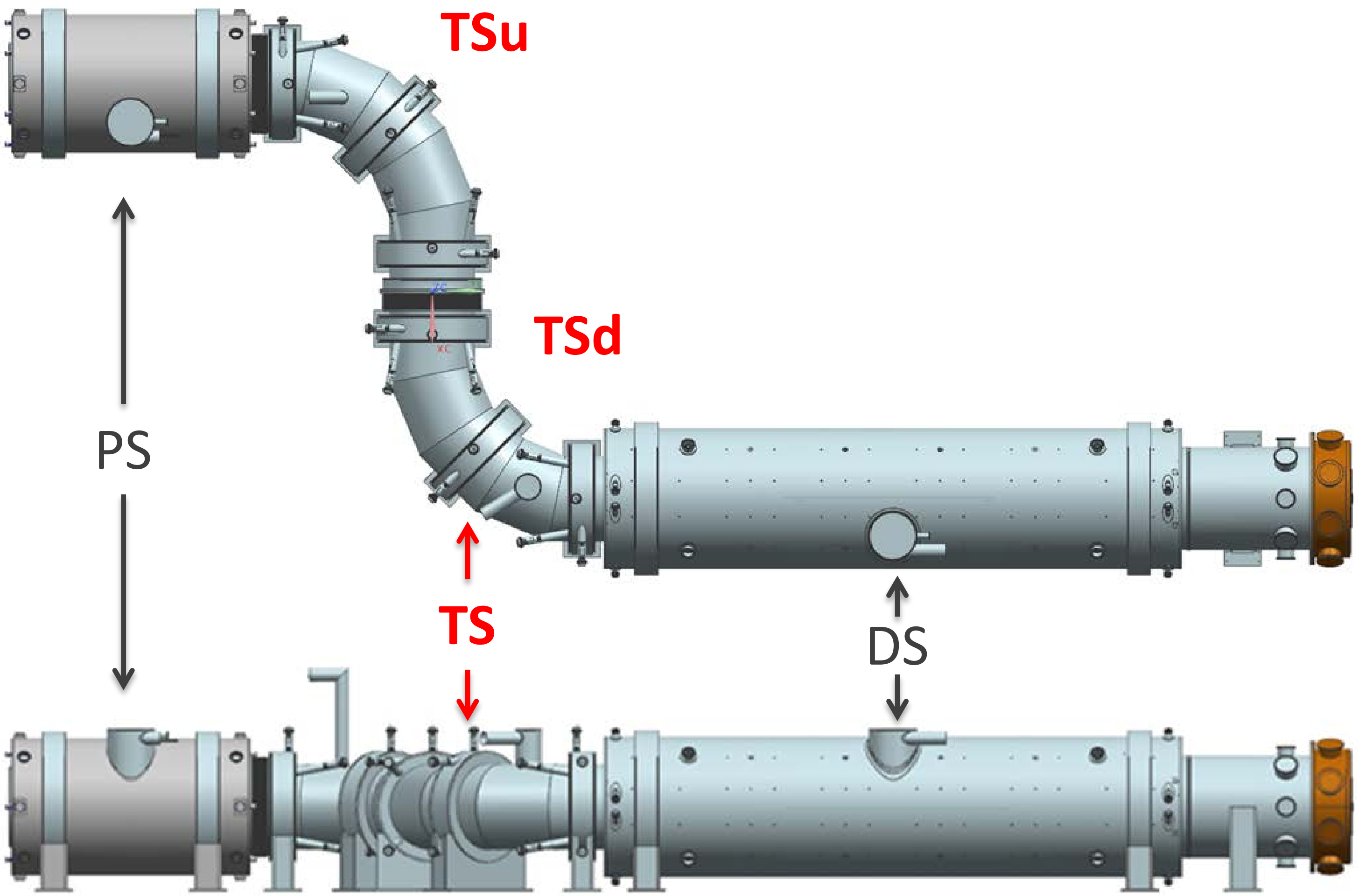
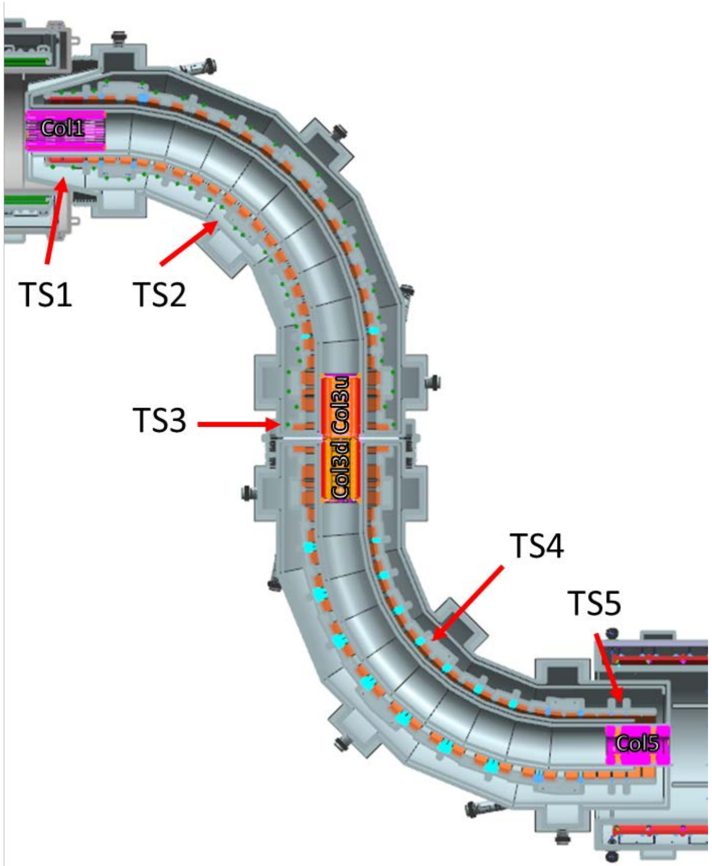
475.04.03 Transport Solenoid

Mauricio Lopes
L3 for the Transport Solenoid
Oct 21-24, 2014

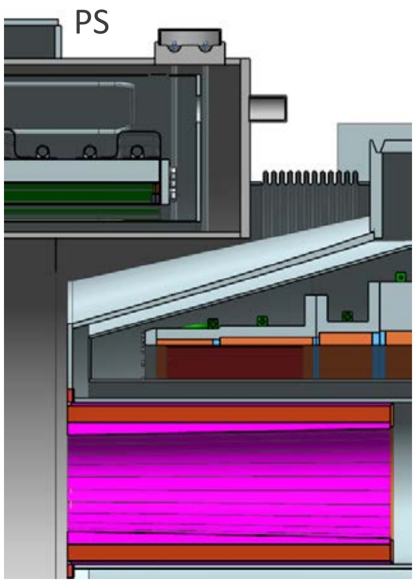
Scope



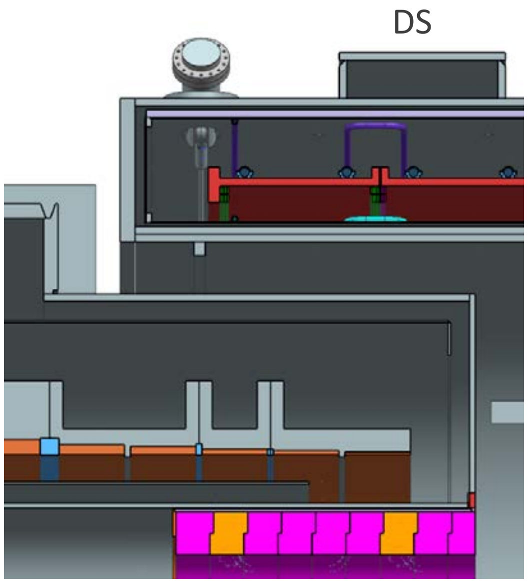
Requirements - Mechanical Requirements



There are four collimator elements. COL3u and COL3d are located in TS3 and they are used to filter particles based on electric charge and momentum.



Due to space constraints, the primary proton beam pipe must be routed through the TS cryostat. When the TS is at full power, there is a net axial force of around 130 Tons pulling the TS and PS together.

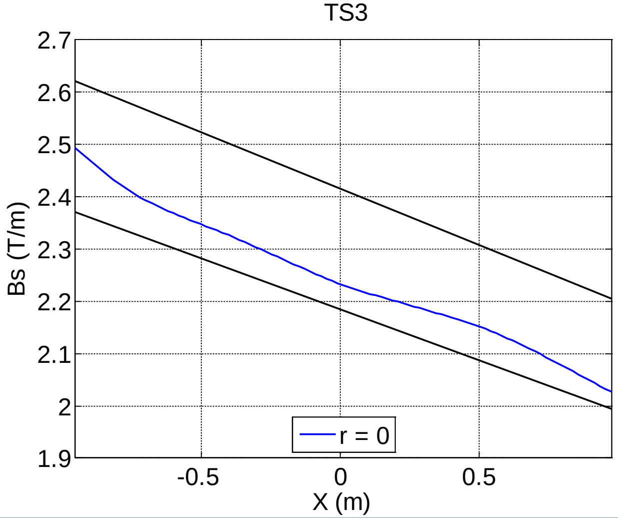


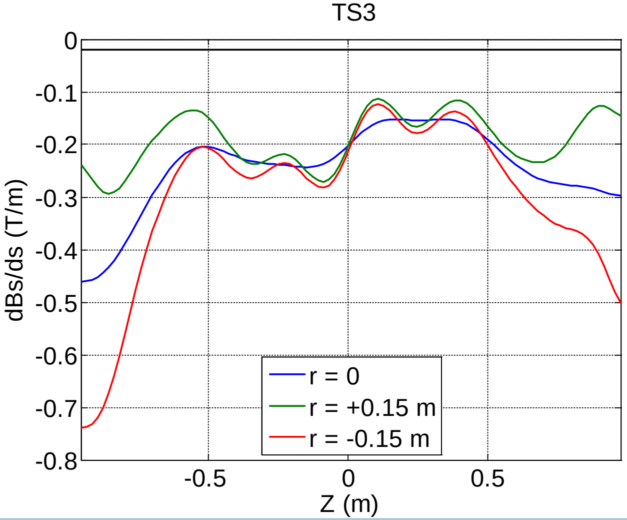
There is a physical overlap of around 940 mm between the DS and TS cryostats. When the TS is at full power, there is a net axial force of around 100 Tons pulling the TS and the DS together.

DocDB 947

Requirements - Magnetic Requirements

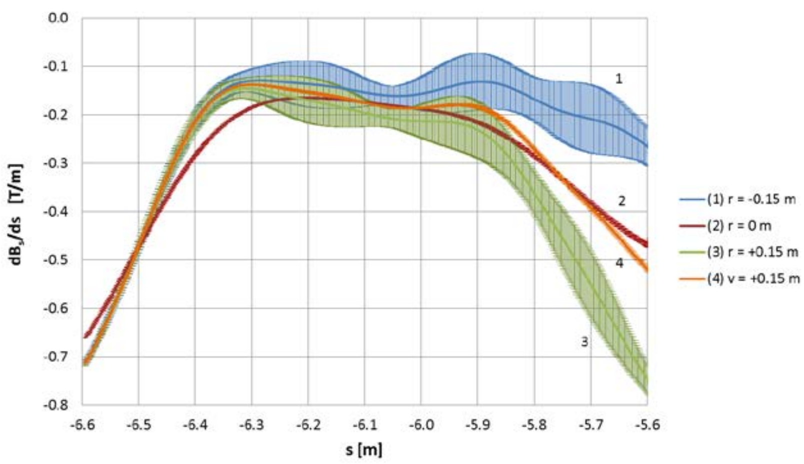
Region	s_{min} (m)	s_{max} (m)	$B_{initial}$ (T) ±5 %	B_{final} (T) ±5%	R_{max} (m)	dB_s/d_s (T/m)	dB_s/d_r (T/m)	Ripple (T)	Where
TS1	-6.58	-5.58	2.50	2.40	0.15	< -0.02	na	na	r=0, r=0.15 m
TS2	-5.58	-0.98	na	na	0.15	na	> 0.275	±0.02	r < 0.15 m
TS3	-0.98	0.98	2.40	2.10	0.15	< -0.02	na	na	r=0, r=0.15 m
TS4	0.98	5.58	na	na	0.15	na	> 0.275	±0.02	r < 0.15 m
TS5	5.58	6.58	2.10	2.00	0.15	< -0.02	na	na	r=0, r=0.15 m

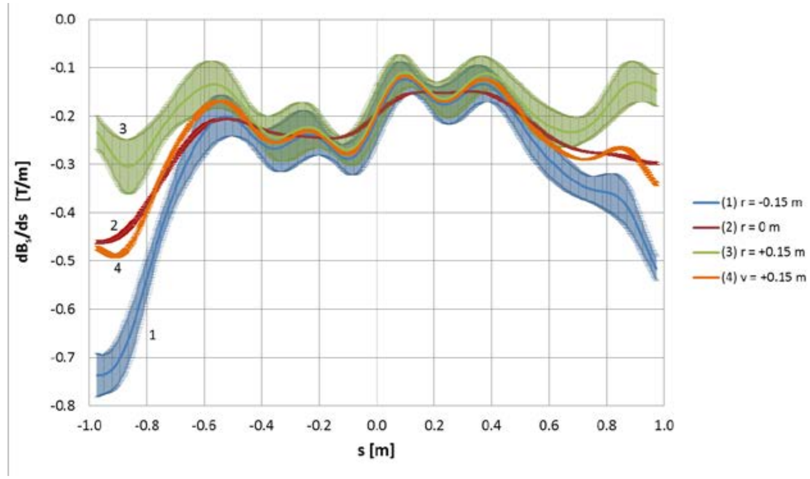


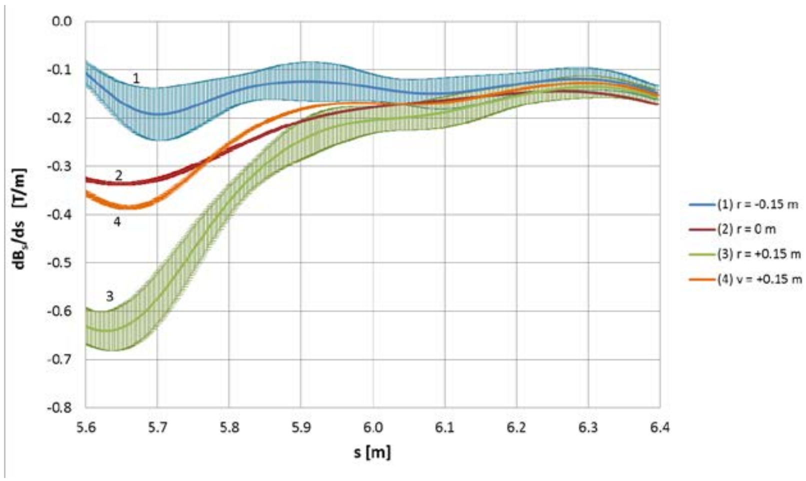


DocDB 947

Requirements - Magnetic Requirements



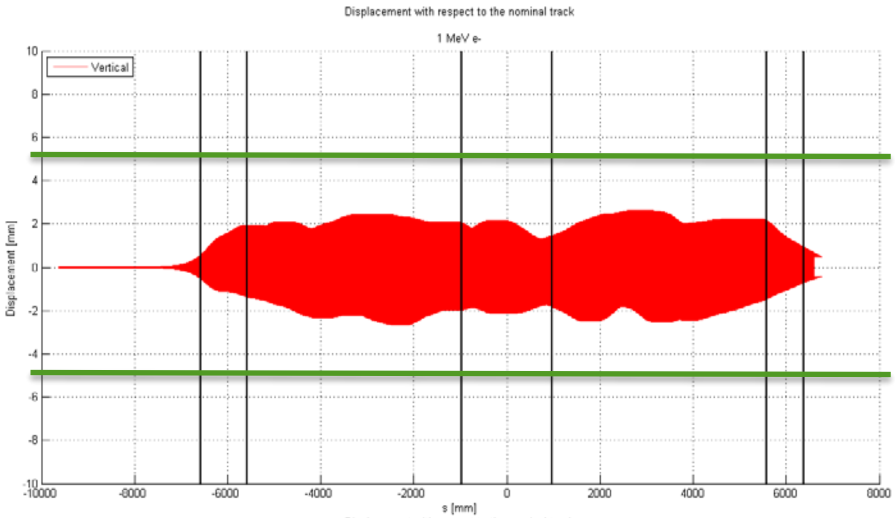




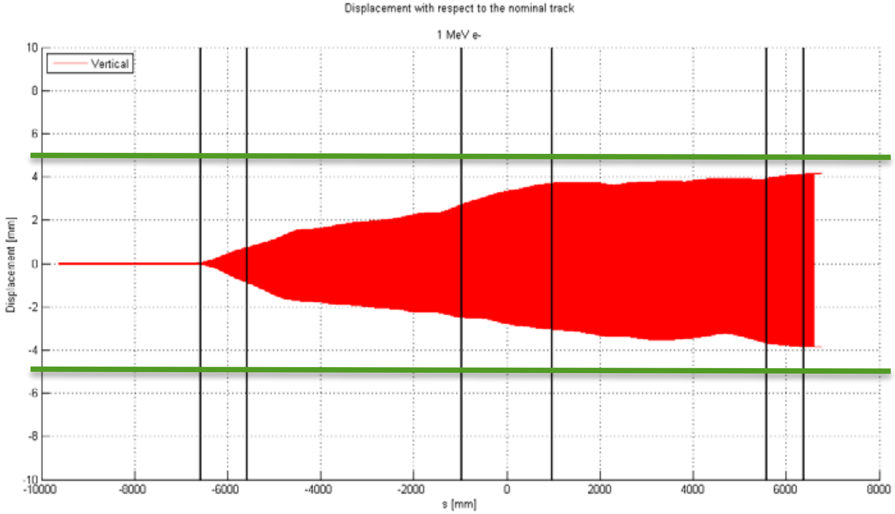
Error type	Maximum error	Maximum logitudinal gradient (T/m)		
		TS1	TS3	TS5
Radial	10 mm	-0.072	-0.072	-0.083
Radial	2 mm	-0.114	-0.106	-0.115
Vertical	10 mm	-0.103	-0.082	-0.104
Longitudinal	10 mm	-0.023	-0.009	-0.060
Longitudinal	2 mm	-0.111	-0.096	-0.109
Pitch	10 mrad	-0.120	-0.092	-0.116
Pitch	2 mrad	-0.124	-0.112	-0.12
Yaw	10 mrad	-0.108	-0.086	-0.105
Yaw	2 mrad	-0.121	-0.107	-0.119

DocDB 2156

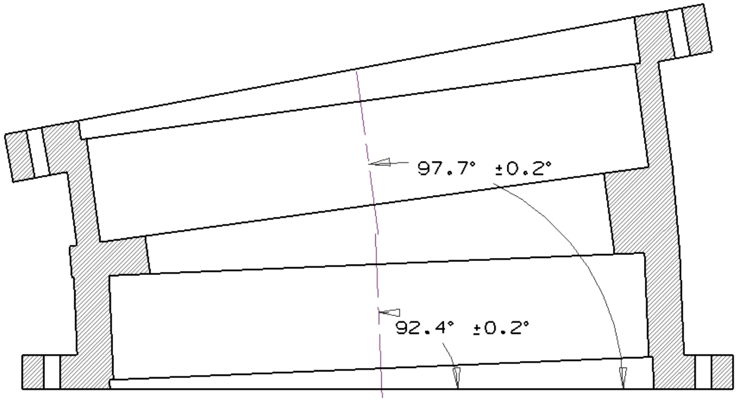
Requirements - Magnetic Requirements



ΔV = 10 mm



ΔP = 5 mrad



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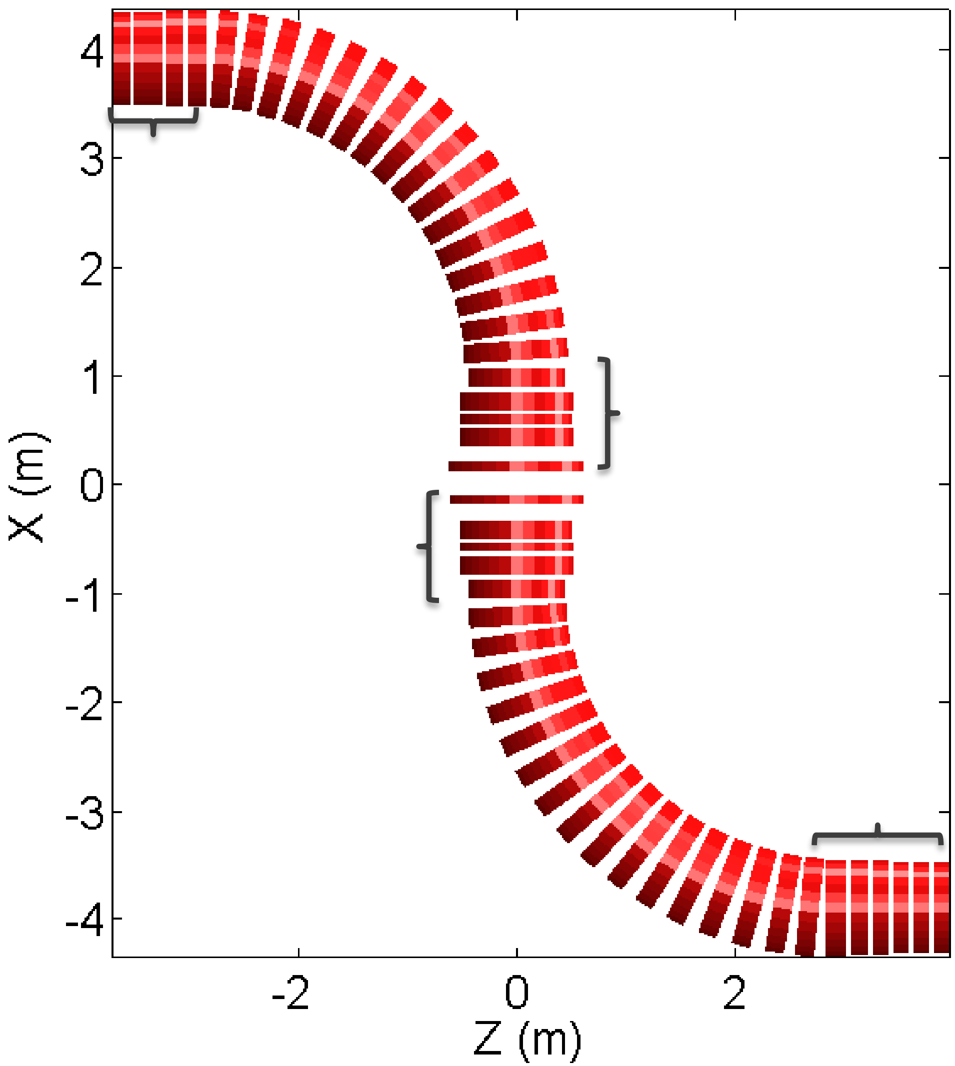
Design – Magnet System



- TS is formed by 52 SC solenoid coils.
- Most coils have the same aperture. TS3 coils have slightly bigger aperture to help with the large gap between cryostats.
- Each cryostat is powered by a different 2kA power supply (nominal current 1730 A)
- Each magnet has a pair of two 200 A trim power supplies (TPS).
- The TPS allows field matching with the adjacent magnets and gives an extra knob to control backgrounds.
- The coils that form the curve sections had their angles adjusted to center the particle distribution with respect to the axis of the solenoids.

