# STRUCTURE AND FEEDBACK STABILIZATION OF RESISTIVE WALL MODES IN DIII-D

L.C. JOHNSON, M. OKABAYASHI, A. M. GAROFALO, E.J. STRAIT,
J. BIALEK, M.S. CHANCE, M.S. CHU, E.D. FREDRICKSON,
R.J. LA HAYE, J. MANICKAM, A. NAGY, G.A. NAVRATIL, R.T. SNIDER,
J.T. SCOVILLE, A.D. TURNBULL, and M.L. WALKER

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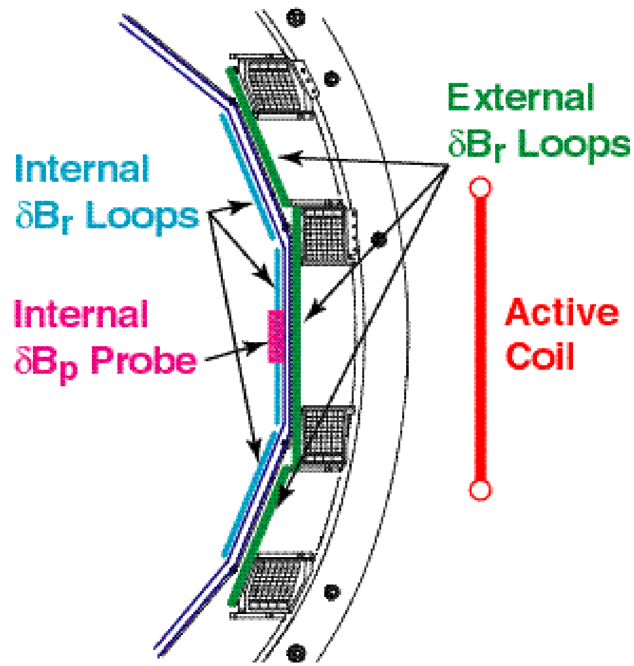
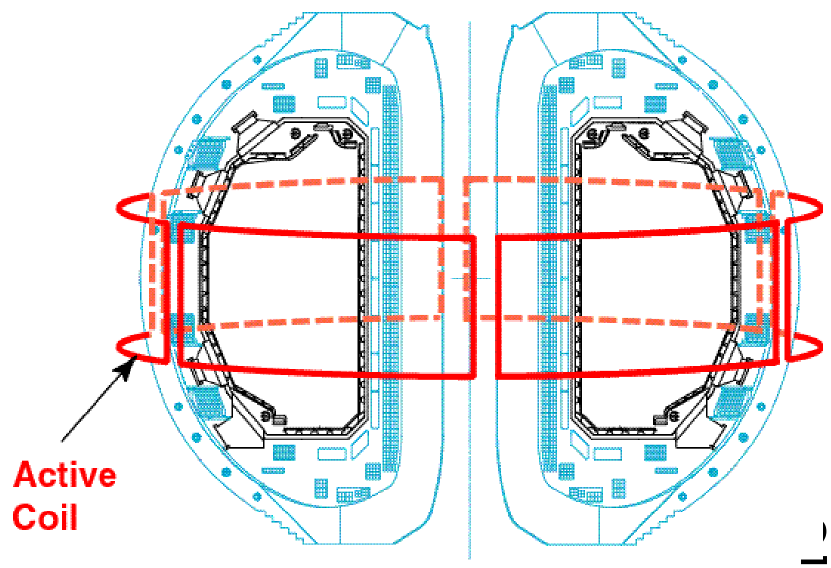
# ABSTRACT


- Resistive wall modes (RWM) limit the performance of DIII-D discharges when beta exceeds the no-wall ideal stability limit. These n=1 global kink modes grow on the slow time scale of magnetic diffusion through the surrounding conductive vacuum vessel wall.
- Active feedback stabilization experiments in 2000 suppressed RWMs for periods 50 times longer than the resistive penetration time of the wall.
- Experiments in 2001 have demonstrated dramatic improvements in active control capability, owing largely to an extensive new set of magnetic sensors installed inside the vacuum vessel after the 2000 campaign.
- The new magnetic sensors, together with existing external sensors and a toroidal array of x-ray cameras, have also afforded better characterization of the previously observed mode structure.

# THE ACTIVE FEEDBACK STABILIZATION SYSTEM ON DIII–D

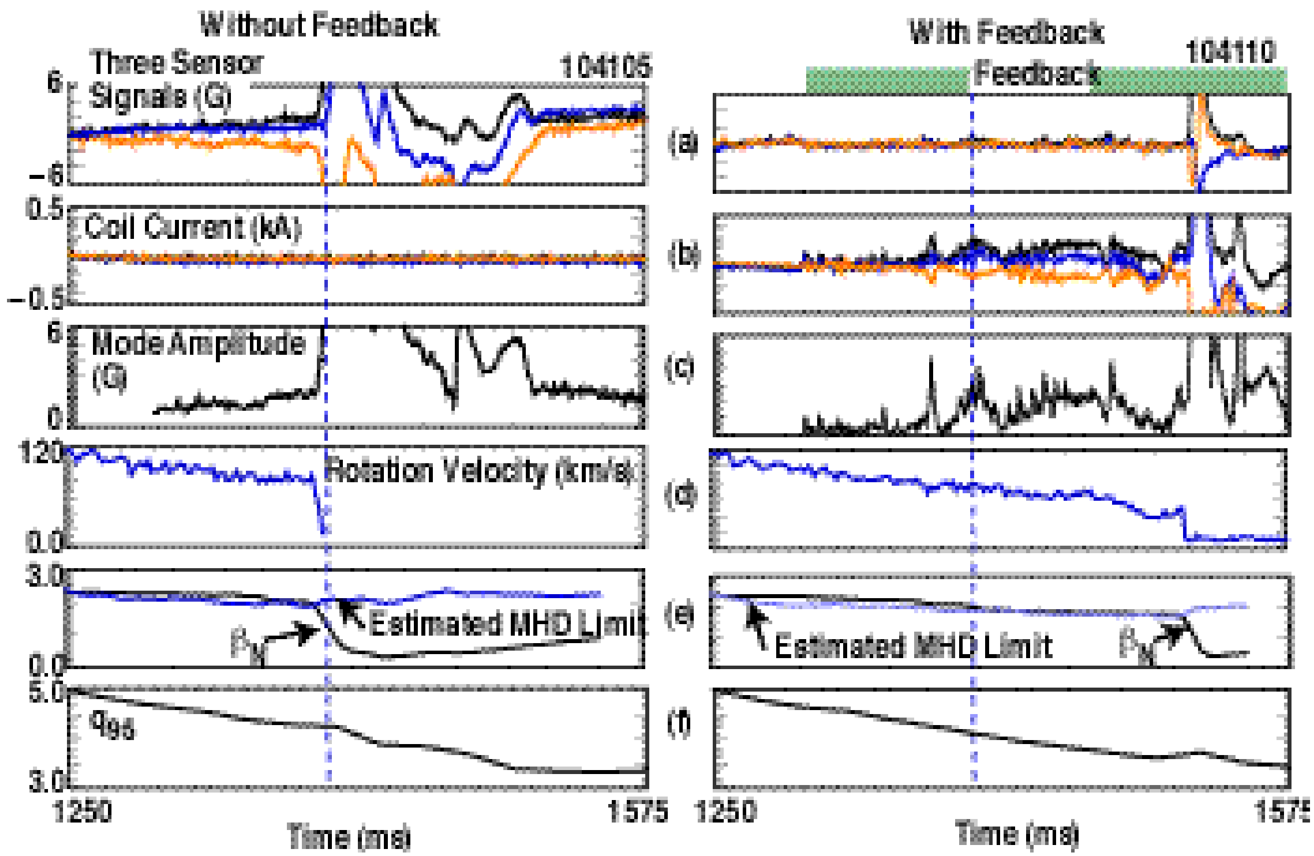
- Resistive wall modes (RWM) have been under study on DIII-D for several years.
- Experiments on active magnetic feedback stabilization of these modes began in 1999.
- Internal and external magnetic loops and probes, arranged in toroidal arrays, detect slowly growing n=1 magnetic perturbations from RWMs.
- 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.



