WBS 1
Stellarator Core
Overview

B. Nelson
and the WBS 1 team

NCSX Preliminary Design Review
October 7, 2003
PPPL

Presentation Outline

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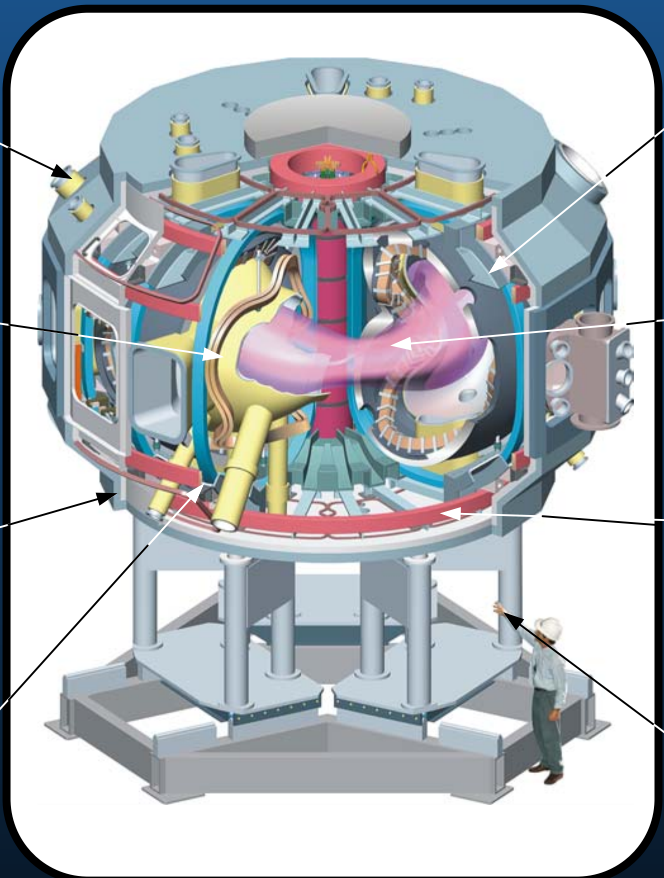
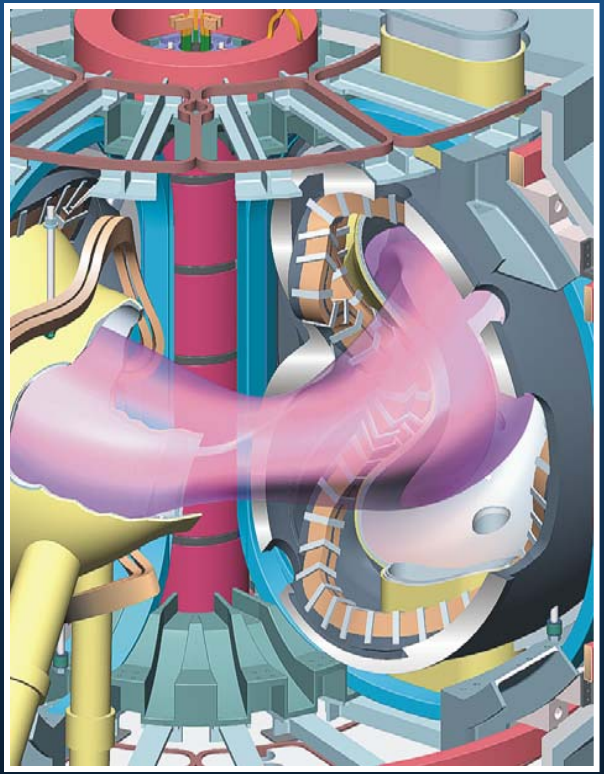
- For the major stellarator core systems:
  - Requirements (what must the system do?)
  - Design (what and why?)
  - Design evaluation (does it work? Is there margin? what R&D is planned to answer the questions and verify the design?)
- Cost and schedule overview
- Risk and remaining issues

Cutaway view of machine assembly





Four coil systems are required

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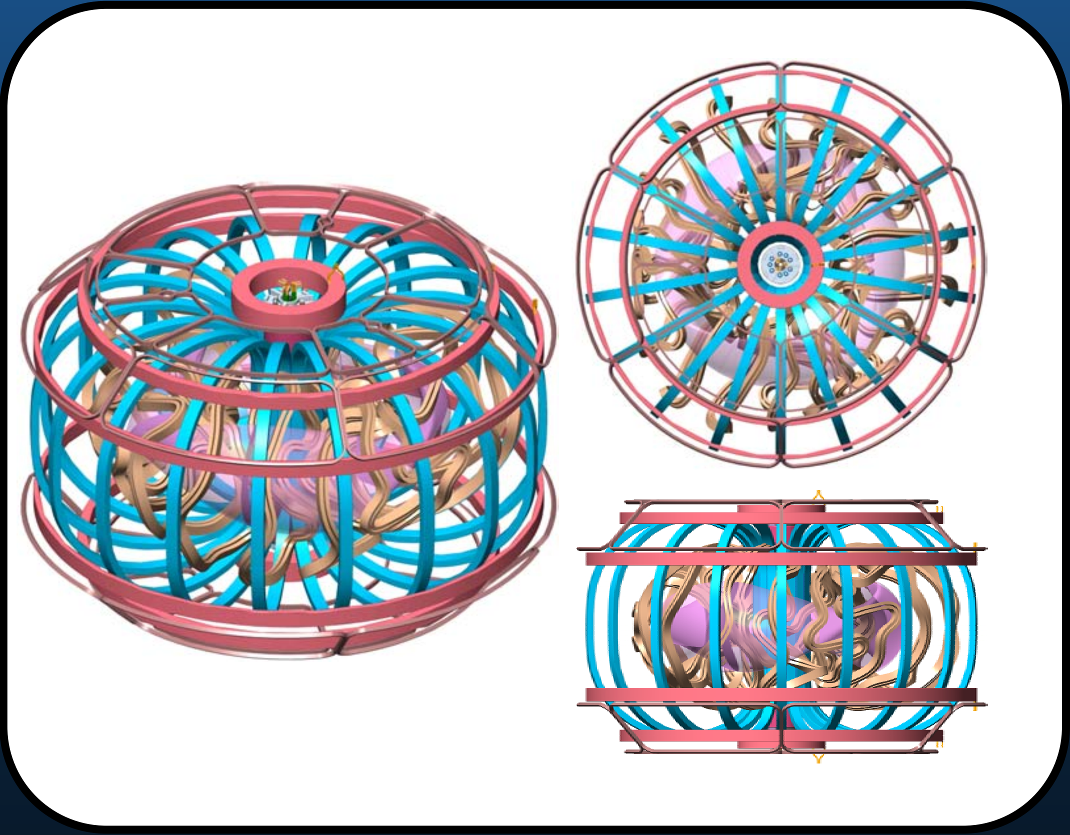
Coil set	Function, Coil set provides:
Modular coils	Basic quasi-axisymmetric magnetic configuration
Poloidal field coils	Inductive current drive, plasma position control, plasma shaping
Toroidal field coils	Addition or subtraction of toroidal field for control of magnetic transform
Trim Coils	Control of magnetic flux surface quality



Coil System Requirements

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- Meet performance and flexibility requirements in specified scenarios
  - Up to 2 T, 15 minute rep rate
  - Independent control of modular and PF coils, variable background TF field
- Provide sufficient winding accuracy
  - Limit islands to <10% of toroidal flux
  - +/- 1.5 mm assumed for installed accuracy
- Accommodate access for tangential NBI, RF, vacuum pumping, diagnostics, and personnel access
- Ensure voltage and current requirements match existing TFTR power supplies
- Coils must be buildable

Reference Operating Scenarios drive coil and power supply performance requirements

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- There are 7 reference scenarios, 2 @ room temperature and 5 @ low temperature
- Room temperature:
  - 0.5 T First Plasma: 0.27 s pulse for initial operation
  - Field line mapping: Low field (~0.1 T), 10 s pulse for flux surface mapping
- Cryogenic Temperature:
  - 1.7 T Ohmic
  - 1.7 T High Beta
  - 320 kA Ohmic
  - 1.2 T Long Pulse: 1.7 s pulse
  - 2 T High Beta

Waveforms drive coil performance requirements

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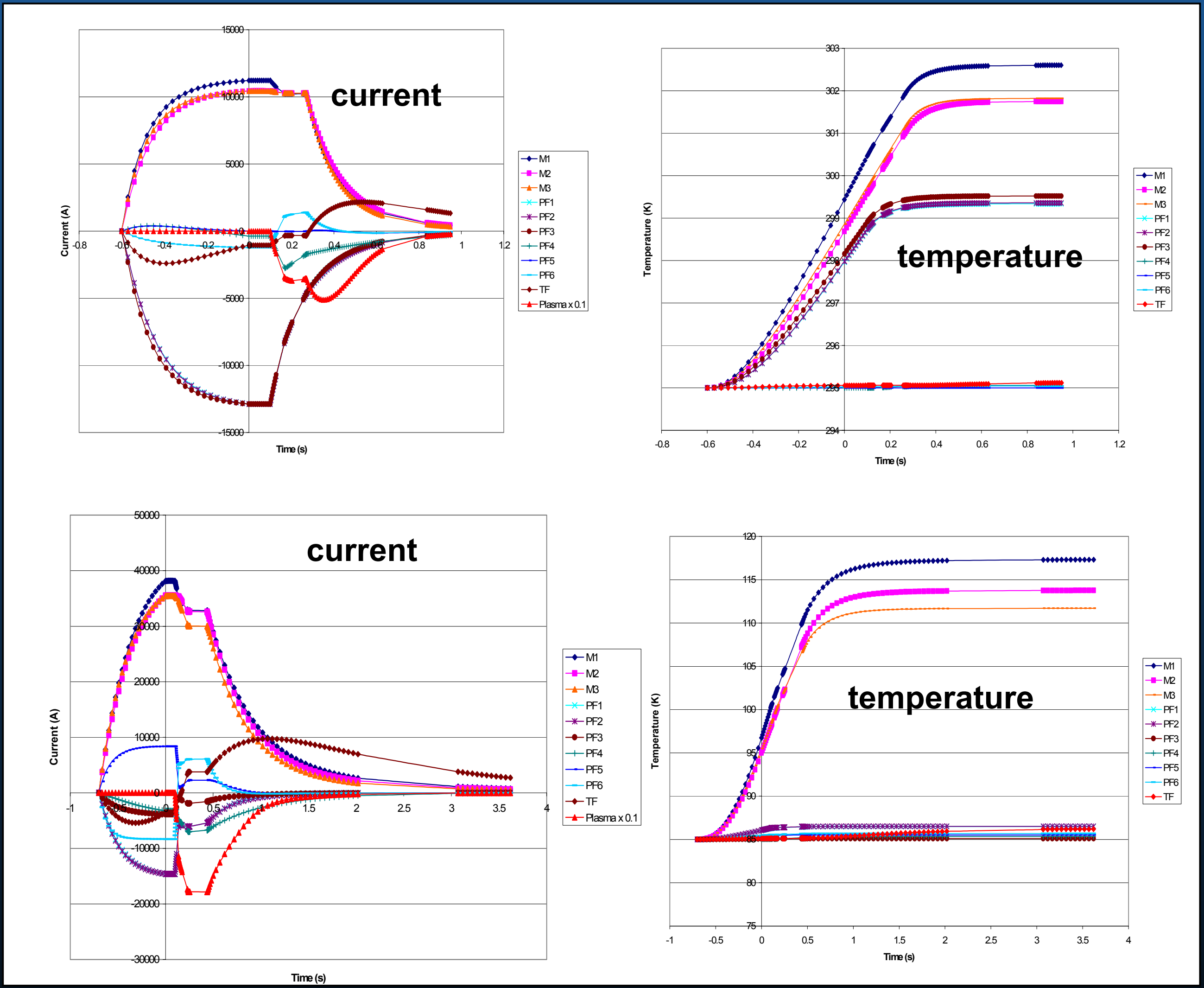
- First Plasma
  Room Temperature

- 1.7T high beta
  LN_2 Temp



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How accurate do the coils have to be?

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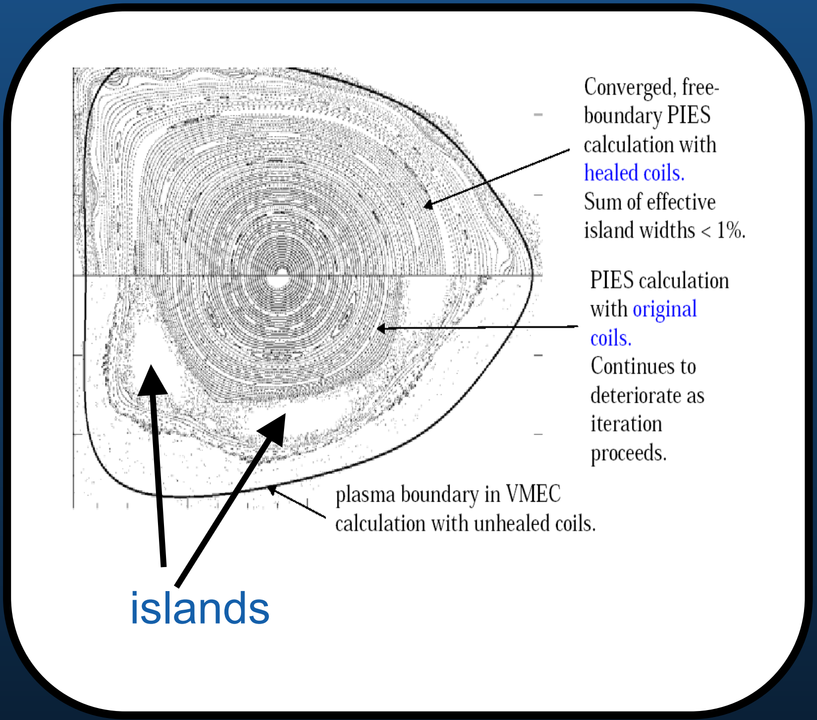
- Stellarator coils must be very accurate to produce flux surfaces of sufficient quality
- Errors in winding geometry can produce islands, which "short circuit confinement" [A. Reiman, NCSX CDR]
- "The toroidal flux in island regions due to fabrication errors, magnetic materials, or eddy currents shall not exceed 10% of the total toroidal flux in the plasma." [ref. GRD, Rev. F]
- Assumed accuracy requirement: Installed coil winding center within 1.5 mm of theoretical (3 mm T.P.)
- Effect of variations and combinations of winding errors studied systematically by A. Brooks using VACISLD code

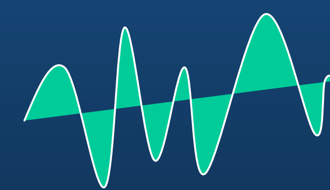


What did study show?

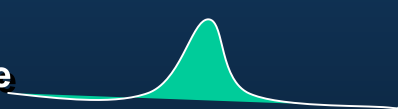
Art's study concluded:

- Errors in Modular Coils have a much larger impact on field errors than do errors in TF or PF coils

- For random tolerance stack-up for different tolerances in Modular, TF and PF:
  - Softening Tolerance on TF & PF from +/-1.5 to +/-3.0 mm appears acceptable
  - Softening Overall Tolerance on Modulars not acceptable.
  - Softening Modular Tolerance based on plasma separation (+/- 1.5mm near plasma to +/-3.0 far from plasma) has minimal impact



- For short "wavelet" type deformation on Modular Coils:
  - Coil-to-Plasma Separation < 30 cm has strongest impact on island size
  - In-plane and Out-of-Plane deformations do not differ significantly



- Impact of broad deformations of Modular Coils
  - Increasing extent of deformation above 0.5 m does not increase max island size

What geometry errors are ok?

