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Design Aspects of Compact Stellarators: NCSX and QPS

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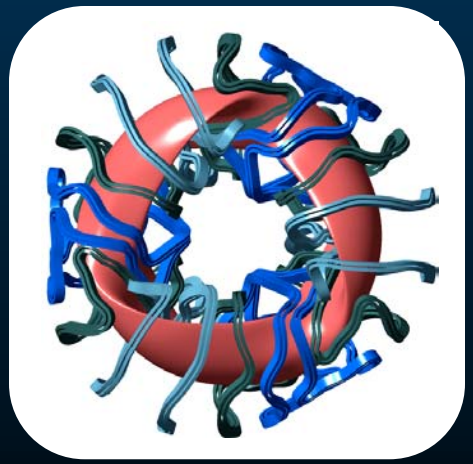
Why build a compact stellarator?

- 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 or provide vertical stability
  - Low aspect ratio resulting in high power density and improved economics

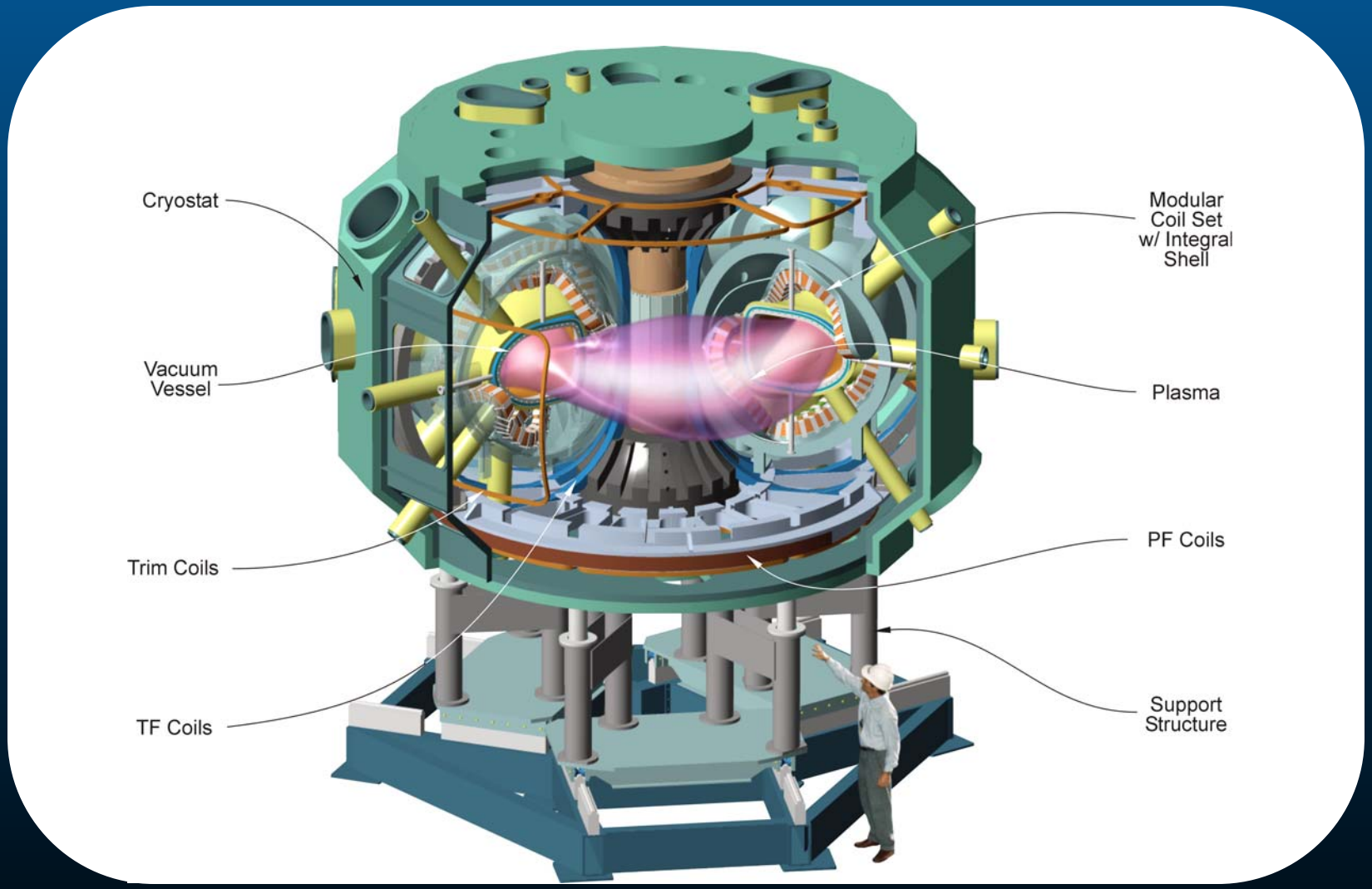
- Compact stellarators require 3-D shaping of the last closed magnetic flux surface, and a small bootstrap current to provide a fraction of the rotational transform.*



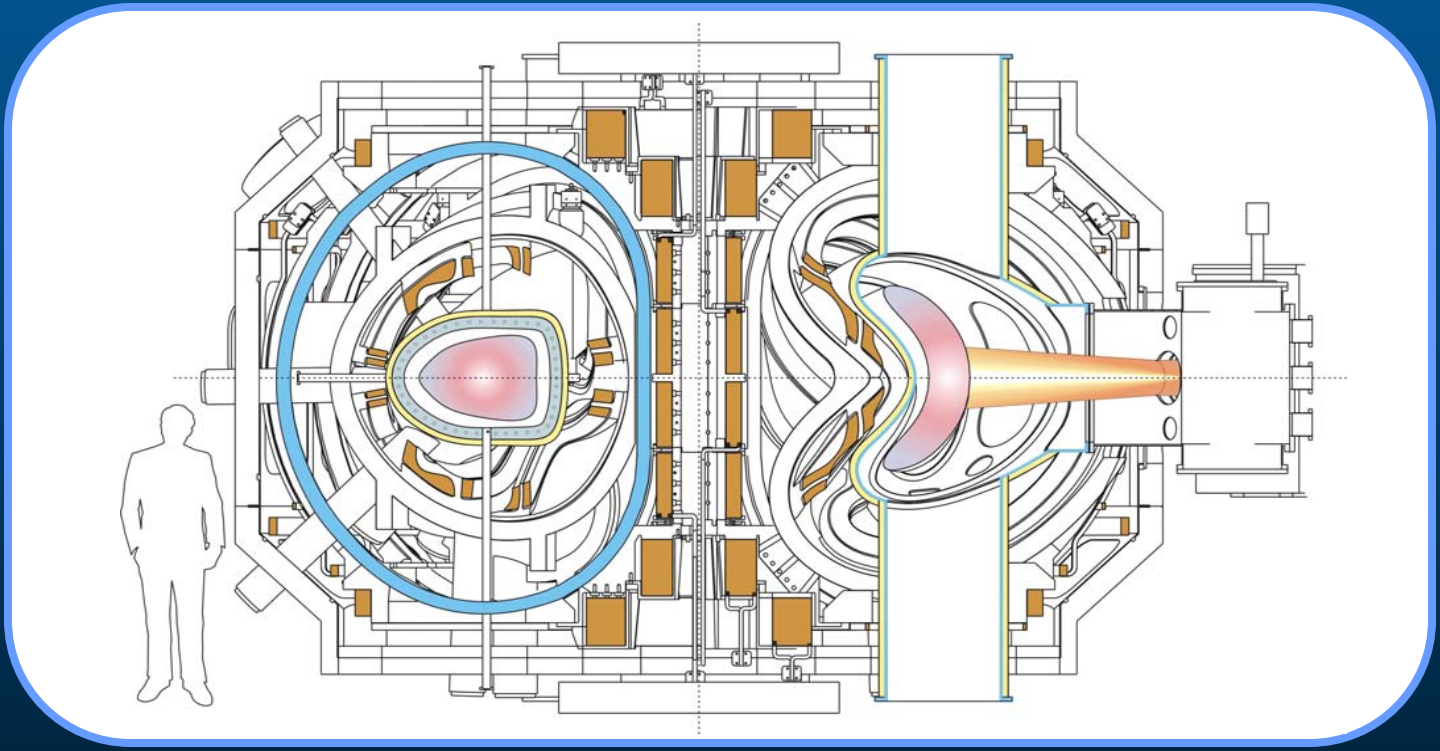
*Reiersen, 18th SOFE

(http://www.pppl.gov/ncsx/pvr/Physics_Validation_Report/Entire_PVR_Report.pdf)

NCSX Stellarator Core



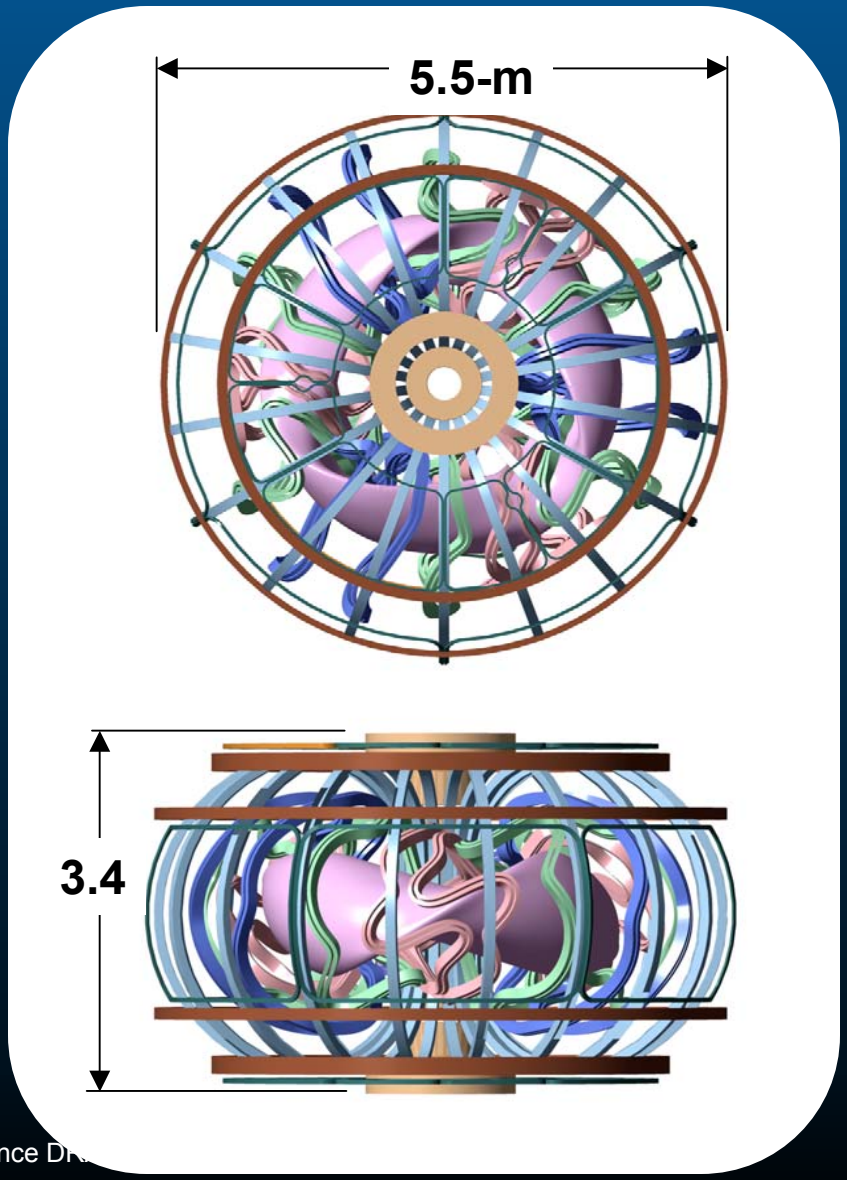
NCSX Basic parameters



Major radius	1.4 m
Bmax, from mod coils	2 T
Plasma current	Up to 350 kA
TF coil configuration (no.)	+/- 0.5 T, 1/R (18)
Plasma heating	3 MW NBI, (6 MW NBI future upgrade) 6 MW ICH (future upgrade)

NCSX Coil Set Assembly

Coil set	Function:
Modular coils	Basic quasi-axisymmetric magnetic configuration
PF coils	Inductive current drive, plasma position control, plasma shaping
TF	Addition or subtraction of toroidal field for control of magnetic transform
Trim coils	Control of magnetic flux surface quality

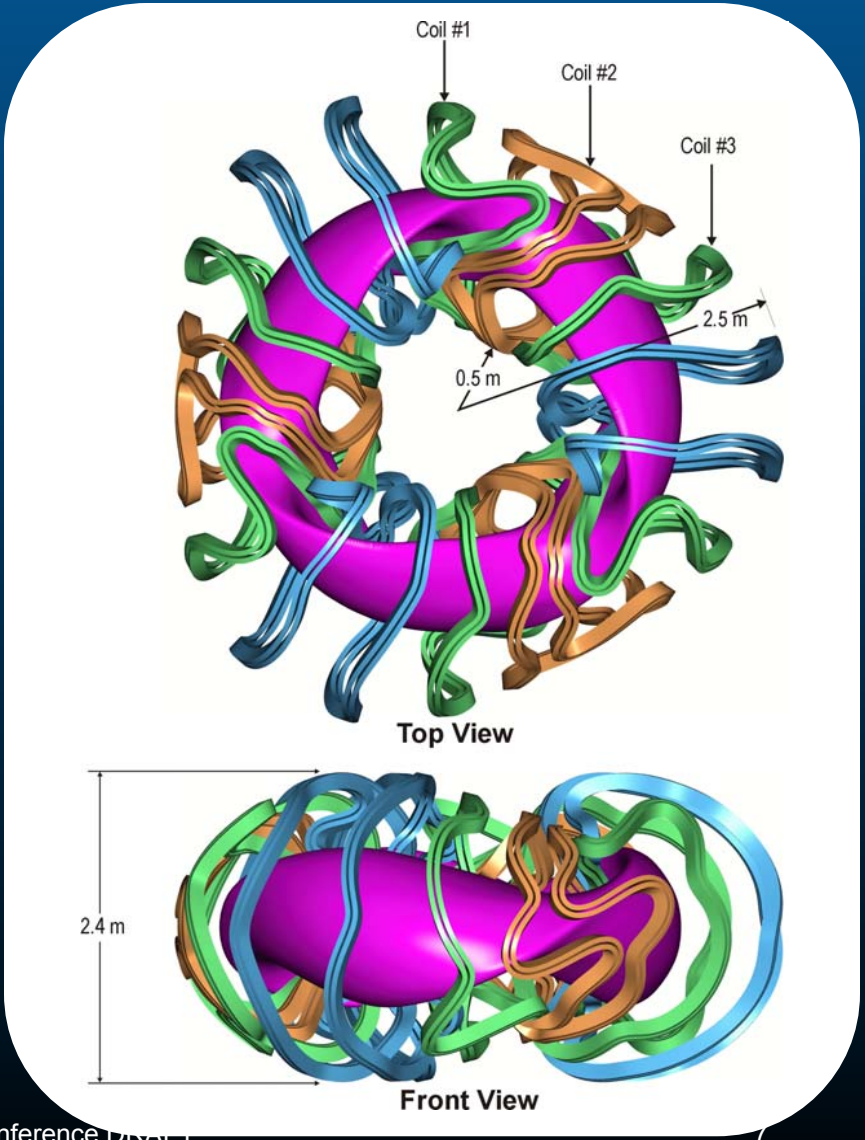


Coil System Requirements

- Meet performance and flexibility requirements in specified 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 assumed for installed accuracy
- Accommodate access for tangential NBI, RF, vacuum pumping, diagnostics, and personnel access
- Limit conductor current to ~ 24 kA peak to match existing TFTR power supplies
- Coils must be “buildable”

