NCSX Construction Accomplishments and Lessons Learned

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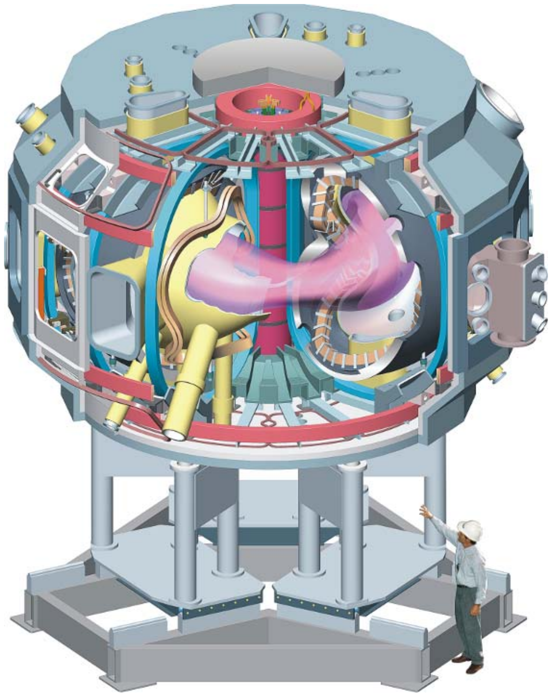
for the NCSX Team

Introduction

- NCSX Mission
  - To test a compact, quasi-axisymmetric stellarator configuration.
- Conceptual design, completed in 2003
  - Major Radius, R=1.4 m
  - Magnetic field of B=1.2 to 2.0 T
  - Pulse length of 0.3 to 2 seconds
- Core Coils Systems (all cryoresistive)
  - 18 Modular Coils
  - 18 Toroidal Field Coils
  - 4 pairs of Poloidal Field Coils
  - 48 coil trim coil set

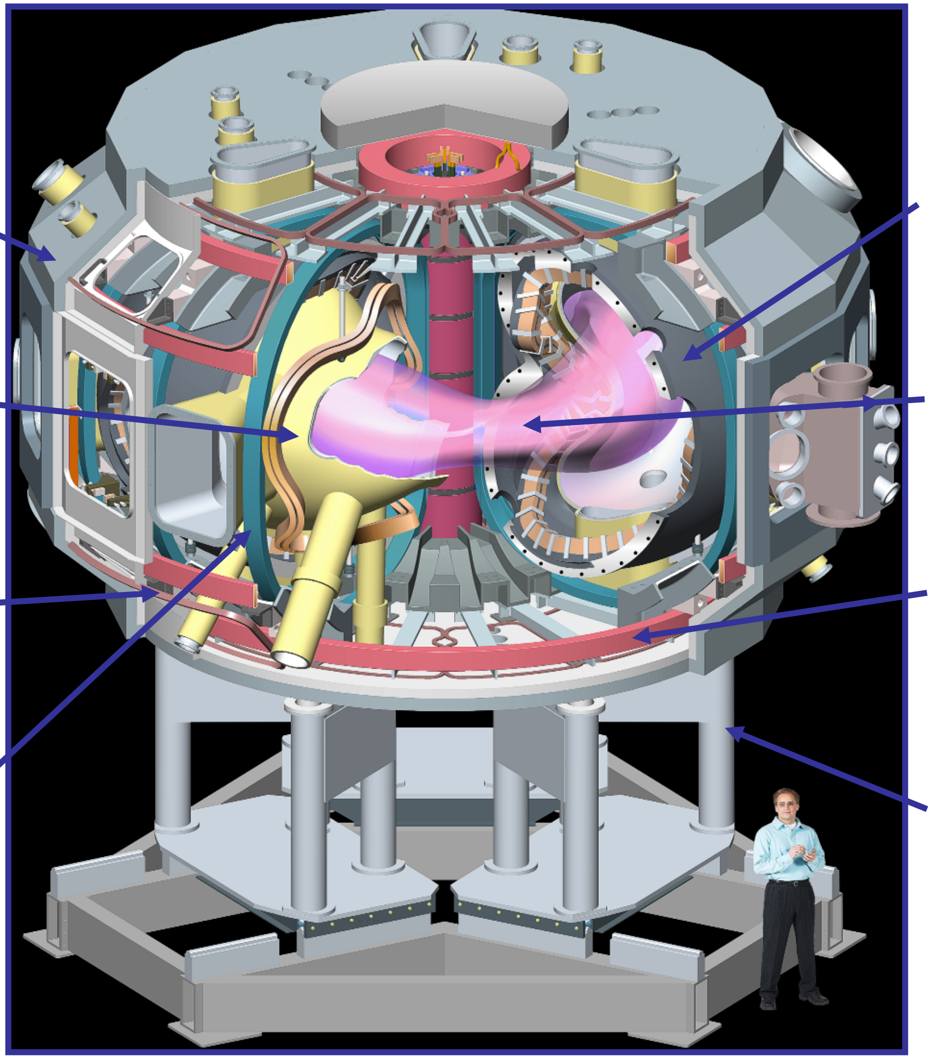


- Although the project was cancelled in May, 2008, much was accomplished and learned that will be discussed in this presentation.
- NCSX demonstrated the feasibility of fabrication and assembly of QA stellarators.