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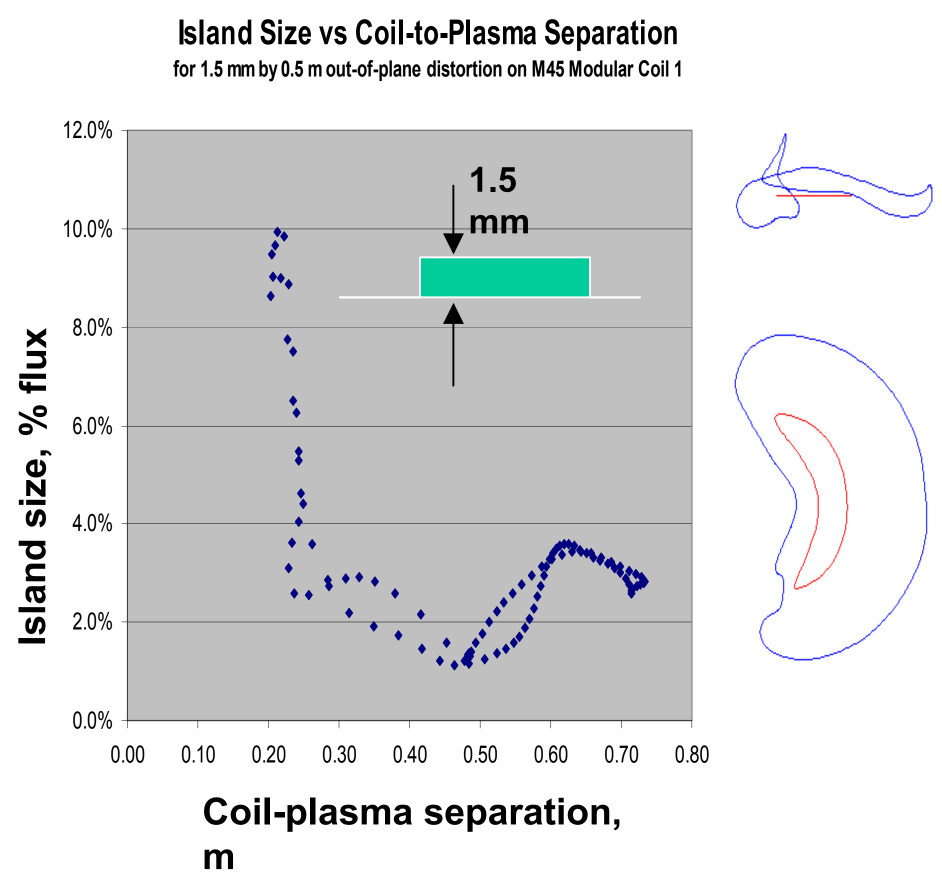
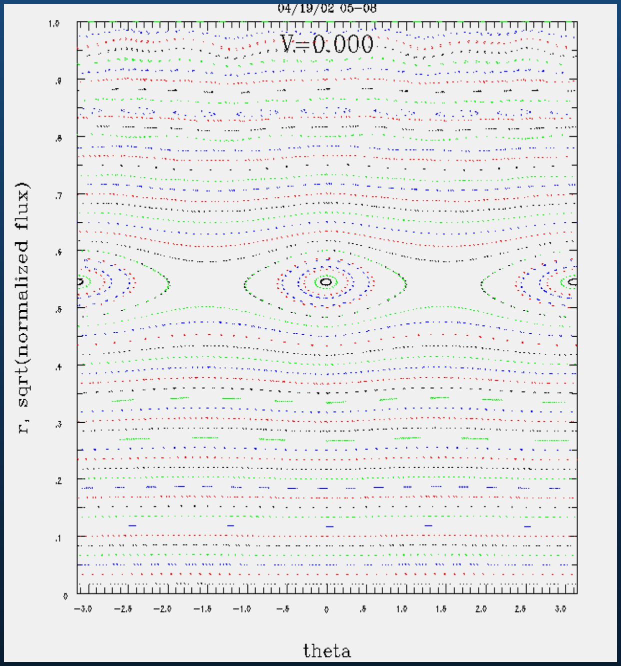
- Modular Coils
  - General tolerance on modular coils remains at +/- 1.5 mm
  - Perturbations > 1.5 mm may be ok for plasma-to-winding separation > 30 cm
- Tolerance on TF and PF can be relaxed to +/- 3 mm
- The islands shown can be further reduced with external trim coils



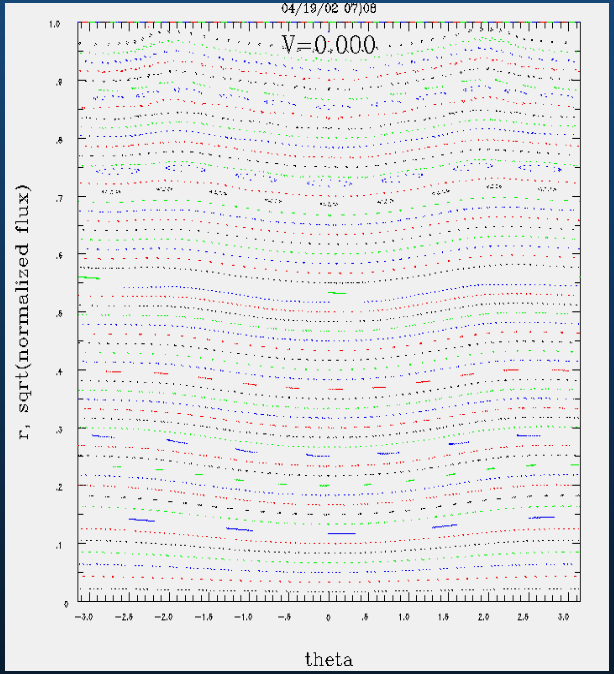
External trim coils heal islands

- Systematic study performed to quantify effect of coil geometry errors (modular, TF, PF)
- +/- 1.5 mm coil accuracy specification looks reasonable, especially with external trim coils



Largest Islands from any modular coil distortion

(2mm distortion of single M1 coil)



Island suppression using correction coils

Note: edge is preserved

Coil System Requirements

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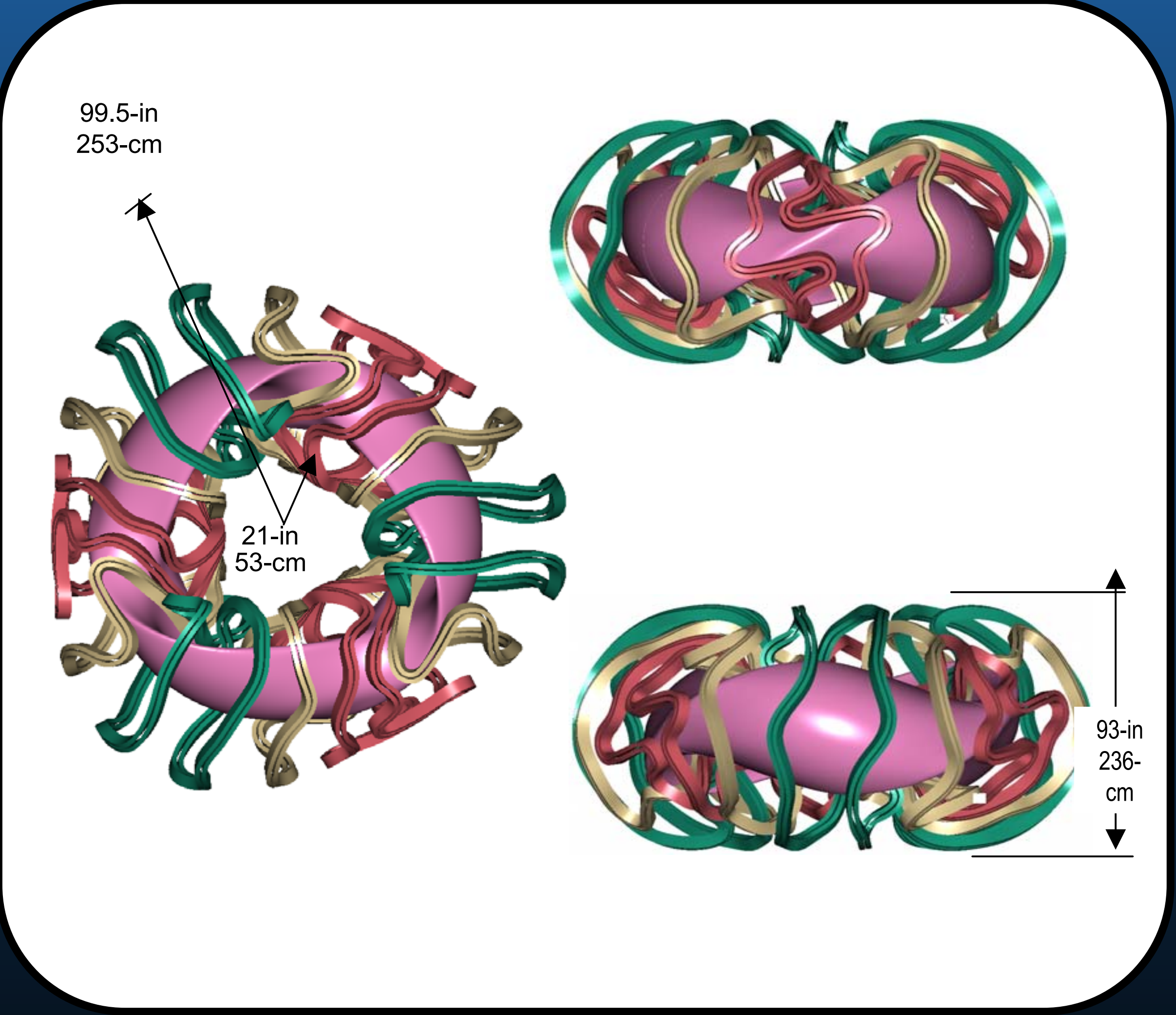
- Ensure voltage and current requirements match existing TFTR power supplies
- Coils must be buildable

Modular Coil Configuration

- 18 coils, 3 field periods
- Optimized for physics performance consistent with NBI access and engineering constraints.
- Coils wound with flexible cable conductor into cast-and-machined forms
- Coils pre-cooled to LN_2 temperature to allow high current density



Compact design requires careful space allocation

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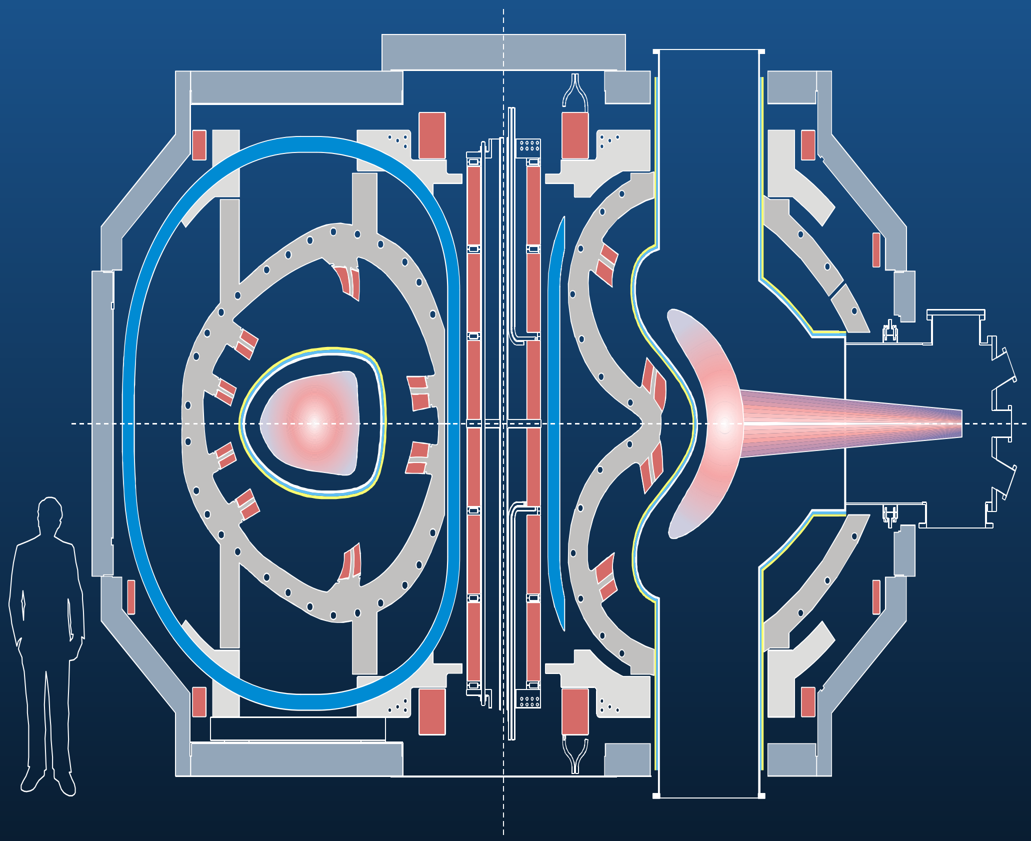
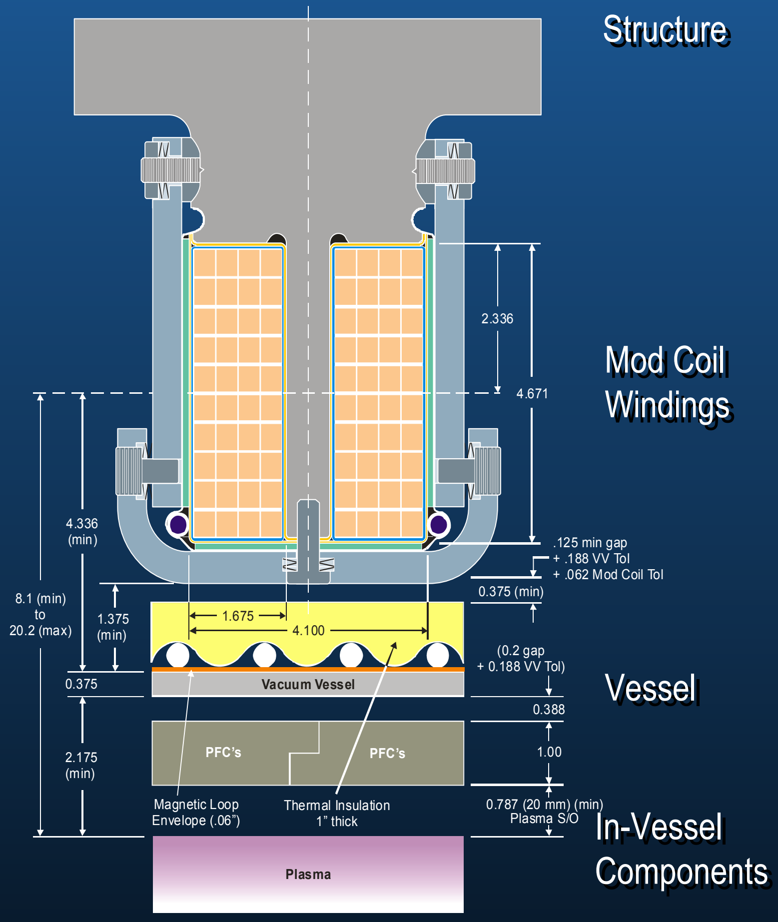
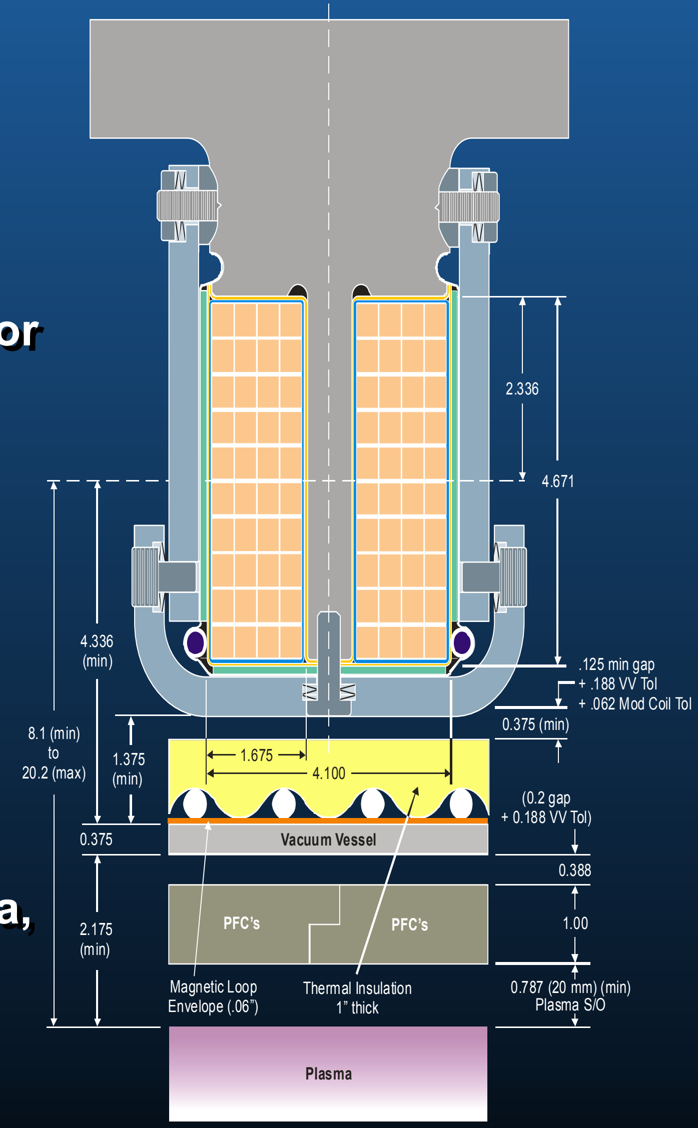