NCSX Modular coil configuration

- 18 coils, 3 field periods, 3 coil types
- 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

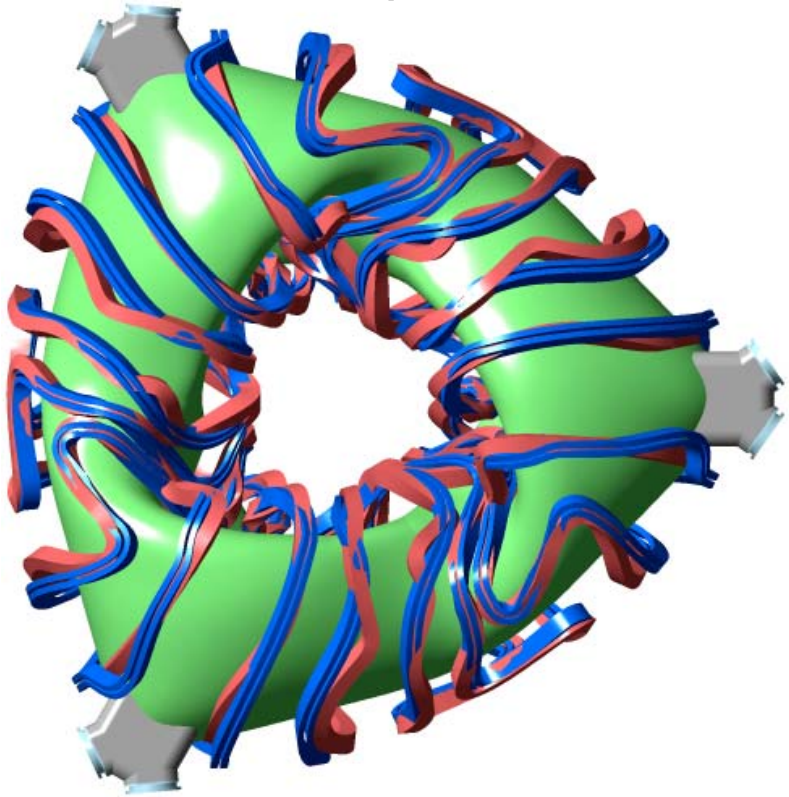


Coil geometry optimized for physics and engineering properties

- COILOPT and STELLOPT codes merged, so plasma properties 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

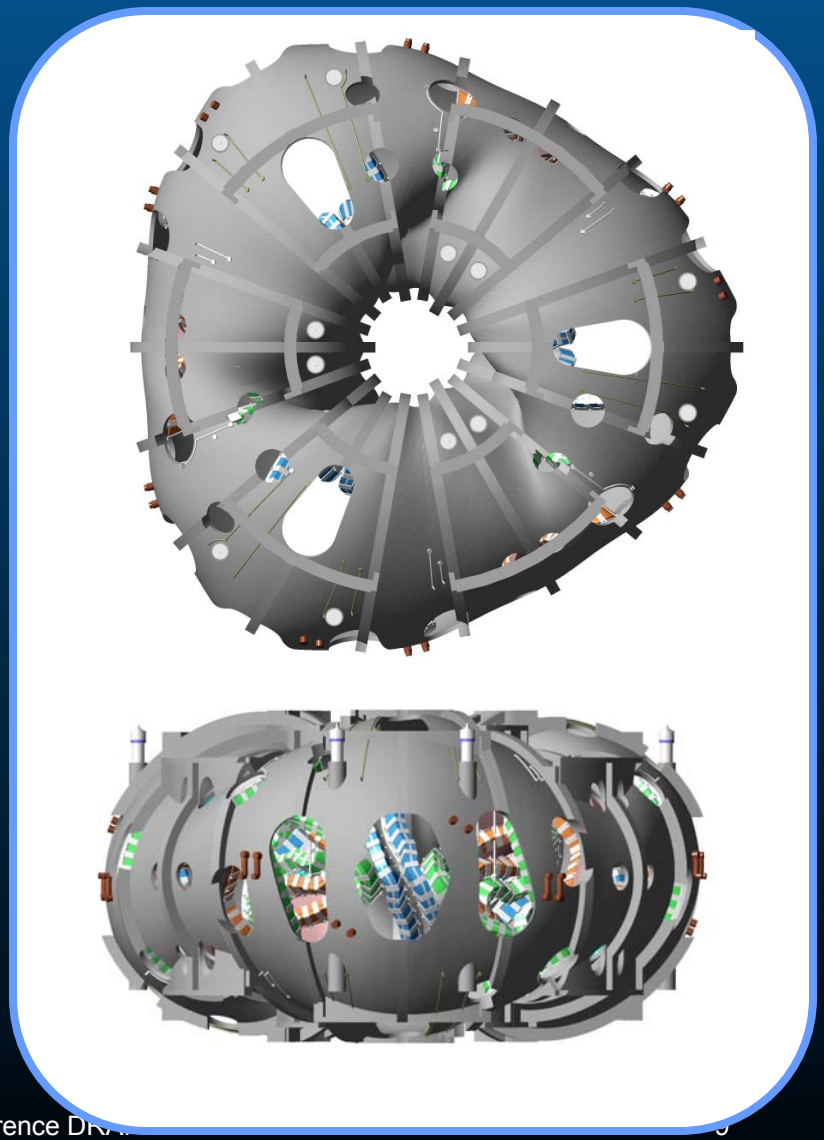
Example of coil improvement

Blue coils much smoother with larger bend radii and more space between coils



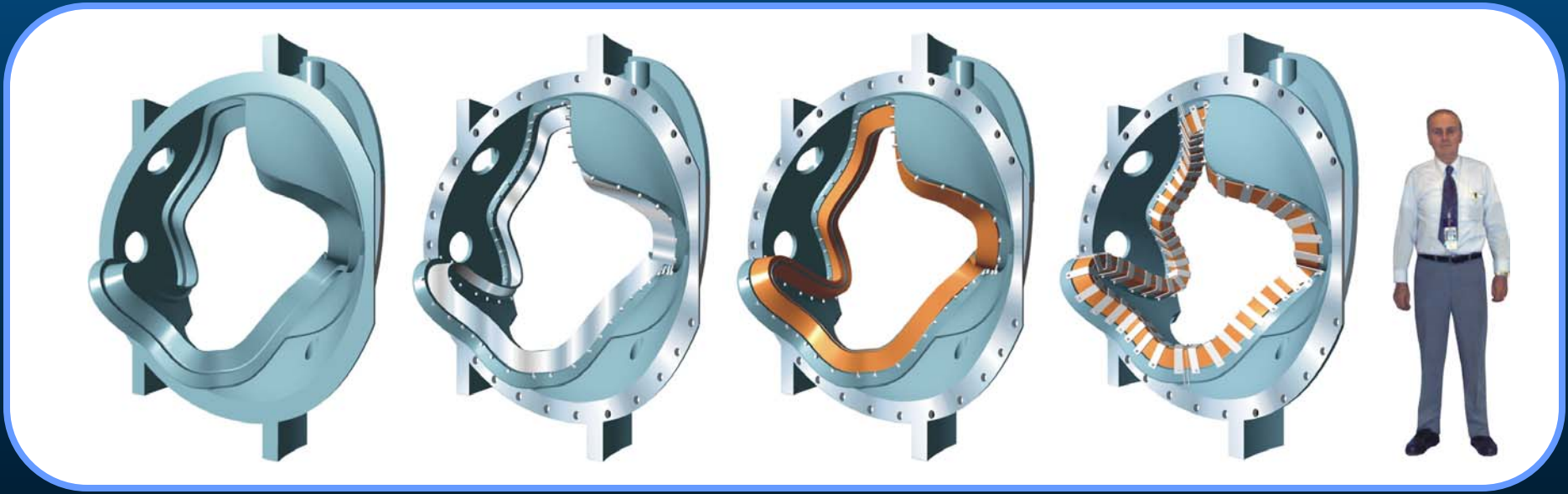
Continuous shell forms robust structure

- Shell consists of individual modular coil forms that are bolted together
- Penetrations for access are provided wherever needed
- Thickness can be varied to optimize / reduce stresses
- Provides machine base for other components
- Stellarator symmetry preserved, at least one toroidal break per field period



Modular coil manufacturing sequence

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



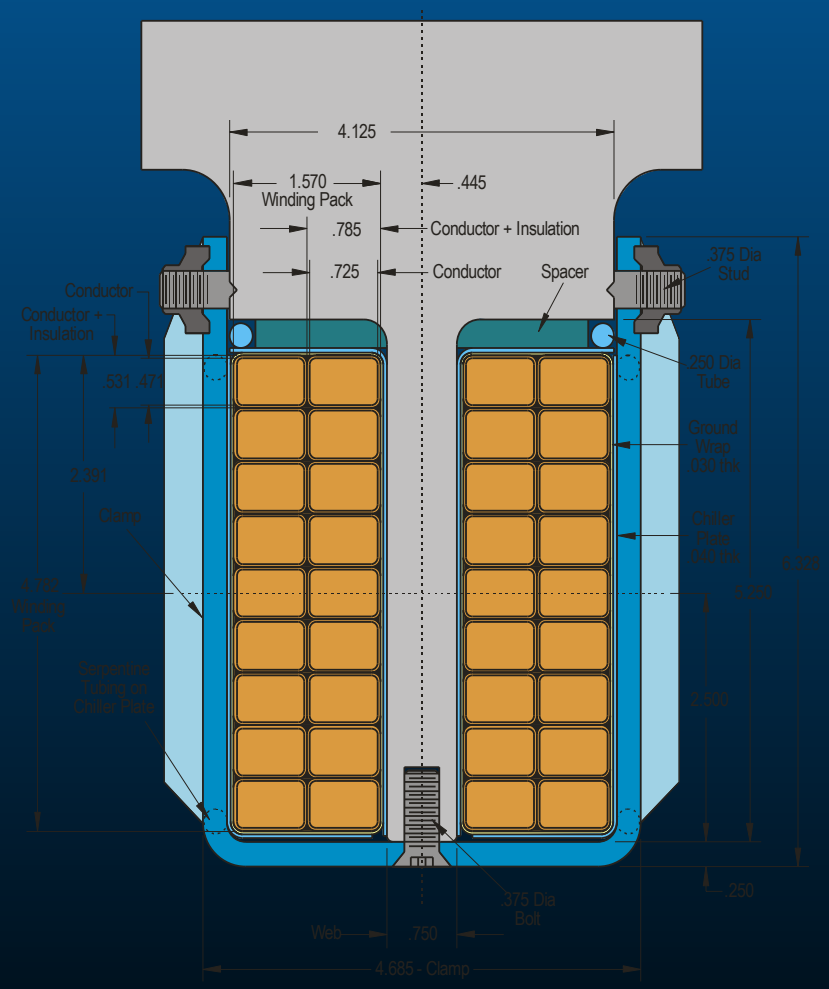
Rough casting

Features are machined

Conductor wound directly into structure

Auxiliary support clamps are installed

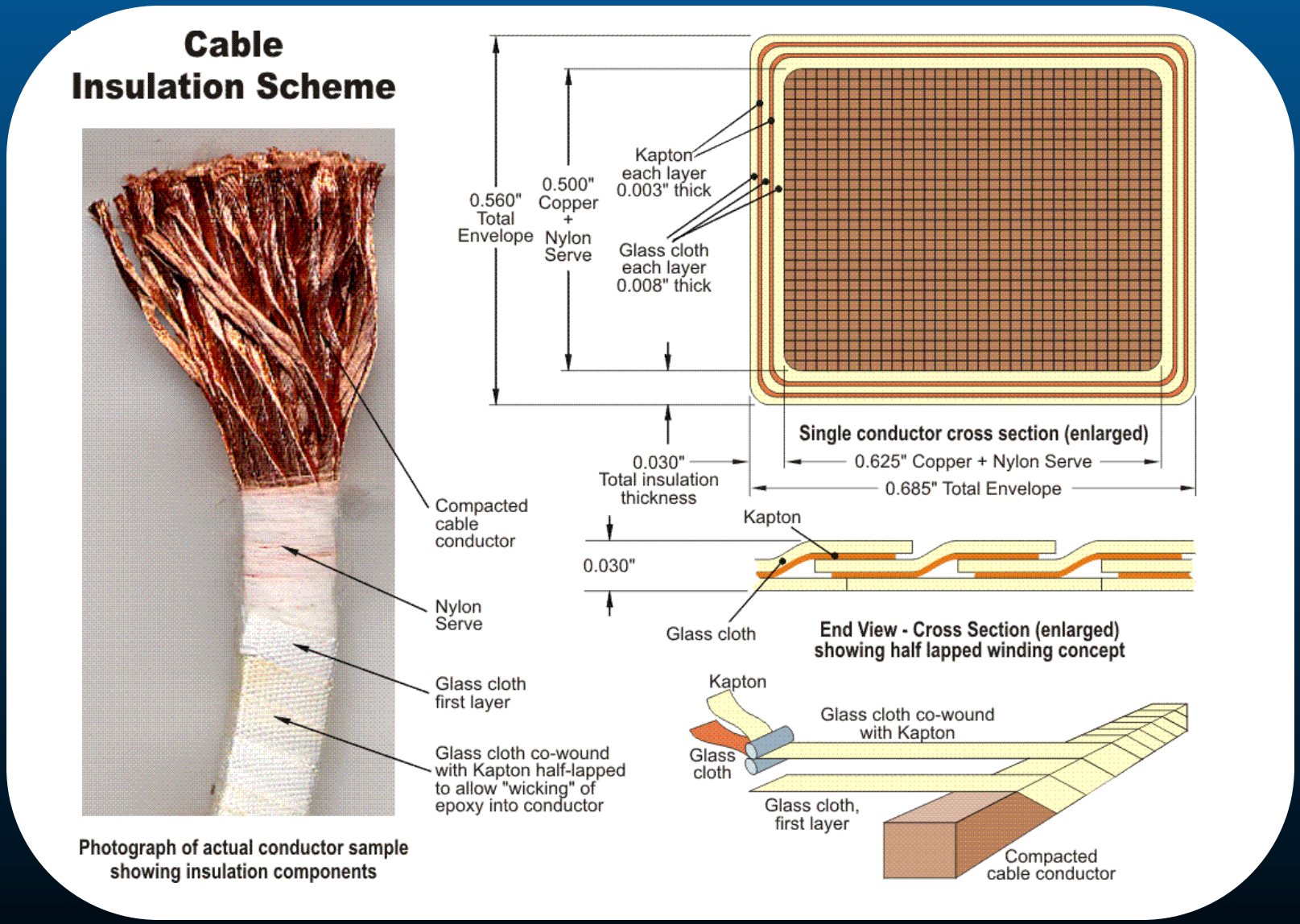
NCSX Modular coils wound with flexible cable directly on coil structure