# CLOSED-LOOP EXPERIMENTS IN 2000 USED EXTERNAL $\delta B_r$ SENSORS

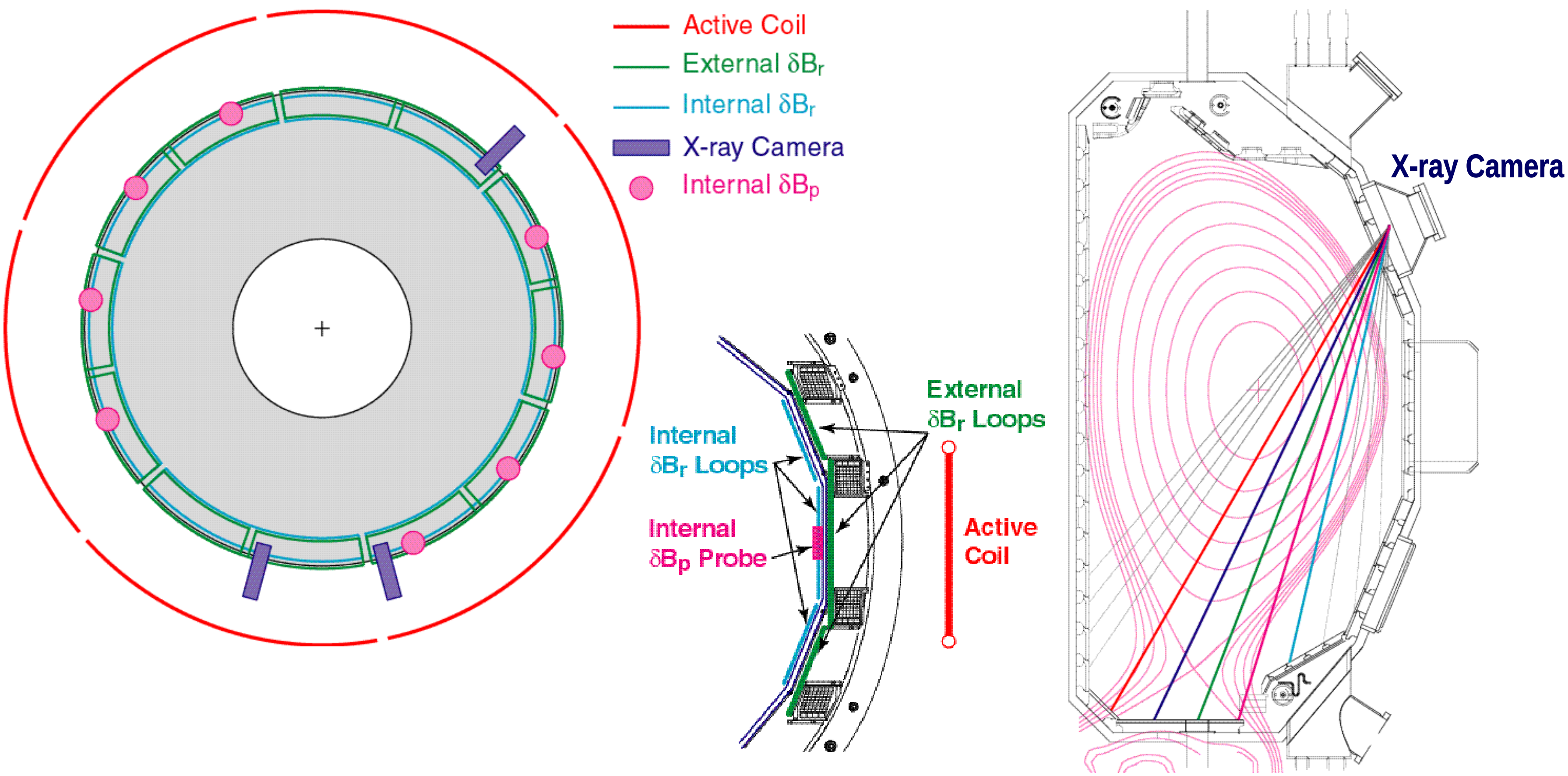
- Most experiments in 2000 used Smart Shell logic, where the feedback system attempts to null the net radial flux through the sensor loops.



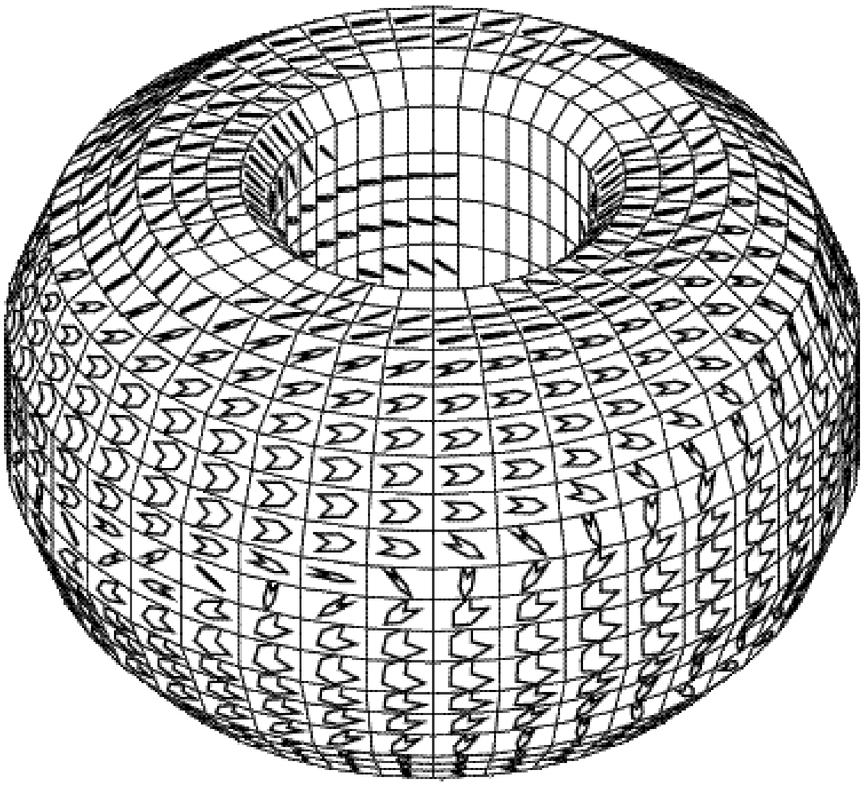

- Other experiments used Explicit Mode Control logic, where the feedback system attempts to suppress the residual flux from the mode after subtracting contributions from the active coils.

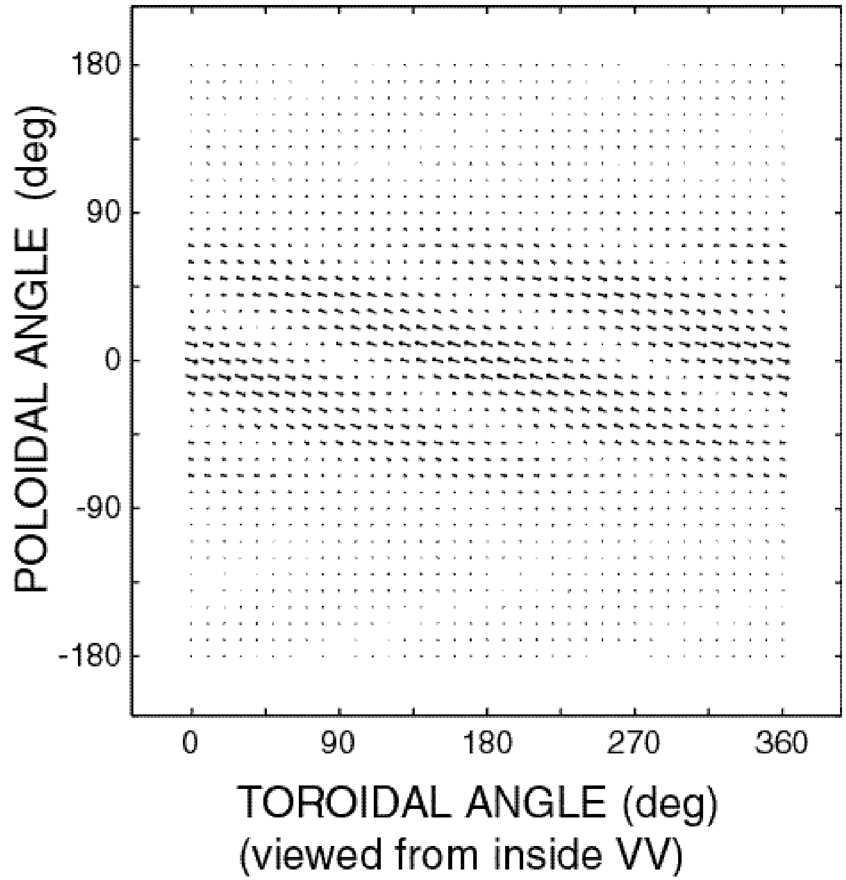
# DIII–D HAS EXTENSIVE RESISTIVE WALL MODE DIAGNOSTICS

- Thirty external $\delta B_r$ loops and 18 internal $\delta B_r$ loops measure toroidal and poloidal structure of radial field perturbations from RWMs.
- Four pairs of diametrically opposed internal $\delta B_p$ probes measure poloidal field perturbations on the vacuum vessel midplane.
- Identical x-ray cameras at three toroidal locations show RWM internal structure.



