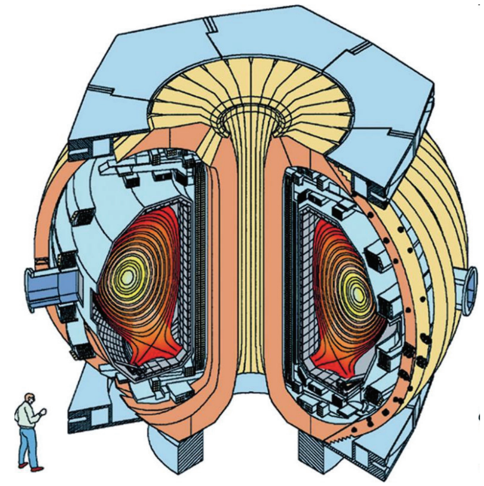
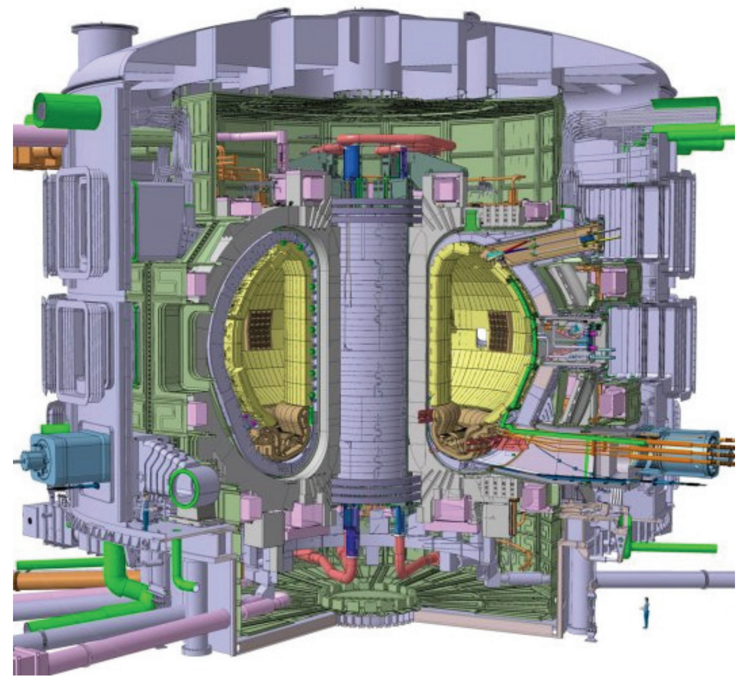
# ITER Test Blanket Module Error Field Simulation Experiments at DIII–D

by
M.J. Schaffer



Presented at
the Twenty-Third IAEA
Fusion Energy Conference
Daejeon, Republic of Korea



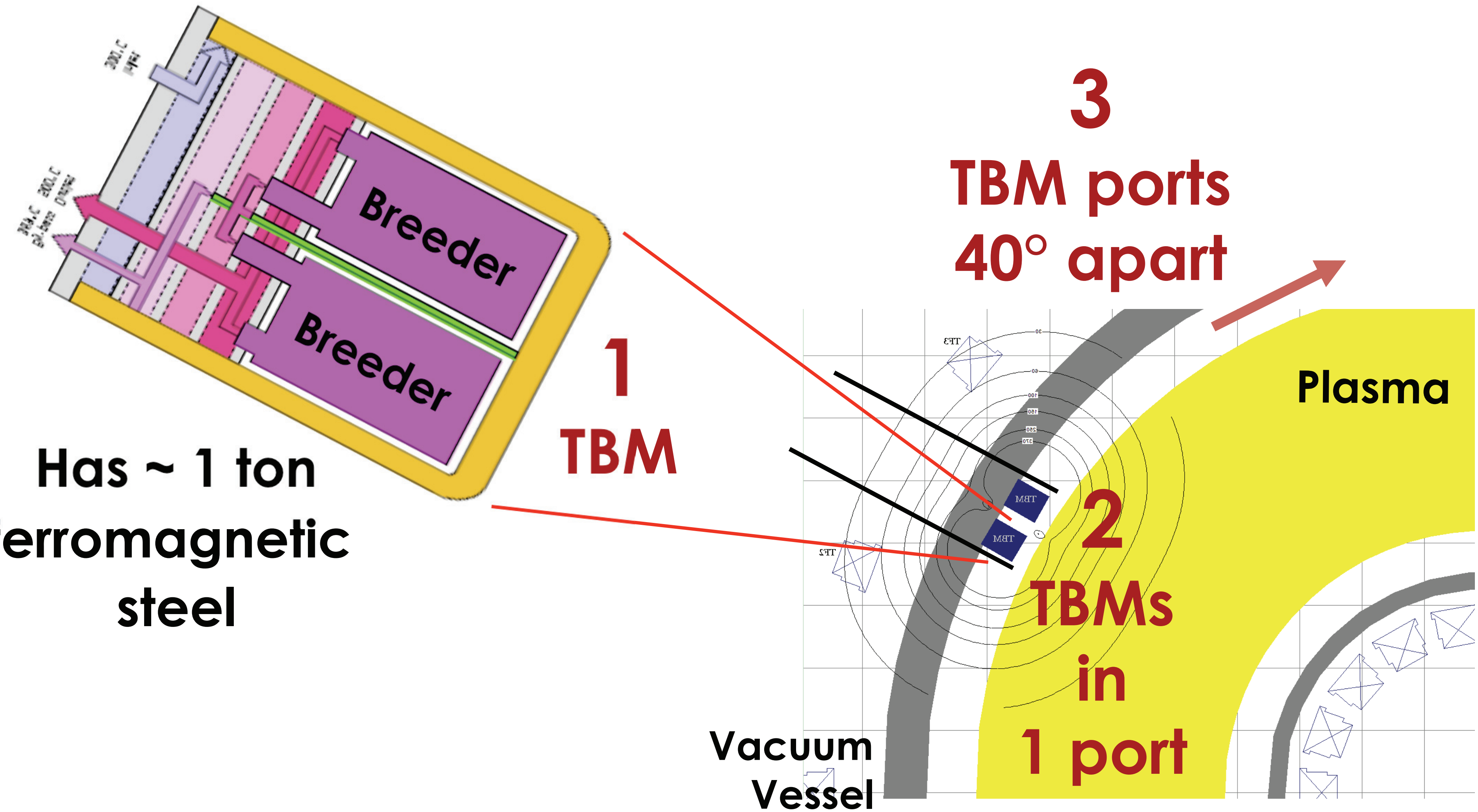
October 11-16, 2010

# A Large International Team Participated

M.J. Schaffer[1], J.A. Snipes[2], P. Gohil[1], P. de Vries[3], T.E. Evans[1], M.E. Fenstermacher[4], X. Gao[5], A.M. Garofalo[1], D.A. Gates[6], C.M. Greenfield[1], W.W. Heidbrink[7], G.J. Kramer[6], R.J. La Haye[1], S. Liu[5], A. Loarte[2], M. F. F. Nave[8], T.H. Osborne[1], N. Oyama[9], J-K. Park[6], N. Ramasubramanian[10], H. Reimerdes[11], G. Saibene[12], A. Salmi[13], K. Shinohara[9], D.A. Spong[14], W.M. Solomon[6], T. Tala[15], J.A. Boedo[16], V. Chuyanov[2], E.J. Doyle[17], M. Jakubowski[18], H. Jhang1[19], R.M. Nazikian[6], V.D. Pustovitov[20], O. Schmitz[21], R. Srinivasan[10], T.S. Taylor[1], M.R. Wade[1], K.-I. You[19], L. Zeng[17], and the DIII-D Team[1]

