NCSX Physics Mission and Requirements

Hutch Neilson

for the NCSX Team

Princeton Plasma Physics Laboratory
Oak Ridge National Laboratory

NCSX Construction Feasibility Review

Princeton, NJ

October 31, 2007

Topics

1. NCSX mission
2. Physics design
3. Field error requirements
4. Controlling field errors in design and fabrication.
   – Tolerances, trim coils.
5. Experimental verification plans
6. Summary

Role of Compact Stellarators in Fusion R&D

Stellarators solve critical problems for magnetic fusion.

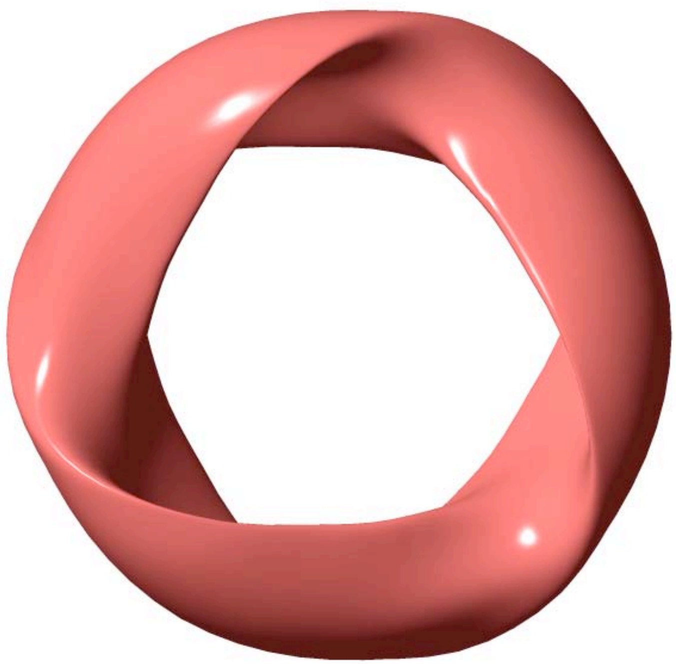
- Steady state without current drive.
- Stable without feedback control or rotation drive. No disruptions.

Compact Stellarators (CS) improve on previous designs.

- Quasi-axisymmetric magnetic field.
  - Good confinement.
  - Link to tokamak physics: can build on ITER burning plasma R&D.
- Lower aspect ratio.

NCSX Mission

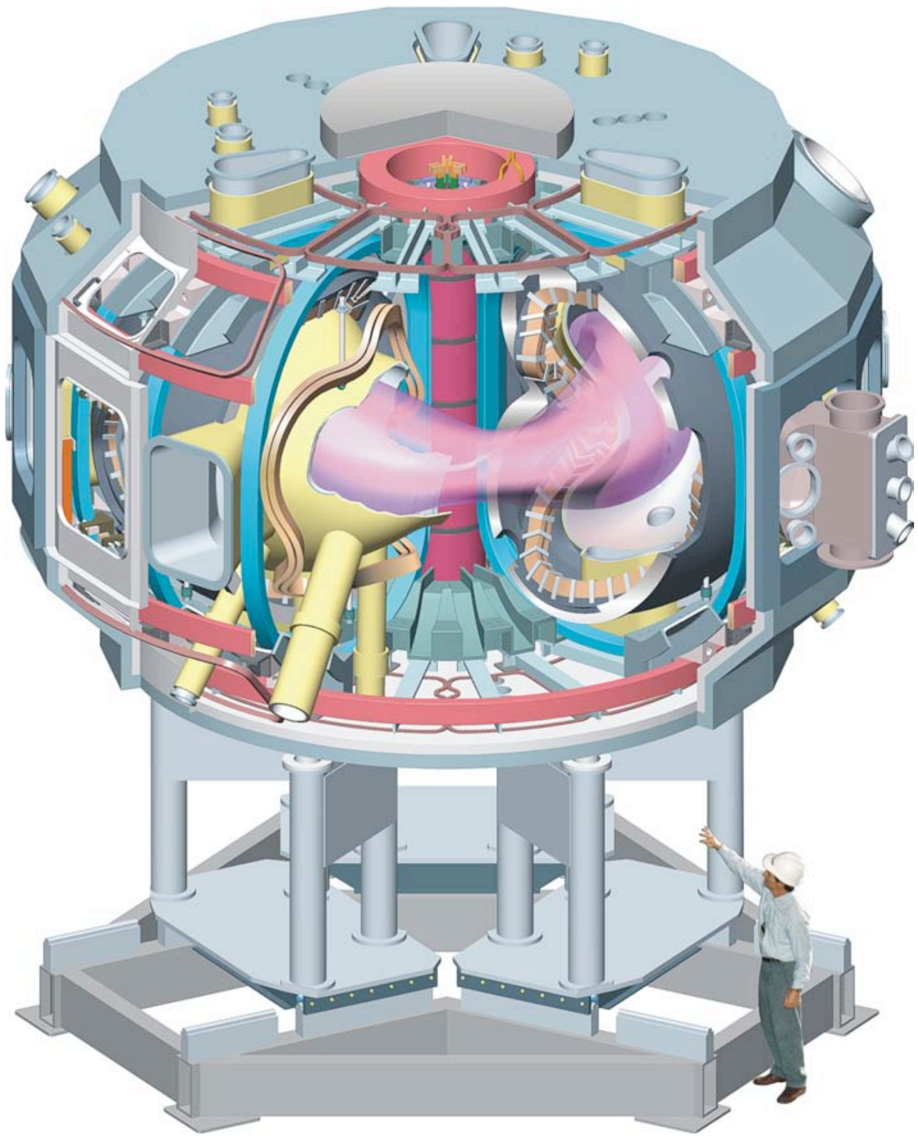
- Assess attractiveness of compact stellarators for MFE.
- Advance 3D plasma physics.



