NCSX Stellarator Core

Design Progress and Plans

B. Nelson for the NCSX Team

NCSX Project Review
May 9-10, 2006
PPPL

Presentation Outline

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- 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
  - Procurement plans
  - Remaining risks
- Summary

Cutaway View of Stellarator Core

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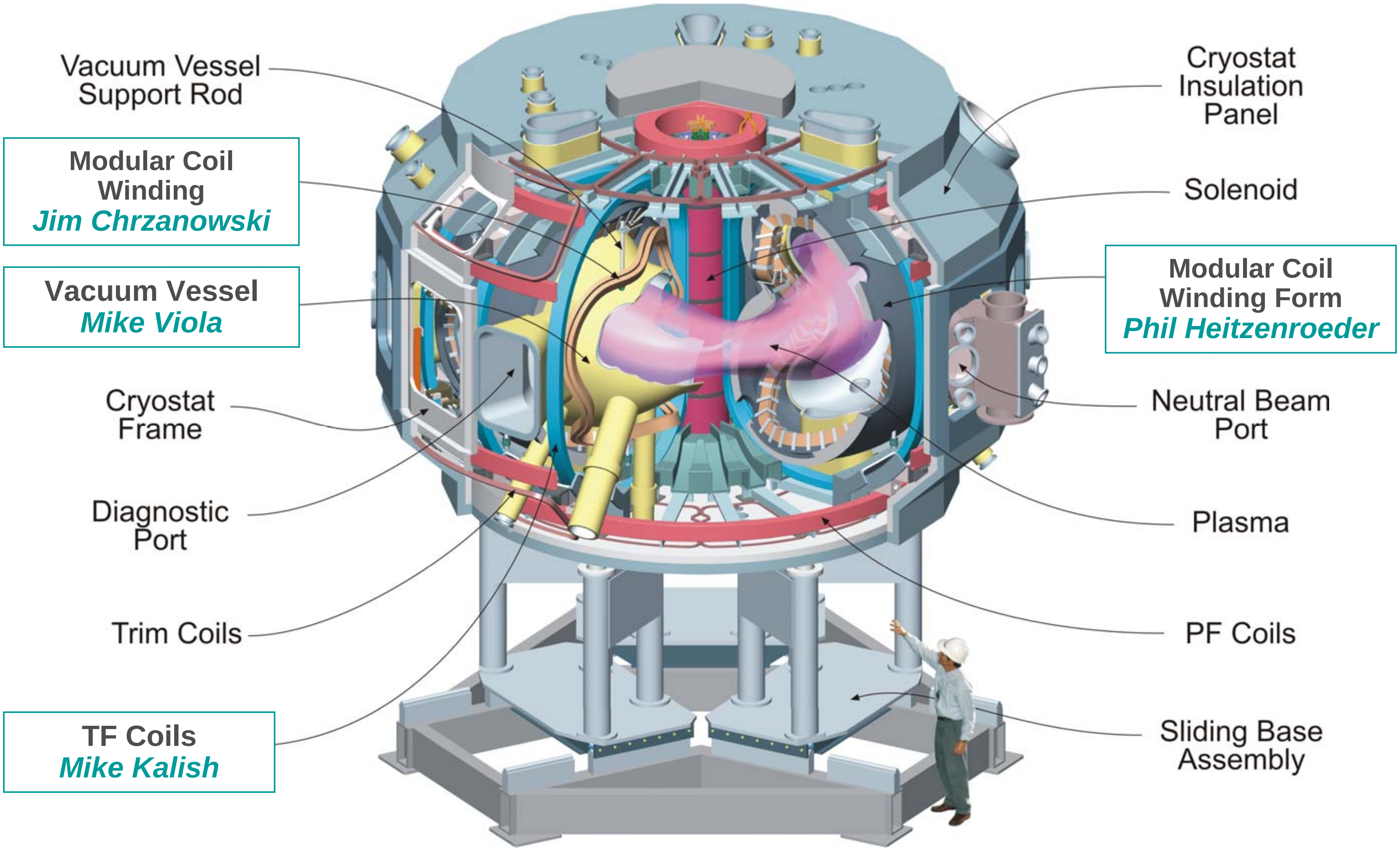

On track for completion of Vacuum Vessel

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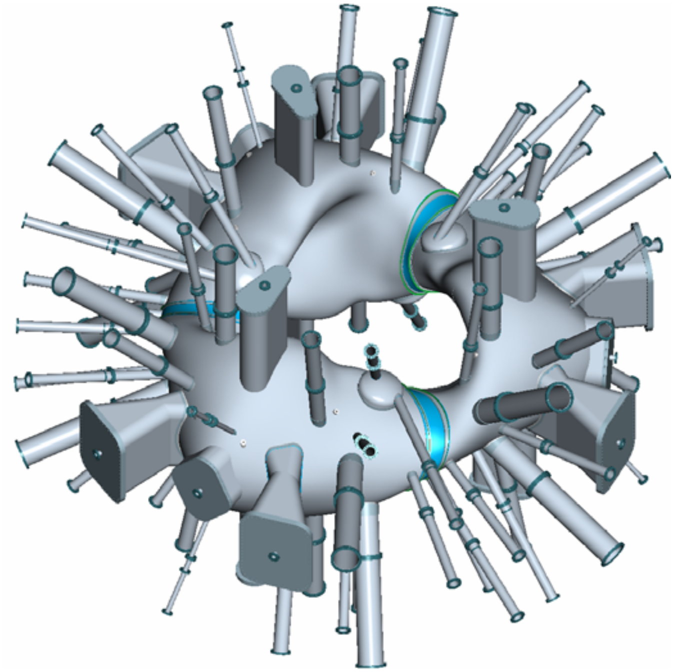
- **Recent accomplishments**
  - VVSA on track for May-Sept delivery – *Viola*
  - Passed leak check and thermal cycling, measured deflection confirms analysis
  - Heating and cooling system design complete, headers, tubes, clamps, on order
  - Thermal insulation boot design complete, drawings nearly complete
  - Structural support design complete, in fabrication at PPPL
  - I&C design complete
- **Design complete by: June 2006**
- **Procurement complete by: Sept 2006**



Vacuum Vessel ancillaries well defined

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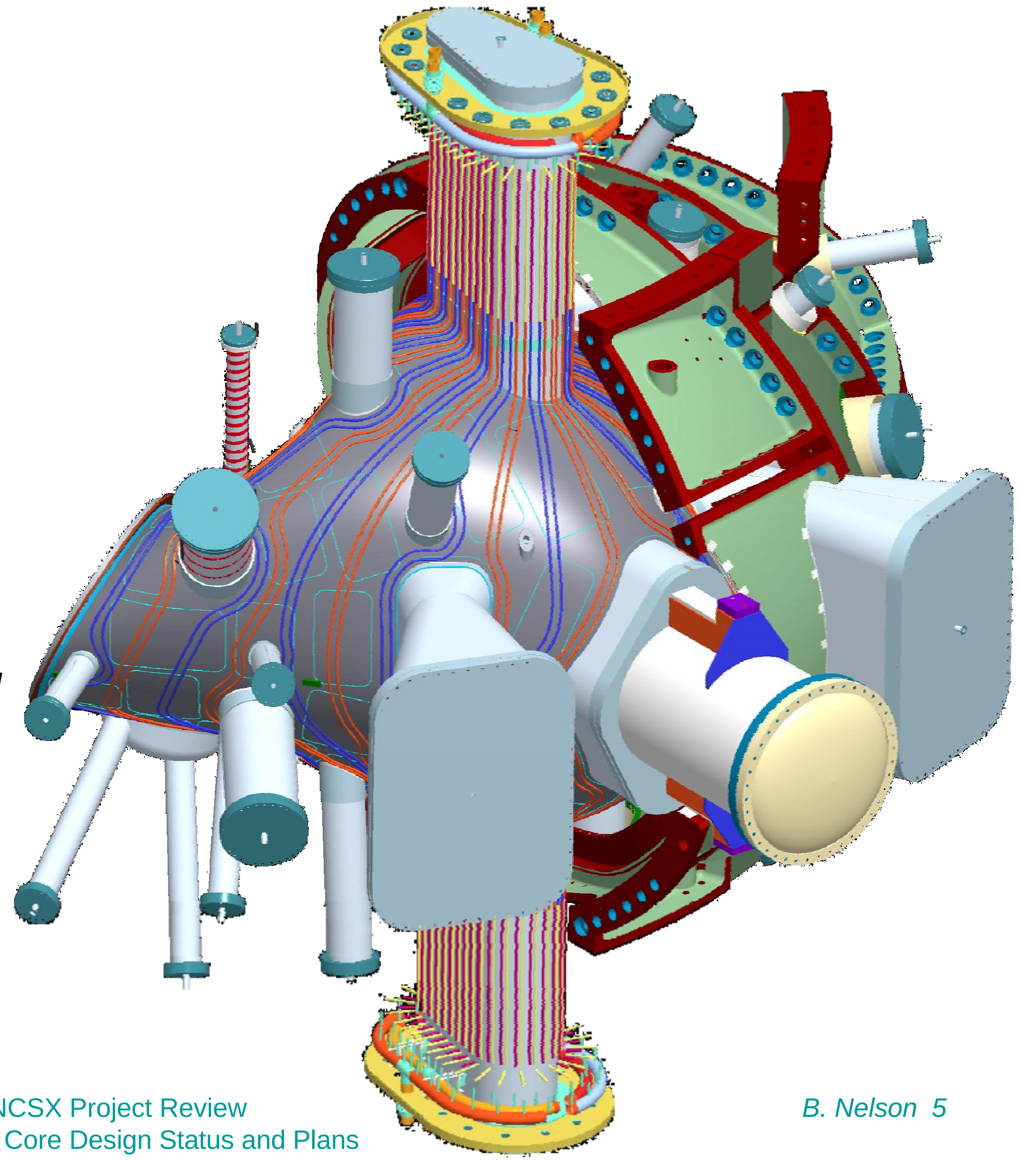
VV ancillaries include:

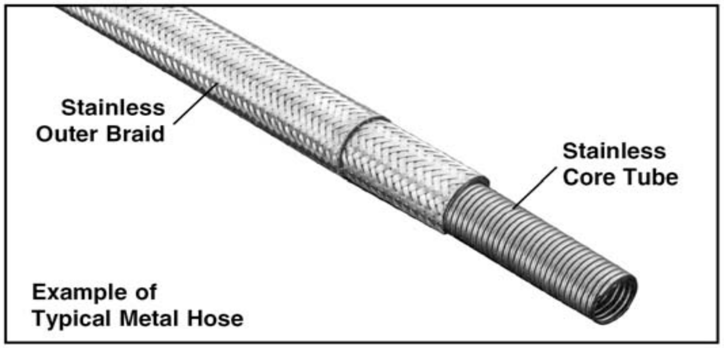
- flux loops
- coolant tubes
- thermocouples
- headers
- diagnostic feed through flanges
- lateral supports
- heater tapes

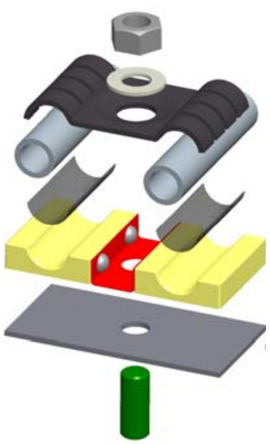
These components will be installed in station 1 of field period assy - Reiersen

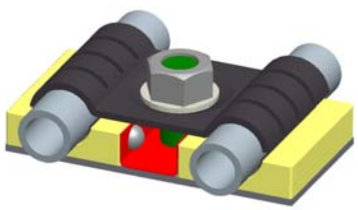


Cooling design modified to improve performance

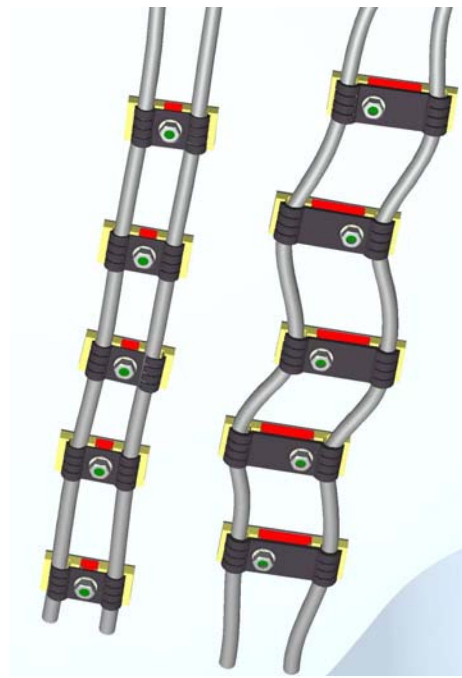
- Design uses standard, corrugated stainless tubing with braided reinforcement clamped to vessel

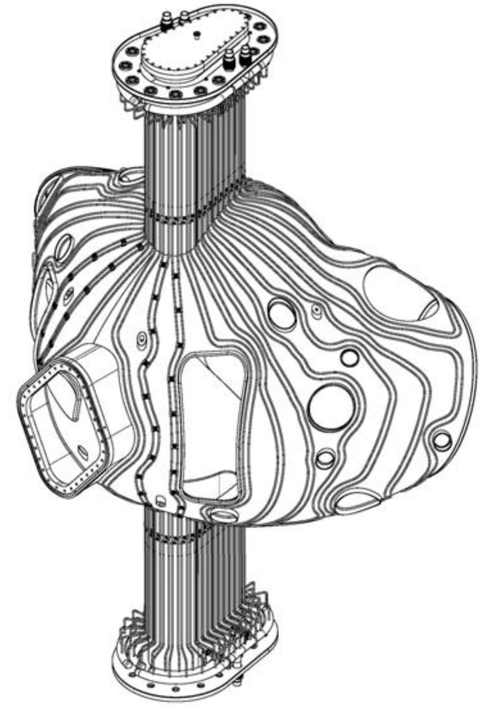


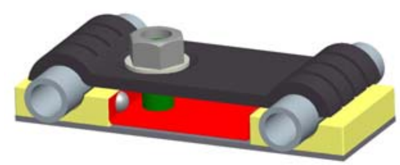




Typical saddle clamp



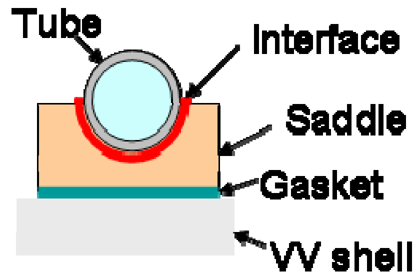




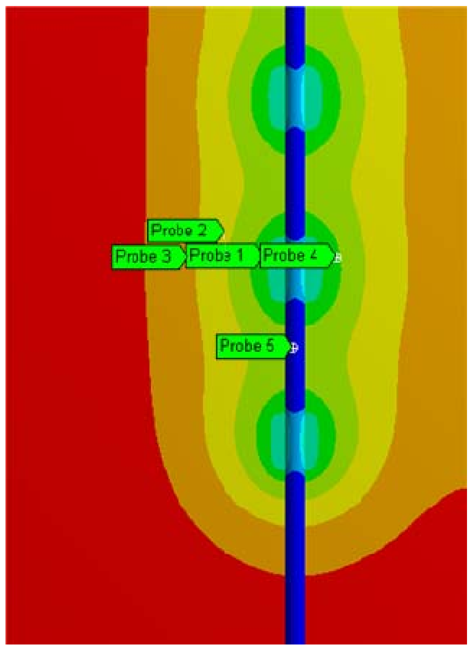
Offset clamp for better tube-tube spacing

Cooling tube design tested to benchmark analysis

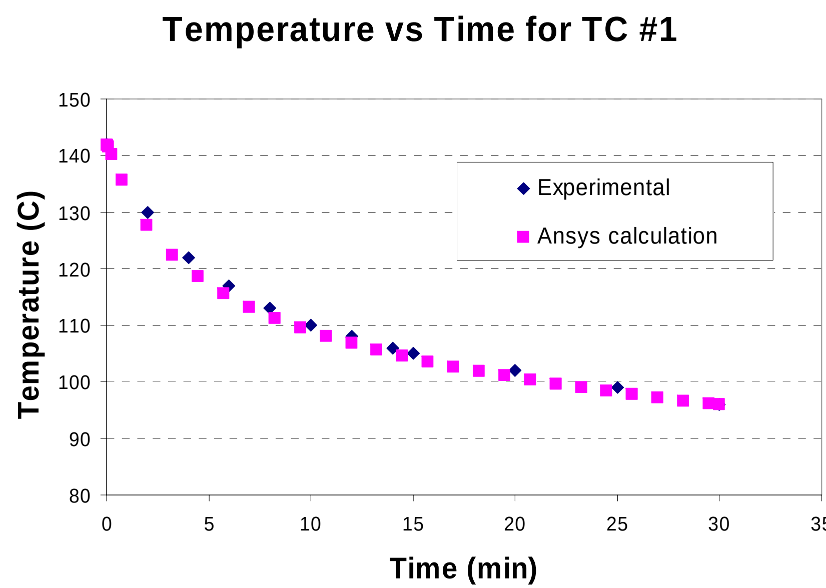
- Air used as coolant
- Various gaskets, interface materials tested and grafoil selected for both
- ***Design provides adequate cooling***