An overview of the major accomplishments

- A new stainless steel alloy was developed.
- CAD/CAM modeling techniques were developed for NCSX's complex geometry and an "almost paperless" manufacturing process developed.
- Analyses were brought to a new level of complexity and sophistication.
- Metrology expertise was developed and it was brought into high level of use at PPPL.
- A trim coil set was developed which can mitigate dimensional deviations and provide flexibility in the disposition of assembly tolerances.
- Effective assembly techniques were developed and demonstrated.
- All of the modular coils, the vacuum vessel segments, and TF coils were fabricated and tested.
- The feasibility of fabricating and assembling QA stellarators was demonstrated.

NCSX Components



All windings are cryo cooled copper.

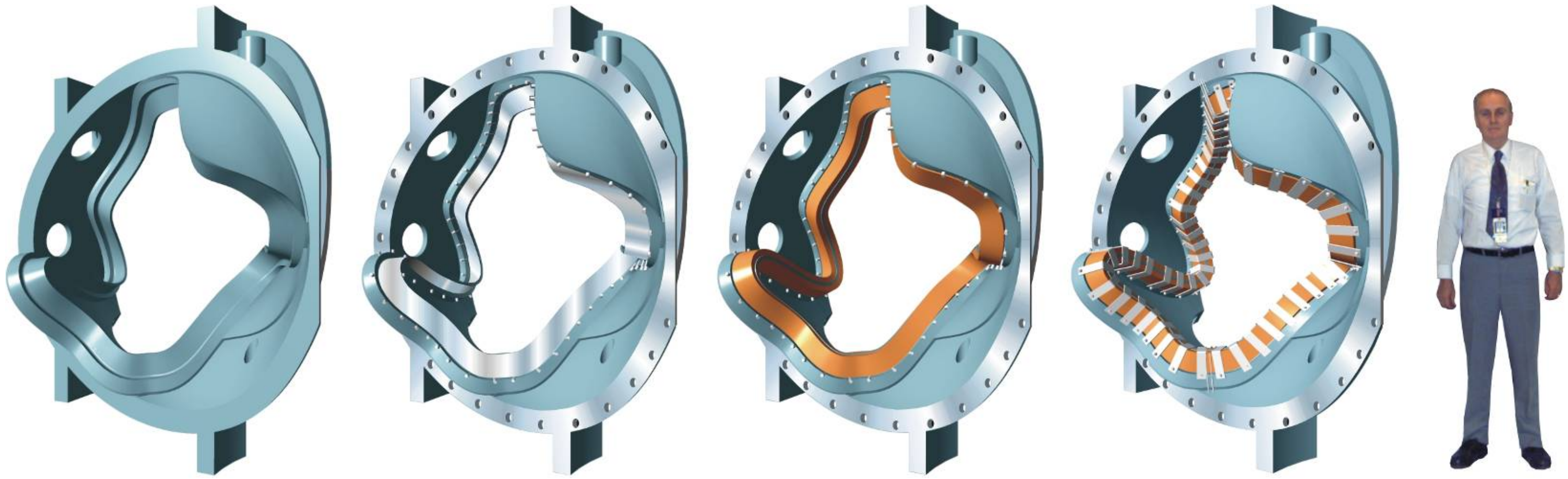
“Stellalloy” was developed

	C	Mn	Si	Cr	Ni	Mo	P	S	N
Min. %	.040	2.3	--	18.0	13.0	2.1	--	--	.24
Max. %	.070	2.8	0.7	18.5	13.5	2.5	0.035	0.025	.28

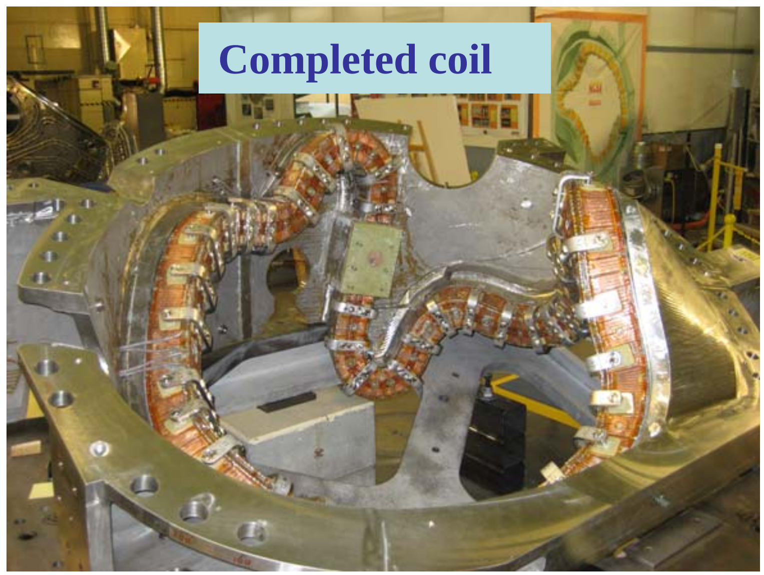
At 77 K	Specification	C1	C2	C3	A-1
Elastic Modulus	144.8 Gpa	160.9	176.1	171.9	175.8
0.2% Yield Strength	496.4 Mpa	678.5	642.6	669.5	670.9
Tensile Strength	655 Mpa	1174.0	1129.6	1124.8	1146.6
Elongation	32.0%	55.7%	54.3%	55.7%	56.0%
Charpy V – notch	47.4 J	104.9	113.9	134.6	106.2

