NCSX Stellarator Core

Design Status and Plans

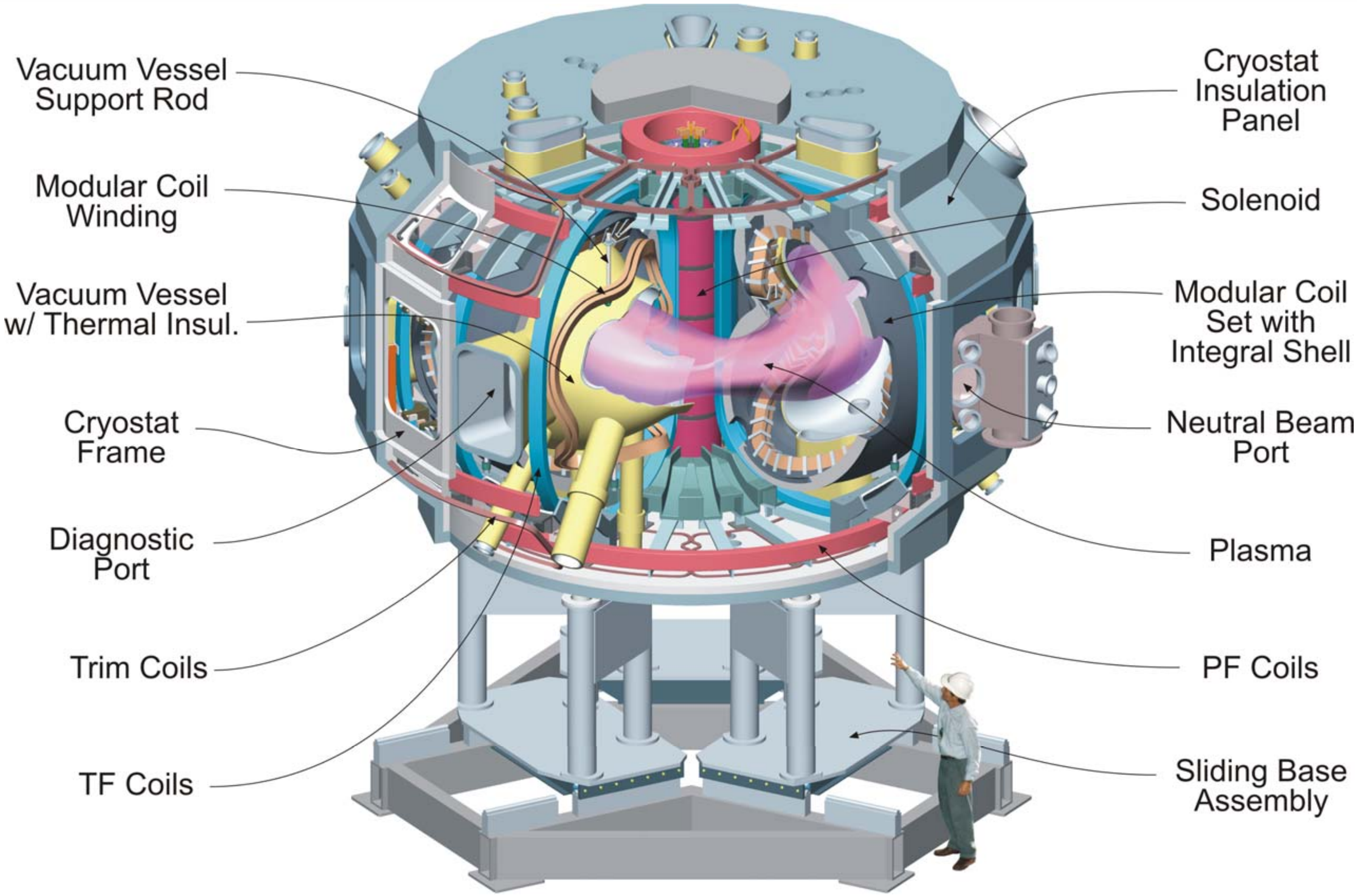
B. Nelson for the NCSX Team

NCSX Project Review
August 15-17, 2007
PPPL

Presentation Outline

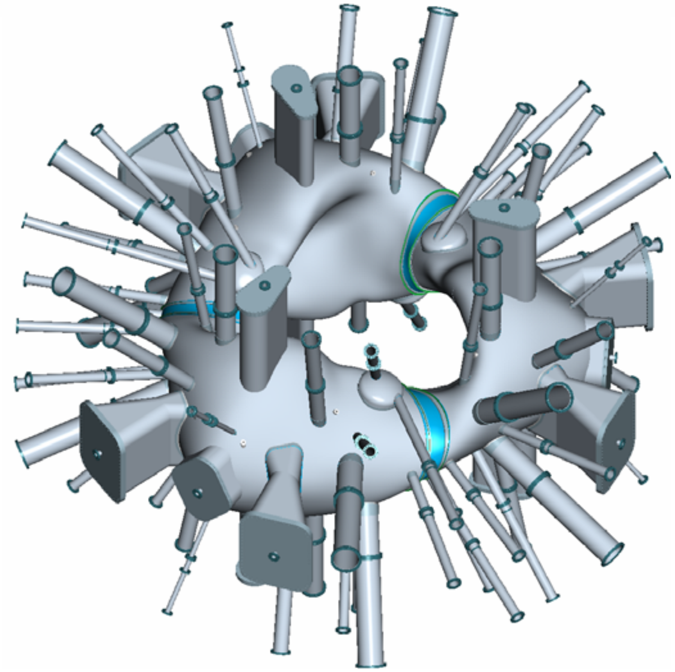
- Overview of the Stellarator Core Design
- Status and plans for the major subsystems
  - Recent accomplishments
  - R&D results, fabrication experience and design evolution
  - Design plans – timing, cost estimates for ORNL design work
- Summary

Cutaway View of Stellarator Core



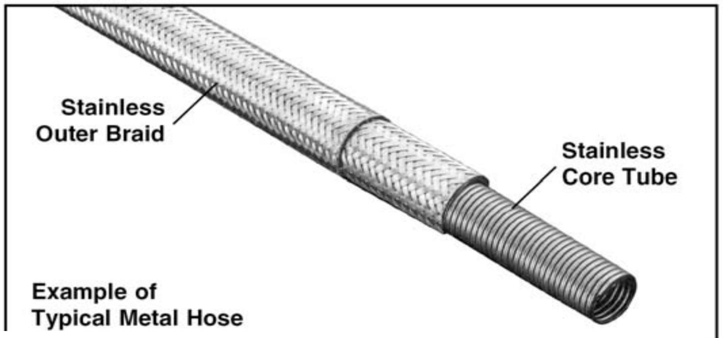
Vacuum Vessel design, fab is complete

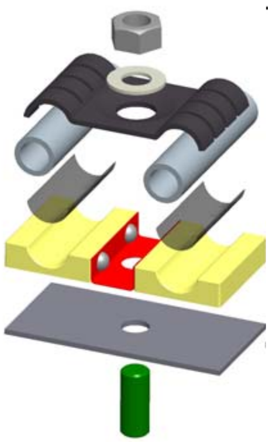
- **All three vacuum vessel sector assemblies (VVSAs) delivered**
  – All passed leak check, VVSA-1 also passed thermal cycling, measured deflection confirms analysis
- **Auxiliary system design complete**
  – Heating and cooling system headers, tubes, clamps, heaters installed on VVSA-1,2, in-process on VVSA-3
  – Thermal insulation boot design and drawings complete
  – Structural support design complete, in fabrication at PPPL
  – I&C design complete

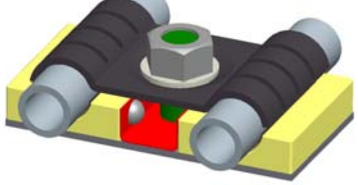


Cooling design modified to improve performance

- Design uses standard, corrugated stainless tubing with braided reinforcement clamped to vessel
- Saddle clamp modified for better contact to vessel