# CODES PREDICT INDUCED CURRENTS IN CONDUCTING WALL



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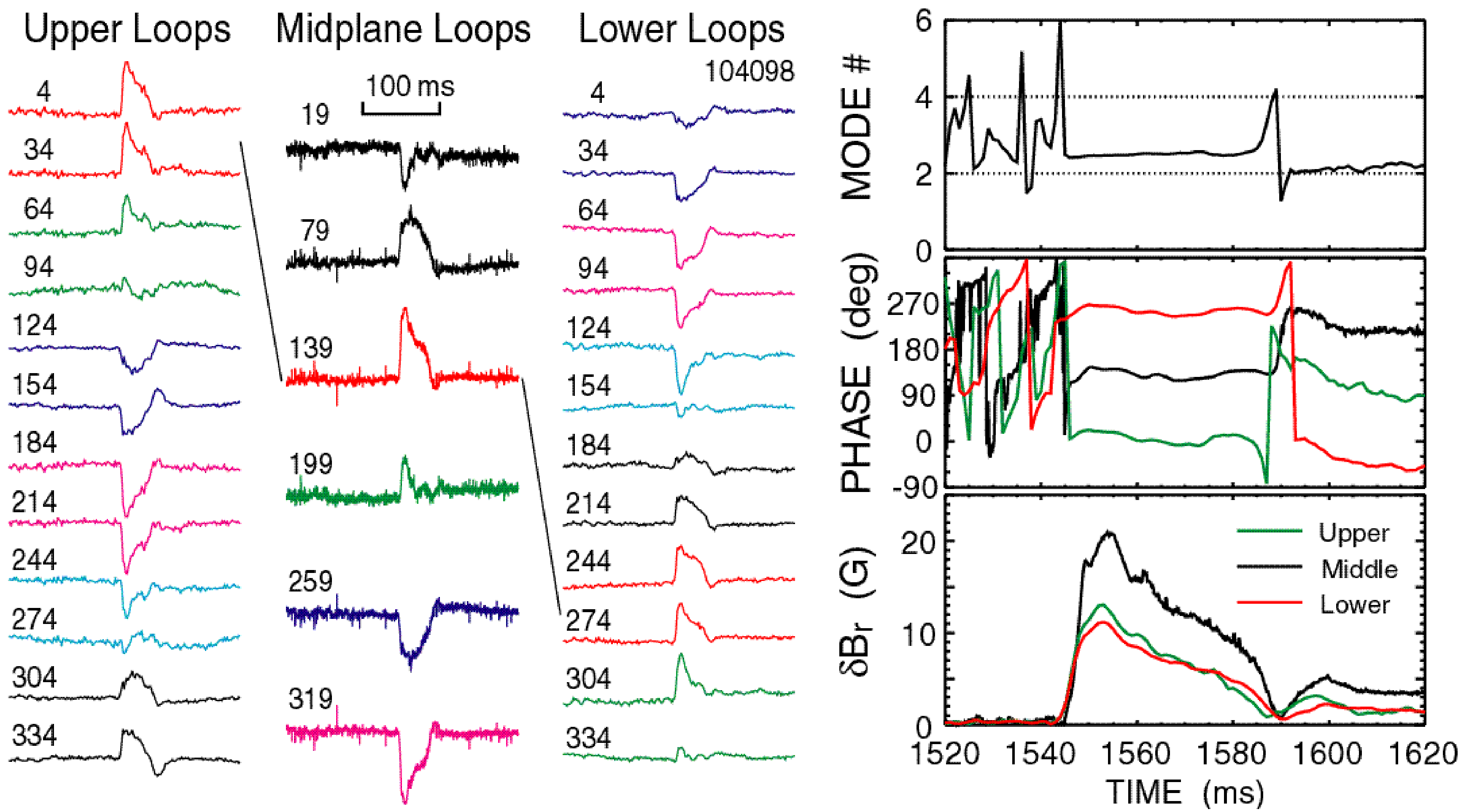
# $\delta B_r$ LOOPS MEASURE RWM HELICAL STRUCTURE AT WALL

- This figure shows typical data from the 30-loop array of external $\delta B_r$ sensors and resulting mode analysis for a discharge without feedback.
- All three toroidal arrays show similar but phase shifted behavior.
- This helical structure is in agreement with expectations.



# CODES PREDICT RWM INTERNAL STRUCTURE

- Plasma displacements predicted by MHD stability codes are mainly poloidal but with net radial components.
- Toroidally separated soft x-ray cameras can observe non-axisymmetric radial displacements.

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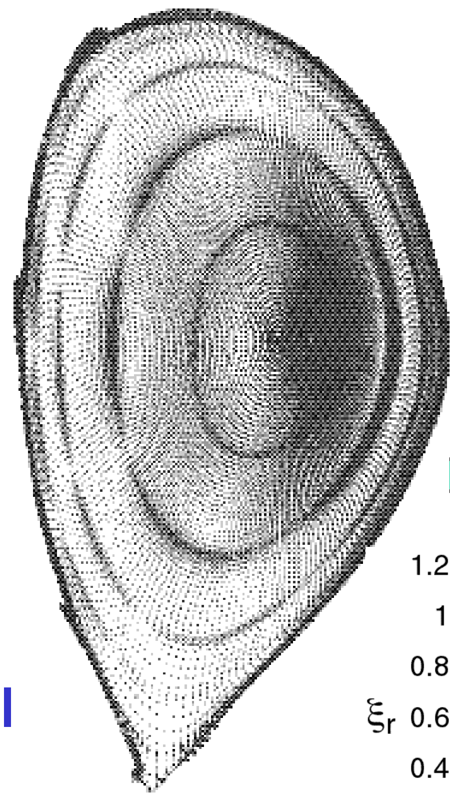

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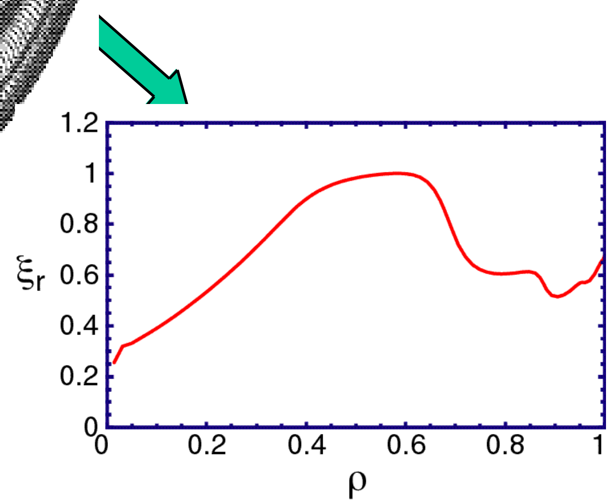
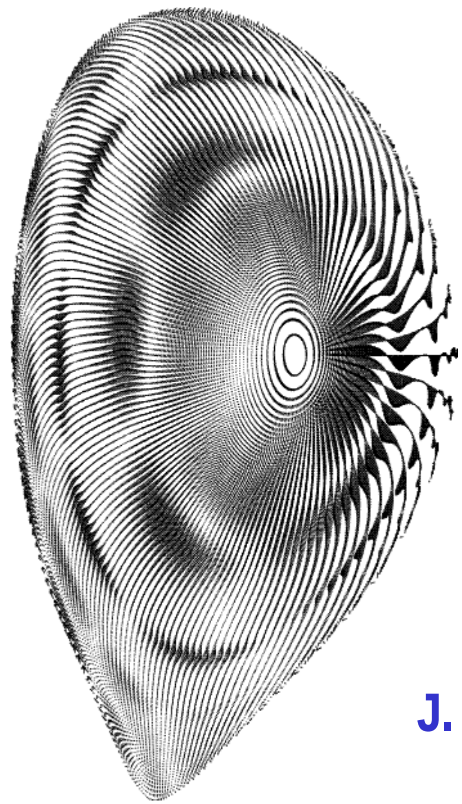


