Status of QOS Engineering Studies

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US-Japan Stellarator Workshop
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Presentation Outline

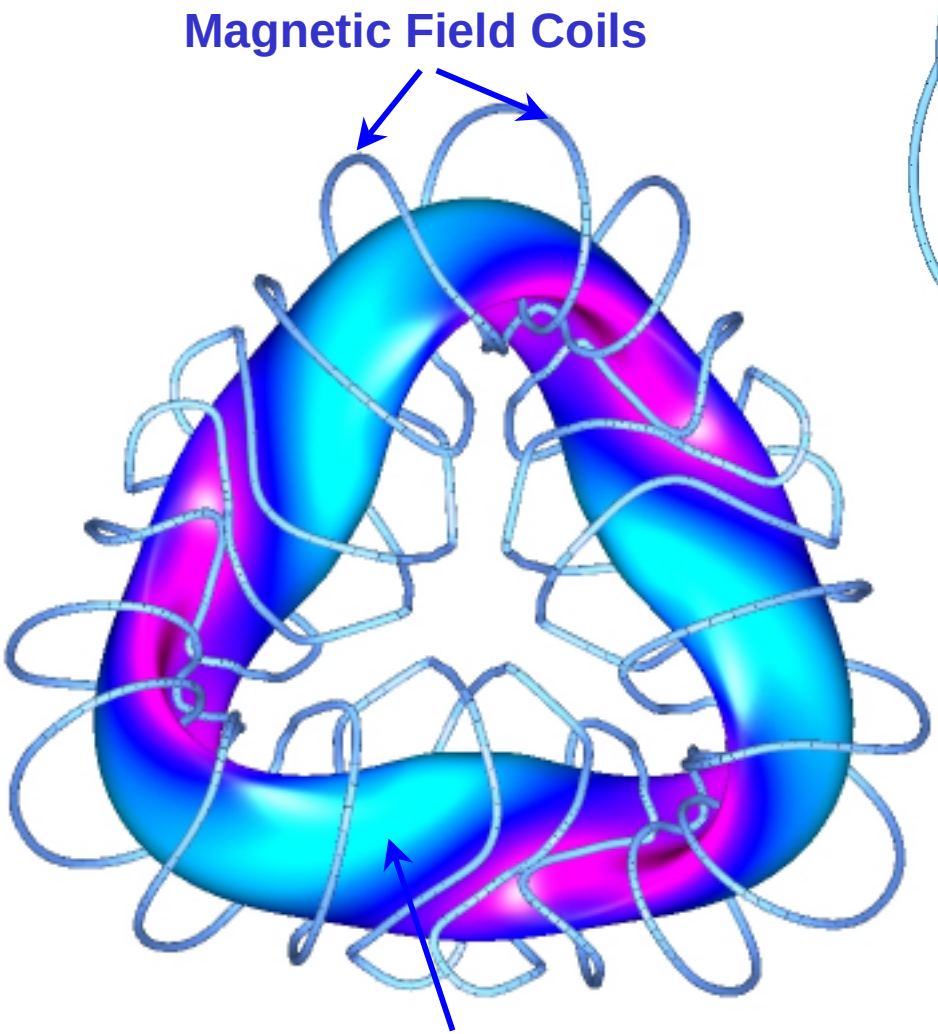
- Baseline parameters and goals
- Stellarator core configuration and evaluation
  - Modular coils, structure, vacuum vessel
  - *What is the design concept?*
  - *How do we build it?*
  - *Will it work?*
- Ancillary systems
- Next steps

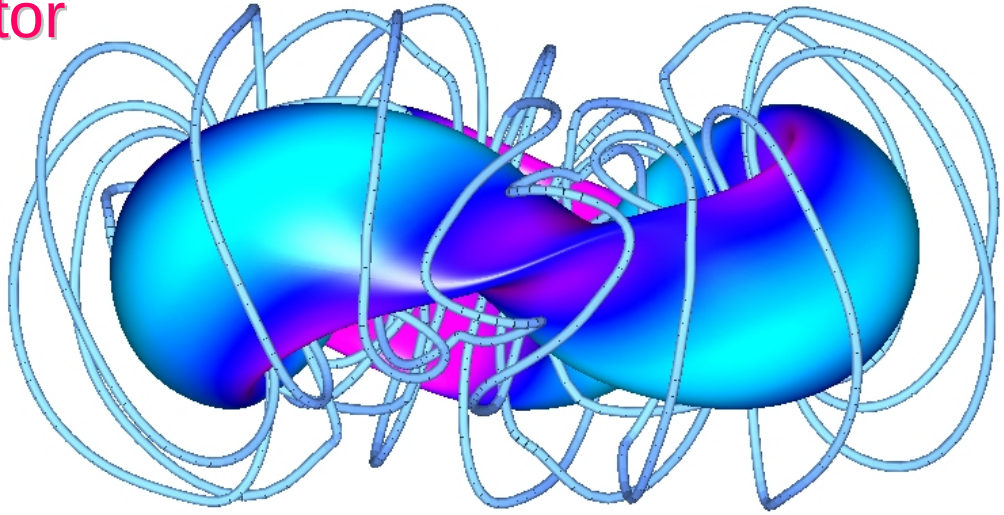
Baseline parameters for QOS design studies

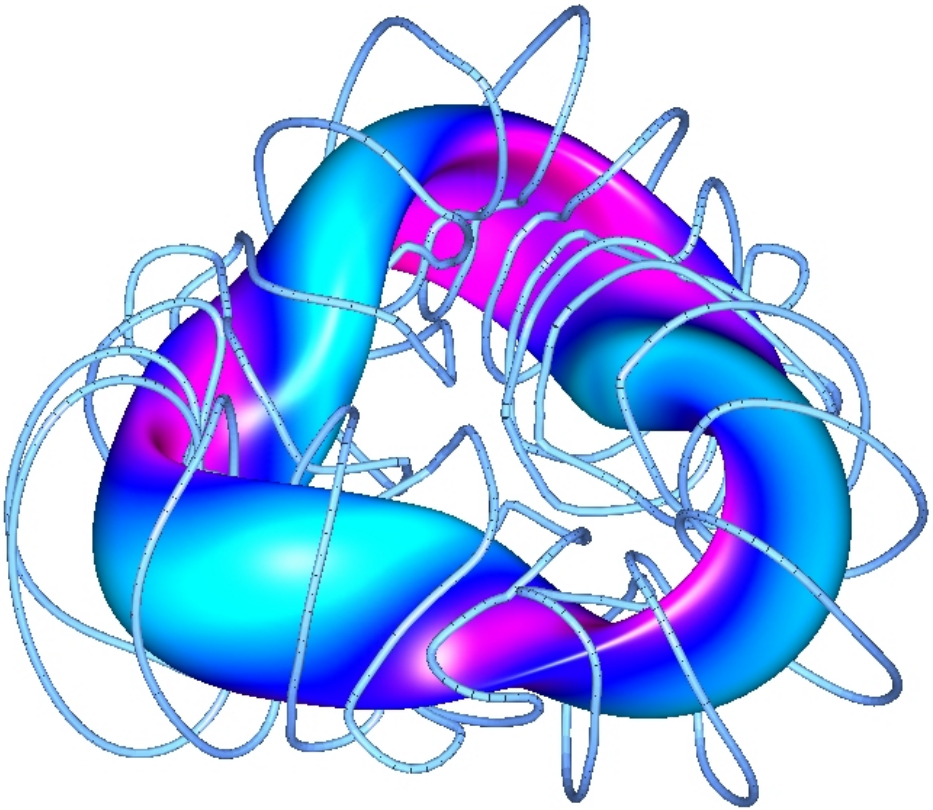
- Pre-assembled unit, consisting of vacuum vessel, modular coils, PF coils, and structure
  - Minimum cost is essential
  - Uses existing power supplies, cooling system, diagnostics, ICH antennas and power supplies, ECH system, etc.
- QOS A3.6 plasma selected for study
  - 3 field periods
  - $\langle R_0 \rangle = 1$ m
  - a = .28 m
  - $B_0 = 1$ T

3 field period compact stellarator

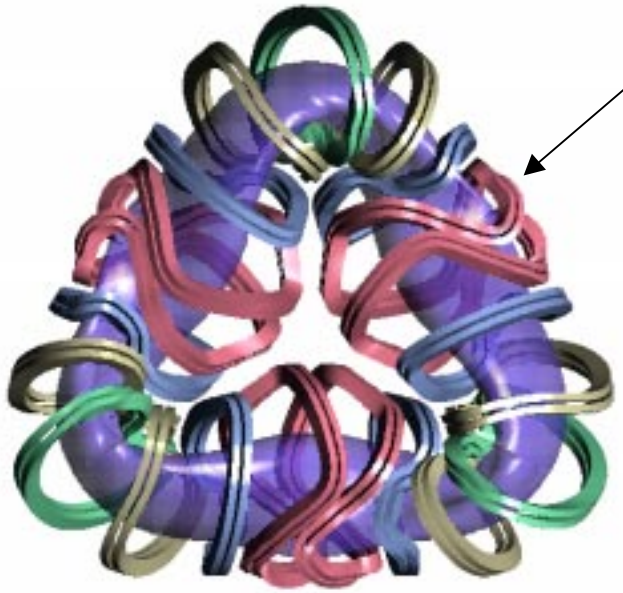
this slide courtesy of D. Spong

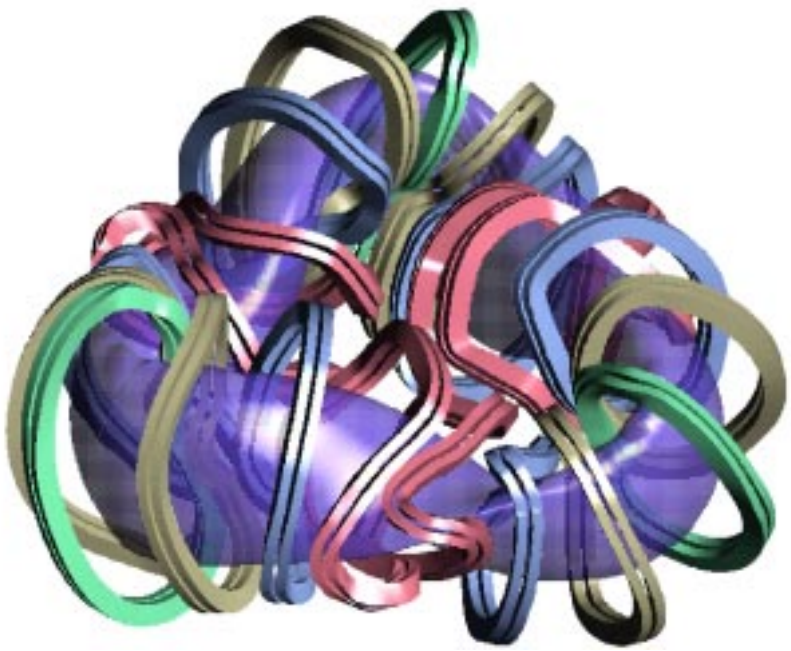


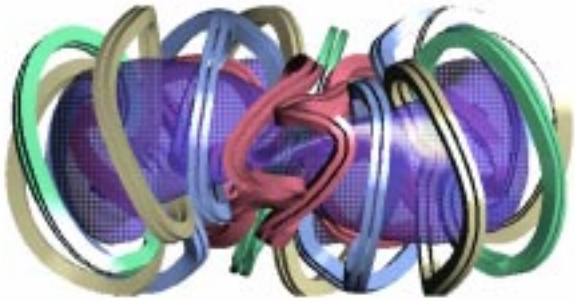




Modular Coil Design Basis / Requirements







Modular Coil set

7 coils per period, 4 types of coils

Average coil length (1-turn)	3.1-m
Min dist from plasma to coil edge	7-cm

Modular coil winding support concept

"I-Beam" provides accurate winding form and structural support

- Windings located on either side of I-Beam
- Loads transmitted to vertical webs, then to upper and lower reaction plates
- Coils can be pre-tested at full current
- Hard features can be used to measure and adjust coil position