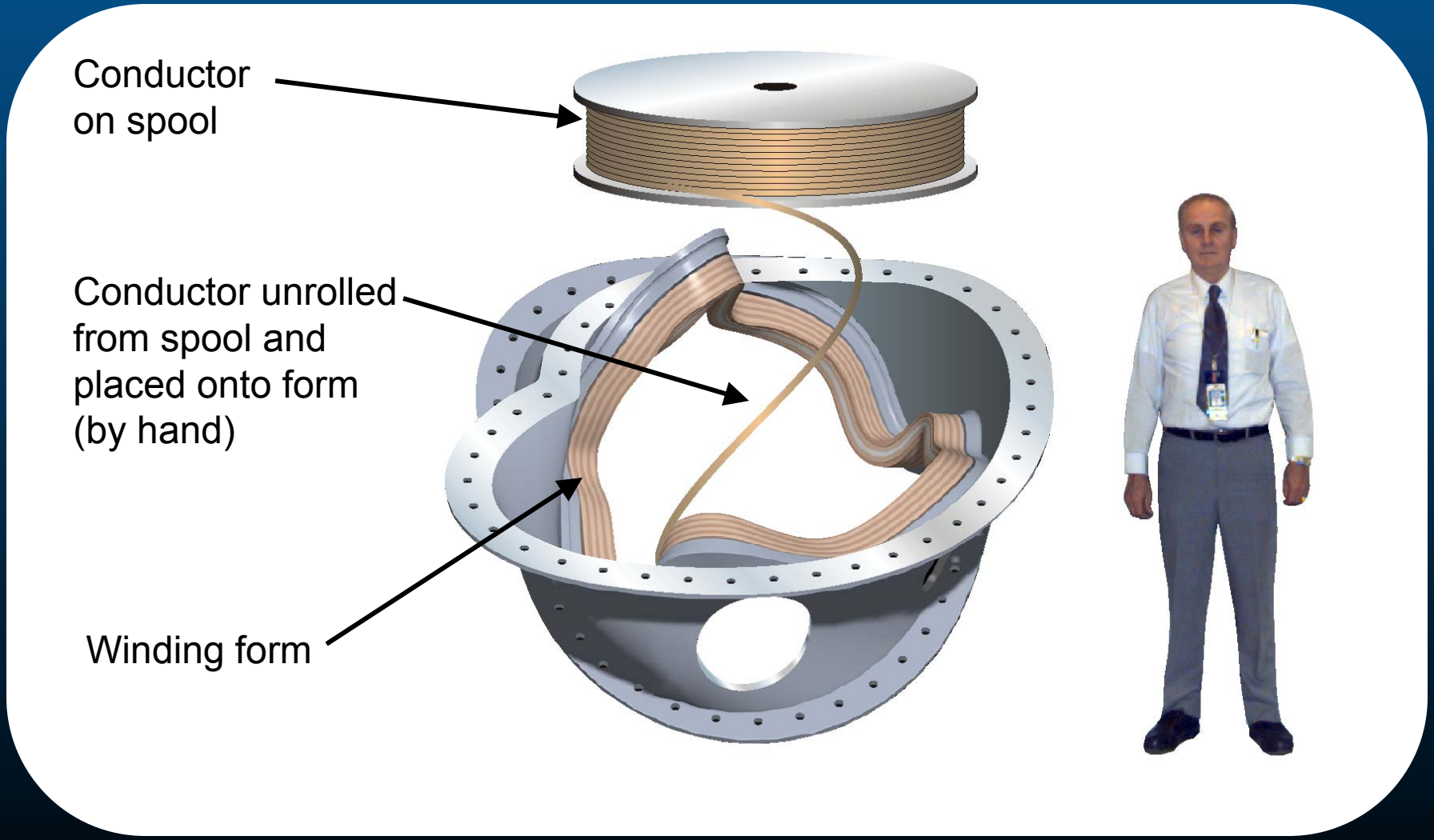
- **Parameters:**
  - Coil Envelope = 2 x 120 x 40 mm
  - Current / Coil = up to 827-kA-turns
  - Number of Turns = 36
  - Nominal current / turn = 23 kA
  - Conductor Size = 13.3 x 16.6 mm
  - Net Current Density = 13.9-kA/cm2
  - Conductor oper. Temp. range 85-125 K

- **Flexible cable used to wind coil**

Cable insulation scheme



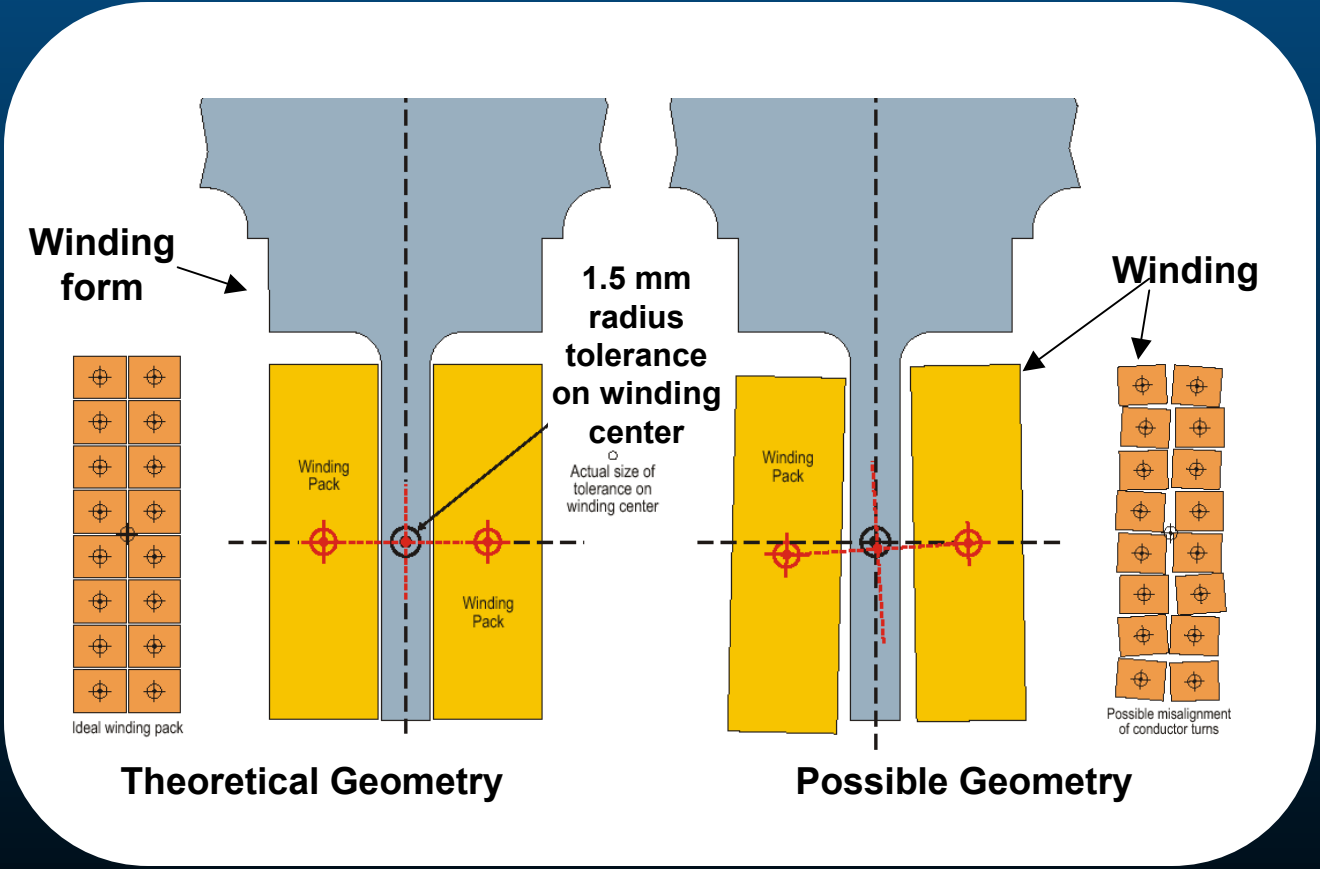
Modular coil winding process



Modular coil winding accuracy

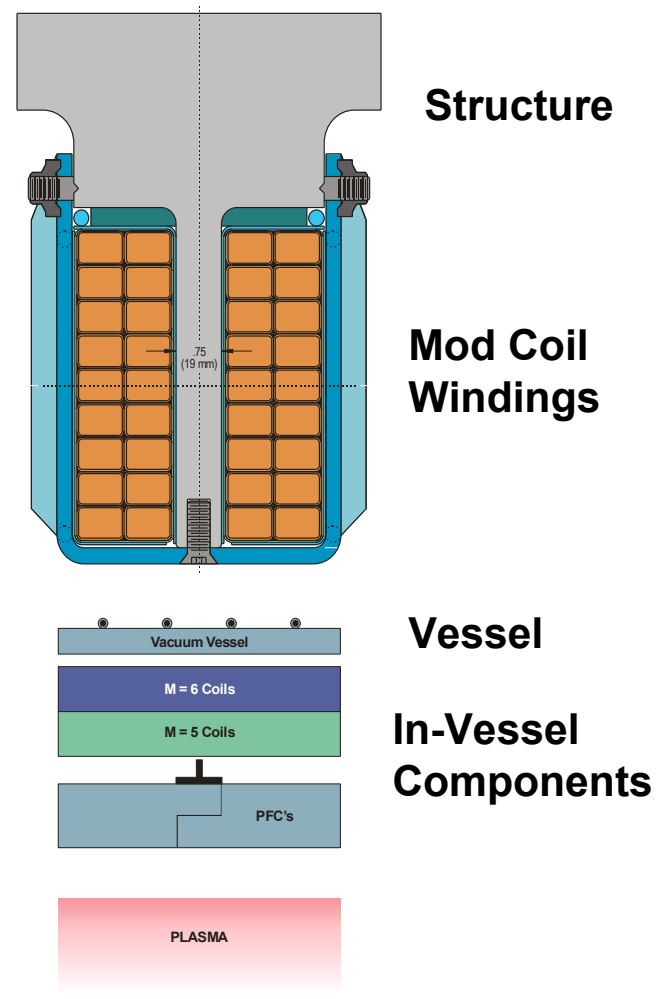
Winding position must be continuously monitored and adjusted to avoid tolerance stack-up

- Form machined to high accuracy
- Windings can be placed to high accuracy relative to each other in form via constant measurement
- Final position of coil form in assembly can be adjusted for optimum fit using shims at assembly flanges



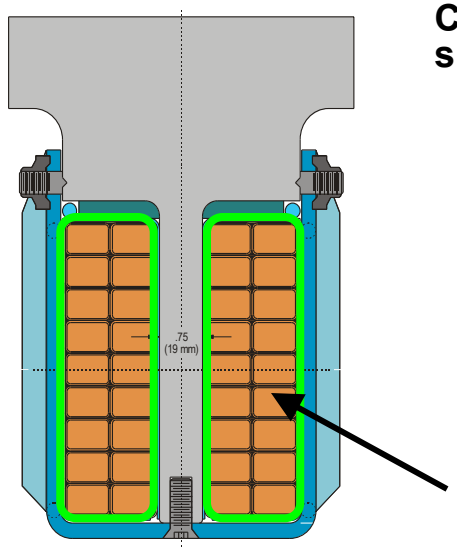
Coil envelope requires cryo-resistive coils

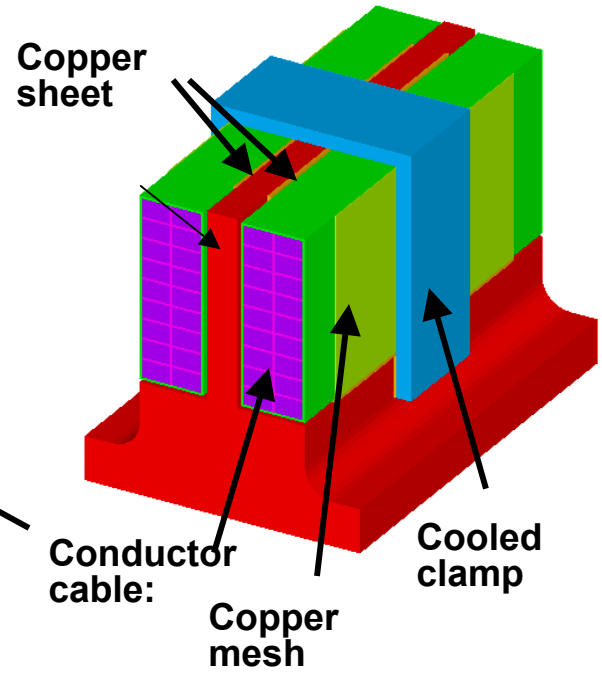
- Current density of ~ 14 kA/cm^2 requires too much power, has too much temperature rise for room temperature coils
- Cryo-resistive coils have advantages:
  - ~ 7 x increase in copper conductivity
  - Lower temperature rise per pulse
  - Much less power
  - Materials become stronger at low
  - temperatures
- Compact winding also avoids magnetic reconstruction problems associated with low current density, large cross section stellarator coils



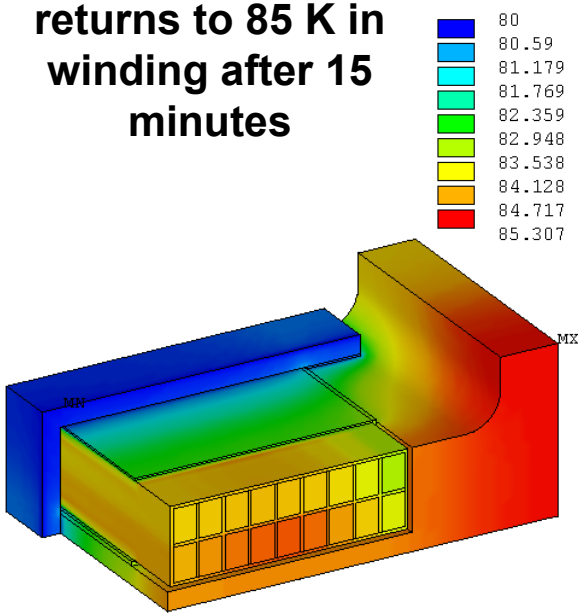
Modular coils cooled by conduction

- Winding undergoes adiabatic temp rise, 15 min. allowed for cooldown
- Max temperature rise limited by thermal stresses (dT ~ 45 K)
- Heat conducted via copper strips to cooling lines on clamps



