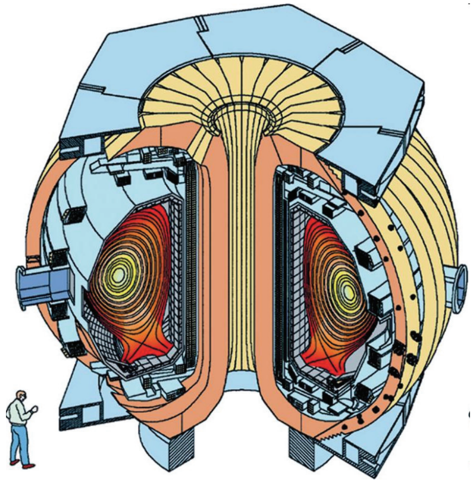
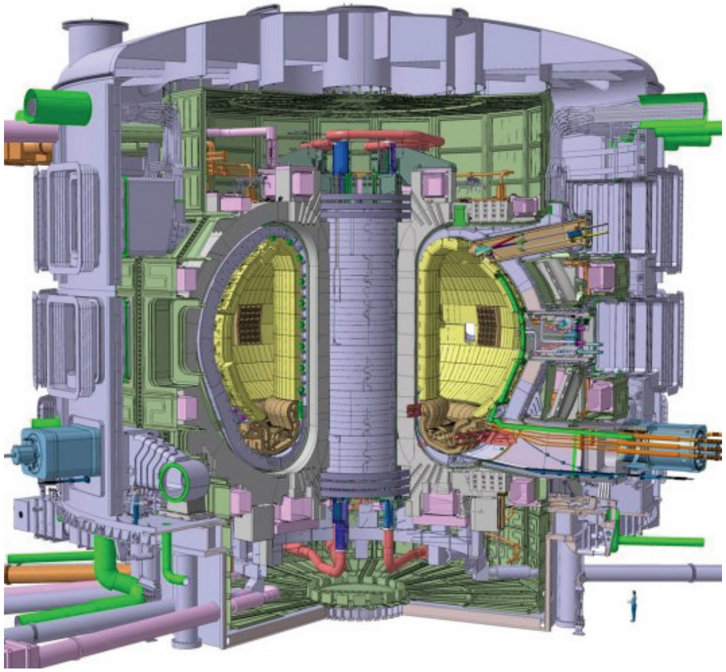
ITER Test Blanket Module Error Field Simulation Experiments

by
M.J. Schaffer



DIII-D

ITER



Presented at

Fifty-Second Annual Meeting
APS Division of Plasma Physics
Chicago, Illinois, USA

November 8–12, 2010

Paper BI3.00001

A Large International Team Participated

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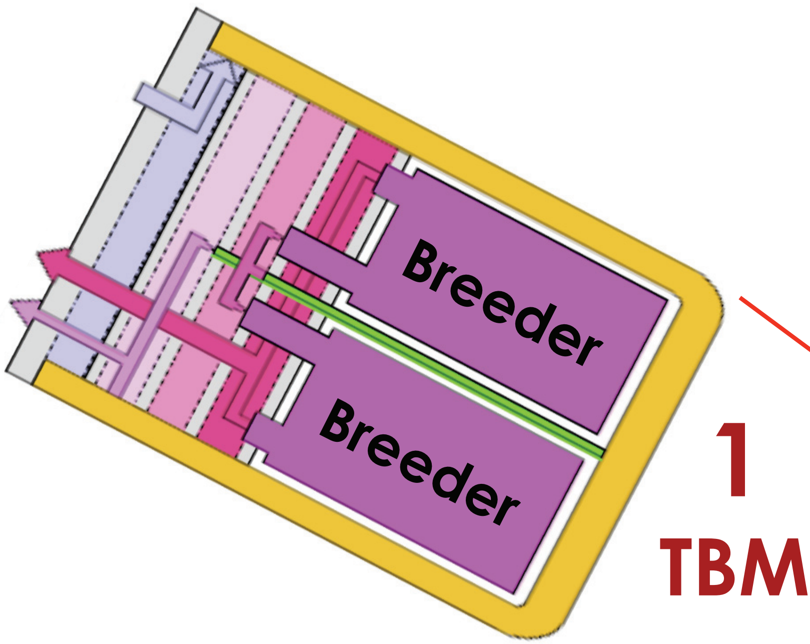
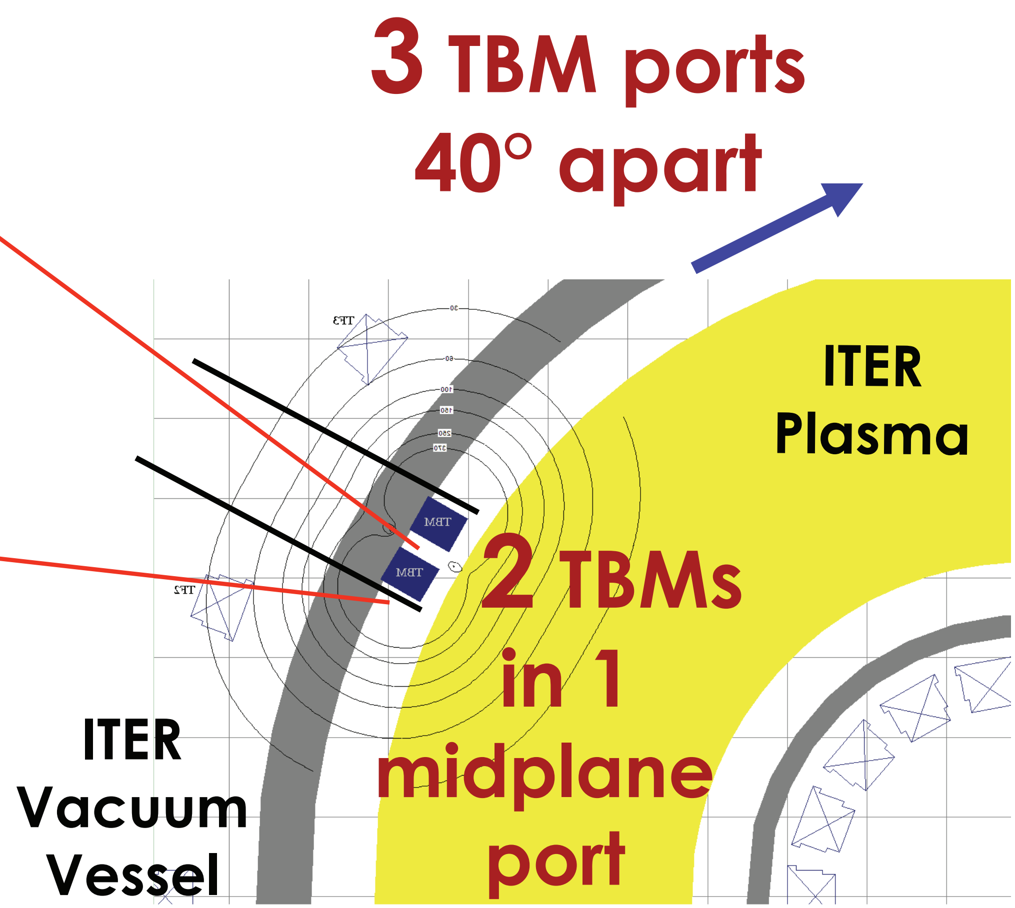
Concern Raised About the Impact of Ferromagnetic Test Blanket Modules (TBMs) on ITER Performance