NCSX Plasma

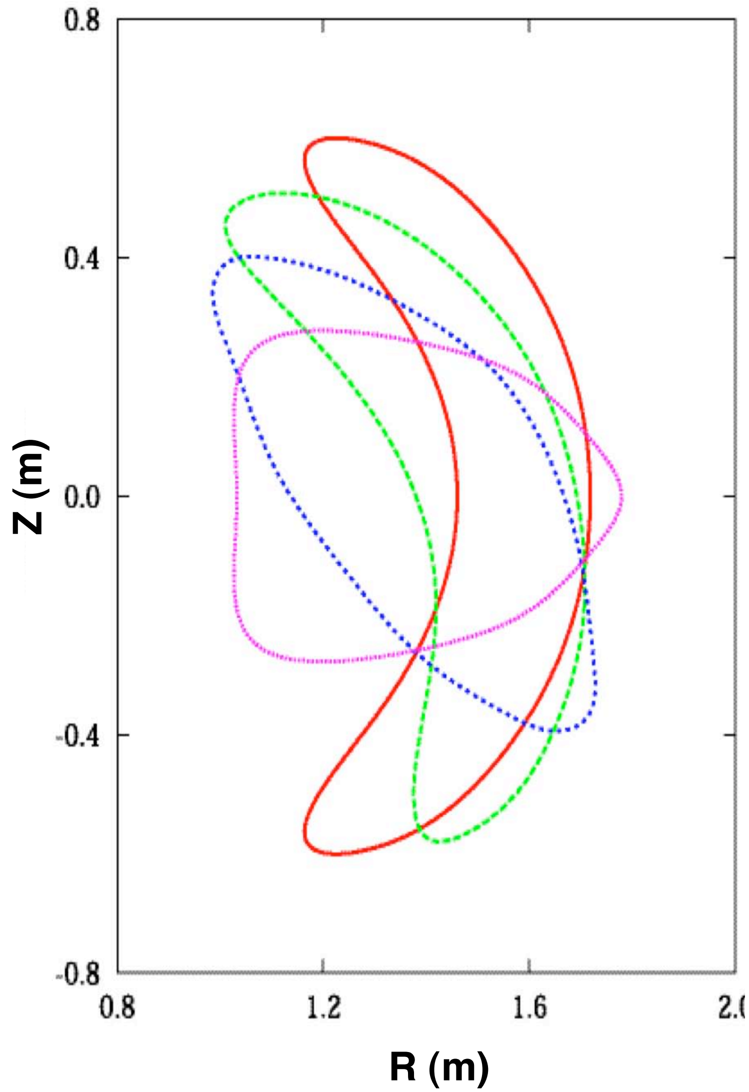
3D geometry has benefits and costs.

NCSX Machine Design



- Major radius: 1.4 m
- Magnetic field (pulse length)
  - 2.0 T (0.2 s)
  - 1.2 T (1.7 s)
- Flexible coil set
  - Modular, TF, PF, trim
- Coils cooled to LN2 temperature
- Vacuum vessel bakeable to 350 C.
- Accommodates 12 MW of plasma heating
  - Neutral beams, RF.

Stellarator Configuration is Optimized for Attractive Physics Properties



Plasma Cross Sections

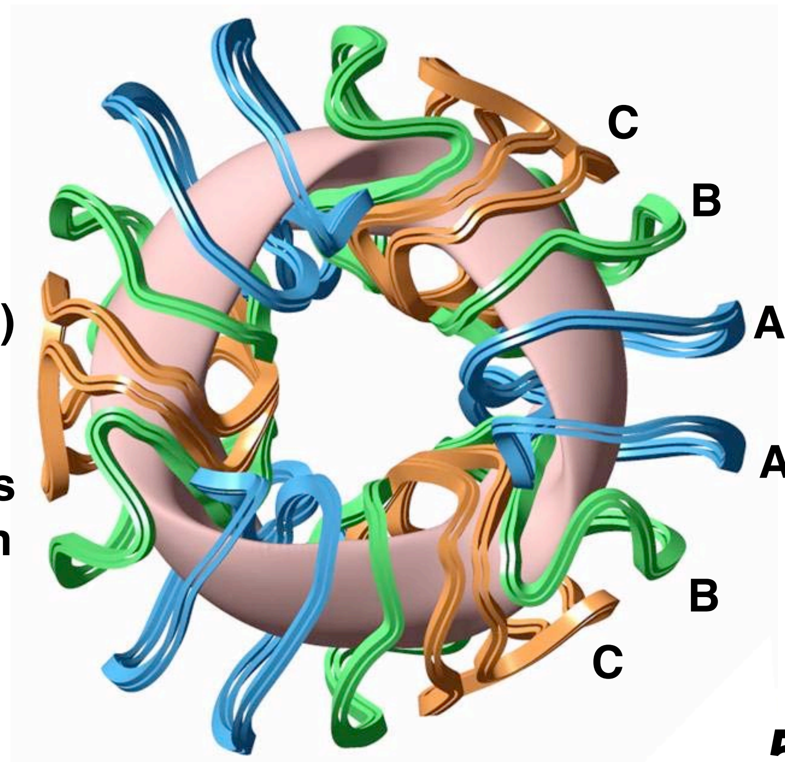
- Aspect ratio R/⟨a⟩ = 4.4; 3 periods.
- Quasi-axisymmetric; ripple ≤ 1.5%
- MHD stable at high β (4.1%).
- Good magnetic surfaces at high β.

