Measuring Error Fields in ITER Before Its First Plasma*

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Challenge to Meet Implicit ITER Requirement for Detecting Error Fields < 5 × 10^{-5}B$_T$

- Primary concern has been components with toroidal periodicity *n* = 1

$$B_{\mathrm{TMEI}} \equiv \sqrt{0.2B_{1,1}^2 + 1.0B_{2,1}^2 + 0.8B_{3,1}^2} \le 5\times 10^{-5} B_{\mathrm{T0}} \text{ (at } q = 2 \text{ surface)}^{*}$$

  - Recent study shows higher poloidal harmonics may also be important[‡]

- Desirable to measure error fields in ITER ***as-built*** to characterize basic coil perturbations
  - Requires TF & PF coils at operating temperature and under EM loads

- Accurate positioning and alignment of sensors required to detect perturbations ~0.1 mT in presence of background fields 2 - 5 T
  - Ferromagnetic Inserts (FI) to reduce TF ripple affect local measurements

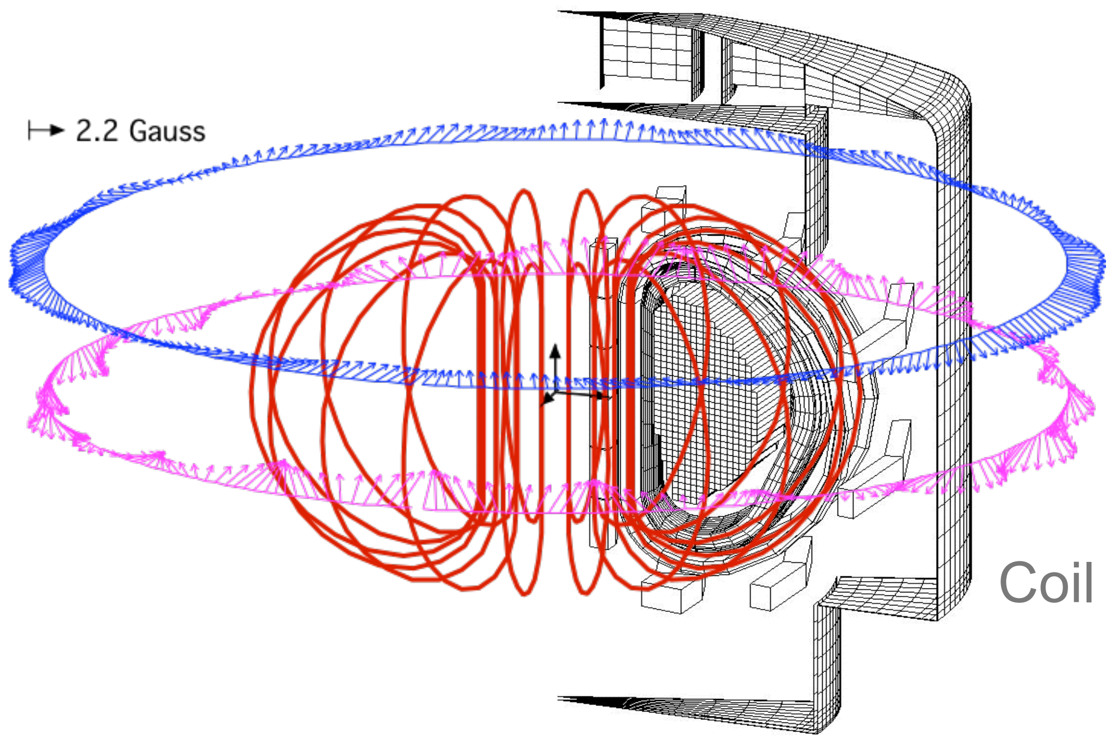
- Approach adopted depends on accuracy deemed necessary
  - Ensure 18 Correction Coils in ITER can provide first-order compensation
  - Plasma response can then reveal more subtle features of error fields

[*] *ITER Physics Basis, Nucl. Fusion* **47** (2007) S128–202 [‡]Menard et al. *report ITER_D_4GFSS3*

Measurements *Outside* TF Coil Could Identify Some Manufacturing and Assembly Defects

- Only field *errors* ($m,n \neq 0$) are present outside TF coil envelope
- Ripple (n = 18) component decays roughly as R^{-n} so low-n components dominate at large R
- Model TF as 18 filamentary coils and apply low-order perturbations

