STABILIZATION OF RESISTIVE WALL MODES BY PLASMA ROTATION

by

E.J. STRAIT

with

R.J. LA HAYE, J.T. SCOVILLE, A.D. TURNBULL, A.M. GAROFALO,* G.A. NAVRATIL,* E.D. FREDRICKSON,†
L.C. JOHNSON,† M. OKABAYSHI,† M. GRYAZNEVICH,‡ and E.A. LAZARUS∆

*Columbia University
†Princeton Plasma Physics Laboratory
‡UKAEA Fusion
∆Oak Ridge National Laboratory

Presented at
41st Annual Meeting of the Division of Plasma Physics
Seattle, Washington

November 15–19, 1999

DIII–D NATIONAL FUSION FACILITY SAN DIEGO · Columbia University · PPPL PRINCETON PLASMA PHYSICS LABORATORY · ornl · UKAEA Fusion · GENERAL ATOMICS

Abstract Submitted
for the DPP99 Meeting of
The American Physical Society

Sorting Category: 5.1.1.2 (Experimental)

Stabilization of Resistive Wall Modes by Plasma Rotation[1] E.J. STRAIT, R.J. LA HAYE, J.T. SCOVILLE, A.D. TURNBULL, General Atomics, A.M. GAROFALO, G.A. NAVRATIL, Columbia University, E.D. FREDRICKSON, L.C. JOHNSON, M. OKABAYASHI, Princeton Plasma Physics Laboratory, M. GRYAZNEVICH, UKAEA Fusion, E.A. LAZARUS, Oak Ridge National Laboratory — Slowly rotating resistive wall modes (RWMs) are often observed in DIII–D plasmas which exceed the ideal MHD beta limit calculated without a wall. Theory predicts that sufficiently large plasma rotation in the presence of a resistive wall should stabilize the RWM. Improved stability is found with the broader roation profile obtained by reducing the beam voltage at constant power. Recent counter-injection experiments should help determine which velocity is relevant for stabilization, by separating the diamagnetic and $E \times B$ contributions to the fluid rotation. Slowing of plasma rotation is often observed above the no-wall stability limit, and could be consistent with magnetic braking by field errors or small-amplitude RWMs. If the slowing cannot be avoided, active feedback stabilization will be required.

[1]Supported by U.S. DOE Contracts DE-AC03-99ER54463, DE-AC02-76CH03073, and DE-AC05-96OR22464, and Grant DE-FG02-89ER53297.

☐ Prefer Oral Session
☒ Prefer Poster Session

E.J. Strait
strait@fusion.gat.com
General Atomics

Special instructions: DIII-D Poster Session 1, immediately following CL Hsieh

Date printed: July 16, 1999

Electronic form version 1.4

CAN THE RESISTIVE WALL MODE BE STABILIZED BY PLASMA ROTATION?

- Beta greater than the ideal MHD no-wall limit has been sustalned for durations >> τ_W (resistive wall time)

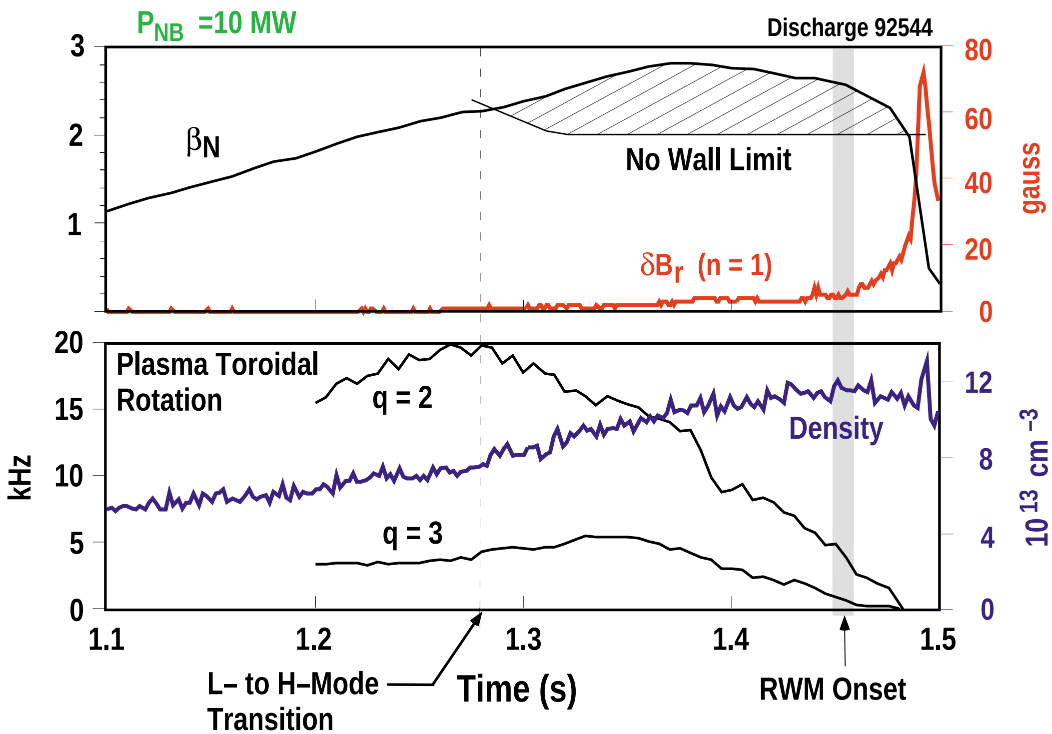
- However, a gradual slowing of rotation prevents $\beta > \beta^{no\text{-}wall}$ for long pulses

