CTH- Status, plans and opportunities

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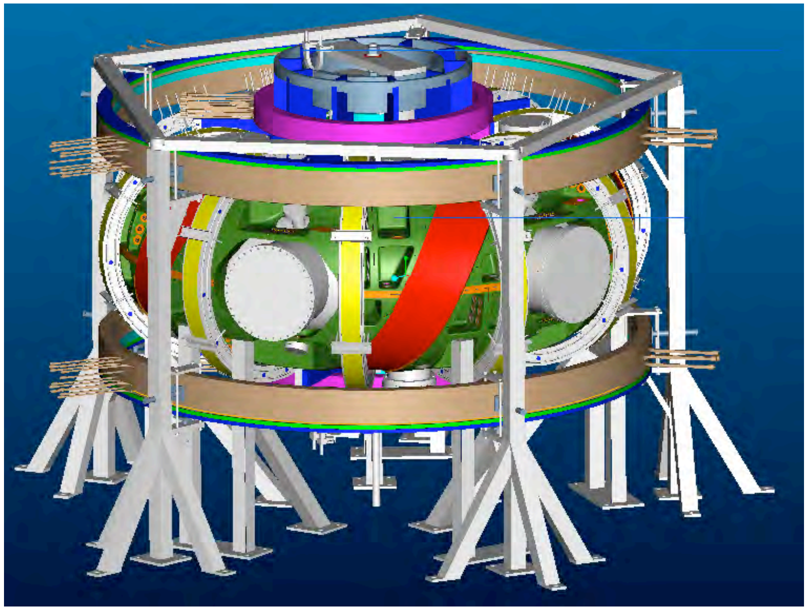
Advertisement for next US/Japan Stellarator workshop

- Last one was Feb. 2004 in Kyoto
- 2-1/2 day workshop
- Current plan: to be held in Auburn right before or right after DPP meeting in Philadelphia
  - Oct. 25-27 or Nov. 6-8
- Expect about 5 Japanese visitors
- Looking for representation from US stellarator labs & theory groups
  - ~ 25 attendees

Overview of Compact Toroidal Hybrid (CTH)



Areas of investigation

- Effect of controlled static islands
- 3-D equilibrium reconstruction
- disruption avoidance in current-driven stellarators

Torsatron configuration with additional:

- Ohmic plasma current for stability studies
- TF coils for vacuum iota control
- Shaping vertical field (SVF) coils for variation of vacuum shear and elongation
- Set of error correction coils

5 field periods

R_o = 0.75 m, R/<a> ≥ 4

B_o ≤ 0.6 T

I_p ≤ 50 kA; $\Delta\iota$ ≤0.5

P_{in}= 20 kW ECRH @18GHz

100 kW OH

Vacuum ι(a): 0.2 – 0.6

Discharge duration: 0.5 s

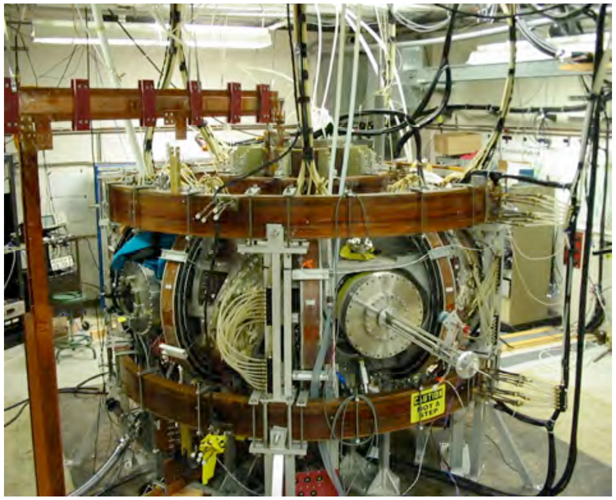
w/ OH: 0.1 s

Compact Toroidal Hybrid to contribute to NCSX research

- <u>Similarities to NCSX</u>
  - Operation with plasma current; current-driven instabilities, potential for disruptions.
  - Strong modification of vacuum equilibrium; need of new reconstruction methods.
  - Controllable rotational transform spanning major rational surfaces
  - Low aspect ratio

- <u>Key differences with NCSX</u>
  - CTH non-symmetric; no optimized confinement or viscosity
  - Low-β, low temperature; resistive time scales shorter
  - focus on equilibrium & stability
  - Scale of effort

Progress and status



Basic assembly completed Winter 2005

- First plasma
- Initial alignment & field mapping
  - -Precision $\Delta x/R \sim 1/500$ sought
  - -Measurement of flux surfaces, magnetic islands
  - -Initial tests of island correction

Recent installation, alignment, and final mounting of all poloidal coils, including OH stack

- Improved coil positions; repaired shorted coil
- Now field mapping with all equilibrium coils
- Magnetic island control studies continuing
- ECRH ready for 2nd harmonic X-mode heating at 0.33 T, fundamental O-mode at 0.66 T.

