Engineering Design of the NCSX

PAC Meeting

December 2-3, 1998

NCSX Engineering Team

NCSX Engineering Team

- **ORNL**
  - **Brad Nelson, Paul Goranson, Dave Williamson, Mike Cole, Bob Benson, Paul Fogarty**
- **PPPL**
  - **Wayne Reiersen, Bob Simmons, Art Brooks, Tom Brown, Fred Dahlgren, Ron Hatcher, Phil Heitzenroeder**
- **Raytheon**
  - **Aleksandr Georgiyevskiy**

Outline

- Engineering Design Plan
- PBX options
  - Impacts of plasma configuration improvements
  - New concepts for saddle coil design
  - New liner concept
  - PBX mockup
  - Updated cost estimate
- New machine option

Engineering Design Plan

- **Develop integrated suite of design tools**
  - **Coil design (NESCOIL+)**
  - **3D modeling (Pro/E)**
  - **EM and structural analysis tools (ANSYS, SPARK)**
- **Perform concept development concurrent with physics design**
  - **Identify requirements based on physics needs**
  - **Develop innovative solutions**
  - **Assess cost-performance trade-offs**
  - **Iterate to optimize physics performance at fixed cost**

Engineering Design Plan (2)

- **Establish parameters for conceptual design by February '99**
  - **Select plasma configuration**
  - **Establish design basis requirements**
  - **Make system level design choices**
    - **PBX modification or new machine?**
    - **Modify PBX through a port? Disassemble TF?**
  - **Establish machine configuration**
- **Conduct Physics Validation Review in May or June'99**
- **Complete conceptual design by September '99**

Design Concept Development

- **Major choice: new machine or modify PBX**
  - **Main focus on PBX options**
  - **New machine option only recently begun**

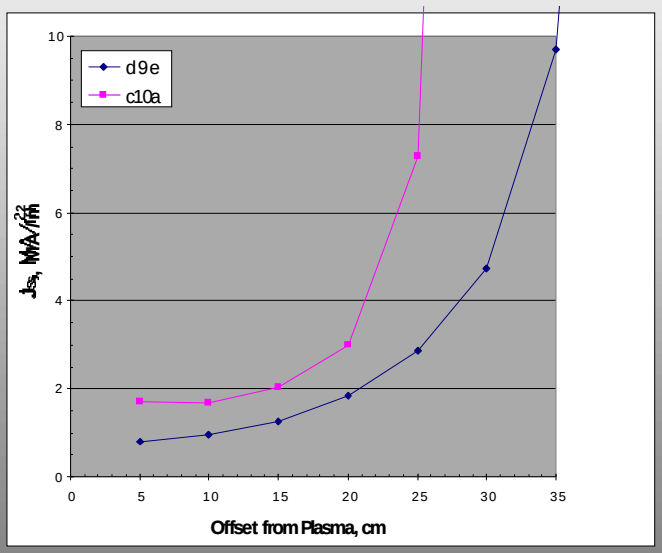
- **Pivotal factors include**
  - **Performance requirements**
  - **Experimental flexibility**
  - **Plasma configuration**
  - **Design feasibility and technical risk**
  - **Cost**
  - **Schedule**

Plasma Configuration Improved Since Pre-Conceptual Design

- **Pre-conceptual design based on d9e plasma**
  - **2 periods, non-monotonic iota profile with low shear**
  - **40% external transform**
  - **PBX compatible, 1T field**
  - **Saddle coils used to provide non-axisymmetric fields**
- **Recent designs based on c10 plasma**
  - **3 periods, monotonic iota with modest shear and shaping to stabilize external kink**
  - **PBX compatible, higher field (1.2T)**
  - **Saddle coils used for PBX option**
  - **Modular coils being investigated for new machine option**
- **Lower A plasma configurations being explored by physics**

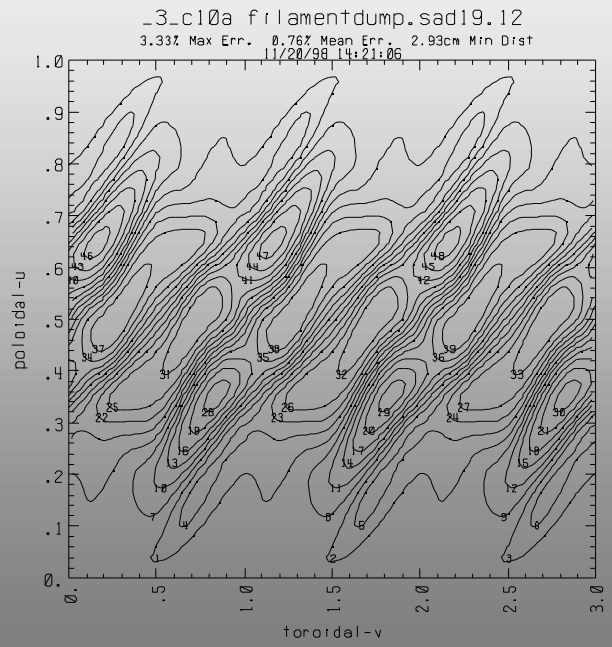
Plasma Configuration Improvements Led to More Complex Coils

- **Higher current density**
- **Greater sensitivity to plasma offset**
- **More coils required to achieve same fit**
- **Cost impact TBD**

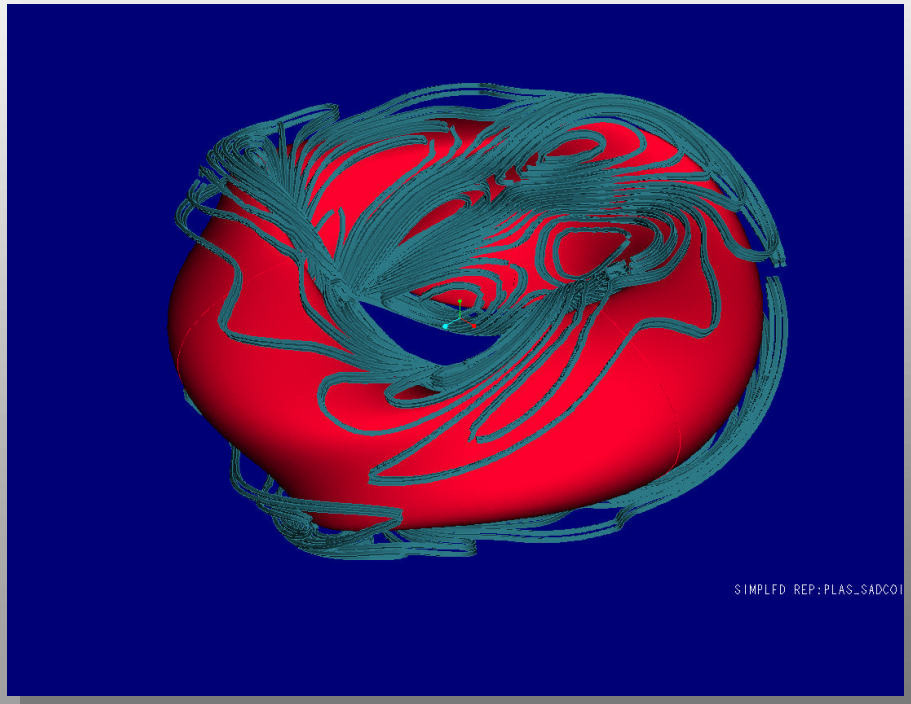


Saddle Coil Design for PBX Option

- **6 sets of 8 nested saddles**
- **12.5cm offset inboard, 19cm offset outboard**
- **2.9cm minimum filament separation**
- **Good fit to B_{norm}**
  - **3.3% max error**
  - **0.8% mean error**
- **Reconstruction with VMEC not yet achieved**