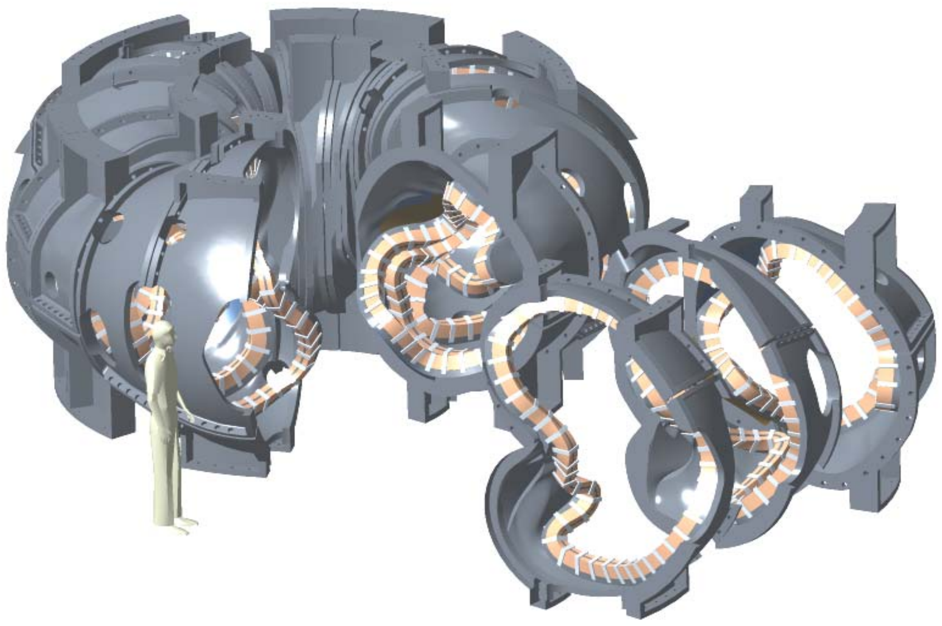
Coil envelope requires cryo-resistive coils

- Initial, low field operation will be at room temperature
- Current density of ~ 15 kA/cm2 requires too much power, has too much temperature rise for room temperature coils.
- Cryo-resistive coils have advantages
  - ~ 7 x increase in copper conductivity
  - Lower temperature rise per pulse
  - Much less power
  - Materials become stronger at low temperatures
  - Coils can be located closer to the plasma, have tighter bend radii, etc.

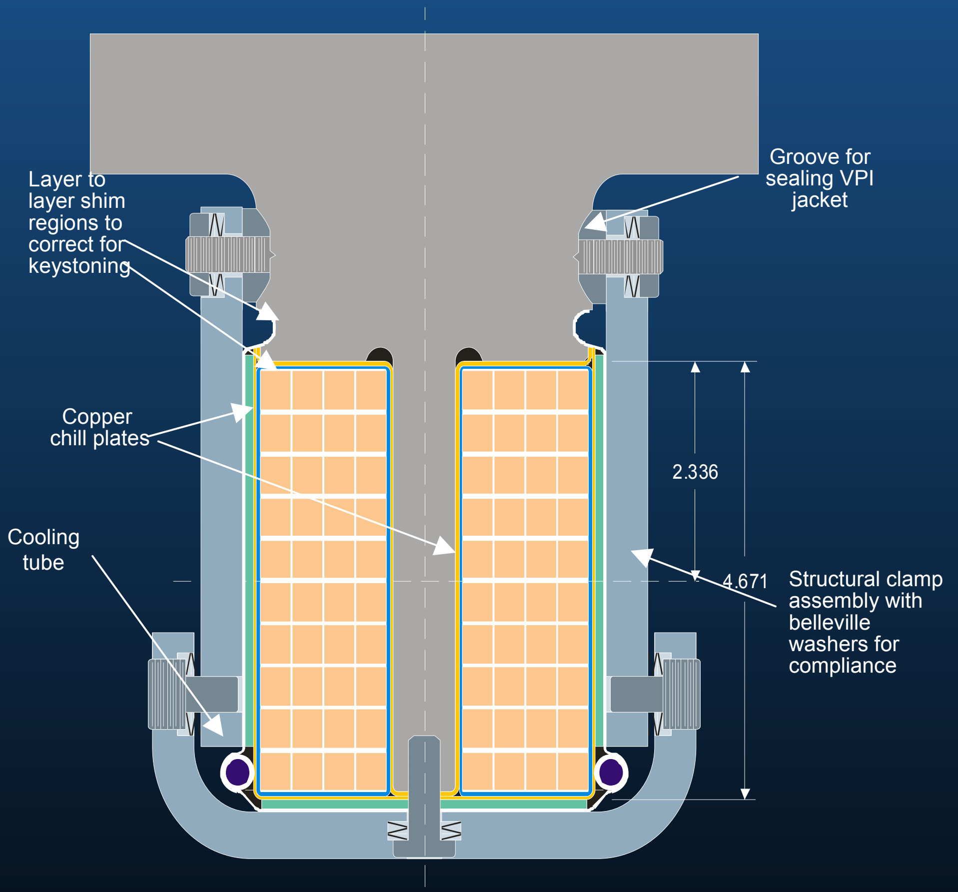


Continuous shell forms robust structure

- Shell consists of individual modular coil forms that are bolted together
- Penetrations can be provided where needed
- Thickness can be varied to optimize / reduce stresses
- Provides “machine base” for all other components
- Stellarator symmetry preserved, toroidal and poloidal electrical breaks

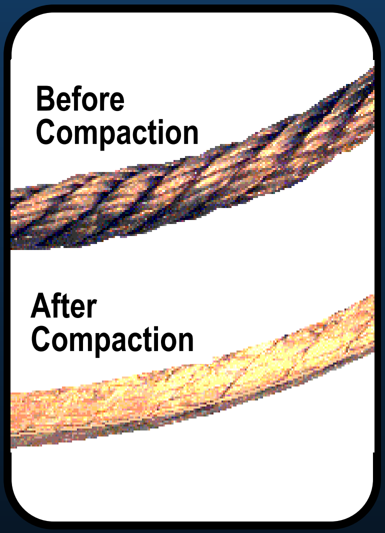


Modular Coils wound on “tee” structure



Parameters:

- Coil Envelope = 2 x 4.671 x 1.675 inches
- Current / Coil = up to 831-kA-turns
- Number of Turns = 20 (M1,M2) and 18 (M3)
- Max current / turn = 41.55 kA
- Conductor Size = .351 x .391 in (8.9 x 9.9 mm)
- Cu Current Density = 15.1-kA/cm2 (max)
- Conductor operating temp. range 85K-125K



Flexible cable used to wind coil

Three types of modular coil assemblies

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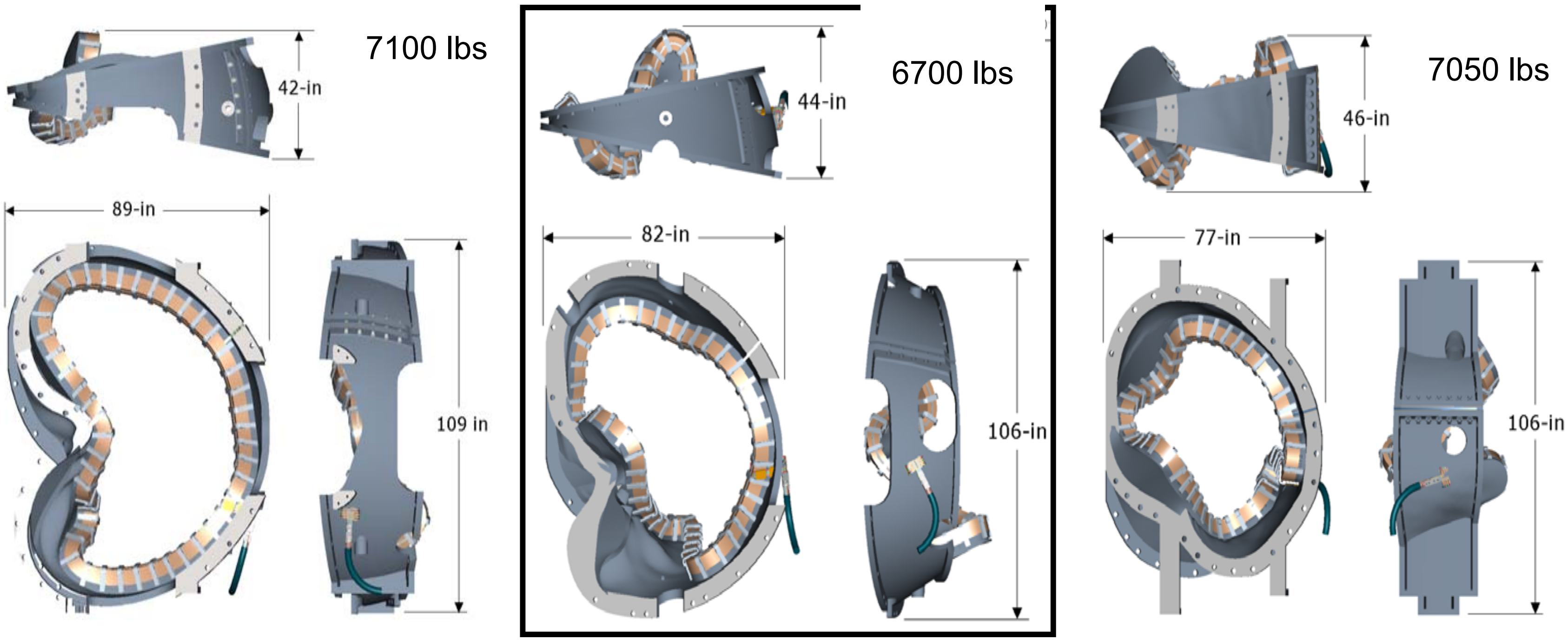

M1 **M2** **M3**

Modular coil designed for strength / accuracy

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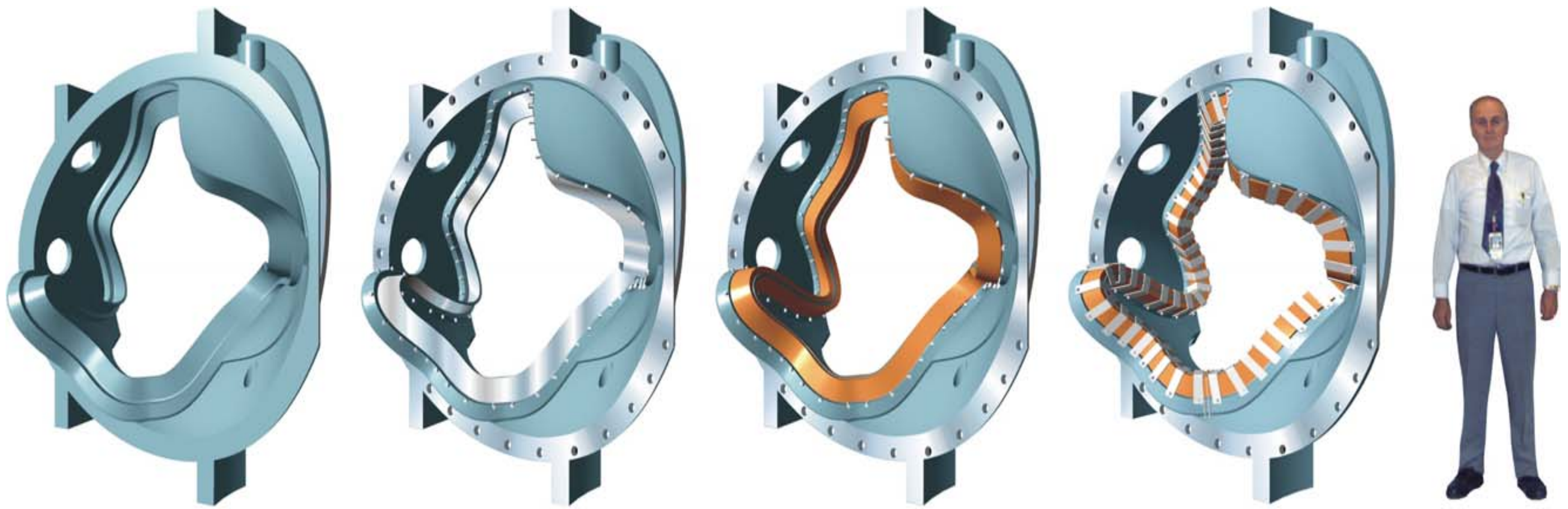
- Continuous support for strength and accuracy of winding
- Single machined part provides winding form and assembly features
- Winding never removed from coil form

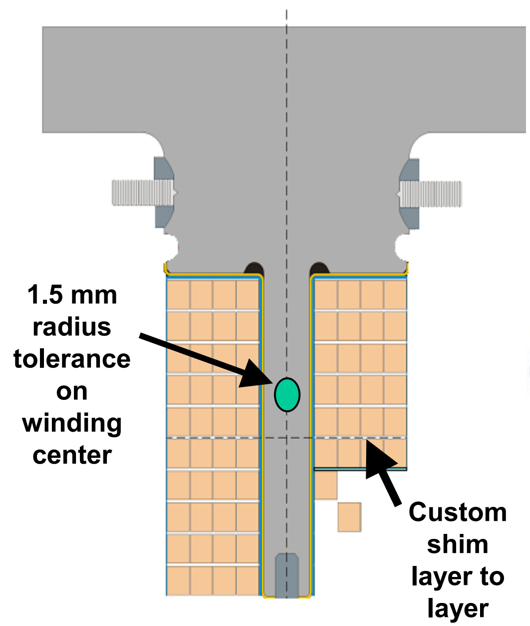


Casting | Machining | Winding & Vacuum Impregnation | Finished

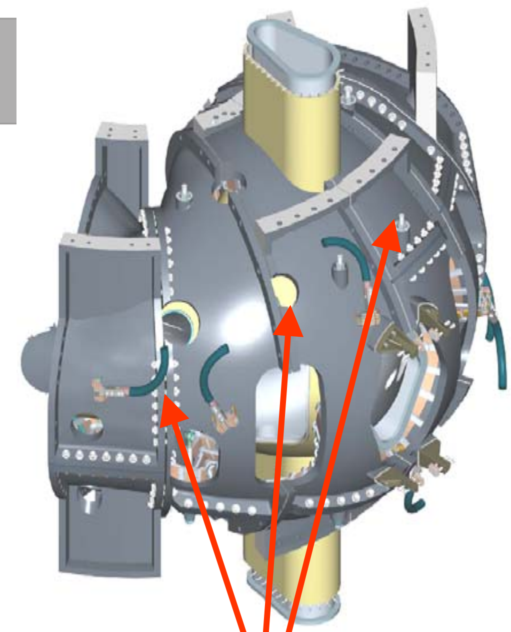
Modular coil accuracy achieved by shimming