Exploded view

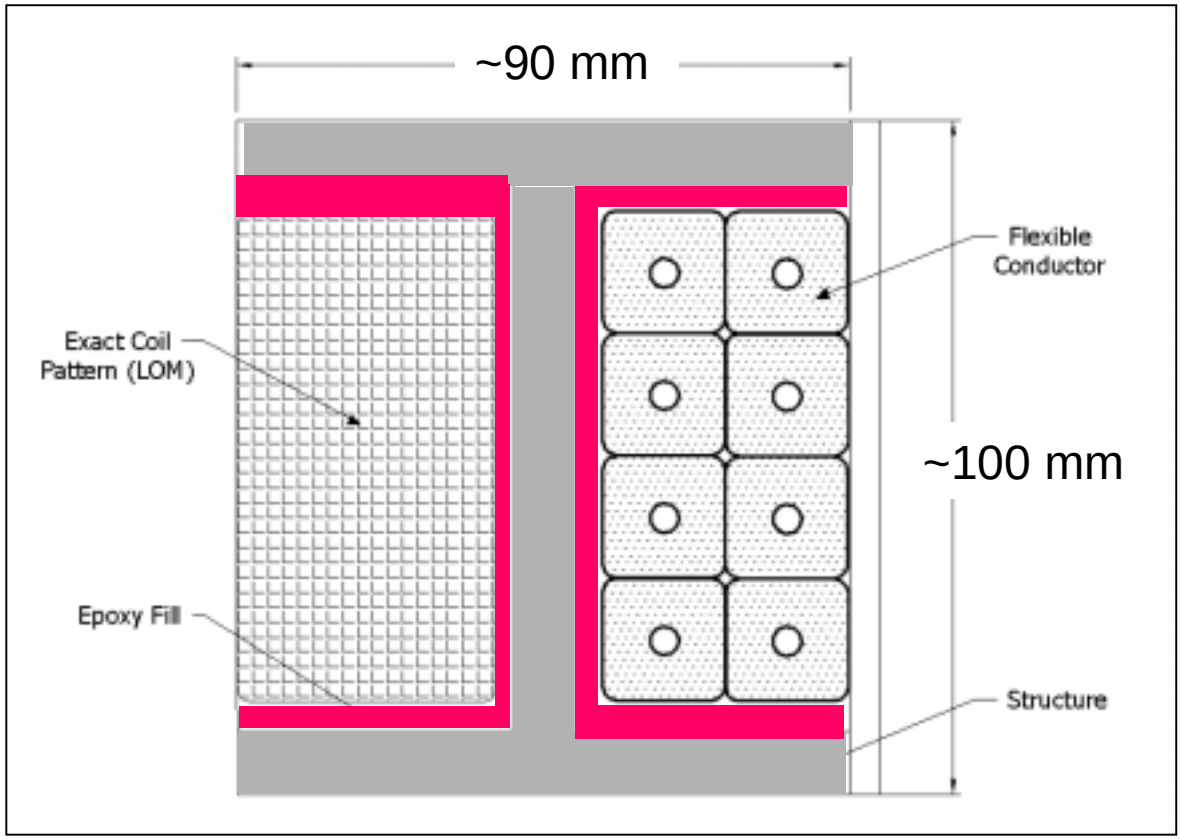
Coil 3

Assembled view

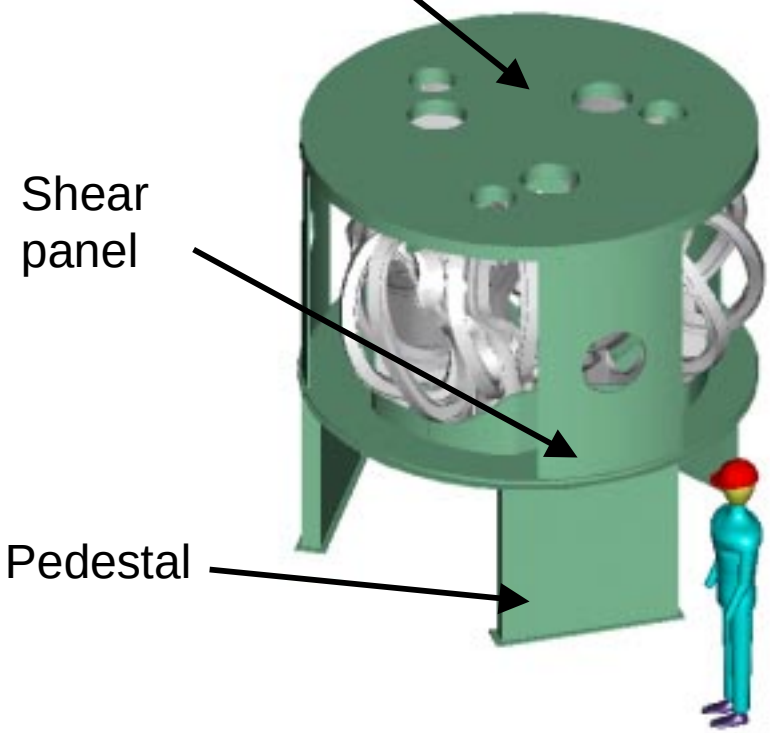
Modular coil concept

Molded winding cavity intended to minimize machining cost

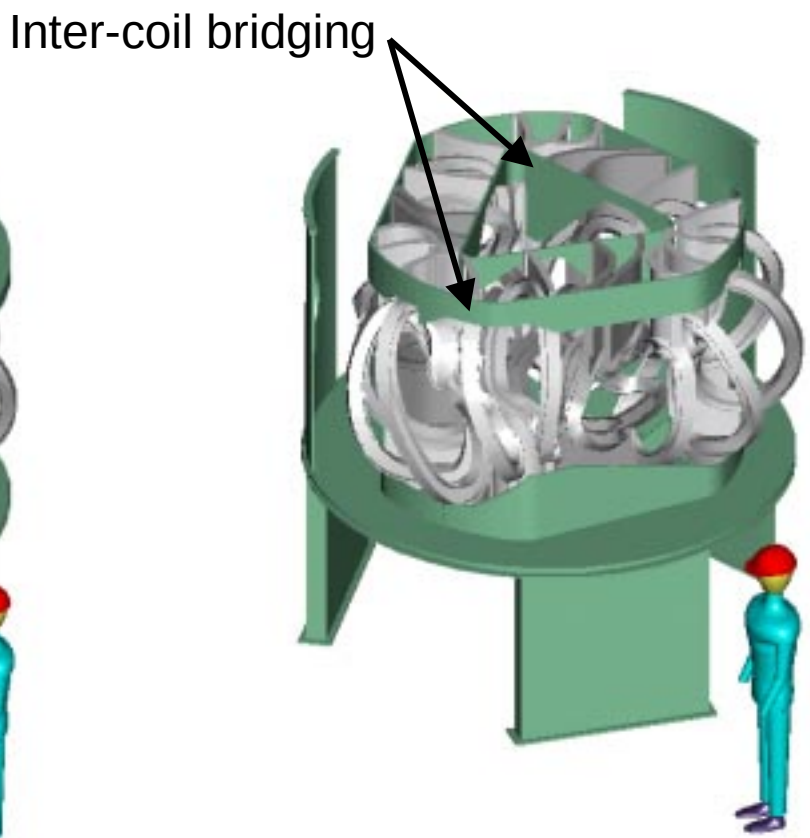
- "I-Beam" structure can be weldment or casting
- Pattern made by stereolithography is positioned in structure
- Epoxy fills void between pattern and structure
- Pattern is removed
- Accurate cavity is left to receive conductor



