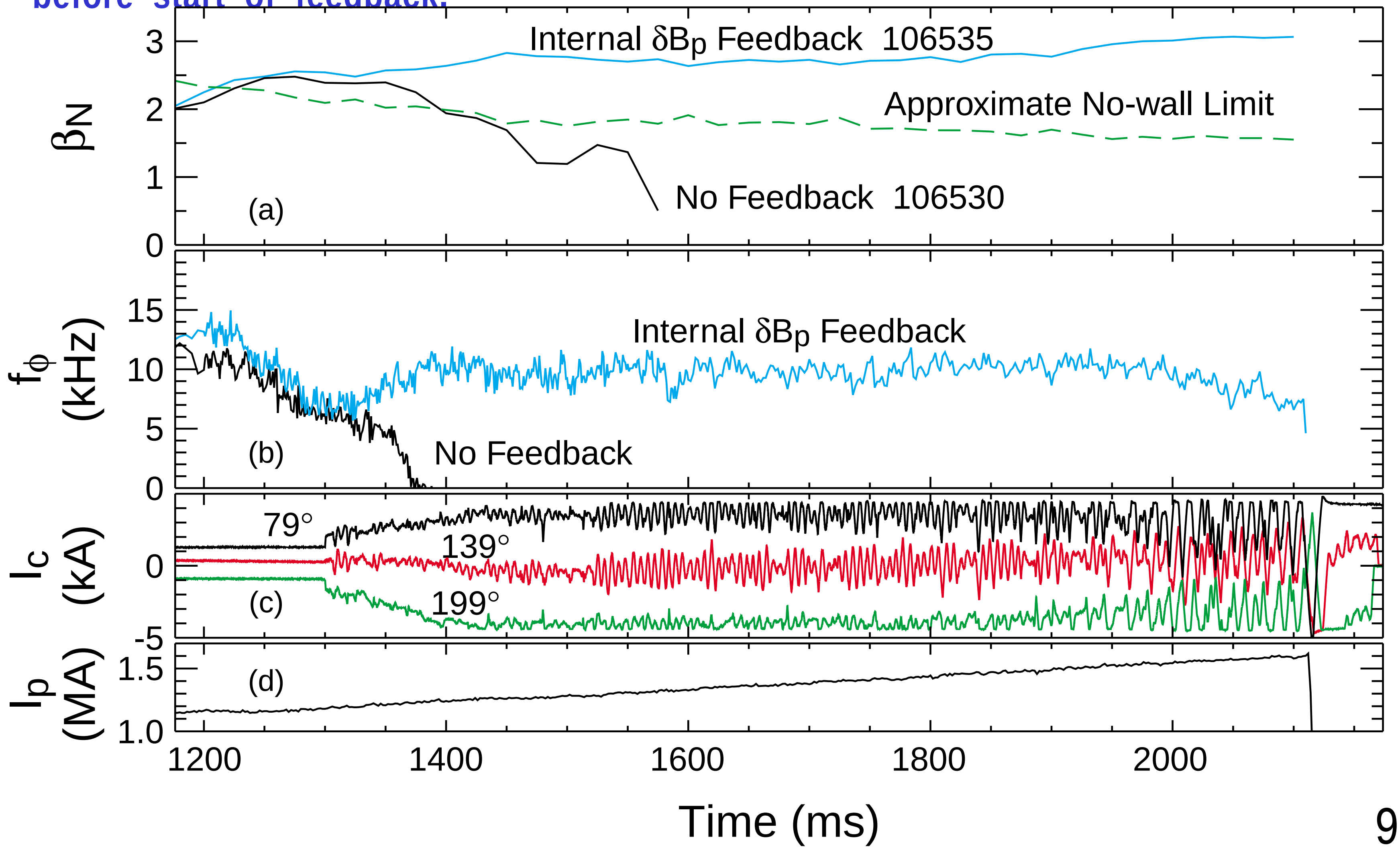
- Calculations show that the no-wall ideal MHD stability limit for normalized plasma pressure $\beta_N = \beta/(I_p/aB)$ is well represented by $\beta_N^{\text{no-wall}} \approx \lambda \ell_i$, where ℓ_i is the plasma internal inductance and λ is approximately constant for similar plasma configurations. (A.D. Turnbull *et al.*, RP1.003)
- For $\beta_N \sim \beta_N^{\text{no-wall}}$ non-axisymmetric magnetic error fields exert a braking torque on toroidal rotation.
- Magnetic braking experiments at different β_N values confirm calculated no-wall limits.
  - For $\beta_N < \beta_N^{\text{no-wall}}$ the plasma is insensitive to error fields.
  - If pre-programmed error field correction is turned off when $\beta_N \geq \beta_N^{\text{no-wall}}$ plasma rotation stops and RWM grows.
  - If pre-programmed error field correction is maintained when $\beta_N \geq \beta_N^{\text{no-wall}}$ plasma rotation continues and RWM does not grow.