Test article, 3 saddle clamps on curved surface



Equivalent analytical model



Analysis matches test

Loose fill provides better thermal insulation

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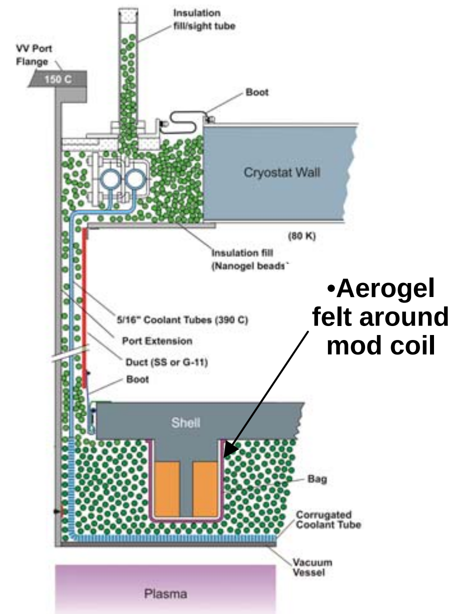
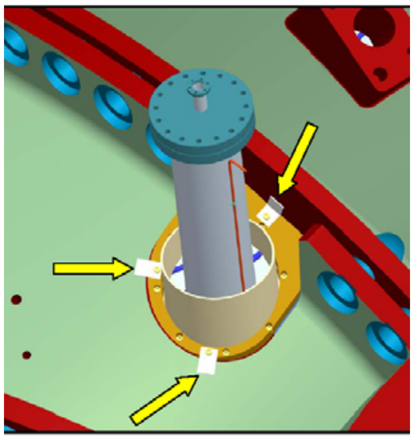
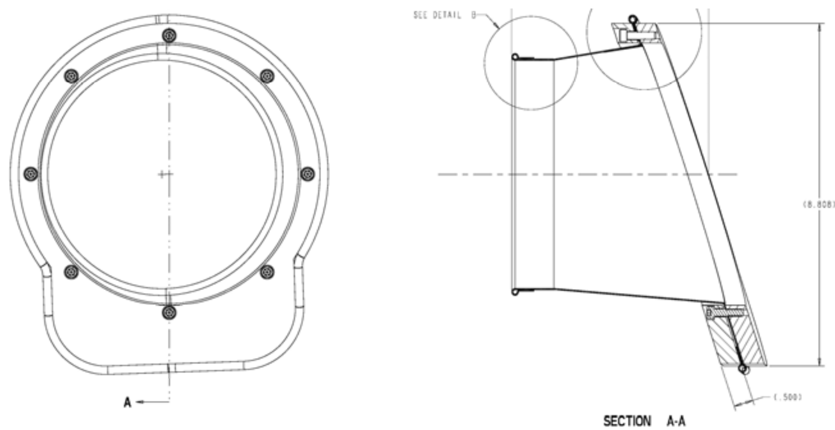
- **Thermal insulation is loose fill of nanogel-type beads**
  - Inexpensive ($100 / ft^3)
  - Better insulation (1/3 heat leak of batt-type insul)
  - Current product not rated to 350C, but expect this will be available soon (or we process it)
  - ***Safety personnel involved*** in selection of fill to assure no hazard from dust, flammability, etc.
- **Boots retain fill around ports, sewn from flat patterns**







As-built VV sectors require assy flange mods

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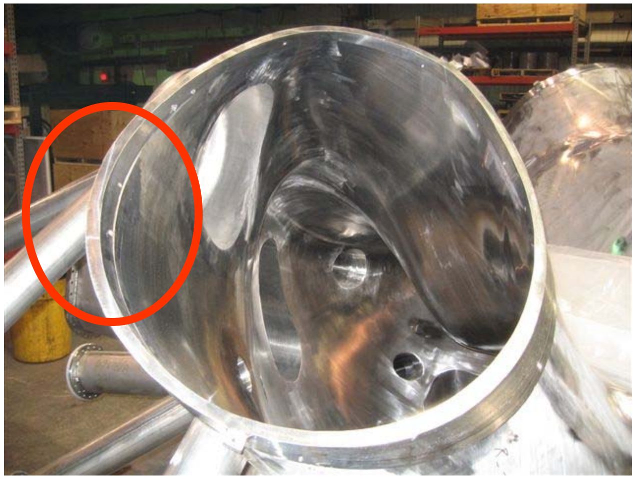
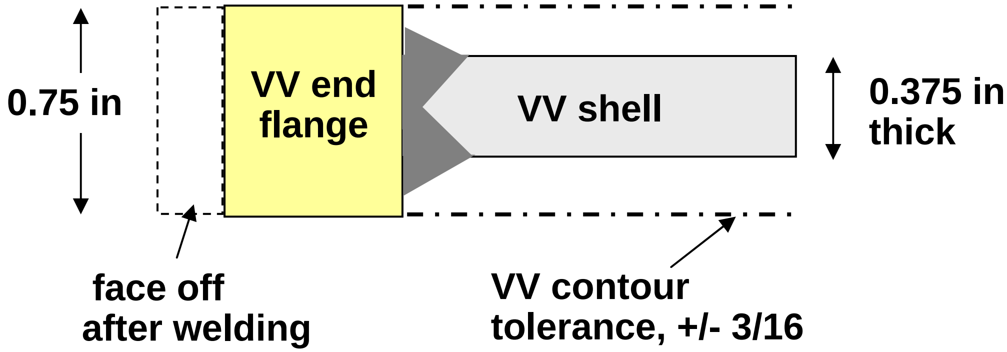
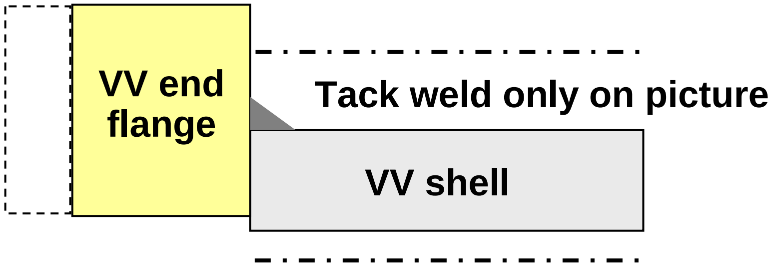
Surface of end flange is beyond surface of shell





Nominal condition



As-built condition

End flanges needed for final assembly weld

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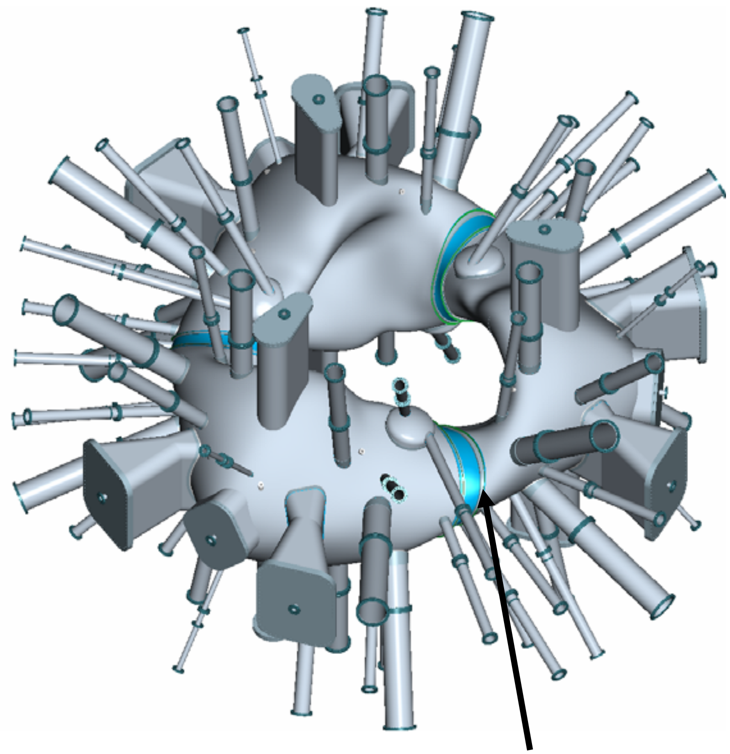
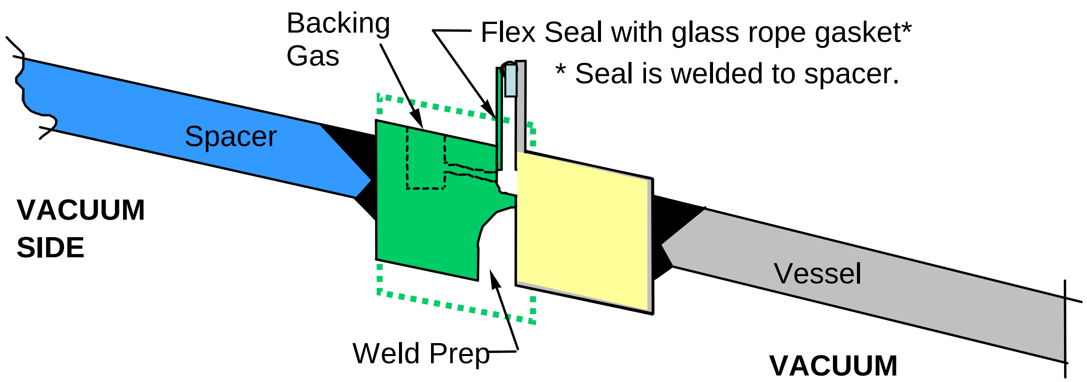
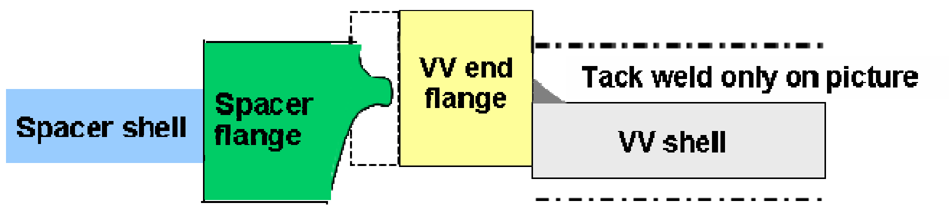