Support Structure Concept



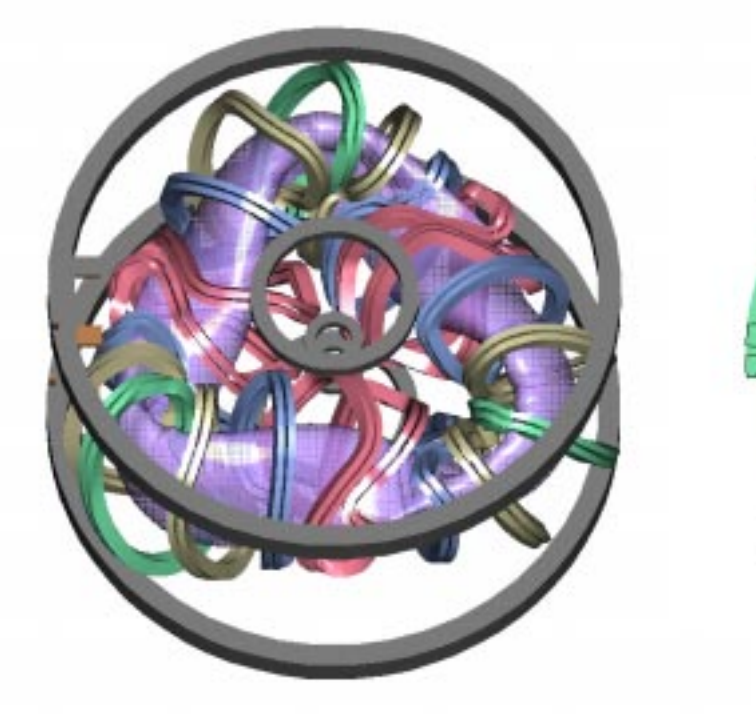
Complete structure

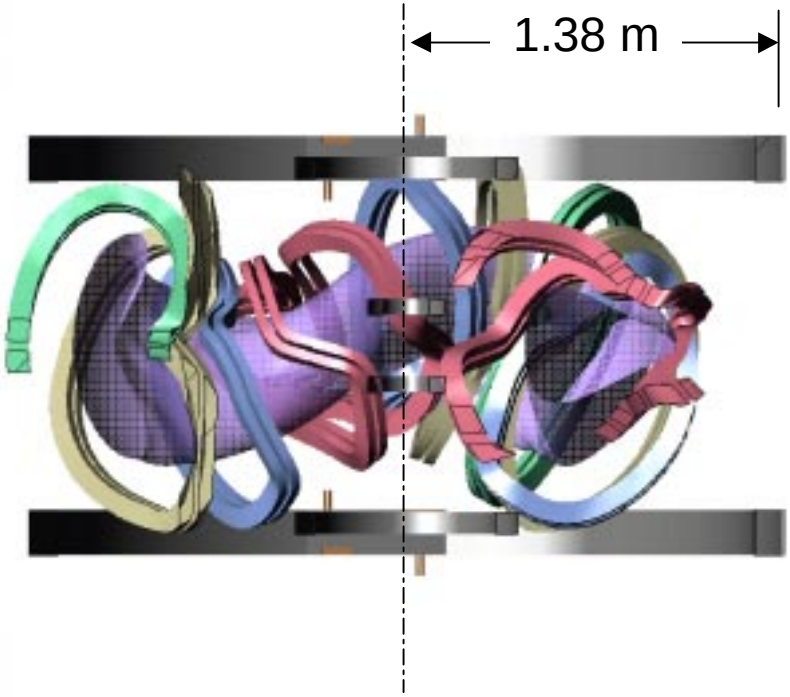


Upper reaction plate and one shear panel removed

PF Coils are also required

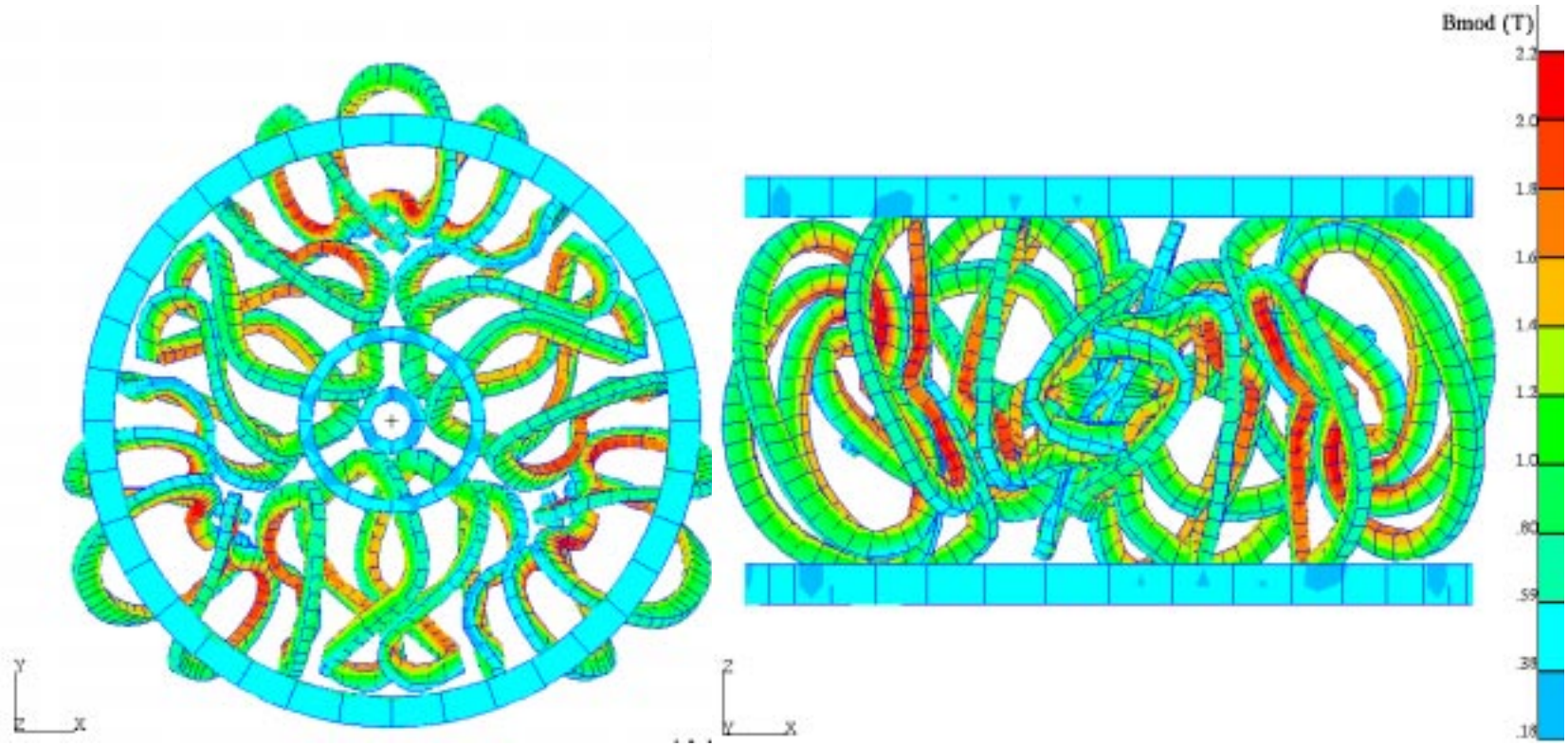
- Three sets of PF coils required for flexibility, position control
  - –Outer PF coil set exists, salvaged from ATF
  - –Inner and mid PF coils are new
- All coils would be conventional, water cooled copper





What are magnetic fields on the coil set?

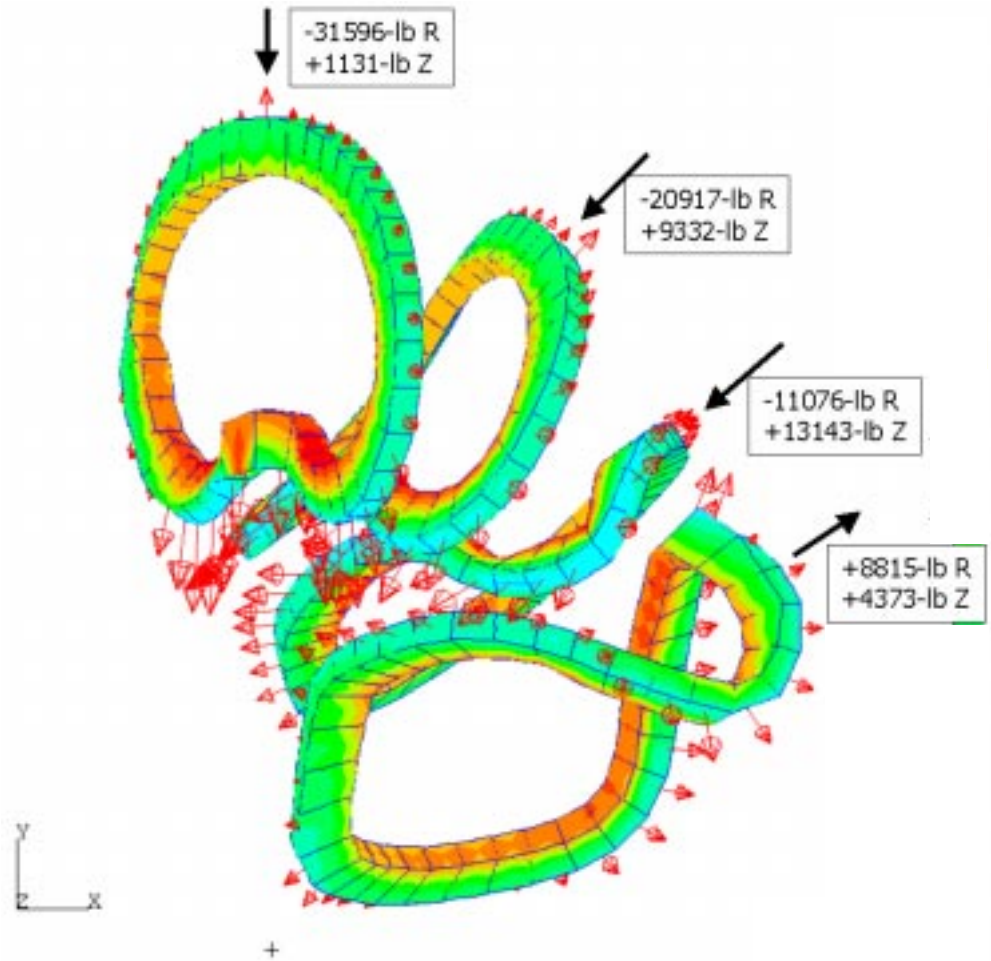
- Maximum field at coil surface is 2.2-T for parameters calculated
- Bmax/B0 ≅ 2 (~.8 to 1.4 Tesla toroidal field at plasma center)
- QOS, A3.6 coil set



Plan view

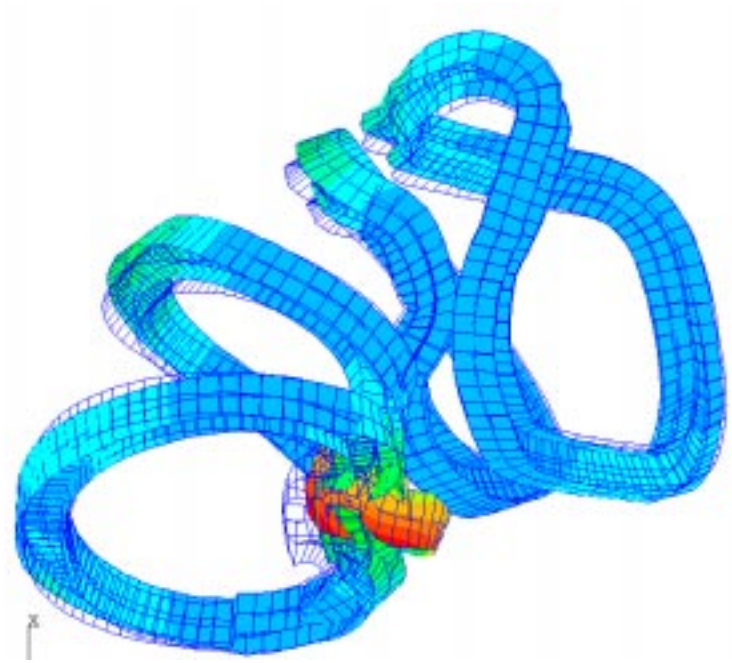
Elevation view

What are the forces on the modular coils?

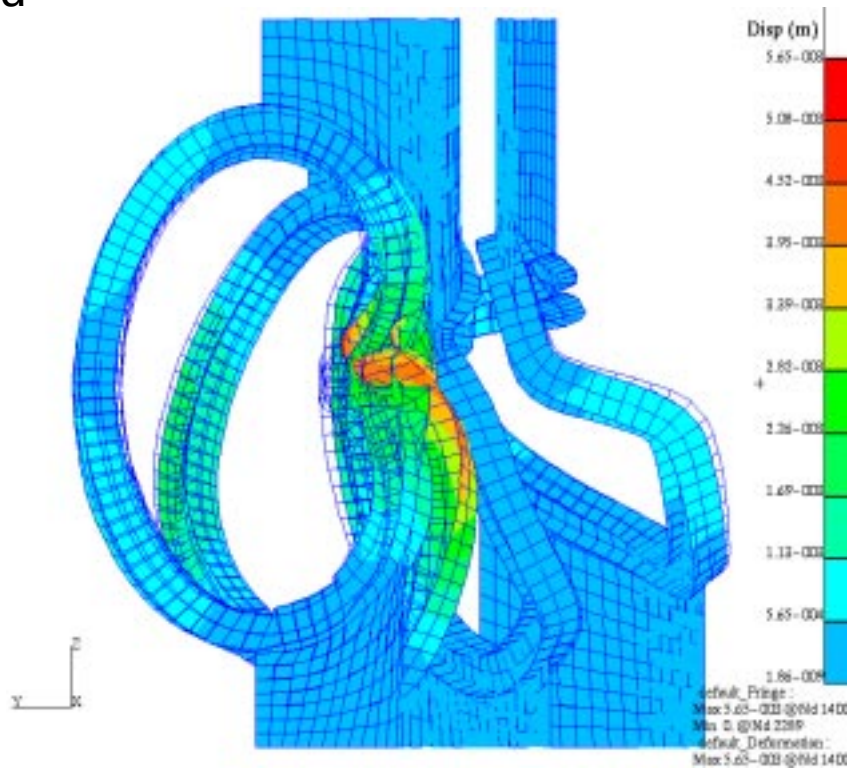


Modular Coil Deflection

- Maximum deflection is 5 mm in nose of coils 3 and 4, ~ 1 mm typically
- Structure must be locally reinforced