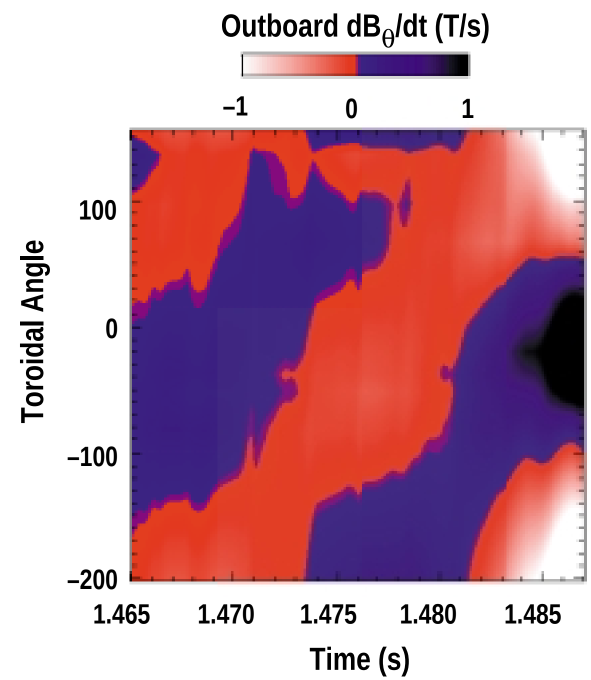
  – Typical deceleration rate $\frac{1}{\Omega}\frac{d\Omega}{dt} \sim (100\ \text{ms})^{-1}$

- Is rotational slowing an unavoidable consequence of operation above the no-wall limit?

PLASMA STABILIZED BY ROTATION AND RESISTIVE WALL ABOVE NO-WALL β_N-LIMIT FOR ~200 ms

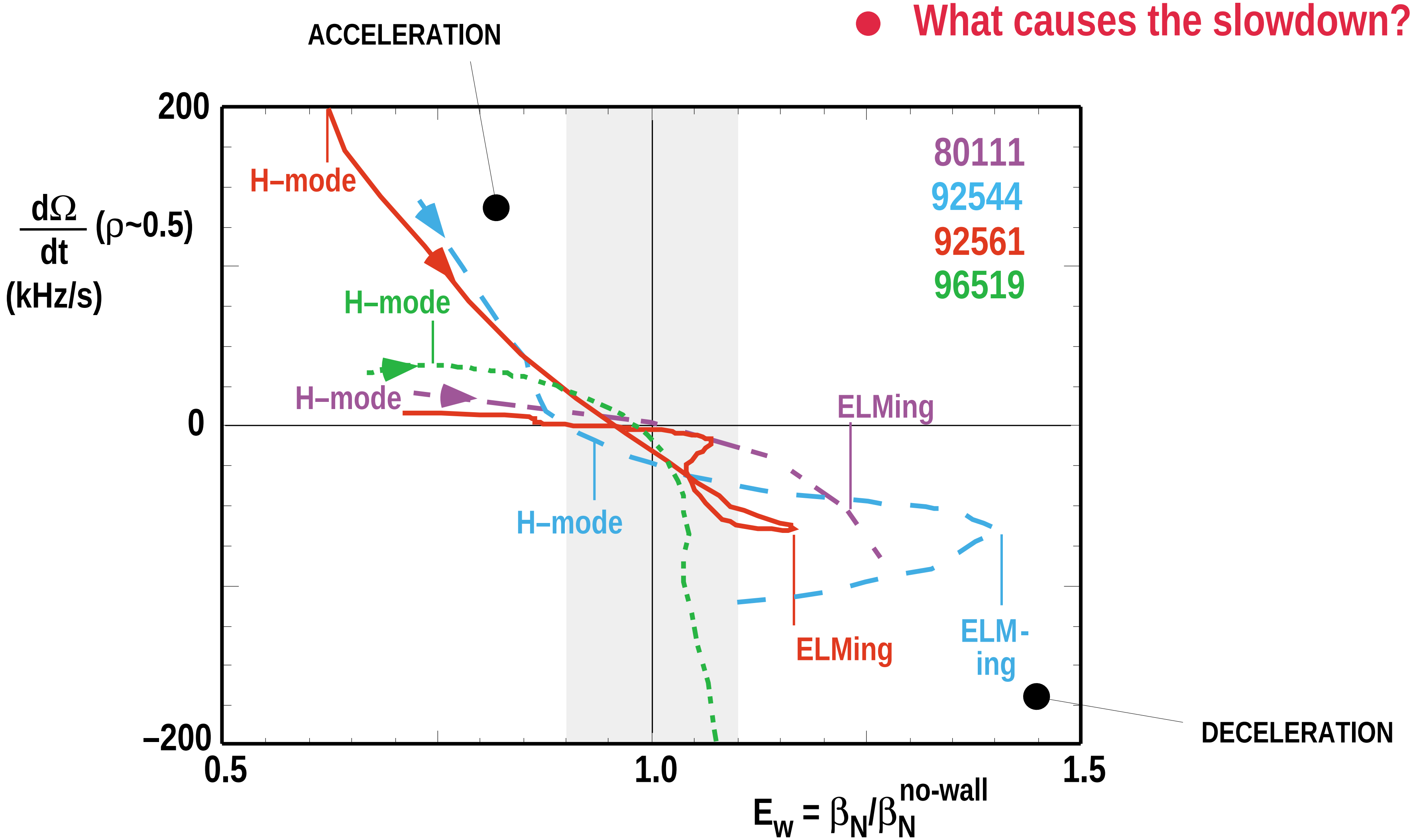
- Wall-stabilized duration is much longer than wall time ($\tau_W \lesssim 6$ ms)
- Plasma rotation slows continuously when β exceeds the no-wall limit
- Slowly rotating n = 1 mode starts to grow after toroidal rotation of q = 3 surface has decreased below 1–2 kHz





