NCSX Stellarator Core

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Presentation outline

- **Introduction**
  - **Why build a compact stellarator?**

- **Component description:**
  For each major component
  - **What are the requirements?**
  - **What is our current concept?**
  - **What are the issues?**

- **Machine assembly**

- **Manufacturing studies, R&D**

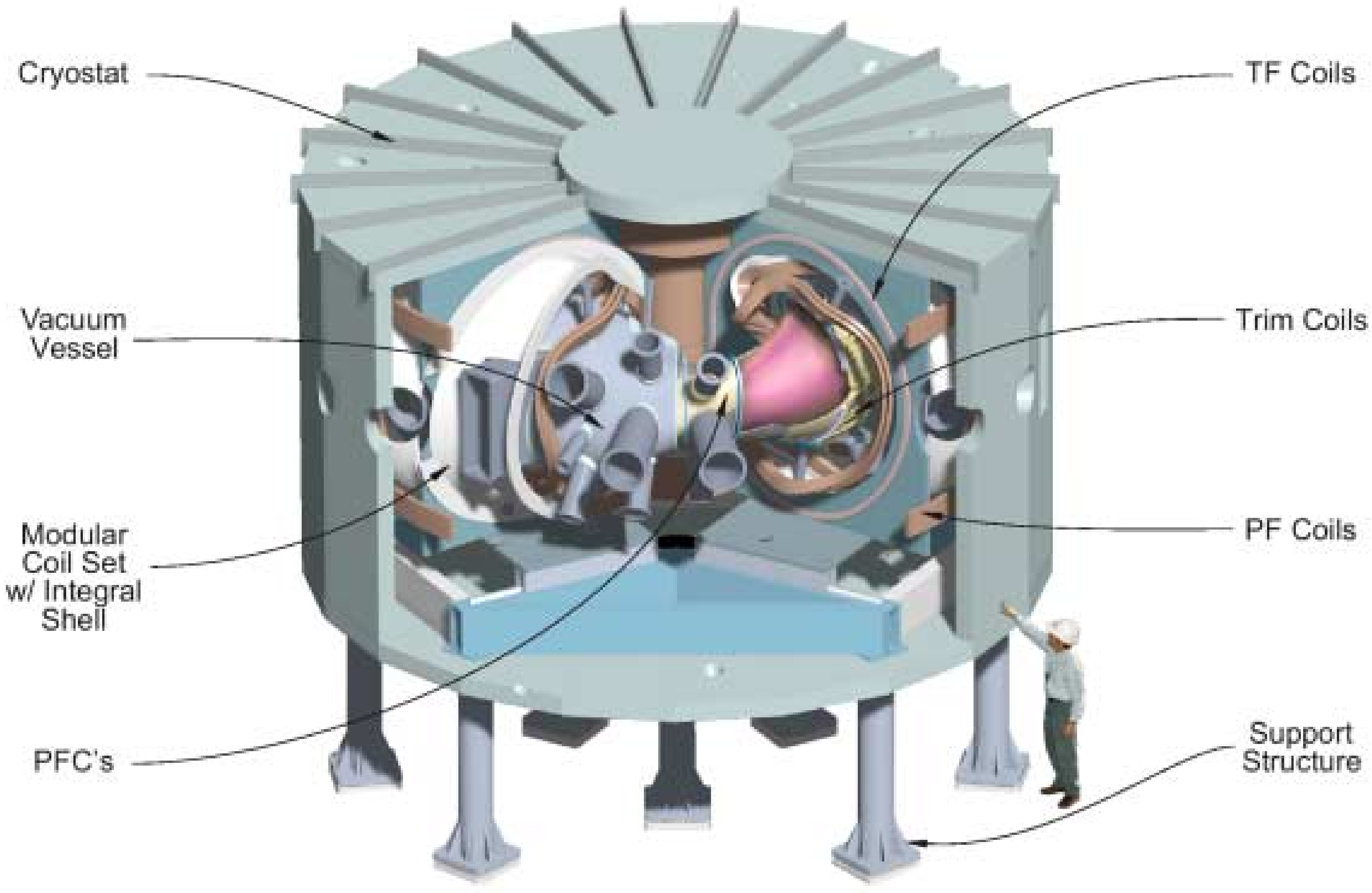
- **Summary**

Why build a compact stellarator?

- **Compact stellarators have tremendous promise, combining the best features of tokamaks and stellarators:**
  - **High beta (>4%) stability**
  - **Excellent confinement**
  - **No tokamak-like disruptions (no VDEs, much smaller plasma current)**
  - **No current drive required for steady state operation**
  - **No conducting wall or feedback system required to stabilize external kink modes**
  - **Vertical stability without a conducting wall or feedback system, even in highly elongated plasma configurations**
  - **Low aspect ratio resulting in high power density and improved economics**

- **Compact stellarators require 3-D shaping of the last closed magnetic flux surface, and a small bootstrap current to provide a fraction of the rotational transform.**

NCSX Stellarator Core concept



NCSX Basic parameters

Parameter	Value
Major radius (m)	1.4
Bmax, from mod coils (T)	2 (TBD)
No. of Modular coils	18
No. of PF coil pairs	5
TF coil configuration (no.)	+/- 0.5 T, 1/R (18) 0.17 T in ref scenario
RF launcher options	Inboard @ v = ½
Ports: @ v = 0 (0 deg) @ v = ½ (60 deg)	Tang., radial, vertical Radial and vertical
PFC configuration	CFC / divertor panels close to VV wall

Modular coil requirements

- **Meet performance requirements**
  - **1.7 T scenario with 0.46s flattop**
  - **1.2 T scenario with 1.24s flattop**
  - **2.0 T with reduced pulse length**
  - **15 minute rep rate (5 minute rep rate for short pulse)**

- **Provide flexibility**
  - **Independent control of modular and PF coils provided**
  - **Variable background TF field**

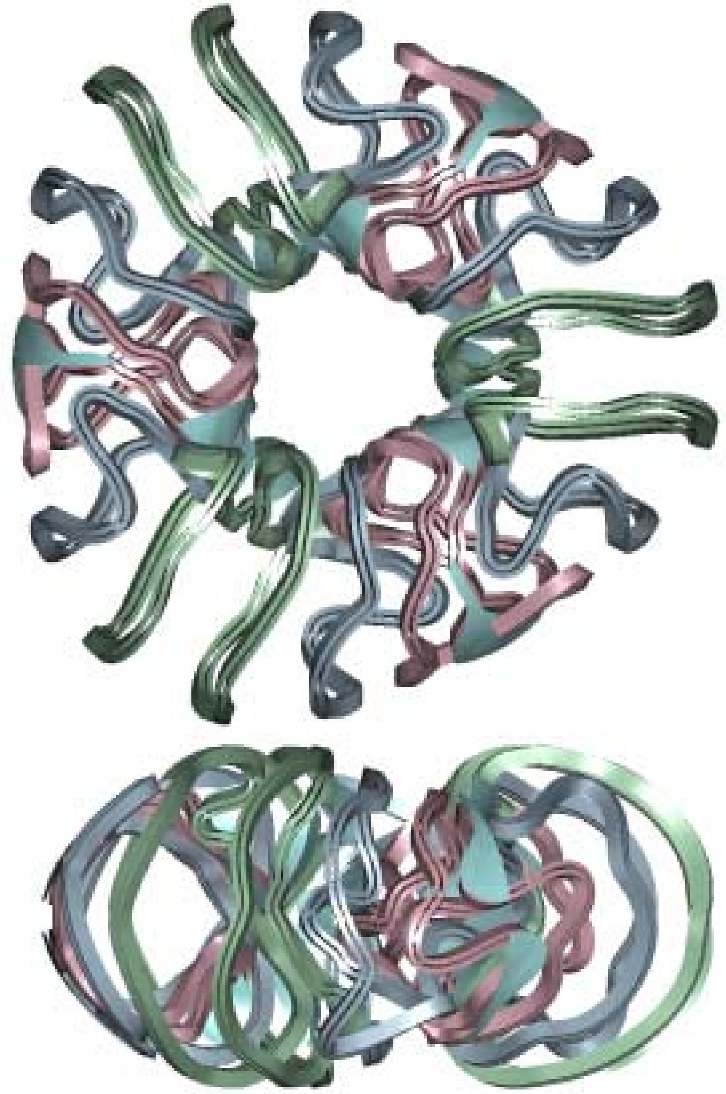
- **+/- 1.5 mm assumed for installed winding accuracy**

- **Coils must provide access for tangential NBI, RF, vacuum pumping, diagnostics, and personnel access**

- **Limit conductor current to ~ 24 kA peak to match with existing TFTR power supplies**

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**



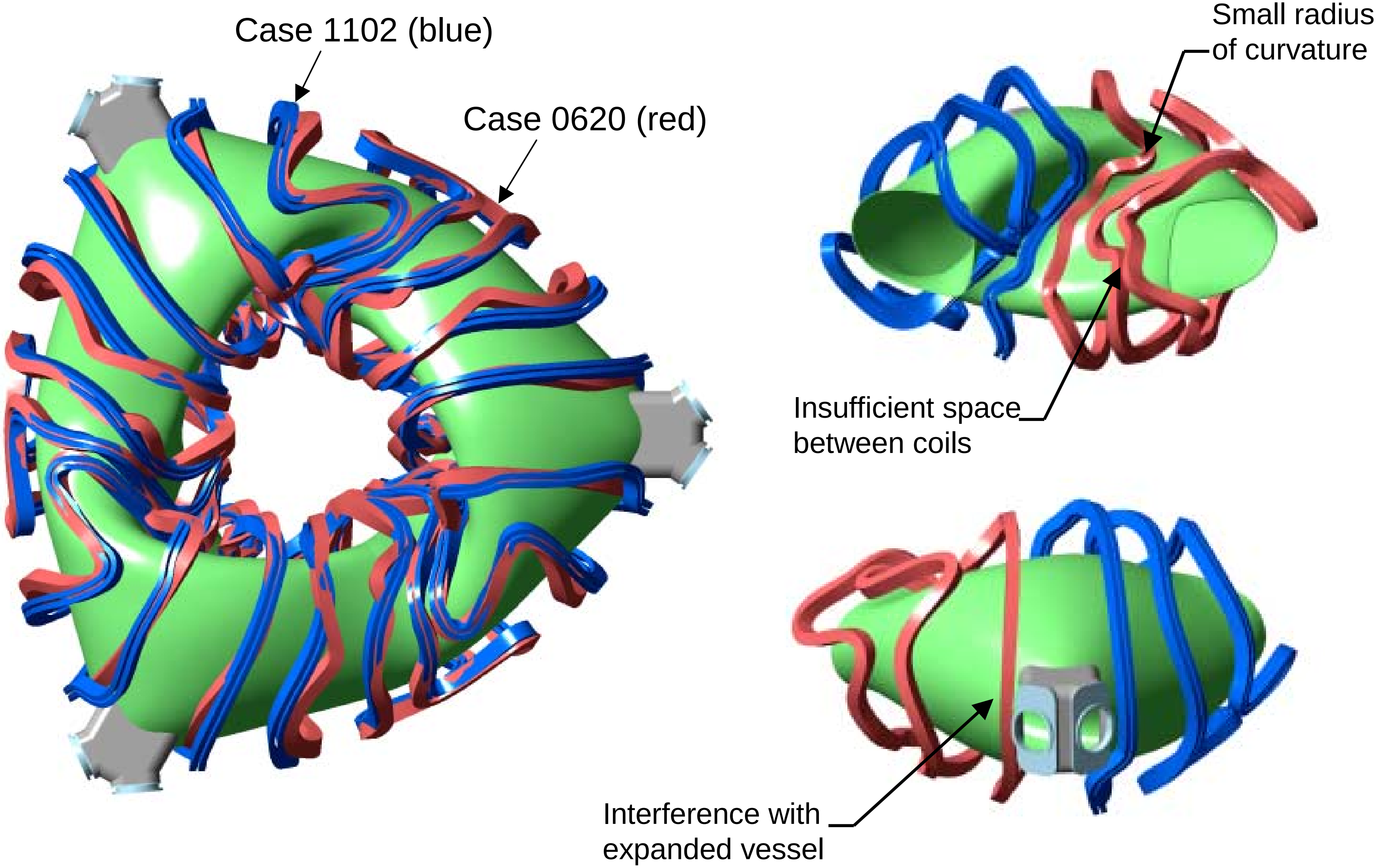
Coil geometry optimized for physics and engineering properties

