# Physics Effects of TBMs on Plasma Operations in ITER

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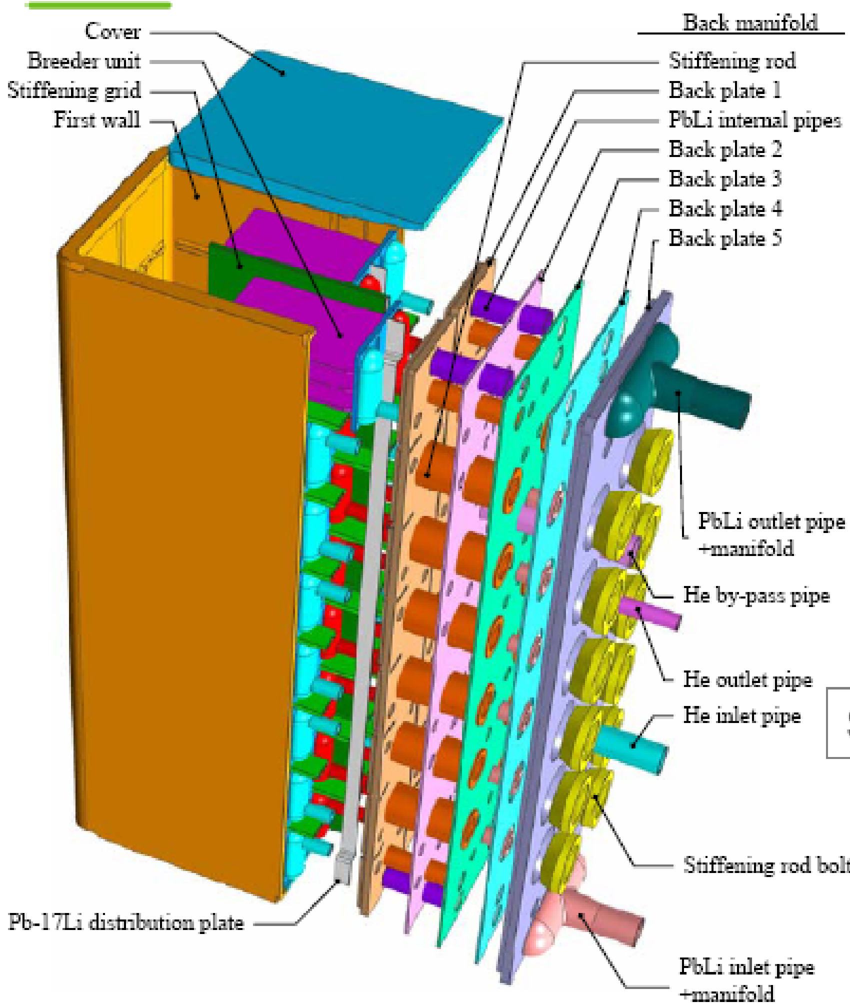
*ITER Organization*

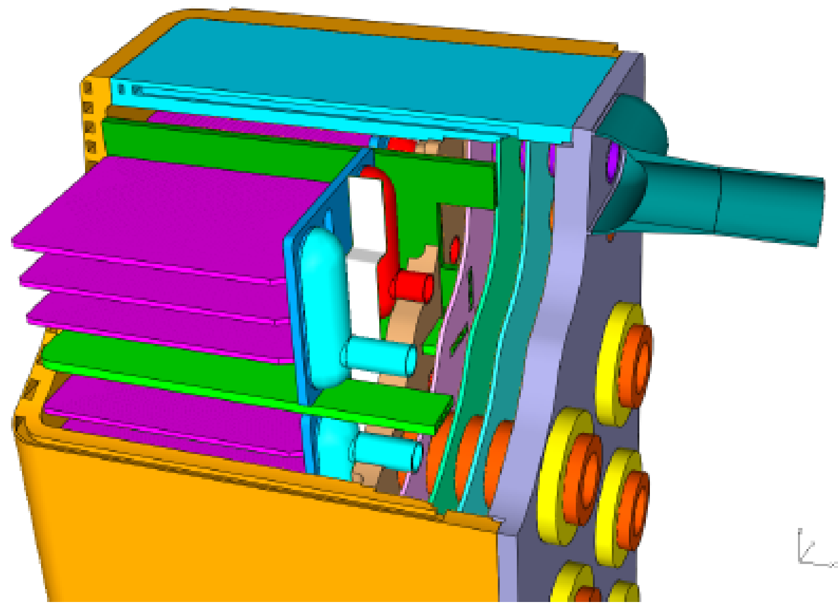
# Helium Cooled Lithium-Lead Test Blanket Module

## The EU TBMs to be tested in ITER (1/3)

Euratom cea




**The HCLL TBM concept**



Size (mm): **484** (tor) x **1660** (pol) x **575** (rad)

- PbLi liquid circulates in Breeder Units
- He cooling (8 MPa, 300-500°C) of all subcomponents (in series)

J-F. Salavy et al. ICFRM-13, December 10 - 14, 2007, Nice, France 9

# Helium Cooled Lithium-Lead TBM Details

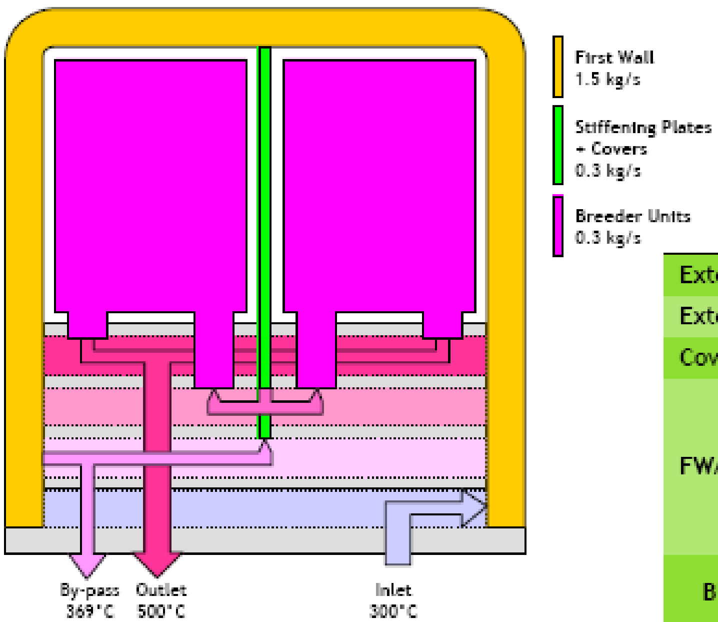
cea

Association Euratom-Cea

## Design Updates (2/3)

Mass of ferromagnetic steel = 1300 kg

Six TBMs to be installed with two in each horizontal port at $\varphi = 0°$ and $\pm 40°$