Saddle Coils and Plasma

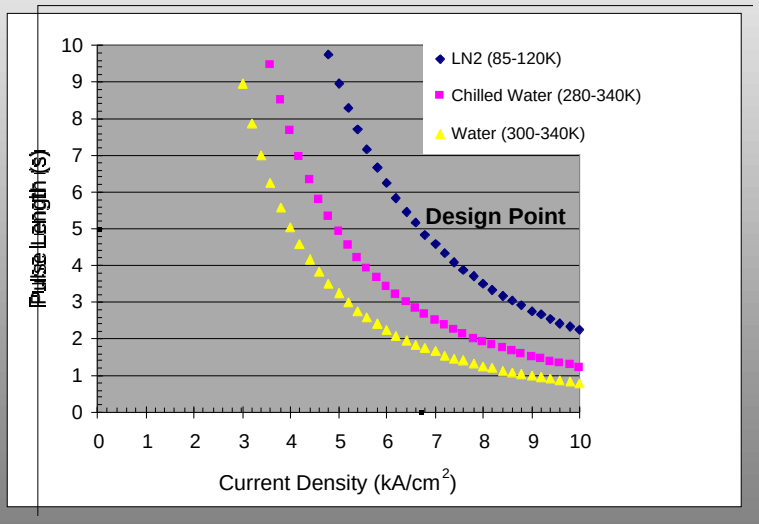


Each Coil Has Two Turns

- **The conductor size is 21mm x 25mm**
- **Conductor current is 27kA**
- **J_{Cu} is 6.7kA/cm^2 based on a 76% copper fraction**
  - **Cabled conductor w/o a coolant channel**
  - **Extruded conductor w/ a 13mm diameter hole**
- **Design based on t_{ESW} of 4.9s**
  - **Ramp saddle coils to full current (0.5s)**
  - **Initiate plasma, ramp to full current (0.5s)**
  - **Heat plasma to full beta (0.5s)**
  - **Maintain plasma at full current and beta (3.1s)**
  - **Controlled rampdown of plasma current and beta (0.5s)**
  - **Ramp saddle coils to zero current (0.5s)**

The Required J^2t Is Achieved by Pre-Cooling with LN_2

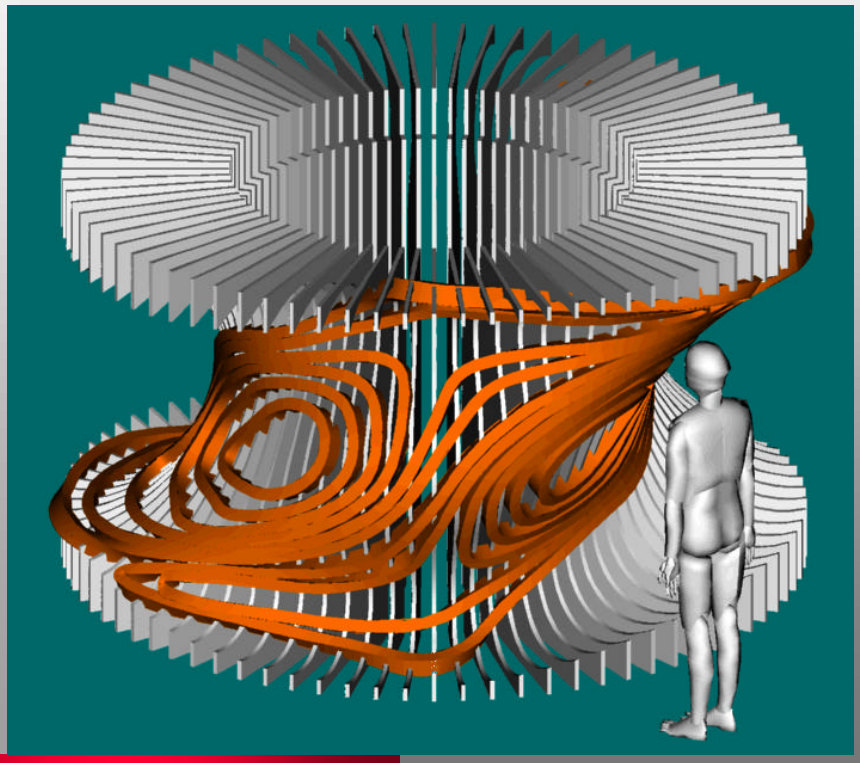
- **LN2 is a triple win**
  - **Higher J means smaller coil envelope**
  - **Smaller coil envelope moves coil closer to plasma , lowering coil current**
  - **Smaller conductor makes conductor easier to wind**



Three Saddle Coil Design Concepts Are Being Investigated

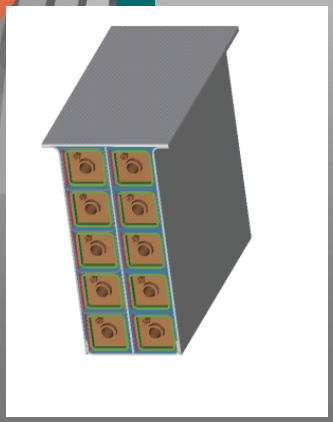
- **Cable-in-Trough**
- **Winding-on-Shell**
- **Discrete Supports**

Pre-Conceptual Design (d9e) Based on Cable-in-Trough Concept



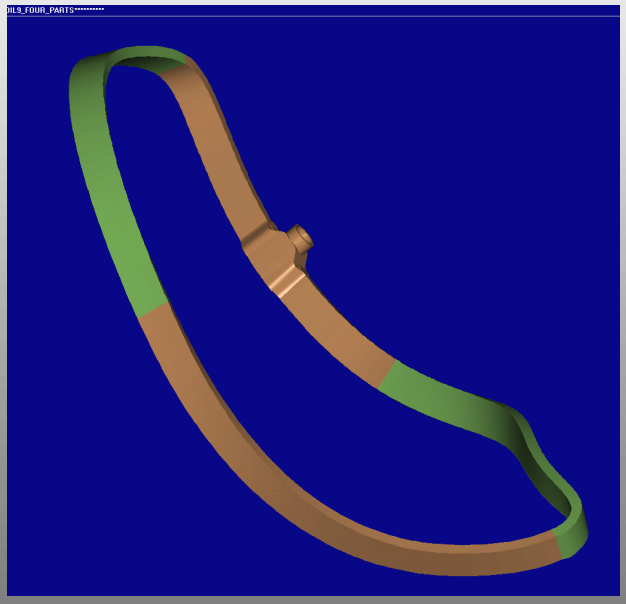
Cable-in-Trough Concept

- Trough initially proposed to be made from flat developments outside, formed in place using notches in structural ribs
- Flexible, water-cooled cable conductor, wound in place
- Can closed and vacuum pressure impregnated with epoxy



Present Concept Based on Pre-Forming Trough

- Forming trough in situ appears difficult
- Pre-forming trough outside and assembling on ribs is more credible approach
- No notches in ribs -- extensive measurements during assembly required
- Two turns per coil in present design, pre-cooled with LN_2



Cabled Conductor Cooled by Conduction to Trough

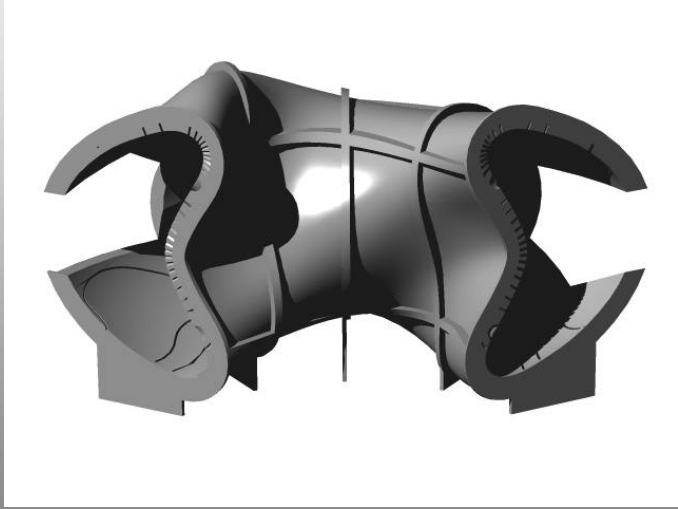
- **Indirect cooling improves copper fraction in cabled conductor, minimizing conductor size**
- **Cooldown time controlled by insulation thickness, material and bonded area**
  - **Good thermal contact between conductor and trough required**
  - **For 1 mm insulation thickness and G10 properties, conductor should cool down within 5 minutes**
- **Aluminum favored as trough material**
  - **Good thermal conductivity**
  - **Thermal stresses arise from differential contraction between the aluminum trough and copper conductor**
  - **Avoiding epoxy bonding of strands may eliminate problem**

Assembly Time Is a Key Issue for Cable-in-Trough Concept

- **Pros**
  - **Ribs and trough segments have modest requirements for port access**
  - **Flexible conductor is readily available**
  - **Winding is straightforward once trough is in place**
- **Cons**
  - **Many pieces to assemble**
    - **Many vertical ribs, trough segments, and attachments**
    - **Requires frequent in-vessel measurements to assemble ribs and troughs**
  - **Not well suited for larger number of saddle coils**
- **Issues**
  - **Assembly time**
  - **Thermal stresses**
  - **Coil spacing with discrete troughs and attachments**
  - **Cost and feasibility of forming trough to required accuracy**
  - **Making structural closure weld**