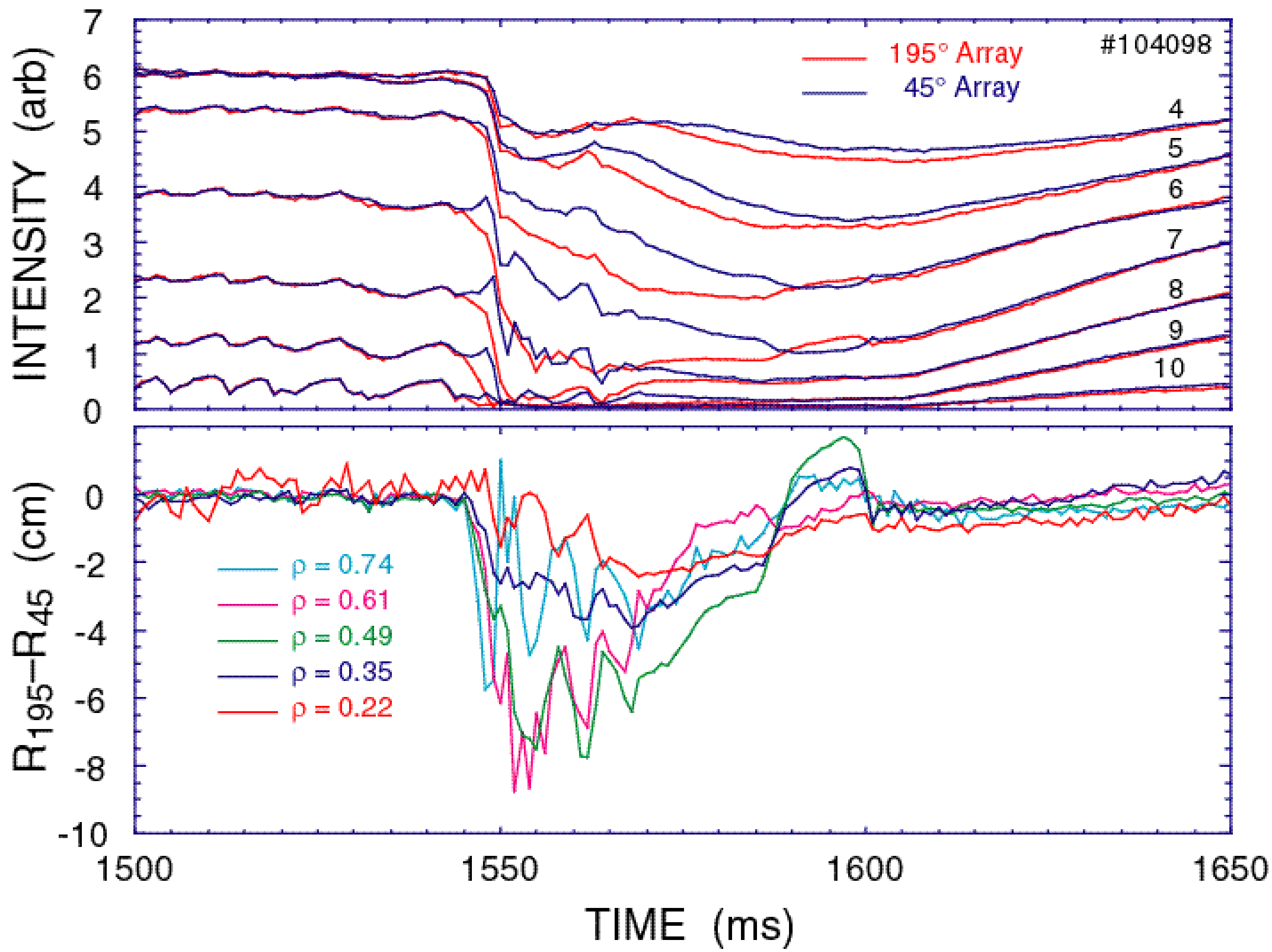



PEST

J. Manickam

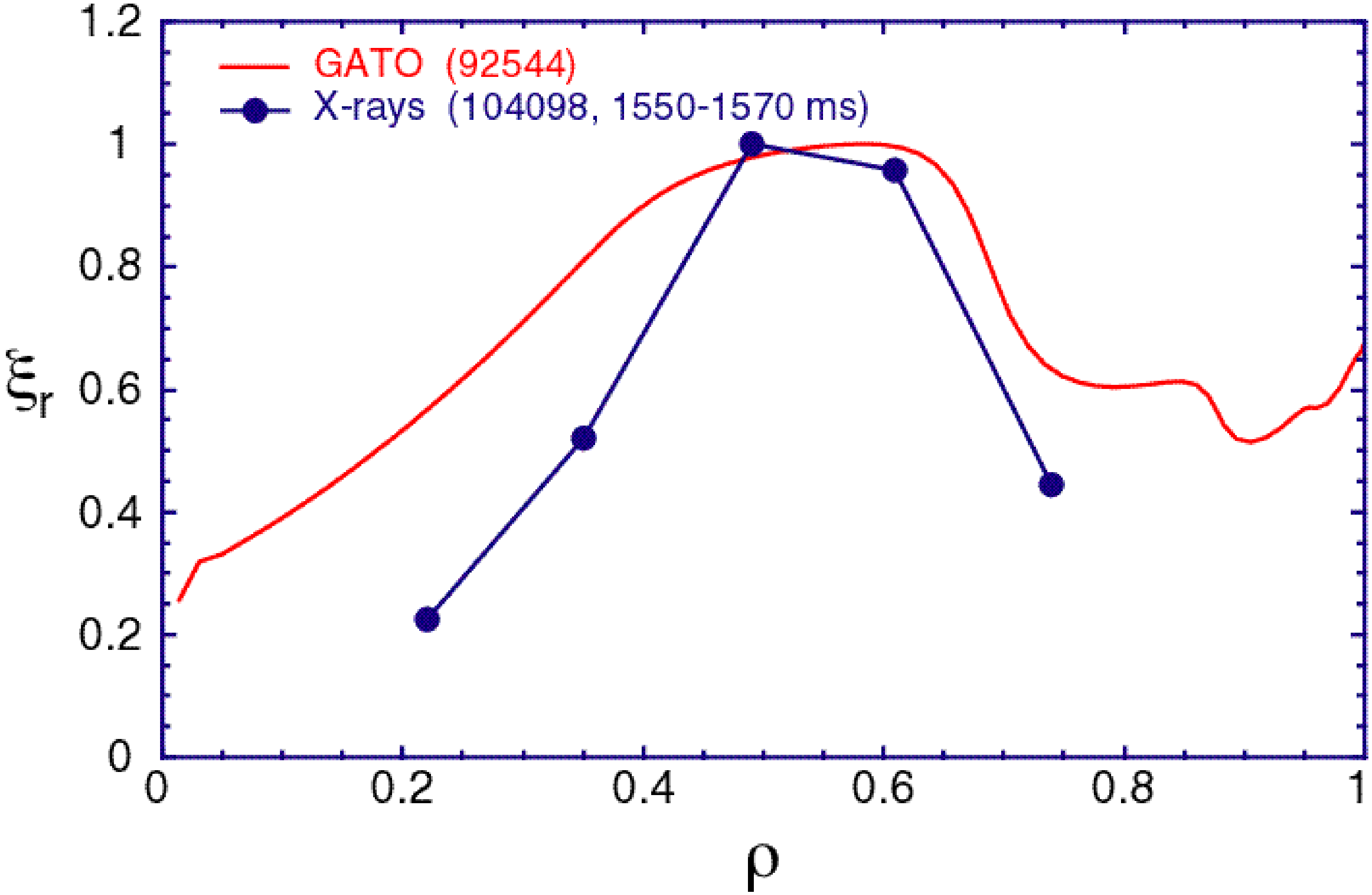
# X-RAY ARRAYS MEASURE RWM INTERNAL STRUCTURE

- **Chord-by-chord comparisons of soft x-ray intensities from toroidally separated poloidal arrays are used to find relative radial displacements between the two toroidal locations at minor radii corresponding to the x-ray sight lines.**



