QPS
Engineering Design

QPS

Presented by B. Nelson for the QPS Team

QPS PAC
December 11, 2002
PPPL

Special thanks and acknowledgement to:
Mike Cole, Paul Fogarty, Tom Hargrove, and Dave Williamson

Presentation Outline

QPS

- Baseline parameters
- Stellarator Component Design
  - Modular coils, VF/TF coils, structure, vacuum vessel
- Assembly
- Summary and plans for CDR
- *In later presentation:*
  - Fabrication / R&D plans, schedule, and infrastructure

Baseline parameters for QPS design

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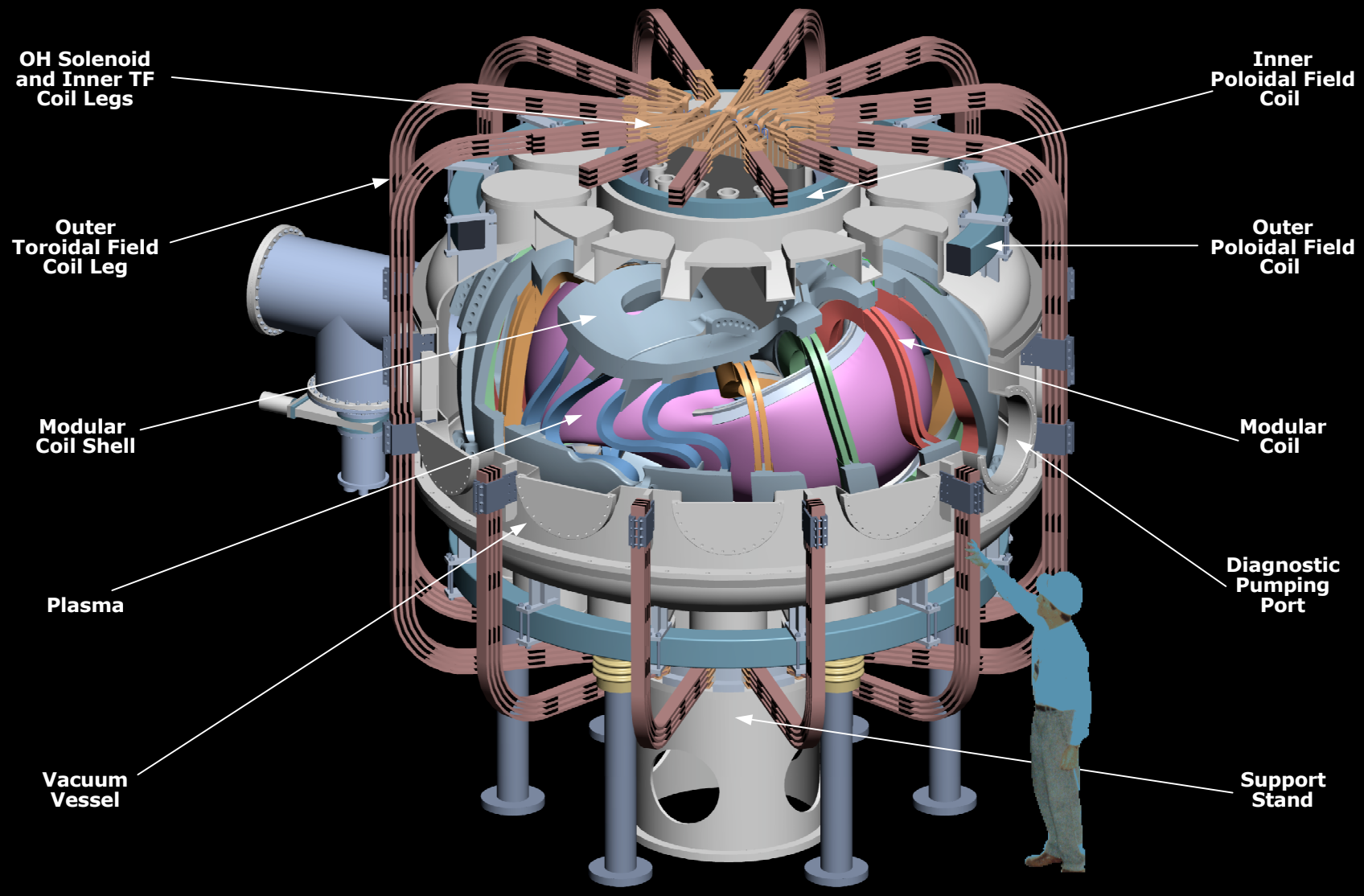
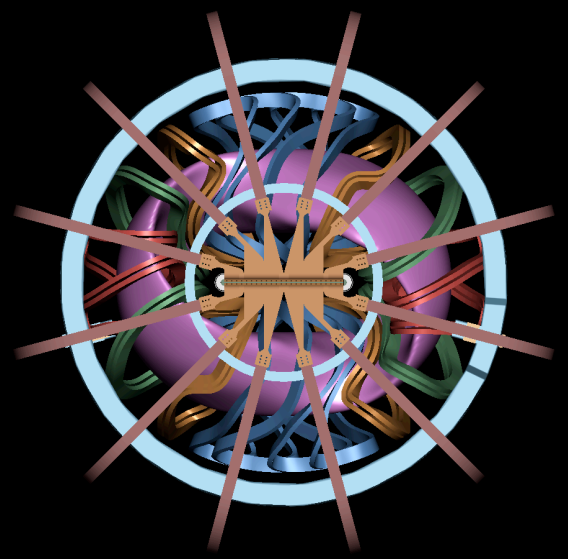
- Moderate size and field
  - $\langle R_0 \rangle \sim .90$ m
  - $\langle a \rangle \sim 0.33$ m
  - $B_0 = 1$ T
- Core components (modular coils, VF and TF coils, and structure) are built off-site and pre-assembled to the extent possible
  - Minimum cost is essential
  - Re-use existing power supplies, cooling system, diagnostics, vacuum pumps, ECH system, etc.

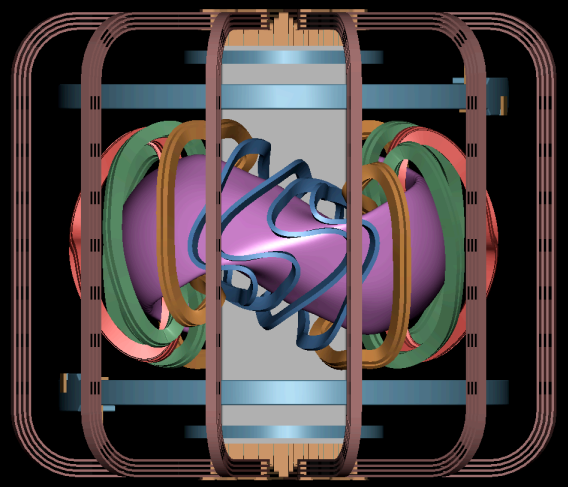
QPS Concept


OH Solenoid and Inner TF Coil Legs
Inner Poloidal Field Coil
Outer Toroidal Field Coil Leg
Outer Poloidal Field Coil
Modular Coil Shell
Modular Coil
Plasma
Diagnostic Pumping Port
Vacuum Vessel
Support Stand

QPS Coil Set

Coil Set	Function, Coil set provides:
Modular Coils	Basic quasi-axisymmetric magnetic configuration
Vertical Field Coils	Inductive current drive, plasma position control, plasma shaping
Toroidal Field Coils	Addition or subtraction of toroidal field for control of magnetic transform





Coil set requirements

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- **Meet performance requirements**
  - 1 T with up to 1 s flattop
  - 15 minute rep rate (5 minute rep rate for shorter pulses)
- **Provide flexibility**
  - Independent control of modular and PF coils provided
  - Variable background TF field +/- 0.2 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**

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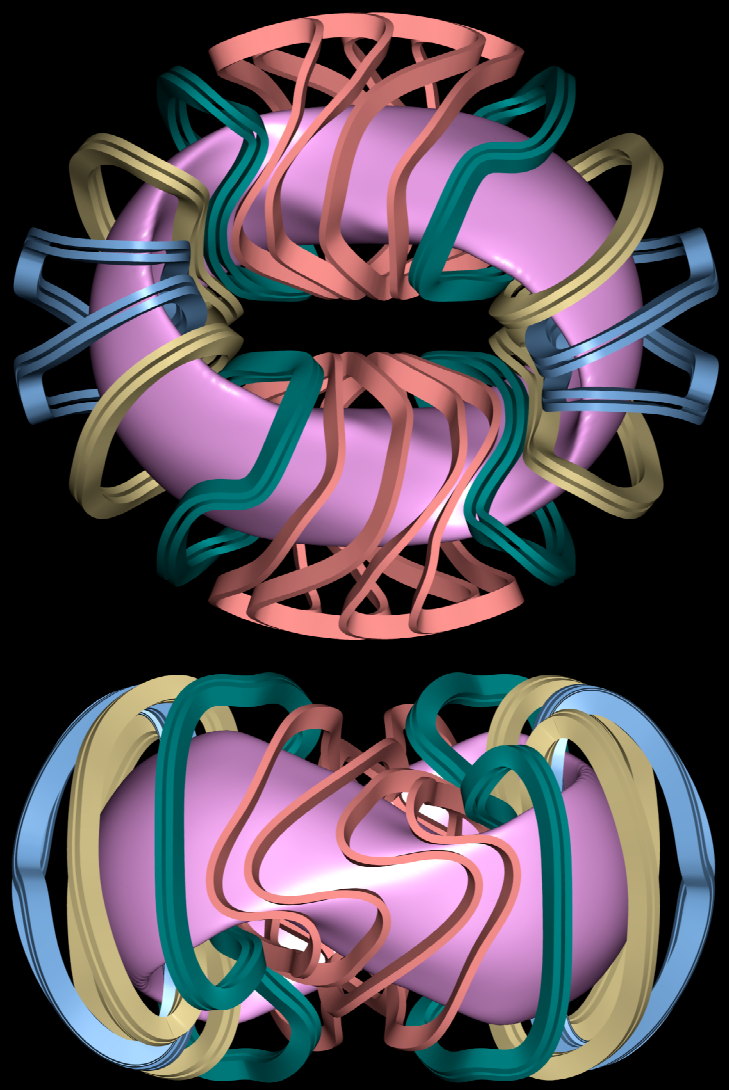
Modular coil configuration



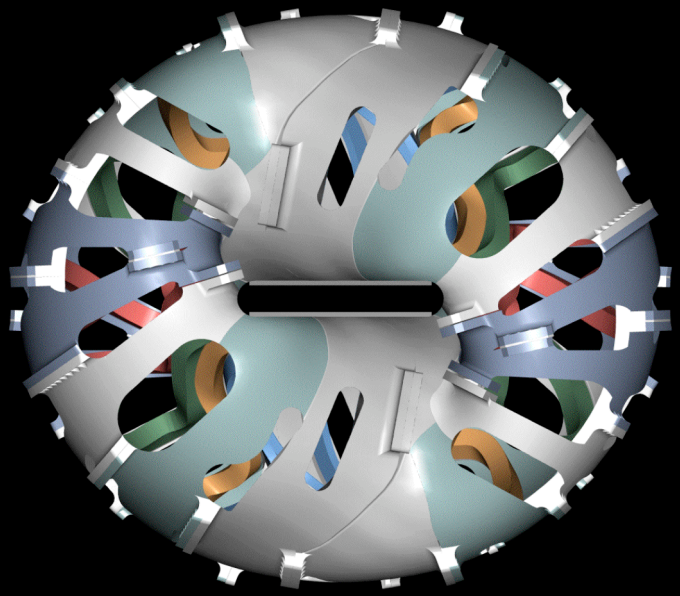
Coil set 0718-6b3

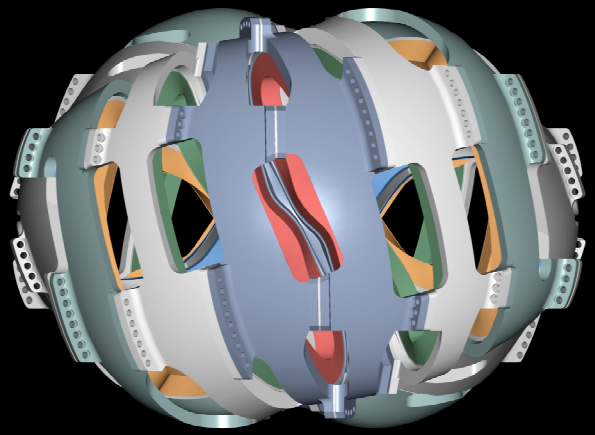
R0 = .90 m, a = .33 m

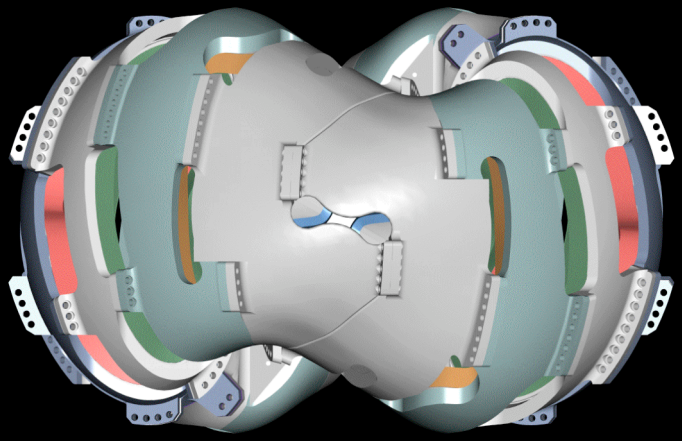
Coil ID	M1	M2	M3	M4A	M4B
Length per turn (in)	172.5	168.7	181.3	179.3	188.1
Min Bend Rad (in)	5.6	4.9	4.3	3.7	3.7
Min Plasma Dist (in)	5.02	5.00	5.93	5.46	5.66
Max Plasma Dist (in)	12.9	12.5	16.4	15.4	15.3
Min Coil-Coil Dist, CW (in)	7.13 M1-M1	5.45 M2-M1	4.34 M3-M2	3.83 M4A-M3	2.44 M4B-M4A
Min Coil-Coil Dist CCW (in)	5.45 M1-M2	4.34 M2-M3	3.83 M3-M4A	2.44 M4a-M4B	5.88 M4B-M4B
Nom Coil Current (kA)	361	361	361	181	181

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
- Stellarator symmetry preserved, at least two toroidal electrical breaks

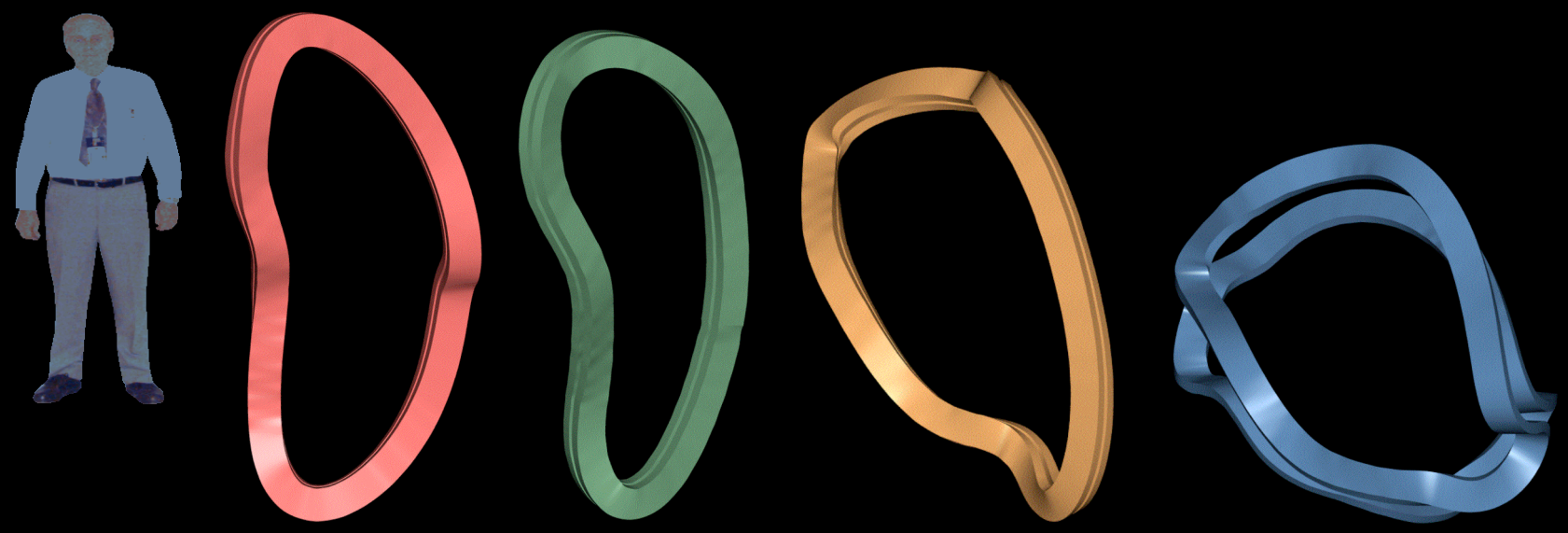






Modular coil geometry

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



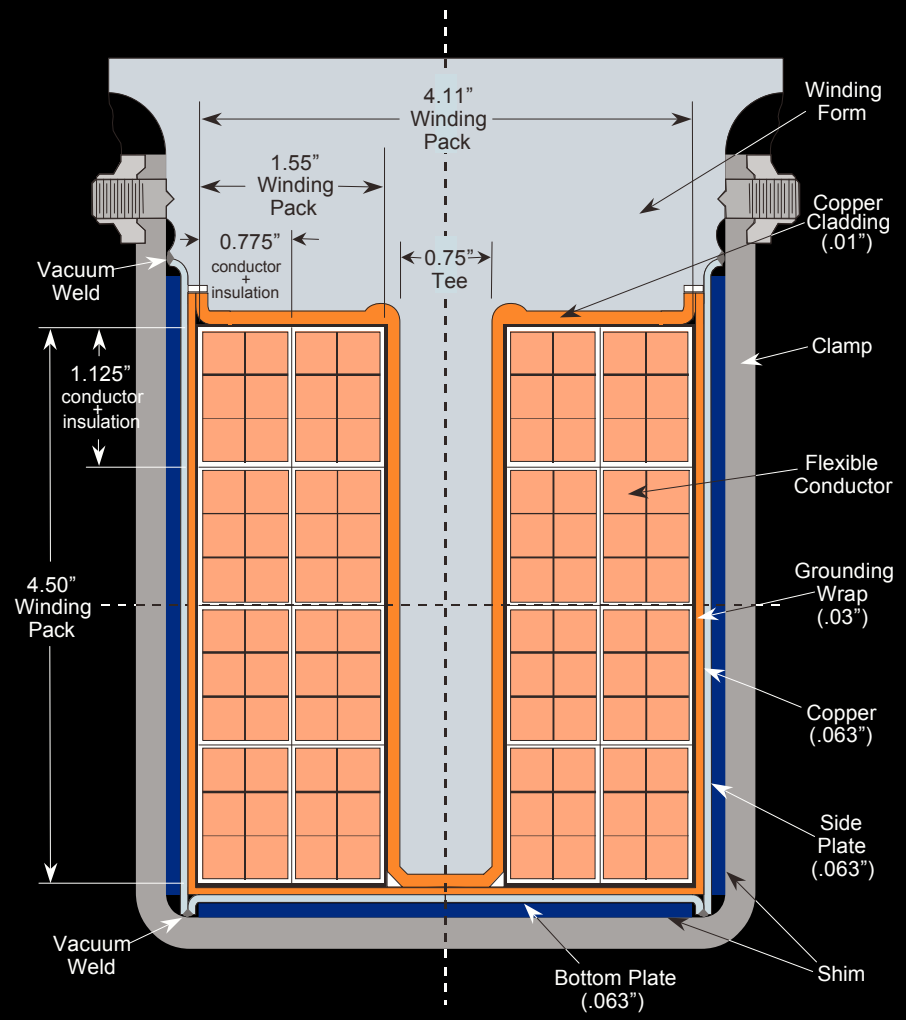
Coil 1
"Bean Section"