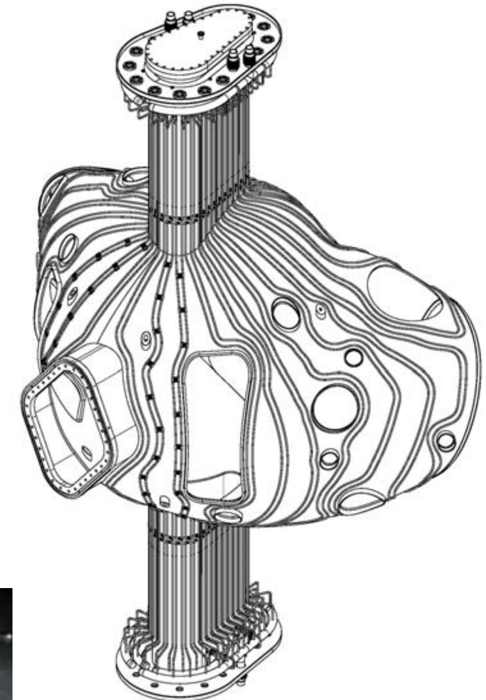






Typical saddle clamp

Modified clamp



.06” square washer

.125 grafoil, softer grade, with setting tool

Only Title III remains for vessel design team

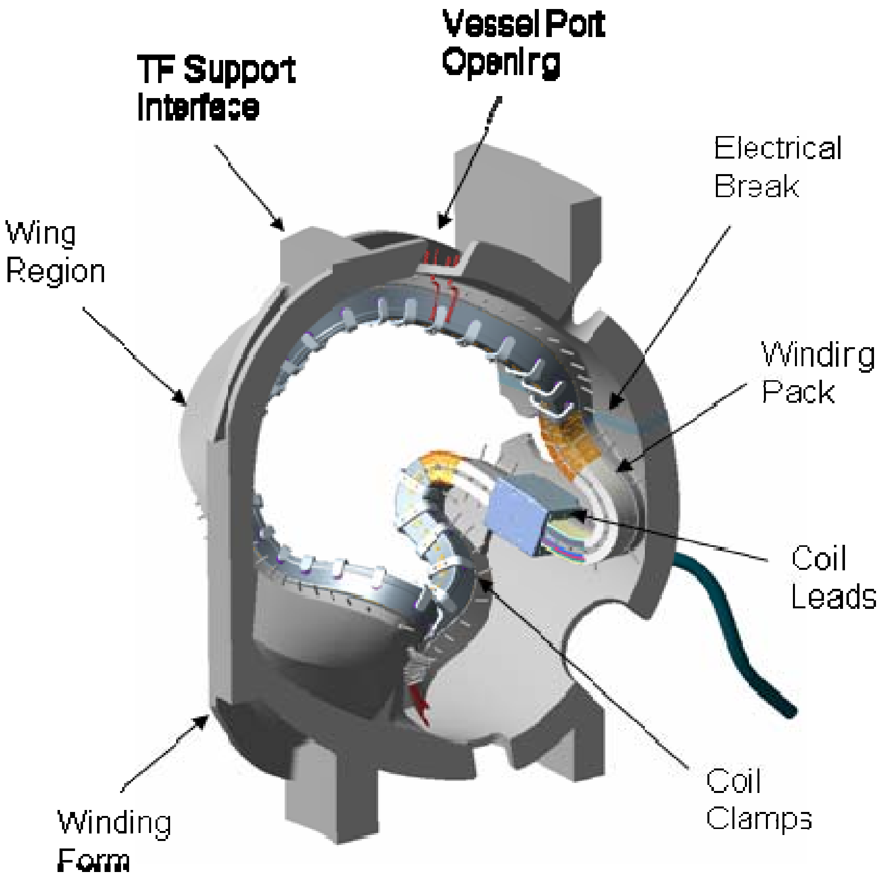
- **Design modifications may be needed as fab and assembly operations proceed, and title III hours must be budgeted**

- **Remaining VV operations/tasks include:**
  - Completion of ancillary installation (well underway, risk retired)
  - Installation of temporary and permanent vessel supports
  - Welding of port extensions (demonstrated by VVSA vendor)
  - Measurement, adjustment, and welding of vessel spool pieces during final assembly

- **These hours are included as LOE under WBS 18, Field Period Assembly and WBS 74, Machine Assembly Planning and Oversight, based on experience with Title III effort to date**

Modular Coil Design has progressed

- **Design progress since December**
  - Completed all component part drawings
  - Completed Type A, B, and C assembly drawings and specification (and successful FDR)
  - Completed and documented almost all the required analysis
  - Completed design and drawings for outboard coil-to-coil bolted connections (and successful FDR)
  - Have path forward on inboard coil-to-coil connections



Modular Coils must be joined together

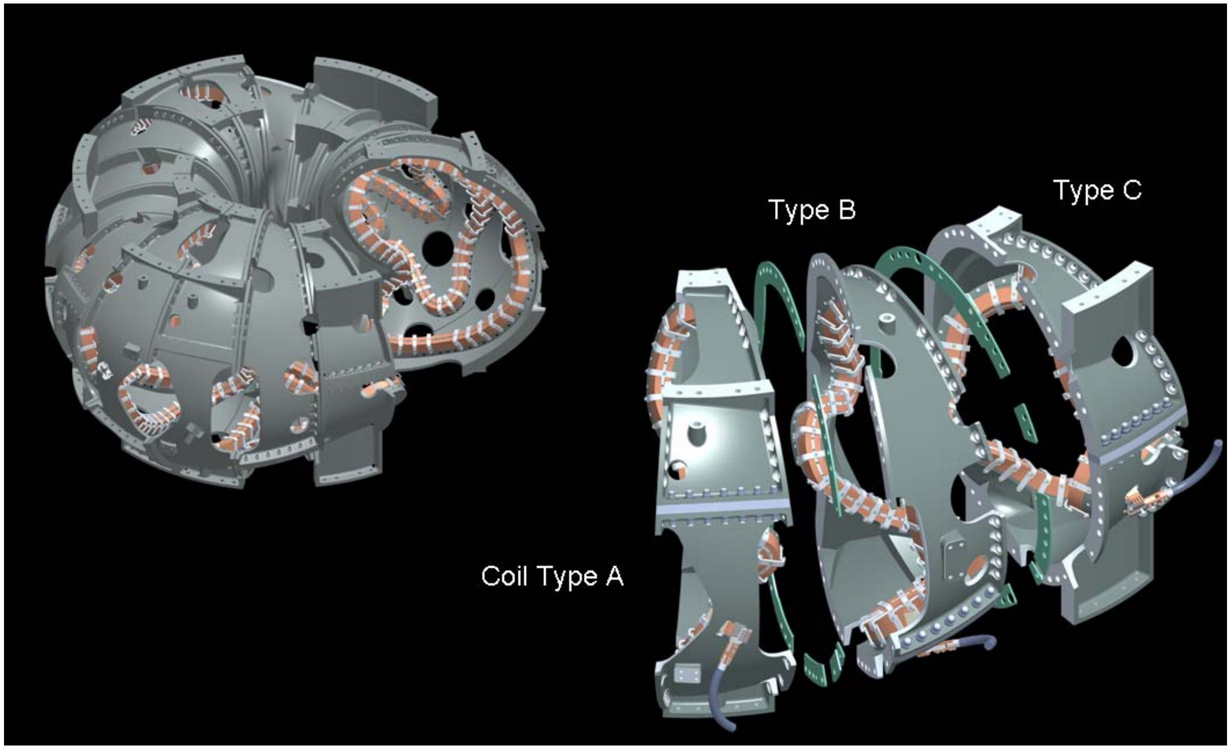
• **Must react compression inboard, tension outboard, shear everywhere**

• **Original concept:**

  – **Coils bolted together to form stiff shell structure, match reamed bushings**

  – **Shims between adjacent coils provide adjustment for proper alignment**

18 coil shell



3-coil exploded view showing original shim concept

Analysis showed issue with coil-to-coil connections

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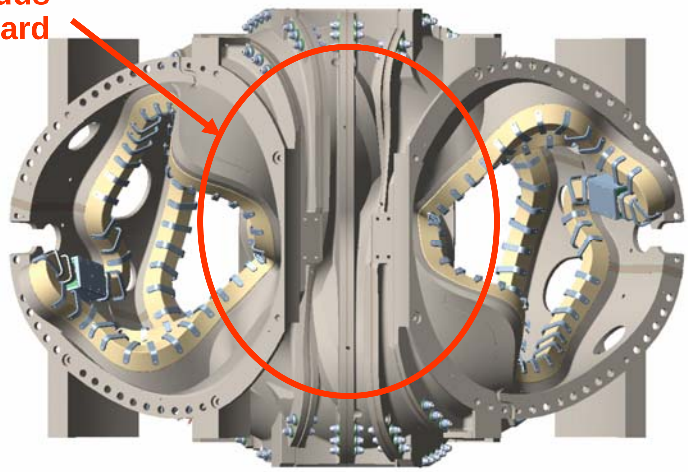
National Compact Stellarator Experiment

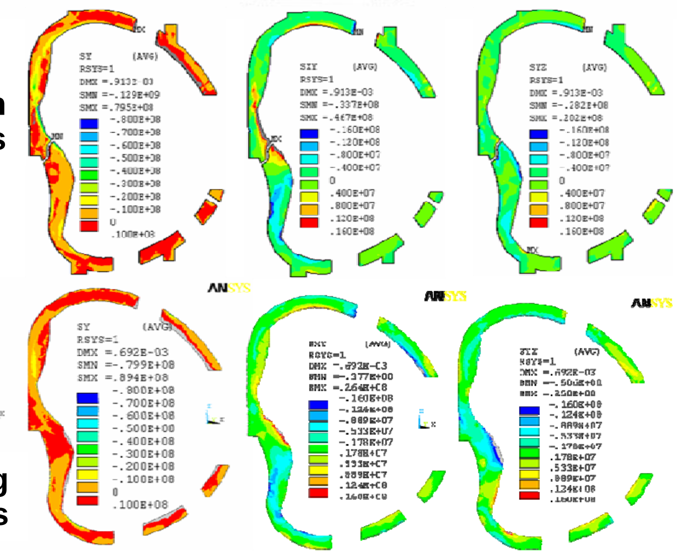
- **No inboard fasteners**
- **Shear load between coils too high for friction connection in inboard region**
  - Shear taken primarily by friction, with some shear in studs
  - No studs in inboard region due to lack of access after assembly
  - Compression load due to magnetic forces not high enough for reasonable friction coefficient
  - Joint may degrade if allowed to slip uncontrollably in service, and studs are overloaded
- **Search was on for a design "fix"**