PLASMA ROTATION SLOWS AS β_N EXCEEDS NO WALL LIMIT

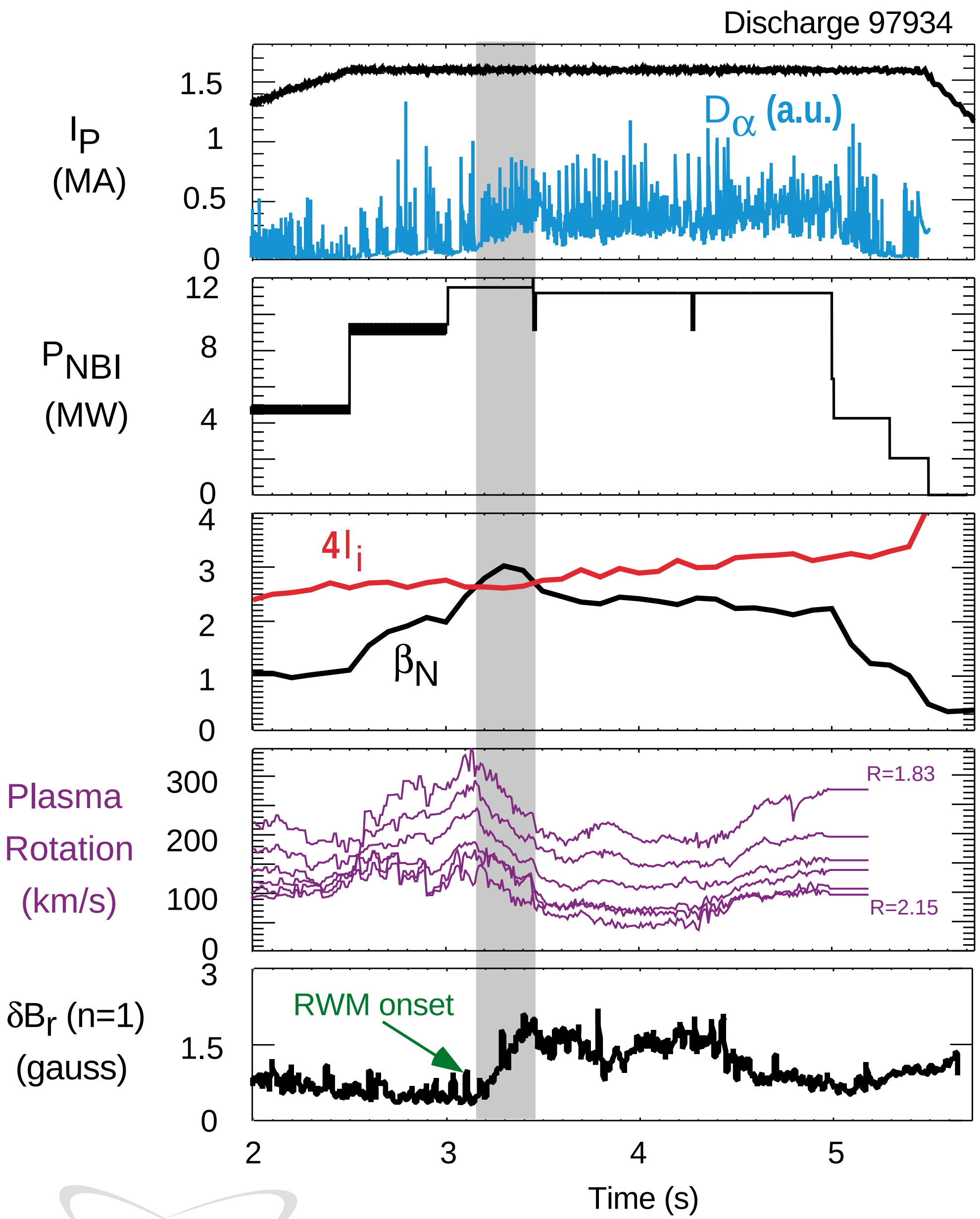
- What causes the slowdown?



DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

Columbia University

ONSET OF SMALL AMPLITUDE RWM CORRELATES WITH ROTATION SLOWDOWN IN AT MODES

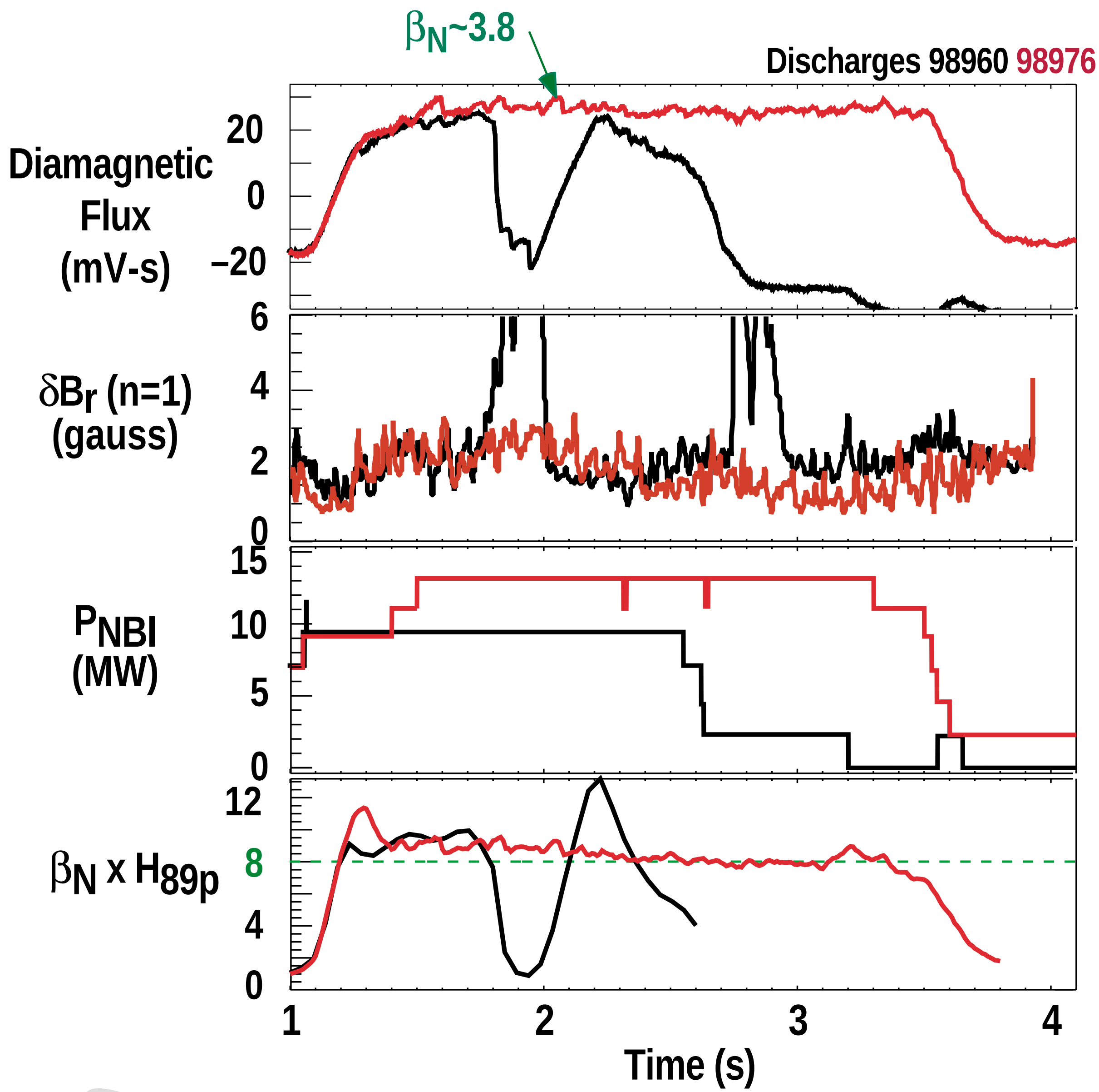


- High q_{min} (~2), low l_i, DND discharges with q_{95}~4.5
- Rotation collapse and confinement degradation begin at mode onset
- Ideal MHD code GATO indicates that the n=1 kink mode is marginally unstable without a wall at 3.2 s ($\beta_N = 4 l_i$)