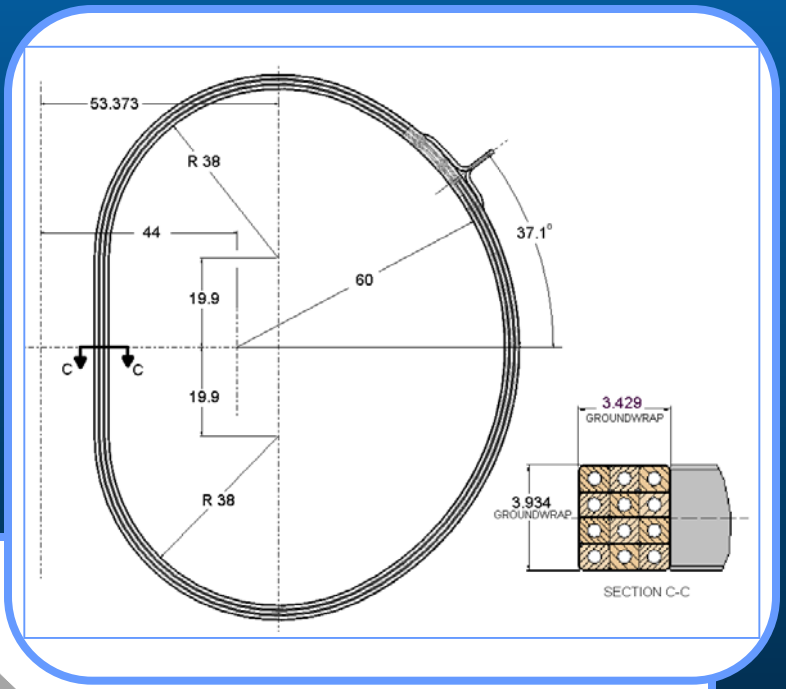


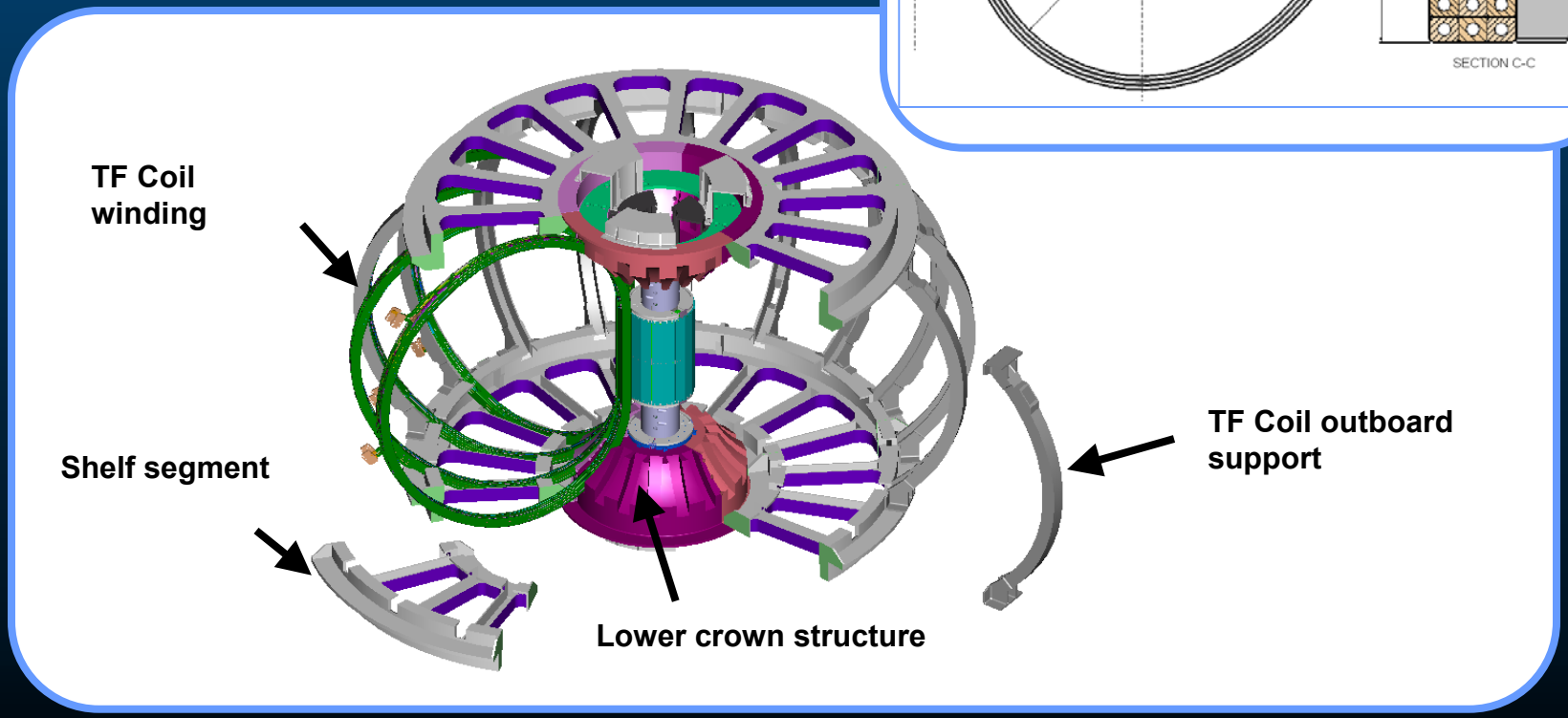
Temperature returns to 85 K in winding after 15 minutes



TF Coils

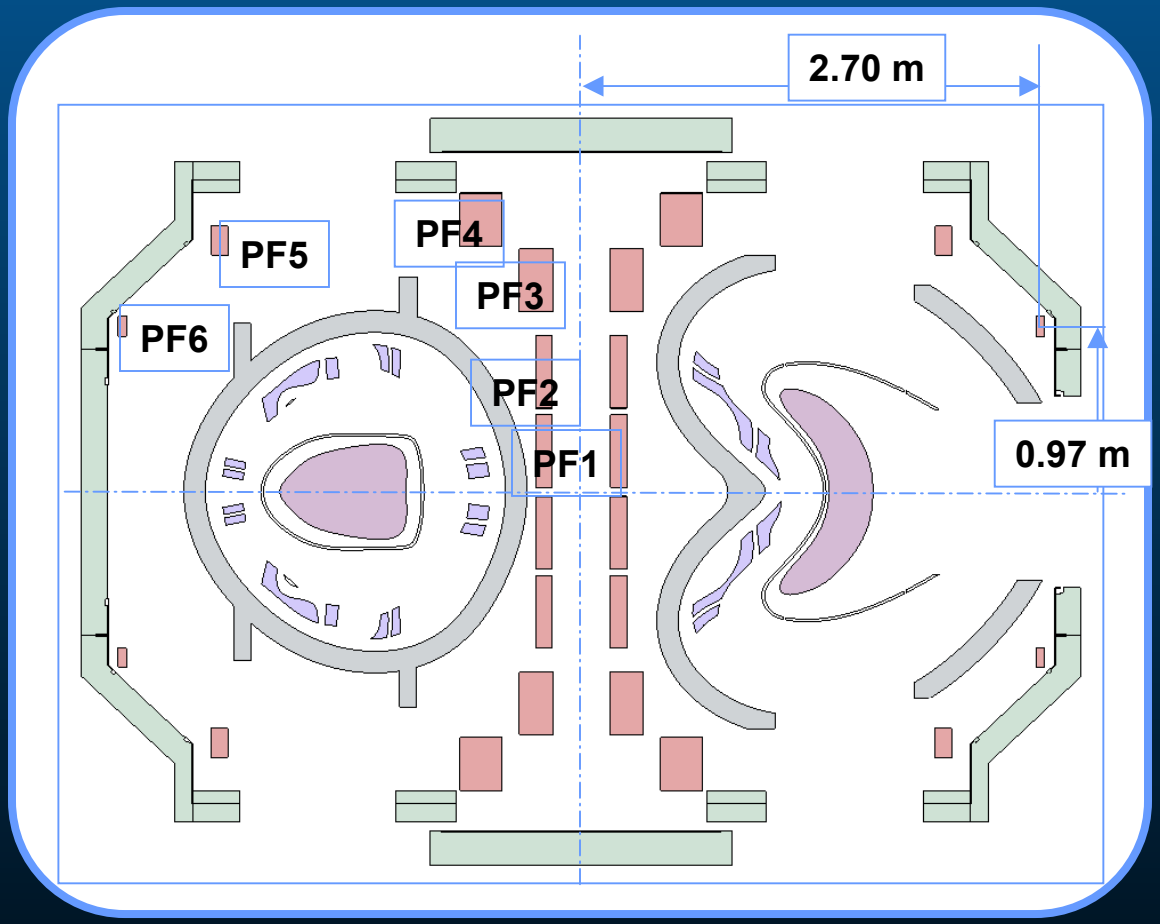
- 18 coils provide +/- 0.5 T
- Supported from external structure
- Wound from hollow copper conductor
- Pre-cooled to LN_2 temperature





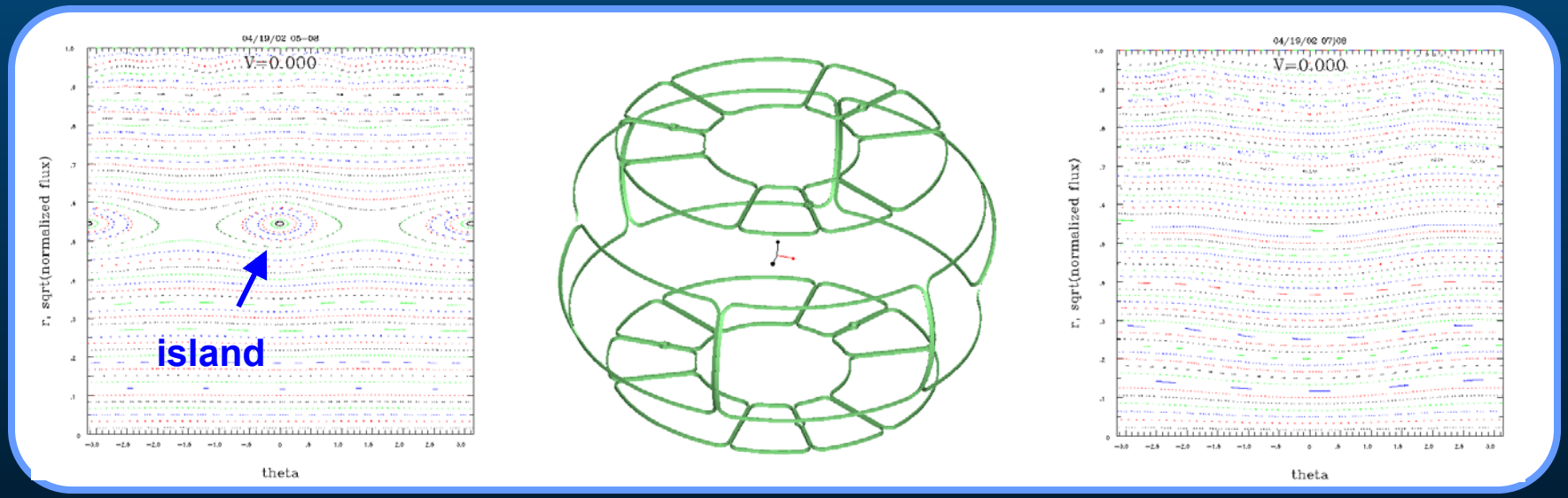
PF Coils

- 6 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 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

- External trim coils provided to mitigate low order field errors from fabrication or assembly inaccuracies
- Coils are independently powered, located outside modular and TF coils
- Systematic study shows suppression of large islands

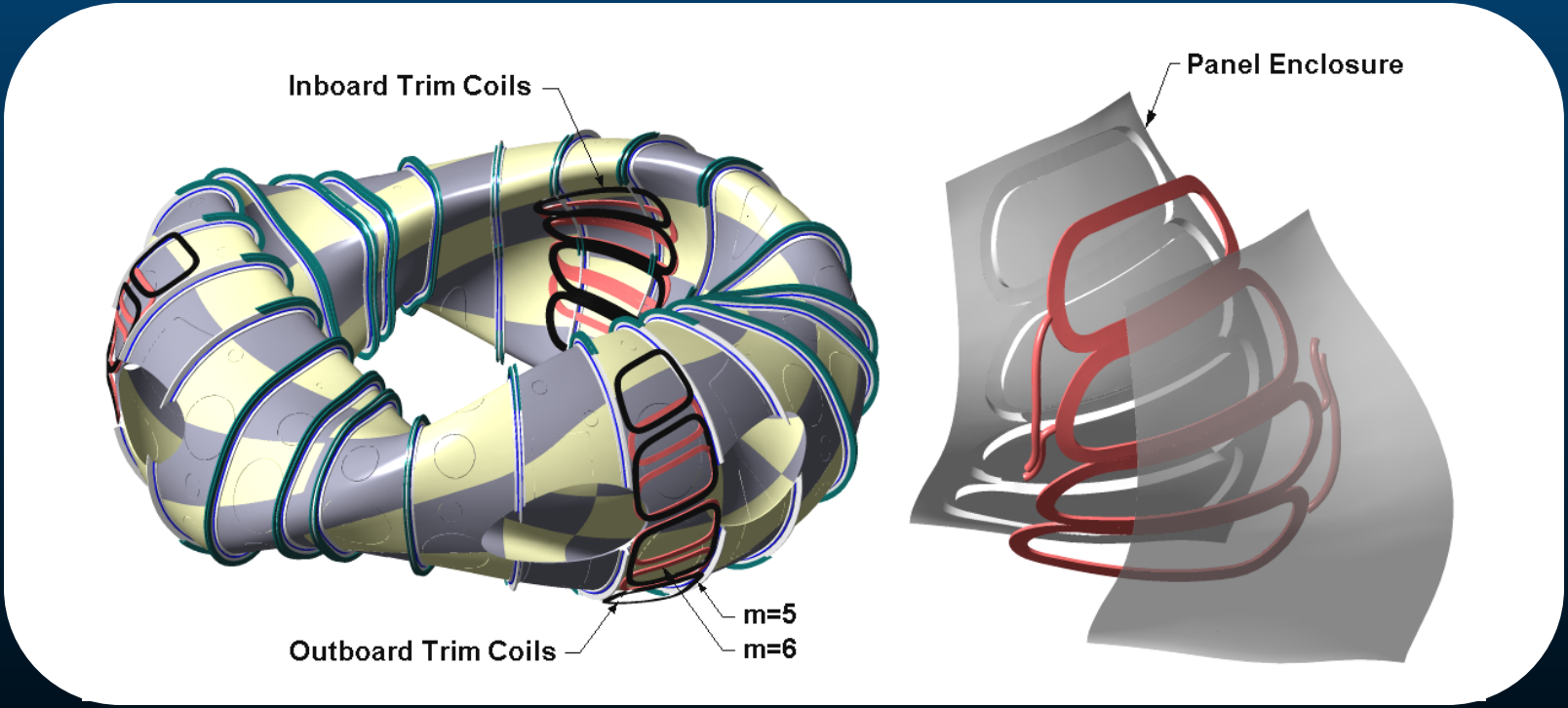


Largest Islands from any modular coil distortion
(2mm distortion of single M1 coil)

Island suppression using external trim coils

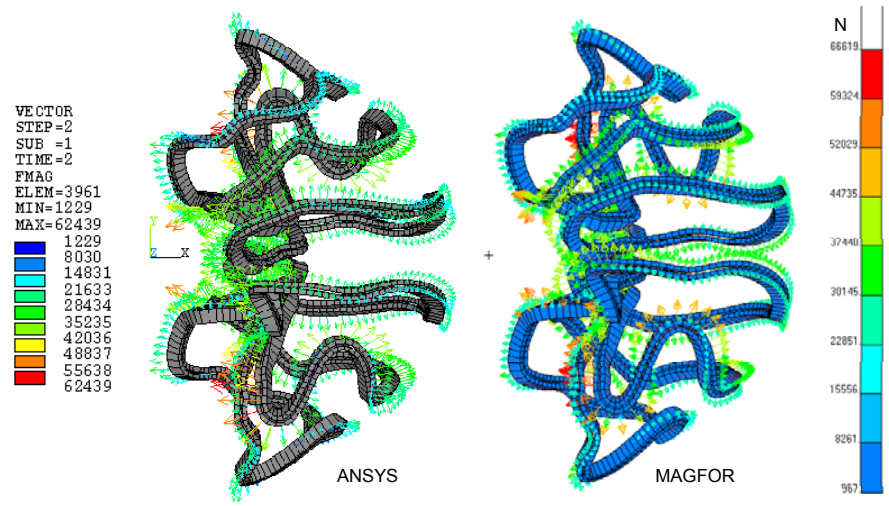
Internal trim coils (upgrade)

- Internal trim coils provided to control m=5 and m=6 resonant field perturbations
- Coils are independently powered
- Located inside the vessel at the v=0 cross-section, can be added later
- Canned for vacuum compatibility