- **COILOPT and STELLOPT codes merged, so plasma and coils are optimized simultaneously**

- **Incorporation of engineering constraints in optimizer has improved winding properties**

  - **Smoother winding surface**
  - **More space between coils (lower current density)**
  - **More clearance to plasma**
  - **More clearance for NBI**

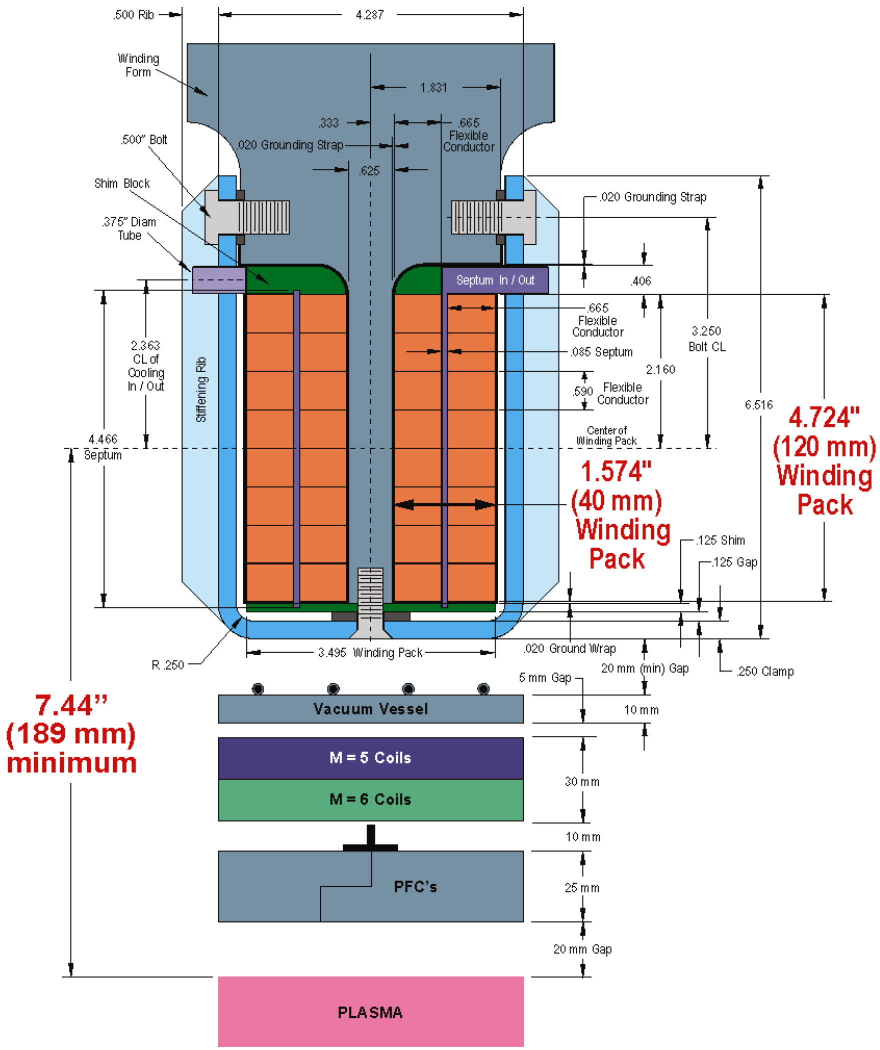
Example of coil improvement using optimization codes and engr. constraints



Continuous shell forms robust structure

- **Shell consists of individual modular coil forms that are bolted together**
- **Penetrations for access are provided wherever needed**
- **Preliminary stress analysis of shell has been performed**
  - **Stresses are well within allowables except for a few localized “hot spots”**
  - **Local problems can be solved with minor changes in local thickness**

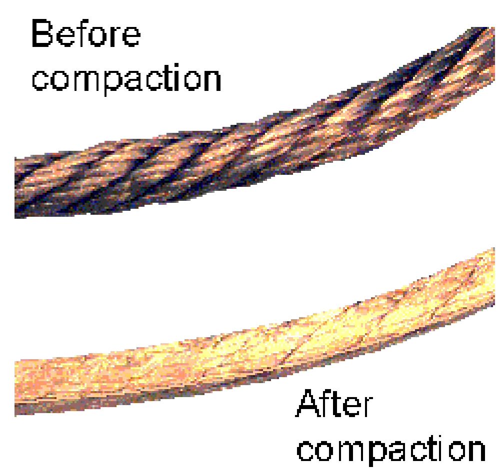
Modular coils wound with flexible cable directly on coil structure



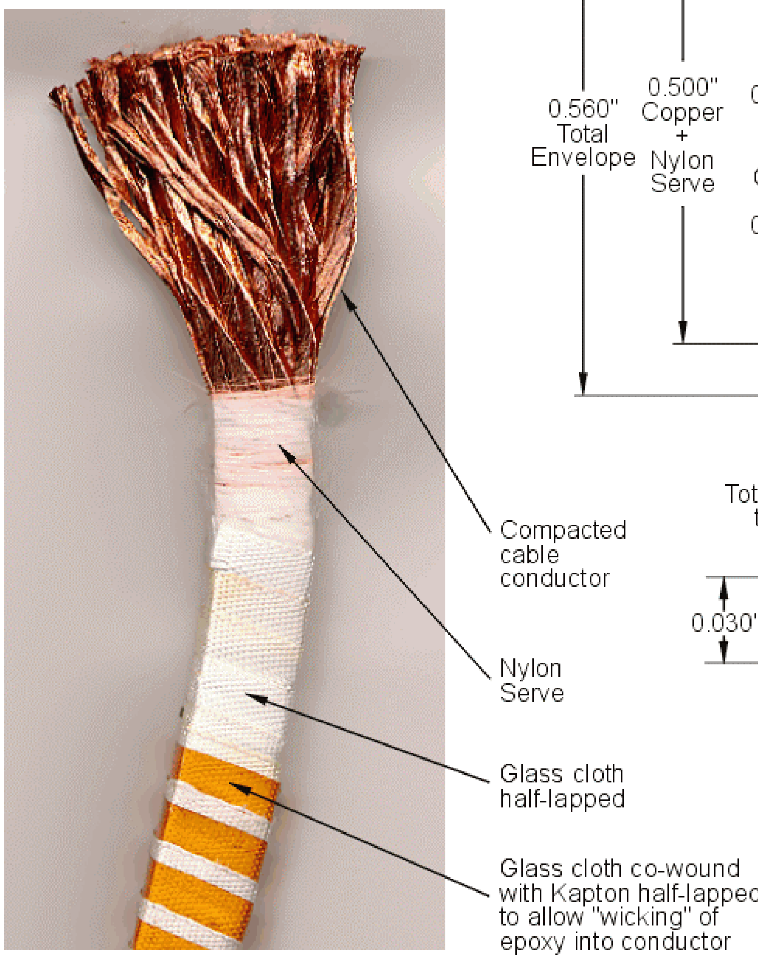
Parameters:

- Coil Envelope = 2 x 110 x 40 mm
- Current / Coil = 649-kA @ 2-T
- Number of Turns = 32
- Nominal current / turn = 20.3 kA
- Conductor Size = 13 x 16 mm
- Net Current Density = 13-kA/cm2
- Total peak power ~ 40 MW

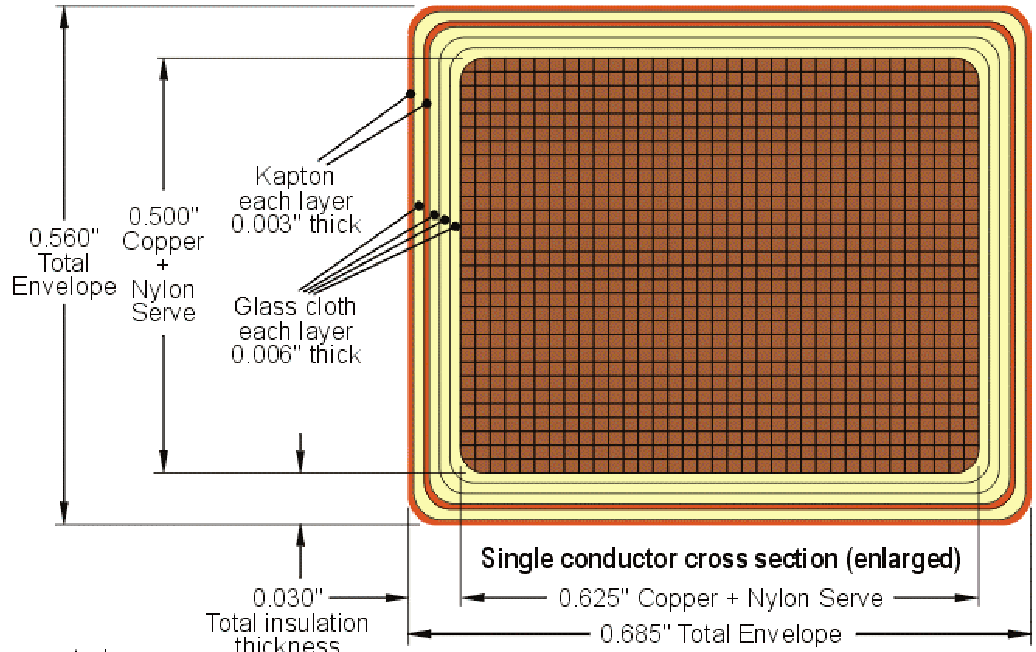
Flexible cable used to wind coil



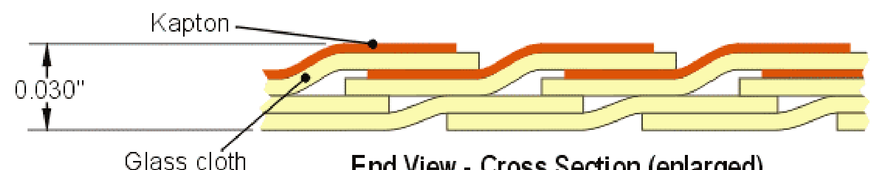
Cable insulation scheme



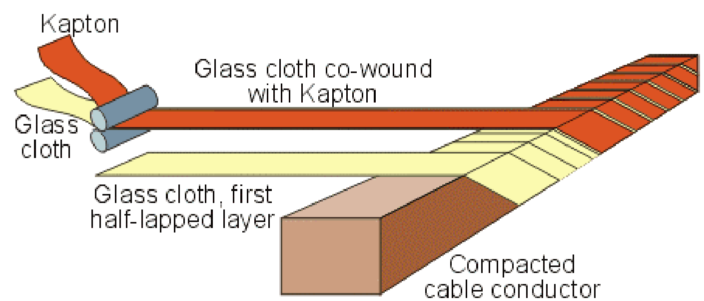
Photograph of actual conductor sample showing insulation components