•New He flow scheme

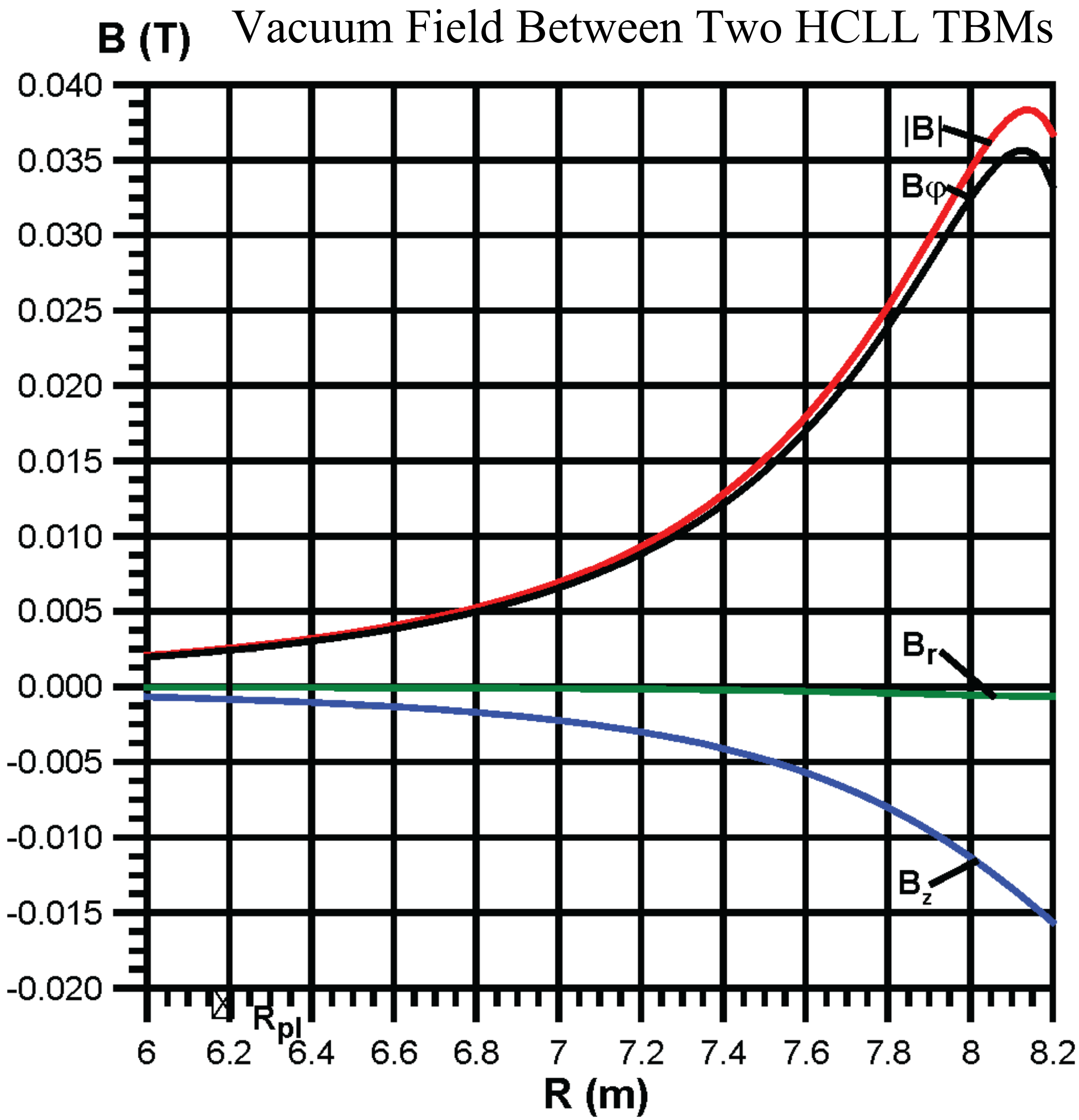
•Preliminary geometric data

| | | |
|---|---|---|
| External max. dimensions (t x p) | | 484 x 1660 mm² |
| External dimensions (r x t x p) | | 573 x 484 x 1655 mm³ |
| Covers thickness | | 30 mm |
| FW/SW | •*Thickness* | 30 mm |
| | •*Channels section (w x h)* | 11 x 12.5 mm² |
| | •*Number of channels passes* | 3 |
| | •*Channels pitch* | 22.3 mm |
| | •*Channel legs per BU* | 9 |
| BU | •*Breeding Cells dimensions (r x t x p)* | 372 x 206.5 x 189.7 mm³ |
| | •*Number of Cooling Plates* | 3 |
| | •*Cooling Plates pitch* | 44.6 mm |
| CP | •*Thickness* | 6.5 mm |
| | •*Number of channels* | 8 |
| | •*Channels cross-section* | 4 x 4.5 mm² |
| SP | •*Thickness* | 11 mm |
| | •*hSP channels cross-section* | 6 x 10 mm² |
| | •*hSP channels number / pitch* | 3 / 15.5 mm |
| | •*vSP channels cross-section* | 6 x 10 mm² |
| | •*vSP channels number / pitch* | 3 / 14.5 mm |

# TBM Effects on Plasma Operations

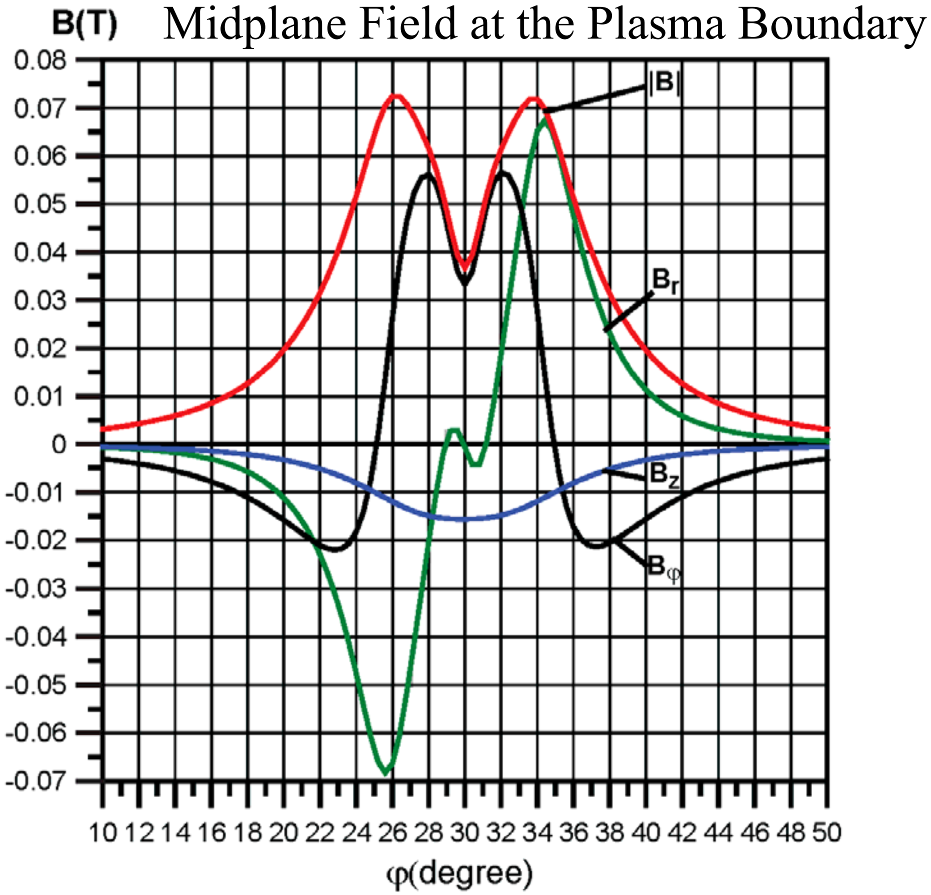
- TBM stray fields effects on plasma breakdown
- Stray field modifications of the plasma equilibrium
- Error field at q=2 surface may produce locked modes
- TBM stray fields will also enhance magnetic braking of $v_{\varphi}$
- Possible effects on access to H-mode
- Expected to reduce thermal confinement in H-mode
- TBM field perturbation increases energetic particle losses
- Relative effects of low and high toroidal mode numbers
- Effects of TBM correction coils