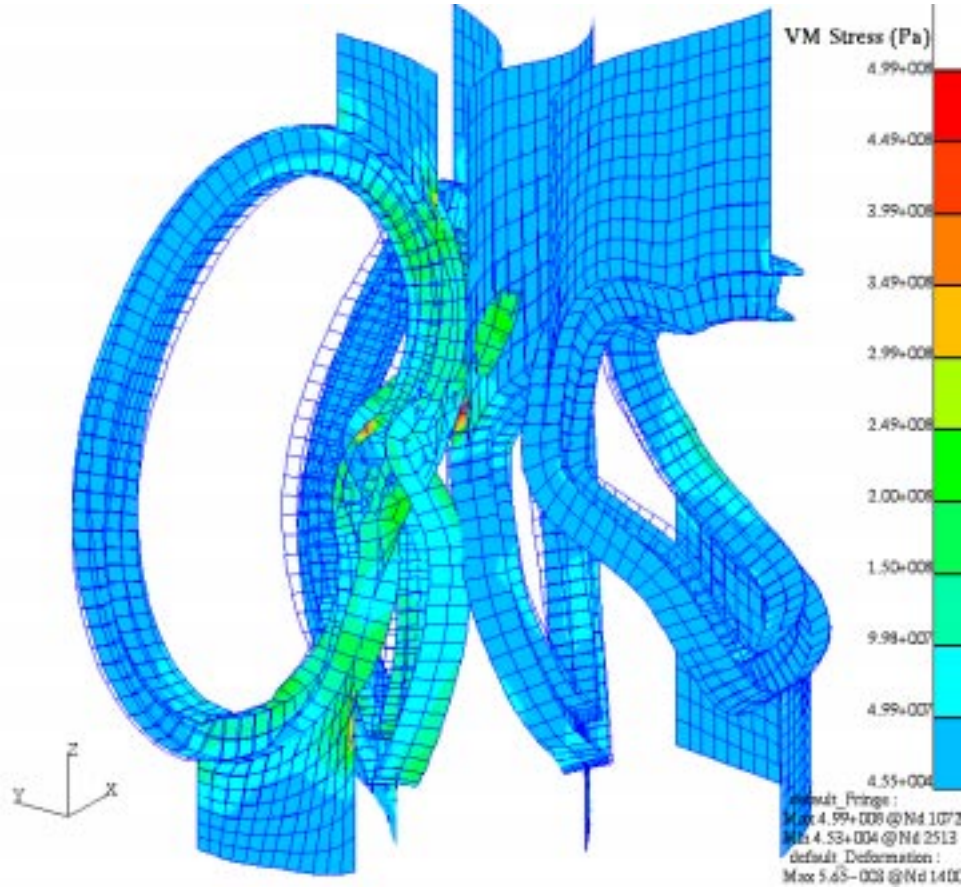
Plan View



Elevation View

Global stresses in non-optimized coil structure

- General stress < 200-Mpa for 1.2 cm section thickness
- Peak stress at inboard side of coils 3 and 4, top of coil 2 > 400 Mpa (may be partly due to modeling, point constraints)



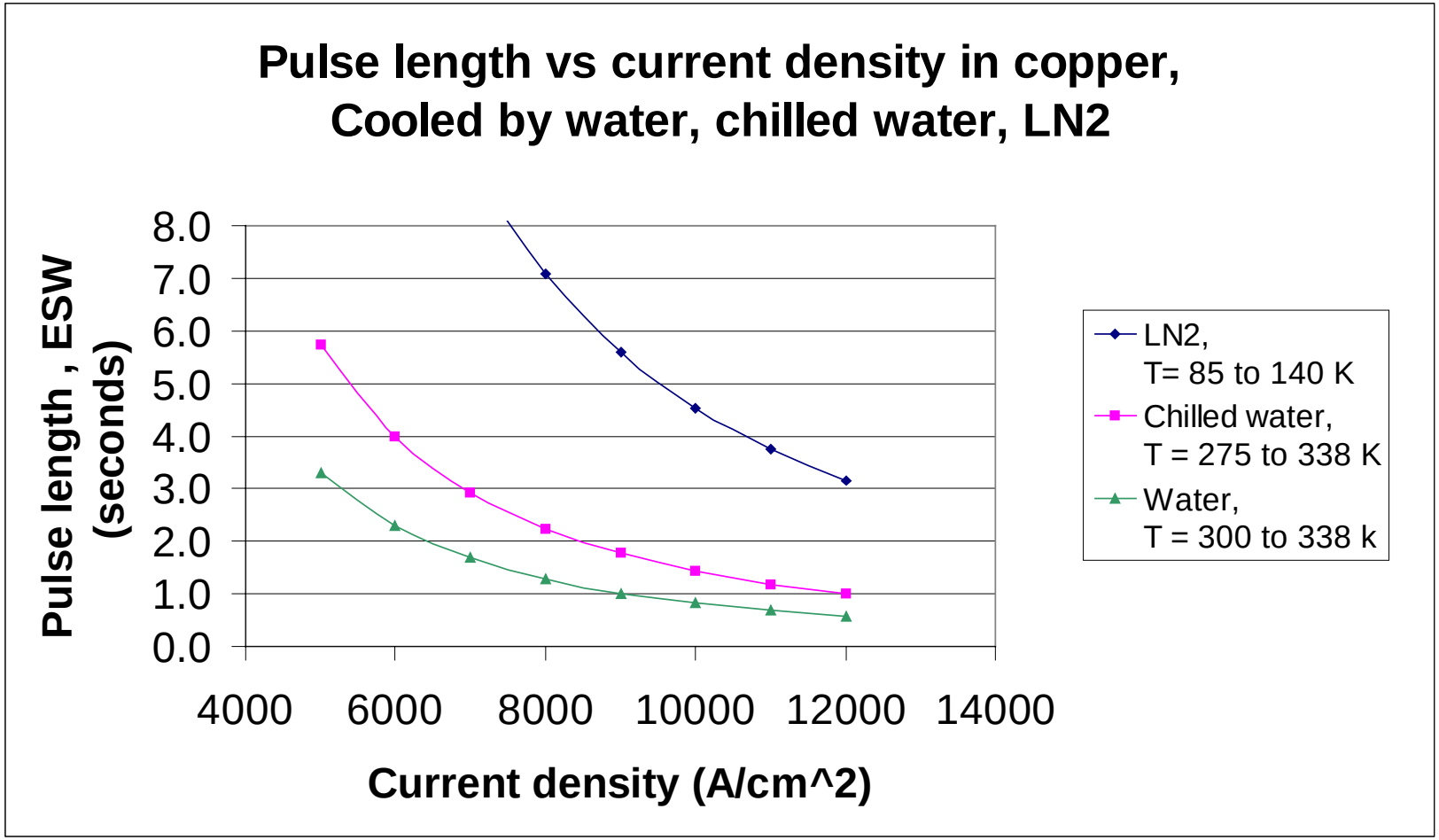
Modular coil current density and pulse length

- Current density determines pulse length for adiabatic heating

- Current density is a function of number of turns, packing fraction in braided conductor, insulation thickness, allowance for tolerance, structure dimensions, etc.

- Baseline design (A3.6)
  - Number of turns per modular coil = 16
  - Current density in copper **~10 kA/cm^2 at 1 T**
  - Pulse length for 45 C temp. rise = ~**1 second** (equiv square wave)
  - Power at end of pulse ~45 MW for coil set

Temperature rise in conductor limits pulse length



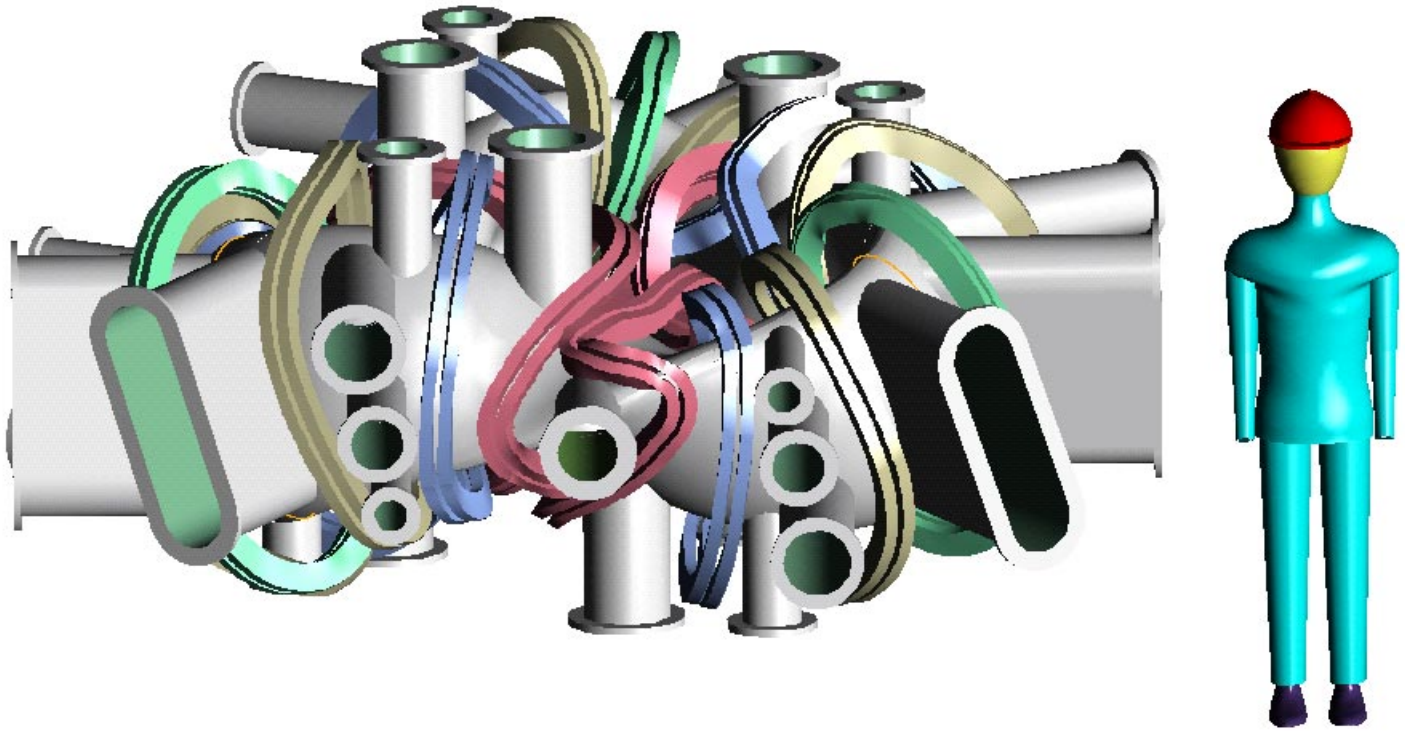
Modular coil concept issues

- Coil geometry must be optimized to include engineering constraints
  - Coil-to-coil spacing
  - Bend radii
  - Coil-to-plasma spacing

- Coil current density is high for cable-type conductor
  - “wet” cable has better cooling, but lower current density
  - rigid conductor is expensive to wind (form) into complex shapes

- Coil stresses and deflections are high, but should be readily reduced
  - section thickness, flange width can be modified locally
  - casting provides relatively simple method to add local reinforcement

Vacuum vessel fits inside modular coils and structure



Material: 6mm thick 304l SS

Ports; 6 @ ~20 cm x 70 cm, 12 @ ~20 cm dia.
+18 smaller ports

Inside surface area: 27 m^2 (with ports)

Enclosed volume: 4.4 m^3

Weight: 1400 kg(without pfc's)

Vacuum Vessel Design Choices

Material

Options -

- 316L or 304L stainless steel
  lowest material cost option
- Inconel 600 or 625
  Low permeability, higher electrical resistivity

Status - 304L is baseline

Fabrication technique

Options -

- Brake bending and welding
- Explosive forming, casting, other

Status - No choice made

Vacuum Vessel Design Choices

Assembly / Design Integration

Options -

- Two pieces per field period
  Best procurement and quality option
- Multiple Pieces (one per coil)
  Coil structure design flexibility

