TBM Mock-up Experiments at DIII-D and Implications for Ferromagnetic Fields

by

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for the International TBM Team

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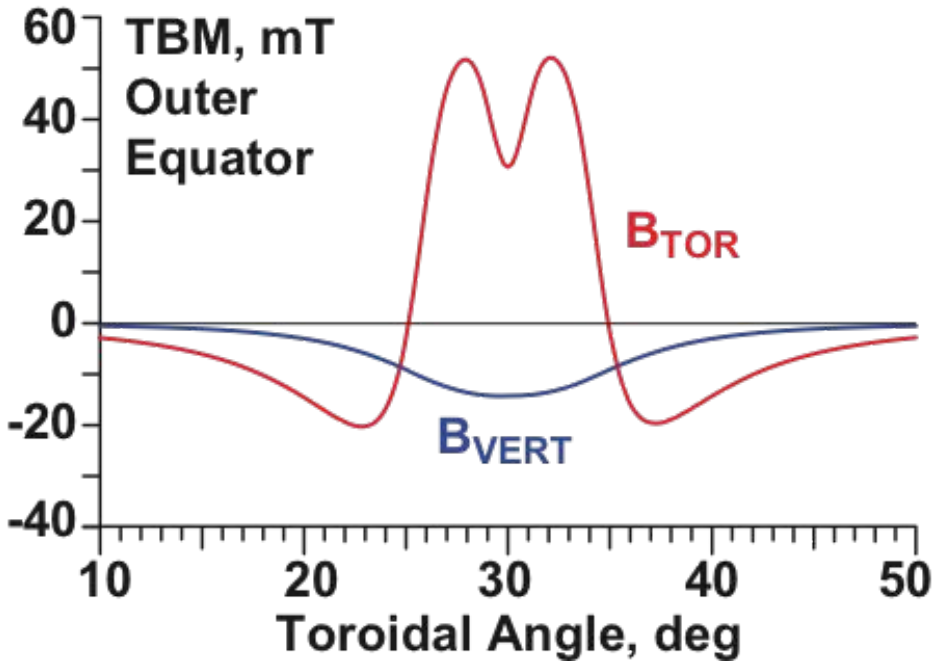
GOAL: Measure Effects of Test Blanket Module (TBM) Ferromagnetism on Plasma for ITER

Ferromagnetic TBM module pair makes a local "speed bump" field error

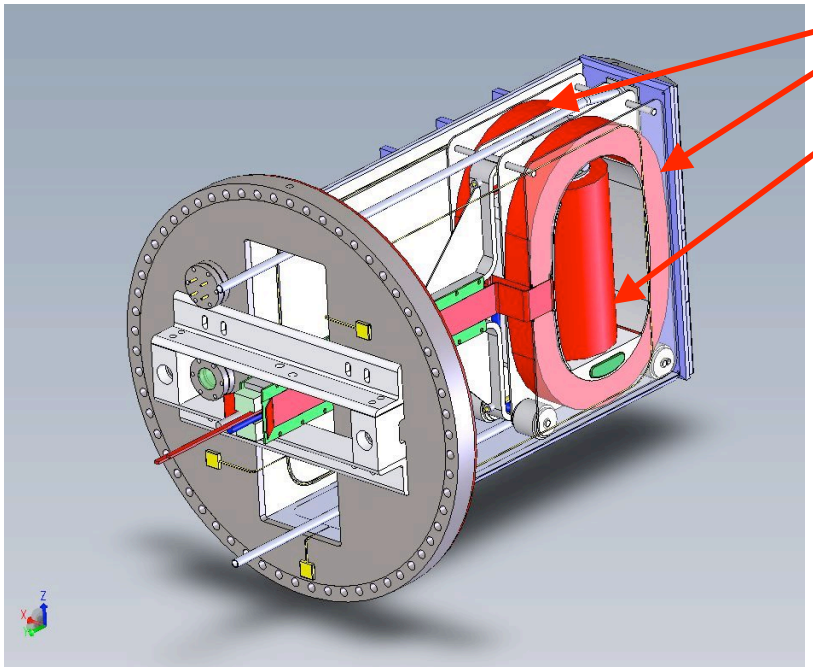


- ~1% mid-to-peak in ITER
- Comparable toroidal field coil ripples in JET & JT60U significantly reduced H-mode confinement
- It is not yet known how to predict consequences of one or a few magnetic "speed bumps"