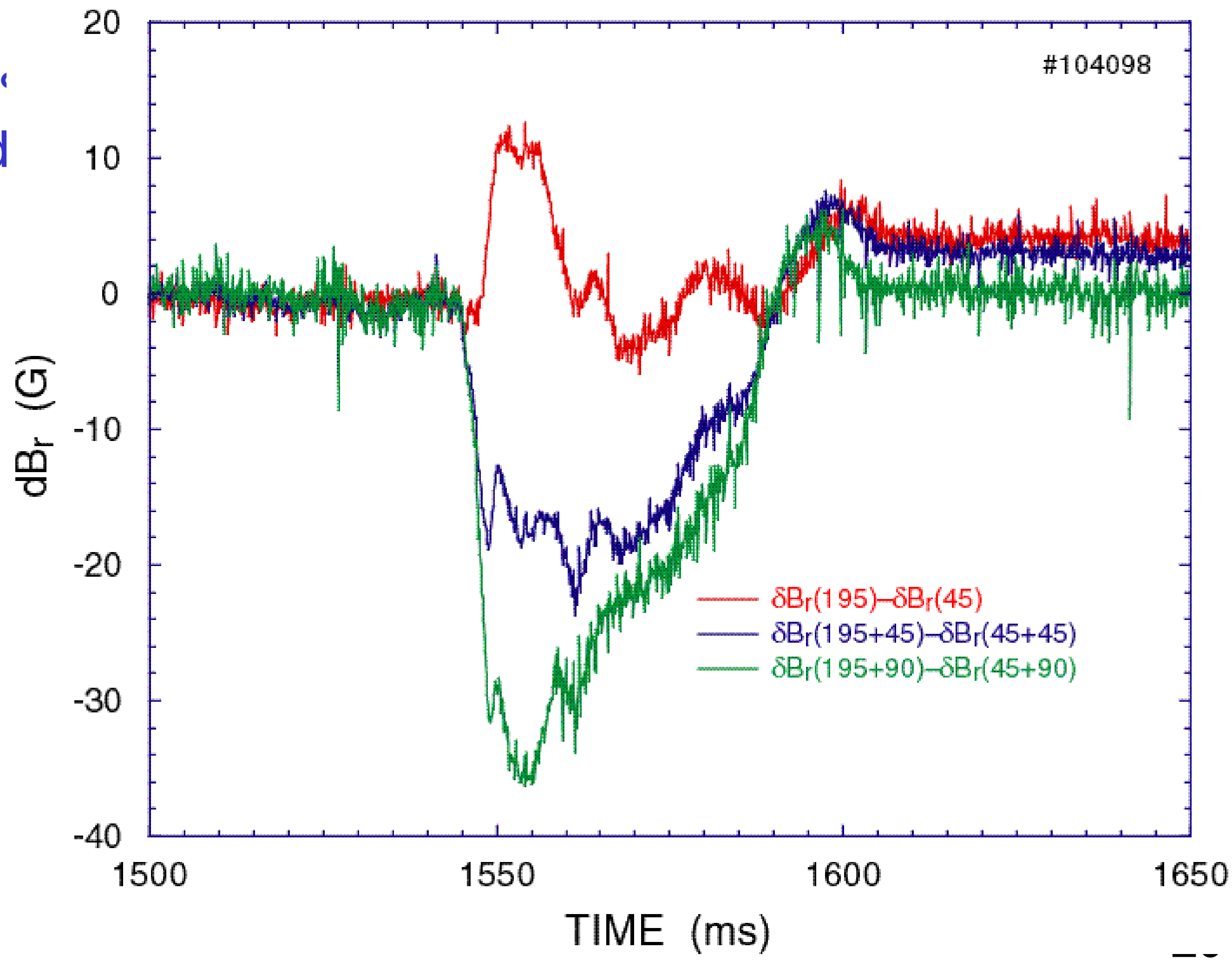
# INTERNAL STRUCTURE FROM X-RAYS AGREES WITH GATO

- Soft x-ray determination of the radial profile of relative radial displacements between two toroidal locations shows kink-like internal structure.
- Normalized radial displacements near the plasma midplane are in general agreement with results from the GATO stability code.



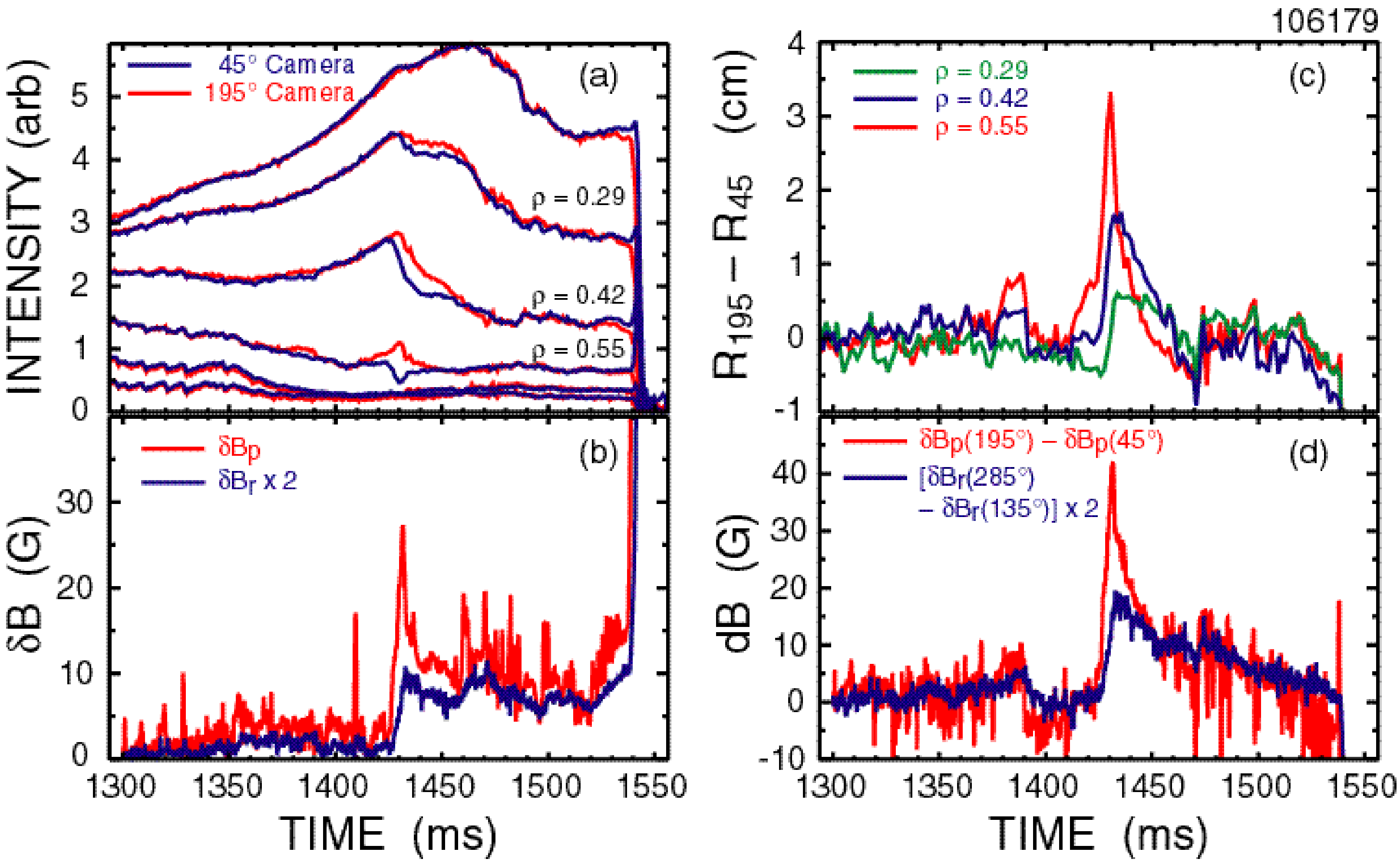
# X-RAY AND $\delta B_r$ DATA SHOW EXPECTED PHASE RELATION