Plasma and Modular Coils

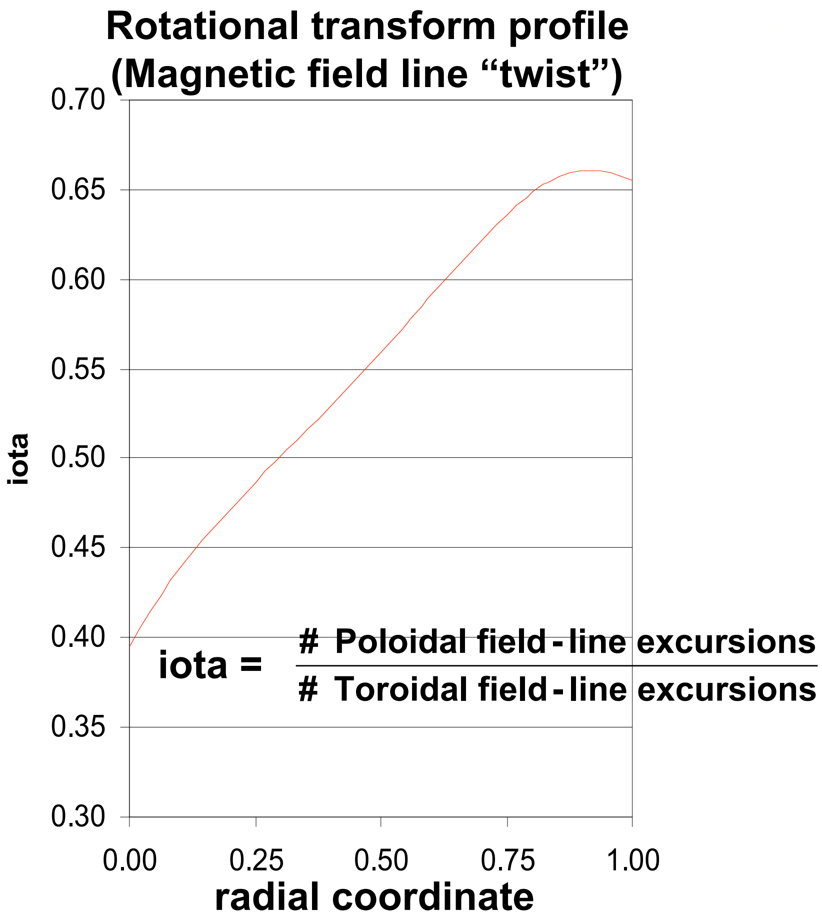
18 coils

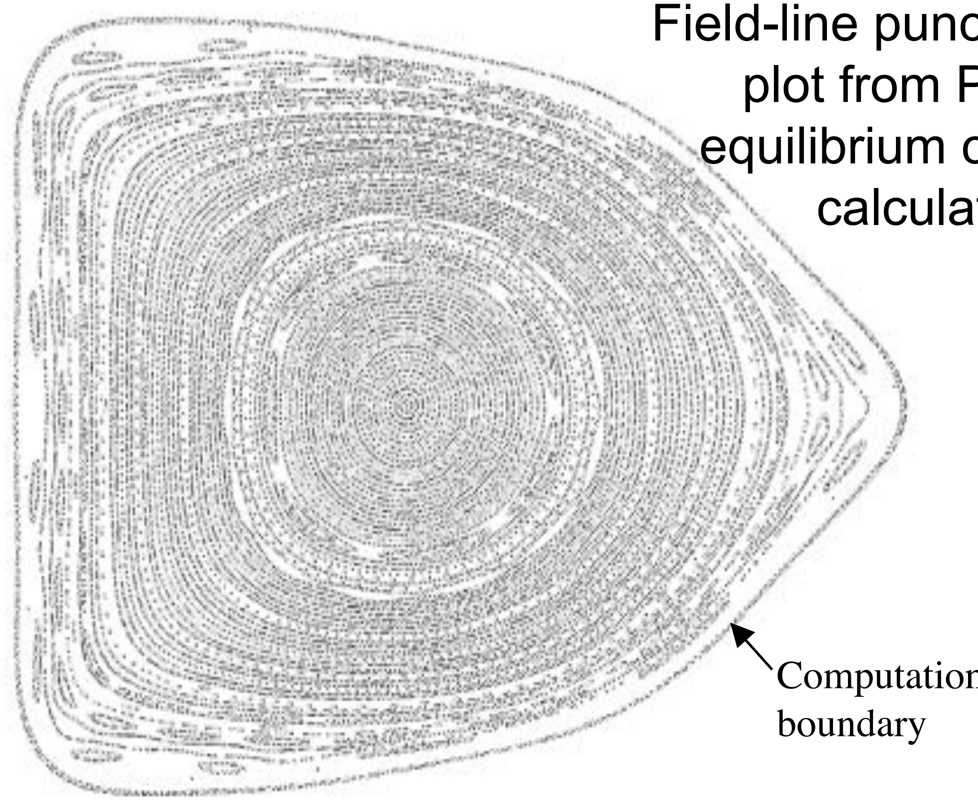
3 types (A, B, C)