Design - Cold Mass Breakdown

- TS has 52 Coils:

  TSu - 25

  TSd - 27

- Coils are housed in Al Shells and they form a coil module. There are 27 Coil modules:

  TSu – 13

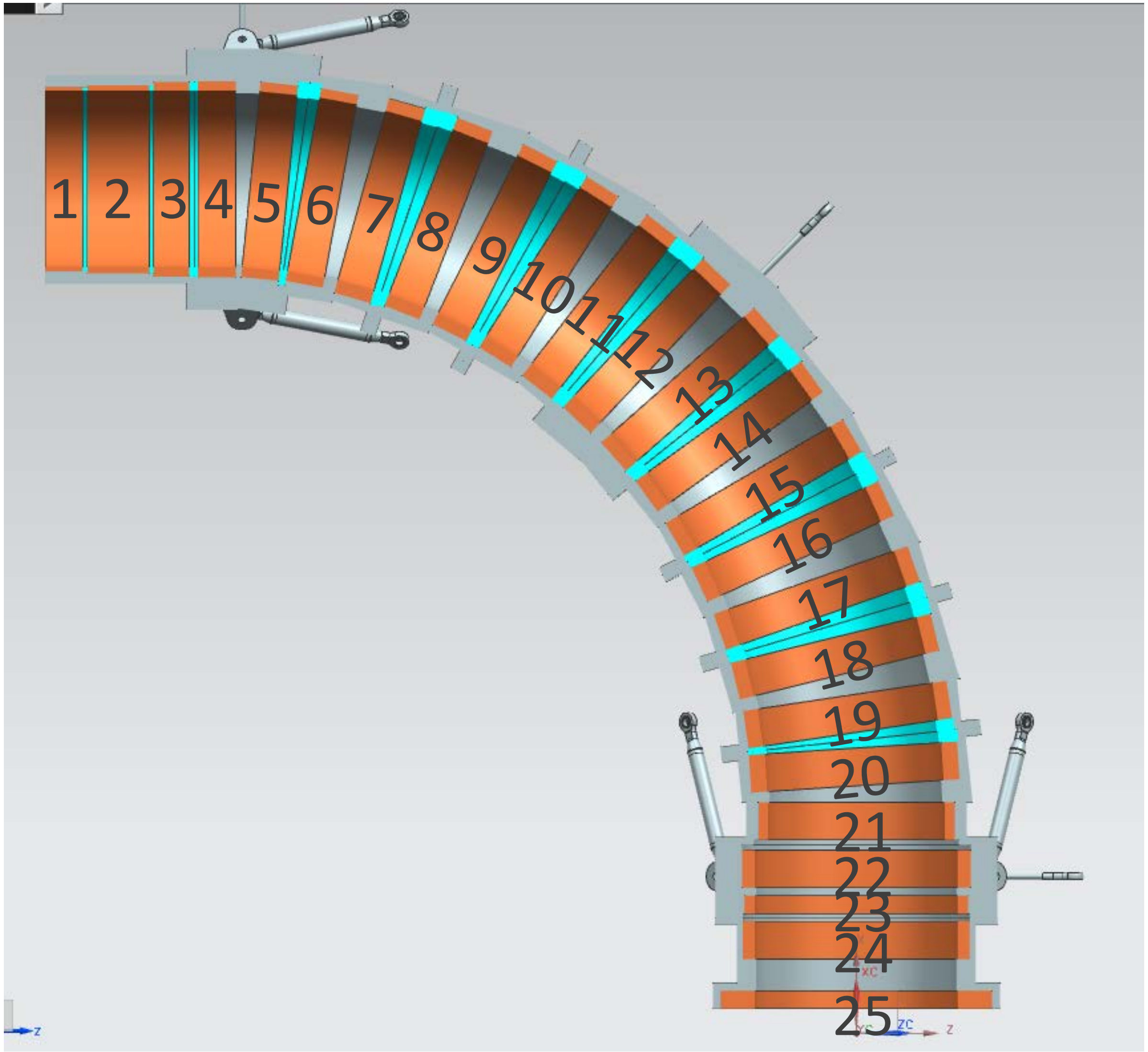
  TSd – 14

- Modules are assembled together (bolted and cryogenic connections) and they form a test unit. There are 14 test units:

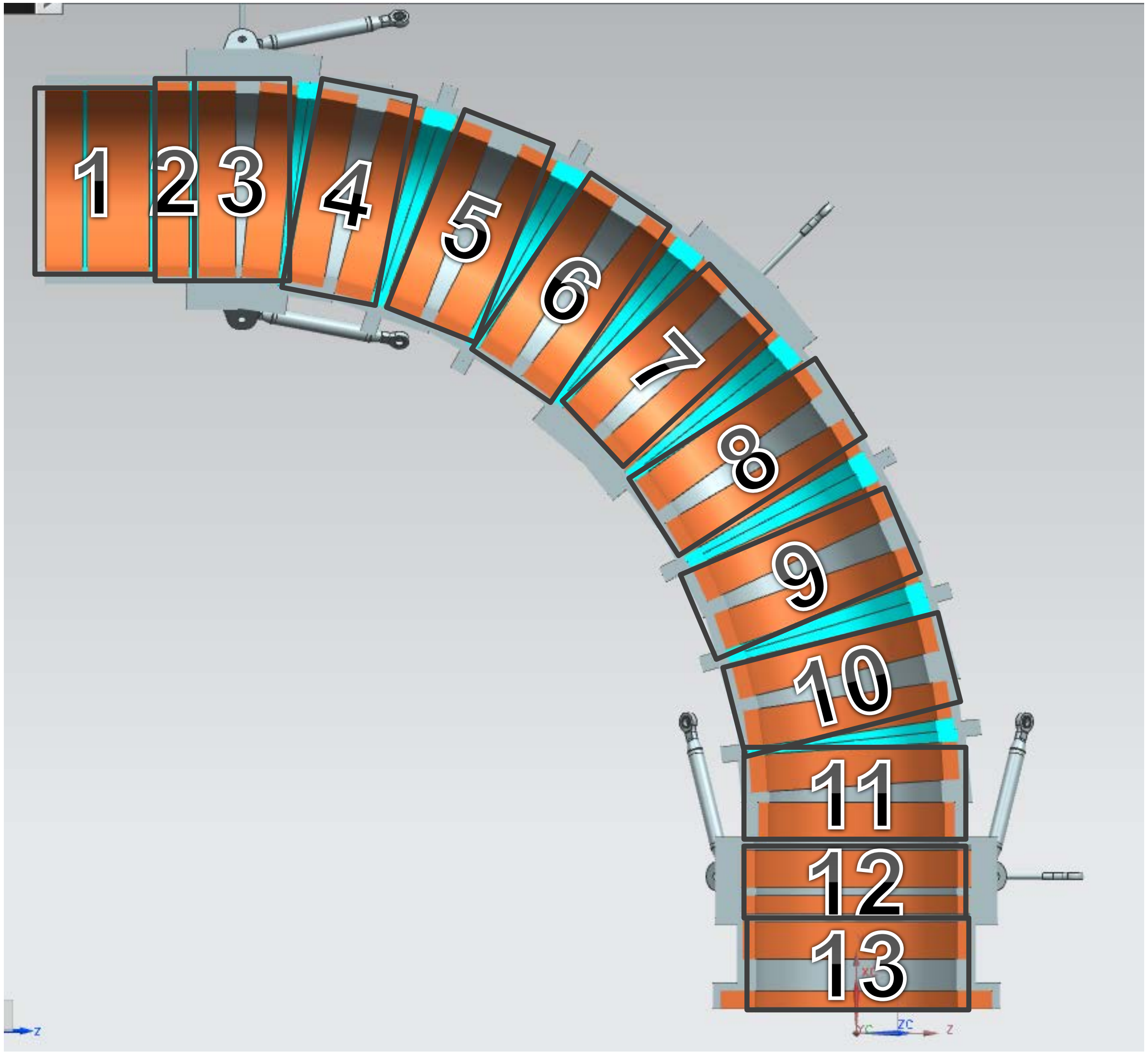
  TSu – 7

  TSd – 7

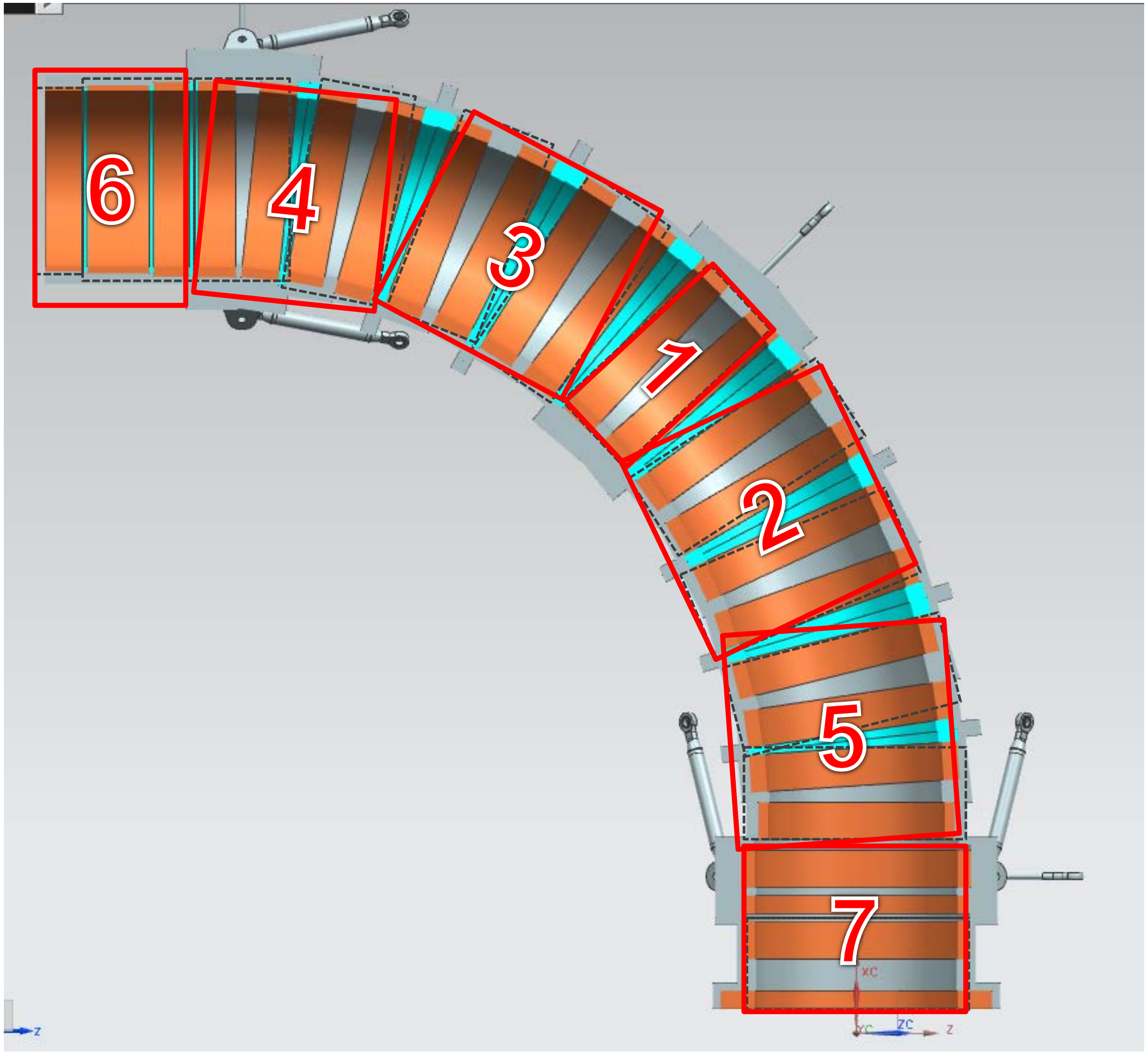
Design – TSu Coils



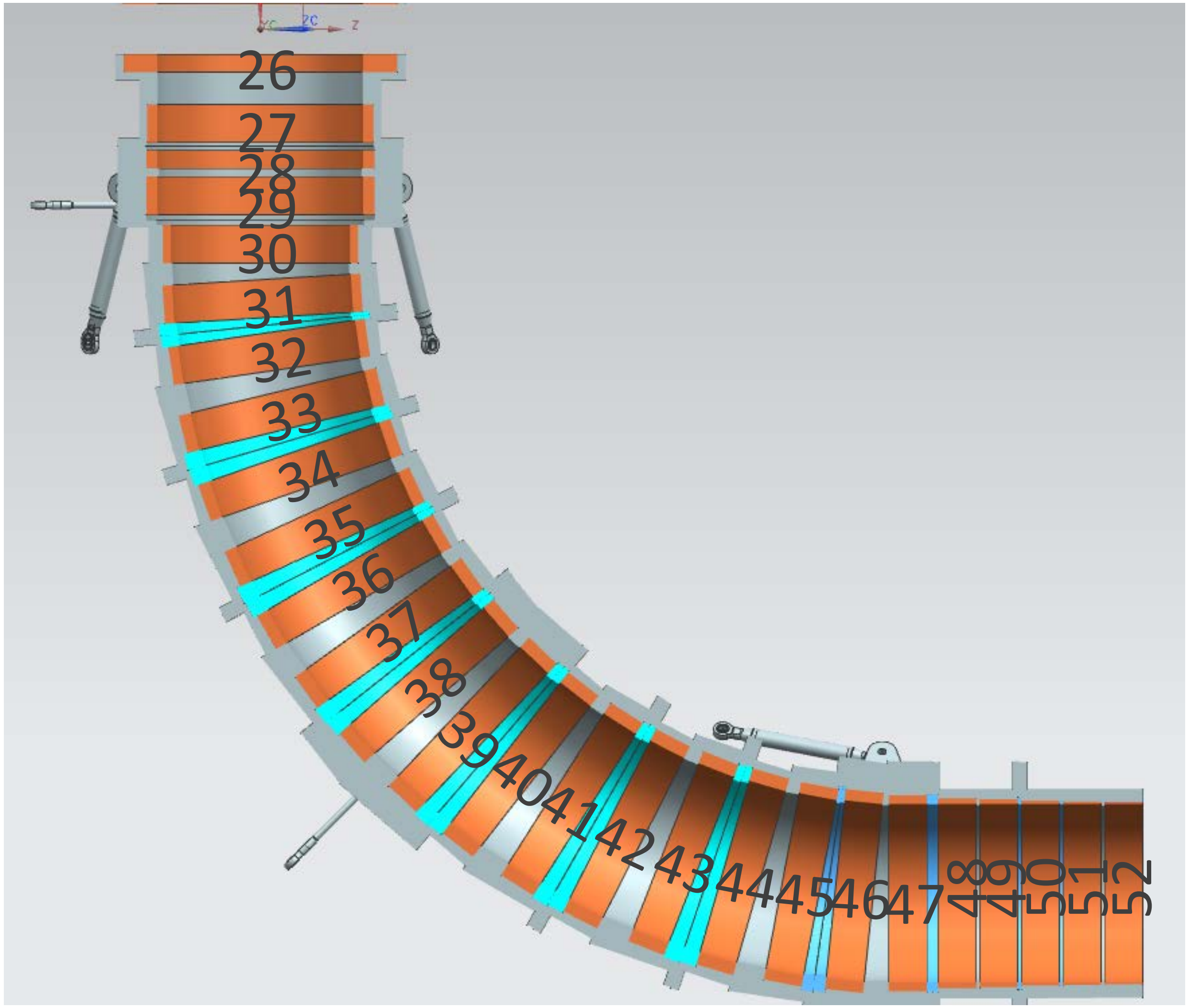
Design – TSu Coil Modules



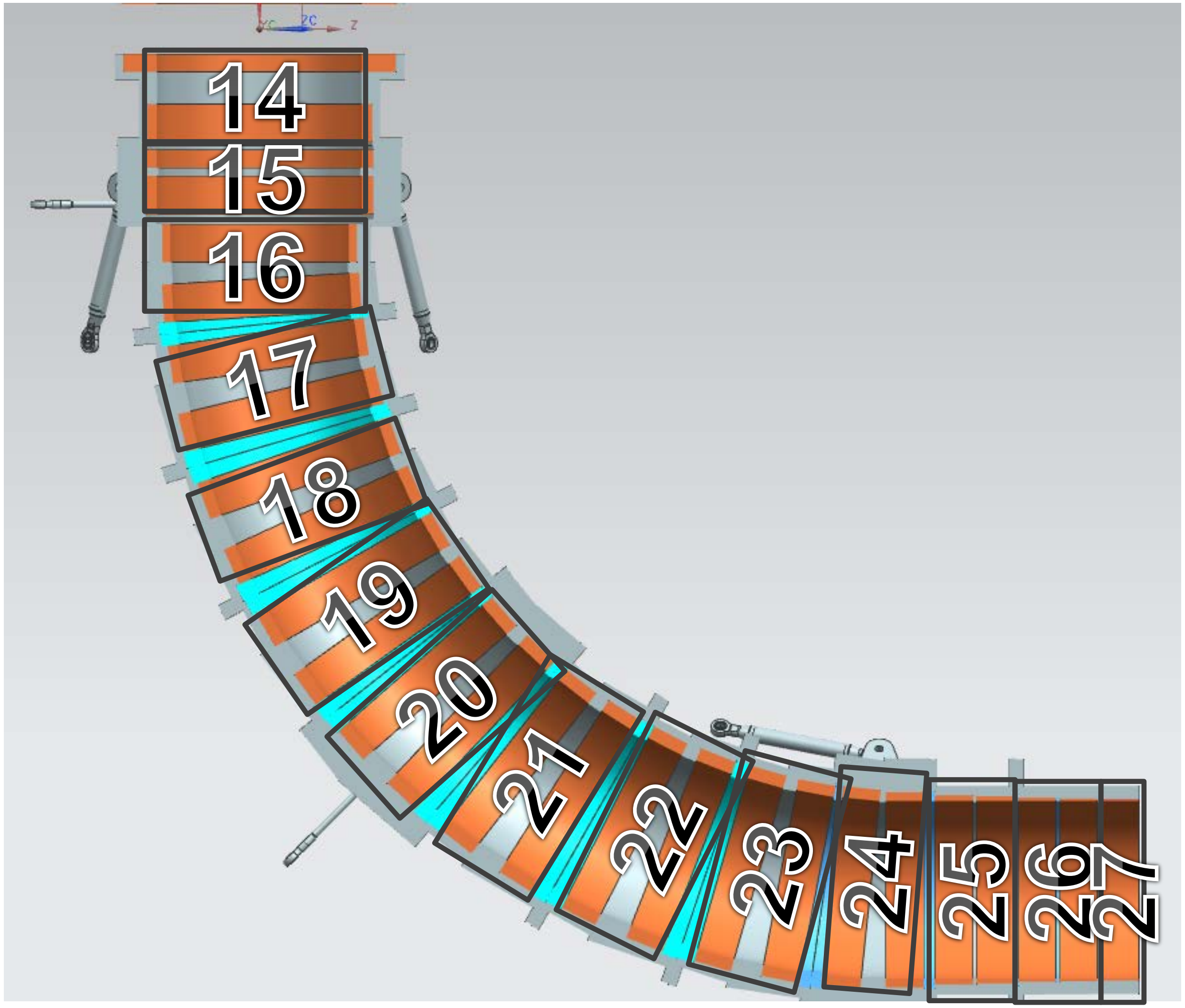
Design – TSu Test Units



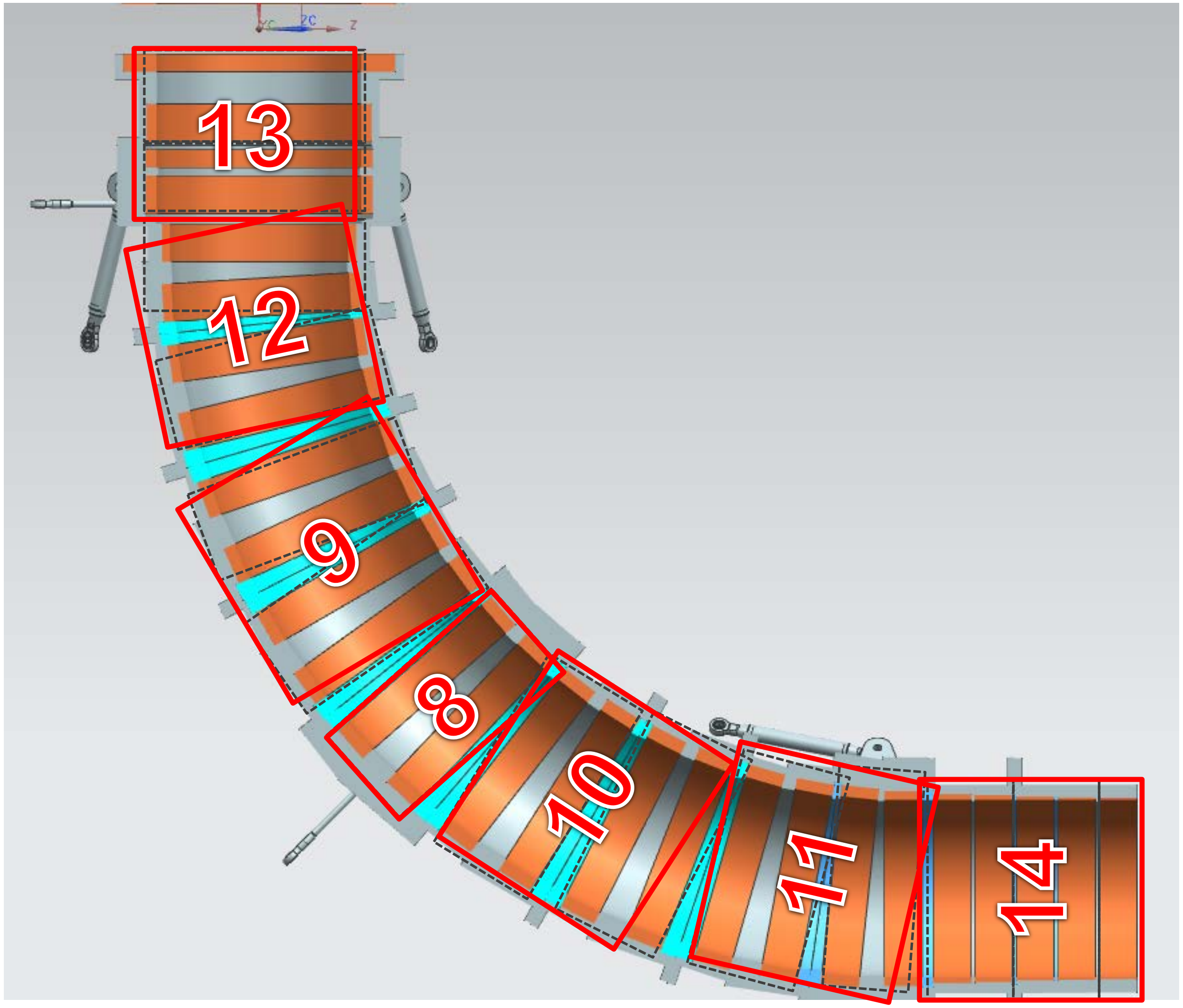
Design – TSd Coils



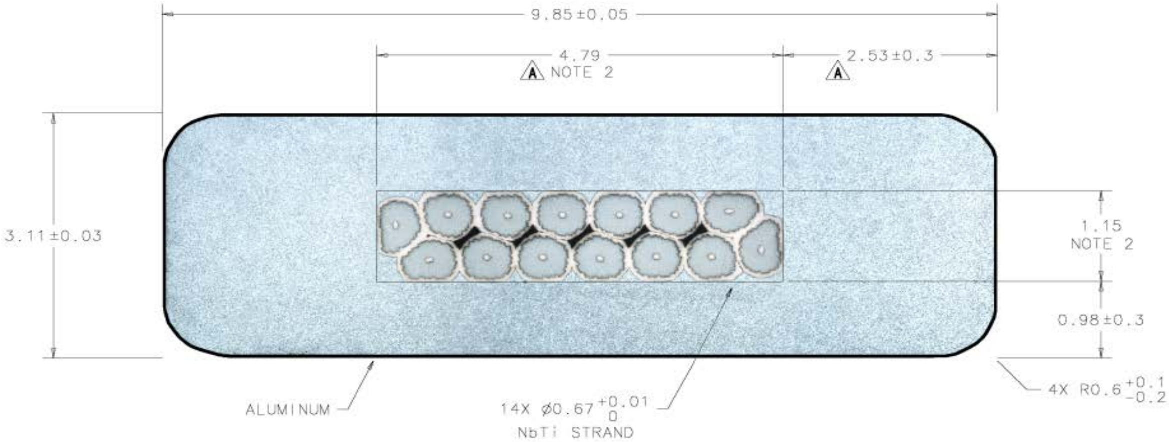
Design – TSd Coil Modules

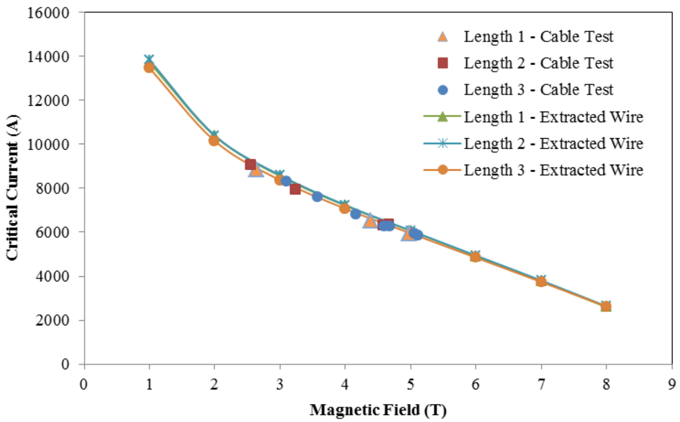


Design – TSd Test Units



Design - Conductor





Conductor Parameter	Unit	Design Value	Measured Value
Cable critical current at 5T, 4.2K	A	5900	5950-6300
Number of strands		14	
Strand diameter	mm	0.67	within tolerances
Strand copper/SC ratio		1 ± 0.05	0.97-1.02
Initial RRR of Cu matrix		150	100-104
Filament size	µm	< 30	25.5-25.7
Strand twist pitch	mm	15 ± 2	15.8-15.9
Rutherford cable width	mm	4.79 ± 0.01	within tolerances
Rutherford cable thickness	mm	1.15 ± 0.006	within tolerances
Al-stabilized cable width (bare) at room temperature	mm	9.85 ± 0.05	within tolerances
Al-stabilized cable thickness (bare) at room temperature	mm	3.11 ± 0.03	within tolerances
Initial RRR of Aluminum stabilizer		> 800	925-1160
Aluminum 0.2% yield strength at 300 K	MPa	> 30	45-56
Aluminum 0.2% yield strength at 4.2 K	MPa	> 40	74-84
Shear strength between Aluminum and NbTi strands	MPa	> 20	35-46

I_{op} = 1730 A

J_{eng} ~ 50 A/mm^2

I_{op}/I_c ~= 58% (at 5.1 K, 3.4 T)

Temp margin = 1.5 K

Successful conductor prototype program completed.

The PO was placed in July 2014

Conductor delivery / Module fabrication

Test Sequence	Module #	TS Coil #	Length	Length units code	Batch delivery S	Batch delivery L	Section #	Magnet
6	1	1	252	L1	-	2	TS1	TSu
		2	560	L2	-	1		
	2	3	513	L3	-	2		
4	3	4	594	L4	-	2	TS2	
		5	594	L5	-	1		
	4	6	594	L6	-	1		
		7	799	S1	2	-		
3	5	8	799	S2	2	-		
		9	799	S3	2	-		
	6	10	799	S4	2	-		
		11	851	L2	-	1		
1	7	12	851	L10	-	1		
		13	851	L11	-	1		
2	8	14	851	L12	-	1		
		15	904	L5	-	1		
	9	16	904	L6	-	1		
		17	904	L7	-	1		
5	10	18	904	L8	-	2		
		19	904	L9	-	2		
	11	20	1010	L3	-	2		
		21	594	L7	-	1		
7	12	22	907	L4	-	2	TS3u	
		23	355	S5	3	-		
	13	24	848	L13	-	3		
		25	1253	L1	-	2		
13	14	26	1220	L14	-	3	TS3d	TSd
		27	732	S6	4	-		
	15	28	382	L13	-	3		
		29	790	S7	4	-		
12	16	30	495	L10	-	1	TS4	
		31	594	L9	-	2		
	17	32	594	L8	-	2		
		33	747	S8	4	-		
9	18	34	747	S9	3	-		
		35	747	S10	3	-		
	19	36	747	S11	3	-		
		37	799	S12	3	-		
8	20	38	799	S13	3	-		
		39	799	S14	3	-		
10	21	40	799	S15	4	-		
		41	799	S16	4	-		
	22	42	799	S17	4	-		
		43	799	S18	4	-		
11	23	44	799	S19	4	-		
		45	696	S20	4	-		
	24	46	696	S21	4	-		
		47	544	L11	-	1		
14	25	48	348	S5	3	-	TS5	
		49	300	L14	-	3		
	26	50	205	L13	-	3		
		51	158	L12	-	1		
	27	52	112	L11	-	1		

Batch #

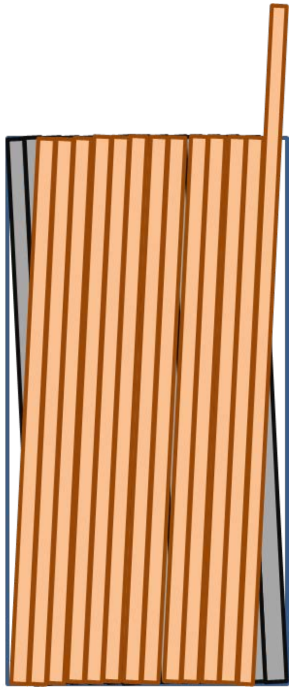
	1	2	3*	4**	
% total	24.6%	24.9%	25.1%	25.4%	
L	7	5	3	1	
S	0	4	8	12	Total (m)
Total length	10780	10900	11020	11140	43840