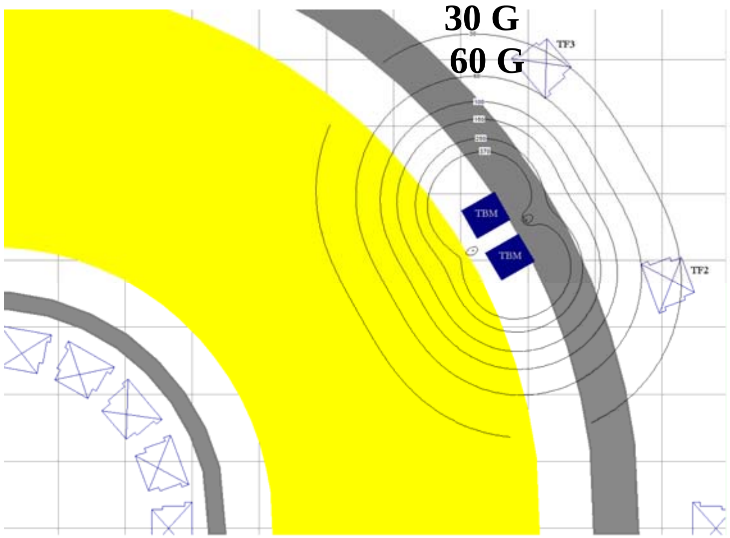
# TBM Stray Fields at Breakdown

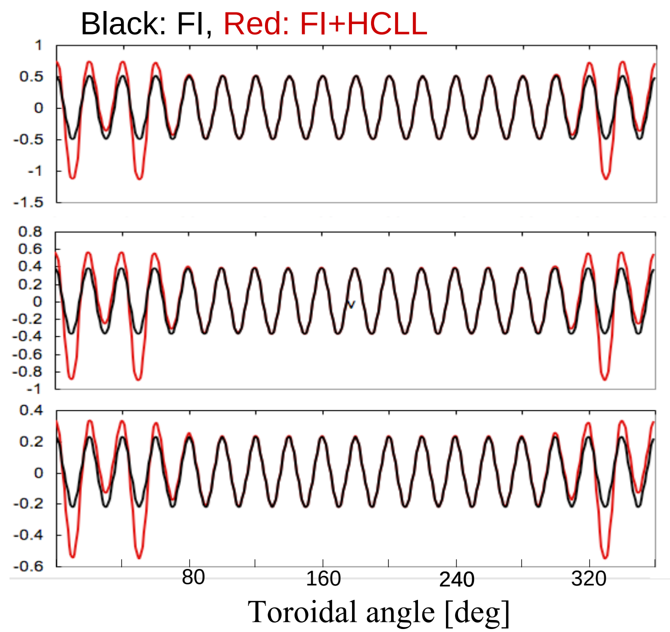



- Recent calculations by Lamzin, et al. estimate peak total stray fields at breakdown ~ 2 mT at $R_0$ in front of two HCLL TBMs
- Since a null for breakdown needs to be less than a few mT, this stray field may be tolerable particularly with ECH assist

# TBM Stray Fields Modify Plasma Equilibrium



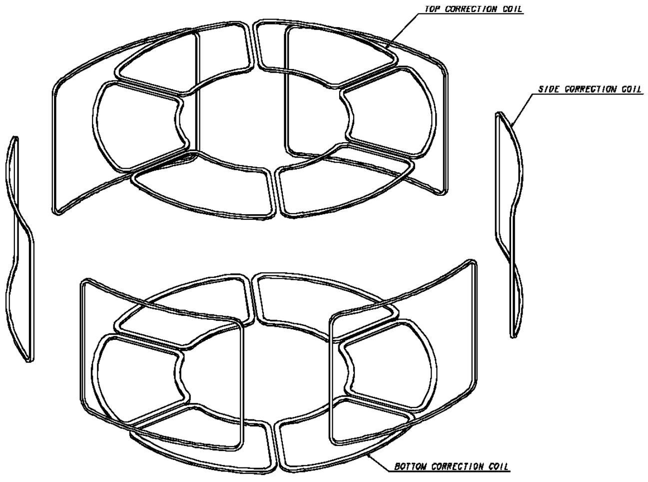




- The magnetic moments in the TBM align with the field and the field lines return through the plasma opposing the field in the plasma reducing the field where it is already at a minimum TF ripple
- The plasma is calculated to bulge out toward the TBMs by ΔR~12 mm locally