(TF and PF coils also included in analysis)



NCSX Coils Are Designed to Produce Good Surfaces at High β





- Surfaces with rational iota (e.g., 1/2, 3/5) are susceptible to islands from resonant field perturbations, i.e., where $\frac{n}{m} = \frac{\text{toroidal mode number}}{\text{poloidal mode number}} = \text{iota}$
- Island width $\propto \left(B_{mn} / m\iota'\right)^{1/2}$ Shear helps.
- Field errors must be controlled in the implementation.

Fundamental Requirement: Minimize Islands

General Requirements Document

3.2.1.5.1 Field Error Requirements

a. Field error correction (trim) coils shall be provided to compensate for fabrication errors.

b. The toroidal flux in island regions due to fabrication errors, magnetic materials, and eddy currents shall not exceed 10% of the total toroidal flux in the plasma (including compensation).

To minimize islands, minimize resonant field perturbations.

Project Strategy for Controlling Resonant Field Errors in Design and Fabrication

1. **System Requirements, Component Specifications**

- Tolerances (±1.5 mm on completed modular coil system).
- Low magnetic permeability (typically $<1.02\mu_0$)
- Low eddy currents. (materials, insulating breaks).
- Low stray fields from leads, coil feeds, crossovers.
- Stellarator symmetric design.
- Minimize deflections under load. (robust structure)

Implementation: P. Heitzenroeder

2. **Provide Trim Coils**

- 24-coil array.

Performance Asessment: A. Brooks

There is Flexibility in Implementing the Requirements

- Physics performance impact is a “soft limit”.
  - Island width scales as (perturbation)$^{1/2}$.
  - Plasma shielding effects are predicted to reduce islands.
  - Effects of assembly errors on other physics properties (effective helical ripple, ballooning stability) are negligible.
- Deviations or non-conformances can be accepted as long as fundamental requirements (i.e., island widths) are satisfied. This can occur if the condition:
  - Is very localized or sufficiently remote from the plasma.
  - Is stellarator-symmetric.
  - Can be compensated by small changes in the coil geometry.
  - Can be compensated with trim coils.

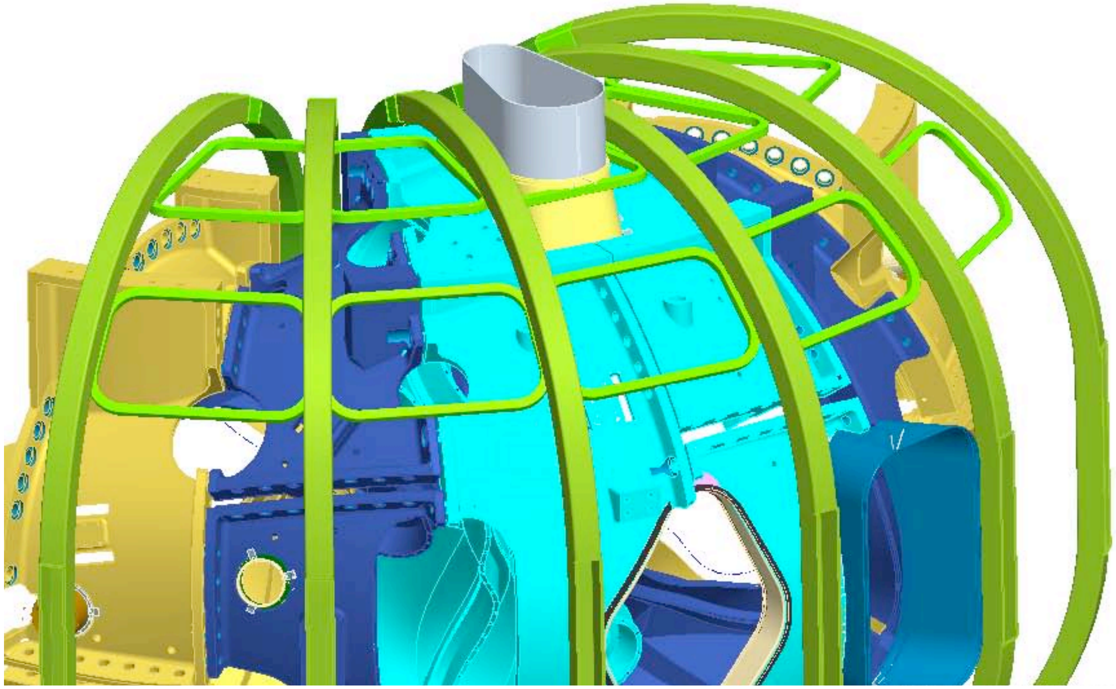
Efficient Tools Were Developed to Evaluate Island Widths