- Mode grows very slowly (« $1/\tau_w$) and rotates slowly, amid fast plasma rotation (≥ 4 kHz)

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

Columbia University

RWMs LIMIT PERFORMANCE OF AT PLASMAS



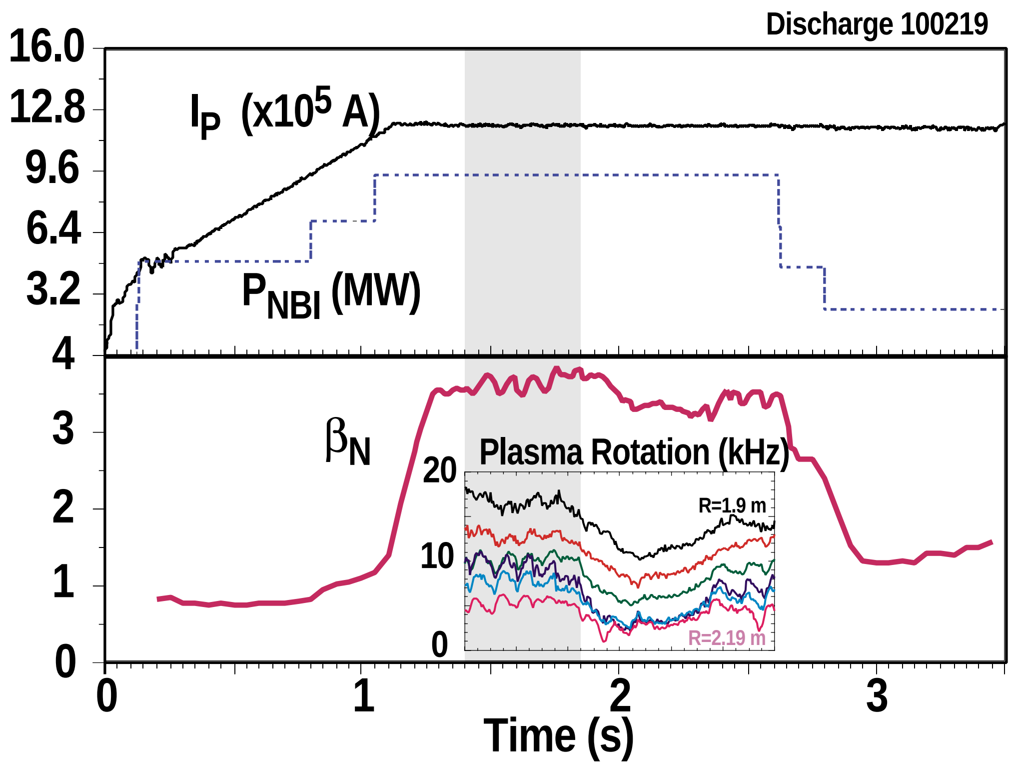
- I_p = 1.2 MA, B_T = 1.6 T
  q_{min} ~ 1.7, q_{95} ~ 5.5
- β_N limited to about 4 l_i (no wall limit) by bursting RWMs
- Higher NBI power improves stability and duration
- 75 % current non-inductive
  >50% bootstrap