Coil 2

Coil 3

Coil 4
"Split Windings"

Modular coils wound with flexible cable directly on coil structure



Parameters:

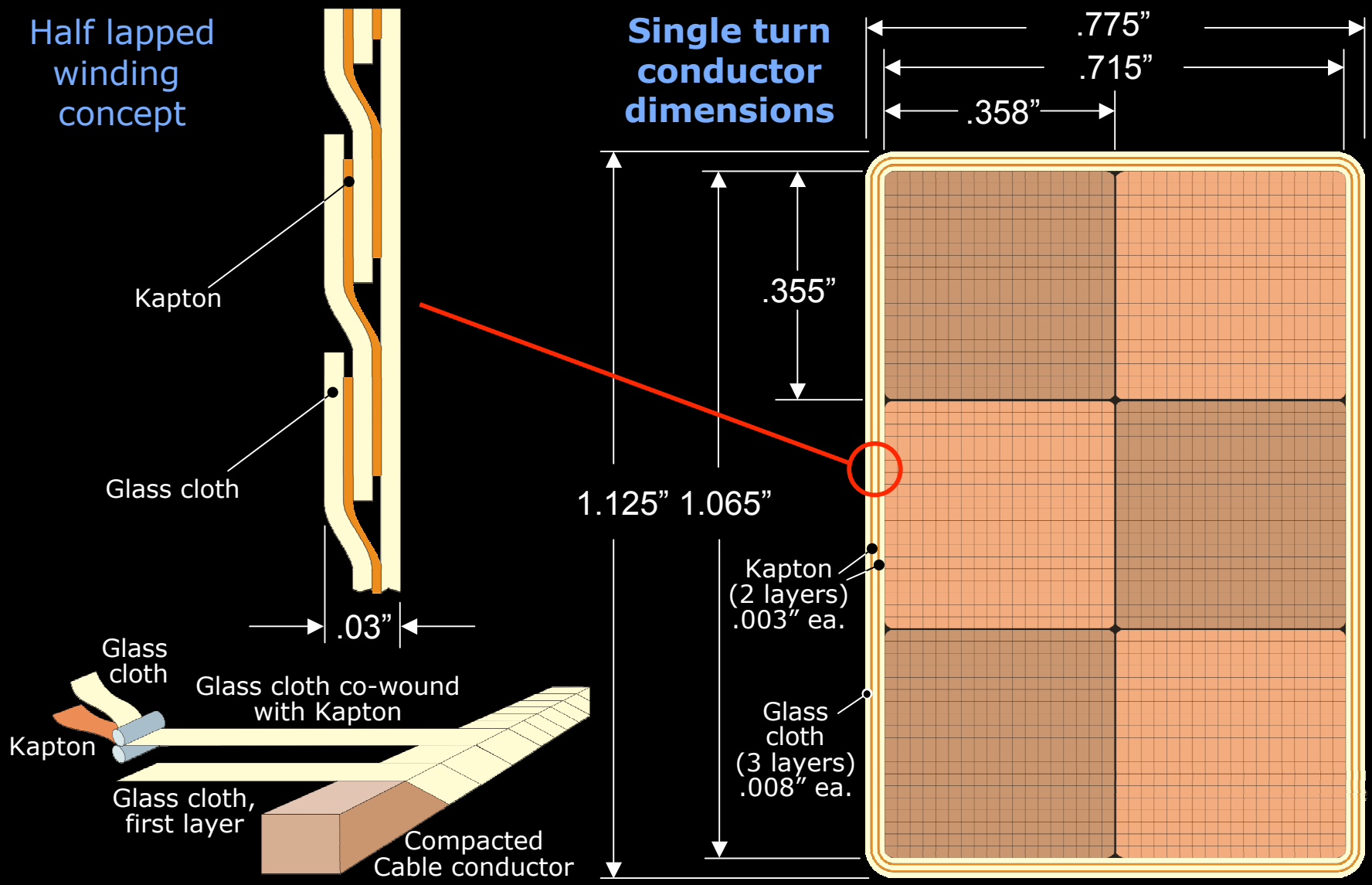
- Coil Envelope ~ 2 x 120 x 40 mm
- Current / Coil = 361-kA @ 1 Tesla
- Number of Turns = 16
- Average length per turn = 4.5 m
- Nominal current / turn = 22.5 kA
- Conductor Size = 18 x 27 mm
- Heat removed via gas-cooled septum
- Net Current Density ~ 7.1-kA/cm2
- Total peak power ~ 40 MW

Flexible cable used to wind coil

Before compaction

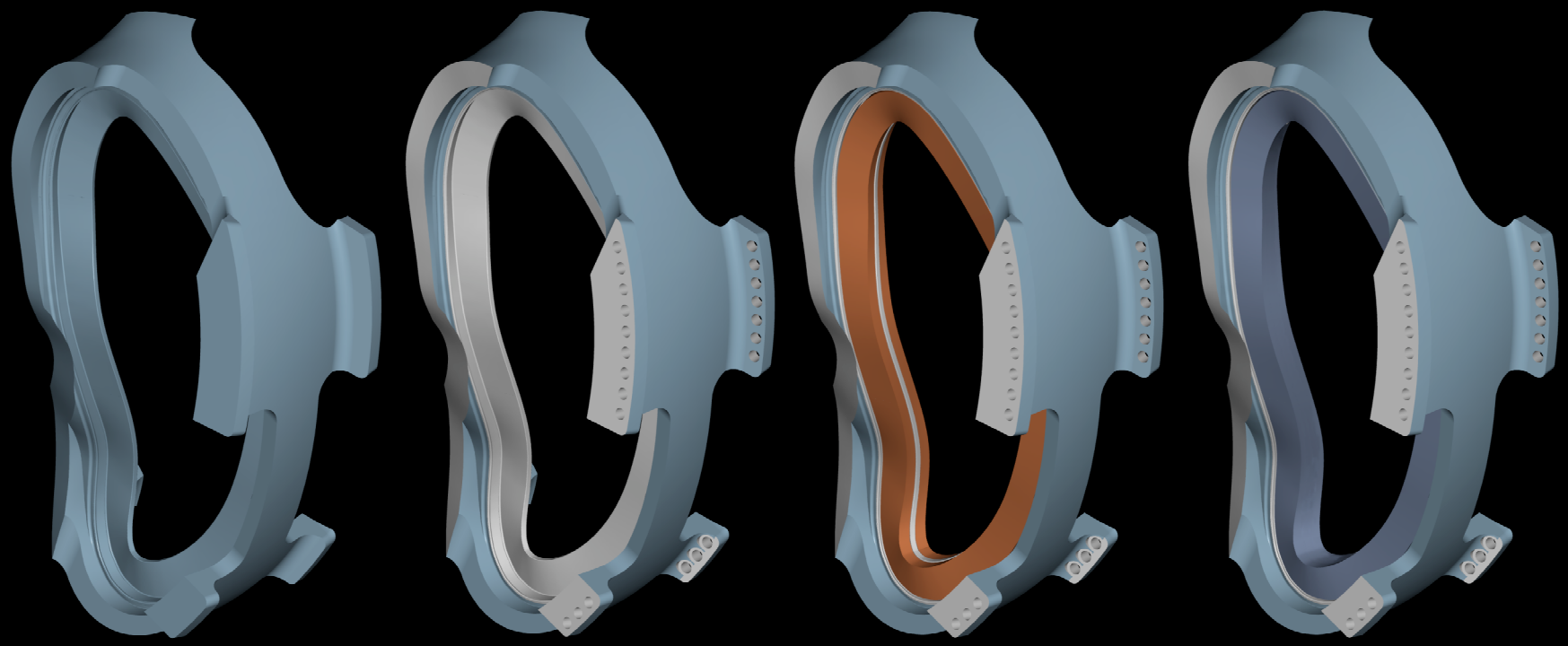
After compaction

Flexible cable wrapped with Kapton and glass cloth



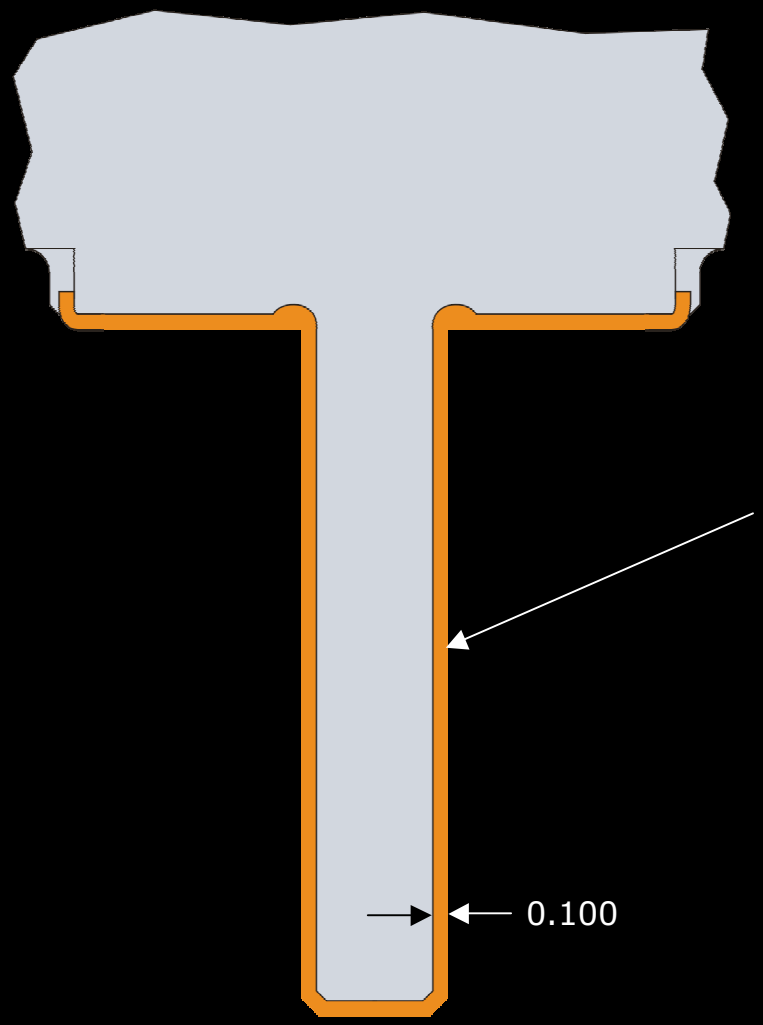
Modular coil manufacturing sequence (M2)

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



Rough casting | Machine winding contour & flange features (~2300 lbs) | Conductor wound directly into structure | Side plates welded to structure

Copper layer is needed for cooling, and is integral part of winding form



Heat Conduction Layer

Options:

1) Varnish SS, electroform with copper
2) Flame spray ceramic/copper, full thickness
3) Flame spray 0.010”, then electroform
4) Copper strips, developed shapes

Copper surface must meet accuracy requirements:

profile within .020 inches , (bilateral tolerance, +/- .01 inches from ref.)

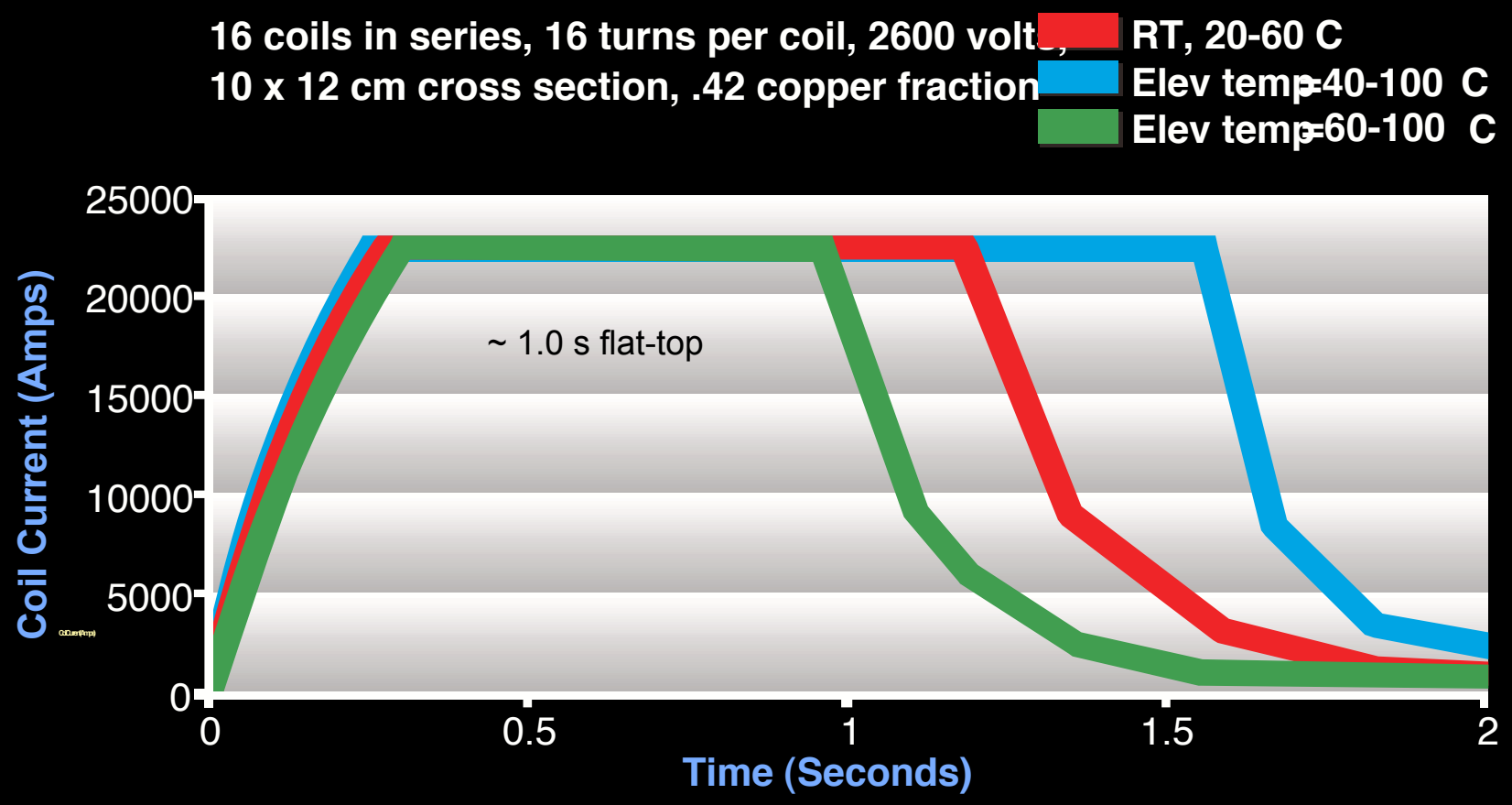
Modular coils face the plasma so the coil operating temperature is important

- 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, under load
  - (could use cyanate ester formulation instead of epoxy)
- Total voltage drop in coils must remain below 650 volts for each coil circuit or 2600 V total
- Current density determines temperature rise (J^2) and voltage drop (J), but voltage is also a function of temperature

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

QPS Modular Coil Current vs. Time, for various operating temperatures

16 coils in series, 16 turns per coil, 2600 volts,
10 x 12 cm cross section, .42 copper fraction



Flat-top time depends on start temperature

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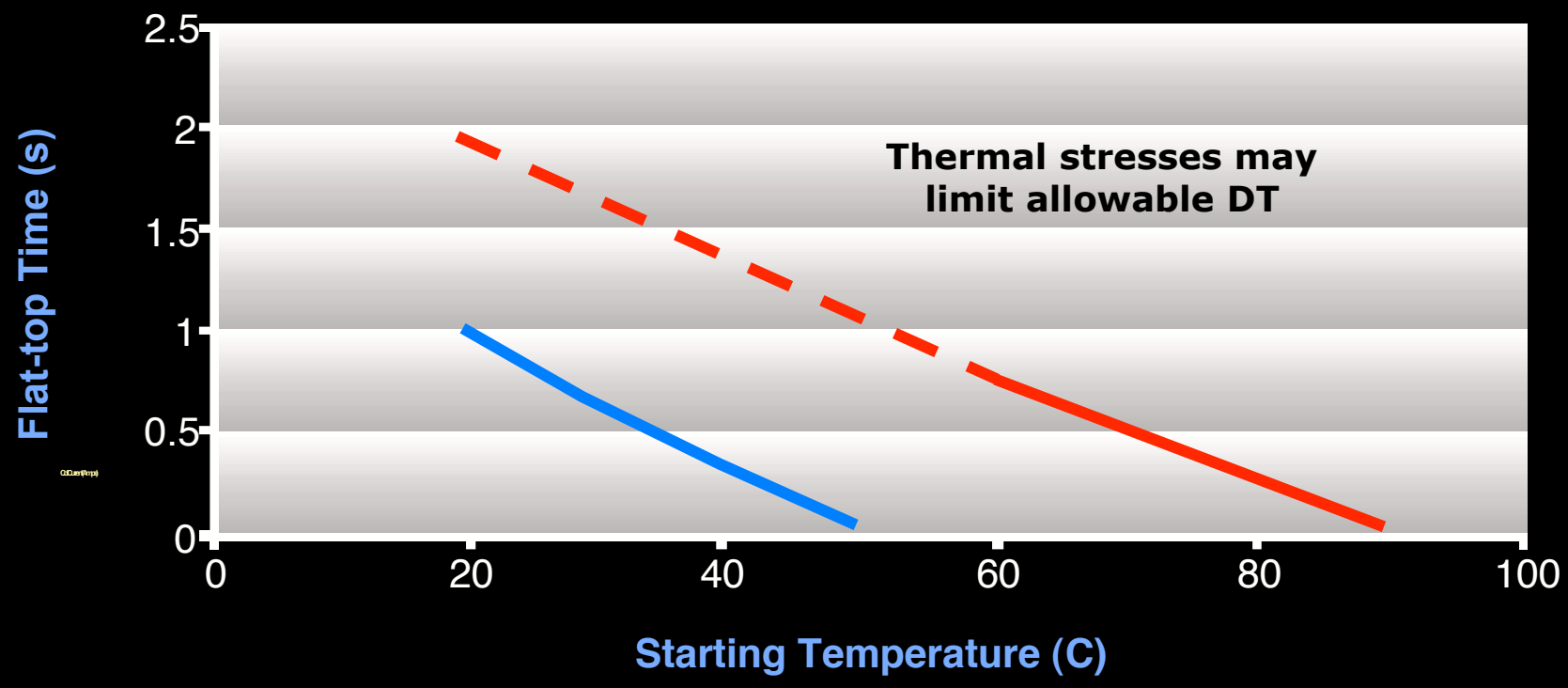
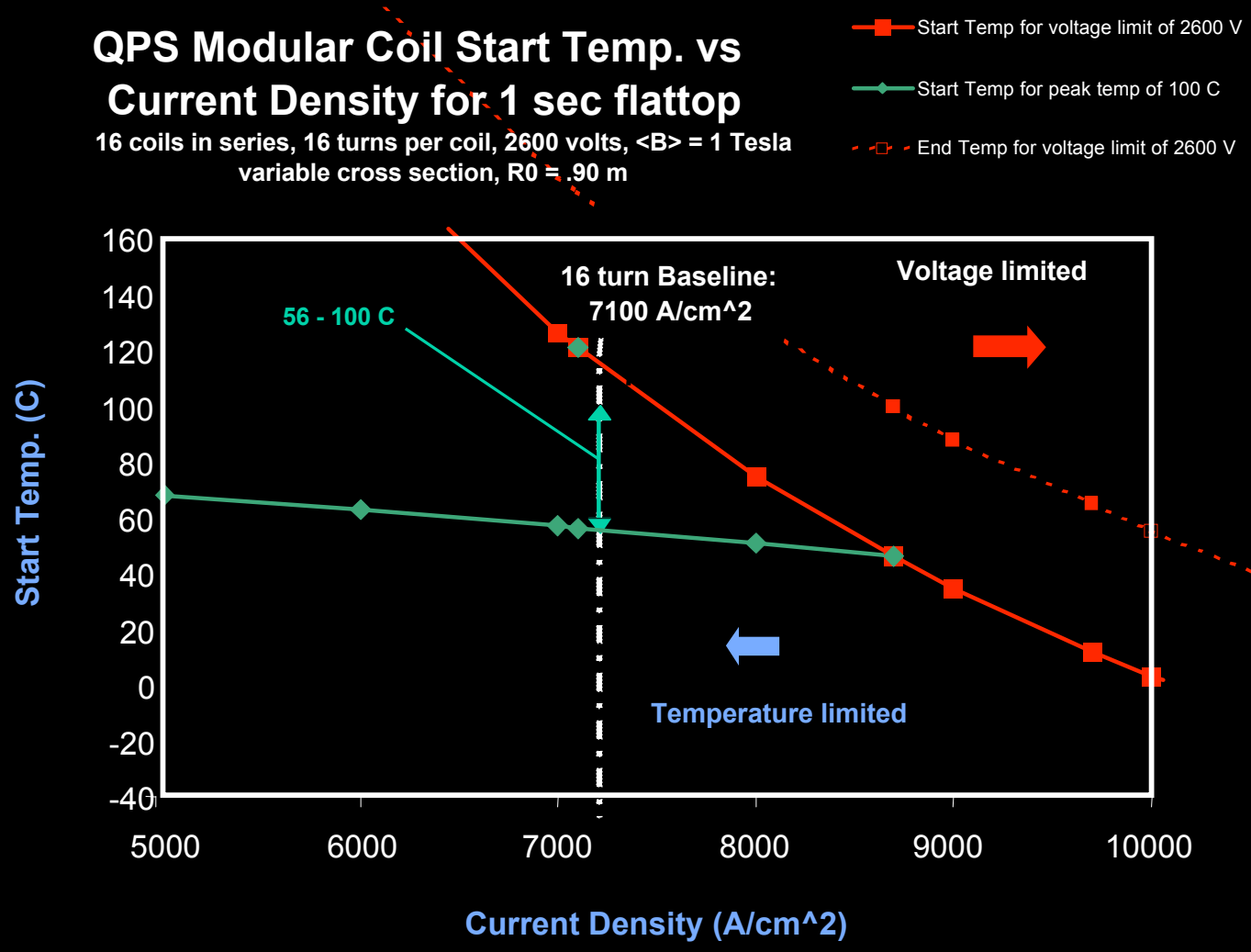
QPS modular coil flat-top time vs. starting temperature