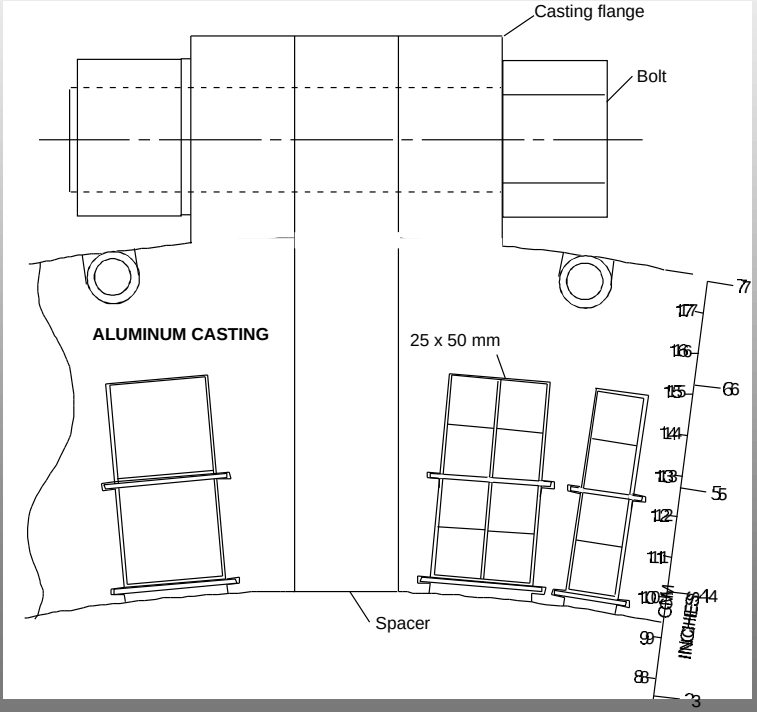
Winding-on-Shell Concept Simplifies Assembly and Reduces In-Vessel Measurement Requirements

- Segmented shell with machined grooves for conductor
- Flexible cabled conductor wound in place
- Grooves sealed and vacuum pressure impregnated with epoxy
- Conductor cooled by conduction to shell which is pre-cooled with LN_2 to 80K
- Aluminum favored as shell material for ease of machining and good thermal conductivity

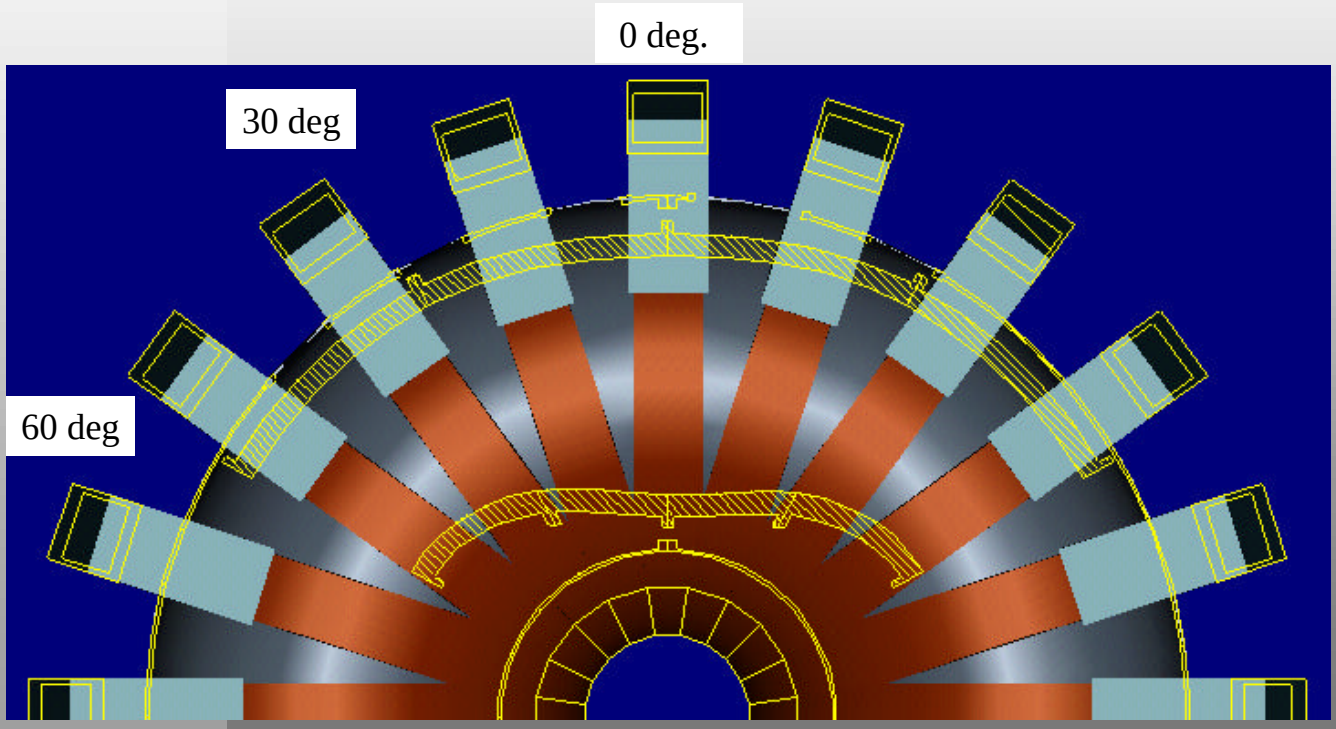


Shell/Winding Cross Section

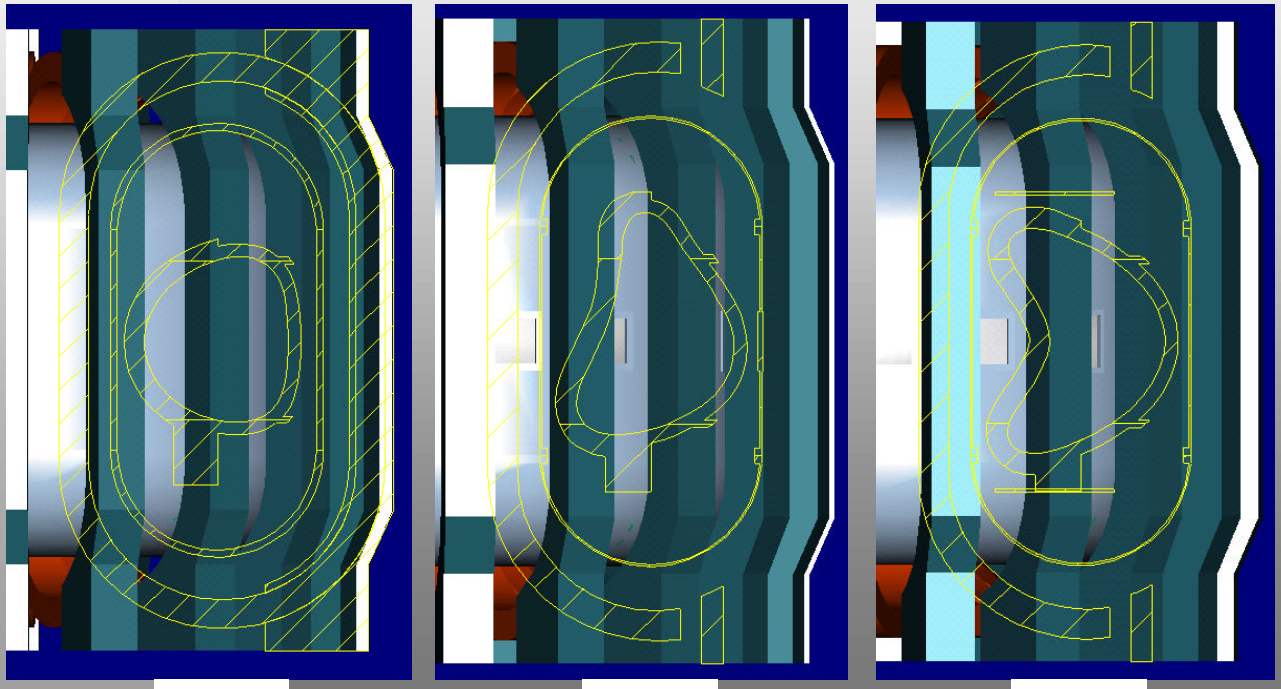
- **Windings placed in grooves in shell**
  - **Two (or more) turns per groove**
  - **Windings retained with spring clips**
- **Cooling lines integral with shell**
- **Spacer plates provide machining adjustment, insulating break, and mounting features**