Calculated by S Putvinski, at plasma surface

Mock-up Approximates Magnetization of Two ITER TBMs in One ITER Equatorial Port

Mock-up Has 2 Racetrack Coils in One DIII–D Equatorial Port

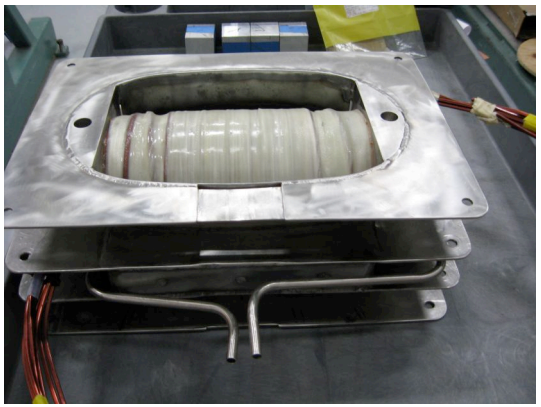


TBM mock-up coil assembly fits into custom port cavity

- **Racetrack coils ⇔ M_{TOR}**
- **Vertical solenoid ⇔ M_{POL}**
  - Separate power supplies for M_{TOR} and M_{POL}, to match q
- **Moveable, $\Delta R \approx 1.0$ 'ITER-meter'**
- **Matches ITER TBM far field**
- **Capable of ~3x ITER $\Delta B/B_0$**
  - Matches surface-average amplitude of the **6 ITER** TBMs
  - Does not match their spectrum

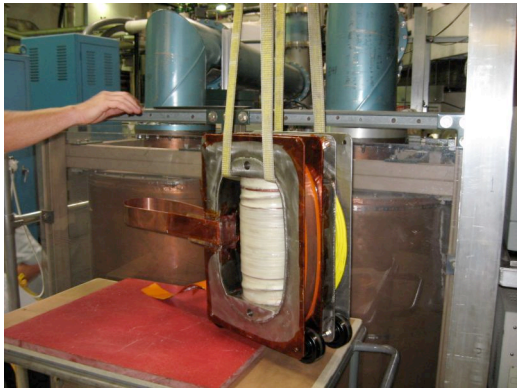
TBM Mockup Baby Book

Solenoid bobbin



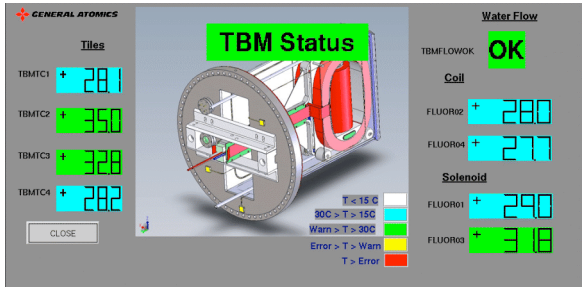
Racetrack bobbin welded to wound solenoid