[1]General Atomics, San Diego, USA, [2]ITER Organization, Cadarache, France, [3]Assoc. EURATOM-FOM, Nieuwegein, Netherlands, [4]Lawrence Livermore National Laboratory, Livermore, USA, [5]ASIPP, Hefei, China, [6]Princeton Plasma Physics Laboratory, Princeton, USA, [7]Univ. of California, Irvine, USA, [8]Assoc. EURATOM-IST, Lisbon, Portugal, [9]JAEA, Naka, Japan, [10]IPR, Gandhinagar, India, [11]Columbia University, New York, USA, [12]Fusion for Energy, Barcelona, Spain, [13]Assoc. EURATOM-Tekes, Aalto Univ., Finland, [14]Oak Ridge National Laboratory, Oak Ridge, USA, [15]Assoc. EURATOM-Tekes, VTT, Finland, [16]Univ. of California, San Diego, USA, [17]Univ. of California, Los Angeles, USA, [18]Max Planck Institute for Plasma Physics, Greifswald, Germany, [19]NFRI, Daejeon, Korea, [20]Kurchatov Institute, Moscow, Russian Federation, [21]FZ Juelich, Juelich, Germany

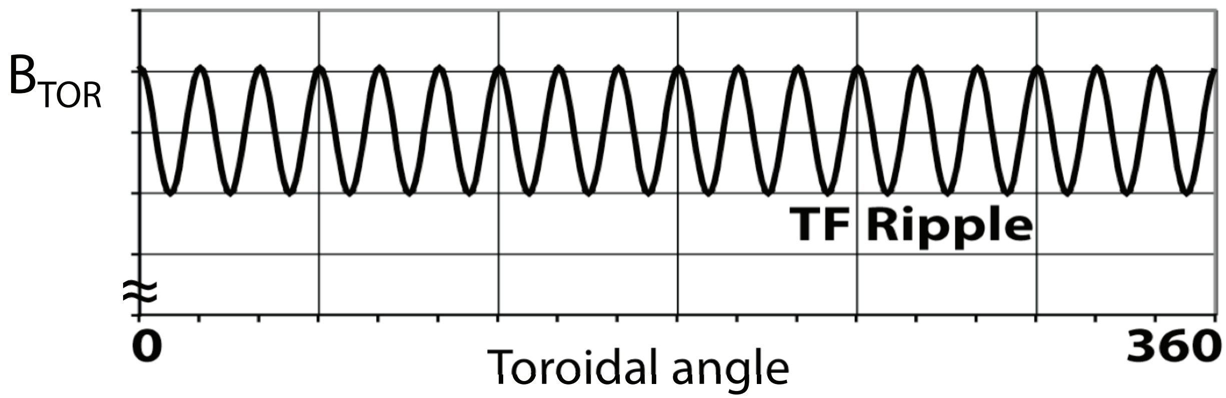
# Concern Raised About the Impact of Ferromagnetic Test Blanket Modules (TBMs) on ITER Performance




Has ~ 1 ton ferromagnetic steel

# It Is Well-Known That Toroidal Field Ripple Has Undesirable Effects on Plasmas

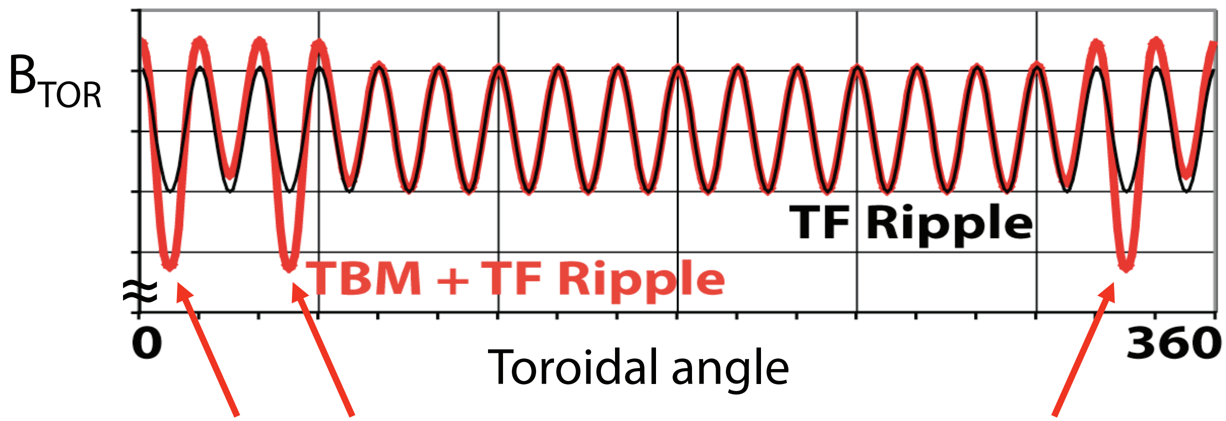
- **Common magnetic field ripples made by toroidal field coils are uniformly periodic**




- **DIII-D matched ITER TF coil ripples for most of the TBM experiments**
  – 0.35 ~ 0.4% ripple for both

# TBMs Complicate Ripple Geometry

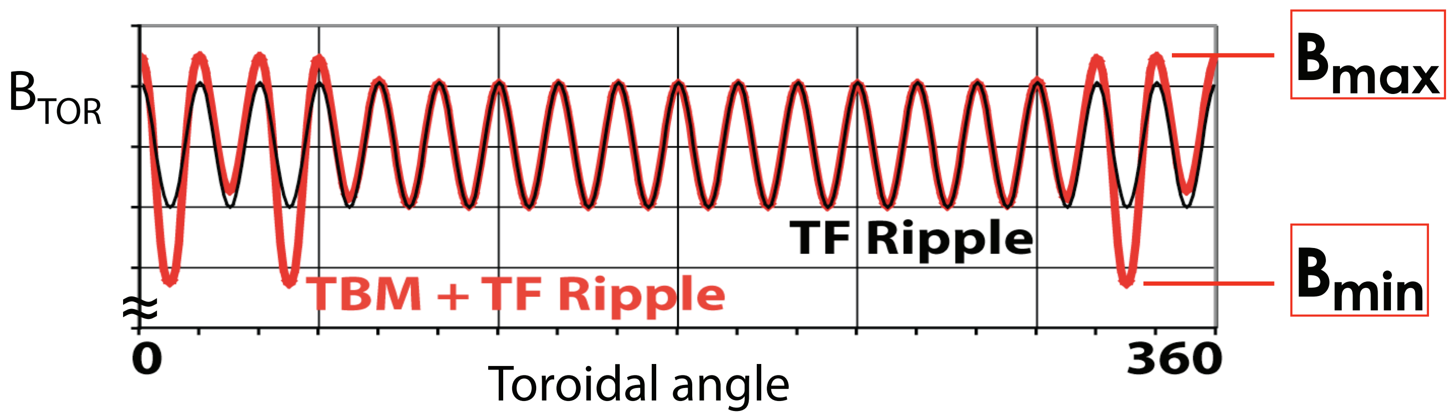
- **Larger perturbations**
- **Broken periodicity**