Plan Section of Shell in PBX



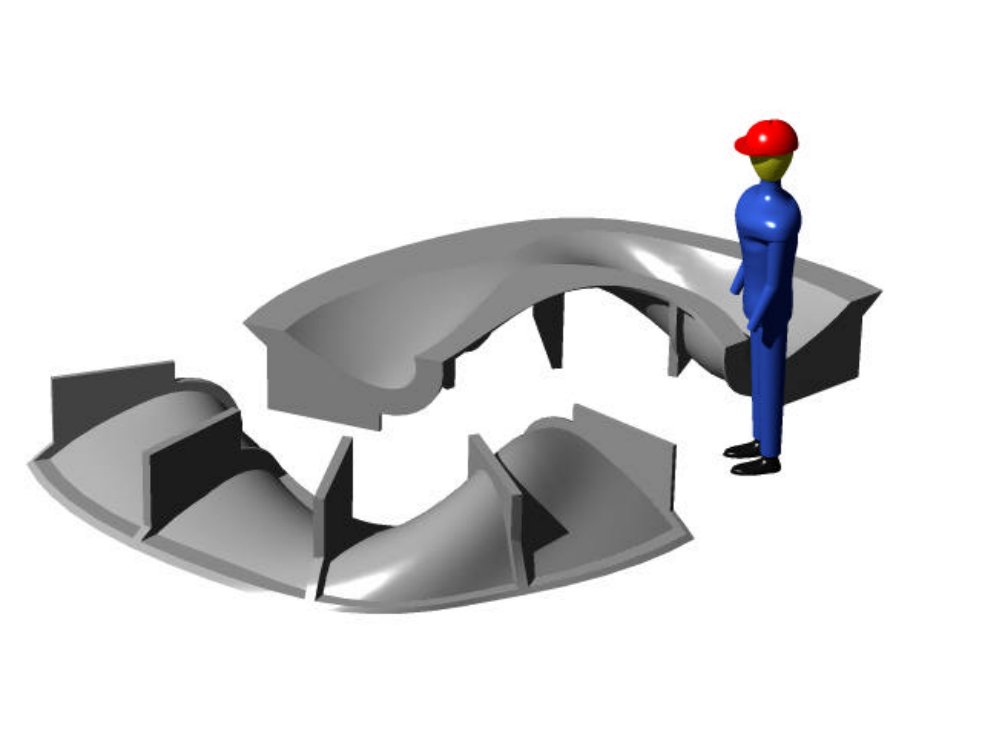
Shell/VV/TF Cross Sections

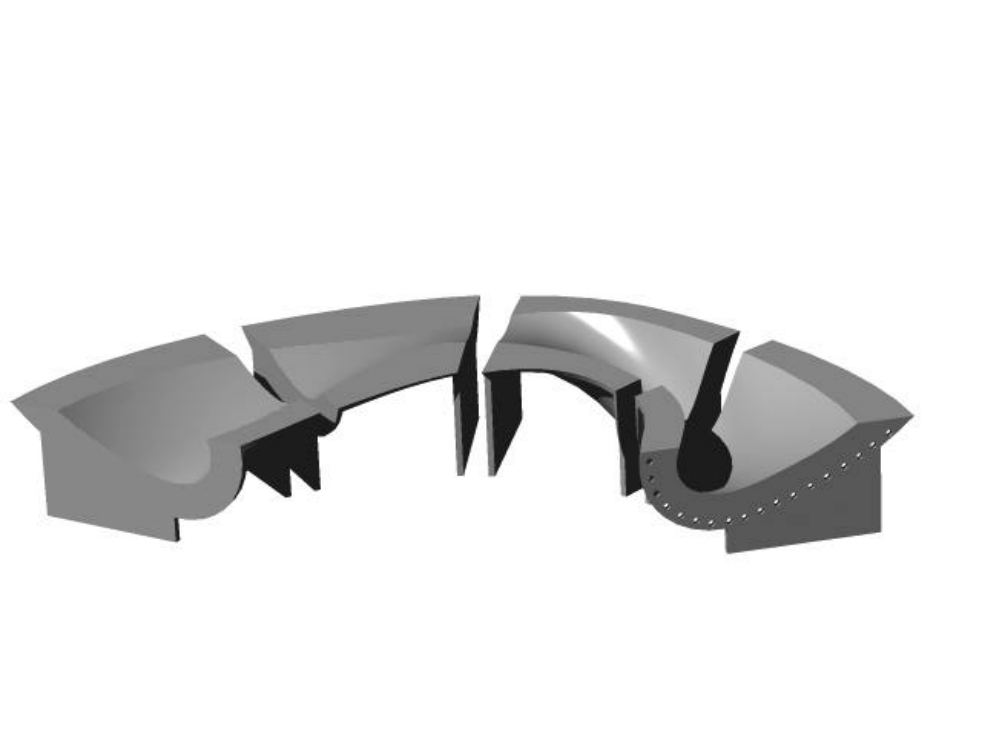


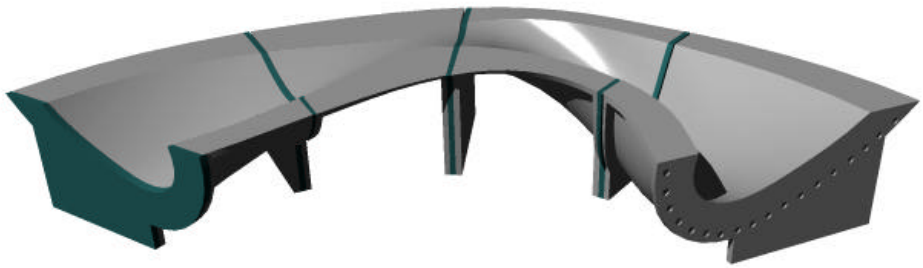
0 deg 30 deg 60 deg

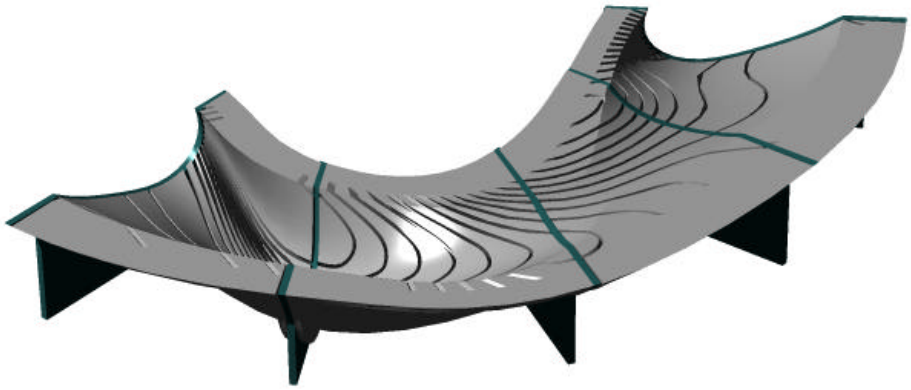
Shell Is Assembled in Pieces Through Horizontal Port

