QPS Engineering Design

Presented by B. Nelson for the QPS design team

QPS PVR

April 24, 2001

ORNL

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UT-BATTELLE

Presentation Outline

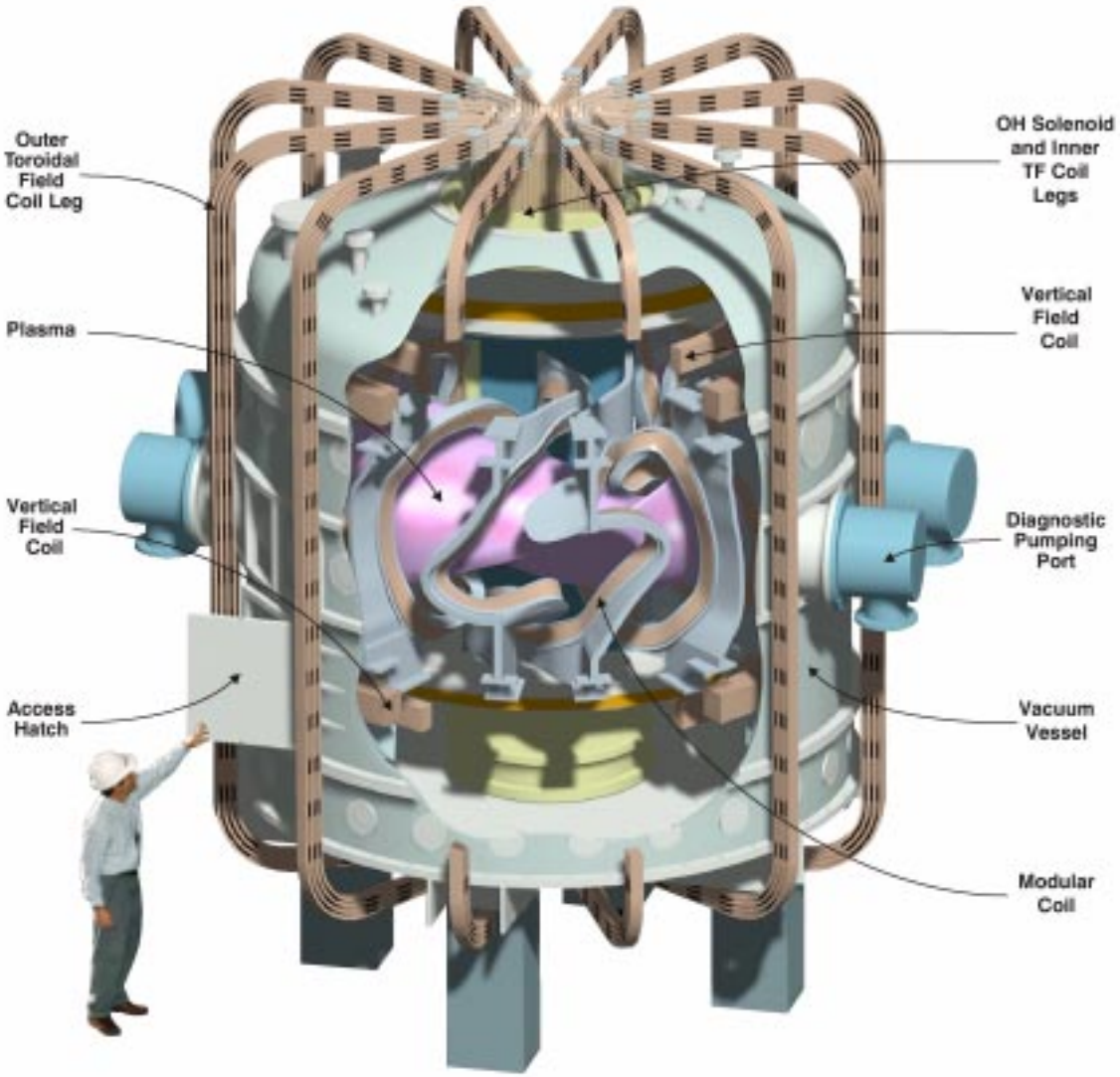
- **Baseline parameters**
- **Stellarator core configuration**
  - **Modular coils, VF/TF coils, structure, vacuum tank**
  - **What are the requirements?**
  - **What is the design concept?**
  - **How do we plan to build it?**
- **Summary and plans for CDR**

Baseline parameters for QPS design

- **Moderate size and field**
  - **<R0> ~ 0.90 m**
  - **<a> ~0.35 m**
  - **B0 = 1 T**

- **Factory assembled unit desired, consisting of modular coils, VF and TF coils, and structure**
  - **Minimum cost is essential**
  - **Uses existing power supplies, cooling system, diagnostics, vacuum pumps, ECH system, etc.**

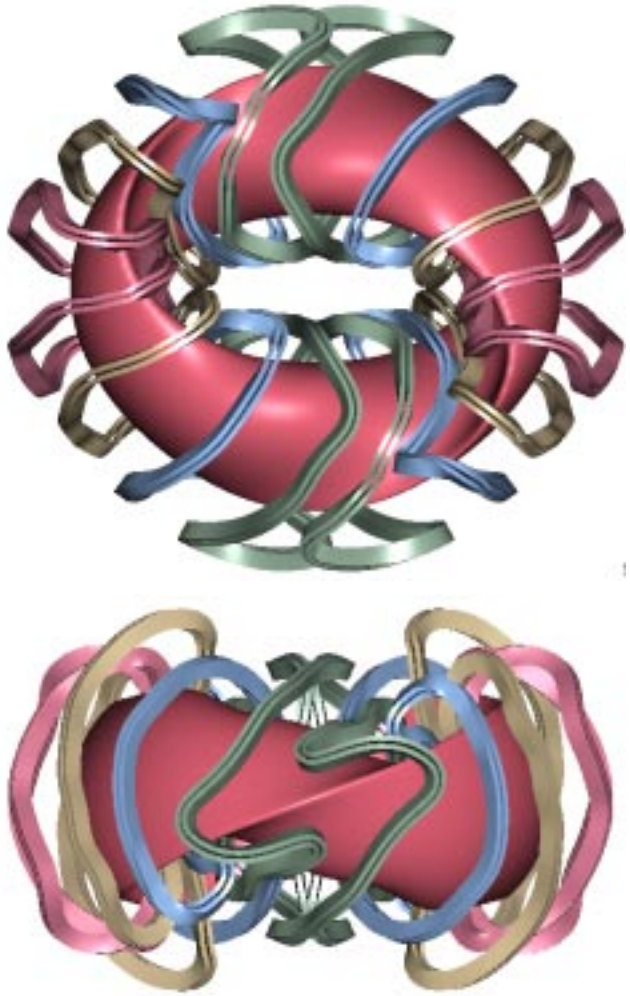
QPS Concept


Outer Toroidal Field Coil Leg
Plasma
Vertical Field Coil
Access Hatch
OH Solenoid and Inner TF Coil Legs
Vertical Field Coil
Diagnostic Pumping Port
Vacuum Vessel
Modular Coil

Modular coil requirements

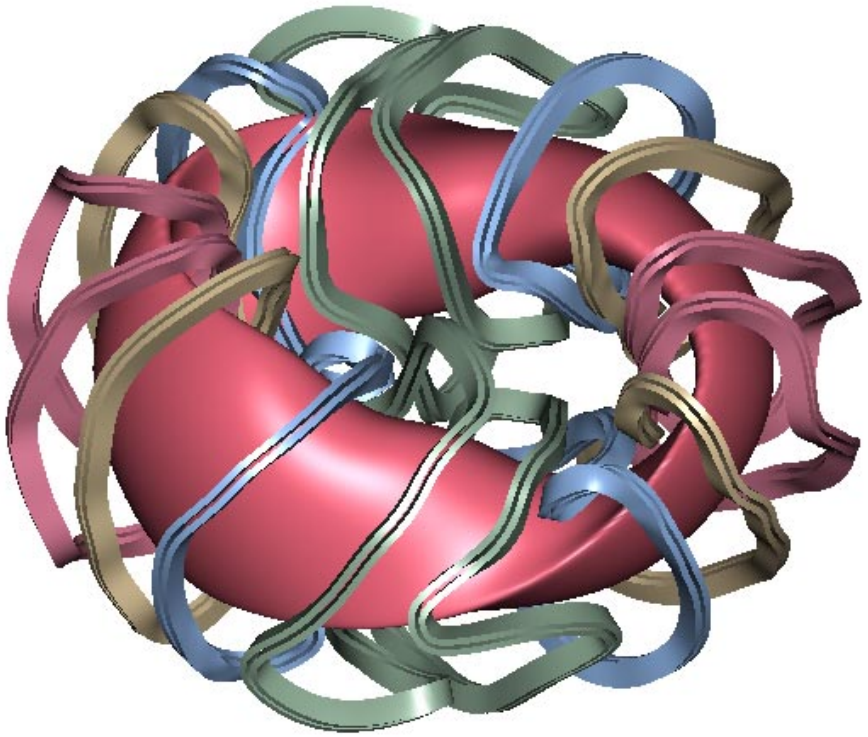
- **Meet performance requirements**
  - **1 T with 0.5 s flattop**
  - **10 minute rep rate (5 minute rep rate for shorter pulses)**
- **Provide flexibility**
  - **Independent control of modular and PF coils provided**
  - **Variable background TF field +/- 0.15 T**
- **+/- 1 mm assumed for winding accuracy**
- **Coil structure should maximize access for heating and diagnostics**
- **Limit conductor current and voltage drop to match existing power supplies**

Modular coil configuration



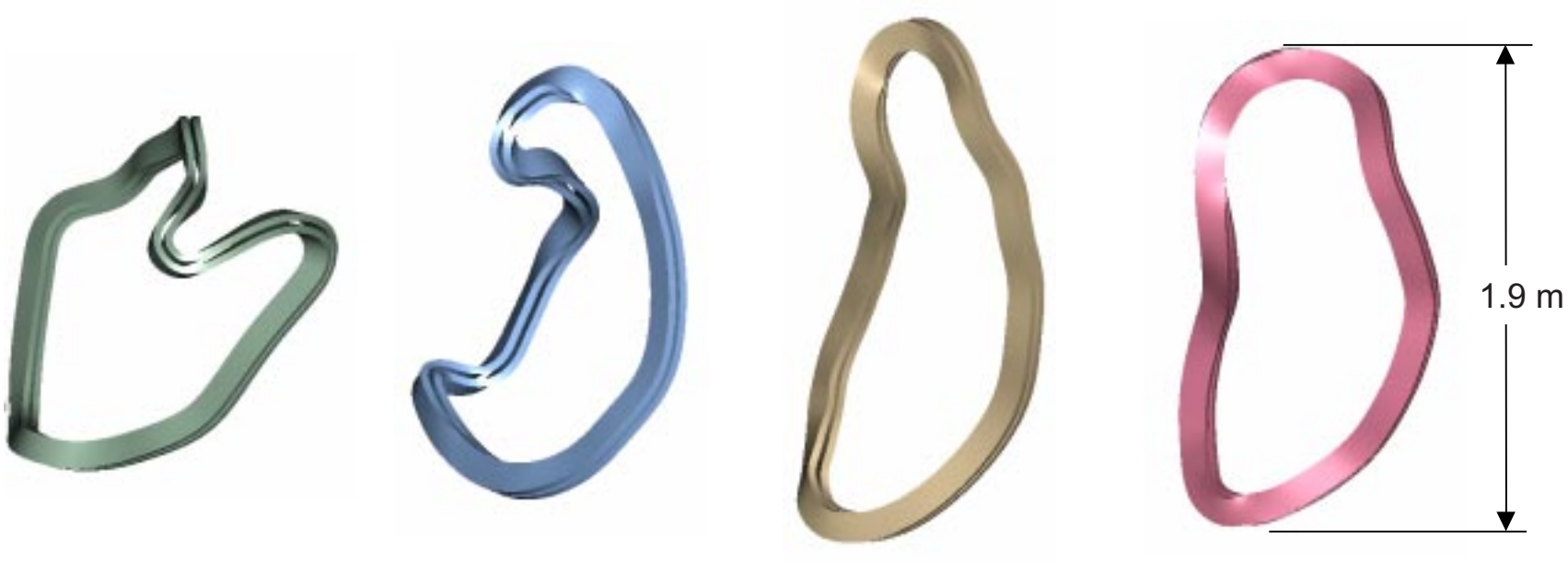
Coil set 0213b2 (as scaled)

R0 = 0.90 m, a = 0.35 m



Modular Coil Geometry

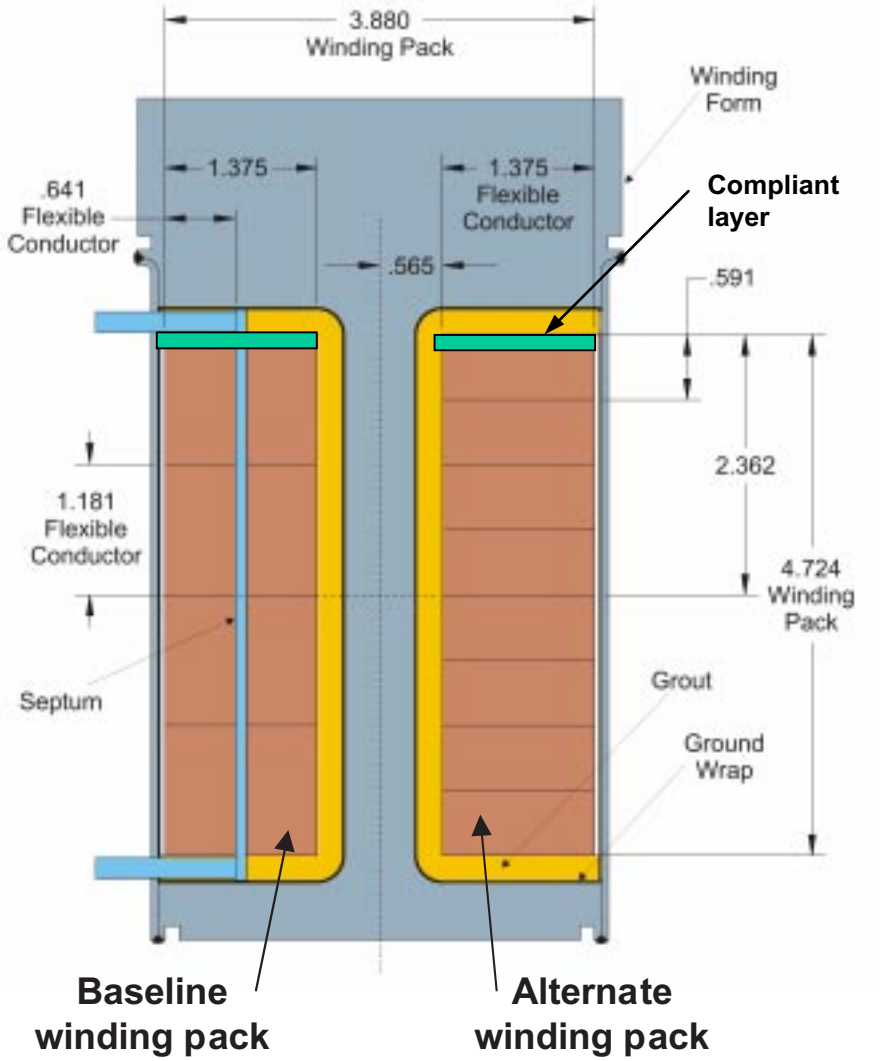
Cross section shape and size depends on details of bending radius, twist, coil-coil spacing, coil-plasma spacing