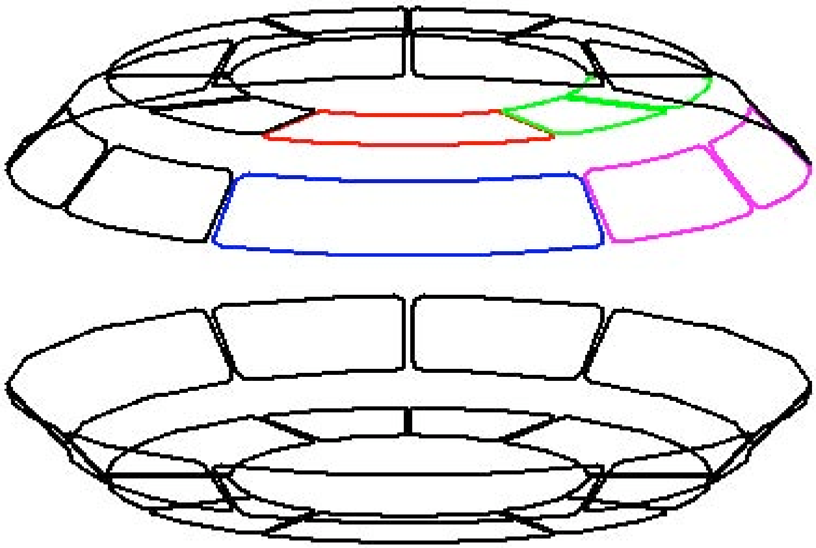
- Existing equilibrium codes have limitations as design tools:
  - VMEC: assumes good surfaces, stellarator symmetry.
  - PIES: assumes stellarator symmetry. Slow.

Solution: small-perturbation approximation (A. Brooks)

- Field perturbations are superposed on an island-free (VMEC) plasma equilibrium.
  - Perturbed field = VMEC field + perturbation field.
  - This is an approximation (plasma response neglected).
- An analytic predictor (VACISLD) was developed to evaluate island width.
- A field line tracing routine (TraceBrtp) was developed to examine effects of both symmetric and symmetry-breaking field errors.

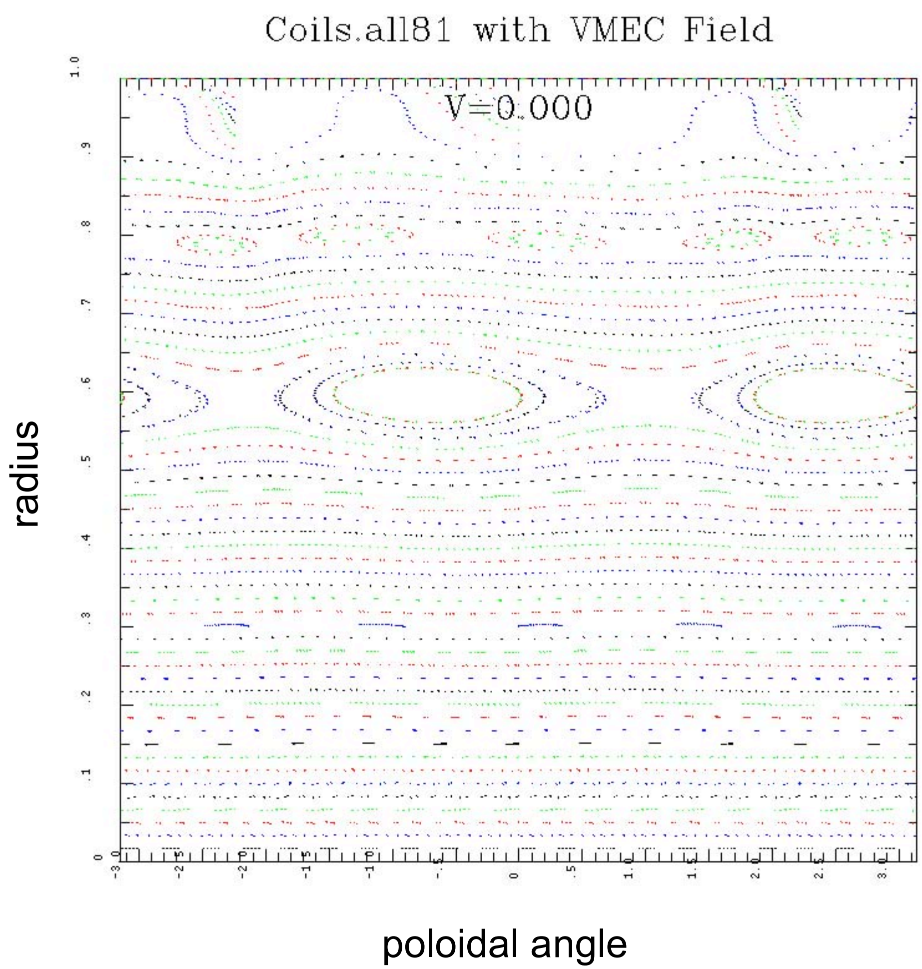
Trim Coils Can Compensate for Fabrication Errors