Field joints are welded at custom-machined spacers



Oversized spacer flanges are machined to match vessel profile for final assembly



Offset flange prevents adequate weld

Solution: Allow weld overlay on flange surface

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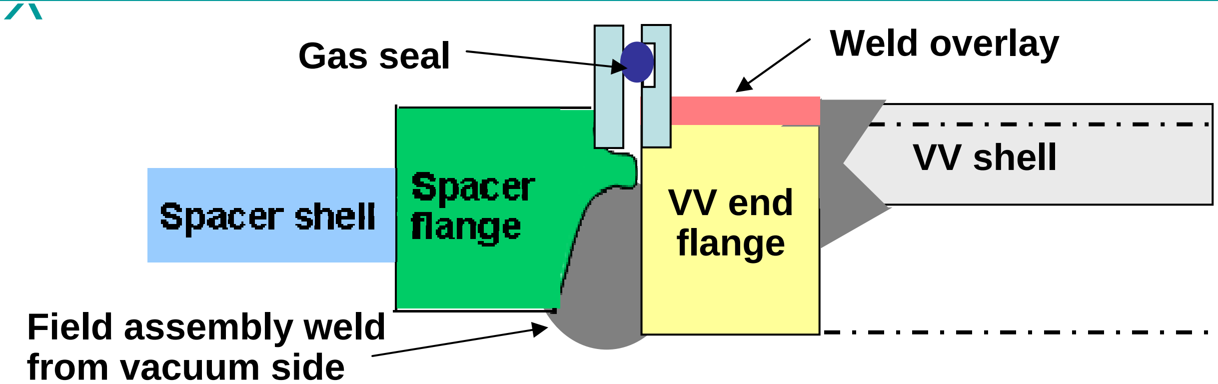
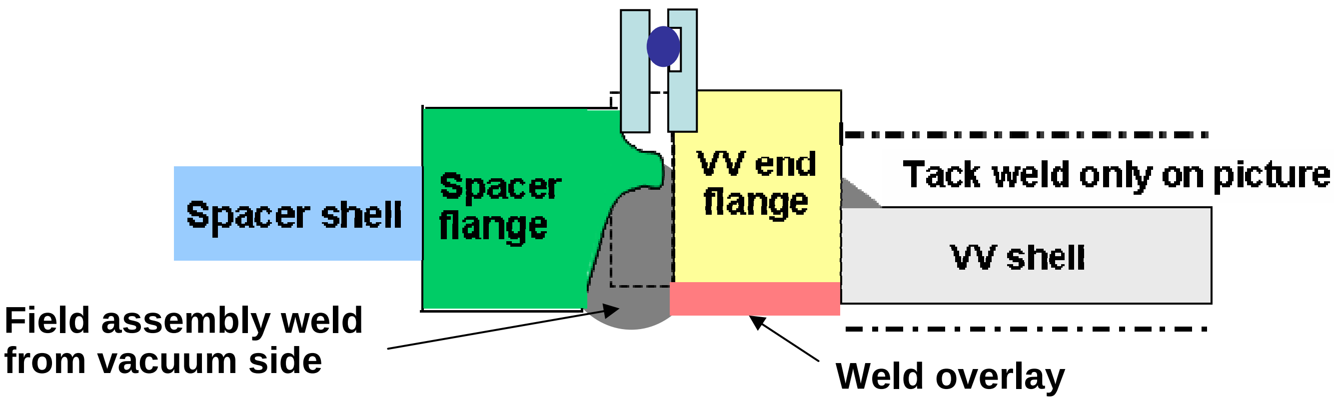


Overlay outside performed during factory welding



Overlay inside performed during final assembly welding

Current Vacuum Vessel risks addressed

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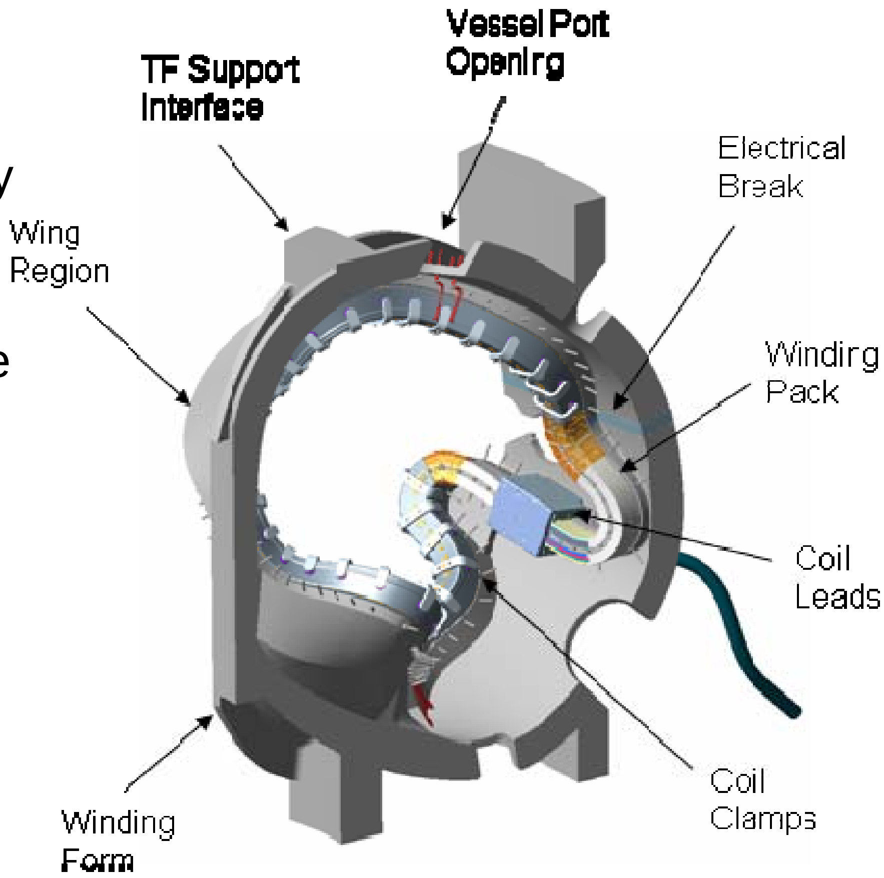
- **Are appropriate steps being taken to control design and Title III costs?**
  Design is nearly complete, Title III becoming more streamlined
- **Will the vendor supply accurate components on schedule?**
  VVSA #1 almost complete, geometry workable: Viola
- **Will the vessel leak?**
  No leaks in VVSA#1, including thermal cycling, hard vacuum achieved
  Provisions made for helium leak check of field welds
- **Can we make assembly welds?**
  Geometry issues with VVSA end flanges addressed
  Field joint weld R&D successful
- **Will the heating / cooling system work?**
  Analysis says yes, small scale tests confirm
  Need to finalize loose fill insulation good to 350C

Modular Coils

- **Recent accomplishments**
  - Modular coil winding forms on track for timely delivery – *Heitzenroeder*
  - Completed Types C and A details, nearly finished Type B
  - Winding form design details have been tweaked to improve fabrication schedule of winding forms - *Heitzenroeder*
  - Type C production winding uncovered a few additional issues that have been addressed
  - First Type C coil ready to test
- **Complete design: Sept 2006**
- **Complete procurement: Dec 2007**