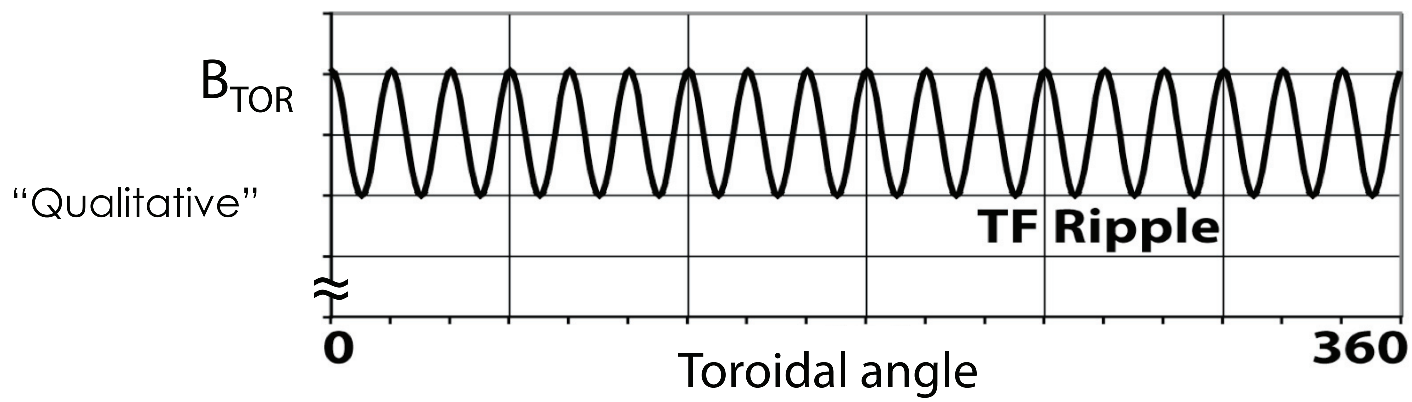




- **Has ~ 1 ton of ferromagnetic steel**
  - Thermal and neutronic ITER technology missions
  - B-field bumps

Toroidal Field Ripple Has Undesirable Effects on Tokamak Plasmas (Fast Ion Loss, Confinement Loss…)

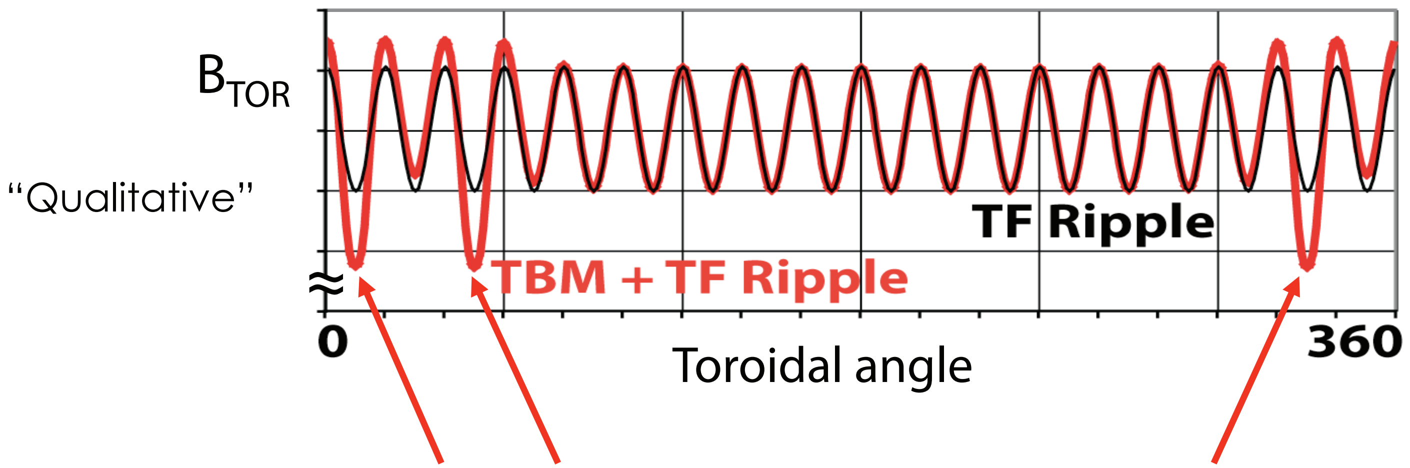
- **Common magnetic field ripples from discrete toroidal field coils are uniformly periodic**



- **DIII-D matched the ITER TF-coil ripple amplitude for most TBM experiments**
  – 0.35 ~ 0.40% for both

TBMs Complicate Ripple Geometry

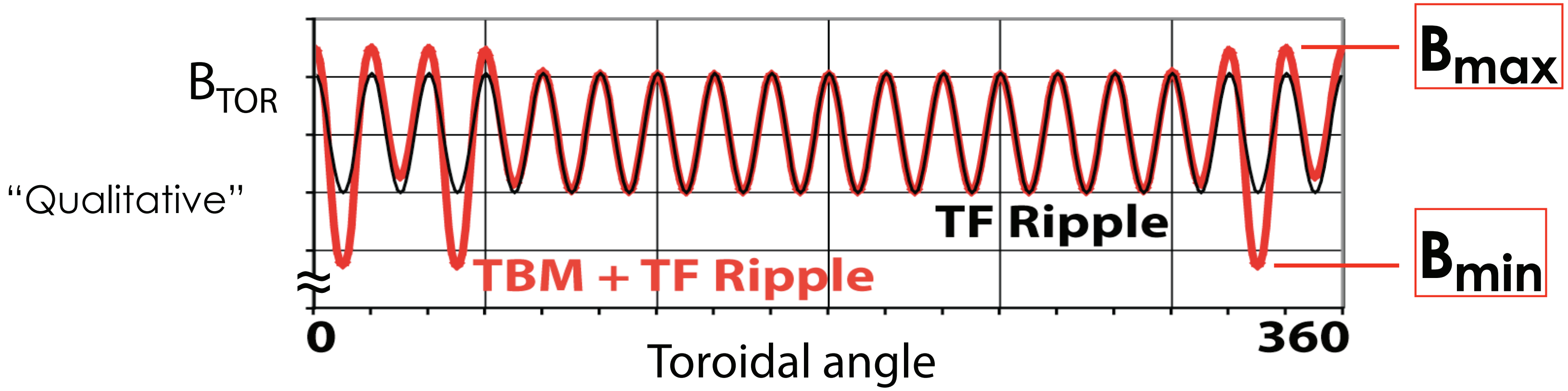
- **Larger perturbations**
- **Broken periodicity**



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

Use the Combined "Local Ripple" $\equiv \delta$

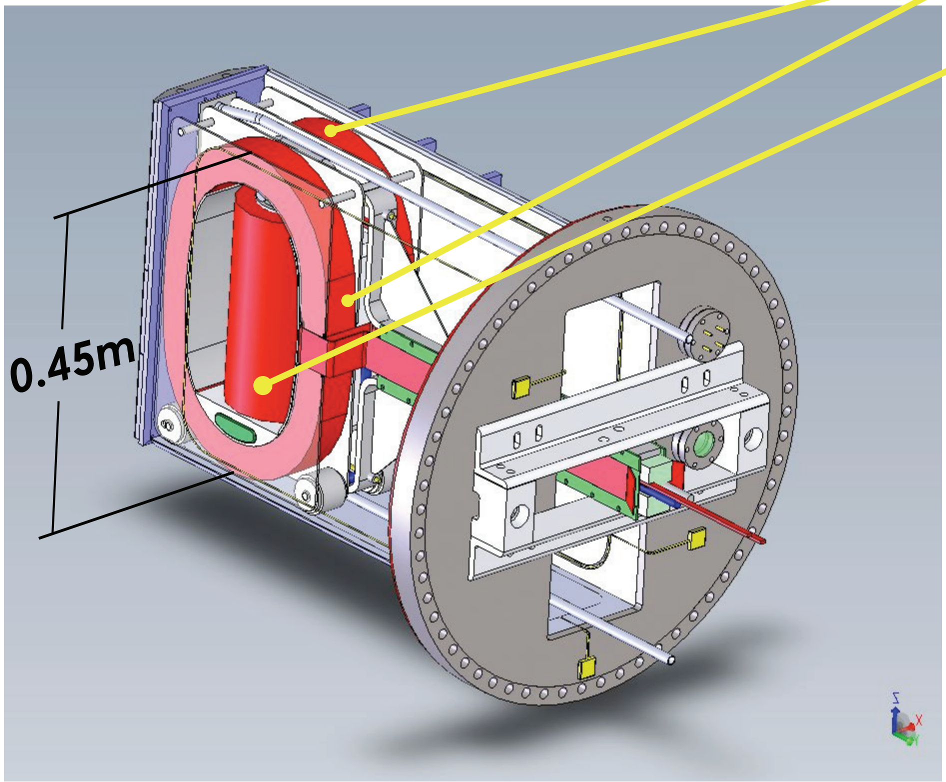
$$\delta = \frac{B_{max} - B_{min}}{B_{max} + B_{min}}$$