Inconel port cavity with graphite tiles



With first Cu-ribbon racetrack coil

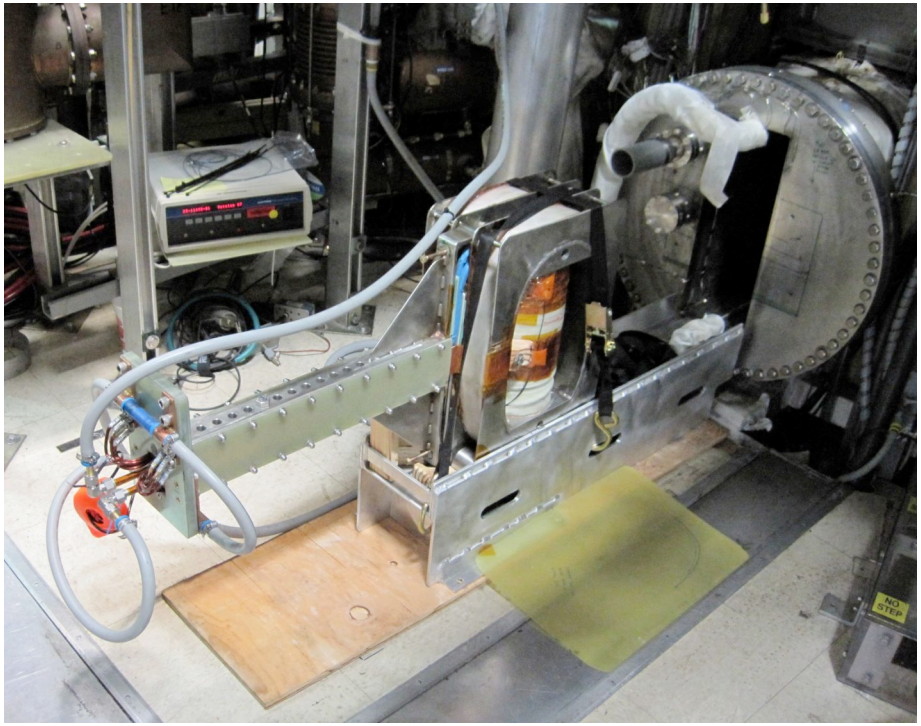
Test fit with all coils



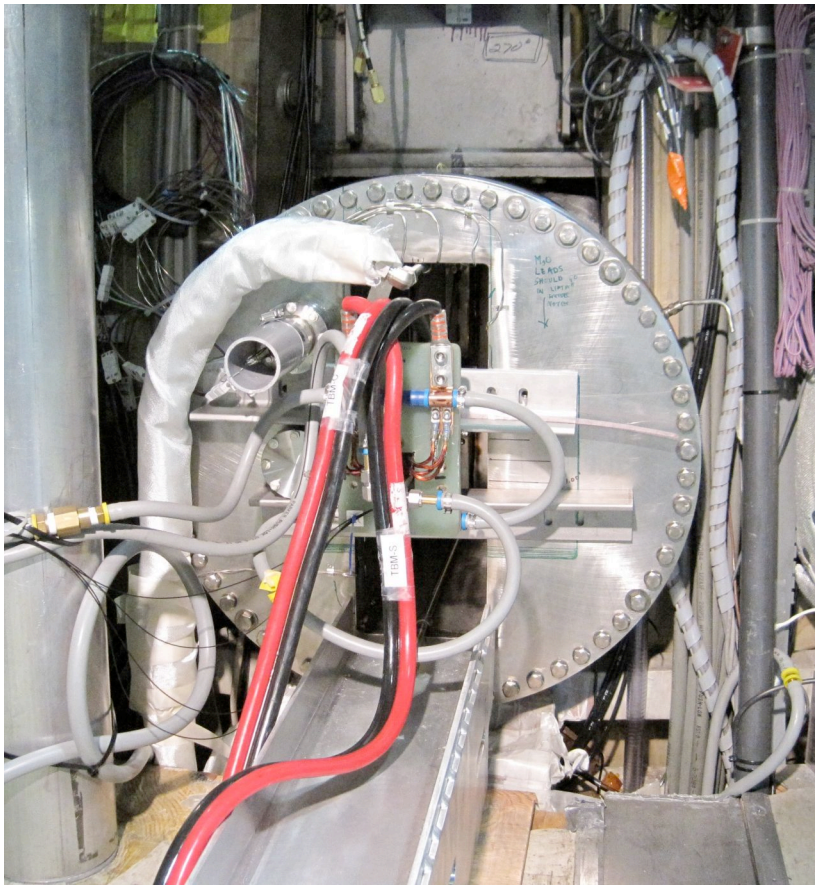
Status Display in Control Room

DIII-D TBM Mock-up Is About as Tall as a Scaled-Down ITER TBM