Modular Coil topics

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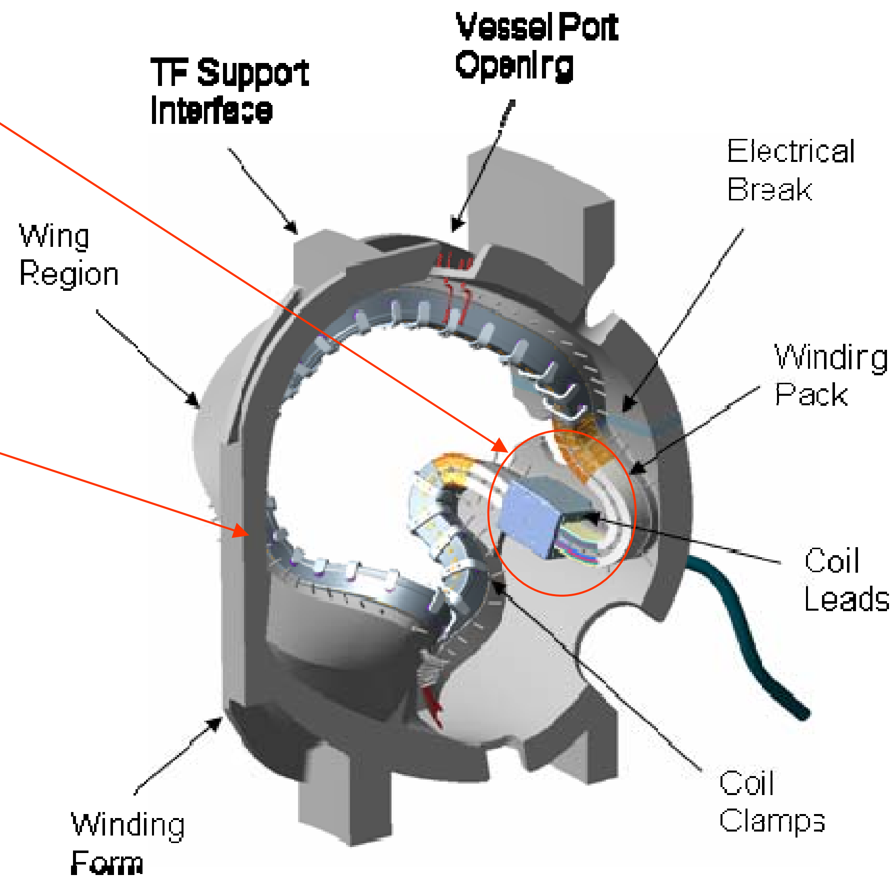
- **High resistance joint at leads**
  - C1 coil showed high resistance at some lead connections
  - Soldered connection will work – *Chrzanowski*
- **Shear connection in inboard region of coil to coil flange joints**
- **Coil testing**
  - Full current test of C1 planned



Analysis shows issue with coil-to-coil connections

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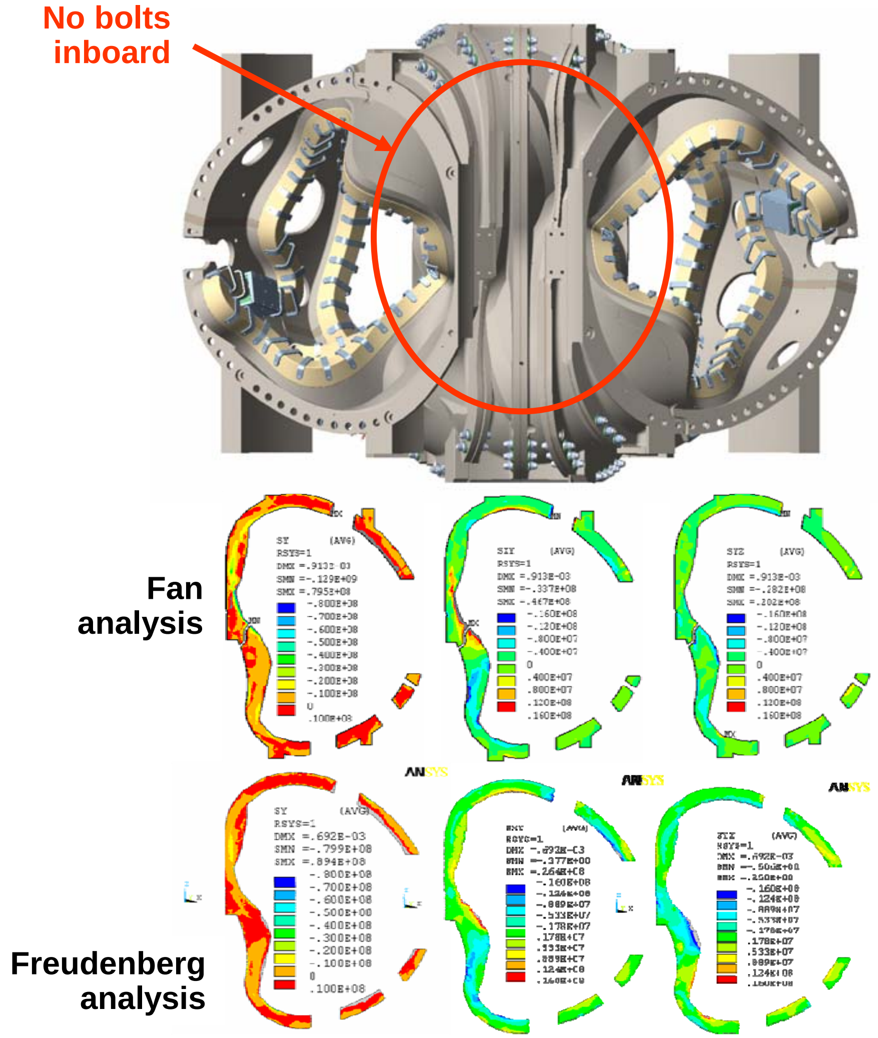
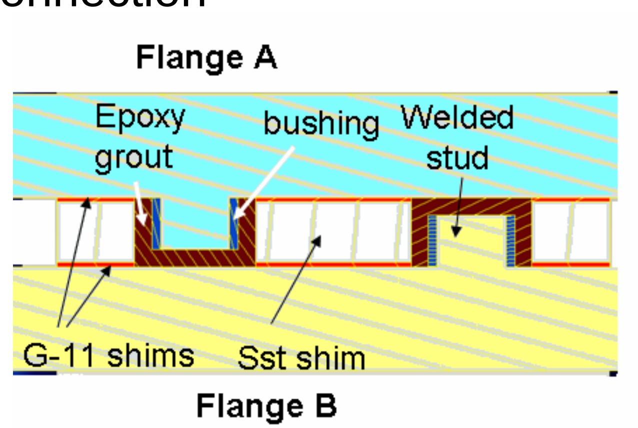
- **Shear load between coils too high for friction connection in inboard region**
  - Shear taken by combination of friction and shear in bolts
  - No bolts in inboard region due to lack of access after assembly
  - Compression load due to magnetic forces not high enough for reasonable friction coefficient
  - Joint may degrade if allowed to slip in service, but need for fix is still under investigation



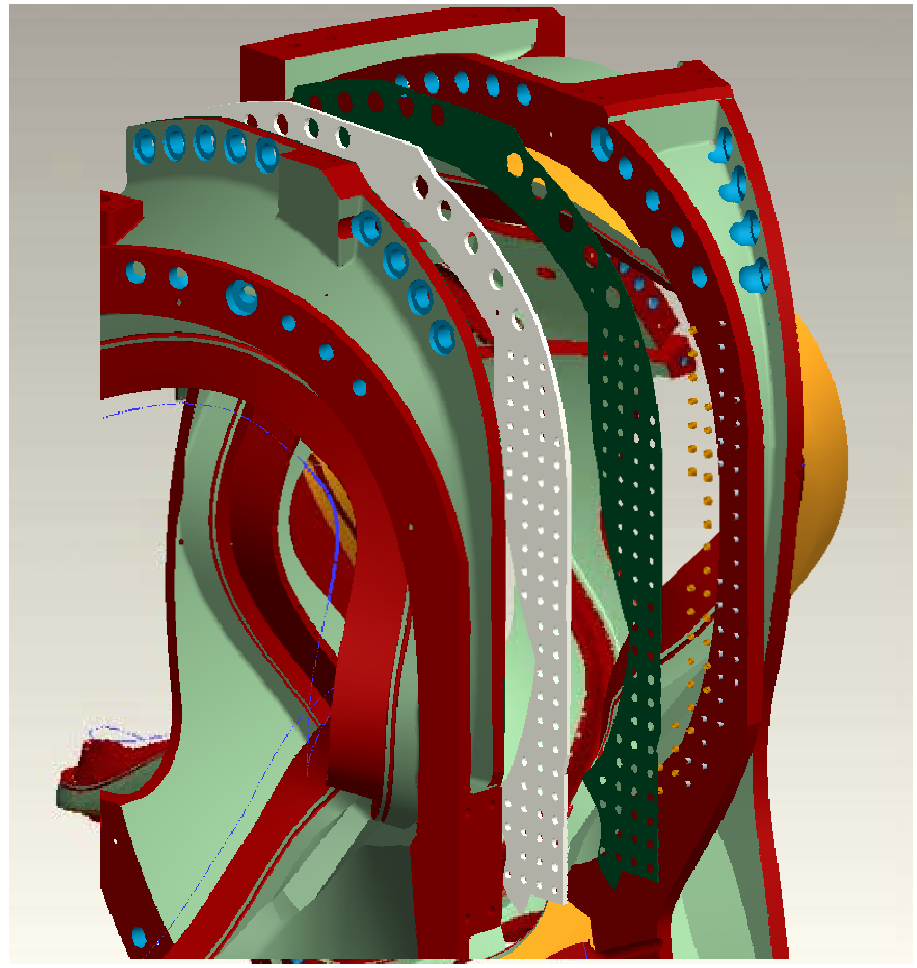
Joint AB normal and shear force distribution