Status - **Two pieces per field period chosen as baseline**

Heating / Cooling

Options -

- Water/Steam
- inductive heating, air cooling

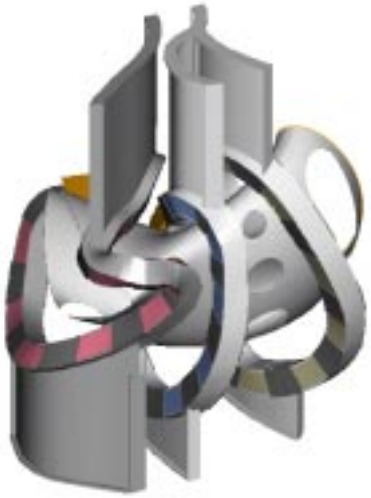
Status - **inductive heating and air cooling chosen for baseline**

Proposed Assembly scheme

Coils threaded over half period of vessel

Coil 3

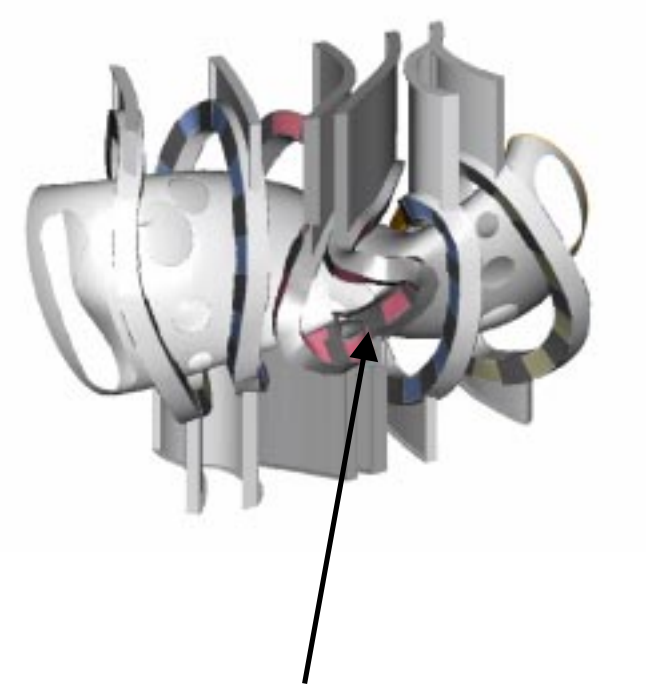
Coil 2 added



Coil 1 added

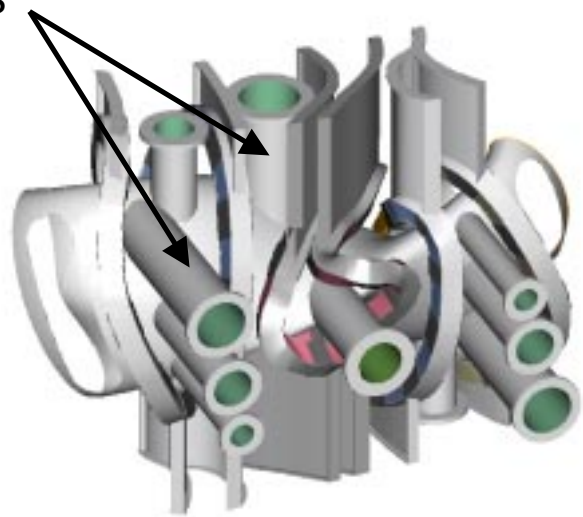
Proposed Assembly scheme

Half period sub-assemblies joined at center port to form full period



Shop weld joint

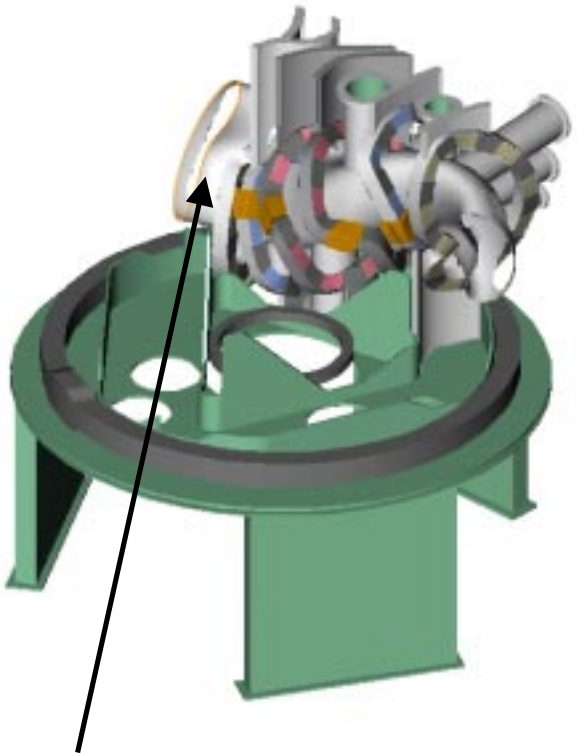
Port extensions

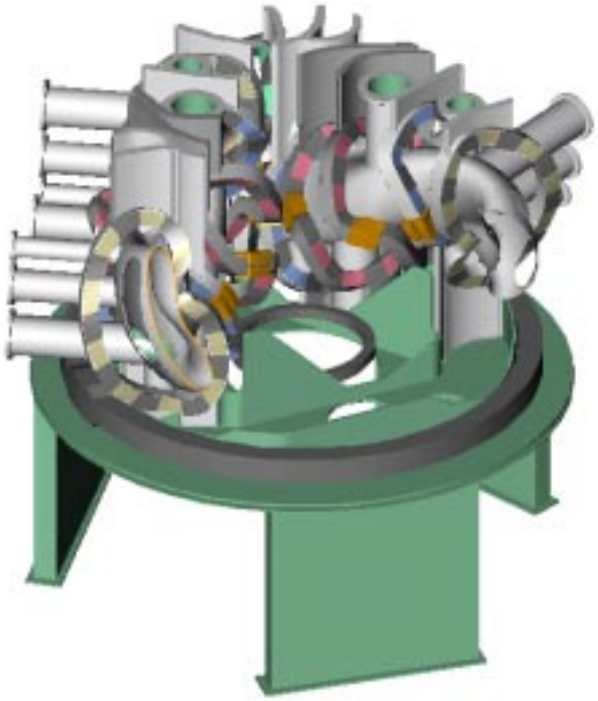


Round port extensions added to form coil/vessel sub-assembly

Proposed Assembly scheme

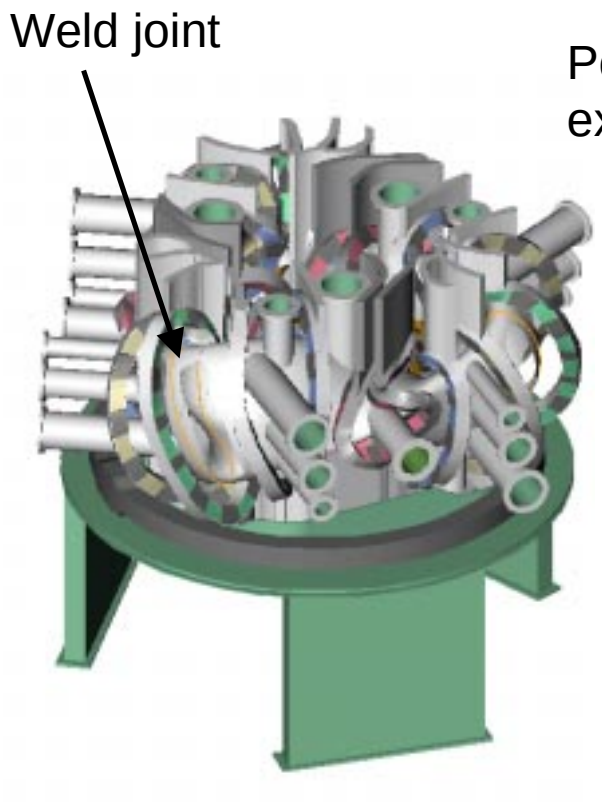
Full period sub-assemblies joined at ends port to form torus