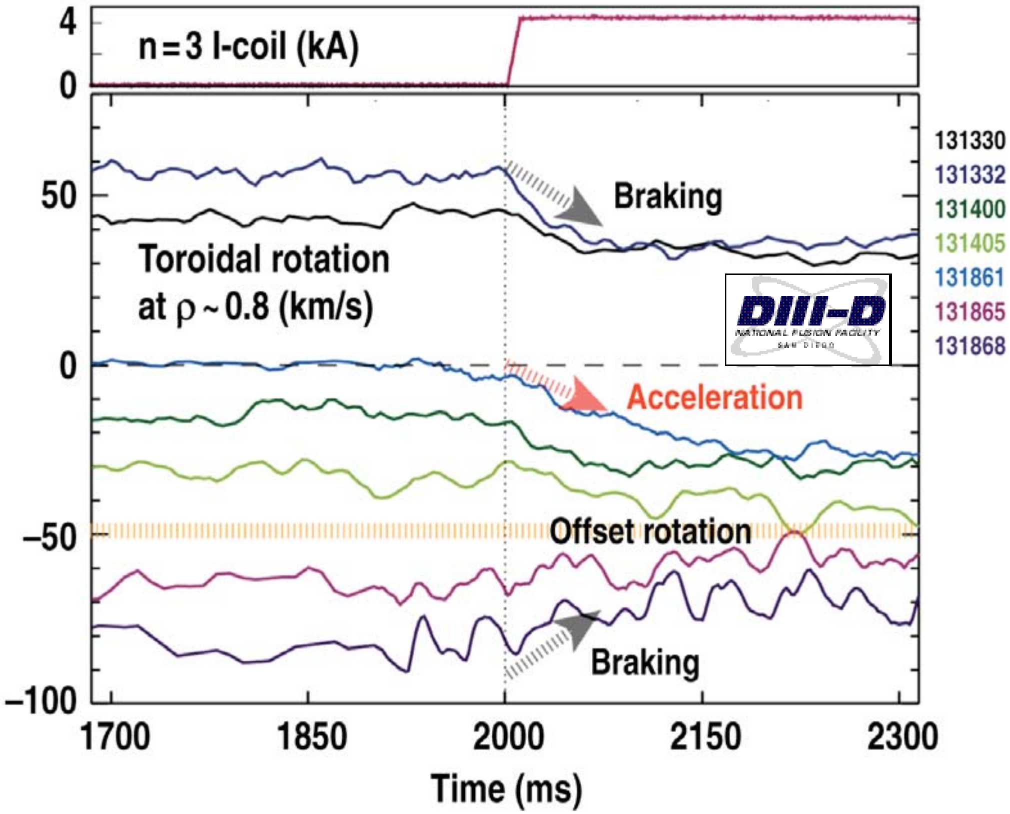
# Vacuum TBM Stray Fields at q=2 Can be Corrected

- Calculated vacuum TBM stray fields at q=2 for six 1.6 ton JA water cooled TBMs: $B_{1,1}/B_0 = 2.1 \times 10^{-5}$, $B_{2,1}/B_0 = 5.7 \times 10^{-6}$, $B_{3,1}/B_0 = 9.8 \times 10^{-6}$
- Calculated correction coil currents required to compensate are: -8 kAt Top, -0.1 kAt Side, 10 kAt Bottom, which are within the 140 kAt Top, 200 kAt Side, and 180 kAt Bottom current limits
- Note that the total stray field from all sources is expected to be $|B|/B_0 < 11 \times 10^{-5}$ which can be corrected with currents of ±70 kAt, 50 kAt, 100 kAt in the top, side and bottom coils




- However, vacuum fields do not include the plasma resonant field amplification effects that can enhance magnetic islands
- Low toroidal mode numbers fall off less rapidly deep into the plasma
- Plasma effects still need to be included in these stray field calculations

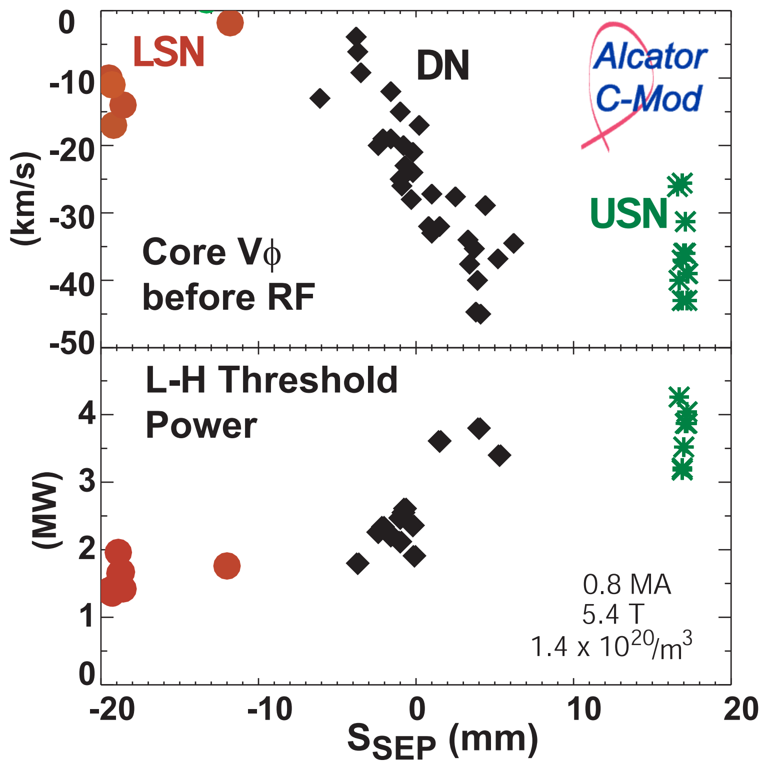
# TBM Stray Fields Can Enhance Magnetic Braking

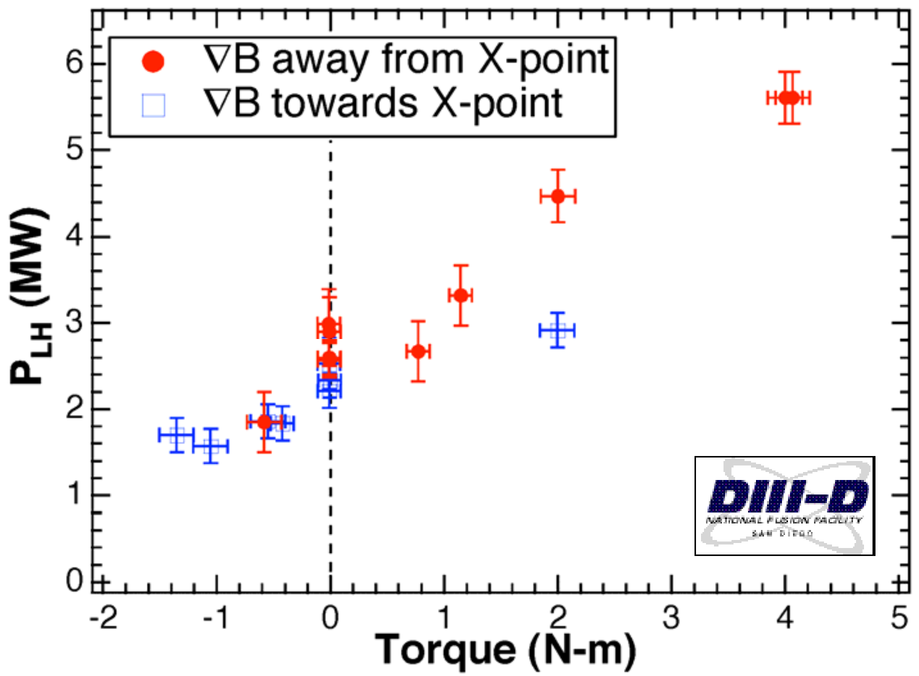



- Plasma rotation can be substantially reduced through magnetic braking with magnetic field perturbations
- DIII-D finds substantial slowing down of the plasma toroidal rotation when they energize the n=3 I-coils to stabilize ELMs