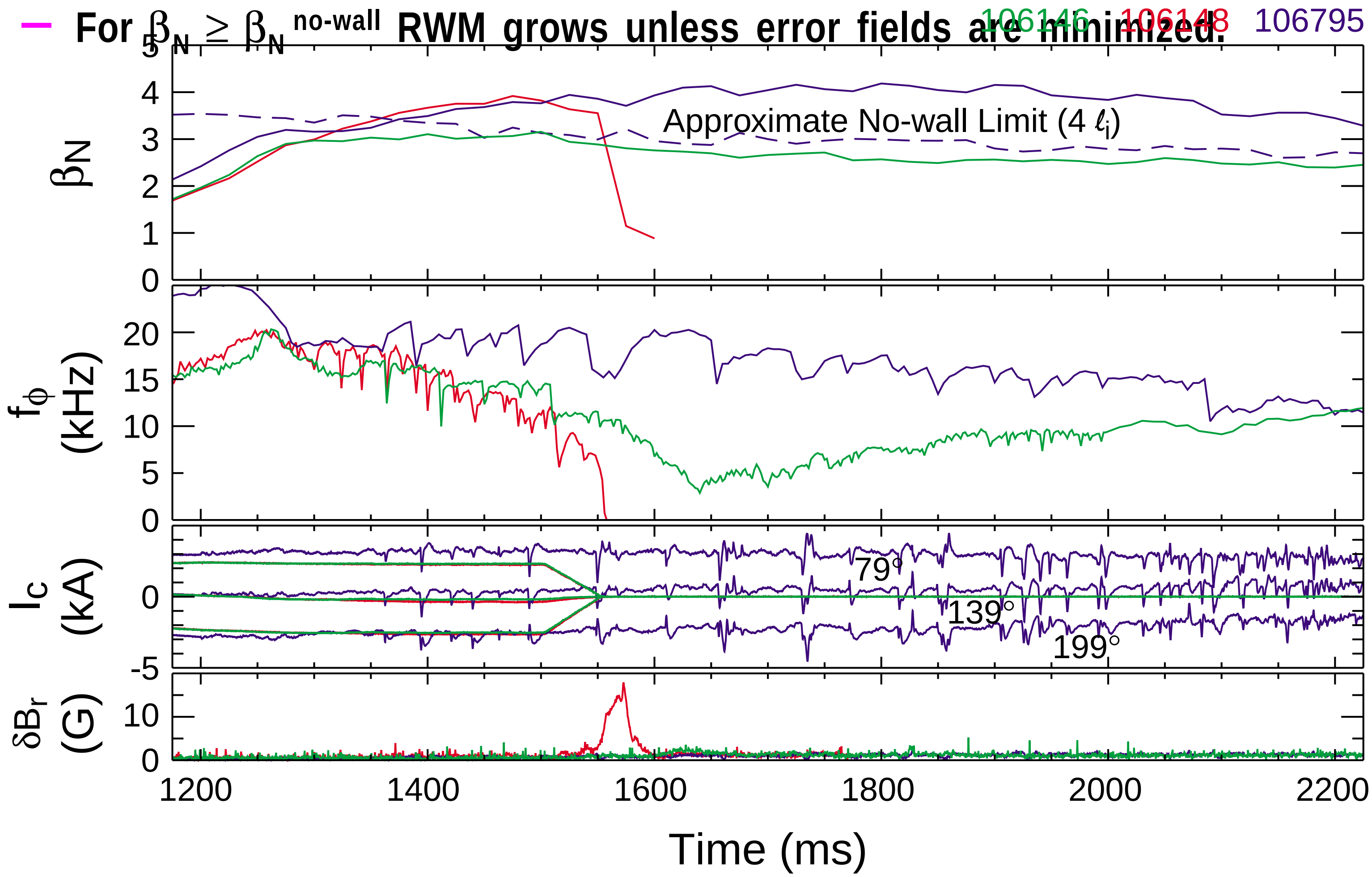
δB_p FEEDBACK GIVES LONG DURATION STABILIZATION

- In a plasma with slow I_p ramp, Explicit Mode Control feedback with δB_p sensors gives stable operation for almost a second (150 τ_W) at β_N approaching twice the no-wall stability