- **Magnetized TBM steel makes 3 local "dips"**
- **Cannot predict consequences, NEED EXPERIMENTS**

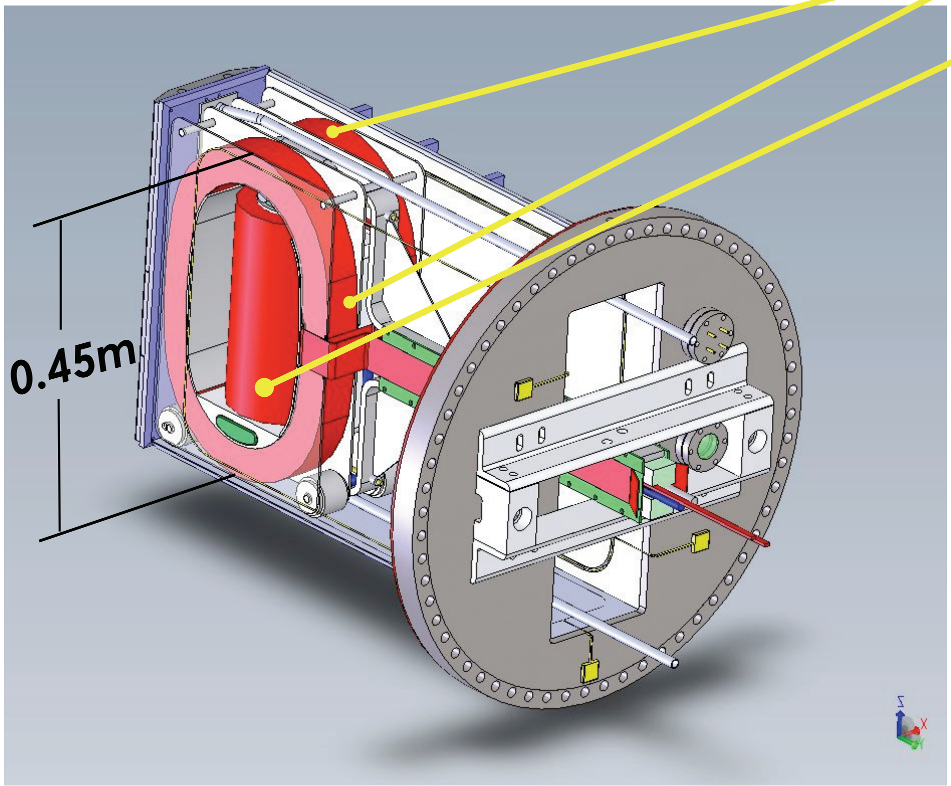
# Use the Combined "Local Ripple" δ

$$\delta = \frac{B_{max} - B_{min}}{B_{max} + B_{min}}$$



# We Designed a Mock-up of the TBM Field to Measure Its Effects on DIII-D Plasmas for ITER

## Mock-up Approximates the Magnetization at One ITER Port




Racetrack coils ~ $M_{TOR}$ TBM

Vertical solenoid ~ $M_{POL}$ TBM

- **Matches ITER TBM field well**
- **Moveable, ΔR = 0.28 m**
  - 1.0 m in ITER
- **Up to ~3 x ITER local ripple**
  - To match **surface-average amplitude** of **3 ITER** TBM ports

# Experimental Results Showed that Most TBM Effects Were Small, and the Remainder May Be Correctable

**Nil or Small Effects on**

- Plasma Startup
- L-mode Confinement
- L-to-H Transition
- ELM Characteristics
- ELM Control by RMP
- Global Fast Ion Loss
- Divertor Power

**Of Concern* if Scaling is Unfavorable**

- Braking of plasma rotation
- Reduction of H-mode confinement

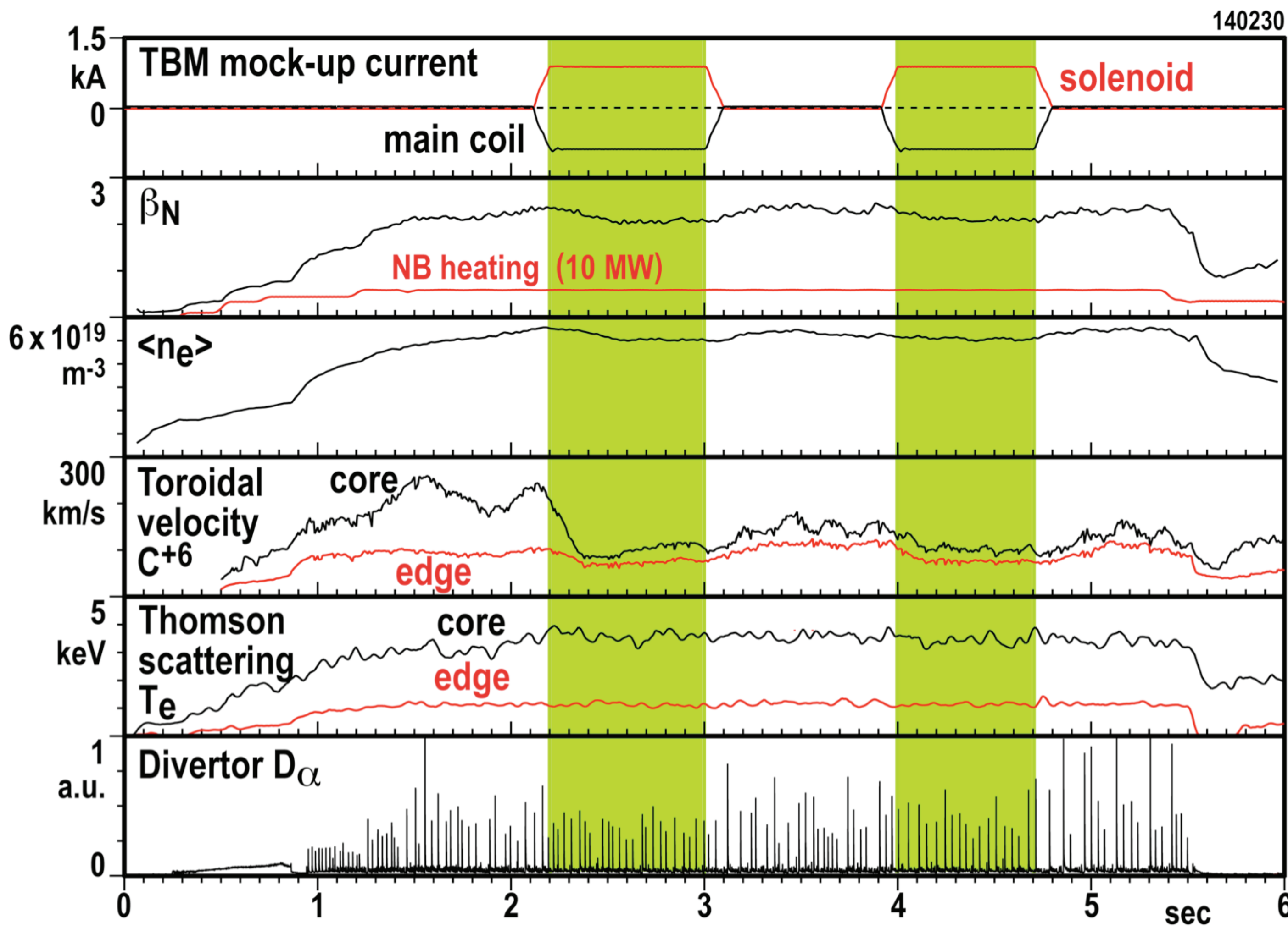
(both at high ß)