Pin connection proposed to carry shear

- Pins stud-welded to each flange face on 2 inch centers (no WF mod)
- Shim has holes to receive pins, half from one flange, half from the other
- Pins are insulated with G11CR bushings
- Grout is injected at assembly to fill gaps and form zero-clearance shear connection



Section thru pin connection



AB joint, highest shear region

Pin connection will be tested with simple fixture

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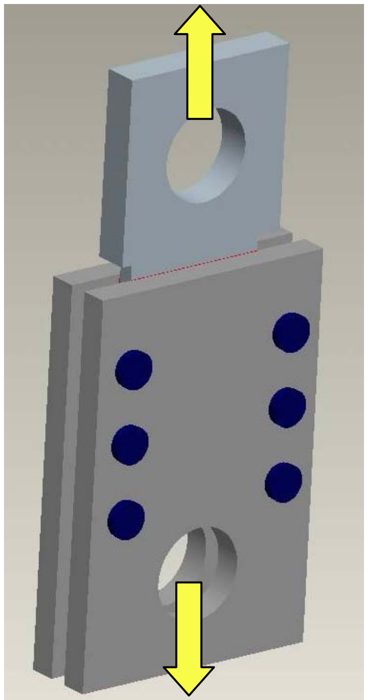
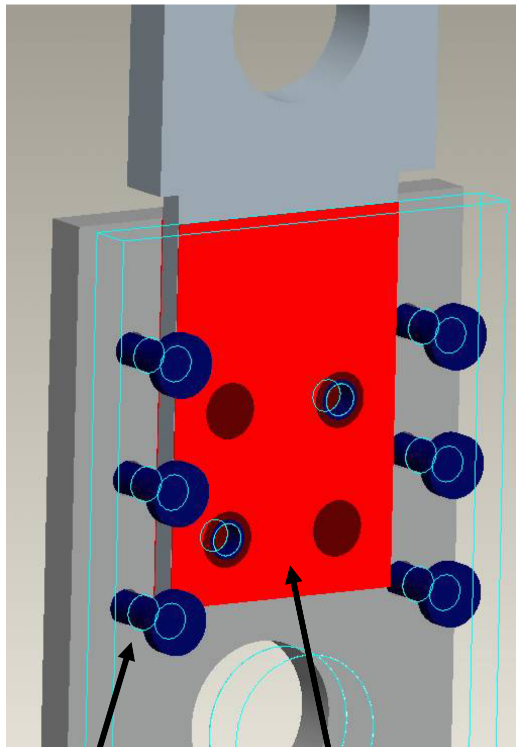
Test fixture pulls shim against flange pins



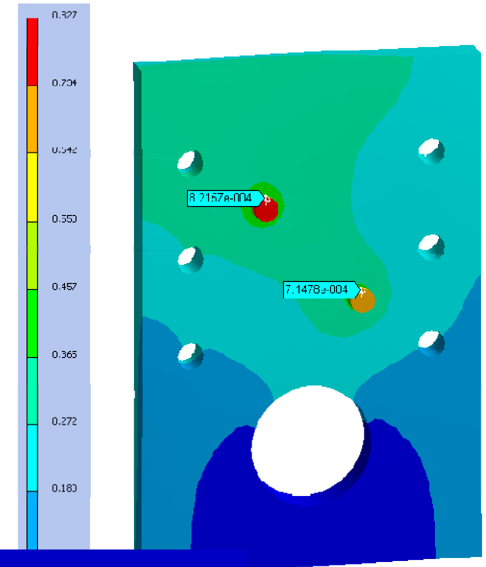
8000 lbs

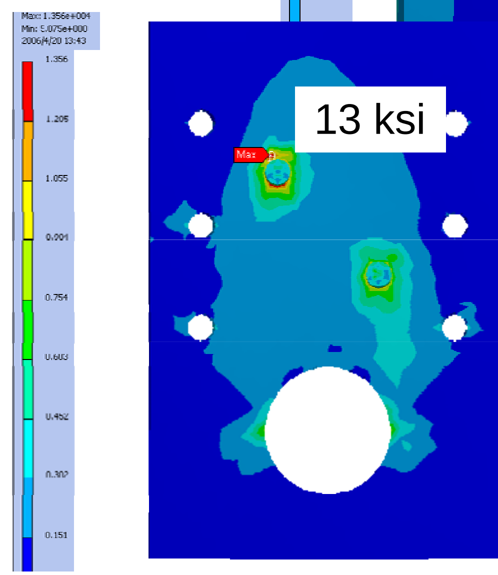


Clamp bolts adjust normal force

4 shear pins in symmetric array

vertical deflection of pin plate





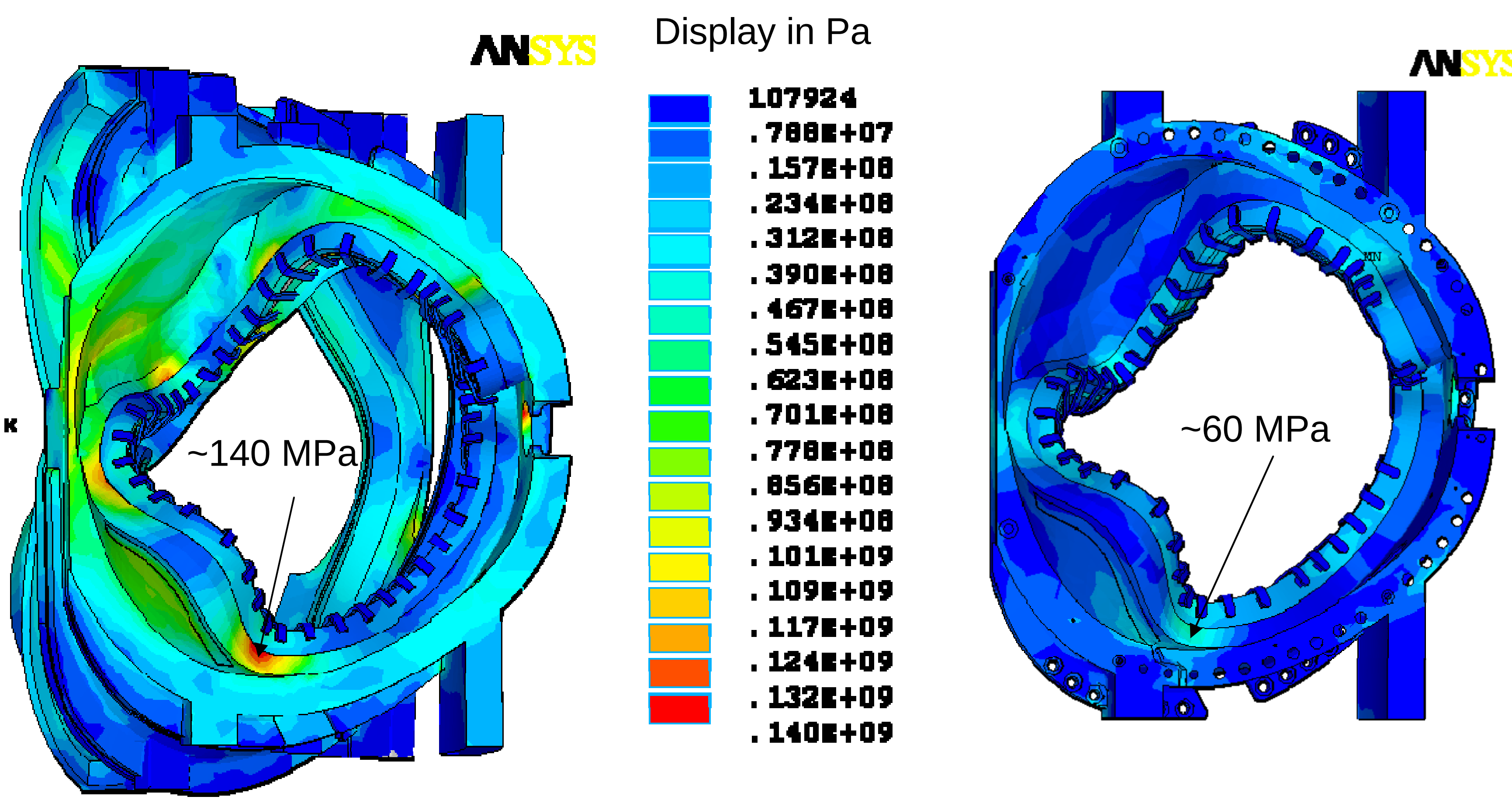
Stress in pins, plate

Balance between shear and bending

Coil C1 ready to test at full current

- **Coil test stand prepared, will operate simultaneously with NSTX to share resources**
- **Testing will confirm performance in several areas**
  - Initial cooldown (Coil will have thermocouples on winding form, plumbing, winding temperature inferred from coil resistance)
  - Temperature rise, cooldown between pulses
  - Structural response (Coil instrumented with 15 strain gages)
  - Geometric changes: Fiducial points, clamp positions, gaps measured before and after testing
  - Poloidal break bolt torque measured before and after testing
  - Joint resistance monitored before, during and after testing
- **Results of testing will be compared to analysis. If concerns are raised, testing of other coils will be considered.**