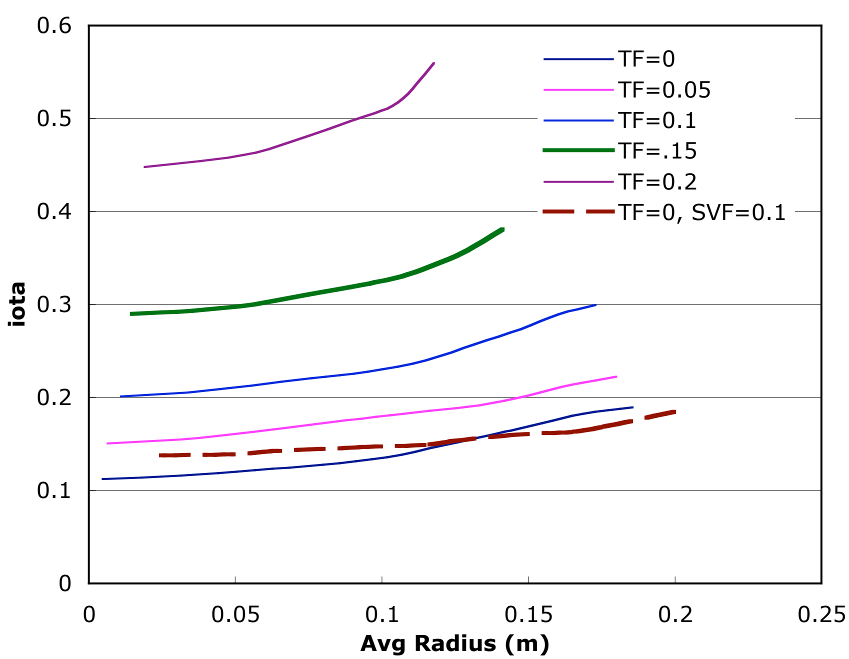
Equilibrium diagnostics

- Ex-vessel magnetics
  - Flux loops, Rogowski coils
- In-vessel magnetics
  - •segmented rogowski coils, (B-dot probes)
- Langmuir probes
- SXR arrays (to be installed later)
- mm-wave interferometry/polarimetry (internal B-field diagnostic under scoping devel.)

Stability studies facilitated by flexibility of CTH configuration

Vacuum rotational transform highly variable with auxiliary toroidal field (TF); can avoid major resonances at edge for range of internal plasma currents

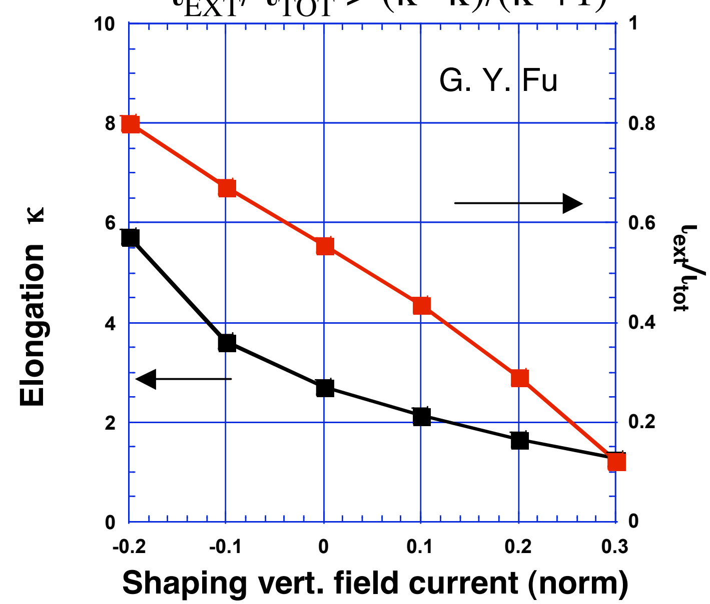
Can independently vary shear in both positive & negative direction