16 coils in series, 16 turns per coil, 2600 volts,
10 x 12 cm cross section, .42 copper fraction



Baseline current density allows 1 s flat-top



Cyanate ester may be better choice than epoxy

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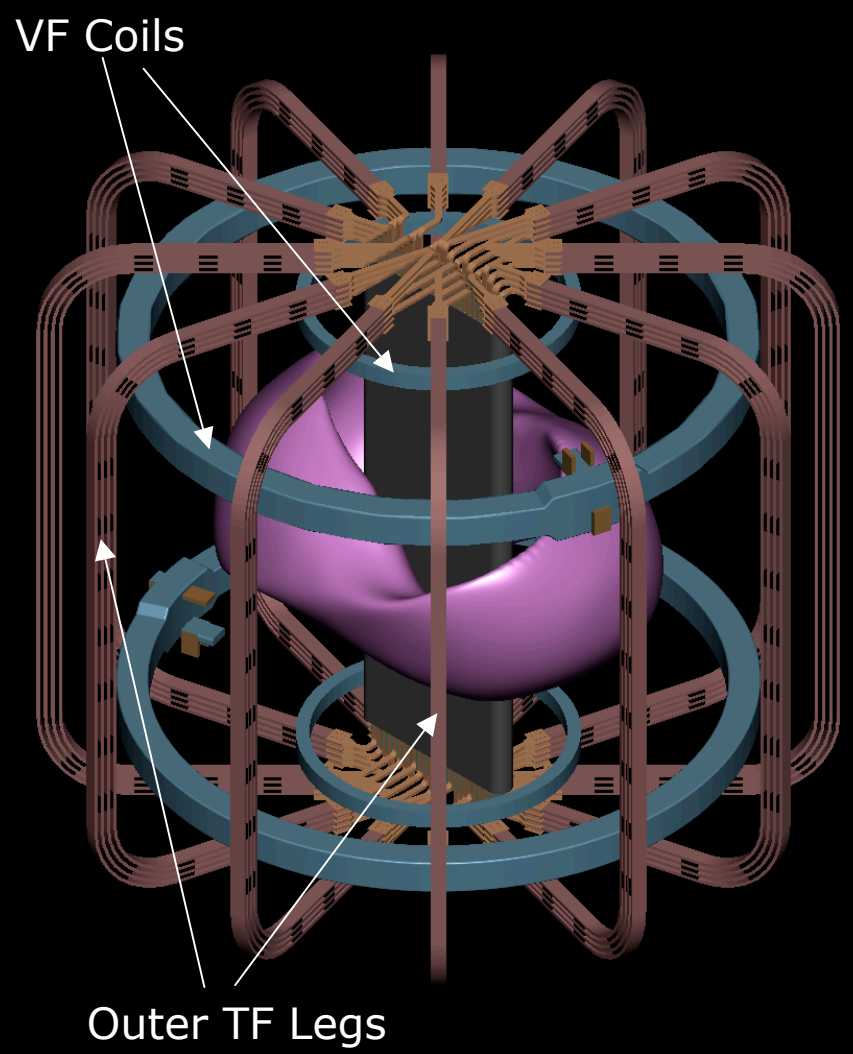
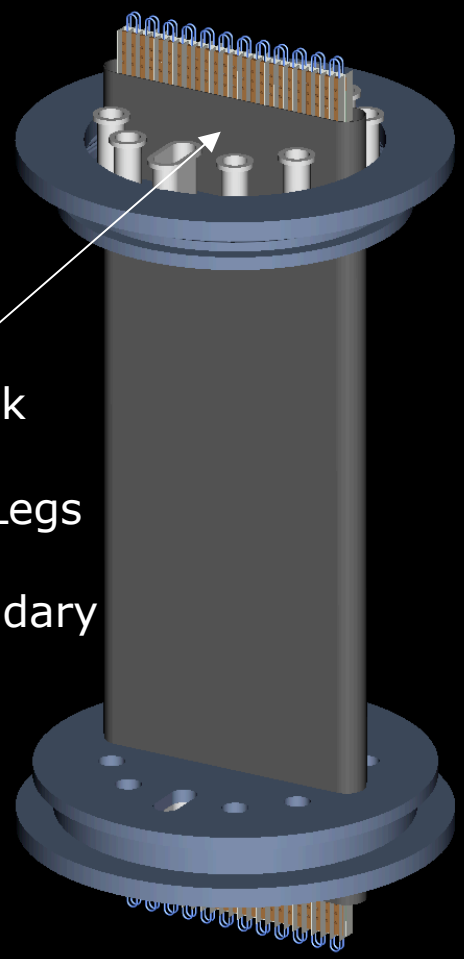
- Composite Technology Development (CTD) has developed high temperature Cyanate ester material – CTD 403
  - Room temp processing (100 centi-poise), pot life at least 24 hours, maybe several days
  - Curing at 150C, glass transition temp at 180 C
  - Operate at full load at >100C, short time at 150C
  - "catalyst cure, does not start until certain temperature)
  - mold shrinkage is less than epoxy, may be on the order of 1% over 10 inch
- Material properties good for both CTD 101K and CTD 403
  - Shear at 76K, > 100 Mpa for both CTD 101K and CTD 403
  - Compression, 1.3 Gpa, 1.23 Gpa respectively
  - Modulus at 76K, 16.7 Gpa, 15.1 Gpa
- Bakeout temperature will depend on thermal stress and creep properties of cable/epoxy composite

TF and VF Coils



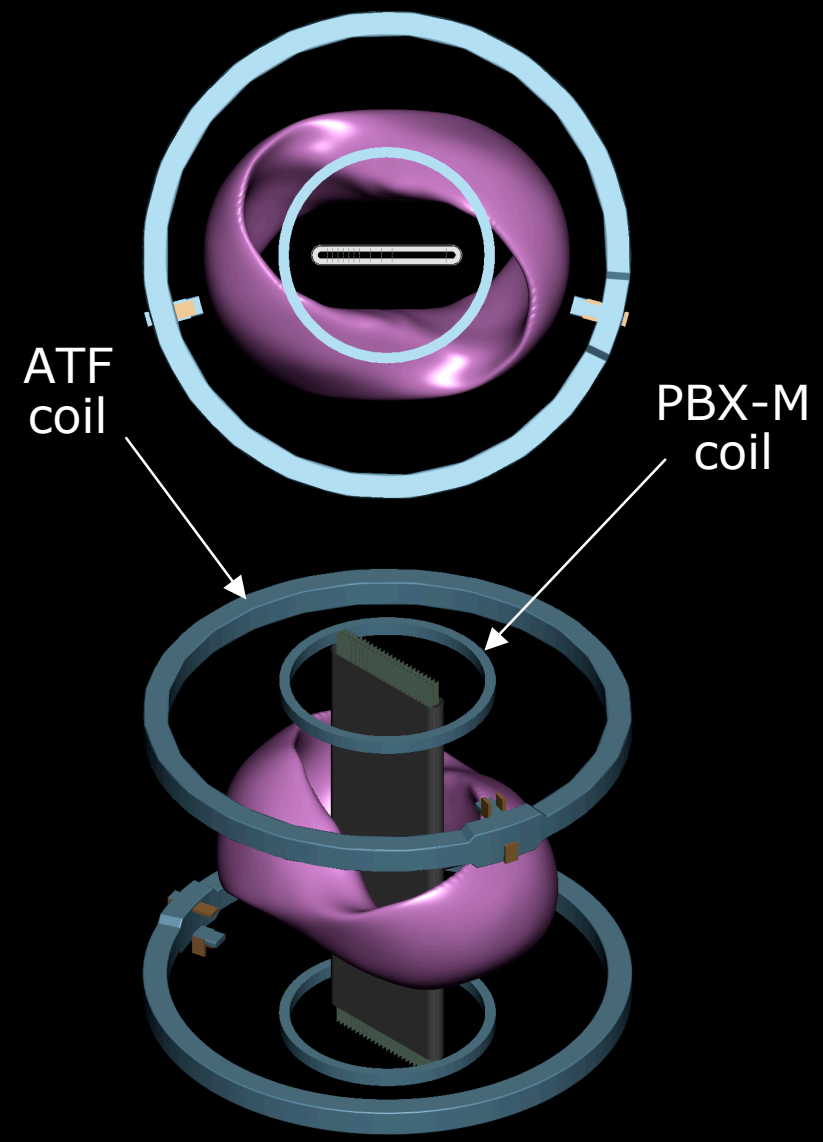


Center Stack Includes:

- TF Inner Legs
- Solenoid
- Vac. boundary

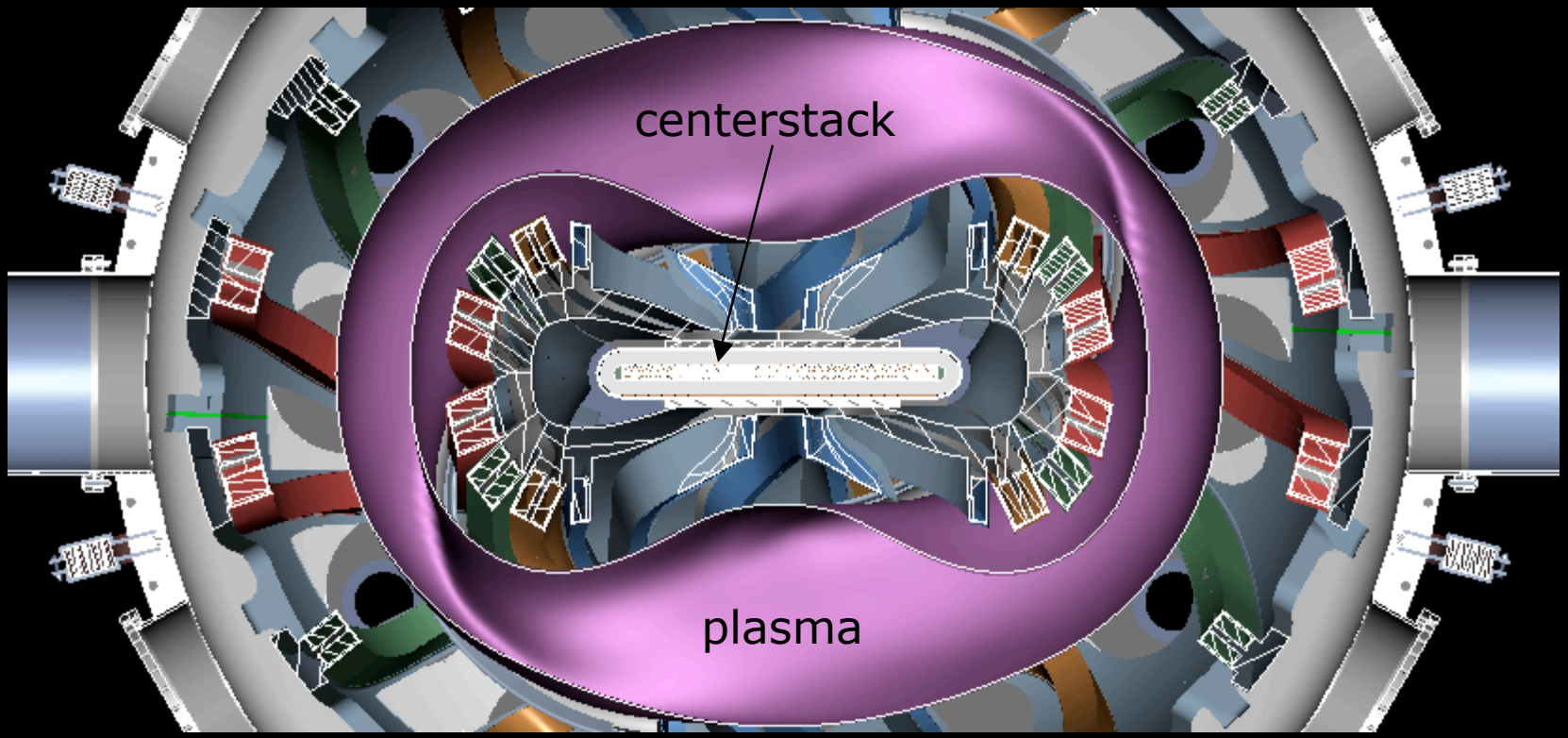
VF / Trim Coils / Solenoid

- 2 pairs of VF coils are included in design
- VF coils already exist:
  - ATF Mid-VF coils
    - 24 turns / coil
    - 300 kA-turns cont. rating
  - PBX-M OH-5 coils
    - 8 turns / coil
    - 160 kA-turns pulsed rating
- Solenoid requires new set of windings



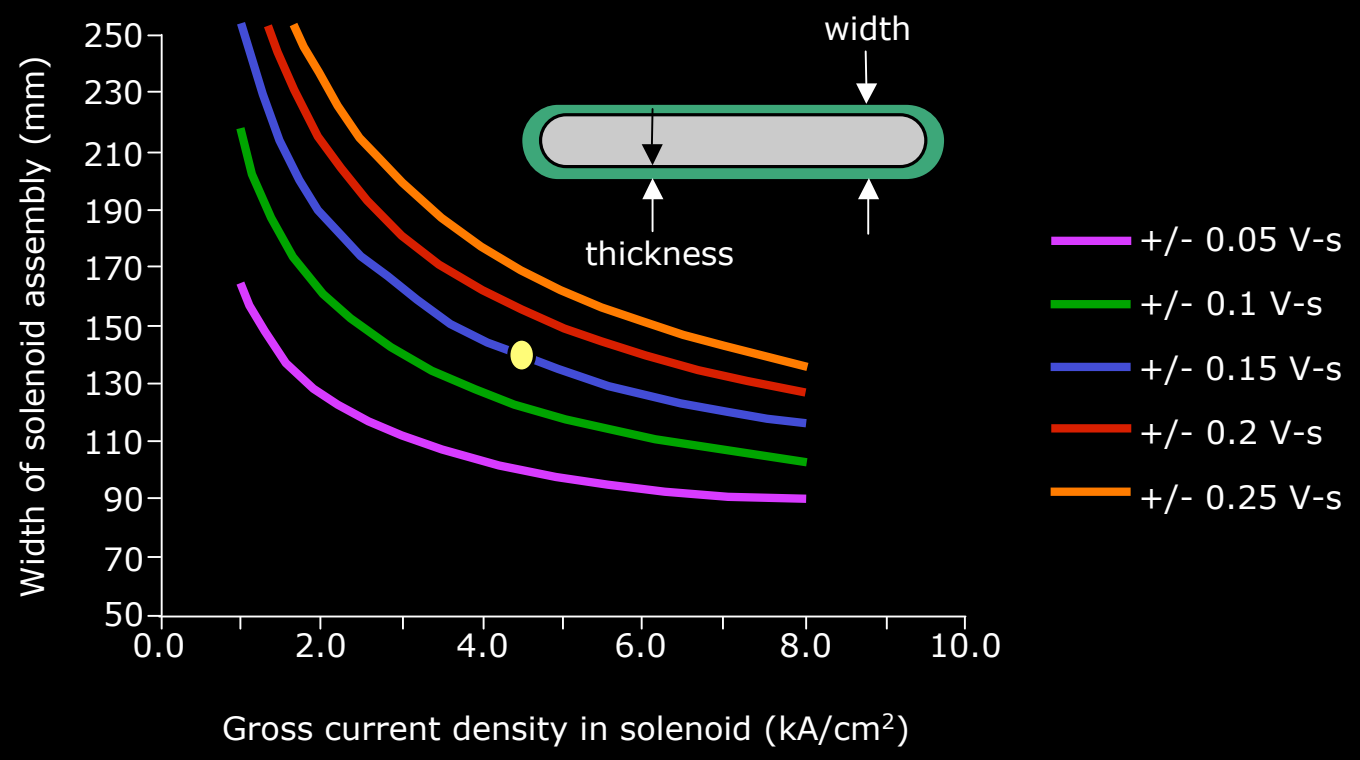
Limited room for centerstack

- Centerstack includes TF coils, OH solenoid and vacuum casing
- Available clear vertical bore is ~ 15 x 100 cm



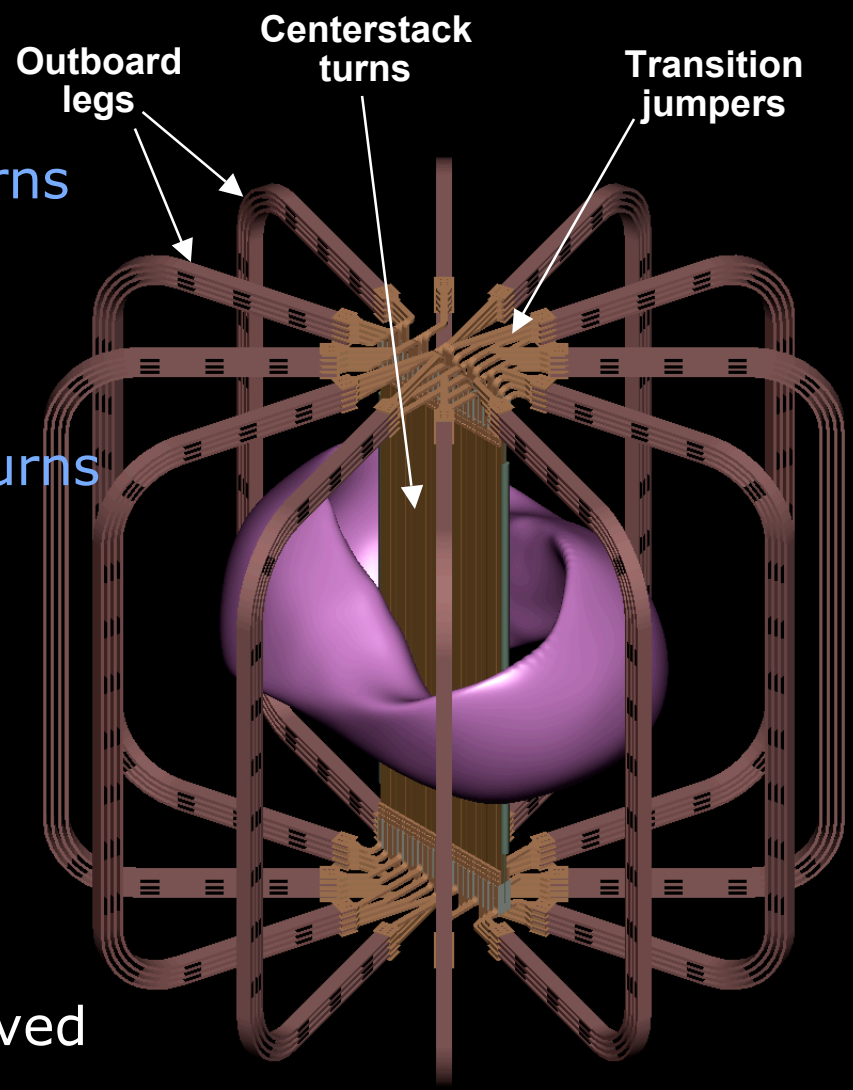
Design point for solenoid provides +/- 0.15 Vs