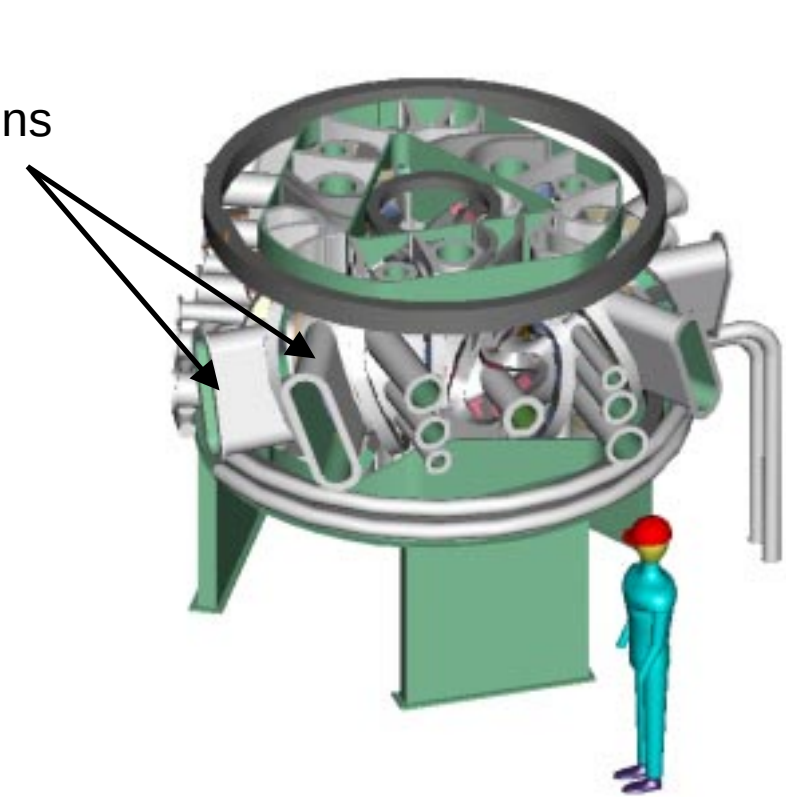


Field weld joint located under coil 4

Proposed Assembly scheme

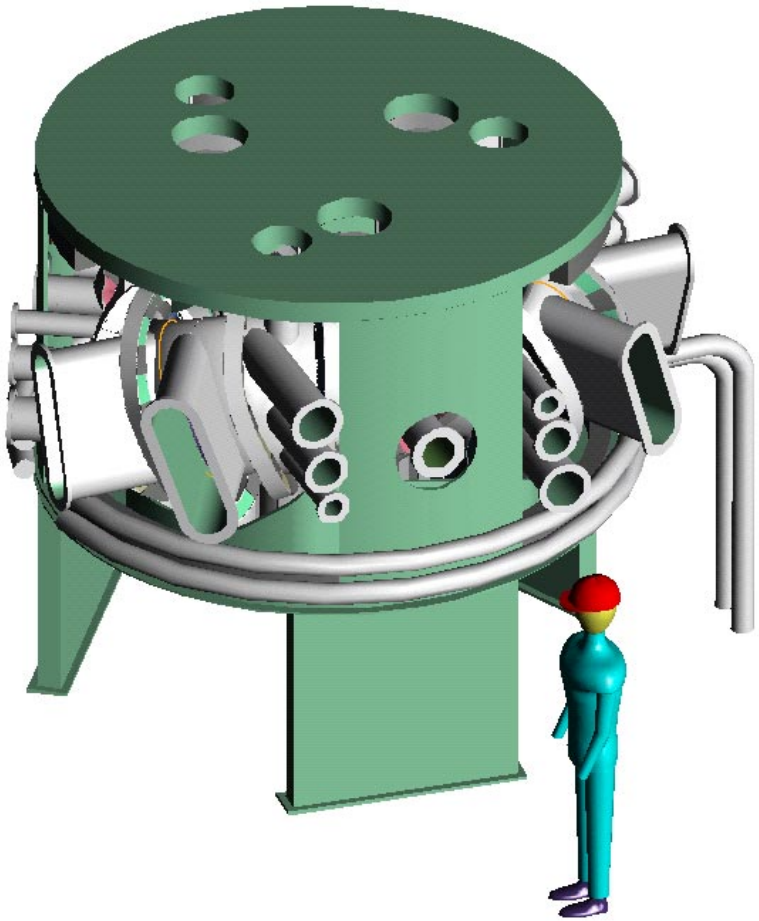


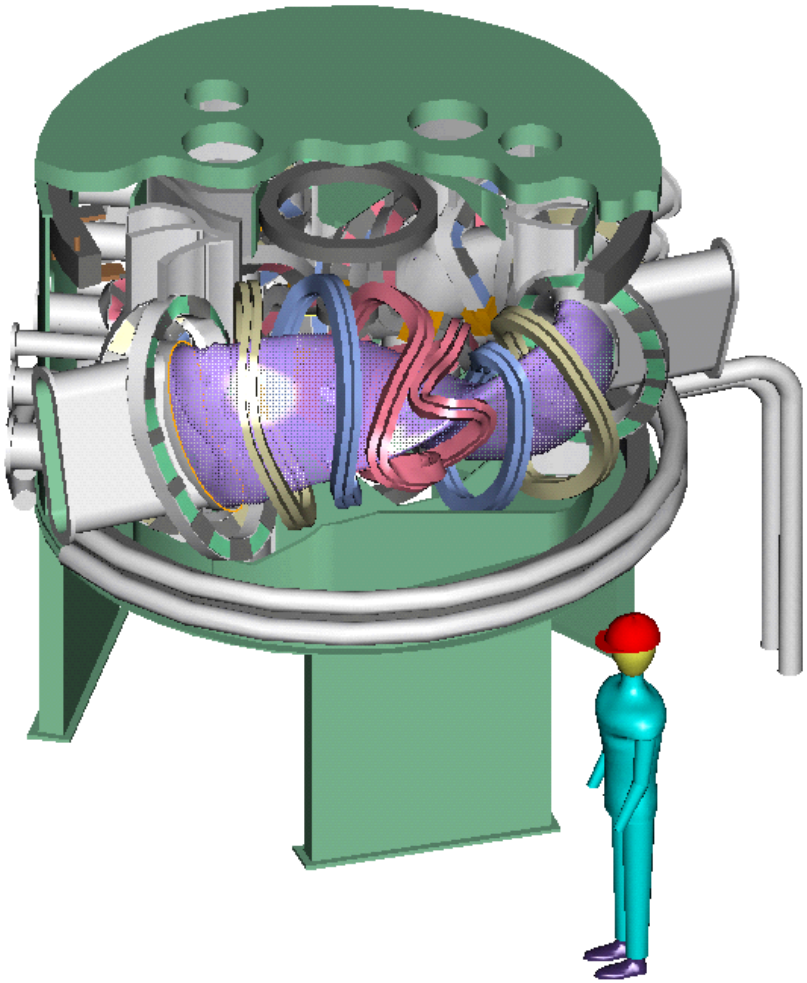
Final vessel welds made at ends of field periods



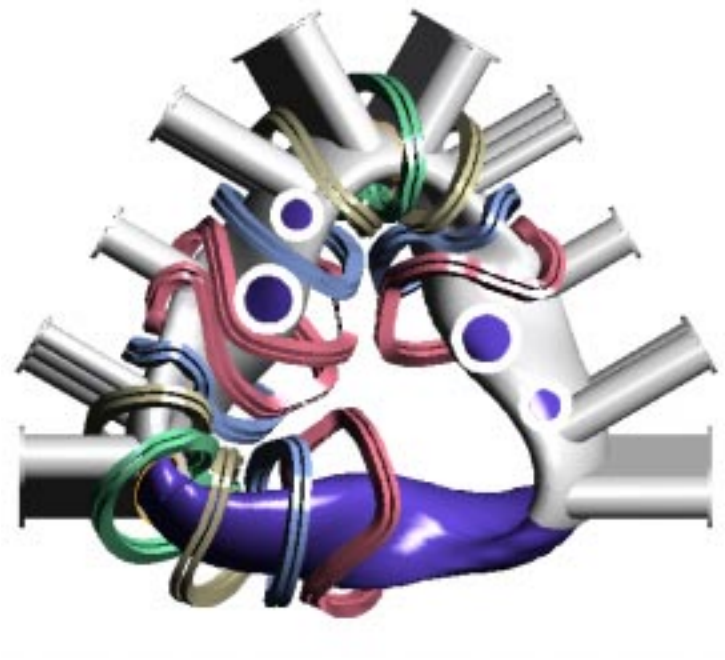
Oblong port extensions and bridging structure added to form complete coil/vessel assembly

Finished assembly

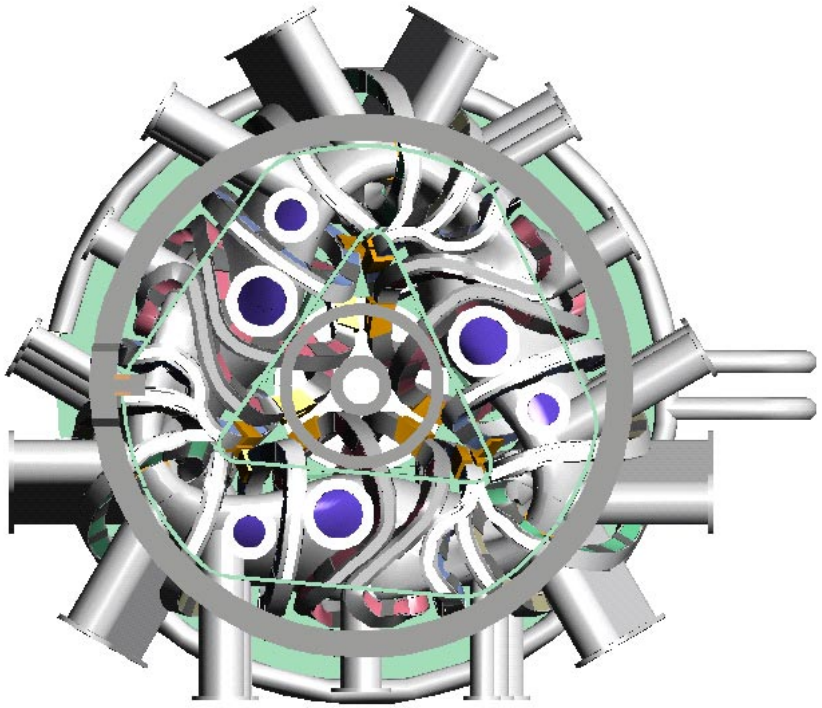




QOS design concept retains good access to plasma



Plasma, modular coils
and vessel



With structure

Heating Systems

- **ICRF**
  - –2.0 MW, 6-20 MHz, 30 second rating
  - –1.5 MW, 40-80 MHz, 30 second rating
  - –Transmission lines in place from transmitters to QOS enclosure
  - –Two, complete folded waveguide assemblies exist, could be adapted to QOS for direct electron heating

- **ECH**
  - –0.6 MW, 53 GHz, continuous rating
  - –0.4 MW, 28 GHz, continuous rating
  - –Waveguides in place to QOS enclosure
  - –2 launchers with steering mirrors available for QOS

Ancillary Systems

- **Fueling**
  - gas puffing system available and can be adapted to QOS
  - pellet injector available

- **Vacuum Pumping**
  - pumping tower and controls available from ATF
  - base pressure of 1E-9 torr for impurities and 1E-7 for H is possible using two large ports and two 2000 l/s turbopumps

- **Diagnostics**
  - 2 mm interferometer, reflectometer, Thomson scattering, various spectrometers are available
  - need magnetic loops

Ancillary Systems

- **Power supplies:**
  - modular coils: 7 solid state modules rated at 650 V, 30 kA pulsed (7.5 kA continuous)
  - PF coils: 3 solid state supplies rated at 625 V, 15 kA pulsed (~ 3 kA continuous)

- **Cooling System:** 40 MW demineralized water system, 20,000 GPM

- **Control room:** Existing ATF control room with safety ground

- **Safety enclosure:** Existing ATF enclosure with 2 x 20 T crane access

Engineering feature summary

- Modular coil concept intended to minimize cost:
  - flexible conductor wound by hand on integral support structure
  - molded winding cavity avoids expensive contour machining
  - coils threaded over six identical vessel segments

- Machine designed for maximum access
  - Ports include: 6 @ ~20 cm x 70 cm, 12 @ ~20 cm dia., +18 more
  - Coil structure does not interfere with access ports

- Maximum use made of existing equipment and facilities
  - Power supplies, control room, safety enclosure, cooling system
  - Heating, fueling and vacuum pumping systems
  - Diagnostics (TBD)

Status of Engineering Activities
Issues addressed so far (to some extent)

- Modular coils: Geometry, fields/forces/stresses, cooling/pulse length, structural support, power supply matching, fabrication ideas
- PF coils: Geometry, re-use of ATF coils
- Vacuum vessel: Geometry, fabrication ideas, access port layout, cooling/heating, pumping
- Heating and diagnostics: Use of existing equipment, power supplies
- Cost and schedule: ROM tabulation, logic

Status of Engineering Activities
Issues not yet addressed

- Modular coils: Fabrication tradeoffs, location accuracy, lead layout, optimized structure, fault conditions
- PF coils: Stresses, structural supports, fault conditions
- Vacuum vessel: Stress analysis, fabrication tradeoffs
- Heating and diagnostics: diagnostic layout, magnetic loops
- Cost and schedule: vendor quotations, durations

Summary and Conclusion

- **We have selected a baseline design configuration and fabrication concept for further study**
  - Water cooled copper braid wound into molded cavities on steel forms
  - Contoured vacuum vessel with maximum port access
  - Maximum re-use of existing components and facilities

- **Baseline design developed around A3.6 coils is workable**
  - ~1 second flat-top at 1 Tesla
  - Structure needs reinforcement / optimization

- **Coil set is still evolving**
  - Coil geometry will evolve as engineering constraints are identified
  - Coil groups working to optimize coils for physics and engineering constraints