* to ITER High-Gain Mission

**May Be Correctable**

- n=1 error compensation eliminated TBM contribution to *locking* in *L-mode* experiments
- Numerical model predicts n=1 compensation will reduce *braking* in *H-mode* plasma

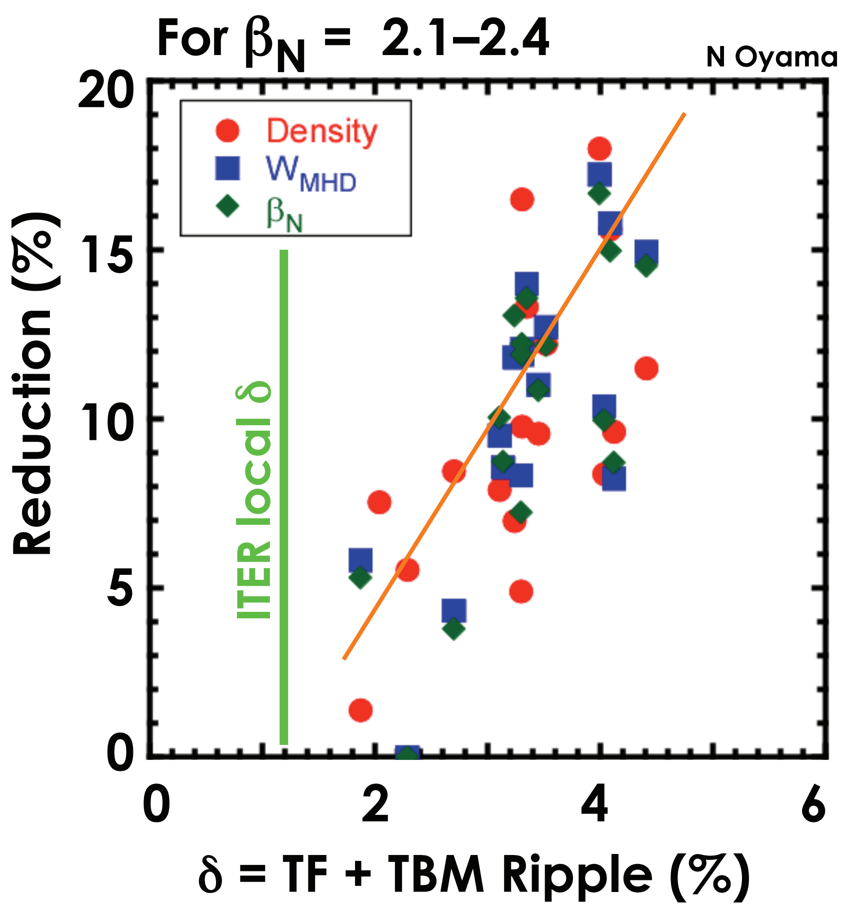
# Greatest TBM Effect Was Toroidal Velocity Reduction – $\beta$, $n_e$, $T_e$ Were Less Affected

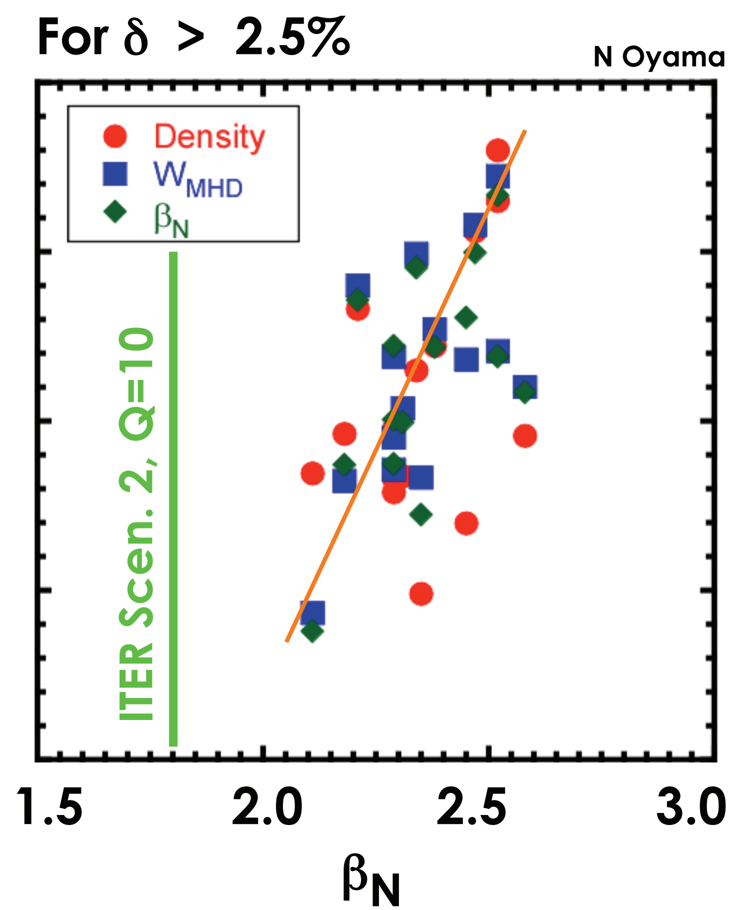



- Making local ripple $\delta$ = 3%
- Moderate reductions
- Large velocity reduction
- No effect on $T_e$