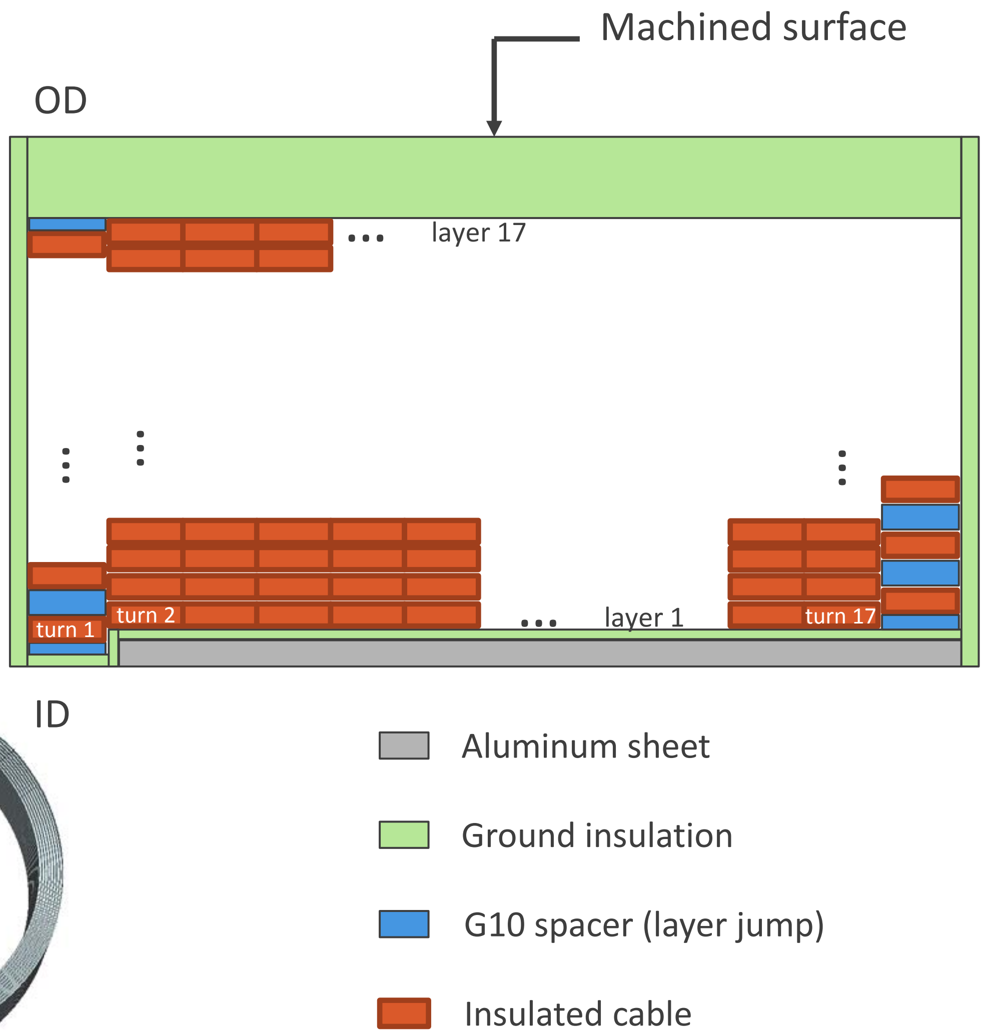
* Long length are 2 + 1 spare

** Long length is a spare. Short lengths are 10 + 2 spares

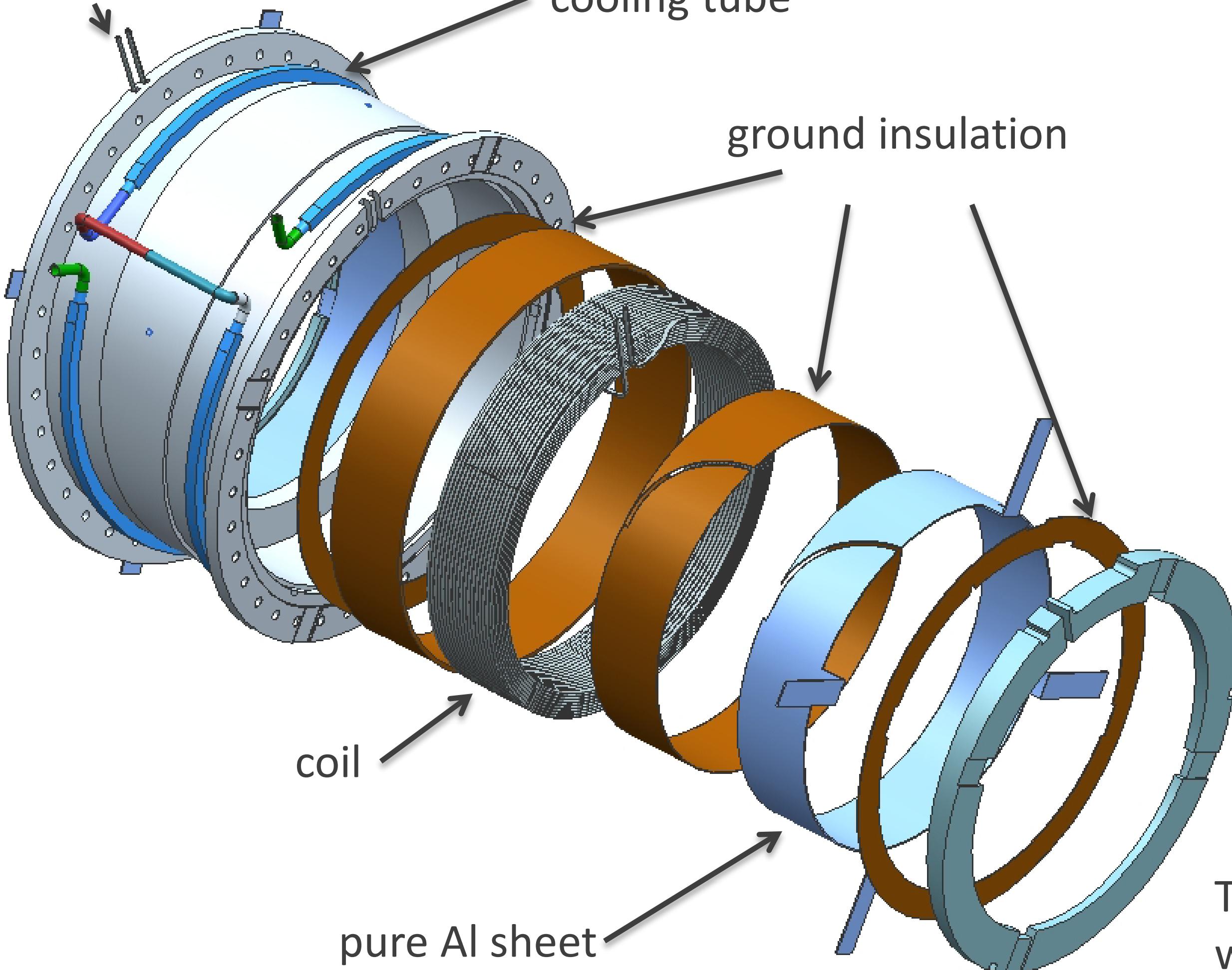
10 % of spare conductor included

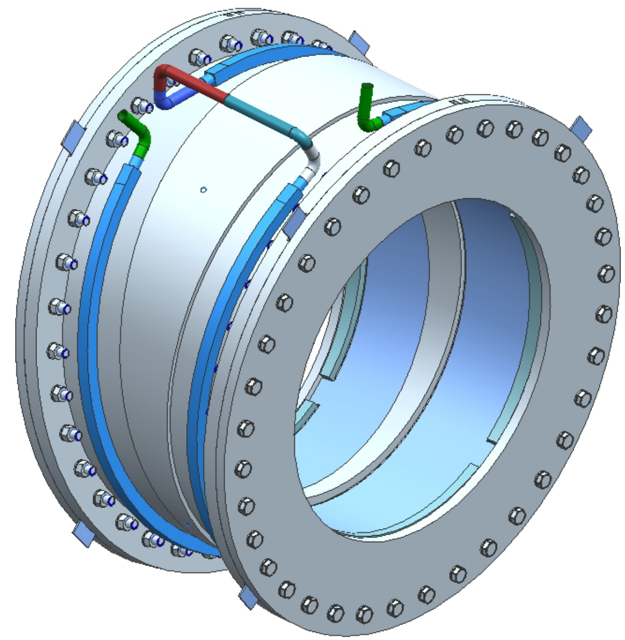
Coil Winding





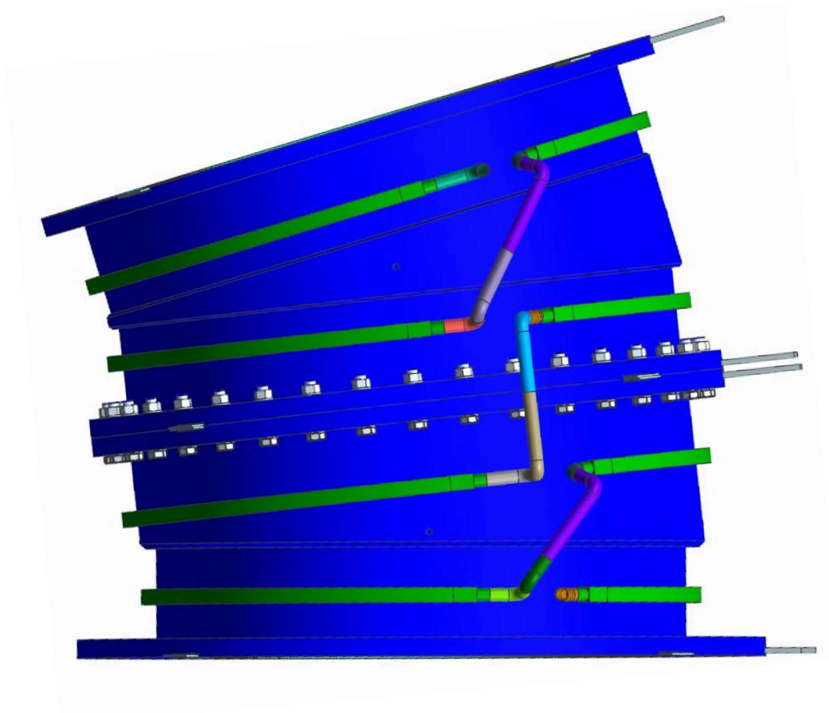
Design – Coil Module

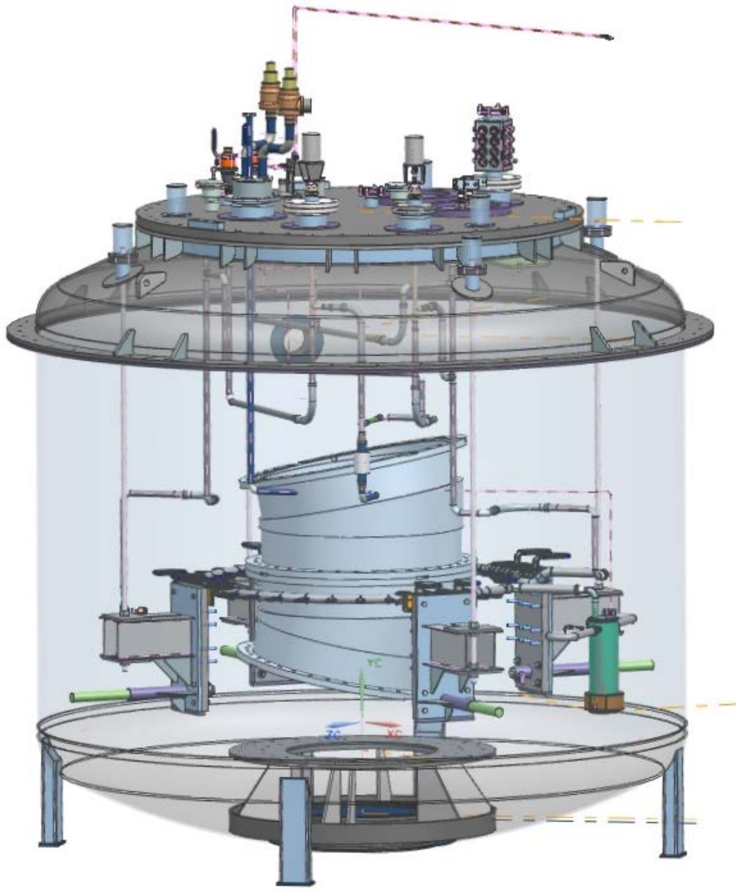




The coils are epoxy impregnated with the ground insulation and the Al sheet.

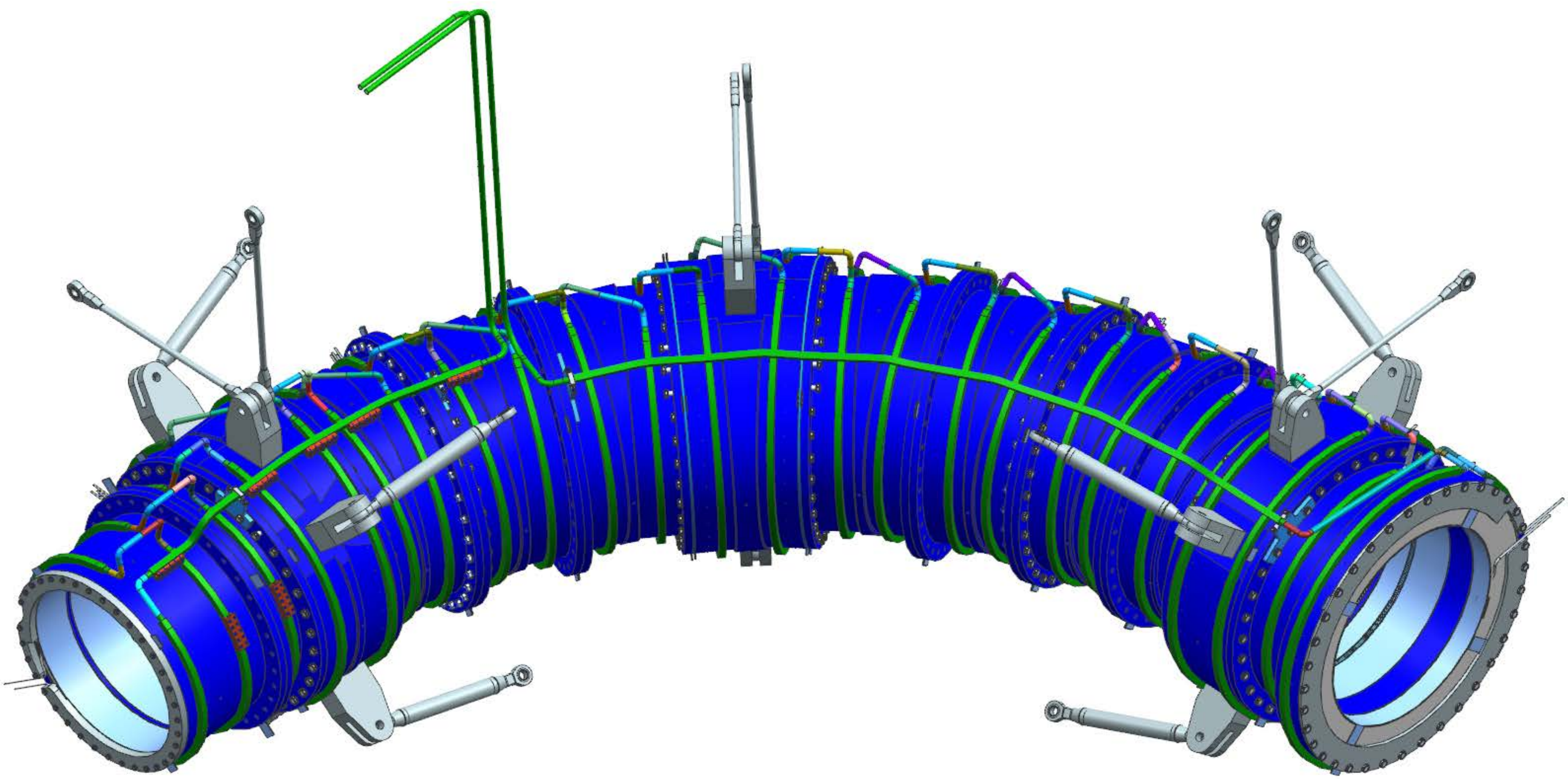
Design - Test units



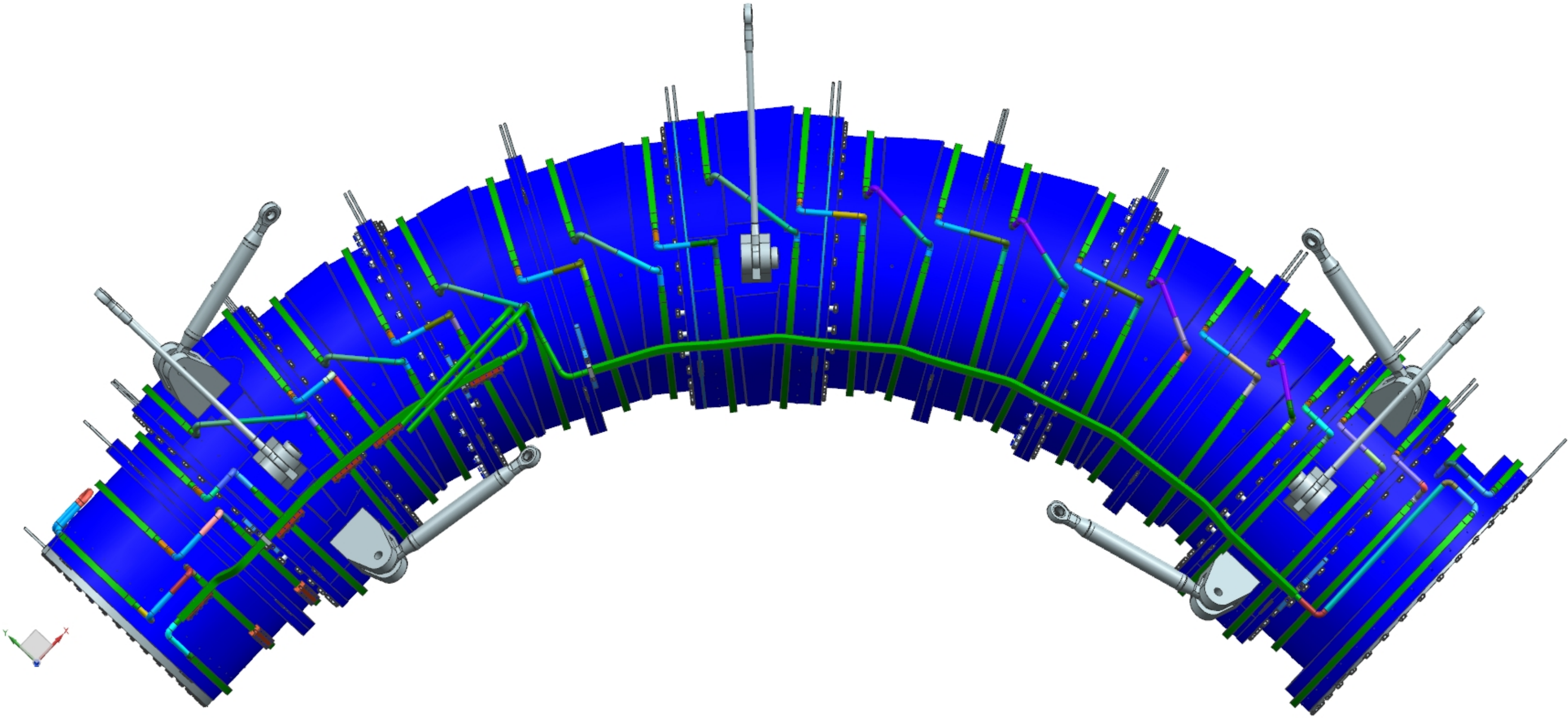


We will test all 52 coils in our test cryostat (in the CHL building).

