WBS 1
Stellarator Core
Design Overview

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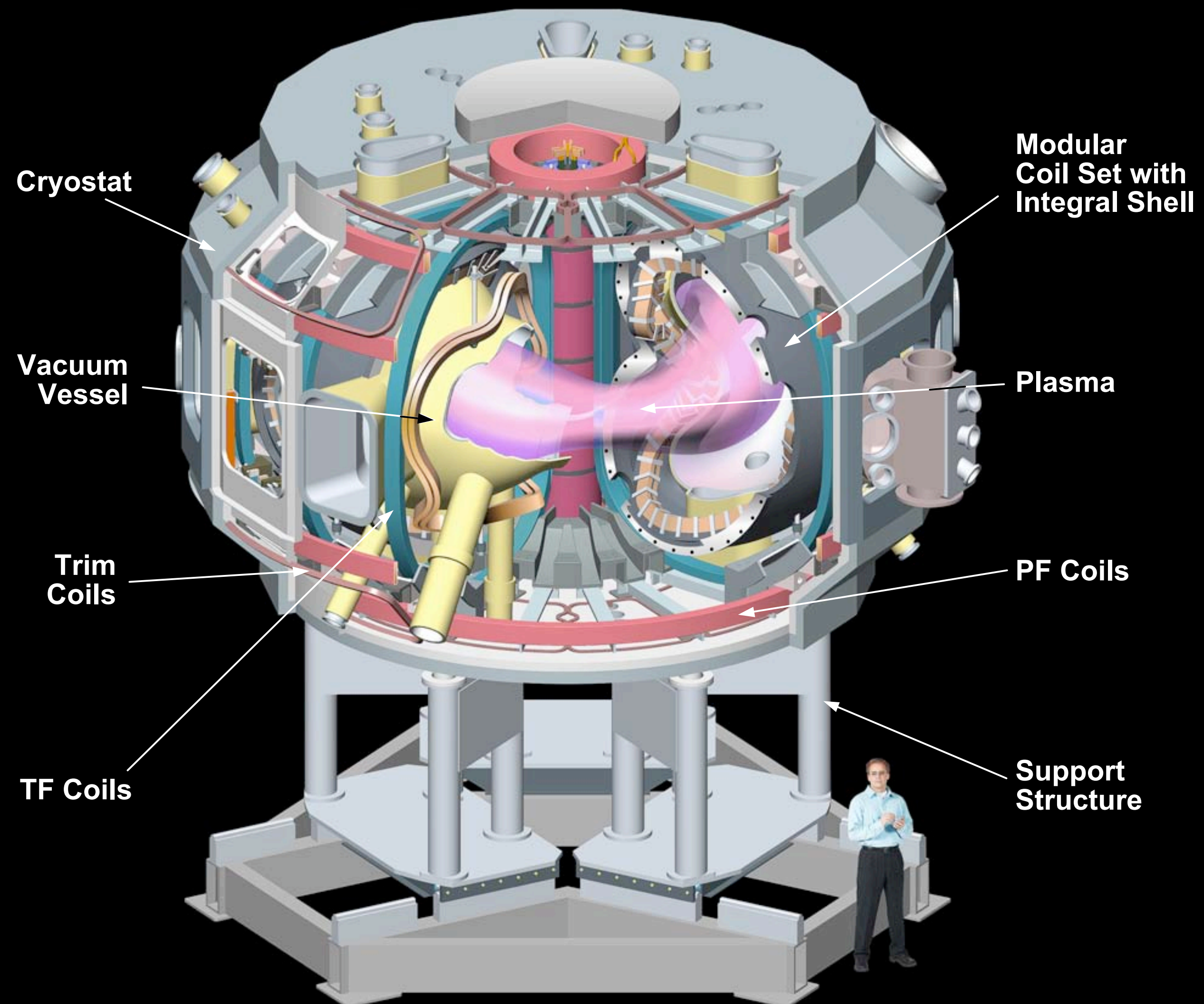
and the WBS 1 team

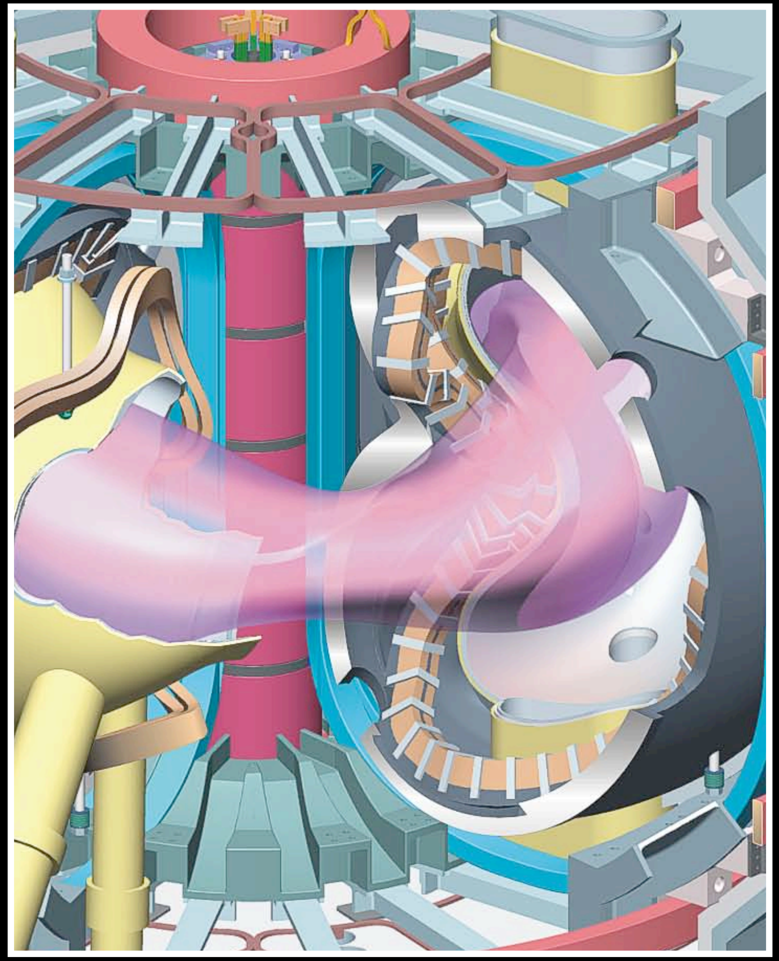
NCSX Final Design Review for
Vacuum Vessel Subassembly and Modular Coil Winding Forms
May 19, 2004
PPPL

Presentation Outline

- 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?)
- Status and schedule overview
- Risk and remaining issues

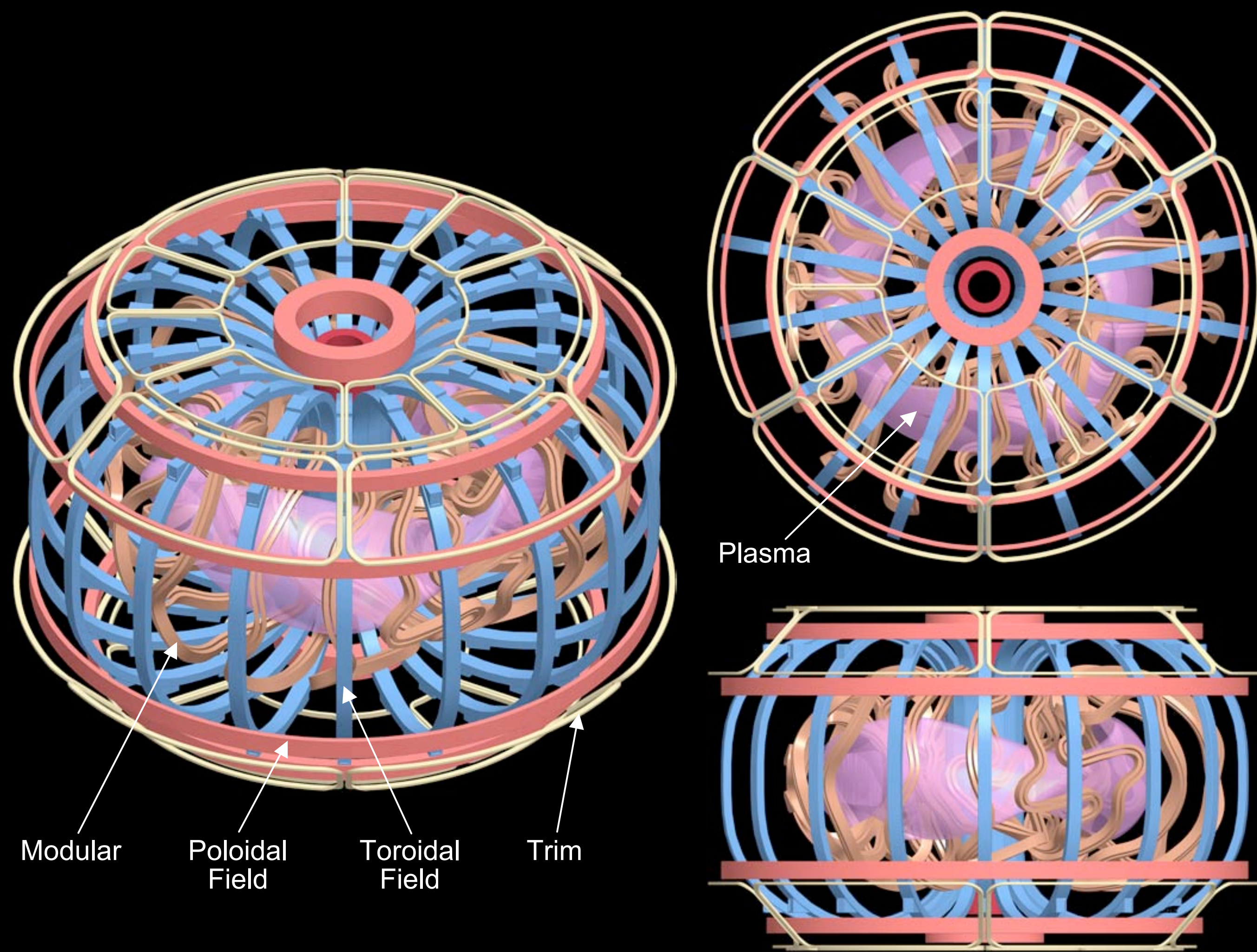
Cutaway view of machine assembly





Four coil systems are required

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

- Meet performance and flexibility requirements in specified operating 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 installed accuracy
- Accommodate access for tangential NBI, RF, vacuum pumping, diagnostics, and personnel access
- Ensure voltage and current requirements match existing D-site power supplies
- Coils must be buildable

Reference Operating Scenarios drive coil and power supply performance requirements

- There are 7 reference scenarios, 2 @ room temperature and 5 @ low temperature

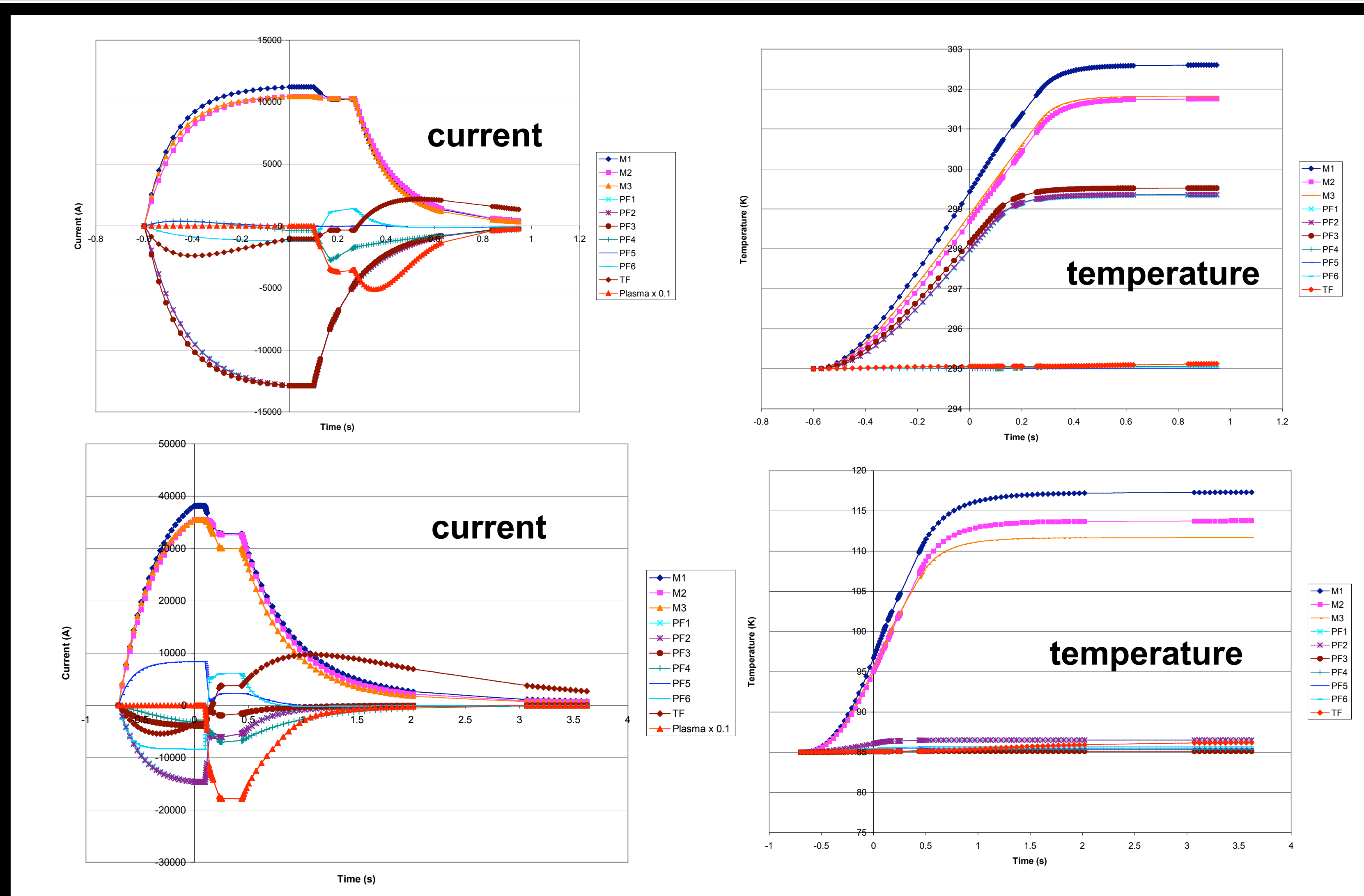
- Room temperature:
  - 0.5 T First Plasma: 0.27 s pulse for initial operation
  - Field line mapping: Low field (~0.1 T), 10 s pulse for flux surface mapping

- 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

- **First Plasma Room Temperature**

- **1.7T high beta LN_2 Temp**



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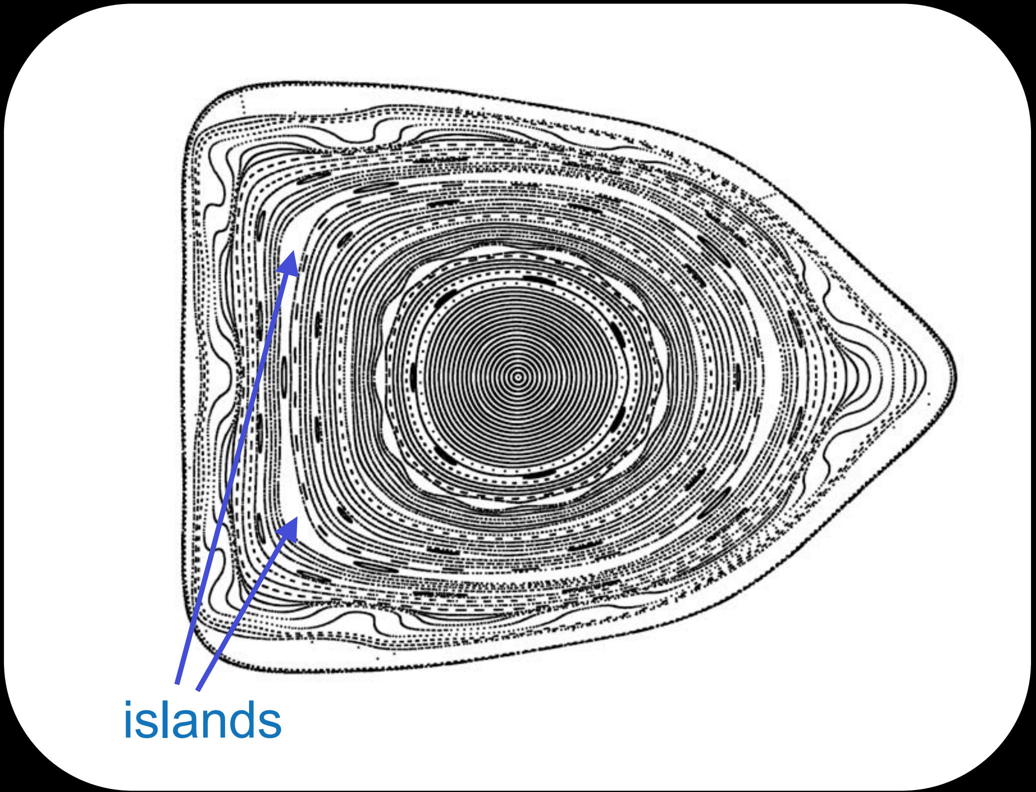
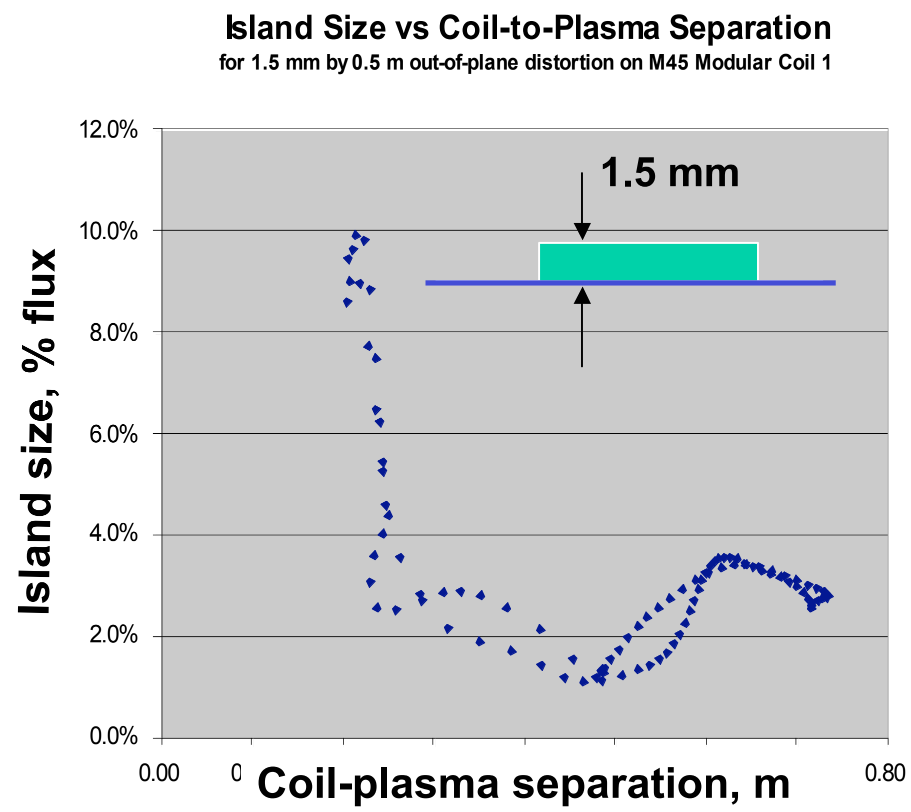
How accurate do the coils have to be?

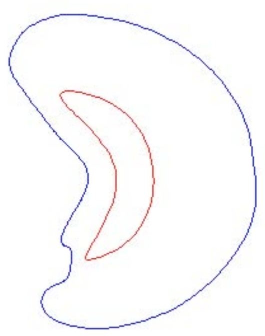
- Stellarator coils must be very accurate to produce flux surfaces of sufficient quality
- Errors in winding geometry can produce islands, which “short circuit confinement” [A. Reiman, NCSX CDR]
- “The toroidal flux in island regions due to fabrication errors, magnetic materials, or eddy currents shall not exceed 10% of the total toroidal flux in the plasma.” [ref. GRD, Rev. 0]
  - Permeability < 1.02
  - Stellarator symmetry must be preserved
  - Eddy current time constants < 20 ms
  - Accuracy of windings within +/- 1.5 mm
- Effect of variations and combinations of winding errors studied systematically by A. Brooks using VACISLD code



What geometry errors are ok?