- **ITER expects to have $\delta \approx 1.2\%$**

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

Mock-up Approximates the Magnetization within One ITER TBM Port



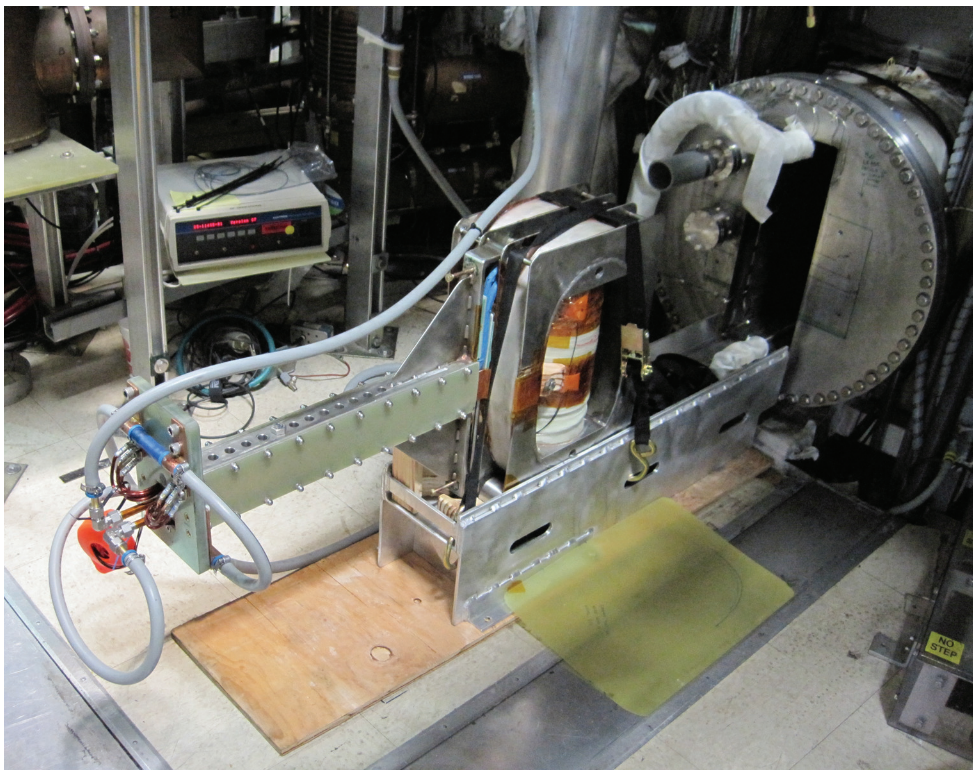
Racetrack coils ↔ TBM M_{TOR}

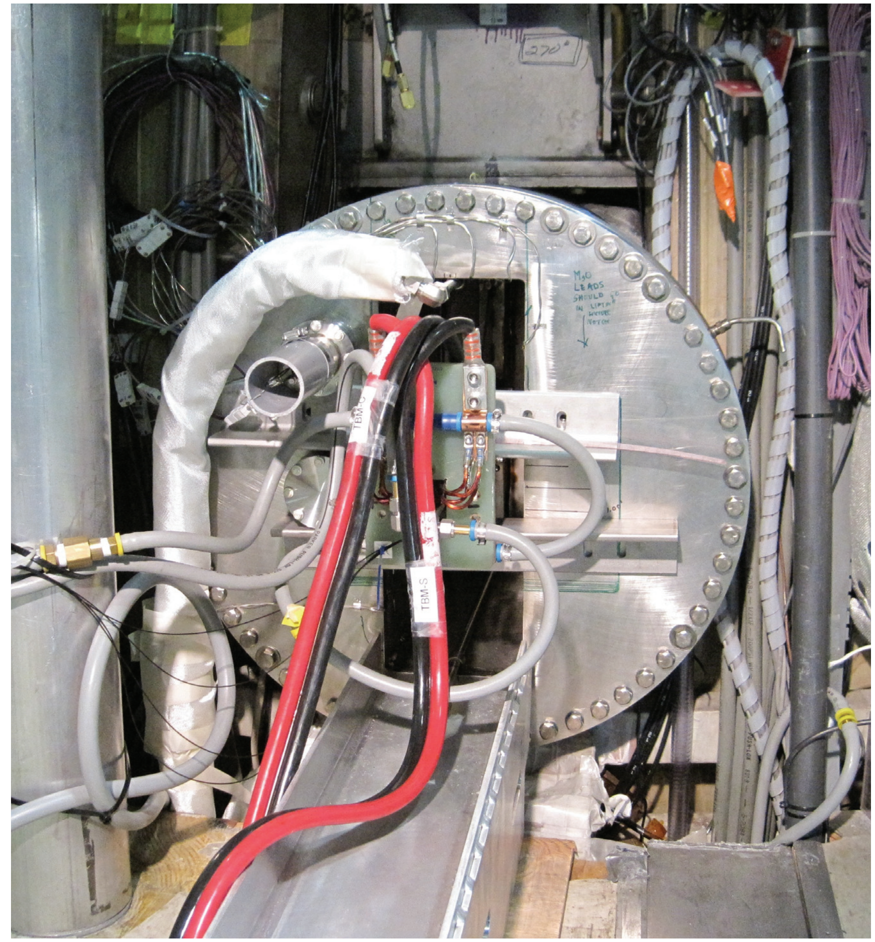
Vertical solenoid ↔ TBM M_{POL}

- **Matches ITER TBM field well**
  - M_{POL}/M_{TOR} vary to match q
- **Movable, ΔR = 0.28 m**
  - 1.0 m in ITER
- **DIII-D local ripple ~3 x ITER local ripple**
  - Same surface-average ripple amplitude as 3 ITER TBM ports

TBM Mock-up at its DIII-D Midplane Port

Mock-up secured in its channel, cooling water attached

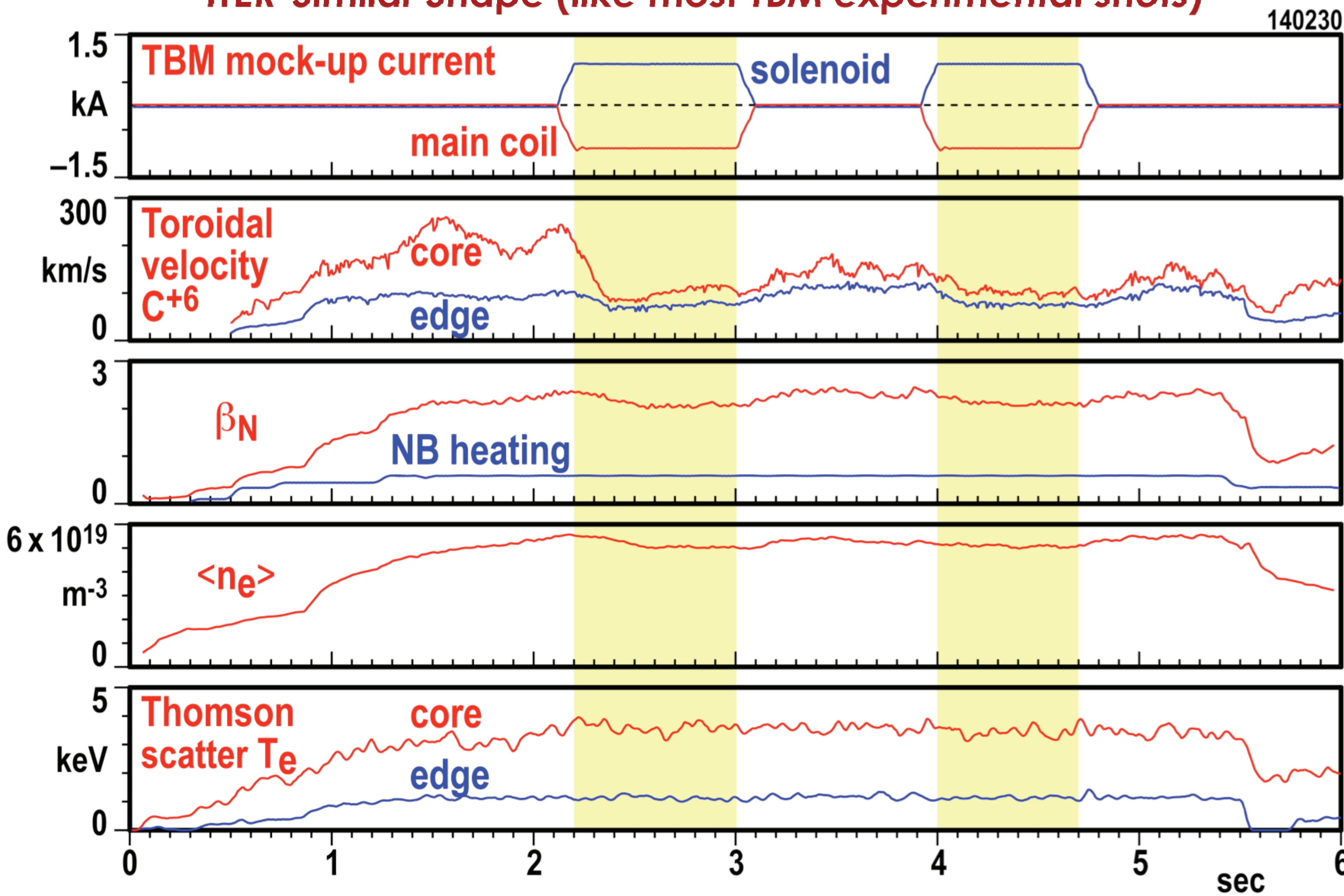




Mock-up rolled into port

Greatest Effect of TBM Field Was on Toroidal Velocity – β, n_e and T_e Were Much Less Affected

