Field Error Control

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Field error control

Objective

Assure that field errors will not compromise NCSX performance

Approach

1. **Establish preliminary tolerance requirements based on historical precedent**
2. **Assess impacts assuming preliminary tolerance requirements**
3. **Assess impacts from known sources of field errors**
4. **Assess cost sensitivity to tolerances**
5. **Finalize tolerance requirements based on both performance and cost**
6. **Incorporate trim coils to enhance flexibility**
7. **Use state-of-the-art measuring equipment for fabrication and assembly**

Historical tolerances

- **A true position tolerance (TPT) of ~0.1% is the historical norm – *this is our starting point!***

- **HSX (R=1.2m)**
  - **Perturbation studies: 5mm displacements resulted in increased stochasticity in the edge. 2mm displacements did not have noticeable effects.**
  - **Misalignment of field periods was a more of a concern than random errors in individual coils (D. Anderson)**
  - **Assembled to within 1mm measured on 6 pts per coil. Well-formed surfaces with no visible magnetic islands (S. Anderson, ISW99).**
- **LHD (R=3.9m)**
  - **Width of m/n=1/1 islands measured at 8cm, 2/1 islands at 5cm**
  - **2mm coil misalignment would only account for 4cm islands**
  - **Ferromagnetic material and errors from leads are suspected causes of larger than expected islands**
- **W7-X (R=5.5m)**
  - **TPT of a few thousandths of nominal values specified (Wanner, ISW99)**
  - **Coil cases being machined to within 2mm at critical points (Hanberg)**

Impact of allowable perturbations

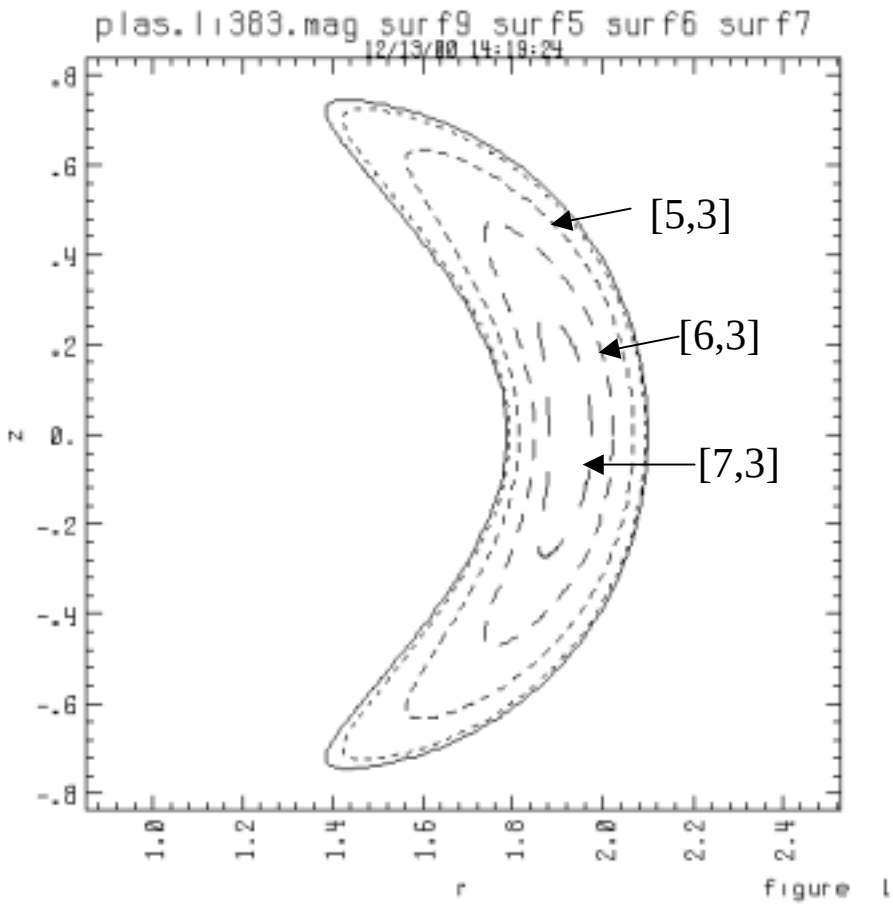
- **Impose perturbations on ideal coil geometry and calculate resonant field at plasma. Analytically predict island size due to the perturbation.**