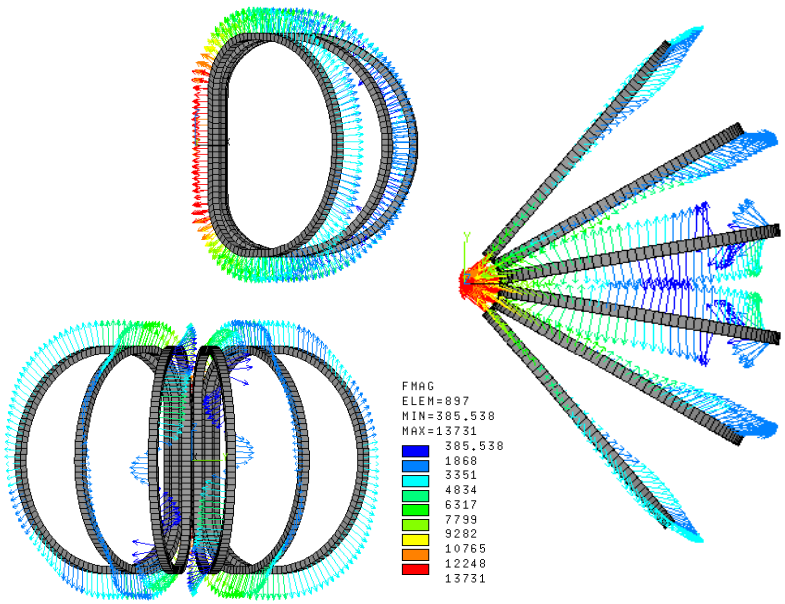


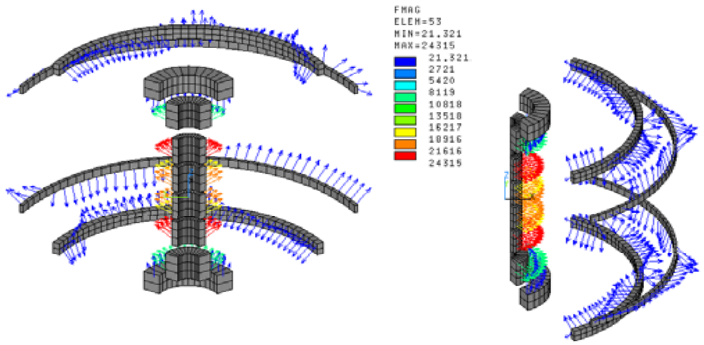
Coils experience complex forces

- Modular coils see net centering force
- TF, PF coils have interaction with mod coils



independent calculations, worst case for modular coils (2T, low beta at zero sec)

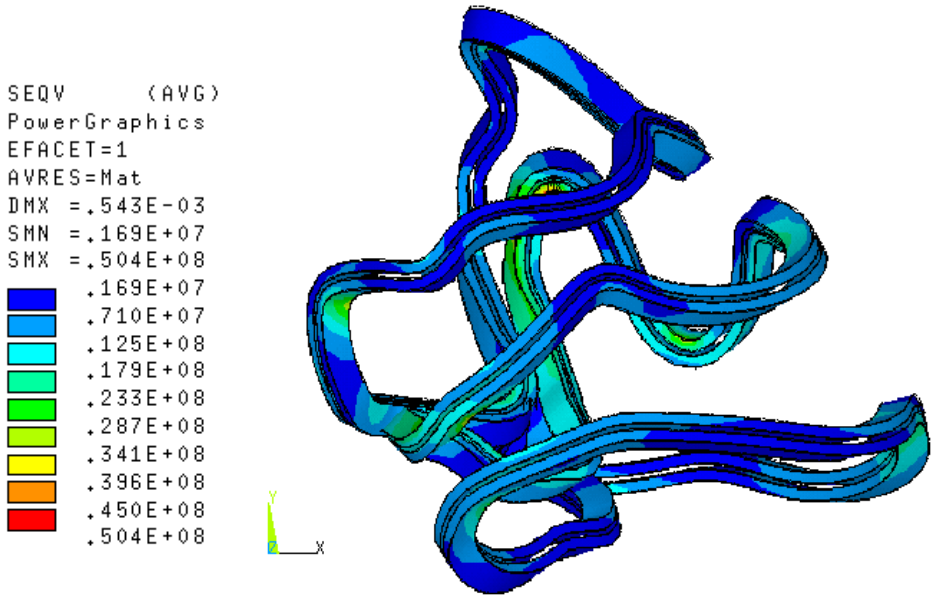




350 kA ohmic scenario worst for TF, PF

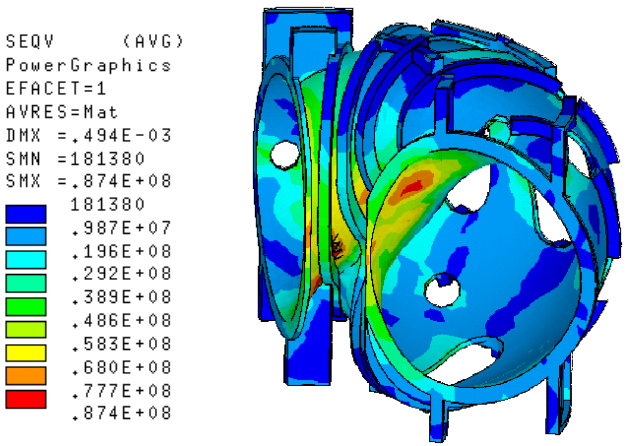
Stresses are relatively low

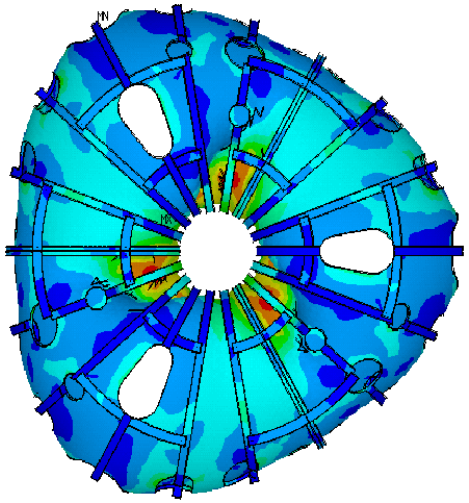
- Modular coil winding strain tracks cast winding form, stress depends on winding properties
- Winding form structure stress is low



Max. Seqv = 50.4 Mpa (7.31 ksi)

Note: the Young's modulus of the winding is consistent with the "hard coil" , or 1/2 the modulus of solid copper

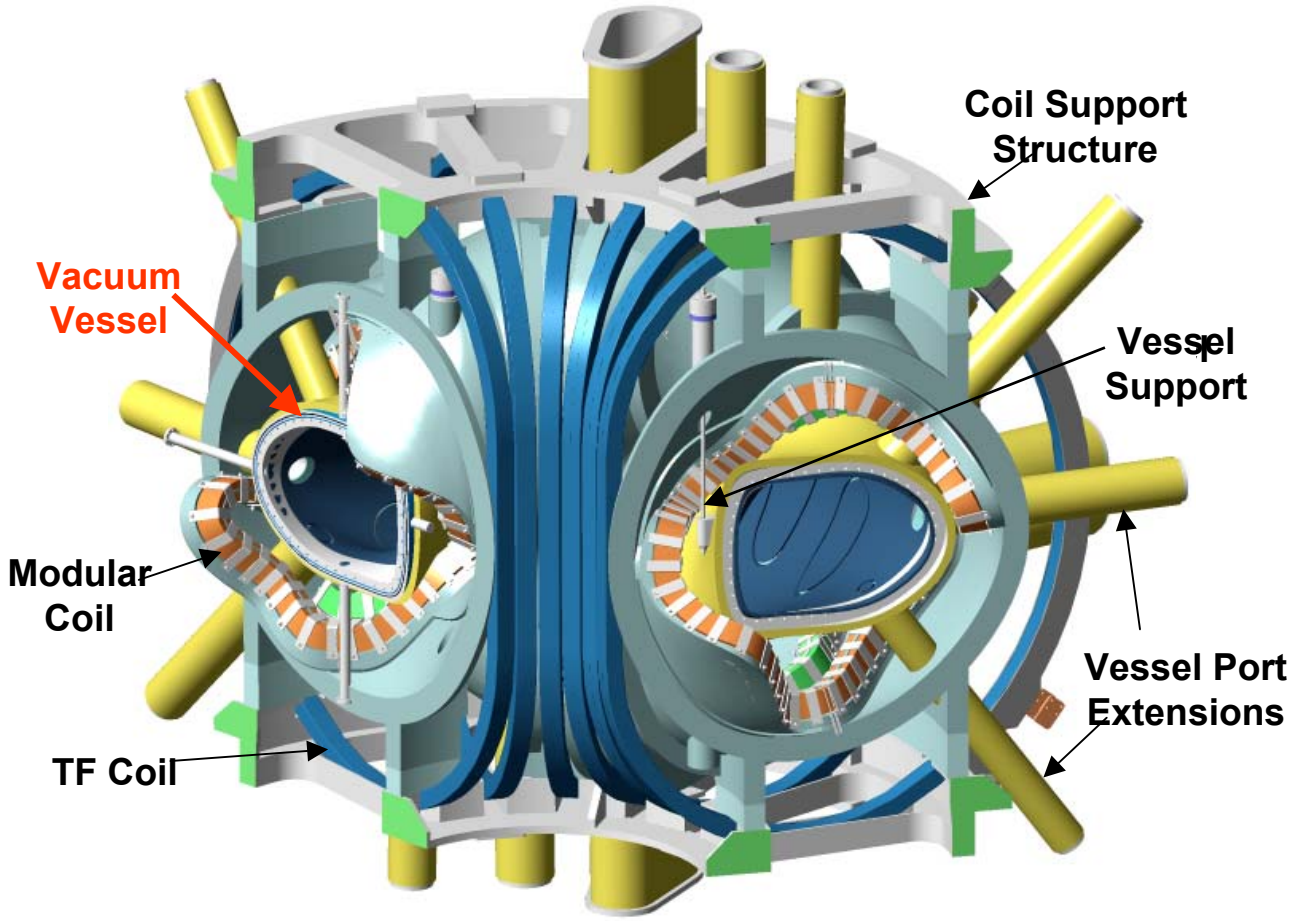




Von Mises stress distribution

Max. Seqv = 87.4 Mpa, F.S. ~4

Inside the NCSX coil set is a vacuum vessel

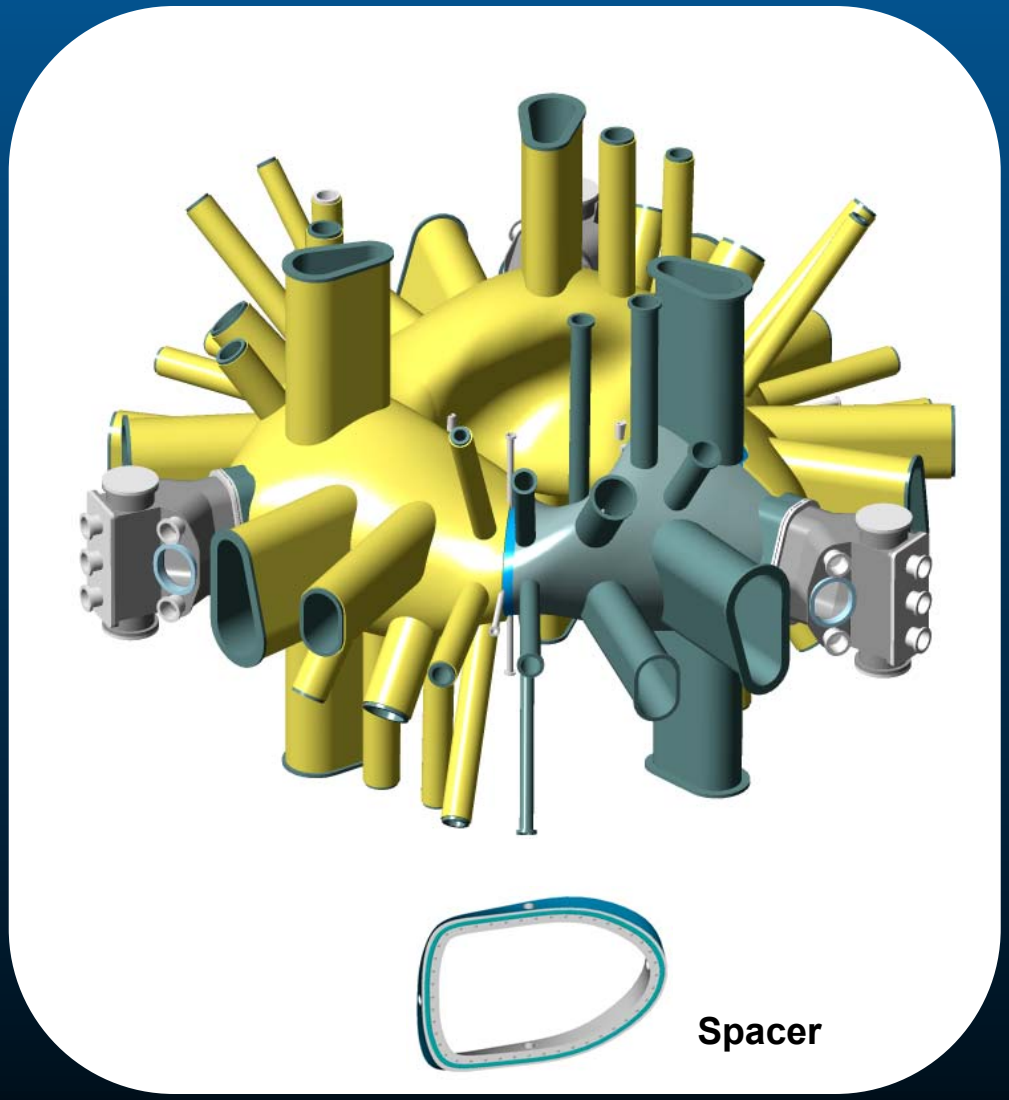


NCSX vacuum vessel requirements

- Provide good clean vacuum environment
  - Vessel must be bake-able to 150 C
  - Accommodate PFCs baked at 350 C
- Minimize field errors
  - Low permeability (< 1.02 nominal goal)
  - Stellarator symmetry
  - Short time constant
- 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
- Provide access ports for diagnostics, vacuum pumping, heating systems, and personnel access

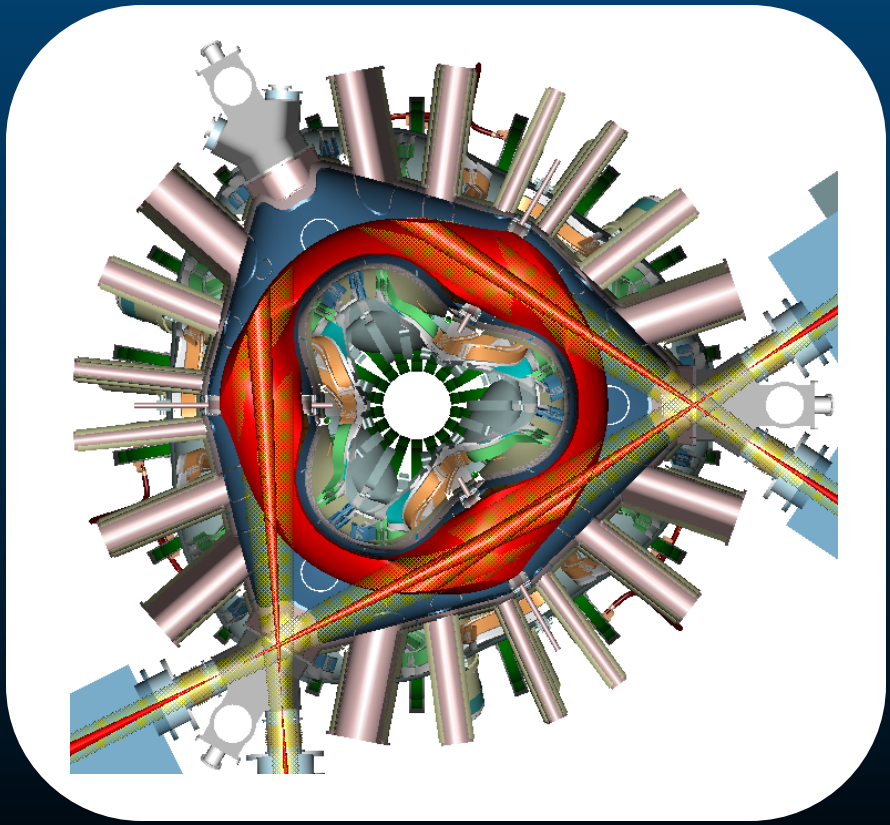
Vacuum vessel design concept

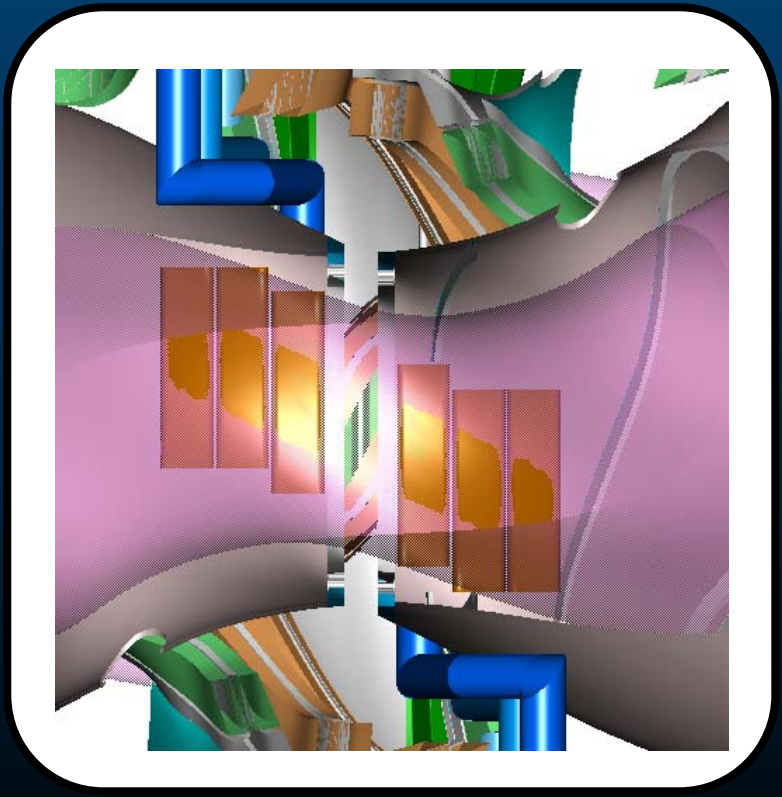
- Shell material — Inconel 625
- Thickness — 9.5 mm
- Time constant — 5.3 ms
- Total wt w/ports — ~ 12000 lbs
- Bolted joints connect field periods
- Traced with He gas lines for heating (to 150C) and cooling
- Solomide foam insulation between VV and cold mass
- 99 separate access ports
- Spacers used between field periods to provide fitup capability