- This alloy avoids the necessity of water quenching and concerns about distortion.
- It is a variant of CF8M stainless steel named Stellalloy by MetalTek International, its developer.
- Has low magnetic permeability (<1.02), good welding characteristics, and good static and fatigue properties. Exceptionally good elongation, even at 77K.

All 18 Modular Coils Have Been Fabricated & Tested

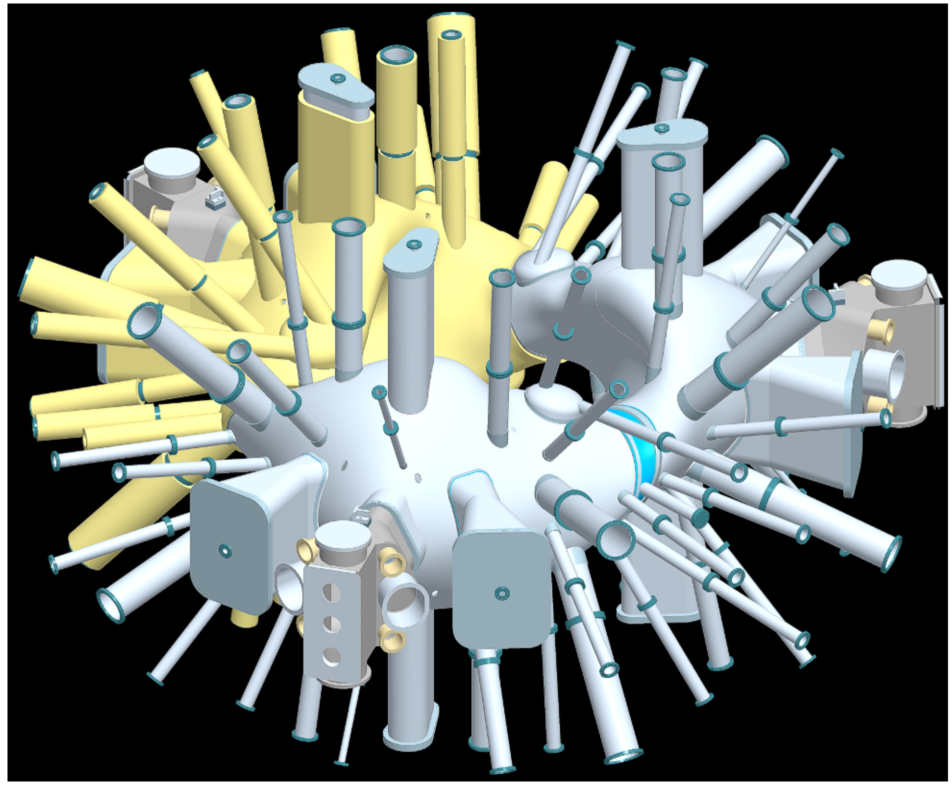


Cast Machine Wind & VPI Install clamps



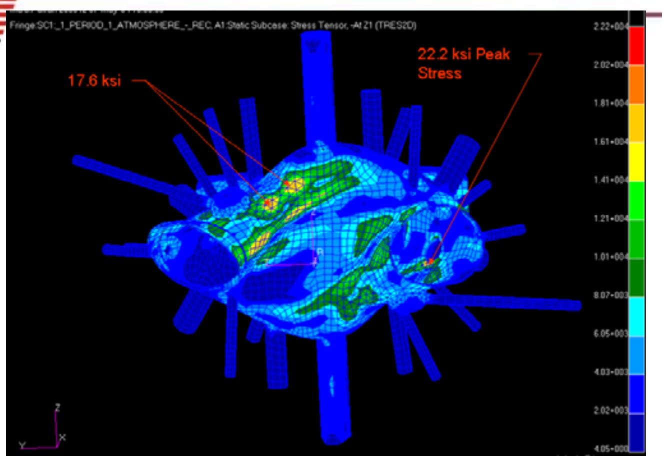
NCSX's Unique Vacuum Vessel was successfully fabricated