DIII-D port is considerably narrower than a scaled ITER TBM port

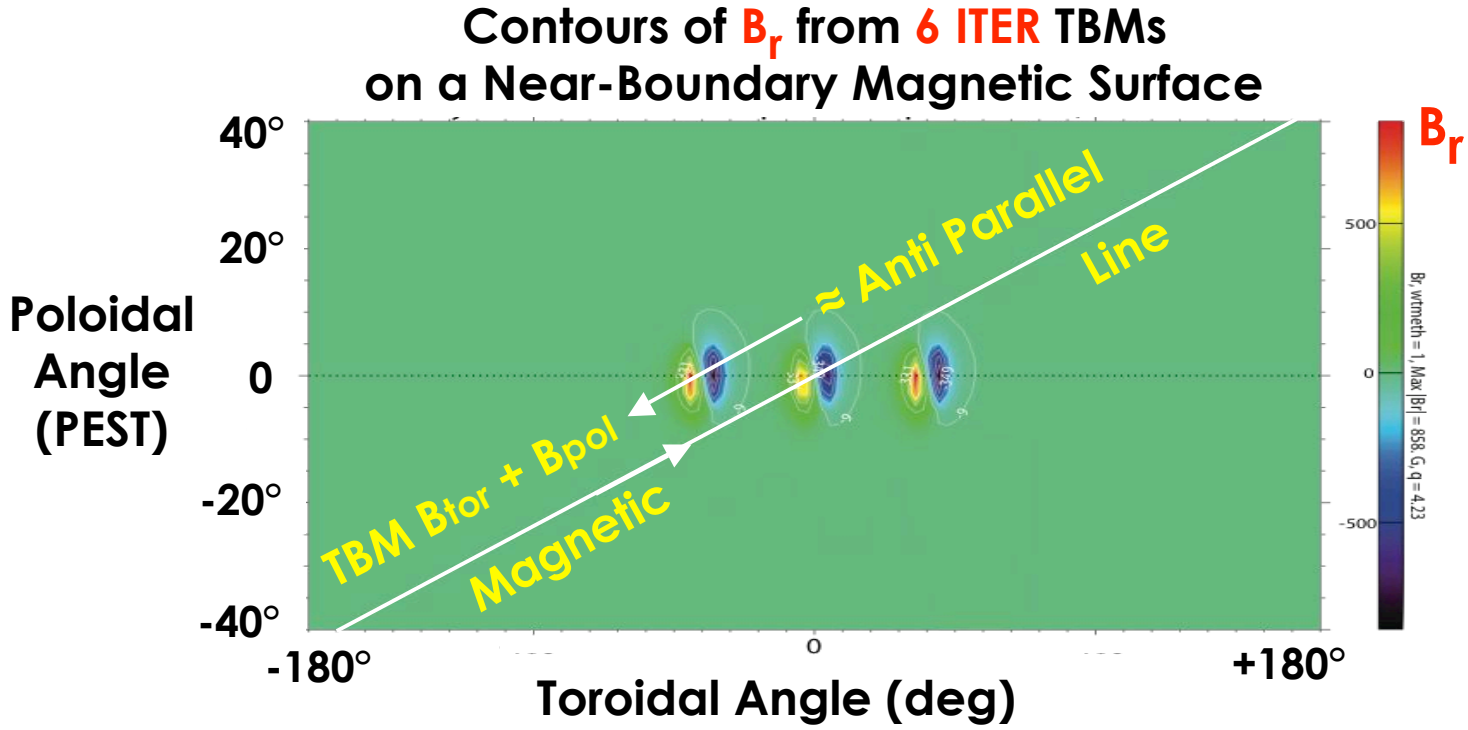


Mock-up secured in its channel with cooling water attached



Mock-up rolled into equatorial port cavity

NET Effect of TBM Error Field on Magnetic Lines is Small. Effects on Plasma?