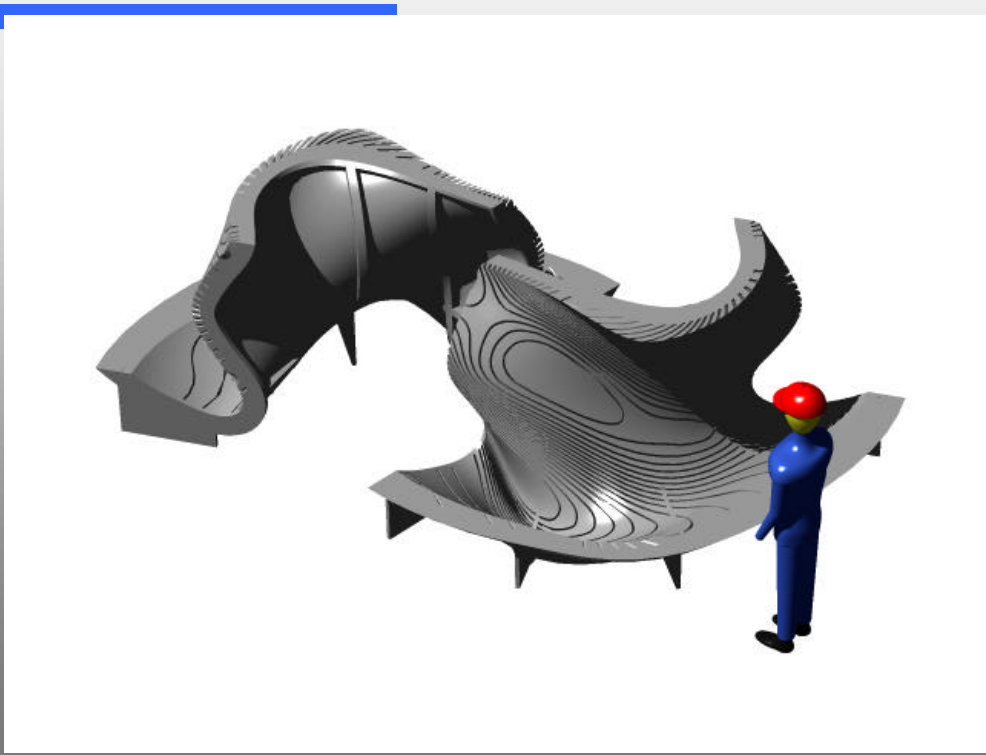
- **Shell is high precision, machined and pinned structure**
- **Assembled in few pieces**
- **Once assembled and positioned, few in-vessel measurements required**
- **Machined grooves locate conductor with high precision**
- **Resistive breaks required to reduce error fields due to eddy currents**
- **Responses to initial inquiries on cost and fabricability were encouraging**