Access for tangential NBI and RF

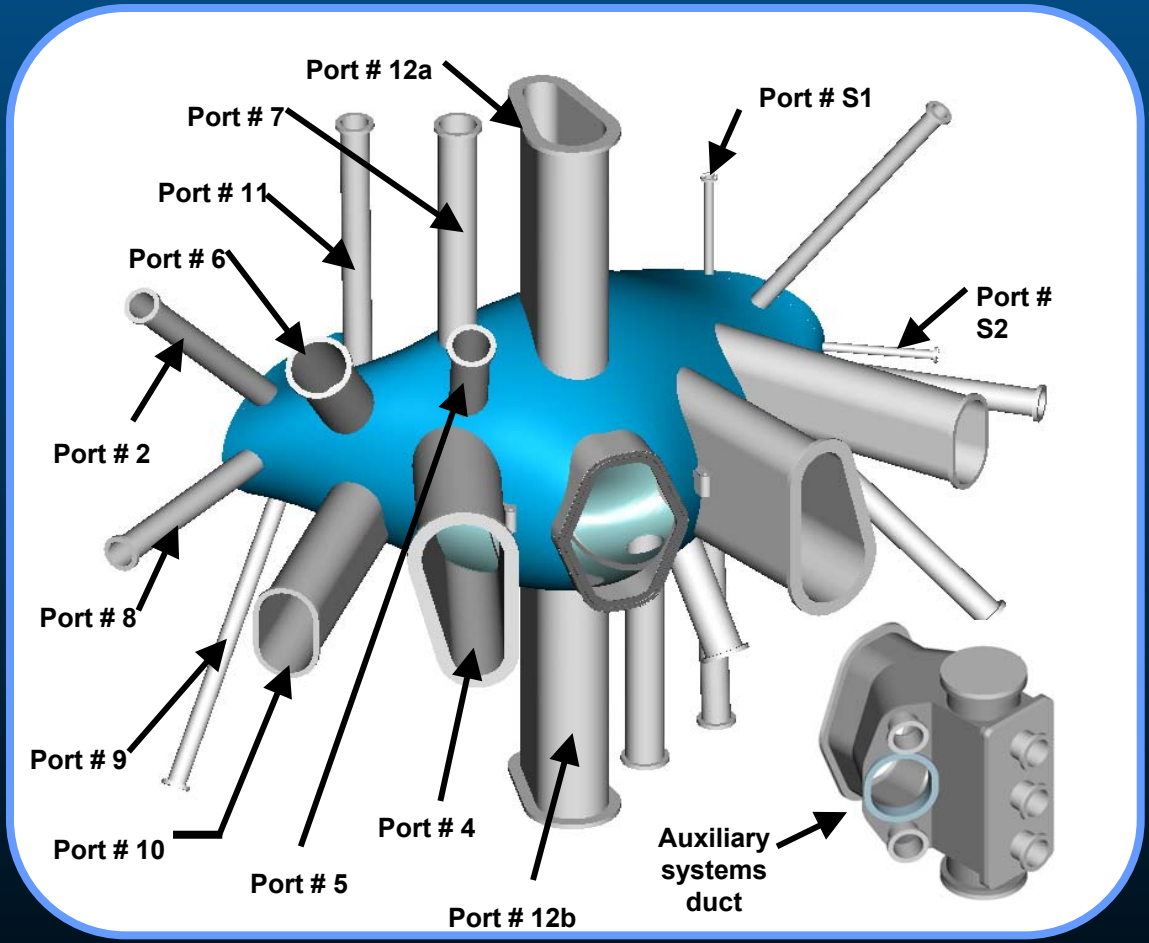
- 3 locations accommodate co- and counter- neutral beams
- 3 arrays of RF launchers can be installed on inboard regions
- Vacuum pumping through NB ducts



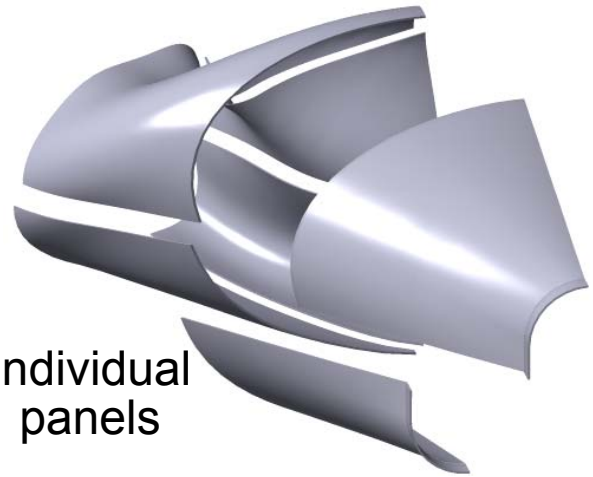


Diagnostic and personnel access

- 99 separate ports for diagnostics, heating and access
- Ports are stellarator symmetric
- Personnel access available through NBI or other large ports

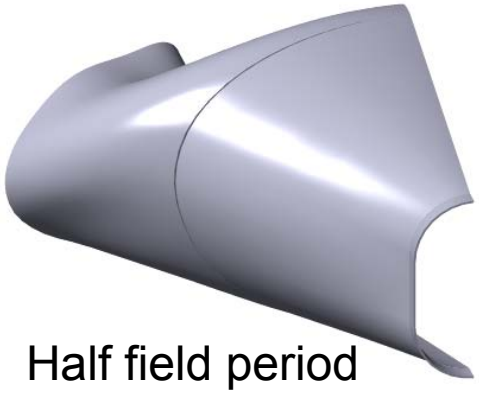


Vessel fabrication concept



Individual panels

Full field period with port stubs

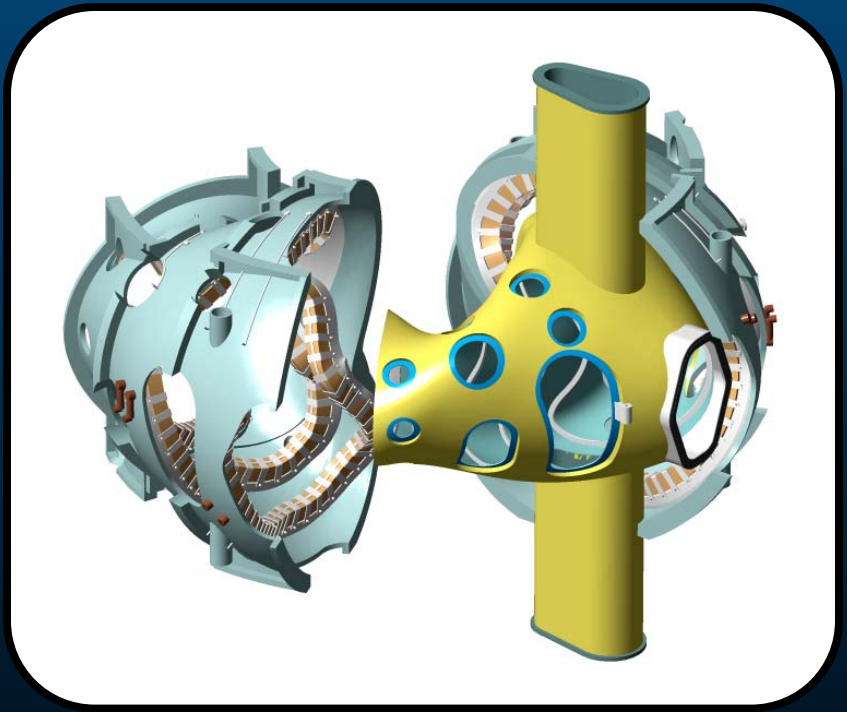


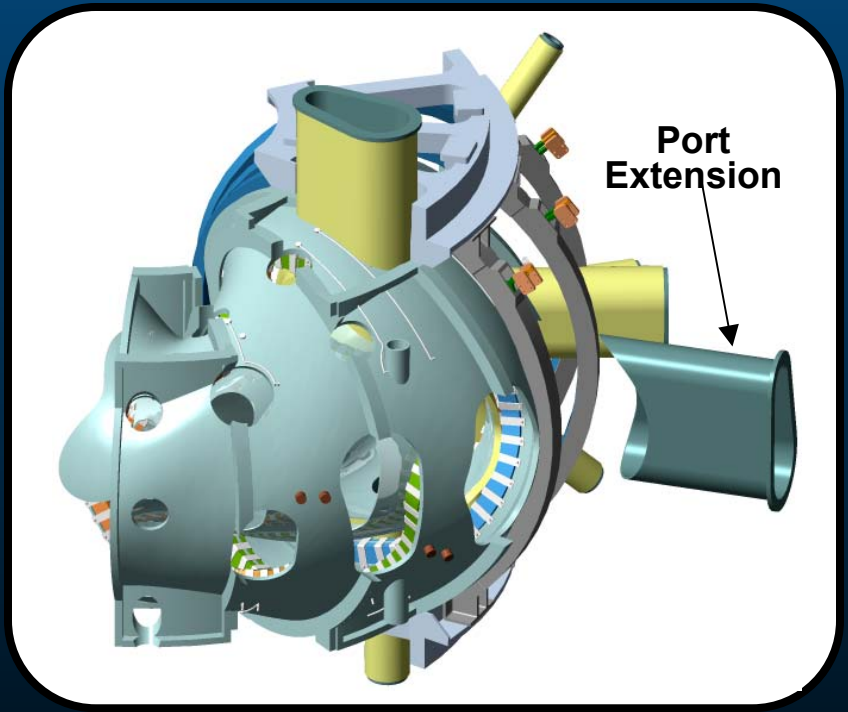
Half field period

Half field period repeats 6 times to form complete shell (Movie)

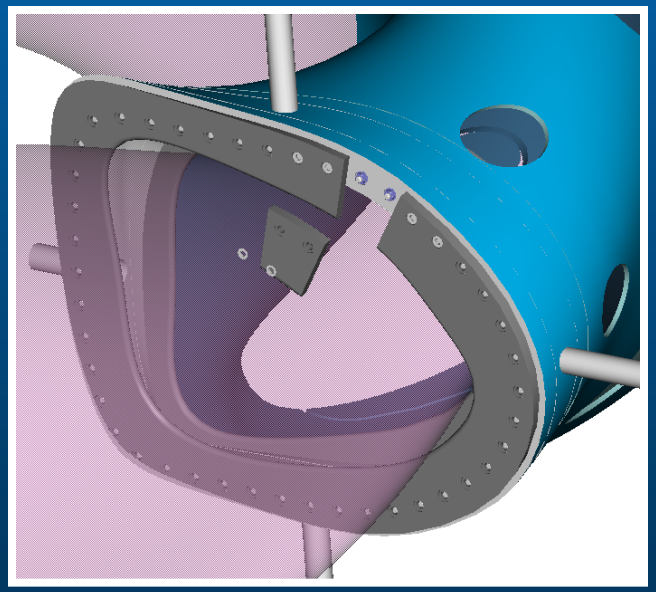
Field period assembly concept

- 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 STL models*



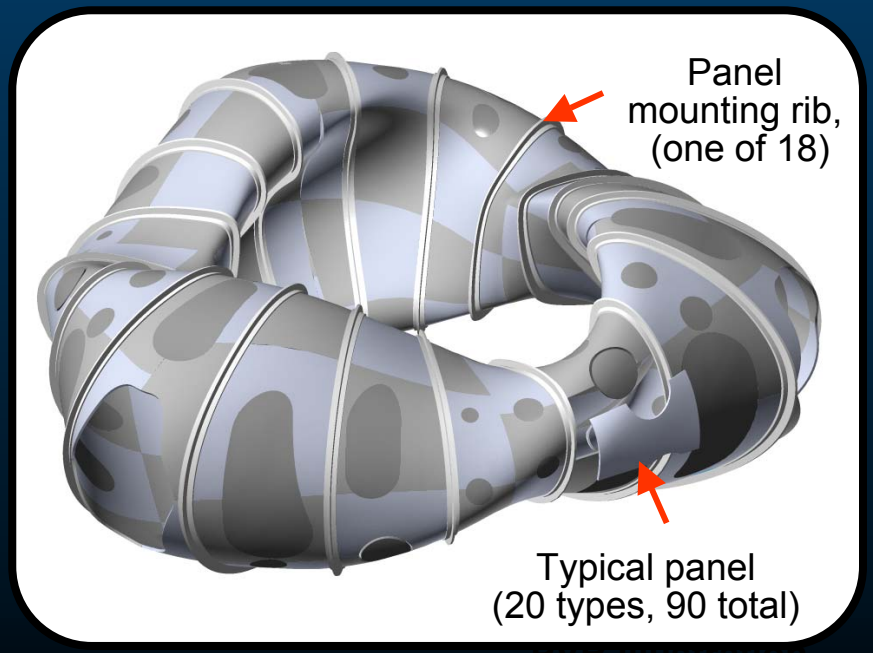


PFC design concept



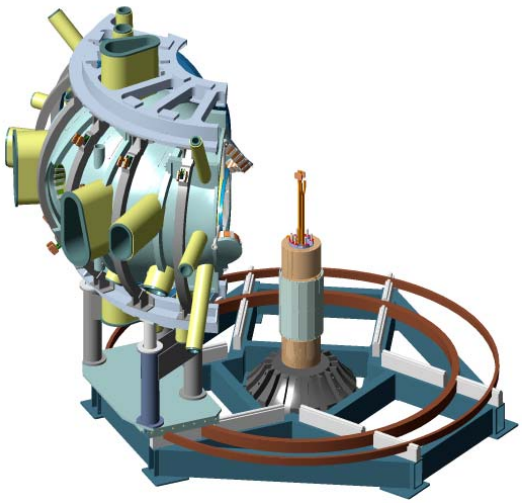
- Limiters provided day one at each assembly flange
- Simple, flat graphite tiles attached to flange bolts with tee-nuts