Centerstack width vs. current density in solenoid
length = 900 mm, 70 mm reserved for TF + can + clearance

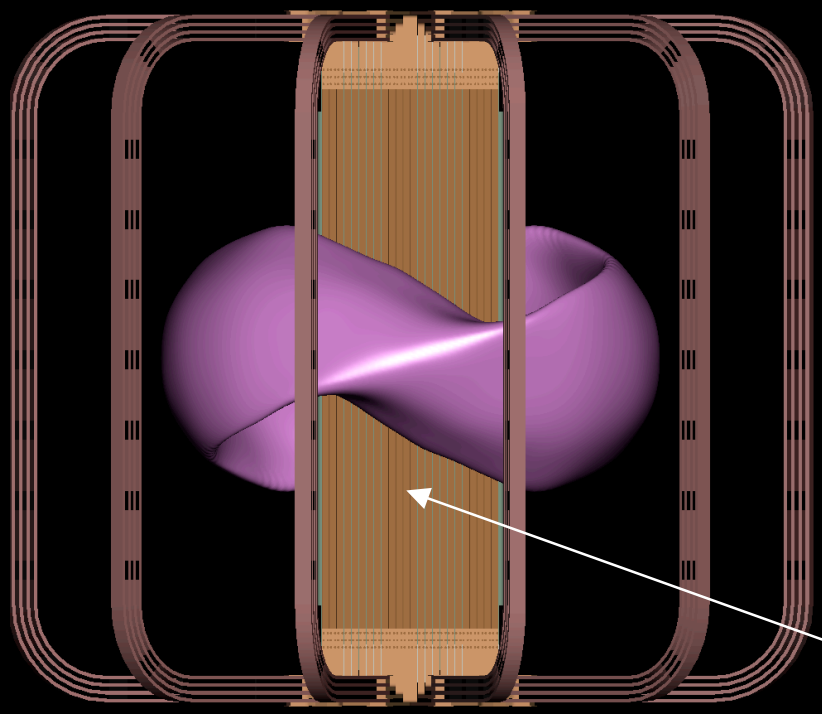


TF coils

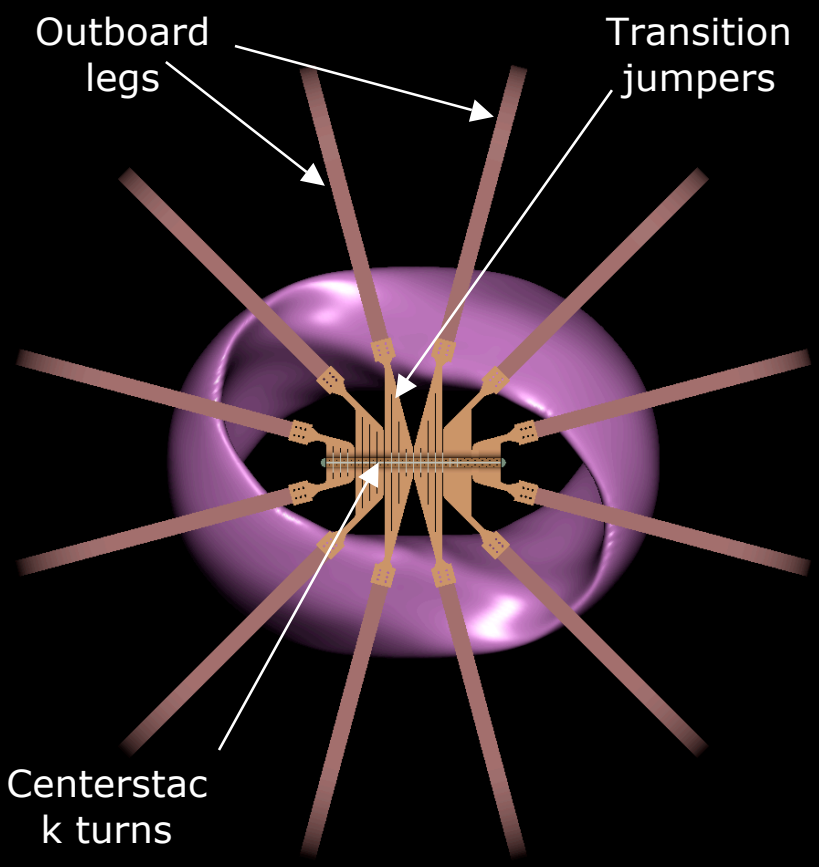
- 48 turns
  - 1.5 x .75 in. centerstack turns
  - 3.5 x .75 in. outboard
- +/- 0.2 T (~19 kA / turn)
  - ~2800 A/cm^2 centerstack turns
  - ~ 1130 A/cm^2 outboard
- 12 return leg bundles
- Odd shape requires transition jumpers at center stack
- Stellarator symmetry is preserved



TF Coils (2)

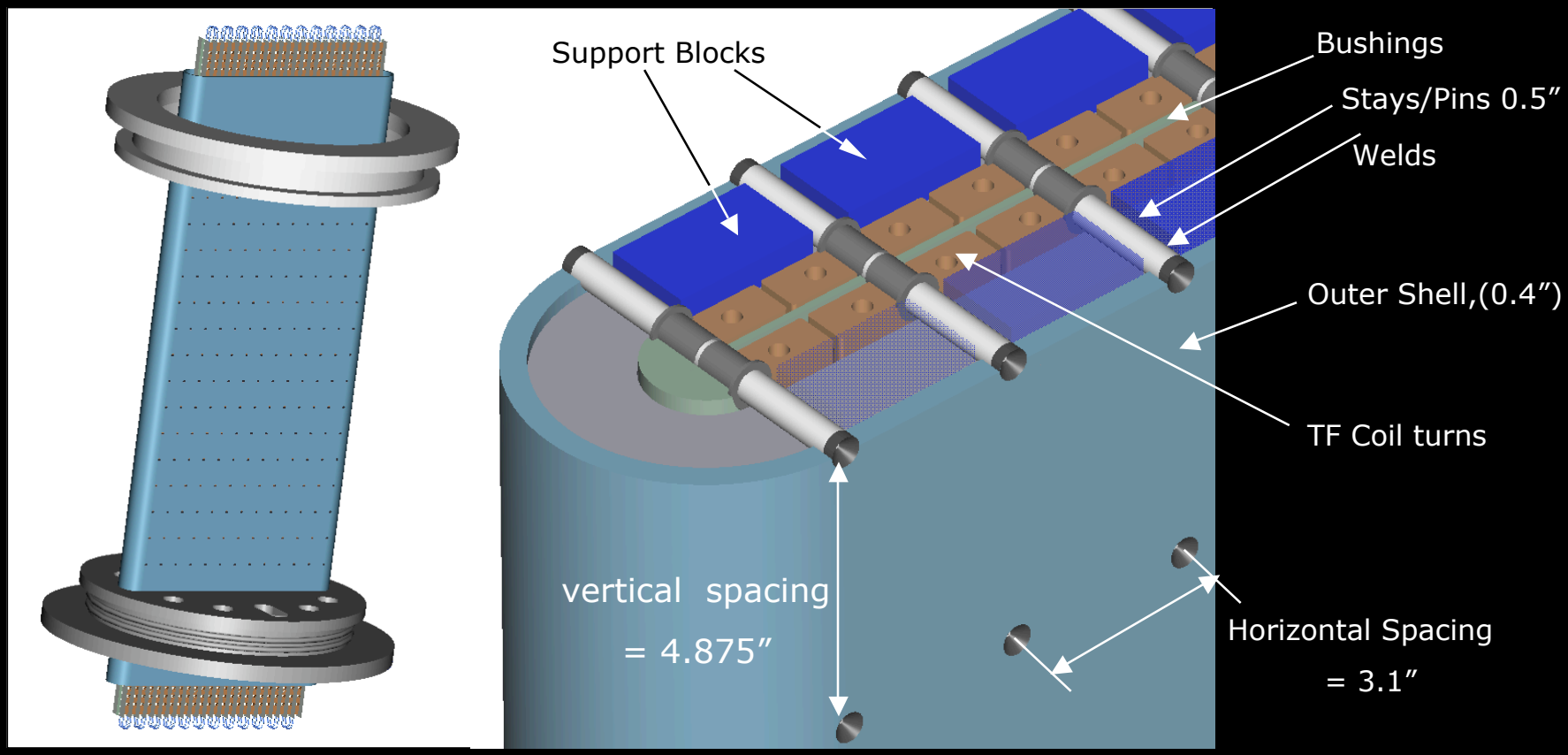


Elevation view



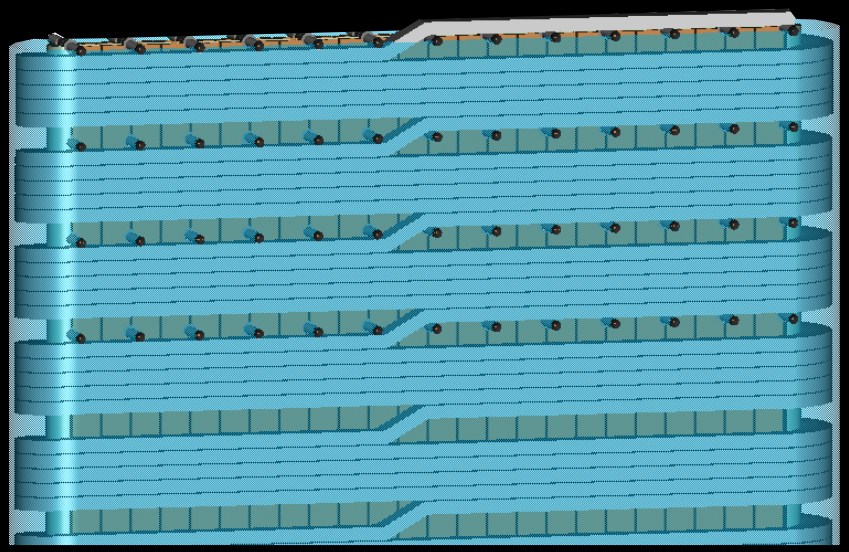
Plan view

Centerstack integrates solenoid, TF coils

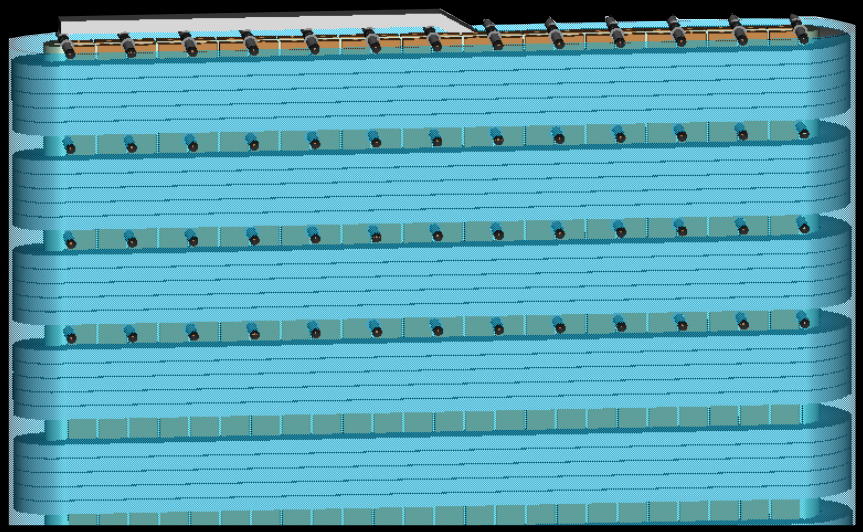


- Forces will require ties across winding, solenoid divided into at least 16 modules
- Present configuration limited to +/- 0.15 V-S by pressure on can

Solenoid windings routed around pins



FRONT



BACK

- Centerstack with four rows of pins and solenoid wrappings
- Winding divided into 16 turn groups
- Return bus not shown

Coils match up with existing power supplies

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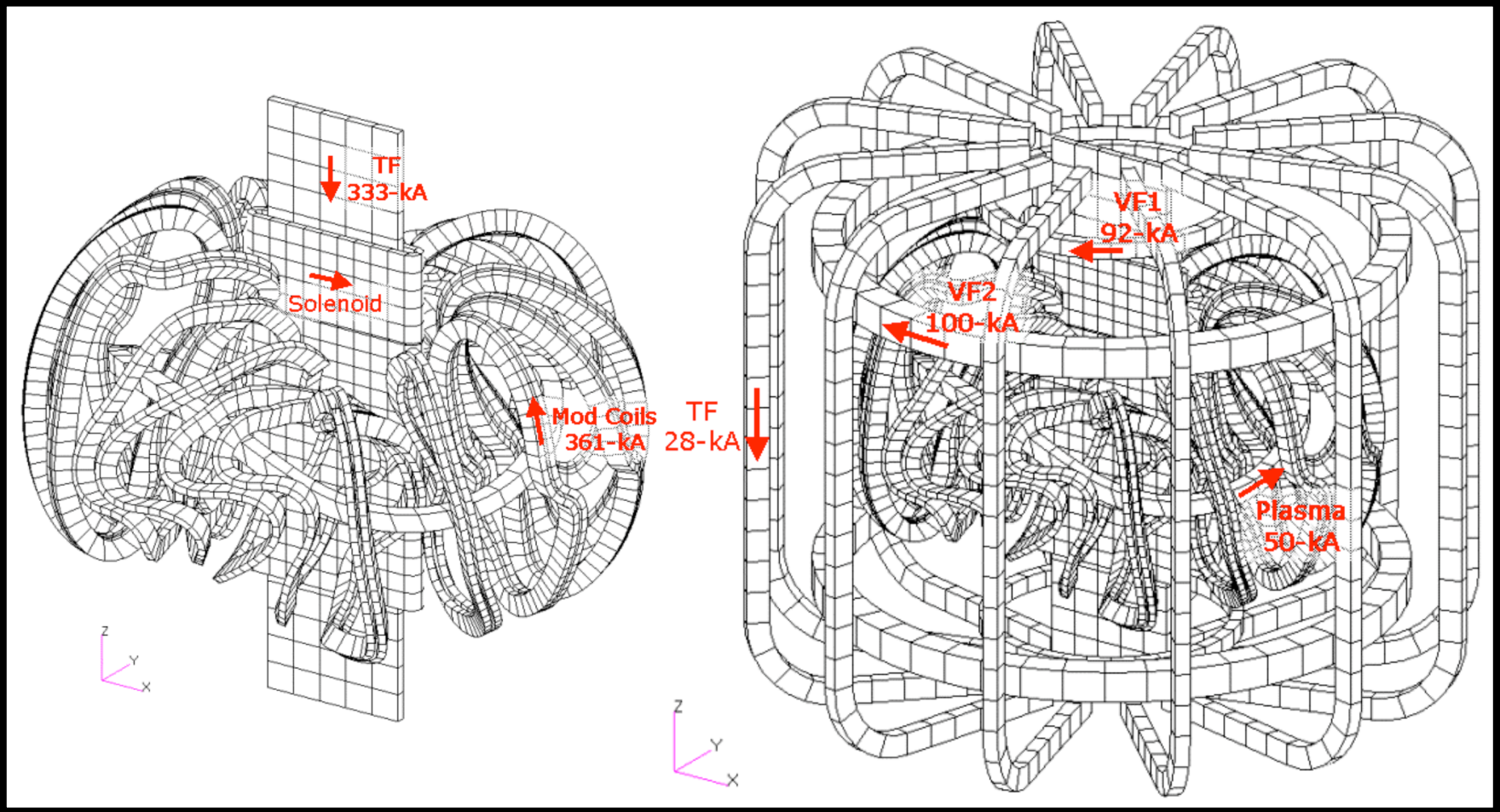
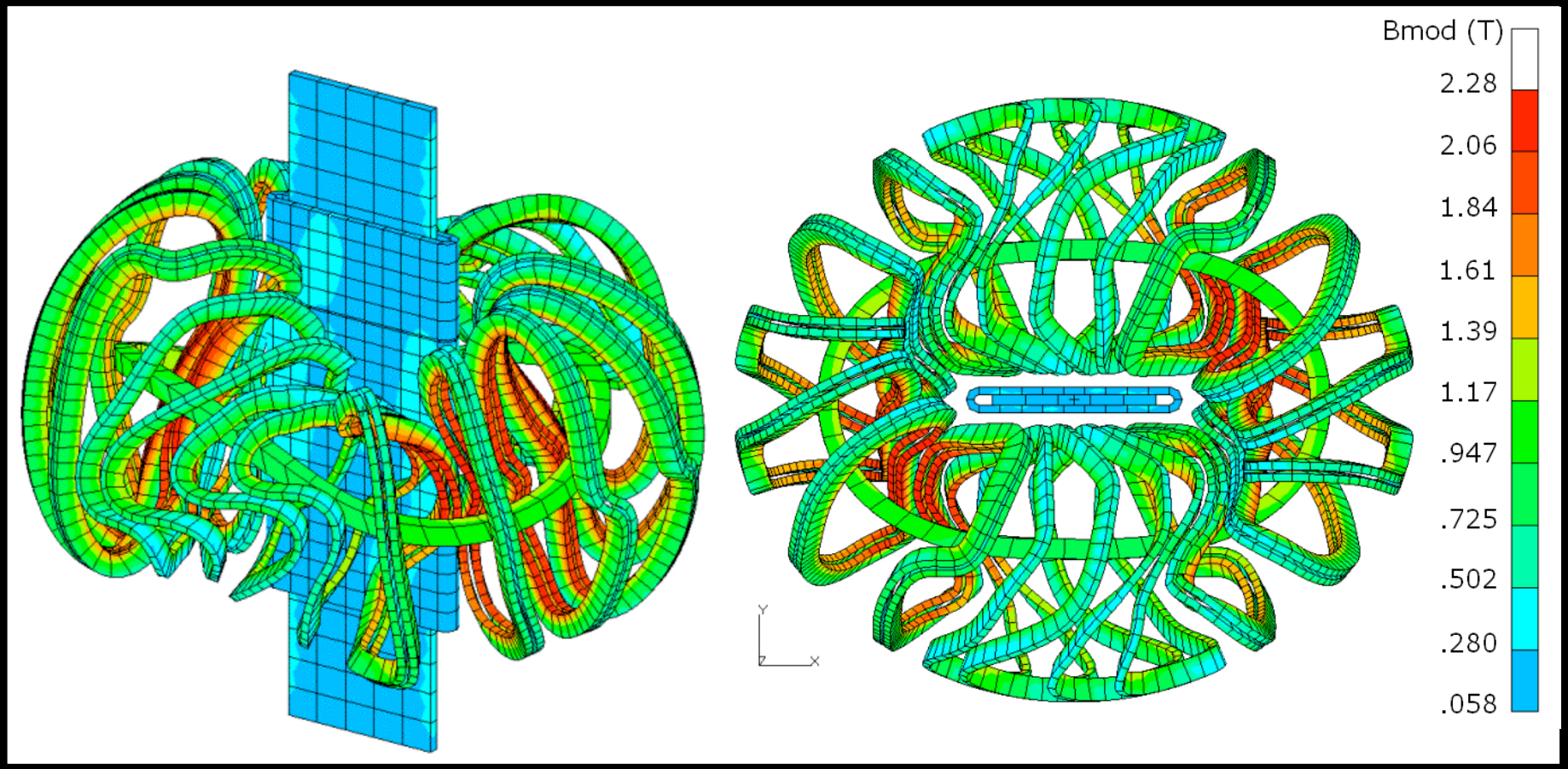
Coil Set	Power Supply
Modular Coils, 4 groups of 4 coils, 160 total turns	Existing ATF helical field power supplies, 4 each 650 V open circuit voltage, 30 kA pulsed current
OH solenoid 1 solenoid	Existing ATF VF coil power supply 625 V, 15kA pulsed
PBX-M OH-5 coils 1 pair	Existing ATF VF coil power supply 625 V. 15 kA pulsed rating
ATF Mid Coils 1 pair	Existing ATF VF coil power supply 625 V. 10 kA pulsed rating
TF coils 1 circuit, 48 total turns	Existing ATF helical field power supplies, 1 each 650 V open circuit voltage, 30 kA pulsed current