Winding position continuously monitored and adjusted to avoid tolerance stack-up

- **Form machined to high accuracy**
  - **Flanges to +/- 0.01 in**
  - **Contours to +/- 0.01 in**
- **Windings can be placed to high accuracy relative to each other and the form via constant measurement and custom shimming**
- **Final position of coil form in assembly can be adjusted for optimum fit of as-built winding packs using shims at assembly flanges**



- **Conductor wound in layers**
- **Each layer custom shimmed**



Custom shims at flanged joints between adjacent coil winding forms

Tolerance budget apportioned in thirds

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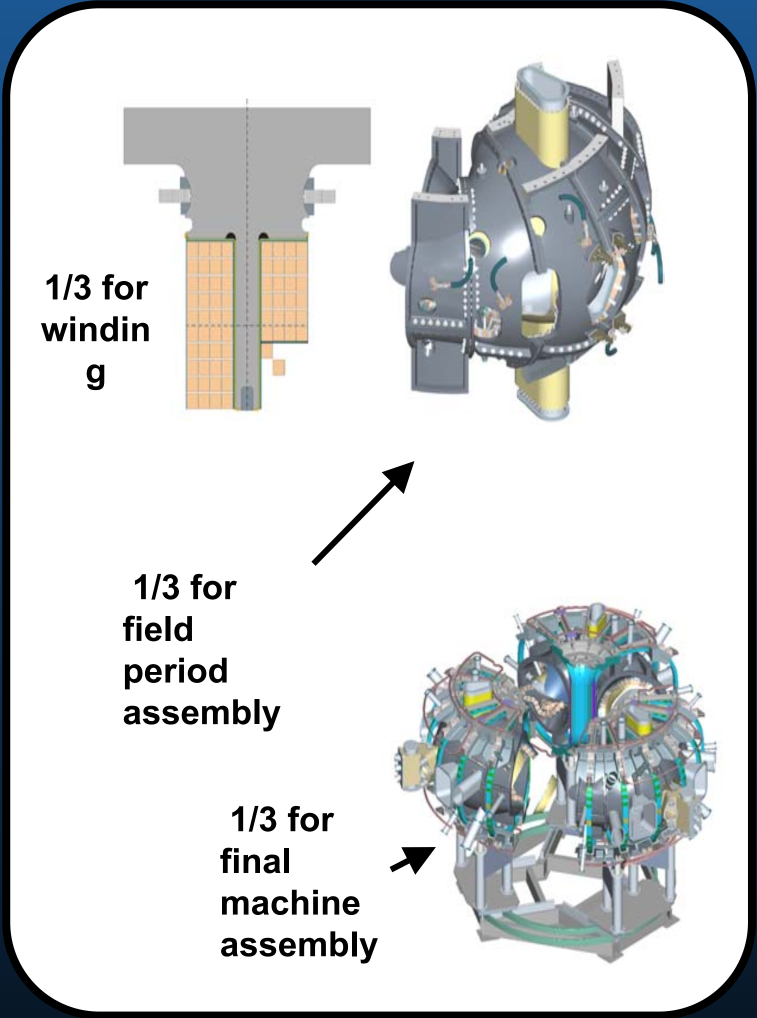
Element	Tolerance budget	Comment
Winding form	+/- 0.01 in.	Baseline on drawing
Copper cladding	TBD	Could be used to improve winding form tolerance if shims are allowed
Insulated conductor size	+/- 0.01 in.	Based on NEEWC input
VPI process	TBD	Assumed to be small
Total for Coil Winding	+/- 0.02	
Assembly of coil in field period	+/- 0.02	Adjusted to best fit, coil-to-coil with custom shims
Assembly of field periods	+/- 0.02	Adjusted to best fit with custom shims
Total tolerance	+/- 0.06 in. (+/- 1.5 mm)	Minimum value, may be relaxed according to location around winding



4-in-hand winding has advantages

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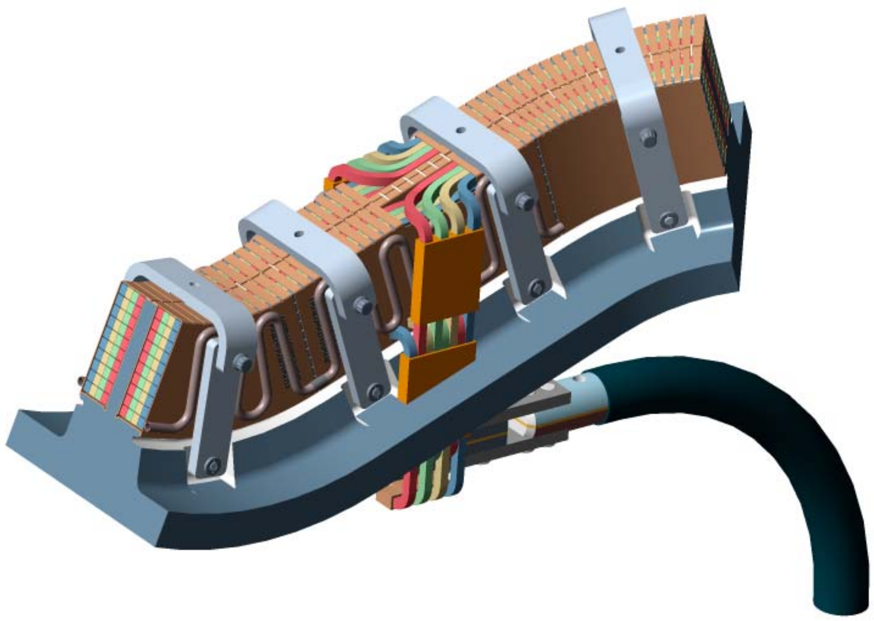
- Smaller conductor reduces keystoning – huge advantage
- Low turn-to-turn voltage reduces insulation thickness, eliminates on-site taping operation
- Winding does not start in the middle of the turn, no need for extra spool
- Winding arrangement workable at lead location – turns bundled for connection to coax lead



Lead location minimizes field errors

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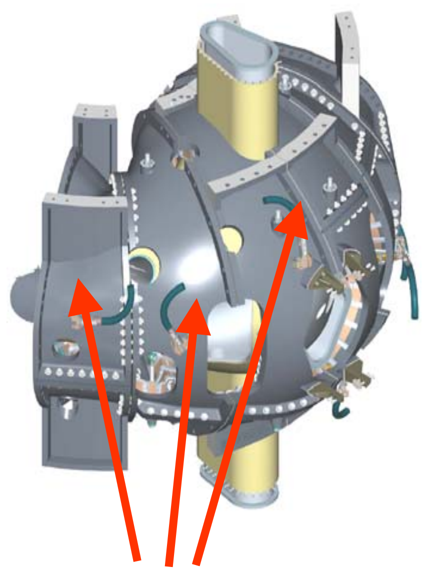
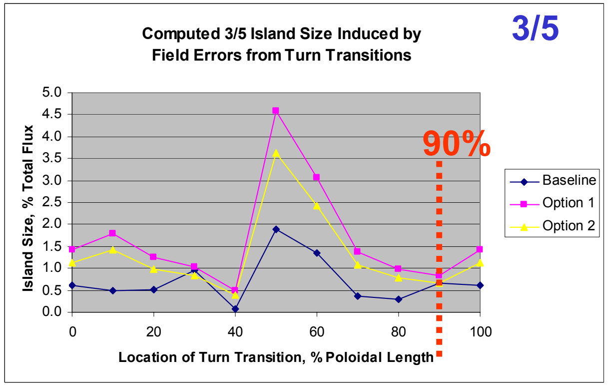
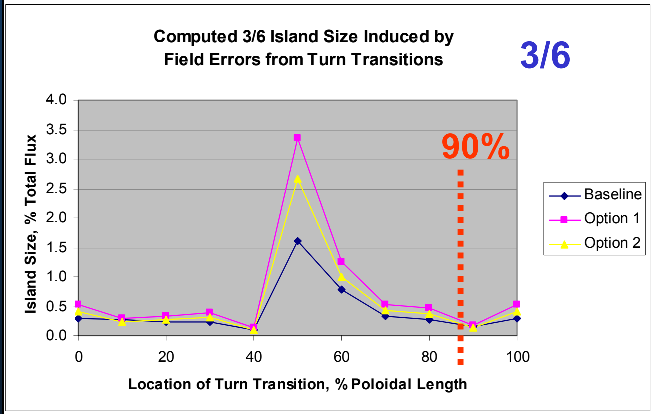
- Field errors from leads are mitigated by lead placement and the use of coaxial feeds
- Modular coil leads are near the "90%" location outboard

Lead detail and coax feed



Modular coil lead locations

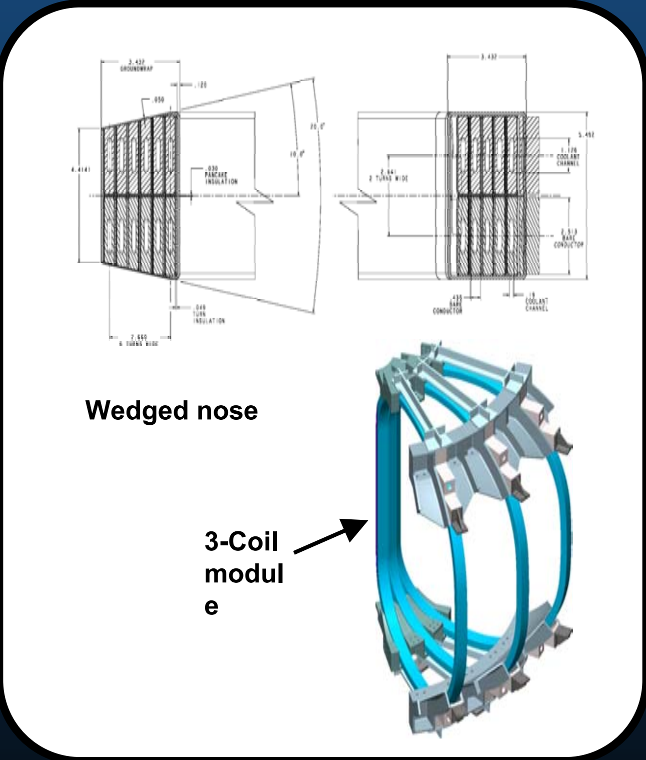


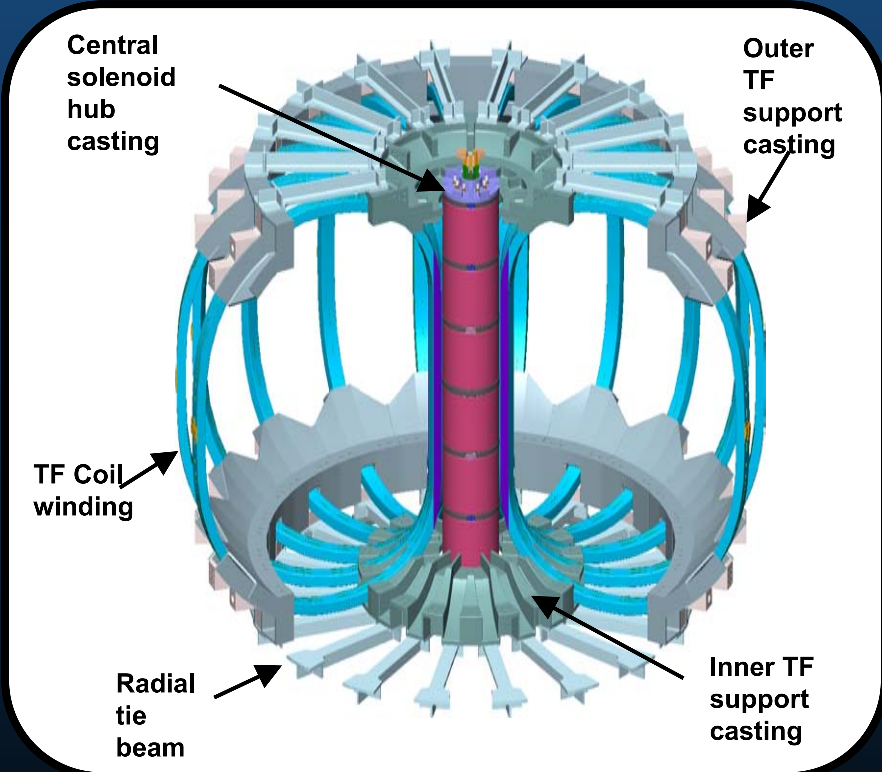


Islands from 3/5 and 3/6 field errors

TF Coils and structure have conventional design

- 18 coils provide up to +/- 0.5 T for flexibility beyond reference scenarios
- Wound from hollow copper conductor and vacuum pressure impregnated with epoxy
- Supported from external coil support structure , Centering load supported by wedging
- Pre-cooled to LN_2 temperature, temp rise < 5K





6 pairs of PF Coils

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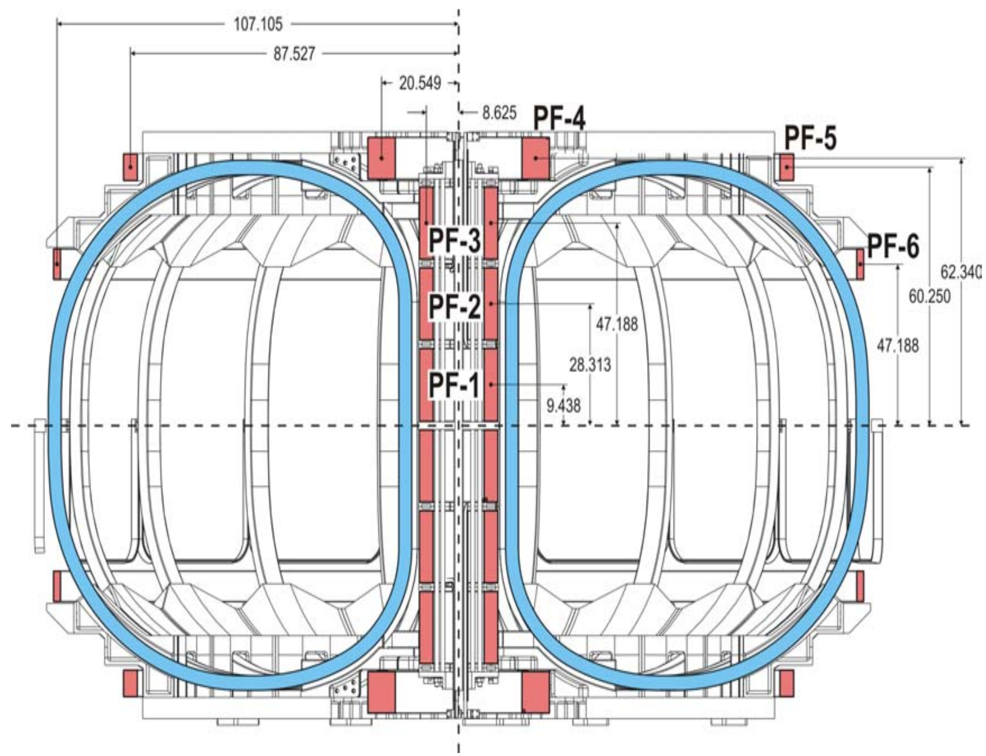
- 6 pairs of PF coils provide inductive current drive and physics flexibility, (3 pairs of coils form central solenoid assembly)
- Require ~2 V-s to drive 320 kA plasma current
- PF coils located outside modular and TF coils, supported from external coil support structure
- Wound from hollow copper conductor, glass-epoxy insulation
- Pre-cooled to LN_2 temperature, temperature rise < 5K



External Trim Coils fit outside

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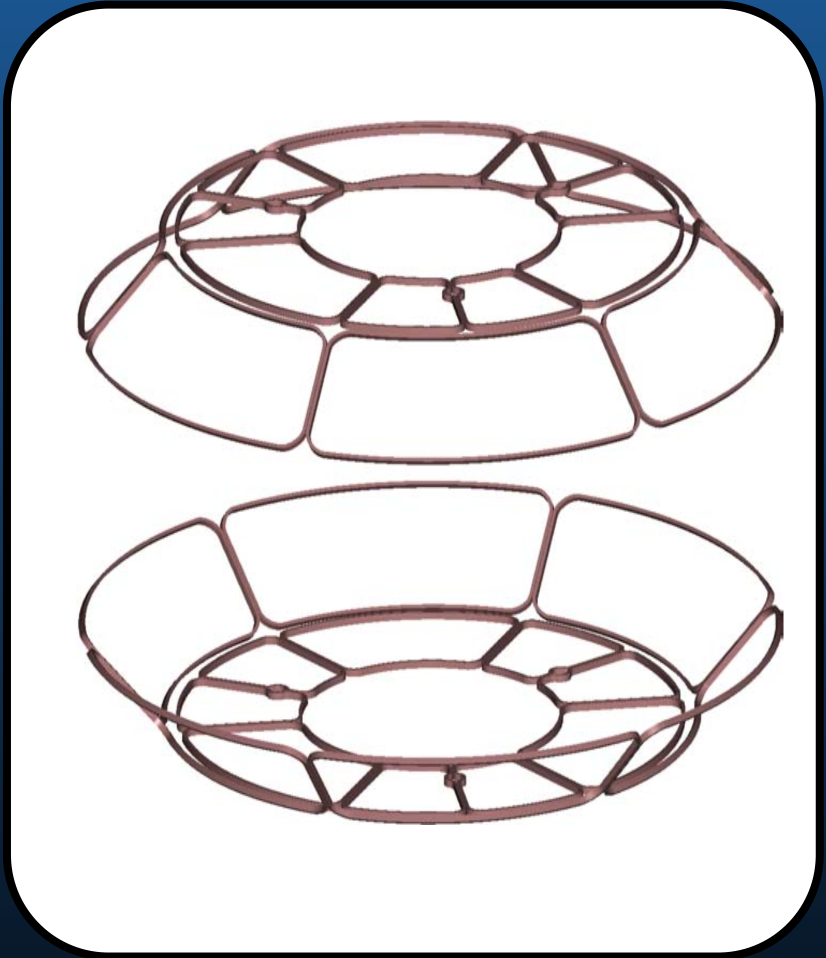
- External trim coils provided to mitigate low order field errors from fabrication or assembly errors
- Coils are independently powered
- Located outside modular and TF coils, supported from external coil support structure
- Wound from copper conductor, glass-epoxy insulation
- Pre-cooled to LN_2 temperature



Will the stellarator core design work?