TF coil perturbation
dR(n=1) = 10mm,
dZ(n=2) = 10mm



R = 18m,
Z = 5m

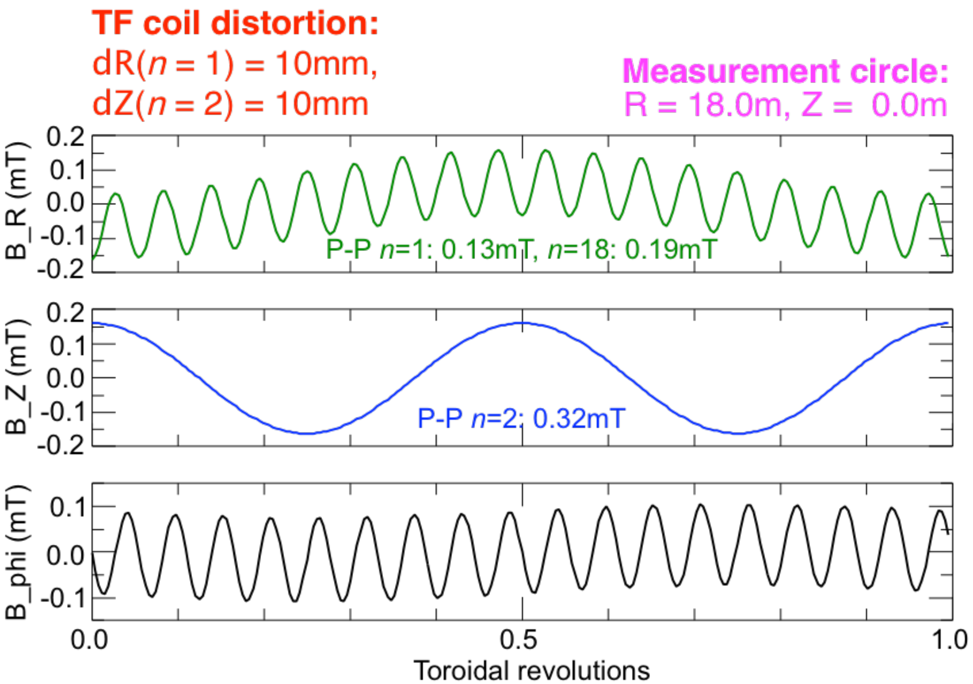
R = 18m,
Z = 0m

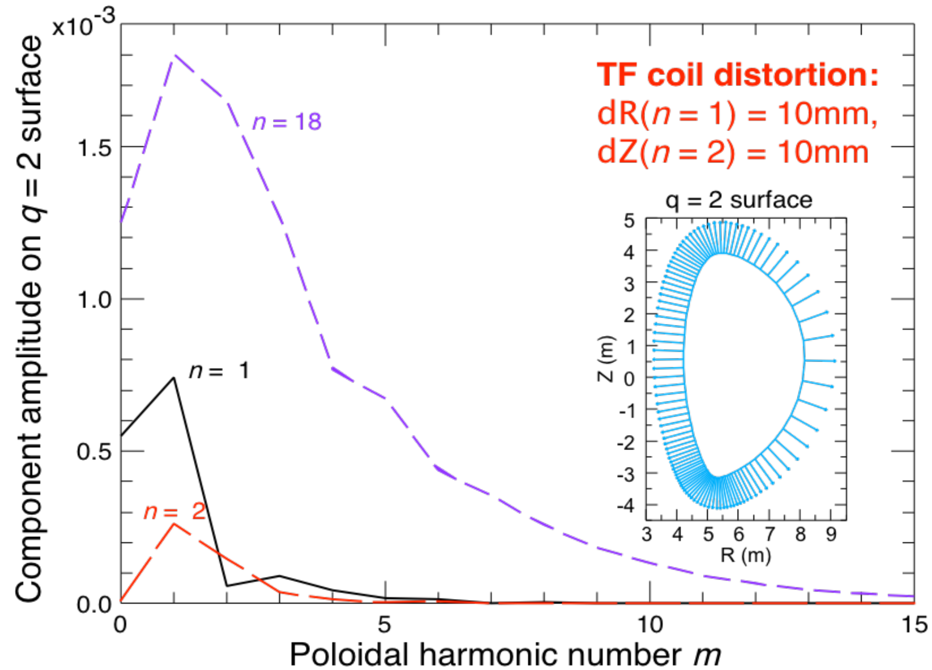
Coil cryostat

- Measure B_R, B_Z at well defined locations with Hall-effect sensors
  - Discriminate from background field by measuring with TF on and off