Coil 1 Coil 2 Coil 3 Coil 4

bean section

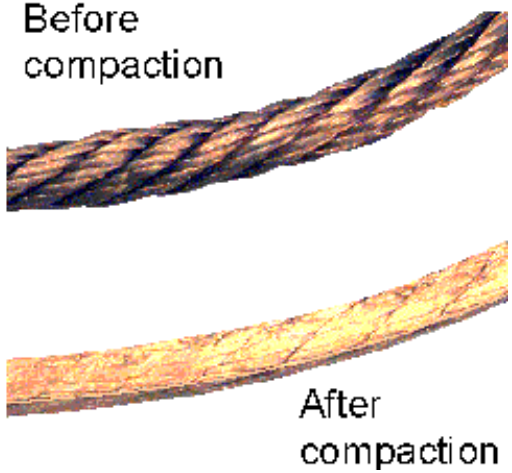
Modular coils wound with flexible cable directly on coil structure



Parameters:

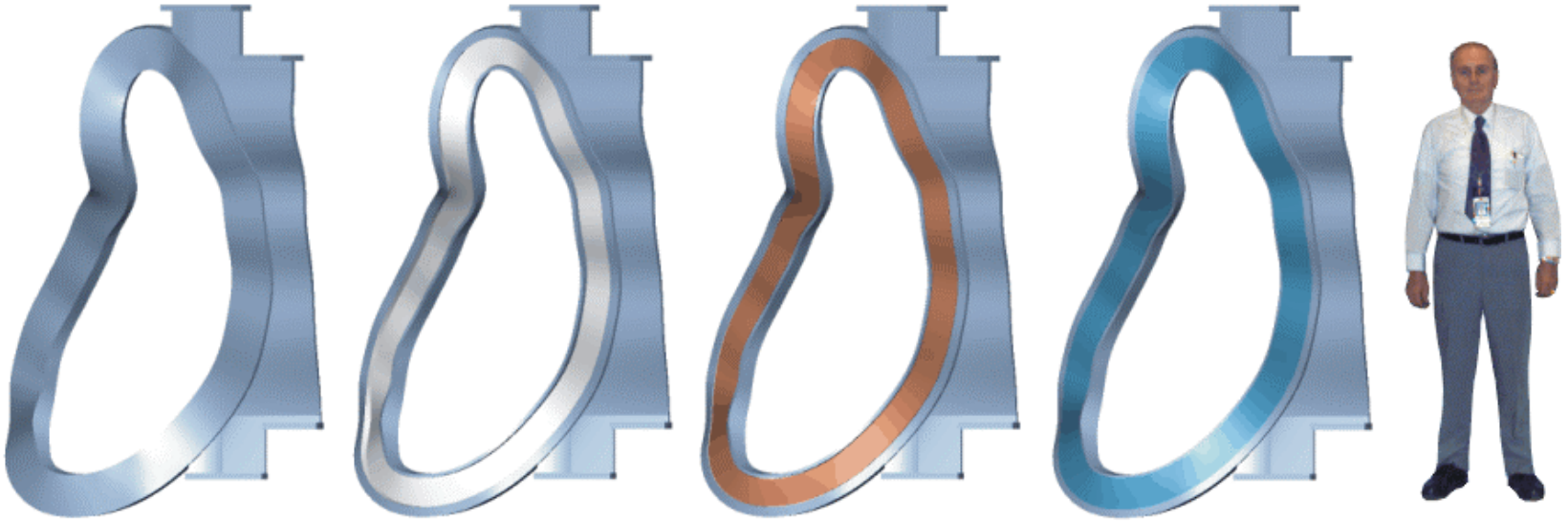
- Coil Envelope ~ 2 x 120 x 34 mm
- Current / Coil = 337-kA @ 1 Tesla
- Number of Turns = 16
- Avg length per turn = 5.07 m
- Nominal current / turn = 21.1 kA
- Conductor Size = 16 x 30 mm
- Heat removed via gas-cooled septum
- Net Current Density ~ 8-kA/cm2
- Total peak power ~ 45 MW

Flexible cable used to wind coil



Modular coil manufacturing sequence

- **Continuous support for strength and accuracy of windings**
- **Castings repeated four times for each coil type**



Rough casting

Features are machined, winding cavity grouted

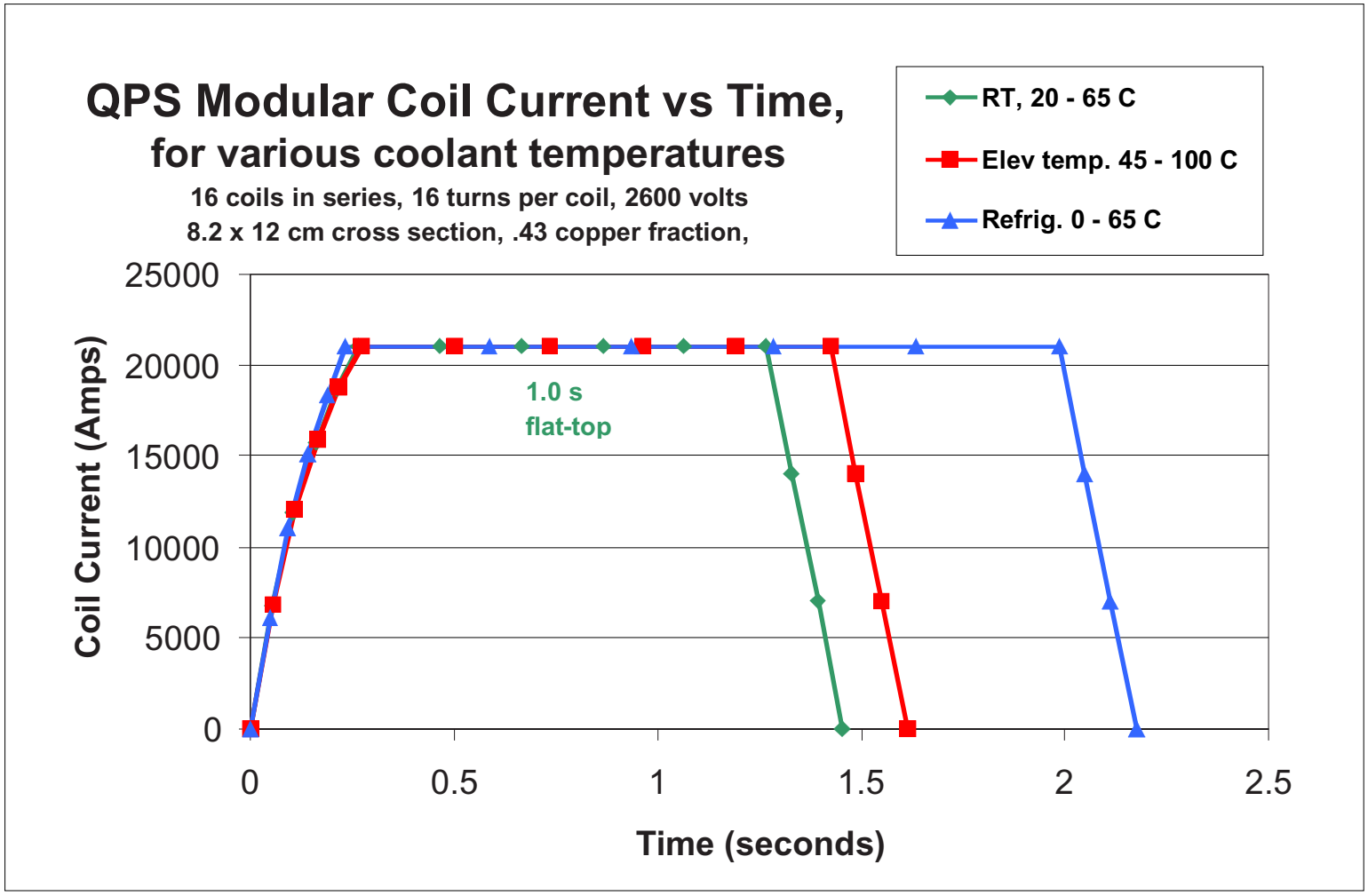
Conductor wound directly into structure

Side plates welded to structure

Ramp rate and flat-top considerations

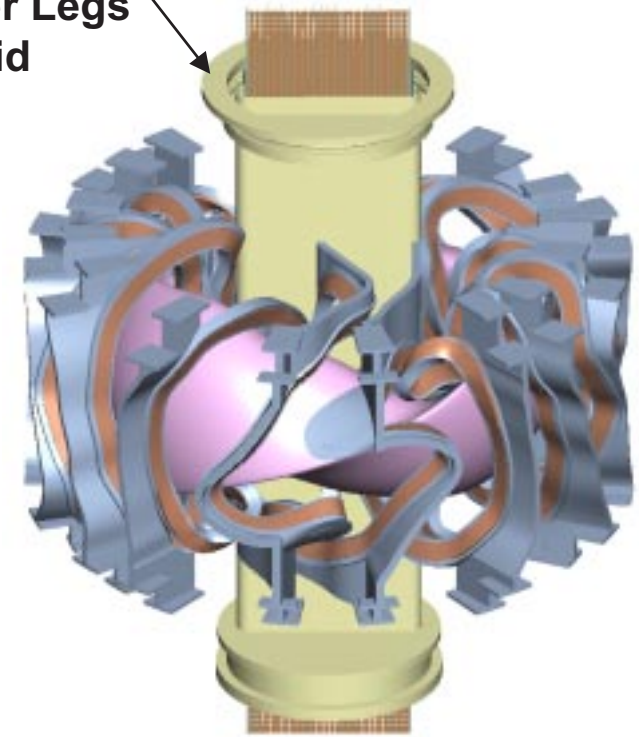
- **Temperature limits**
  - **Max temp depends on epoxy used, RT cure epoxy limited to ~ 65C, heat cured epoxy can go to 100C**
  - **Min temp depends on thermal isolation of coils and compatibility with plasma vacuum**
- **Power supply limitations**
  - **4 solid state modules rated at 650 V, 30 kA pulsed (7.5 kA continuous)**
  - **3 solid state supplies rated at 625 V, 15 kA pulsed (~ 3 kA continuous)**
- **Eddy current decay time in structure**
  - **Error fields not completely symmetrical due to casting variations**
  - **I-Beam castings have <10 ms time constant**

Coil parameters, power supply, cooling temp. determine pulse waveform and flat-top time