No studs inboard



Fan analysis

Freudenberg analysis



Joint AB normal and shear force distribution

No option met all design requirements

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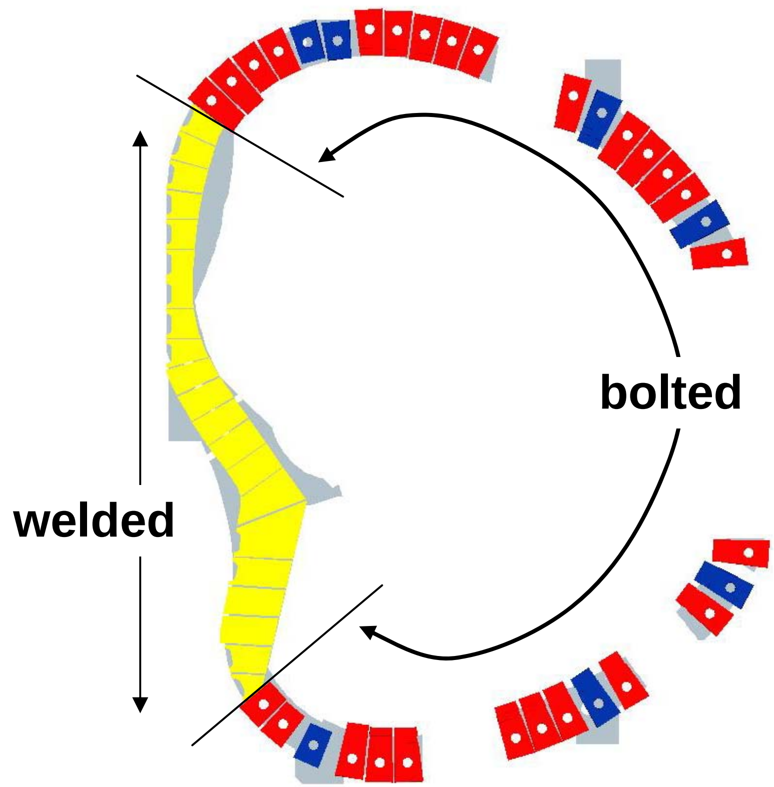
- **Project searched for good solution for more than one year**
- **Dozens of ideas were evaluated against the set of requirements**
  - Carries all loads (~15 ksi compression, ~ 4000 lbs per running inch shear)
  - Shear stiffness of connection is adequate to avoid overloading of studs
  - Does not connect winding forms electrically
  - Does not exceed permeability limits
  - Retains function over life of machine
  - Does not distort winding forms
  - Can be installed reliably
  - Finite cost and schedule
- **None of the options could meet all the requirements simultaneously**
- **Revisited requirement for electrical insulation in inboard region**

Solution is now at hand

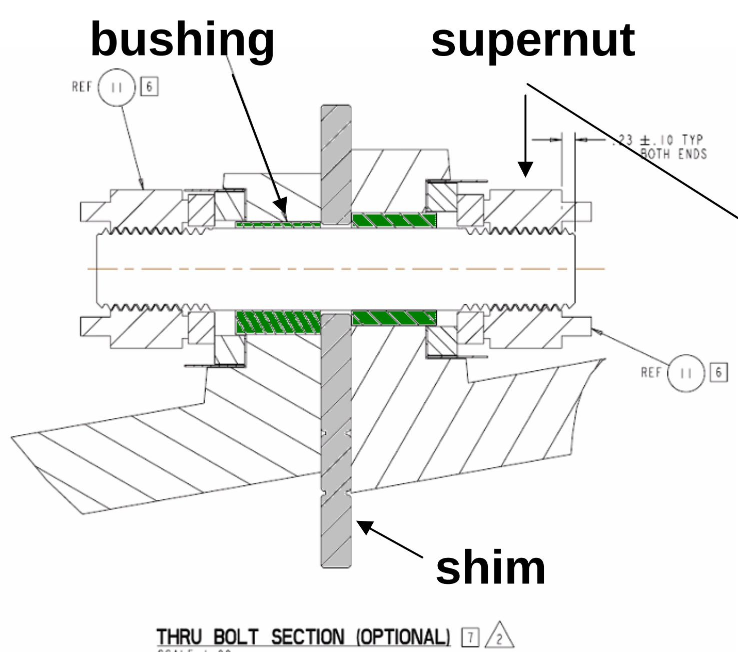
- Requirement for electrical isolation at joints relaxed in inboard region at A-A, A-B, and B-C coil-to-coil joints
- Time constant of shell increases from 18 to 27 ms – this is OK
- Welding is best solution for inboard connection
  - No extra machining of coil forms
  - No slipping, won't loosen
  - Reduces potential shear stress in studs

  Heitzenroeder to discuss
- Outboard region is still bolted

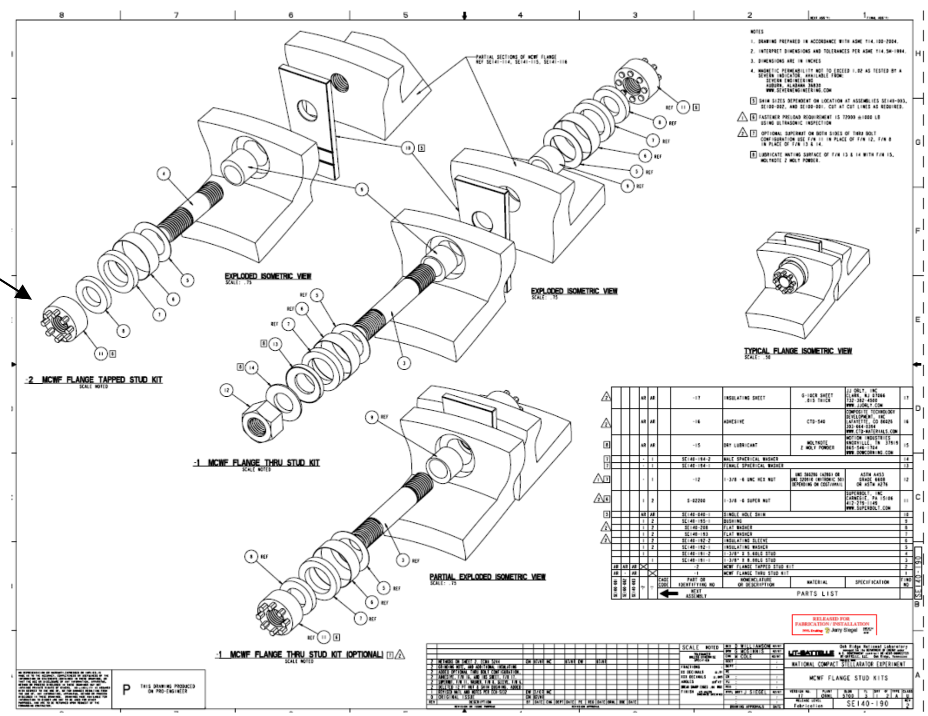


Outboard region design complete

- Combination of thru-studs and studs in tapped holes
- G10 CR bushing, washer, and coated shim provide electrical insulation
- “Supernut” provides 75 kip pre-load with <40 ft-lb torque and accommodates out-of-parallel condition