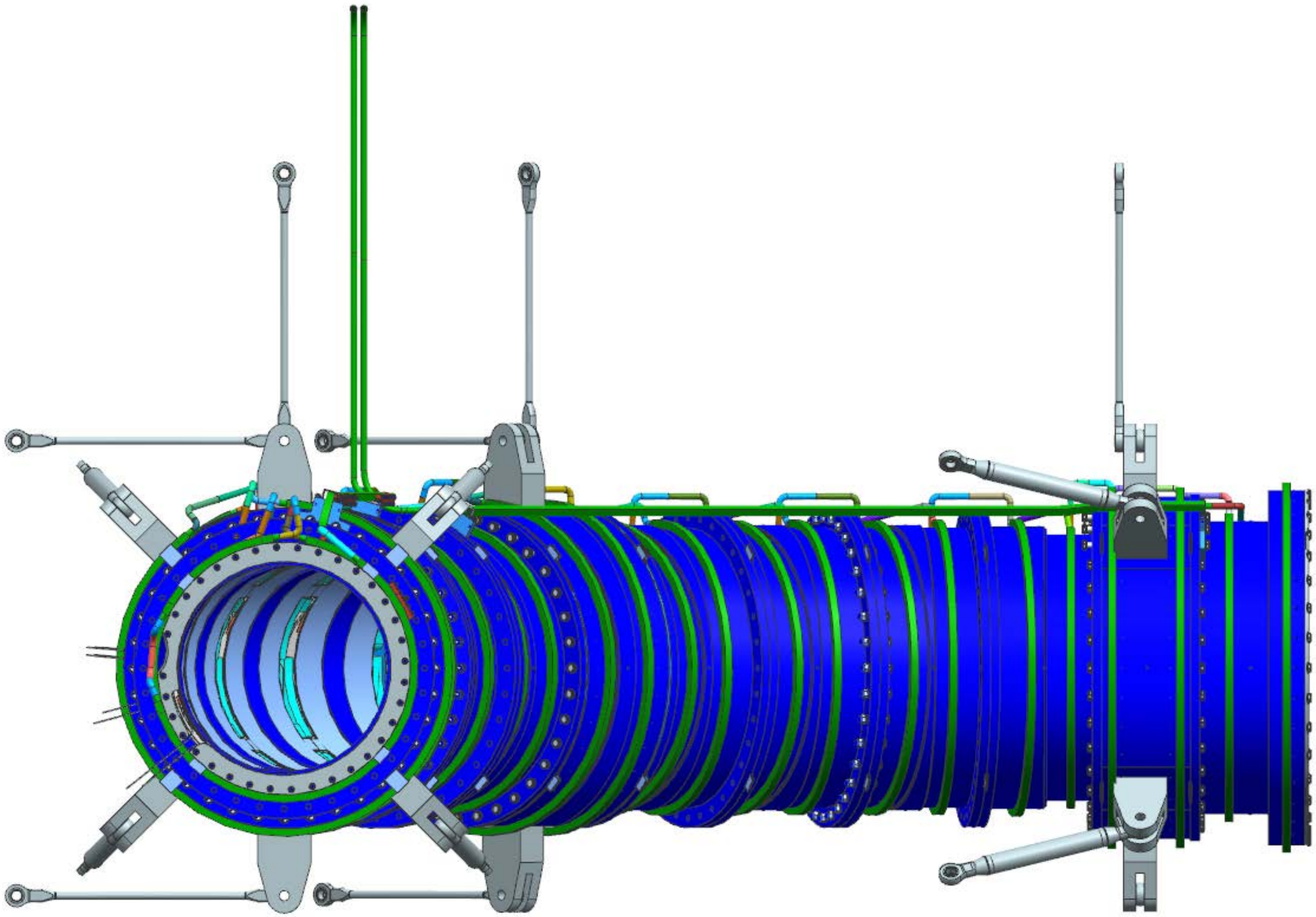
Design – Cold mass assembly



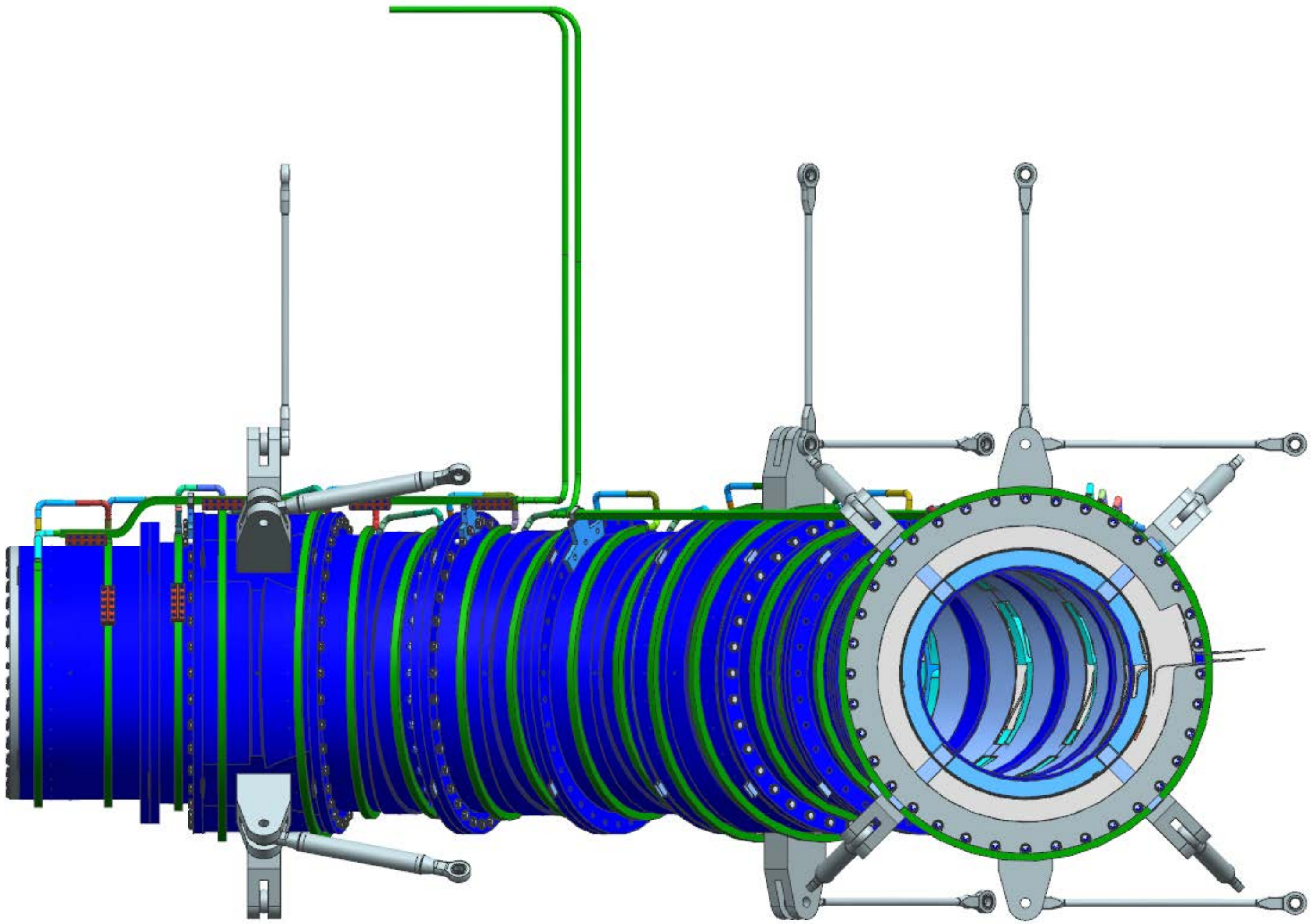
Design – Cold mass assembly



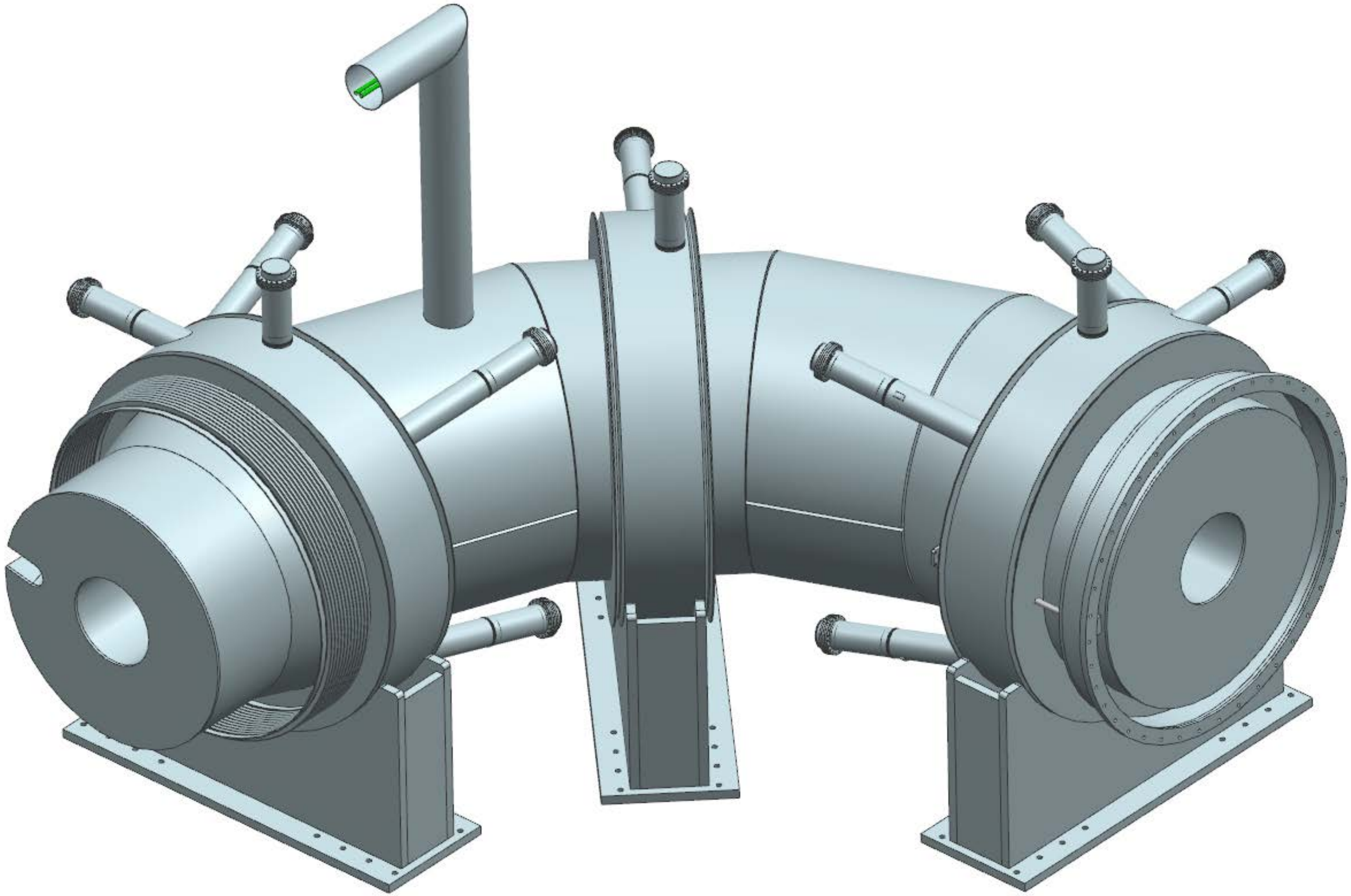
Design – Cold mass assembly



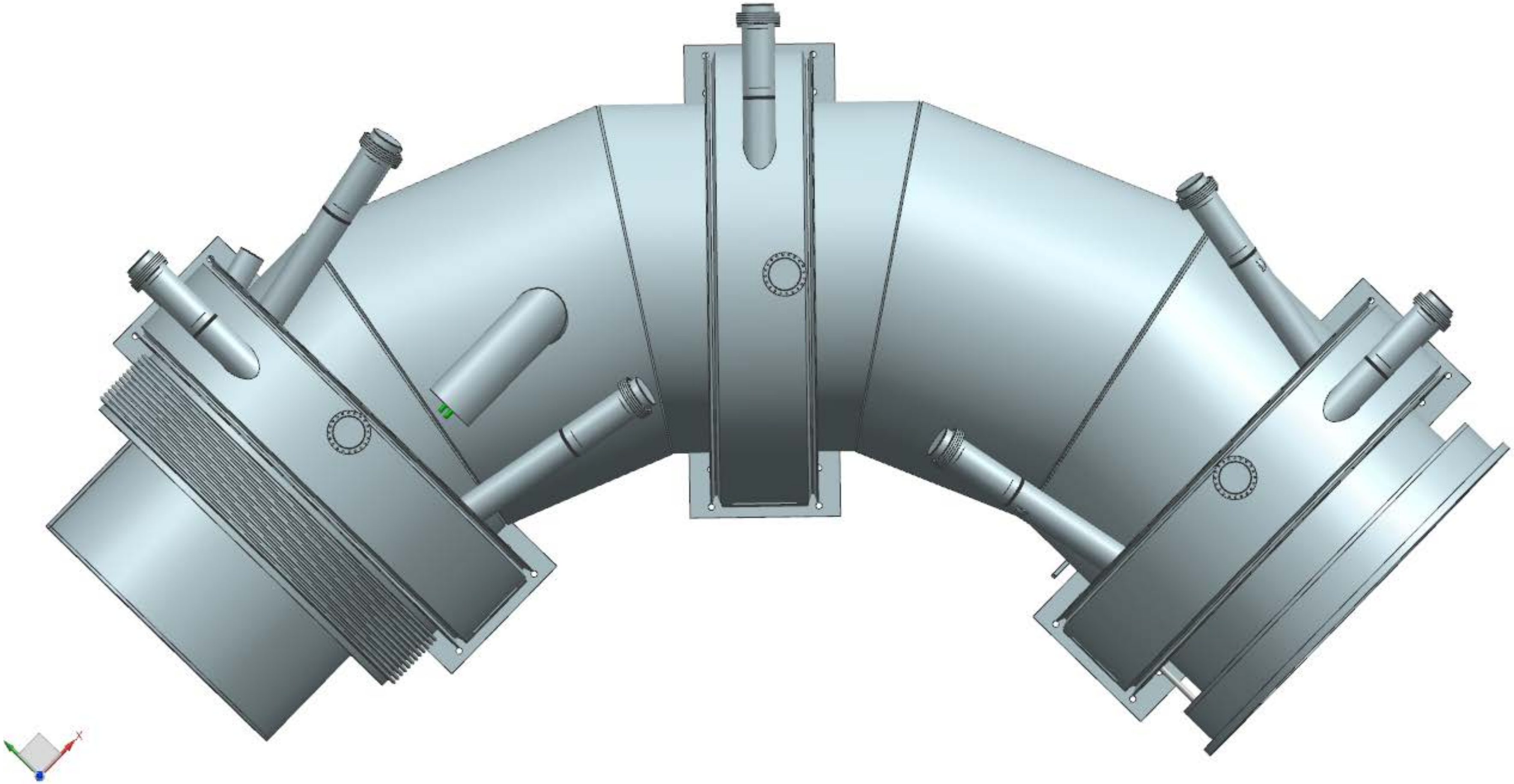
Design – Cold mass assembly



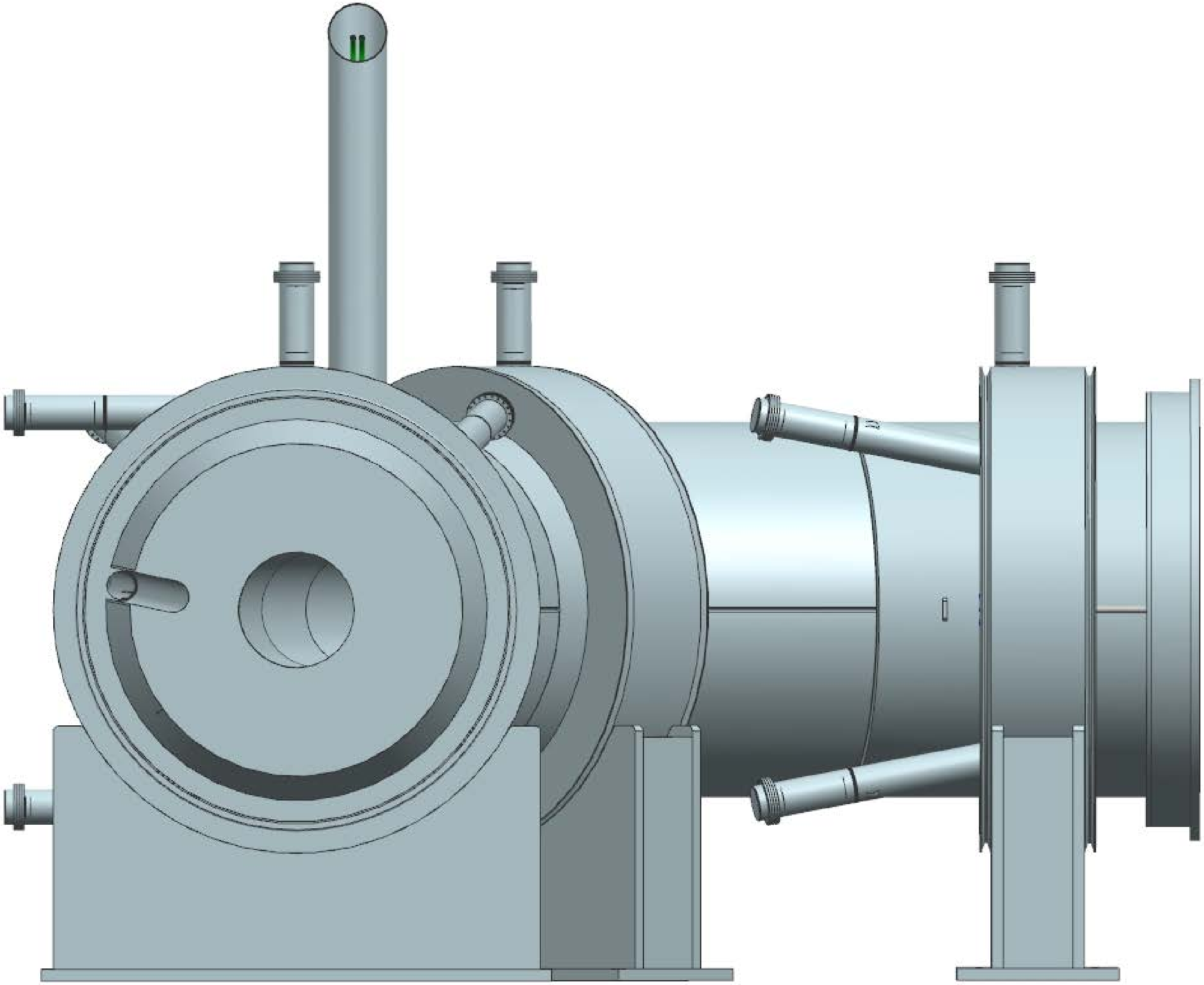
Design – Cryostat assembly



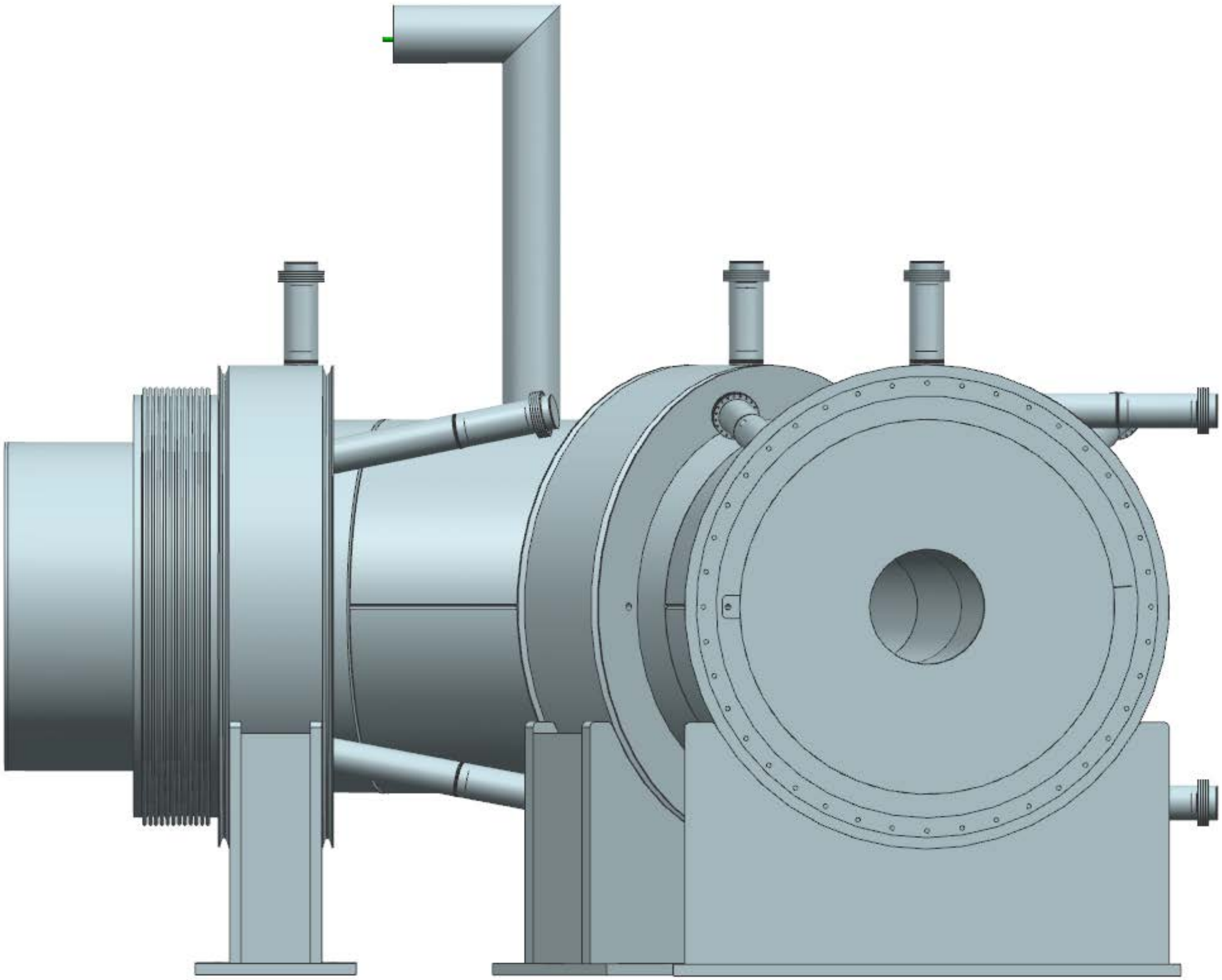
Design – Cryostat assembly



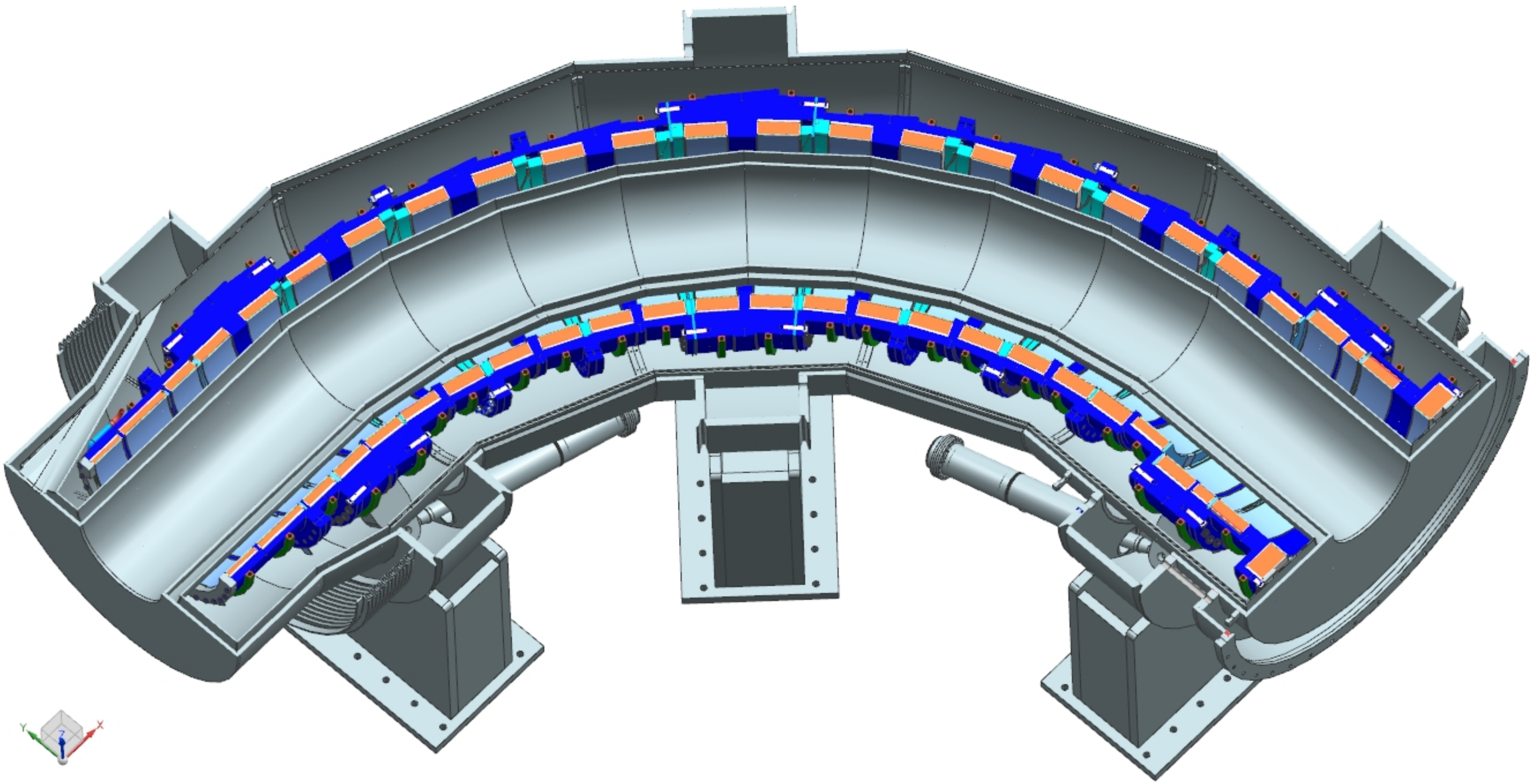
Design – Cryostat assembly



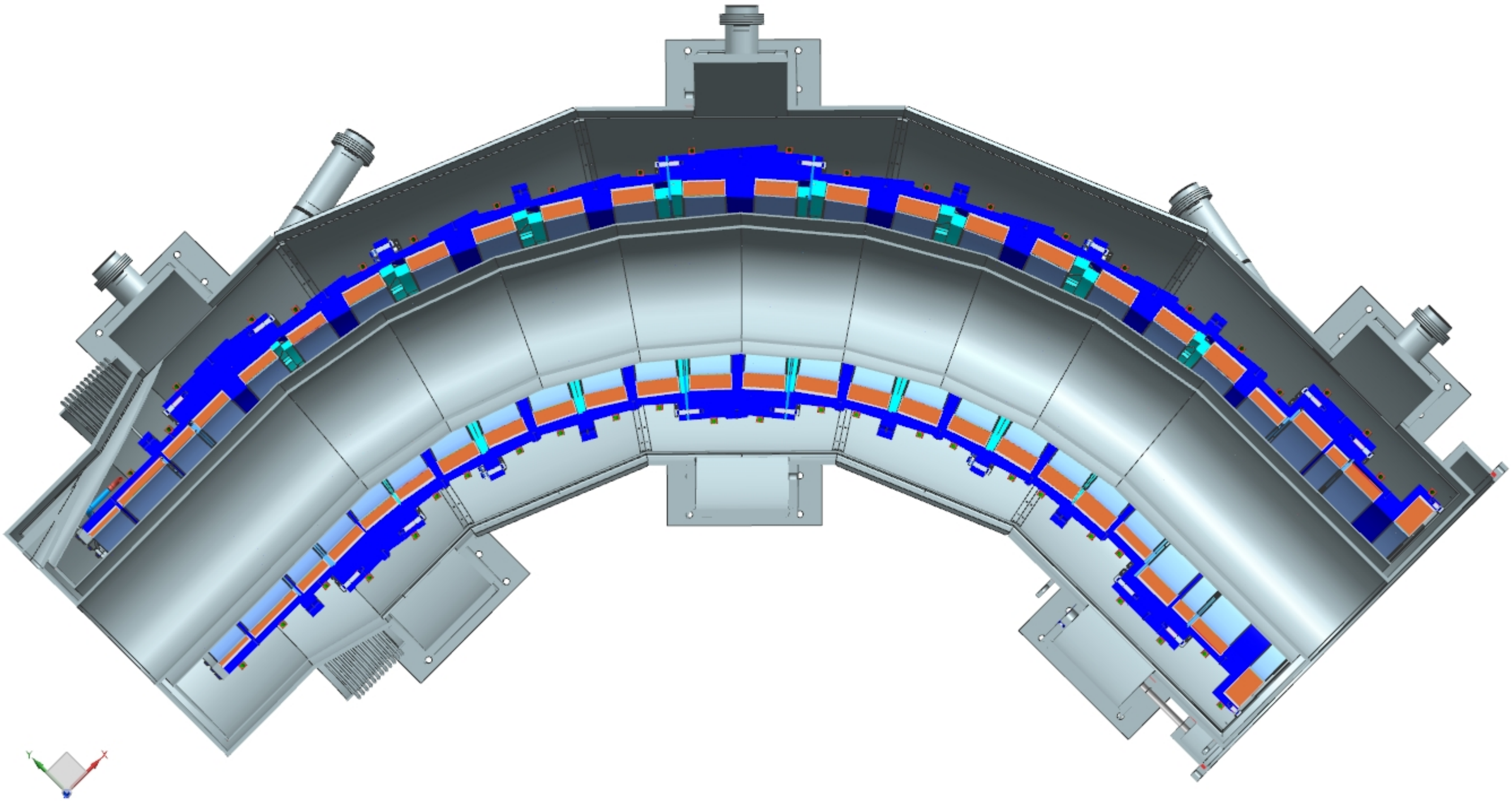
Design – Cryostat assembly



Design – Cryostat assembly

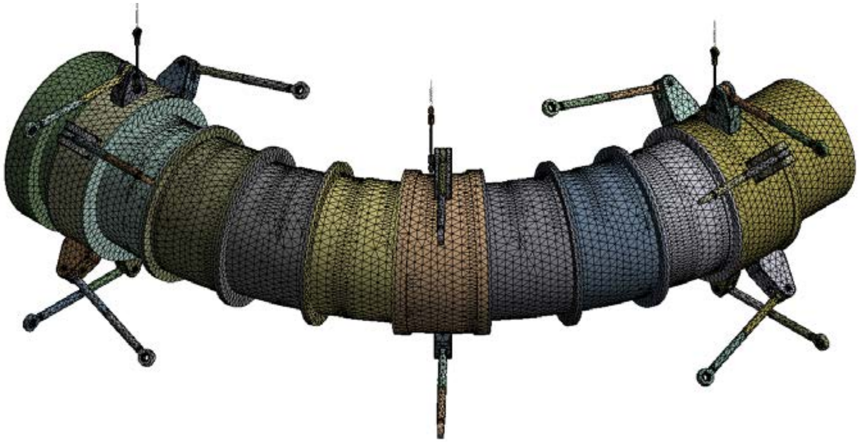


Design – Cryostat assembly

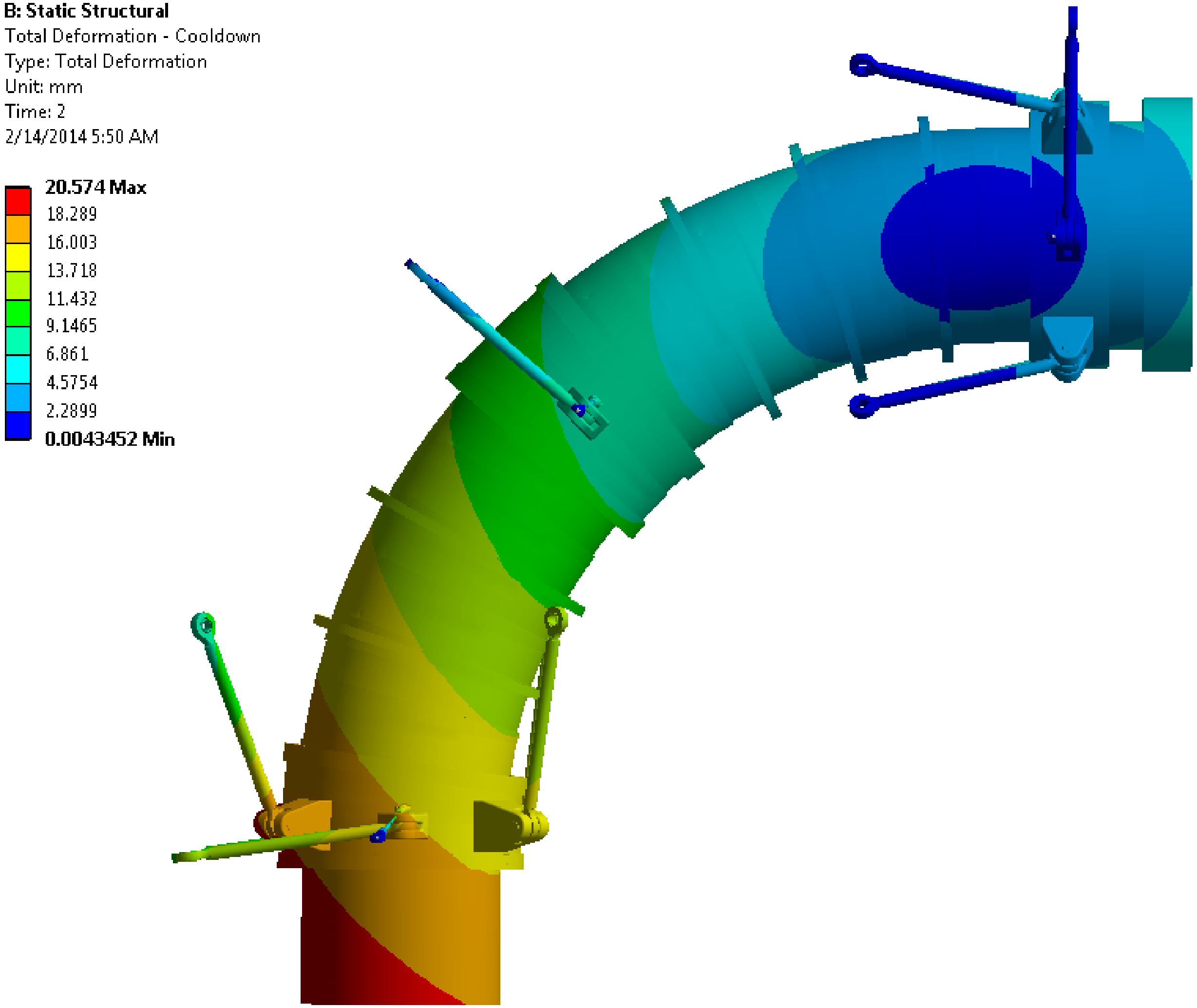


Design – Structural Analysis

- The magnetic forces for each load case were calculated by the ANSYS program and verified by comparison to the Opera forces from the magnetic design work.