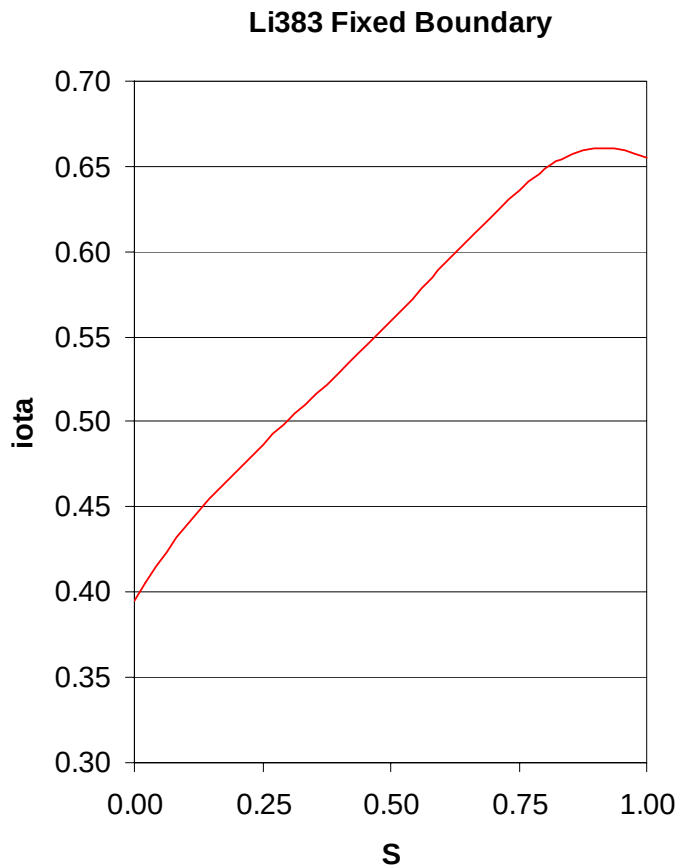
- **Analytically predicting induced island size in the core**
  - **Plan is to benchmark analytic estimates against PIES for a perturbation that preserves stellarator symmetry, then use the analytic estimate for general perturbations**
  - **Calculations based on reference plasma configuration**

- **Global perturbations (all modular coils affected) are being addressed first**

3 resonant surfaces were targeted

- Iota=0.6 (5/3, 10/6), 0.5 (2/1, 4/2, 6/3, 12/6) and 0.43 (7/3, 14/6)





Perturbations affecting all coils were addressed first

- **Goal is to limit the toroidal flux in islands to <10%**
- **Half is budgeted for islands from known sources, half for islands due to construction errors (TBR)**

Coil Distortions Errors

(2 mm max, m=0…6)

Impose distortions of each modular coil of form:

$dR = 2mm * \sin(m\theta)$

$dZ = 2mm * \sin(m\theta)$

$d\phi = 2mm * \sin(m\theta)$

Repeat for cosine distribution

Coil Assembly Errors

(2 mm max, n=0…6)

Displace or Rotate each modular coil about it's centroid:

$dR = 2mm * \sin(n\phi)$ $Rot(R)= 2mm * \sin(n\phi)$

$dZ = 2mm * \sin(n\phi)$ $Rot(Z)= 2mm * \sin(n\phi)$

$d\phi = 2mm * \sin(n\phi)$ $Rot(\phi)= 2mm * \sin(n\phi)$

Repeat for cosine distribution

2mm perturbations appear marginally OK based on analytic modeling

- Island sizes (as a % of the toroidal flux) were predicted for each perturbation….
  - < 5.0% islands on 2/1 surface due to centroidal displacements
  - < 3.9% islands on 2/1 surface due to coil rotations
  - < 3.0% islands on 5/3 surface due to coil distortions
  - Same experience as HSX

- Islands due to misalignment of coils (rigid body motions) are larger than those due to coil distortions

- 2/1 islands are larger than 5/3 islands although 2/1 surface is deeper in plasma

Field errors from known sources

- Known sources are being inventoried and include
  - Bending magnets and iron yokes in PBX beamlines
  - Coil transitions and leads
  - Building steel

- Analysis is presently underway to determine the error fields at the plasma. Findings will be available prior to the CDR.