ITER-Similar Shape (like most TBM experimental shots)



Making local ripple δ = 3%

Large core velocity reduction

Moderate reductions

No effect on T_e

Experimental Results Showed That Most Other TBM Mock-up Effects Were Small

Little or No Effects on:

Plasma Startup

L-mode Confinement

L-to-H Transition [P Gohil, UO4.xxxx9]

H-mode Pedestal (except n_e)

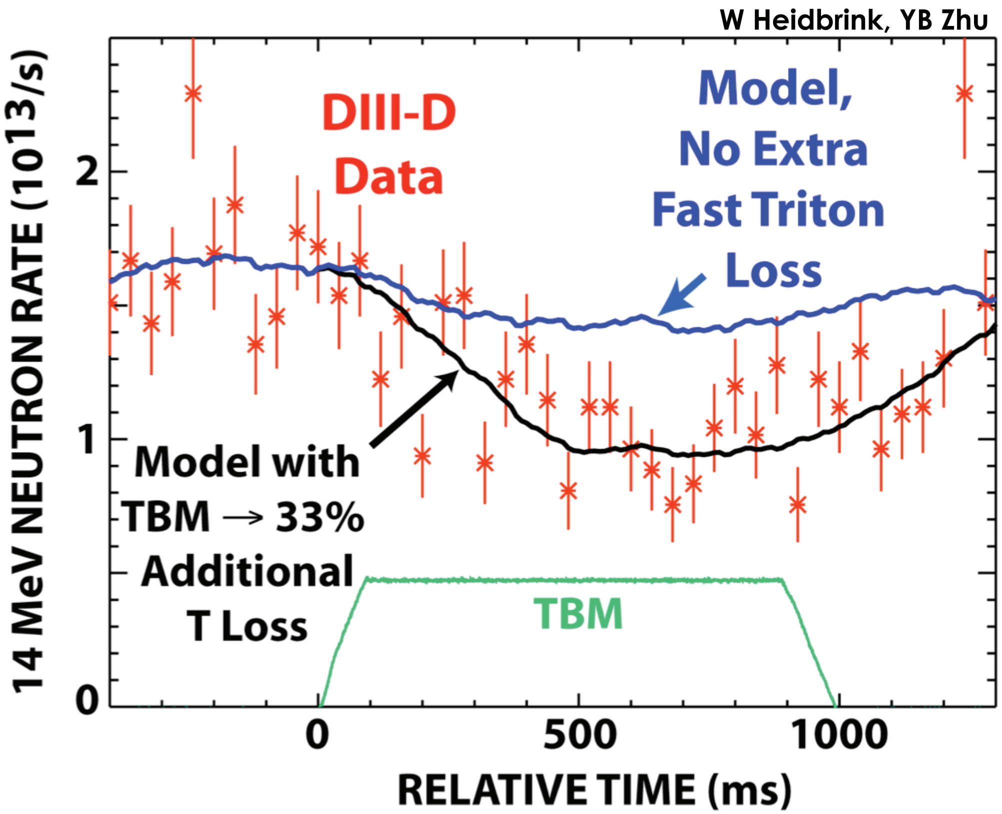
ELM Characteristics

ELM Control by RMP

Thermal Loss to Bumper Limiters

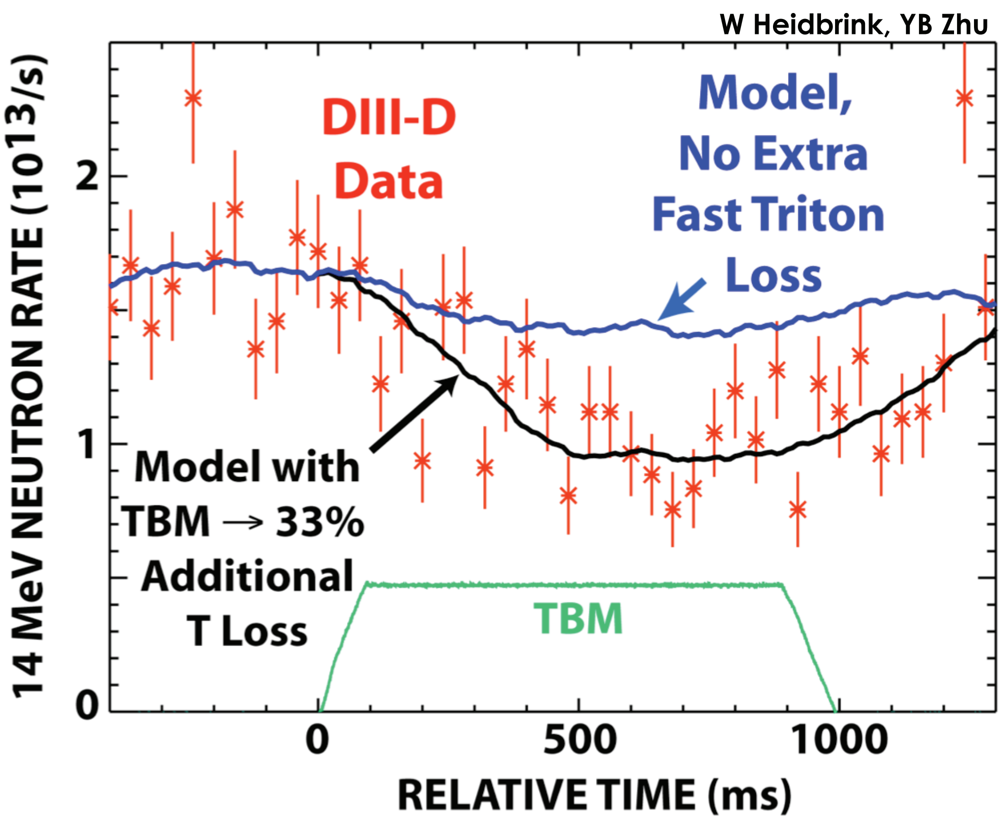
Divertor Power Distribution

Experimental Results Provide Validation of Fast Ion Loss Models for TBM-like Error Field



- Blue curve if TBM caused no loss of 1-MeV DD fusion tritons

Experimental Results Provide Validation of Fast Ion Loss Models for TBM-like Error Field



- Blue curve if TBM caused no loss of 1-MeV DD fusion tritons
- **Simple model gives 33% additional loss of T ions**
  - T orbits large in DIII-D
  - Model agrees with data

[YB Zhu, UP9.xxx57]