- The results of the calculations show that the coils, the support system, cold mass support attachment points, cryostat support attachment points, and cryostat elements are sufficiently strong to withstand the expected loads.

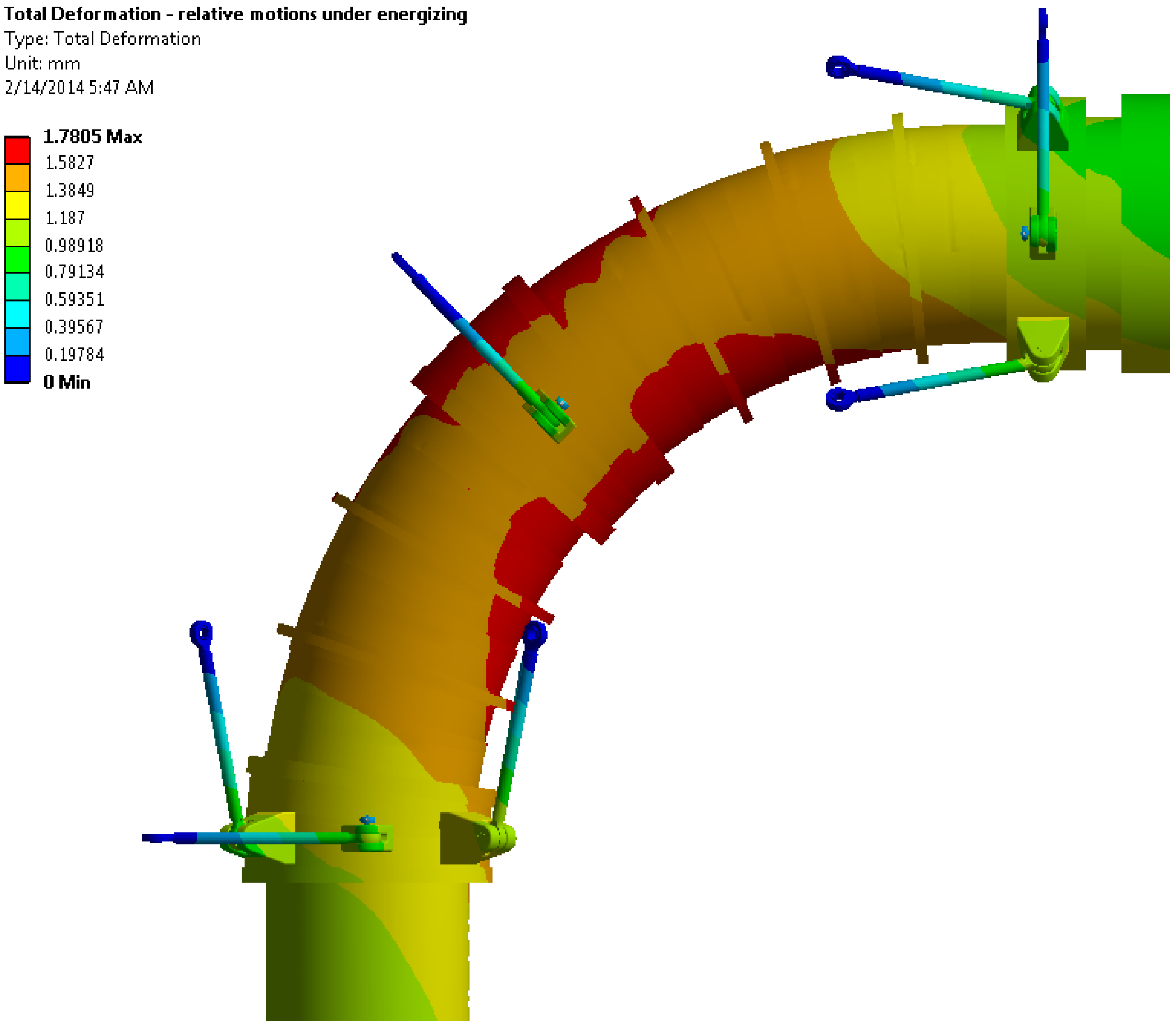


Design – Structural Analysis



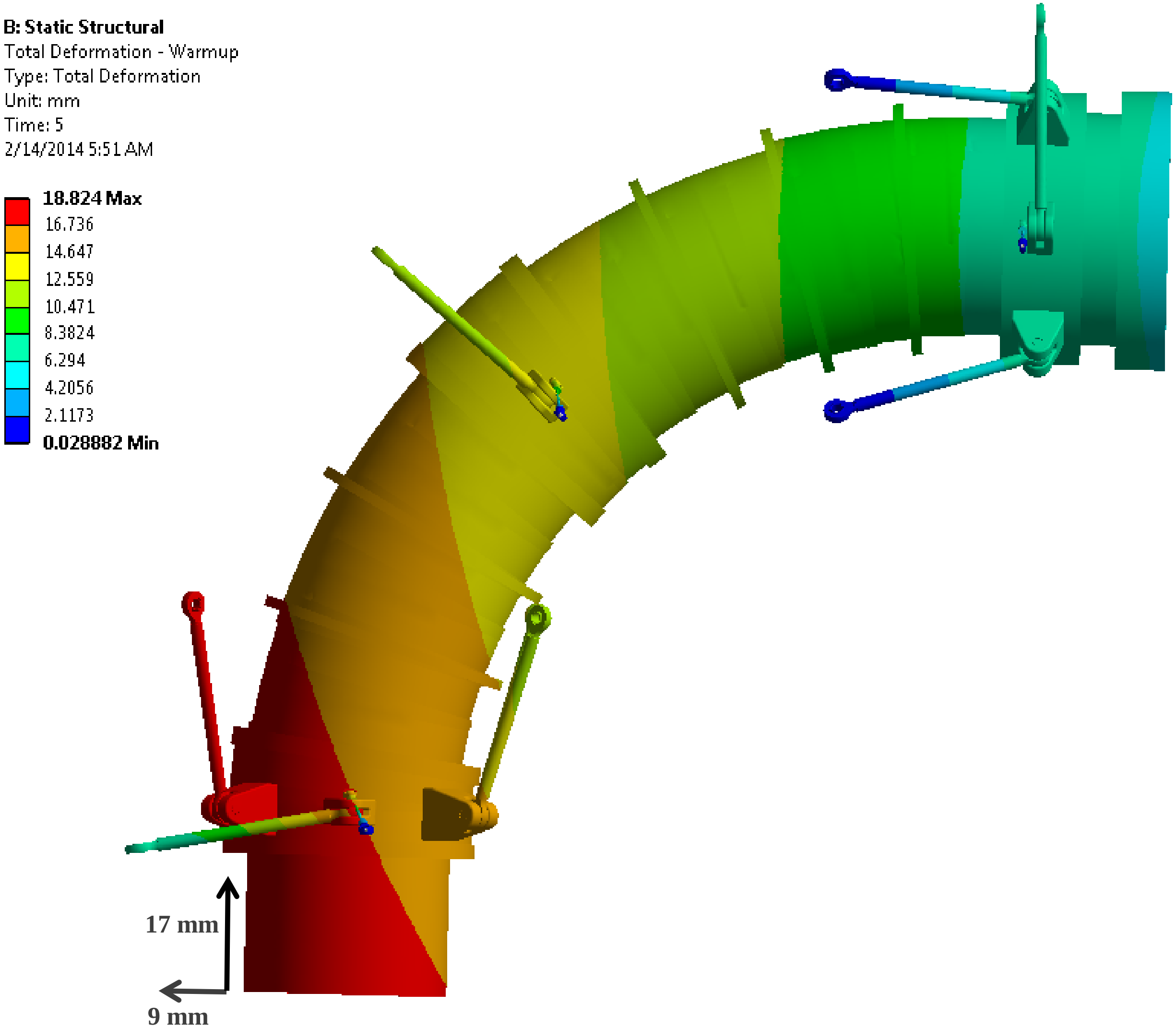
Cold mass displacements due to the cooldown

Design – Structural Analysis



Cold mass displacements due to energization (relative to cool down)

Design – Structural Analysis



Cold mass displacements due to the warm up

Design – Structural Analysis

Support	Load Case		
	Normal Operation	PS off	TSd Off
Upstream Axial 1	158	0	250
Upstream Axial 2	169	0	262
Upstream Axial 3	151	0	208
Upstream Axial 4	164	0	220
Downstream Axial 1	175	371	***-121***
Downstream Axial 2	176	**374**	*-119*
Downstream Axial 3	192	294	*-62*
Downstream Axial 4	204	309	*-53*
Upstream Radial 1	159	51	70
Upstream Radial 2	154	18	64
Downstream Radial 1	140	0	94
Downstream Radial 2	134	3	88
Center Radial 1	283	14	165
Center Radial 2	263	18	145
Gravity 1	24	24	24
Gravity 2	28	27	28
Gravity 3	20	19	20