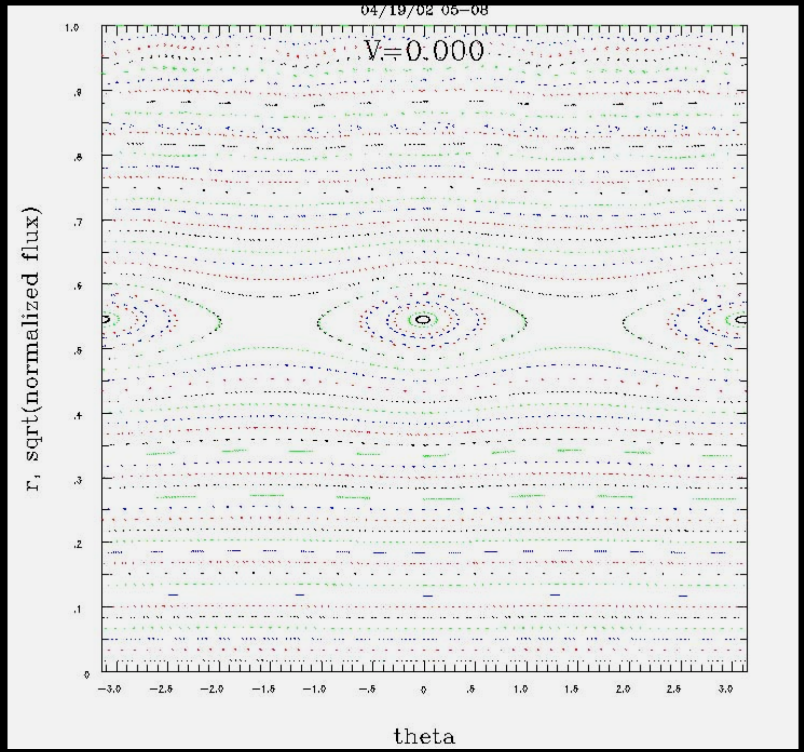
- Modular Coils
  - General tolerance on modular coils remains at +/- 1.5 mm
  - Perturbations > 1.5 mm may be ok for plasma-to-winding separation > 30 cm
- Tolerance on TF and PF can be relaxed to +/- 3 mm
- External trim coils will be used to further reduce islands





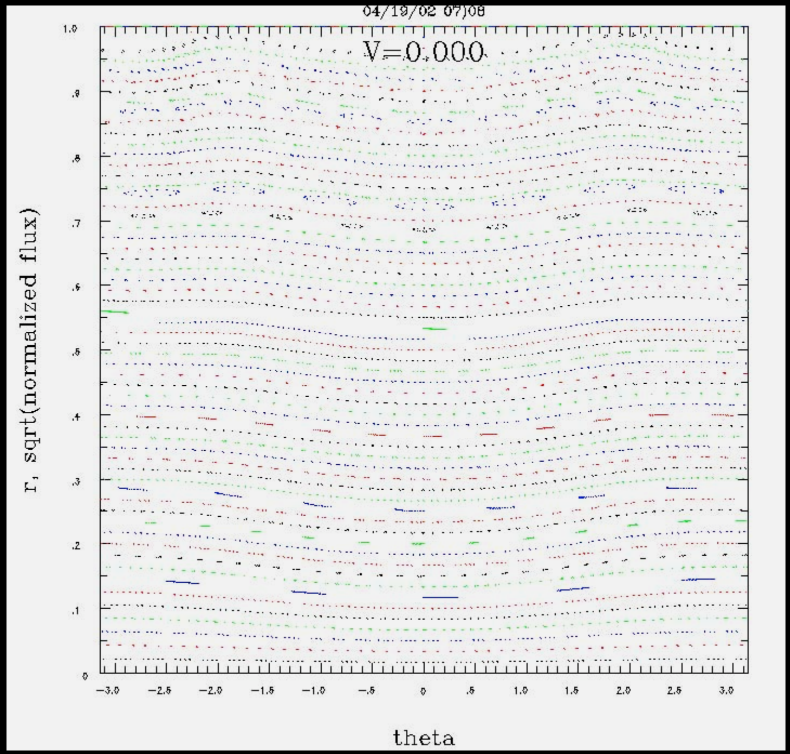
External trim coils heal islands

- **+/- 1.5 mm coil accuracy specification looks reasonable, especially with external trim coils**



Largest Islands from any modular coil distortion

(2mm distortion of single Type A coil)



Island suppression using correction coils

Note: edge is preserved

Coil System Requirements

- Meet performance and flexibility requirements in specified scenarios
  - Up to 2 T, 15 minute rep rate
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- Ensure voltage and current requirements match existing D-site power supplies
- Coils must be buildable

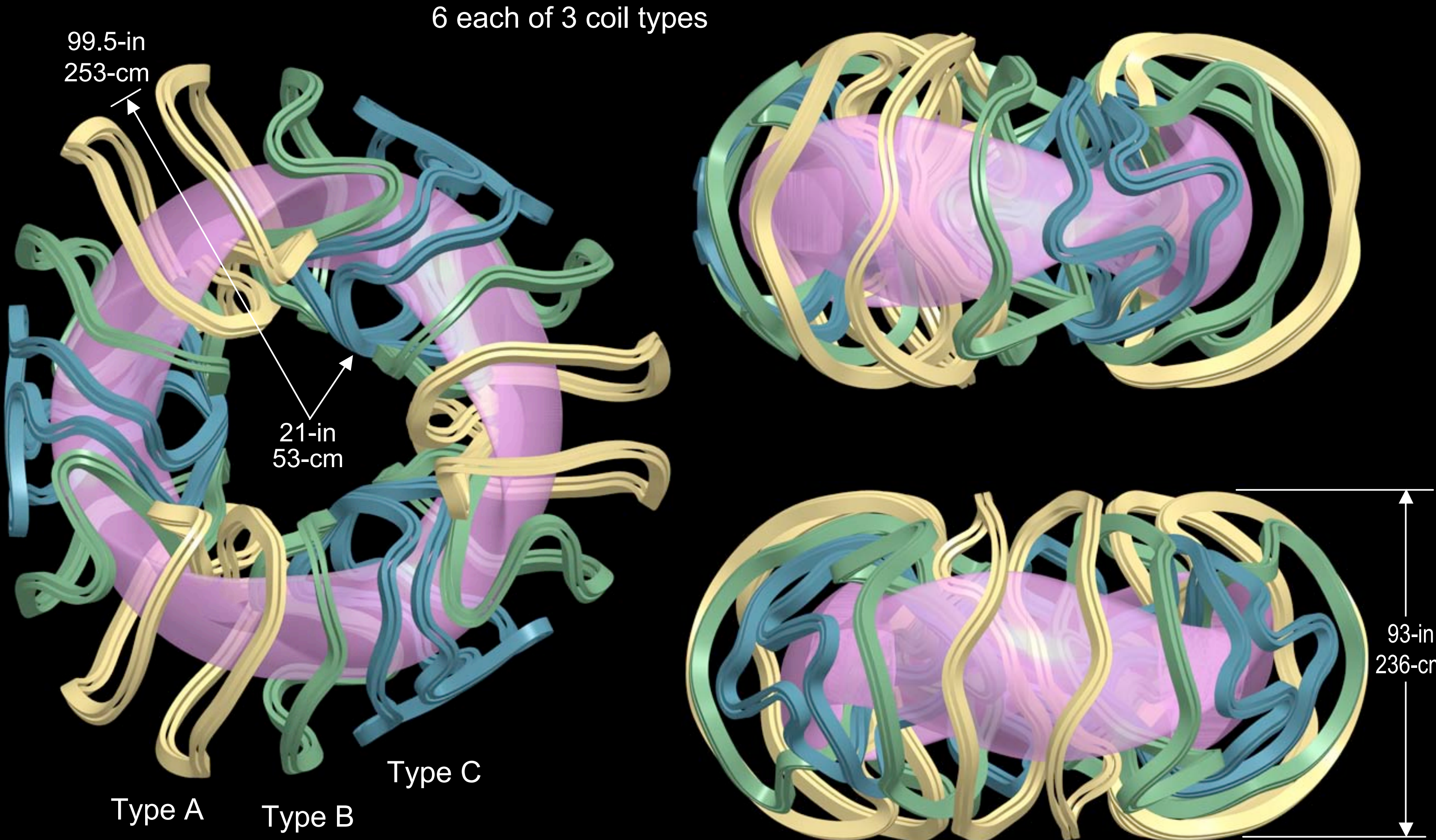
Modular Coil Configuration

- 18 coils, 3 field periods

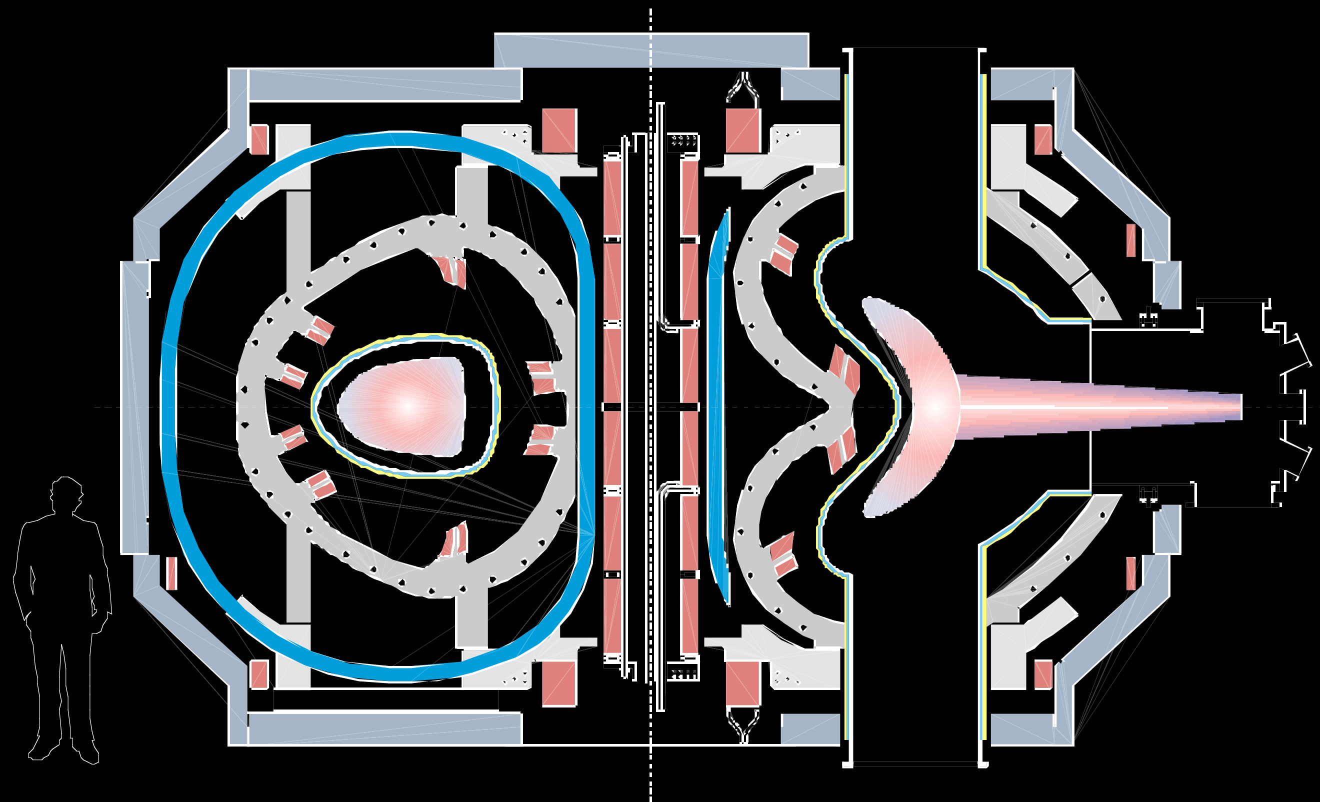
- Optimized for physics performance consistent with NBI access and engineering constraints.

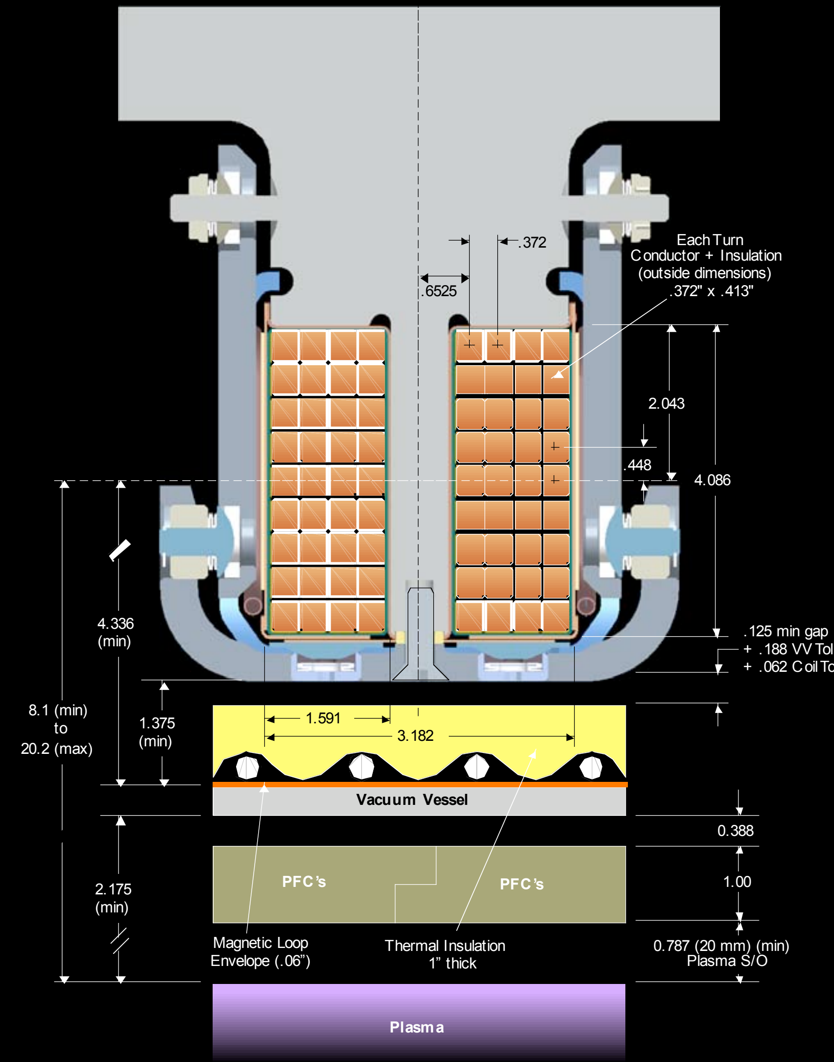
- Coils wound with flexible cable conductor into cast-and-machined forms

- Coils pre-cooled to LN_2 temperature to allow high current density



Compact design requires careful space allocation





Structure

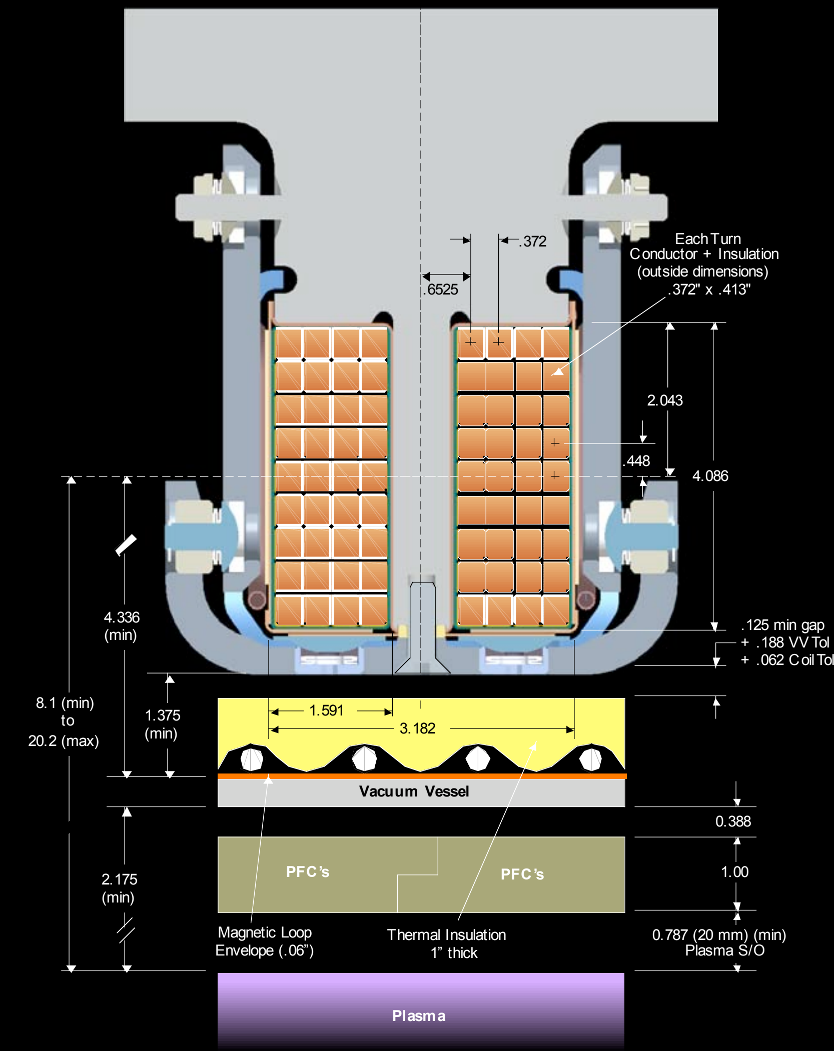
Mod Coil Windings

Vessel

In-Vessel Components

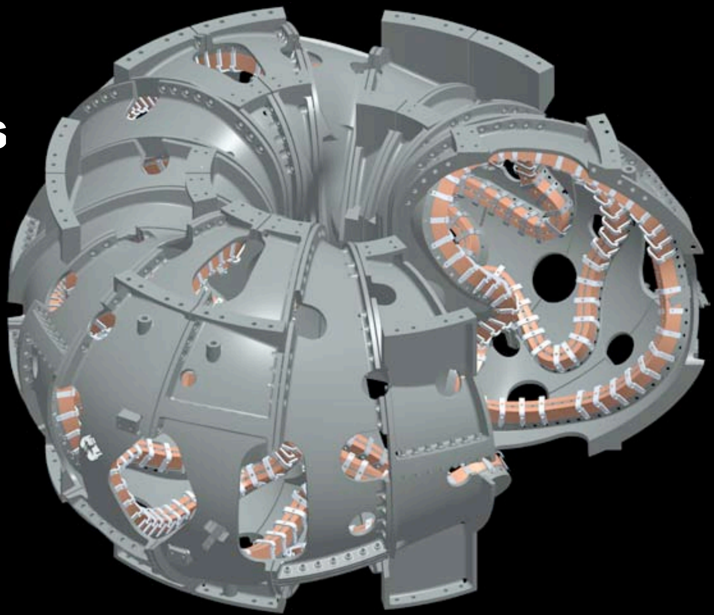
Coil envelope requires cryo-resistive coils

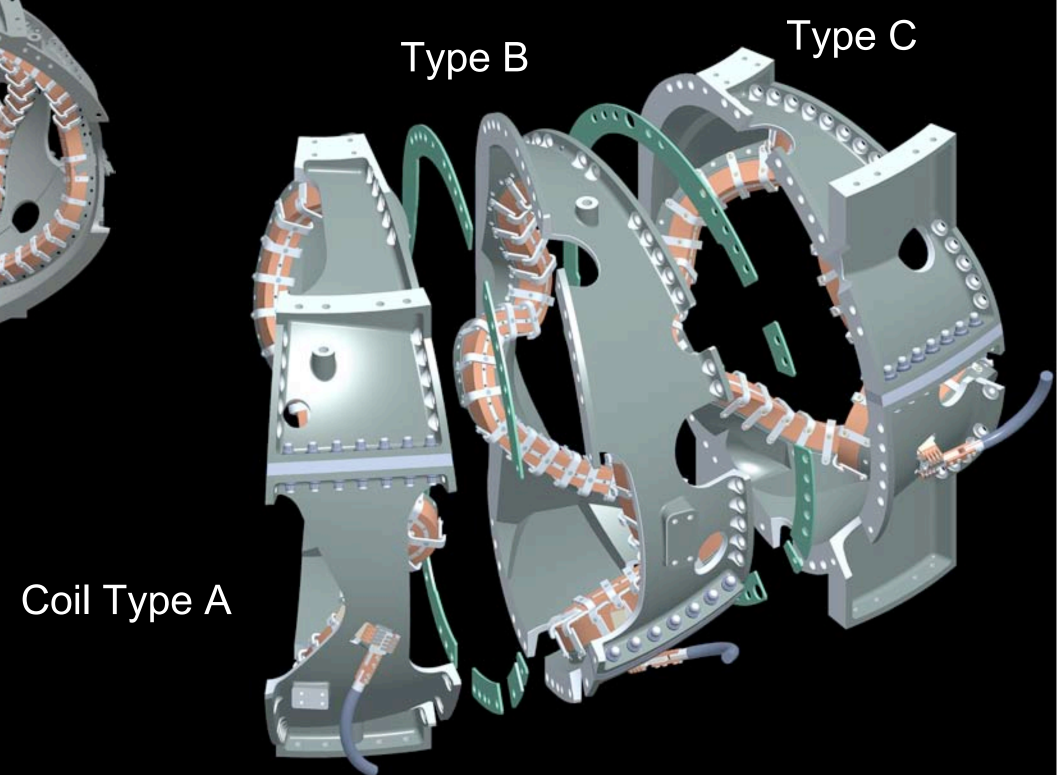
- Initial, low field operation will be at room temperature
- Current density of ~ 15 kA/cm2 requires too much power, has too much temperature rise for room temperature coils.
- Cryo-resistive coils have advantages
  - ~ 7 x increase in copper conductivity
  - Lower temperature rise per pulse
  - Much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



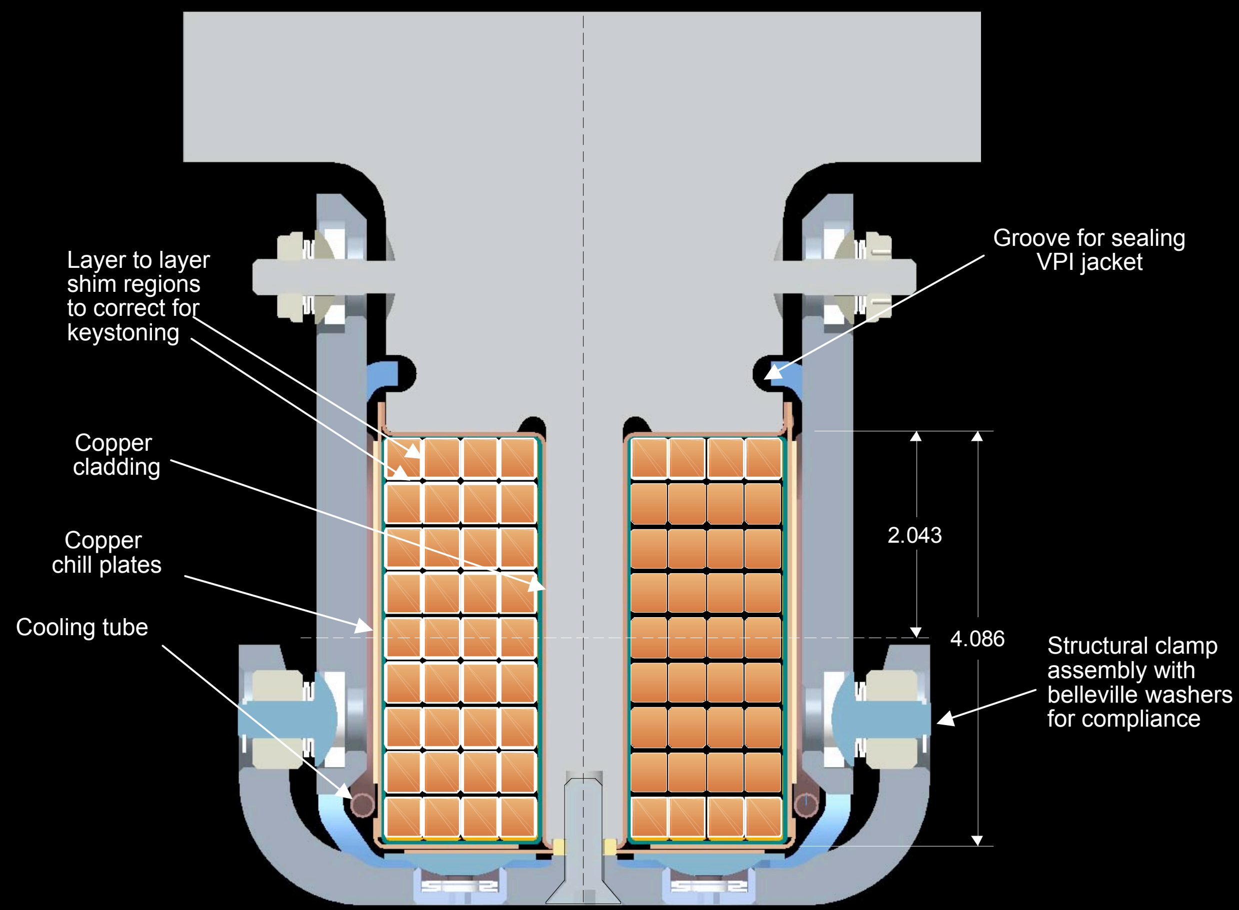
Continuous shell forms robust structure

- Shell consists of individual modular coil winding forms that are bolted together
- Penetrations can be provided where needed
- Provides "machine base" for all other components
- Stellarator symmetry preserved, toroidal and poloidal electrical breaks
- The set of winding forms represents one of the two primary subjects of this review