Single conductor cross section (enlarged)



End View - Cross Section (enlarged) showing half lapped winding concept



Modular coil manufacturing sequence

- **Continuous support for strength and accuracy of windings**
- **Shell segments repeat 6 times**

Rough casting

Features are machined

Conductor wound directly into structure

Auxiliary support clamps are installed

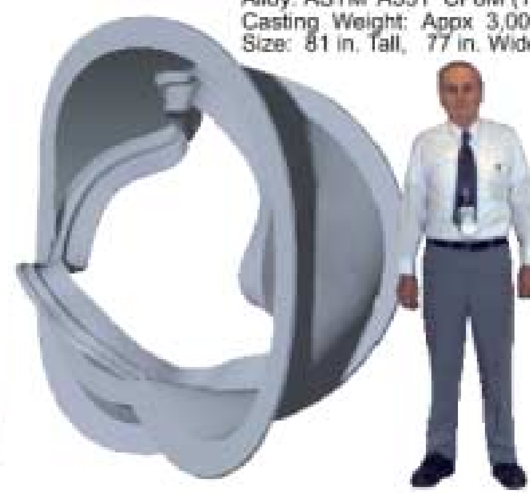
note: PVR geometry

Modular coil-form castings are within present state-of-the-art

Pulper Rotor
Alloy: Grade 318 (Modified CF8M)
Casting Weight: Appx 6,500 lb.
Size: 6 ft. Dia, 8 ft. High

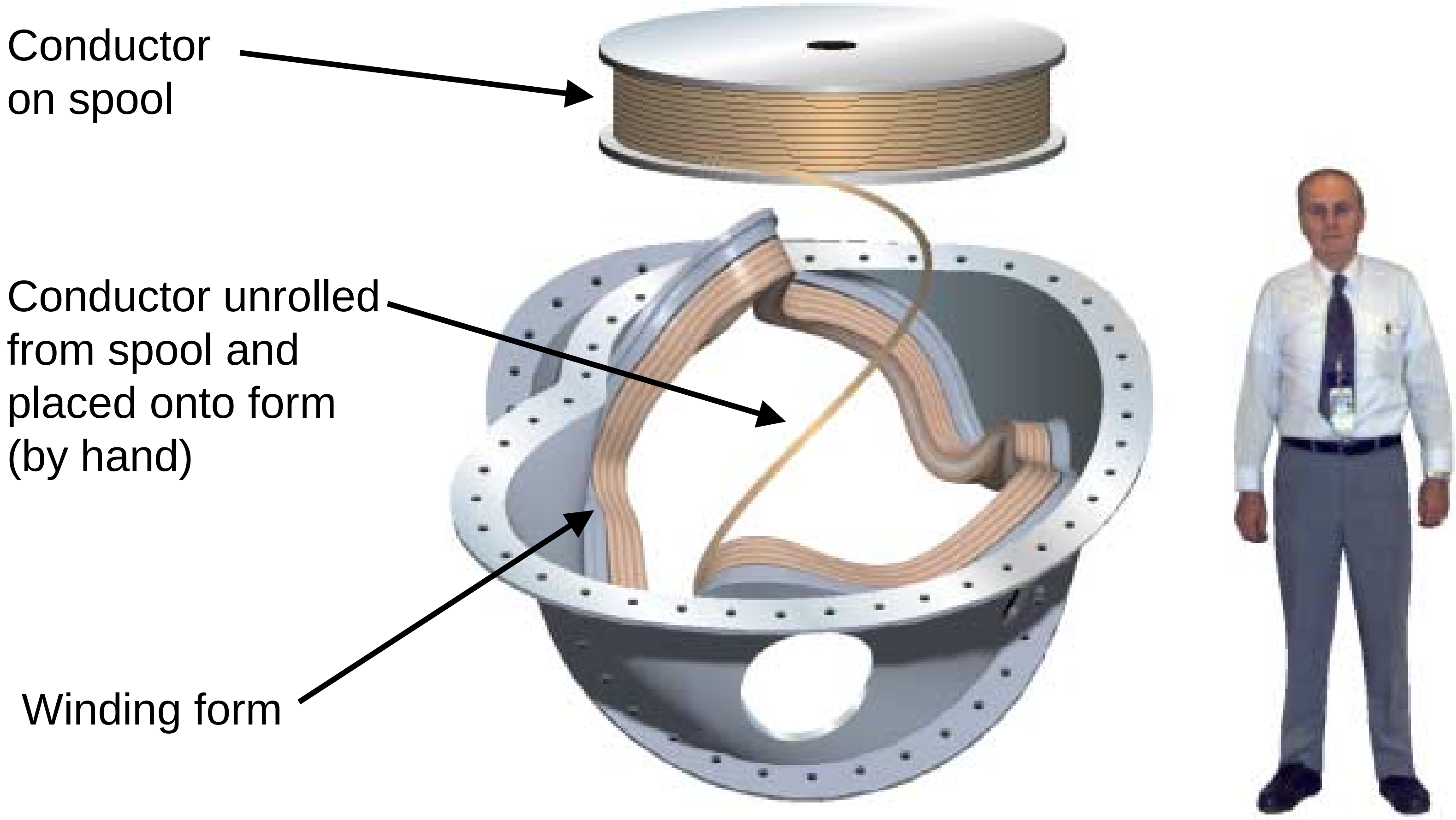
Vertical Pump Impeller
Alloy: ASTM A743 CD4MCU
Cast Weight: Appx 8,000 lb.
Size: 5 ft. Dia, 4.5 ft. High

Coil Winding Form
Alloy: ASTM A351 CF8M (TBD)
Casting Weight: Appx 3,000 lb.
Size: 81 in. Tall, 77 in. Wide