limit. In this case, error field correction was intentionally de-tuned before start of feedback.



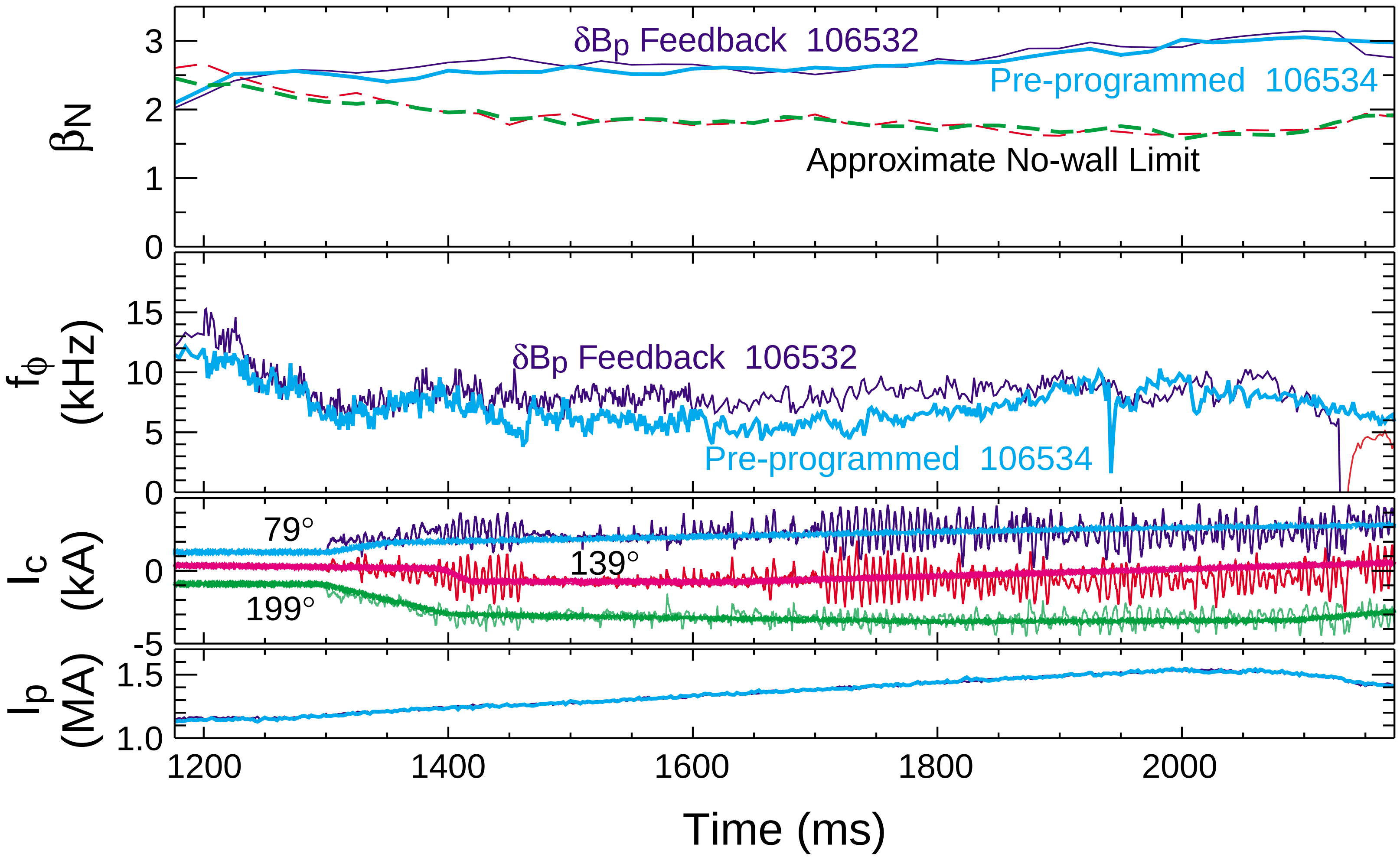
PLASMAS WITH $\beta_N^{\text{no-wall}} \approx 4\ell_i$ ARE SIMILAR TO $\beta_N^{\text{no-wall}} \approx 2.4\ell_i$ CASES