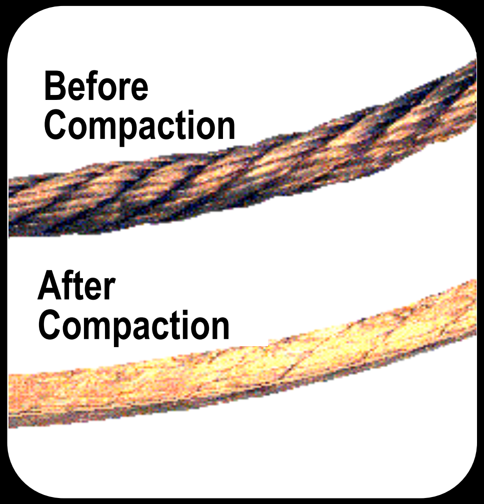


Modular Coils wound on “tee” structure



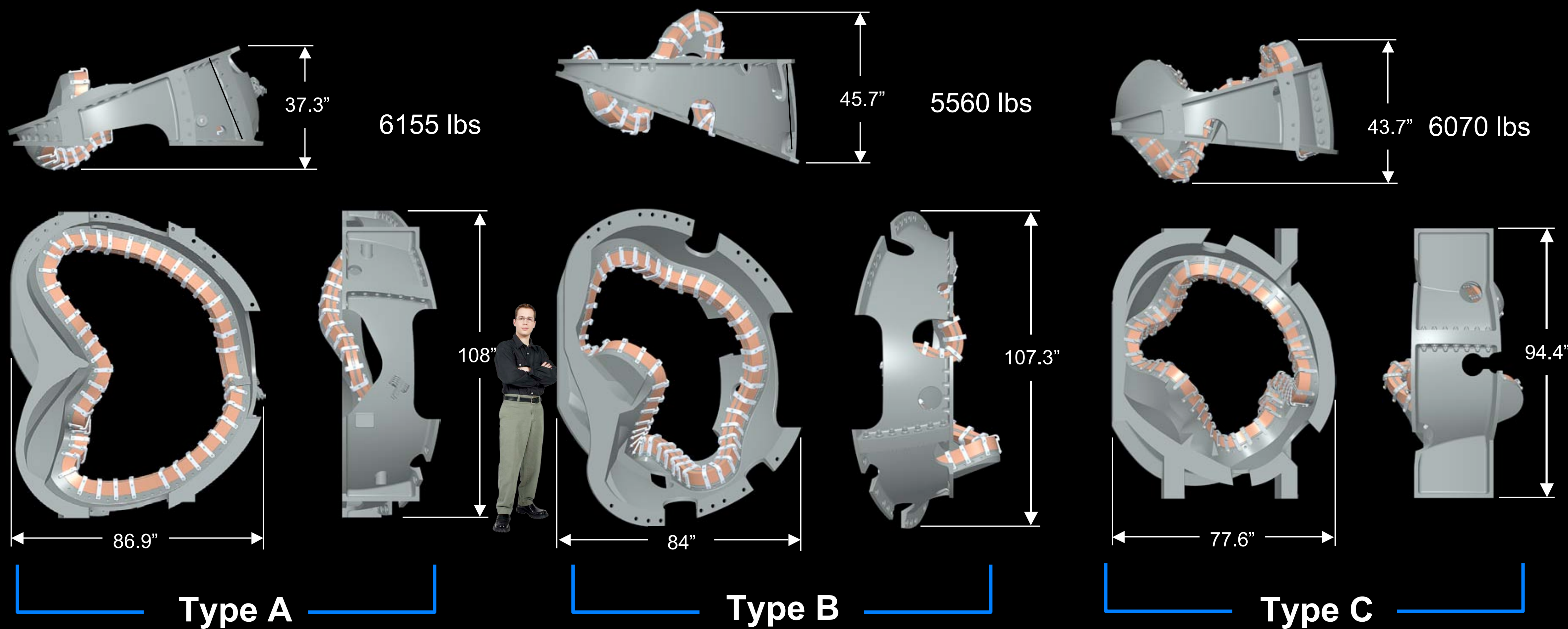
Parameters:

- Coil Envelope = 2 x 4.671 x 1.675 inches
- Current / Coil = up to 831-kA-turns
- Number of Turns = 20 (Type A,B) and 18 (C)
- 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



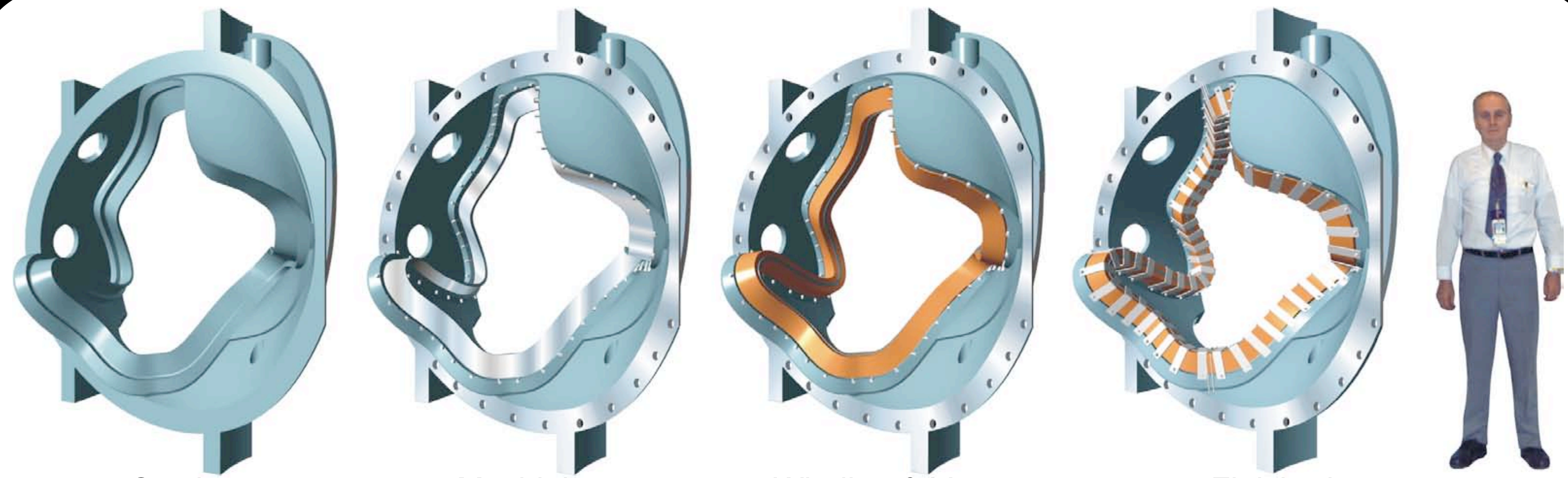
Flexible cable used to wind coil

Three types of modular coil assemblies



Modular coil designed for strength / accuracy

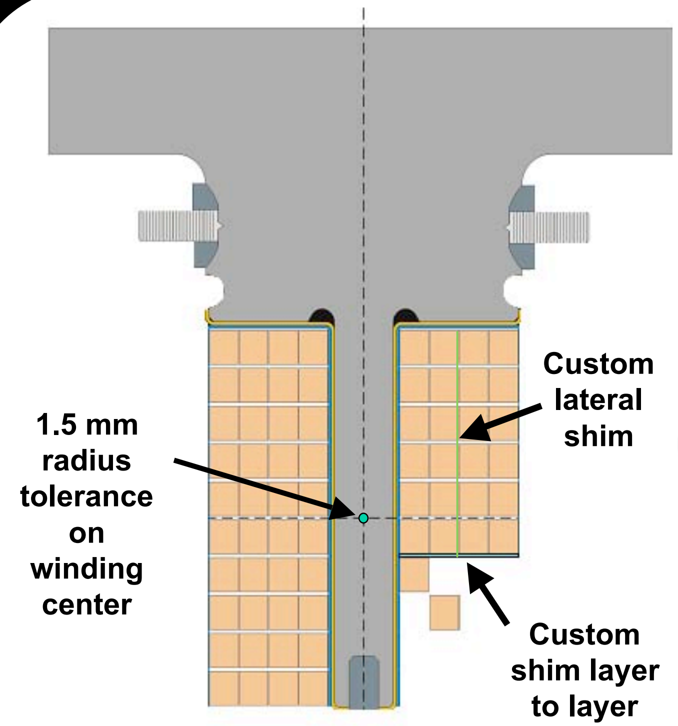
- Continuous support for strength and accuracy of winding
- Single machined part provides winding form and assembly features
- Winding never removed from coil form



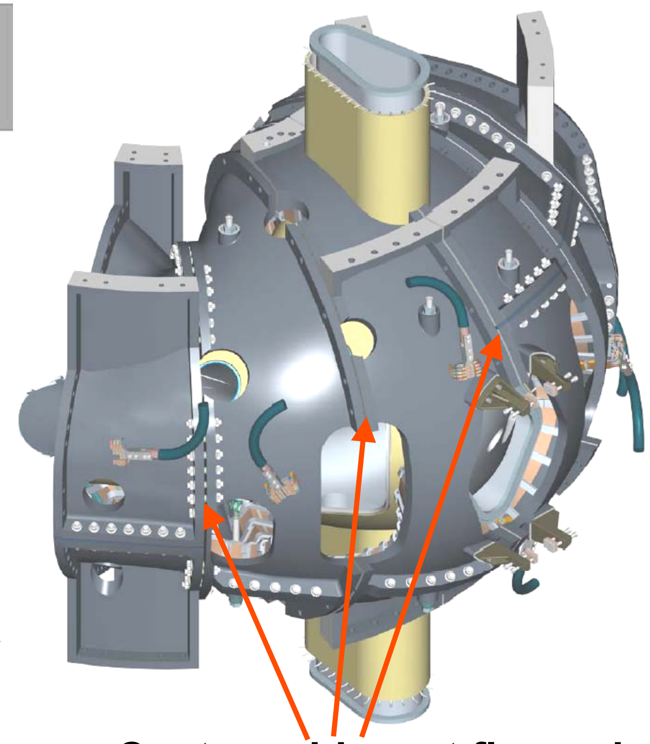
Modular coil accuracy achieved by shimming

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

Mod coil positions can be optimized during assembly

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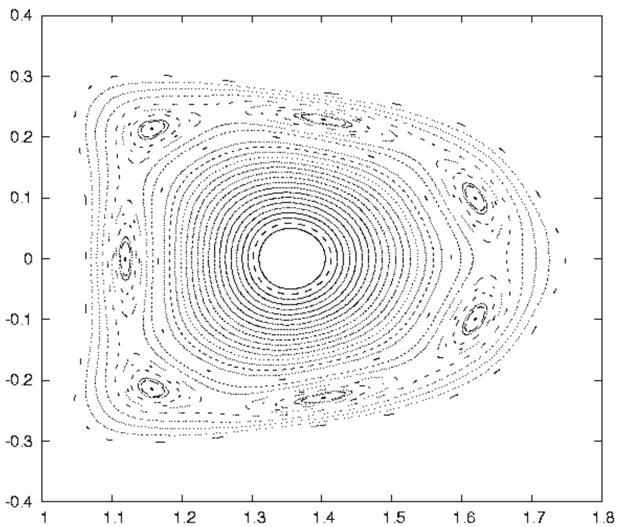
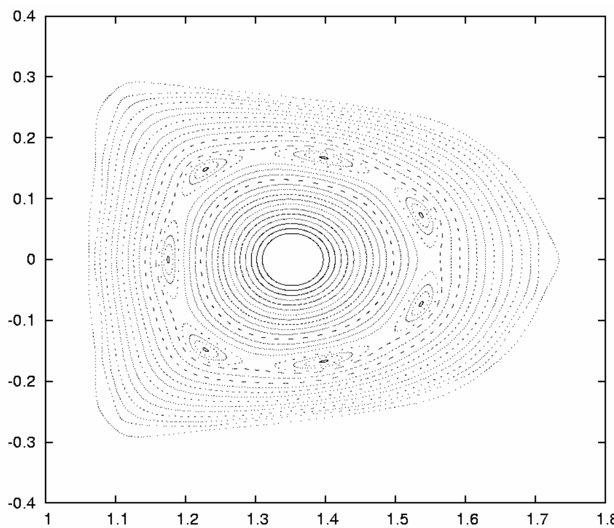
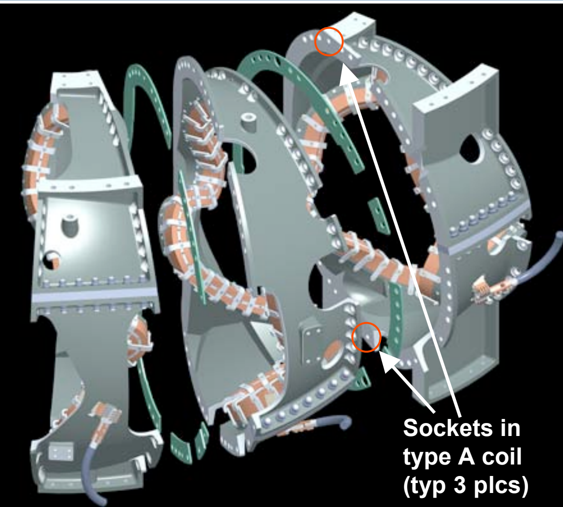
- Optimization of coil position can reduce island size

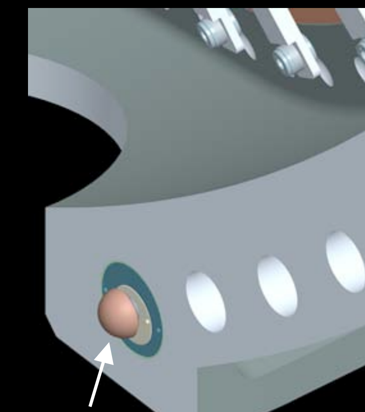


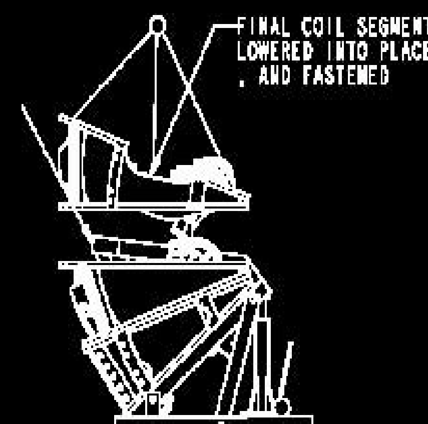
Mod coils in nominal positions



Mod coil positions optimized to reduce m=7 islands



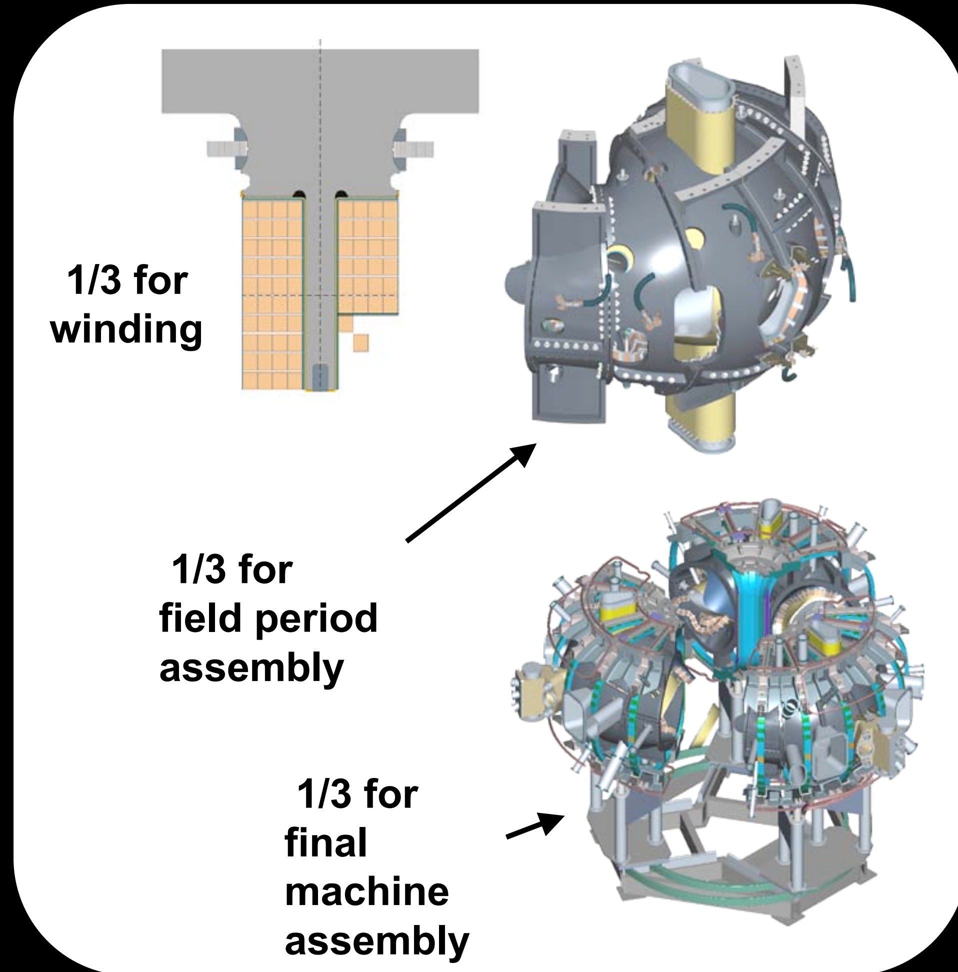




Ball adjustable in all directions

Tolerance budget apportioned in thirds

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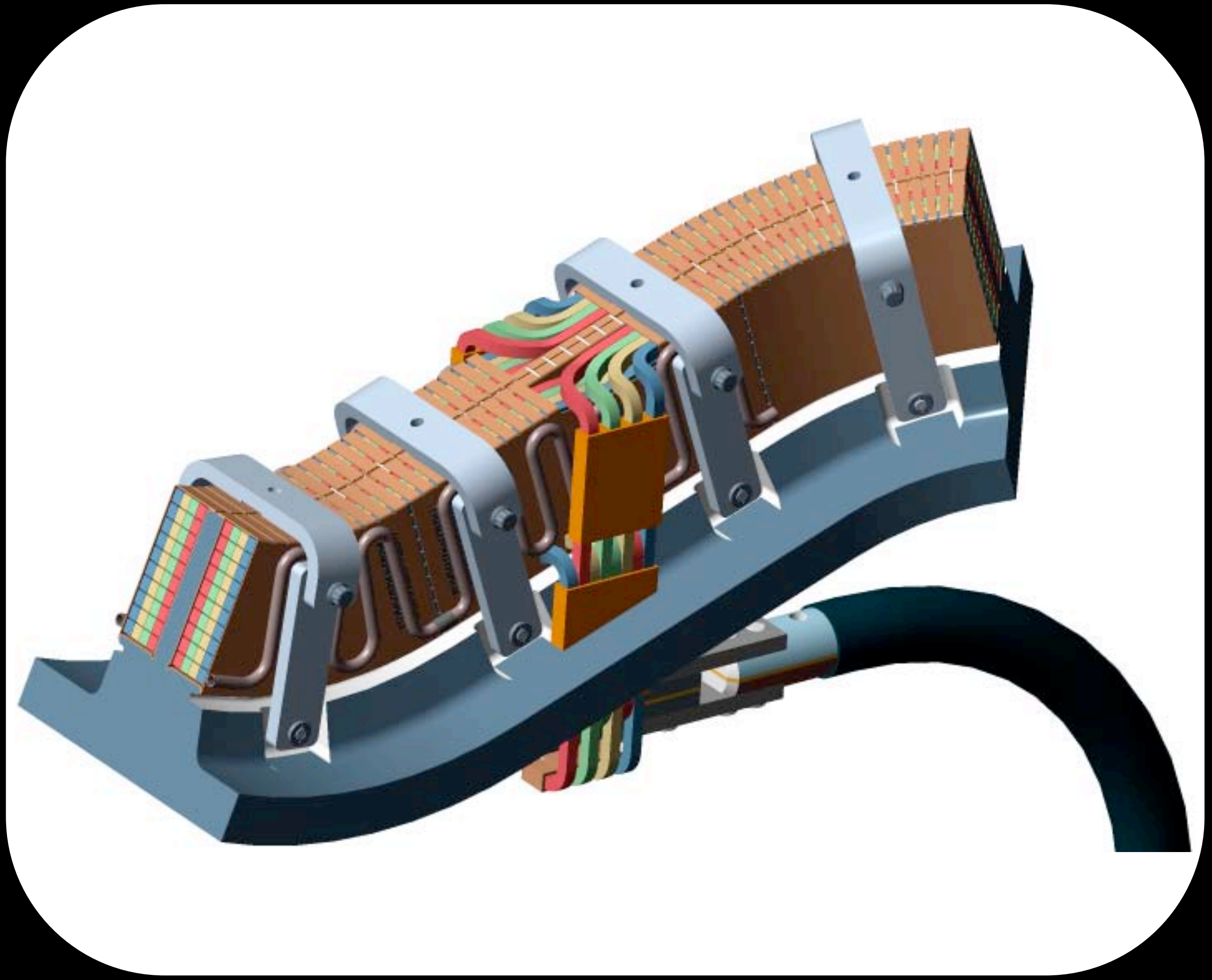
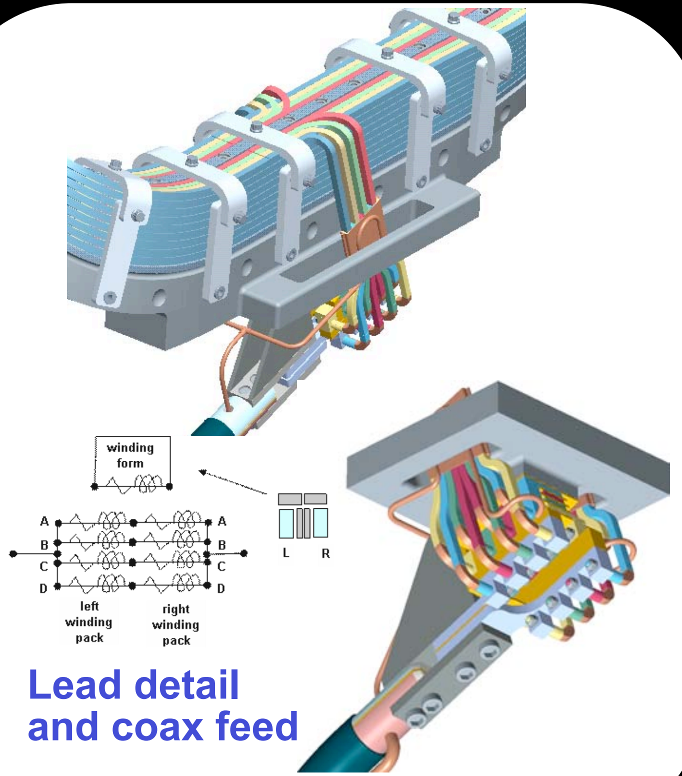
- Smaller conductor reduces keystoning – huge advantage
- Low turn-to-turn voltage reduces insulation thickness, eliminates on-site taping operation
- Winding does not start in the middle of the turn, no need for extra spool
- Winding arrangement workable at lead location – turns bundled for connection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