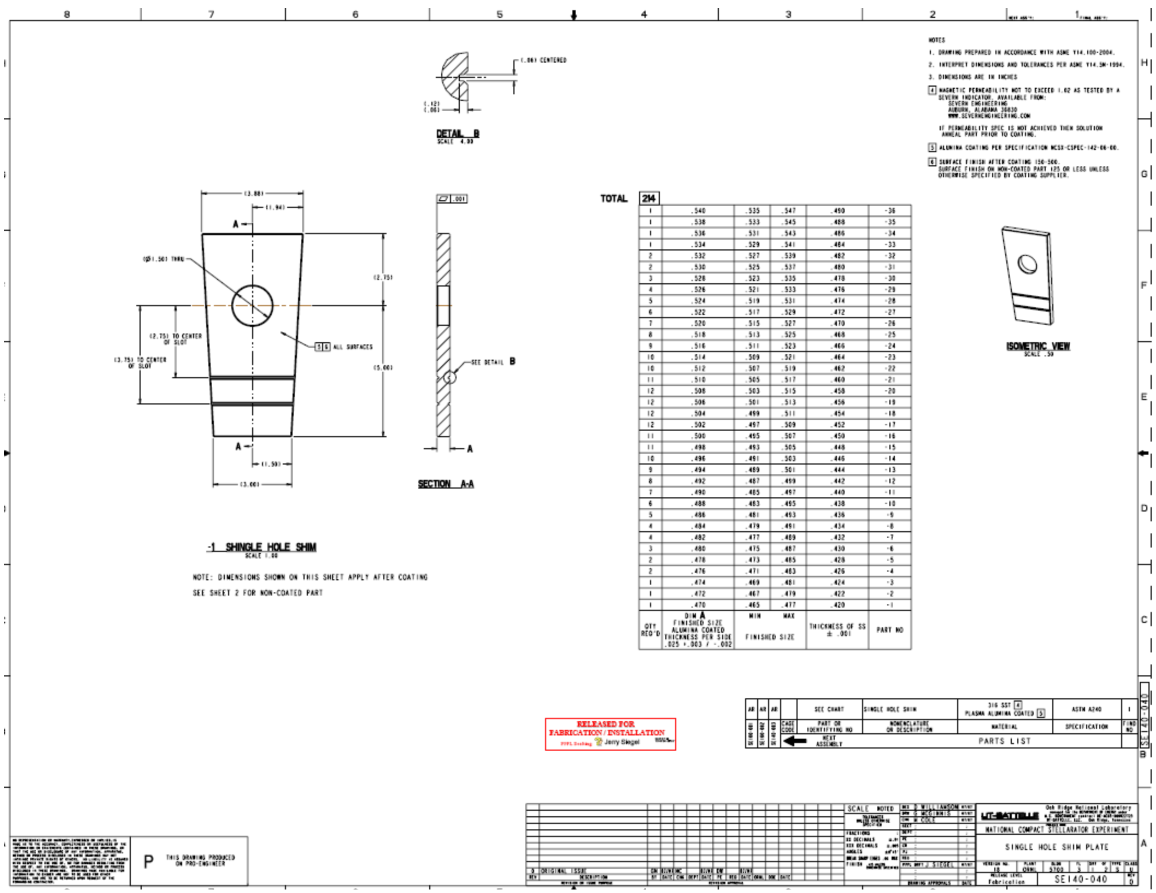


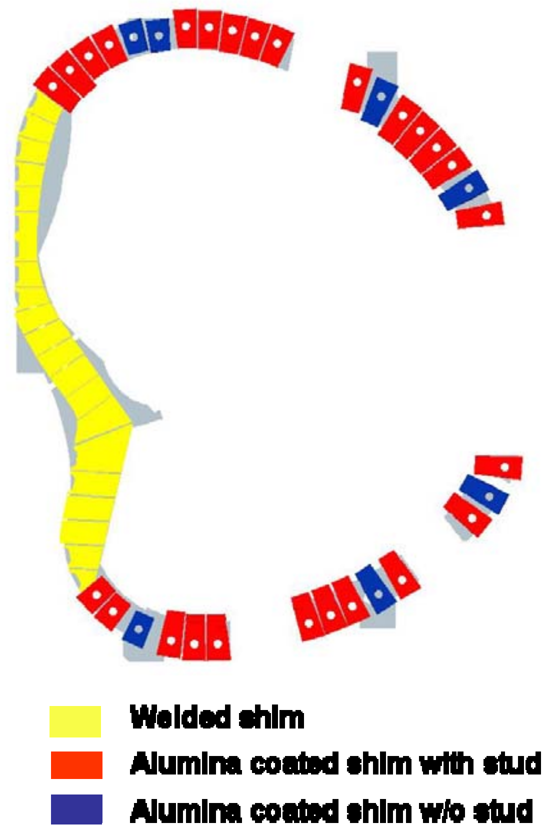
THRU BOLT SECTION (OPTIONAL) 7 2
SCALE 1.00



Shims are alumina coated

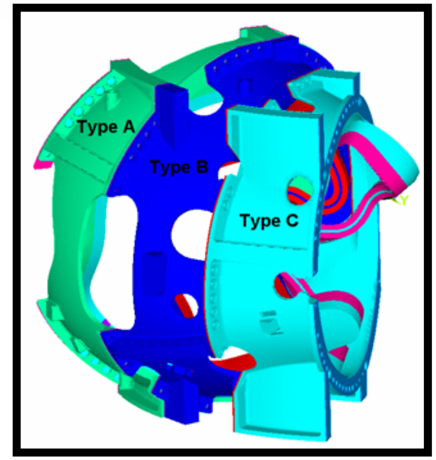
- Provides high friction coefficient (~0.6) and electrical insulation
- Shims are “universal” in shape, procured to a range of thicknesses

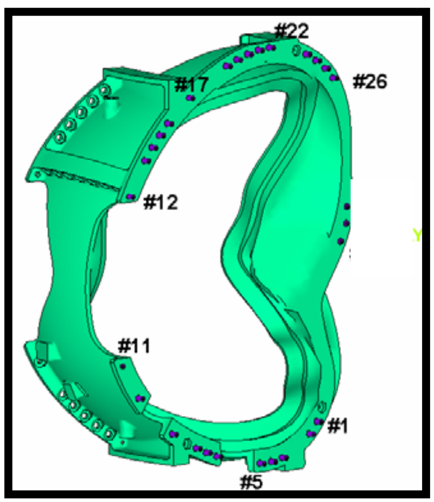


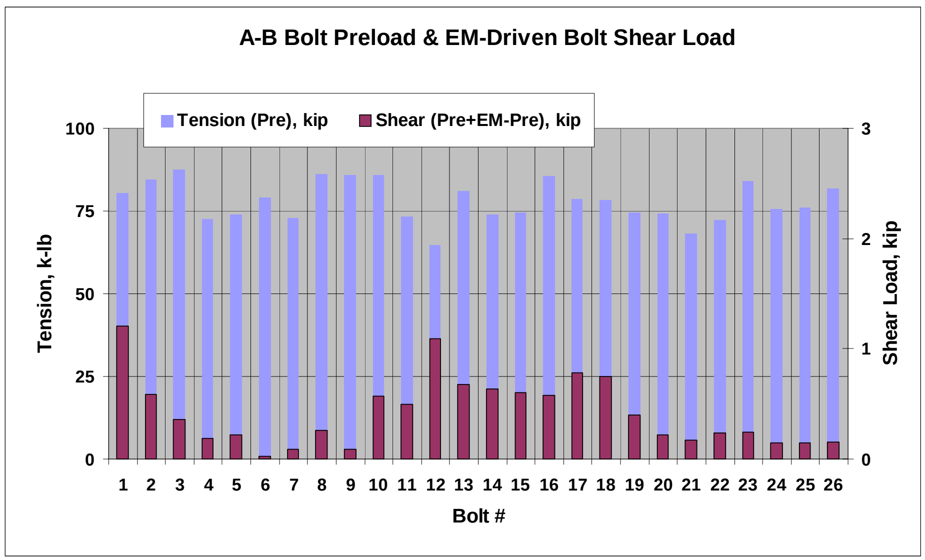


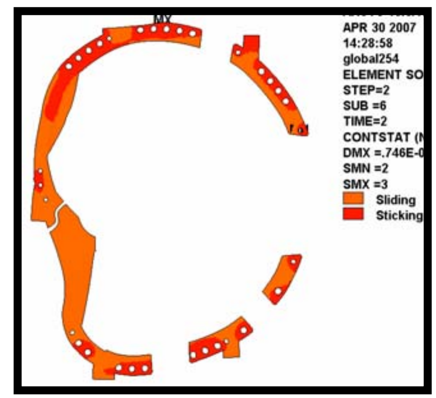
Analysis indicates workable solution

- Sliding contact at coil-to-coil joints, bolt preload, friction coefficient of 0.4 in bolted regions
- Preload, shear stress calculated at each stud location
- Sliding monitored at flange face
- No sliding in bolted regions, shear load low (< 3 kips vs 9 allowable)



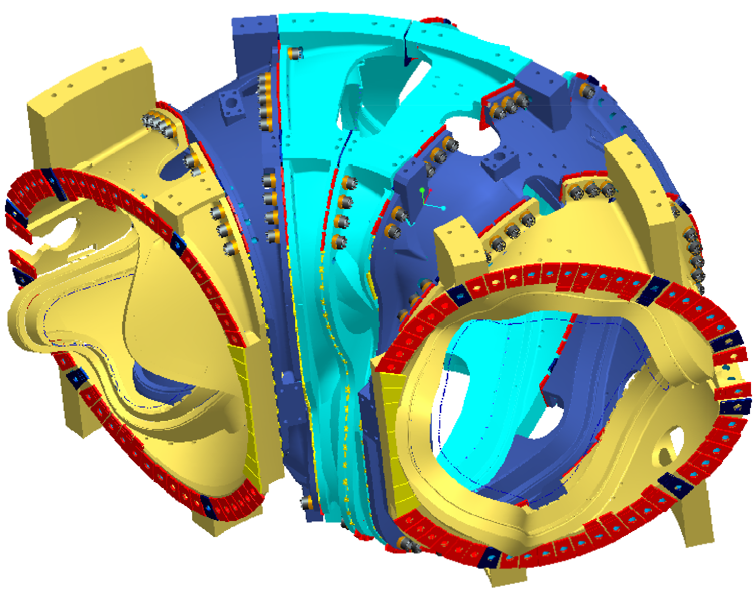






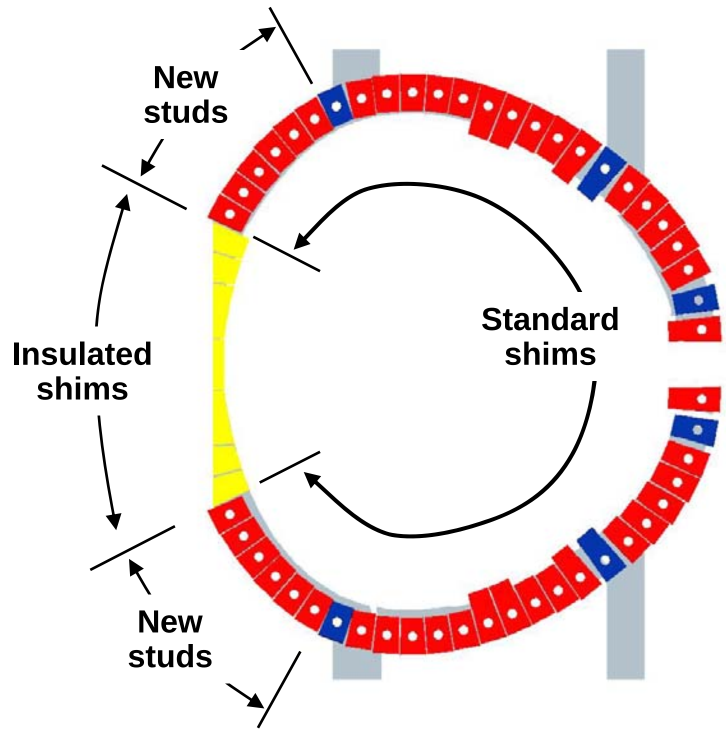
C-C connection is special case

- C-C must retain electrical isolation requirement
- 12 additional studs will be added to each C-C joint, 6 above and 6 below the midplane