Ideal vertical stability predicted to improve with increasing ι_{ext}/ι_{tot}

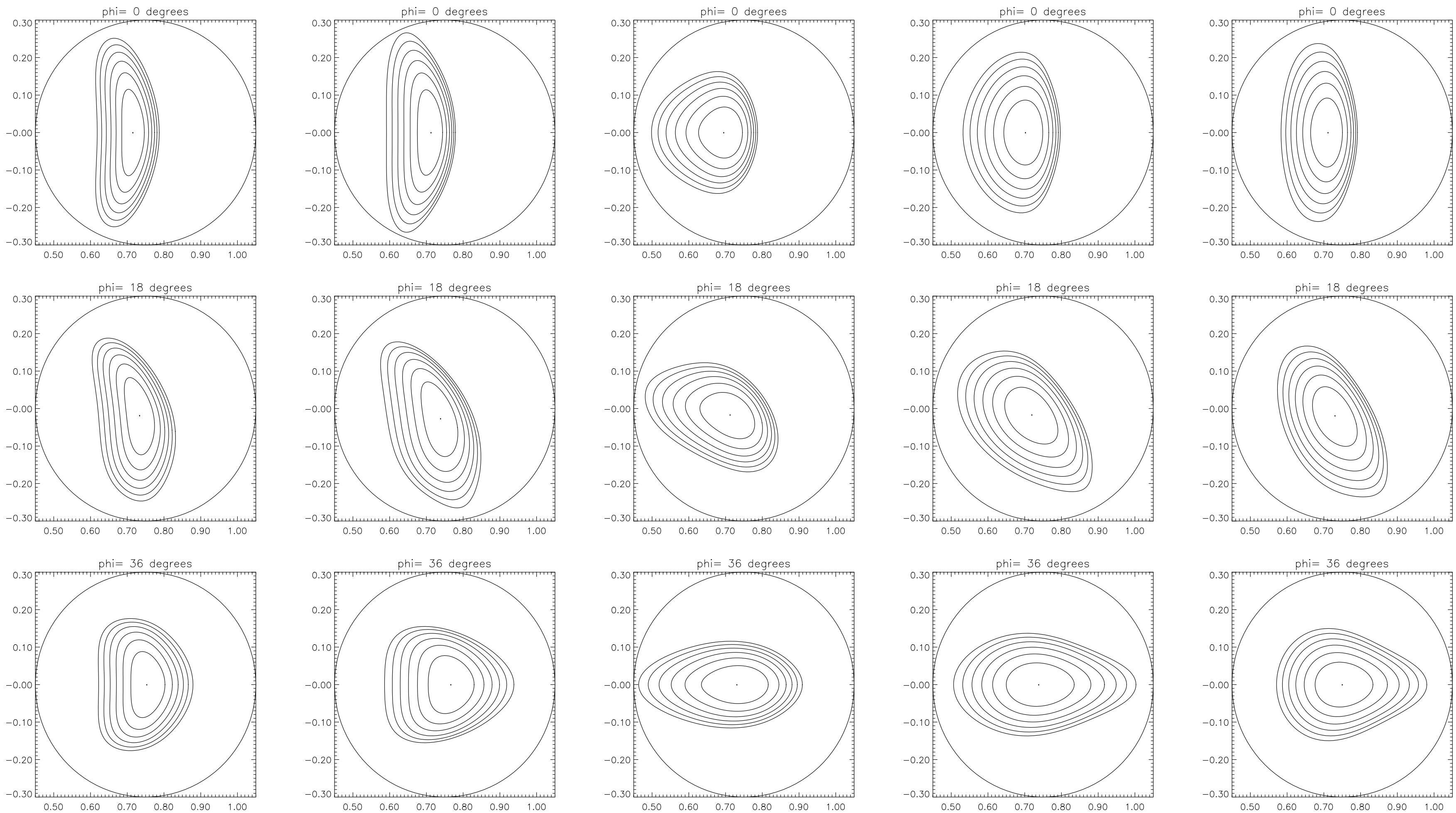
Red trace is minimum value of fractional external transform required to stabilize vertical displacement

$$\iota_{EXT}/\ \iota_{TOT} > (\kappa^2-\kappa)/(\kappa^2+1)$$



- Analytic modeling consistent by spot checks with TERPSICHORE ideal MHD stability code
- Ideal kink stability also generally predicted (in 1-D) to improve with increasing ι_{ext}/ι_{tot}

