ARIES-CS Coil Configuration and Structural Design

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and the ARIES-CS Team

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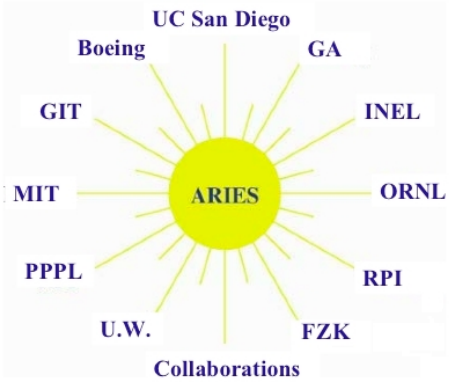

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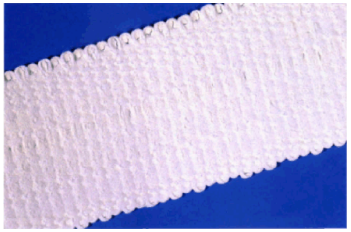
Outline

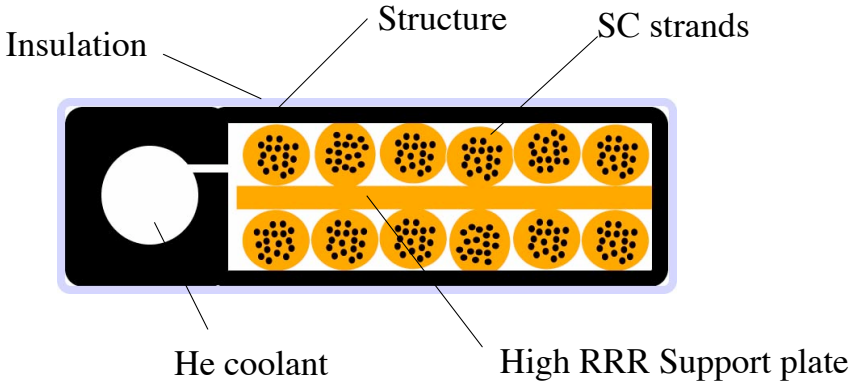
- Coil Configuration
- Coil Structure
  - Concept
  - Analysis
  - Advanced Fabrication
- Summary

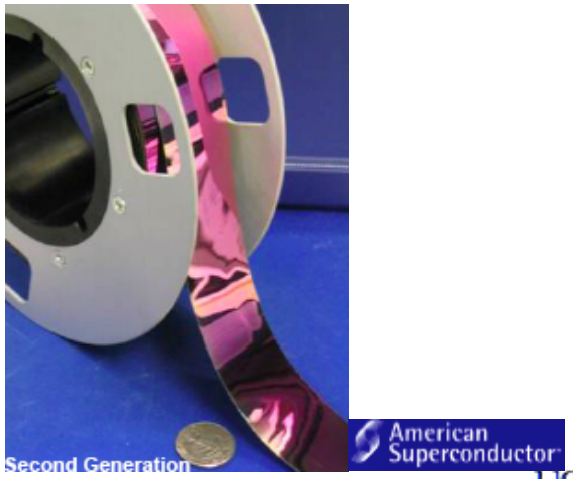
Superconductor Options and Implications

- **Nb_3Sn wind and react (most conservative)**
  - **Conventional design (ITER-like), but with high temperature inorganic insulation**
  - **Presently being tested for VLHC design (3-D winding in cos-□ magnets)**
- **Nb_3Sn react and wind (less conservative)**
  - **Thin cross section (low strain during winding)**
  - **MIT magnet for LDX (floating coil)**
  - **Low conductor current, internal dump**
- **High Tc (most aggressive)**
  - **Epitaxially deposited on structure**
  - **YBCO 2-generation superconductor**
  - **Potential for low cost (comparable to NbTi)**



Ceramic insulation tape





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Impressive Progress in Development of High Performance Nb_3Sn

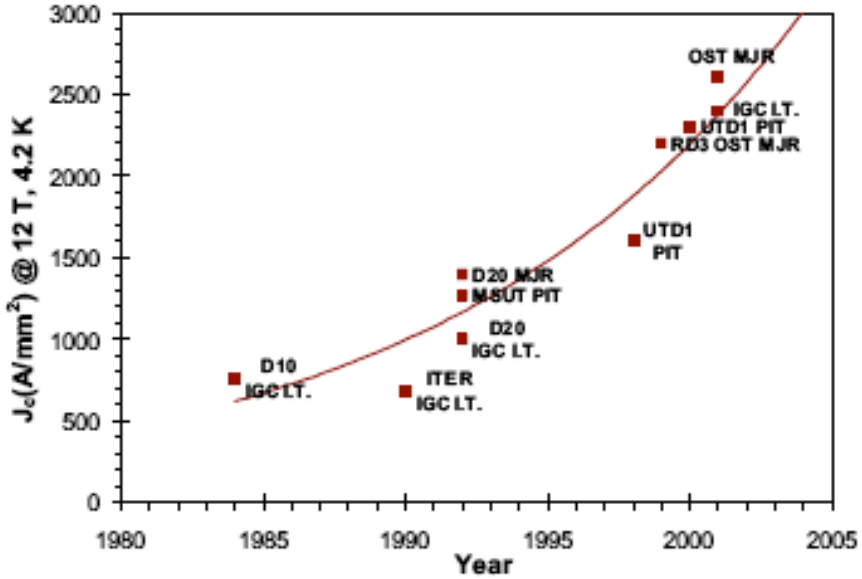


Fig. 4. Summary of Nb_3Sn conductor development over the past 20 years (Courtesy of R. Scanlan)

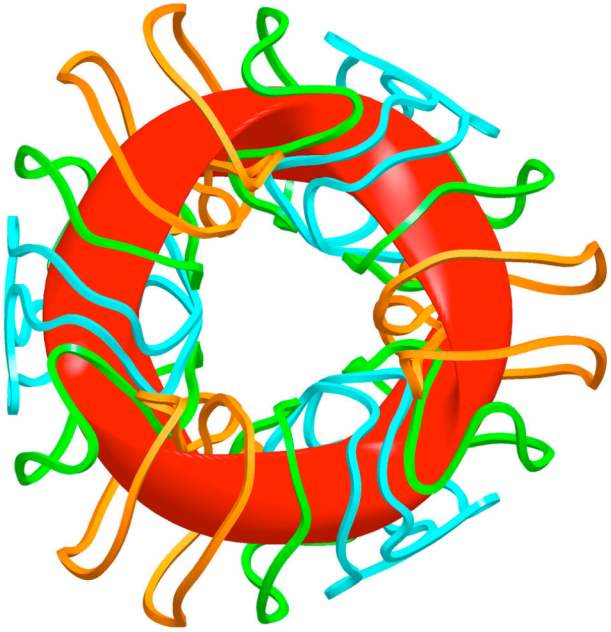
CONDUCTOR GOALS AND PRESENT STATUS

Specification	Target Value	Present Achieved
Jc (noncopper, 12T, 4.2K)	3000 A/mm2	2600-2900 A/mm2
Effective filament size	Less than 40 microns	100-120 microns
Minimum piece length	> 10 km	250-1000m
Wire cost	Less than $1.50/kA-m (12T, 4.2K)	$5.0-7.75/kA/m
Heat treatment times	Less than 200 hrs	148 hours