- However, when the plasma rotation is already near zero, the same n=3 perturbation can accelerate the plasma in the cntr-Ip direction
- The effects of TBM magnetic perturbations on the plasma rotation need to be studied in detail

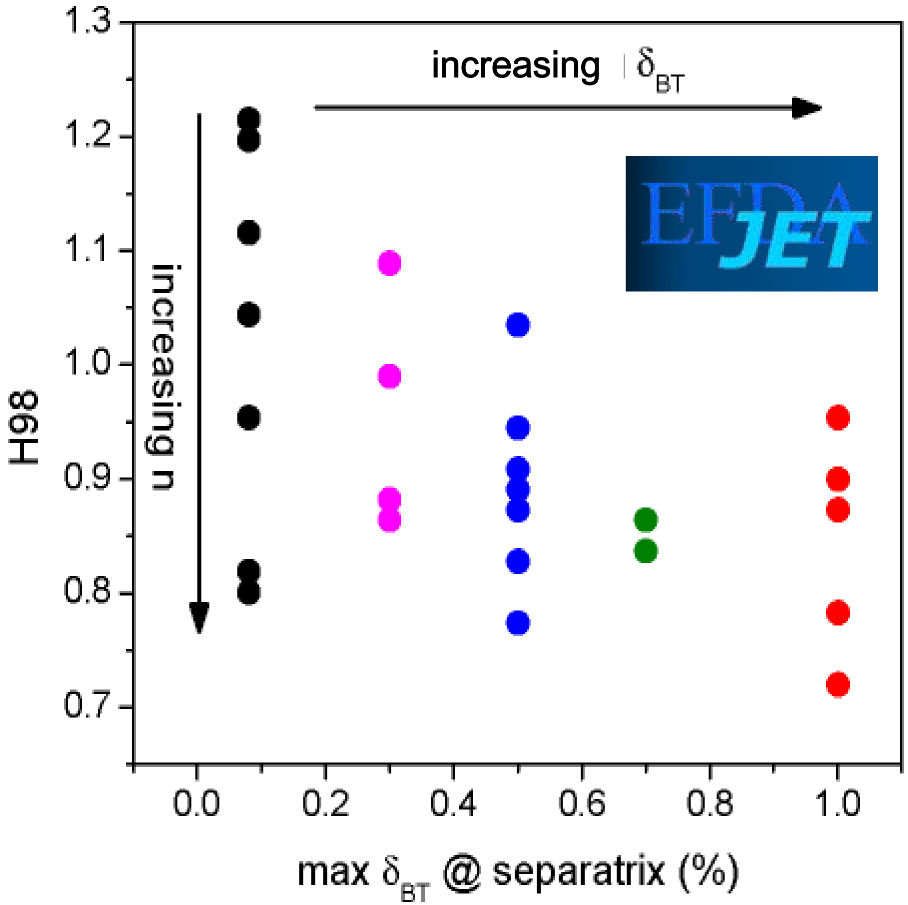
# TBM Stray Fields May Affect H-mode Access




- Plasma rotation is linked to the H-mode threshold in C-Mod and DIII-D
- Changes in the plasma rotation or in the edge pedestal region could make it more difficult to achieve H-mode
- H-mode experiments with a mock-up TBM are needed to address this issue

# TBMs May Reduce H-mode Confinement

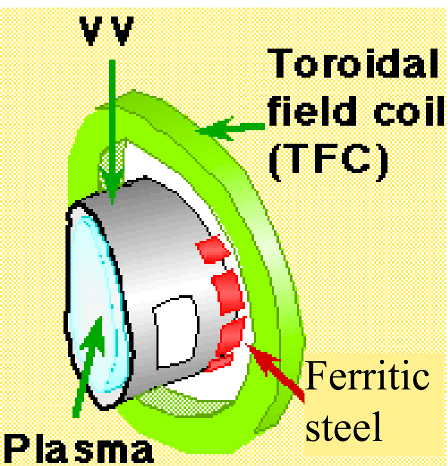



- JET experiments varying TF ripple show that energy and particle confinement degrade with increasing ripple in H-mode
- The degradation is strongest at the lowest density and lowest ν*
- NB driven co-Ip rotation also decreases and even goes cntr-Ip at the highest ripple values
- Strong gas puffing is required to compensate for density pumpout with increasing ripple ➔ more demands on fuelling system

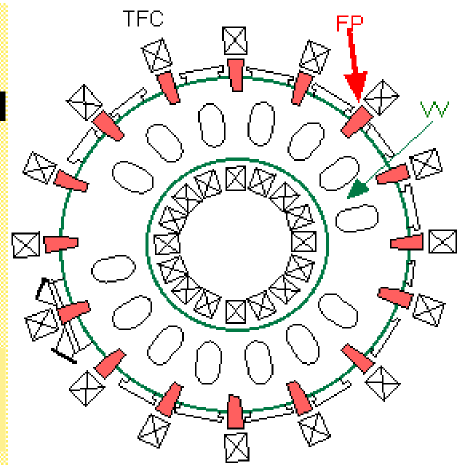
- Localized ripple due to TBMs is likely to have similar or stronger effects
- H-mode experiments with a mock-up TBM are needed to address this issue

# Effectiveness of TF ripple reduction by ferritic steel was first demonstrated in JFT-2M

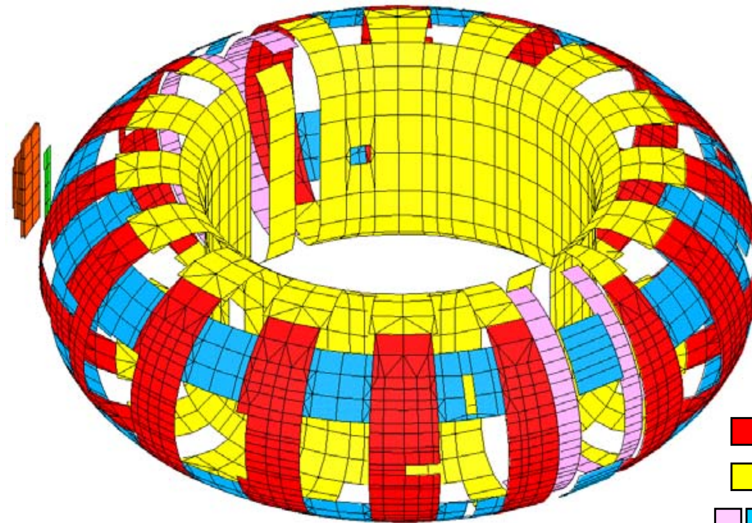
Ferritic steel was inserted between each TF coil and vacuum vessel