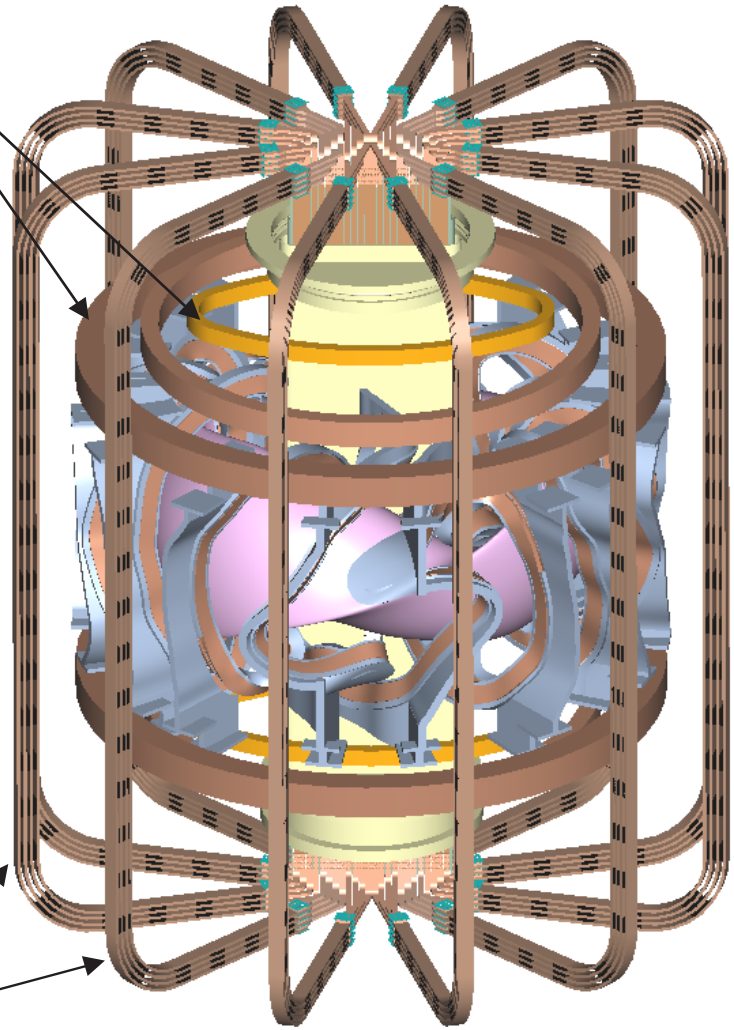
TF and VF coils

Center Stack Includes:
- ¥ TF Inner Legs
- ¥ Solenoid



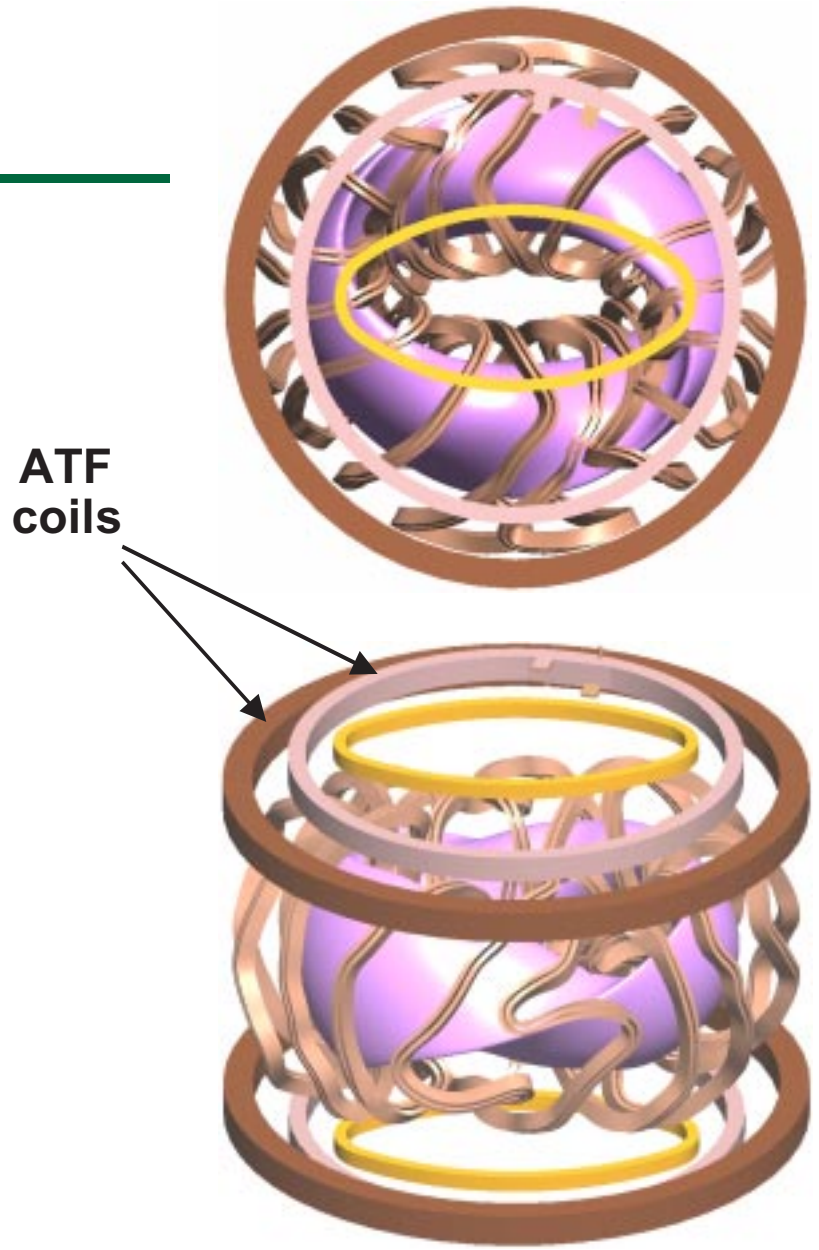
VF Coils

Outer TF Legs



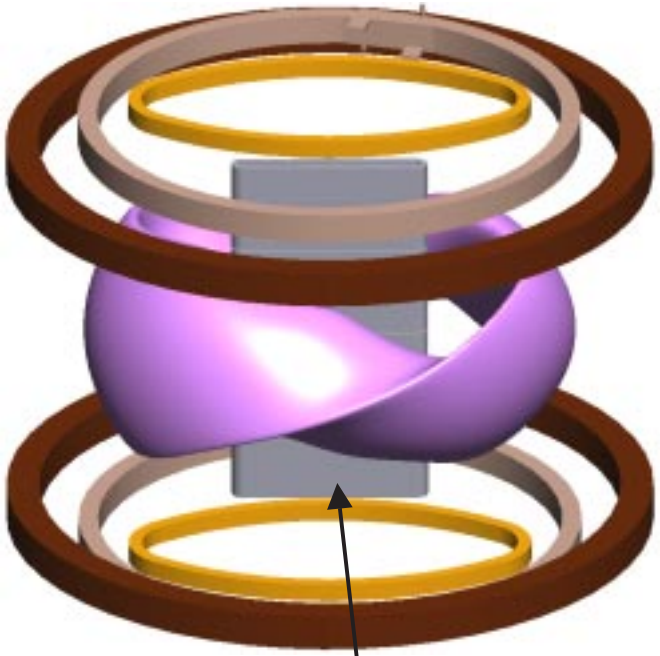
VF / Trim Coils

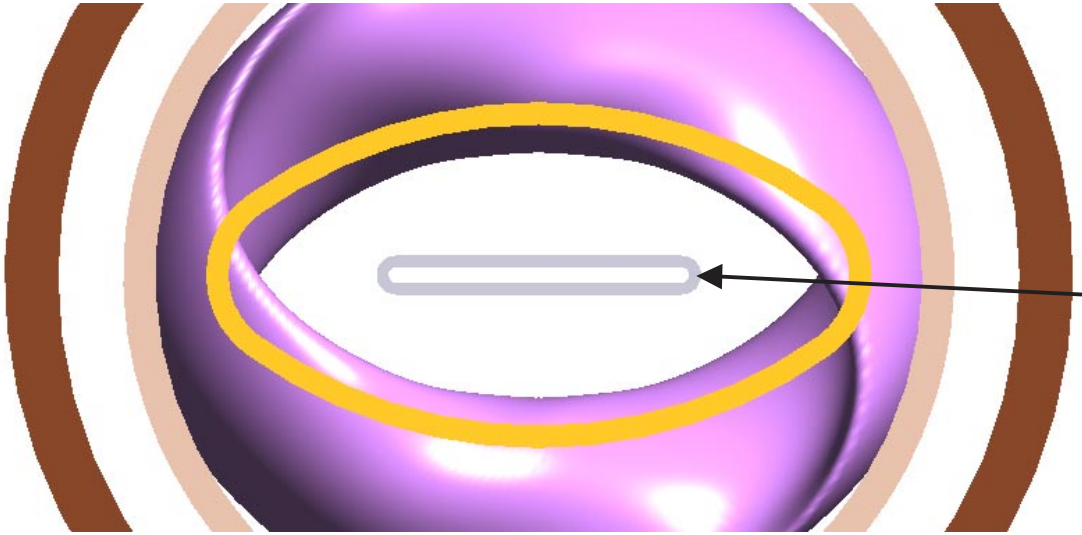
- 3 pairs of VF coils are included in design
- Planar coils are assumed
- Combination of existing ATF coils and new coils
- Elliptical shape for mid/inner VF coil pair is planned



OH solenoid / return coils

- Central solenoid is limited to oblong shape by modular coils
- Plan to use VF / trim coils for outer return coils
- Present configuration limited to +/- 0.15 V-S by power supply
- Forces will require ties across winding

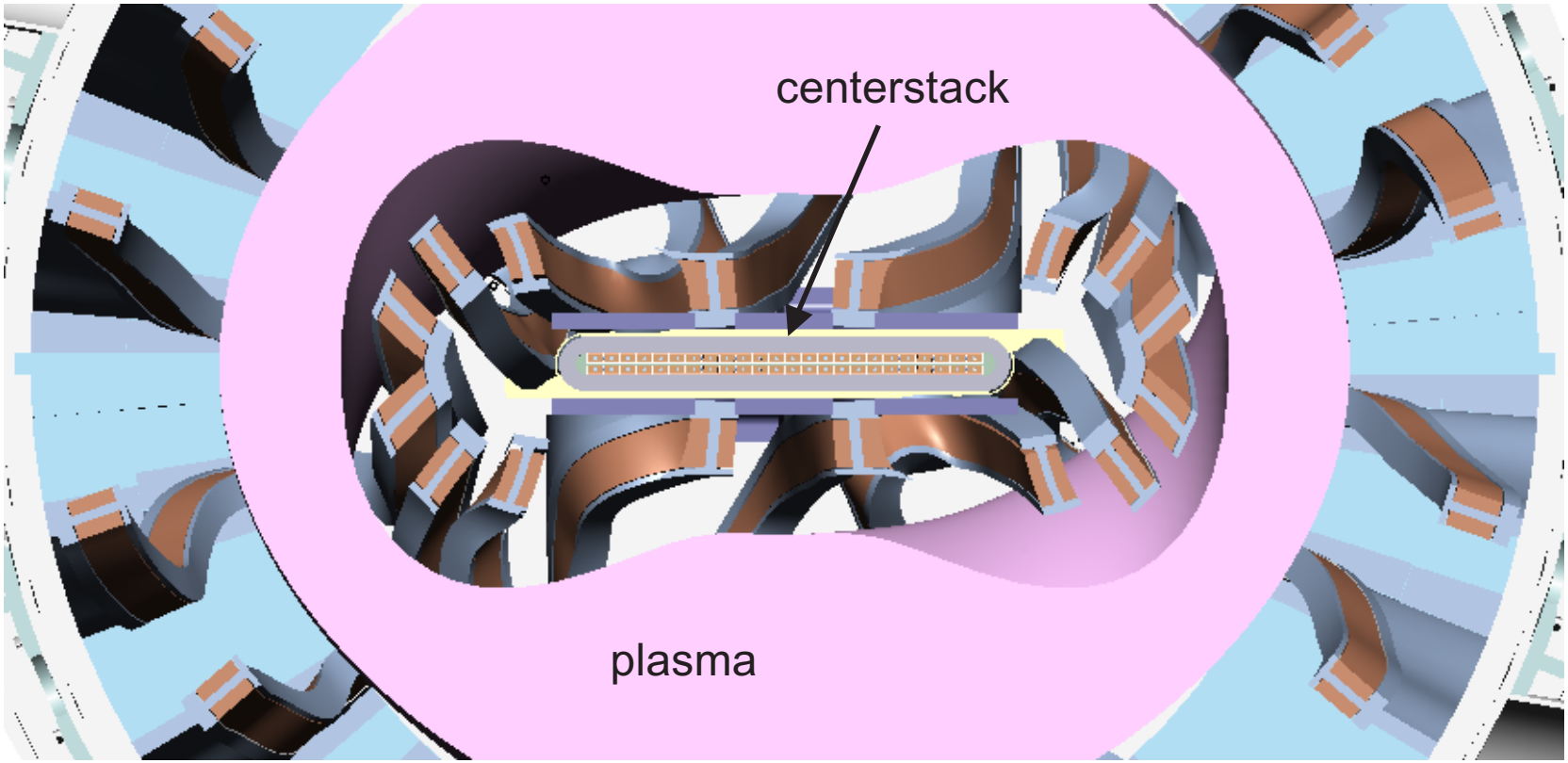




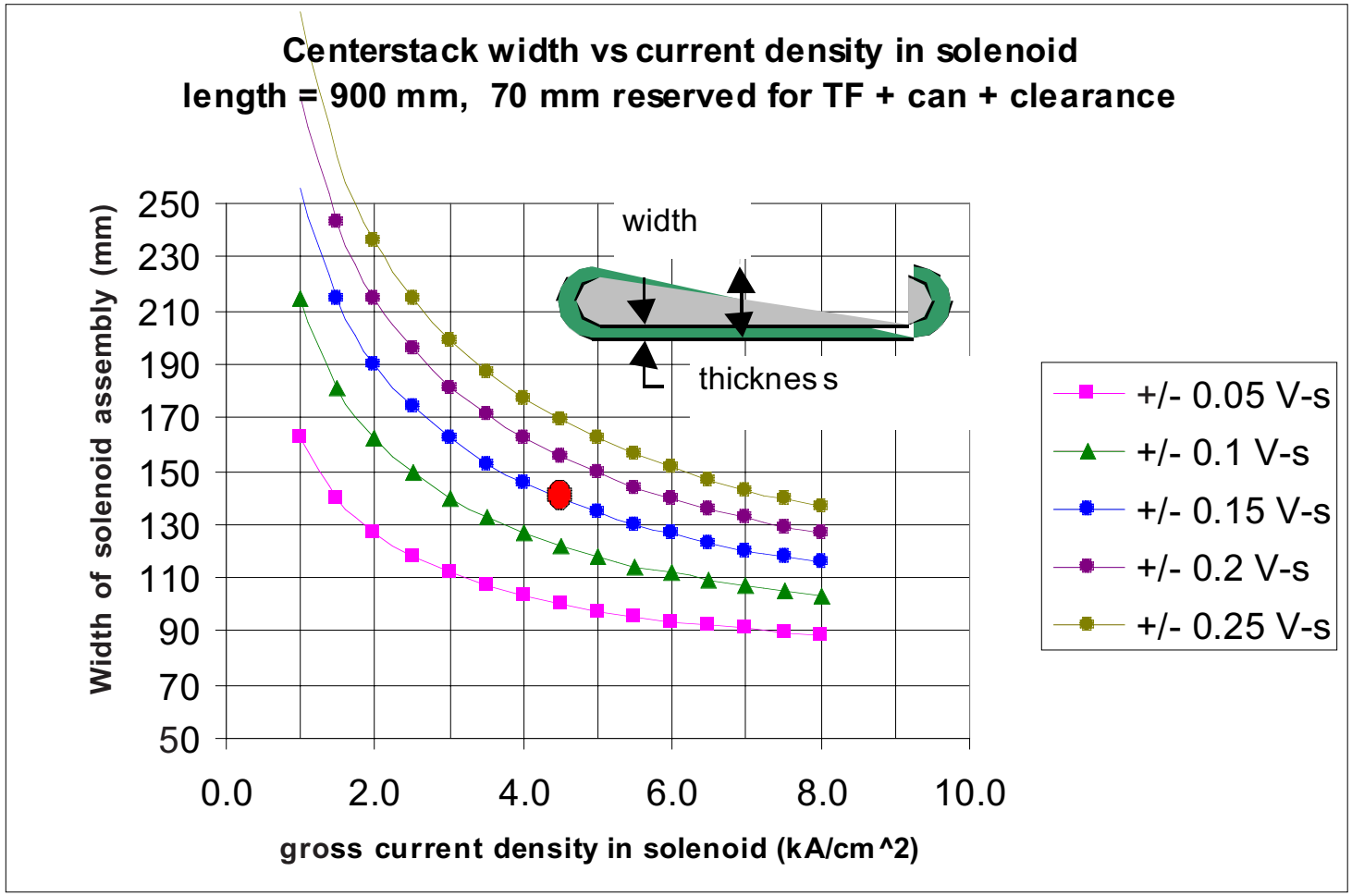
OH solenoid

Centerstack occupies oblong space

- **Limited room for TF coils, OH solenoid and vacuum casing**
- **Available clear vertical bore is ~ 14 x 90 cm**