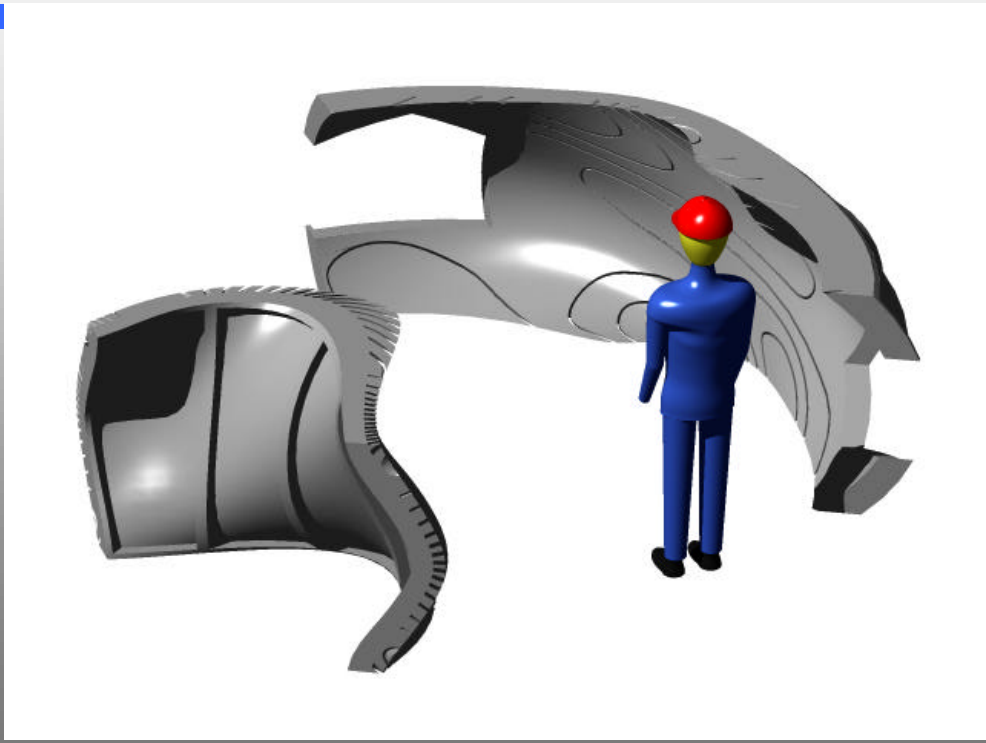


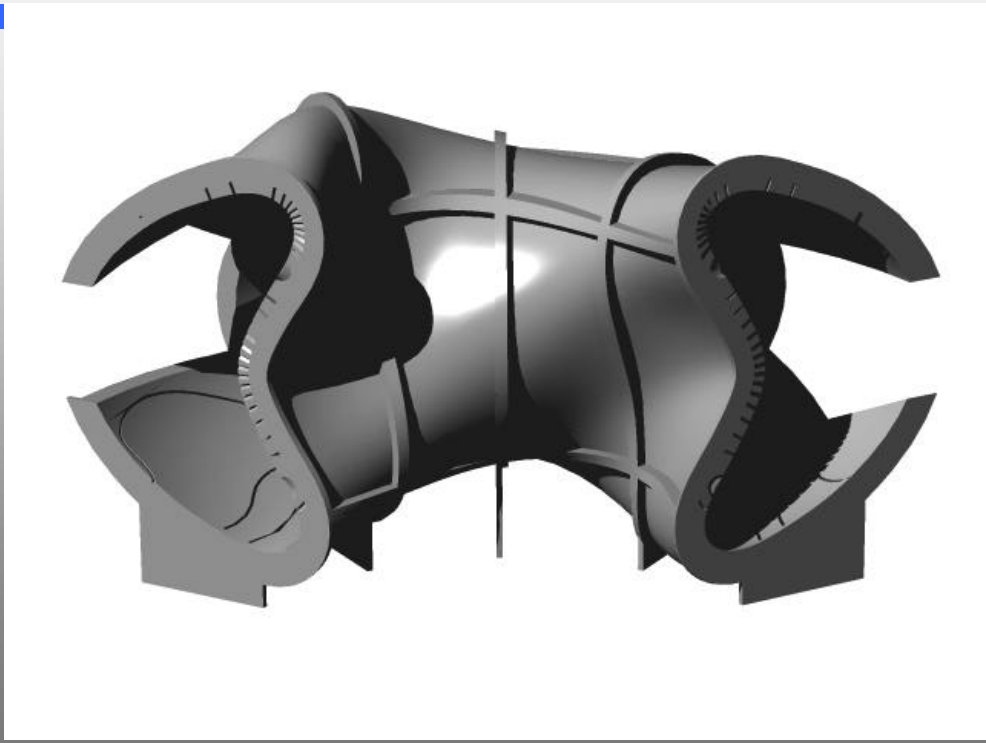


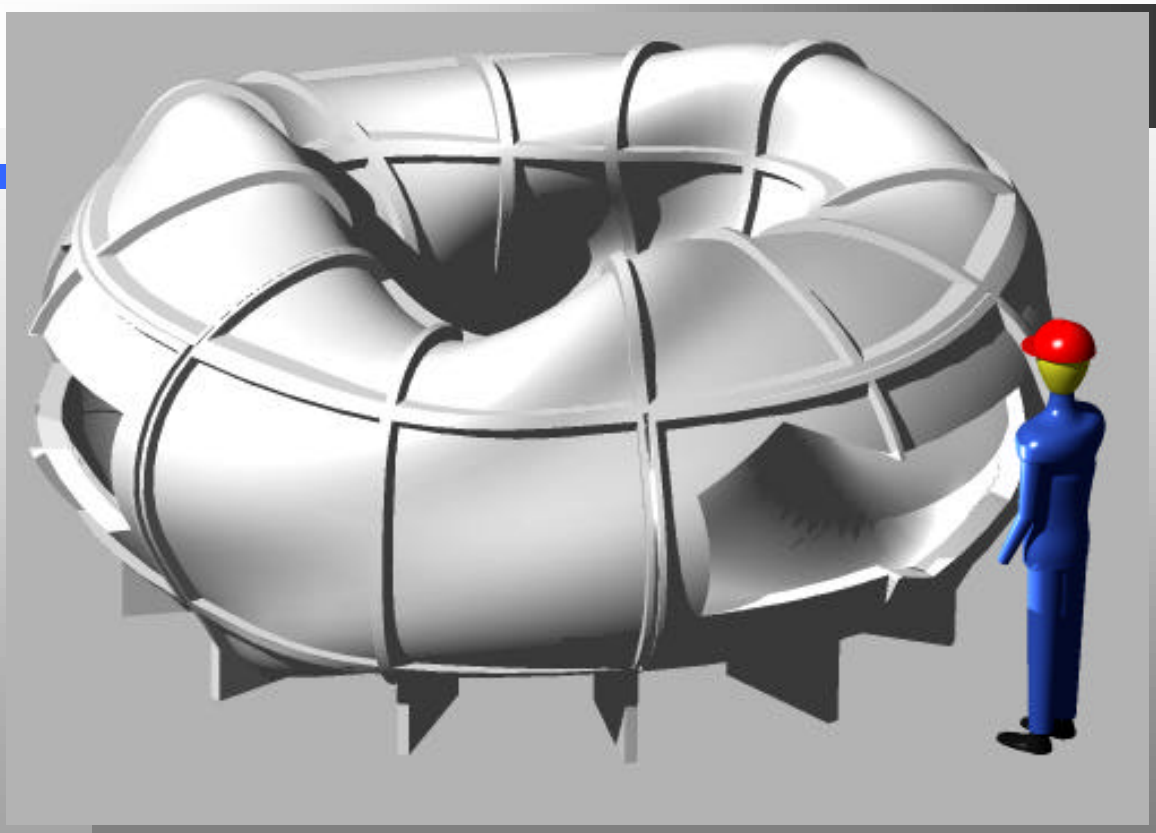










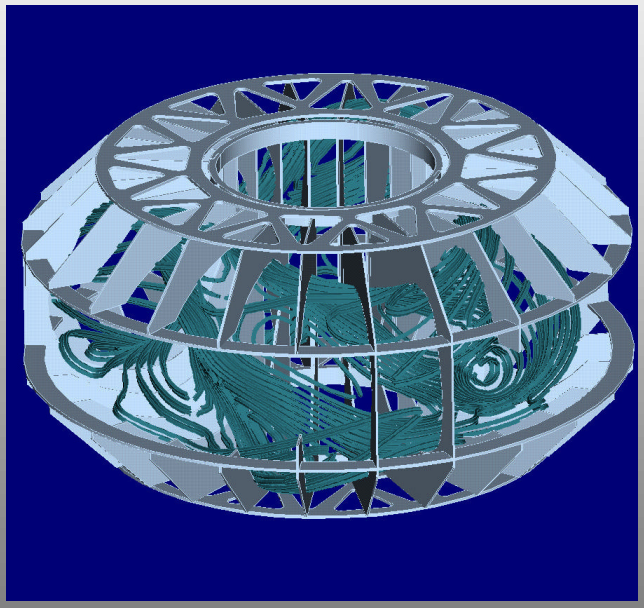


Thermal Stresses Are a Key Issue for Winding-on-Shell Concept

- **Pros**
  - **Adaptable to larger numbers of saddles, spiral winding**
  - **Assembled in fewer pieces**
  - **Fewer in-vessel measurements required**
  - **Robust to changes in geometry**
- **Cons**
  - **Larger port opening required for assembly than other options**
- **Issues**
  - **Thermal stresses arising from differential contraction between Cu conductor and Al shell**
  - **Larger port opening may require (partial) disassembly of TF**
  - **Supporting conductor in regions of tightest spacing**
  - **Field errors from eddy currents in the segmented Al shell**

Discretely Supported Conductor Offers Alternative Approach

- Rigid conductor segments formed outside vessel
- Conductor segments attached to SSt rib structure with fittings
- Segments joined via electro-forming or induction brazing to form coils
- Coils are self-supporting between ribs
- Conductor is solid copper with coolant hole in center for LN_2 cooling



Coils Isolated from Plasma by Low Conductance Liner

- **Conductor segments are pre-insulated but not canned**
- **Low conductance liner envisioned to adequately isolate coils from plasma**
  - **Bolted construction favored over welded for maintainability**
- **Coil region would be separately pumped**
- **Outgassing from coils at cryogenic temperatures (80-120K) should be reduced**

Assembly Time Is a Key Issue for the Discrete Support Concept

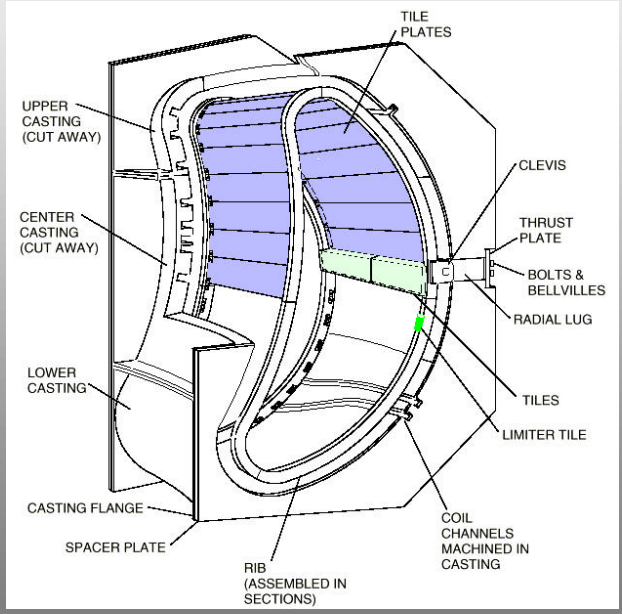
- **Pros**
  - **Modest port access requirements**
  - **No support channel (trough or grooved shell) to fabricate, seal, and VPI**
  - **Direct cooling avoids cooldown stress and eddy current problems associated with aluminum trough or shell**
- **Cons**
  - **Many pieces to assemble, requiring frequent measurements**
  - **Not well suited for larger number of saddle coils**
- **Issue**
  - **Assembly time**
  - **Cost and feasibility of accurately forming conductor segments**
  - **Joining conductor segments**
  - **Vacuum isolation of uncanned coils**

Field Errors Must Be Minimized in All Design Concepts

- **Relevant factors include…**
  - **Proximity, geometry, and placement of leads and crossovers**
  - **Conductor current**
  - **Geometric accuracy of coils**
  - **Coil deflections during operation**
  - **Eddy currents from aluminum support structures (shell/trough)**
  - **Permeability of welds**

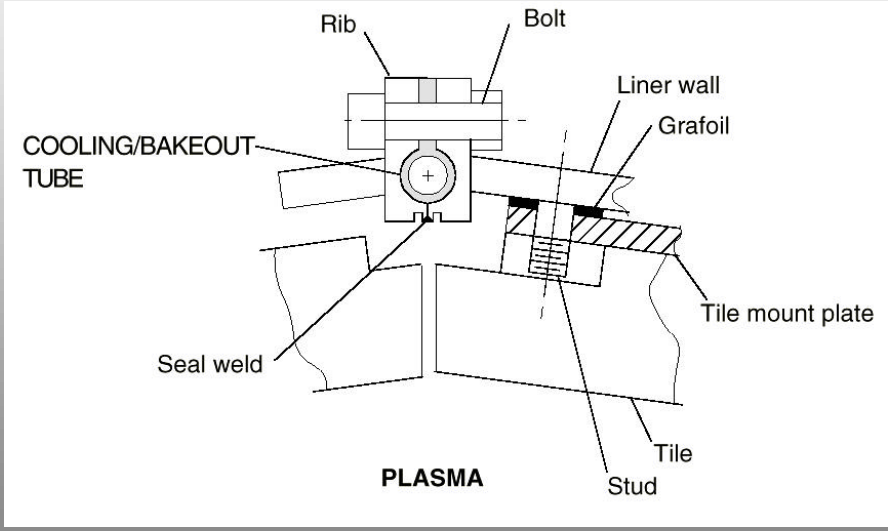
Liner Design and Fabrication

- Frame and panel design
- Frame consists of radial rings
  - Supported from saddle coil structure
  - Free to grow thermally
  - Cooled/heated for operation and bakeout
- Panels are flat plates bolted to radial rings
  - Tiles mounted to panels
  - Special panels for penetrations



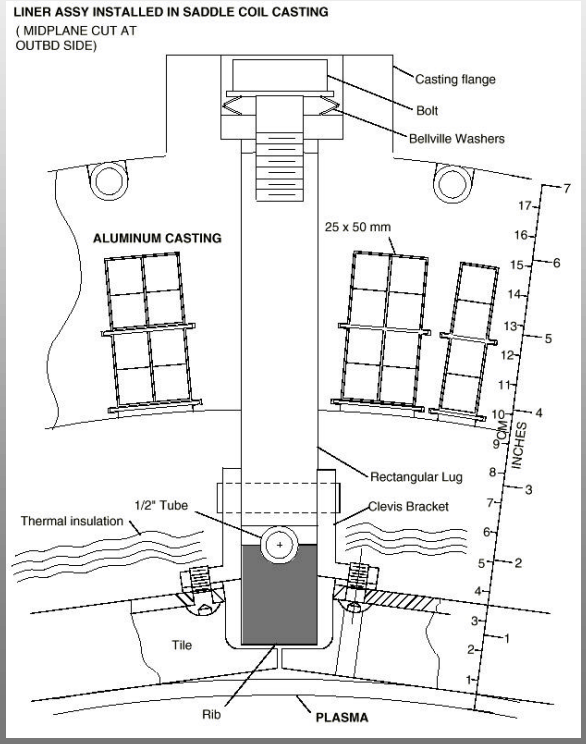
Vacuum Tight Liner Is An Option

- **Similar to baseline, but seal welded at assembly**
- **Liner wall must be brake-formed and welded at seams**
- **Appropriate for modular coil design**
- **May be needed for discretely supported saddle coil option**