Shell material :   Inconel 625
Thickness : 0.375 inch
Time constant: 5.3 ms
Total wt w/ports ~ 20,000 lbs
Welded joints connect field periods
Traced with He gas lines for heating (to 350C) and cooling

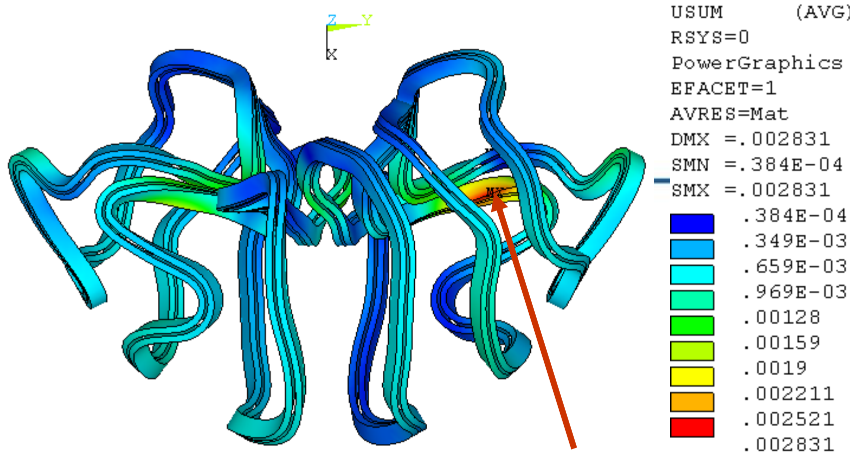


Advanced metrology was critical to achieving NCSX's tolerance objectives

Complex analyses were performed and a robust design developed.

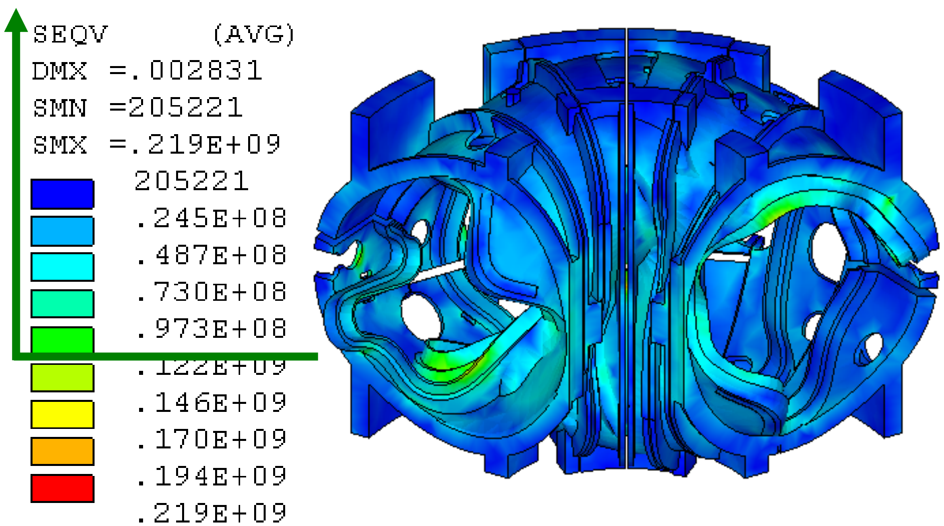


VDE + pressure + gravity tresca stress



Displacements are very low due to rigid structures. The max. centroid coil displacement is 2.2 mm, in a small localized region.

<100 MPa



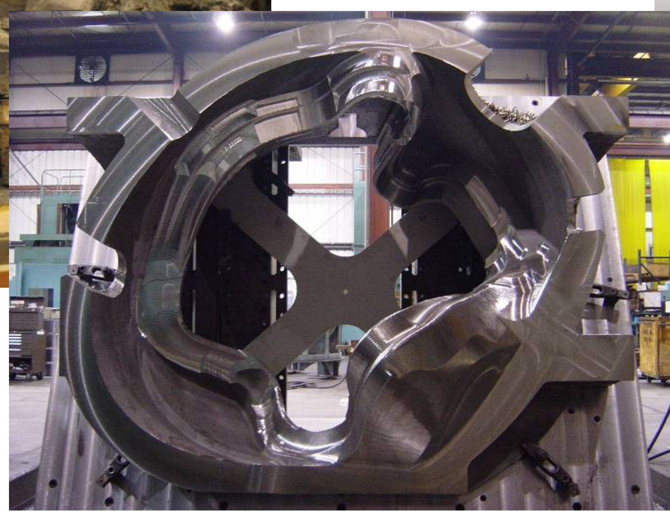
- **Max. stress is 219 MPa.**
  - •Allowable = 327 MPa.
  - Factor of Safety (F.S.) on allowable is 1.5 (based on *specified* material properties for Stellalloy; based on *actual* FS~2.5
- Average stress is <100 MPa.