Flexibility of CTH Equilibrium



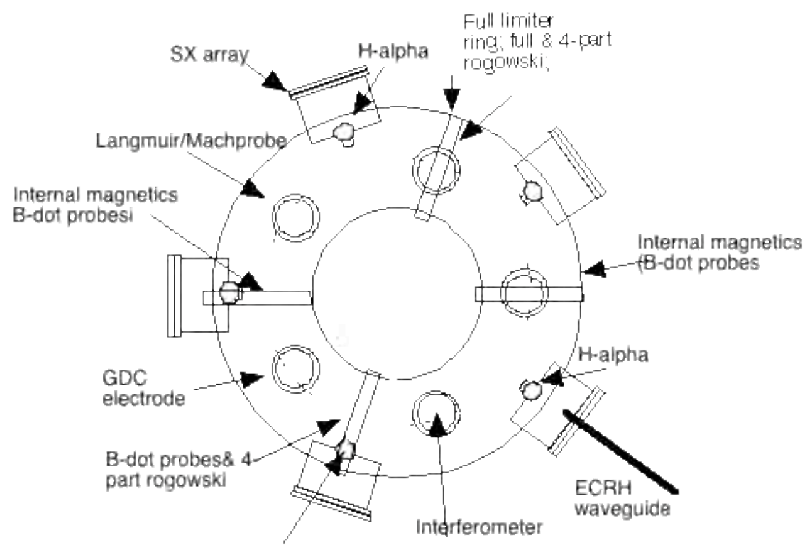
I_{TF} =0.0	I_{TF} =0.26	I_{TF} =0.13	I_{TF} =0.13	I_{TF} =0.13
I_{SVF}=0.00	I_{SVF} =0.00	I_{SVF} =0.48	I_{SVF} =0.0	I_{SVF} =0.48
I_p=0kA	I_p=0kA	I_p=0kA	I_p=60kA	I_p=60kA

Shaping flexibility => magnetic diagnostics far from plasma

- difficult to infer characteristics of current profile

- Initial in-vessel magnetic diagnostic consists of 2 segmented (4-part) rogowski coils at symmetry planes ($\phi = 0$ and π/N) to measure current moments, as in W7-AS

- Plans for internal B measurement with Faraday rotation; should try shielded probes inserted into low density discharge in near future.



Measurement of vacuum flux surfaces

Objectives

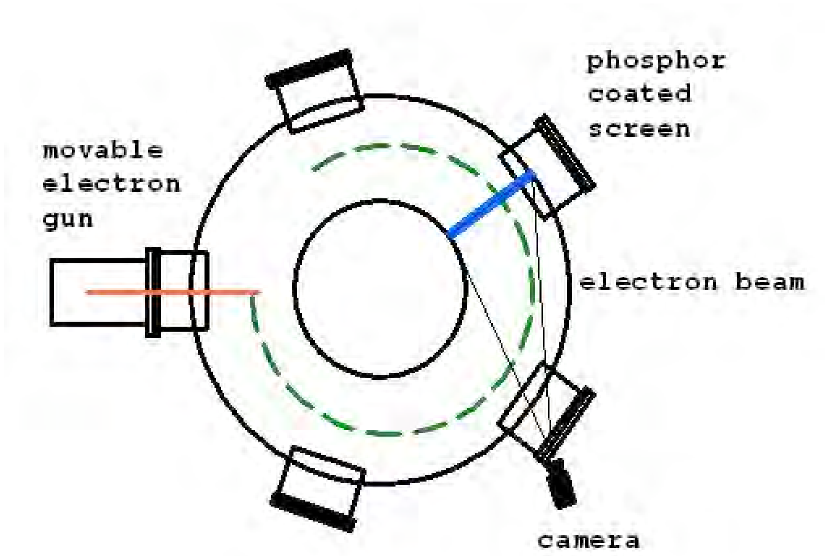
- Identify bad or misplaced coils
  $\Rightarrow$ hopefully doesn't **require** field mapping…