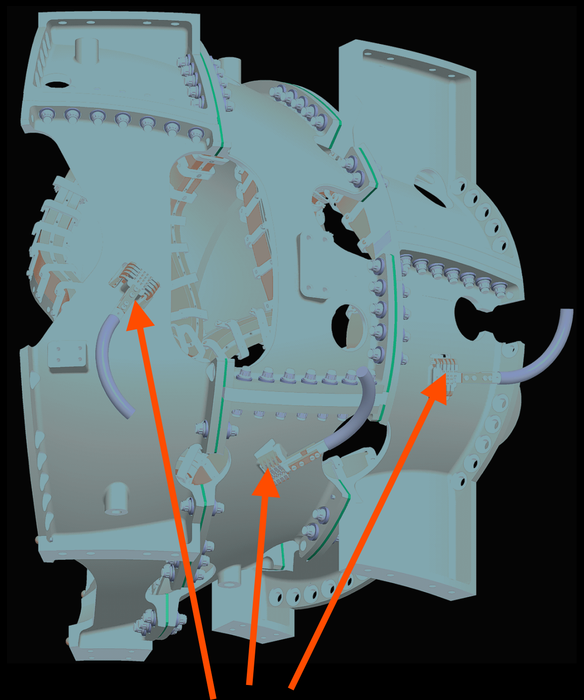


Lead location minimizes field errors

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

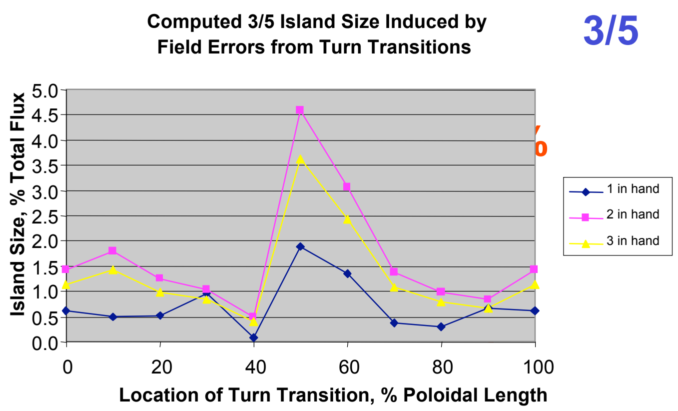


Lead detail and coax feed

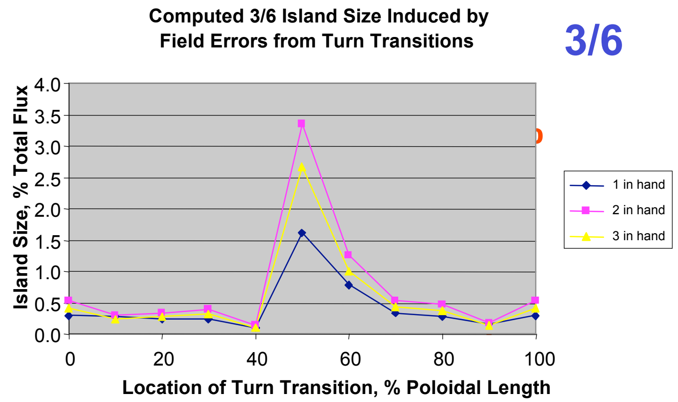


Modular coil lead locations

3/5



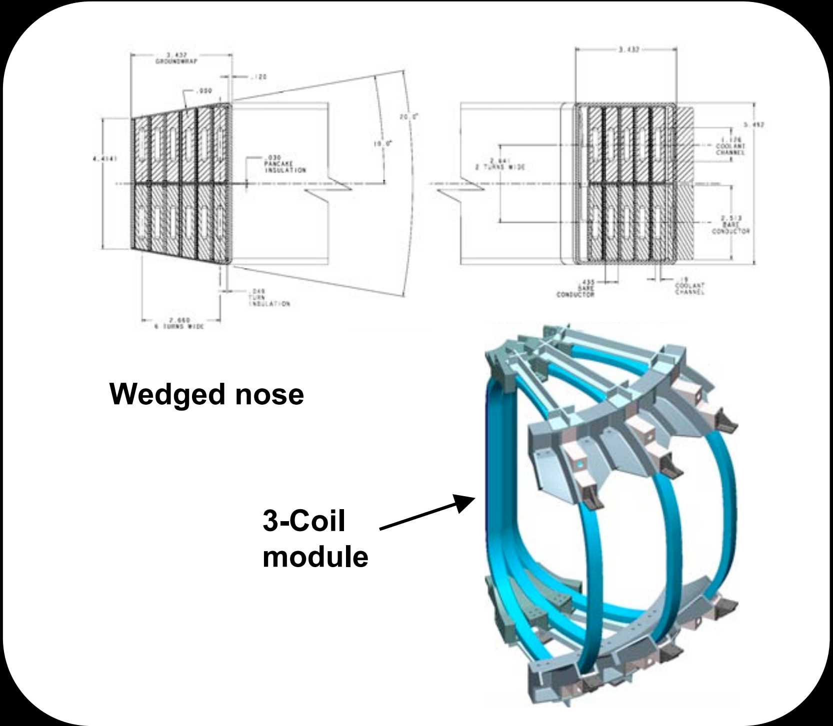
3/6

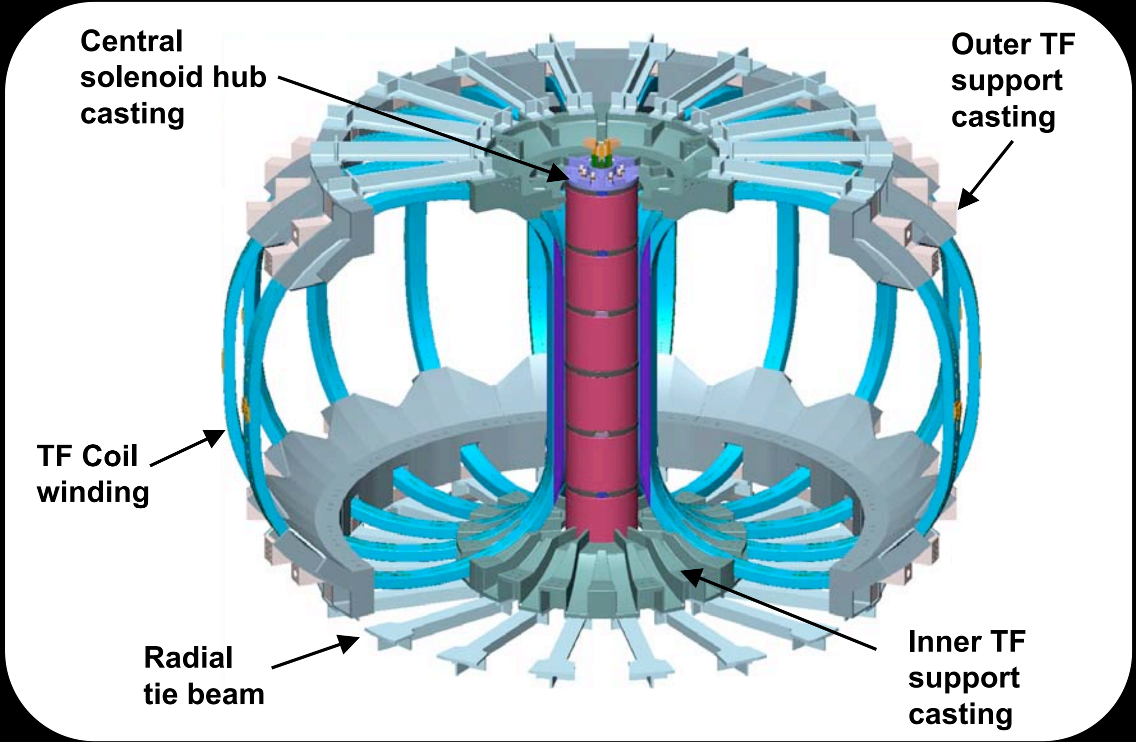


Islands from 3/5 and 3/6 field errors

Toroidal Field Coils, structure have conventional design

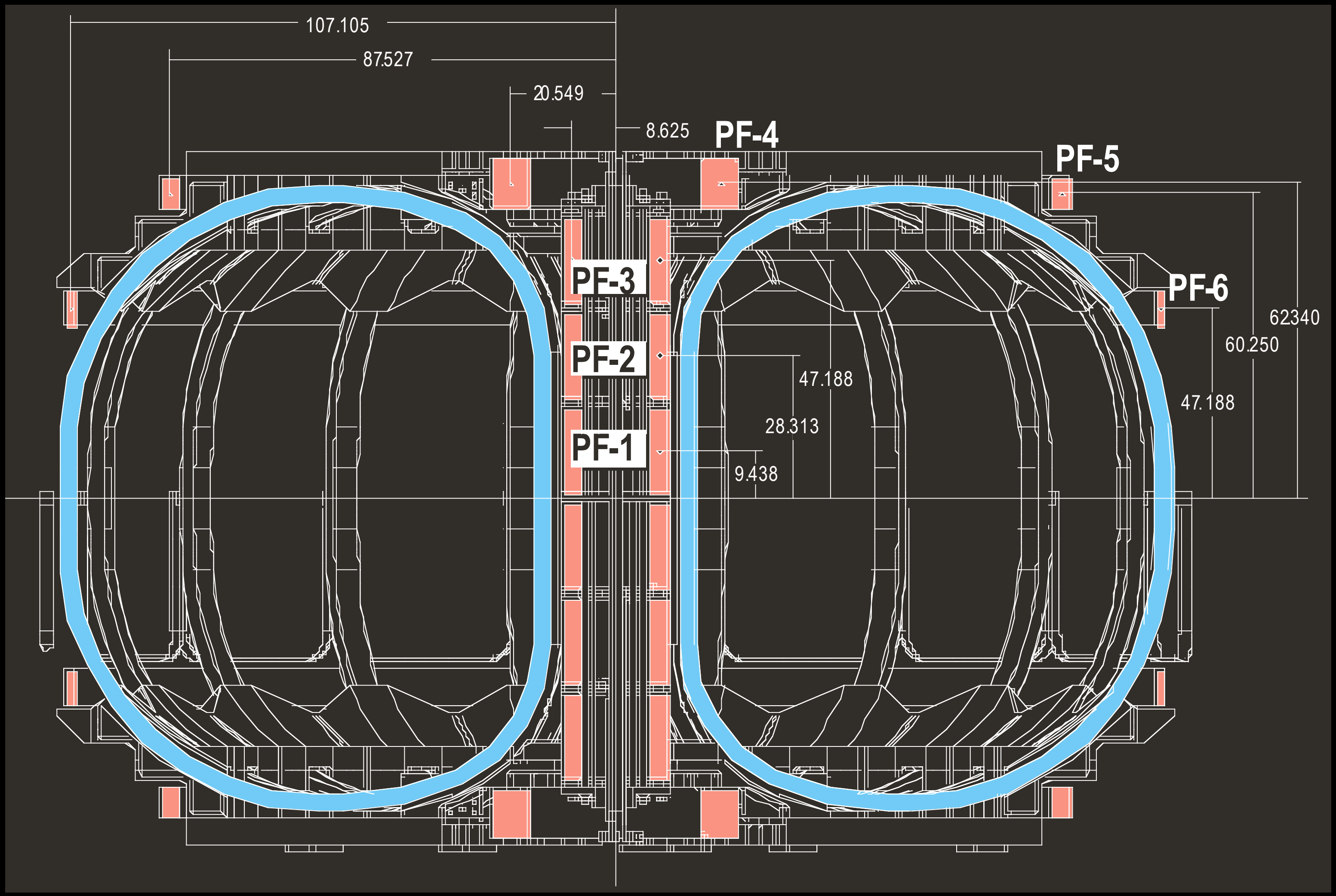
- 18 coils provide up to +/- 0.5 T for flexibility beyond reference scenarios
- Wound from hollow copper conductor and vacuum pressure impregnated with epoxy
- Supported from external coil support structure , Centering load supported by wedging
- Pre-cooled to LN_2 temperature, temp rise < 5K





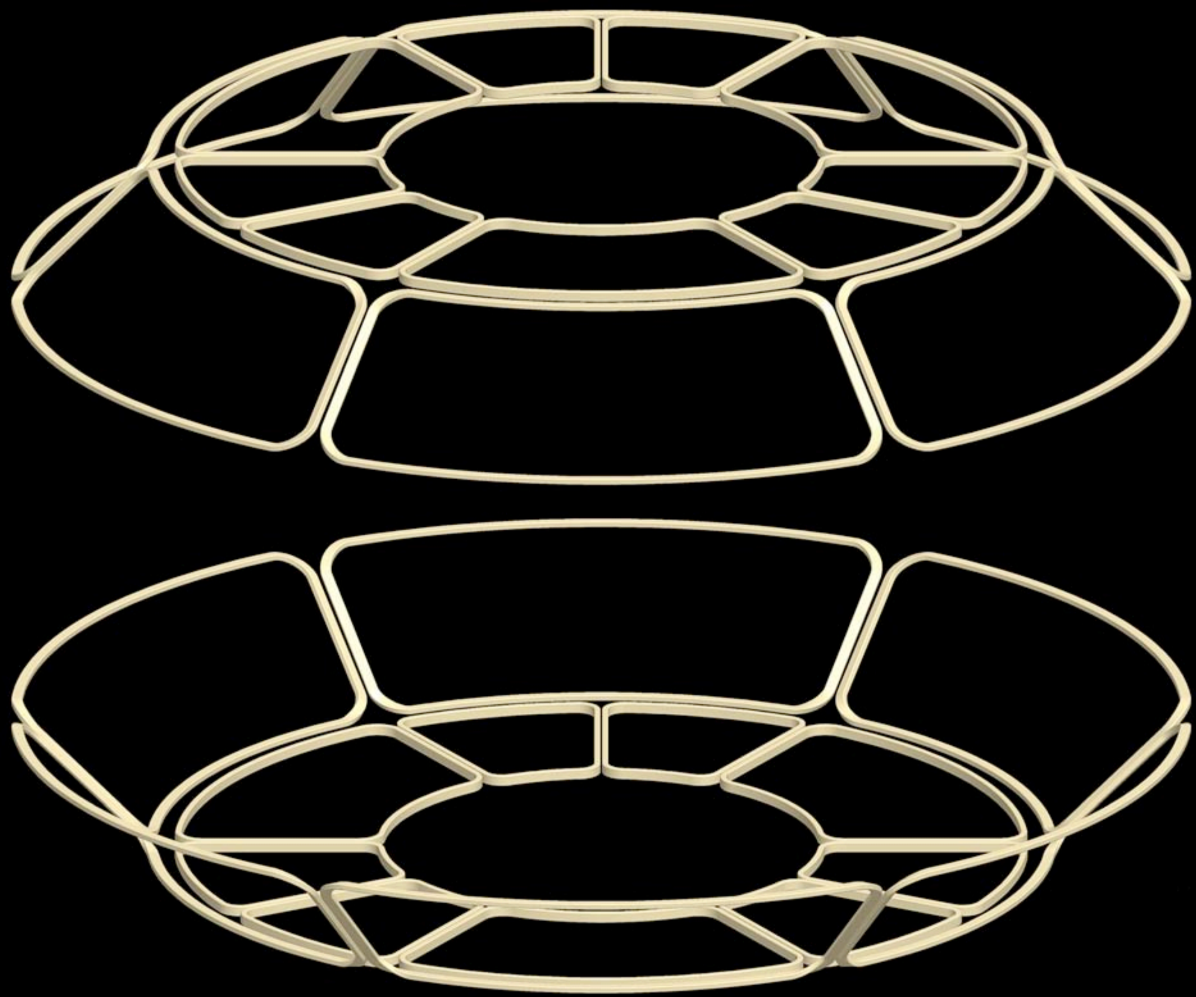
6 pairs of Poloidal Field Coils

- 6 pairs of PF coils provide inductive current drive and physics flexibility, (3 pairs of coils form central solenoid assembly)
- Require flux swing to drive 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

- External trim coils provided to mitigate low order field errors from fabrication or assembly errors
- Coils can be 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 coil set design work?

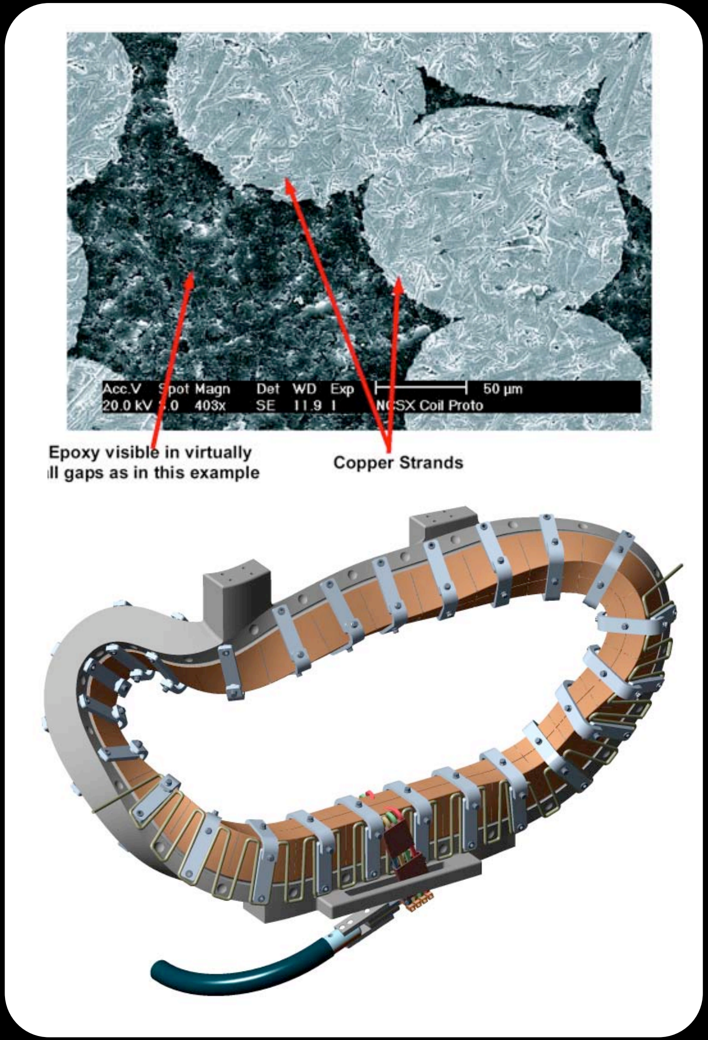
- Coil Design is being verified by analysis and R&D

- R&D
  - Epoxy impregnation tests and conductor characterization
  - Winding tests on forms with full scale cross section
  - Full scale prototype winding form (from two suppliers)
    - Contracts in place
    - Production of winding form prototypes underway
  - Full scale prototype coil

- Analysis
  - EM analysis (Field and force analyses, eddy currents)
  - Stress analysis
  - Thermal analysis

Conductor behavior is being characterized

- Winding / handling
  - Keystoning and insulating tests completed
  - 3-D prototypical winding tests
- Vacuum Pressure Impregnation
  - Individual conductor samples
  - Straight “tee” section
  - Racetrack coils (2)
- Material Properties – impregnated conductor @ temp.
  - mechanical tests (tension, compression, flexure, fatigue)
  - Thermal tests (CTE, conductivity)
  - Electrical resistance (12% higher than equivalent solid)
- Integrated Coil Performance
  - 2 Racetrack coils built and partially tested
  - 3-D coil with all prototypical features by July



Modular Coil Design Analysis

- 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 credible*
  - Electromagnetic field and forces: 2 independent calcs within 4%
- Structural analysis involves several models which are focused on:
  - Global deflection and stress in the winding forms *Acceptable*
  - Nonlinear behavior of the windings due to thermal and EM loads *In progress*
  - Deflection and stress in the clamps and other local supports *Acceptable*