Fabricating NCSX's components with our industrial partners







Energy Industries of Ohio

C. A. Lawton

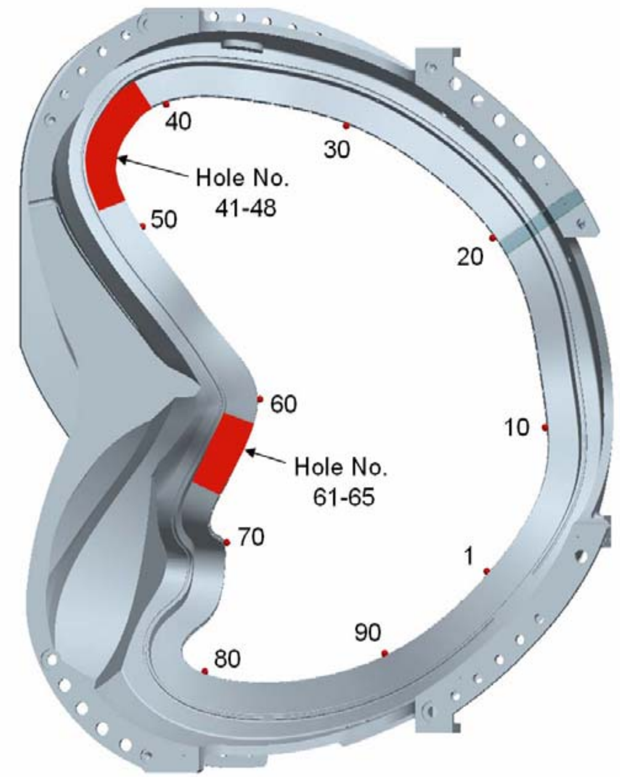
Major Tool & Machine

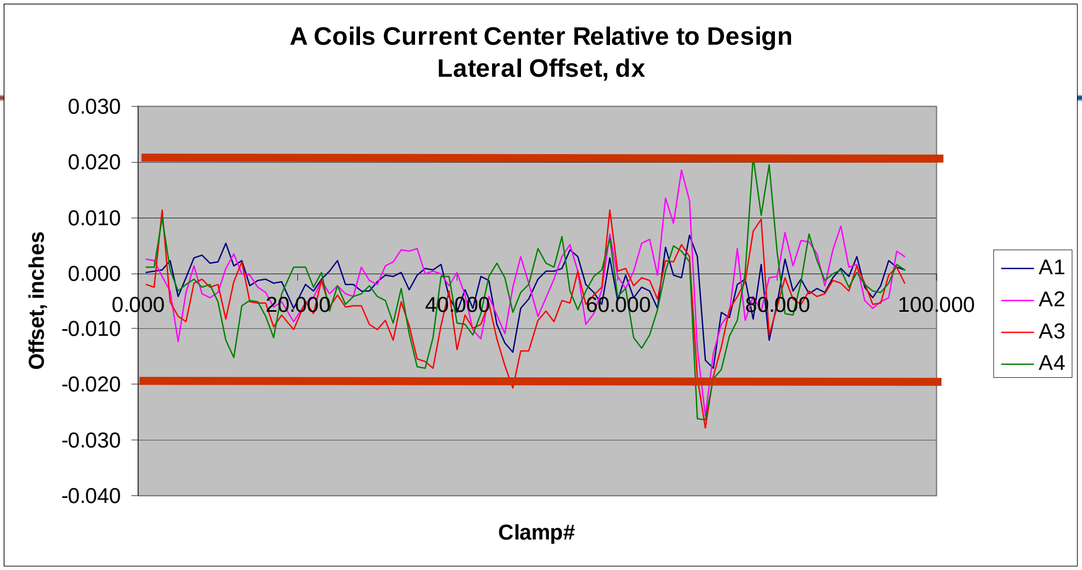
MetalTek, Inc.