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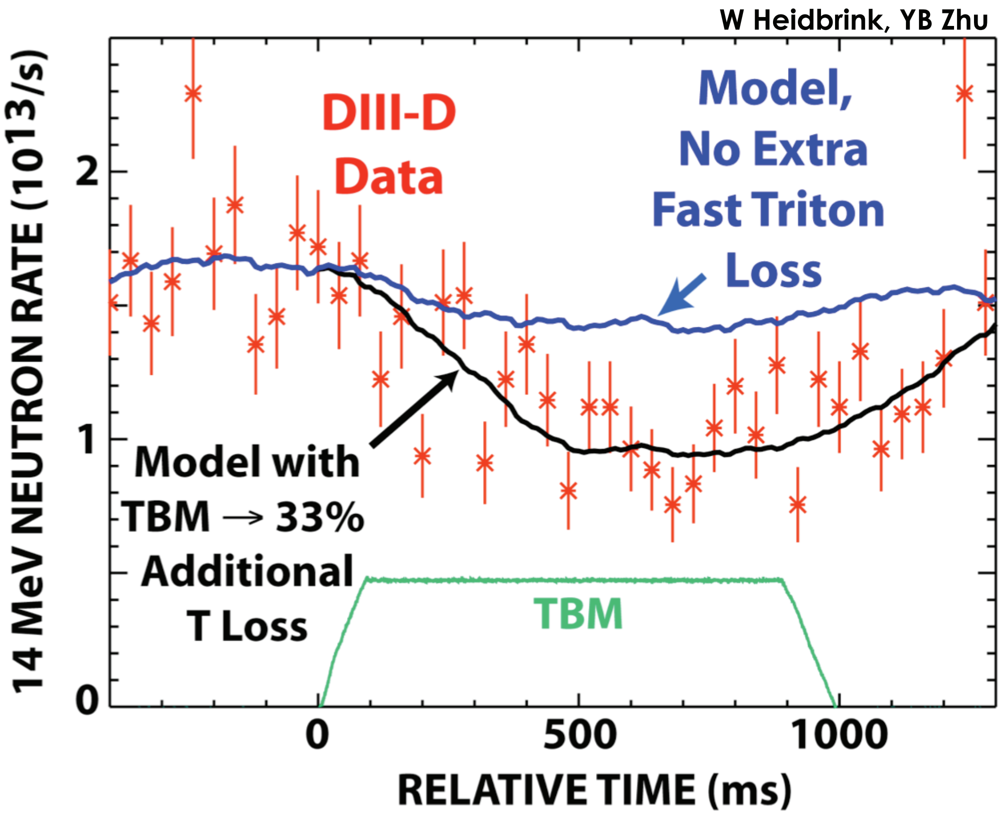

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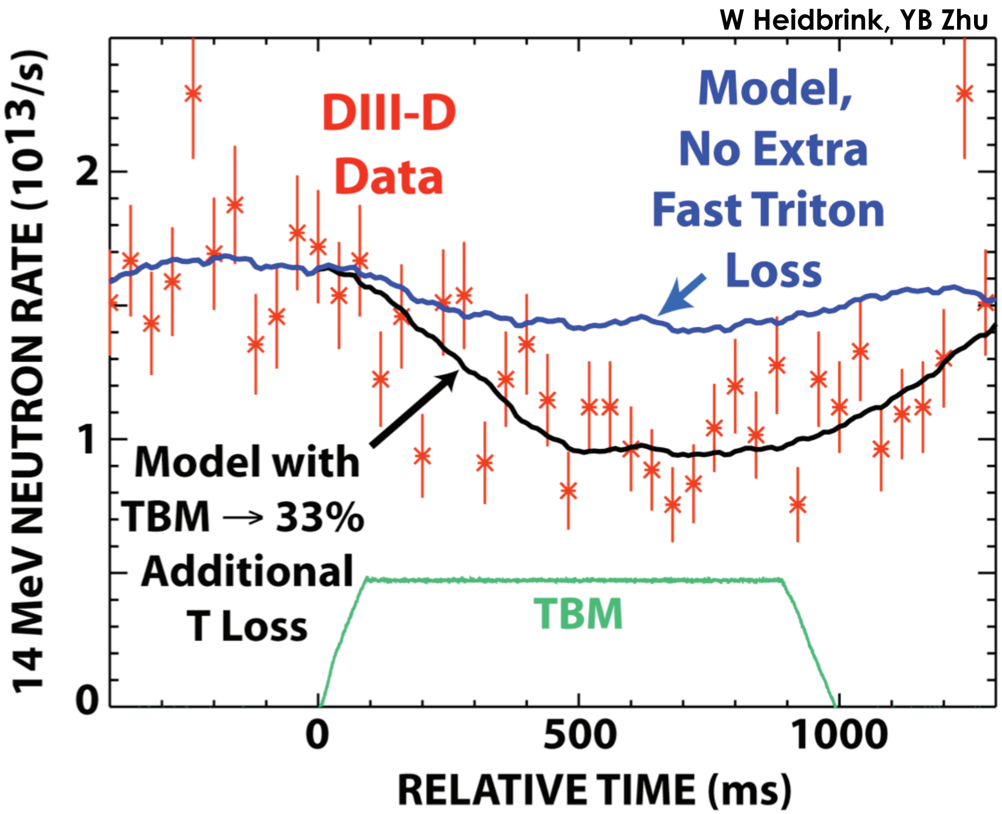

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- **Four fast-ion codes account for measured heating of TBM mock-up protection tiles**
  - SPIRAL, ASCOT, OFMC, DELTA5D

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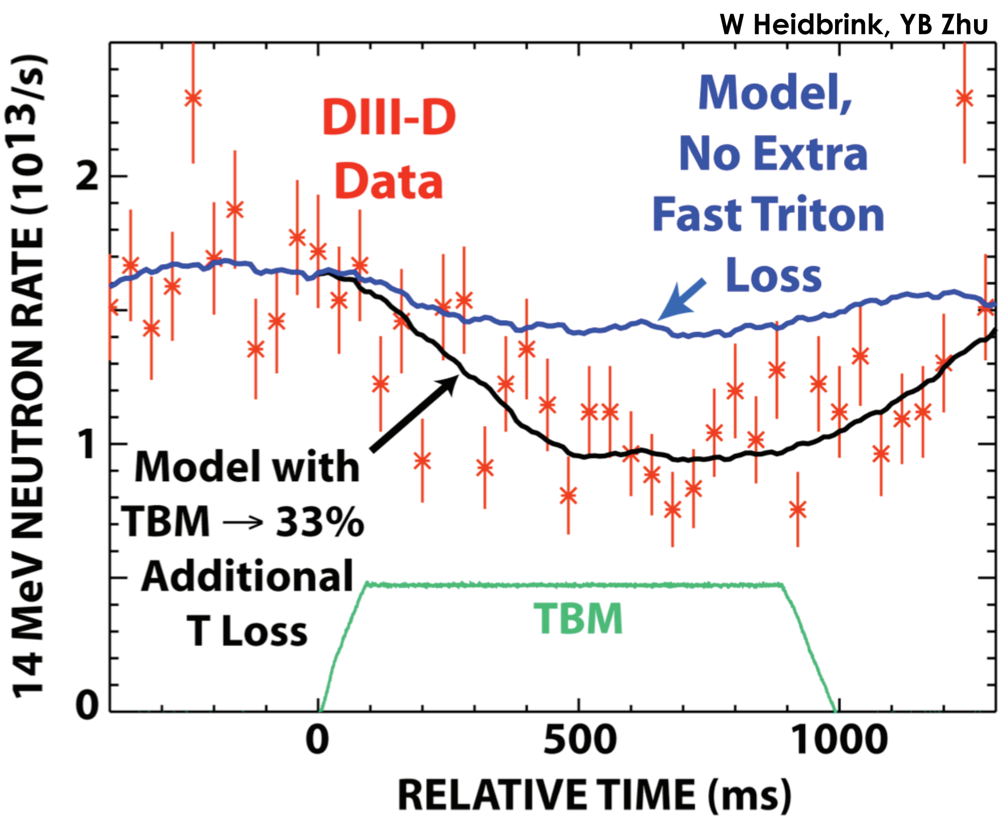
Experimental Results Provide Validation of Fast Ion Loss Models for TBM-like Error Field



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- **Simple model gives 33% additional loss of T ions**
  - T orbits large in DIII-D
  - Model agrees with data
- **SPIRAL full orbit code also computes 33% T loss**
- **Three fast-ion codes account for measured heating of TBM mock-up protection tiles (in progress)**
  - SPIRAL, ASCOT, OFMC , DELTA5D
- **These and similar models predict small, acceptable fast ion losses for ITER**

[YB Zhu, UP9.xxx57] [G Kramer, XO4.xxxx4] [D Spong, BI3.xxxx6]

A Few TBM Error Field Effects May Be of Concern to ITER, but … They May Also be Correctable