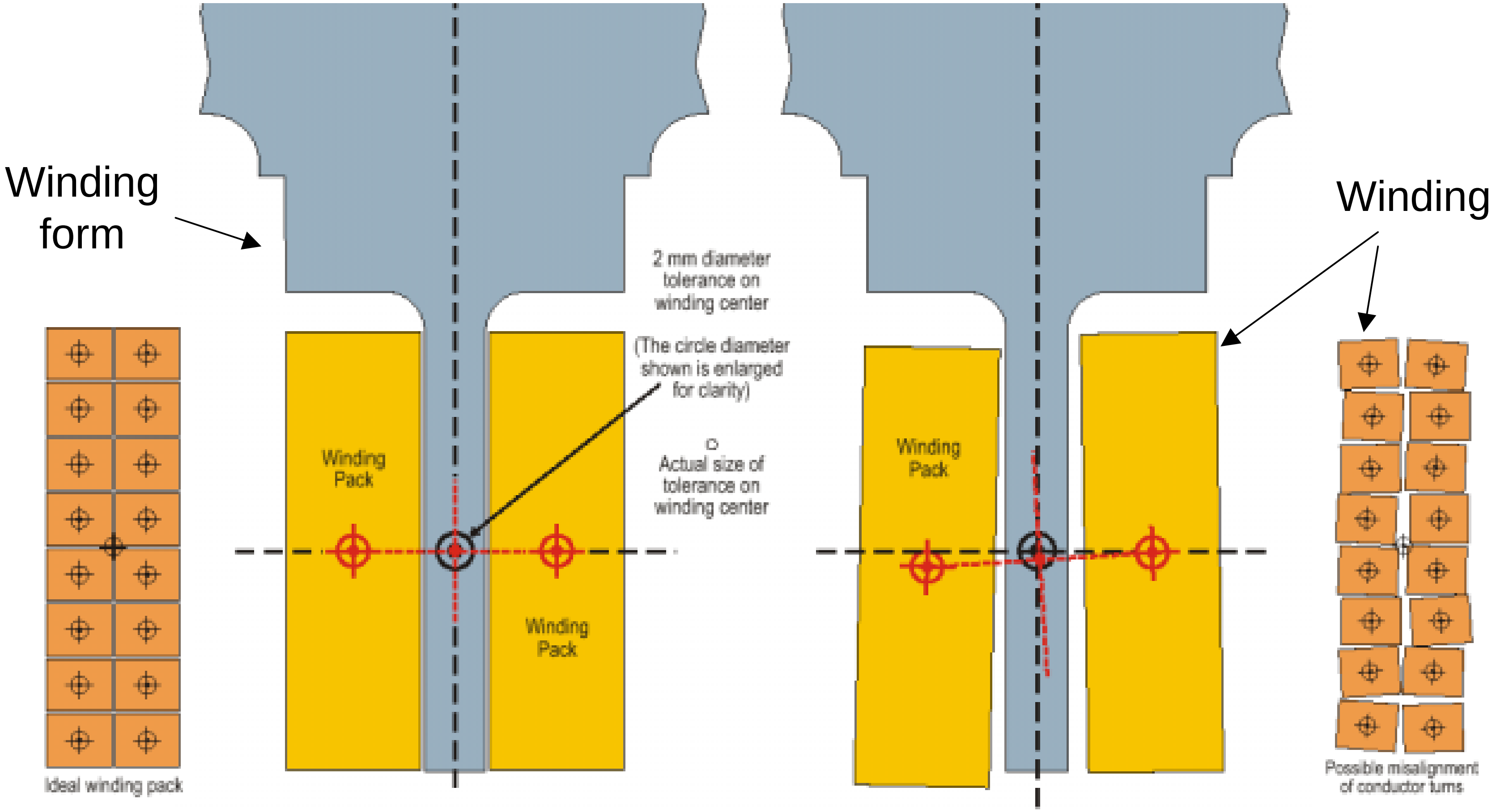


W7-X Coil Winding Form
Alloy: G-X2CrNiMoN 18 14

Modular coil winding process

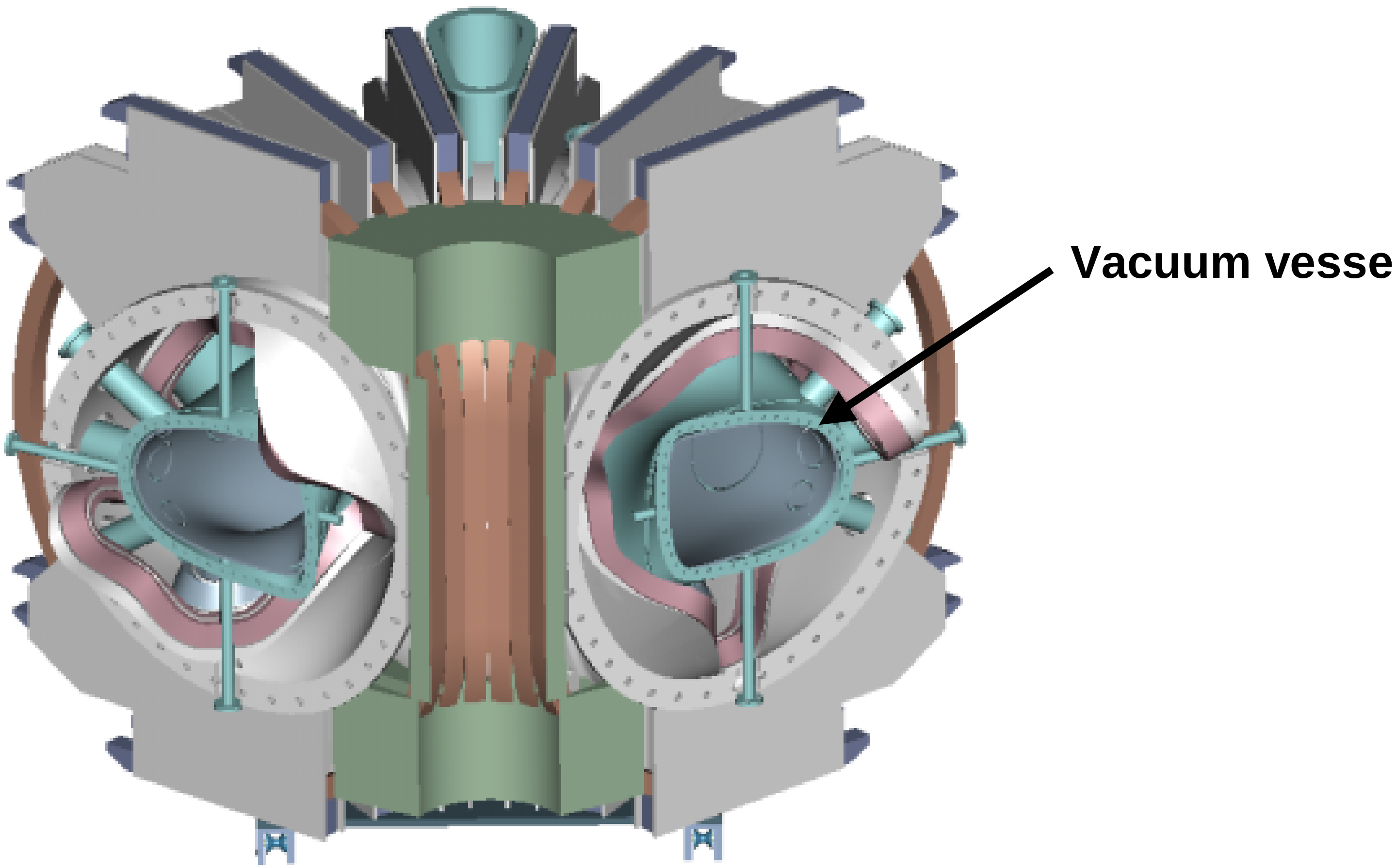


Modular coil accuracy requirement based on current center of winding



theoretical geometry **possible geometry**

The vacuum vessel must fit inside the modular coil set



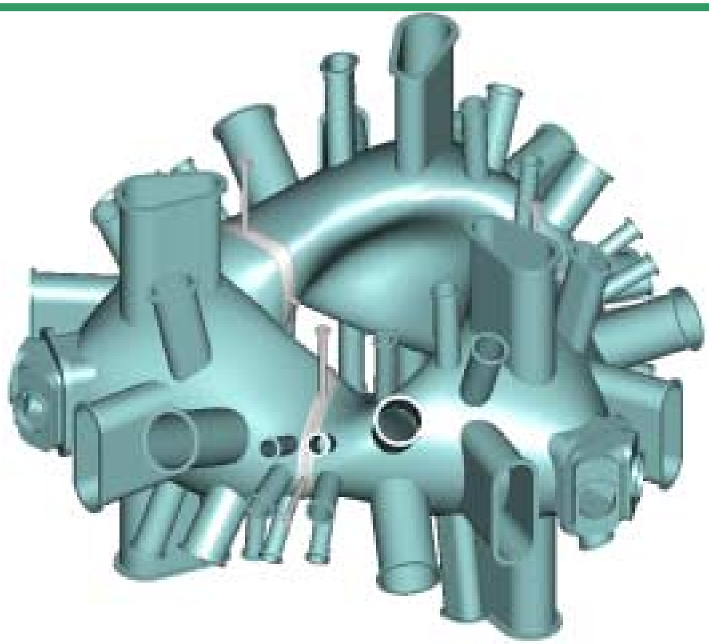
PVR illustration

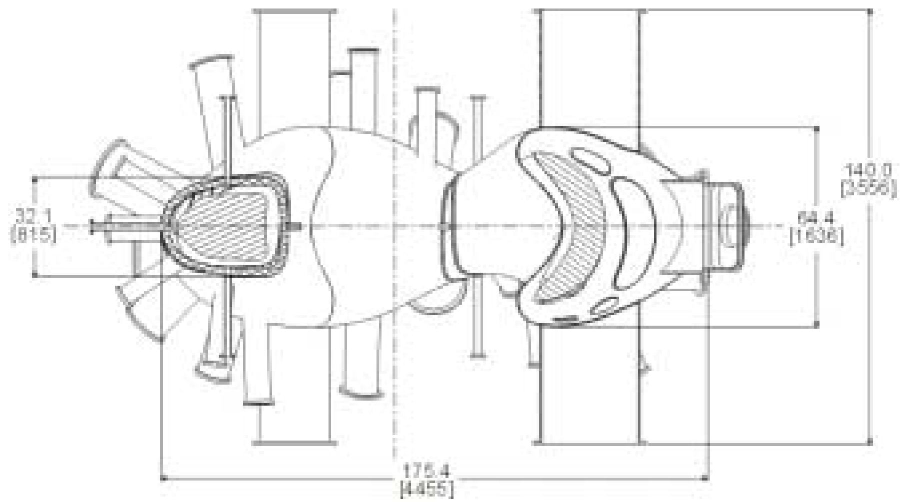
Vacuum vessel requirements

- **Vessel must be bake-able to 150 C**
- **Low permeability (< 1.02 nominal goal)**
- **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 internal liner, trim coils, magnetic sensors**
- **Provide access ports for diagnostics, vacuum pumping, heating systems, and personnel access**

Vacuum vessel design concept

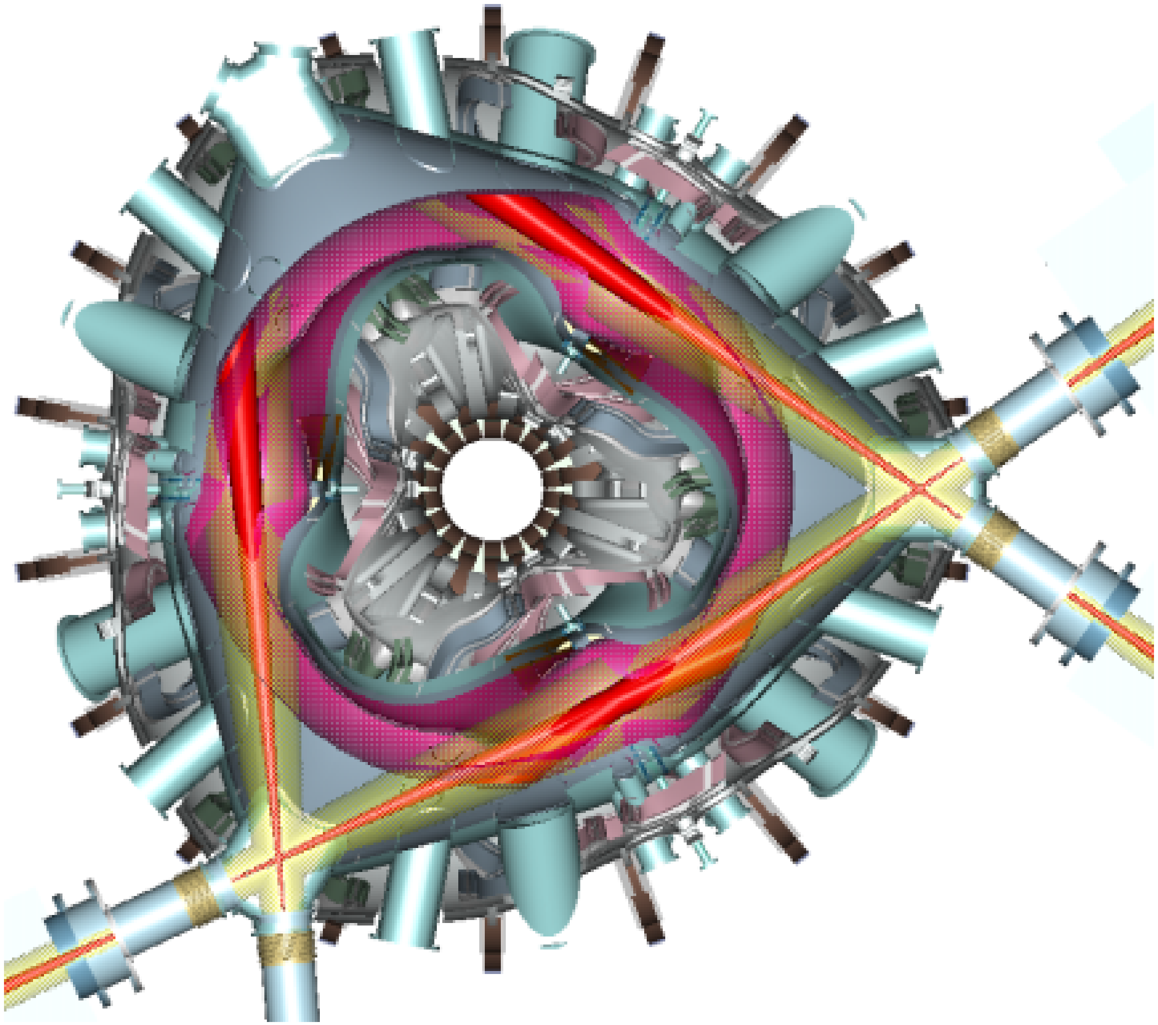
- **Shell material** **Inconel 625**
- **Thickness** **.375 inch**
- **Time constant** **< 10 ms**
- **Total wt w/ports** **~ 12000 lbs**
- **Bolted joints connect field periods**
- **Traced with He gas lines for heating (to 150C) and cooling**
- **Combination Microtherm and Solomide foam insulation between VV and cold mass**



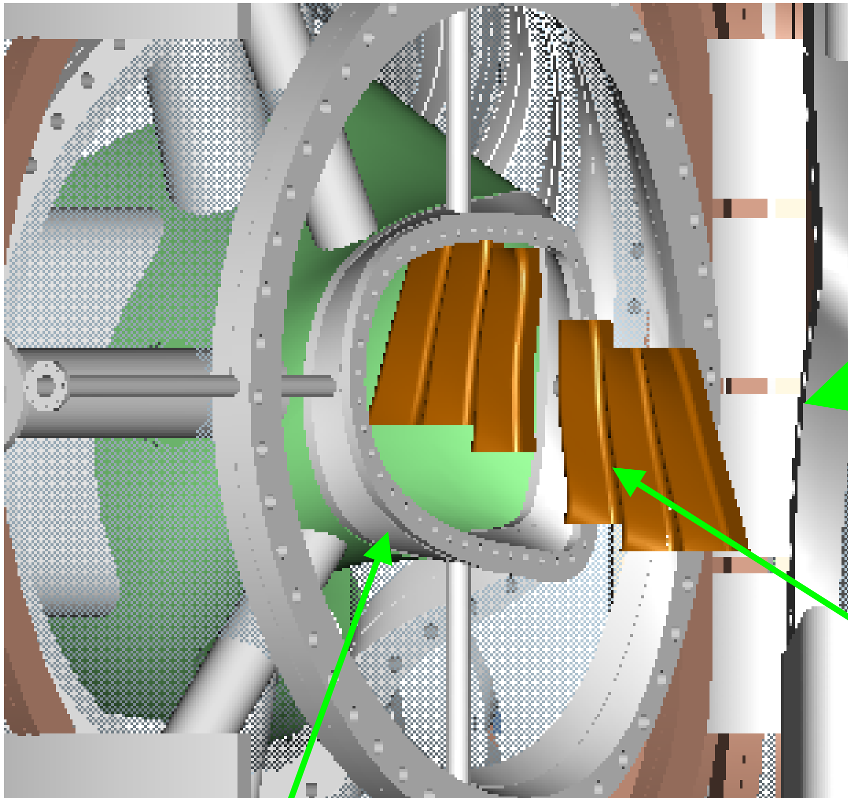


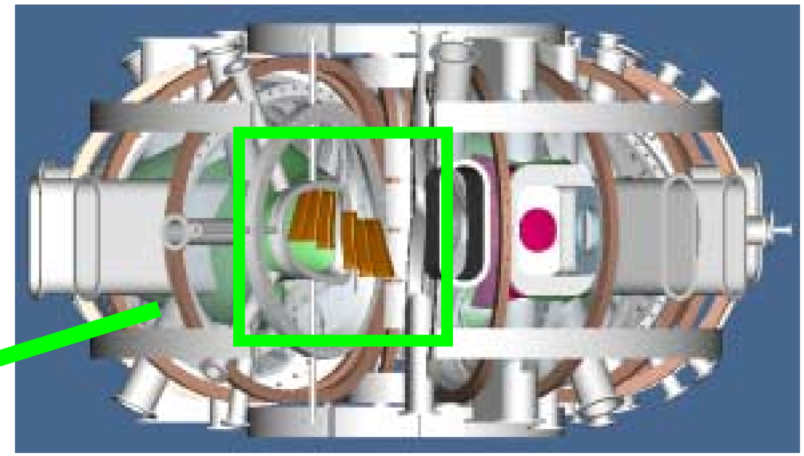
Access for tangential NBI

- **Up to 4 neutral beams in combinations of co- and counter-**
- **Vacuum pumping through NB ducts**