Radial Build Allows Room for Some Plasma Growth (Δa) in PBX

- **Liner (7.5cm)**
  - **5 cm nominal liner depth**
  - **7.5 cm at support bracket includes thermal insulation**
- **Coil Assembly (13cm)**
  - **Includes cover plate (0.5cm), winding (5.5cm), structure (2cm), cooling channels (1.5cm), and the casting flange (3.5cm)**
- **Available real estate**
  - **3cm inboard for SOL + Δa**
  - **4cm outboard for SOL + Δa**

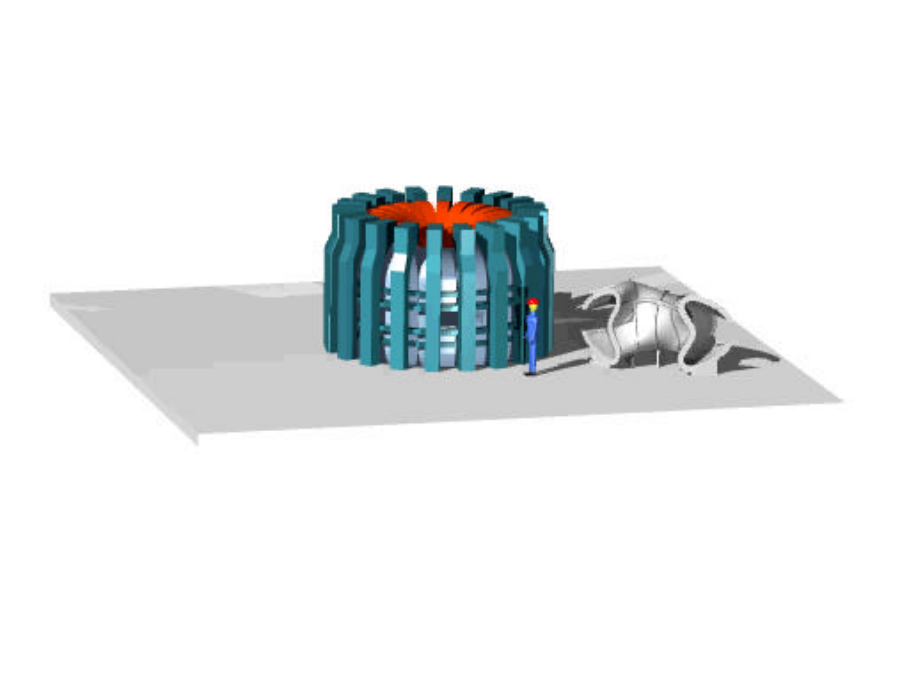


Assembly in PBX

- **Feasibility of fabrication and assembly in PBX must be demonstrated**
  - **Structure assembly**
  - **Winding, potting**
  - **In-situ measurement**
  - **Liner assembly**
- **Issues**
  - **Will parts fit through opening?**
  - **What is the assembly time?**
- **Propose to demonstrate operations on full scale mockup and prototypes of coils and liner**

Assembly Process

- **Assembly is through port opening in PBX-M**
  - **Preassembly outside**
  - **Disassembly**
  - **Re-assembly**

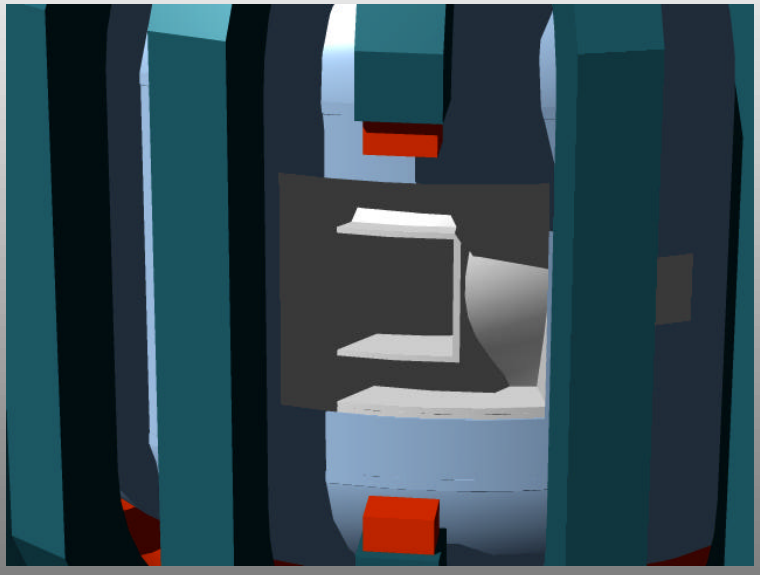


PBX-M Mockup

- Wooden mockup of PBX-M vacuum vessel and structure
- Modular design includes 90 degree sector with
  - Vessel envelope
  - 16” x 40” access port
  - Internal I-beam structures
- Provisions for adding internal structure, windings

PBX-M Port Opening

- Current, planned opening is 16”x48”
- Removing coil case sides gains 2” in width
- If one TF coil removed or “jointed”, opening can be enlarged to 48”x48”
- Option to rotate internal structures during assembly being explored



Pre-Conceptual Design Cost Estimate Updated

- **Cost dropped $5.9M to $29.8M**
- **Technical changes**
  - **Changes in liner concept**
  - **Elimination of F-H coils**
  - **Reduced number of electrical circuits**
  - **Deferred re-work of C-site MG set**
  - **Added use of PLT bay as staging and laydown area**
- **Re-estimates**
  - **Project Mgmt & Support (WBS 9)**
  - **PPPL labor rates and indirect costs**
- **Accounting adjustments**
  - **Conceptual design excluded from TPC and reduced allocations**
- **Needs to be updated for c10 plasma and new design concepts**

WBS	Original Estimate (FY-99K$)	Current Estimate (FY-99K$)
1 – Torus Systems	$14,092K	$12,589K
2 – Auxiliary Heating Systems	$ 1,421K	$ 1,468K
3 – Fueling & Vacuum Systems	$ 58K	$ 62K
4 – Power Systems	$ 3,499K	$ 1262K
5 – Utility Systems	$ 299K	$ 322K
6 – Central I&C Systems	$ 1,965K	$ 2,113K
7 - Diagnostics	$ 1,270K	$ 1,340K
8 – Site Prep/Startup	$ 1,398K	$ 1,993K
9 – Project Mgmt & Support	$ 4,543K	$ 6,358K
Contingency @ 25%	$7,137K	$ 5,797K
Subtotal	$35,689K	$33,303K
Accounting Adjustments		($3,521K)
Total	$35,689K	$29,783K

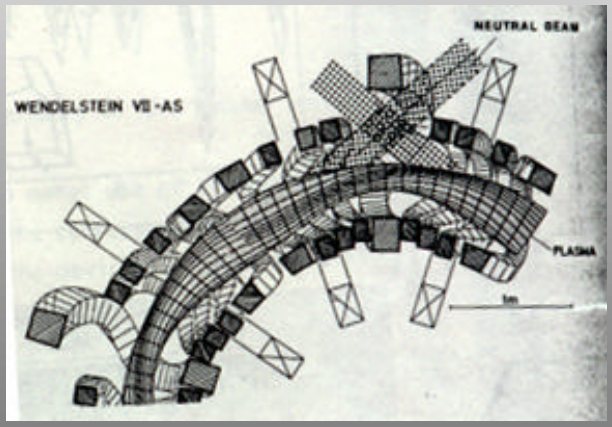
Cost Comparisons with Similar Projects in Progress

- **Purpose is to establish gross reasonableness**
- **NSTX comparison complete**
- **ATF, W VII-AS, and HSX costs are being tallied, normalized to FY99$, and reviewed**