Analysis indicates full current of 36.5 kA will not overstress winding form or winding pack- *test is safe*



C1 in array

C1 in test (alone)

Plans for completing mod coil design

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- **Complete final detail parts for type B assemblies**
  - Lead blocks (checking)
  - Chill plates and cladding (side B)
  - Geometry files for winding measurements

- **Complete 3-coil, 6-coil, and 18 coil assemblies**
- **Complete connecting hardware details**
- **Document analysis and reconcile with final testing results**
- **Continue Title III engineering for winding forms and coil winding**

- **Risk of further cost increases reduced by experience with Type C coil, detail of estimate**

Cost/schedule detail

Current Mod coil risks have been addressed

NCSX

- **Are appropriate steps being taken to control design and Title III costs?**

  Design is nearly complete, Title III is becoming more streamlined

- **Is the shear problem in the nose region of the shell resolved?**

  Solution in hand, will require small R&D and design effort

- **Is the high resistance in the lead electrical joint resolved?**

  Soldered design solves problem

- **Have any retired risks returned?**

  No. Accurate fabrication of winding pack with adequate structural and thermal behavior has been demonstrated

PF coil design complete through PDR

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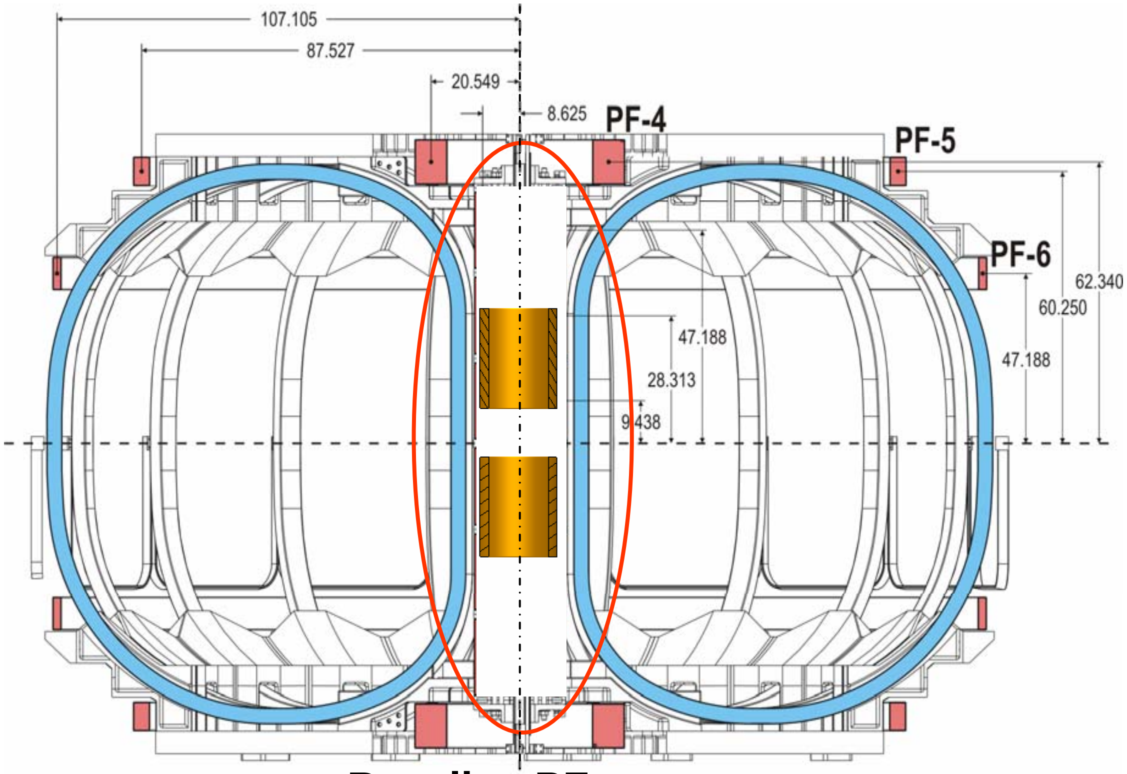
- Coils are conventional, copper conductor in epoxy glass matrix
- Baseline plan is to procure the new PF coils from industry
- Central solenoid support structure will be modified for NSTX PF1A coils



Baseline PF set

Coil services options tested

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- **Commercial kickless cable planned for connecting coils to external buswork**
  - Low stray field, low forces, low price, relatively easy to route around machine
  - Electrical testing of sample showed low voltage standoff pole to pole (< 1kV) requirement is 7.5 kV
  - Issue being addressed by FlexCable
- **Teflon tubing planned to connect coils to LN2 distribution manifolds**
  - Same design used on C-Mod at MIT
  - Tests indicate this will work at NCSX pressures (< 10 atm)
- **Coil services design carried out in FY07**

Baseline cryostat consists of insulated panels

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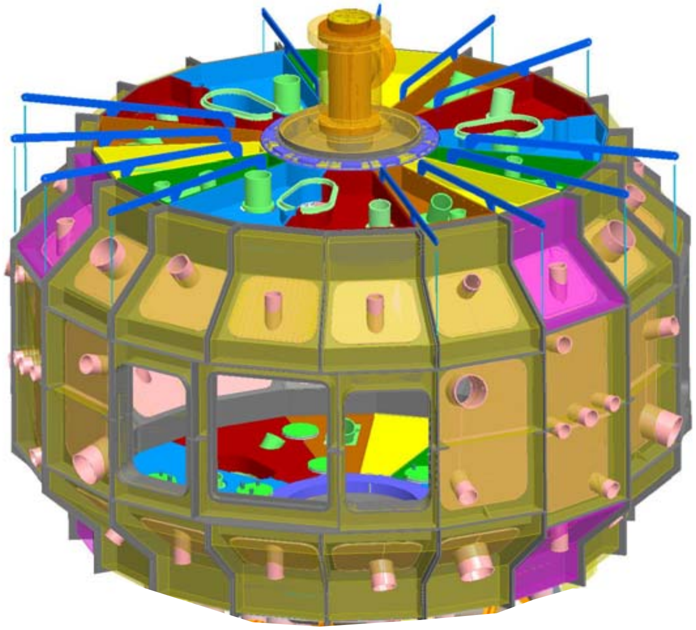
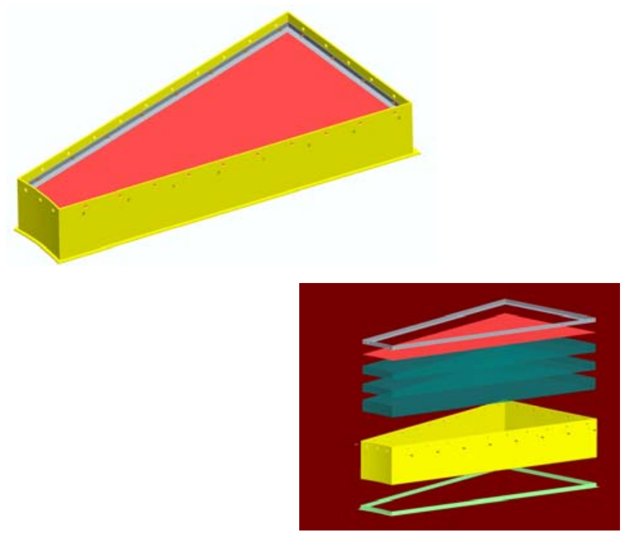
- Must accommodate details of all internal components
- Less expensive options being investigated
- Final design in FY07