RF launchers accommodated + radial access at v = ½ planes





RF launcher array

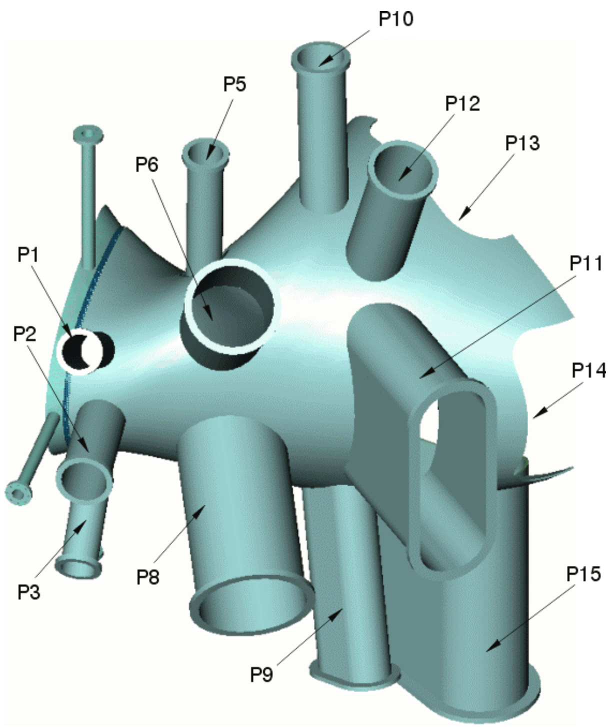
Inboard around v = ½ plane

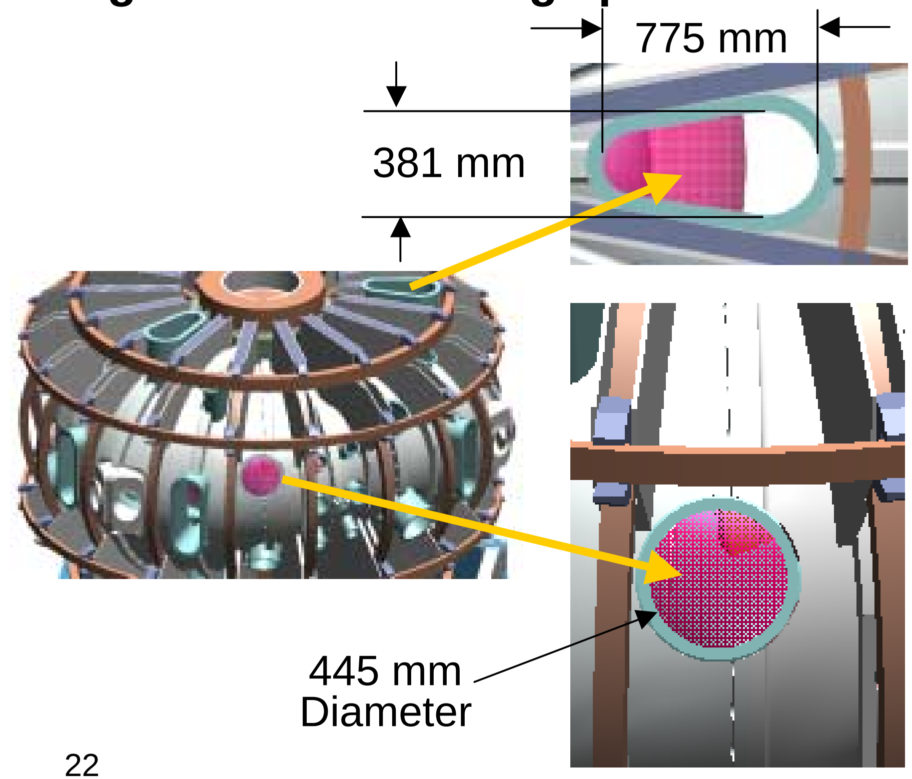
“spacer” at VV joint

for radial diagnostic views

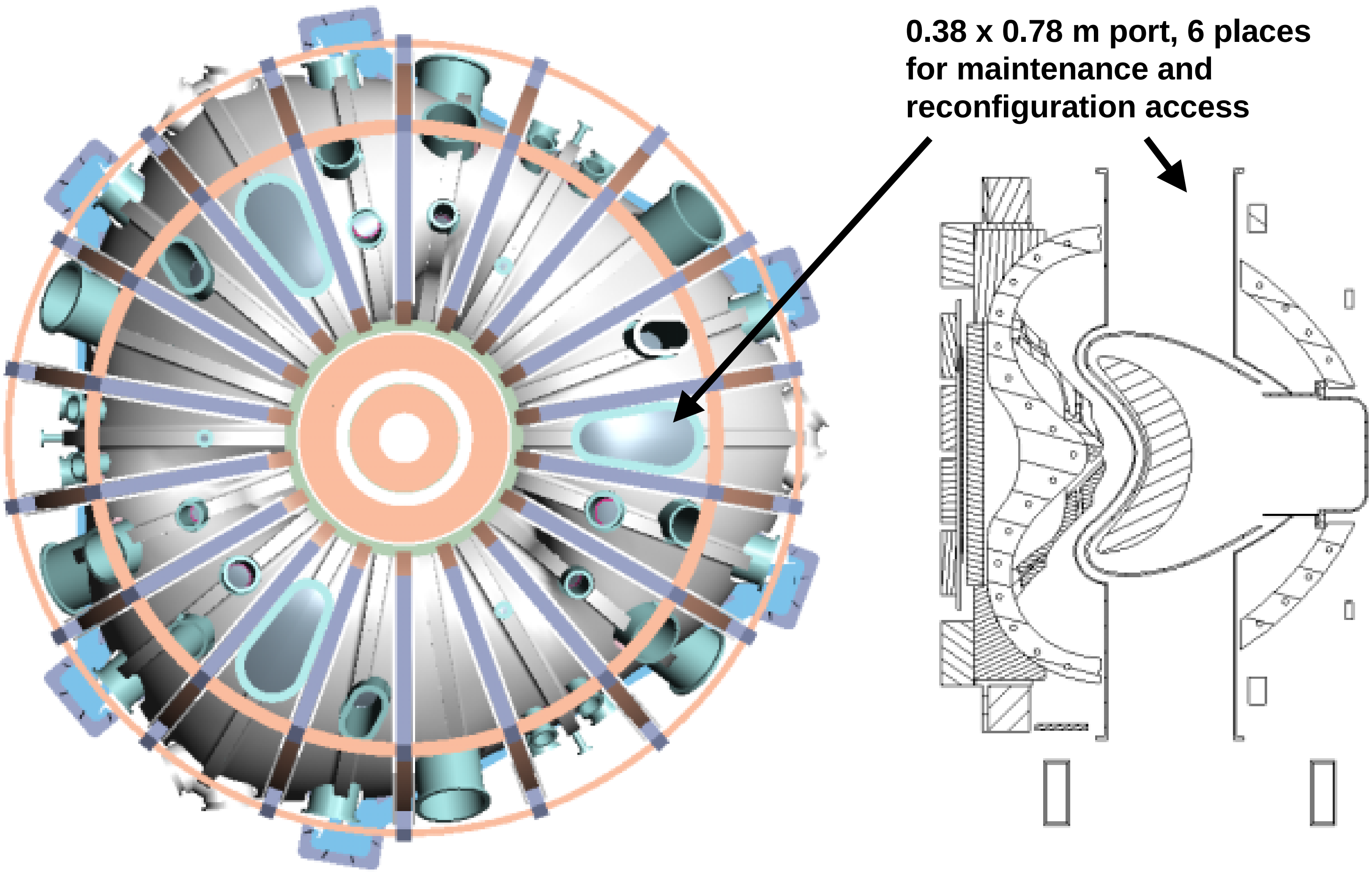
Diagnostic and personnel access

- **90 separate ports for ~100 different diagnostics**
  - **The number and sizes of ports appear to match diagnostic requirements**
  - **Geometric requirements for specific diagnostics are being addressed**
  - **Ports are stellarator symmetric**
- **Personnel access available through NBI or other large ports**

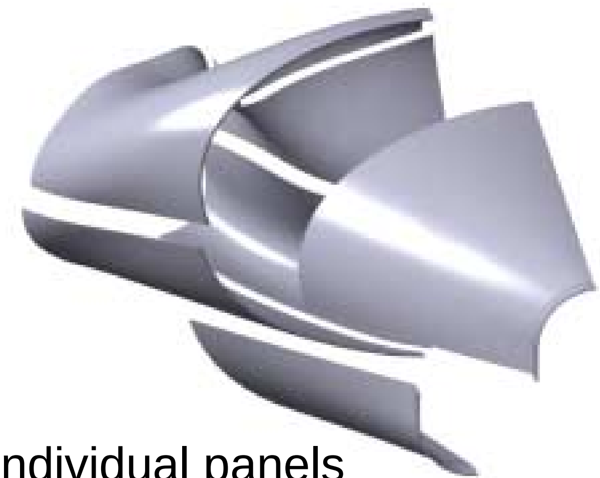




New coil set has improved access for maintenance



Vessel fabrication options include: press forming, explosion forming, or casting



Individual panels

Half field period

Full field period with port stubs

Half field period repeats 6 times to form complete shell

PVR illustrations

PFC requirements

- **Basic requirements**
  - **Initial system configured for ohmic operation**
  - **Accommodates carbon surfaces, bakeable to 350C**
  - **Staged to include NBI armor, trim coil armor, inboard limiter / coverage, divertor plates, energetic ion loss armor**
  - **Geometry insures long connection length (> 120 m) for field lines**
  - **Provide penetrations, accommodate in-vessel diagnostics mounted on VV**

- **Ultimate capability**
  - **Full coverage of surfaces with carbon**
  - **12 MW for 1.2 s**
  - **Provision for divertor baffles and pumping**