WBS	NCSX (FY-99K$)	NSTX (FY-99K$)
1 – Torus Systems	$12,589K	$ 8,904K
2 – Auxiliary Heating	$ 1,468K	$ 1,762K
3 – Fueling & Vacuum	$ 62K	$ 1,265K
4 – Power Systems	$ 1,262K	$ 2,012K
5 – Utility Systems	$ 322K	$ 570K
6 – Central I&C Systems	$ 2,113K	$ 2,131K
7 - Diagnostics	$ 1,340K	$ 1,111K
8 – Site Prep/Startup	$ 1,993K	$ 2,877K
9 – Proj Mgmt & Support	$ 6,358K	$ 3,764K
Subtotal w/o Contingency	$27,506K	$24,396K
Contingency @ 25%	$ 5,797K	
Subtotal	$33,303K	
Accounting Adjustments	($3,521K)	
Total	$29,783K	

New Machine Option

- **Built around c10 plasma**
  - **Amp-m substantially (2.5x) higher for modular coils**
- **W VII-AS configuration used as starting point**
  - **Modular coils**
  - **Planar TF coils for flexibility**
  - **New PF system for current drive, plasma shaping, and position control**
  - **Internal vacuum liner**



Wendelstein VII-AS

R=2.0m

WVII-AS

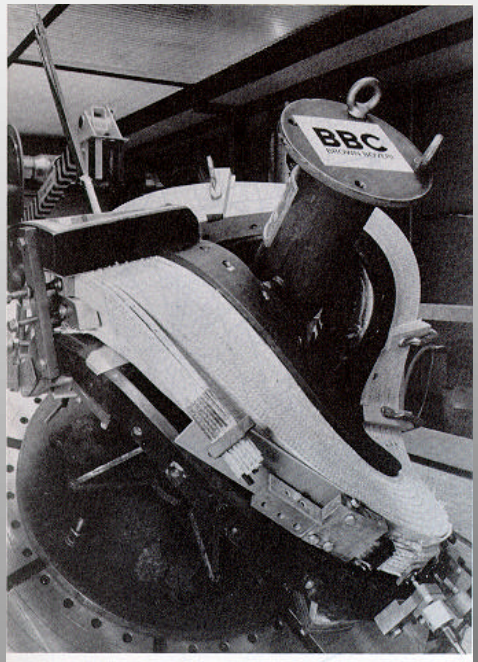


Fig. 8. Winding device and mold for a nonplanar coil.

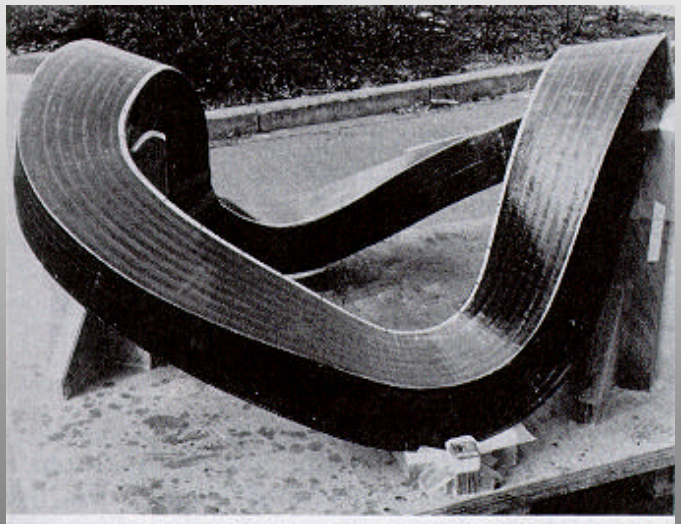
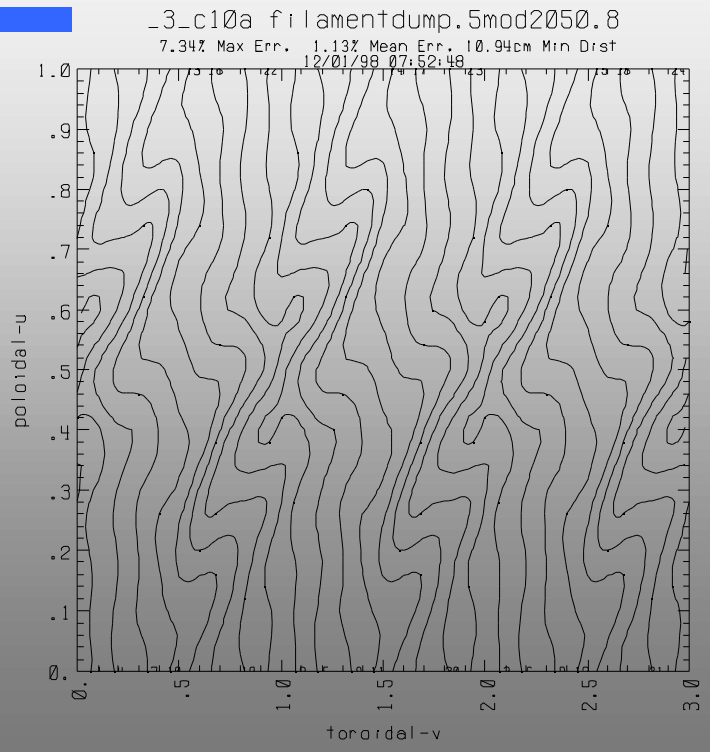


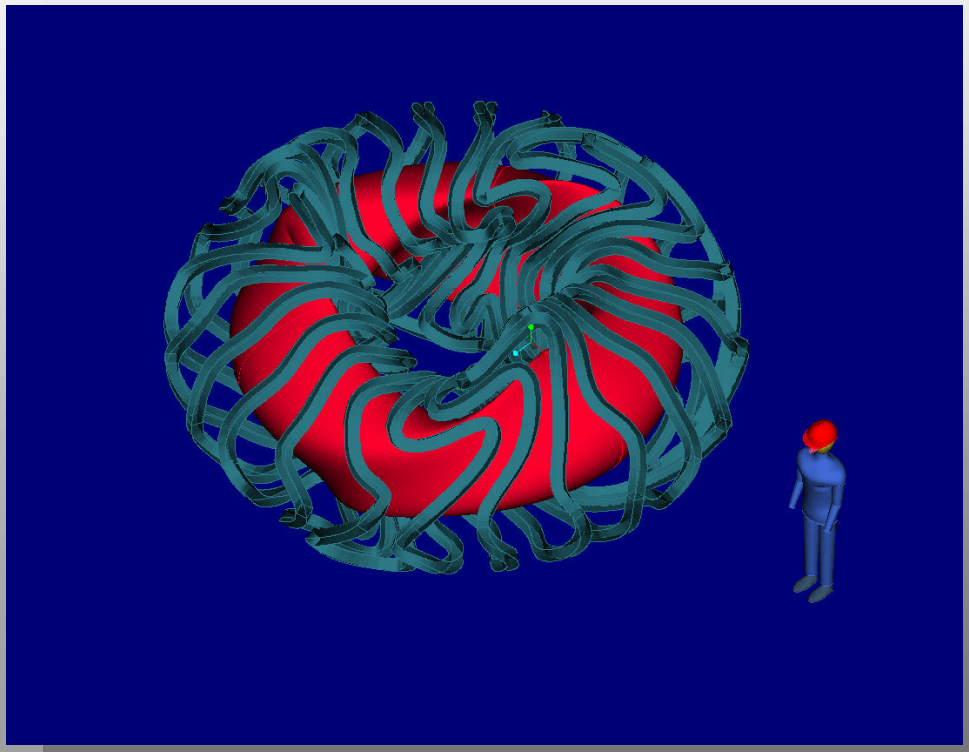
Fig. 9. Impregnated and cured coil.

More Work to Do on Modular Coil Design

- **Reconstruction is fair with 8 coils per period but...**
- **Coil geometry is convoluted in vicinity of "separatrix"**
- **Access is needed for tangential NBI**



Modular Coils and Plasma



Summary

- Design concept development has been focused on PBX options
- Several innovative options for constructing saddle coils have been developed
  - Pre-cooling with LN2 is being pursued to meet current density and pulse length requirements
  - Feasibility and affordability look promising
- An attractive concept for a bakeable liner has been developed
- Development of a new machine option is underway
  - WVII-AS configuration used as a starting point
  - More work needed on magnetic design of modular coils

Summary (2)

- **Development of the PBX and new machine options will continue for the purpose of establishing…**
  - **Satisfactory performance**
  - **Technical plausibility (including fabrication and assembly)**
  - **R&D requirements**
  - **Cost**

- **Selection of the reference option for conceptual design will be based on the above factors and perceived risks**