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- Coil Design is being verified by analysis and R&D

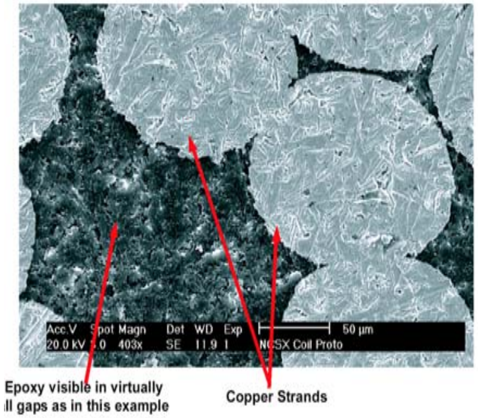
- R&D (later talks by P. Heitzenroeder, J. Chrzanowski)
  - Epoxy impregnation tests and conductor characterization
  - Winding tests on full scale forms
  - Full scale prototype winding form (from two suppliers)
    - Contracts will be awarded soon
    - Details of winding form must be finalized, in conjunction with suppliers
  - Full scale prototype coil

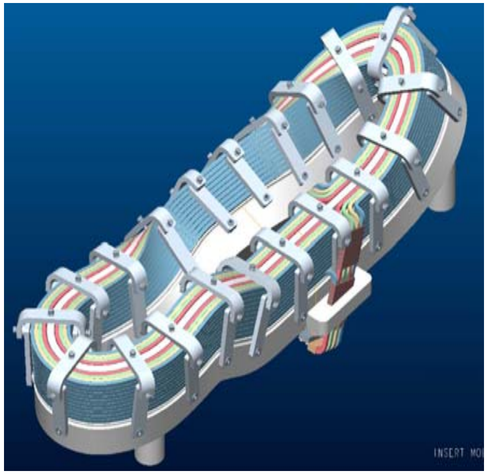
- Analysis (later talks by D. Williamson, L. Myatt)
  - EM analysis (Field and force analyses, eddycurrents)
  - Stress analysis
  - Thermal analysis

Later talk by J. Chrzanowski

Conductor behavior is characterized

- **Winding / handling**
  - keystoning tests
  - Insulating tests
- **Vacuum Pressure Impregnation**
  - Individual conductor samples
  - Straight “tee” section
  - Racetrack coils (2)
- **Material Properties – impregnated conductor**
  - mechanical tests (tension, compression, flexure vs temp.)
  - Thermal tests (CTE, conductivity)
  - Electrical resistance (12% higher than equivalent solid)
- **Integrated Coil Performance**
  - 2 Racetrack coils built and partially tested
  - “twisted” racetrack by January





Design Analysis

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- Preliminary design analysis has been completed for
  - Coil and lead field errors: *Acceptable with trim coils*
  - Eddy currents in modular coil structure: *> 20 ms time constant*
  - Thermal and thermo-hydraulic response: *15 minute cooldown plausible*
  - Electromagnetic field and forces: 2 independent calcs within 4%
  - Stress due to thermal and electromagnetic loads

- Structural analysis involves several models which are focused on:
  - Global deflection and stress in the winding forms
  - Nonlinear behaviour of the windings due to thermal and EM loads
  - Deflection and stress in the clamps and other local supports

- A detailed deflection and stress analysis of the assembly is in progress

Later talk by D. Williamson

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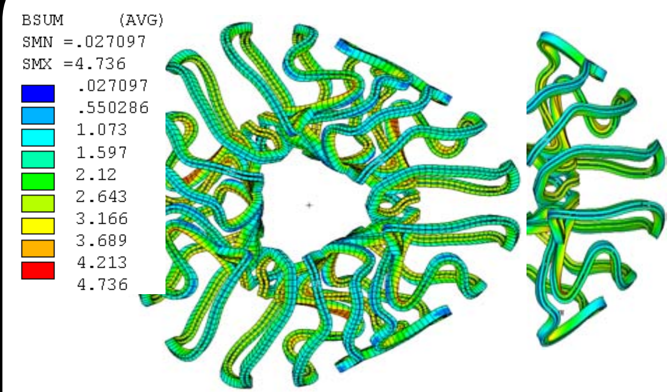
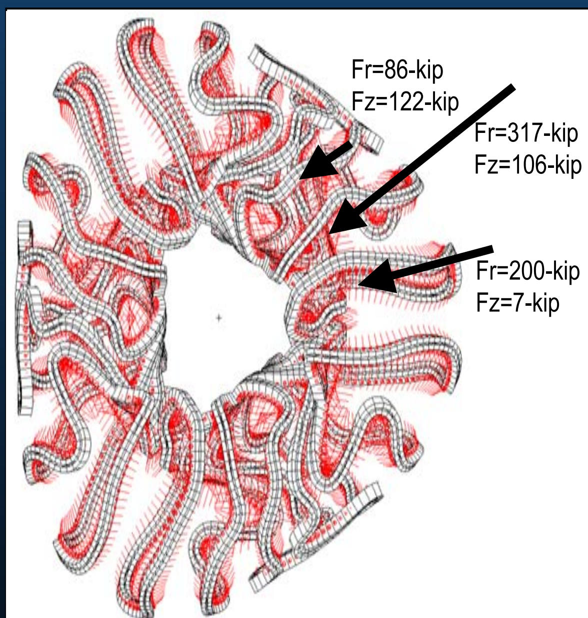
Structural Analysis of Coil Set - Forces

- **Fields and forces analyzed for 7 reference operating scenarios with peak currents**
- **Worst case loading conditions selected for stress analysis**
- **Two independent calculations performed as check of field and force calculations (agreement to 4%)**



2T ref case worst for mod coils



Net EM Force on Modular Coils								
Coil	Field/Force Component	0.5-T 1st Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T L. Pulse	320-kA Ohmic
	Max Field at Coil (T)	1.2	0.2	4.2	4.2	4.9	2.9	4.2
M1	Net Radial Load (kip)	13	1	152	152	200	76	147
	Net Vert Load (kip)	0.5	0	9	9	7	5	7
M2	Net Radial Load (kip)	20	1	228	228	317	113	230
	Net Vert Load (kip)	7	0	84	84	106	42	79
M3	Net Radial Load (kip)	5	0	57	57	86	29	62
	Net Vert Load (kip)	8	0	95	95	122	47	89

350 kA ohmic scenario worst for TF, PF

Later talks by Fan, Williamson, Freudenberg

Structural analysis of modular coils

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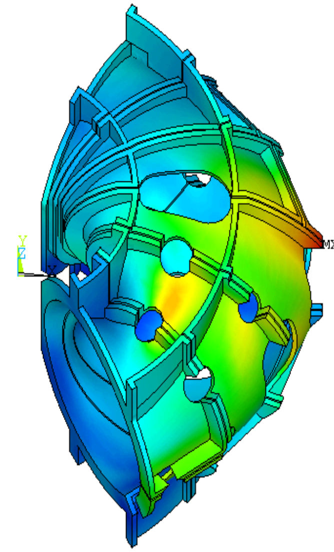
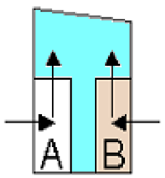
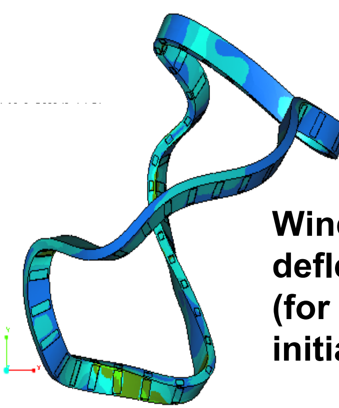
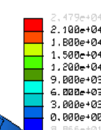
- Winding supported continuously by shell structure
- Structural response depends on:
  - stiffness properties of composite winding,
  - initial strain in conductor (thermal and cure shrinkage)
- Winding form has safety factor > 2 on stress (VM stress = 35 ksi)
- Windings have higher deflection due to initial thermal strain
  - For initial strain of 0.08%, stress ~ 16 ksi (S.F. = 1.3)
  - For initial strain of 0.0%, stress ~ 10 ksi (S.F. > 2)
  - Key issue is cure shrinkage
- Further non-linear analysis planned during final design

Shell has maximum deflection ~ 1 mm (for max loads)







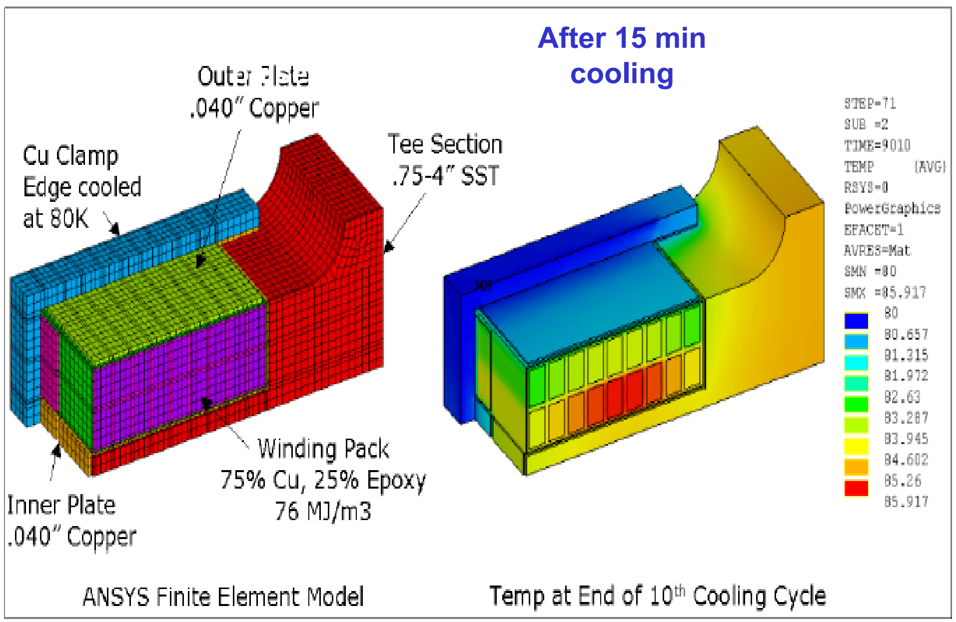


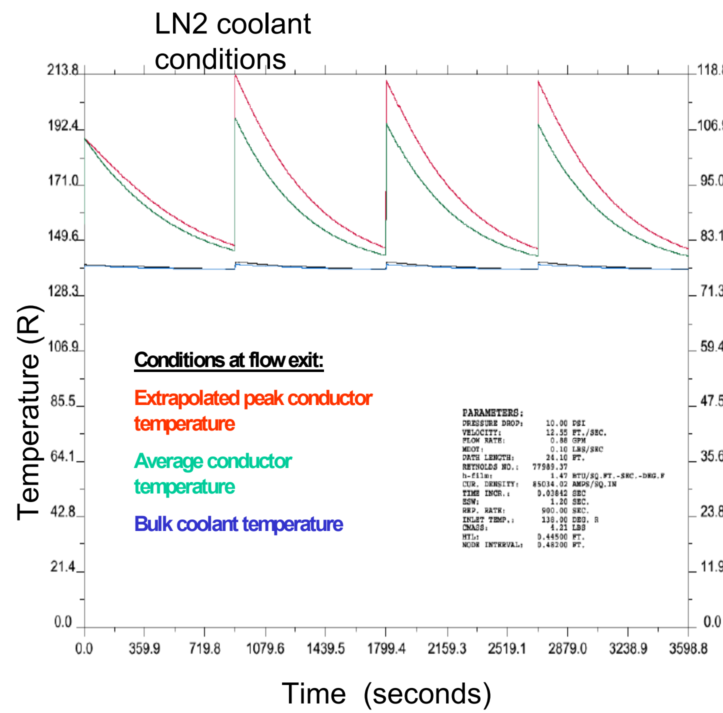
Winding has max deflection ~2 mm (for max loads and initial strain)

(**) 60 ksi corresponds to 1/2 minimum ultimate stress, extrapolated to 77 K

Winding Thermal Response

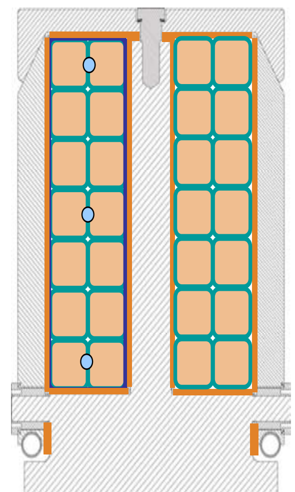
- Winding heats adiabatically from 85 to almost 125 K during pulse
- Cooling is provided by conduction to chill plates, which are traced with LN2 coolant lines
- Cool-down in 15 minutes calculated
- Cool-down of racetrack coil almost as good

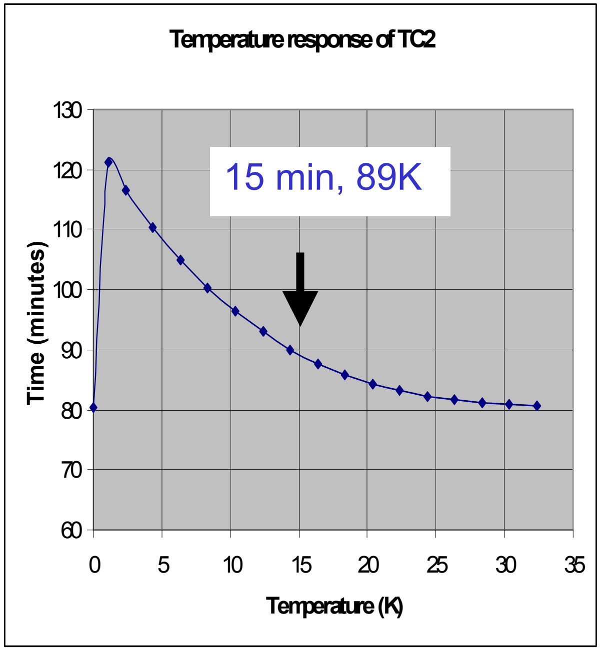




Winding cooldown has been tested

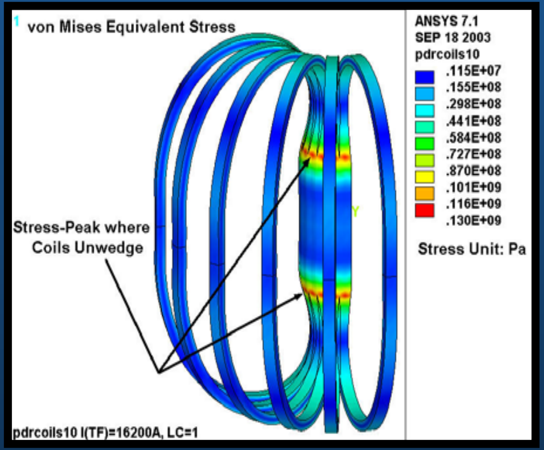
- Racetrack coil wound and Vacuum impregnated with epoxy at PPPL
- Coil tested to 6.5 kA at ORNL
- 65 second pulse achieved 40K temperature rise
- Cool-down slightly slower than expected