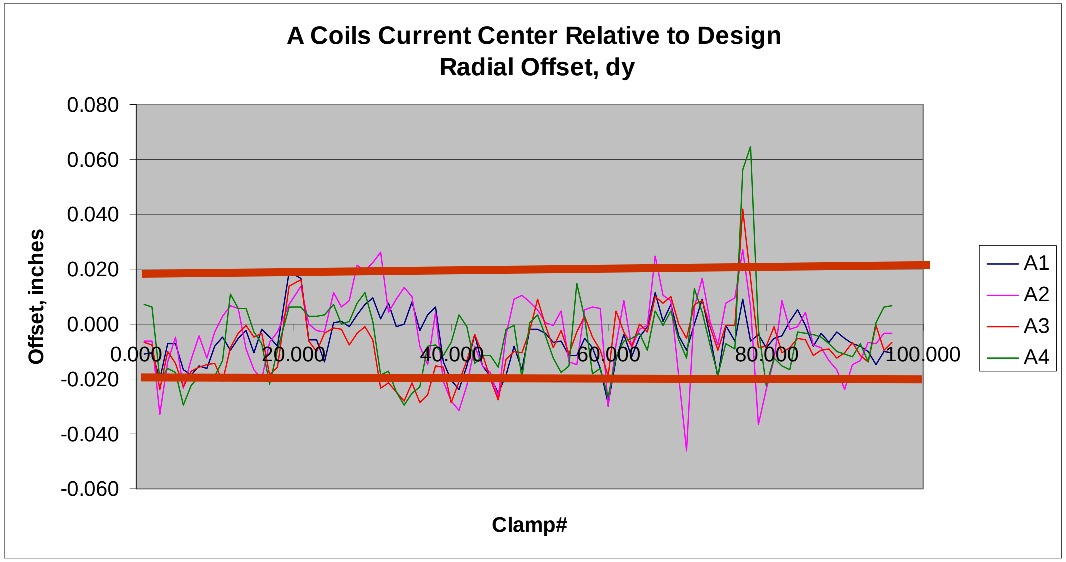
Satisfactory dimensional accuracy was achieved.

NCSX
National Compact Stellarator Experiment

Example: Modular Coils - Type A Lateral & Radial Offsets







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