Measurements at 0.1mT Level Can Detect Low-*n* Errors at q = 2 Surface of Order $5 \times 10^{-4} B_{T0}$

- Decompose normal component from perturbed TF on q = 2 surface

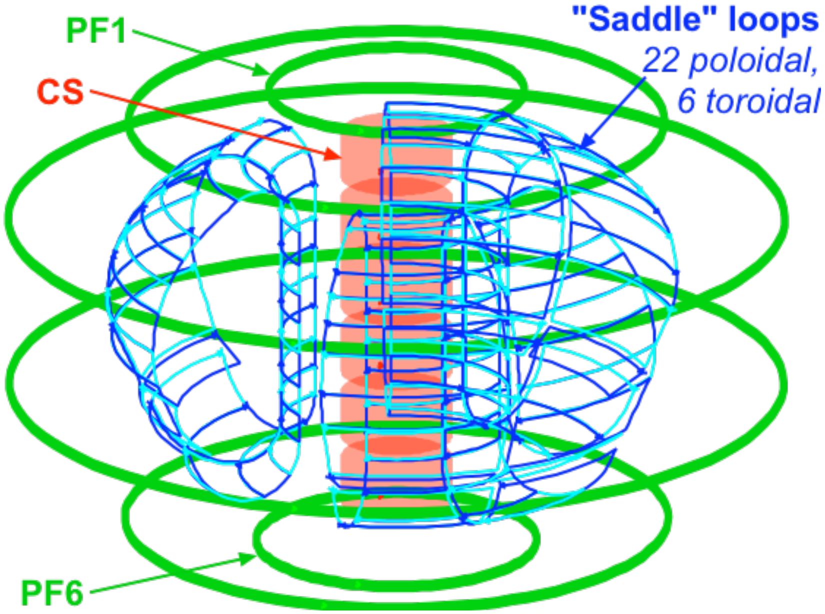


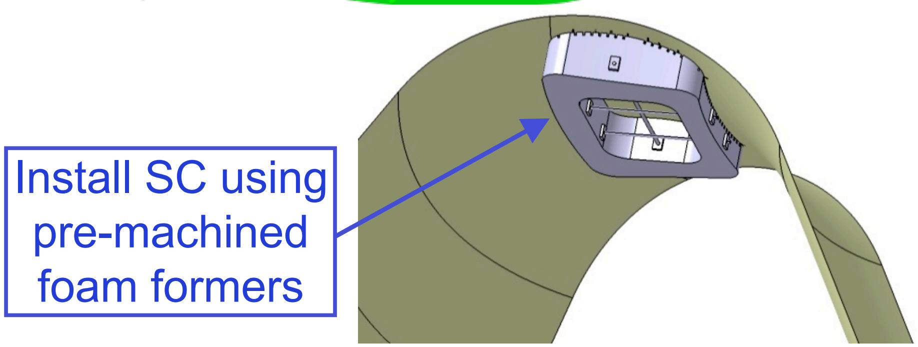


- Assessed effects of FI by modeling them as discrete dipoles
  - n = 1 variation of M_{sat} by 5% only slightly affects sensitivity to n = 1
- Including |B| data from array of NMR sensors at inboard midplane of vacuum vessel improves separation of low-*n* components somewhat
- For higher accuracy, would need to perform electron beam mapping

Planned "Saddle" Coils in ITER Can Be Used to Characterize Field Errors from PF Coils

- Saddle Coils (SC or Partial Flux Loops) mounted on Vacuum Vessel inner wall, toroidally span all or part of a VV sector (40°)
- 22 SC span poloidal circumference in 6 of 9 VV sectors