Structural Analysis of Coil Set - Forces

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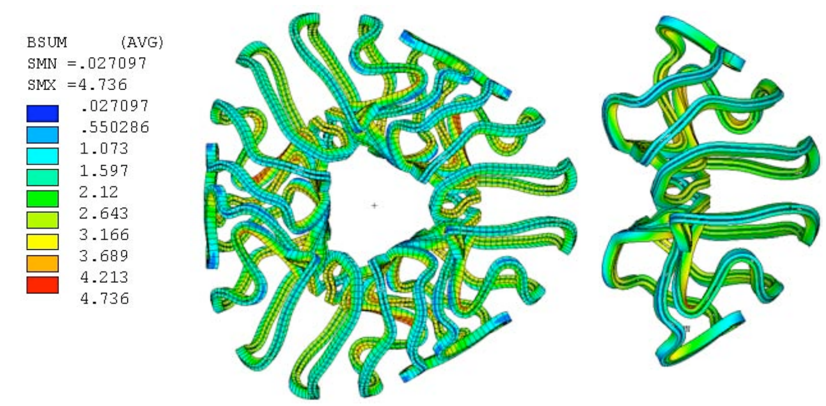
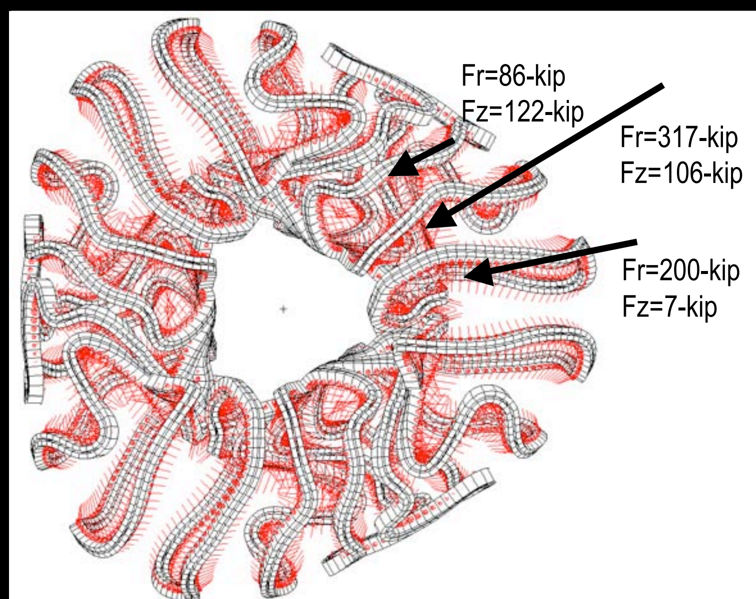
- Fields and forces analyzed for 7 reference operating scenarios with peak currents
- Worst case loading conditions selected for stress analysis
- Two independent calculations performed as check of field and force calculations (agreement to 4%)



2T ref case worst for mod coils



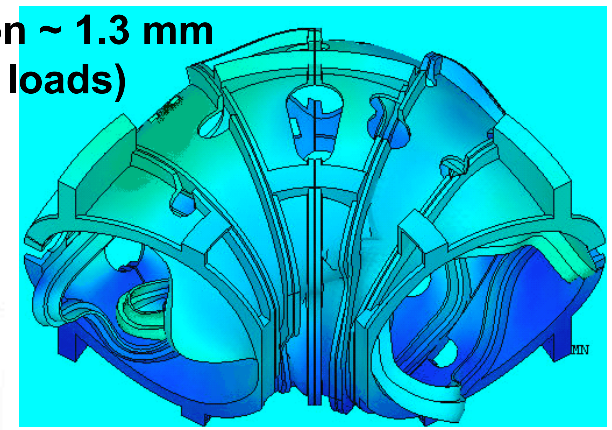
Net EM Force on Modular Coils								
Coil	Field/Force Component	0.5-T First Plasma	Field Mapping	1.7-T Ohmic	1.7-T High Beta	2-T High Beta	1.2-T Long Pulse	320-kA Ohmic
	Max Field at Coil (T)	1.2	0.2	4.2	4.2	4.9	2.9	4.2
Type A	Net Radial Load (kips)	13	1	152	152	200	76	147
	Net Vert Load (kips)	0.5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

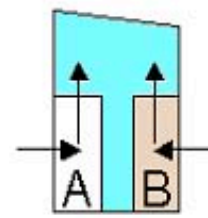
Structural analysis of modular coils

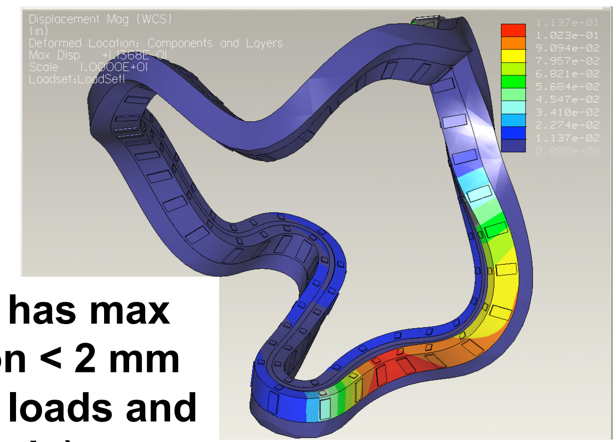
- **Winding supported continuously by shell structure**
- **Shell stresses and deflections are low**
  - **Max primary stress 28 ksi, factor of safety ~ 2 on minimum properties**
  - **Max deflection ~ 1.3 mm**
  - **Max bolting stresses low, factor of safety 2 on bolts, 5 on insulation**
  - **All inboard regions in compression**
- **Structural response of winding depends on:**
  - **stiffness properties of composite winding,**
  - **initial strain in conductor (shrinkage relative to winding form)**
- **Linear models predict max strain ~ 0.1%**
- **Non-linear models predict strain up to 0.17%**
- **Further non-linear analysis of the winding pack behavior will be completed during final design of winding assembly**

Safety factor, S.F. = allowable stress / actual stress

Shell has maximum deflection ~ 1.3 mm (for max loads)







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

Fatigue tests show robust winding pack

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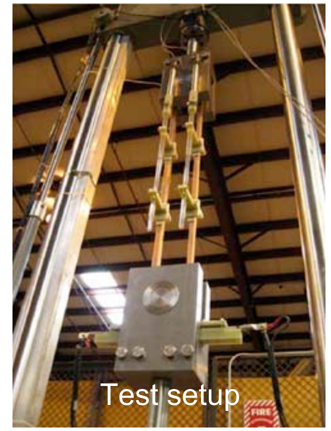
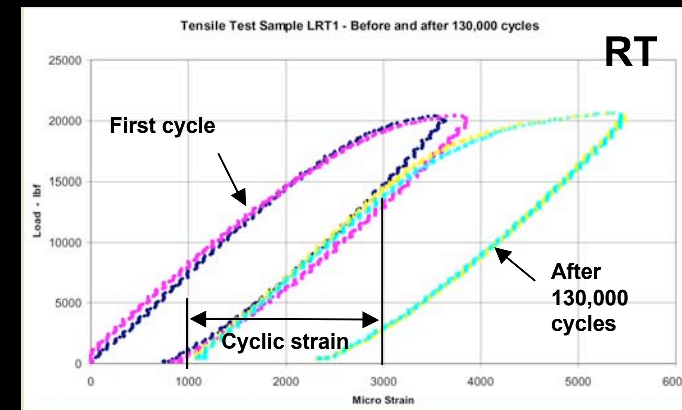
- Fatigue tests performed on 4-turn racetrack coils at RT and LN2 temperatures
- Coils had 2 thicknesses of glass insulation around each conductor, no ground wrap

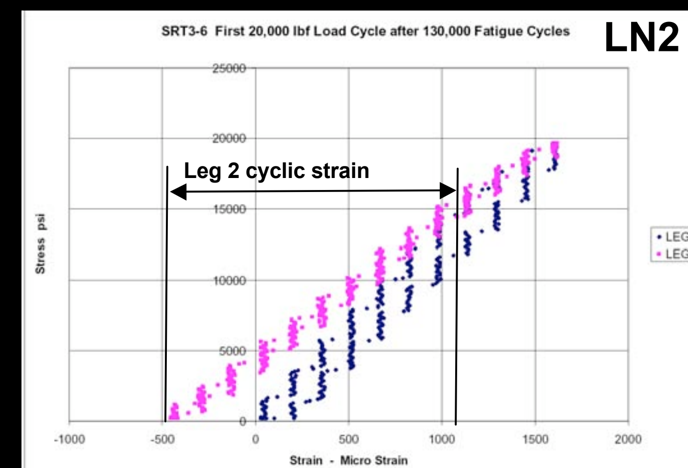
- RT tests:
  - 130,000 cycles at 0 to 14,000 lbs or 0.2% strain
  - No electrical or mechanical degradation observed
  - Stress strain curves appear very similar before and after testing

- LN2 tests:
  - 150,000 cycles at 15,000 lbs, up to 0.15% strain
  - No electrical or mechanical degradation
  - Testing will continue to failure or 20 x life


Test setup


Racetrack coil leg after 130,000 cycles

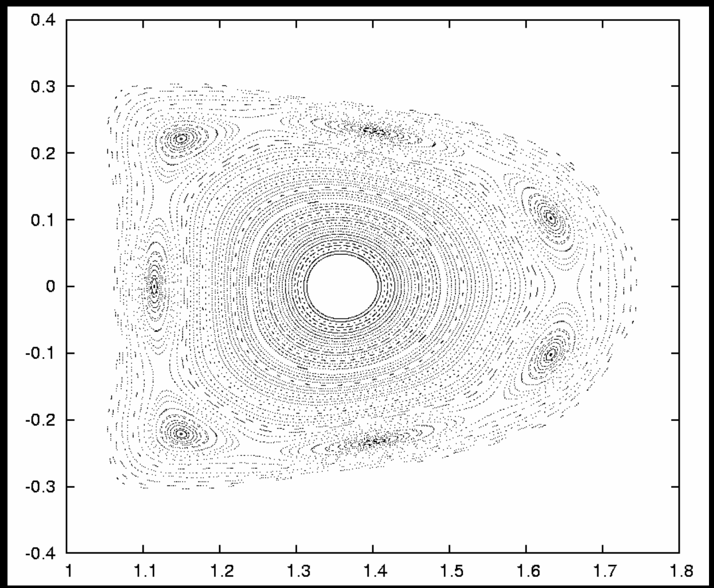




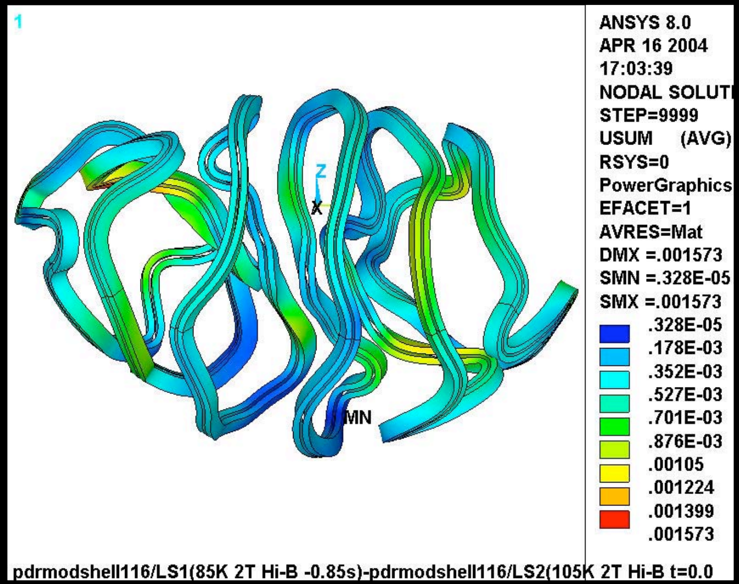
Ref T. Kozub, J. Chrzanowski

Winding structural deflections are ok

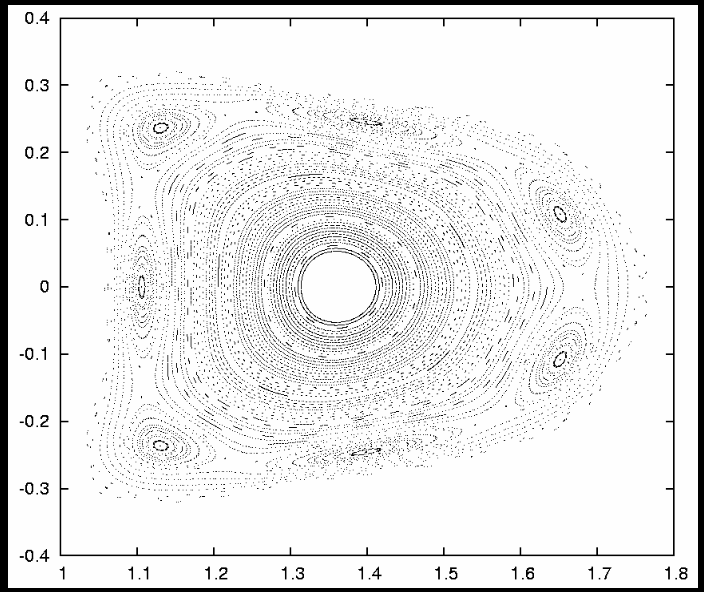
- Typical deflected shape analyzed in comparison to theoretical shape
- Vacuum configuration does not change



Magnetic surfaces from “perfect” coils



Deflected shape of windings (2T operating loads)



Magetic surfaces from deflected coils

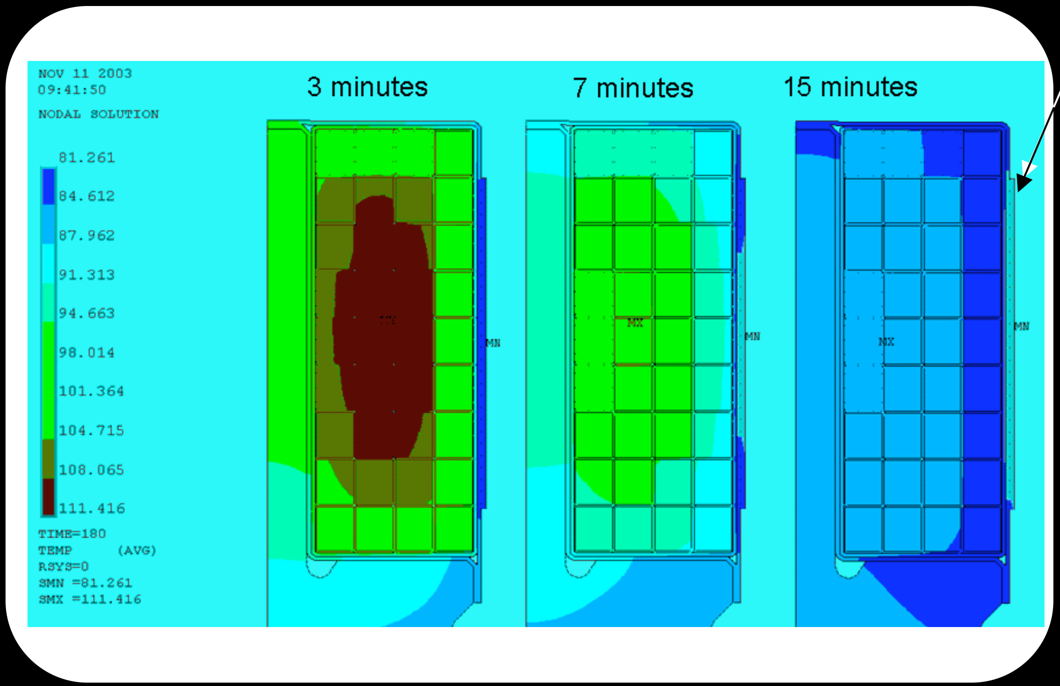
Ref. Strickler et al, (magnetics)

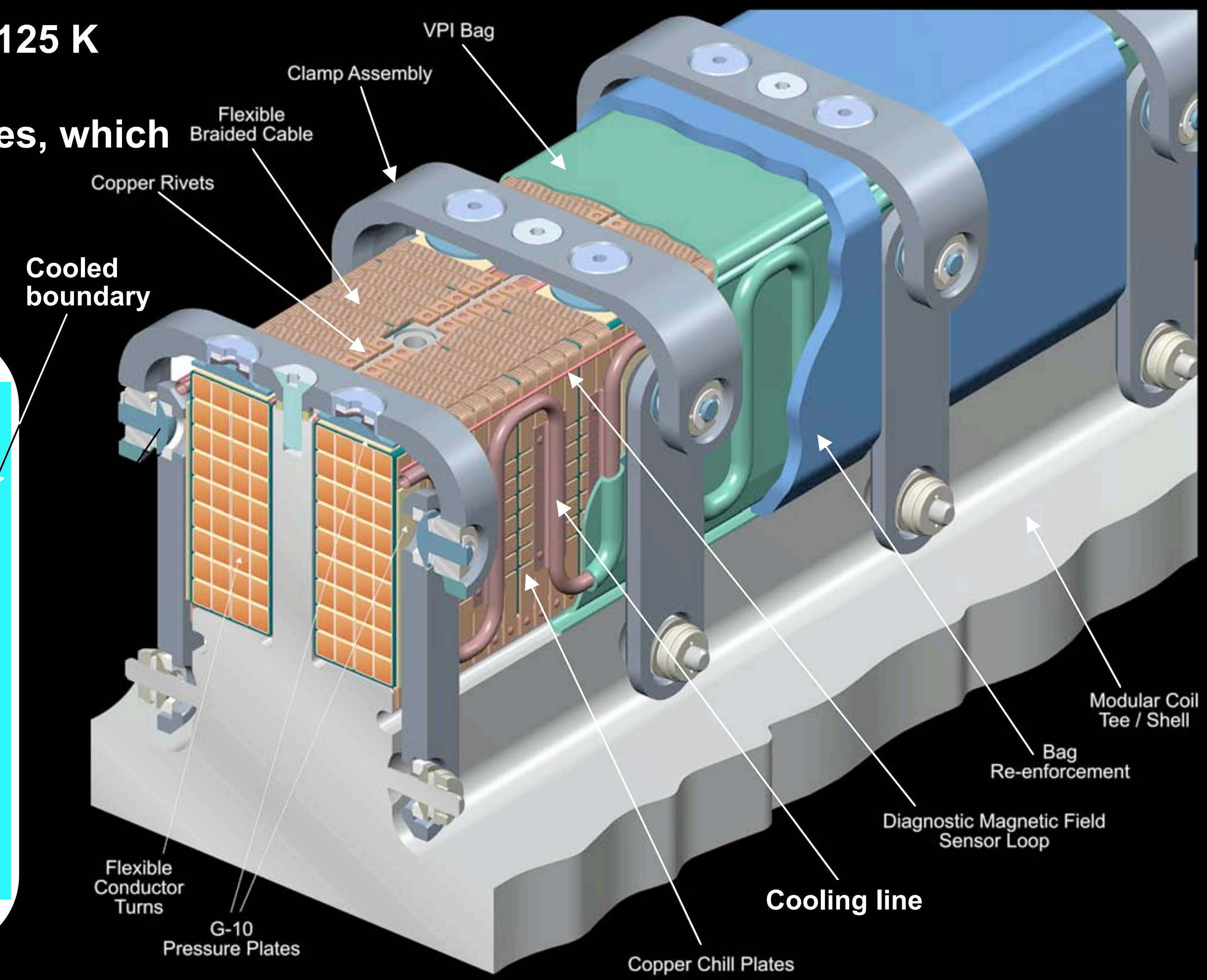
Ref. Myatt (structure)

Winding Thermal Response

NCSX

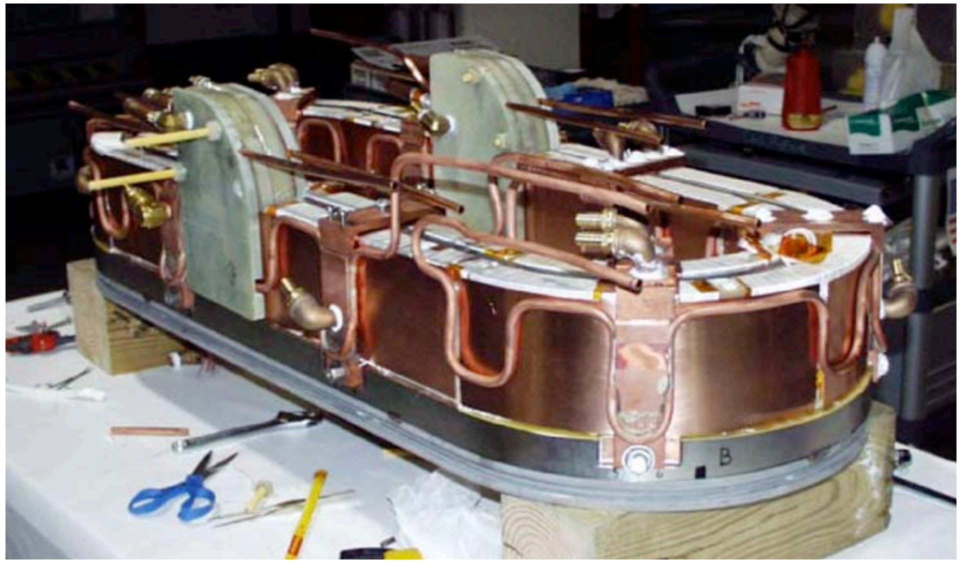
- Winding heats adiabatically from 85 to almost 125 K during pulse
- Cooling is provided by conduction to chill plates, which are traced with LN2 coolant lines
- Cool-down in 15 minutes calculated
- Cool-down of racetrack coil almost as good