Coil currents for nominal configuration

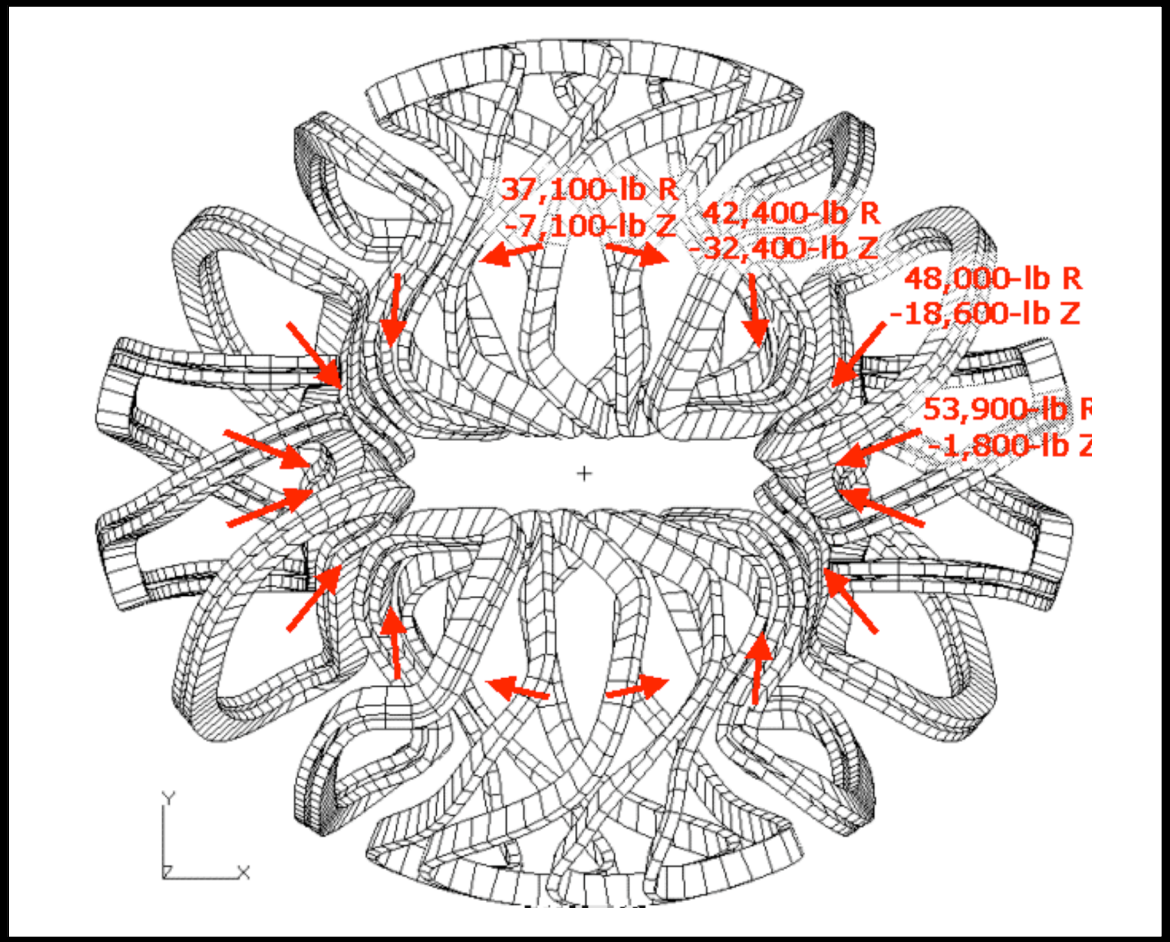


Magnetic field distribution from all coils

Bmax/Bo = 2.28, with external TF field of -0.11T



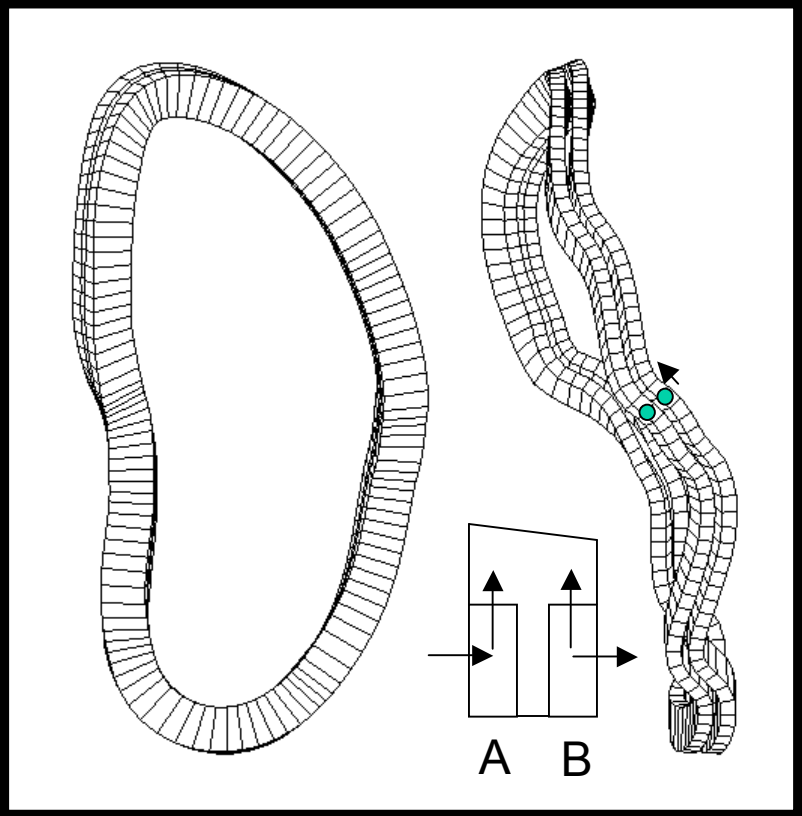
Modular coil forces

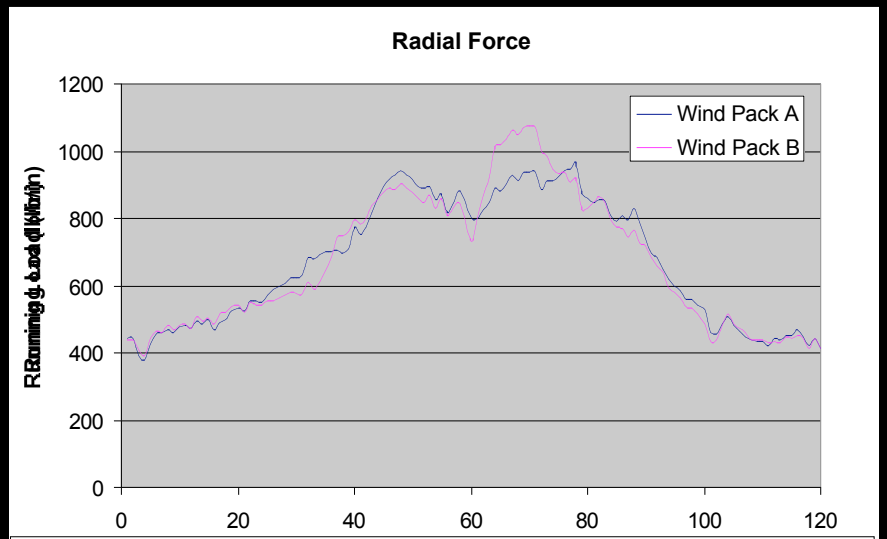


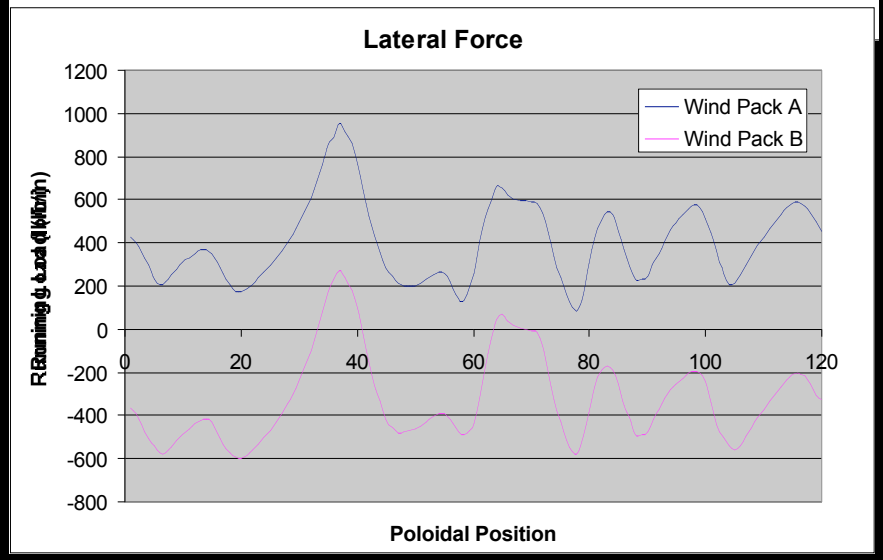
Max centering load = 54 kips

Modular coil forces

Coil M1 (0408a2 coil set)

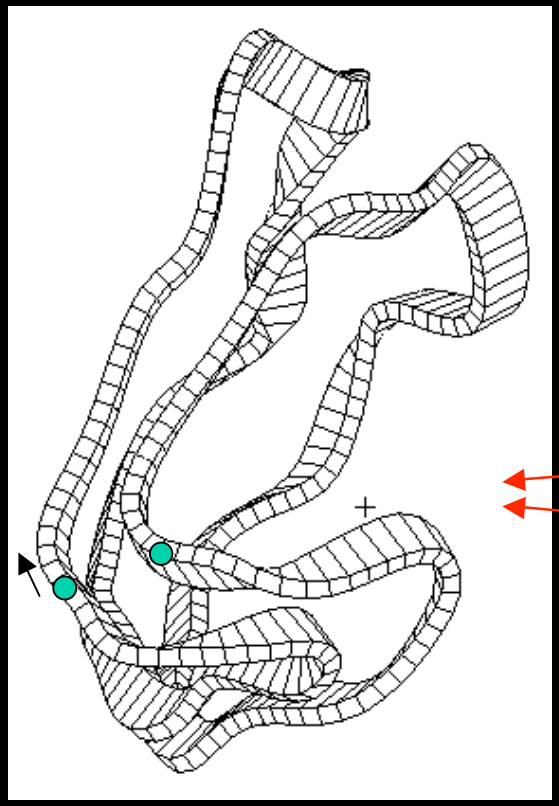


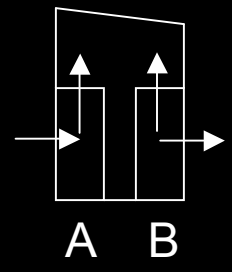


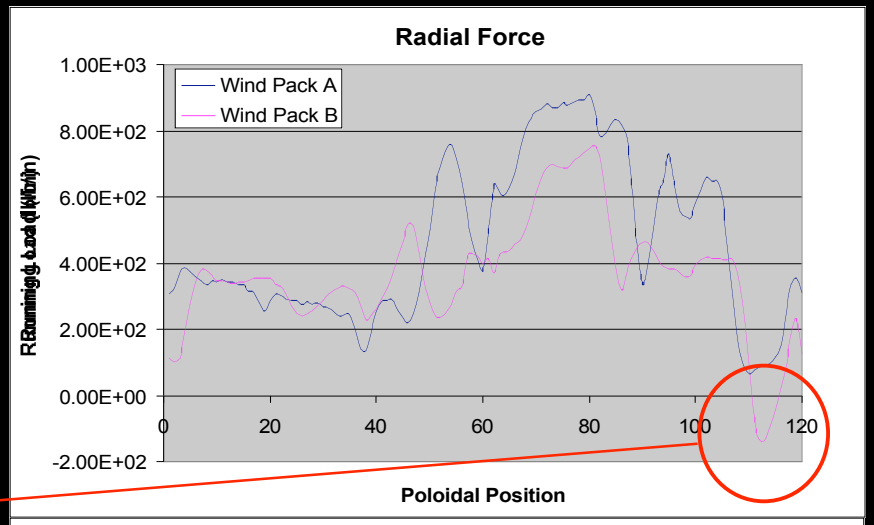


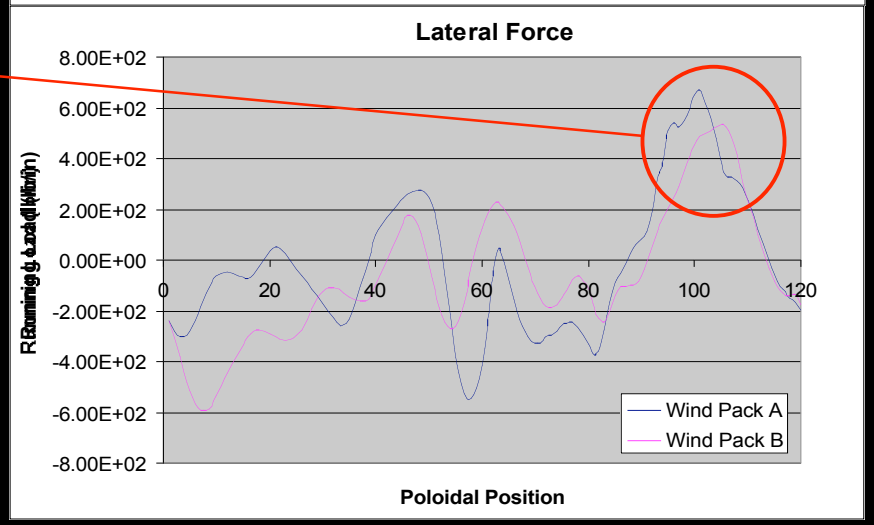
Modular coil forces

Coil D (0408a2 coil set)



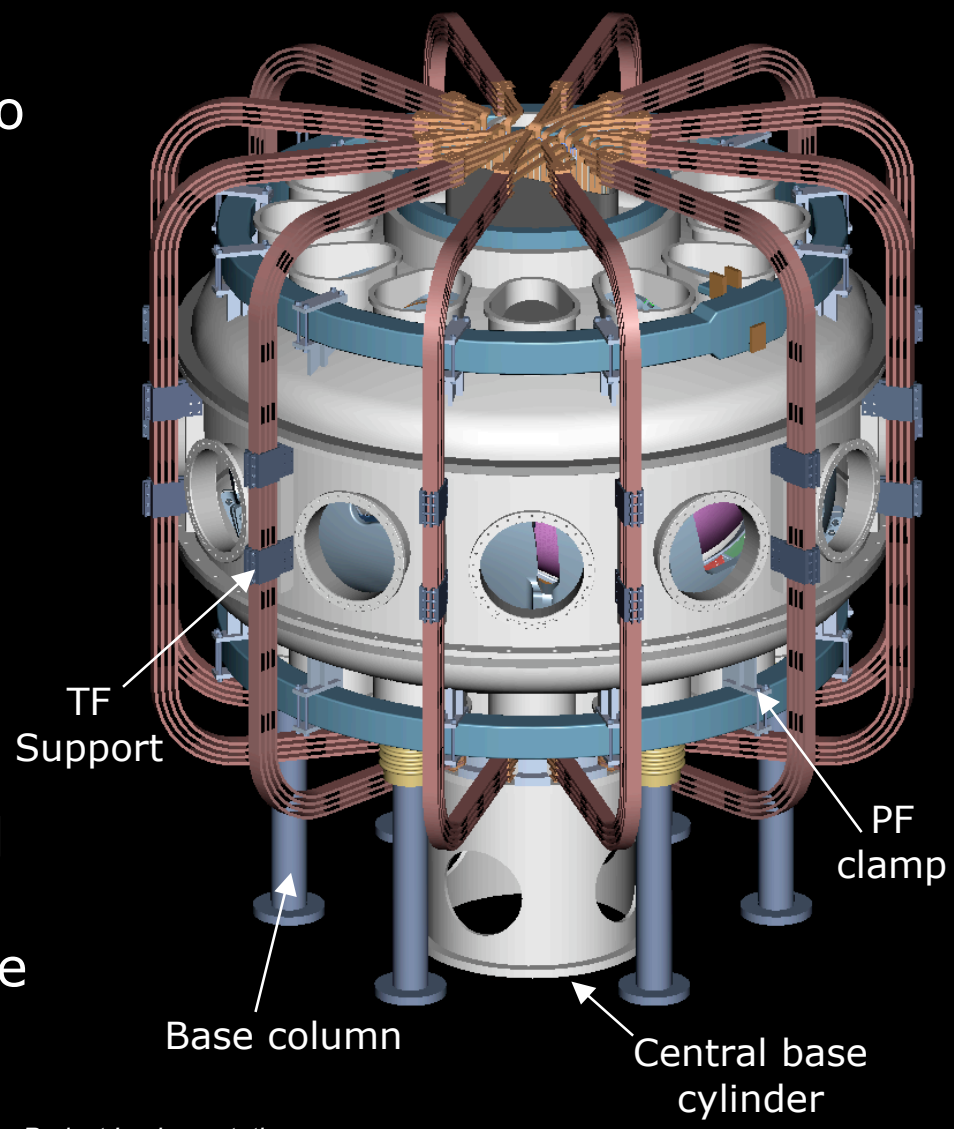






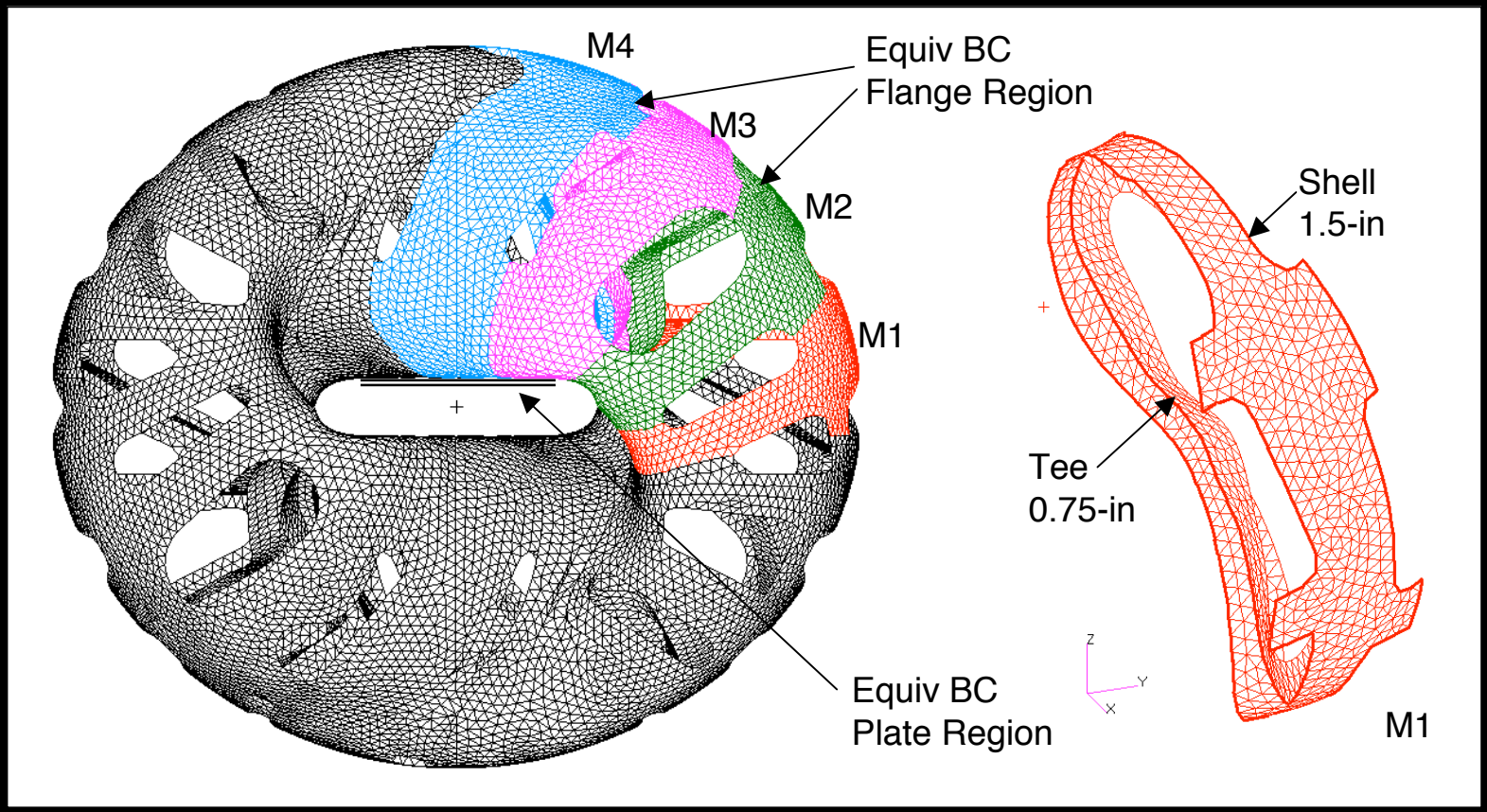
Machine Structure

- Modular coils form self supporting shell connected to base columns
- VF coils supported from vacuum vessel domes
- Solenoid and centerstack also supported from central base cylinder
- TF coil return legs supported from vacuum vessel spool piece, may need out-of-plane support from domes