Cost sensitivity to tolerance requirements

- **Manufacturing studies will be performed during conceptual design by our industrial participants to assess the cost sensitivity to tolerance requirements**

- **Tolerance requirements will be finalized based on consideration of both performance and cost**

Trim coils will be provided to reduce problematic field errors

- **Our plan is to have an acceptable reference plasma configuration *without trim coils***
  - **Modular coils will be healed so that if they are perfect, the plasma will be island-free**
  - **Tolerances will be set such that if they are met, islands will include <10% of the toroidal flux (including known sources of field errors)**

- **Trim coils will be provided to extend our range of flexibility**
  - **Initially, trim coils will be installed inboard of the plasma at v=0 to fix 5/3 and 6/3 (symmetry preserving) resonances**
  - **The device will be capable of accommodating additional trim coils outboard of the plasma at v=0 as a future upgrade**
  - **The design of trim coils to address symmetry-breaking resonances (the 2/1 for example) is planned – because the mode numbers are low, the coils should not have to be right up against the plasma (e.g. DIII-D) so it has not been our highest priority**

Measuring equipment

- **Ultra-high precision measuring equipment is required for coil fabrication and machine assembly**

- **State-of-the-art laser measuring and coordinate measuring machines are available at PPPL to facilitate final assembly of NCSX**