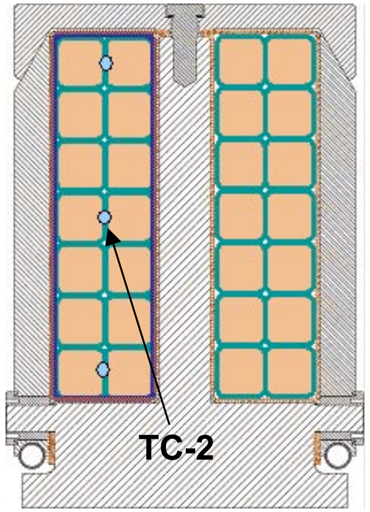


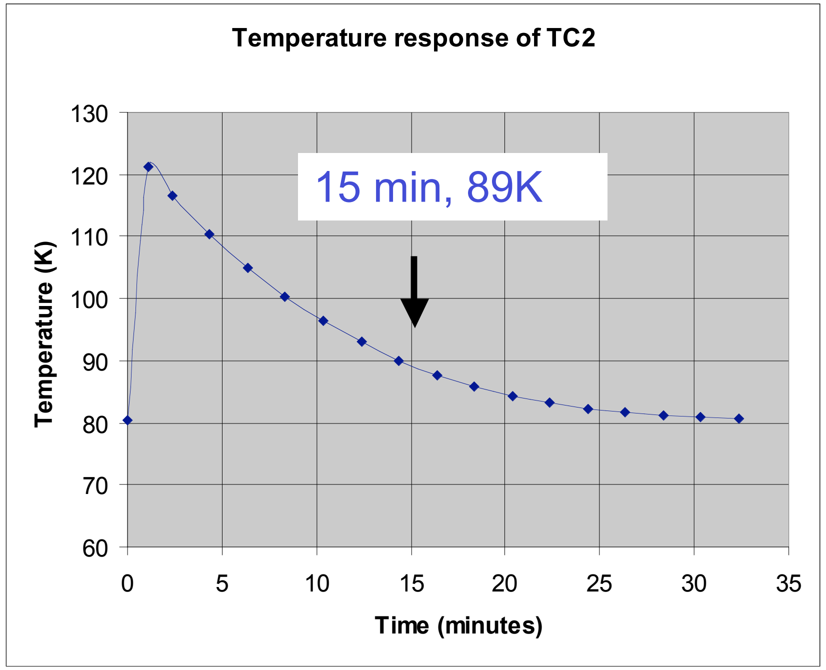


Winding cooldown has been tested

- 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







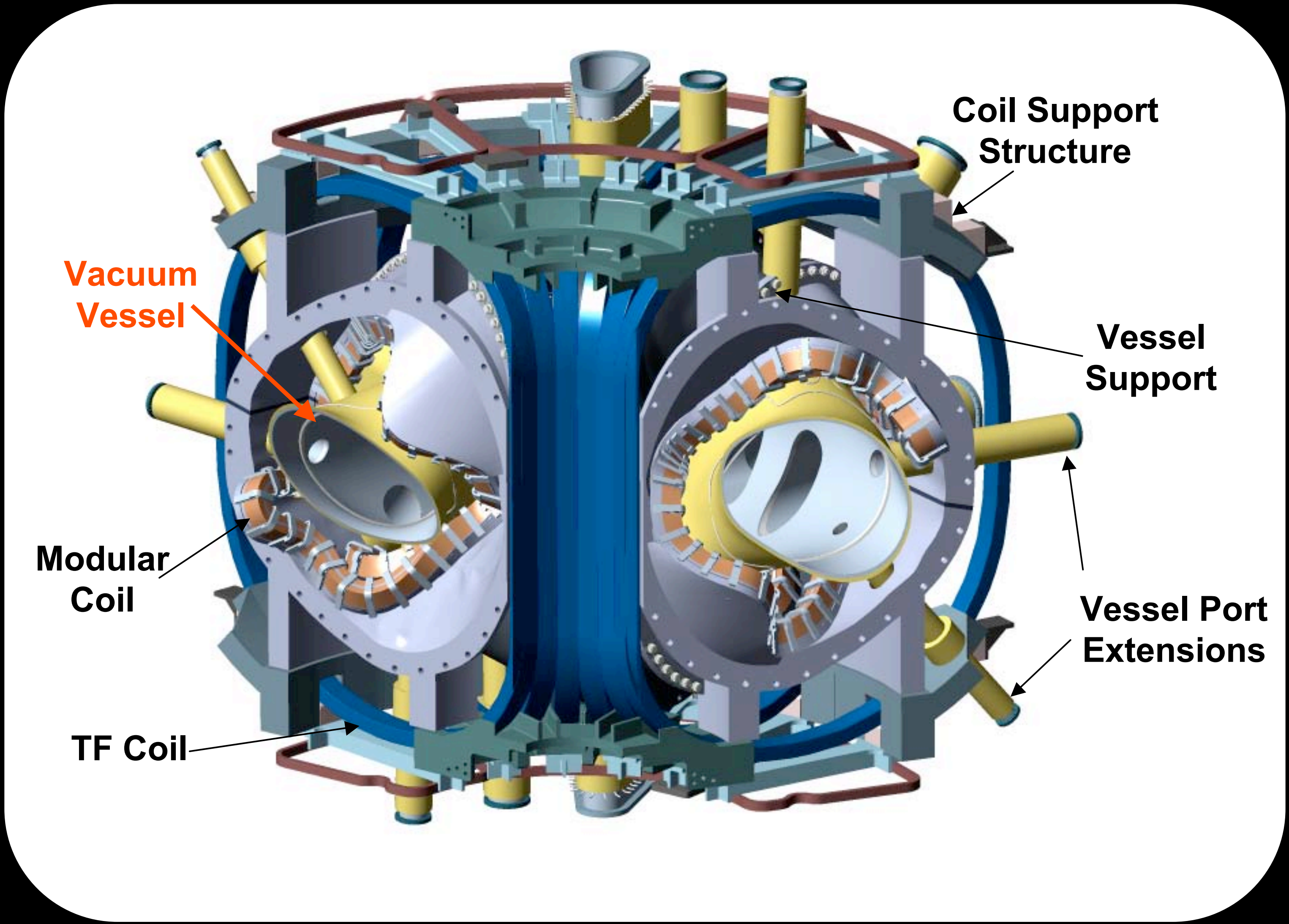
We are ready to procure winding forms

NCSX

- Specifications
  - System Requirements Document – NCSX-BSPEC-140-00 Complete
  - MCWF Product Specification – NCSX-CSPEC-141-03-00 Complete
- Winding form models and drawings:
  - Winding form parts In Final Checking
  - Winding form assemblies, with poloidal break hardware In Final Checking
  - Shell assembly Details, Flange shims, hardware, pillow shims 75% - not req'd. for MCWF procurement
- Analysis
  - Winding form limit analysis (no winding stiffness assumed) Complete
  - Linear combined analyses of shell and windings Complete for MCWF
  - Non-linear analysis of winding sliding on winding form 75% complete - not req'd. for MCWF procurement
- R&D
  - Winding form R&D 80% - awaiting delivery of prototypes and fatigue testing of casting alloy coupons
  - Winding pack material property R&D 75% static, 25% fatigue
  - Winding R&D (Winding, measuring,VPI, etc.) 75%
- Procurement
  - Winding form Contract Award on track for August '04

Inside the coil set is a vacuum vessel

NCSX

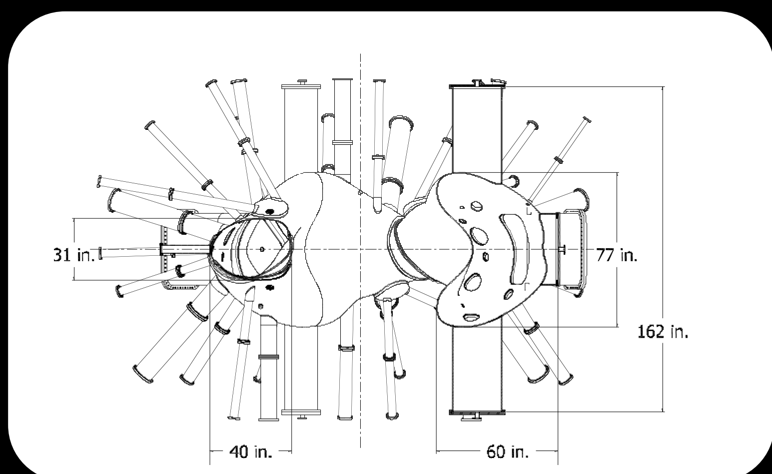


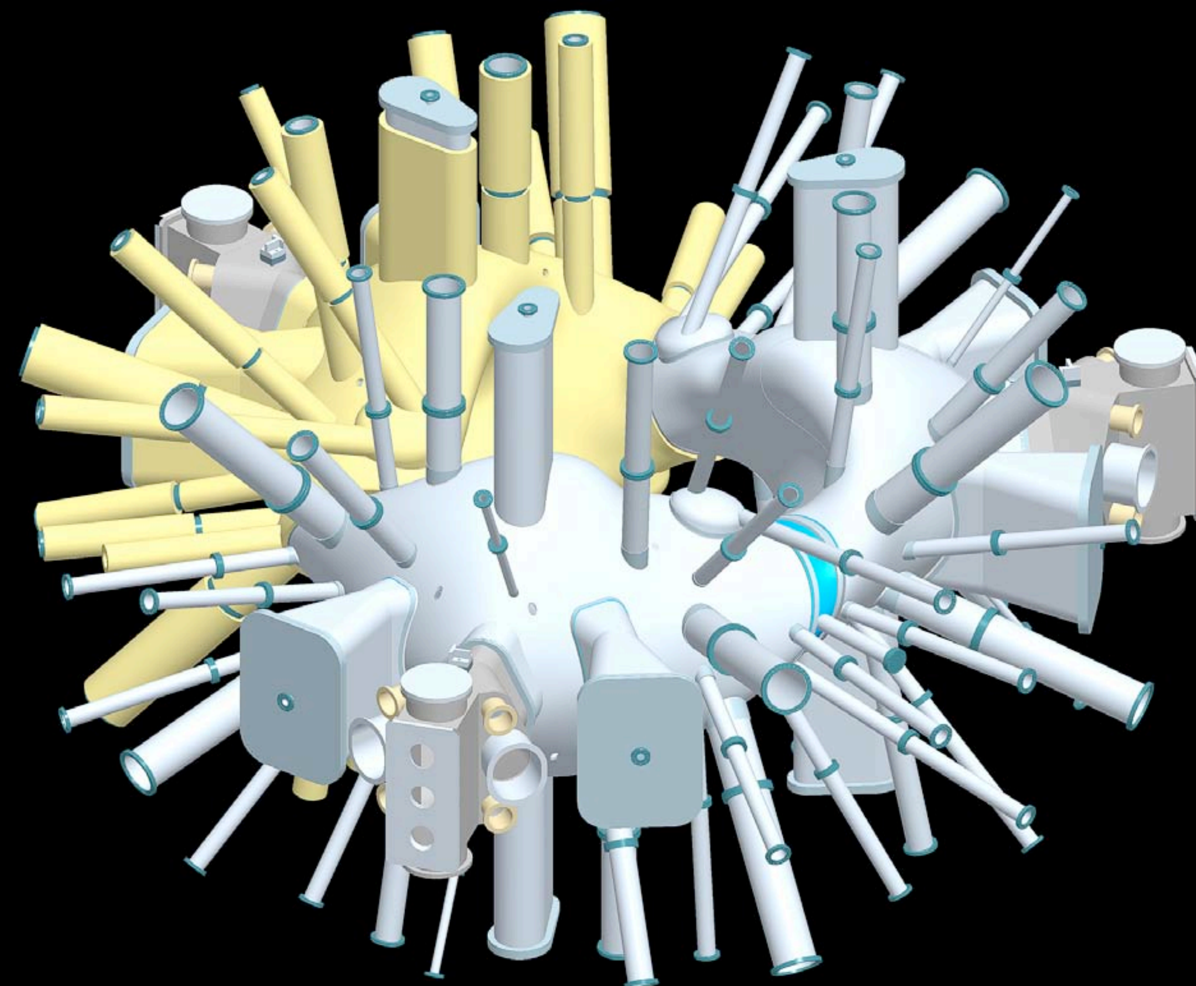
Vacuum Vessel Requirements

- Provide good clean vacuum environment
  - Vessel must be bake-able to 350 C
  - Accommodate full set of PFCs
- Minimize field errors
  - Low permeability (< 1.02)
  - Stellarator symmetry
  - Short time constant (< 10 ms)
- 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

- 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 350C*) and cooling
- Microtherm insulation between VV and cold mass

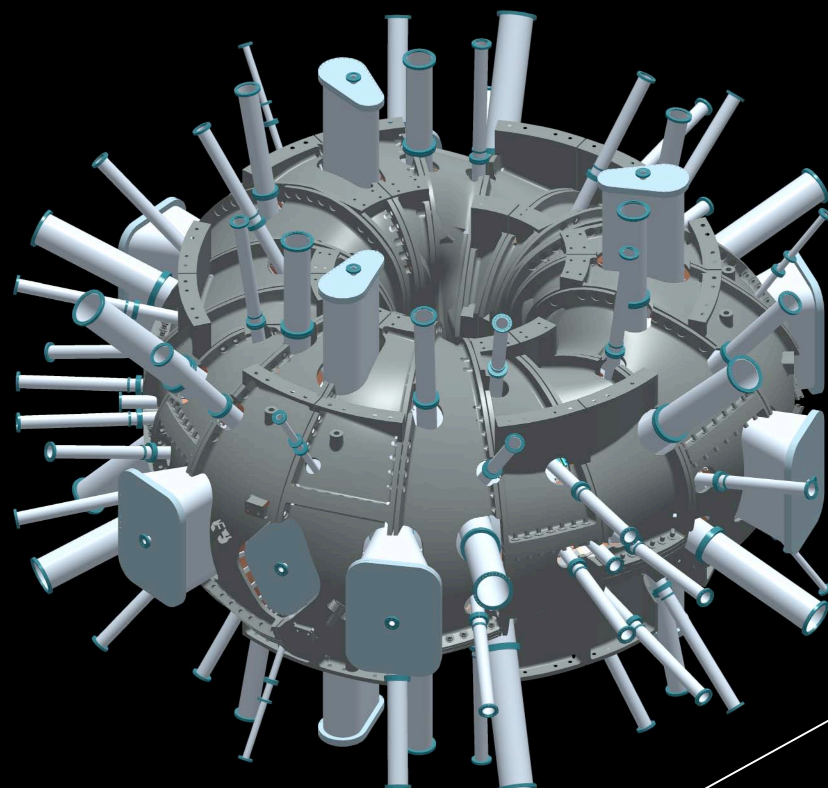


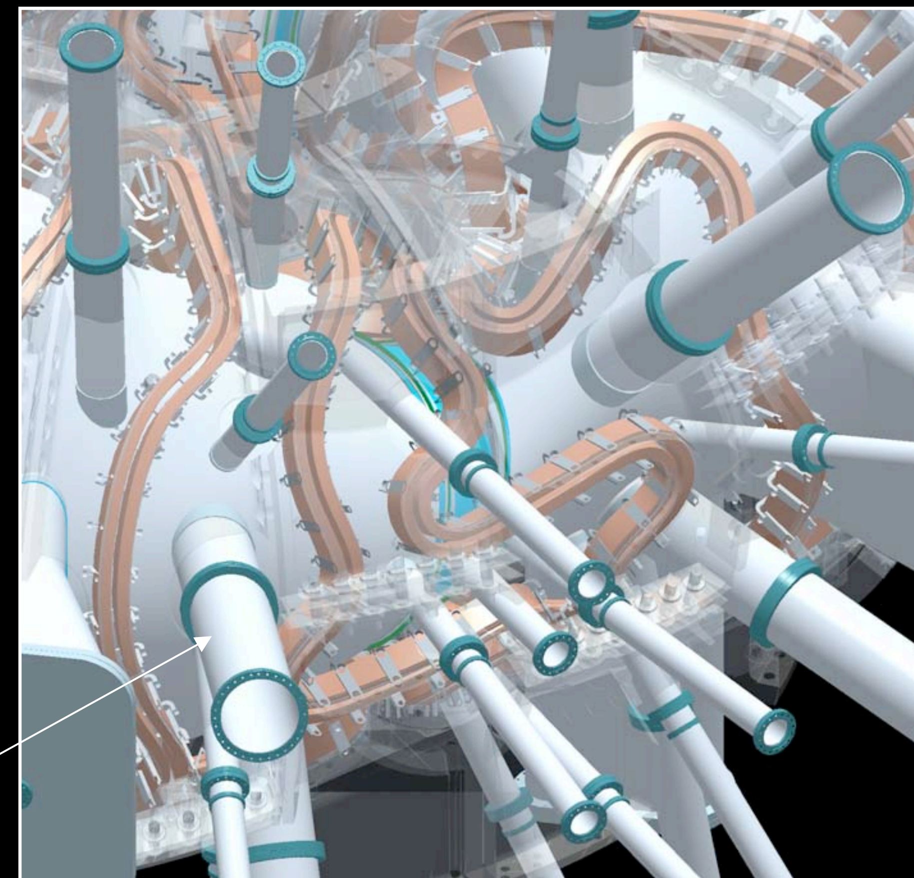


*new since PDR

Vessel ports integrated with mod coils

- 90 ports – excluding NBI transition duct (33 more than PDR design)
- First flange just outside shell
- Removeable extension can be modified for specific diagnostics





Removeable extension, typical

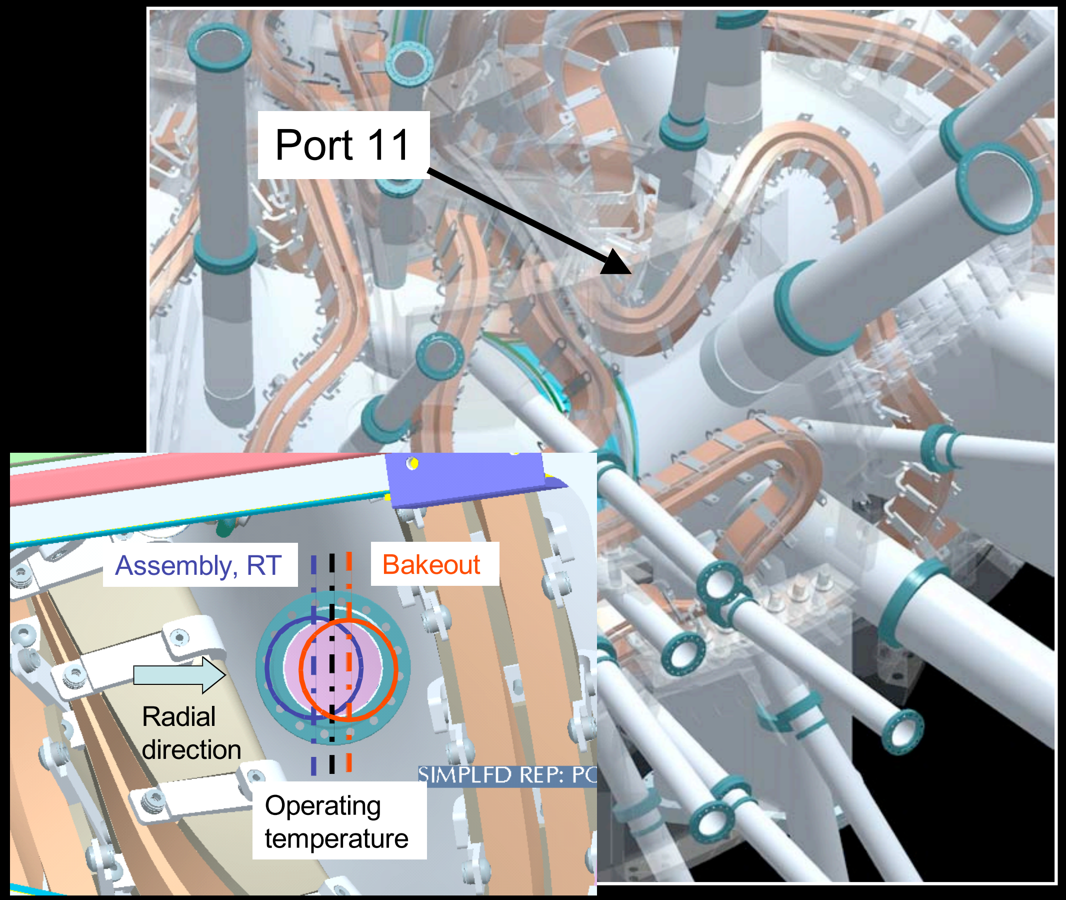
Clearance checks for Vessel ports

- **Ports must maintain adequate clearance to mod coils, mod coil shell, and other components over full operating range**
  - Temperature of VV from RT to Bakeout (350C)
  - Temperature of coil set from RT to 77K
  - Deflections of VV from loading conditions
  - Tolerances

- **Nominal clearances provided at operating temperature: VV at RT, mod coils at 77K**
  - 1.5 inch nominal radial clearance to mod coils
  - 2 inch clearance to shell openings

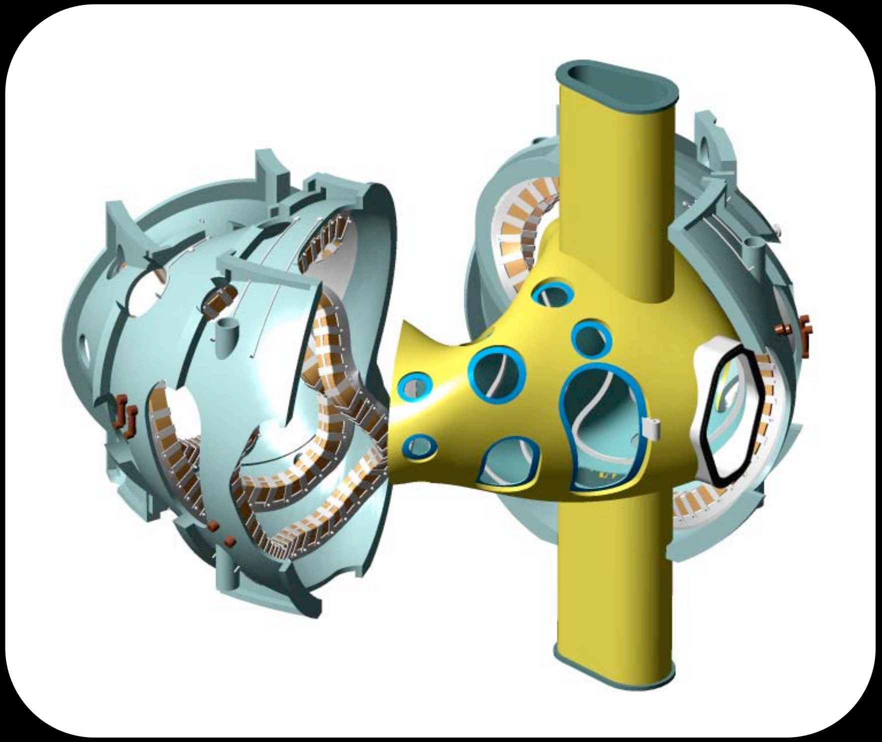
- **Port 11 represents worst case**
  - Nominal clearance, operating conditions: 1.53 in
  - Port tolerance - 0.13 inches
  - Coil fab/assembly tolerance - 0.06 in
  - Coil position optimization -TBD in
  - Bakeout motion - 0.26 in
  - Deflection under load at tight spot - 0.01 in
  - Minimum clearance (to clamp) at bakeout 1.07 in