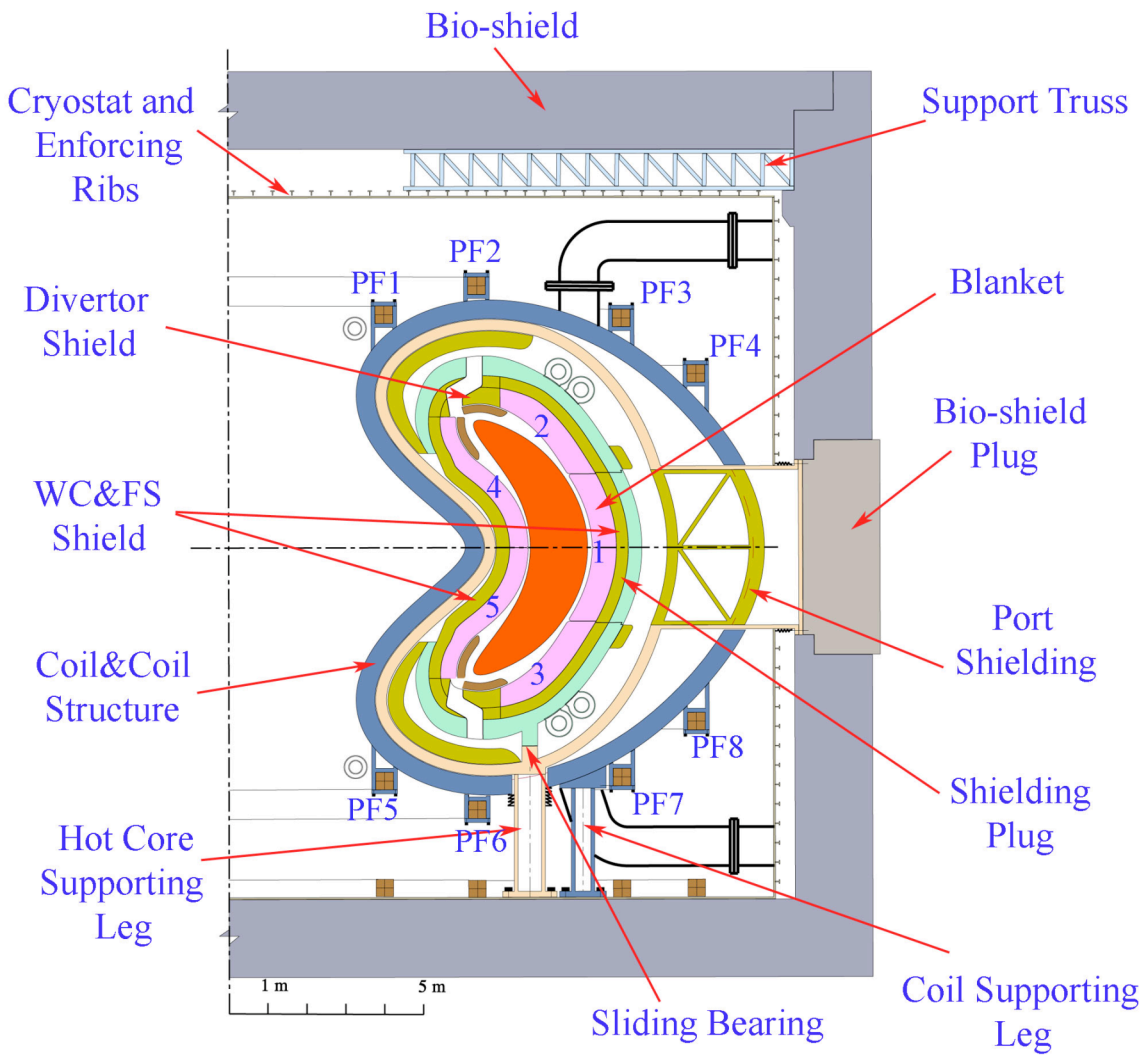
Scaling Laws for Modeling Large Superconducting Solenoids, M. A. Green and A. D. McInturff, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. I I , NO. I , 2292(2001)

Desirable Plasma Configuration should be Produced by Practical Coils with "Low" Complexity

- Complex 3-D geometry introduces severe engineering constraints:
  - Distance between plasma and coil
  - Maximum coil bend radius
  - Coil support
  - Assembly and maintenance
- Superconductor: Nb_3Sn wind-and-react Cable-in-Conduit Conductor, wound on preformed structure ($B \leq 16T$)
- Coil structure
  - JK2LB (Japanese austenitic steel chosen for ITER Central Solenoid)
  - Similar coefficient of expansion as SC, resulting in reduced SC strain
  - Avoid stress corrosion associated with Incoloy 908 (in the presence oxygen in the furnace during heat treatment)
  - Potentially lower cost
  - YS/UTS @4Ksimilar to Incoloy 908 (1420/1690 MPa)
  - Need more weld characterization data



Vacuum Vessel Internal to the Coils in Design Configuration for Port-Based Maintenance Scheme



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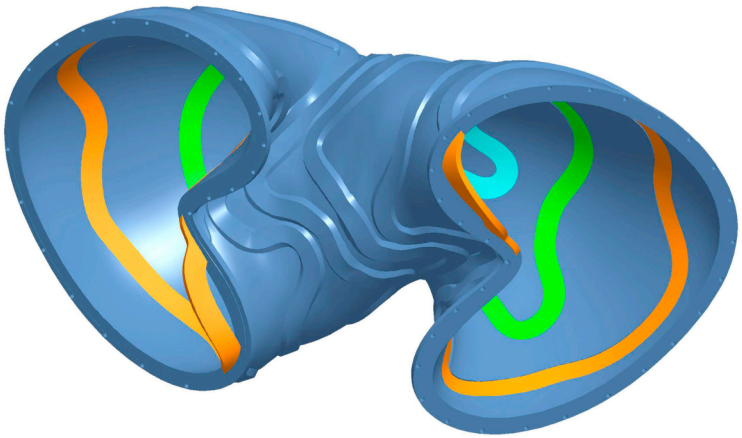
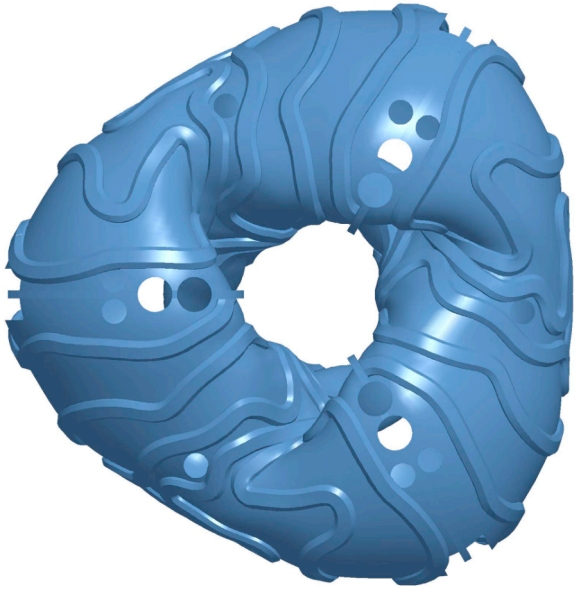
Coil Support Design Includes Winding of All Coils of One Field-Period on a Supporting Tubular Structure