PFC design concept

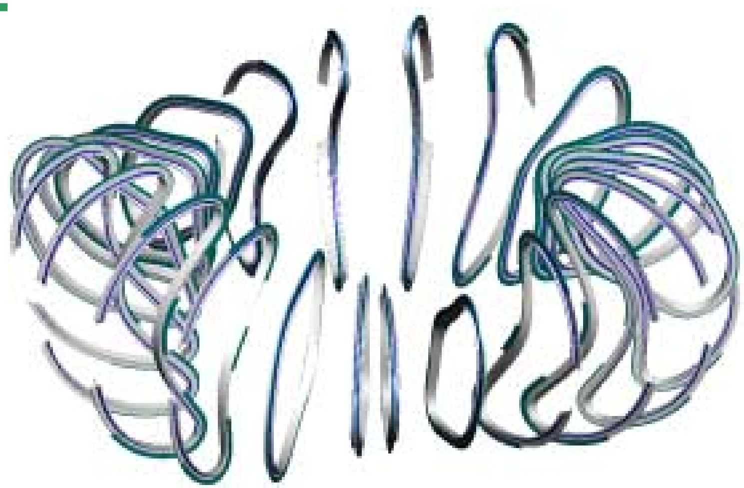
- **Staged implementation planned**
  - **Initial coverage with low Z tiles mounted on poloidal ribs to form array of poloidal limiters**
  - **Panels for NB armor and divertor region will be provided for initial auxiliary heating**

- **Full coverage provided by mounting molded carbon fiber composite (CFC) panels on poloidal ribs**
  - **Panel size based on advice from BFG aerospace (~ 60 cm square, 1 cm thick)**

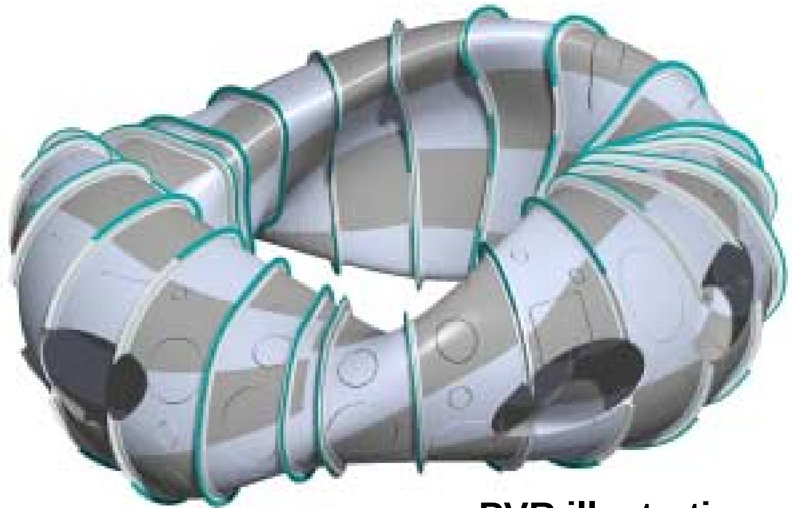
- **Ribs are separately cooled / heated with He gas for bakeout (350C) and normal operation**

- **Ribs are registered toroidally to VV but allowed to grow radially and vertically**

Poloidal ribs



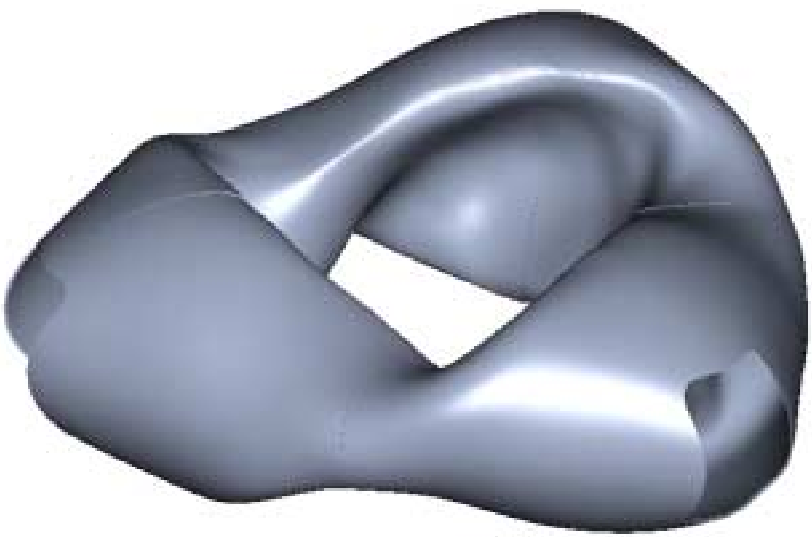
CFC panels mounted on poloidal ribs



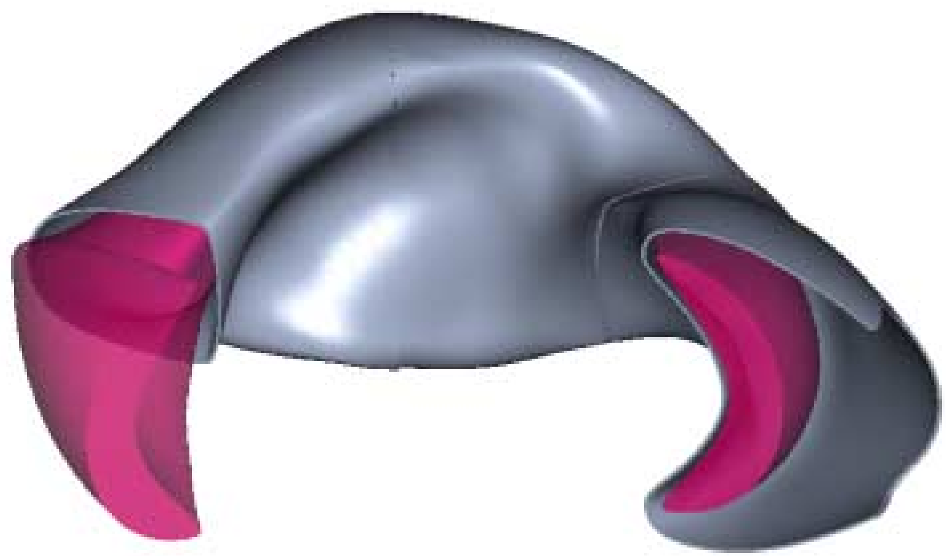
PVR illustration

PFC envelope maximized inside vessel

- **PFC envelope is pushed out to vessel wall to provide maximum plasma shape flexibility**
- **Divertor envelope is still evolving, but baffles for neutral particle control will be accommodated**