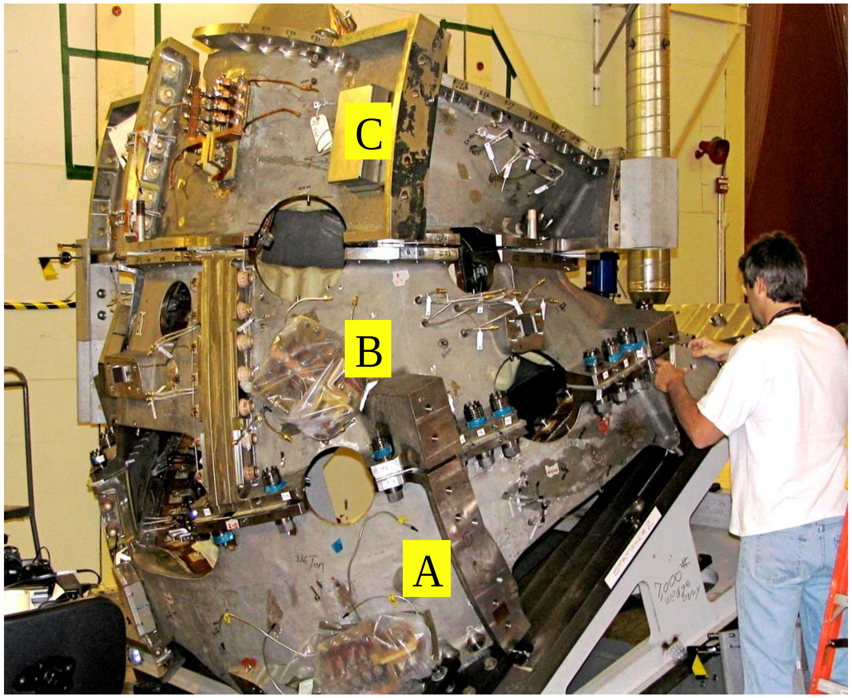
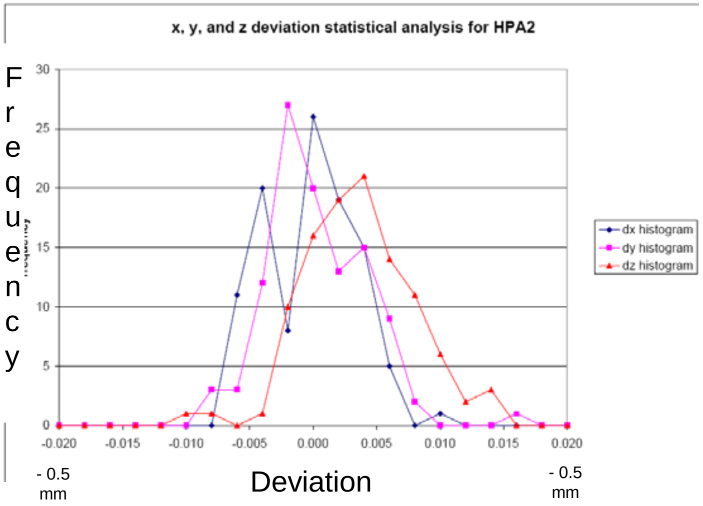
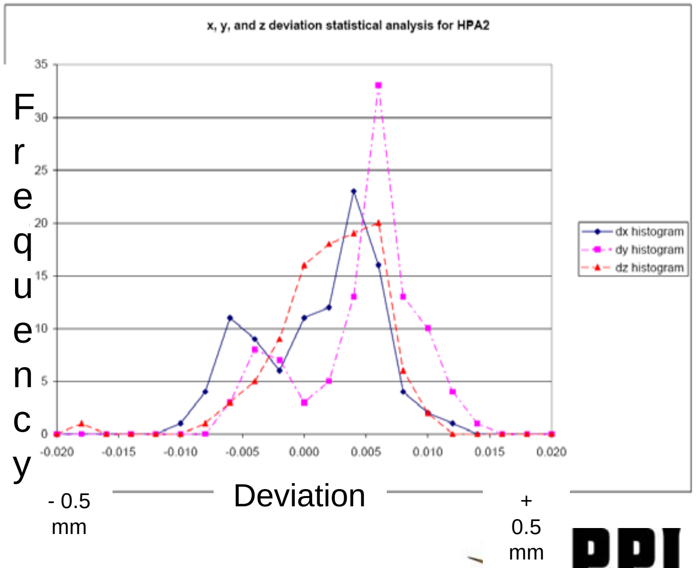
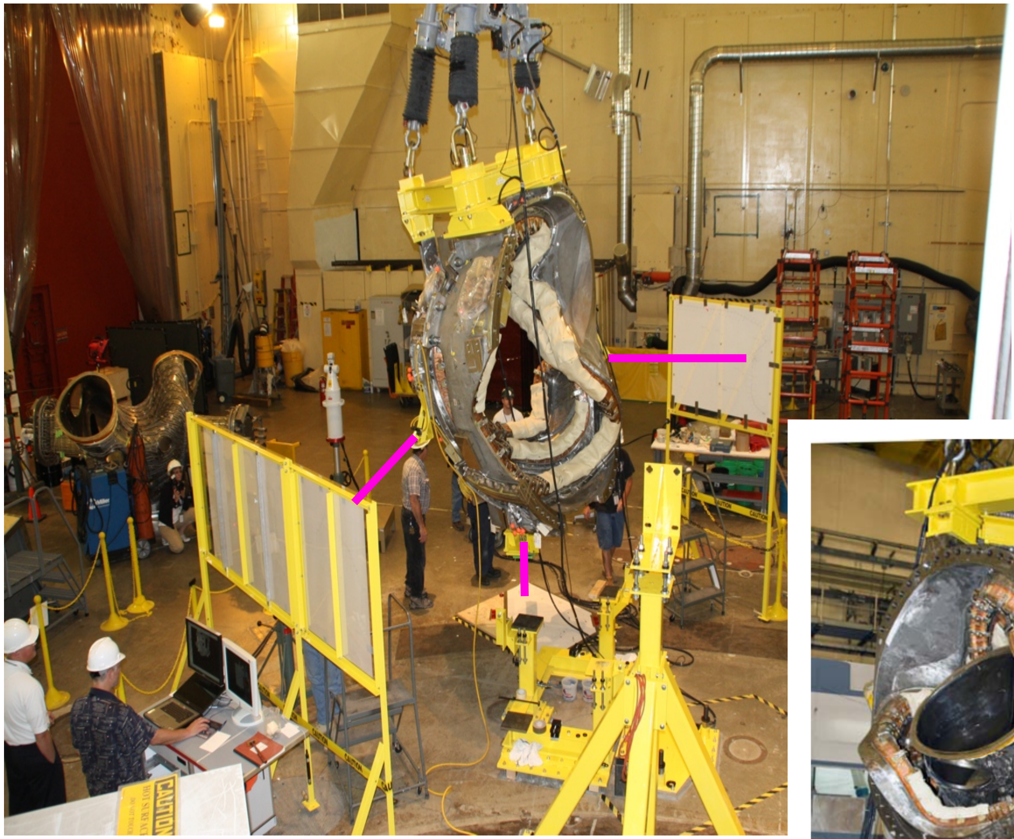
Two half periods were assembled within tolerances