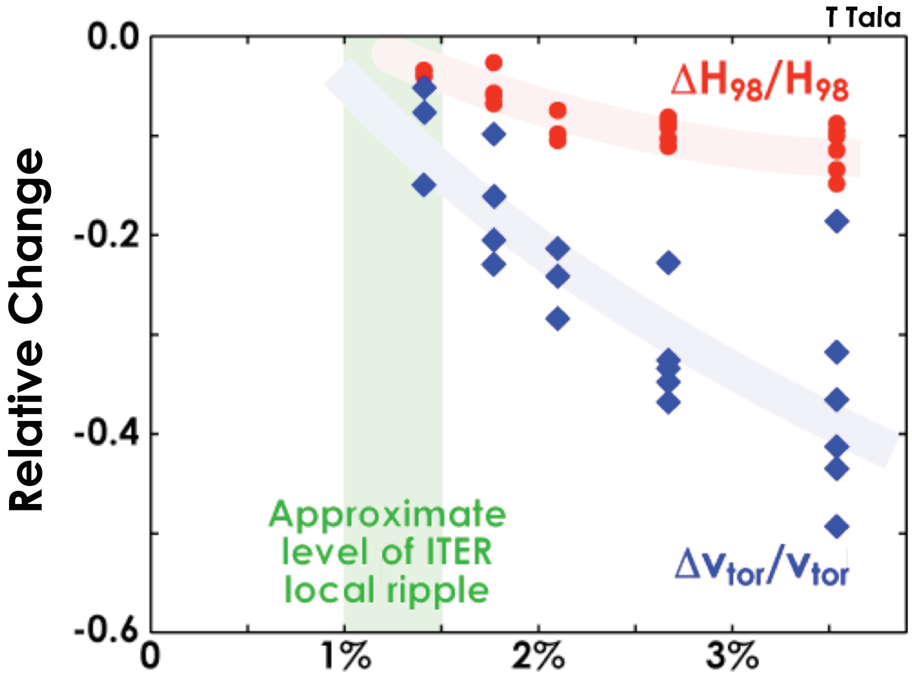
# TBM Effects Were Small at ITER Baseline Parameters. – We Did Systematic Scans at Higher Ripple and β.