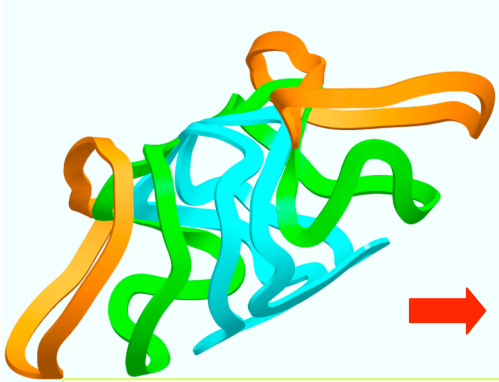
- Winding internal to structure.
- Entire coil system enclosed in a common cryostat.
- Coil structure designed to accommodate the forces on the coil



- Large centering forces pulling each coil towards the center of the torus. →
- Out-of plane forces acting between neighboring coils inside a field period. →
- Weight of the cold coil system. →
- Absence of disruptions reduces demand on coil structure.

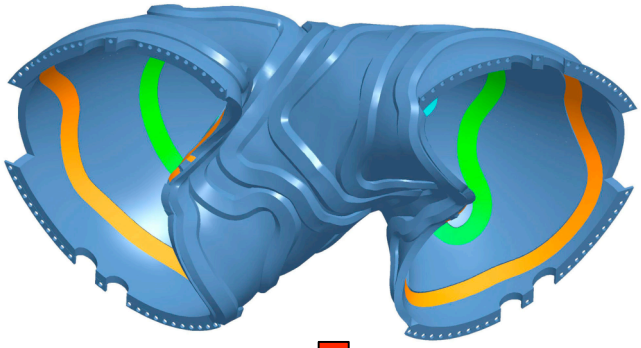
- Reacted by connecting coil structure together (hoop stress)
- Reacted inside the field-period of the supporting tube.
- Transferred to foundation by ~3 legs per field-period. Legs are long enough to keep the heat ingress into the cold system within a tolerable limit.

Coil Assembly Steps

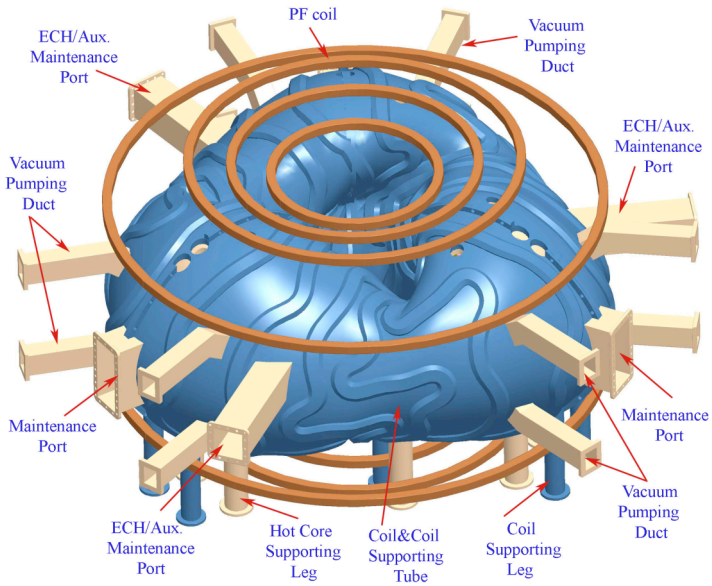


Superconductor: Nb_3Sn

Coil structure: JK2LB



- **Internal winding of modular coils into grooves in the coil supporting tube (6 coils per field period)**
- **Supporting tube composed of inter-coil structure, coil cases, coil strong-back and flanges.**
- **The three coil supporting tubes mechanically connected together to form a strong and continuous ring to react all the magnetic forces.**



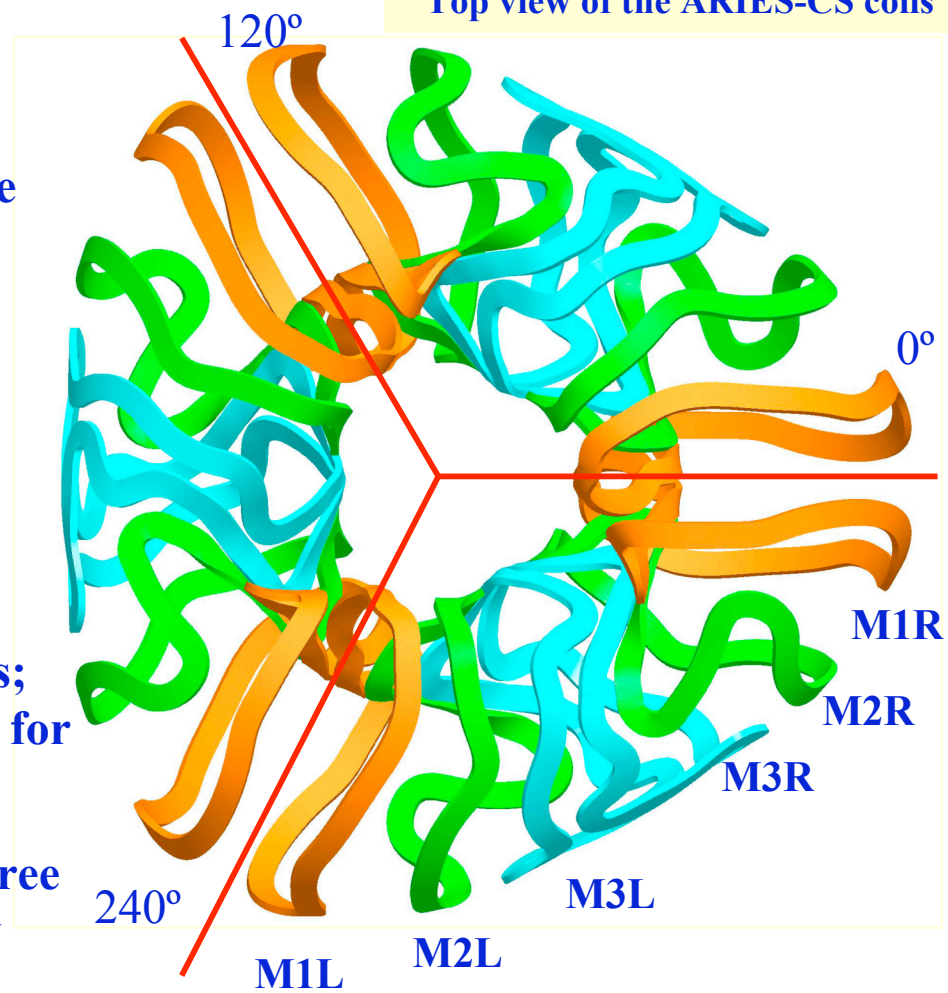
Detailed EM and Stress Analysis Performed with ANSYS for 3-Field Period ARIES-CS Coil Configuration (NCSX-like)