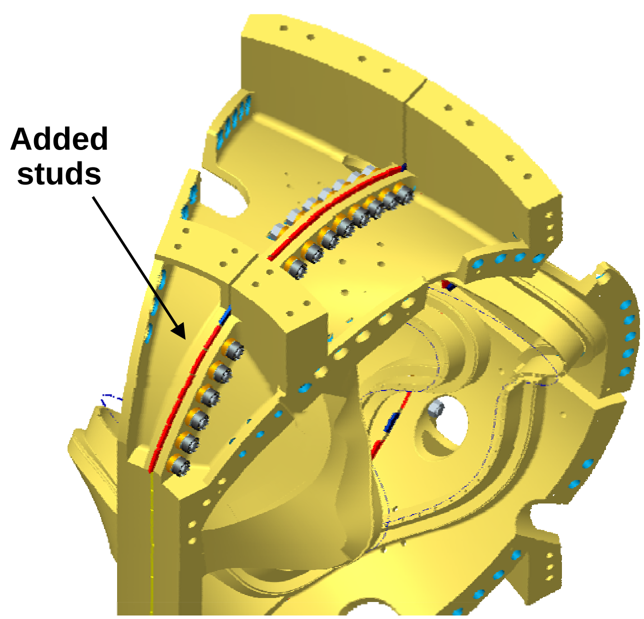
6 coil (field period) assembly

C coils on the ends

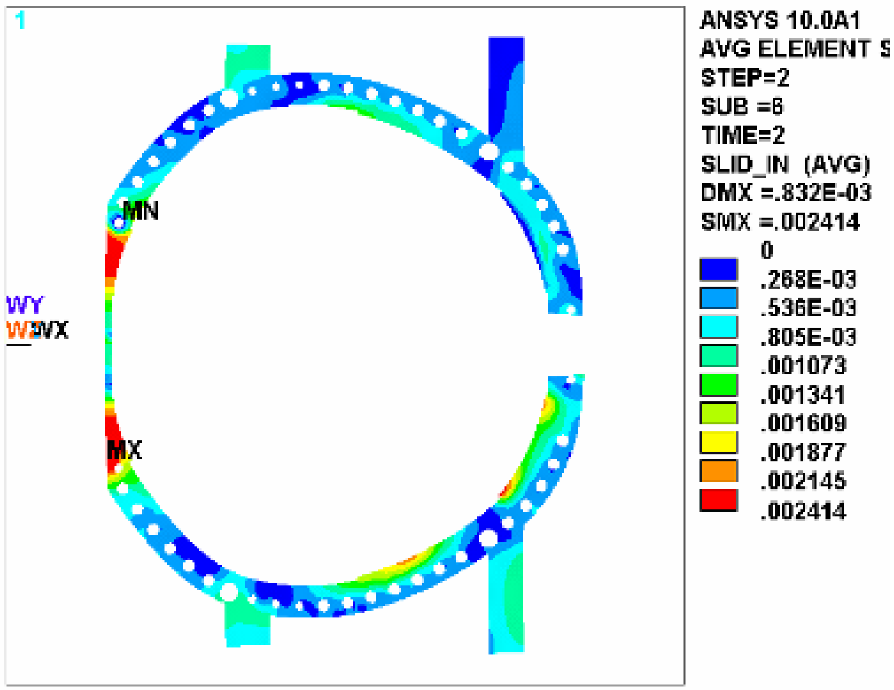


Added studs solve C-C connection problem

- Slippage negligible, even with low friction coefficient in inboard region
- Access, special tooling being evaluated with mockup (Heitzenroeder)
- Stud tension monitored during operation



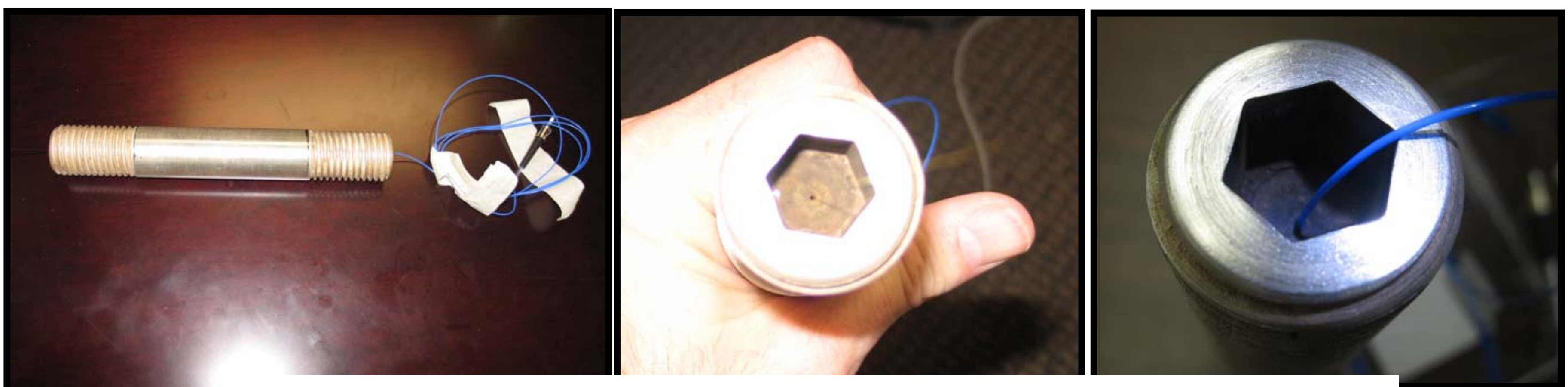
C-C joint



Contact slippage plot

Mod coil instrumentation has been specified

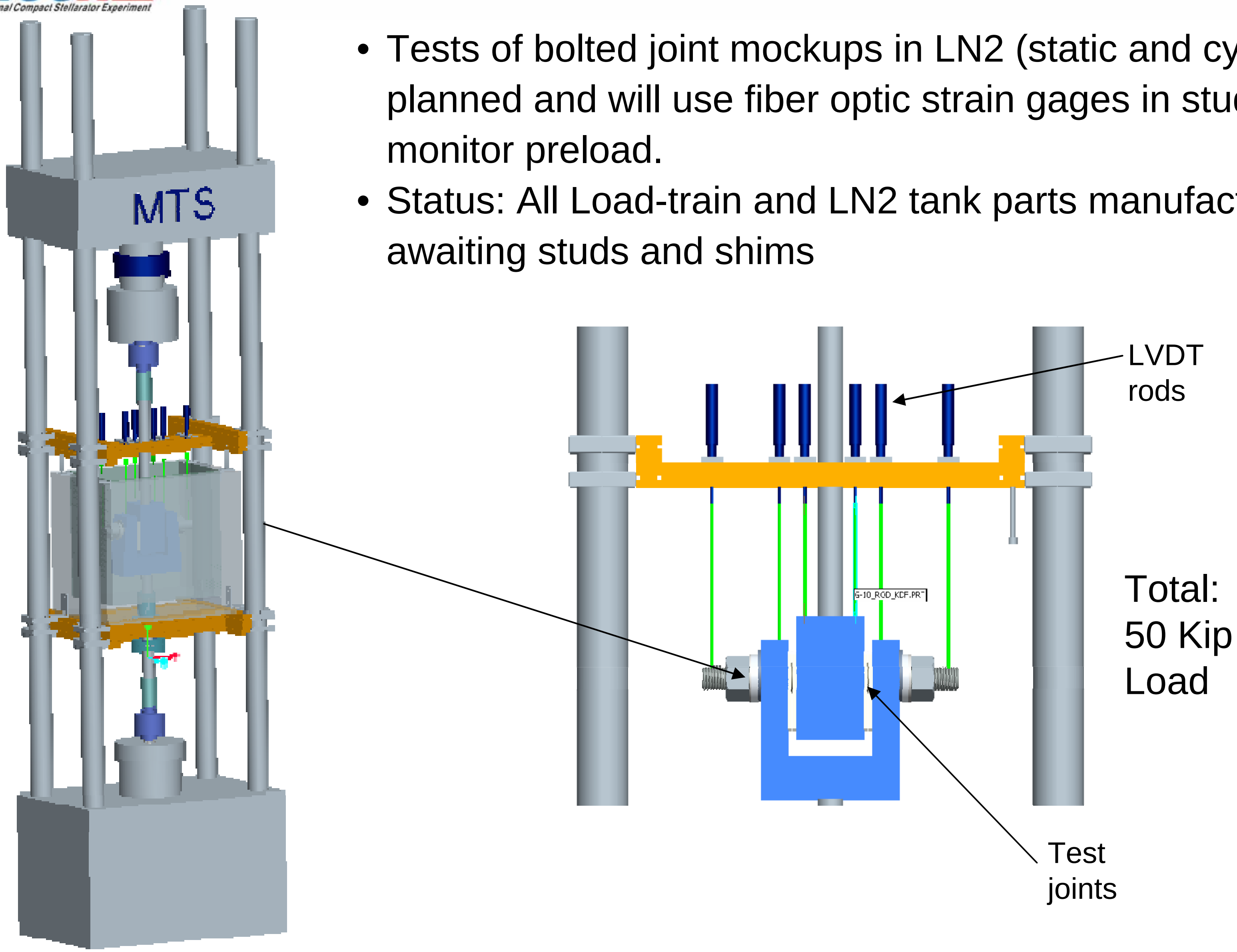
- T/C schedule included on each coil assembly drawing
- Fiber-optic strain gages used to check analysis, monitor changes in performance
  - Gages unaffected by magnetic field, need no additional electrical isolation
  - Significant testing indicates some scatter on absolute measurements but very good repeatability over many cycles, at LN2 temperature
  - Gages can be installed in studs (.02 hole EDM-ed) and calibrated to provide very accurate indication of stud preload during operation



Trial installation of fiber optic gage in 1.375 dia stud

Shear Tests planned to confirm joint behavior

- Tests of bolted joint mockups in LN2 (static and cyclic) are planned and will use fiber optic strain gages in studs to monitor preload.
- Status: All Load-train and LN2 tank parts manufactured, awaiting studs and shims



Remaining tasks in MC design

- Complete welded connection shim design based on R&D results (Heitzenroeder) - **FDR: Sep 07**
- Complete C-C connection design using mock-up to study access for bolting and developing long reach tools and procedures – **FDR: Jan 08**
- Test performance of connection assembly – **Tests complete: Oct 07**
- Document analysis and reconcile with final design details and testing results - **Closeout: FDR Jan 08**
- **1338 hours in MC assembly design, 6632 hours in coil interface hardware design**

Design task estimate example

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- Based on estimate of drawings, specs, analysis, reviews and average number of hours for each per labor category per task