- TBM B_r acts ≈ equally in and out along a magnetic line
- Net displacement of line ≈ 0
- <u>Generic</u> result for small ferromagnetic objects near plasma

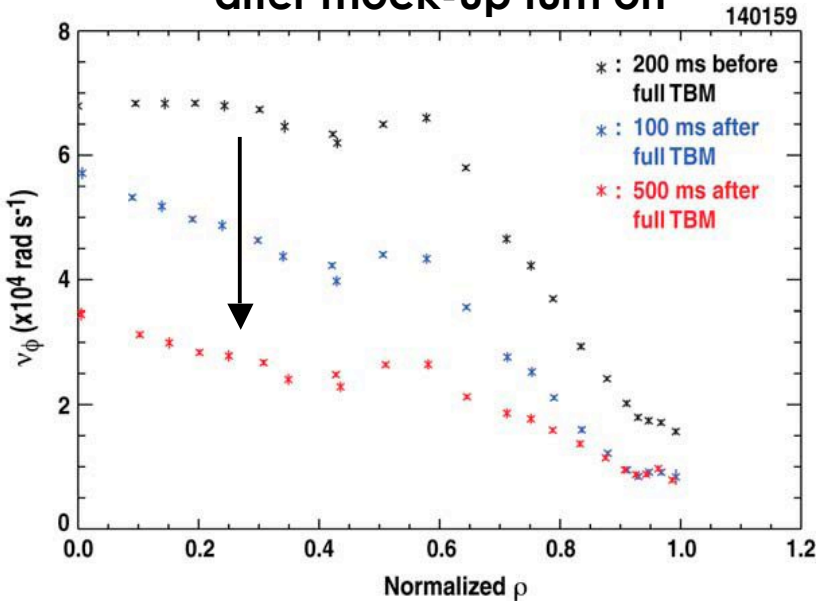
RESULTS (1)

- TBM mock-up reproduced many features of the error field from 2 ITER TBMs in 1 ITER port
  - Greatest difference from ITER was not having 3 ports
  - Mock-up applied over 3 times ITER local TBM ripple
- DIII–D experiments used ITER-similar plasmas
  - Similar shape, edge collisionality, TF-coil ripple
- Plasma initiation was unaffected by TBM field
- L-to-H-mode power threshold unaffected
- L-mode plasmas were weakly affected

RESULTS (2)

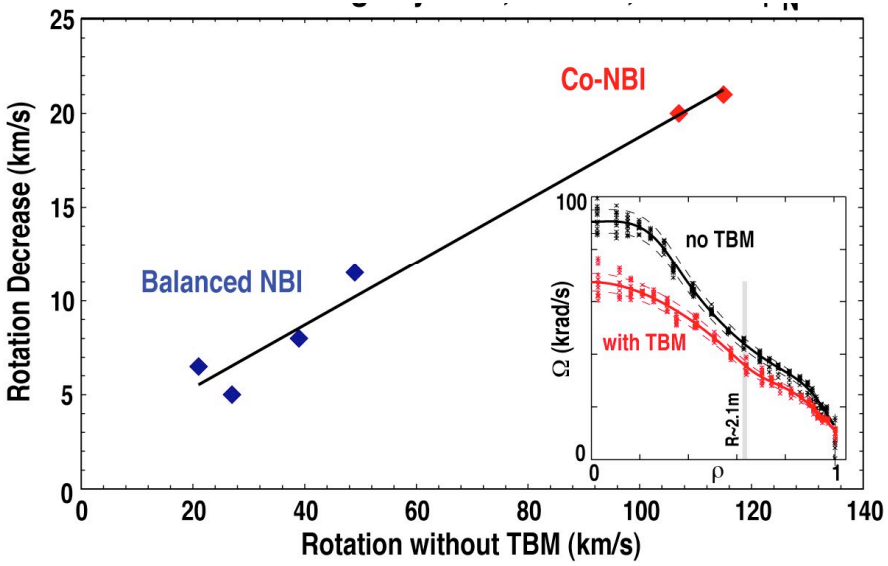
- Rotation reduction was the largest TBM effect
  - Had characteristics of a non-resonant braking torque
  - Not dominated by resonant magnetic braking