Of Concern to the
ITER High-Gain Mission*

Locked modes

Braking of plasma rotation

Reduction of H-mode confinement

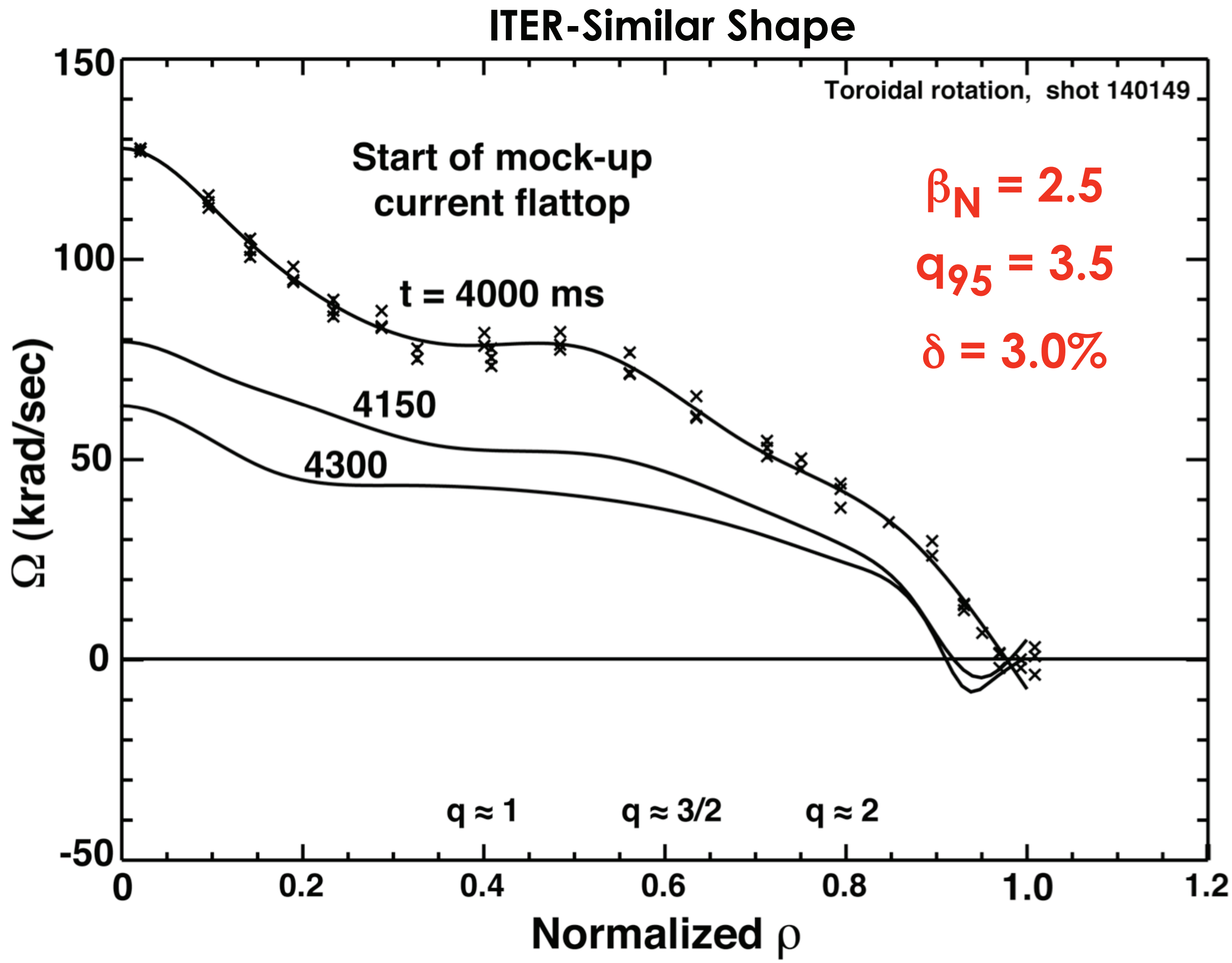
* if scaling is unfavorable and affects fusion gain

They May Be
Correctable:

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

Example: High Mock-up Field Locked Co-injected H-mode Plasma Rotation at High β

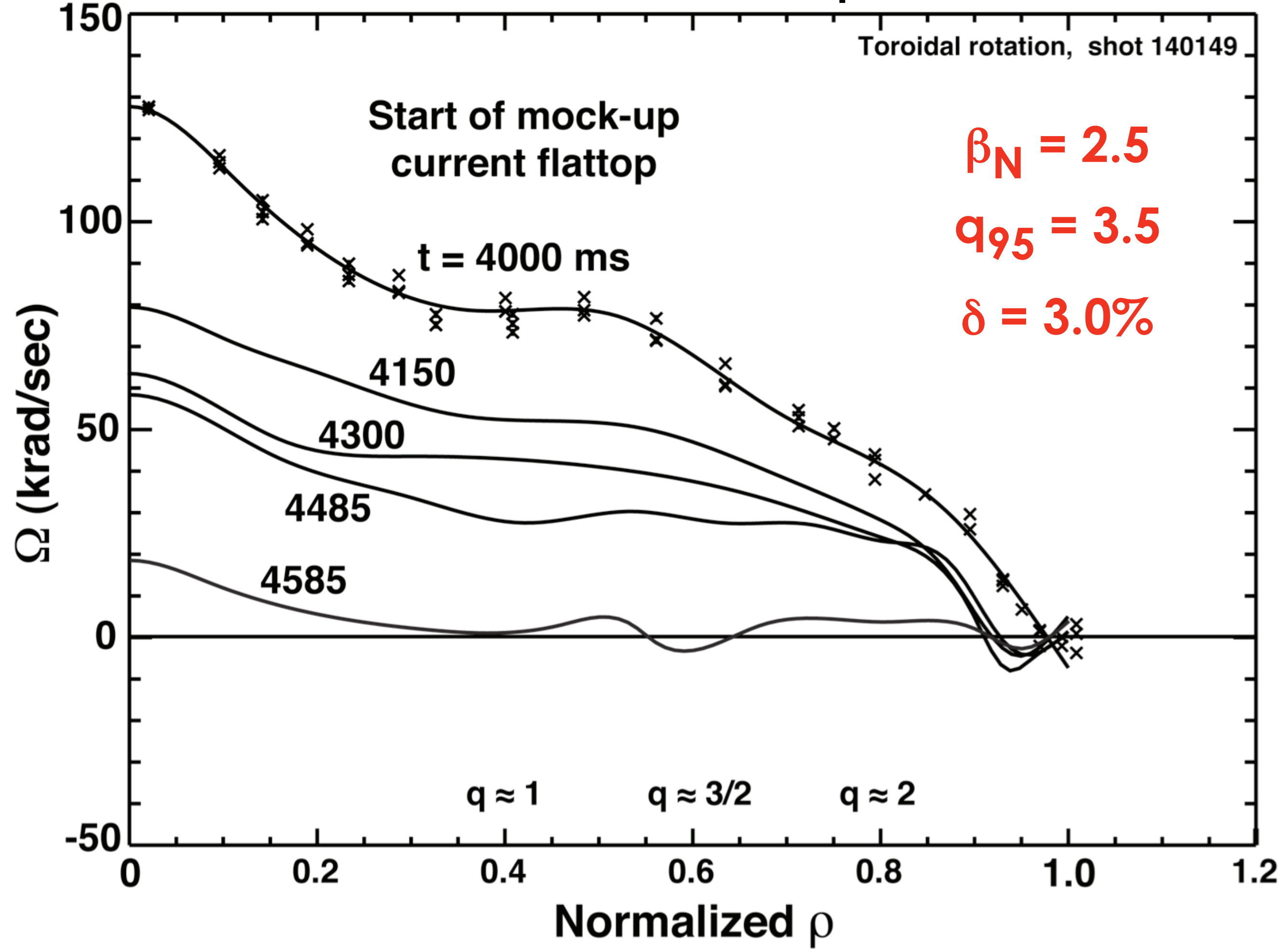
- **Plasma slowed**
  - To ~50% of initial rotation in 300 ms
  - $\Delta\Omega/\Omega \approx$ constant across plasma
  - But not quite in steady torque balance