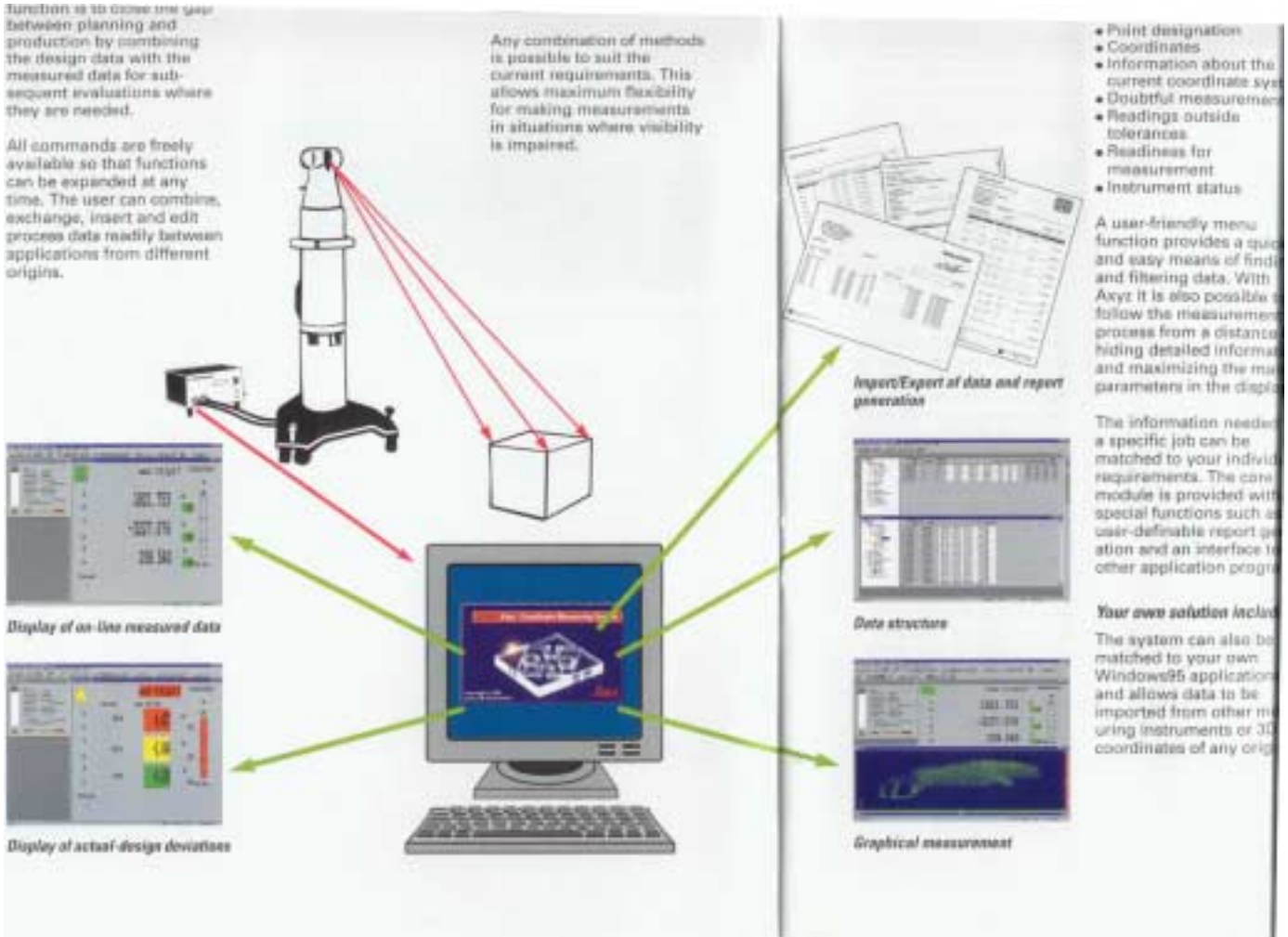
FARO arm for mechanical measurement

- 7-Axis articulated arm
- 12 ft. spherical working volume
- Measurements have an accuracy of +/- 0.007 inches (0.178 mm)
- Operates with CAD based software to display and store measured data
- *Used successfully on HSX and NSTX*

Leica laser measuring system

- accurate within 10 parts per million for non-moving targets

- similar to system being used on W7-X



Laser measurement of W7-X coil case

Summary

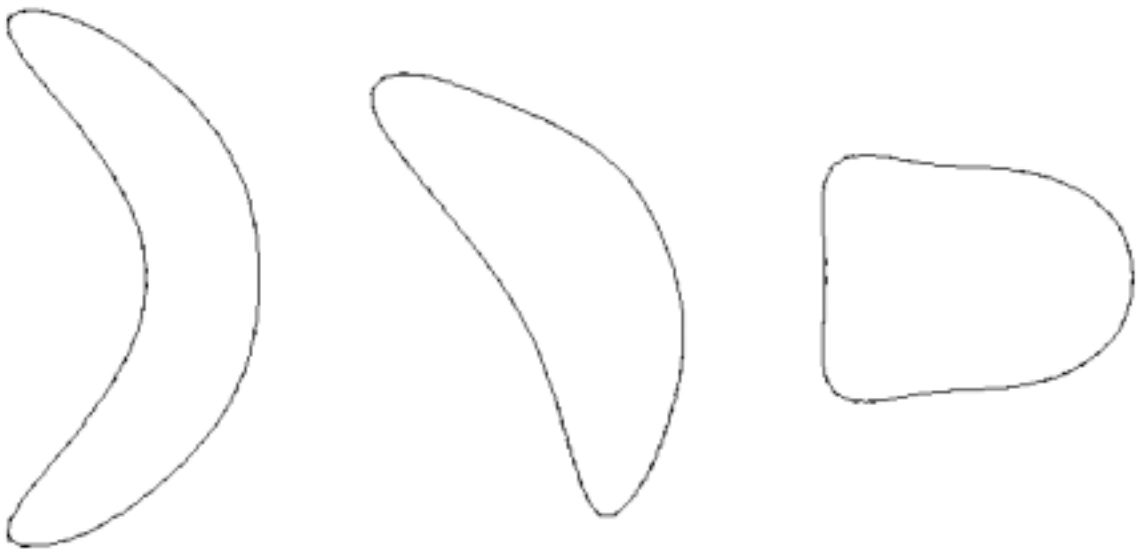
- **A practical plan has been put together to assure that field errors will not compromise NCSX performance**

- **Key elements of this plan are…**
  1. **Establish preliminary tolerance requirements based on historical precedent**
  2. **Assess impacts assuming preliminary tolerance requirements**
  3. **Assess impacts from known sources of field errors**
  4. **Assess cost sensitivity to tolerances**
  5. **Finalize tolerance requirements based on both performance and cost**
  6. **Incorporate trim coils to enhance flexibility**
  7. **Use proven state-of-the-art measuring equipment for fabrication and assembly**

Postscript – Comparison of single and multifilament coil representations show little difference