Velocity profiles before and after mock-up turn on



Slowing is across the whole plasma

Rotation Decrease by TBM at R ≈ 2.1 m

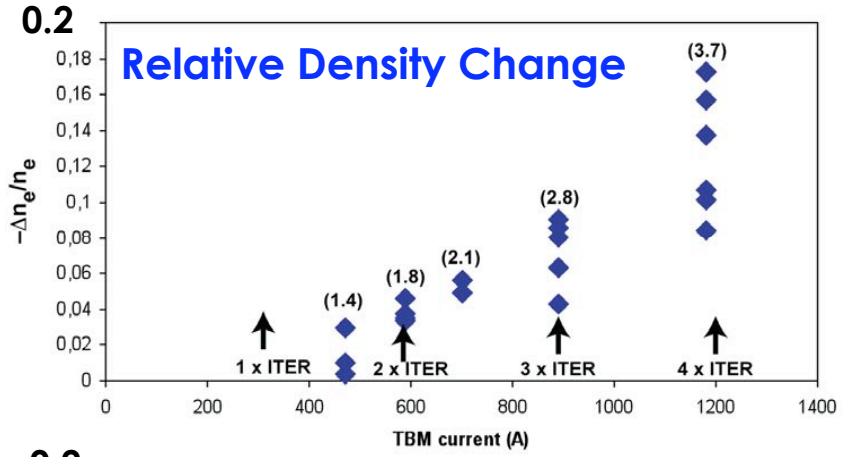


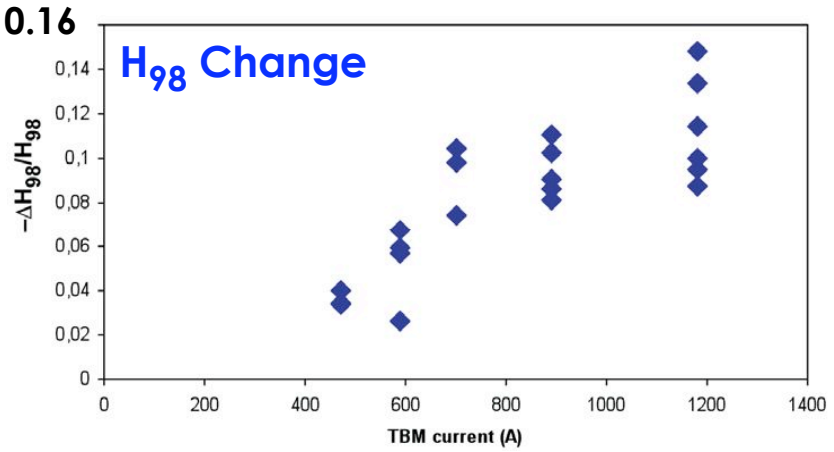
Decrease is proportional to initial velocity

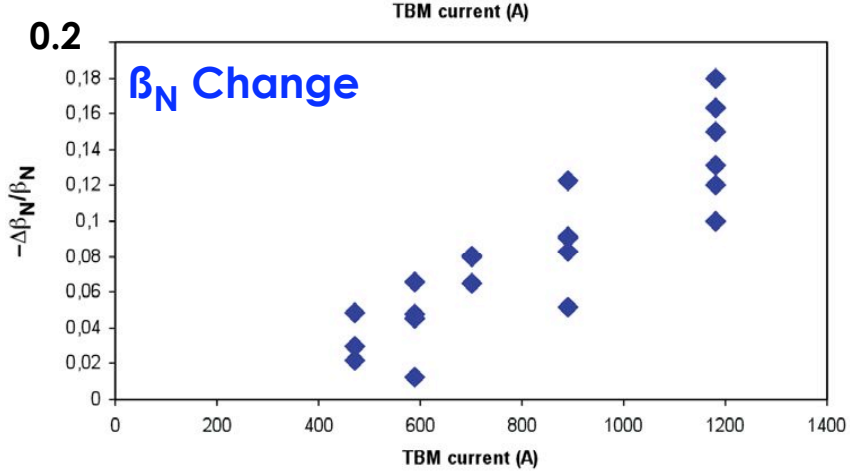
RESULTS (3)