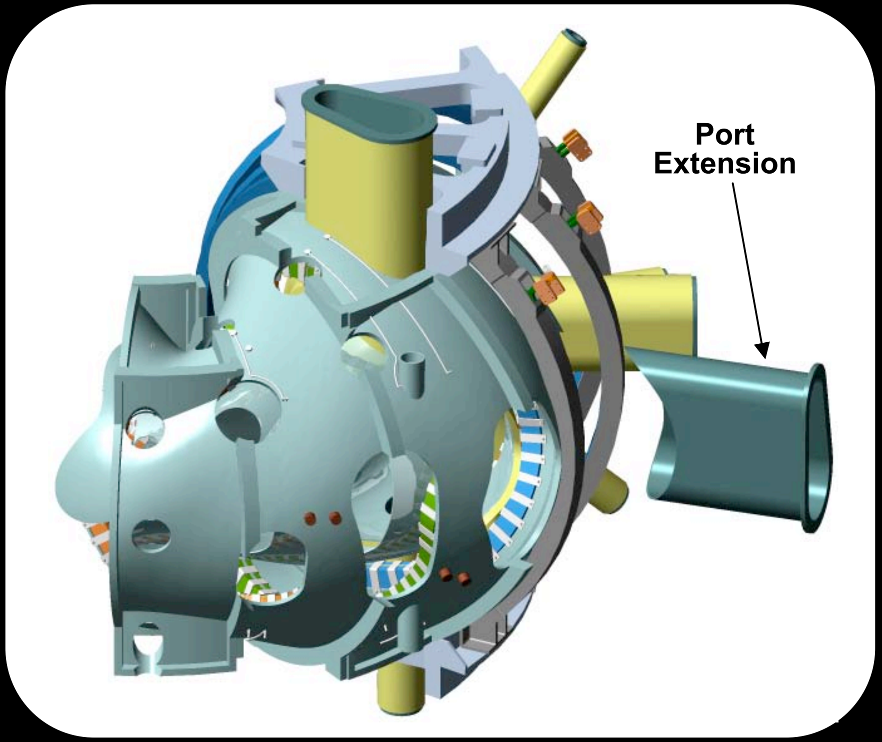
- **All port locations being re-examined during final checking**



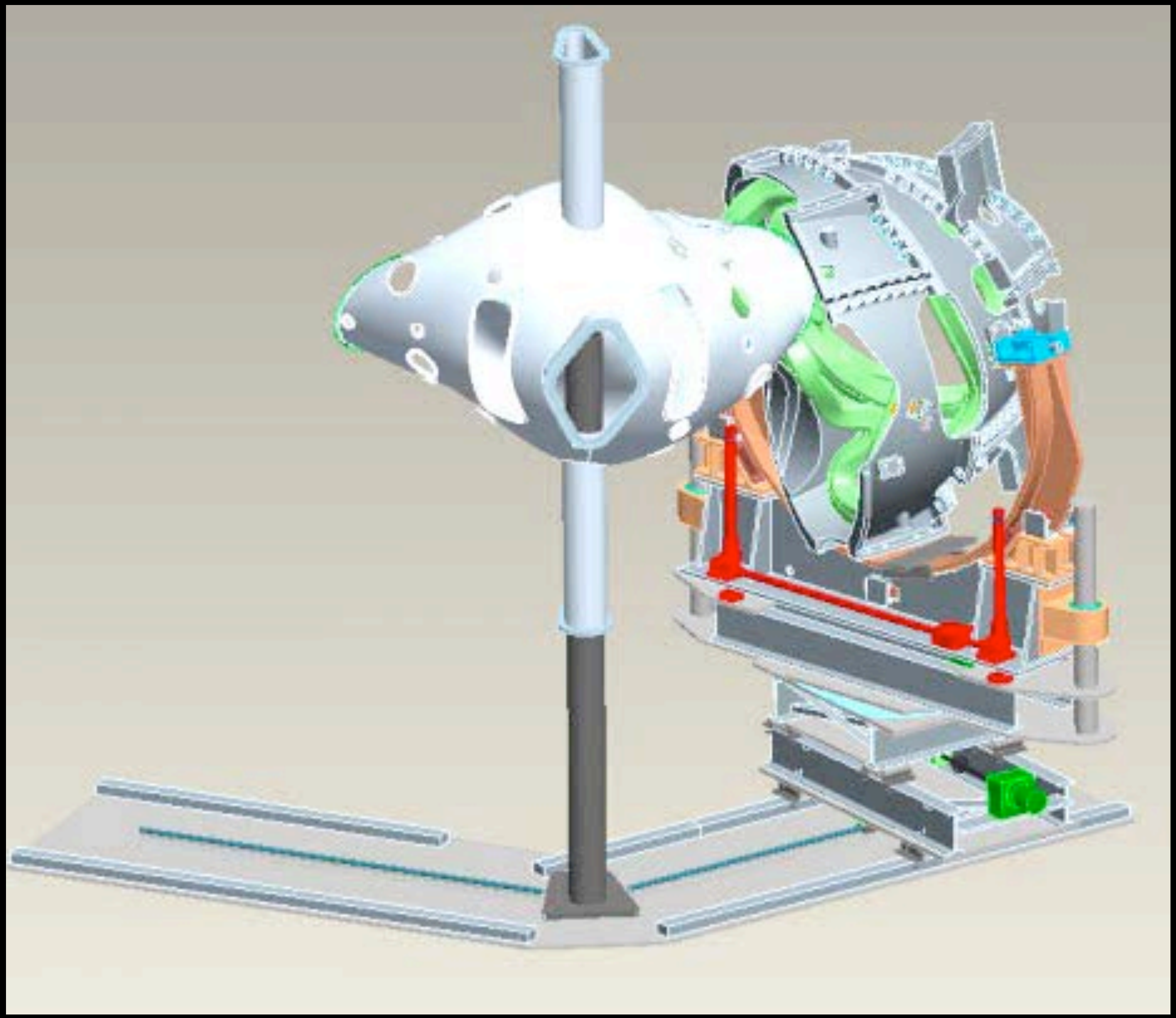
Ports welded on after mod coils are positioned

- 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 movie*

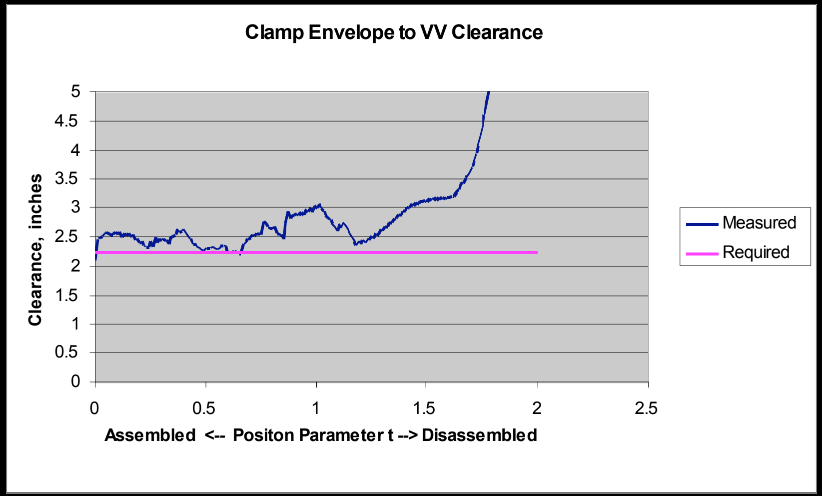




Mod coil trajectory over vessel is defined

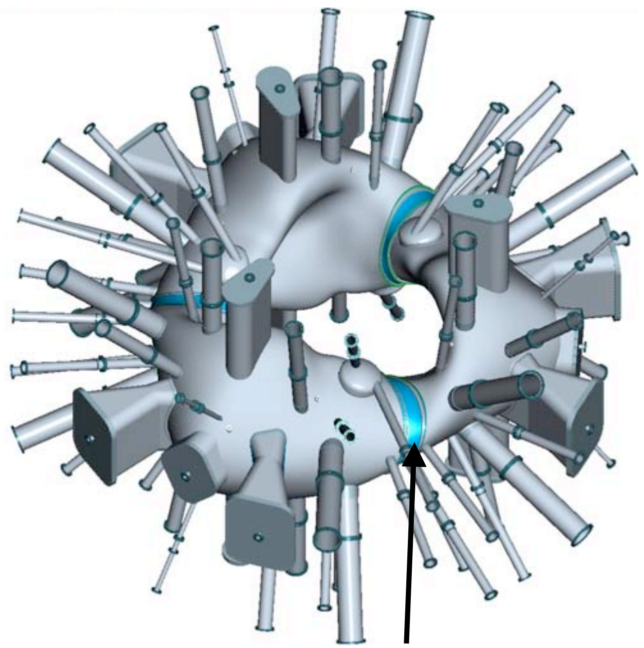


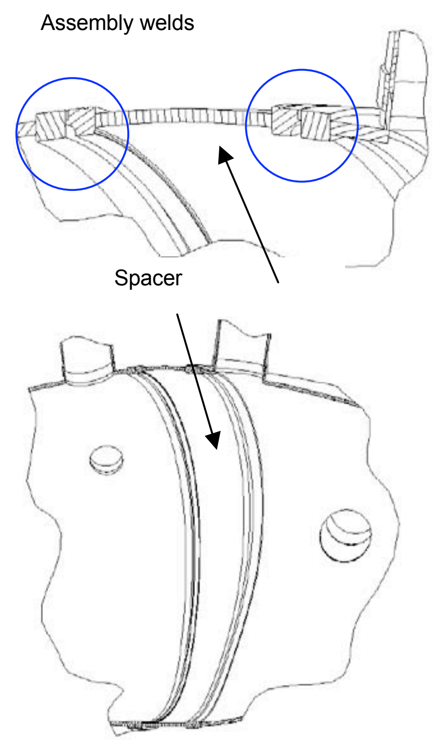
- Detailed analyses completed for trajectory of 3-coil subassembly over vacuum vessel
- Fixture / mechanism designed to provide required motion
- Clearances checked among components continuously along trajectory

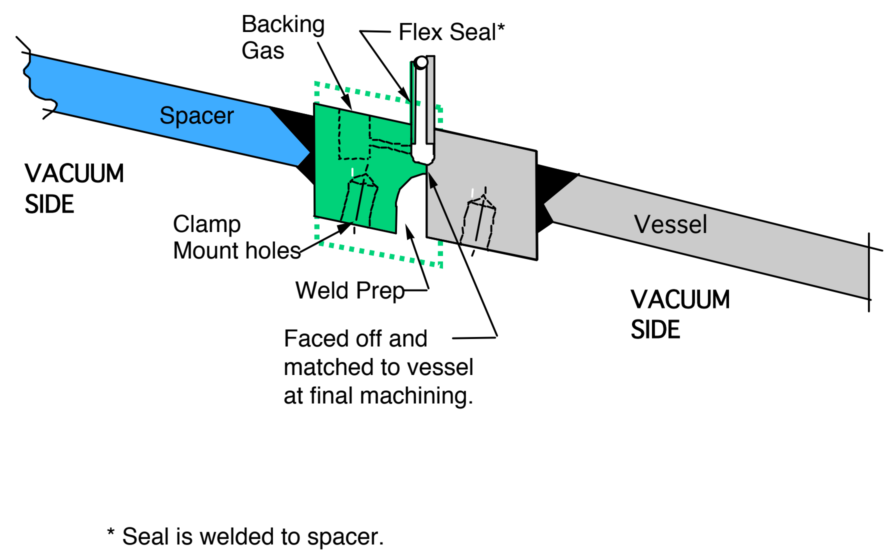


Vessel Field Joint is welded

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

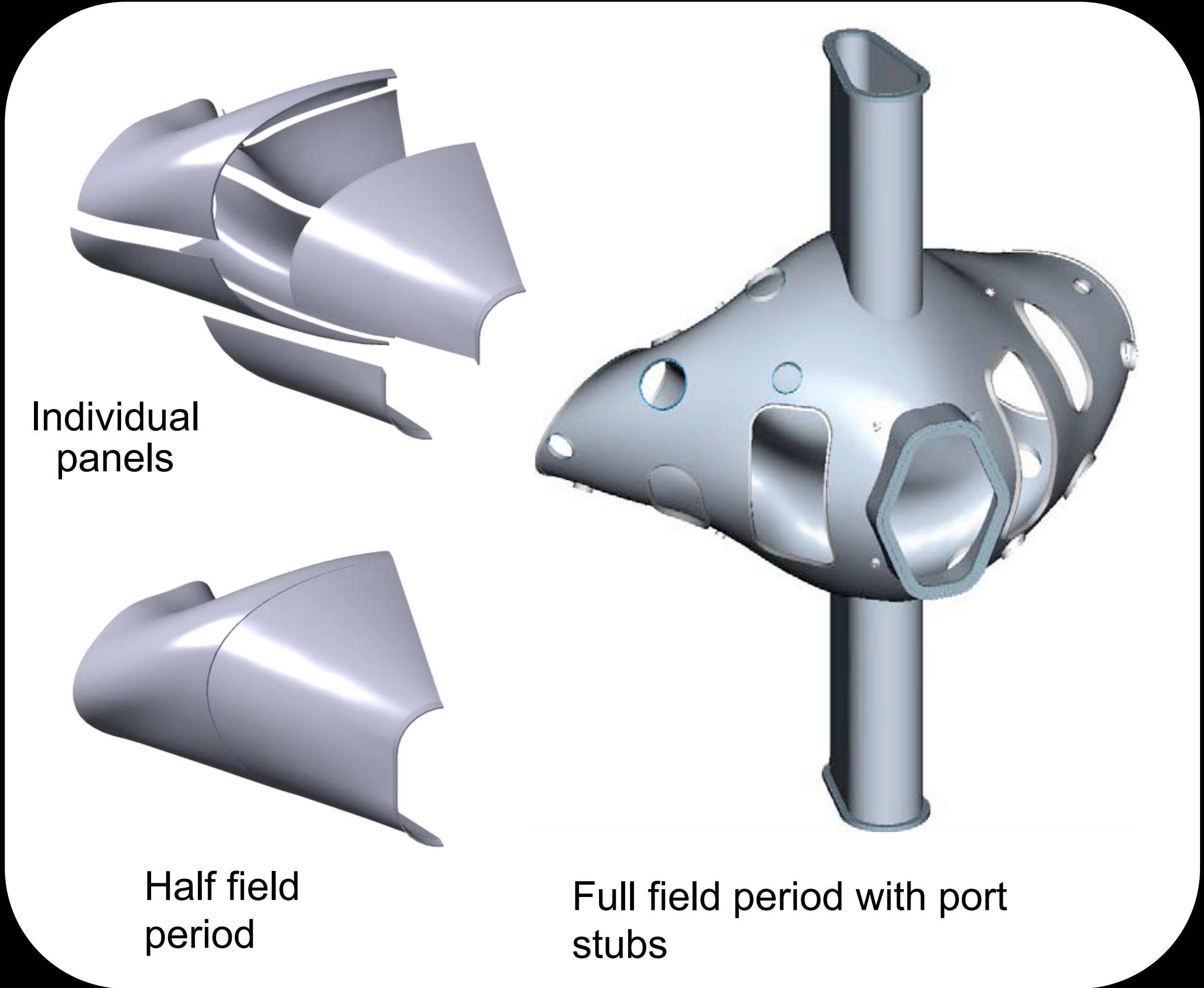

Spacer between field periods





Vacuum Vessel Fabrication Concept

- **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 0.25 in. (ports), 0.12 in. (shell),
  - tresca stress: 16 ksi, safety factor > 2 in welds
- Disruption loads:
  - max vertical load of 18,000 lbs, deflections 0.45 in. (ports), .25 in. (shell)
  - Tresca stress ~ 28 ksi for combination of VDE, pressure, gravity loads, safety factor > 2 in shell, > 1.2 in welds
- Buckling: critical pressure =10 x max pressure (vacuum + VDE load)

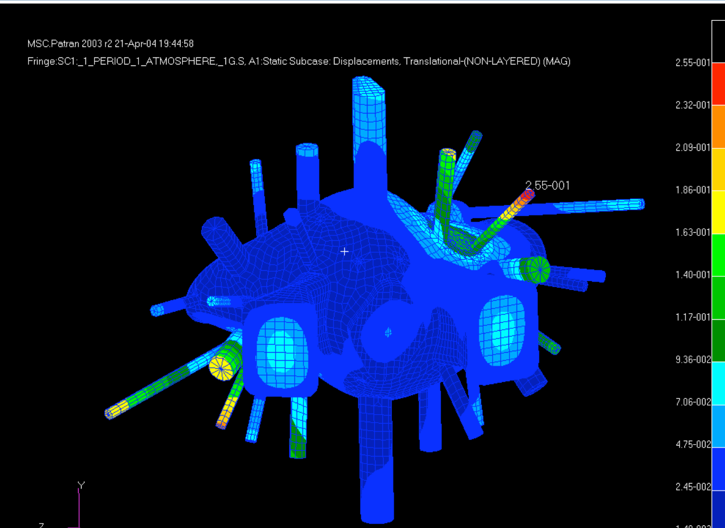
Thermal analysis:

- Pre-shot load on cold systems, vessel at 40C: 13 kW
- 350 C Vessel bakeout load on cold systems: 43 kW

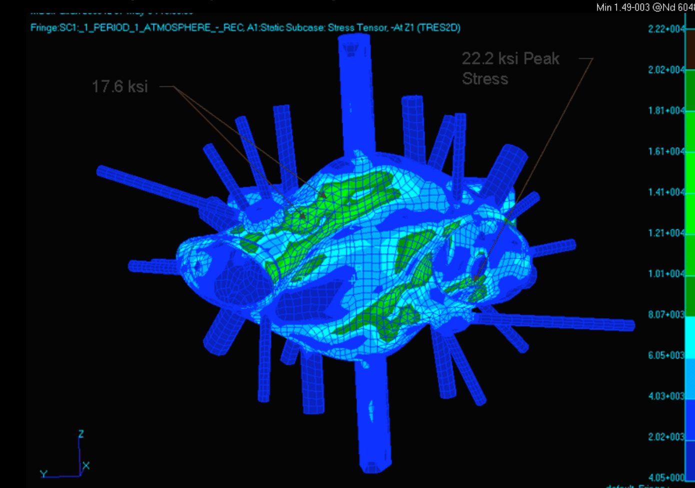
EM analysis:

- Time constant 5.3 ms compared to 10 ms requirement

Safety factor, S.F. = allowable stress / actual stress



1 atm + gravity loading, total deflection



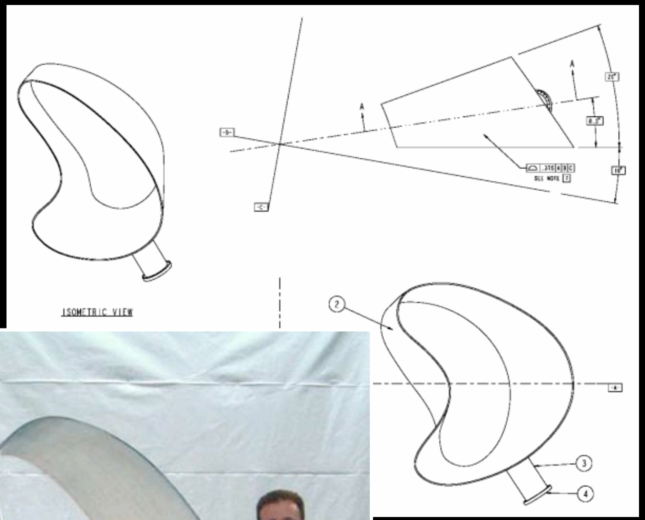
VDE + pressure + gravity tresca stress

Vessel design verified by R&D

- **Manufacturing studies**
  - 5 vendors funded to provide manufacturing feasiblity and cost studies
  - Completed during conceptual design phase
  - Showed vessel concept is feasible

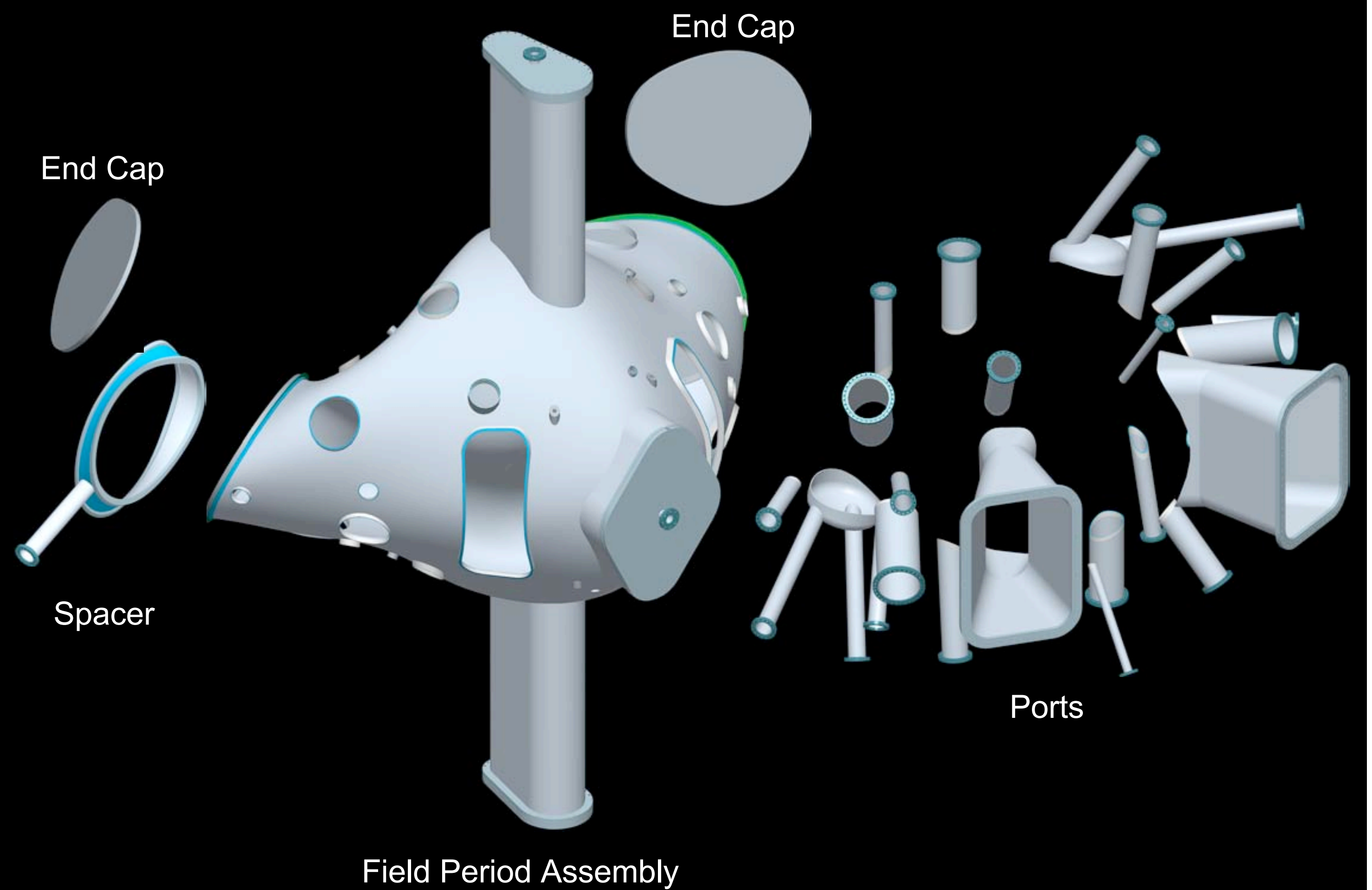
- **Vessel fabrication prototyping and qualification**
  - 2 vendors on board to develop processes and build full scale partial prototypes
  - Prototypes due, one has arrived
  - Both vendors will be qualified to bid on production vessel