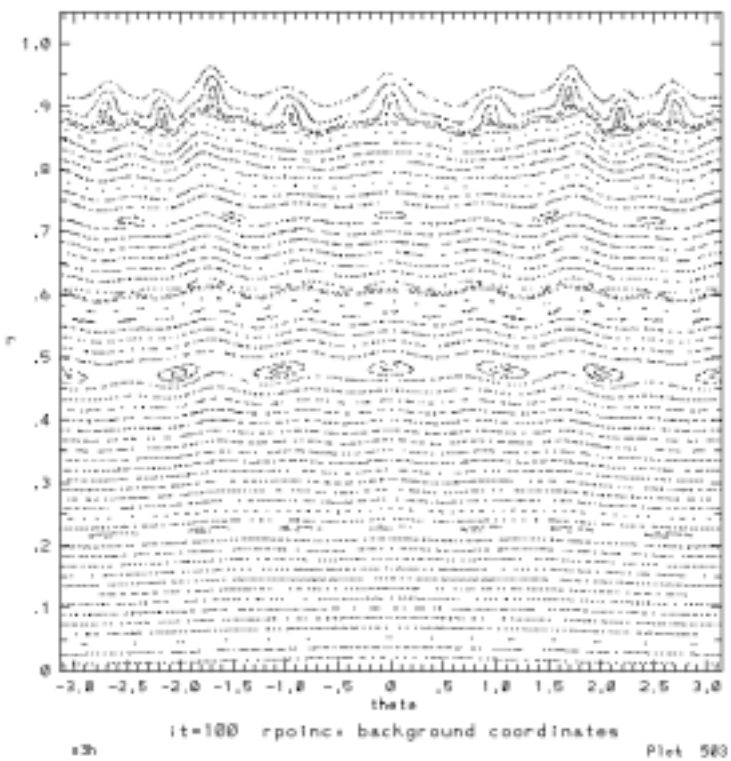
- B_{norm} errors are virtually unchanged
  - Single filament, unhealed (0.570% avg, 2.660% max error)
  - Single filament, healed (0.598% avg, 2.801% max error)
  - Multi-filament, healed (0.606% avg, 2.788% max error)

- Ditto for VMEC boundary (1mm avg, 4.8mm max separation)

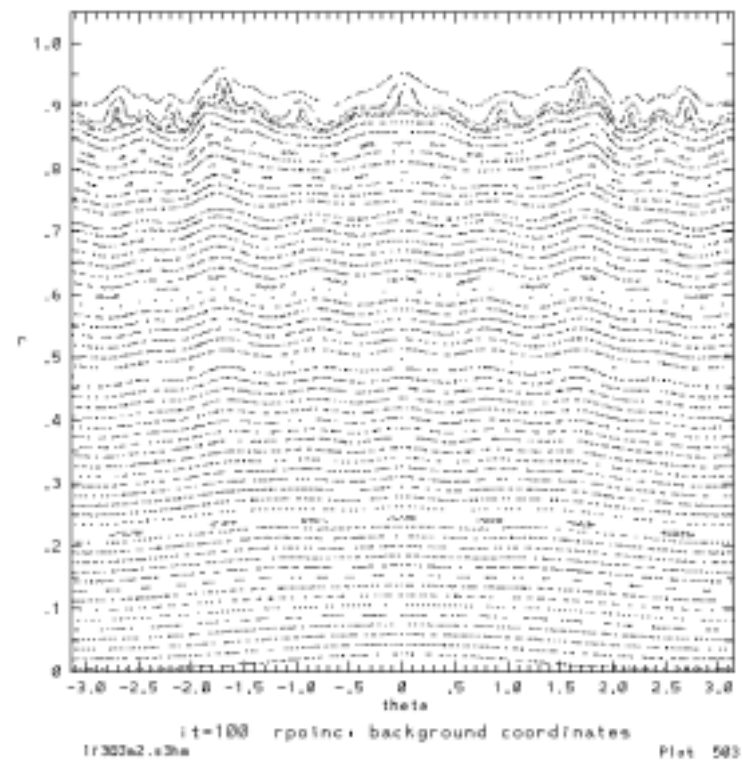


PIES results actually look better with the multi-filament representation

Note: PIES results not converged, shown after 100 iterations



Single filament, healed



Multi-filament, healed