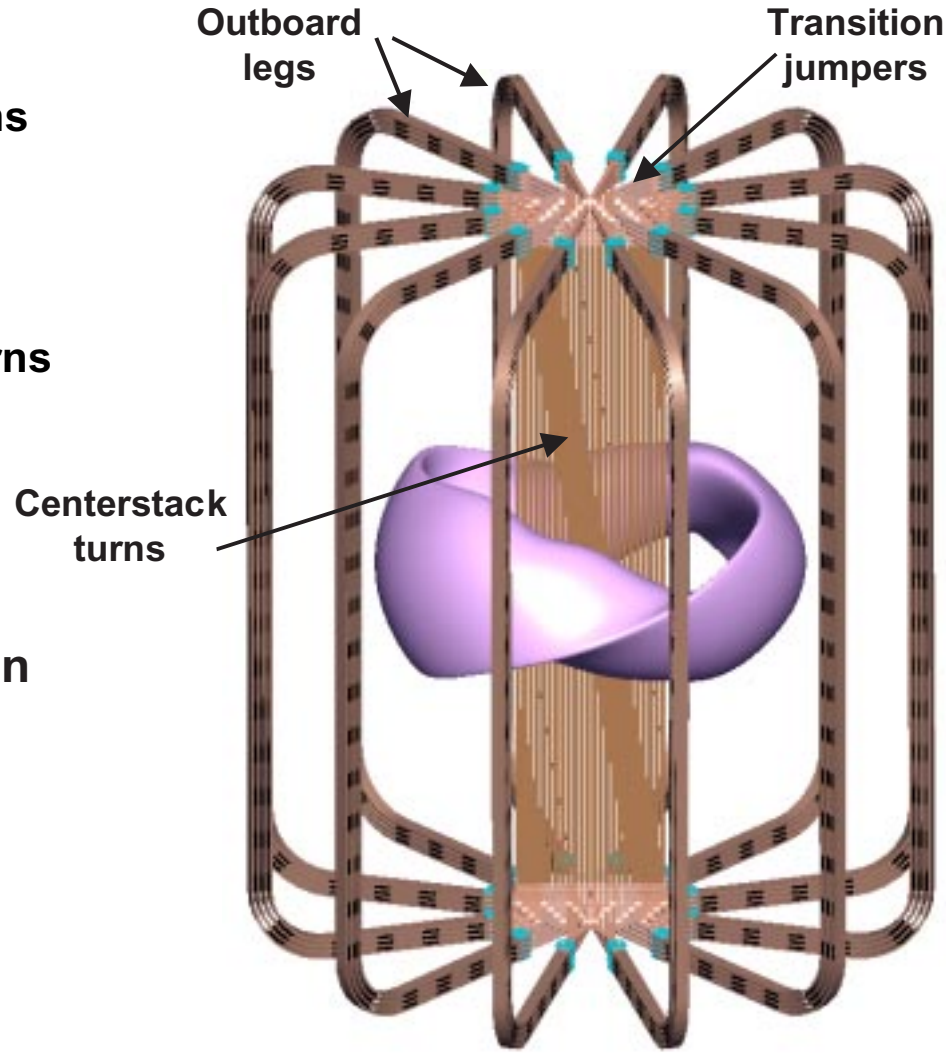


What space is needed for solenoid?

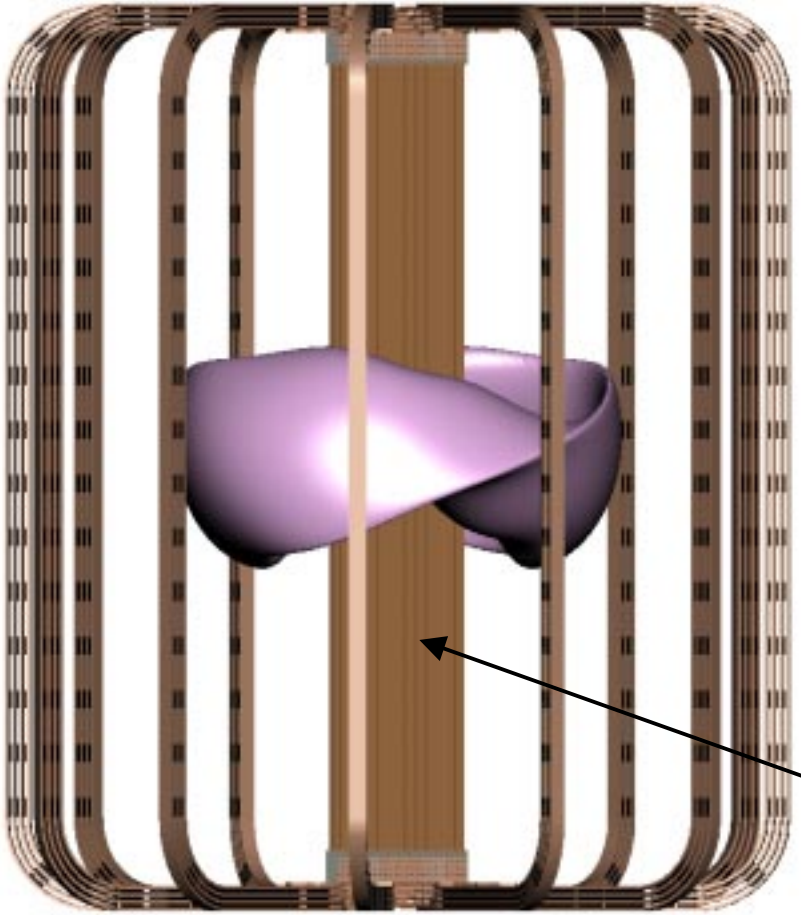


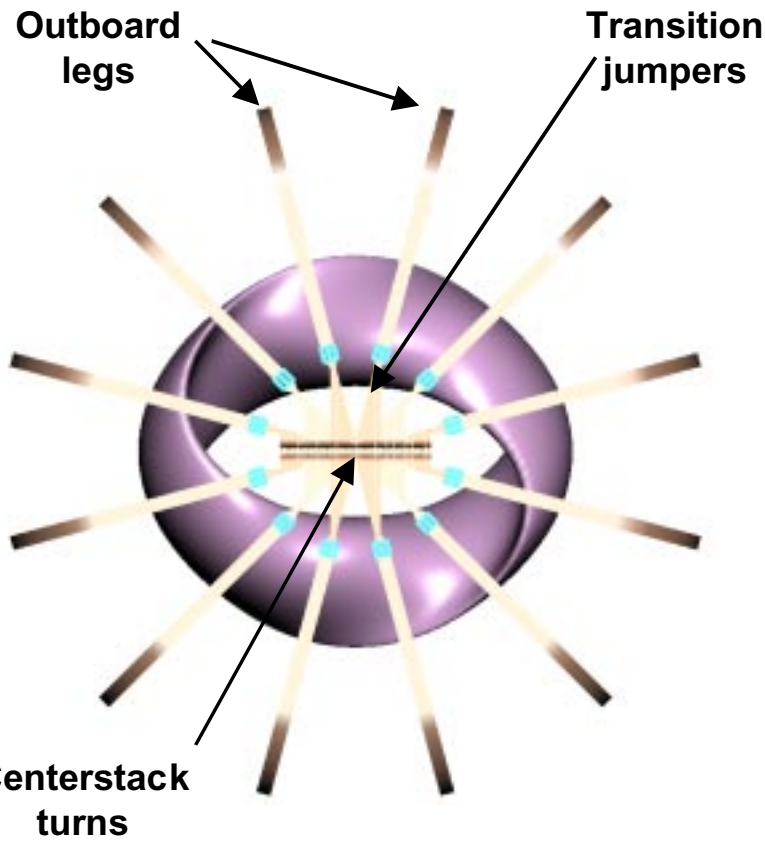
TF coils

- **48 turns**
  - **1.5 x .75 in. centerstack turns**
  - **3.5 x .75 in. outboard**
- **+/- 0.15 T (14 kA / turn)**
  - **~2100 A/cm^2 centerstack turns**
  - **~ 850 A/cm^2 outboard**
- **12 return leg bundles**
- **Odd shape requires transition jumpers at center stack**
- **Stellarator symmetry is preserved**



TF coils (2)





Elevation view

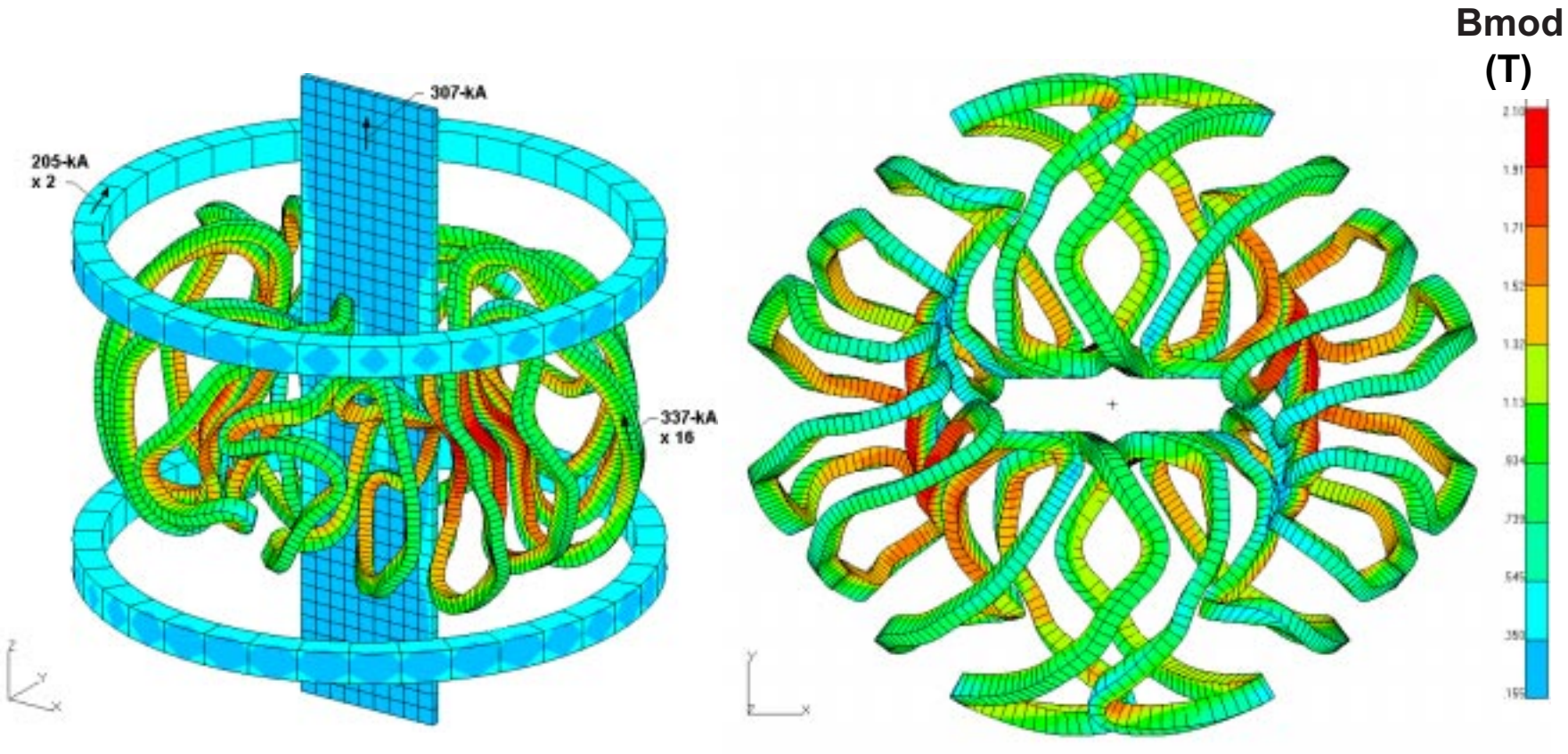
Plan view

Coils match up with existing power supplies

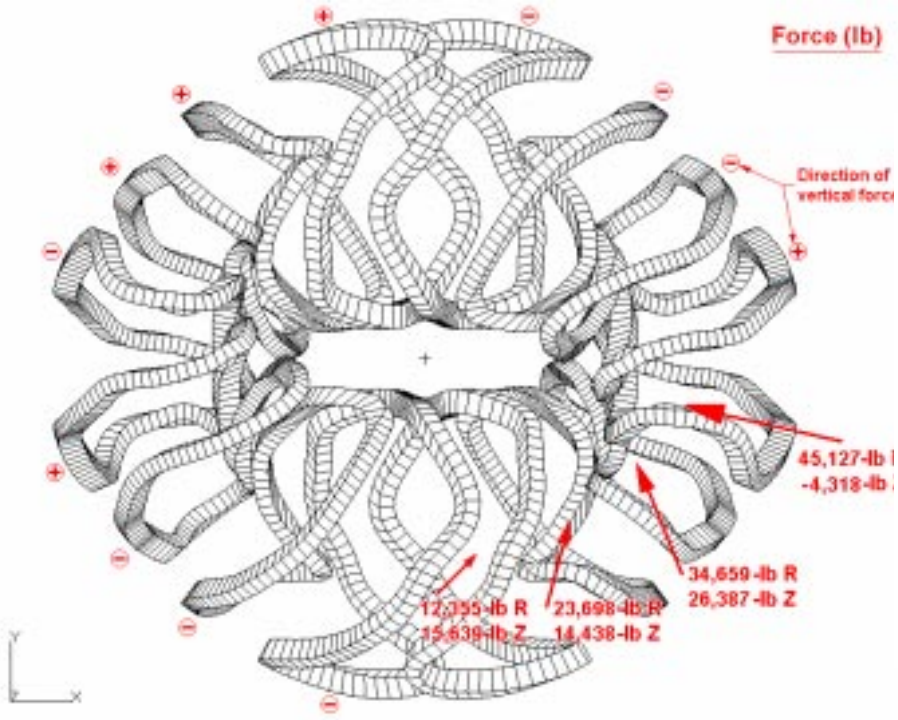
Coil Set	Power Supply
Modular Coils, 4 groups of 4 coils	Existing ATF helical field power supplies, 4 each 650 V open circuit voltage, 30 kA pulsed current
OH solenoid 1 solenoid	Existing ATF VF coil power supply 625 V, 15kA pulsed
Mid PF coils 1 pair	Existing LCTF power supplies x 2 12 V, 25 kA
Outer PF coils 2 pairs	Existing ATF VF coil power supply 625 V. 10 kA pulsed rating
TF coils 1 circuit, 48 total turns	Existing ATF VF coil power supply 625 V. 15 kA pulsed rating