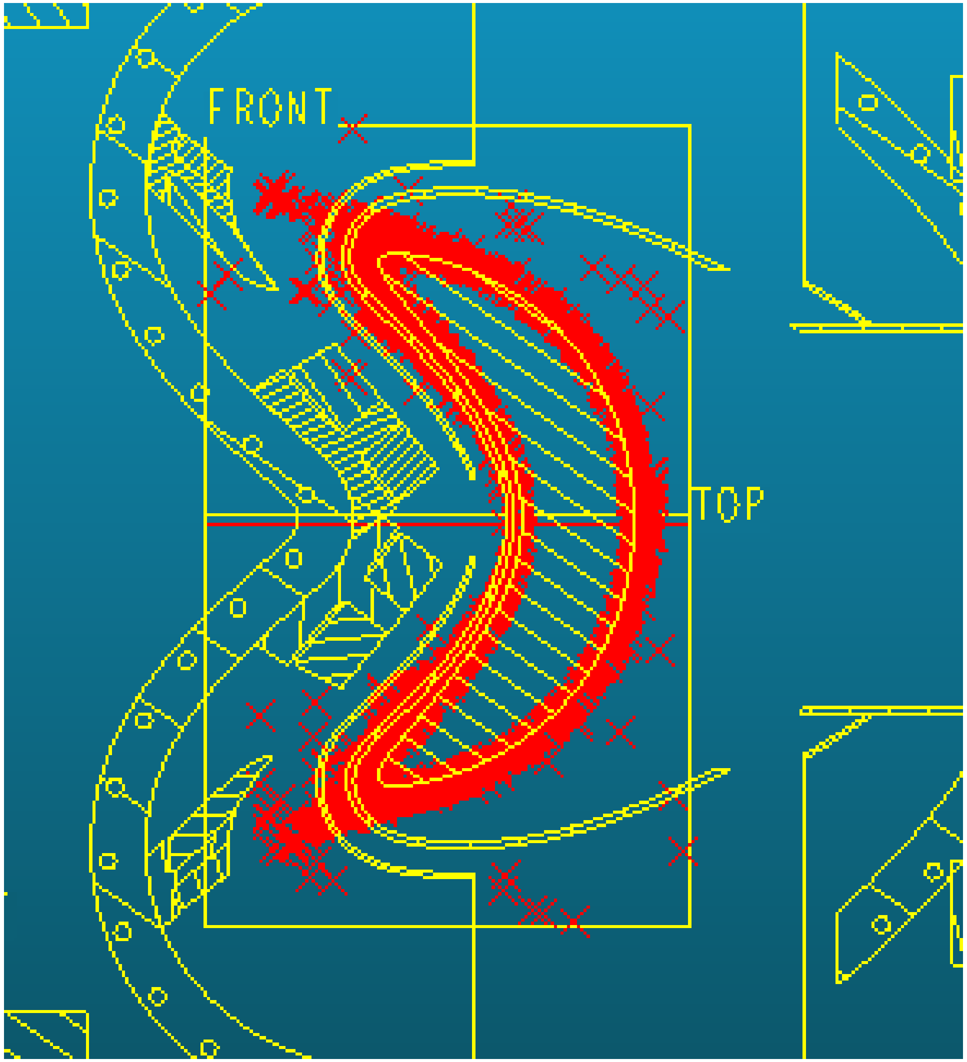


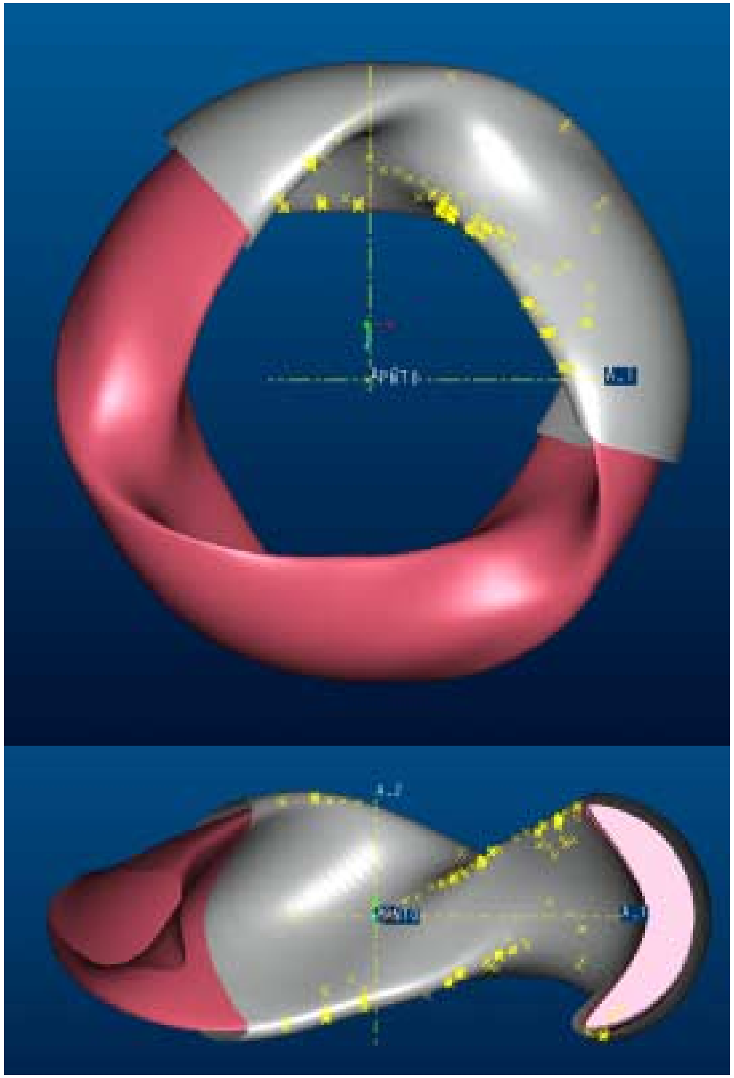
PFC envelope



PFC envelope with plasma

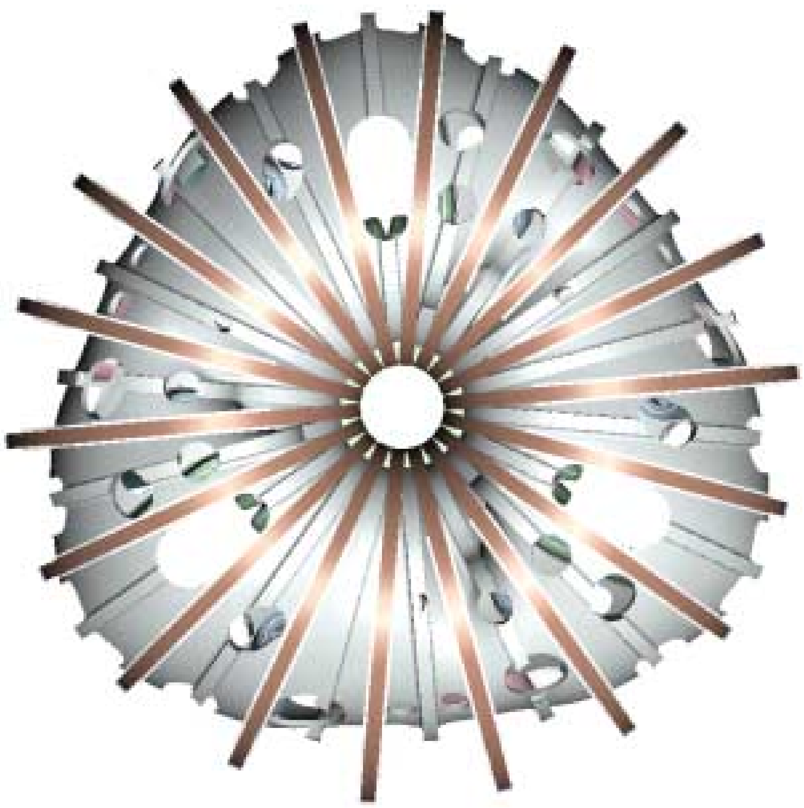
Field lines tend to stay in FW region except in "bean tips"

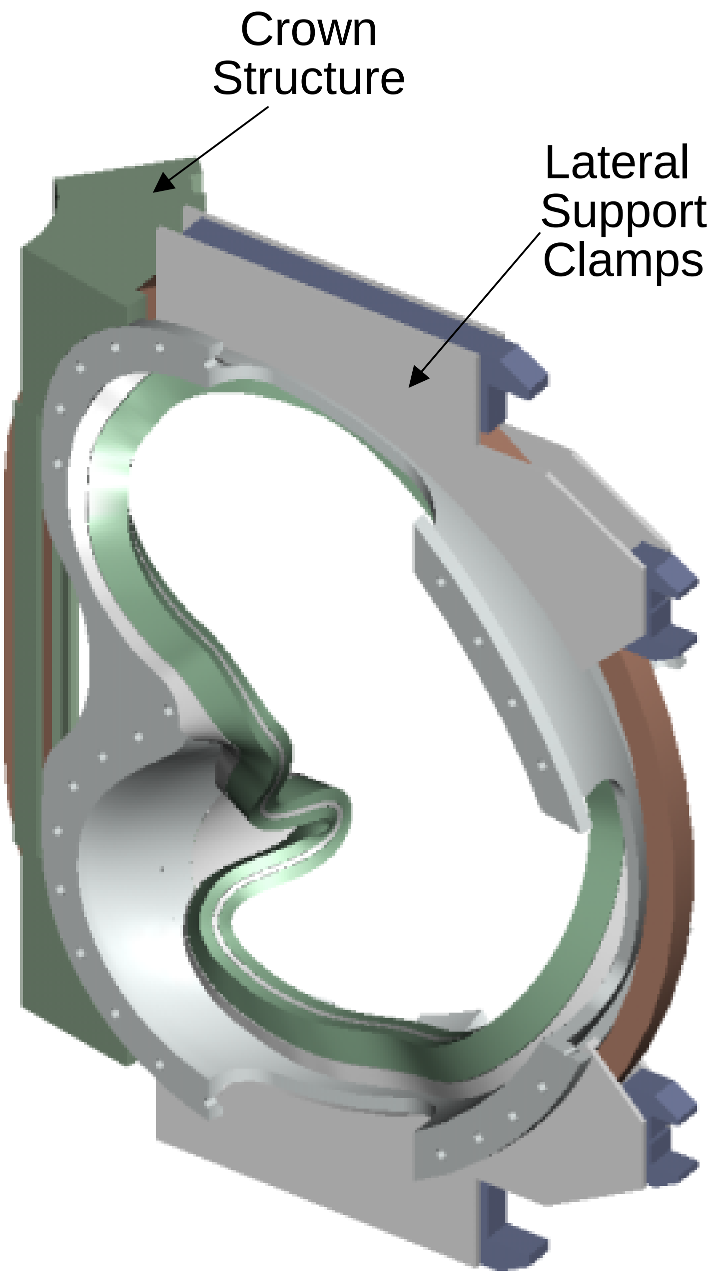




TF Coils

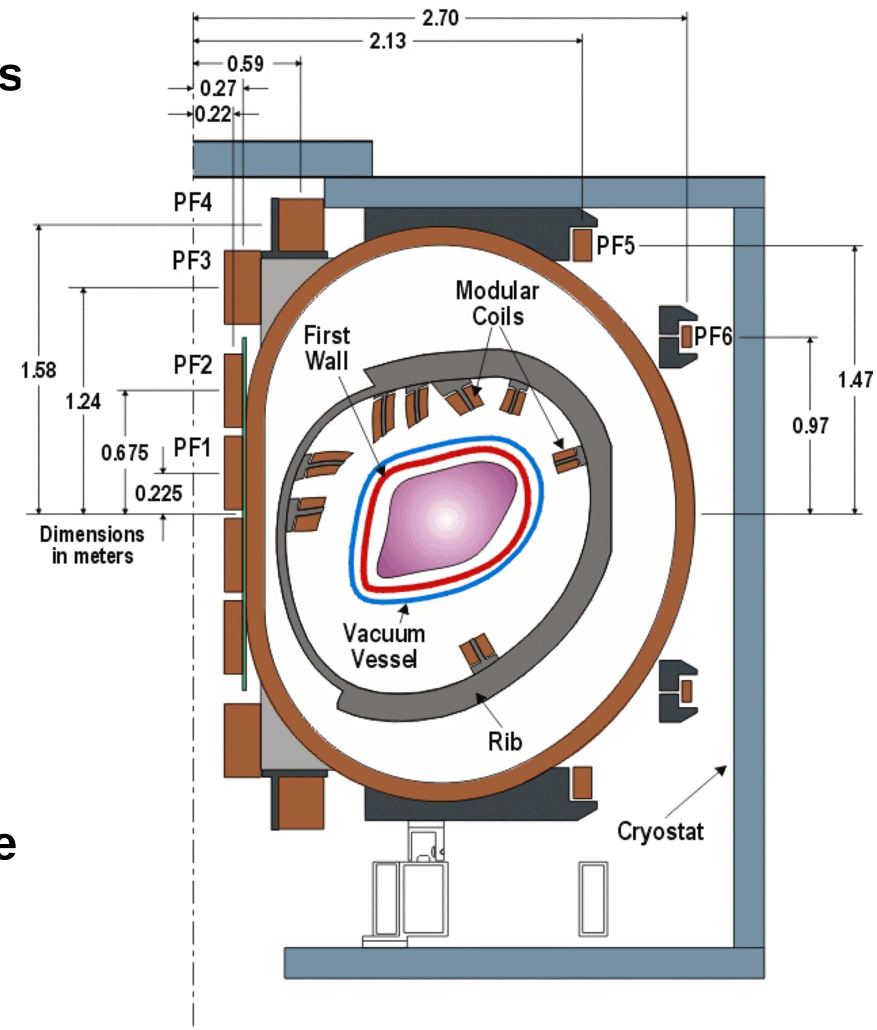
- **18 coils provide +/- 0.5 T**
- **Supported from modular coil shell**
- **Wound from hollow copper conductor**
- **Pre-cooled to LN_2 temperature (like modular coils)**





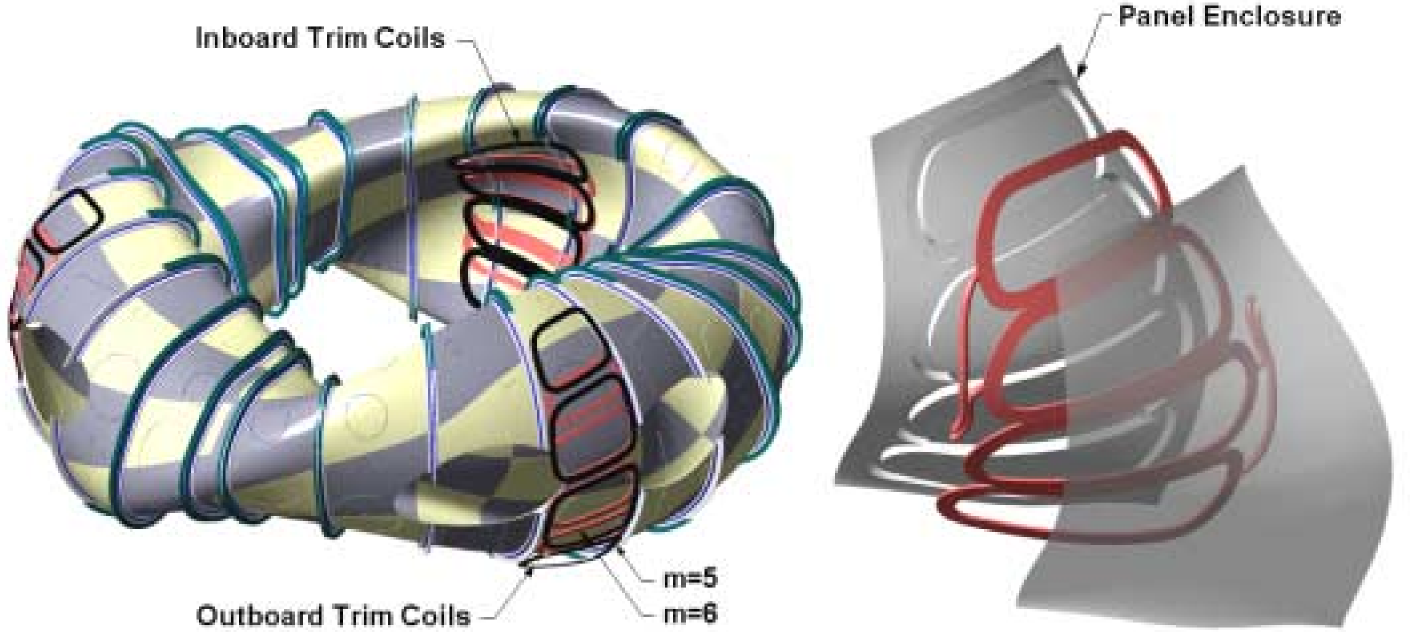
PF Coils

- **5 pairs of PF coils provide inductive current drive and physics flexibility**
- **Require ~2 V-s to drive 350 kA plasma current**
- **PF coils located outside modular and TF coils, supported off shell structure**
- **Wound from hollow copper conductor, glass-epoxy insulation**
- **Pre-cooled to LN_2 temperature (like modular and TF coils)**