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Backup slides

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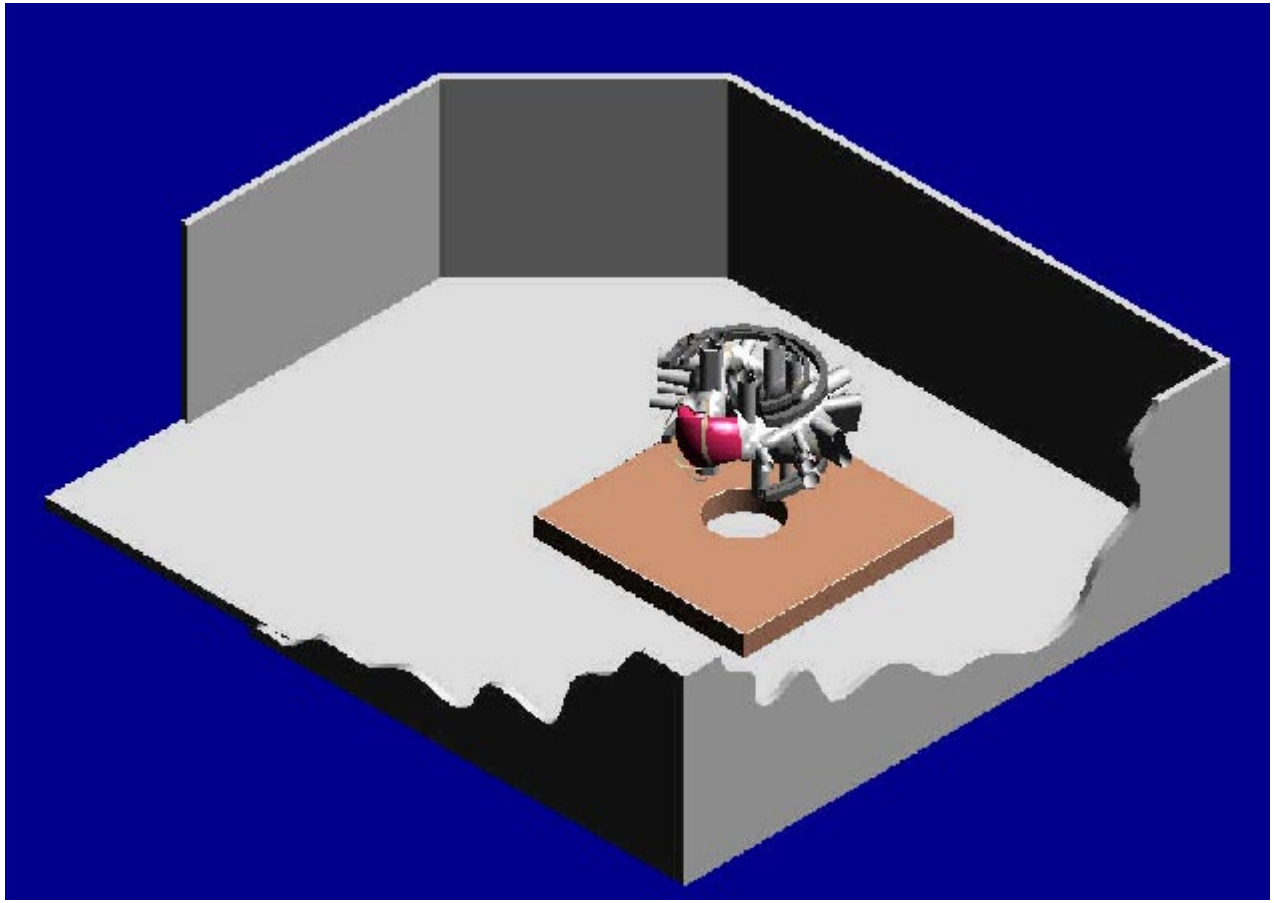
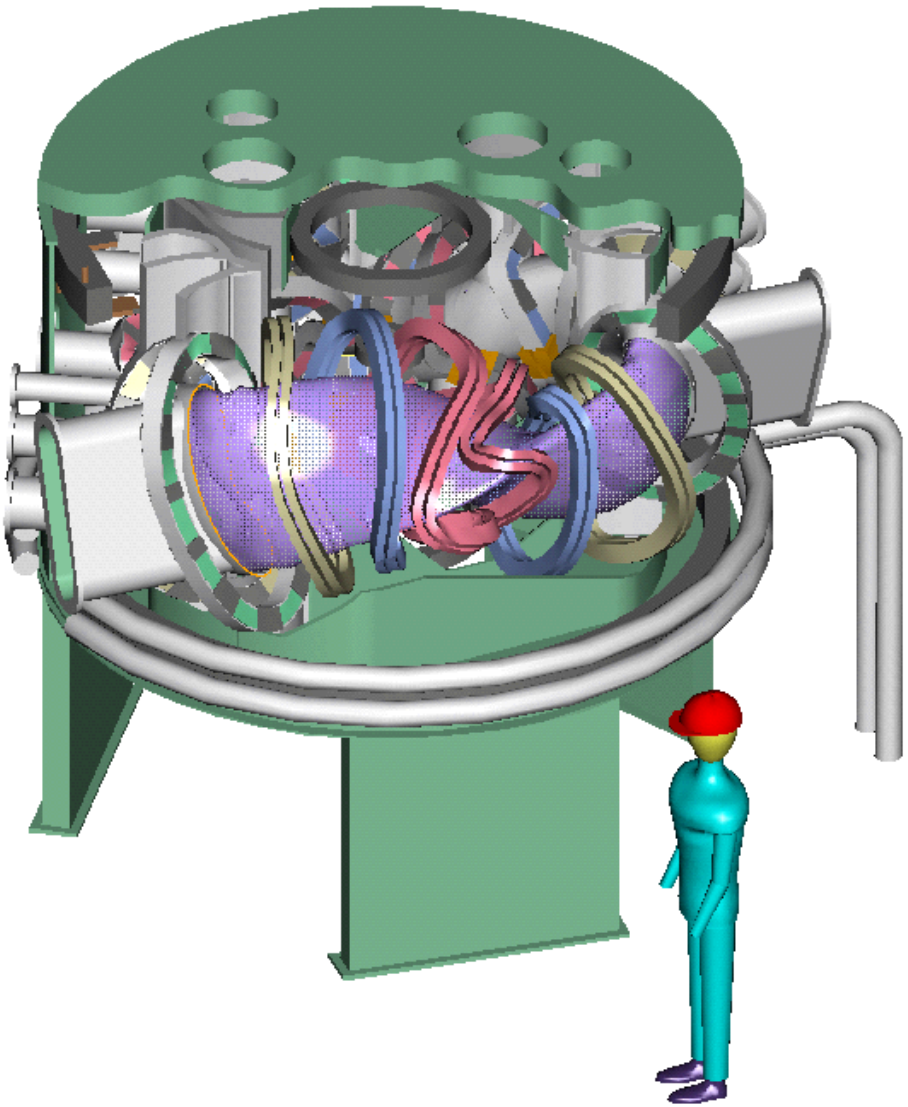
QOS in the ATF Facility



Proposed QOS Design Concept

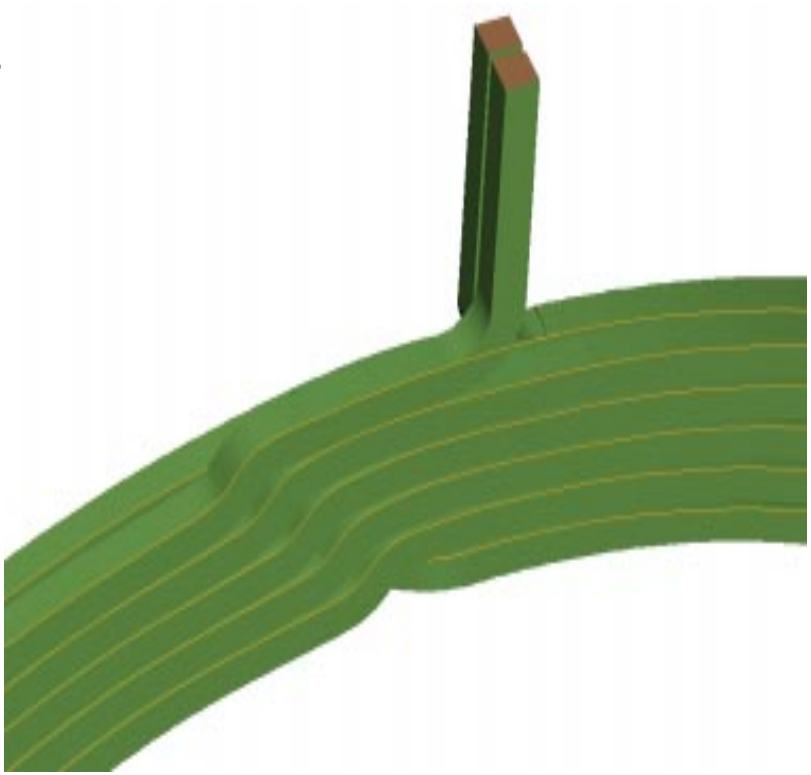
- Modular coils with integral local structure
- Upper and lower reaction plates
- 3 sets of PF coils
- Plasma-shaped vacuum vessel



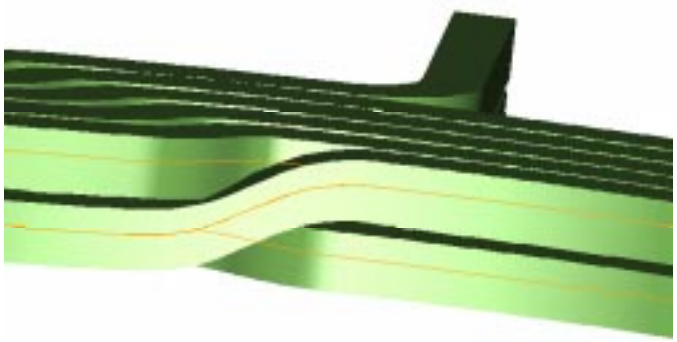
Coil Crossovers and Leads

- Single pancake winding on each side of "I-beam"
- occurs in a pocket on the plasma side of
- Layer-to-layer transitions overlap
- Leads transition to coaxial configuration