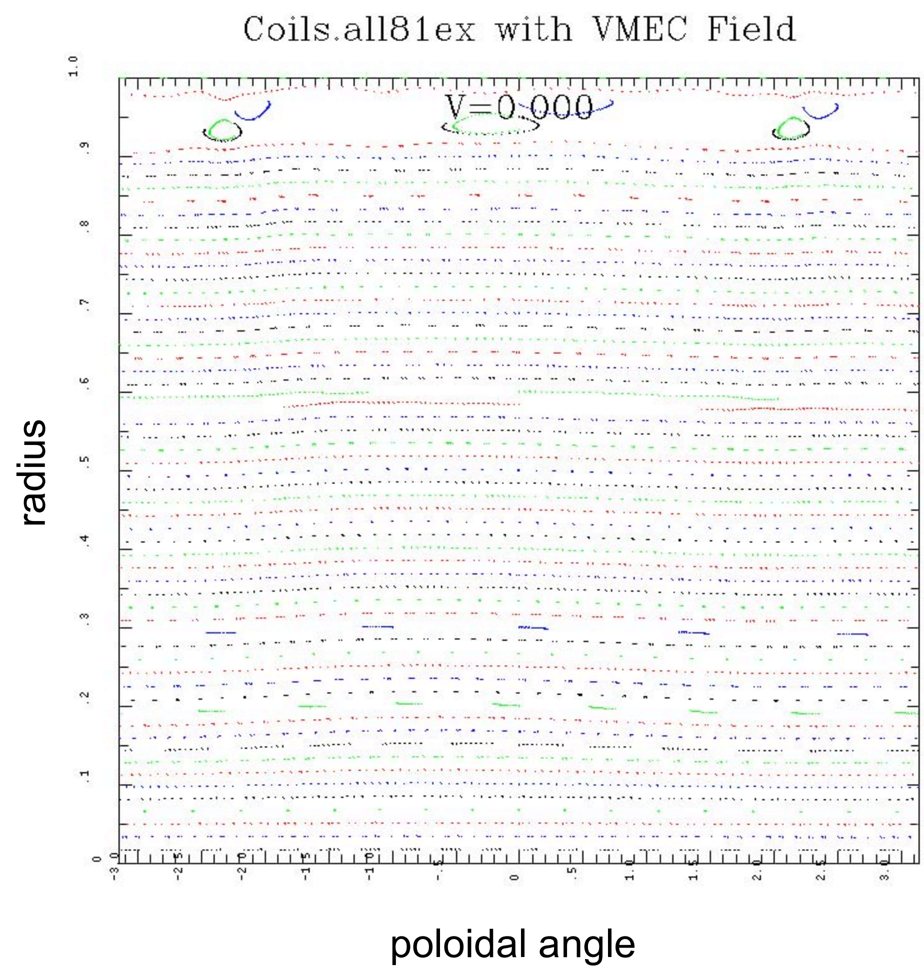




- 24-coil set controls low-order (n = 1, 2, 3) resonant errors.
- Moderate currents (20 kA-turns) can compensate for coil displacements within the ±1.5 mm tolerance envelope.
  - Islands reduced to <<10%.
- Performance margin provides capability to compensate for non-conforming conditions.

Trim Coils Can Compensate for Fabrication Errors





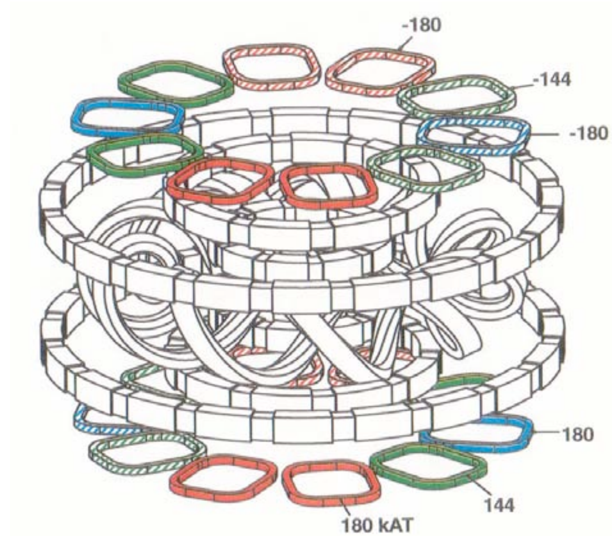
m=2/n=1 island due to construction errors within tolerance