- **18 modular superconducting coils (6 per field-period)**
- **Due to twofold mirror symmetry per field period, only three different coils shapes are needed to make up the complete coil set.**
- **Coils were designed for baseline configuration**

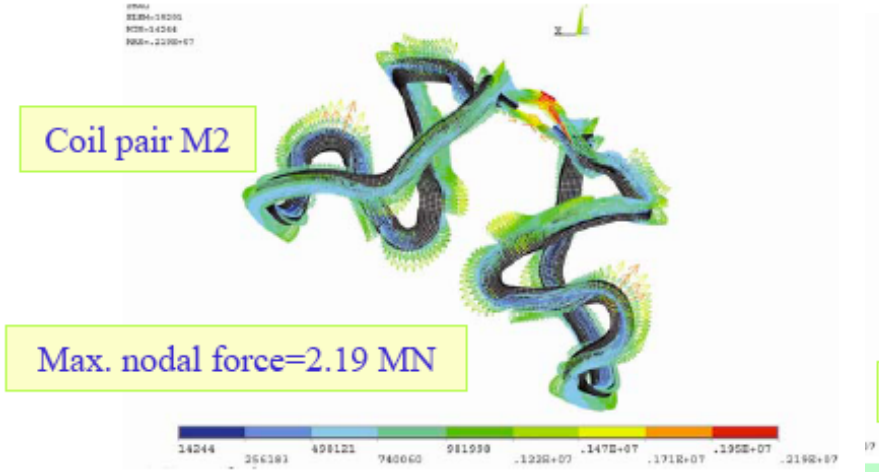
  Major radius R=7.75 m;
  Aspect ratio A=4.5;
  Plasma magnetic field B=5.7 T;

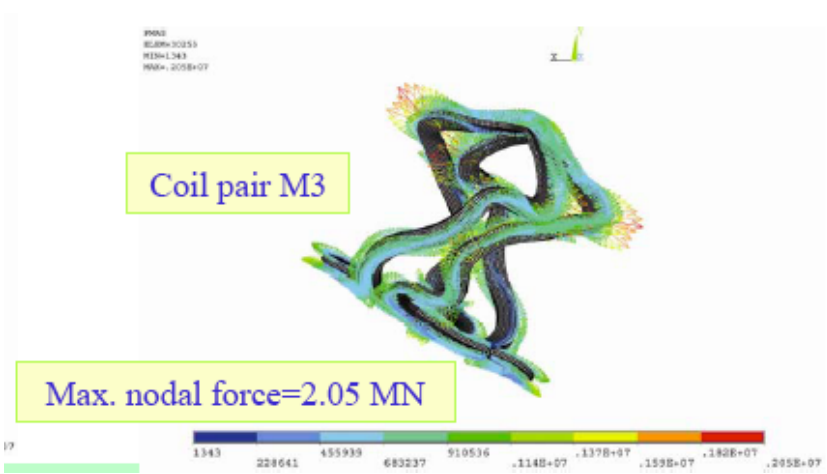
- **EM analysis to calculate magnetic flux density and EM forces in the modular coils; the resulting EM forces then used as input for structural analysis.**
- **Considering threefold cyclic symmetry (three field-period) of the coil configuration, only the coils within a 120-degree region (one field-period) were considered in the ANSYS EM model.**

Top view of the ARIES-CS coils

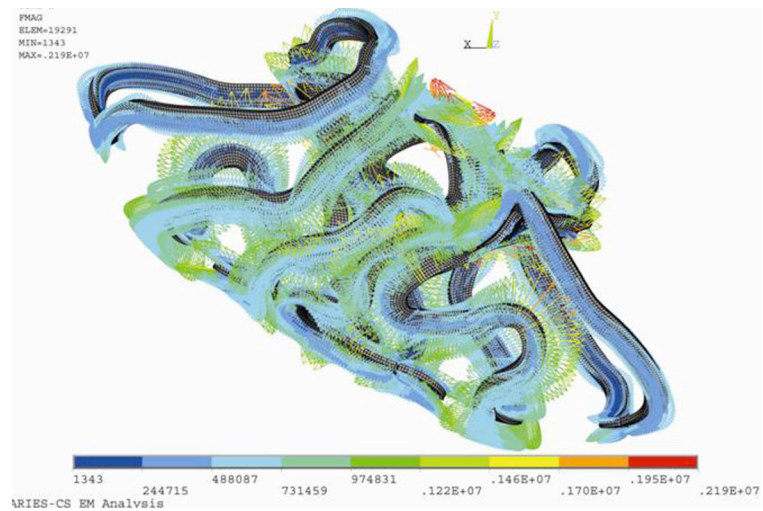


EM Results Show Symmetrical Nodal Force Distributions





- **Geometry of modular coils was imported from Pro/E CAD model.**
- **Plasma current and corrective PF coils play a relatively small role in EM loads on the coil structure, and are not included in the analysis.**
- **Maximum local magnetic field and nodal forces occur in the modular coils where there are small bend radii.**



All coils in One field-period

Net Forces in the Modular Coils from EM Analysis

	F_r (MN)	$F_{\square}$ (MN)	F_z (MN)
M1L	-58.5	377.2	22.6
M1R	-58.5	-377.2	-22.6
M2L	-257.3	178.5	-150.7
M2R	-257.3	-178.5	150.7
M3L	143.2	51.1	-141.7
M3R	143.2	-51.1	141.7
Sum of all 6 Coils	-345.2	0	0

- There are no net forces in toroidal and vertical directions.
- EM results confirm that no net forces are transferred from one field-period to the next.
- The net force in the radial direction, -345 MN, represents the centering force pushing the coils inwards.