- Full liner of molded CFC panels deployed later during operation
  - Self-supporting and separately baked to 350C
  - Allows 150C vessel bakeout (beneficial for ports, windows, magnetic diagnostics)

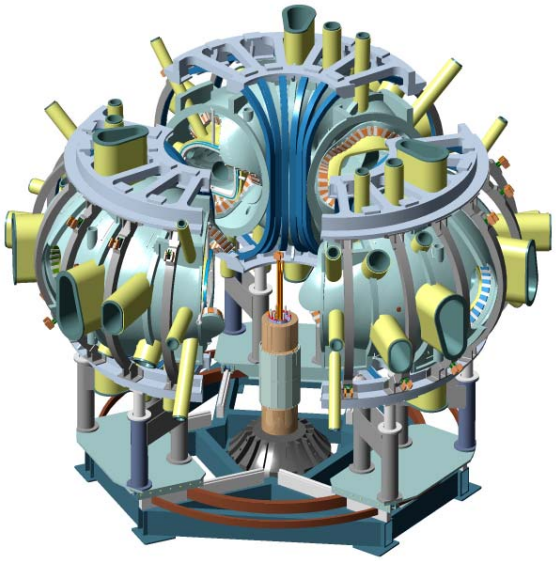


PVR illustration

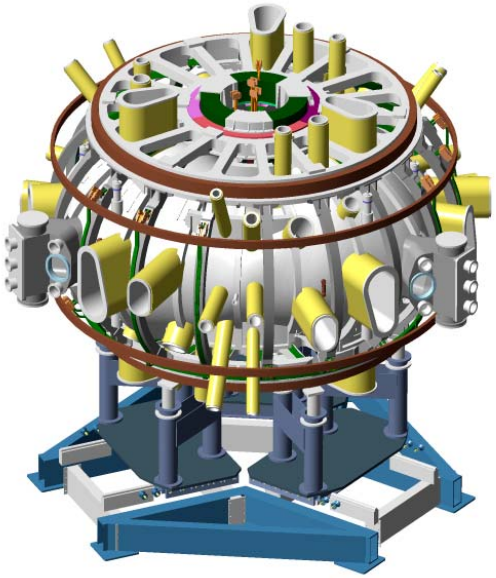
Field periods are assembled on machine structure in NCSX test cell



One field period sub-assembly placed on support stand in retracted (~500 mm) position



Three field period sub-assemblies in retracted positions

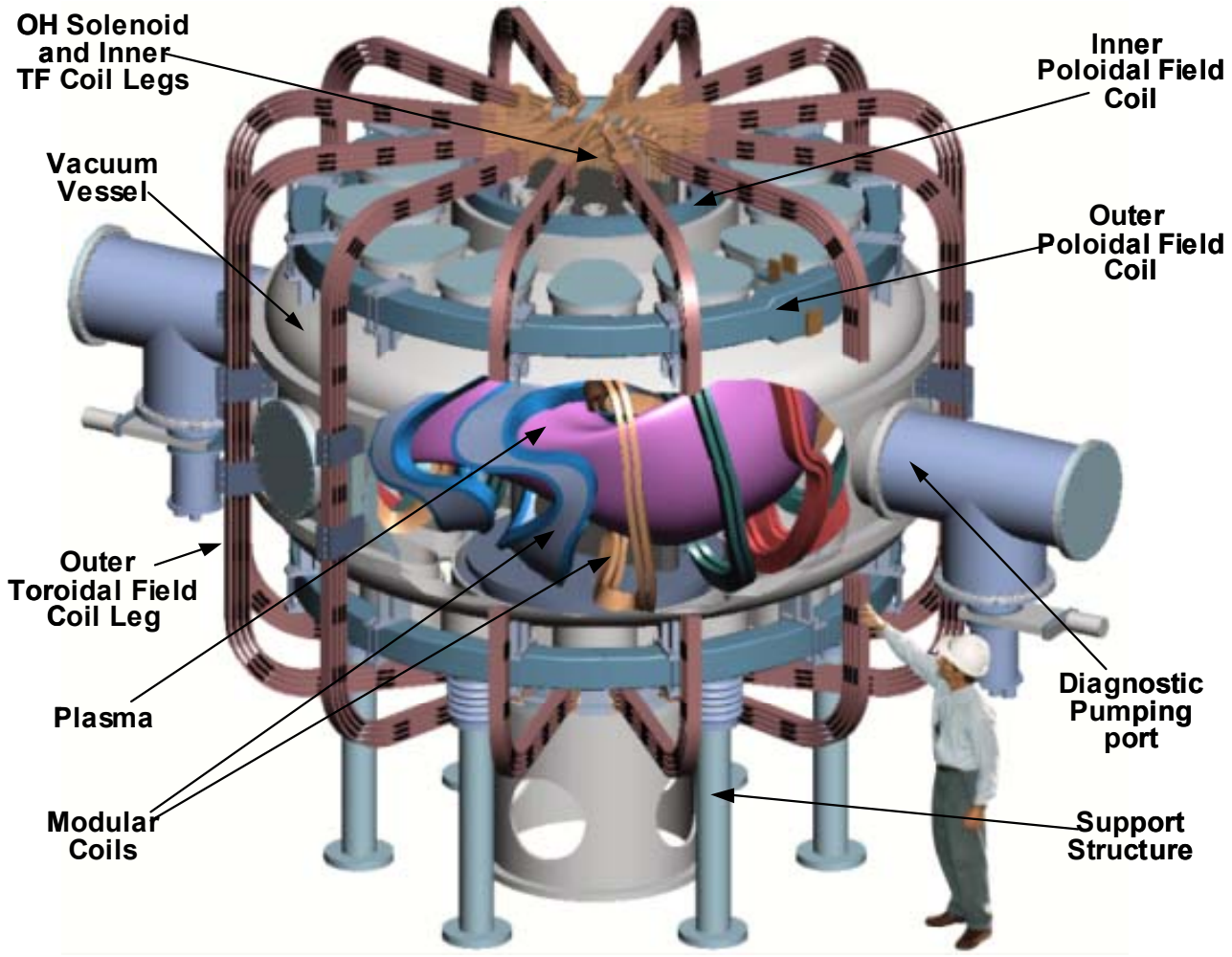


Field period sub-assemblies bolted together and PF coils installed in final position

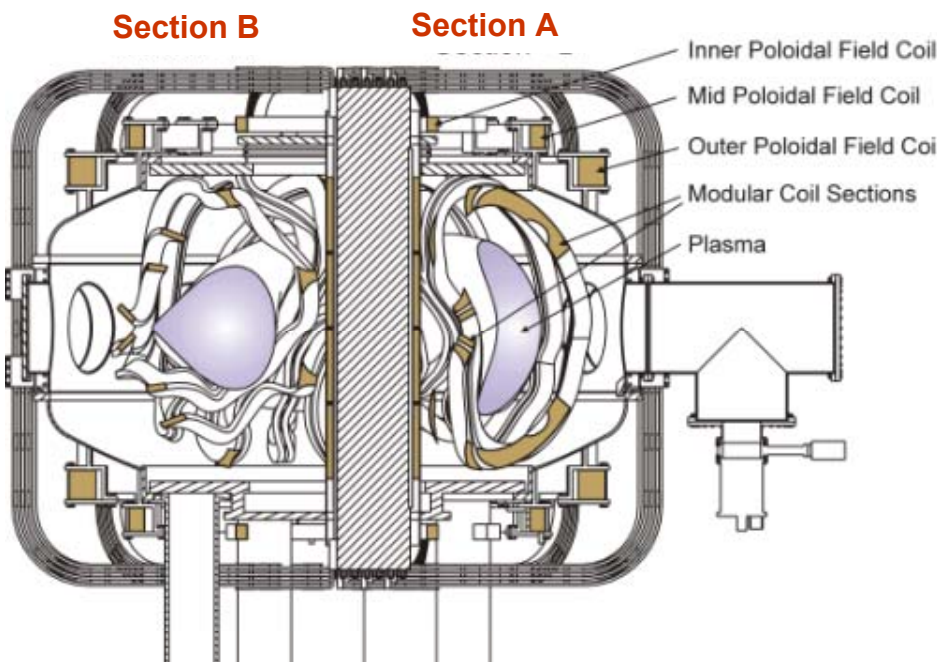
NCSX Core

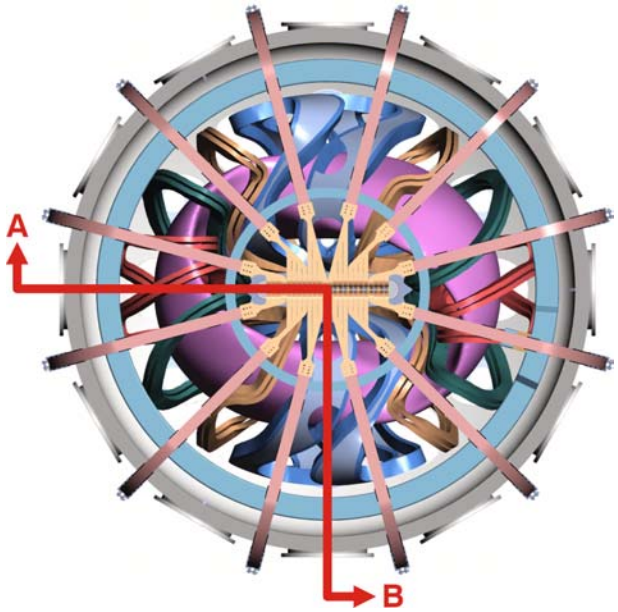
Assembly Sequence

QPS Stellarator Core



QPS Basic parameters

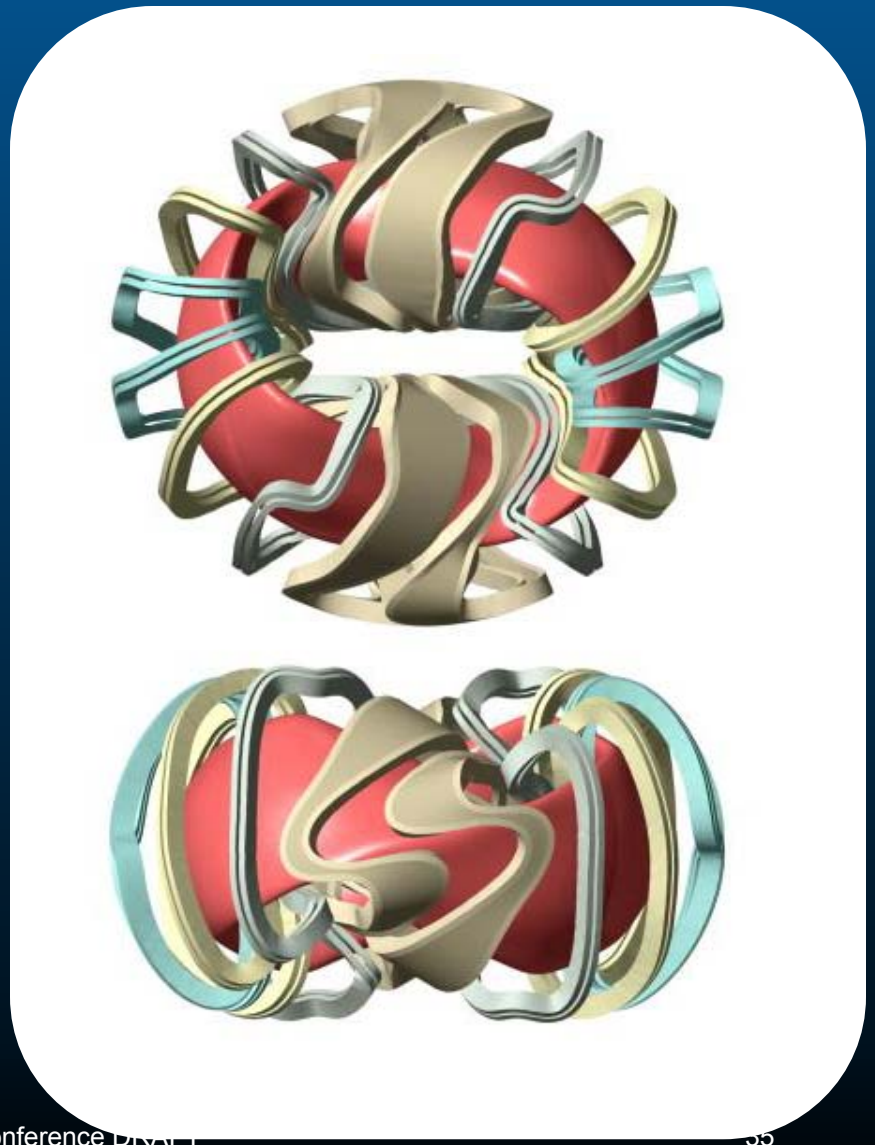




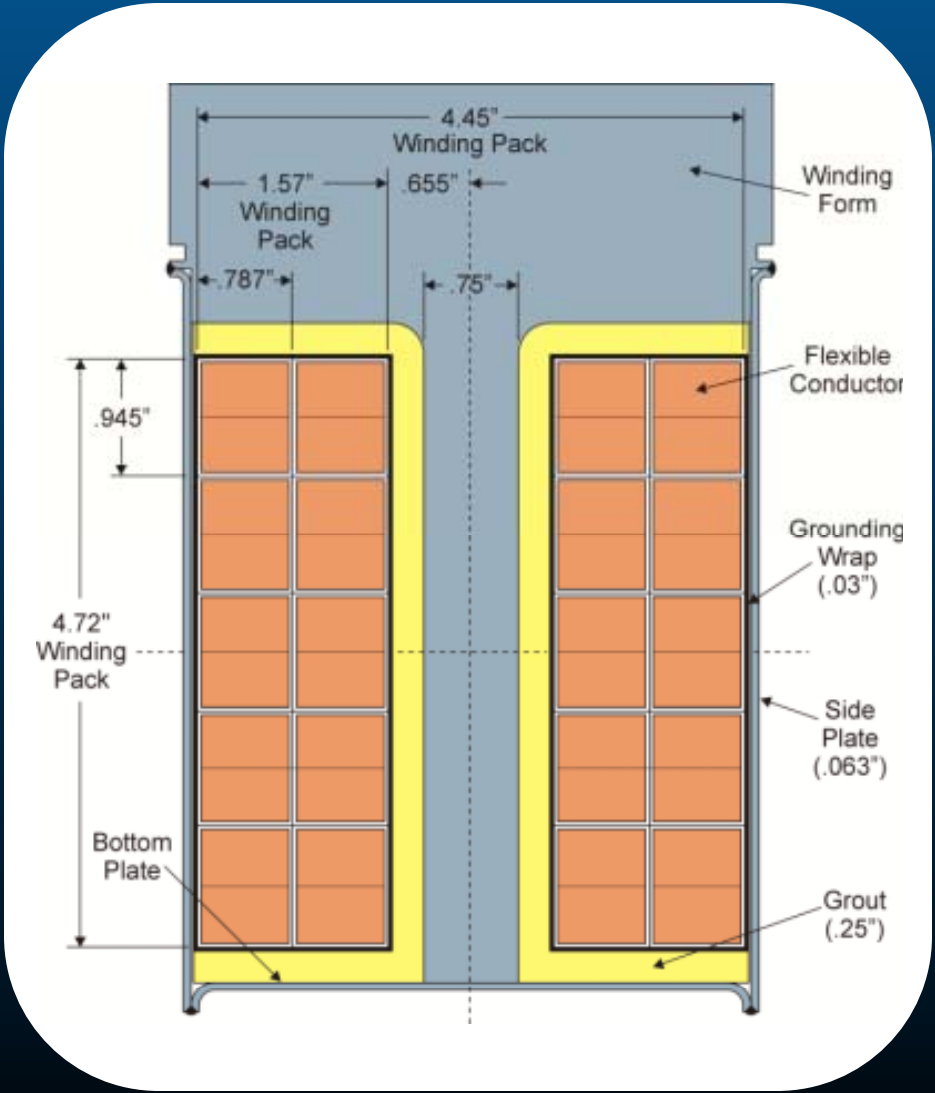
Major radius	0.9 m
Bmax, from mod coils	1 T
Plasma current	< 150 kA
TF coil configuration (no.)	+/- 0.2 T, 1/R (18)
Plasma heating	1 to 3 MW ECH and ICH