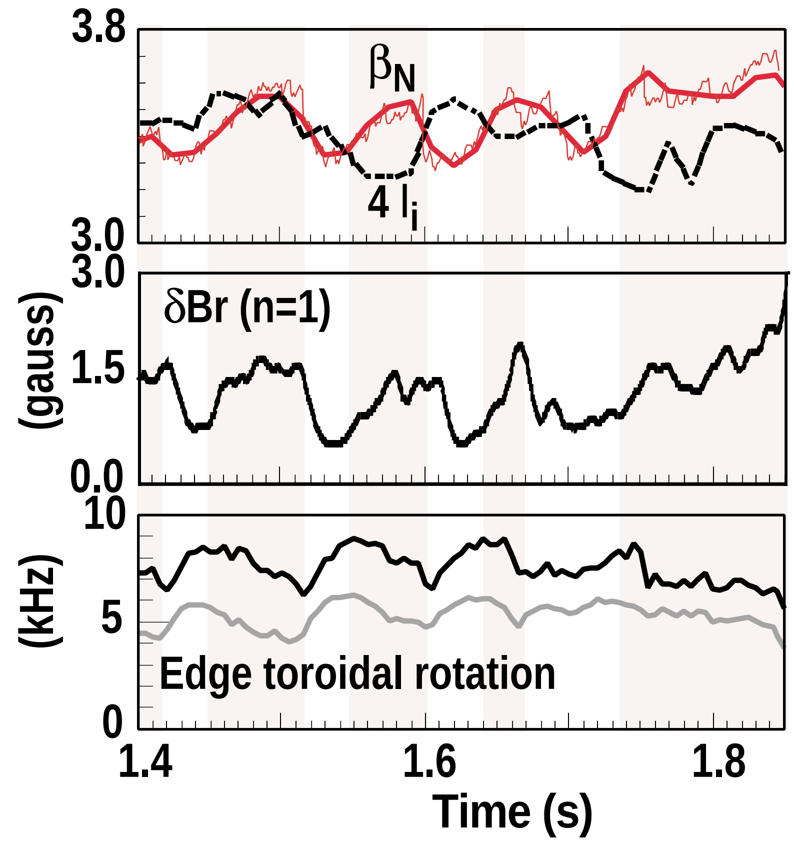
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

333–99

Columbia University

RWM BURSTS SELF-STABILIZE THROUGH SMALL BETA COLLAPSES





- Plasma rotation slows during β_N "peaks", recovers in β_N"valleys"

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

333–99

Columbia University

PLASMA ROTATION INSUFFICIENT FOR COMPLETE RWM SUPPRESSION

- In conditions of improved detection, small amplitude, slowly growing (often $\gamma << 1/\tau_W$) RWMs can usually be observed when β_N > no wall limit

Working hypothesis

☞ The plasma rotation does not completely suppress the RWM, but slows the growth rate.

The electromagnetic torque from the RWM reduces the plasma rotation.

— The confinement degradation due to small amplitude RWMs (e.g. through tearing or reduced E×B shear) can decrease β_N < no wall limit, leading to beta saturation or rollover

— If the plasma rotation decreases below a critical value while β_N > no wall limit, the mode growth transitions to a $1/\tau_W$ rate, usually leading to a minor disruption

WHY DOES PLASMA ROTATION DECREASE?

- Slowing of plasma rotation is observed when β exceeds $\beta_{crit}^{no-wall}$

- Possible causes for the slowing include electromagnetic drag from

  - A small-amplitude RWM
    (slowing is consistent with δB ~ a few Gauss at the wall)

  - A small island driven by coupling to the ideal MHD instability
    (the wall has reduced the growth rate to a resistive time scale)

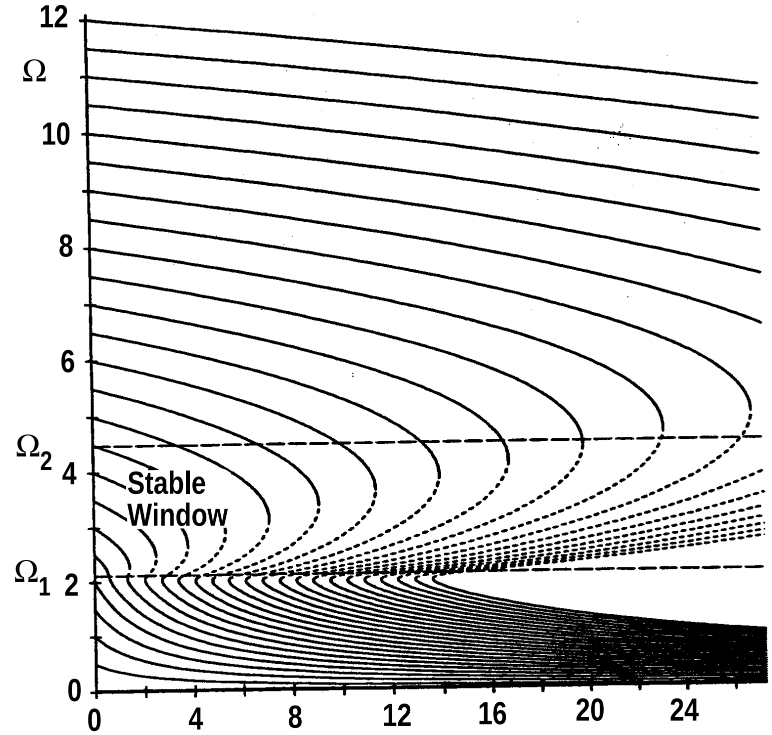
- Other MHD activity and increasing density have been eliminated as likely causes of the rotational slowing