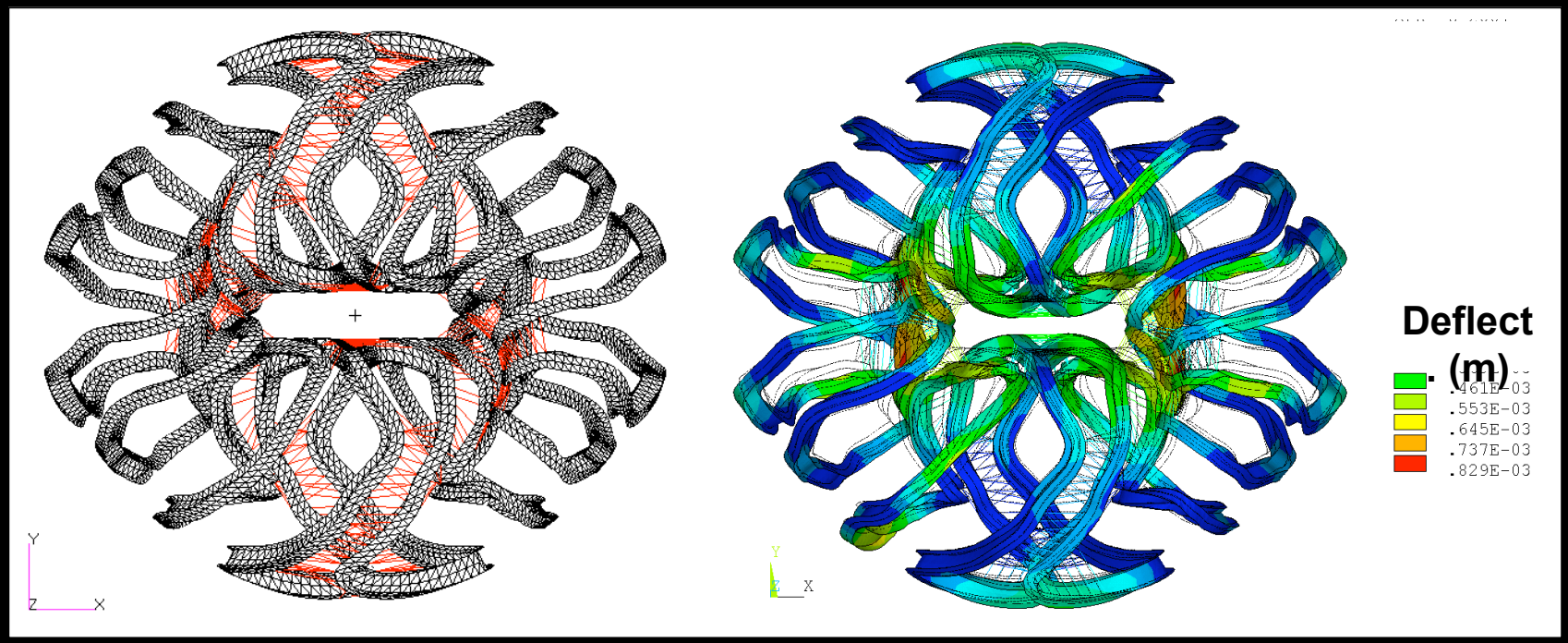
Modular coil structural analysis (in process)

- Plate element model of shell and tee (~130,000 dof)
- EM forces applied by mapping element body force to tee nodes (60 nodes poloidally)
- Flange and inboard plate connection made by nodal equivalencing
- Model can also be used to optimize shell thickness, cutouts



Modular coil structural analysis (from PVR)

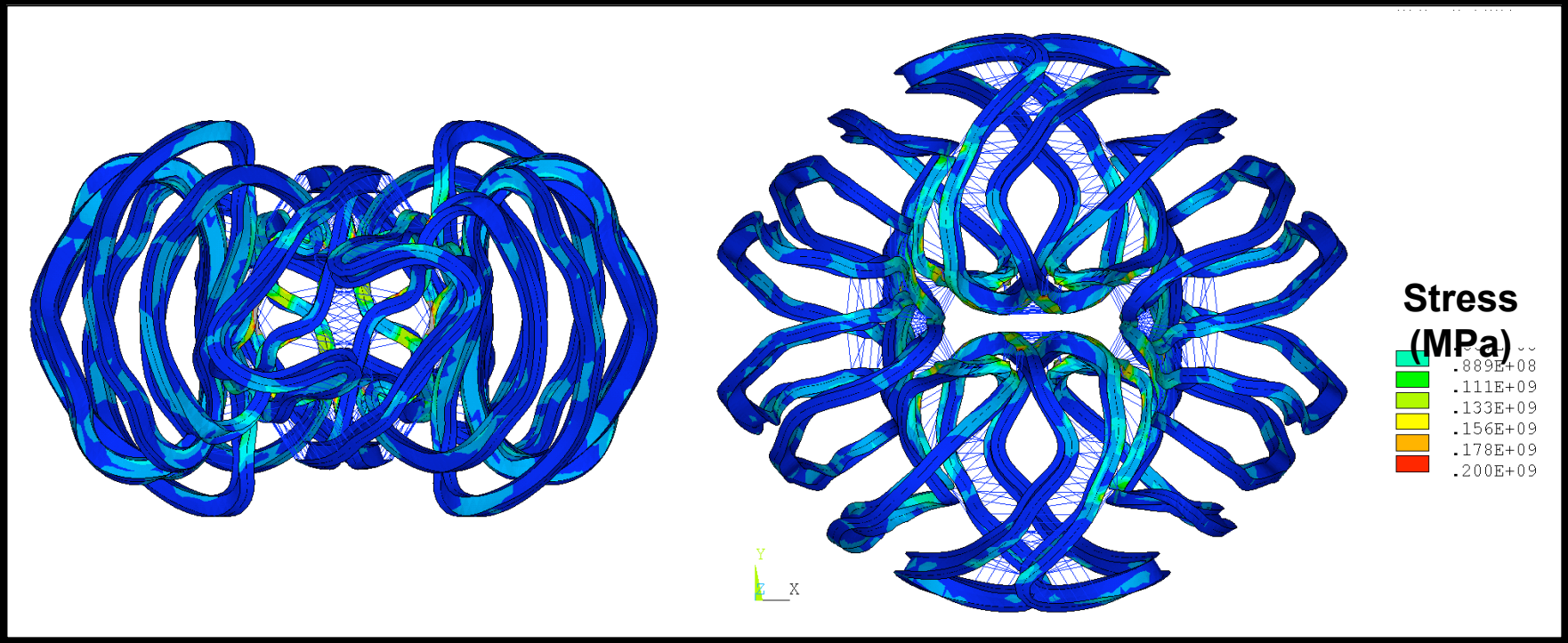
- Coil-to-coil structure shown is sufficient to limit maximum deflection to less than 1 mm *(PVR model)*



Structural FEA model **Deflections under load**

Stress in modular coil structure (from PVR)

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

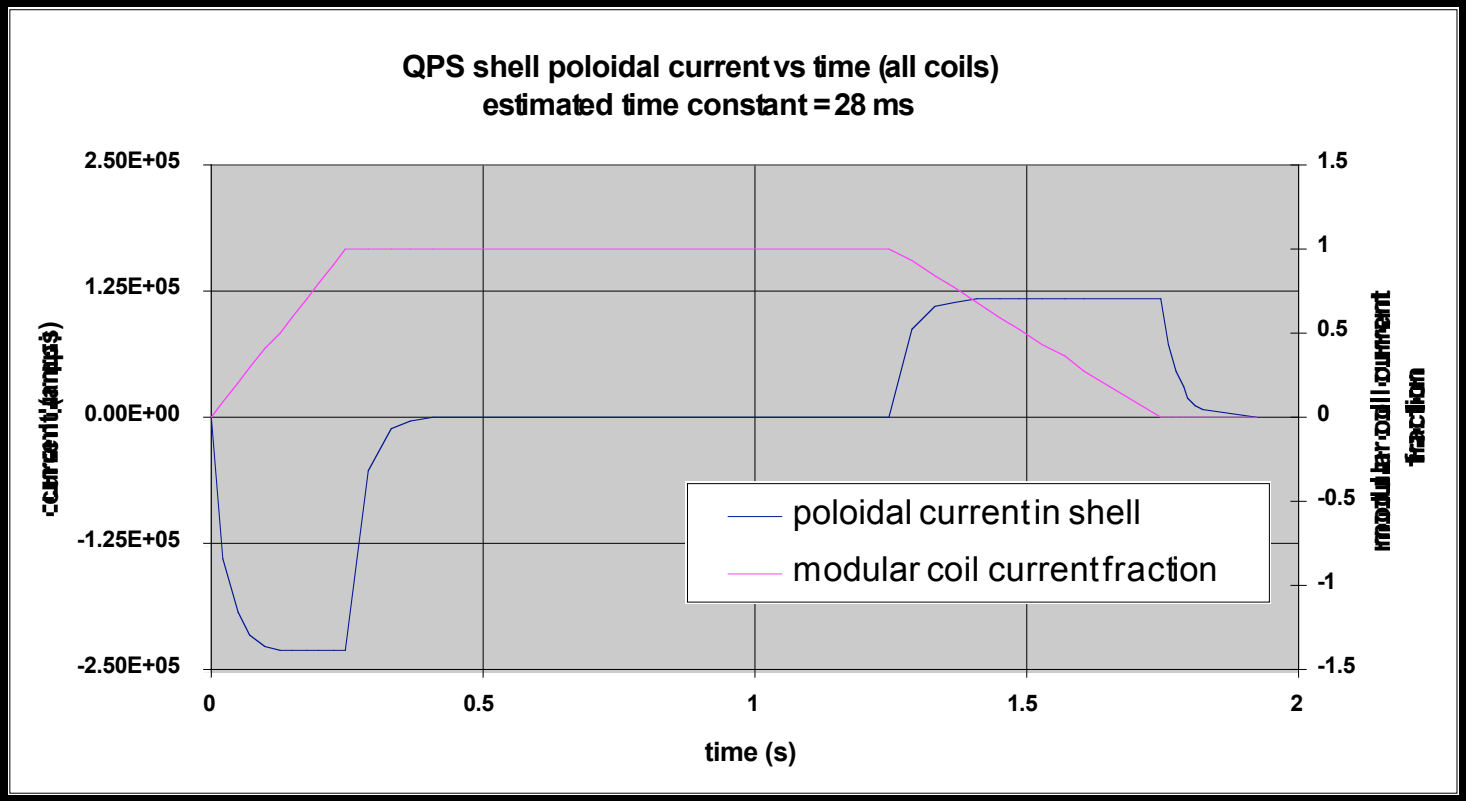


Stress distribution, elevation view

Stress distribution, plan view

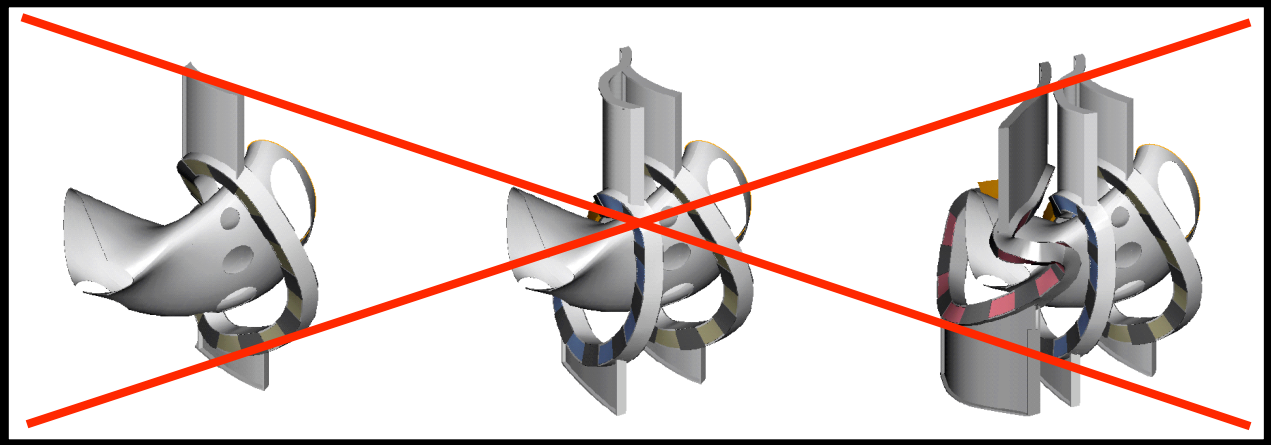
Eddy currents in shell structure

- Poloidal currents induced in shell during coil transients
- Effective flat-top time of pulse reduced ~ 100 ms
- 3-D model in progress for better estimate
- Copper cooling surfaces must be electrically isolated and segmented



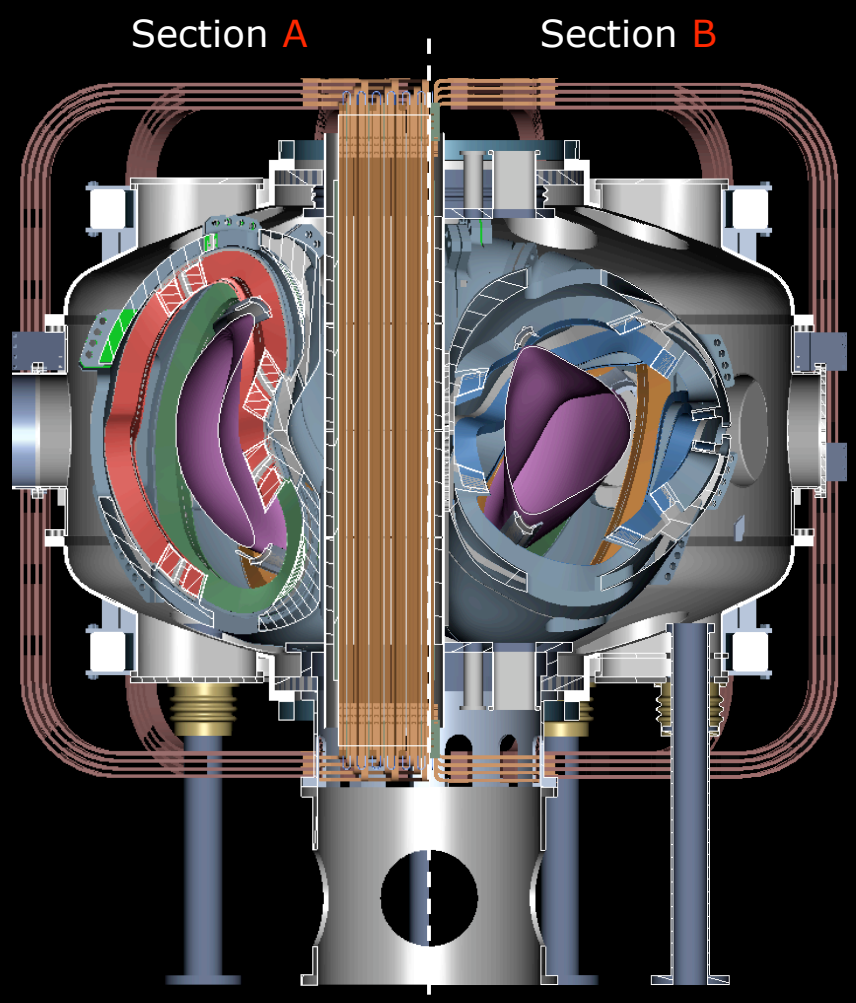
QPS will use external vacuum vessel

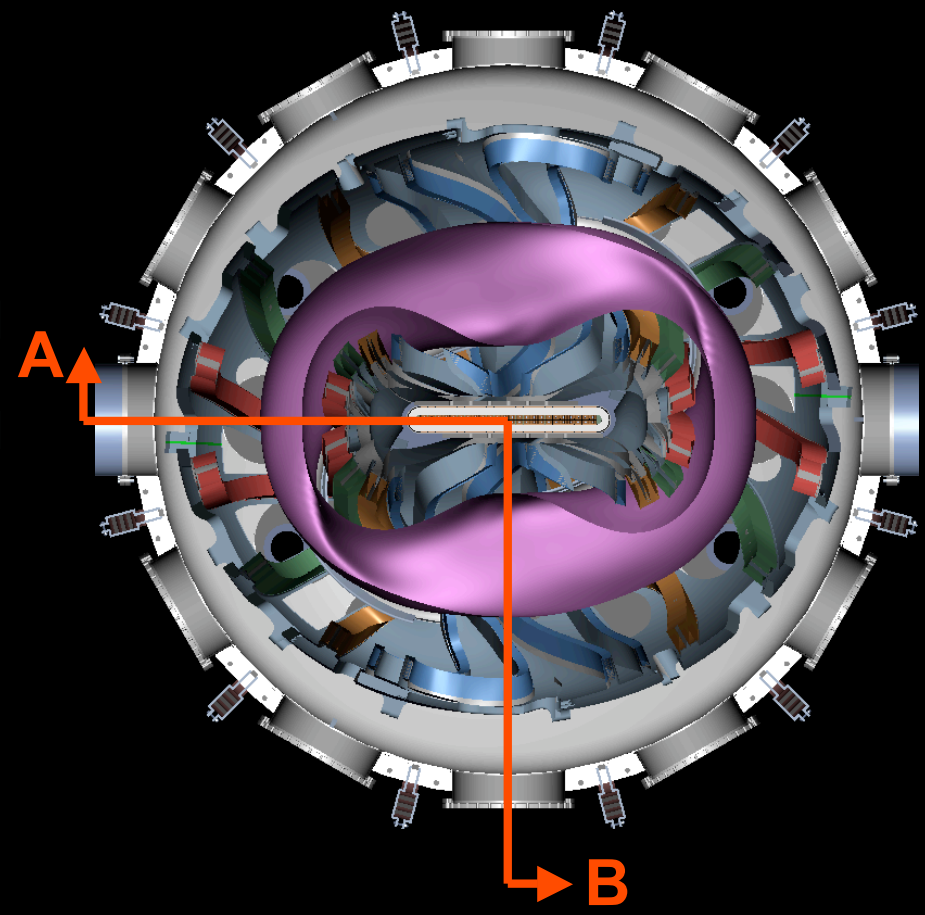
- Eliminates complex vacuum vessel fabrication
- Provides maximum distance from coils to plasma for greater shape flexibility – e.g. larger plasma or shifted position