Example: High Mock-up Field Locked Co-injected H-mode Plasma Rotation at High β

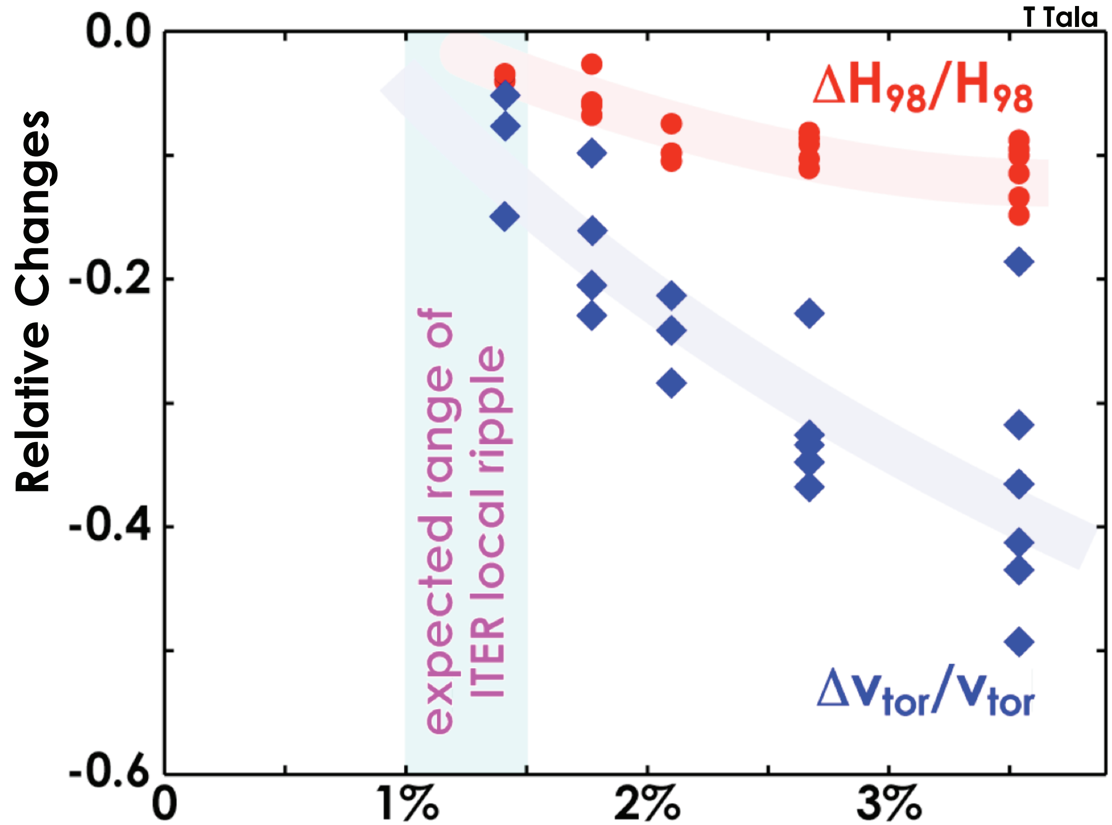
- **Plasma slowed**
  - To ~50% of initial rotation in 300 ms
  - $\Delta\Omega/\Omega \approx$ constant across plasma
  - But not quite in steady torque balance
- **Gradually slowed**
- **Locking ensued**
  - Possibly at q=1 and q=3/2 surfaces

ITER-Similar Shape



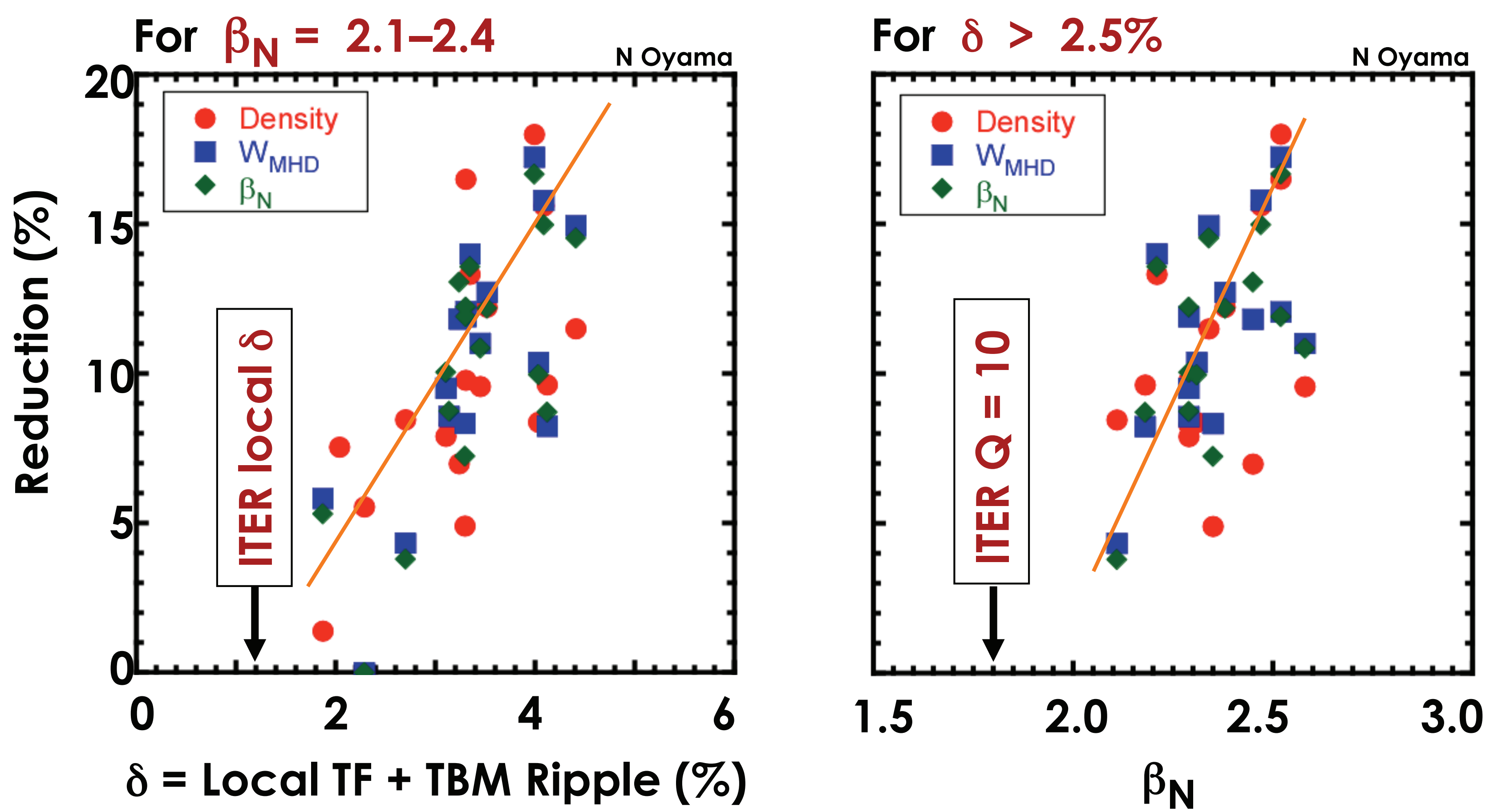
TBM Field Reduced H-mode Confinement Much Less Than Toroidal Velocity

- **Confinement change was ~ 1/3 of the velocity change**
  - Similar to confinement vs. angular momentum relation observed by PA Politzer et al., NF, 2008.