- **Amplitude and phase of $\delta B_r$ from midplane saddle loops are used to find relative difference in $\delta B_r$ between 195° and 45° toroidal locations for comparison with relative displacements deduced from x-ray arrays.**
- **Maximum $\delta B_r$ is expected to be 90° clockwise (viewed from above) from maximum radial displacement.**
- **Results confirm expected 90° toroidal phase difference.**



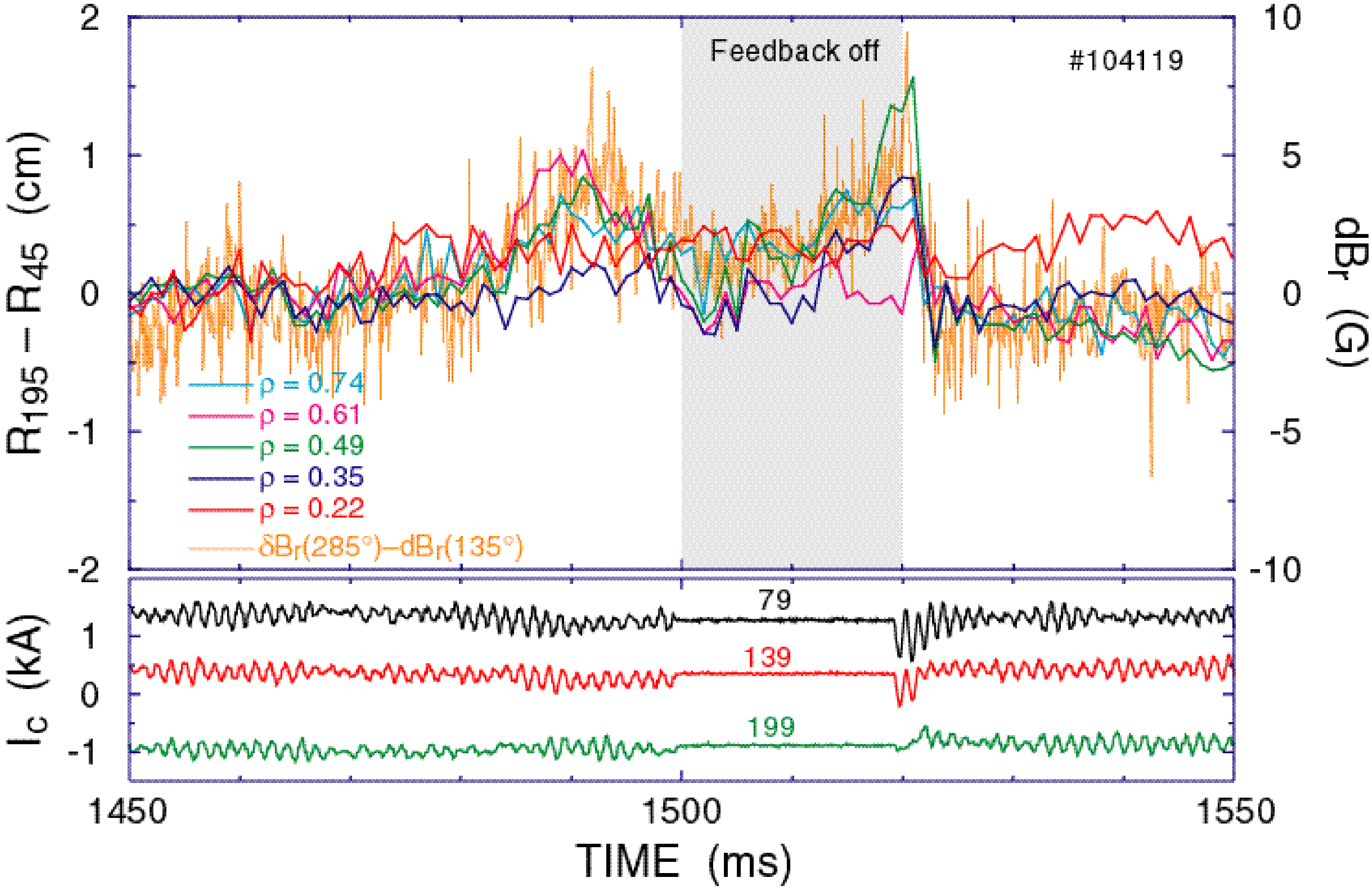
# MODE STRUCTURE IS RETAINED DURING ACTIVE FEEDBACK

- In this example of Smart Shell feedback using internal midplane $\delta B_r$ loops, RWM mode amplitude is held at moderate level for ~100 ms.
- Internal radial displacement is well correlated with differences in $\delta B_p$ from internal probes and phase-shifted $\delta B_r$ from external midplane saddle loops.



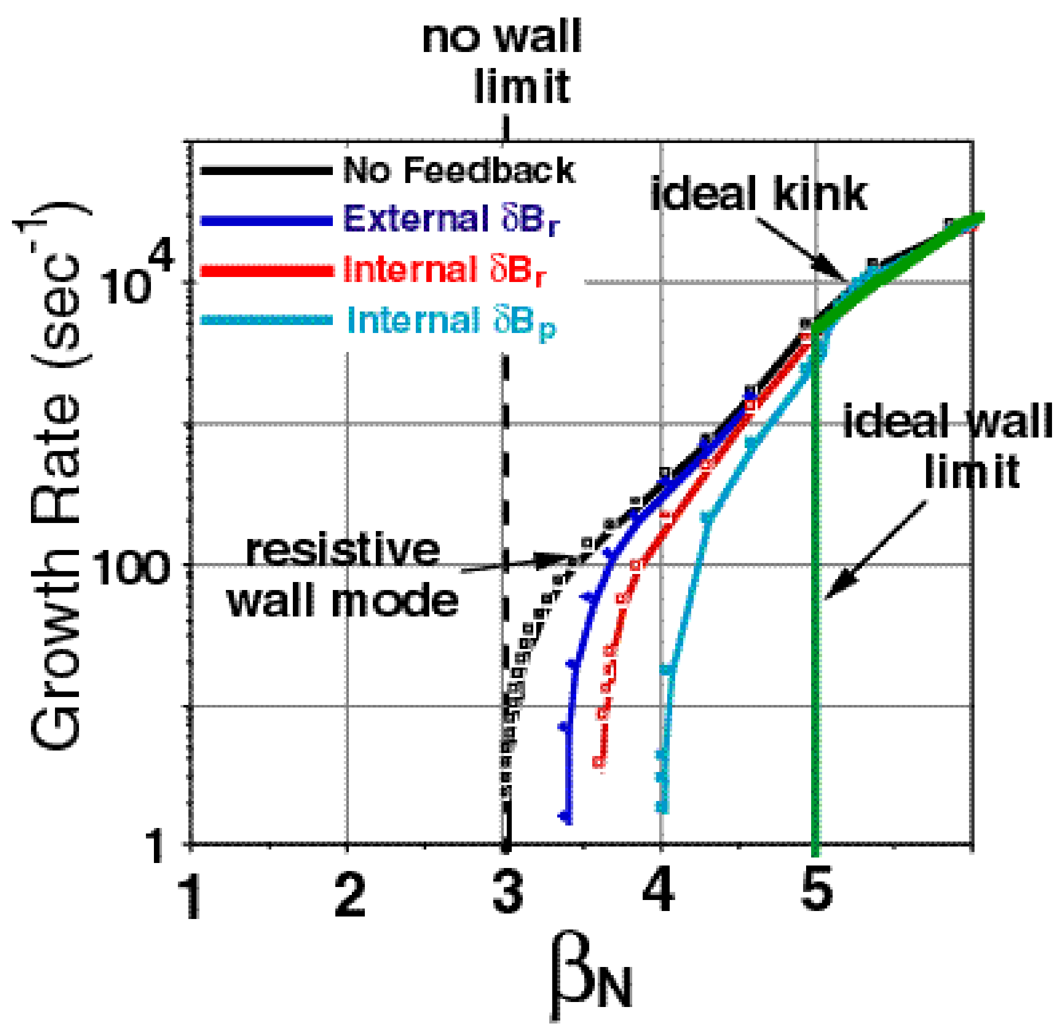
## MODE GROWTH IN GATED-OFF PERIOD DEMONSTRATES CONTROL

- In this example of long-duration (>50 $\tau_w$) active stabilization, mode is controlled until feedback is gated off, then grows.
- Control is re-established when feedback is switched back on.