Engineering and Technician Hours

Color Key
- ORNL (yellow)
- PPPL (light blue)

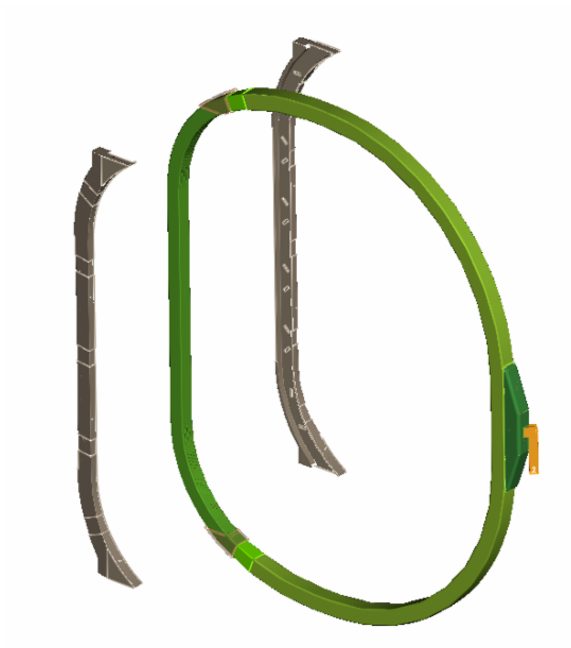
		Total Engr hours	Total Tech hours		Pro-E models (avg)	Pro-E models (complex)	assy dwgs	Detail drawings	installation dwg	cooling schematic	electrical schematic	I&C schematic	stress analysis	thermal analysis	special analysis (electromagnetics)	assy/install specs and procedures	procurement/fab and associated specifications	R&D reports	peer, preliminary and final design reviews	Planning	
				multiplier	40	80	100	60	40	0	0	20	240	40	160	40	40	80	40	16	1
				unit	hrs/model	hrs/model	hrs/dwg	hrs/dwg	hrs/dwg	hrs/dwg	hrs/dwg	hrs/dwg	hrs/calc	hrs/calc	hrs/calc	hrs/proc	hrs/spec	hrs/report	hrs/rev	hrs/wk	hr
Outboard Interface Design																					
IH4-020	Prepare outboard shim dwgs and release	60	0					1													
INTRF-045	FDR outboard shims	40	0																1		
	resolve and issue shim drawings	60	0					1													
Bolted Joint Tests																					
	Tension Tests of Bolted Joint																				
1421-3067	Procure 2 studs f/joint test.Use existing part	8	48																		
1421-3075	Setup test fixture &perform JHA & pre-job brief	8	16																		
1421-3077	Meas joint deflect vs preload & loss of preload	24	24																		
1421-3079	Measure joint deflec & preload v. temp @80K	24	24																		
1421-3084	Measure joint deflection&preload v. cooldown cyc	24	24																		
1421-3087	Perform pullout tests for tapped holes	24	24																		
1421-3081	Meas joint deflect & preload v. time (days) at R	160	160																		
1421-3090	Document&conduct review of test results	40	0																1		
	Bolt Shear Test at 77k																				
1421-3112B	Procure/fab parts for test&initial assembly	40	0														1				
1421-3115B	Assemble & test	320	100																		
1421-3119B	Document test results	80	0															1			
Inboard Interface Design																					
IH1-001	Coil to coil analysis	520	0										2						1		
1421-3125	Determine geometry&location of high COF shims&pl	80	0			1															
1421-3127	Structural analyses to performance rqmts for bol	240	0										1								
1421-3132	PDR to review requirements, design,&development	40	0																1		

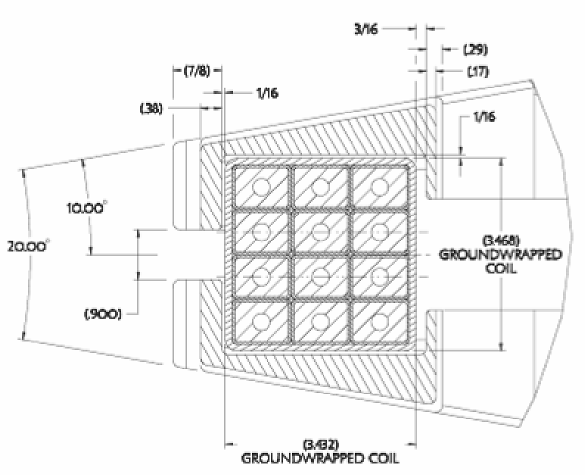
Title III remains a major effort for MC design team

- **As with VV, design modifications may be needed as fab and assembly operations proceed, and title III hours must be budgeted**
- **Remaining modular coil operations/tasks include:**
  - Completion of coil winding, potting (well underway, risk retired)
  - Installation of strain gages, thermocouples
  - 3-coil and 6-coil assemblies
  - Measurement, adjustment, and connection at CC joint during final machine assembly
- **These hours are included as LOE under WBS 18, Field Period Assembly and WBS 74, Machine Assembly Planning and Oversight, based on experience with Title III effort to date**

TF coil design complete, procurement ongoing

- Fabrication in process – first coil complete and tested
- R&D indicated excellent fatigue strength of winding pack
- Kalish to discuss details in breakout session



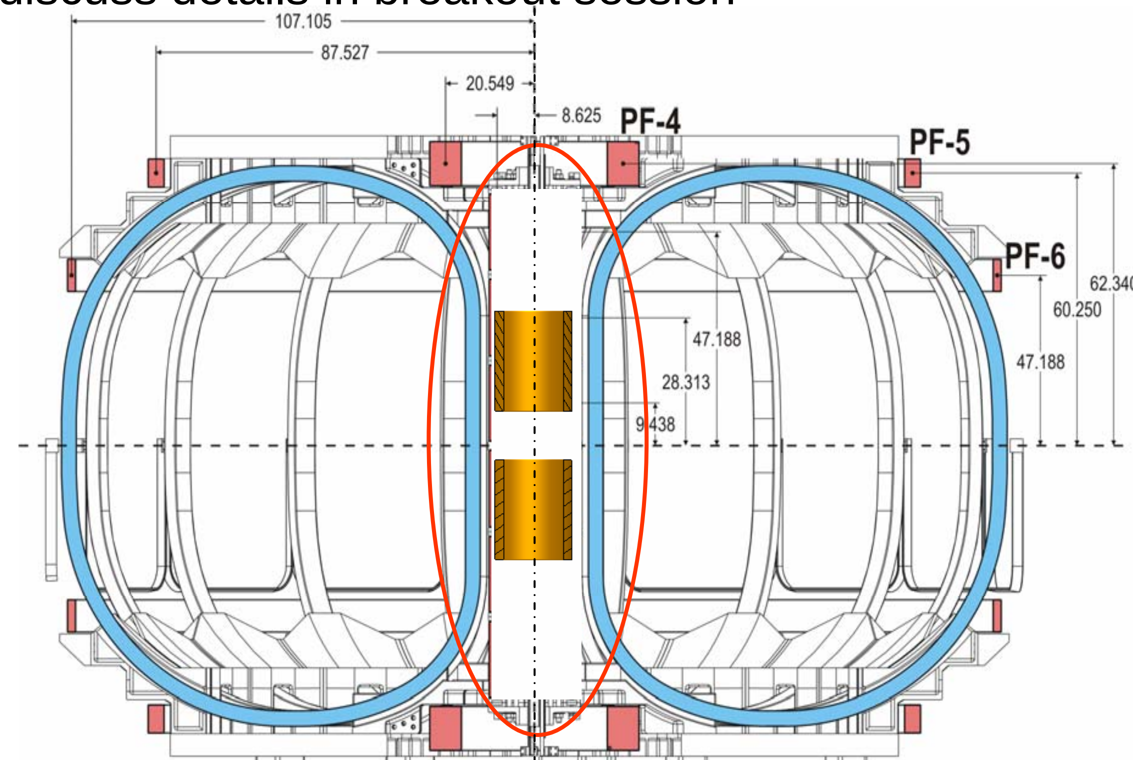


Wedge structures and winding

TF coil assembly in cryostat

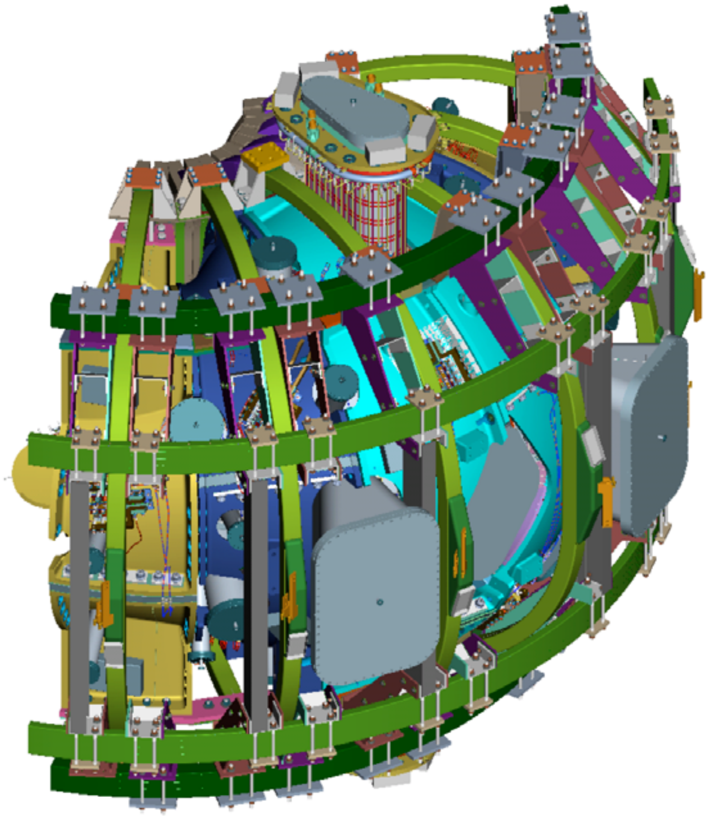
PF coil preliminary design ongoing

- Coils are conventional, copper conductor in epoxy glass matrix
- Baseline plan is to procure the new PF coils from industry
- Central solenoid support structure will be modified for NSTX PF1A coils
- Kalish to discuss details in breakout session