Material Properties for the Coil Supporting Structure

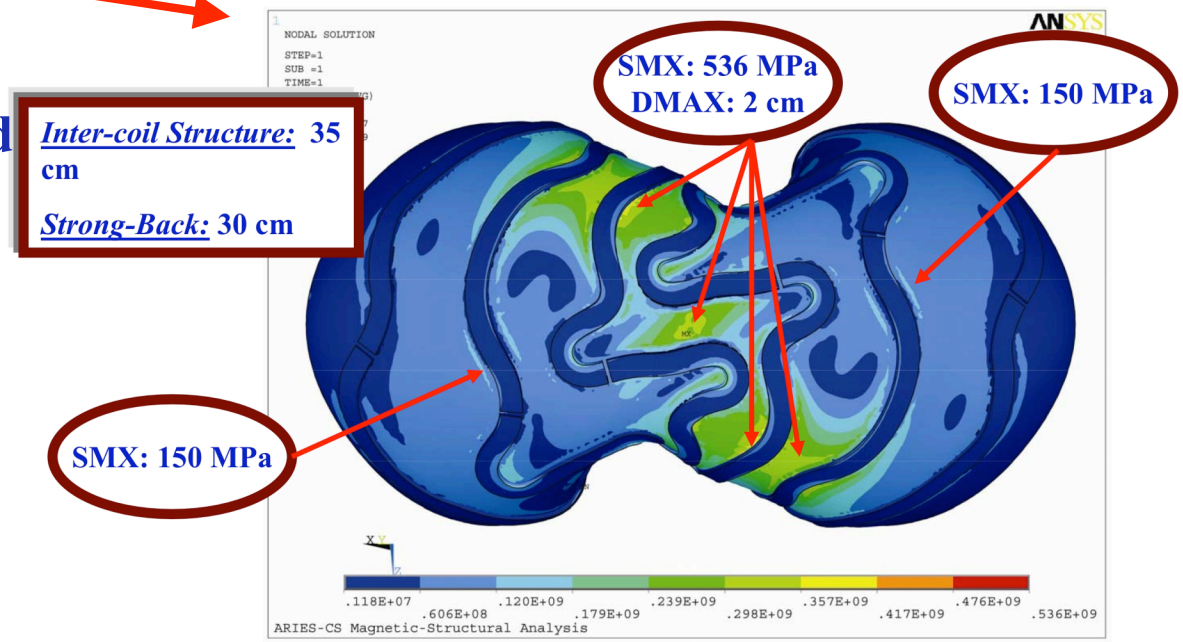
Material	Incoloy 908 (4K)	JK2LB(4K)
Yield strength	1227 MPa	1420 MPa
Tensile strength	1892 MPa	1690 MPa
Modulus of elasticity	1.823×10^2 GPa	~2.0×10^2 GPa *
Elongation	28.5%	25%
Poisson's ratio	0.303	0.3*
Design stress	**818 MPa**	**946 MPa**

- **The design stress is taken as 2/3 of the yield strength at 4 K.**

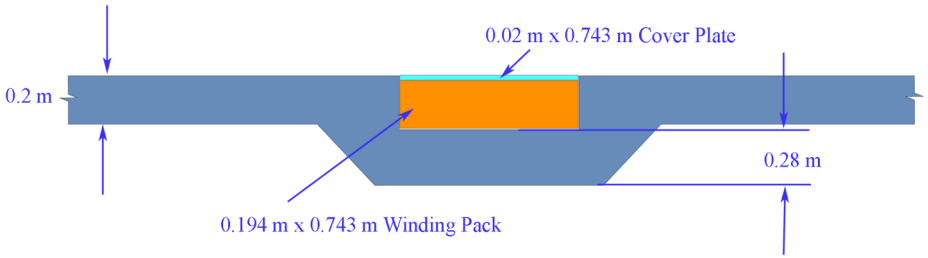
*** Recommended by H. Nakajima, ITER Superconducting Magnet Technology Group, Japan Atomic Energy Agency (JAEA).**

Detailed EM and Stress Analysis Performed with ANSYS

- Shell model used for trade-off studies
- Selected cases with 3-D solid model done for comparison to help better understand accuracy of shell model and effect of penetration
- Both peak deformation and stress occur in localized regions.



- As a first-order estimate, structure thickness scaled to stress & deflection results to reduce required material and cost; e.g. in this case:
  - Avg. thickness inter-coil structure ~20 cm
  - Avg. thickness of coil strong-back ~28 cm



3-D Solid Model Analysis Performed to Help Better Understand Effects of Penetrations Through the Coil Supporting Tube

- **A number of penetrations and openings are required for ARIES-CS configuration and maintenance scheme:**
  - Maintenance ports: 3.85 m (w) x 1.85 m (h)
  - ECH ports: 1.76 m (w) x 1.78 m (h)
  - Coolant access pipes: OD~0.78 m
  - Hot supporting legs: OD ~1.0 m

- **Penetrations could affect the local stress distributions and cause higher local stresses in the coil supporting tube.**

- **Maintenance ports at both ends of the coil supporting tube were included in the solid model to determine if enforcement ribs would be needed.**