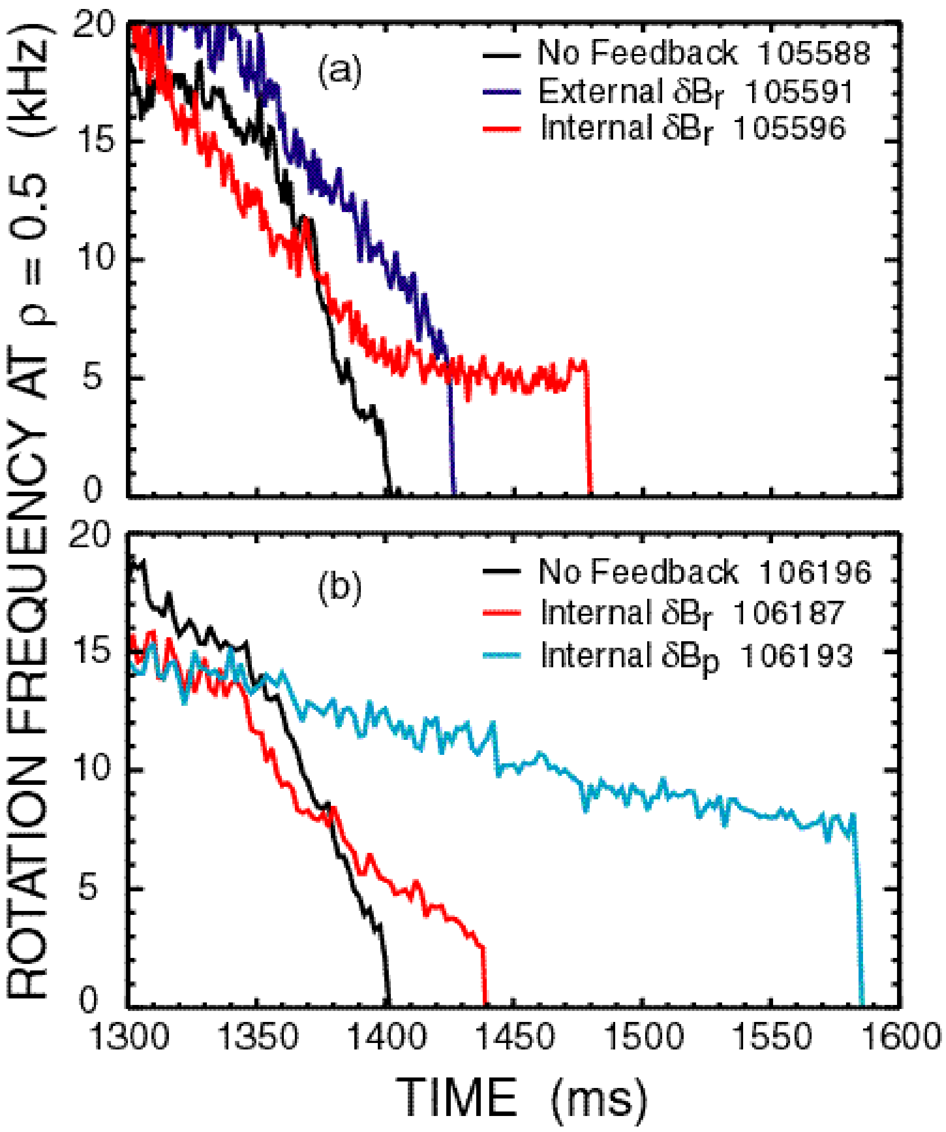
# VALEN PREDICTS BETTER CONTROL WITH INTERNAL SENSORS

- **VALEN code calculations, with Smart Shell logic and no plasma rotation, predict:**
  - Properly designed internal $\delta B_r$ sensors will enable greater control capability than that possible with external saddle loops.
  - Internal $\delta B_p$ sensors will offer even greater advantages because of insensitivity to radial fields from the active coils.



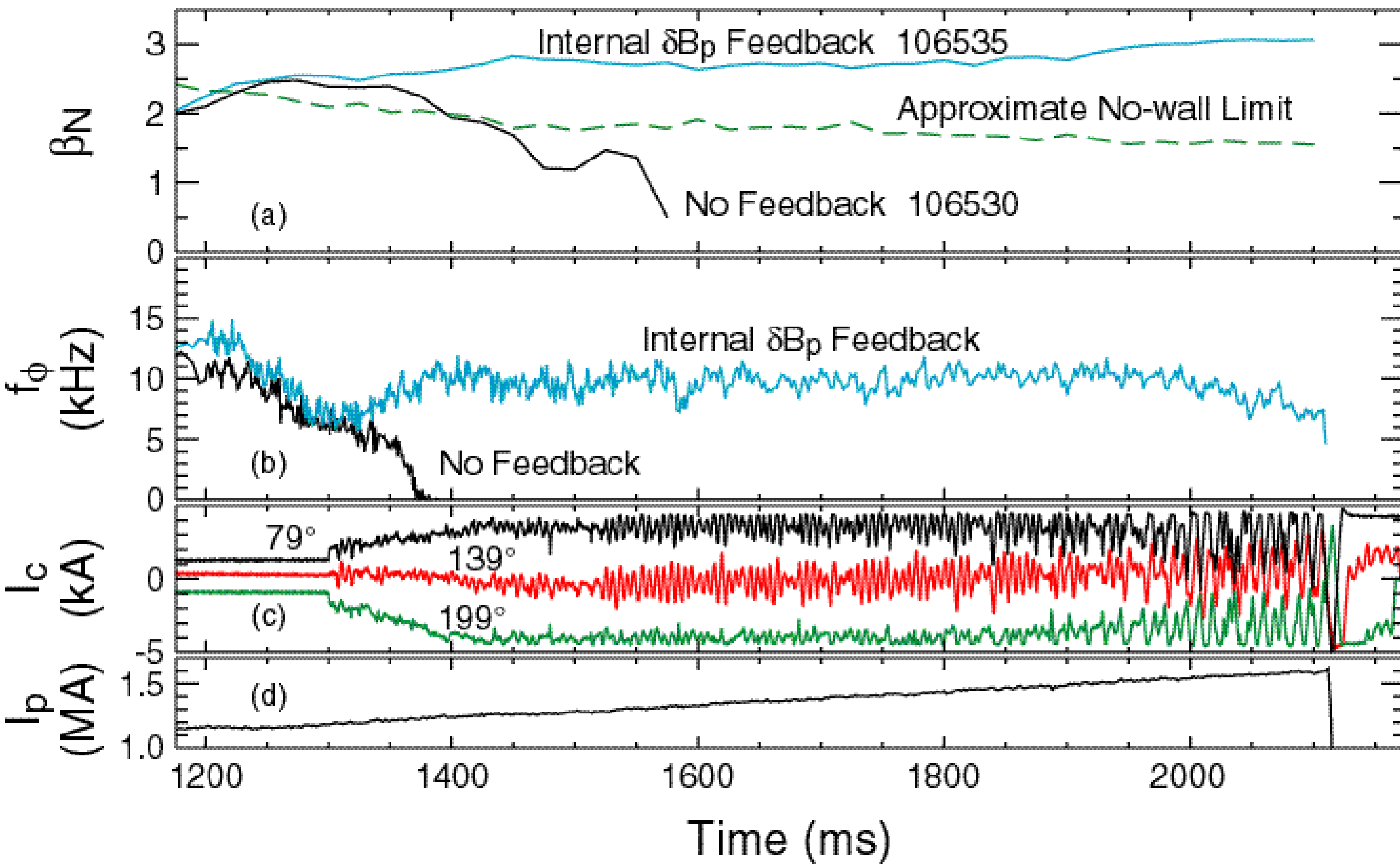
# INTERNAL SENSORS ENABLE IMPROVED ACTIVE CONTROL

- 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 $\delta B_r$ loops are more effective than external loops in controlling the RWM.
- Internal $\delta B_p$ probes with Explicit Mode Control feedback are far more effective than either internal or external $\delta B_r$ loops and Smart Shell feedback.