Trim coils

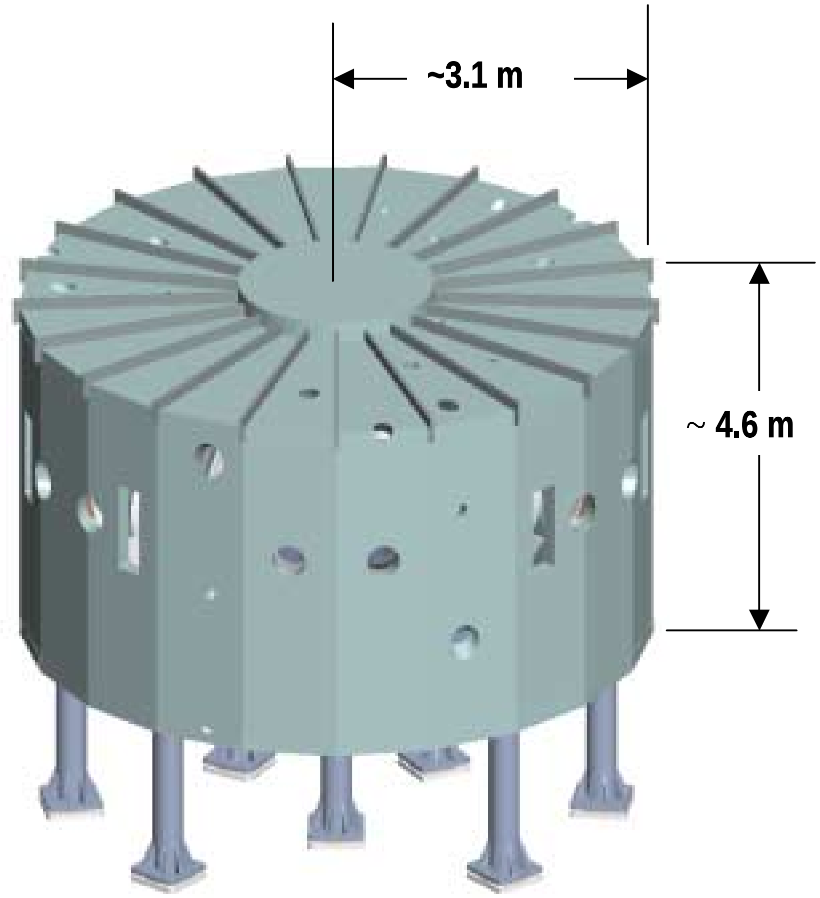
- Provided to mitigate field errors on m=5 and m=6 resonant surfaces
- Located close to inboard v=0 cross-section
- Must accommodate coils at outboard midplane
- Mounted off vacuum vessel, behind PFCs
- Canned for vacuum compatibility



PVR illustrations

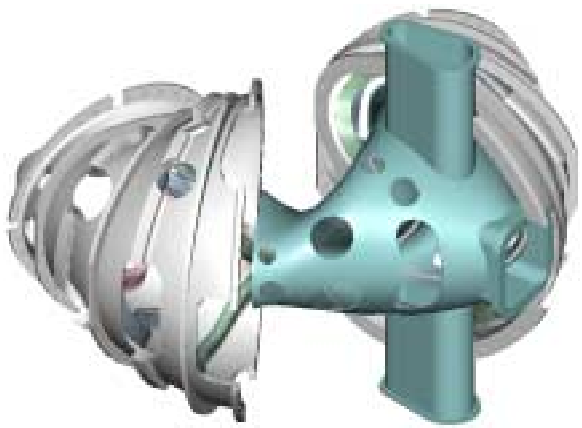
Cryogenic coils enclosed in a common cryostat

- **Cryostat design uses commercial concept - substructure sprayed with urethane foam**
- **Inexpensive construction facilitates maintenance access**
- **Holes provided for all vacuum vessel port extensions**
- **Silicon rubber "Gortiflex" boots to seal between vessel port extensions and cryostat**
- **8" thickness reduces heat leaks to air but still will require local heaters/blowers to avoid condensation**



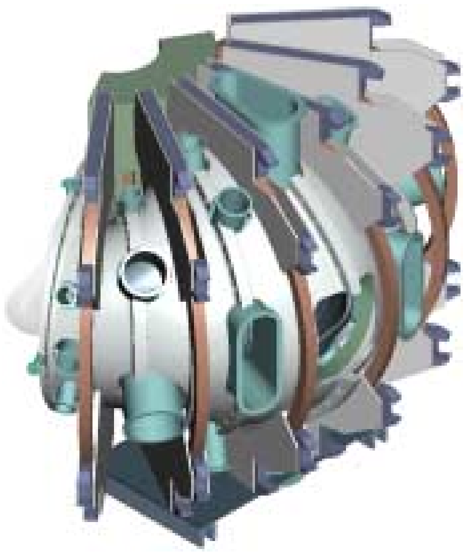
Modular and TF coils and VV will be pre-assembled in field periods

- **Pre-assembly can be performed in TFTR test cell or NCSX test cell**



Rotate modular coils over vacuum vessel ½ period

Add TF coils and out-of-plane support structure

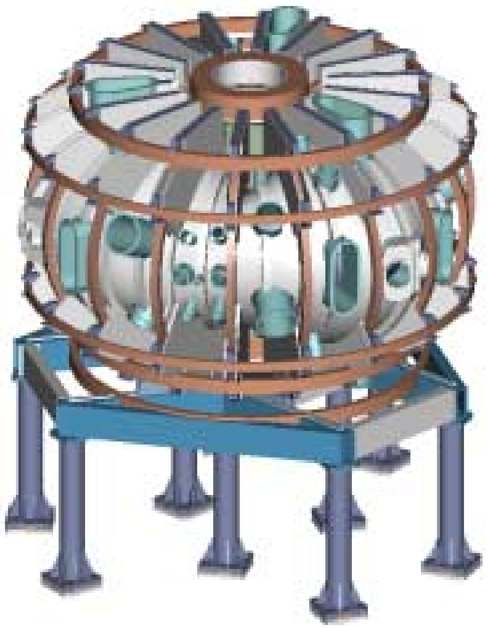


Add vacuum vessel port extensions to complete field period sub-assembly

Field periods are assembled on machine structure in NCSX test cell

Field period lowered onto machine base in position ~ 500 mm radially outward

3 field periods in position prior to radial assembly step



Field periods connected after radial motion, PF coils raised/lowered into position

NCSX
Stellarator Core
Assembly Sequence

Manufacturing studies

- **Vacuum Vessel and Modular Coils are most difficult challenges from manufacturing and cost viewpoint**
- **Input has always been solicited from industry, but now we will fund industry to participate**
- **8 different proposals will be funded to perform manufacturing studies (vendors selected Nov 13)**
  - **3 integrated modular coils manf studies**
  - **3 integrated vacuum vessel manf studies**
  - **2 studies devoted to castings, covering both the modular coils and vacuum vessel**
- **Manufacturers will recommend a manufacturing process, suggest design modifications and needed R&D, schedule, and budgetary cost**

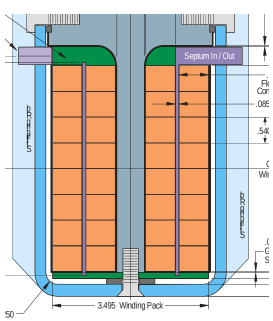
R&D is planned to reduce risk

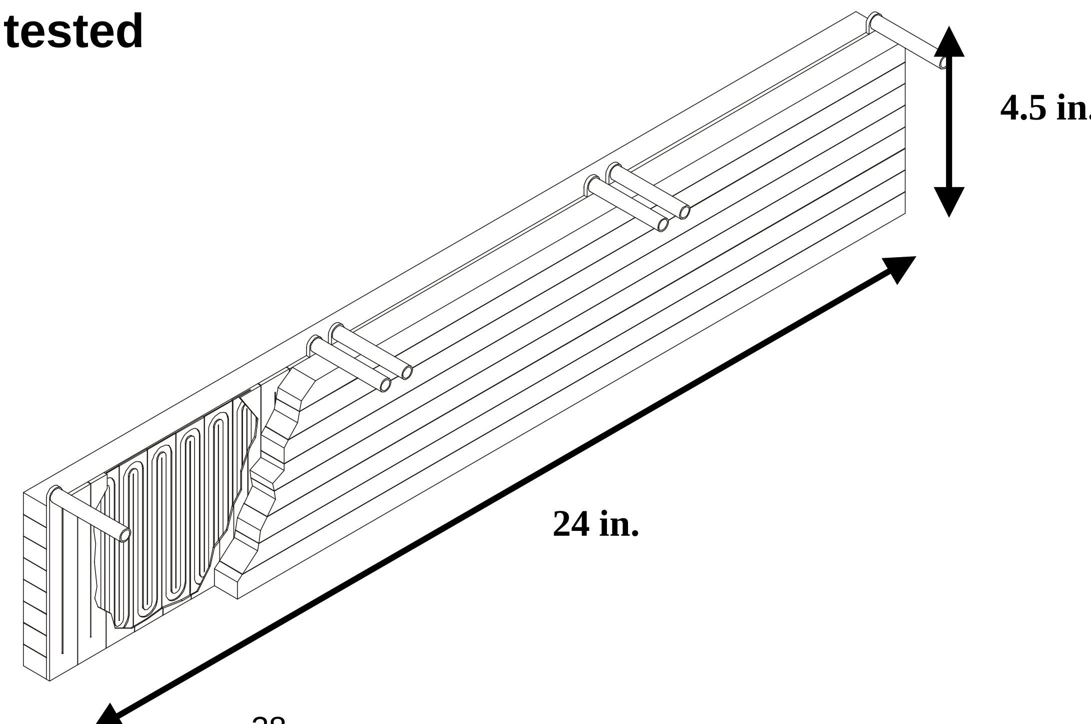
- **Vacuum Vessel**
  - **Partial prototypes using different processes**
  - **Full scale prototype of half field period using selected process**

- **Modular Coils**
  - **Epoxy impregnation tests**
  - **Winding tests on full scale form**
  - **Machining simulations**
  - **Full scale prototype coil**

Near term winding / potting R&D

- **Propose to create one or more full scale winding packs, or “logs” in straight length of about 24 to 30 inches**
- **Sections could be taken to determine quality of epoxy fill**
- **“log” could be loaded in various ways to determine composite stiffness in tension, compression and bending for use in FEA models**
- **Cooling can also be tested**





Summary

- **NCSX design concept has been developed that meets performance requirements**
  - **Modular coil set that meets physics and engineering constraints**
  - **Shell structure is robust and provides needed accuracy**
  - **Large vacuum vessel with numerous ports provides adequate access for heating, diagnostics and maintenance.**
  - **TF, PF, and trim coils for flexibility**
- **Manufacturing study subcontracts will provide industrial input improving design/fabrication of modular coils and vacuum vessel**
- **Project is on track for a conceptual design review in May, 2002**