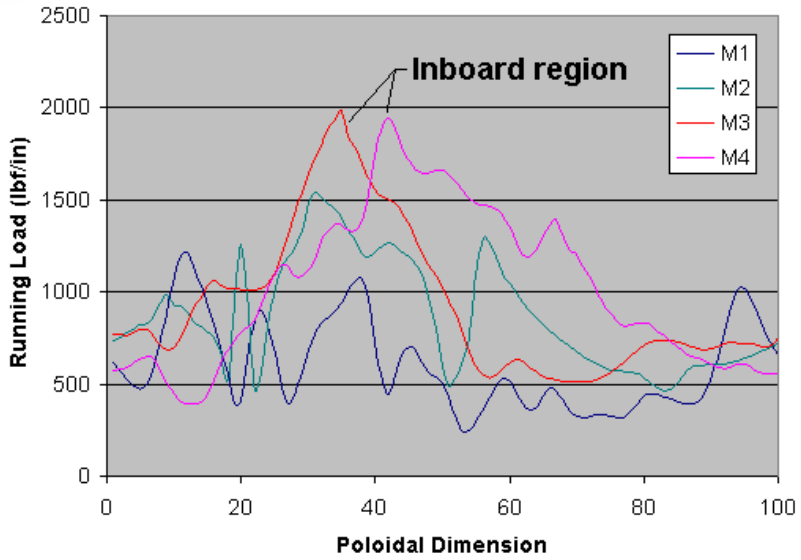
Magnetic field distribution from all coils

Bmax/Bo = 2.1, with external TF field of -0.06T



Modular coil forces



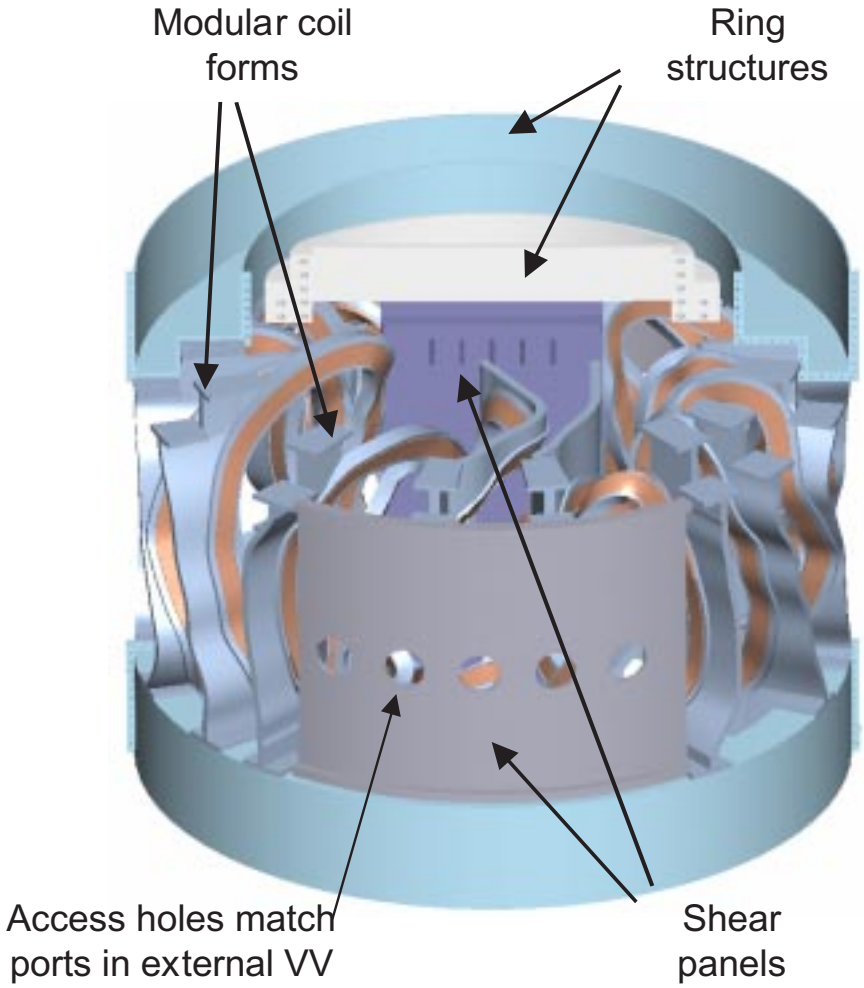


Max centering load = 45 kips

Max running load = 2000 lbs/in

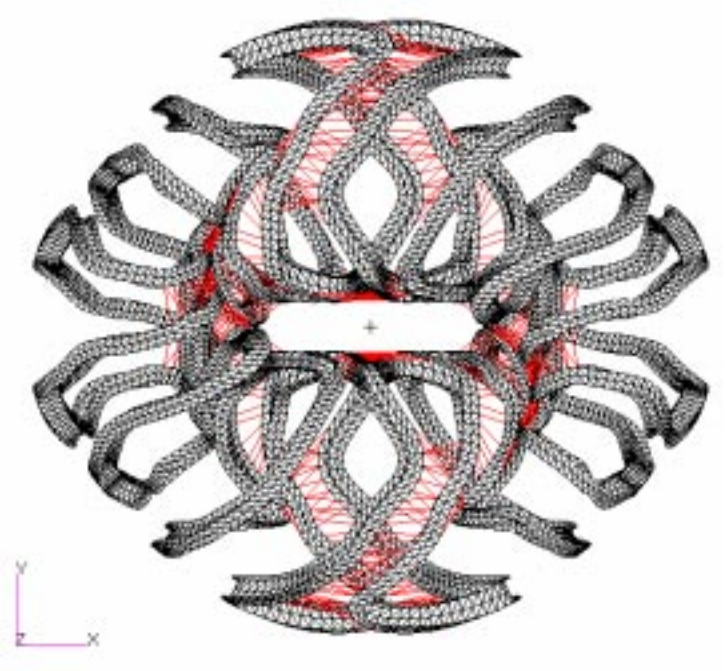
Machine Structure

- Modular coil winding form provides primary structure
- Coil forms connected to VF coil ring structures and inboard shear panels
- VF ring structures connected with shear panels for twisting and separating forces
- Coil-to-coil structure is more efficient and will be pursued during conceptual design

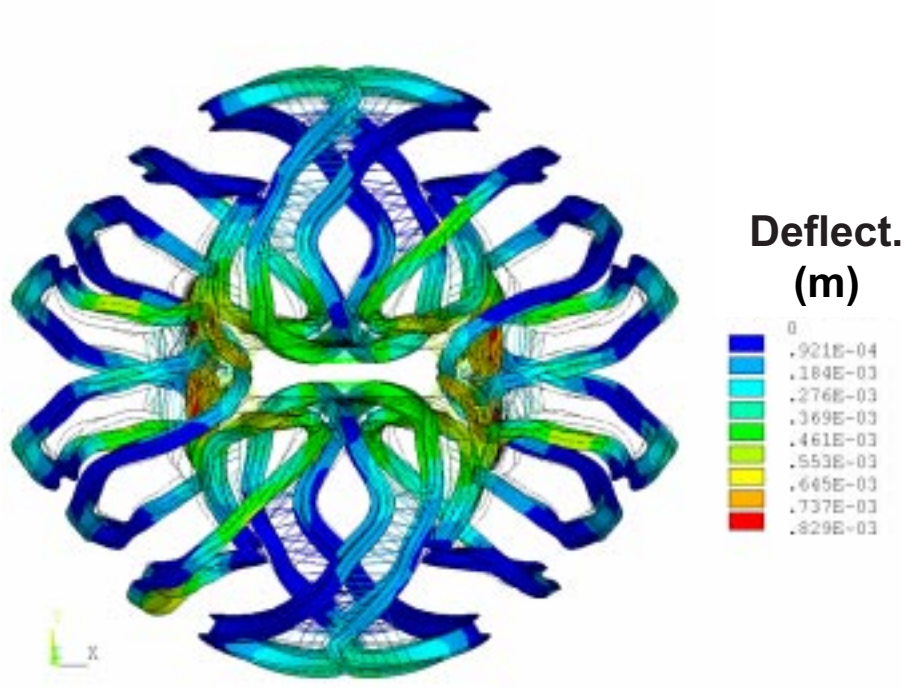


Modular Coil Structural analysis

- **Coil-to-coil structure shown is sufficient to limit maximum deflection to less than 1 mm**



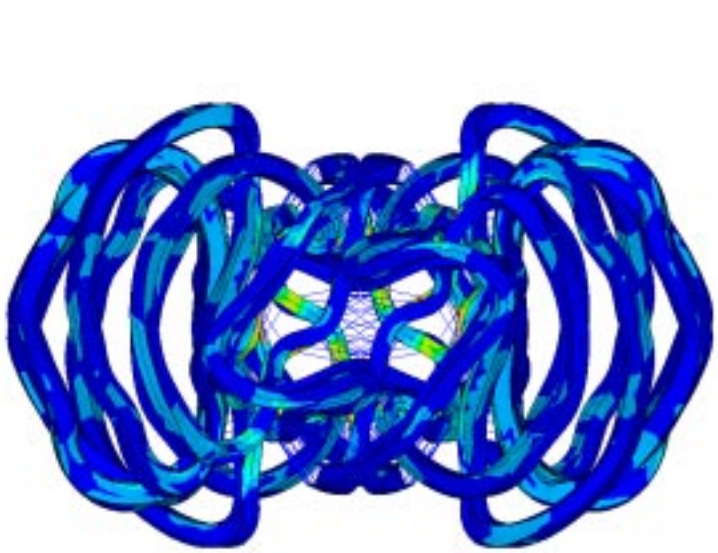
Structural FEA model



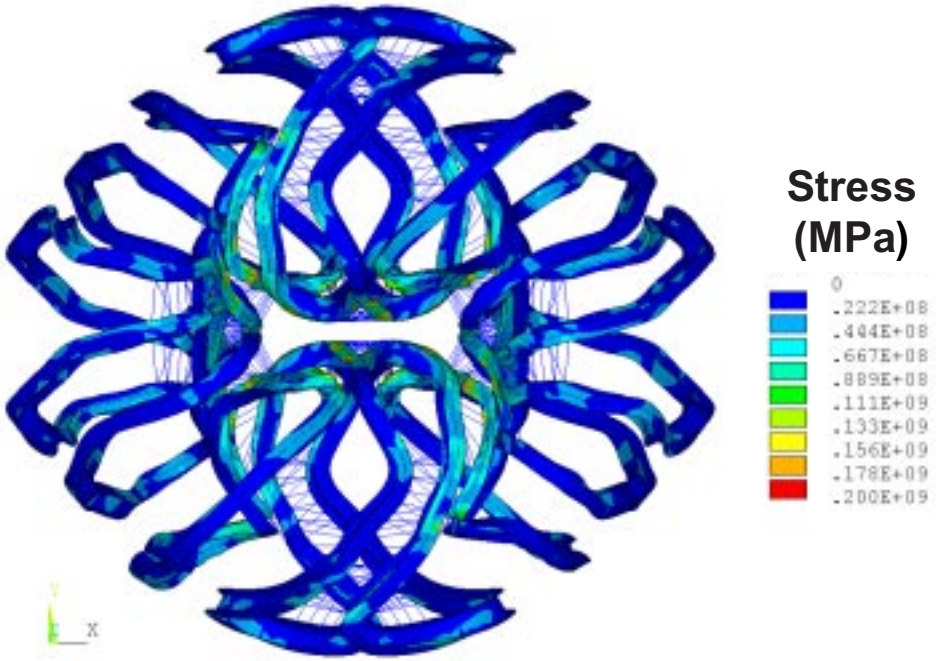
Deflections under load

Stress in modular coil structure

- **Stresses limited to ~ 200 MPa (in local regions)**
- **Stress in most areas < 100 MPa**