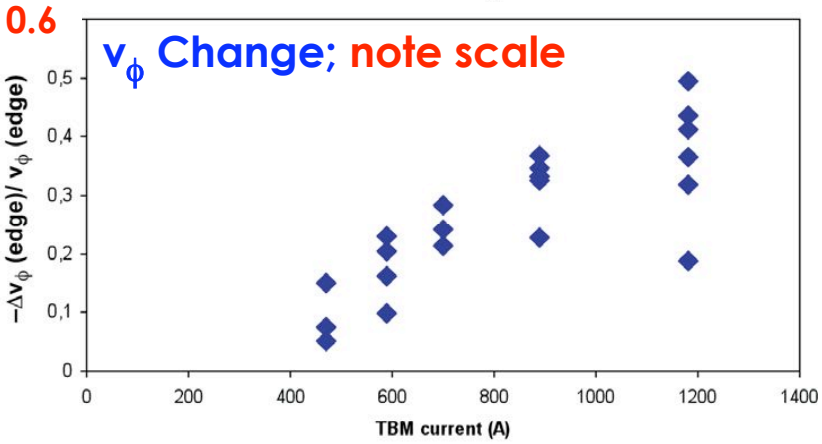
- H-mode confinement was reduced by TBM mock-up
  - Density, ß, stored energy, H98, energy confinement times were reduced as much as ~20%
    - > tested up to ~4 times local ITER TBM bump
  - TBM effects increased with plasma ß
  - Less than 10% changes for $ß_N < 2$
    - > ITER inductive scenario plans $ß_N = 1.8$
  - H-mode confinement reductions showed no strong dependence on edge collisionality

Reductions of Density, Beta, Confinement Factor and Toroidal Rotation Increased with Mock-up Current









RESULTS (4)

- TBM field had no significant effect on suppression of ELMs by n=3 resonant magnetic perturbations
- TBM field sometimes enhanced amplitude of MHD, especially in high-performance plasmas
- TBM effects on global fast ion losses were smaller than diagnostic error bars
  - Consistent with numerical modeling
- TBM field caused local heating of mock-up cavity protection tiles for small plasma-wall gap at maximum mock-up coil current

RESULTS (5)

- TBM Mock-up field reduced tolerance to plasma locking by an n=1 error *test* field
  - At low and high-ß
- Re-optimization of DIII–D empirical n=1 error correction restored no-TBM tolerance to locking (at low ß, Ohmic)
  - TBM n=1 errors, though small, are the most critical
    - > n=1 errors are simple to correct
  - Consistent with IPEC prediction
    - > Good understanding
- Did not have time to test:
  - Does n=1 error compensation restore tolerance to locking for high-ß H-mode plasmas, too?
  - Does n=1 compensation also reduce TBM braking?

In Closing

- **TBM mock-up experiments provided essential data to the ITER Organization**
  - **TBM consequences on plasmas appear to be smaller than feared**
  - **Theory to extrapolate confinement to ITER is not yet mature**
    - > **Mock-up data will help benchmark theory**
  - **Results should be applicable to other small (with respect to plasma) ferromagnetic error fields**

- **Future experiments are needed to determine if n=1 error compensation alone:**
  - **Will safeguard tolerance to locking in H-mode**
  - **Will affect plasma braking**