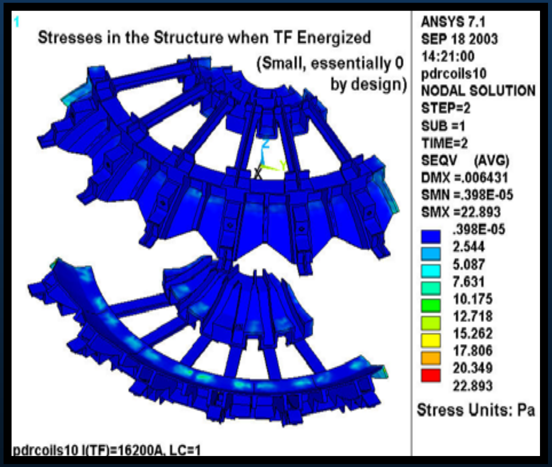




TF and PF Coil Analysis

- **Stresses are well within limits for PF coils:**
  - Stress in copper < 7 ksi, safety factor > 3
- **High stresses in TF coils occur at top of wedged section:**
  - Stress in copper < 7 ksi, safety factor > 5 (bending + membrane)
  - Stresses will be reduced by extending wedging features
- **Stresses in structure very low:**
  - Stress in steel < 7 ksi, safety factor > 7





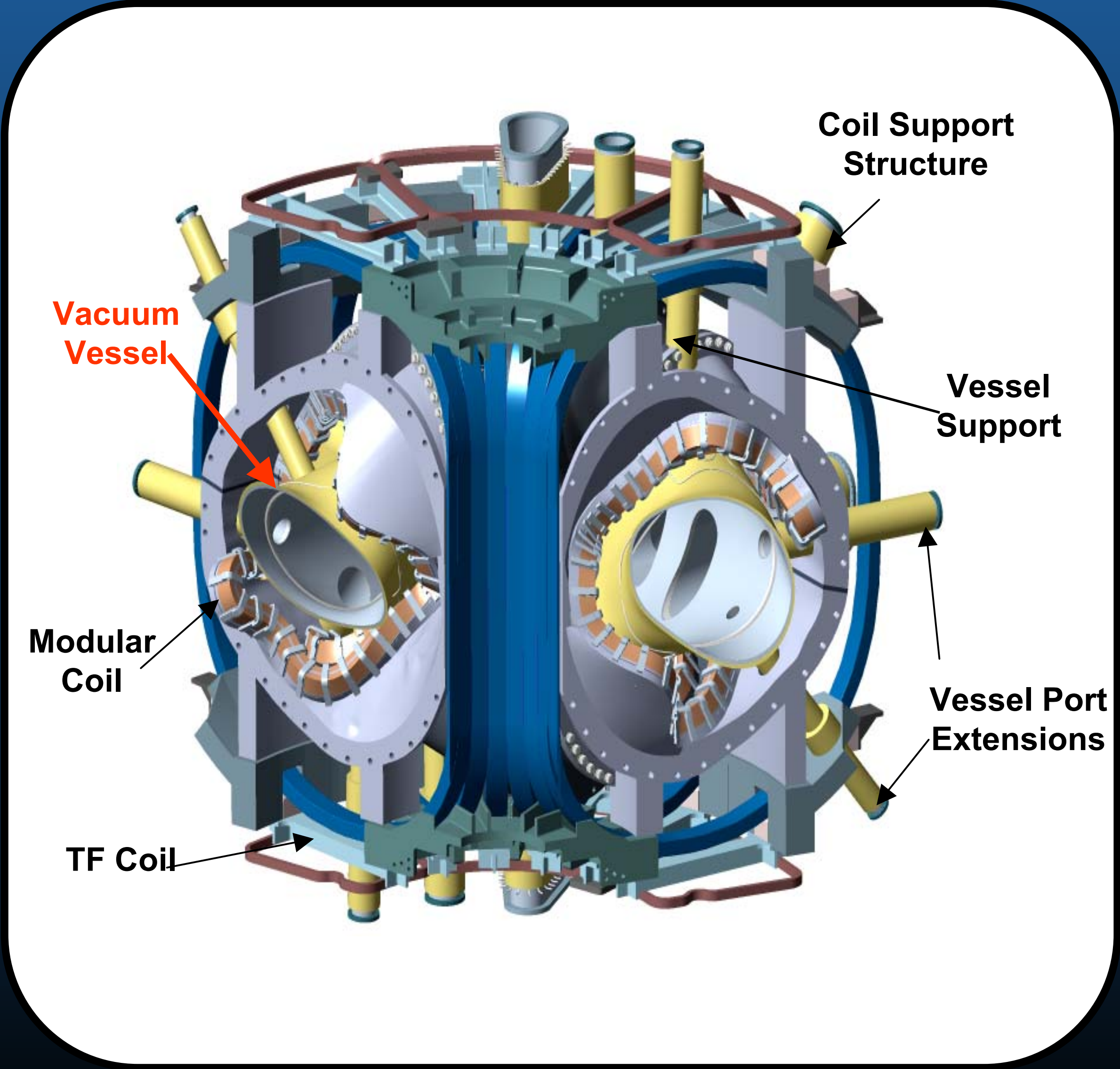
Coil Protection systems

NCSX

- Fault conditions must be evaluated in addition to normal operating conditions for coils
- However, the present plan is to avoid overloads by using an active fault detection system
  - The fault detection system will be programmed to monitor the signals from voltage, strain, temperature, and possibly magnetic field sensors on or around the various coil windings and structures as the coils are being energized.
  - If any of the sensor signals are out-of-bounds for the specific current scenario being run, the fault system would crowbar all the power supplies. (The present coil ramp down assumes the power supplies are crowbarred.)
  - The system would guard against control errors and physical faults such as shorted buswork
  - The system does not prevent faults, but prevents the coils from being fully energized in the event of a fault.
  - The system operates in conjunction with the power supply and I&C systems, and would also shut down the coils in the event of a fault during full current operation.

Inside the coil set is a vacuum vessel

NCSX



Vacuum Vessel Requirements

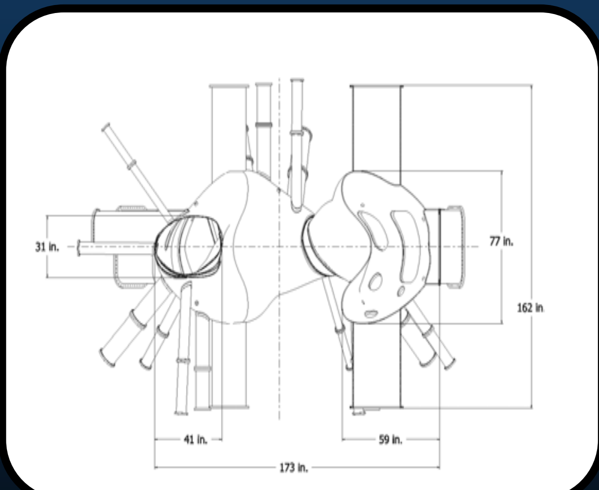
NCSX

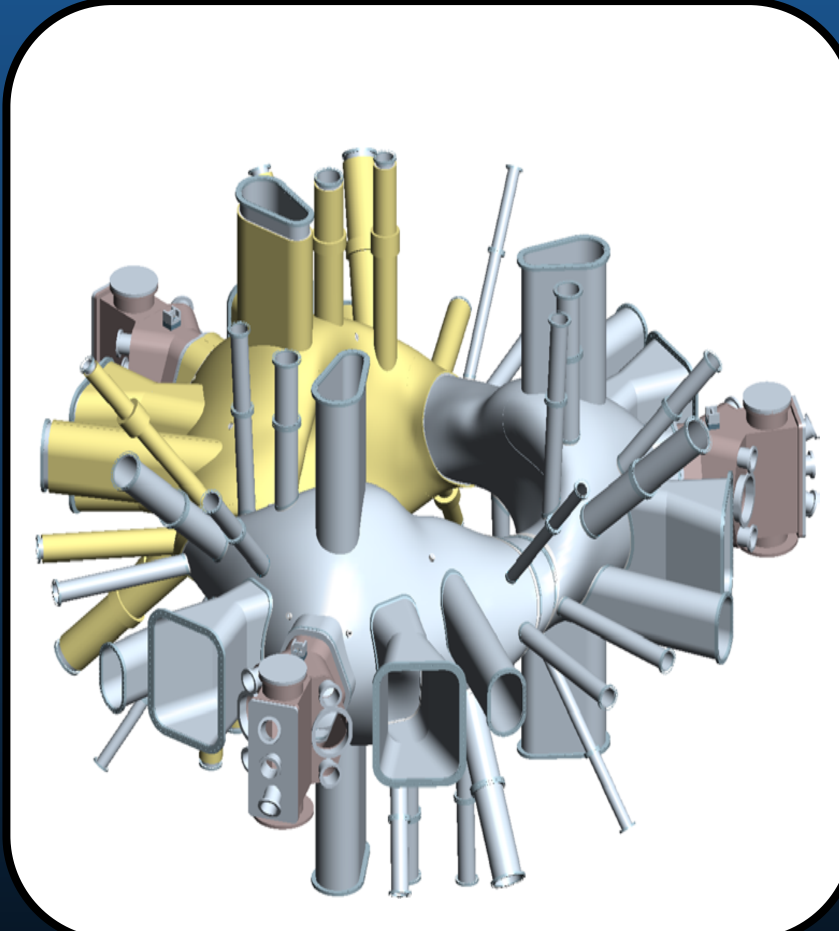
- Provide good clean vacuum environment
  - Vessel must be bake-able to 150 C
  - Accommodate PFCs baked at 350 C
- Minimize field errors
  - Low permeability (< 1.02 nominal goal)
  - Stellarator symmetry
  - Short time constant
- Provide as large a volume as possible for plasma shape flexibility and power and particle handling systems, consistent with assembly of modular coils
- Provide support for internal components such as PFCs, trim coils, magnetic diagnostics
- Provide access ports for diagnostics, vacuum pumping, heating systems, and personnel access

Vacuum Vessel Design Concept

NCSX

- Shell material Inconel 625
- Thickness .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 150C) and cooling
- Microtherm insulation between VV and cold mass

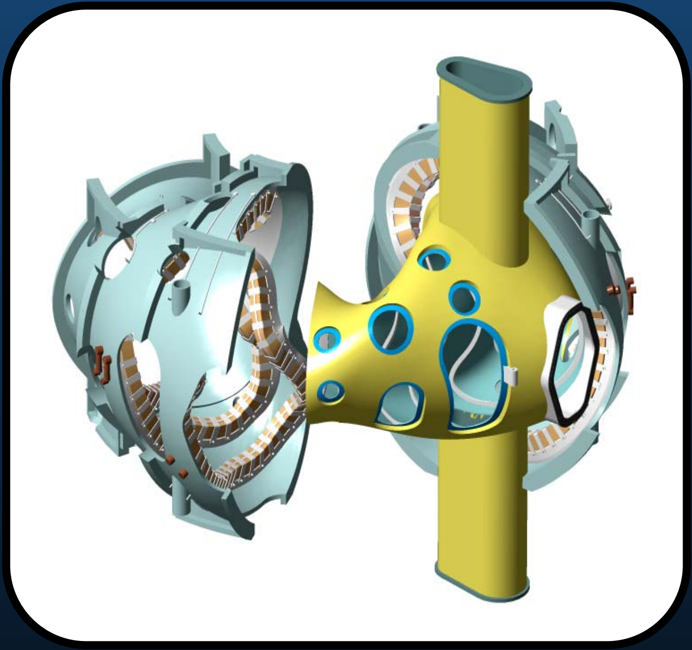


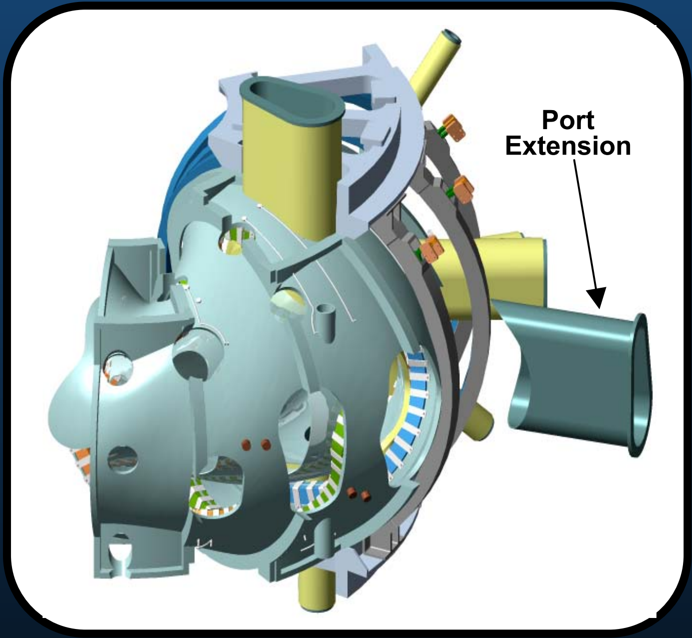


Vacuum Vessel Assembly Concept

NCSX

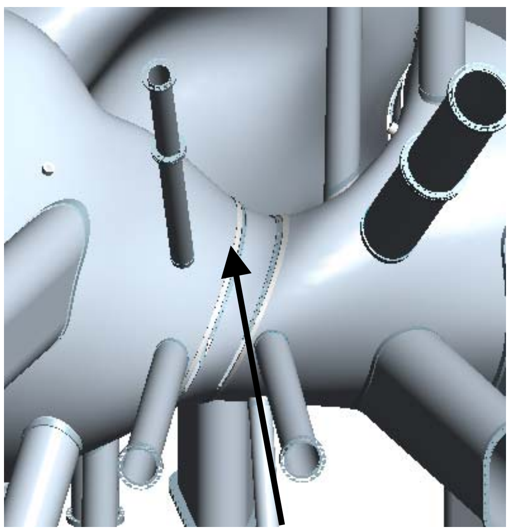
- Vessel is fabricated in field periods
- Modular coils are rotated over field period, then port extensions are welded on
- Vessel is as large as possible consistent with these operations – *see STL models*



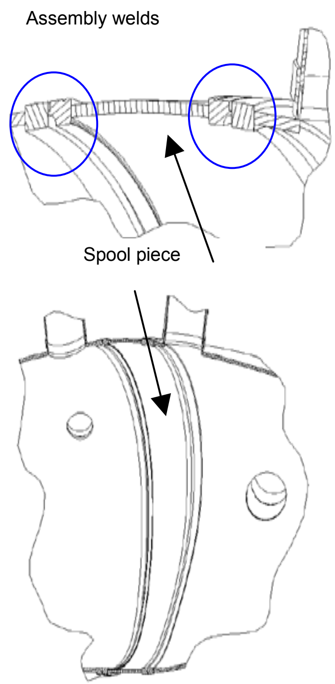


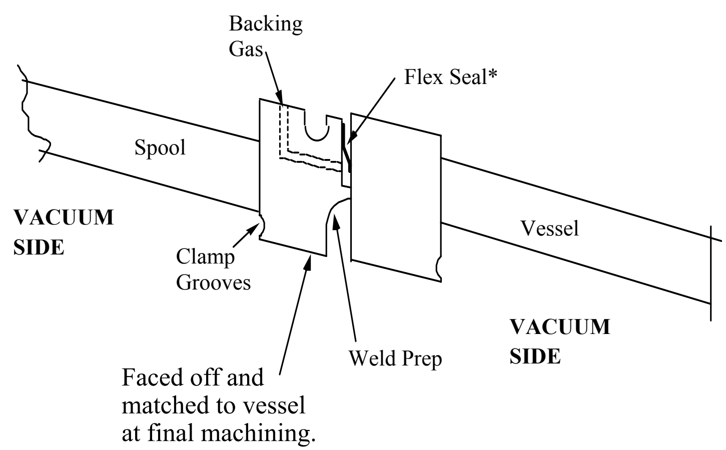
Vessel Field Joint is welded

- Welded flange selected due to low profile, provides maximum clearance to plasma
- Spool piece is machined just prior to final assembly, provides assurance of fit up of three field periods