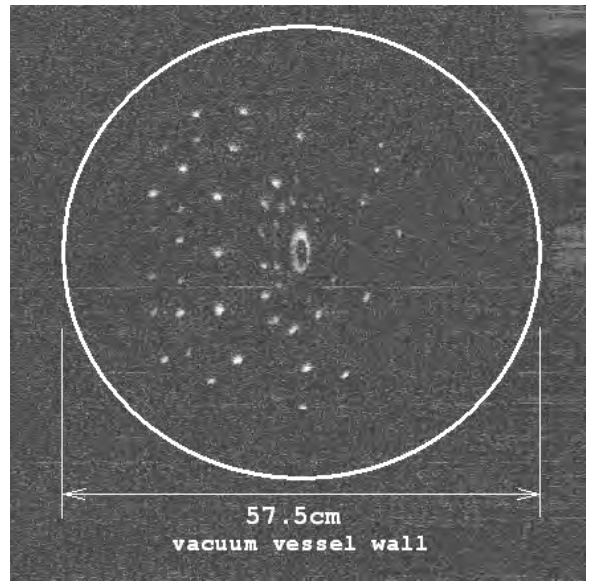
- Comparison with design flux surfaces to update model of vacuum field for equilibrium reconstruction
  $\Rightarrow$Improved coil model; in situ calibration of magnetic diagnostics

- Provide basis for implementing island correction, if needed

NCSX may be using CTH field-mapping hardware, so suggestions for improvement are in everyone's best interests.

Field-mapping set-up



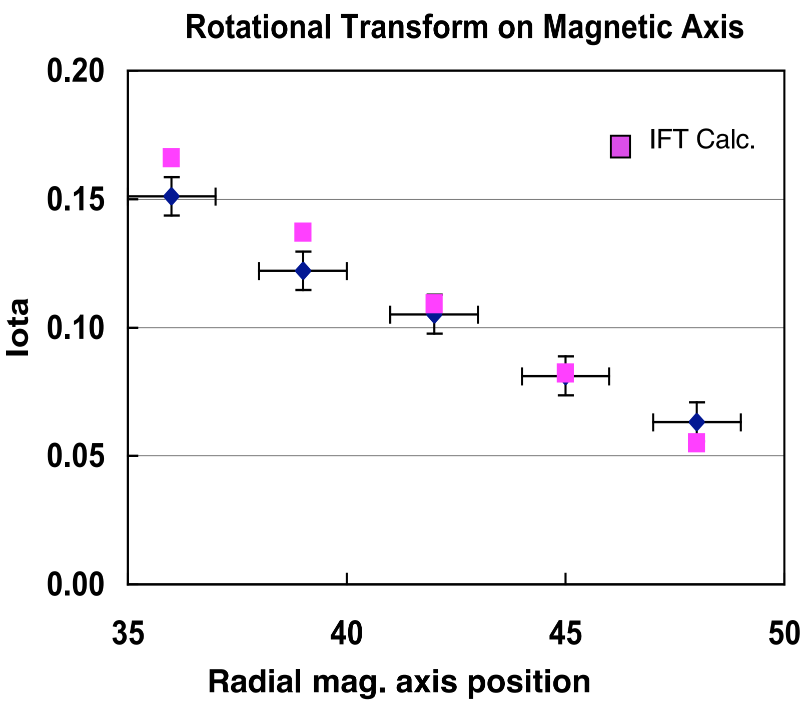


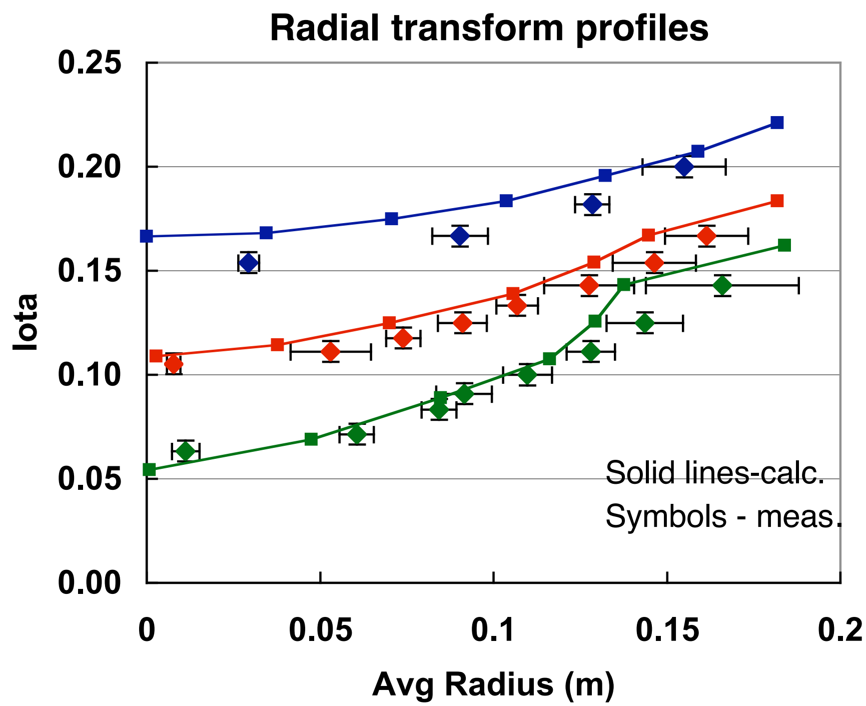
- Image photographed from either phosphor-coated mesh or movable wand
- Image processing software req'd for rotating effective field-of-view
- Most measurements made at one toroidal location; set-up recently rotated toroidally by two field periods