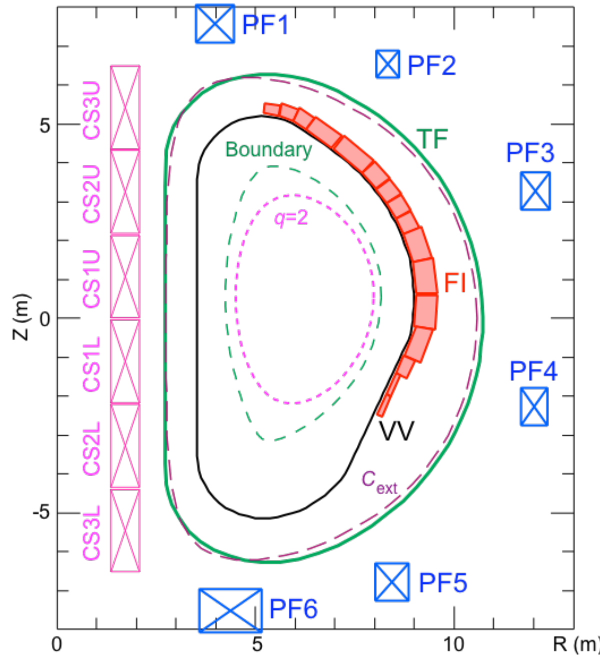


- Conductor positions specified to be known to mm accuracy
- Calculate changes in mutual inductance from perturbations (*e.g.* shifts, tilts) of PF coils and the SC themselves
  - **$\Delta\psi_{max}$ ~ 2mWb typically for perturbations ~$10^{-3}R_0$, I_{PF} = 10kA**
- To measure small changes in mutuals, take one sector as reference and difference equivalent coils in other sectors ⇒ **110 flux differences**

Compensate for Coupling of SC to PF Coils Due to Nearby Ferromagnetic Inserts

- SC are close to FI between inner and outer shells
- Model FI as discrete dipoles (864) to calculate flux through each SC

$$\Delta\psi_j = \frac{\mu_0}{4\pi}\sum_i \oint_{C_j} \frac{\boldsymbol{m}_i \times \boldsymbol{r}_{ij}}{r_{ij}^3} \cdot d\boldsymbol{s}_j$$



- Apply constant TF to saturate FI
- Align each dipole with local *total* field $\boldsymbol{B} = \boldsymbol{B}_{PF} + \boldsymbol{B}_{TF}$: $\boldsymbol{m} = m_0\boldsymbol{B}/|B|$
- For $B_{PF} << B_{TF}$, change in coupling produced by FI $\Delta\psi_{FI} \propto I_{PF}/I_{TF}$
- $\Delta\psi_{FI}$ can exceed that from prototypical PF coil perturbations $\Delta\psi_{PF}$
- If we measure coupling at same I_{PF} and two values of I_{TF}, then

$\Delta\psi_1 = \mu I_{PF0}/I_{TF1} + \Delta\psi_{PF}$ and $\Delta\psi_2 = \mu I_{PF0}/I_{TF2} + \Delta\psi_{PF}$, so

$$\boldsymbol{\Delta\psi_{PF} = (I_{TF1}\,\Delta\psi_1 - I_{TF2}\,\Delta\psi_2)/(I_{TF1} - I_{TF2})}$$

Use Numerical Techniques to Extract Both Coil Displacements and Error Fields from Data

- Allow both perturbations of PF and SC from nominal geometry to be free parameters determined by data from excitation of *all* coils
- In-plane shifts (Δx, Δy) and tilts ($\Delta\alpha_x$, $\Delta\alpha_y$) of 12 PF coils and basic perturbations (ΔR, ΔZ, $\Delta\alpha_\phi$, ΔA) of 132 SC $\Rightarrow$ 576 unknowns **X**
- 110 flux differences × 12 PF coils $\Rightarrow$ 1320 measurements **S**
- Calculate elements of (sparse) matrix $\mathbb{M}$ relating **S** to **X**: $\mathbf{S} = \mathbb{M}\mathbf{X}$
- Use SVD to calculate condition of $\mathbb{M}$ and its pseudo-inverse
  - Matrix is reasonably well conditioned but solution degenerate w.r.t. displacements of reference SC sector
- Determine subset $\mathbf{X}_{SC}$ then recalculate $\mathbb{M}_{PF}$ for coil displacements
- Displacements of each PF coil are well determined by data
  - predominantly from a few SC for each PF coil

Methods Used to Measure Basic Coil Displacements and Error Fields Depends on Accuracy Needed

- Proposed accuracy ($5 \times 10^{-5} B_T$) difficult, time consuming and expensive, *so*
- It is critical to establish what components at what level are really important
- Relatively simple techniques can reveal errors which can be compensated with ITER's (external) Correction Coils
- For TF, arrays of Hall sensors (~100) accurately mounted outside cryostat can reveal errors leading to $n = 1$ components ~$5 \times 10^{-4} B_T$ at $q = 2$ surface
  - For higher sensitivity to TF errors, use electron-beam measurements
- For PF coil errors, measure mutual inductances to full set of Saddle Coils
  - Make measurements with TF applied to saturate Ferromagnetic Inserts and correct for effect on PF coupling by measuring at different TF levels
  - Ideally make use of accurate metrology of loops on inner VV surface, *but*
  - Can also refine flux loop geometry through analysis of full data set to determine coil perturbations responsible for errors ~$5 \times 10^{-4} B_T$