Spool piece between field periods

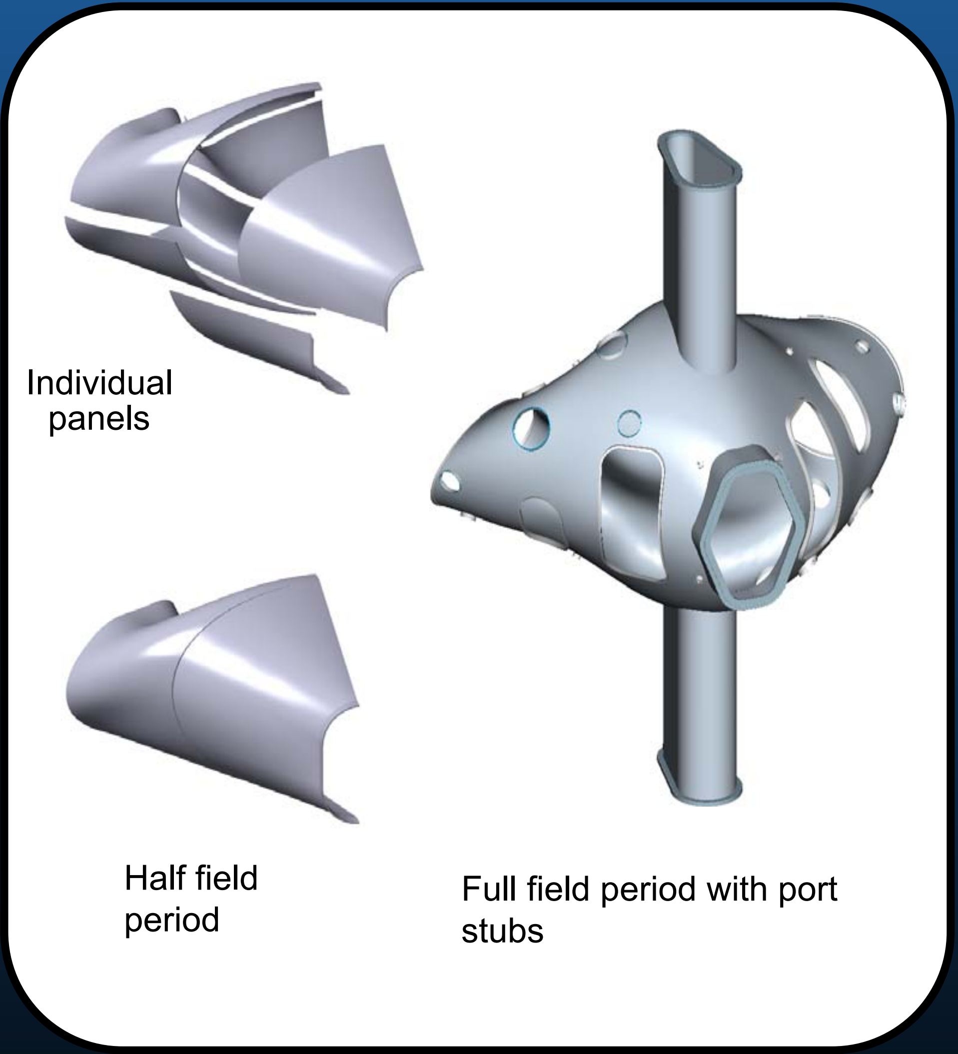




Vacuum Vessel Fabrication Concept

NCSX

- Several options were considered for vessel fabrication, including press forming, explosion forming and casting
- Current plan is to use forming and welding of torus shell
- Half field period repeats 6 times to form complete vessel
- Vendor will deliver vessel with full ports at v=0 plane and port stubs elsewhere so coils can be assembled over vessel

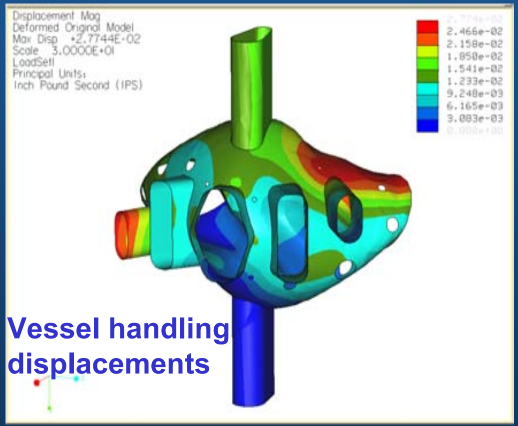


Vessel design verified by analysis

NCSX

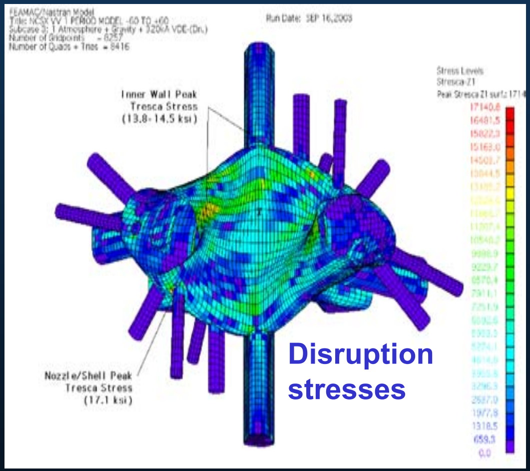
Structural analysis:

- Handling and fixture support loads
  - Deflections < 0.03 in, stress < 5 ksi, Factor of safety > 5
- Gravity and Pressure loads:
  - deflections 0.15 in (ports), 0.06 in (shell),
  - tresca stress: 12 ksi, factor of safety > 2
- Disruption loads:
  - max vertical load of 25,000 lbs, deflections 0.21 in (ports), .13 in (shell)
  - Tresca stress < 17 ksi for combination of disruption, pressure, gravity loads, factor of safety > 1.5
- Buckling: factor of 14 on pressure



Thermal analysis:

- Pre-shot load on cold systems, vessel at 40C: 10.8 kW
- 150 C Vessel bakeout load on cold systems: 18.4 kW
- 350 C PFC bakeout: 11.6 kW removed by vessel



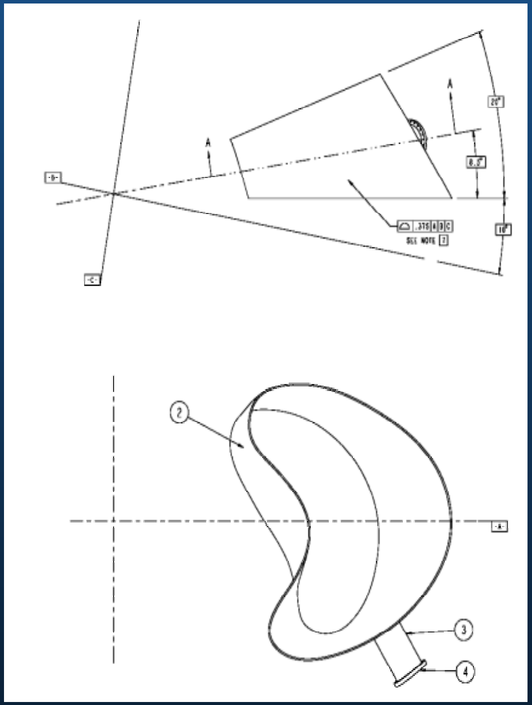
EM analysis:

- Time constant 5.3 ms compared to 10 ms requirement

Vessel design verified by R&D

NCSX

- Manufacturing studies
  - 5 vendors funded to provide manufacturing feasiblity and cost studies
  - Completed during conceptual design phase
  - Showed vessel concept is feasible
- Vessel fabrication prototyping and qualification
  - 2 vendors on board to develop processes and build full scale partial prototypes
  - Prototypes due in November
  - Both vendors will be qualified to bid on production vessel
- Field joint development
  - Prototypes modified to include weld joint details
  - Distortion, temperature behind weld, leak checking operations prototyped
  - Weld procedure finalized

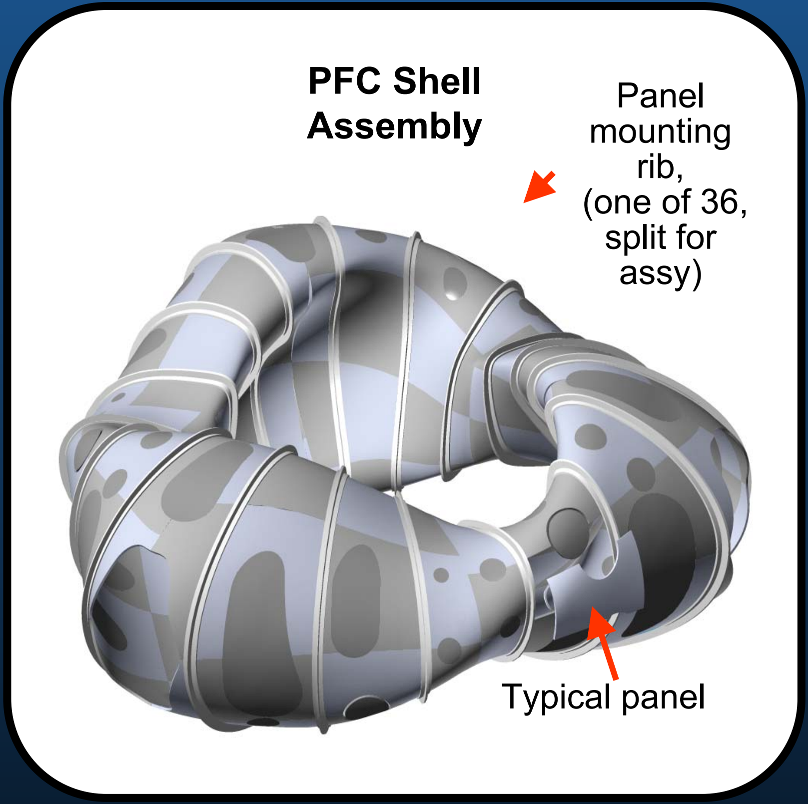


PFC Upgrade Configuration

NCSX

Full liner of molded CFC panels deployed later during operation

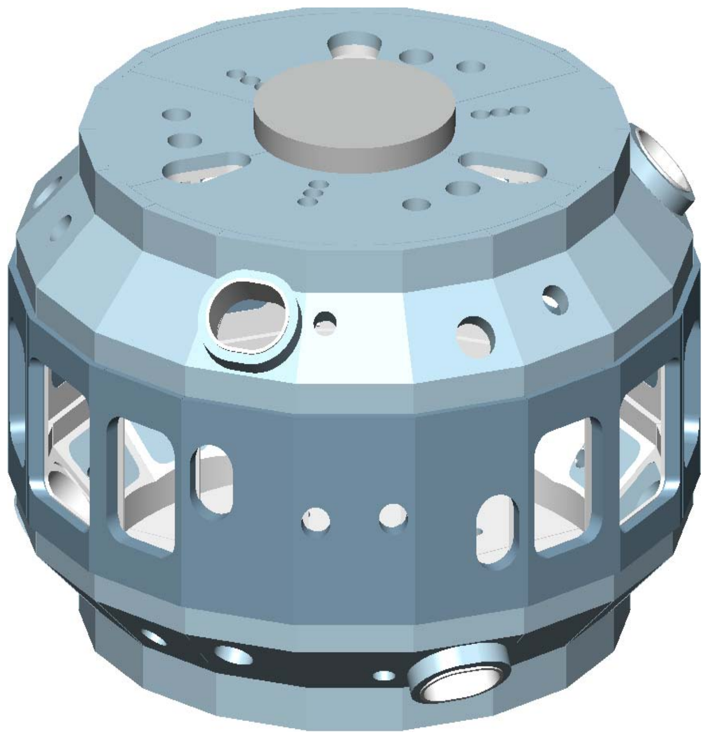
- Self-supporting and separately baked to 350C
- Allows 150C vessel bakeout (beneficial for ports, windows, magnetic diagnostics)
- Liner is offset 7 cm from vacuum vessel surface, provides space for diag, internal trim coils, etc.



Cryostat Concept

NCSX

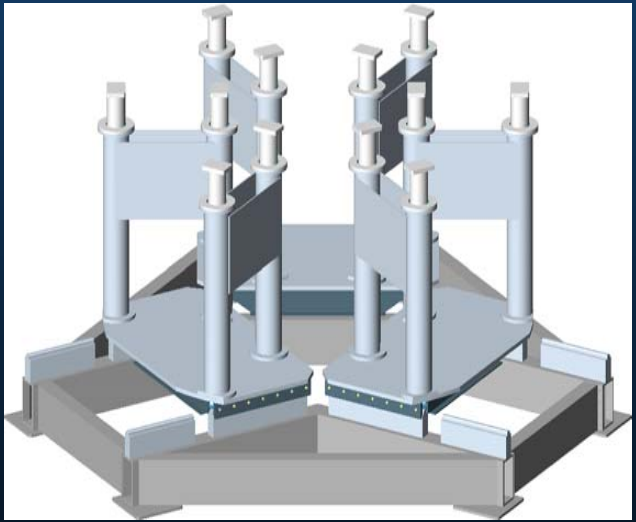
- Cryostat has simple frame and panel design, urethane insulation
- Design influenced by input from MIT and successful C-Mod cryostat
- Holes provided for all vacuum vessel port extensions
- Silicon rubber “Gortiflex” boots to seal between vessel port extensions and cryostat
- 6” thickness reduces heat leaks to air but still may require local heaters/blowers to avoid condensation
- Outer surfaces will be protected by fiberglass panels to provide durable surfaces

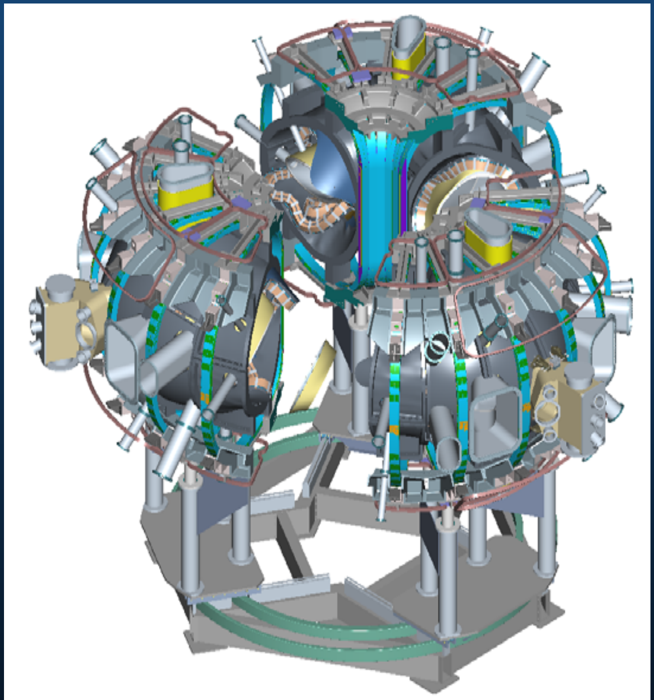


Machine base provides radial motion

NCSX

- Precision, radial sliding supports are needed to assemble machine
- Machine leveling jack on each pad ensures fit-up with structure, slides adjustable for custom trajectory
- Columns must provide thermal isolation, several options available
- Machine can be completely disassembled for maint. or repair.