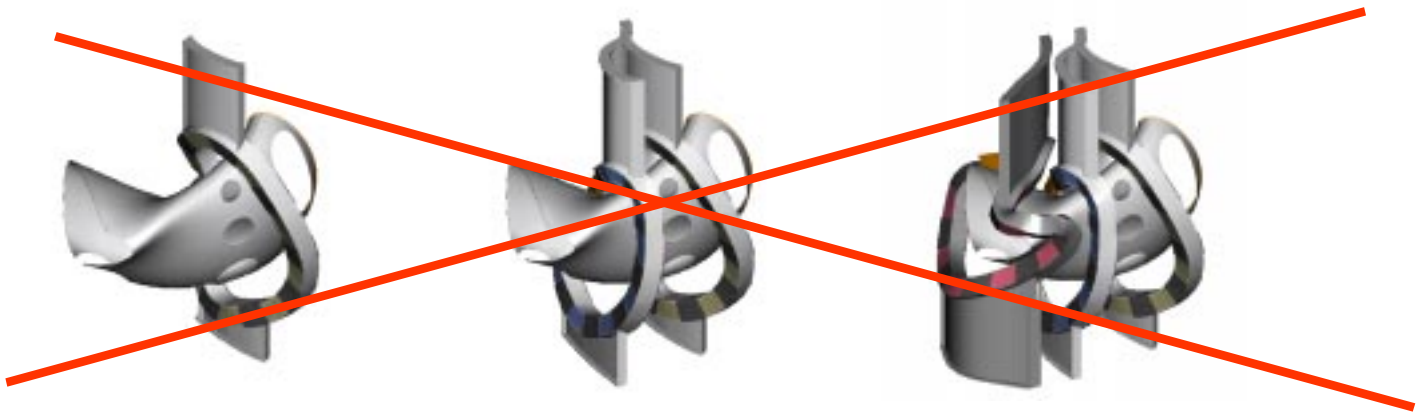
Stress distribution, elev. view



Stress distribution, plan view

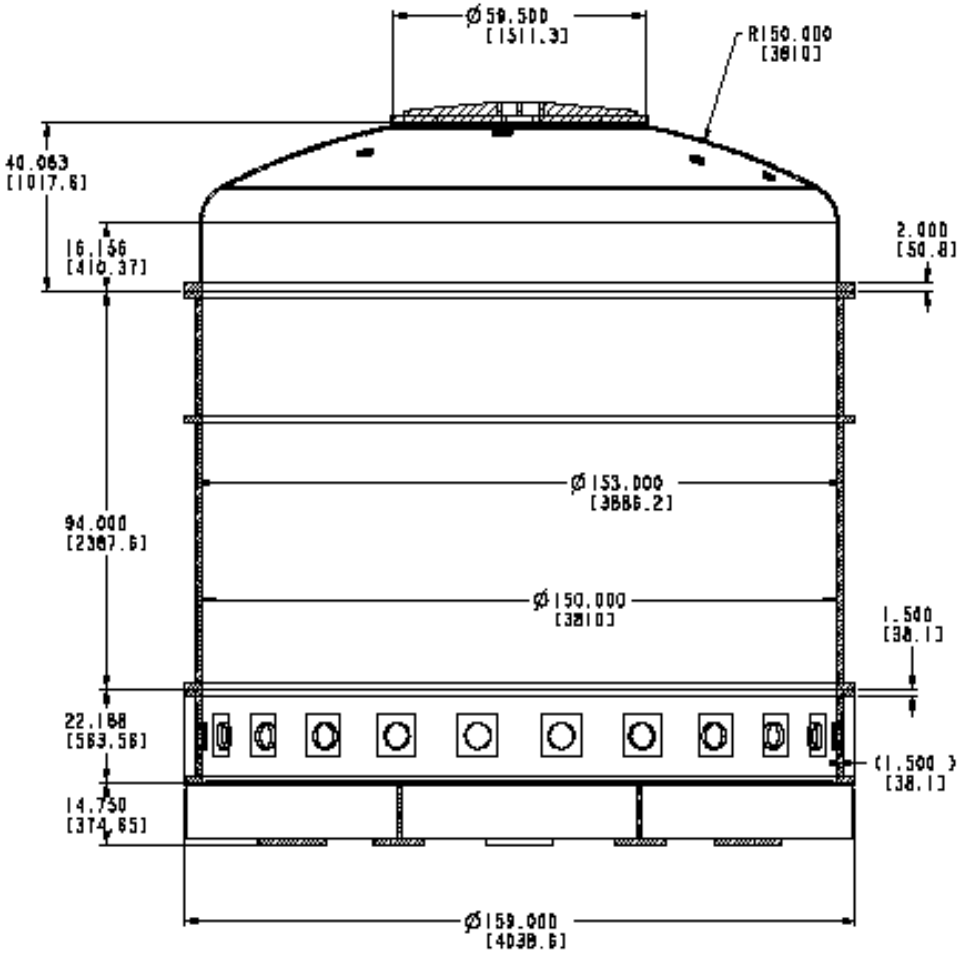
QPS will use external vacuum vessel

- **Eliminates complex vacuum vessel fabrication**
- **Provides maximum distance from coils to plasma for greater shape flexibility — e.g. larger plasma orshifted position**

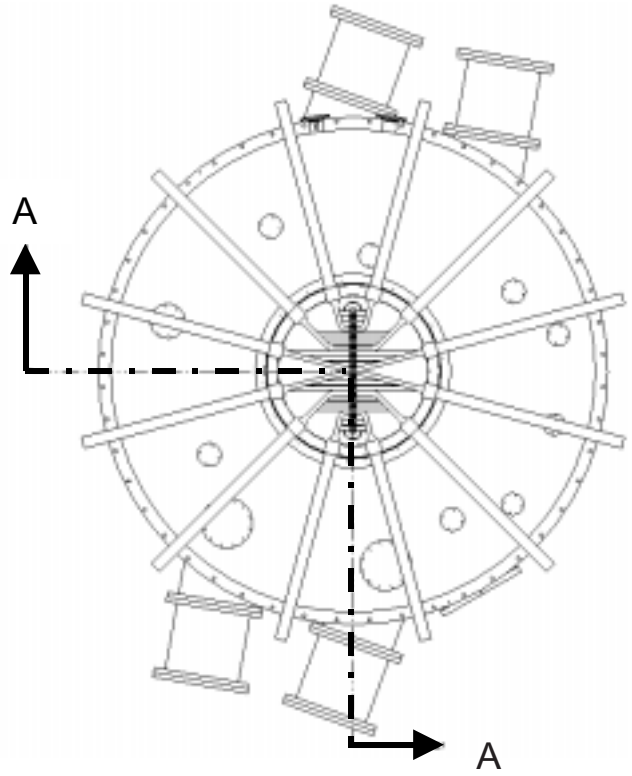


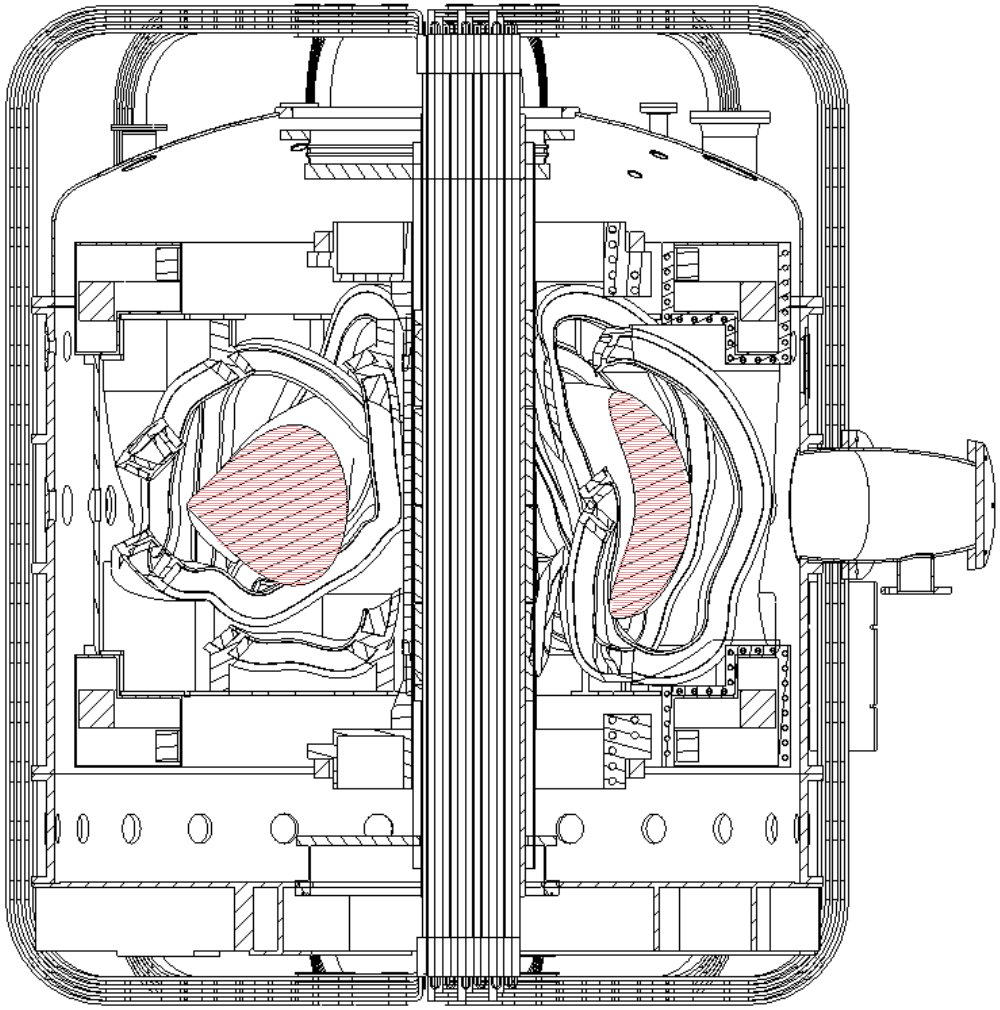
- **Provides more flexibility for structure, since coils do not have to be manipulated over internal vacuum vessel**
- **Bell jar exists (vessel used for ORMAK experiment)**

Existing bell jar vacuum vessel



QPS assembly fits within existing bell jar





Section A-A

External vacuum vessel requirements

- **Clean:** **bake-able to 150 C (need double seals)**
  Minimum oxide buildup on inside of tank

- **No leaks:** **Integrated leak < 1e-5 torr-l/s**
  Base pressure < 1e-8 torr for impurities
  Base pressure < 1e-7 for H

- **Can be re-sealed easily after major opening**

- **Time constant issues may require replacement of aluminum spool pieces with stainless steel**

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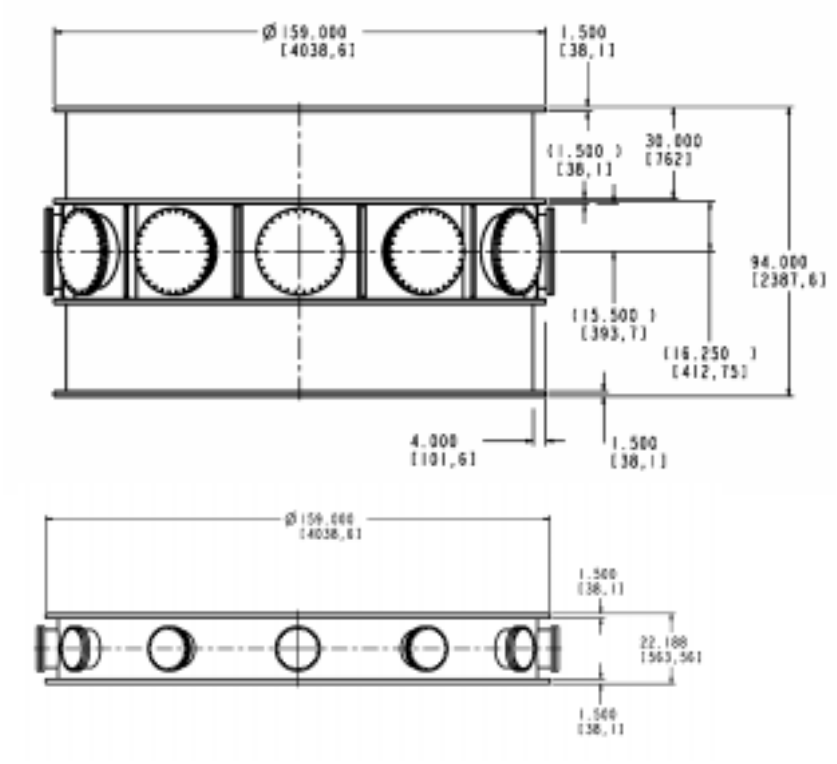
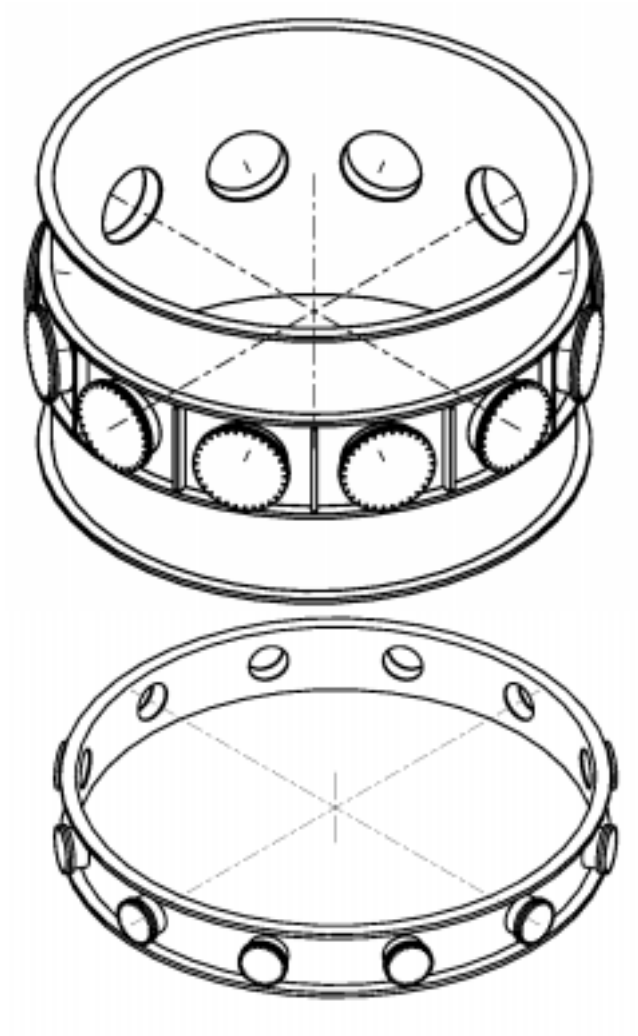
New 304L spool pieces *will* replace aluminum

- **Fewer, larger ports**
- **Lower spool piece could be welded to base to eliminate seal**