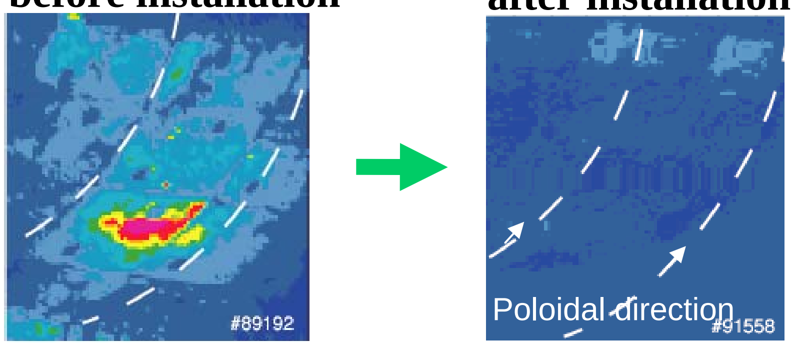

Ferritic steel



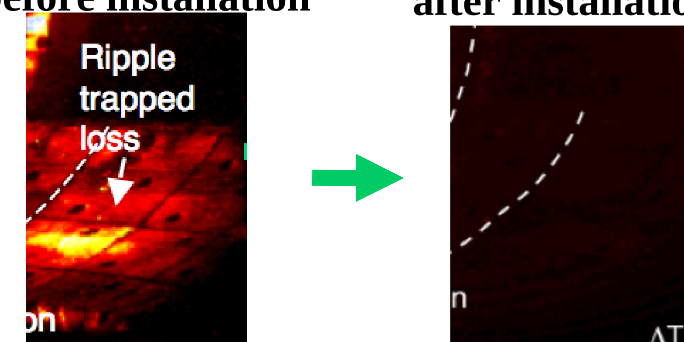

Full covering inside wall in VV => ferritic steel can be used as a structural material in a tokamak (ripple reduced with optimized distribution)




before installation after installation



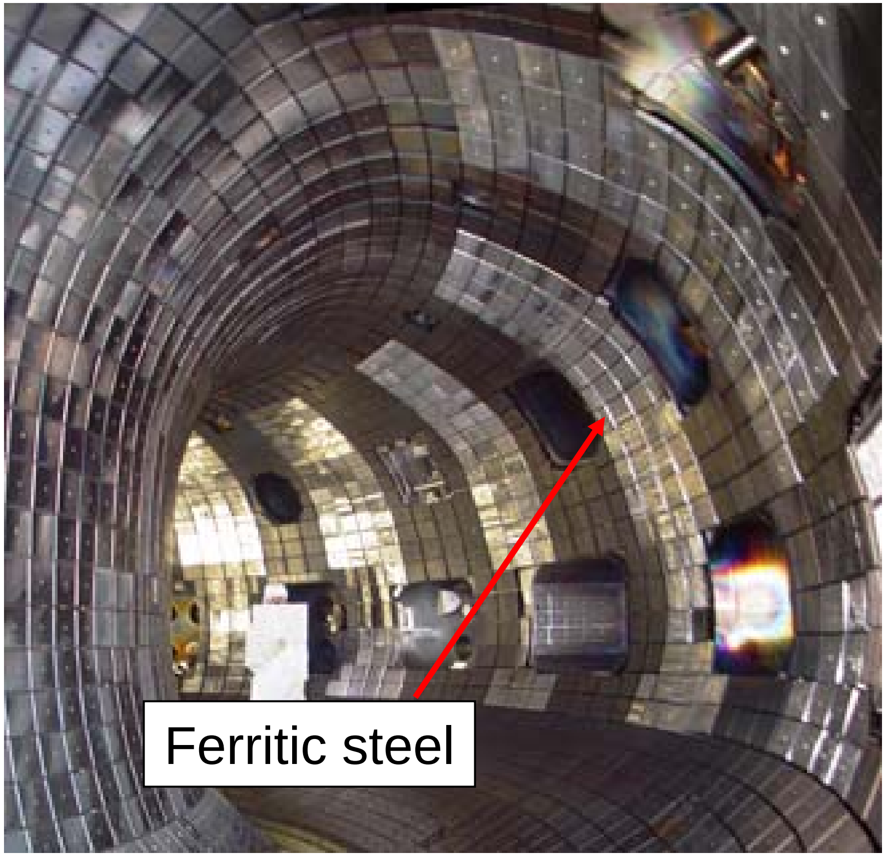

before installation after installation



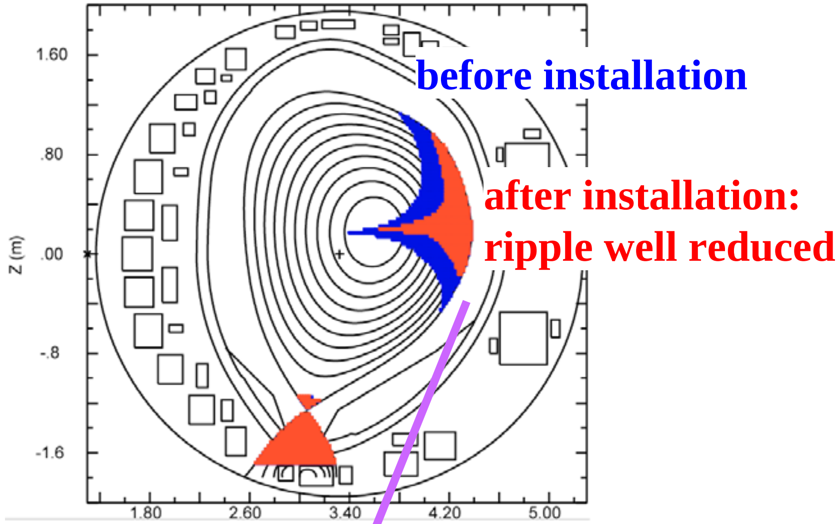

K. Shinohara, et.al.., *Fusion Sci. Technol.* **49** 187 (2006)

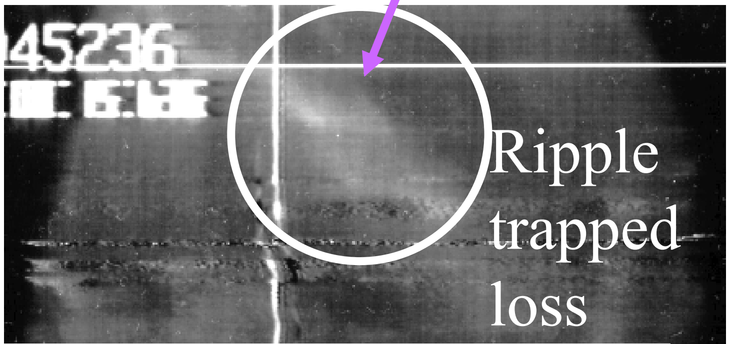
K. Tsuzuki, et.al.., *Fusion Sci. Technol.* **49** 197 (2006)