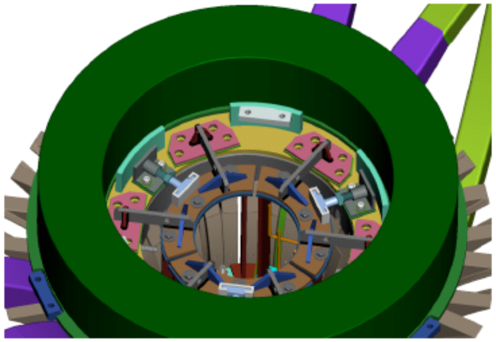
Baseline PF set

TF, PF structure design complete through PDR



Outer PF5 & PF6 Supports

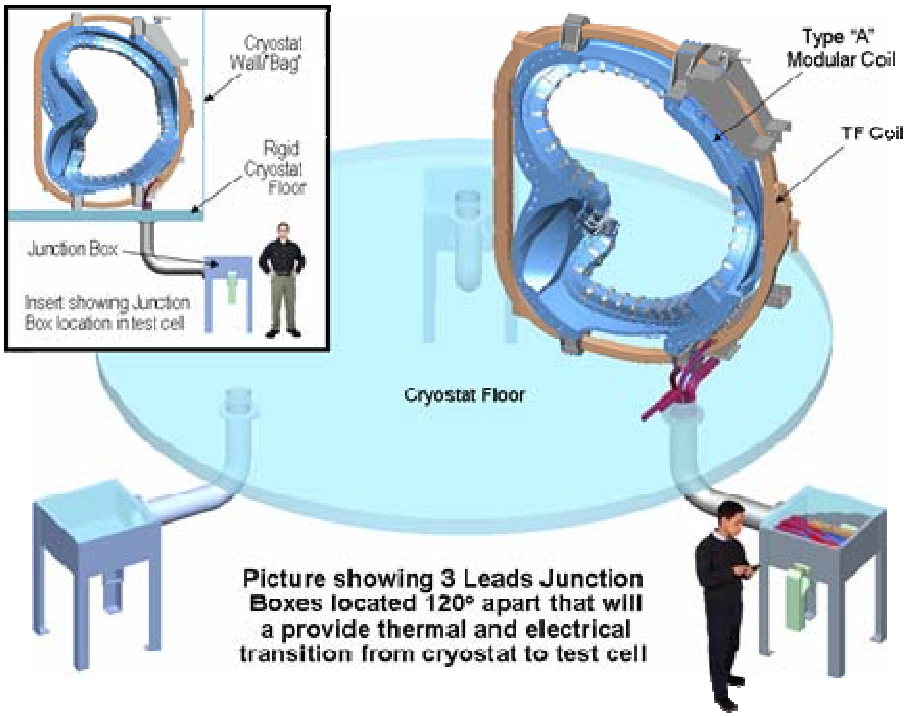
- TF support Brackets are AlAly 5083 -H32 weldments.
- Brackets are bolted directly to the MCWF shell structure or to spacers which bolt to the MCWF.
- Shims are used to provide vertical positioning of the TF coils.

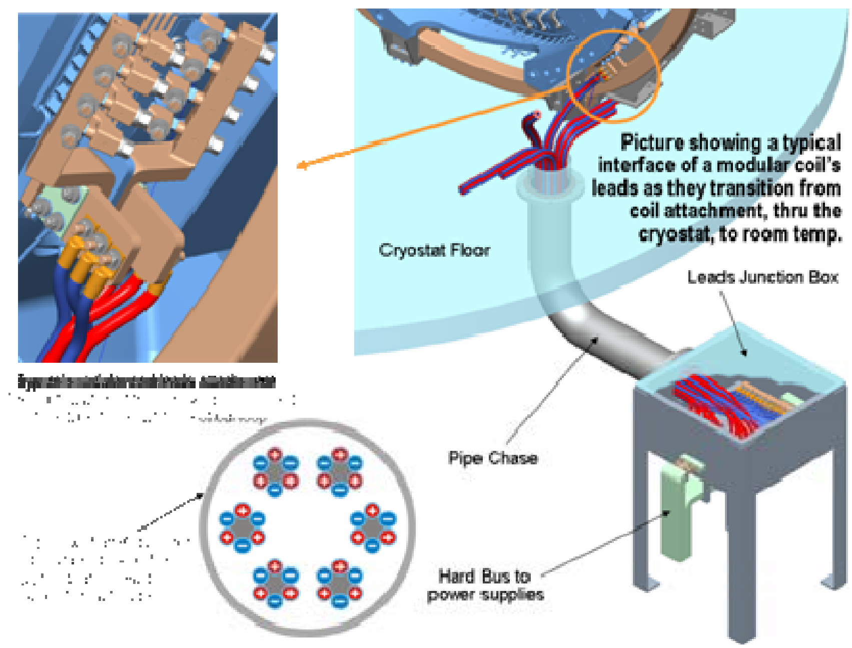


PF4 & CS support

Coil electrical services – concept in place

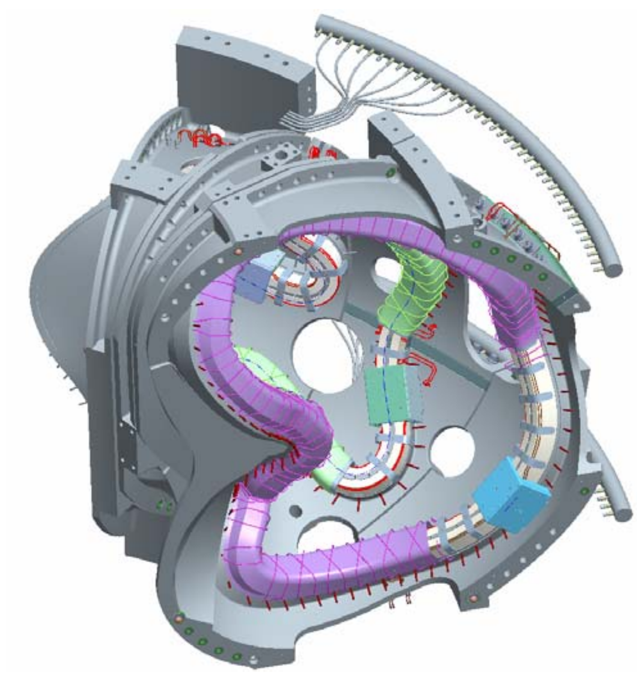
- **Electrical feeds via hexapole cable**
  - Low stray field, relatively easy to route around machine
  - Used for C1 cold test, teflon insulation provides > 7.5 kV
  - Cold to warm transition occurs in junction boxes below cryostat
- **1848 hours estimated for design (at ORNL) based on engineering experience, detailed breakdown of drawings, analysis tasks, FDR – Jul 08**

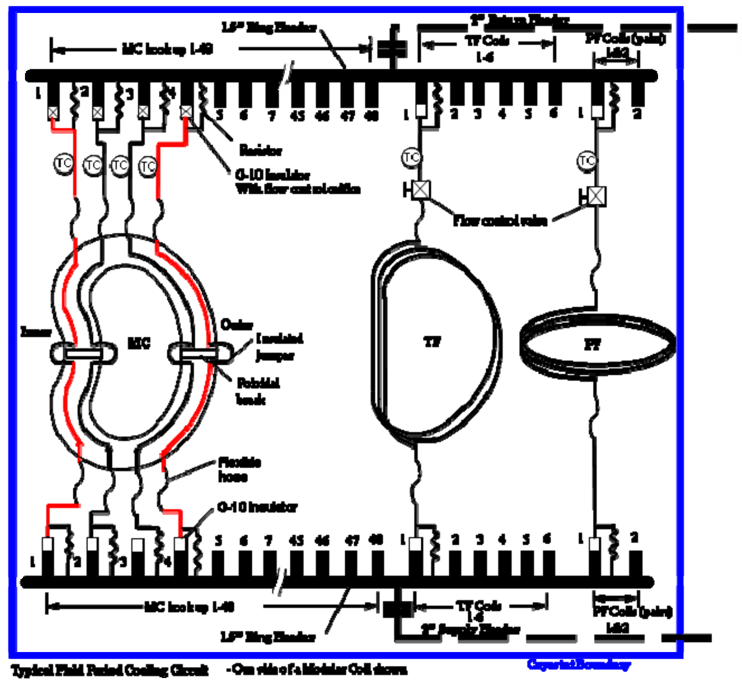




Coil LN2 feeds – concept in place

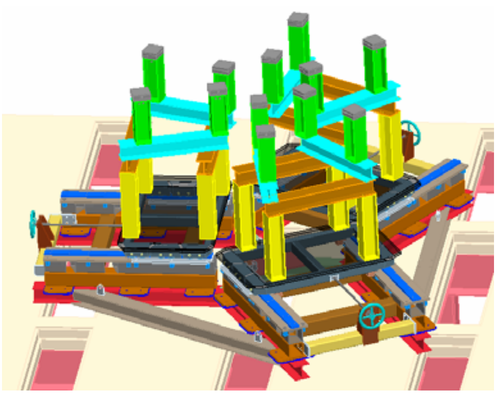
- **Flexible tubing planned to connect coils to LN2 distribution manifolds**
  - Same braided corrugated tubing as used on vacuum vessel
  - Electrical Insulation via Teflon tubing
  - Electrical break via G-10 nipple
- **1056 hours estimated for design based on engineering experience, detailed breakdown of drawings, analysis tasks**