MODELS FOR RWM STABILITY IN A RESISTIVE PLASMA

- **Cylindrical model with external ideal instability and internal resonant surface [J.M. Finn, Phys. Plasmas 2, 3782 (1995)]**
  - **Coupling of ideal mode to a small island allows rotational stabilization**
  - **Applicable to toroidal plasma where external kink always couples to internal resonances**
- **Extended to non-linear model with plasma rotation frequency determined self-consistently from torque balance [C. Gimblett and R.J. Hastie, Phys. Plasmas (to be published)]**

NONLINEAR MODEL ALLOWS SUDDEN CHANGES IN PLASMA ROTATION FREQUENCY AND MODE GROWTH RATES

- Plasma rotation Ω from torque balance is multivalued (depends on mode rotation)
- Growth rate is small ($\gamma << \tau_W^{-1}$) on the upper branch. Rotation slowly decreases as mode amplitude increases
- At the upper knee (if outside the stable window) torque balance is lost, and the rotation frequency drops to the lower branch
- Growth rate is much larger ($\gamma \sim \tau_W^{-1}$) on the lower branch
- Similar to "forbidden" frequency bands for tearing modes [D. Gates and T. Hender, Nucl. Fusion 36, 273 (1996)]

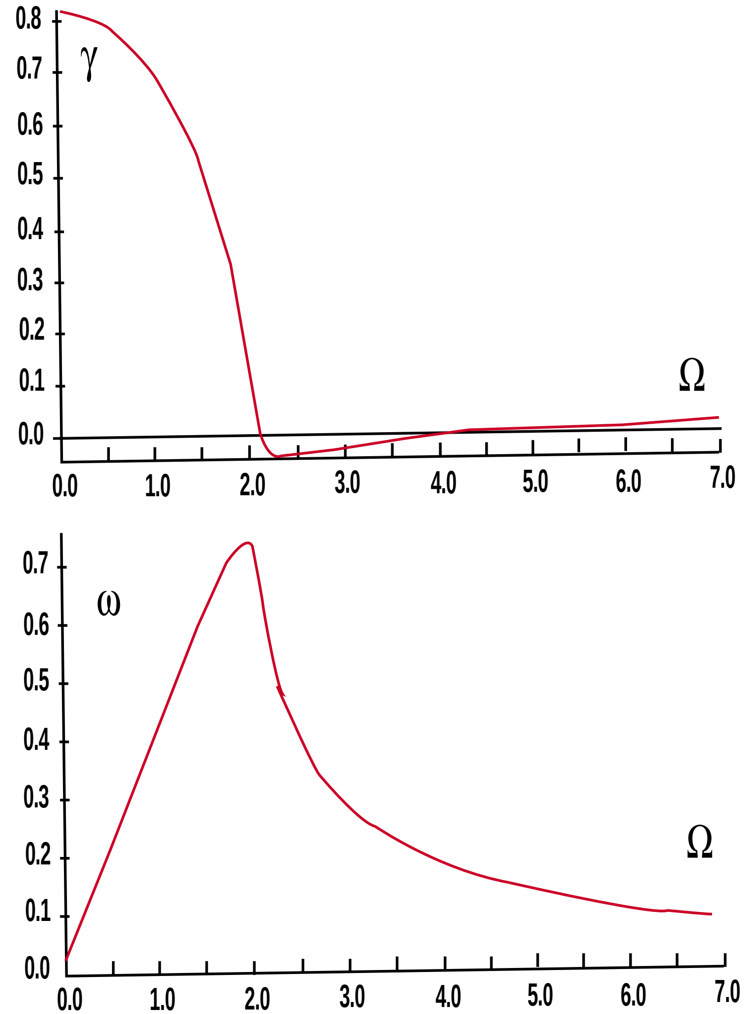


$C = \frac{\text{electromagnetic torque}}{\text{viscous torque}} \propto \delta B^2$ at first wall

(Gimblett and Hastie, Phys. Plasmas, to be published)

ROTATION CAN LEAD TO STABILITY OR SMALL GROWTH RATES WITHOUT COMPLETE STABILIZATION

- WIndow for complete stability in β and r_W/a is small, requires
  - No-wall ideal mode weakly unstable
  - Ideal-wall resistive mode weakly stable
  - Modest plasma rotation $\Omega \gtrsim \tau_W^{-1}$ (unstable for $\Omega\tau_W >> 1$)
- Larger stability window is possible in presence of a saturated island
- Outside the stability window (or if no window exists) growth rate can be very small
  - $\gamma << \tau_W^{-1}$ (1–2 orders of magnitude)
  - Difficult to distinguish from saturated island



[Gimblett and Hastie, Phys. Plasmas (to be published)]