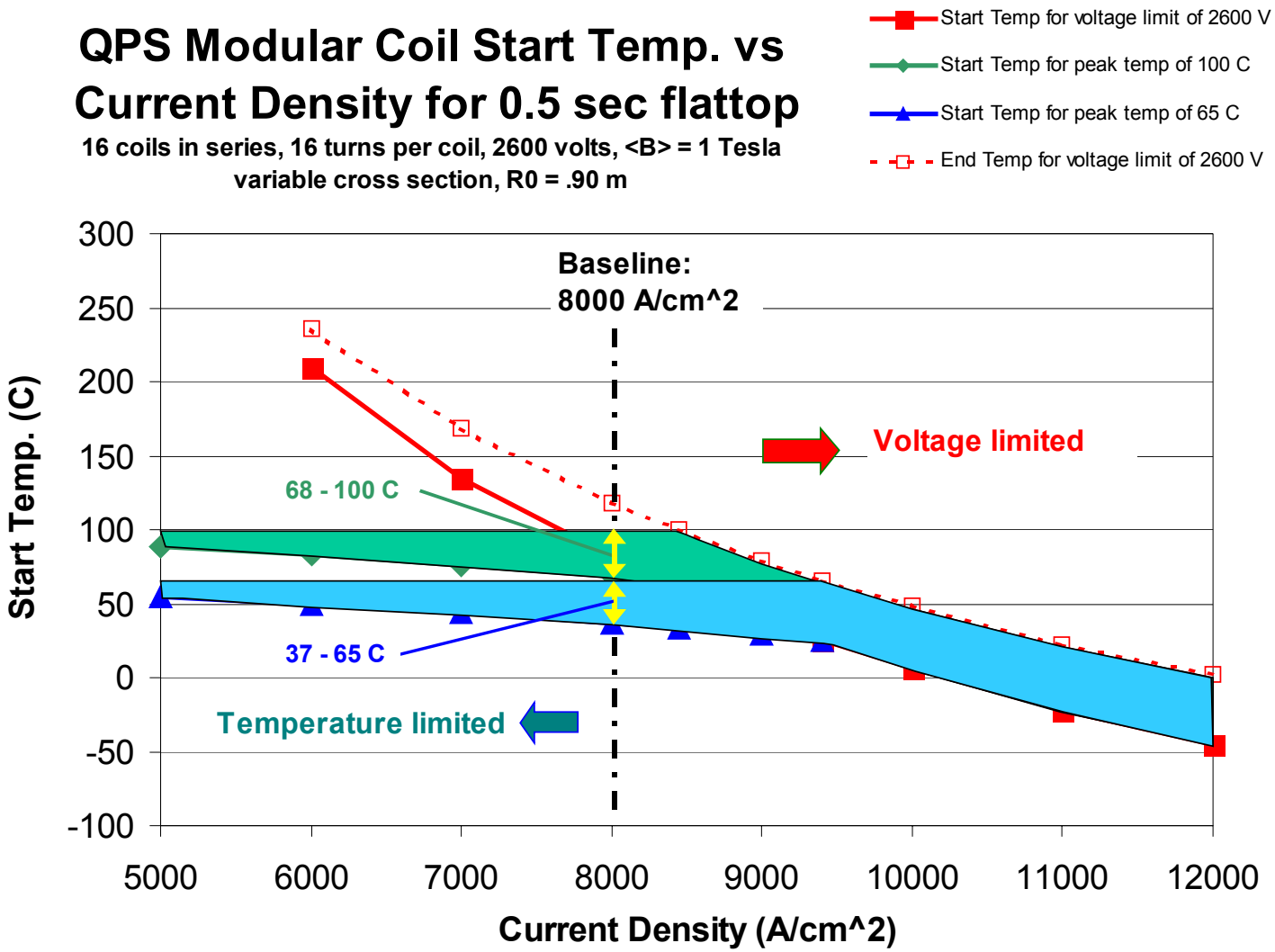




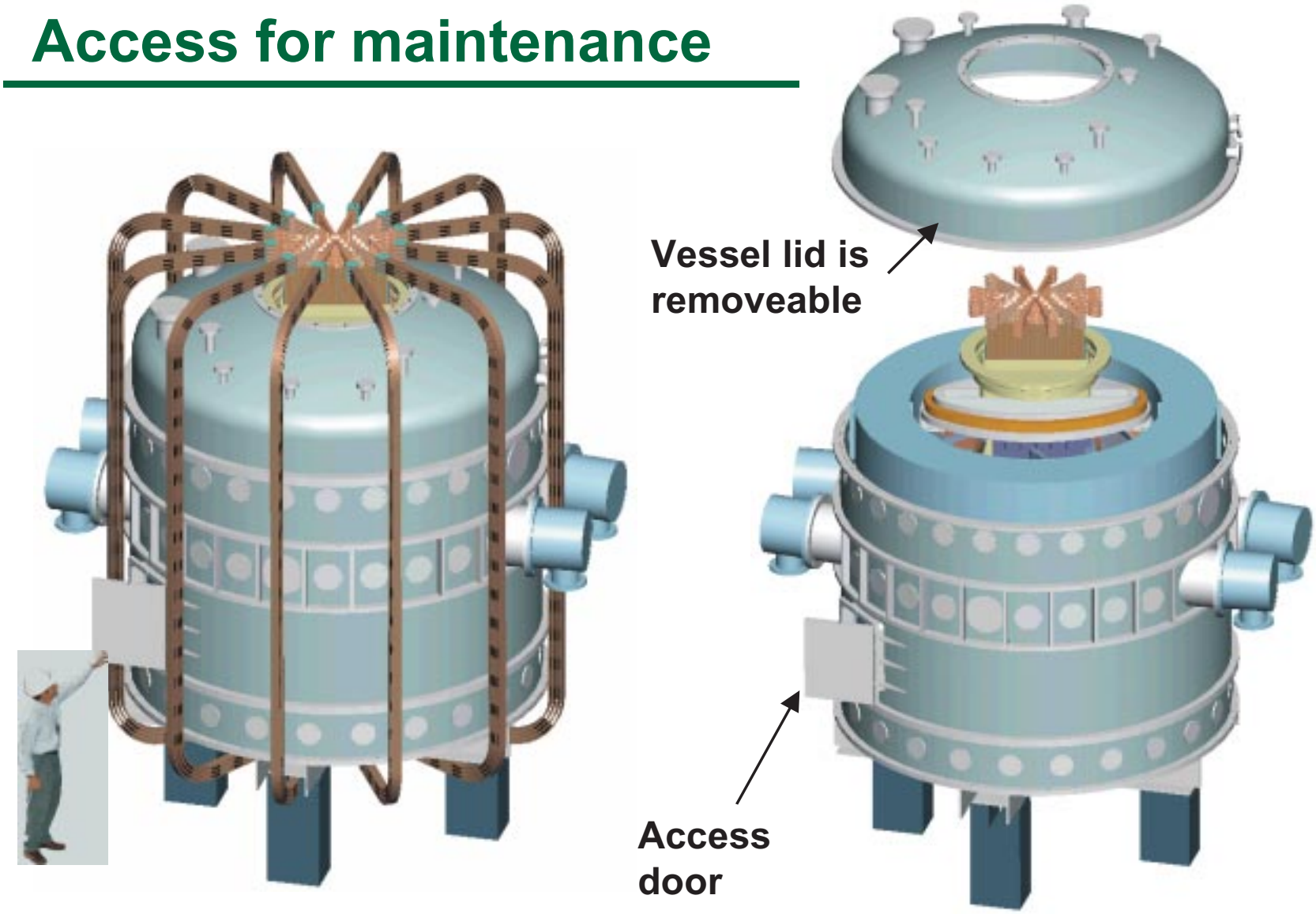
Modular coils face the plasma so the coil operating temperature is important

- **Temperature limited by:**
  - **Epoxy in winding**
  - **Coil resistance and power supply voltage limits**
- **Epoxy temperature depends on curing temperature:**
  - **Room temperature cure epoxy limited to 65C**
  - **Elevated temperature cure epoxy limited to ~ 100C**
- **Total voltage drop in coils must remain below 650 volts for each coil circuit or 2600 V total**
- **Current density determines temperature rise ($\propto J^2$) and voltage drop ($\propto J$), but voltage is also a function of temp.**

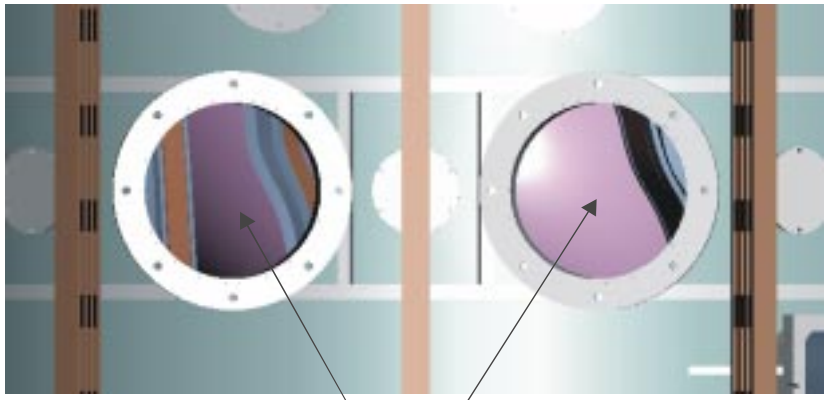
Baseline current density, 8 kA/cm2, does not push voltage or temp limits for 0.5 s flattop



Access for maintenance



QPS Access for diagnostics, heating



Plasma

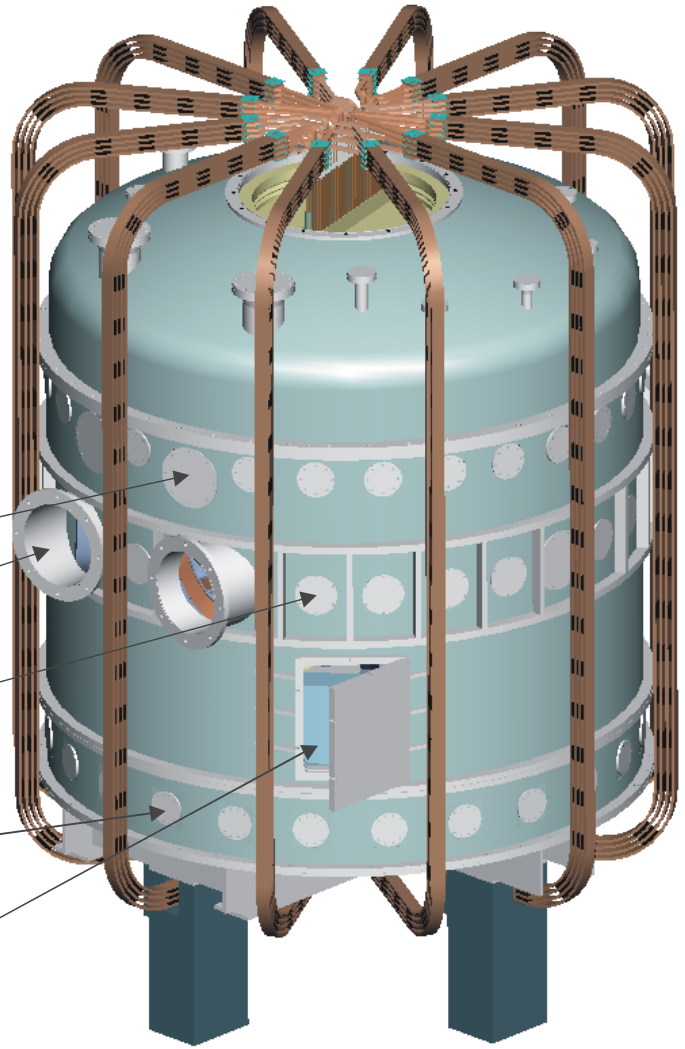
(6) 12 Dia Ports

(4) 22 Dia Ports

(18) 8 Dia Ports

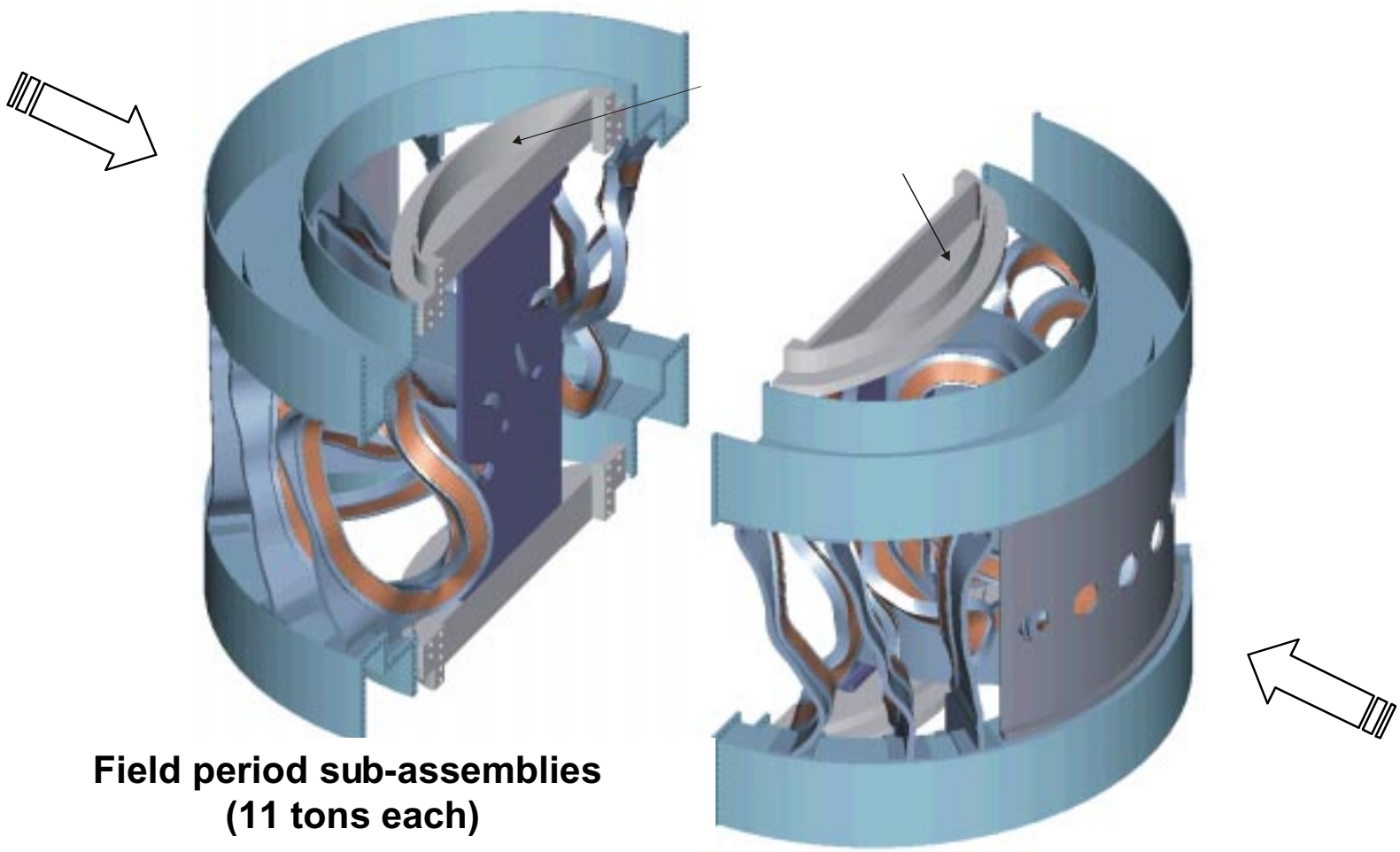
(23) 6 Dia Ports for Coil Leads, Coolant Feeds, etc.