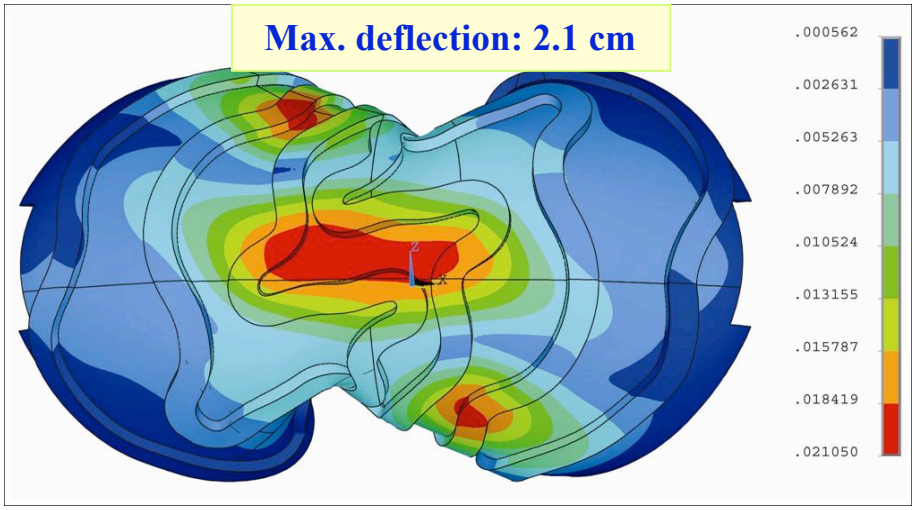
Solid finite element model

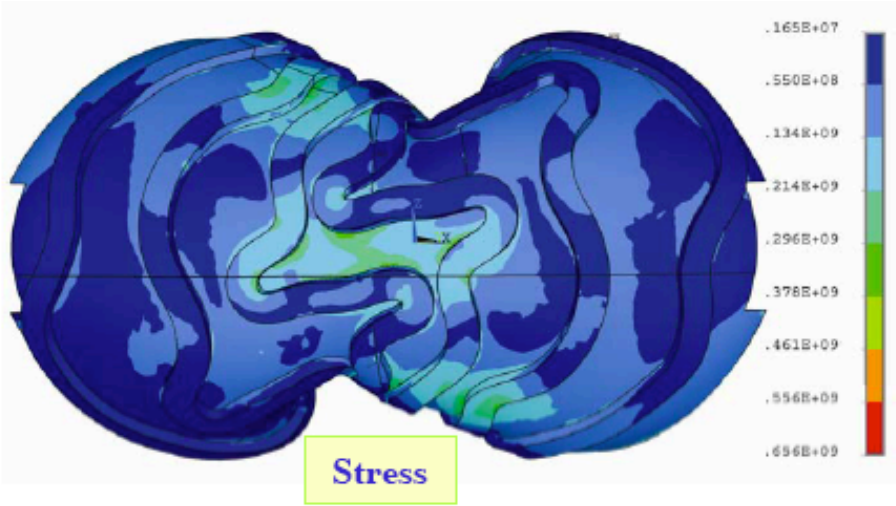
Inter-coil structure: 35 cm

Coil strong-back: 30 cm

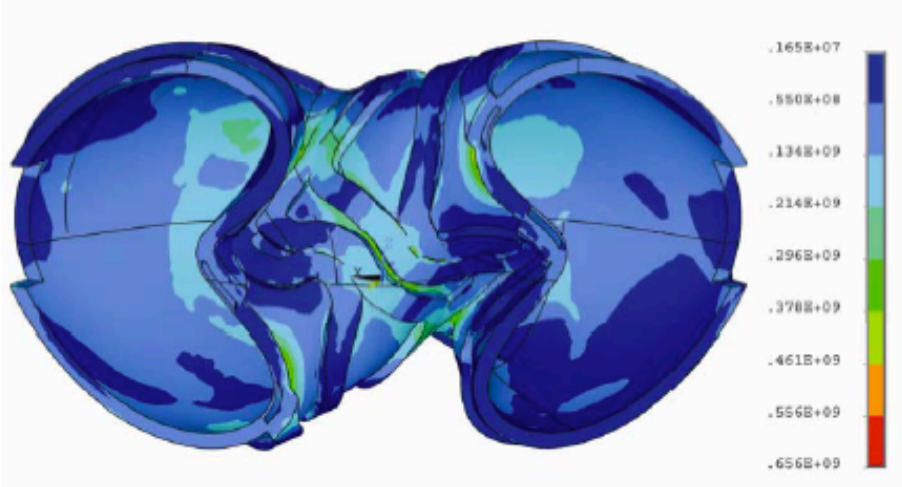
750,000 structural elements

3-D Results Confirm Acceptable Stress Levels in Coil Supporting Tube





- Max. stress for solid model is 656 MPa and max. deflection is 2.1 cm.
- Max. stress occurs at very localized regions.
- Openings/penetrations for maintenance ports at 0º, 120º and 240º are not a major concerns because the deformations and stresses are very small in these regions.



Max. von Mises stress: 656 MPa

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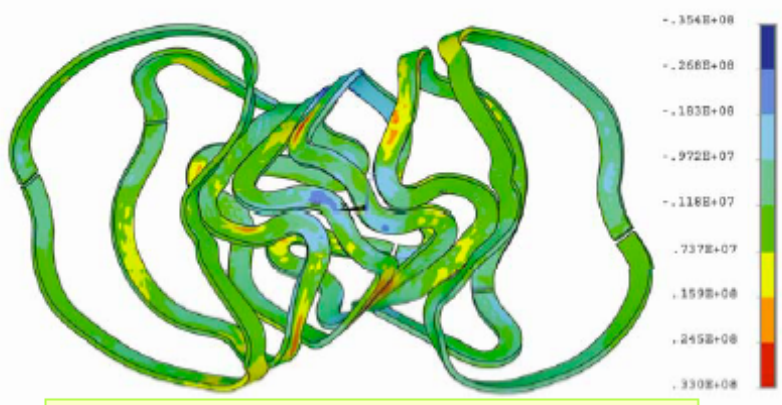
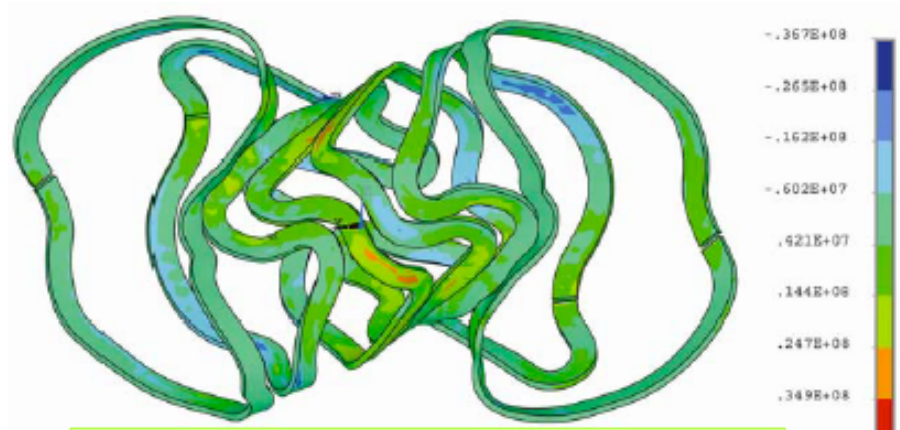
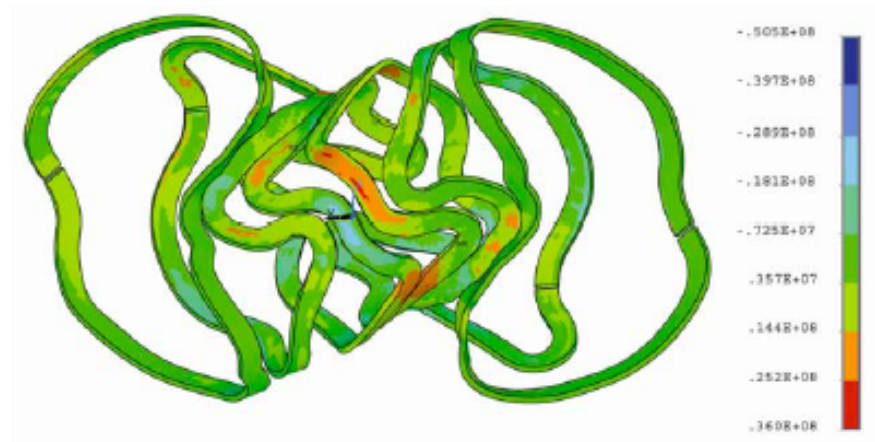
Shear Stresses in the Winding Packs



Max. Shear stress, 35 MPa in x-y plane



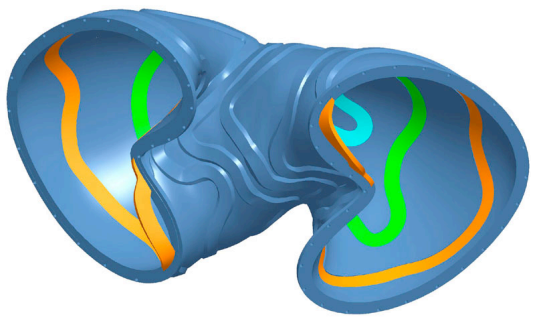
Max. Shear stress, 45 MPa in x-z plane

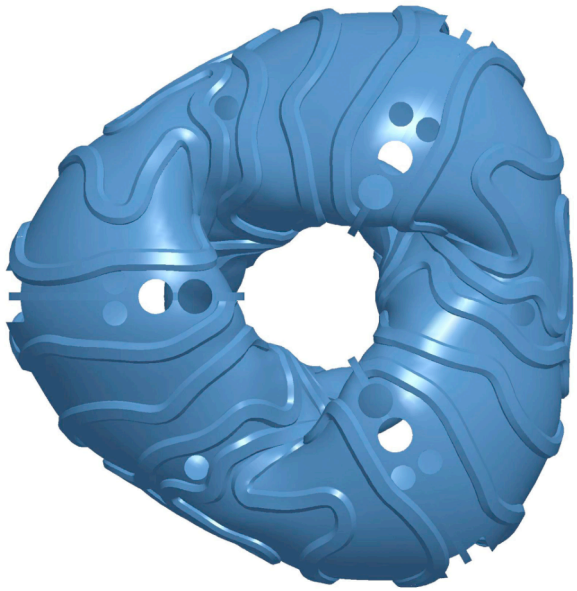


Max. Shear stress, 50 MPa in y-z plane

- **Shear stresses in winding packs is a critical parameter to be used to qualify large-scale electromagnets.**
- **Large shear stresses may cause structural failure of the insulator system.**
- **The shear stresses in most of the winding packs are <20 MPa.**
- **NCSX shear stress test data indicate a failure at 32 MPa. No shear stress test data is available for our coil design.**