in kN

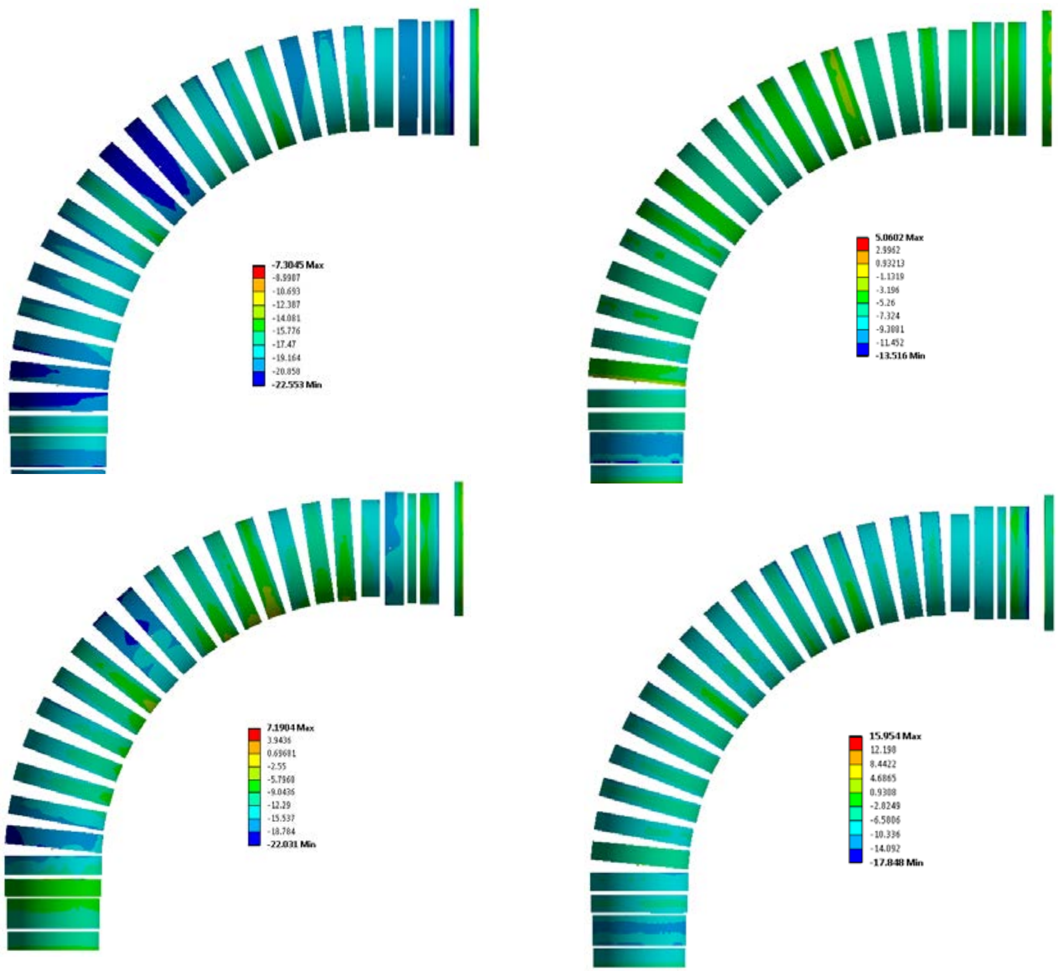
Design Values

Maximum tension	414 kN
Maximum compression	-169 kN

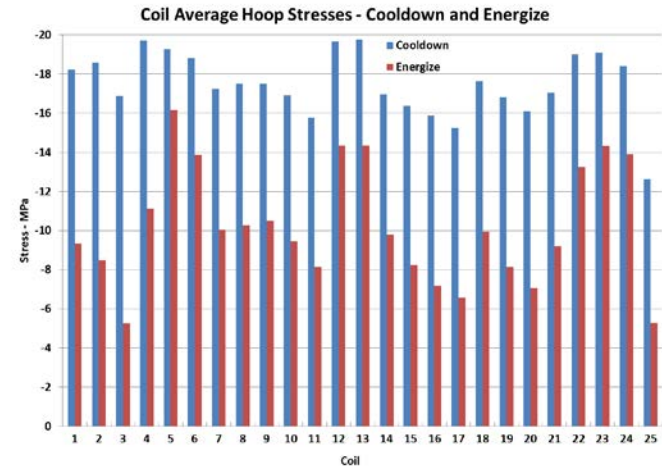
Design – Structural Analysis

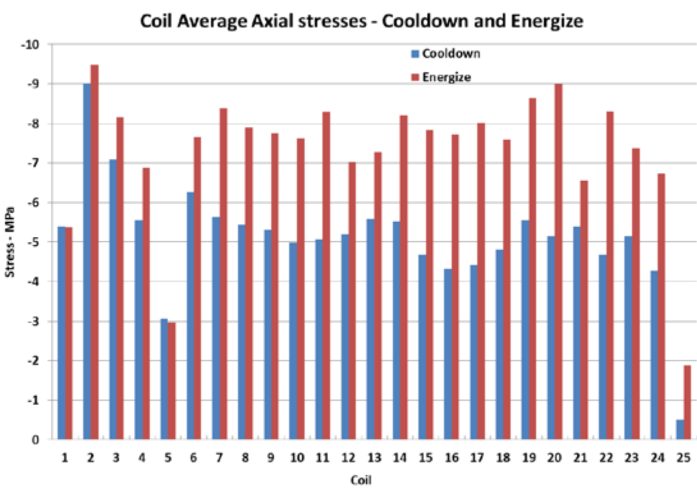
Hoop stress | Axial stress

Cool down / Energize



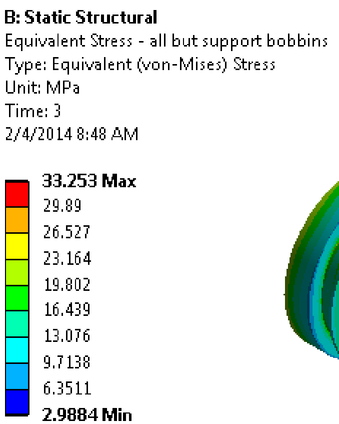
Maximum allowed: 40 MPa

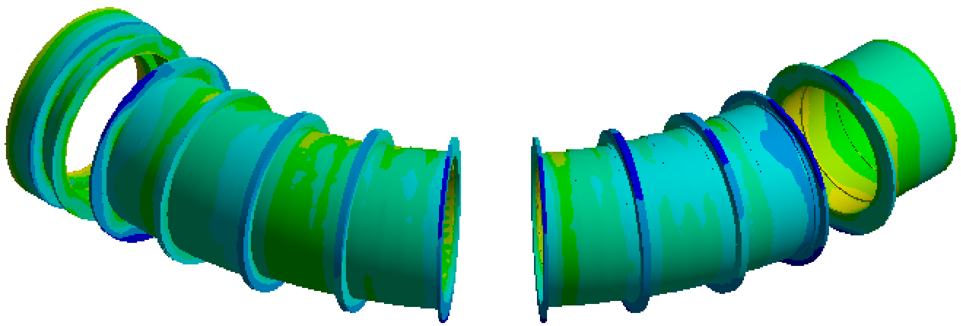




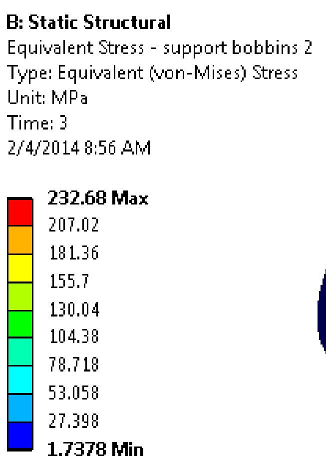
Design – Structural Analysis

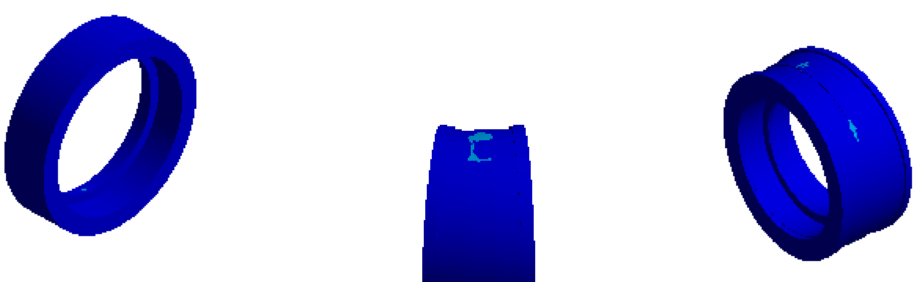
Overall stress are below the maximum allowed: 107 MPa for Al 5083-O



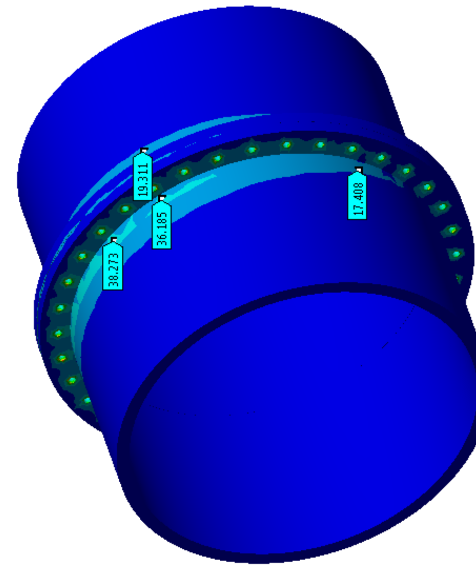


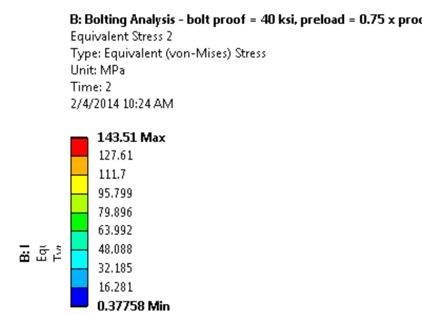
The high stresses are concentrations, numerical artifacts caused by discontinuities in the region of the lug-to-bobbin attachment. This attachment was designed separately using local finite element models and standard weld strength calculations, and not this global cold mass model





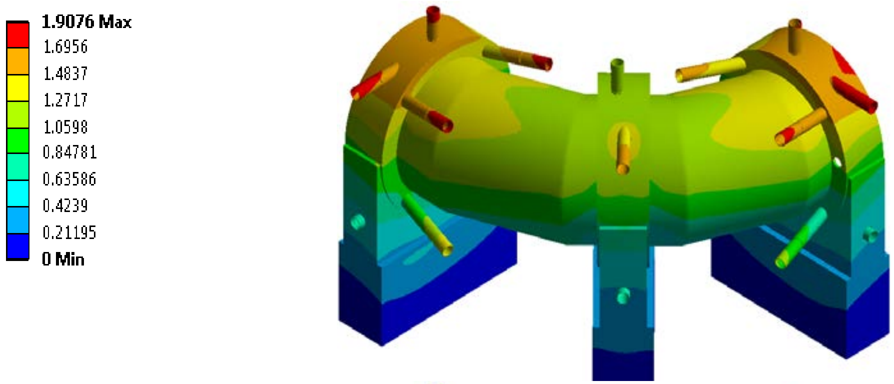
Below 30 MPa



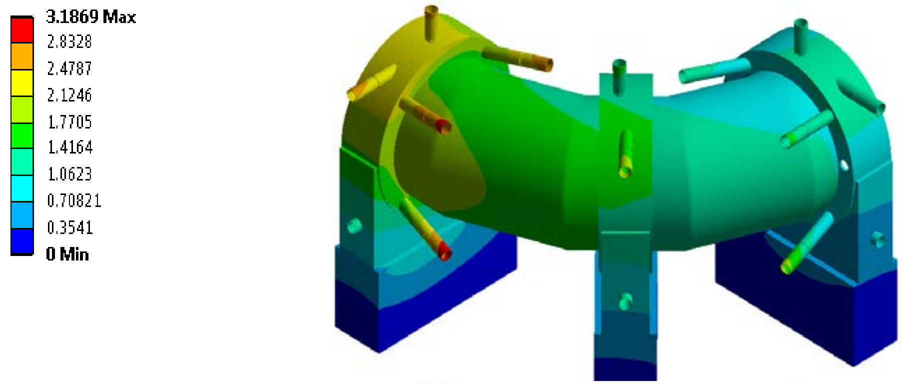


Design – Structural Analysis

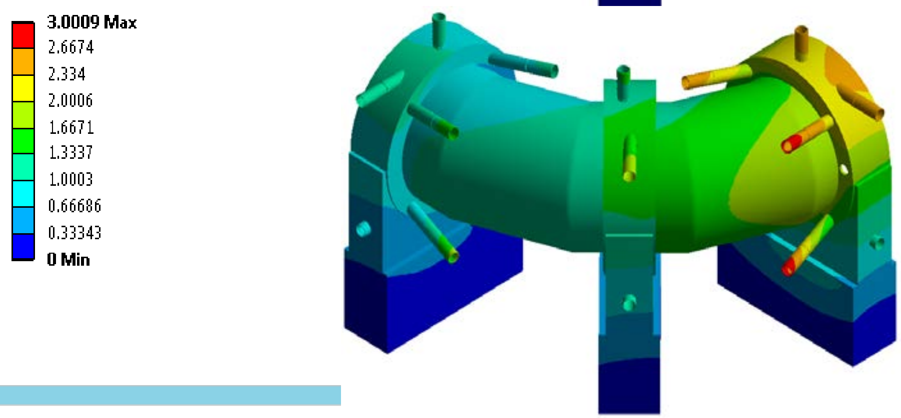
Cryostat displacements (mm)



Normal operation



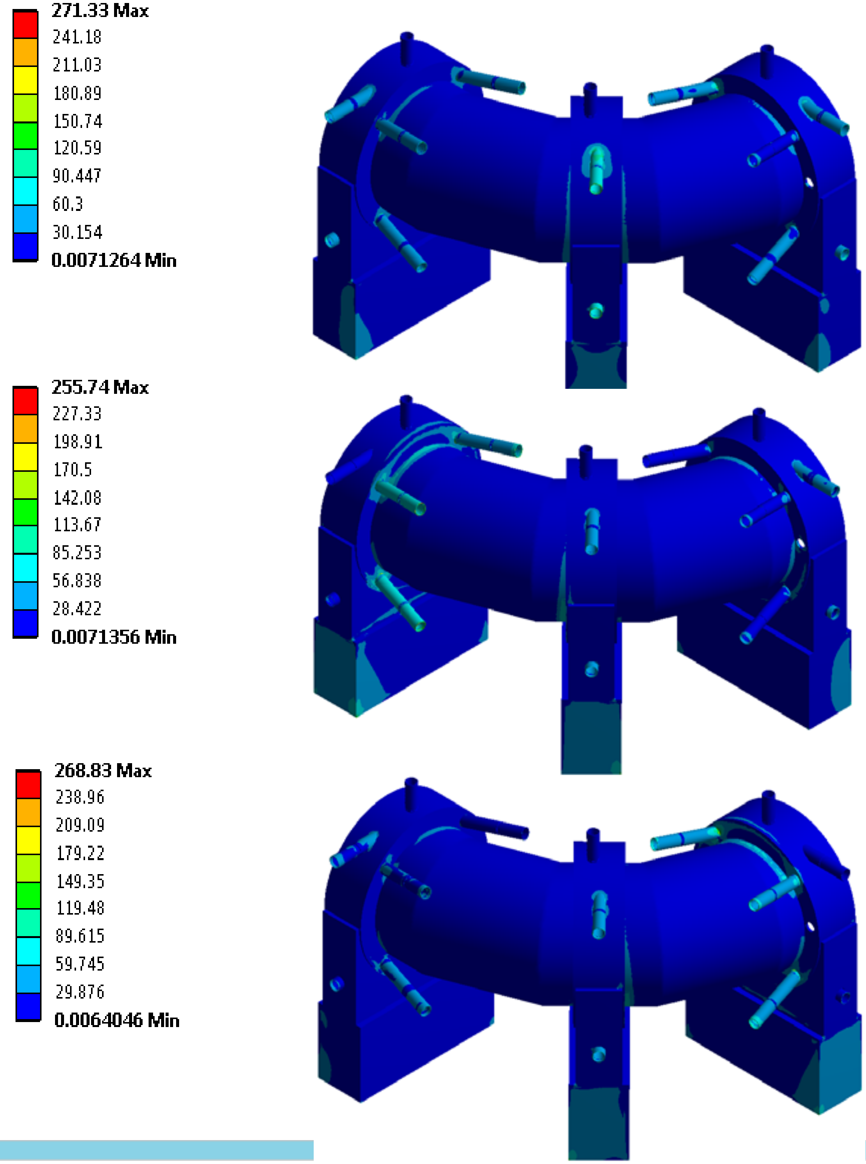
PS Off



TSd Off

Design – Structural Analysis

Cryostat stresses (MPa)



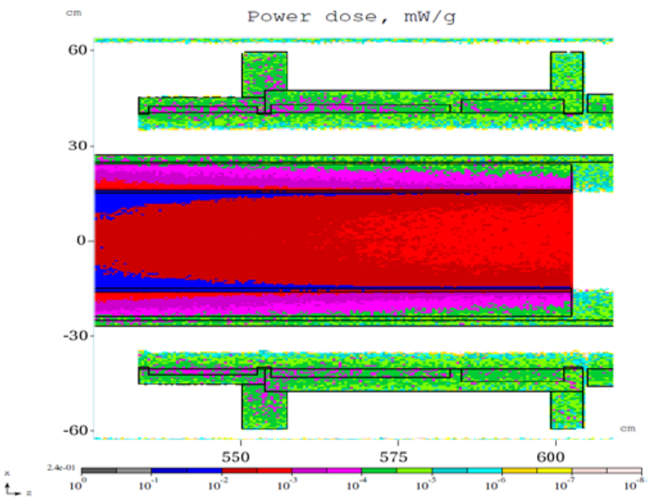
Normal operation

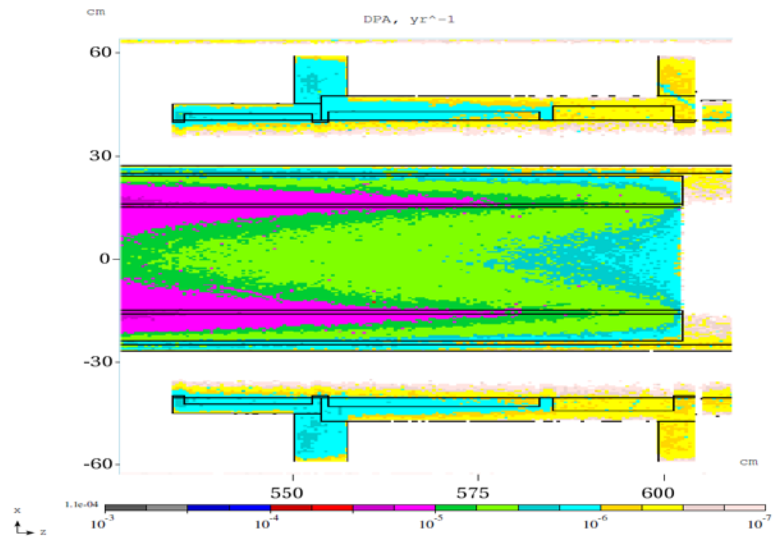
PS Off

TSd Off

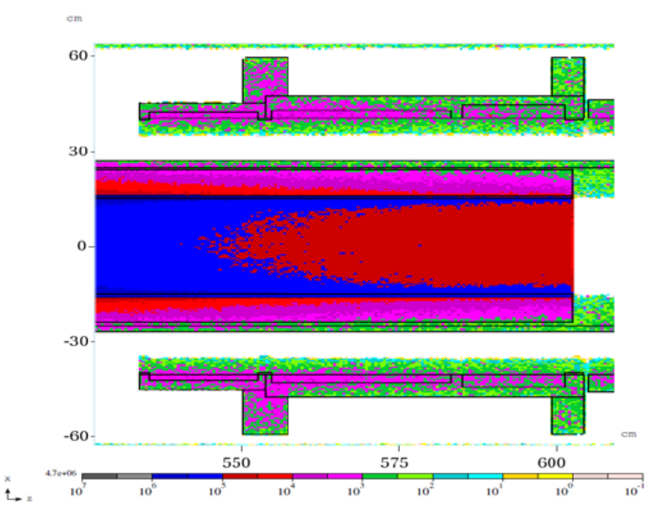
Overall stress are bellow the maximum allowed: 115 MPa for 316L

Design - Radiation analysis





DocDB 4622



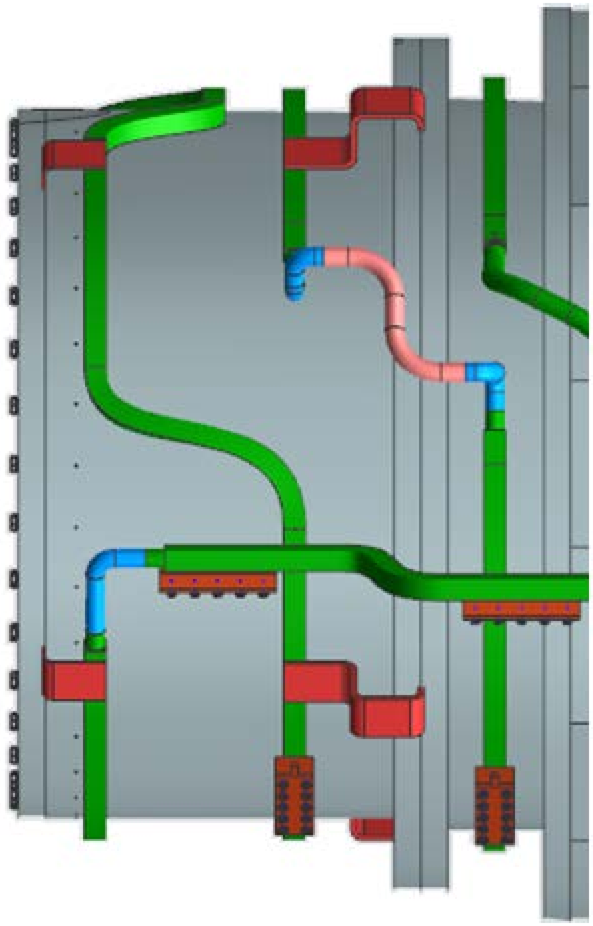
Peak power density $1.3 \cdot 10^{-4}$ mW/g

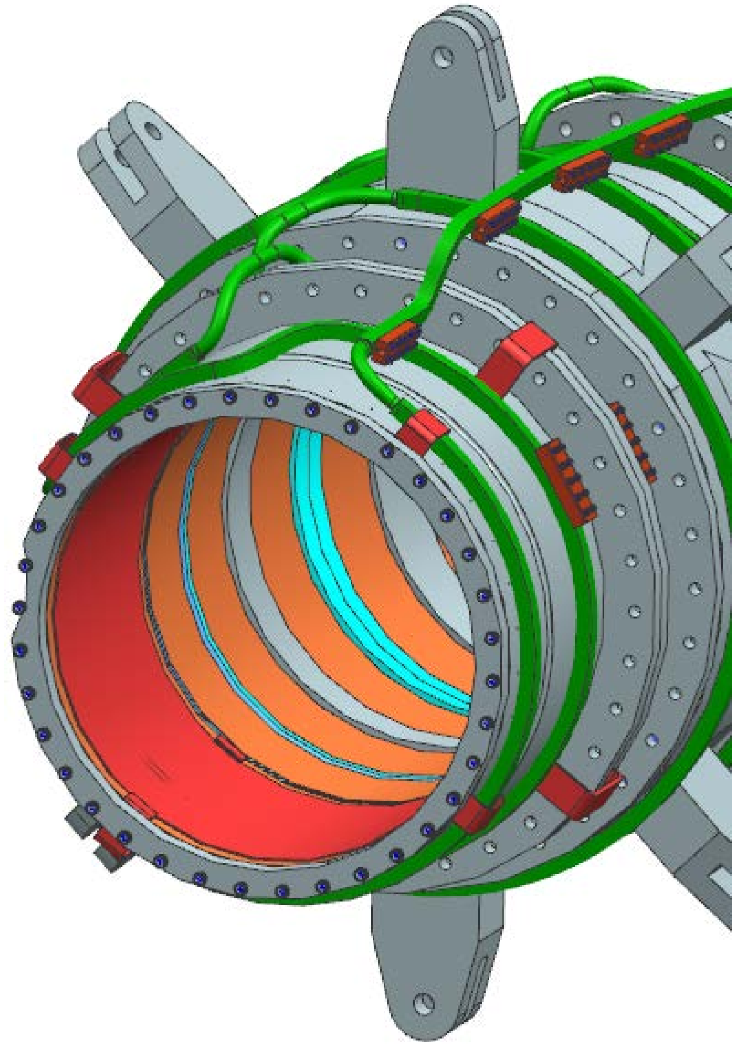
Dose 2.6 kGy/year

DPA $2.6 \cdot 10^{-6}$ (target $<10^{-5}$)