Surface-of-section for low rotational transform; no low-order rational surfaces => no islands

- Low aspect ratio configuration achieved

Field-mapping shows agreement with design





But some deviations from model observed …

How can field mapping help us?

Test effect of inferred coil position errors

Modular & poloidal coil position & orientation errors; dimensional tolerance on coils themselves

In our case, we have continuously-wound helical coil with winding law:

$$\phi = \underline{\frac{2}{5}}\theta + \alpha_1 \cos\theta + \alpha_2 \cos 2\theta \underline{+ \beta_1 \sin\theta + \beta_2 \sin 2\theta} + \cdots$$

$$r_{COIL} = \underline{a_0} + a_1 \cos\theta + a_2 \cos 2\theta + b_1 \sin\theta + b_2 \sin 2\theta + \cdots$$

ϕ: toroidal angle

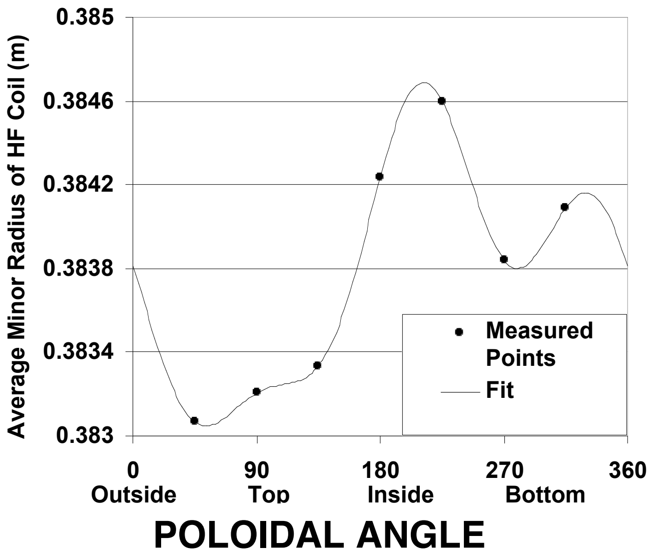
θ: toroidal angle

r_{coil}: helical coil minor radius = 0.385 m nominal

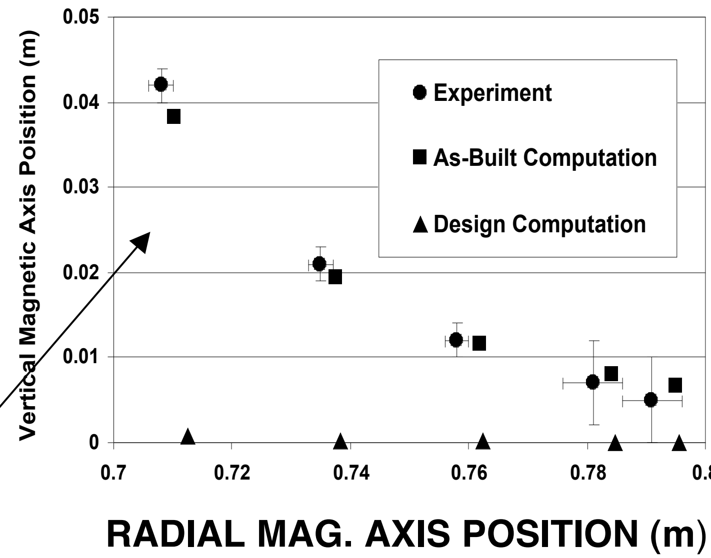
Underlined terms are non-zero in design

Deviations from helical coil winding law may explain observed discrepancies in field-mapping results

Average radius of helical coil measured during construction



Scan of magnetic axis position in R-Z plane



⇒Altered coil geometry to produce “as-built” coil model

Vertical asymmetry in magnetic axis position believed to be largely due to deviations of actual coil configuration from design

As axis is shifted inward in this very low transform case, equilibrium bifurcates

Measured vertical shift equivalent in 2 different field periods; correctable with horizontal field

Can errors in coil placement be directly inferred from field-mapping?