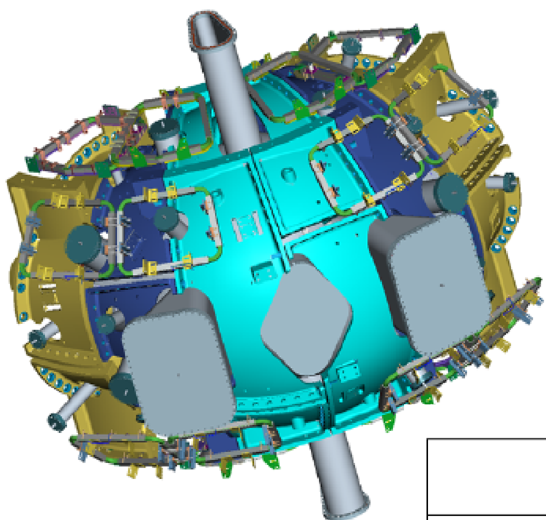


Field Period assembly was demonstrated



A trim coil set was developed to provide flexibility in the resolution of assembly errors

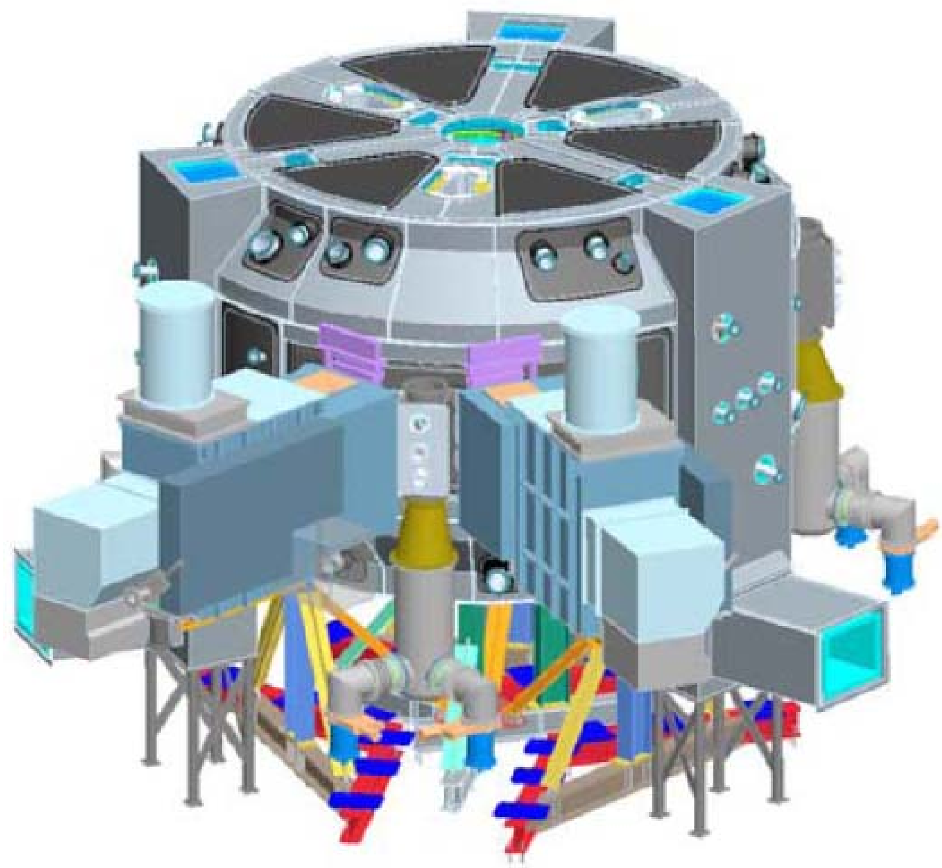
- 48 coils, total
- only 2 coil types
- 20 kAt/coil (121 turns, 167 A)
- 2 sec. pulse every 15 min.
- Cooled by convection in cryostat.



Condition	Total island size, % of total flux	Max. current, kA-t
Projected modular coil assembly errors	3.12	10
Projected errors plus all wings distorted +1 mm	3.88	10
Projected errors plus all wings distorted -1 mm	3.88	10
Projected errors plus wings distorted –1 mm in 1 half period only (non-stellarator symmetric)	3.25	10

A conceptual cryostat design was developed

- Double walled removable panels with Aerogel insulation.
- Coils cooled down by N2 gas transitioning to LN2.
- Modular coil cases cooled by "point to point" cooling.
- Cool-down analyses of structure not completed, but N2 tracing tubing likely.



Lessons Learned

Costs of core components exceeded estimates by a factor of ~2. This is part of the reason why the project was cancelled. Some thoughts on how to improve cost and schedule performance:

- **Be critical and surgical in requiring either small tolerances or restrictive properties such as low magnetic permeability.** This will drive the vendor procurement costs, require extensive in-house engineering time to disposition NCR's, and increase assembly time. The impact is not only in increased cost but schedule stretch-out which has a large management overhead cost.

- **Complete prototyping tasks before procuring critical components.** This may not necessarily reduce cost BUT the ultimate cost of procurement will be better known up front (i.e. MCWF prototype machining).

- **Simplify designs by minimizing the numbers of parts** that need to be detailed, procured, prepared and assembled.

- **Recognize the nature of high tech/high risk projects and avoid prematurely establishing cost and schedule baselines** until a more mature design/fabrication experience base is established.

NCSX
Now

- All files and hardware have been carefully stored, preserving the possibility for a re-start, should that opportunity arise.

Concluding Remarks

NCSX
National Compact Stellarator Experiment

- NCSX's complex geometry presented many engineering challenges that were overcome.
- Our experience on NCSX has greatly increased our understanding and capabilities in:
  - Complex 3-D design & analysis
  - Manufacturing
  - Metrology
  - Multi-site project coordination – NCSX was a joint PPPL/ORNL project and involved industry at a variety of locations.
  - Systems engineering using web-based data dissemination and archiving.
  - Risk-based project management
- **We have become wiser and more capable in design, engineering, and management of high-tech. fusion devices by having had the opportunity of developing NCSX, fabricating the core components, and demonstrating key assembly procedures.**

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