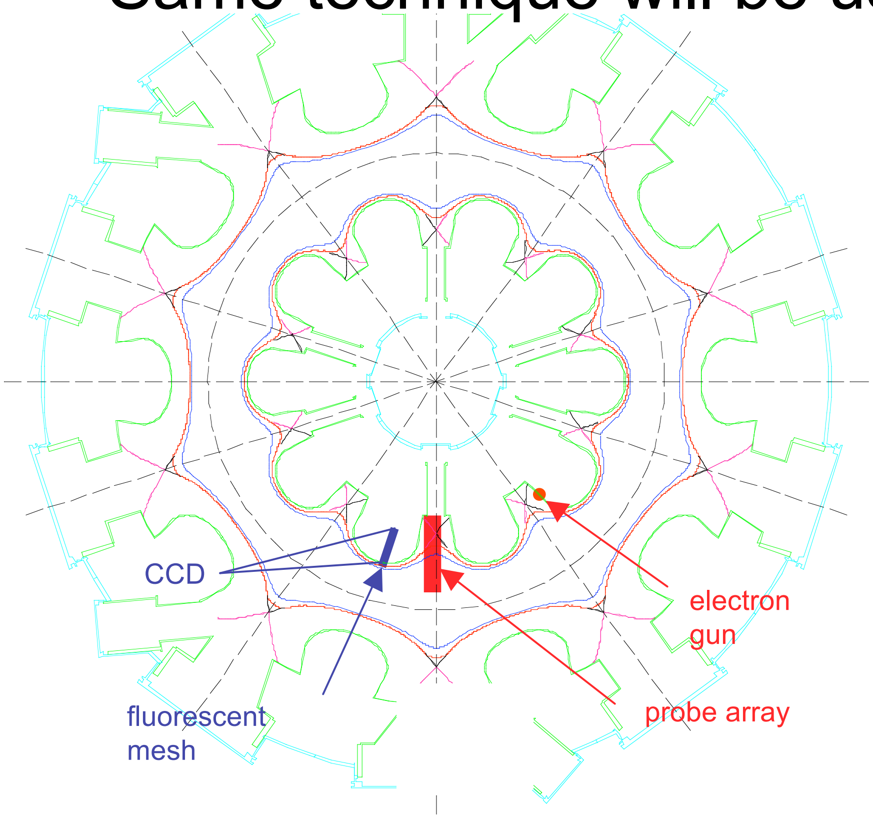
Island suppressed by trim coils

Stellarator Field Error Effects Are Measured

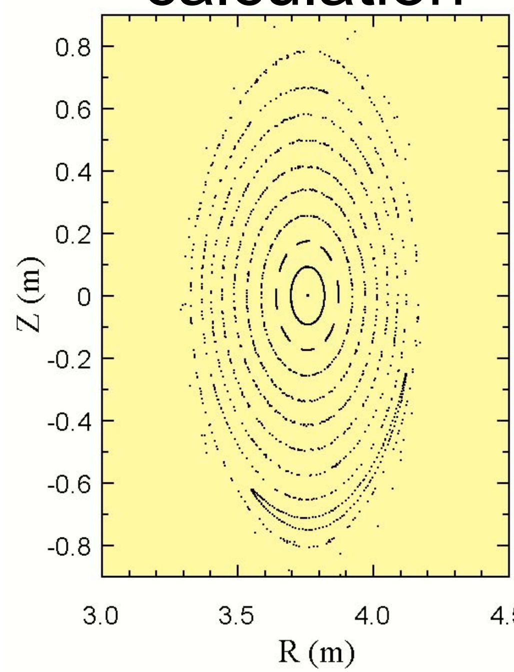
Large Helical Device (LHD), Japan

- Vacuum magnetic surfaces mapped with e-beam and fluorescent mesh.
- Islands seen at ι = 1 and 1/2 surfaces in LHD.
- Same technique will be used in NCSX.