Under investigation by Hanson & Munoz

- Use optimization procedure in Integrable Field Torsatron code to get derivatives of measurements with respect to parameters

    Measurements: magnetic axis, fixed point locations in R, Z, rotational transform

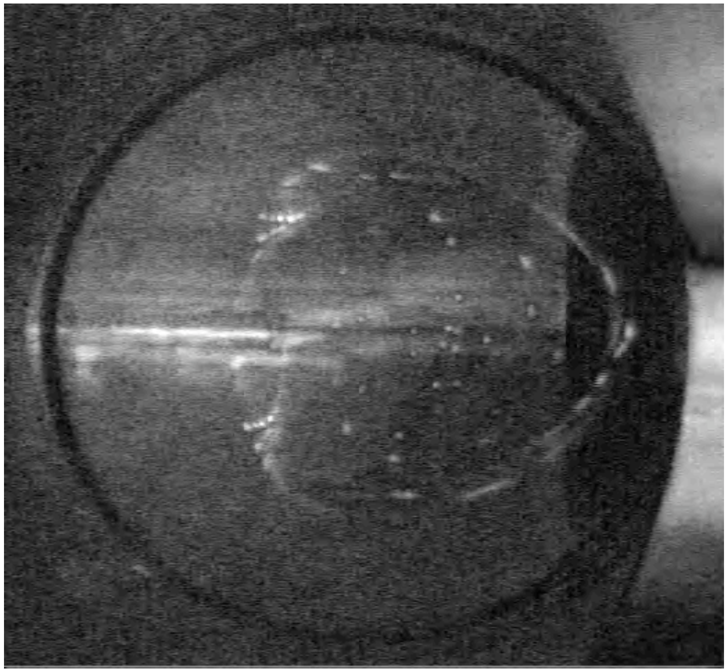
    parameters: magnetic axis, rot. transform, coil current

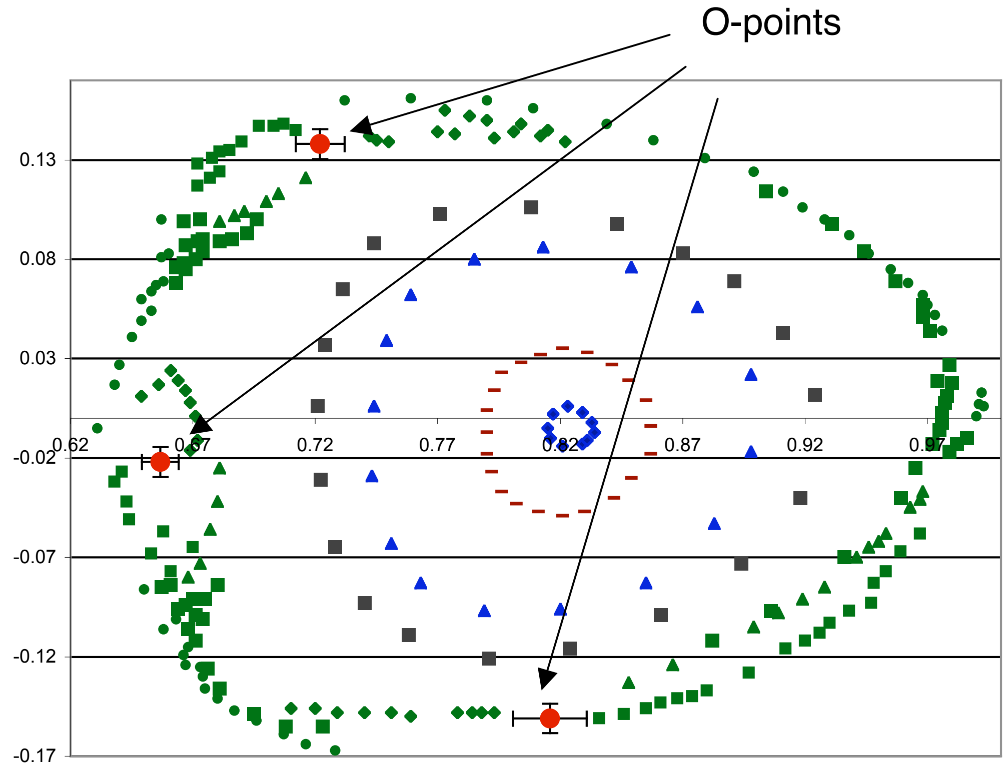
- Obtain req'd change in parameters from SVD analysis

Magnetic islands observed on rational surfaces

With auxiliary TF coils, rotational transform raised to ι(a) ≤ 0.7

- 1/3, 2/5, & 1/2 rational surfaces exhibit islands.