- **Field joint development**
  - Partial and full scale, simplified shape mockups
  - Distortion, temperature behind weld, leak checking operations prototyped
  - Weld procedure finalized



Vacuum Vessel Sub-Assembly, VVSA

- 3 complete VVSAs will be procured
  - 120 degree vessel shell with holes, port stubs, vertical ports, NB port
  - Port extensions with backing rings, leak check tubes, all hardware
  - Spacer with port extension
  - 2 cover plates for ends to allow leak checking single field period and spacer
  - Does not include NB transition duct, nor removeable stainless steel extensions
  - The VVSA represents the other primary subject of this review



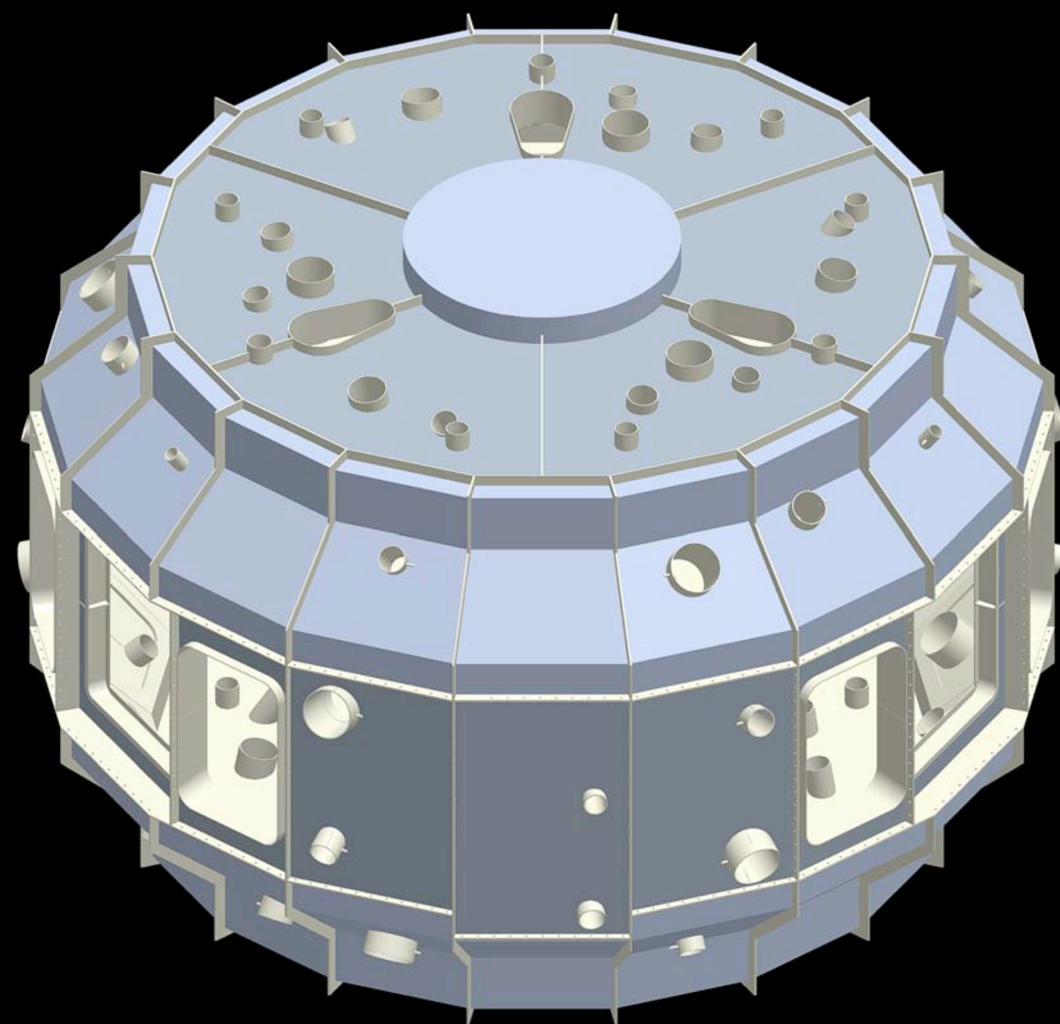
We are ready to procure the VVSAs

NCSX

- Specifications
  - Vac. Ves. System Requirements Doc. – NCSX-BSPEC-120-00 — Complete
  - VVSA Product Specification – NCSX-CSPEC-121-02-01 — Complete
  - Specs for insulation, tubing — Not req'd. for VVSA procurement
- VVSA models and drawings:
  - VVSA shell and ports — Final Checking
  - Spacer and end flanges — Final Checking
- Vessel assembly models and drawings
  - Removeable port extensions, NBI transition duct — 75% - Not req'd. for VVSA procurement
  - Thermal insulation and coolant tracing lines — 50% - Not req'd. for VVSA procurement
- Analysis
  - Basic static vessel analysis for normal and disruption loads — 90% - Sufficient for VVSA Procurement
  - Seismic evaluation and dynamic analysis — 30% - Sufficient for VVSA Procurement
  - Thermal analysis — Complete
- R&D
  - VVSA — 99%
  - Field joint welding — 25% - Not req'd. for VVSA procurement
- Procurement
  - VVSA — Contract Award on track for August '04

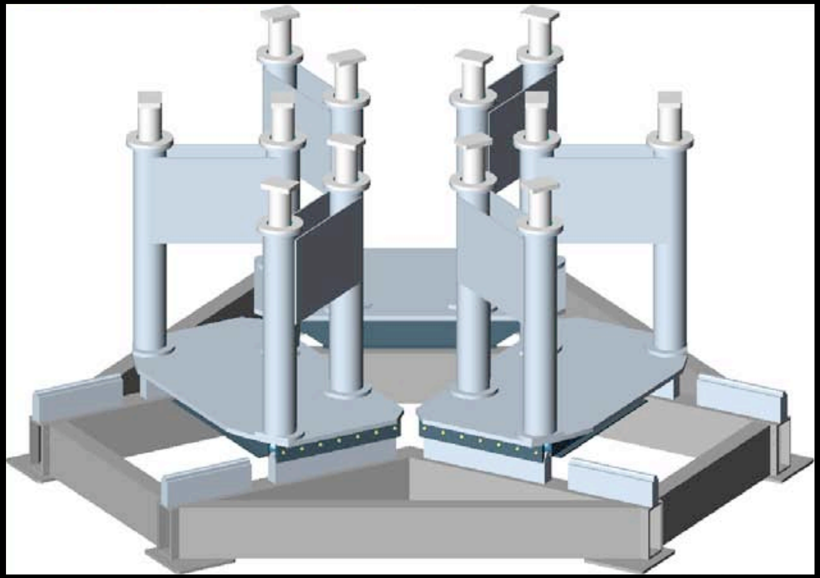
Cryostat Concept

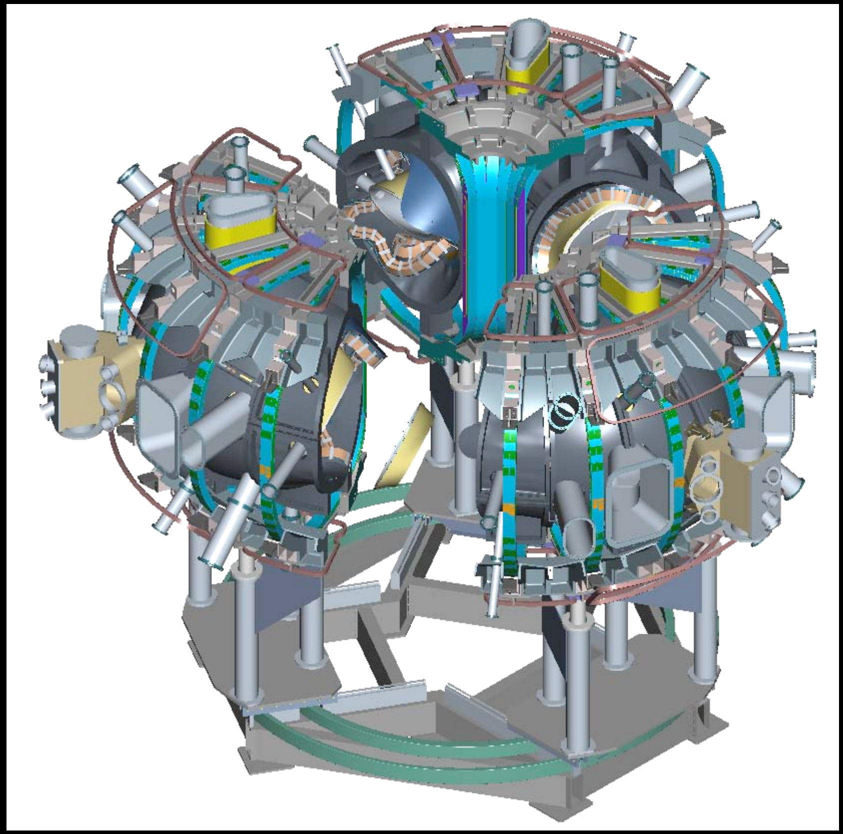
- Cryostat has simple frame and panel design, urethane insulation
- Design influenced by input from MIT and successful C-Mod cryostat
- Holes provided for all vacuum vessel port extensions
- Silicon rubber “Gortiflex” boots to seal between vessel port extensions and cryostat
- 6” thickness reduces heat 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

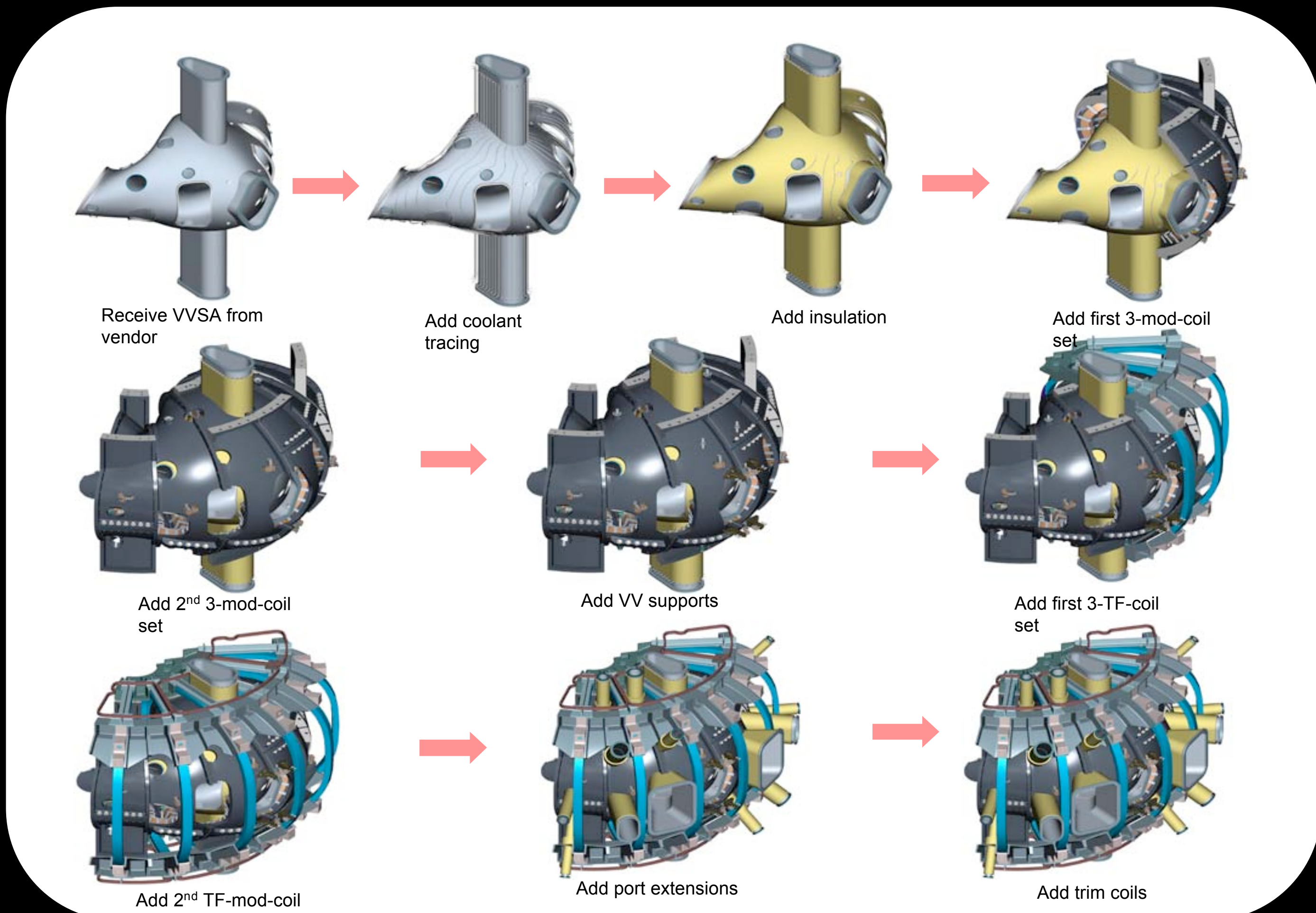
- Precision, radial sliding supports are needed to assemble machine
- Machine leveling jack on each pad ensures fit-up with structure, slides adjustable for custom trajectory
- Columns must provide thermal isolation, several options available
- Machine can be completely disassembled for maint. or repair.



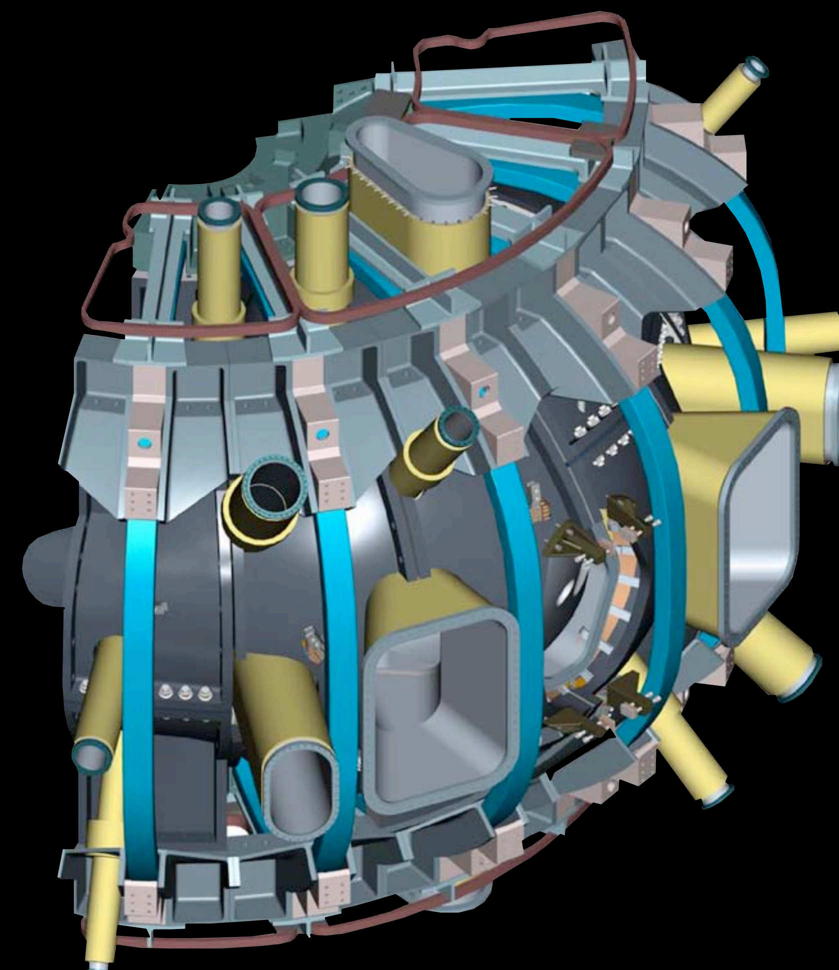


Field Period Assembly

Field Period Components

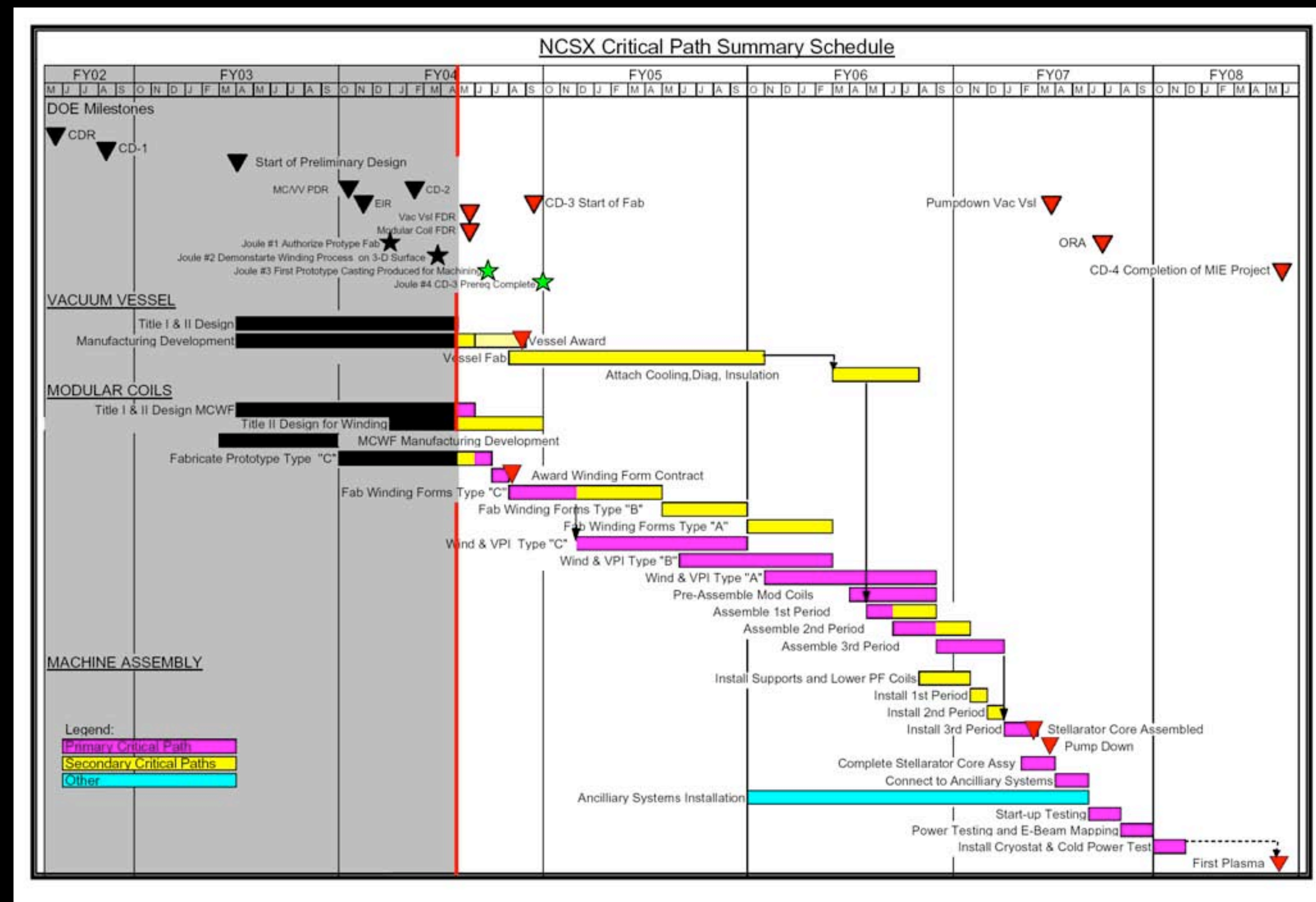


Complete Field Period Assembly



Stellarator Core on critical path

- VV and mod coil FDR by:
  21-May-2004
- Contract award for VVSA:
  24-Aug-2004
- Contract award for winding forms:
  30-Aug-2004
- First mod coil winding form by:
  15-Dec-2004
- First complete VV field period by:
  6-Mar-2006 (sched: 1-Nov-05)
- Finish winding mod coils by:
  8-Aug-2006
- Last field period assembled by:
  4-Jan-2007
- First Plasma by :
  May, 2008



Risk areas addressed by design and R&D

For the 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
- Will the vessel leak?
  Intermediate leak checks include thermal cycling,
  Provisions made for helium leak check of field welds
- Can we make assembly welds?
  Vendor has cut and re-welded port stubs
  Full scale field weld R&D planned
- Should any of the issues delay procurement of the VVSA?
  No

Risk areas addressed by design and R&D

NCSX

For the Modular Coils:

- Does the composite copper/epoxy winding behave as expected, during VPI, cooldown, and operation, and are the allowable stresses understood?
  - *Further tests planned on mechanical and fatigue behavior*
- Can the windings be placed accurately on a twisted, curved winding form?
  - *Winding trials underway*
- Will the cost exceed the budget?
  - *Two winding form vendors qualified through R&D in order to lower risk, cost*
  - *Prototyping activities have narrowed uncertainties*
  - *Casting costs to date near projections, machining TBD*
- Will the schedule slip?
  - *Two qualified vendors provide means to add capacity*
- Should any of the issues delay procurement of the modular coil winding forms?
  - *No*

Risk areas addressed by design and R&D

NCSX

For 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

For Final Assembly of Stellarator Core:

- Will the crane lift the field periods?
  Contract is planned to upgrade crane to 40t
- Will the three field periods come together as planned, without interference
  Simulations say yes, fit check of type C to type C coils is planned

Summary

- Design of the stellarator core is feasible and meets requirements
- The design of the modular coil winding forms and VVSA is complete and we are ready to procure these components.
- Analysis shows components have margin for the design operating scenarios. Additional analysis is planned for the mod coil windings
- Additional R&D is in progress to verify modular coil winding properties, winding techniques, and vacuum vessel field joint welding
- Risks have been identified and mitigation plan implemented