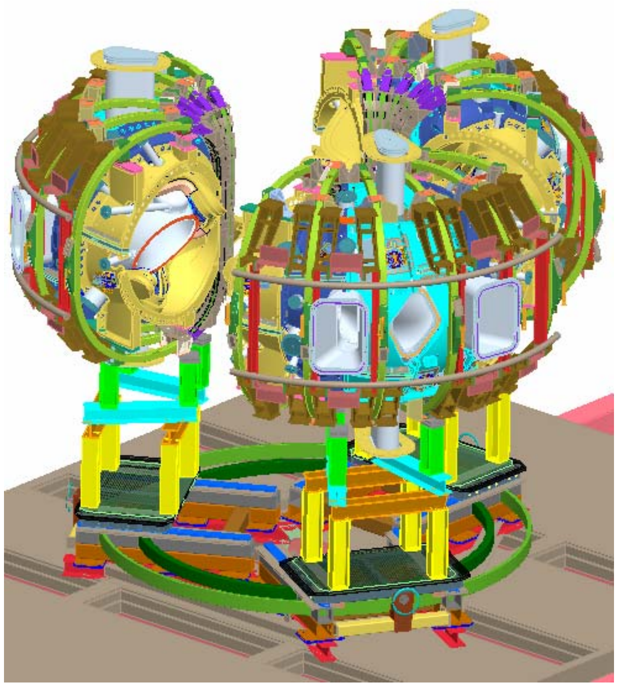


Base support in preliminary design phase

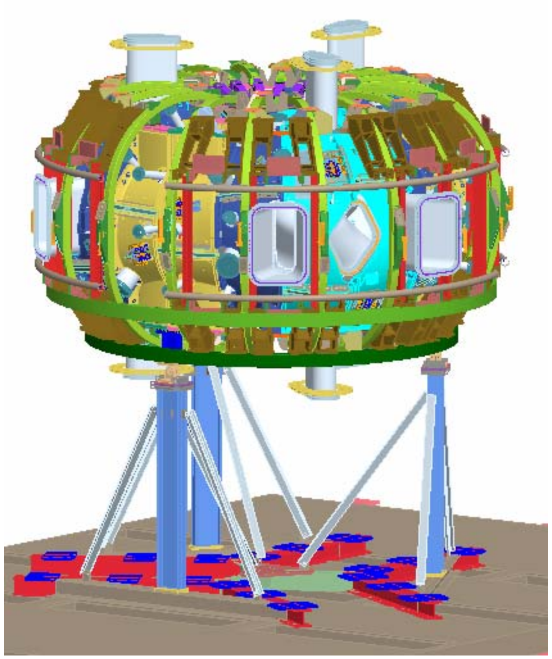
- Approach will use temporary sliding supports for assembly
- Simplified permanent supports will improve access under core



Temporary, sliding supports

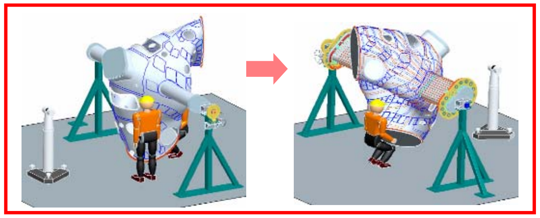


3 field periods retracted

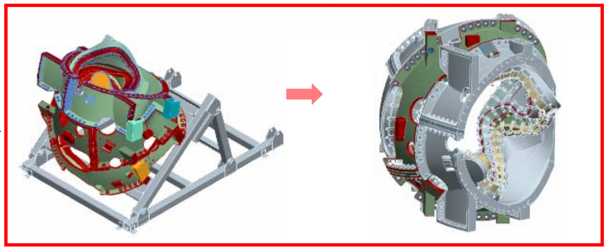


Permanent, stationary supports installed

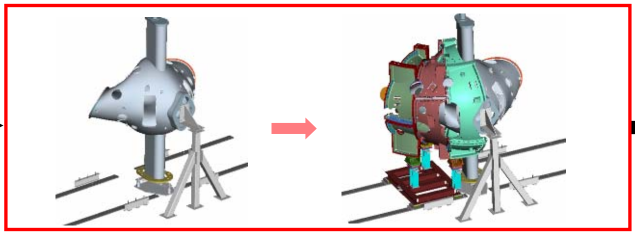
Field Period Assembly completed at 5 stations



Station 1 - VV Prep

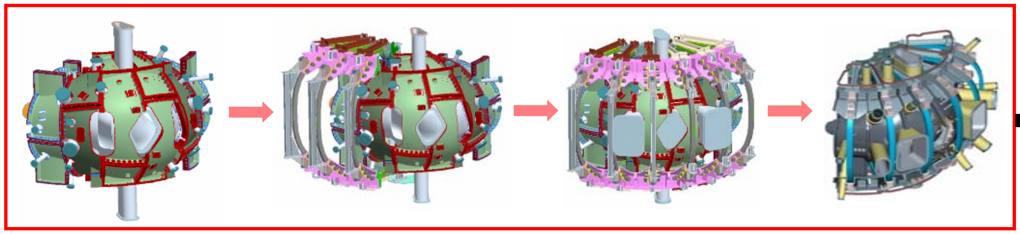


Station 2 - MC Half Period Assembly



Station 3 - MCHP installation over VV Period

Station 4 – TF alignment activities performed at Station 5

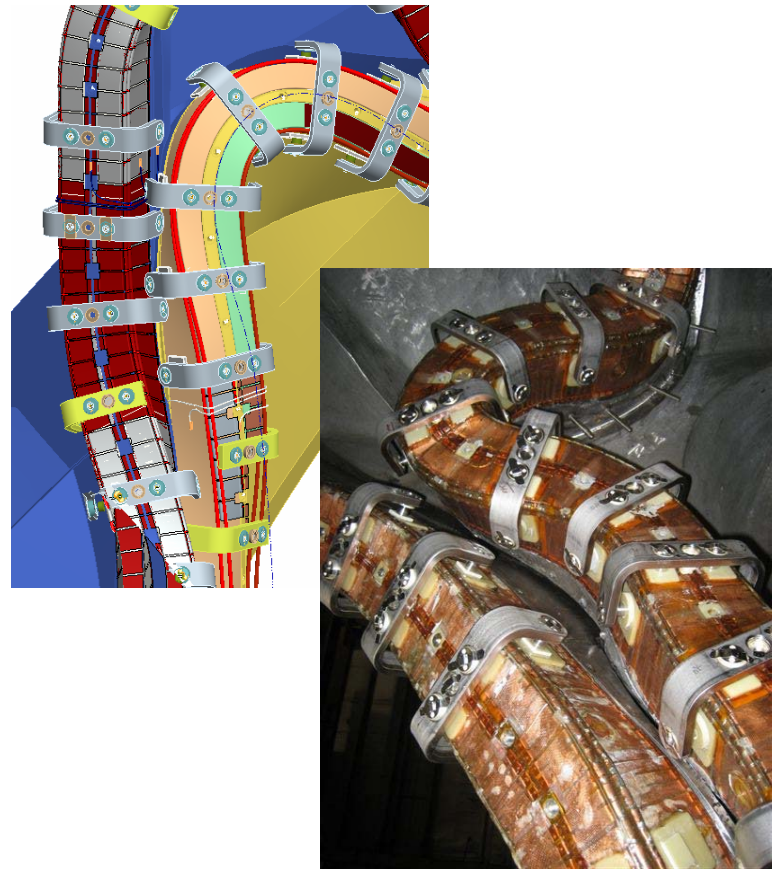


Station 5 - Final FP Assembly

Station 6 - Machine Assembly

Trial coil-to-coil assemblies made

A-B fitup test



looks like the CAD model

Remaining design effort for field period and final assembly includes drawings and specs

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- Mod coils
  - 3-coil, 6-coil, and 18-coil assembly drawings and associated specification of requirement
- Vessel
  - As-built vessel sectors after port extension welding
  - Vacuum vessel spool piece machining drawings
- Field period assembly
  - Assembly drawings of vacuum vessel, coils and structure and associated requirement specification
  - As-built fiducial drawings for field period
- Final assembly
  - Assembly drawing of complete stellarator core and associated requirement specification
  - As-built/assembled drawings/schematics of coil and vessel geometry

Remaining design effort for field period and final assembly includes drawings and specs (2)

- **4692 hours for assembly design and specs, based on number of drawings, specs, reviews**

- **Schedule:**
  - Station 2 work complete Sep 07
  - Station 3 work complete Nov 07
  - Station 5 work complete Apr 08
  - Final assembly work complete Oct 08

Title III effort for design team will continue through FPA and final assembly

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- Field period assembly
  - Design interpretation and modifications as needed
  - **2954 hours of ORNL design engineering, Oct 07 – Nov 09**

- Final assembly
  - Design interpretation modifications as needed
  - **2505 hours of ORNL design engineering, Jan 09 – Jan 11**

- Estimates based on average level of effort for designer and engineer for duration of activity, based on title III experience to date with winding forms, VVSAs, etc.

Summary

- **Design of the major stellarator core components is nearing completion**
  - Vacuum vessel design and procurement complete
  - Modular coil design and procurement nearly complete pending final assembly hardware, overall assembly drawings, final R&D and analysis documentation
  - TF coils in fabrication

- **Remaining risks have been identified and are being mitigated through analysis, confirming R&D, and prototyping**
  - Coil-to-coil assemblies are being fit checked with prototypic processes and hardware
  - Prototypic joint hardware is being fatigue tested

- **The remaining design, R&D, and Title III effort has been re-estimated based on experience and lessons learned to date**