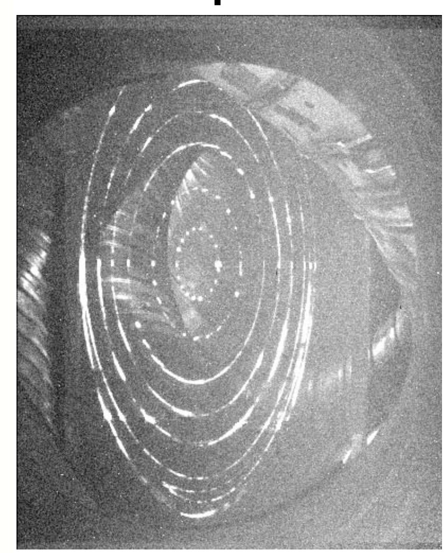




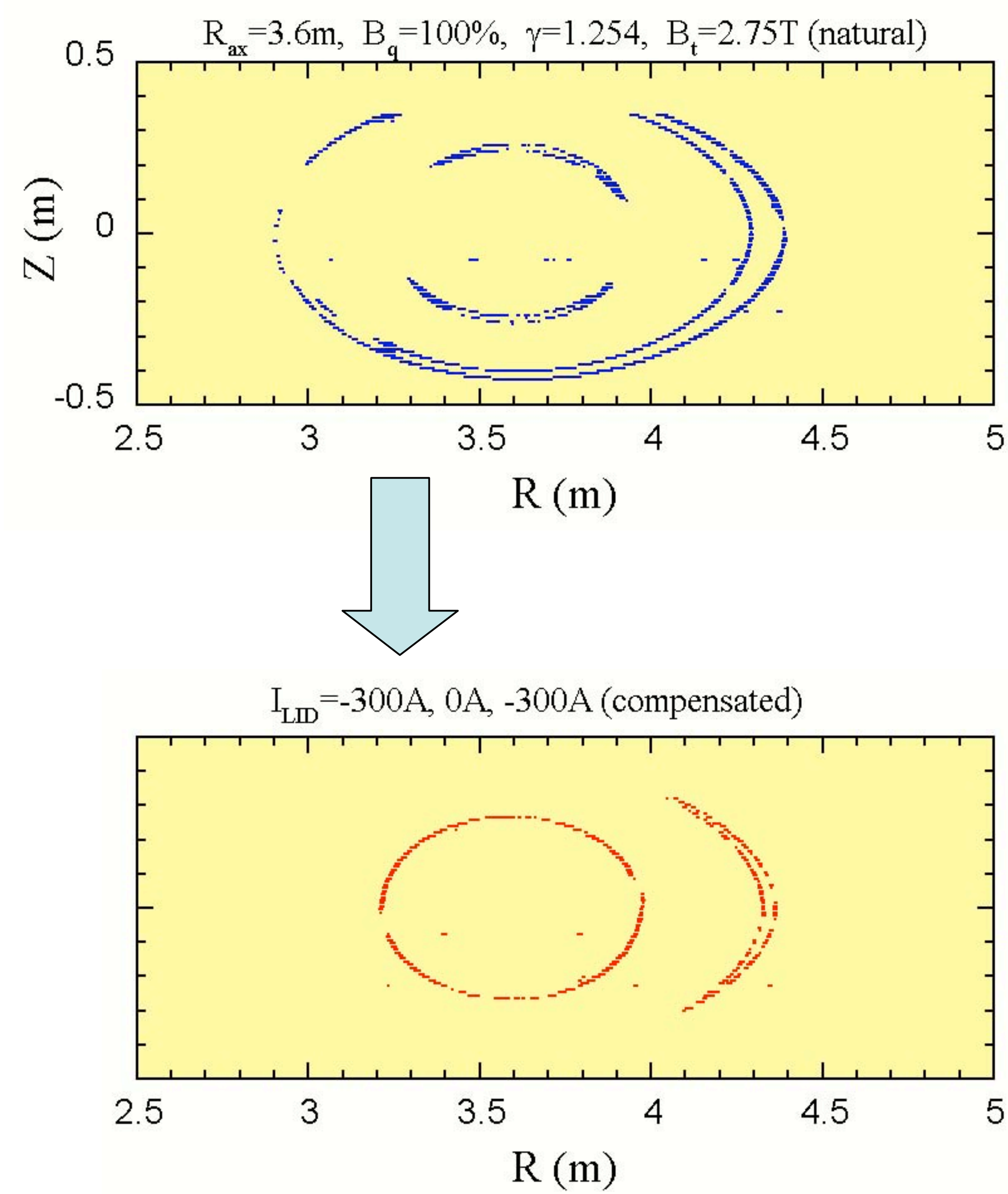
calculation



exp't



Trim Coils Control LHD Islands

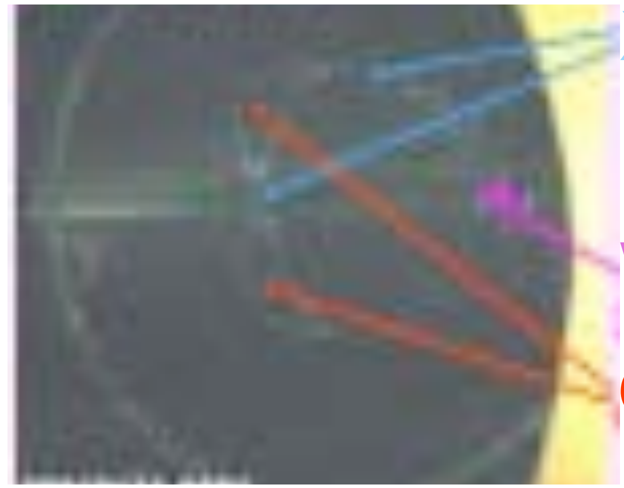


Magnetic Island Control on CTH

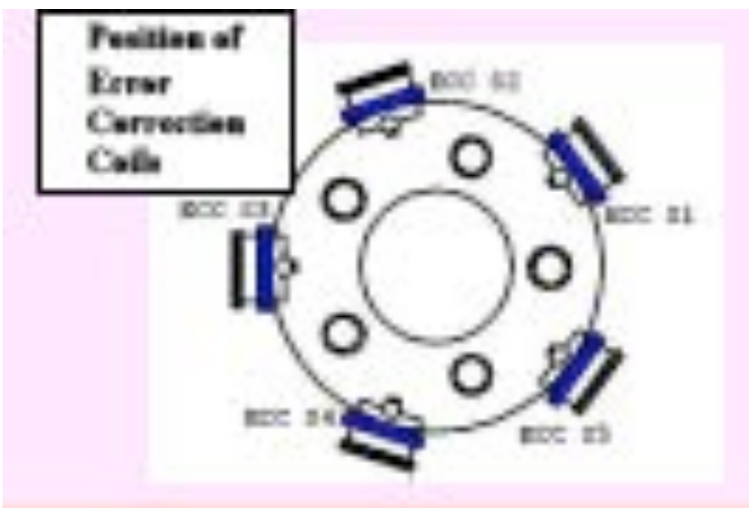
Auburn Univ.

- Detailed island studies yielded "as-built" model for coils
- Exp'ts in correcting single, multiple islands with 5 trim coils
- Will increase to 15 trim coils.

original island



CTH with 5 trim coils



corrected (amp+ phase)

Summary

- Field error requirements, including tight tolerances, are driven by the sensitivity of magnetic surfaces to resonant magnetic perturbations. Islands result.
- Larger errors can be accepted under many conditions as long as fundamental requirement (island width <10%) is satisfied.
- Engineering has developed efficient tools to evaluate island widths due to field errors.
- Trim coils can compensate for construction errors, with margin to mitigate field-error risks.
- Experimental verification tests are planned.