Summary of Advanced Fabrication of the Coil Structure





Material: JK2LB low carbon, boron steel

Mass: ~ 3 x 10^6 kg for 3 field periods

Construction: Monolithic for entire field period

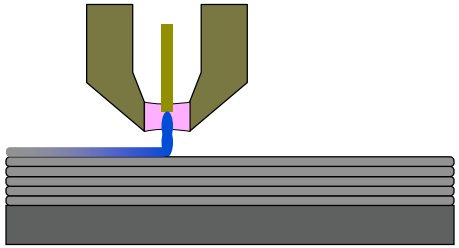
Fabrication Location: At construction site

Fabrication: Additive machining – arc deposition of near net shape, final machining of coil grooves by robot milling machines on inner surface and field period interfaces

Coil Fabrication: Coil cables will be wound into the grooves with robot winding machines

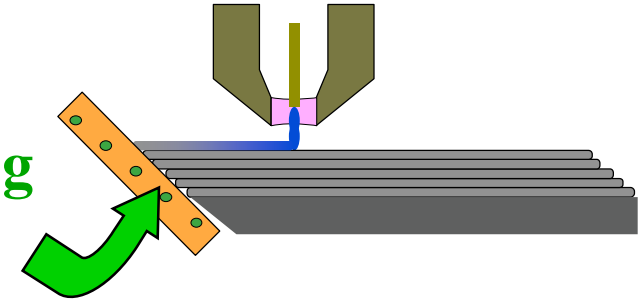
Accuracy of Coils: EM forces will be analyzed to determine displacement. Placement of the grooves will be compensated so the coils will be in proper location when coils are energized.

Plasma Arc Deposition



Planar Features

The deposition wire is fed into the plasma arc and the material deposited in layers

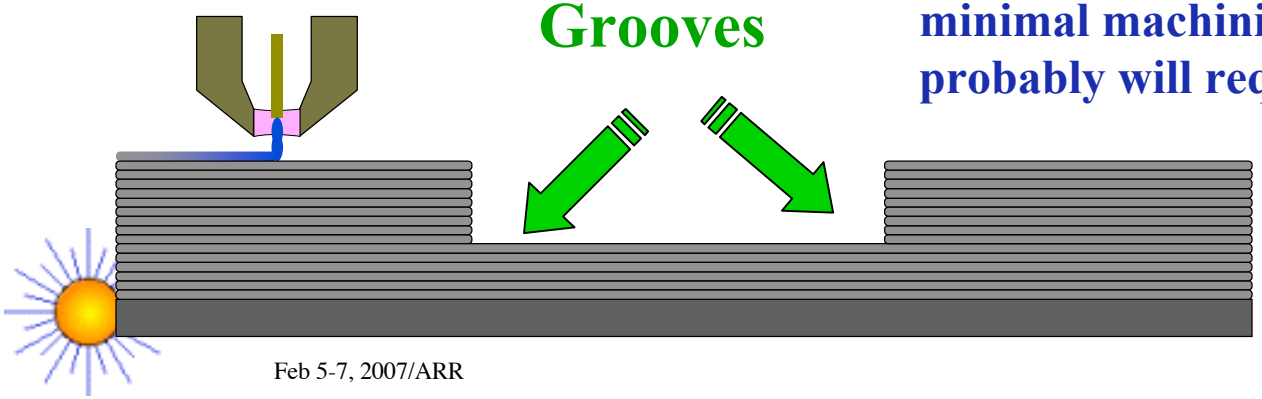


Overhanging Features

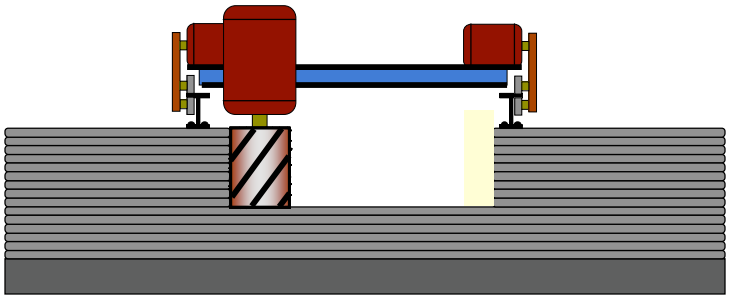
Overhanging features can be created with cooled slip plates

Near Net Shape Grooves

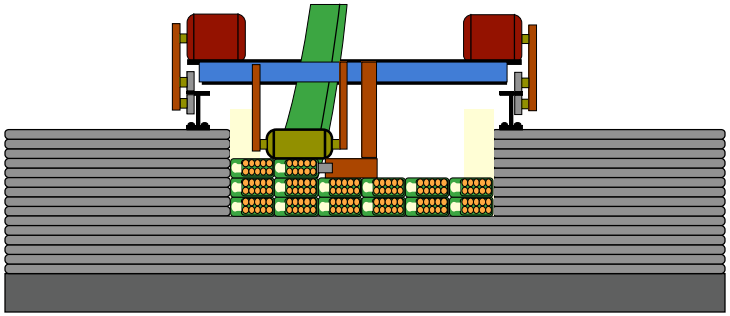
Near net shape grooves can be created as the material is deposited by starting and stopping the deposition. These features require only minimal machining. All other surfaces probably will require no machining.



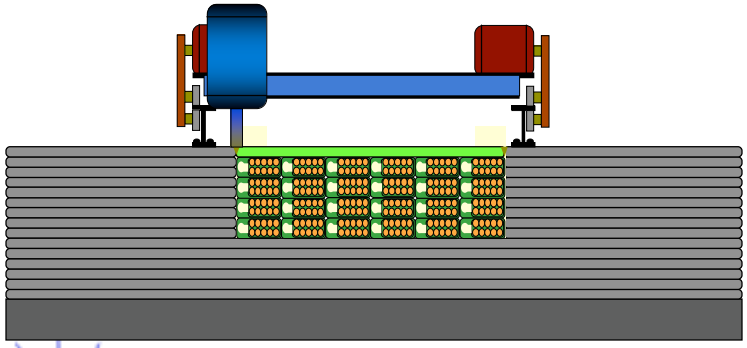
Groove Fabrication



Guide rails and fiducial reference datums will be added to the structure parts to guide the milling machines for final groove machining.