Personnel Access Door



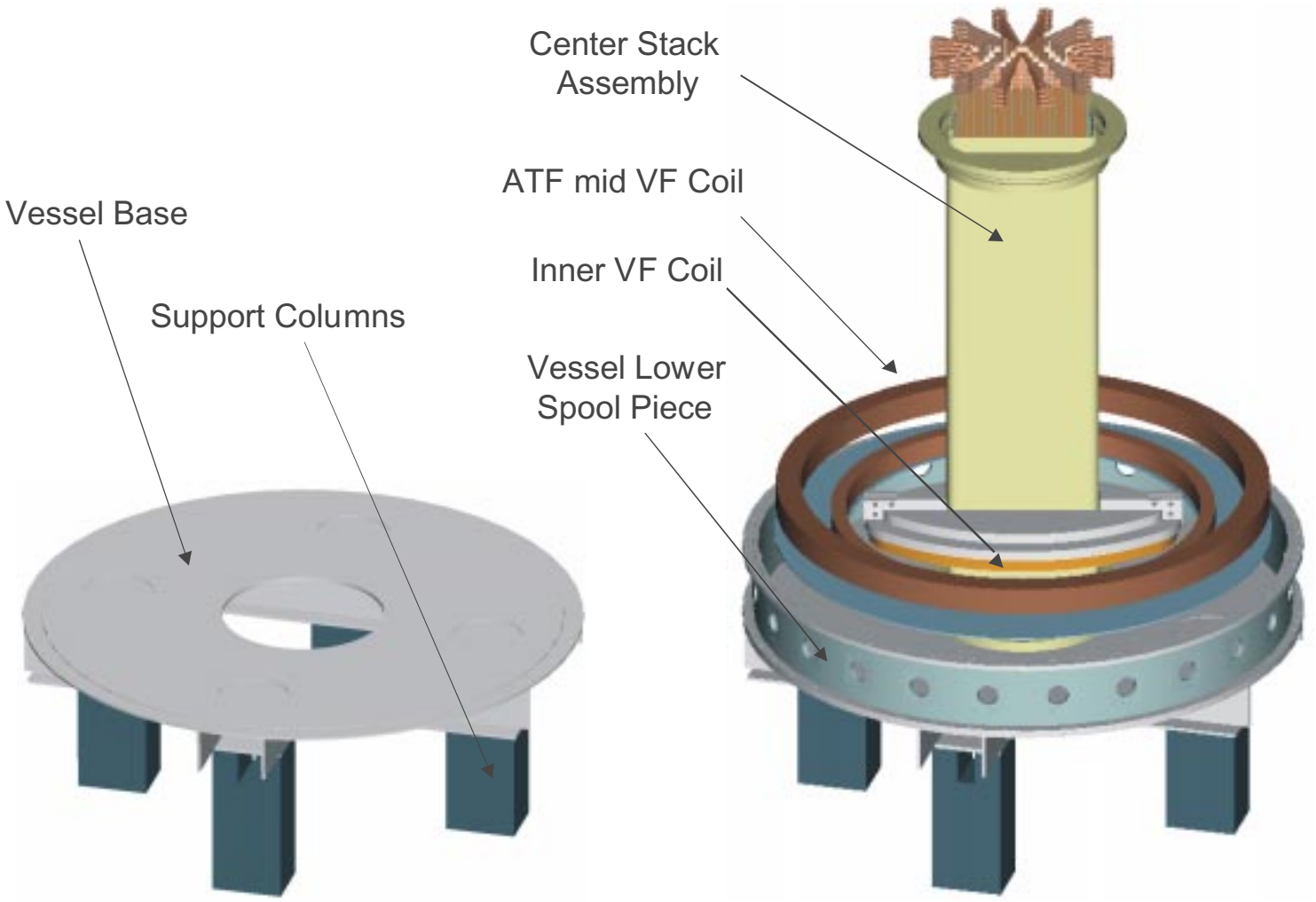
QPS Assembly

Field periods pre-assembled and fit-checked off site

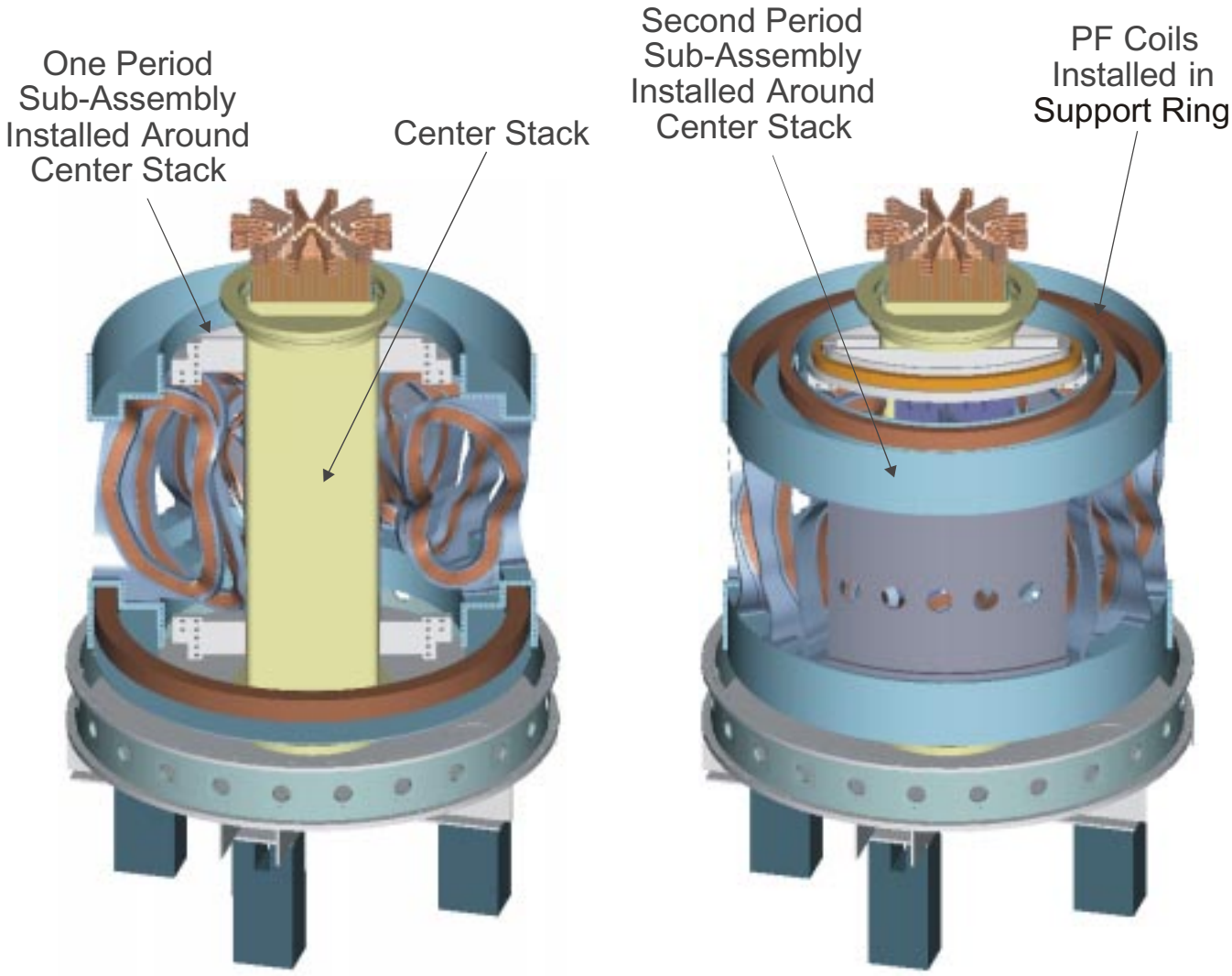


Field period sub-assemblies (11 tons each)

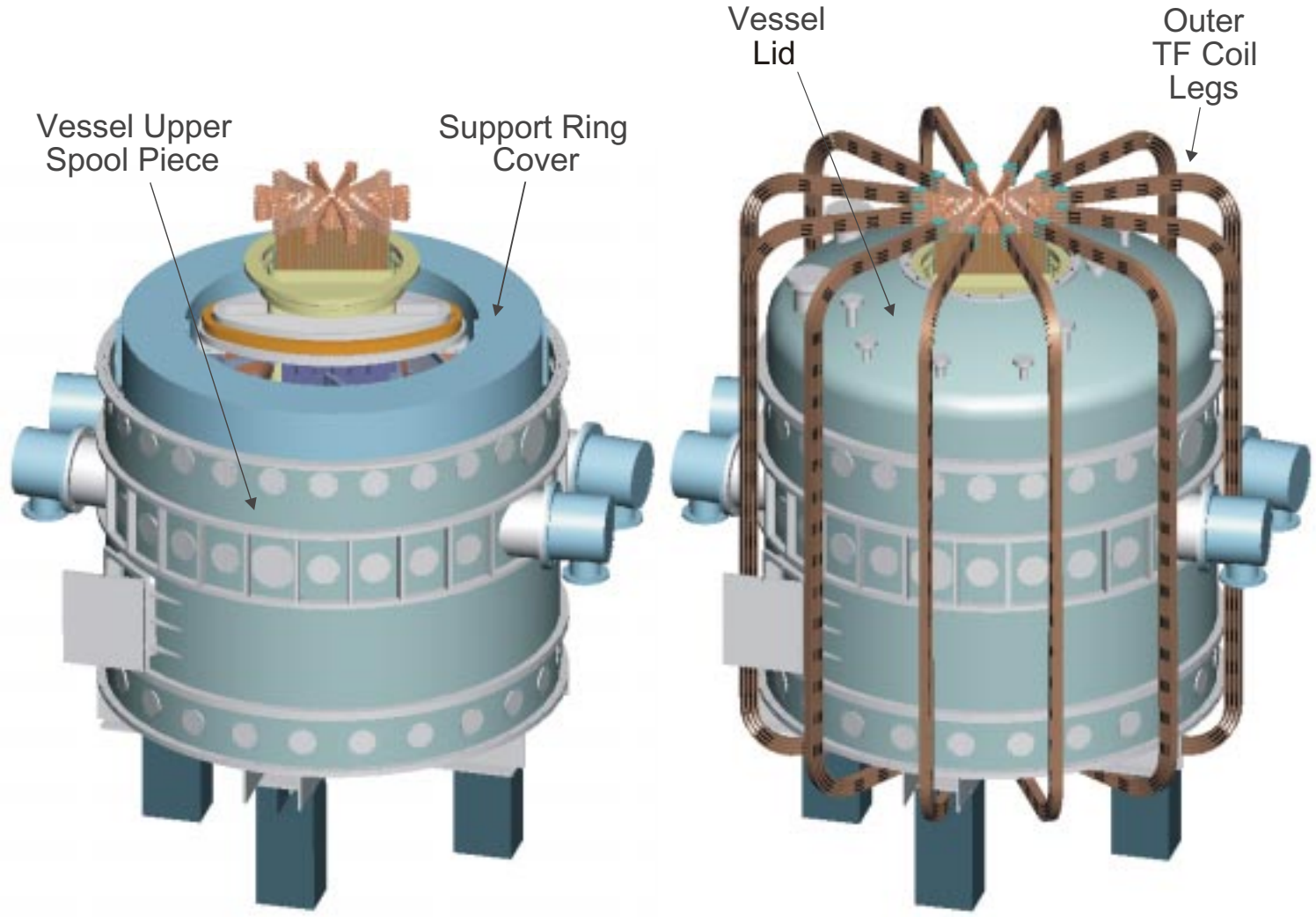
QPS Assembly sequence (cont d)



QPS Assembly sequence (cont d)



QPS Assembly sequence (cont d)



Conceptual design plans: refine concept, address issues

- Improve modular coil geometry
  - Eliminate sharp bends, optimize twist, reduce current density, improve manufacturability in general
- Improve structural design
  - Simplify concept, reduce cost
- Develop more fabrication details (e.g. castings, windings, canning)
  - Involve industry and universities to a larger extent
  - Perform manufacturing studies, limited R&D, prototypes
- Perform tradeoff of OH system
  - Air core solenoid vs iron core, return coil geometry, etc.
- Optimize VF coil number, shape, location
- Understand consequences of changing VV spool pieces from aluminum to stainless
- Finalize design requirements
- Develop bottoms up schedule estimate
- Refine cost estimates

Summary

- We have an initial design concept that meets performance requirements
  - 16 coil, 2 period modular coil set with integrated structure
  - 0.5 s flat-top at 1 Tesla
  - OH, VF, and TF coil sets
  - External vacuum vessel
- We are making maximum use of existing equipment (VF coils, vacuum vessel, etc.) and facilities in order to minimize cost
- We have plans for improving the design, by addressing known issues, refining concepts to reduce cost, and updating cost and schedule estimates for a CDR in April 02