$R_{midout}$ = 2.30 m    $q_{95}$ = 3.5    $B_T$ = 1.7 T    $I_p$ = 1.4 MA

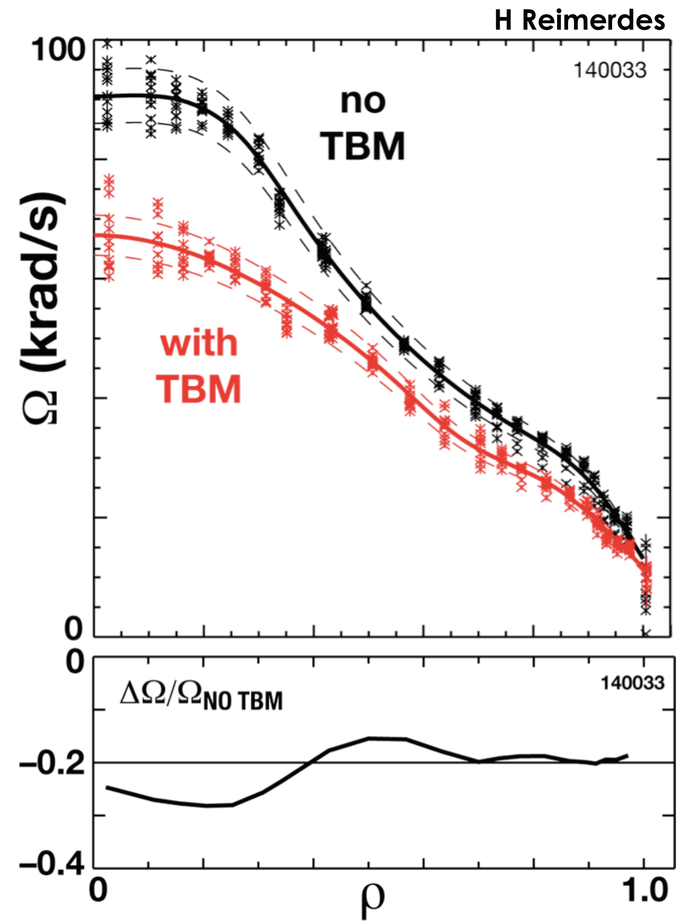


# The TBM Field Reduced Toroidal Velocity Much More Than H-mode Confinement

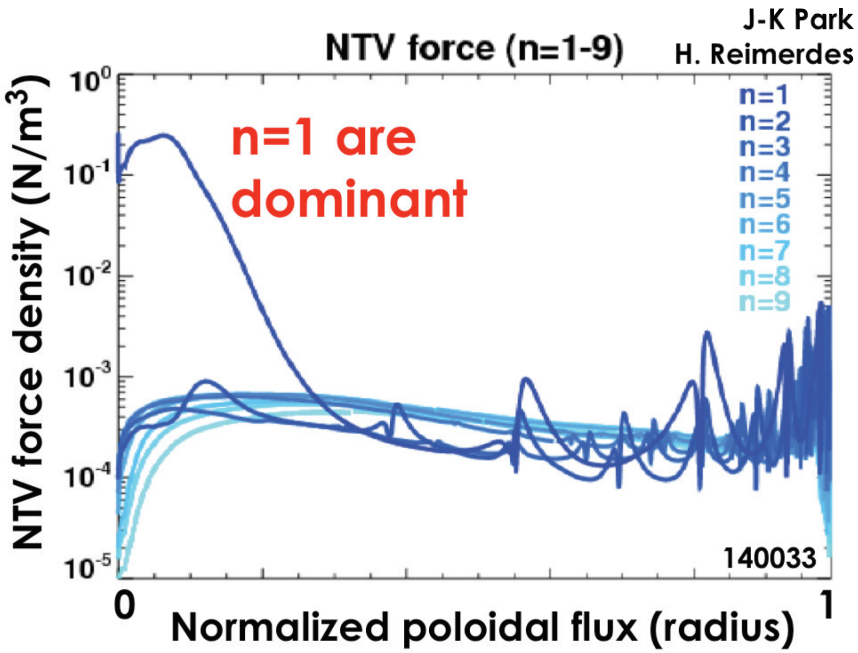


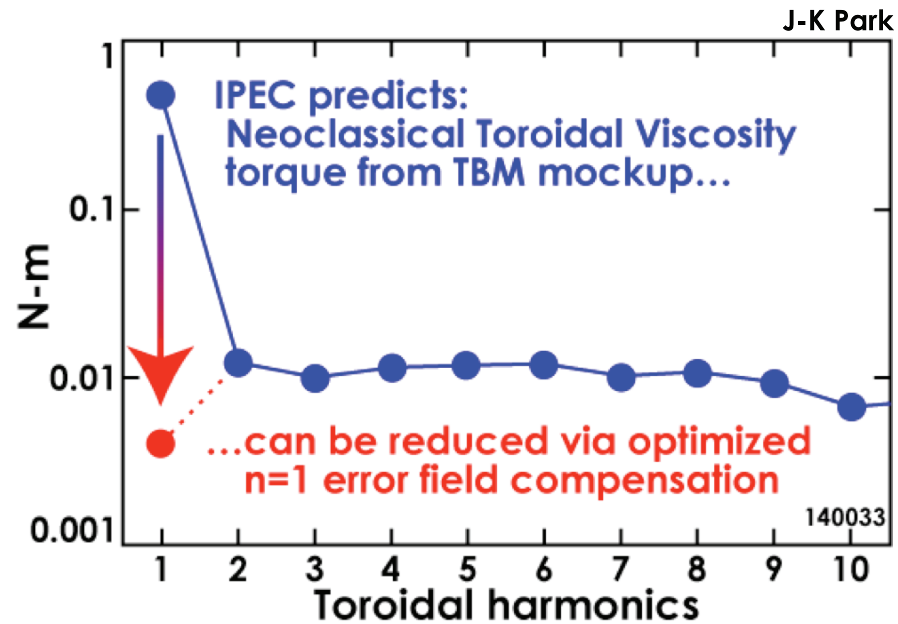

Relative
velocity change
was ~ 3 times the
confinement change




$\Delta\Omega/\Omega \approx$ constant
across plasma radius

# The Ideal Perturbed Equilibrium Code (IPEC) Implicates n=1 Harmonics in Toroidal Rotation Braking

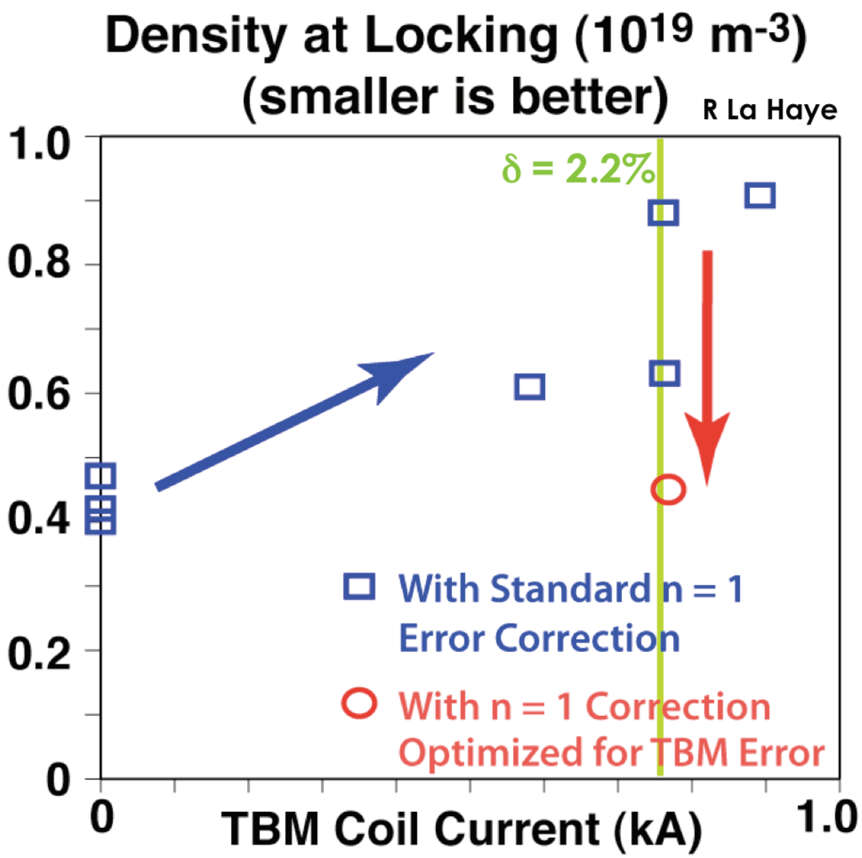



- **Mock-up Neoclassical Toroidal Viscous braking is mostly from n=1 harmonics in central core**
  - n=1 is **amplified** by H-mode

- **A great opportunity…**
- **One expects higher plasma speed and restored confinement**

# n=1 Error Compensation Was Optimized for TBM, and It Restored Locked Mode Tolerance at low ß




Standardized Ohmic Low-Density Locking Test Plasmas

- TBM field raised the low-density threshold for locked mode avoidance
- n=1 compensation restored locked mode tolerance in *low-ß* test
- IPEC analysis and experiment ≈ agree
- Will n=1 compensation also restore H-mode confinement at *high-ß*?

# How to Scale from 1Port in DIII-D to 3 Ports in ITER?

- **If TBM effects vary linearly with ripple mirror ratios, and they also sum linearly, then equivalence is $\delta_{DIII\text{-}D} = 3\ \delta_{ITER}$**
  - for case of 1 DIII-D vs. 3 ITER ports

- **If TBM effects $\propto \delta^{\alpha}$ and $\alpha > 1$, then $(\delta_{DIII\text{-}D})^{\alpha} = (3\ \delta_{ITER})^{\alpha}$ makes TBM effects $9\ (\delta_{ITER})^{\alpha}$ in DIII-D vs. $3\ (\delta_{ITER})^{\alpha}$ in ITER**
  - $\alpha \approx 2$ for DIII-D density reduction data (V Chuyanov)
  - DIII-D TBM experiments may be more pessimistic than ITER reality

- **A different view: ITER rotation may be too small for the TBM error to be important**