QPS Modular coil configuration

- 16 coils, 2 field periods, 4 coil types
- Coils must be “canned” for vacuum compatibility
- Coils wound with flexible cable conductor into cast-and-machined forms
- Coils operate at high temperature to minimize surface adsorption



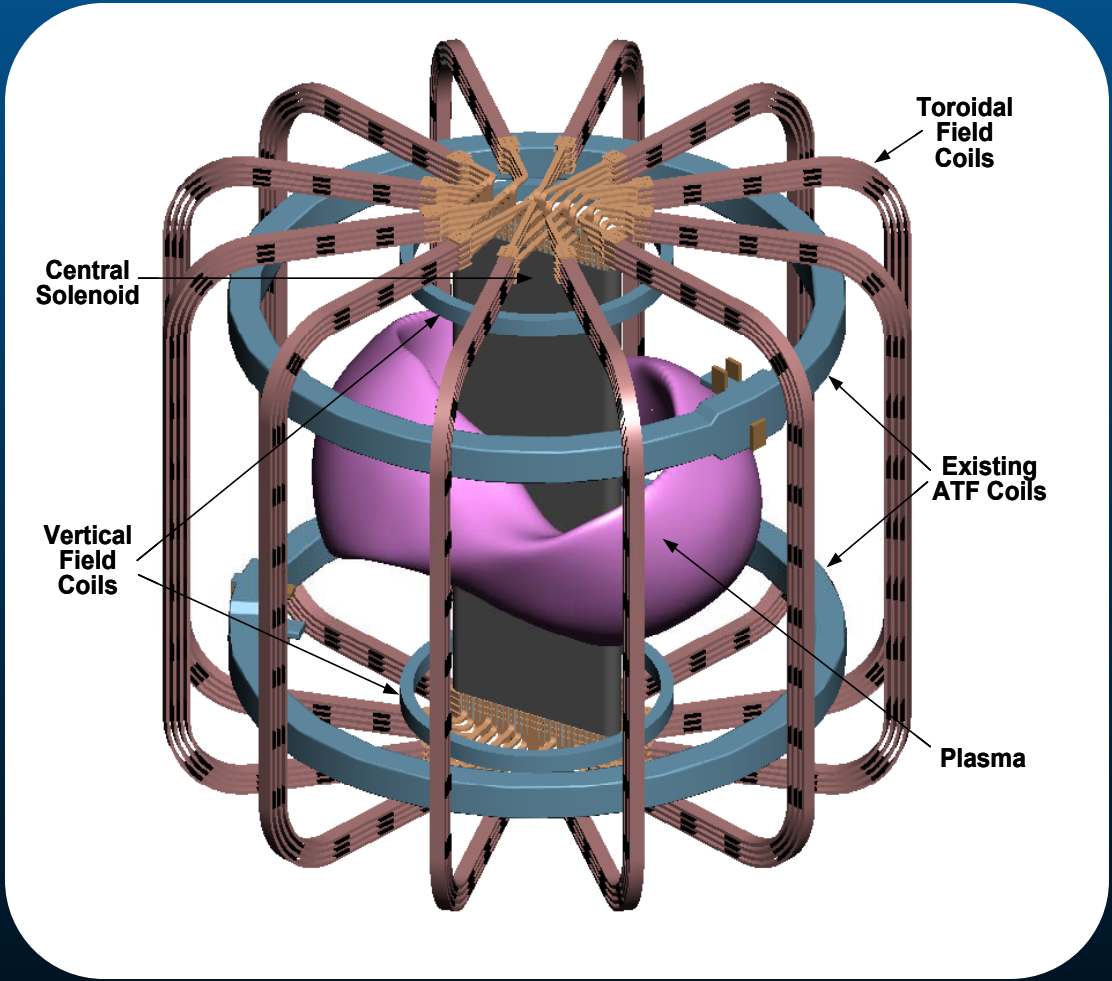
QPS coils use cast winding form *with vacuum can enclosing windings*



- **Parameters:**
  - Coil Envelope = 2 x 120 x 40 mm
  - Current / Coil = up to 360-kA-turns
  - Number of Turns = 20
  - Nominal current / turn = 18 kA
  - Conductor Size = 13.3 x 16.6 mm
  - Net Current Density = 8 kA/cm2
  - Conductor oper. temp. up to 100 C
- **Option for machining or "grouting" winding form, decision depends on cost**

QPS TF and PF Coil Set

- TF Coils:
  - 12 return legs of 4 turns each
  - Joints at top and bottom of centerstack
- PF Coils:
  - 4 OH windings in centerstack
  - 2 pairs of ring coils



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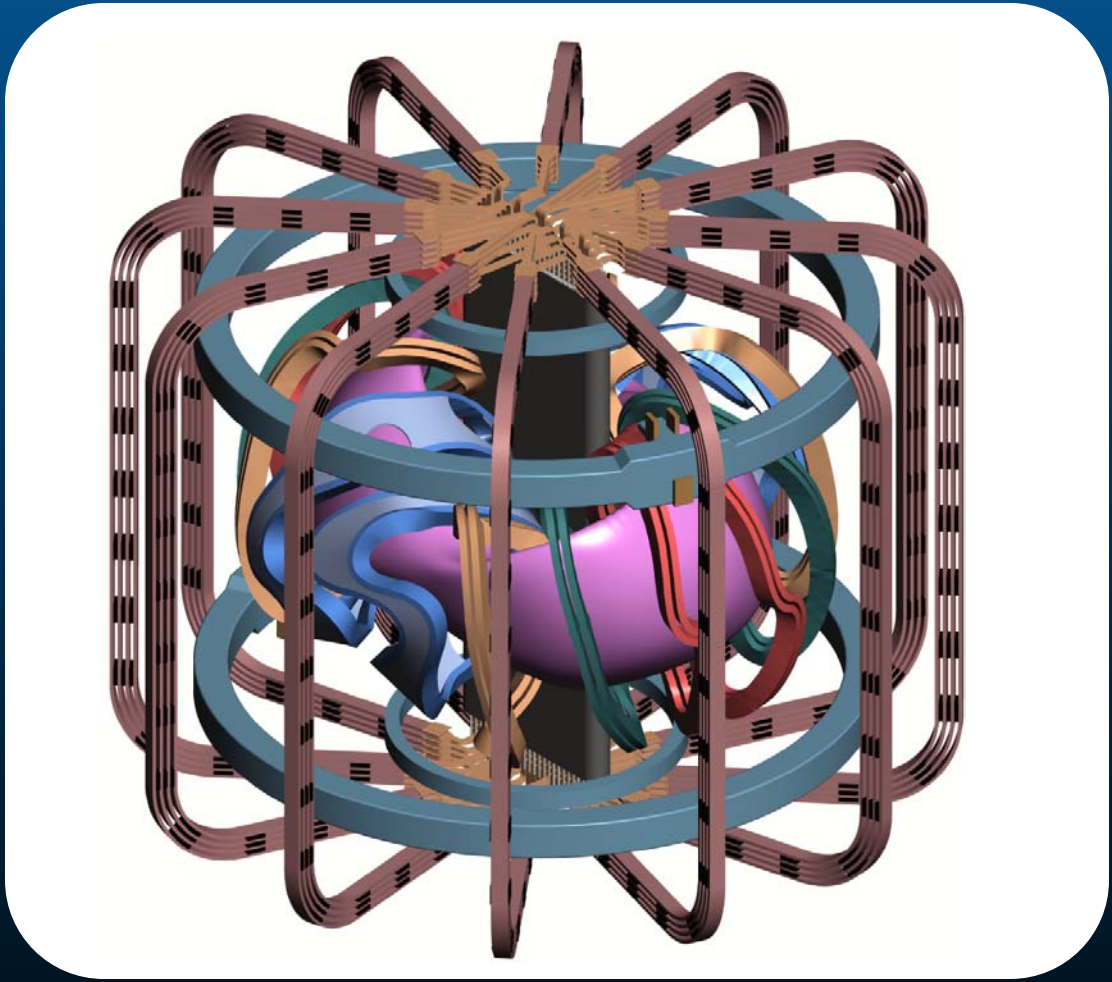
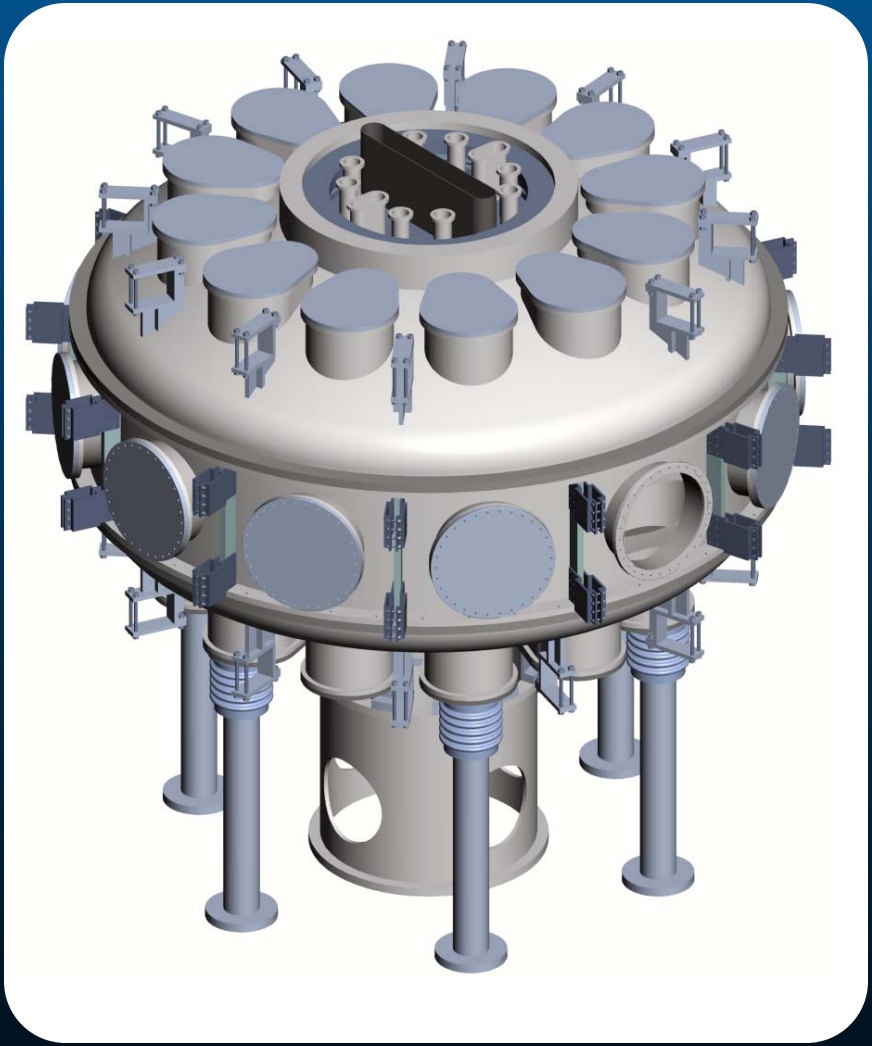


QPS External vacuum vessel

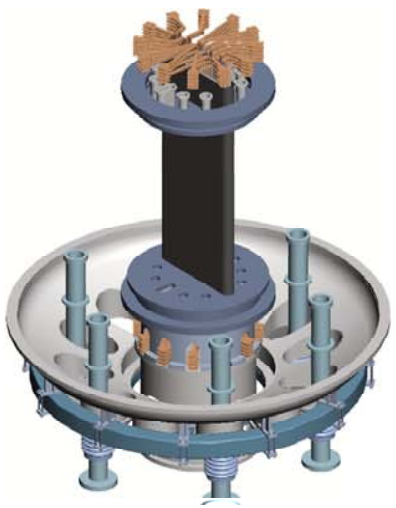
- Simple standard shape outboard, centerstack can inboard
- Good access with large (60 cm) ports around midplane, top and bottom
- PF, TF coils outside, mod coils inside



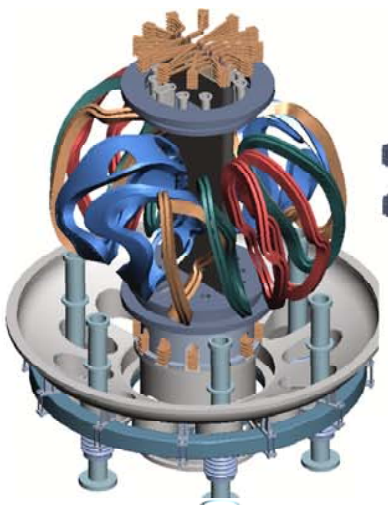
Parameters

Material	316L ss
Nominal outer radius	1.9 m
Maximum height	2.5 m
Inside surface area	~45 m^2
Enclosed volume (with ports)	~21 m^3
Bakout temperature	150 C
Nominal oper. Temp.	20-100 C

The two QPS field periods are assembled around the centerstack

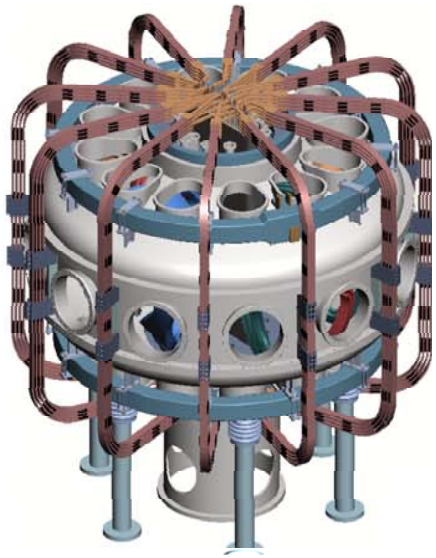


Install centerstack with dome and coils on base



Assemble modular coil field period sub-assemblies with structure around centerstack

Add vessel spool piece & upper dome with PF coils



Move domes to final position, leak check vessel, & install TF coils

R&D is underway to reduce risk

- Modular Coils
  - Manufacturing studies (complete)
  - Epoxy impregnation tests and conductor characterization
  - Winding tests on full scale form
  - Full scale prototype winding form (2)
  - Full scale prototype coil
- Vacuum Vessel
  - Manufacturing studies (complete)
  - Partial prototypes using different processes
  - Full scale prototype(s) of half field period using one or more processes

Summary (1)

- Compact stellarators should combine the best features of tokamaks and stellarators: high beta and good confinement with inherently steady state, disruption free operation

- Two new compact stellarator facilities are planned in US
  - NCSX is a 1.4m, 2T facility at PPPL , aspect ratio of 4.3
  - QPS is a 0.9 m , 1T facility at ORNL, aspect ratio of 2.7
  - Both experiments will be operational in 2007

Summary (2)

- Modular coils represent the biggest engineering challenge
  - Coils are optimized to meet physics and engineering constraints
  - Shell structure is robust and provides needed accuracy
  - Flexibile cable conductor with conduction cooling is planned for ease of winding
- Vacuum vessels are approached differently
  - NCSX vessel is inside modular coil set
  - QPS vessel is external to modular coil set
  - Both vessels have numerous ports and good access
- Manufacturing R&D planned for 2003 will provide industrial input improving design/fabrication of modular coils and vacuum vessel