# Effectiveness of TF ripple reduction was also demonstrated in JT-60U




K. Shinohara, et.al. , Nucl. Fusion **47**, 997 (2007)



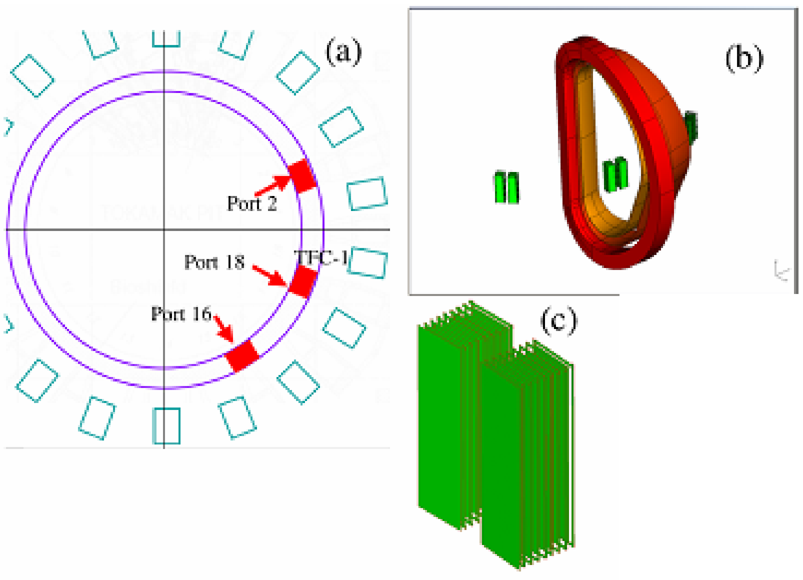



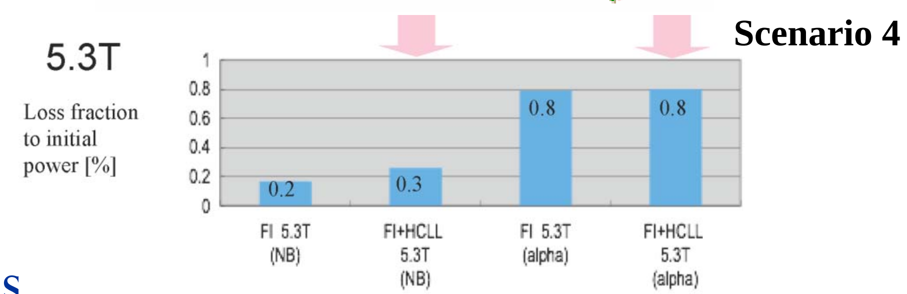

**NB of 22 MW was injected for 1.5 s**

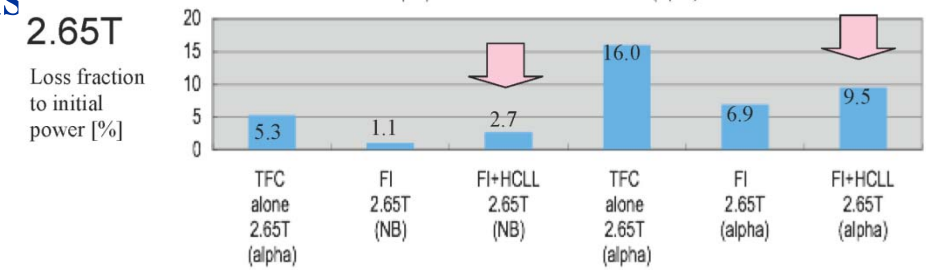
**Temperature increment was <20 $^{o}$C from IRTV measurement ➔**
**heat flux < 0.2MW/m$^2$ (after installation)**
**> 1 MW/m$^2$ (before installation)**

# TBMs Will Increase Energetic Particle Losses

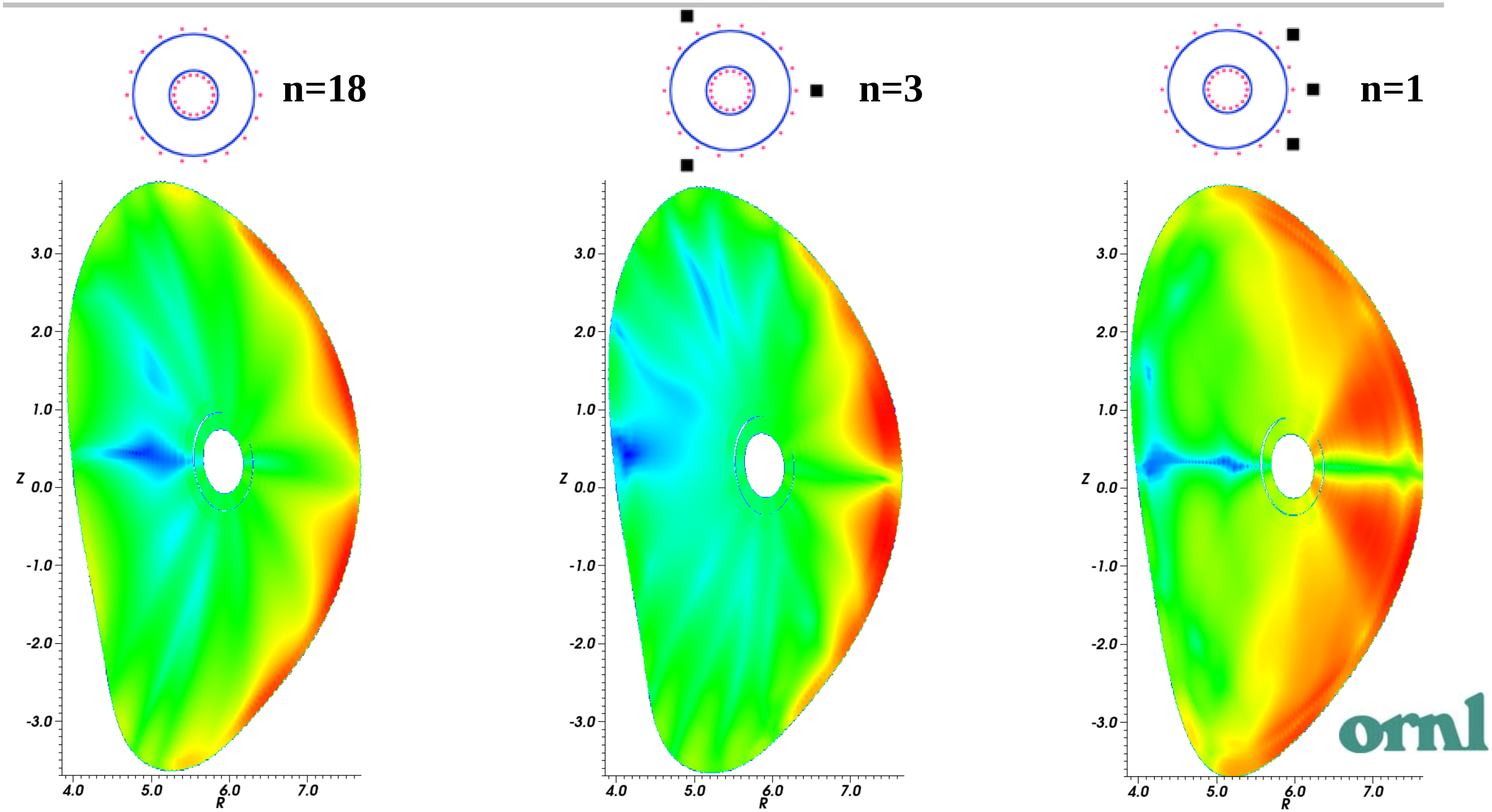
- TF ripple effects on fast ion losses
  - Expected TF ripple with ‘optimized’ ferritic inserts has $\delta_{TF} \leq 0.4\%$
  - Expected fast ion heat loads < $0.5 MW/m^2$
- TBM magnetic perturbation is expected to increase fast ion losses
- Calculations by Shinohara, et al., with 6 HCLL TBMs show the same α particle losses and slightly more NB fast ion losses at 5.3 T
- At 2.65 T, fast ion losses increase substantially up to 2.7% for NB ions
- Substantial α losses preclude DT operation at low field even without TBMs