- High performance, double null plasmas, with no I_p ramp and $\beta_N^{\text{no-wall}} \approx 4\ell_i$, respond to error fields in much the same way as $\beta_N^{\text{no-wall}} \approx 2.4\ell_i$ cases.
  - For $\beta_N < \beta_N^{\text{no-wall}}$ the plasma is insensitive to error fields.
  - For $\beta_N \geq \beta_N^{\text{no-wall}}$ RWM grows unless error fields are minimized.



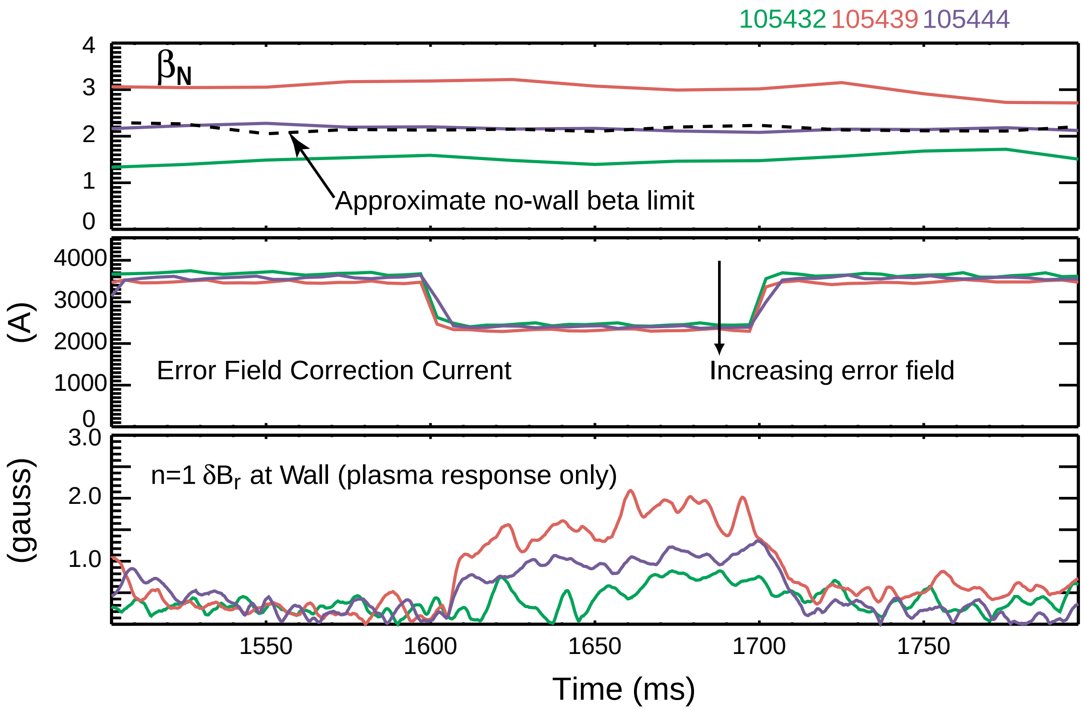
PRE-PROGRAMMING CURRENTS GIVES SIMILAR β_N AND f_ϕ

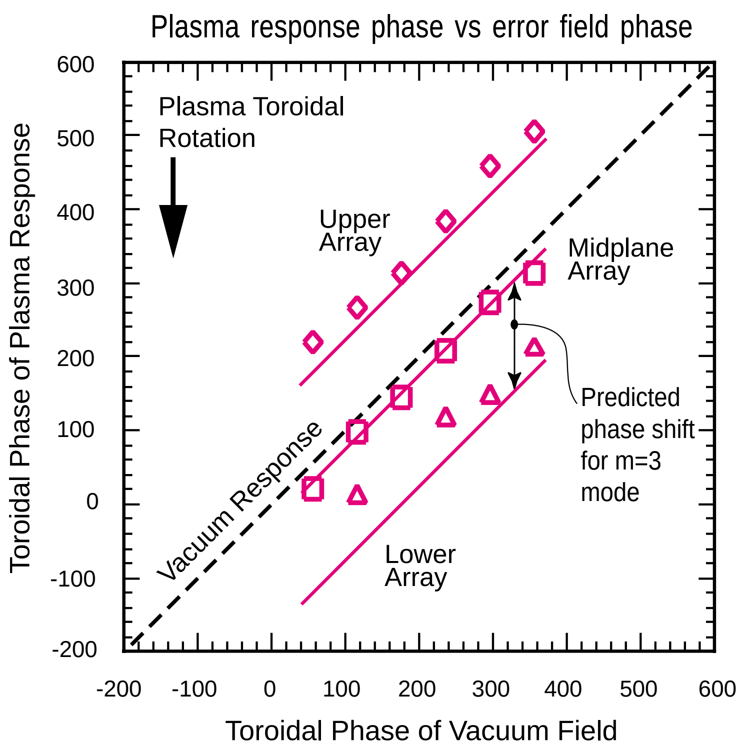
- **In a slow I_p ramp case, pre-programming active coil currents to match δB_p feedback currents from previous shot gives similar β_N and f_ϕ.**