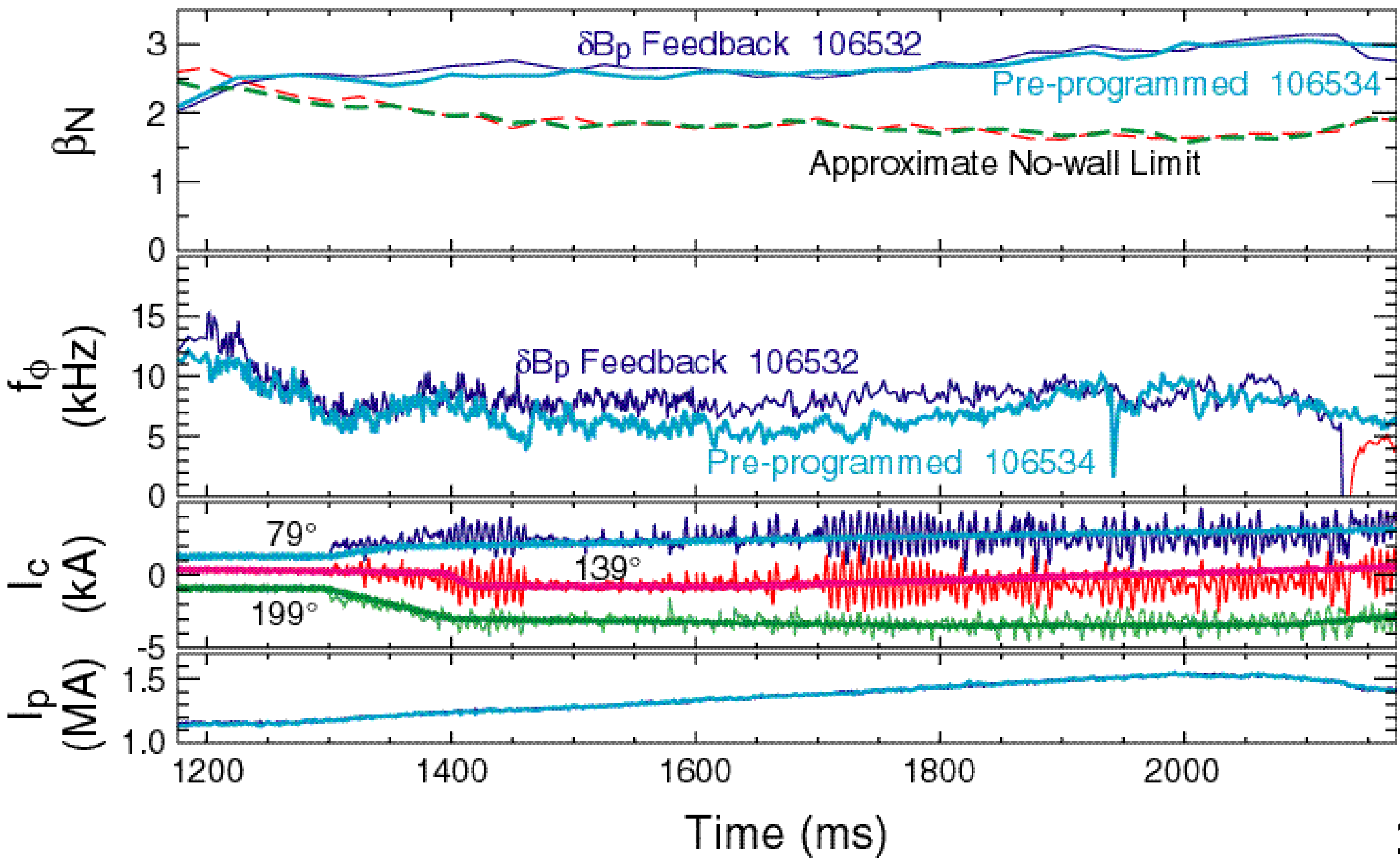
# $\delta B_p$ FEEDBACK GIVES LONG DURATION STABILIZATION

- In plasmas with slow $I_p$ ramp, $\delta B_p$ feedback gives stable operation for almost a second at $\beta_N$ approaching twice the no-wall stability limit.



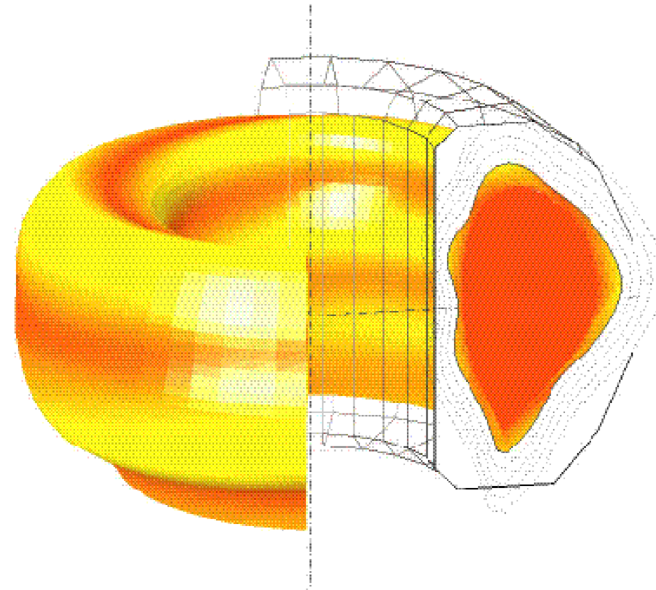
## PRE-PROGRAMMING CURRENTS GIVES SIMILAR $\beta_N$ AND $f_\phi$

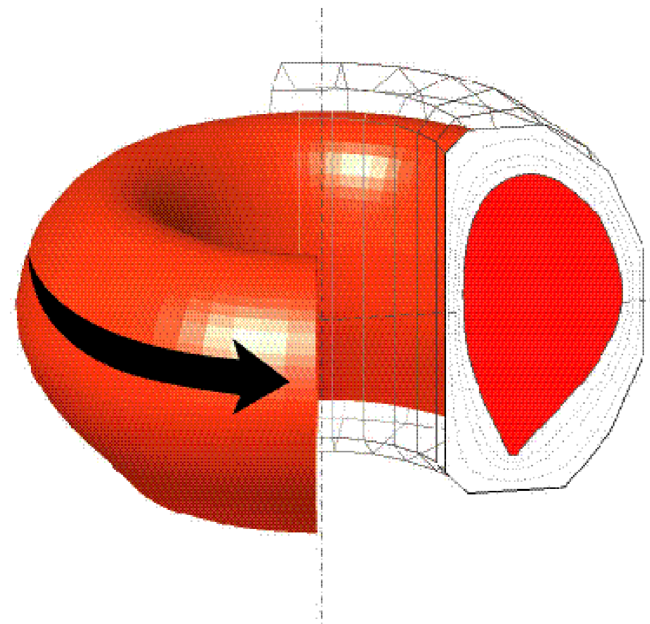
- In a slow Ip ramp case, pre-programming active coil currents to match $\delta B_p$ feedback currents gives similar $\beta_N$ and $f_\phi$.



# ERROR FIELD CORRECTION ALLOWS ROTATIONAL STABILIZATION

- 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 $\delta B_p$ feedback provides dynamic correction of magnetic error fields.
- When error fields are minimized, toroidal plasma rotation can be sustained by torque from neutral beams.
- Rapid toroidal rotation increases the effectiveness of the conductive wall in stabilizing Resistive Wall Modes.





## SUMMARY

- Extensive new arrays of internal magnetic sensors, together with external sensors and toroidally distributed soft x-ray cameras, have been used to confirm the previously observed and theoretically predicted global kink nature of resistive wall modes.
- Closed-loop feedback stabilization experiments using the internal sensors support predicted improvements in mode control with respect to previously reported results using external sensors.
- With active control, plasmas have been sustained for almost a second at pressures approaching twice the no-wall limit.
- Closed-loop $\delta B_p$ feedback has allowed access to regime where sustained toroidal rotation increases effectiveness of resistive wall in stabilizing Resistive Wall Modes.