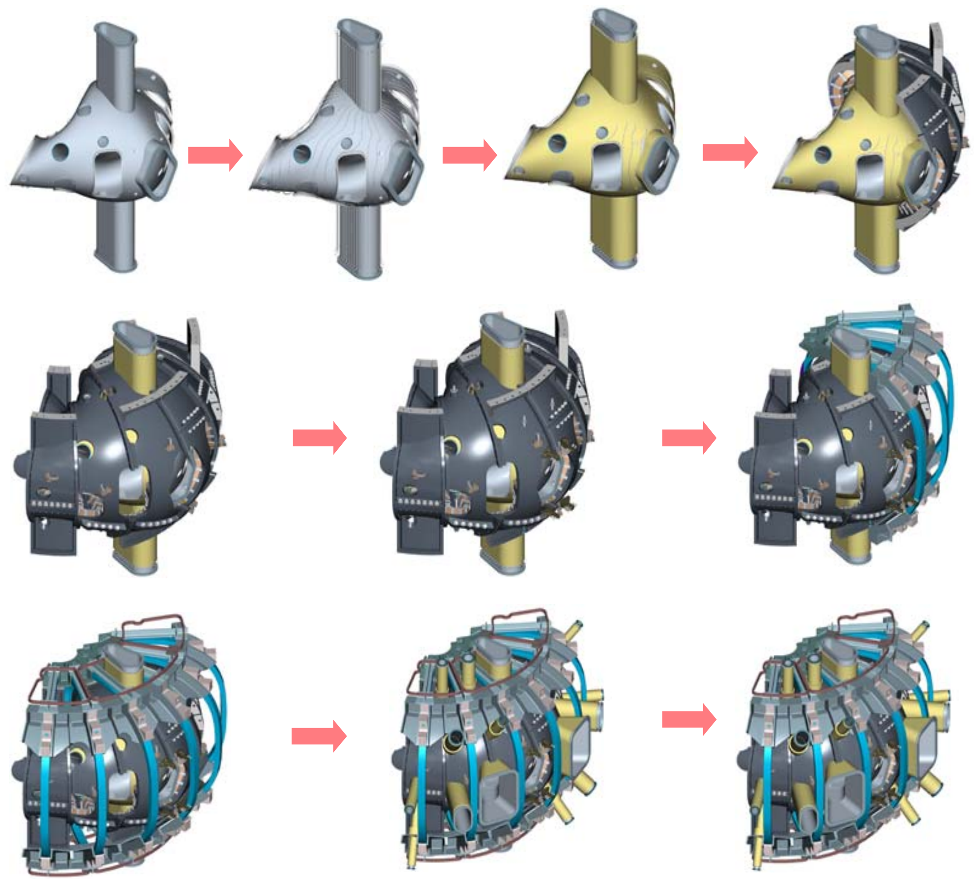




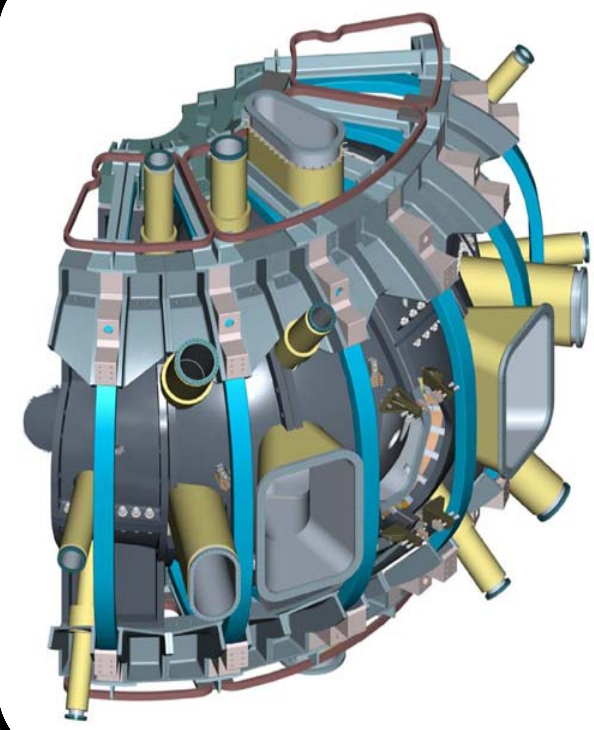
Field Period Assembly

NCSX

Field Period Components

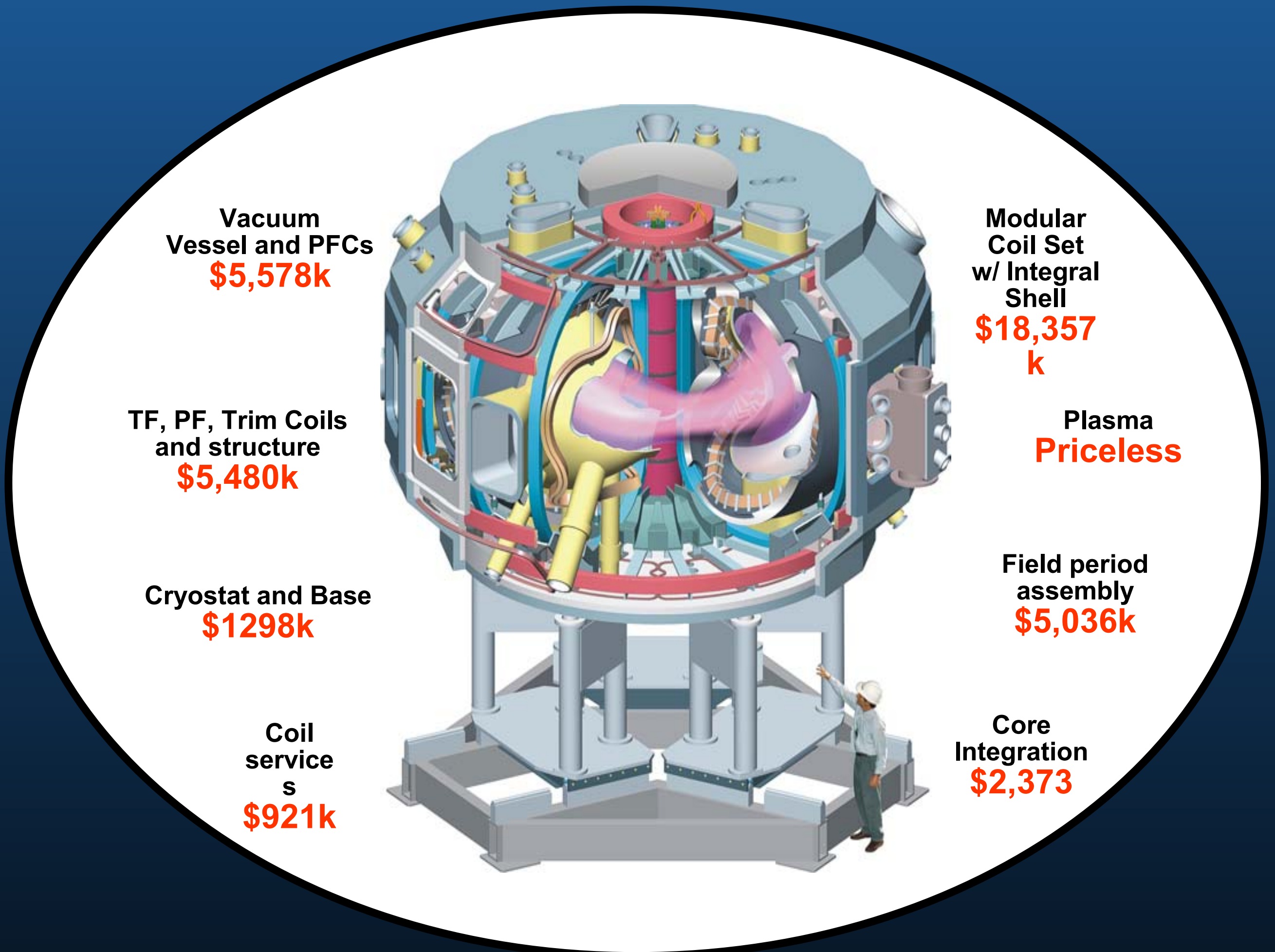


Complete Field Period Assembly



Stellarator Core Cost

NCSX



Stellarator Core on critical path

NCSX

- VV and mod coil FDR by:

  30-Apr-2004

- First mod coil winding form by:

  10-Nov-2004

- First complete VV field period by:

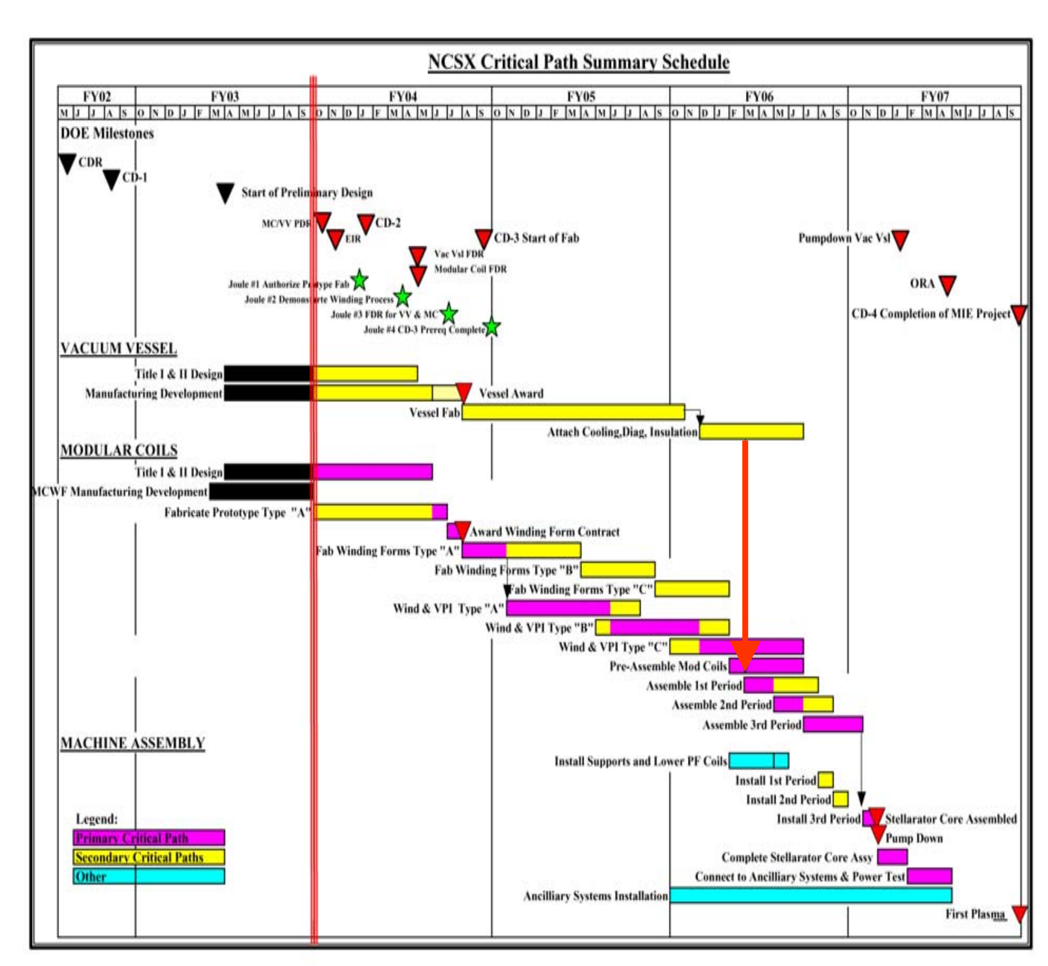
  10-Oct-2005

- Finish winding mod coils by:

  16-June-2006

- Last field period assembled by:

  27-Oct-2006



Cost Estimate Basis

NCSX

- Costs were developed as a bottoms up estimate with significant input from vendors

- Costs were collected in categories of
  - Manufacturing development, - Based on manufacturing recommendations and engineering judgment
  - Design, - Based on listing of reviews, drawings, specifications, analyses and other deliverables
  - Materials and Subcontracts, - based on experience with similar components and, where possible, on vendor input
  - Fab / assembly – Includes in-house activities and is based on experience with similar activities
  - *Installation costs are all included in WBS 7*

- The primary cost items are the modular coils and vacuum vessel

Modular Coil cost and schedule

NCSX

	Start	Finish	FY 2003 O N D J F M A M J J A S	FY 2004 O N D J F M A M J J A S	FY 2005 O N D J F M A M J J A S	FY 2006 O N D J F M A M J J A S	FY 2007 O N D J F M A M J J A S
Design - winding forms	1-Apr-03	29-Apr-04	Winding Forms				
Design - Coil winding	1-Apr-03	28-Oct-04	Coil winding				
R&D - Winding Forms	1-Apr-03	11-Jun-04	Studies	Prototype winding forms			
R&D - Coil winding/VPI/etc.	1-Apr-03	25-Oct-04	racetrack	twisted racetrack prototype			
Production - Winding Forms	28-Jul-04	26-Jan-06		Winding Forms			
Production - Coil Winding / VPI	11-Nov-04	16-Jun-06			Coil winding/VPI		
Cost by year of expenditure			$3,287k	$6,830k	$6,165k	$2,004k	$70k

$18,357k
(+ 34% cont.)

- The winding form costs were estimated by capable industrial suppliers via funded manufacturing studies and R&D contracts – (the estimates are composites of all the input data, not the highest nor lowest costs presented)
- The winding costs were developed by PPPL based on winding experience at PPPL and in-house R&D
- Cost drivers include winding form machining, casting tooling, winding, and potting
- Manufacturing development includes full scale cast and machined coil forms from two different vendors, multiple full scale partial prototype winding and potting tests, and one completed full scale prototype coil

Vacuum Vessel Cost and schedule

NCSX

	Start	Finish	FY 2003 O N D J F M A M J J A S	FY 2004 O N D J F M A M J J A S	FY 2005 O N D J F M A M J J A S	FY 2006 O N D J F M A M J J A S	FY 2007 O N D J F M A M J J A S
Design	1-Apr-03	29-Apr-04	vacuum vessel assembly	insulation, heating/cooling, supports, I&C			
R&D - studies	1-Apr-03	18-Jun-04	R&D studies				
R&D - Prototype, welding	18-Aug-03	31-Mar-04	prototype	field joint welding			
Production - vessel assembly	3-Aug-04	10-Oct-05		vacuum vessel assembly			
Production - insul/support/etc.					insul/supports/etc		
Cost by year of expenditure			$1,328k	$1,482k	$2,603k	$154k	$4k

$5,570k
(+ 35% cont.)

- The vacuum vessel costs were also estimated by capable industrial suppliers via funded manufacturing studies and R&D contracts (estimates used represent a composite of all the input data, not the highest nor lowest costs presented by the suppliers)
- Cost drivers include forming, welding, machining and especially, fixtures
- Manufacturing development includes full scale partial prototypes from two different vendors

Risk areas addressed by design and R&D

NCSX

- Vacuum Vessel :
  - Will the vendors supply accurate, vacuum quality components on schedule?

    Two vendors qualified via R&D phase in order to lower risk, cost
- Modular Coils:
  - Does the composite copper/epoxy winding behave as expected, during VPI, cooldown, and operation?

    Further tests planned on cure shrinkage and mechanical behavior
  - Can the windings be placed accurately on a twisted, curved winding form?

    Twisted racetrack should be complete by end of January
  - Will the cost exceed expectations?

    Two winding form vendors qualified through R&D in order to lower risk, cost
- Field Period Assembly
  - Will the mod coils slide over the vacuum vessel?

    Design analyzed several ways, all geometry fully inspected
  - Are the fixtures and metrology systems adequate?

    R&D with full sized mockups is planned

Summary

NCSX

- **Preliminary Design of the stellarator core is feasible and meets requirements**
- **Analysis shows components have margin for the operating scenarios and load cases considered, *but* additional work is needed to refine the modular coil winding analysis**
- **Additional R&D is in progress to verify both component performance as well as manufacturing procedures**
- **Cost has a sound basis and adequate contingency**
- **Risks have been identified**