- **This demonstrates that <u>Explicit Mode Control</u> feedback with δB_p sensors provides dynamic optimization of error field corrections.**



FOR $\beta_N \sim \beta_N^{no\text{-}wall}$ THE PLASMA AMPLIFIES ERROR FIELDS

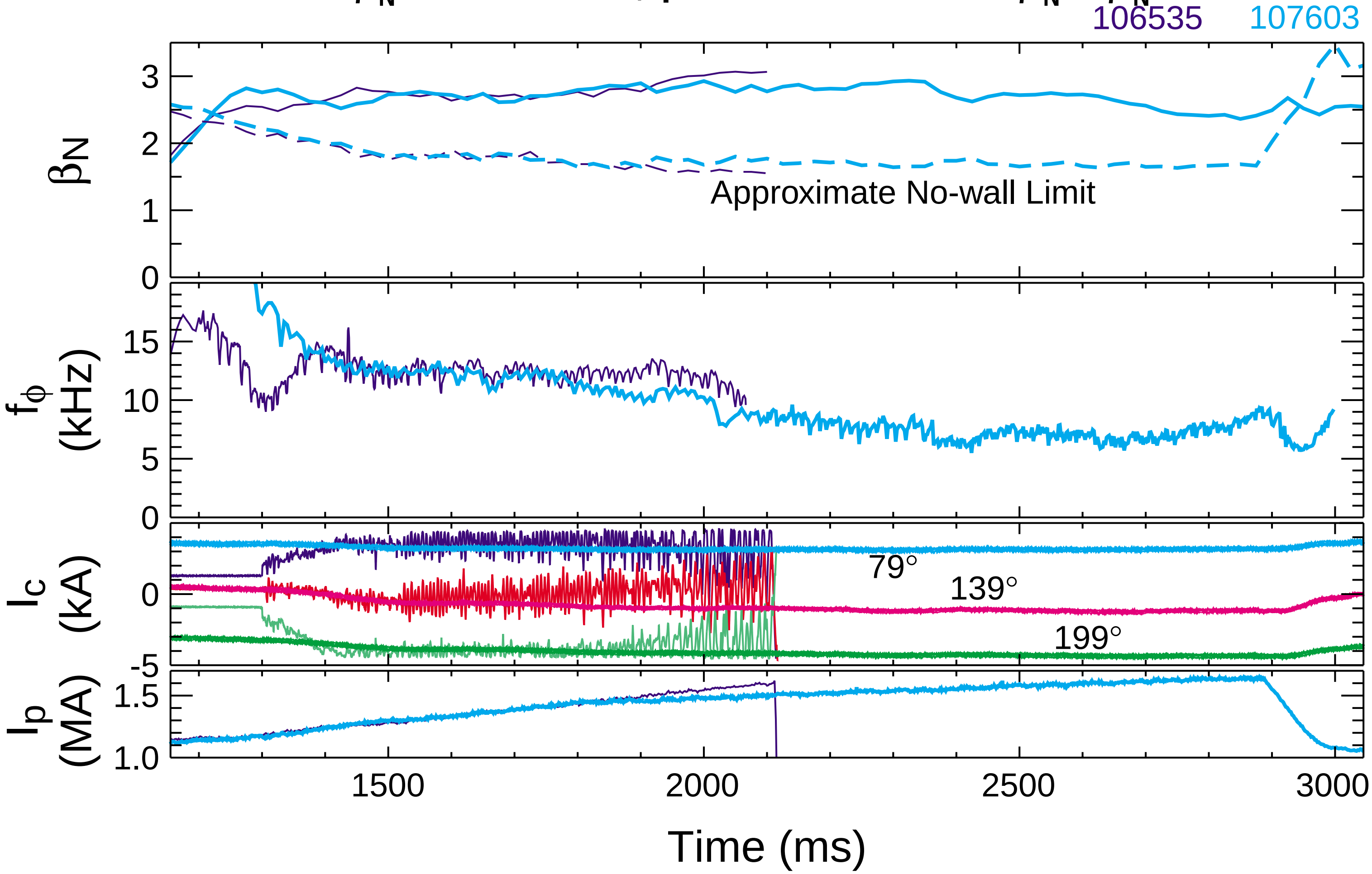
- For $\beta_N \sim \beta_N^{no\text{-}wall}$ the plasma reacts resonantly with non-axisymmetric magnetic error fields. (J.T. Scoville *et al.*, RP1.009)
- Pulsed n=1 error fields with no preferred helicity give rise to nonlinear, helical plasma response.
- Explicit Mode Control feedback with δB_p sensors dynamically adjusts active coil currents so as to minimize plasma response to error fields.