- Provides more flexibility for structure, since coils do not have to be manipulated over internal vacuum vessel
- Provides maximum access for heating, diagnostic systems

QPS mod coils located inside external vessel





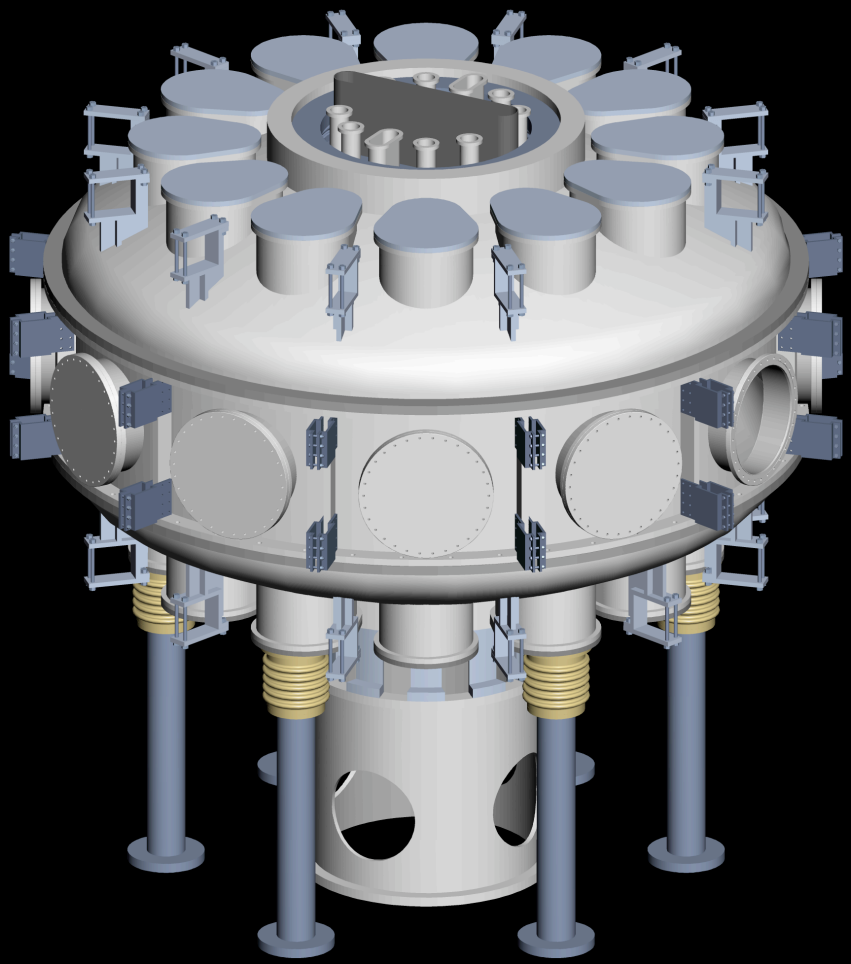
External vacuum vessel requirements

QPS

- Clean: "bake-able" to 150 C (need double seals)
- 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 as well as alignment issues require bellows between centerstack and upper dome

New external tank parameters

- 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

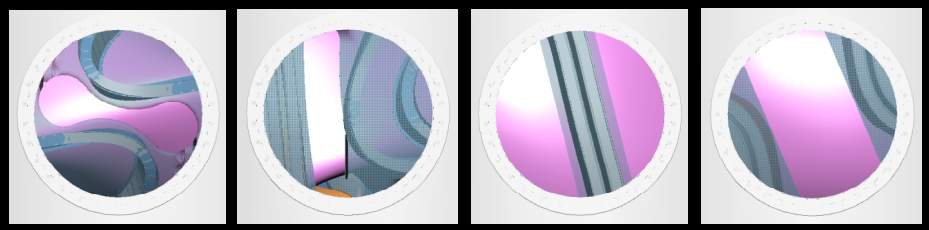


Parameters

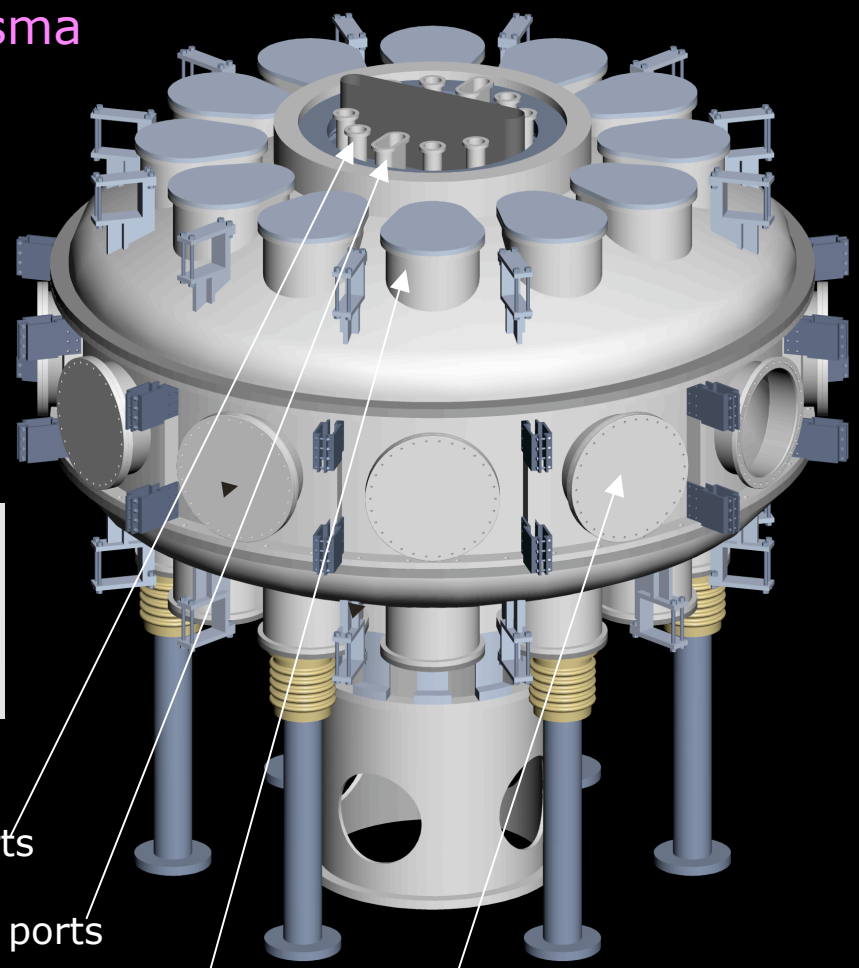
Material	316L ss
Nominal outer radius	1.9 m
Maximum height	2.5 m
Inside surface area	~68 m^2
Enclosed volume (w/ports)	~21 m^3
Bakout temperature	150 C
Nominal oper. Temp.	20-100 C

QPS access for diagnostics, heating

Views looking into vertical ports



Views looking into radial ports



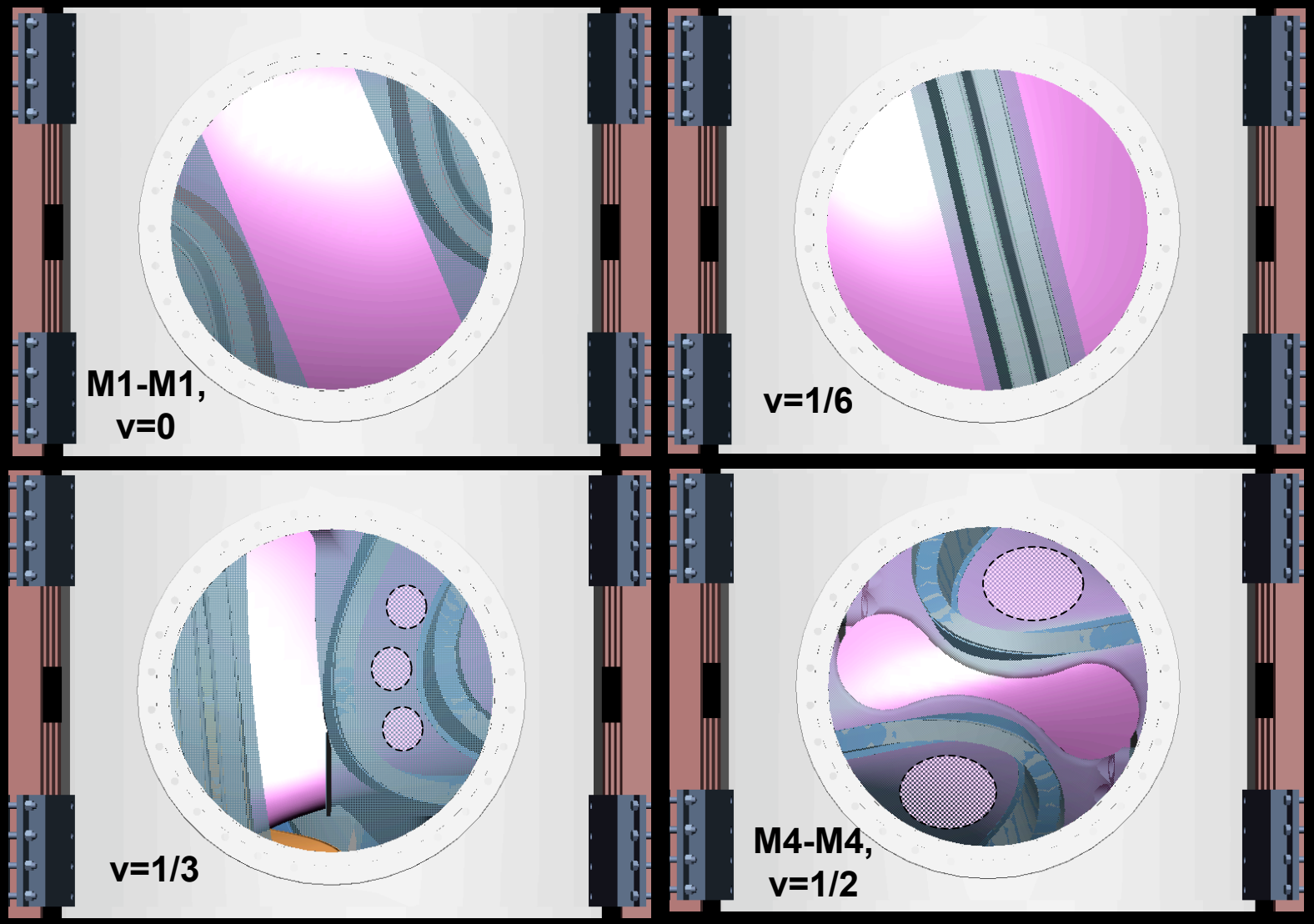
(2 x 8) 2” diameter upper / lower ports

(2 x 2) 2” x 4” upper /lower vert. ports

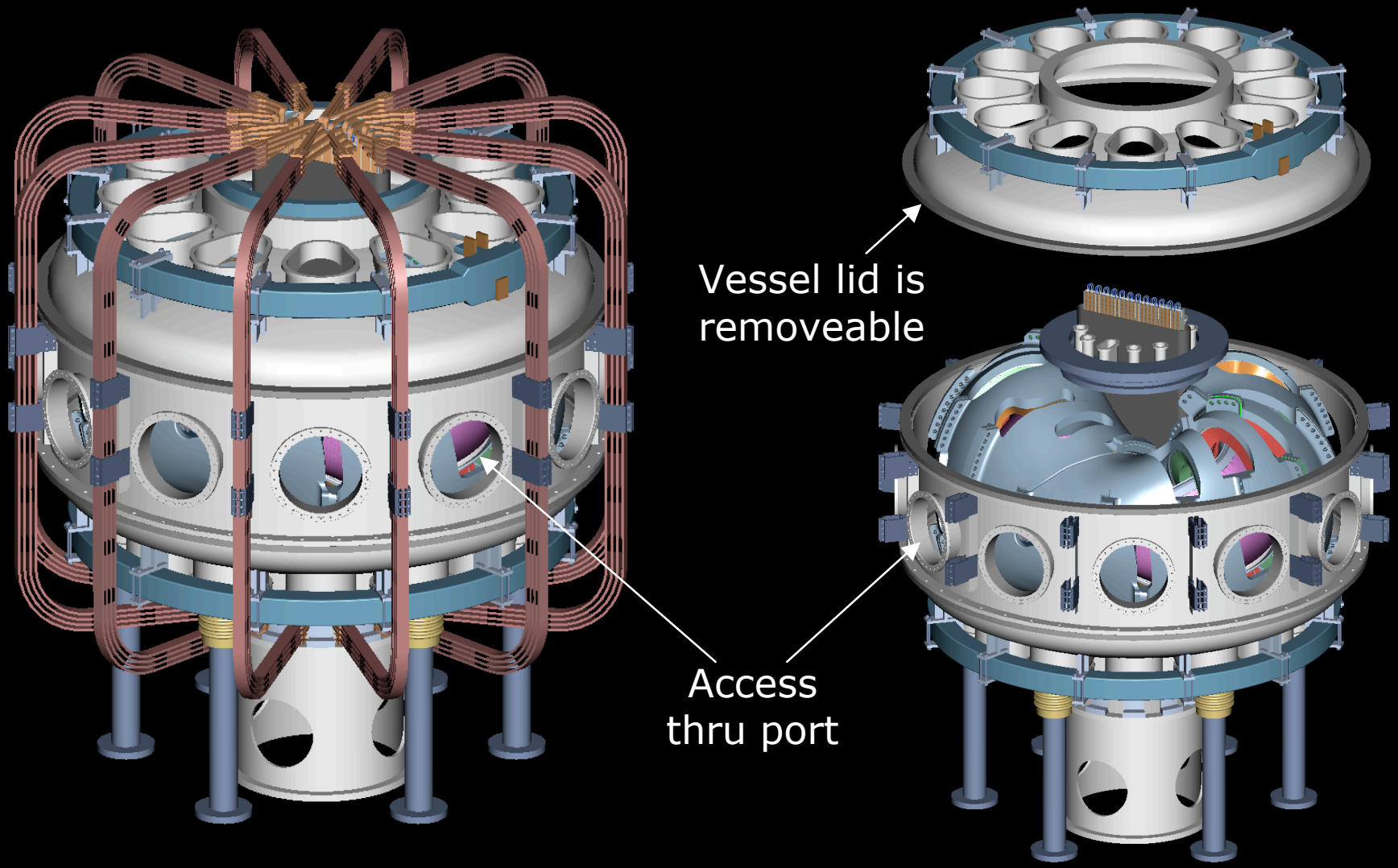
(2 x 12) 12” x 20” upper /lower vert. ports

(12) 24” diameter radial ports

QPS access – midplane port views

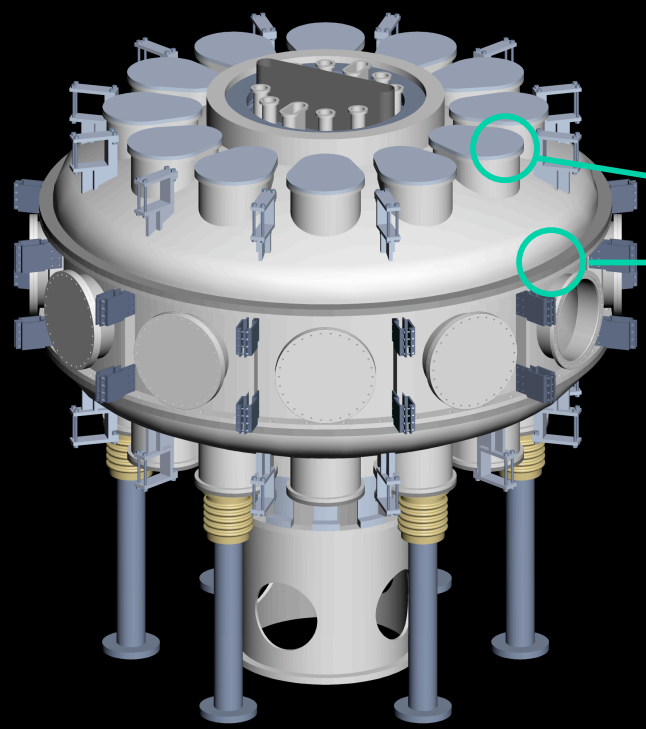


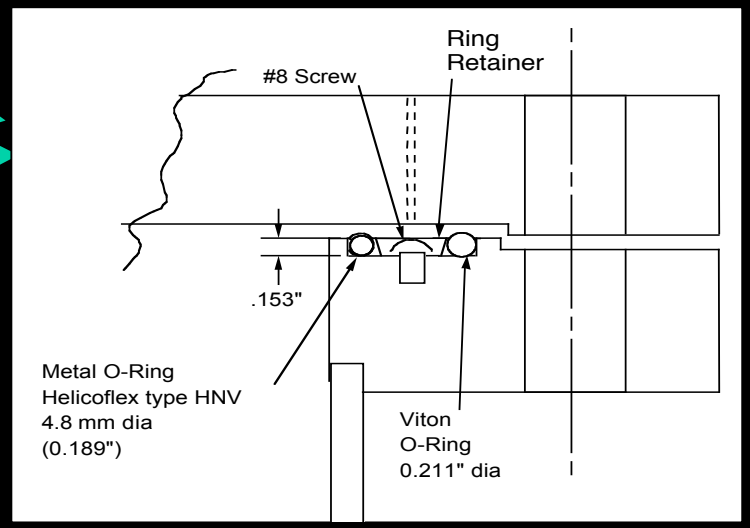
Access for maintenance



QPS has capability for all-metal seals

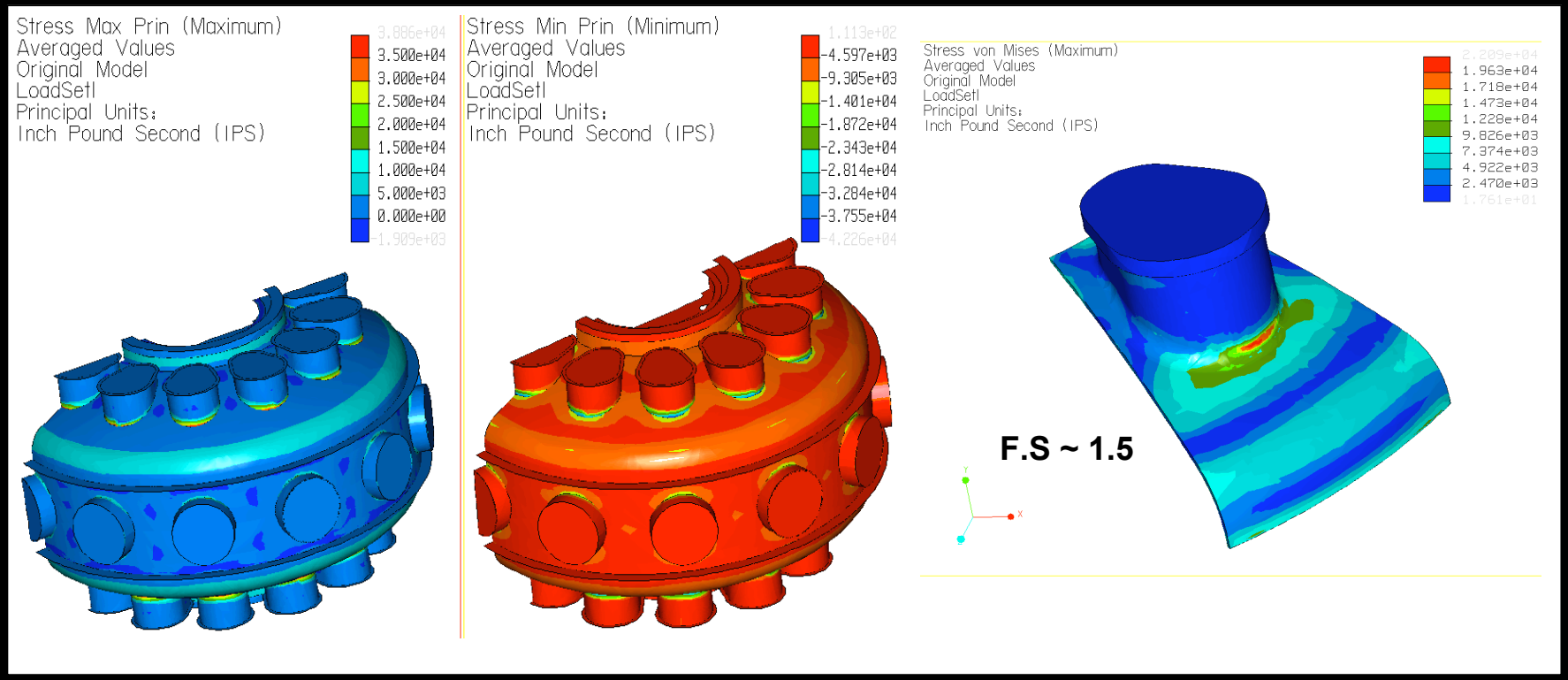
- Standard round ports
  - conflat metal seals
- Non-standard flanges and main vessel seals
  - Double seals with interstitial pumping
  - Universal gland design to accommodate metal or viton