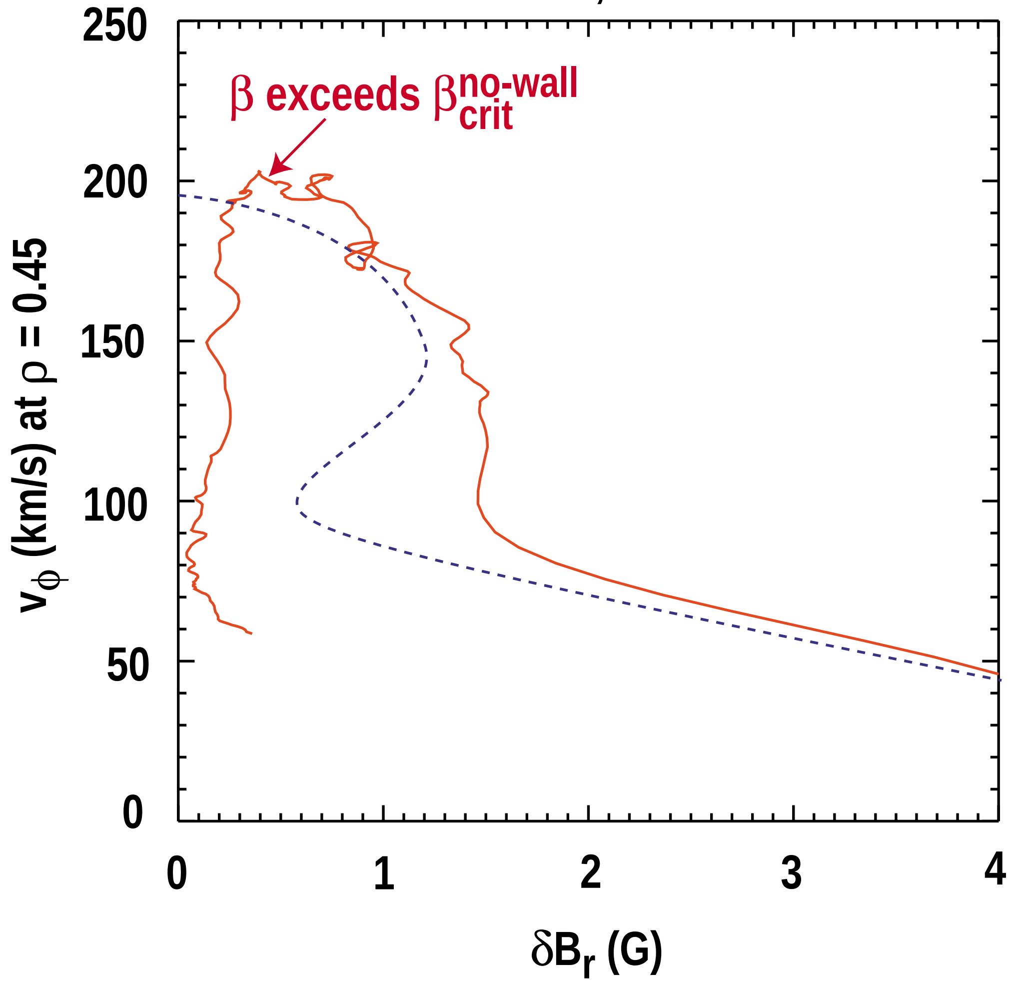
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

333–99

MODEL IS QUALITATIVELY CONSISTENT WITH TRAJECTORY OF DIII–D WALL-STABILIZED DISCHARGES

- Evolution at high beta has three phases:
  - Slow mode growth with constant or slowly decreasing plasma rotation
  - More rapid deceleration of rotation as slow mode growth continues
  - Rapid mode growth



MODEL QUALITATIVELY PREDICTS RESULTS OF VARYING THE TORQUE BALANCE

- Neutral beam torque increased ~20% by reducing voltage 75 $\Rightarrow$ 50 keV (at constant power)
- Greater torque $\Rightarrow$ faster initial rotation

Figures coming

- Rotation profiles ~ identical at transition to faster mode growth (greater torque $\Rightarrow$ longer survival before transition)

Figures coming

- Mode amplitude at onset is a little larger in the case with greater torque

Figures coming

CONCLUSIONS

- **Resistive MHD model predicts several qualitative features of experiments**
  - Very slow initial growth of mode, $\gamma << \tau_W^{-1}$
  - Gradual slowing of rotation, consistent with torque from a very small magnetic perturbation $\left(\lesssim 1 \text{ G at wall} \right)$
  - Sudden decrease in rotation, at a critical rotation frequency and mode amplitude
  - Increase in mode growth rate to $\gamma \sim \tau_W^{-1}$ at the lower rotation frequency
- **If this model applies, active feedback control may be required for sustained operation above the no-wall limit**
- **More quantitative modeling and comparison to experiment is needed**
  - Stability and torque balance in toroidal geometry
  - Existence of islands coupled to ideal-plasma RWM