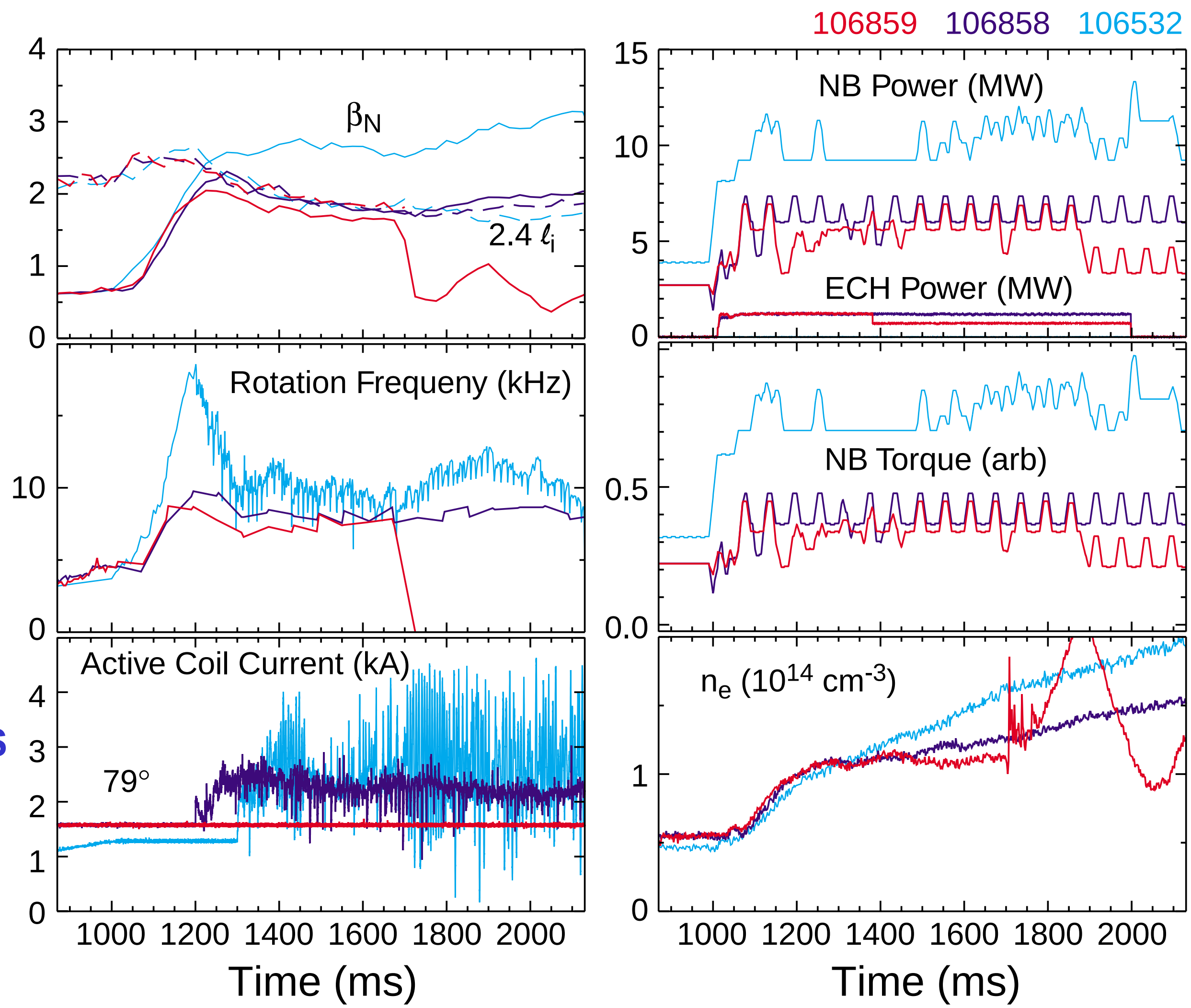
ERROR FIELD CORRECTION ALLOWS $\beta_N > \beta_N^{no\text{-}wall}$ FOR ALMOST 2 S