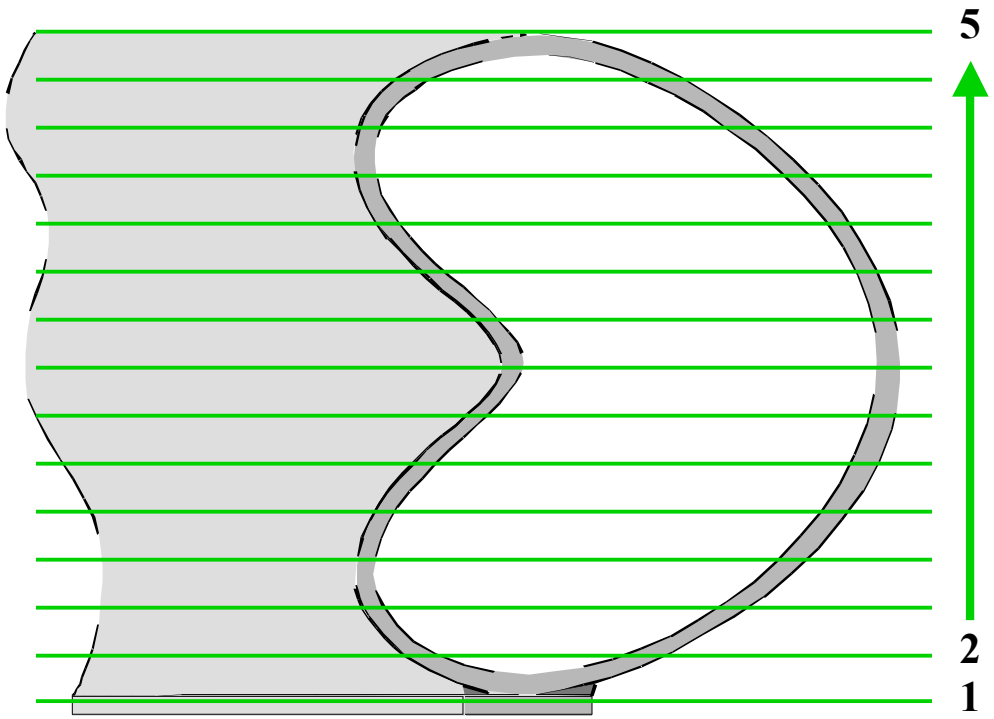


A similar machine will use the same rails and fiducial datums to install the superconducting cables into the coil groove



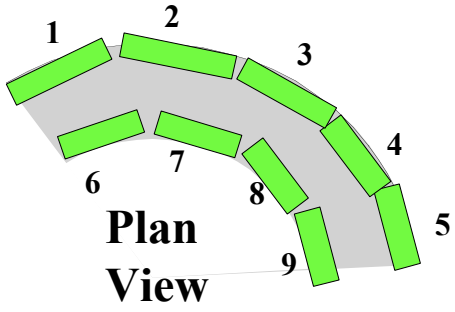
After all the cable is in place for the coil, the cover place will be installed and friction-stir welded in place to secure the coil.

Concept to Fabricate Structure

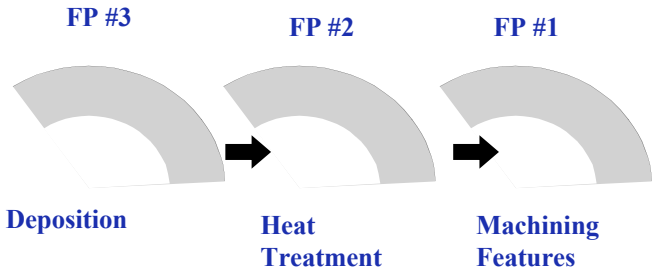


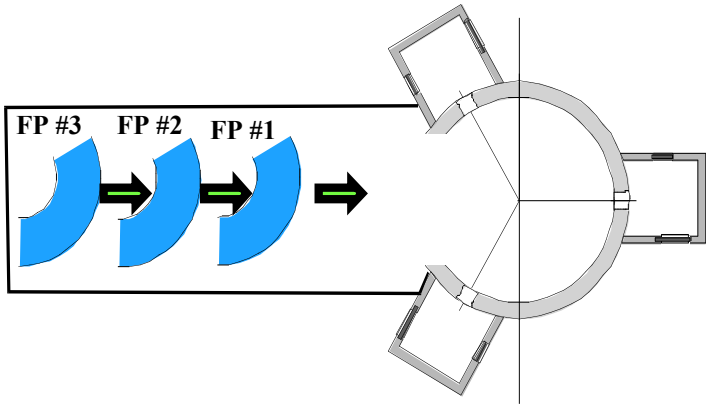
1. Start with solid base
2. Begin to create structure
3. Continue to add layers
4. Ditto
5. Until it is complete for a field period

Staging of Field Period Structures



- Multiple deposition robots will be required to build a field period in roughly a year
- Each deposition robot will be assigned a zone to build





- The most cost effective approach is to construct one field period at a time, but staged to move deposition, heat treatment, and machining equipment from one FP to another as required.
- After the first FP is completed, it will be moved into place in the Reactor Building.
- All three FPs should be completed in roughly 3 years.

- The coil sectors will probably be fabricated close to the Reactor Building and moved inside the Reactor Building

Preliminary Costing

- A preliminary engineering cost estimate has been developed
- Additional detail can be added as needed
- Costs are presented in $2006
- Total mass is 10^6 kg ($393m^3$ x 7800 kg/m^3)
- Cost of specialty steel, JK2LB, in wire form is $20/kg (estimate)
- Build each segment (FP) separately in sequence
- Build Time is driven by deposition rate, but is adjustable by using more robots (10 assumed)

Summary Schedule and Costs

Cost/Segment	$	$29,308,481
Mass Cost/Segment	$/kg	$29.31
Cycle Time for Segment 1	days	380
Additional Time for Each Additional Segment	days	245
Total Time for 3 Segments	days	870

Labor costs are < ½ the cost of raw material costs!

Fabrication Elements	Days	Cost
Deposition	245	$25,720,588
Stress Relief	30	$1,648,000
Coil Channel Machining	24	$591,957
Coil Cable and Cover Installation	61	$592,445
Cooling Channel Machining	8	$359,334
Cooling Channel Closeout	11	$396,157
Segment Totals (d, $)	380	$29,308,481
Total, Three Segments (d,$)	870	$87,925,443

~ 2.4 yr fabrication

This is an approximation of the coil structure fabrication cost using advanced low cost techniques that will have no complexity factor. This compares to much more expensive conventional fabrication approach that has high labor costs and significant complexity factors.

Conclusions

- **Coil supporting system has been designed in integration with ARIES-CS power core configuration and port maintenance scheme.**
- **Innovative process proposed: wind all 6 modular coils in grooves in one coil supporting tube (one per field-period); then bolt three coil supporting tubes together to form a strong ring to react the net radial forces.**
- **The results of the ANSYS analysis indicate that most regions in the coil structure tube are at low stress levels, and the inter-coil structural shell and the coil-strong-back can be thinned down in these regions to reduce the required material and cost, while meeting the given stress and deformation limits.**
- **Advanced rapid prototypic fabrication technique assessed with the potential of significant cost reduction.**