Leads



Turn-to-turn joggle

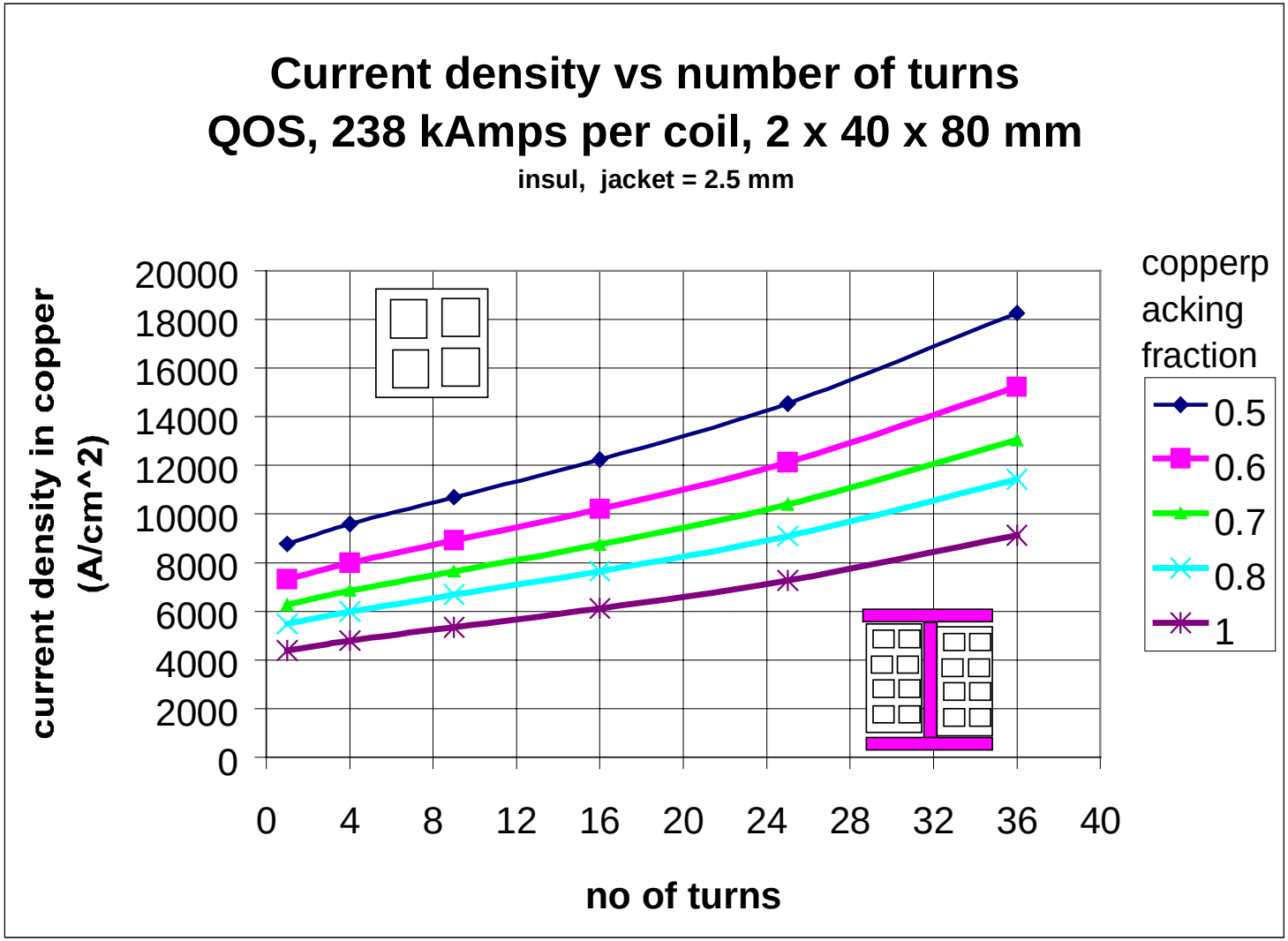


Crossover

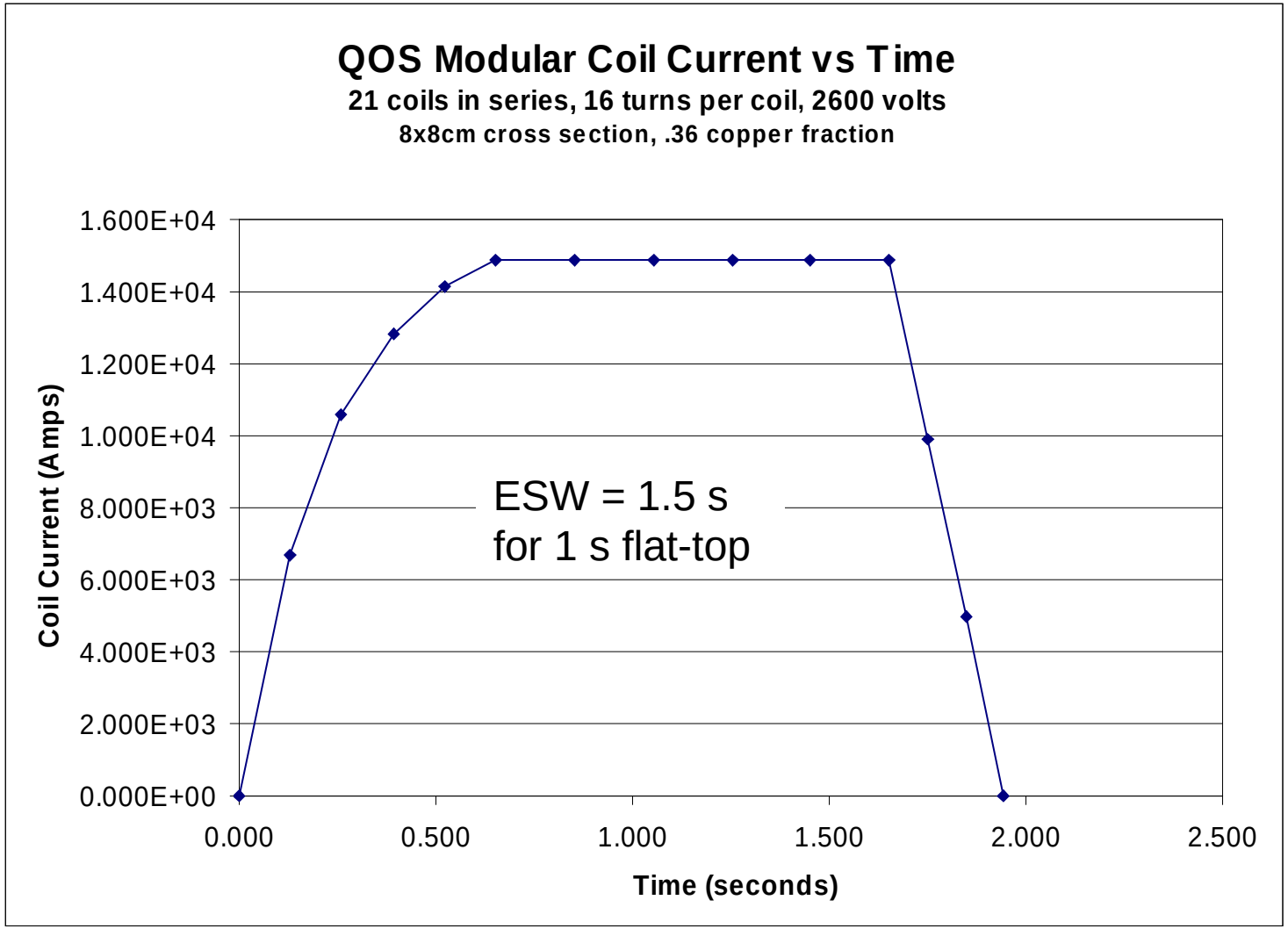
Vacuum Vessel Parameters/Performance

• Total heating power (upgraded)	3.6 Mw
• Average plasma flux	12.5 w/cm^2
• Bake out temperature	150 c
• Operating temperature	20-100 c
• Temperature rise during pulse	5.5 c/sec
• Thermal growth during bake out	3 mm radial
• Pulse duration, goal	4 seconds
• Cool down time between shots	10 minutes

Current Density depends on winding details



Coil parameters, power supply determine pulse waveform



Modular coil thermal parameters

- 238 k-Amp per coil for nominal 1 Tesla operation
- 16 turns per coil, ~3.1 m per turn (.75 MA-m per coil)
- 2 winding packs @ 40 x 80mm cross section
- Cabled conductor with 60% packing fraction and 6mm hole
- Current density in copper ~10-kA/cm2 at 1T
- Approximately 1-s ESW pulse length, 20-45 C temperature rise
- Cool-down in < 10-min with 0.6 m/s water velocity

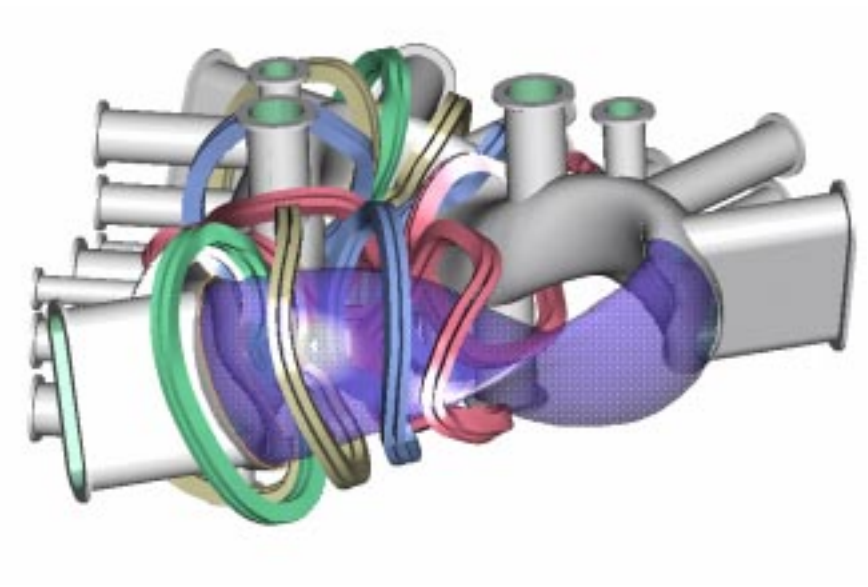
Modular Coil Concept

Design Choices

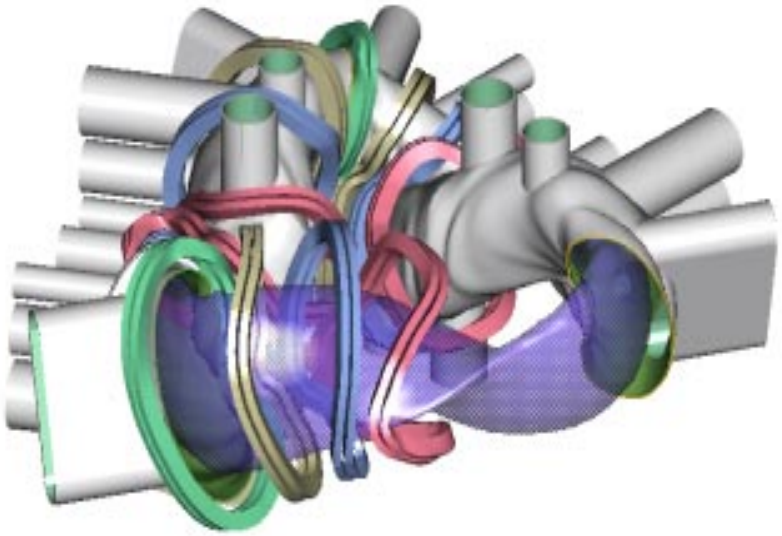
Element	Options	Preference (so far)
Material (Structure)	• Stainless Steel • Aluminum • Bronze	Stainless Steel
Fabrication Technique	• Casting • Welding	Casting
Winding cavity fab.	• machining • molding	molding
Winding process	• Hand lay-up	Hand lay-up
Coil Construction & Leads	• Flexible wet cable • Flexible dry cable	Flexible wet cable
Side Closure	• Welded Cover Plate • Bolted Cover plate	TBD
Cooling	• RT water •Chilled water	TBD

Vacuum Vessel Configuration

- Vessel geometry will be expanded toward coils, away from plasma
- Offset from plasma will be non-uniform



Baseline shape



Expanded shape

Vacuum Vessel Design Choices

W 7 - AS/X Fabrication

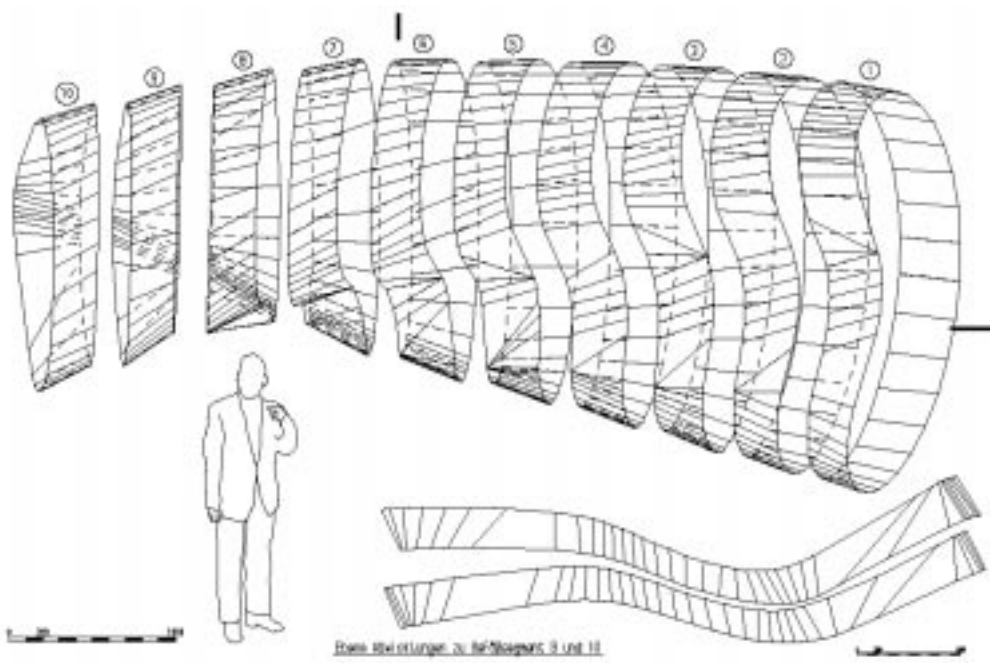


Fig. 5. Design principle of the outer and inner vacuum vessel for the W7-X cryostat.