Baseline Cryostat Assembly

Typical insulated panel

Base support in final design phase

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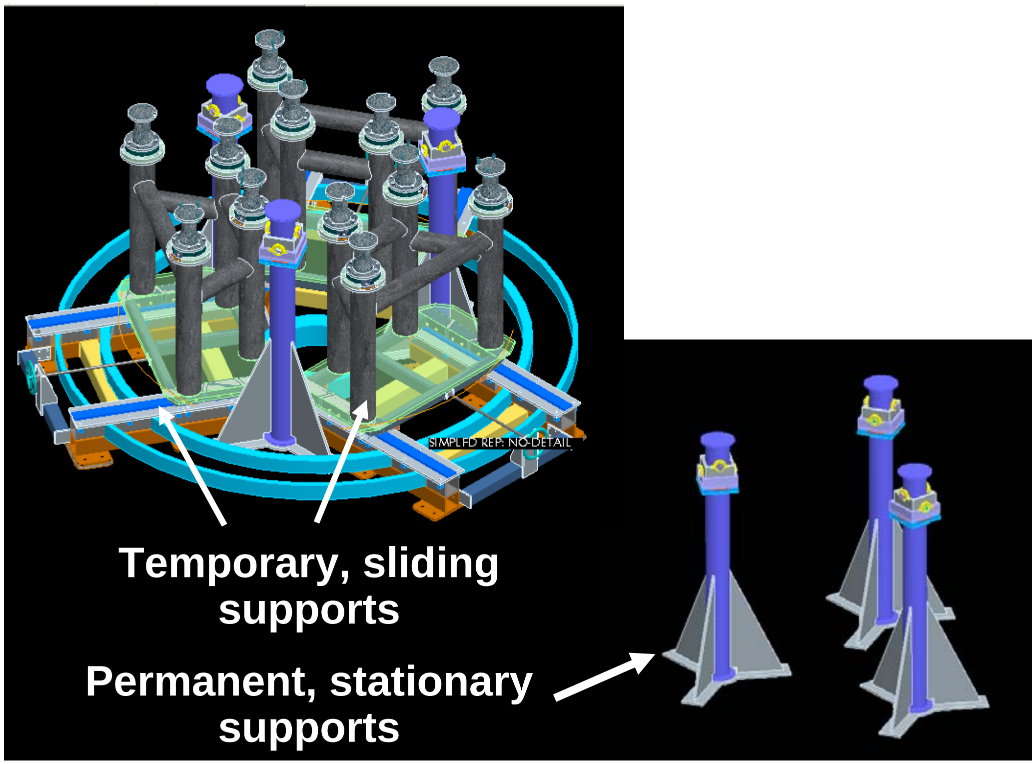
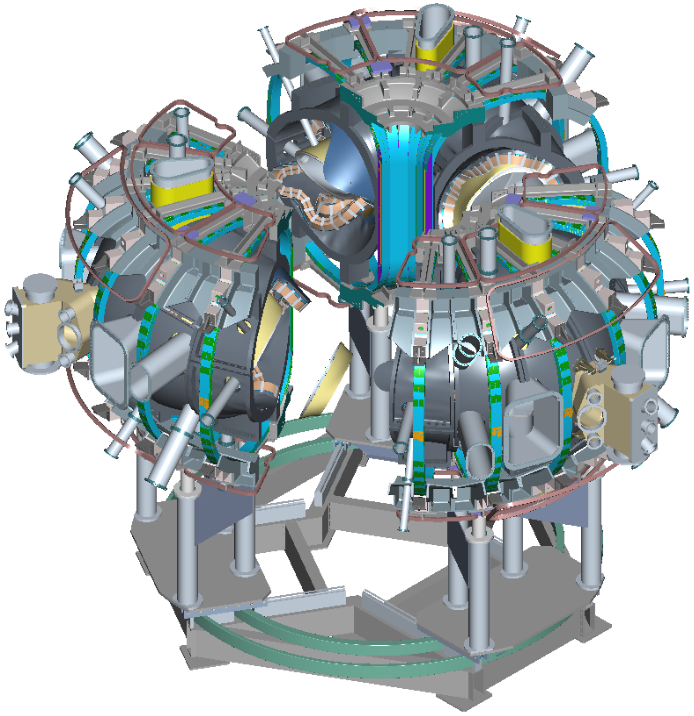
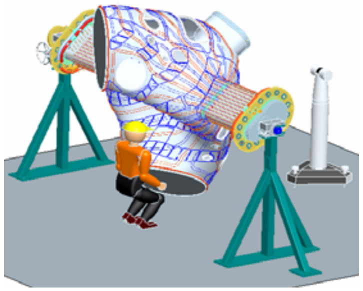
- Baseline concept provides sliding supports for final assembly
- New approach will use temporary sliding supports for assembly
- Simplified permanent supports will improve access under core





3 field periods retracted

Field Period Assembly completed at 5 stations

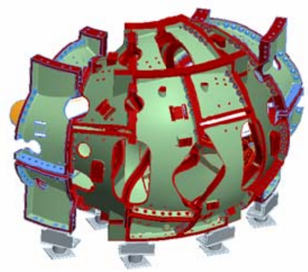


Add coolant tracing, mag loops, etc.

Station 1

prepare VV

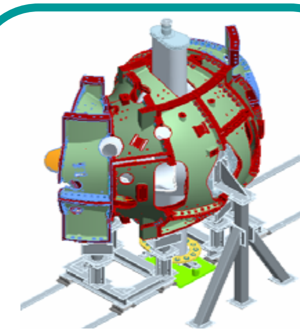
Align and bolt 3 mod coils into 1st half period



Magnetically align next three coils to first three

Station 2

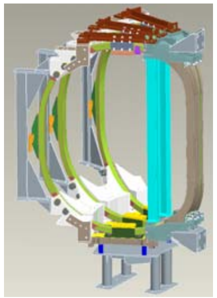
assemble 2 sets of 3 mod coils



Slide first and second 3-mod-coil sets over VV

Station 3

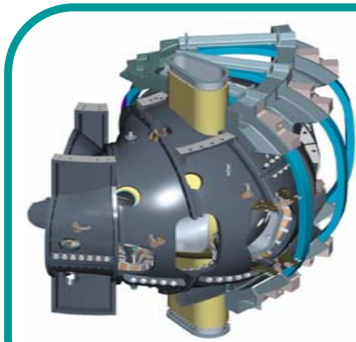
mod coils over VV



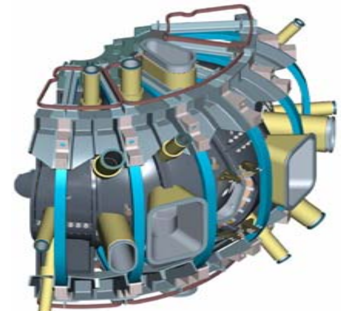
Assemble 3 TF coils with half period of structure

Station 4

TF coil subassembly



Add first 3-TF-coil set



Add 2nd TF set and VV port extensions

- ***Wt. = 40 tons***
- ***Safety key in all aspects***
- ***Reiersen to discuss FPA status, plans***

Station 5

Add TF coils and VV port extensions

Status summary: 62% complete

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WBS	Description		Design / Title III	Title III	R&D	Procure	In-house fab / assy.	Total
1.2	Vacuum Vessel	*spent ($k)*	1,559	482	1,678	4,077	31	7,828
		total ($k)	1,629	559	1,678	5,446	96	9,409
1.3	Conventional Coils	*spent ($k)*	963	43	219	378	326	1,930
		total ($k)	1,191	327	250	2,423	629	4,820
1.4	Modular Coils	*spent ($k)*	4,237	180	8,942	7,356	2,016	22,731
		total ($k)	4,717	440	8,949	11,996	6,161	32,264
1.5	Machine Structure	*spent ($k)*	80	0	0	0	0	80
		total ($k)	213	155	0	1,023	0	1,391
1.6	Coil services	*spent ($k)*	0	0	0	0	0	0
		total ($k)	635	76	0	387	33	1,132
1.7	Cryostat and Base	*spent ($k)*	368	0	0	0	0	368
		total ($k)	680	44	0	808	0	1,532
1.8	Field period assembly	*spent ($k)*	779	121	156	323	319	1,698
		total ($k)	1,008	706	241	386	2,932	5,274
1.9	Core Integration, Mgmt	*spent ($k)*	1,647	97	0	0	0	1,744
		total ($k)	1,858	911	0	0	0	2,769
	Total	*spent ($k)*	9,634	923	10,996	12,134	2,692	**36,379**
		total ($k)	11,933	3,218	11,119	22,469	9,851	**58,591**
		% spent	81%	29%	99%	54%	27%	**62%**

Summary

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- **Design of the major stellarator core components is nearing completion**
  - Vacuum vessel complete except for final assembly dwgs
  - Modular coils complete in mid to late FY06 (assy hardware, overall assy dwgs)
  - Safety is the paramount criteria for all designs
- **The designs of the major components have been improved based on fabrication experience and performance tests**
  - Mod coil design modified in response to C1 winding experience
  - Vacuum vessel cooling tube connections optimized
- **Risks have been identified and mitigated through R&D testing**
  - verified performance of the modular coil design
  - verified feasibility of the vacuum vessel field joint design
- **Plans are in place to complete the design and procurement of the stellarator core components**