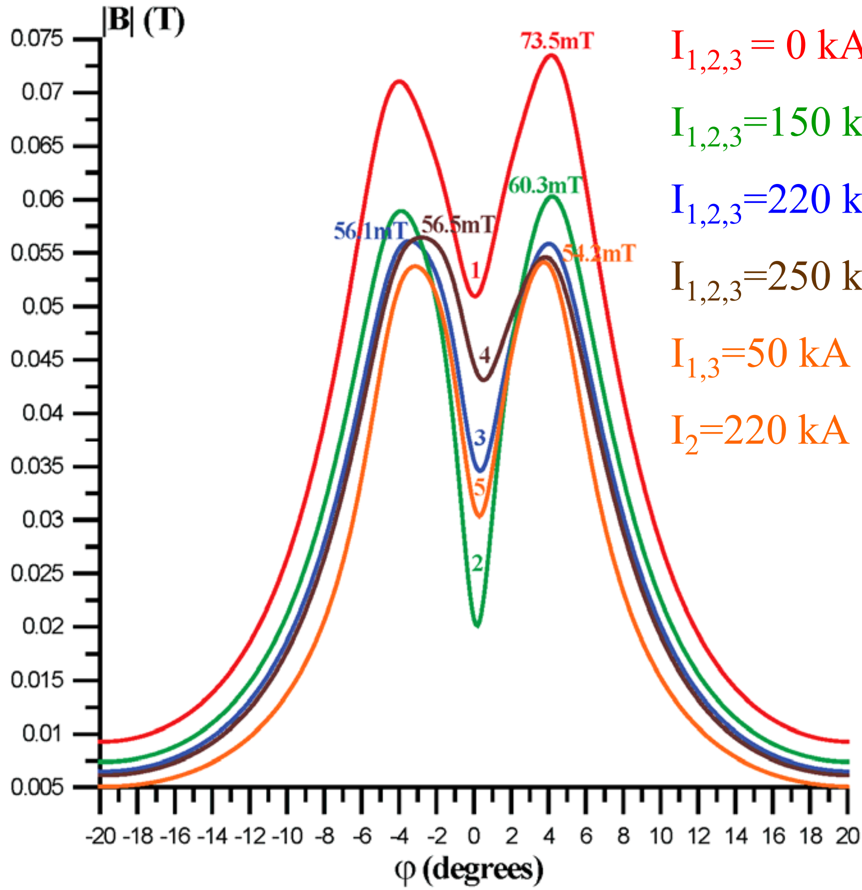
# Low n Numbers Penetrate Deeper into the Plasma




- Localized ripple due to TBMs is likely to have similar or stronger effects
- H-mode experiments with a mock-up TBM are needed to address this issue

# Effects of TBM Correction Coils

Field at the Plasma Boundary at Z=0




$I_{1,2,3} = 0$ kA

$I_{1,2,3}$=150 kA

$I_{1,2,3}$=220 kA

$I_{1,2,3}$=250 kA

$I_{1,3}$=50 kA +

$I_2$=220 kA

- Calculations done by Lamzin, et al, placing 3 correction coils on either side and in between HCLL TBMs
- The optimum correction is ~ 35% with 220 kA in central coil + 50 kA in both side coils
- These would be massive coils with >15 cm cross-section requiring thermal insulation and active cooling
- With no correction coils, the radial decay of the TBM vacuum field requires the front face recessed 92 cm for 0.5% TF ripple at R = 8.2 m

- With a mass of 0.65 tons the TBM should be recessed 35 cm for 0.5% ripple
- To have the TBM closer to the plasma requires reduced mass + correction coils

# Conclusions I

- Effects of TBMs on breakdown are probably tolerable with ECH assist
- Plasma equilibrium outward bulge $\Delta R \sim 12$ mm will require increased gaps to avoid enhanced heat loads
- Calculated m/n=2,1 error field expected to be correctable to avoid locked modes but makes additional demands on correction coils
- Effects on magnetic braking of plasma rotation still need to be assessed
  - Need magnetic braking calculations and rotation experiments with a mock-up TBM
- Possible effect on H-mode threshold can only be assessed with experiment
  - Need H-mode threshold experiments with a mock-up TBM
- Reduced H-mode confinement expected for ripple > 0.5% but needs to be assessed with TBM mock-up experiments in H-mode
  - Need H-mode confinement experiments with mock-up TBM

# Conclusions II

- Enhanced fast ion heat loads expected to be < 0.5 MW/m2 but calculations with 3D plasma equilibrium still need to be checked
  - Need 3D equilibrium calculations of fast ion heat loads with TBMs
- A toroidally symmetric distribution of TBMs would reduce penetration of TBM stray field effects deep into the plasma but calculations need checking
  - Need to quantify change in TBM field penetration with n=3 symmetry
- Placing the TBMs at R=8.73 m (recessed 35 cm) and reducing the mass to 0.65 tons may eliminate the need for correction coils to obtain TBM ripple < 0.5%
  - Need to determine the impact on TBM program of ½ size TBM and 35 cm distance to the first wall