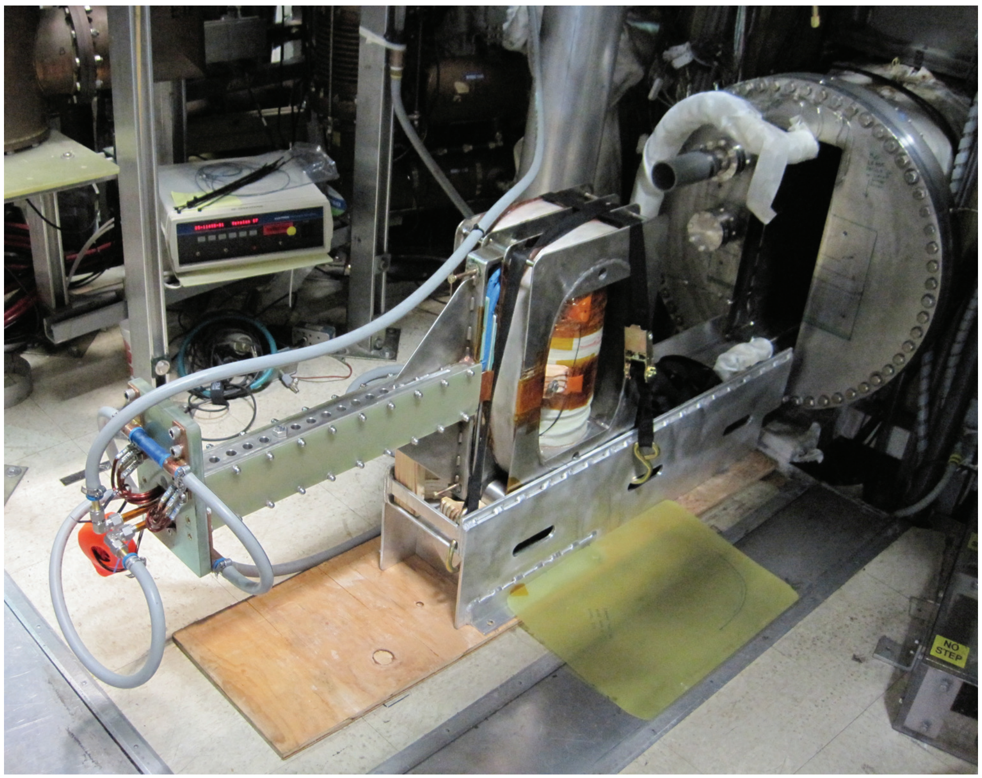
# Summary

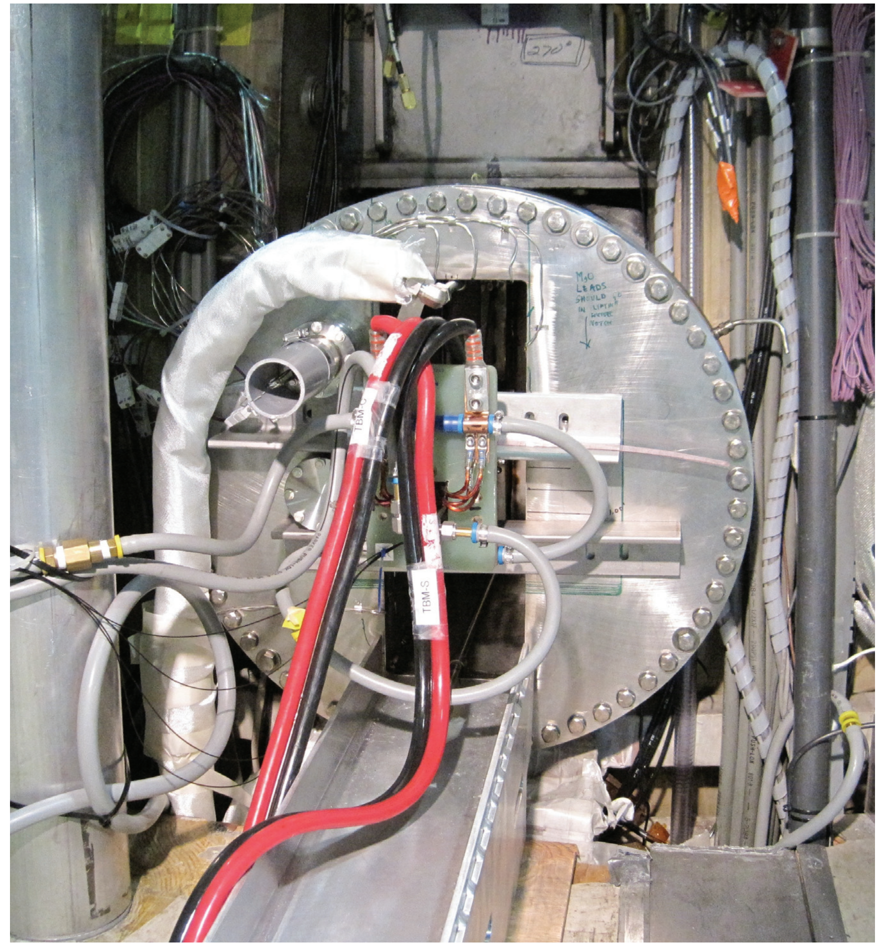
- **DIII-D experiments did not reveal any reason why a TBM-like error field would seriously limit ITER plasma performance objectives**
- **IPEC numerical analysis indicates that NTV braking is dominated by plasma-amplified n=1 TBM error field**
  - IPEC predicts rotation recovery by n=1 compensation
- **A DIII-D experiment demonstrated n=1 compensation of the TBM contribution to locking in OH plasmas**
- **DIII-D plans experiments in 2011 to test if n=1 re-compensation can obviate rotation and confinement degradations in high-ß H-mode plasmas**

# Backup Slides

# TBM Mock-up at its DIII-D Port

**Mock-up secured in its channel with cooling water attached**




**Mock-up rolled into port**

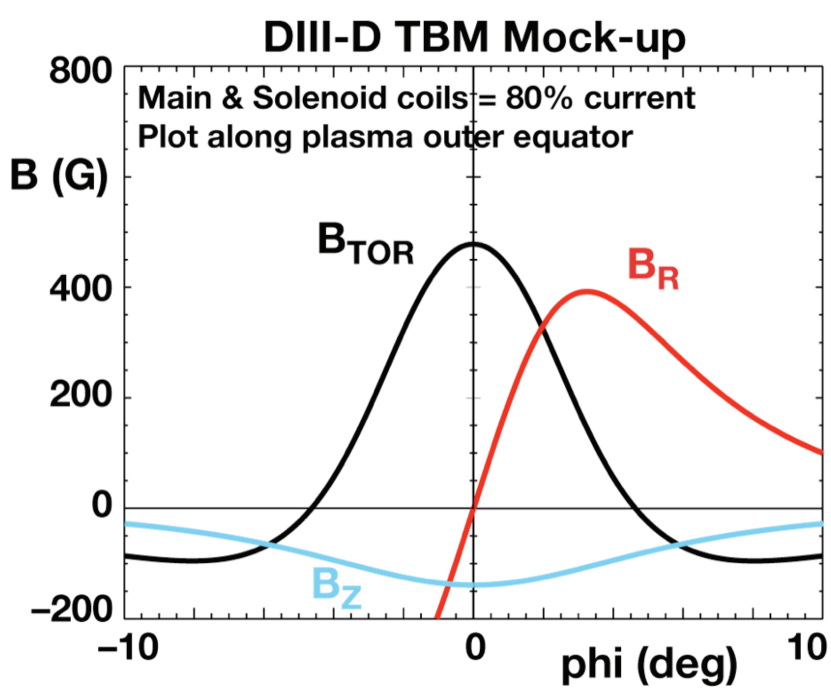
# Two Main Differences Between DIII-D and ITER:

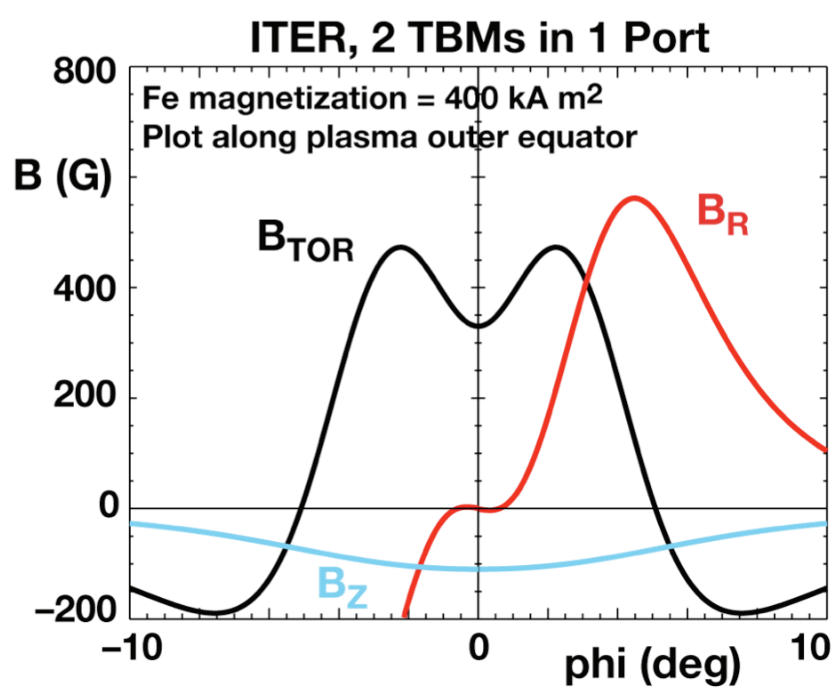
- **1 DIII-D TBM port vs. 3 ITER TBM ports**

  No validated theory for extrapolation

- **Near-field details**

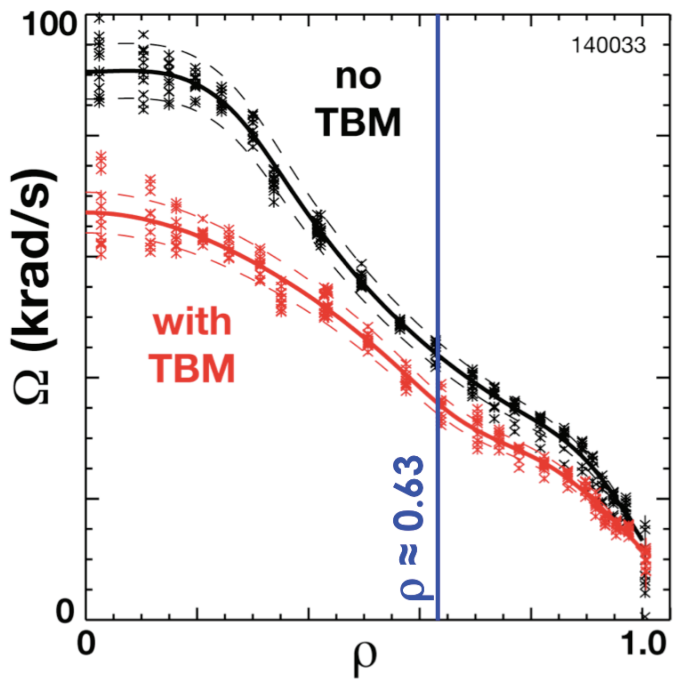
  Limited by DIII-D port width

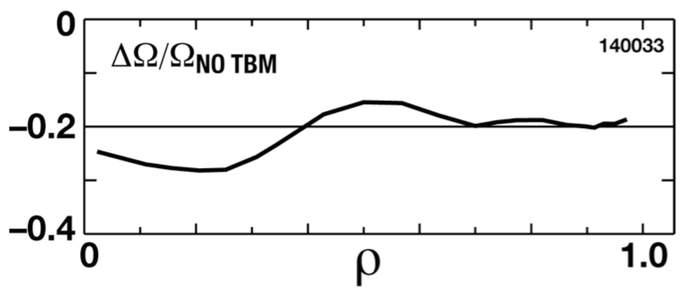


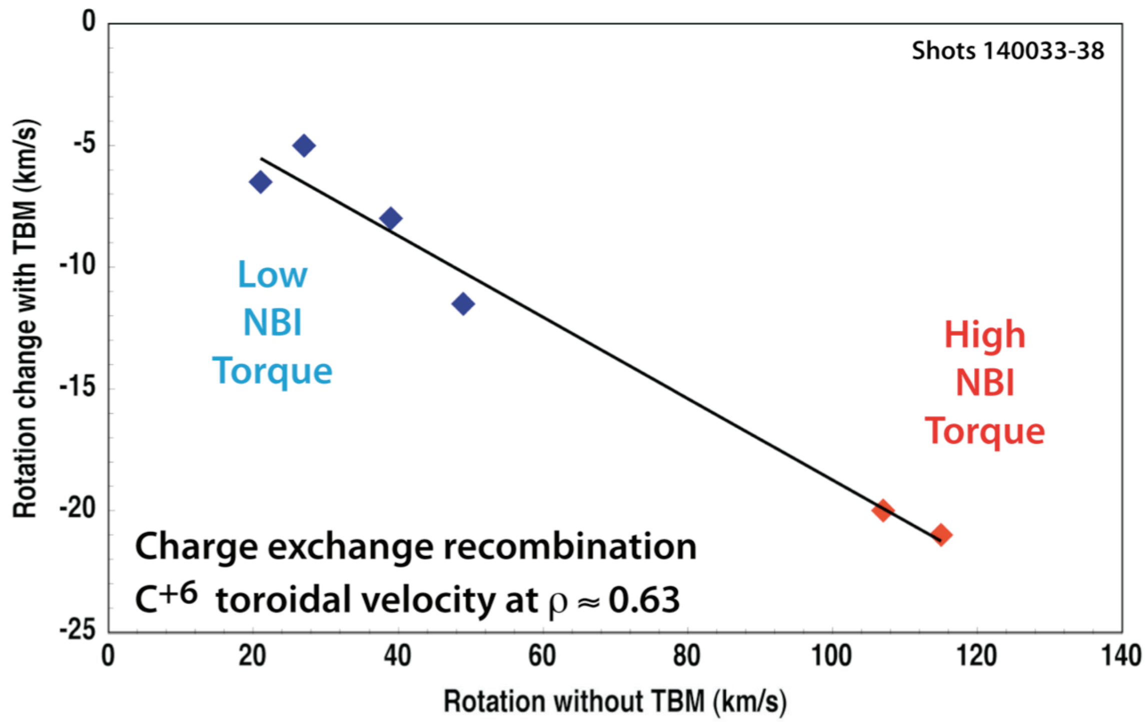
# Mock-up Field Exerts Non-Resonant Braking on Plasma Toroidal Rotation, $v_T = \Omega R$

H Reimerdes




H Reimerdes




- $\Delta\Omega/\Omega$ is ≈ constant, either way