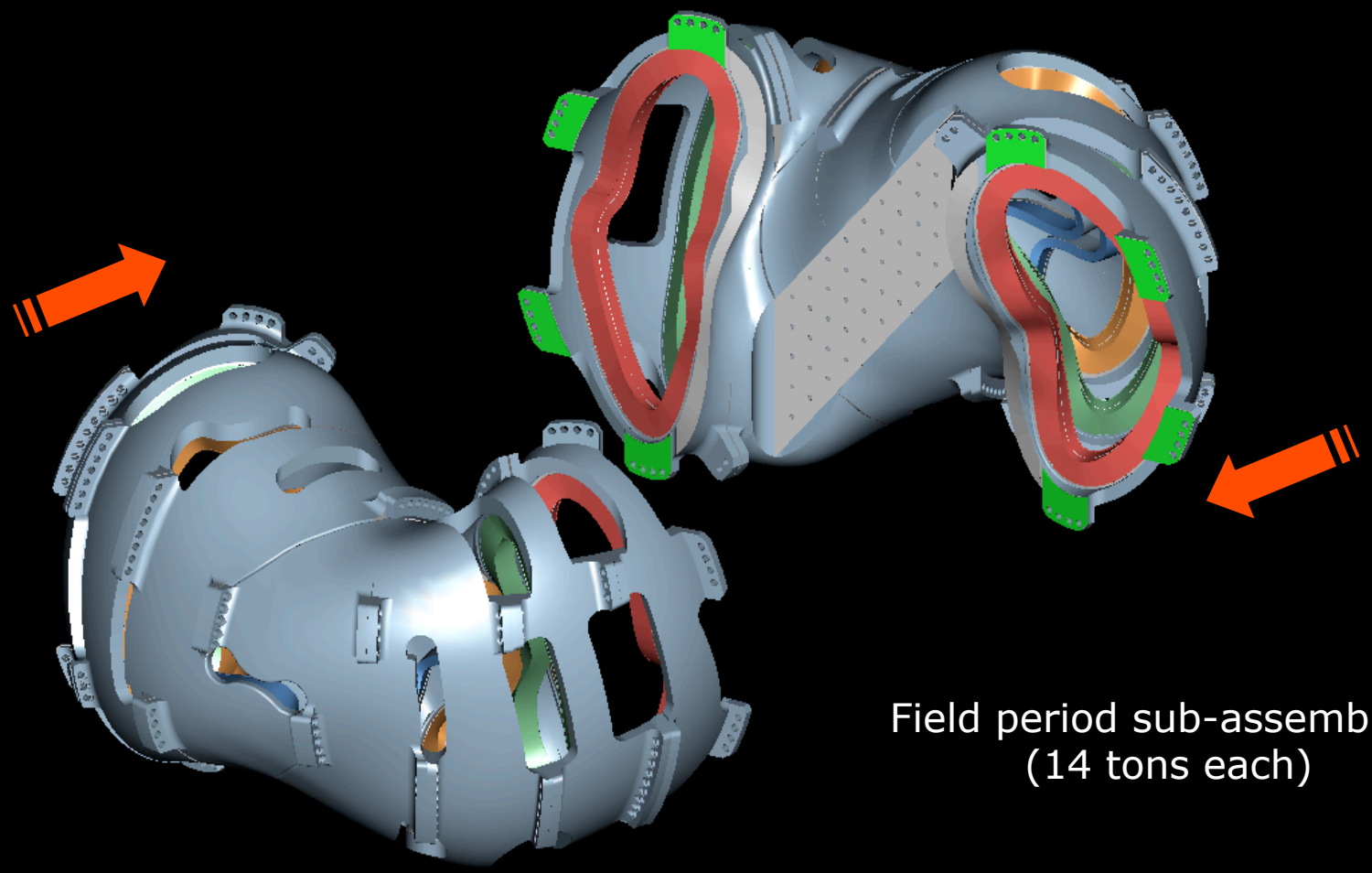
Vessel stresses checked for 1 atm load

- Stresses are within ASME B&PV limits, Sm = 19 ksi @ 300F
- Weld fillet cleans up the "hot spot" on upper ports
- Vessel within external pressure limits, FEA buckling calc. TBD



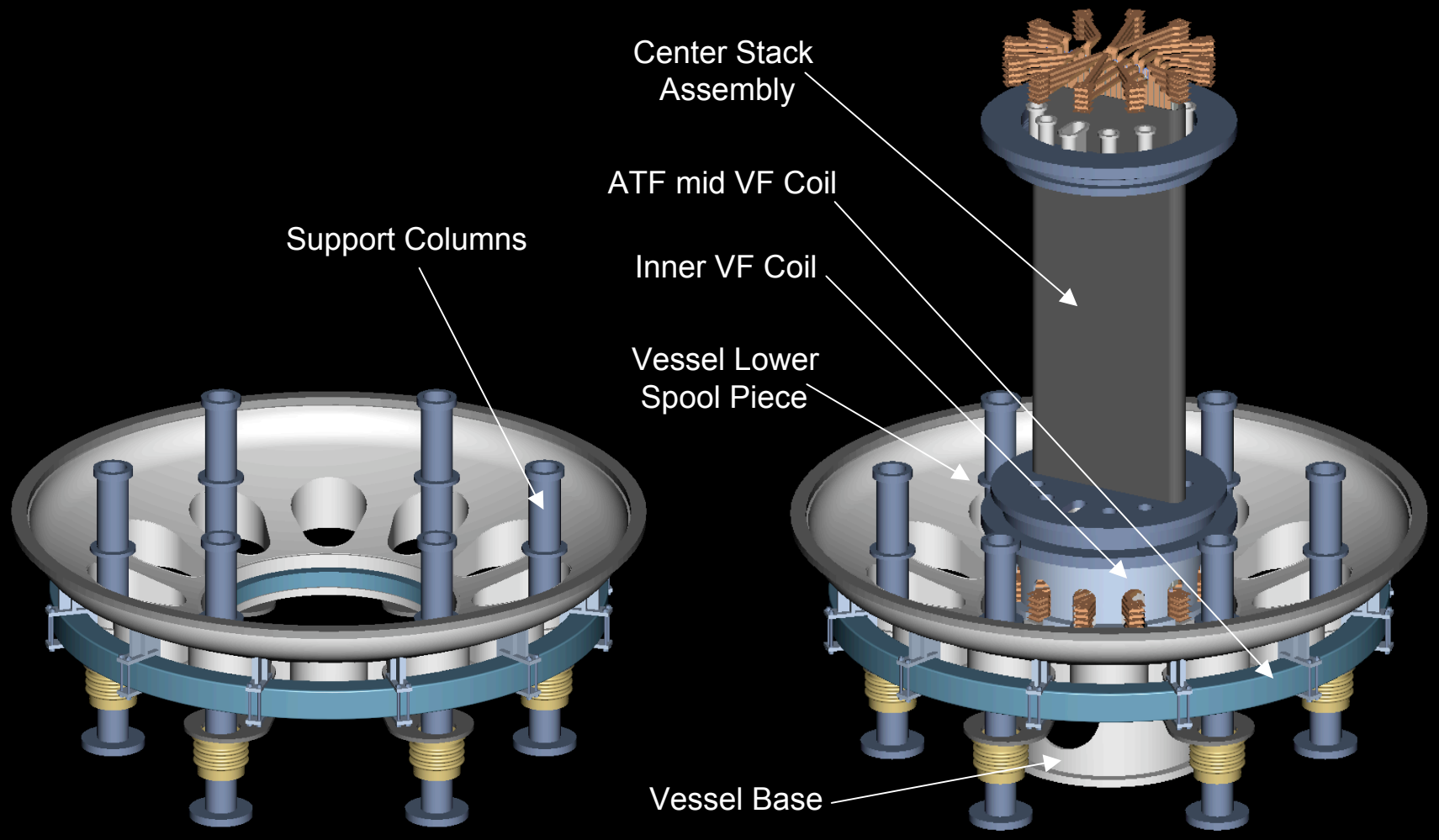
QPS Assembly

Field periods pre-assembled and fit-checked on-site

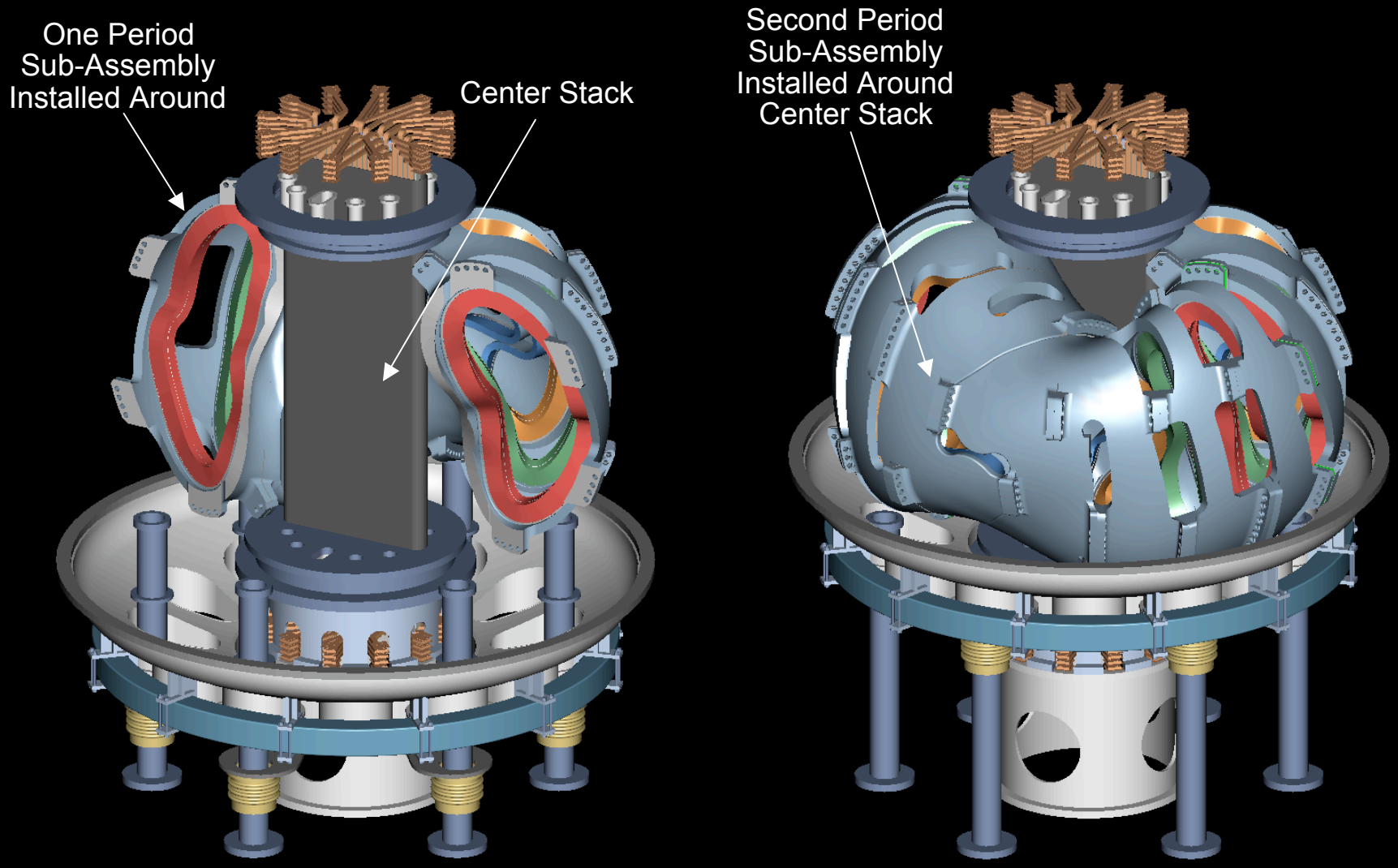


Field period sub-assemblies
(14 tons each)

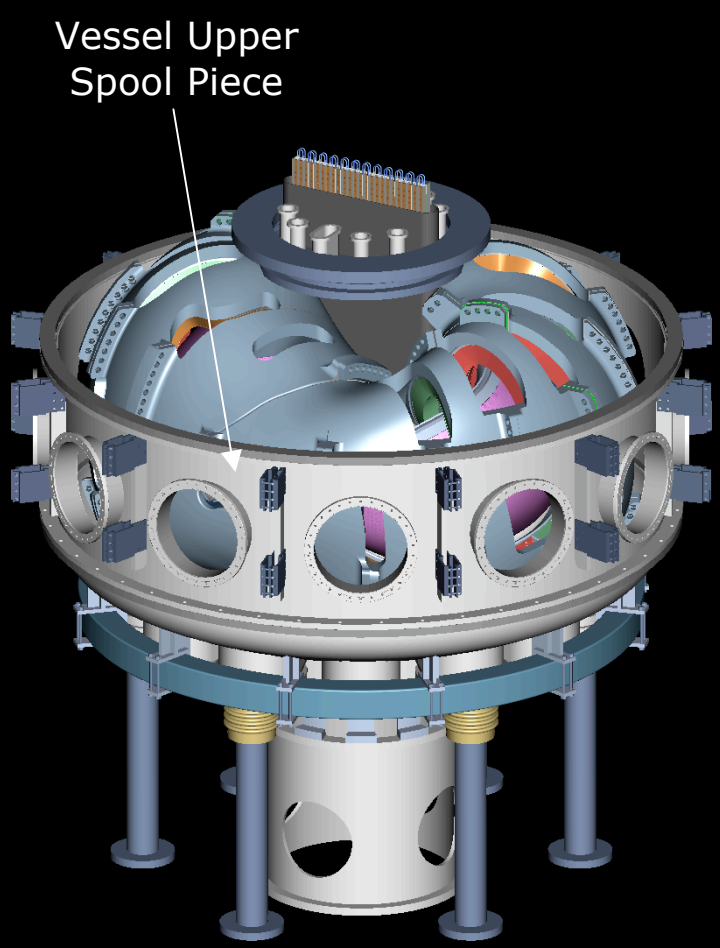
QPS Assembly sequence (cont'd)

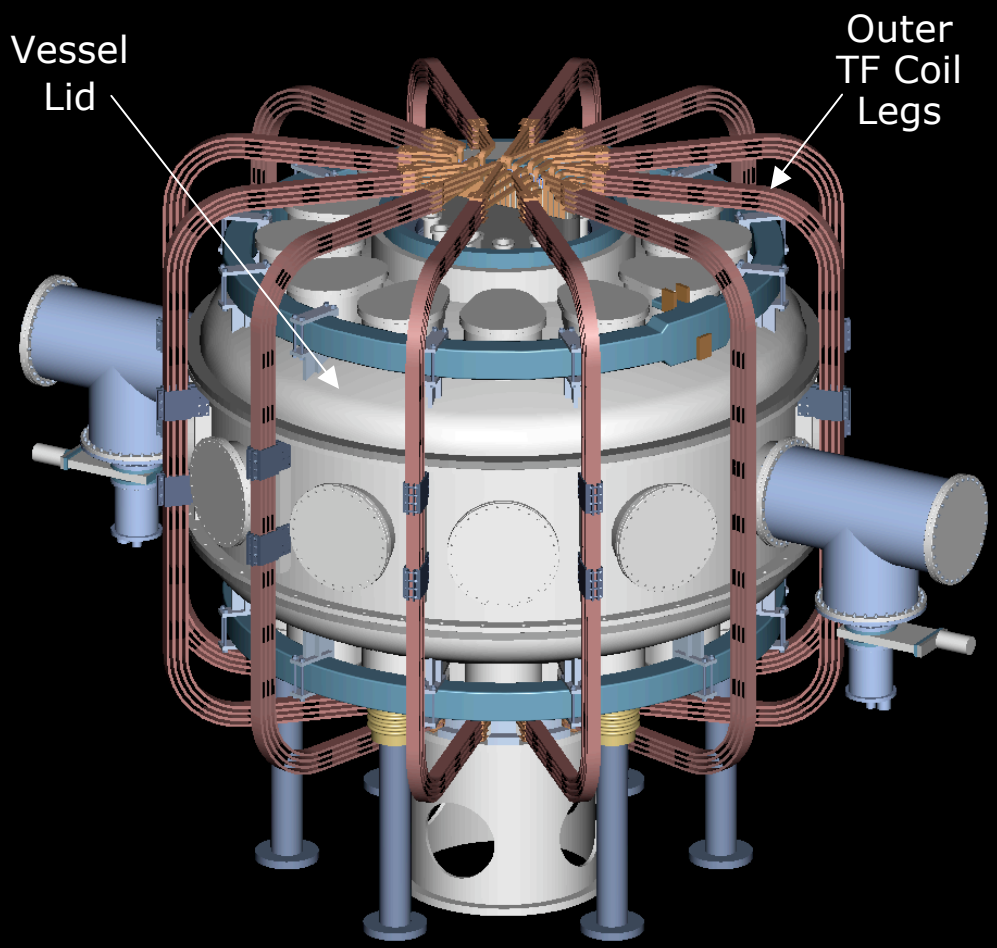


QPS Assembly sequence (cont'd)



QPS Assembly sequence (cont'd)





Conceptual design plans: refine concept, address issues

QPS

- Improve modular coil geometry
  - Try to provide more coil to coil separation in very limited areas, further optimize twist
- Improve structural design
  - Increase access opening sizes based on analysis
  - Incorporate suggestions from manufacturing studies
- Develop more fabrication details (e.g. cooling details, "canning" design)
  - Involve industry and universities to a larger extent
  - Perform manufacturing studies, limited R&D, prototypes
- Finalize design requirements
- Develop "bottoms up" cost estimates
- Refine schedule estimate

Summary

QPS

- We have a design concept that meets performance requirements
  - 16 coil, 2 period modular coil set with integrated structure
  - 1 s flat-top at 1 Tesla
  - OH, VF, and TF coil sets
  - External vacuum vessel
- We are making maximum use of existing equipment (e.g. VF coils) and facilities in order to minimize cost
- We plan to refine the design by addressing known issues prior to the CDR in April '03