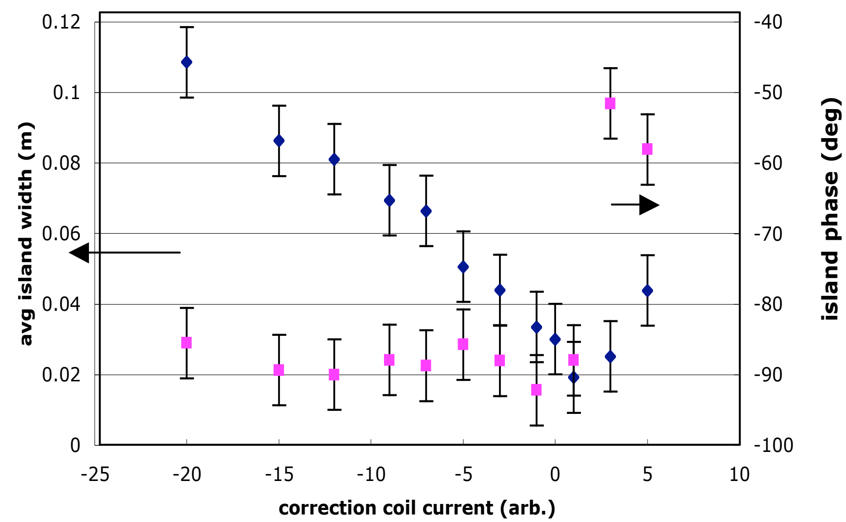
n/m = 1/3 island near the edge for ι(0) = 0.25

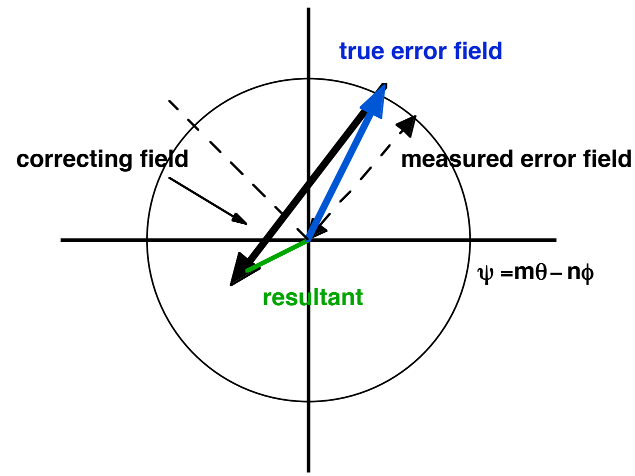
Reducing static island sizes

Fixing static islands - m,n known

- Determine phase of island O or X-points
  $\psi = (m\theta_f - n\phi_f)$ in flux angle coords. (VMEC).
- Compute correction field of opposite phase; generate vector of N elements
  N = no. of independent correction coils
- Apply correction vector of increasing magnitude.
  Island size difficult to measure; phase v. sensitive to minimum size for given vector
- Continue minimization by applying add'l correction orthogonal to original vector at phase jump.

- Error correction procedure needs continued work
- Apply to correction of multiple islands (different rational surfaces in same equilibrium)
- What happens in stellarator plasma? (Reiman's stellarator theory presentation last May)





Near-term plans

- Complete mapping survey to include all coil sets w/ goal of improving vacuum field model as underpinning for 3-D reconstruction of plasmas

  Better approaches for validation/improvement of coil model from vacuum field-mapping?

- Successfully validate procedure for vacuum island correction
- Plasma discharges diagnosed with in-vessel and ex-vessel magnetic diagnostics

  Interface with existing and upcoming (V3FIT) reconstruction procedures

- Measure plasma flow, density, temperature in stochastic edge region
- Initial current-driven instability studies

Avenues for theory & modeling

- Modeling of kink and vertical instability thresholds for 3-D current-driven low-β CTH plasmas

- 3-D equilibrium reconstruction is a major challenge

- Island modification in presence of poloidal flow from ambipolar transport