- **With error field correction by either shot-to-shot optimization or δB_p feedback, long duration operation has been achieved at β_N well above $\beta_N^{no\text{-}wall}$.**
  - **Active coil currents for the two correction methods are about the same.**
  - **When maximum β_N is controlled, plasma is stable at $\beta_N > \beta_N^{no\text{-}wall}$ for > 280 τ_W.**



STUDY OF LOW TORQUE CASES HAS BEGUN

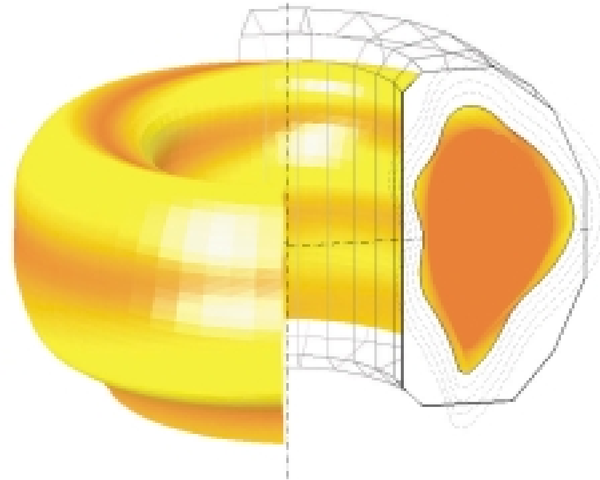
- More nearly perpendicular neutral beams impart less torque.
- 110 GHz gyrotrons provide some of the input power.
- Active coil currents demanded by δB_p feedback are similar to other cases.
- Explicit Mode Control feedback can suppress RWM and sustain rotation at $\beta_N \sim \beta_N^{\text{no-wall}}$.
- Feedback may be acting directly on mode as well as correcting



SUMMARY

- **Error field correction allows rotational stabilization of Resistive Wall Mode.**
- **Stable operation has been sustained for almost 2 s at β_N well above $\beta_N^{\text{no-wall}}$.**
- **When magnetic error fields are minimized, toroidal plasma rotation can be sustained by torque from neutral beams.**
  - **Non-axisymmetric magnetic error fields exert a braking effect on toroidal plasma rotation.**
  - **For plasma pressures above the no-wall ideal stability limit, RWMs grow when rotation stops.**
  - **Closed-loop δB_p feedback provides dynamic correction of magnetic error fields.**
  - **Error fields can also be corrected by shot-to-shot optimization.**
- **Rapid toroidal rotation increases the effectiveness of the conductive wall in stabilizing Resistive Wall Modes.**

Instability grows when rotation stops (amplitude exaggerated)



Plasma is stable when rotation is sustained.