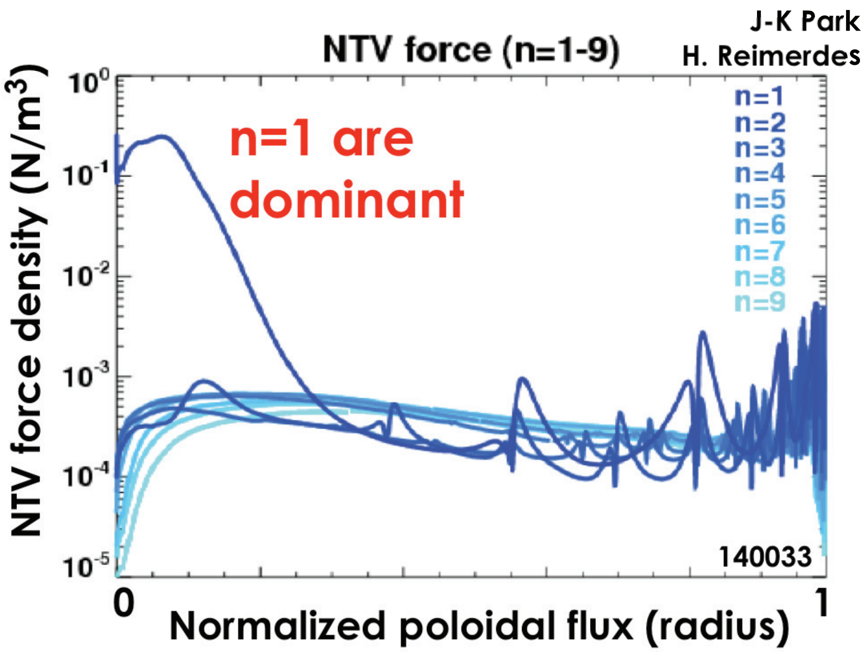


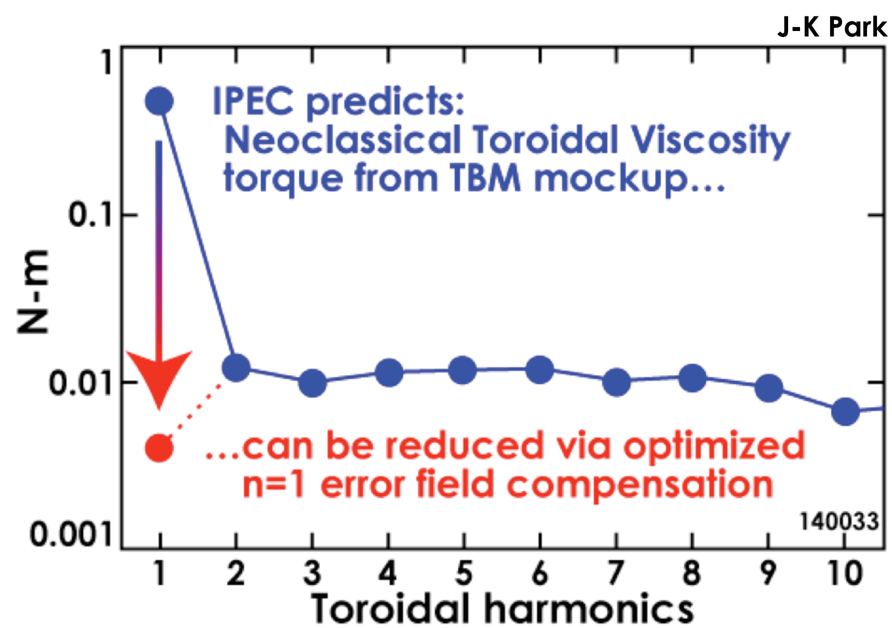
TBM Effects Were Small at ITER Baseline Parameters; We Did Systematic Scans Only at Higher Ripple and β

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



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



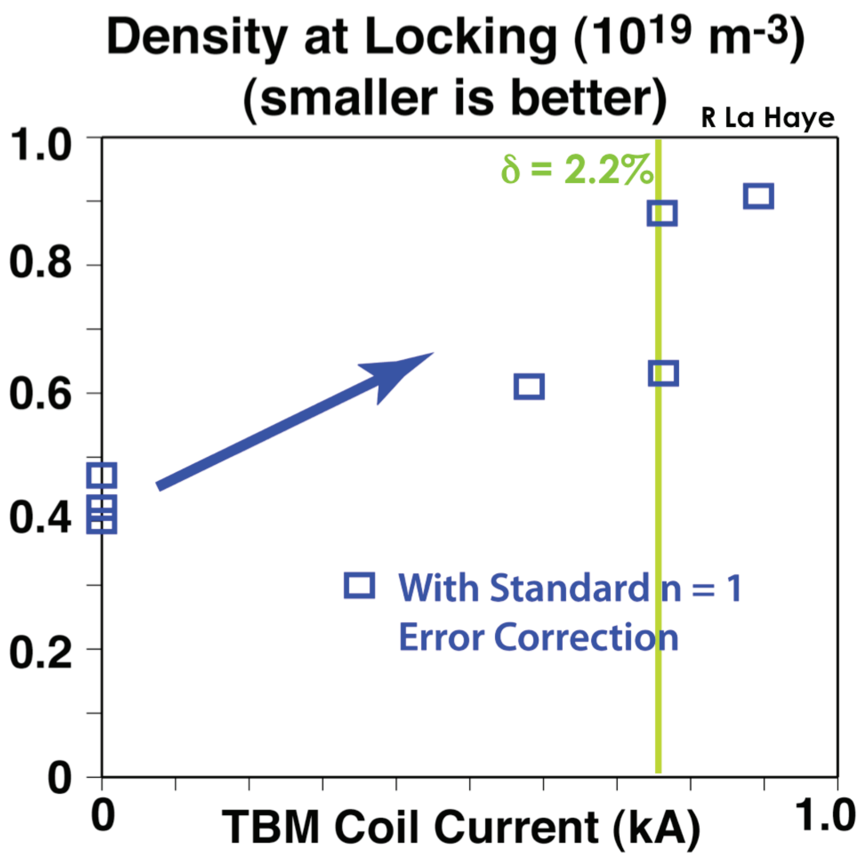


- **Neoclassical Toroidal Viscous (NTV) braking by mock-up field is mostly from n=1 harmonics in central core**
  - n=1 is amplified by H-mode

- **A great opportunity…**
- **Expect to recover higher plasma velocity and thus higher confinement**

[JK Park, PI2.00001, XO4.00003]

DIII-D n=1 Error Compensation Was Re-Optimized with TBM, and It Restored Locked Mode Tolerance at Low β

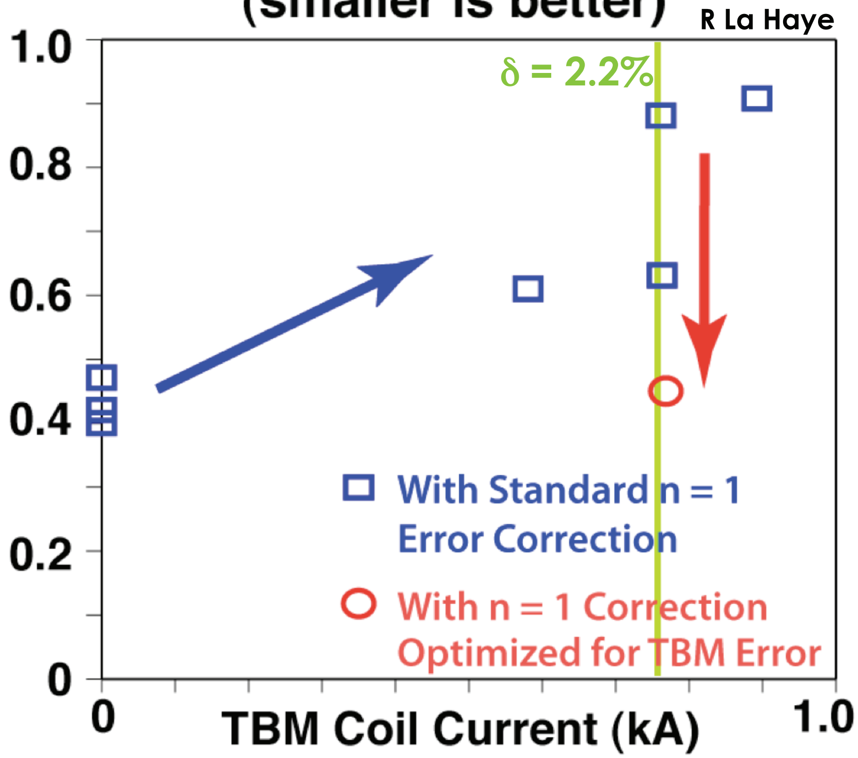


Using Standardized Ohmic Low-Density Locking Test Plasmas

- TBM field raised the low-density threshold for locked mode avoidance
- n=1 re-compensation restored locked mode tolerance in *low-β* test

DIII-D n=1 Error Compensation Was Re-Optimized with TBM, and It Restored Locked Mode Tolerance at Low β

Density at Locking (10^{19} m^{-3})
(smaller is better)



Using Standardized Ohmic Low-Density Locking Test Plasmas

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

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

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

- **If TBM effects $\propto \delta^{\alpha}$, then the $(\delta_{DIII-D})^{\alpha} = (3\ \delta_{ITER})^{\alpha}$ relation would be $3^{\alpha} (\delta_{ITER})^{\alpha}$ 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 of concern**

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 suggests 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 to do experiments in 2011 to test if n=1 compensation can reduce rotation and confinement degradations in <u>high-β</u> <u>H-mode</u> plasmas**