Those numbers give a safety factor around 10

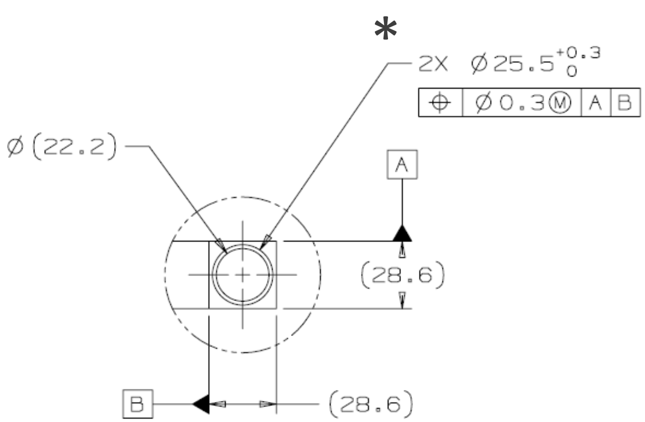
Design – Cooling scheme analysis



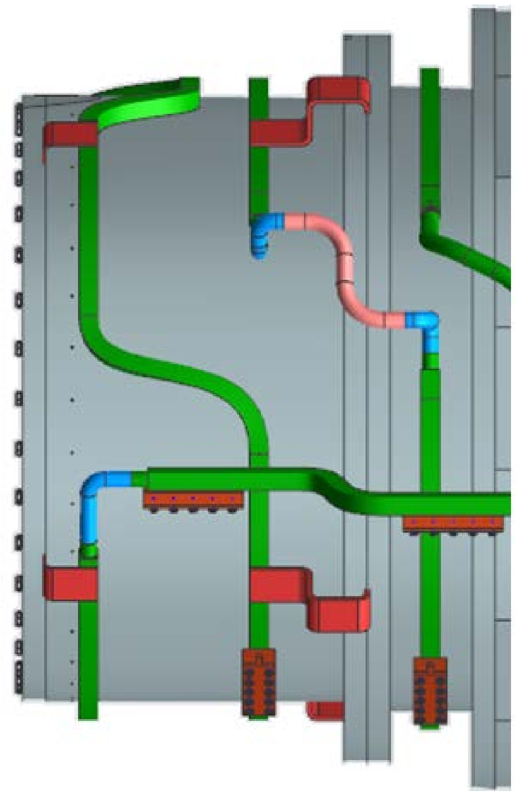


Design – Cooling scheme analysis

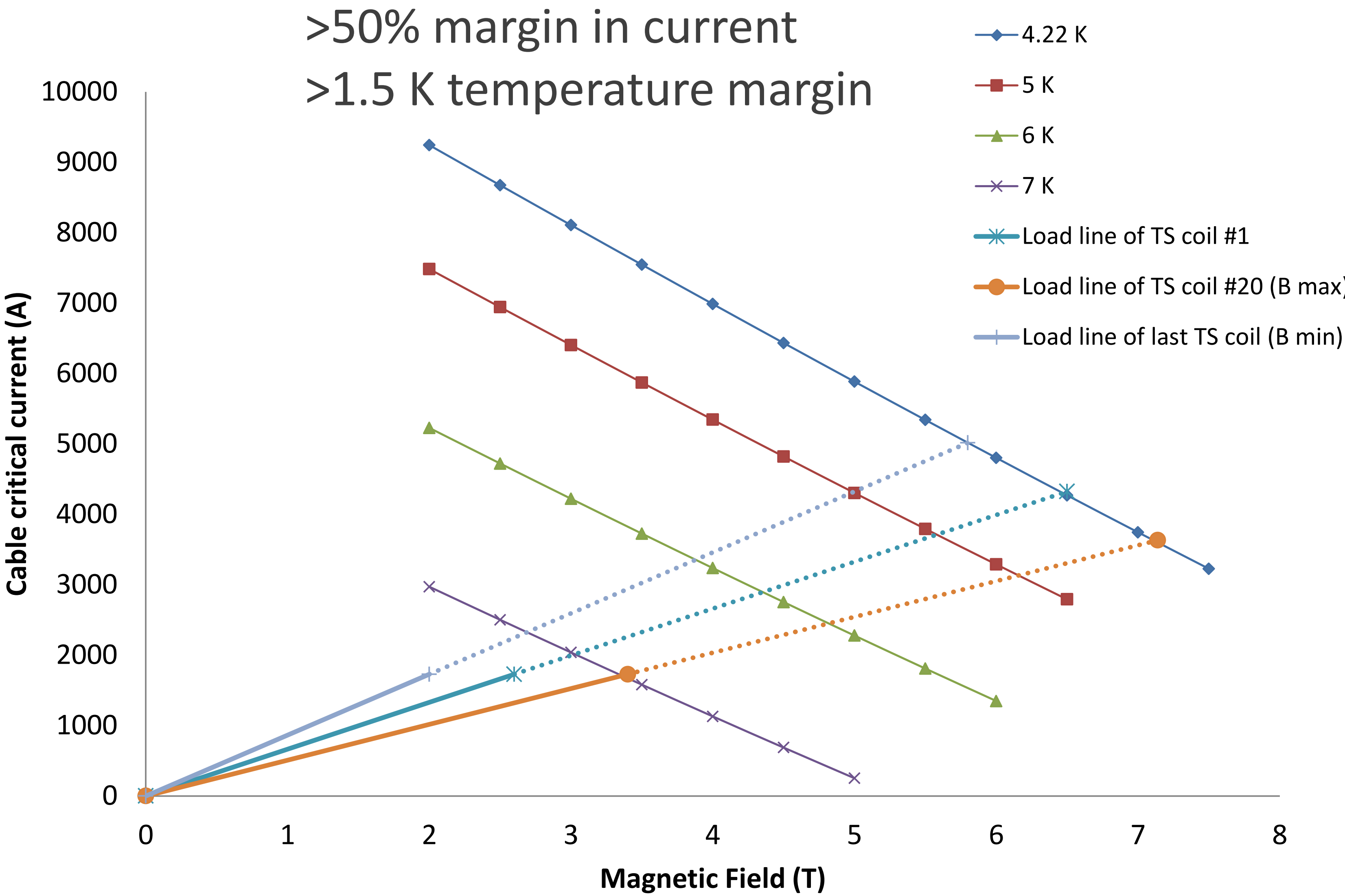
- Helium inlet parameters:
  - T=4.7[K],
  - P=3e5[Pa],
  - flow rate=0.050[kg/s].
- Cooling tube:
  - ID=0.021[m],
  - L~110[m],
  - L_eq~150[m],
  - dP~5e3Pa.



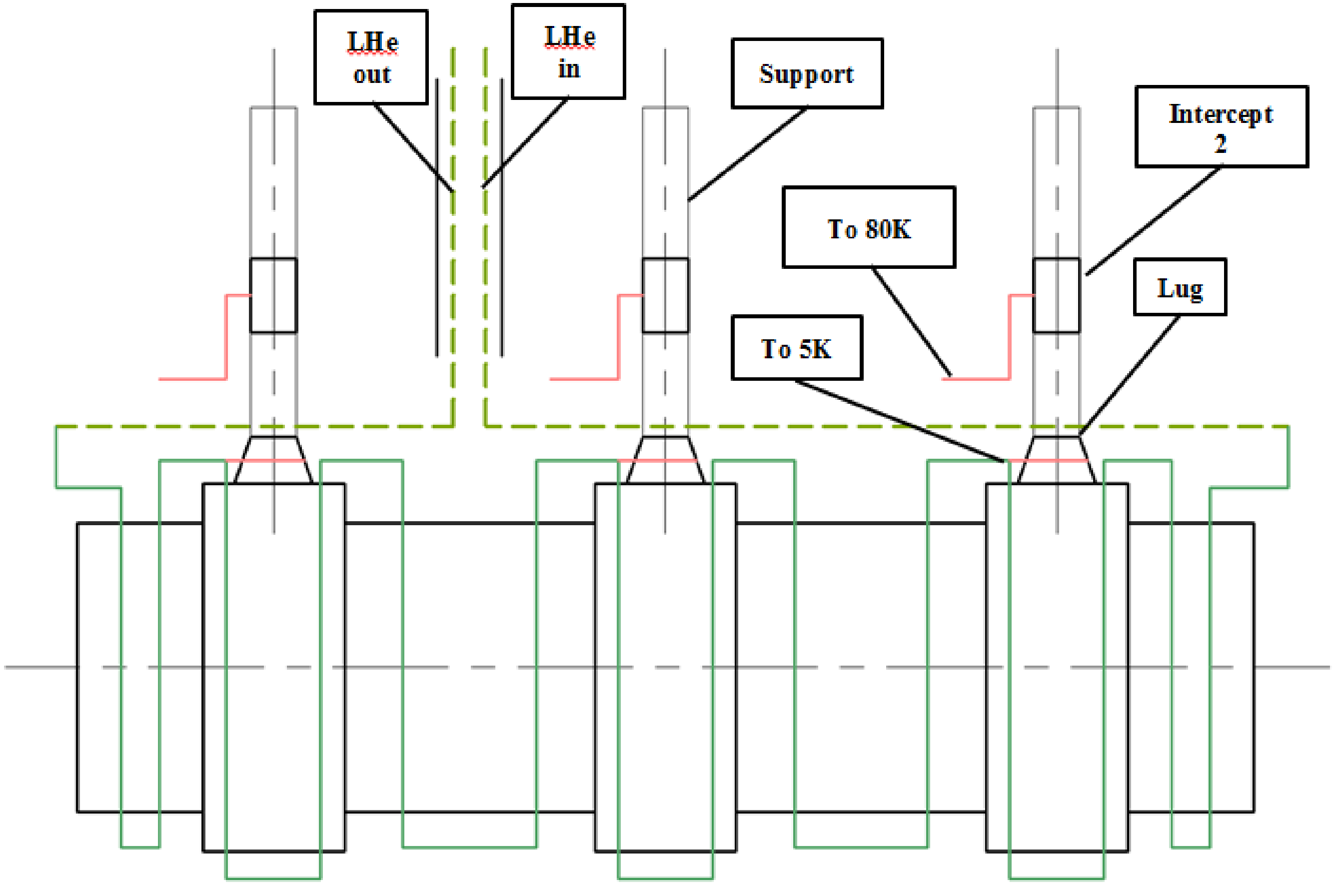
* inches

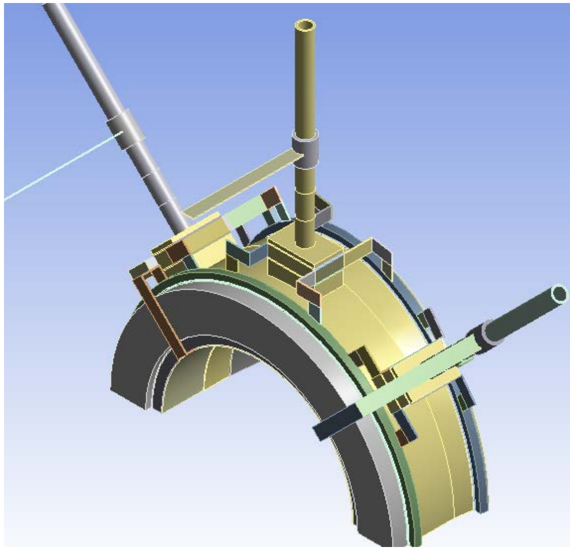


Load Line

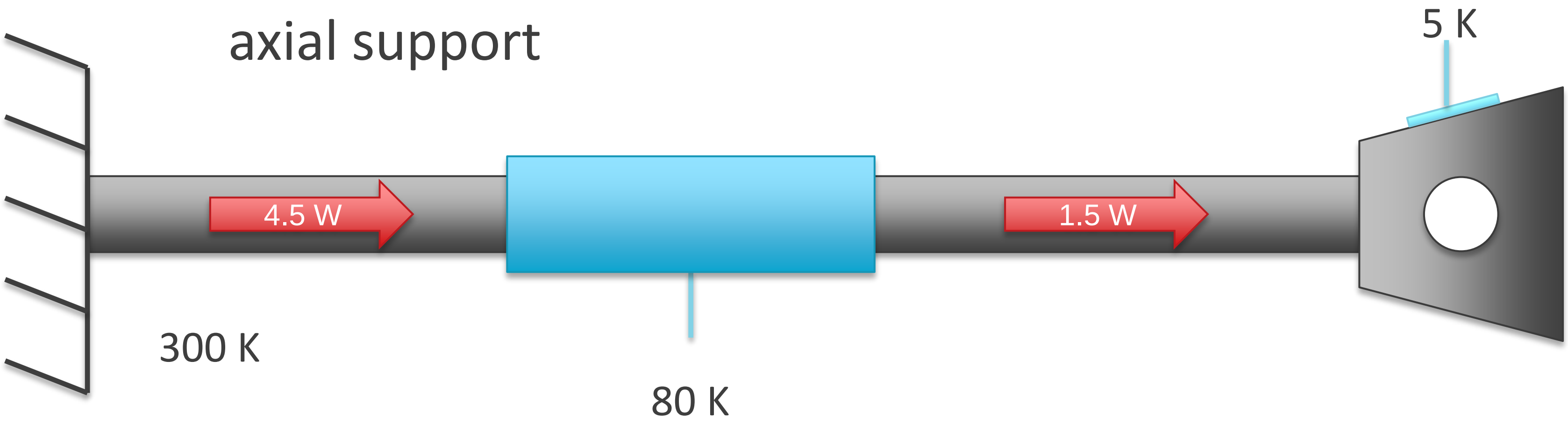

>50% margin in current
>1.5 K temperature margin
Cable critical current (A)
Magnetic Field (T)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
4.22 K
5 K
6 K
7 K
Load line of TS coil #1
Load line of TS coil #20 (B max)
Load line of last TS coil (B min)

Design – Cooling scheme analysis





Design – Cooling scheme analysis

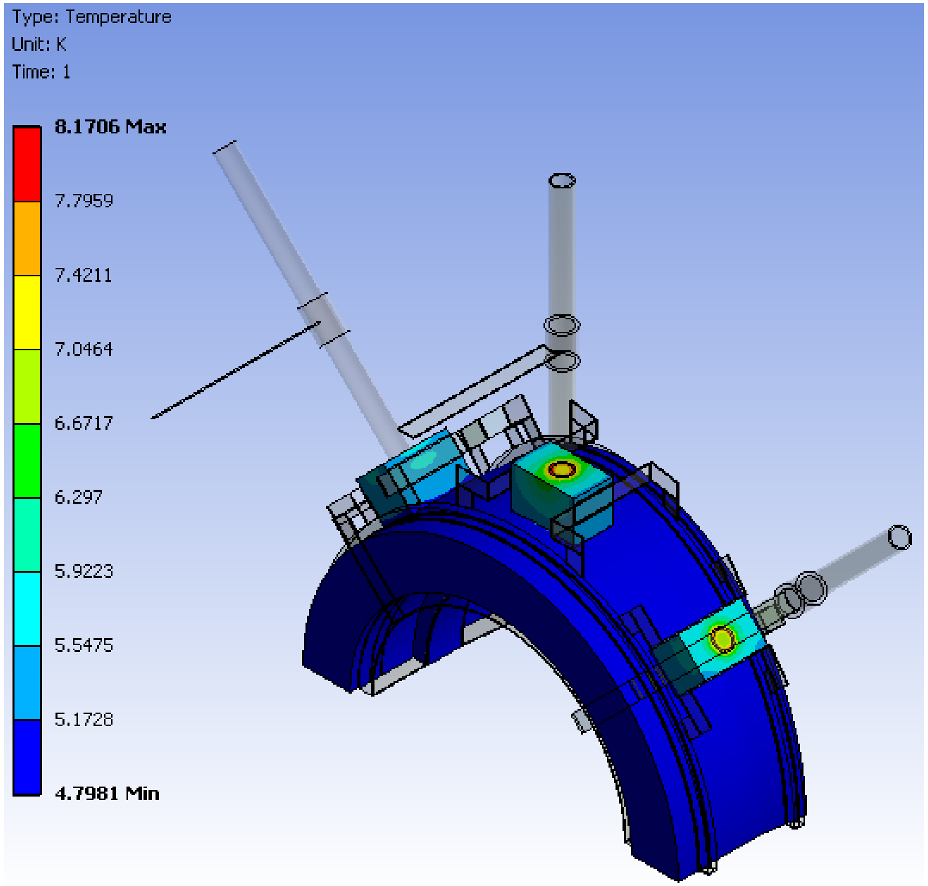


Helium temperature

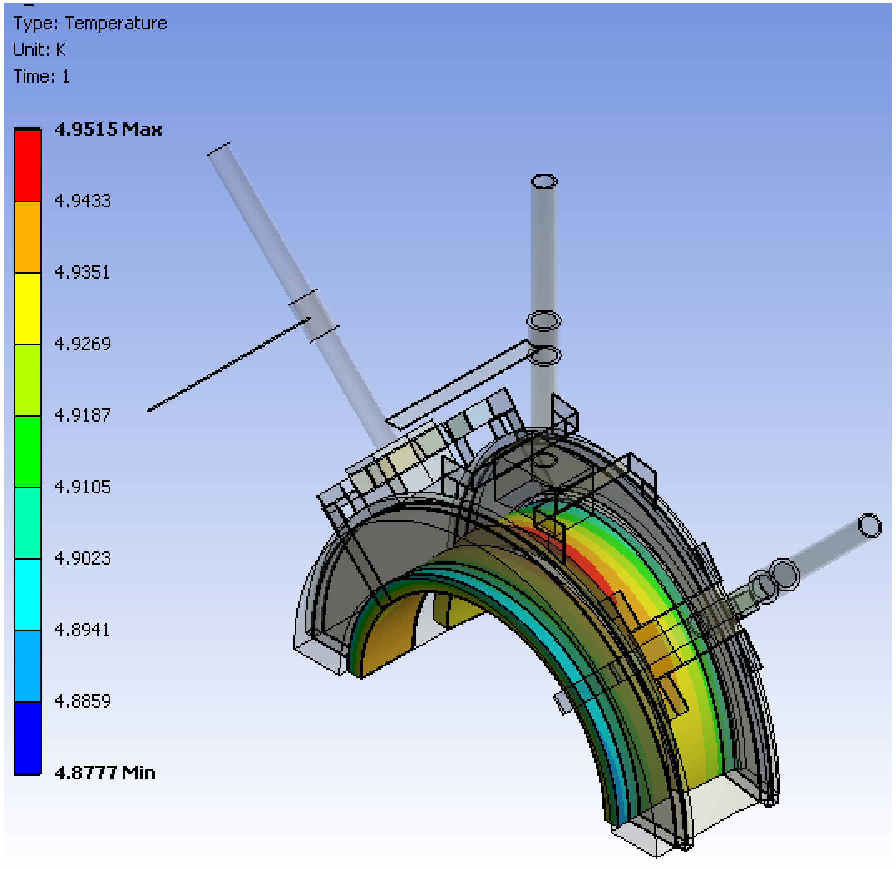
Support section	Coils	Heat (W)				Helium temperature (K)	
		Radiation	Dynamic load	Support load	Total	in	out
	25-24	0.51	0.00	0.00	0.51	4.700	4.701
3	23-22	0.48	0.00	9.00	9.48	4.701	4.736
	21-14	2.11	0.00	0.00	2.11	4.736	4.743
2	13-12	0.60	0.00	3.00	3.60	4.743	4.756
	11-6	1.56	0.00	0.00	1.56	4.756	4.761
1	5-4	0.52	0.00	9.00	9.52	4.761	4.795
	3-1	0.76	0.05	0.00	0.81	4.795	4.797

Design – Cooling scheme analysis

Aluminum bobbin



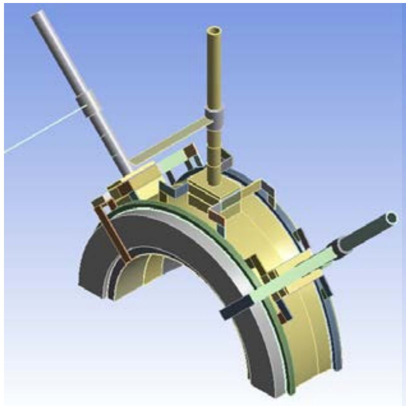
Coil



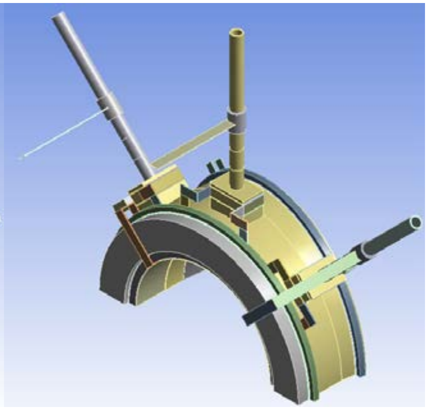
Design – Cooling scheme analysis

Maximum temperature of coil

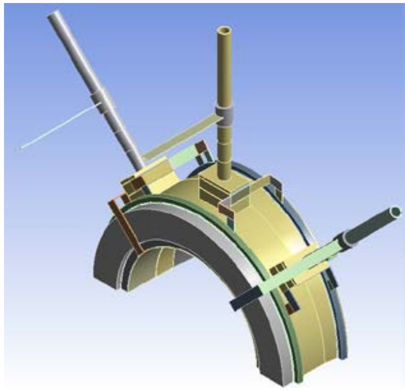
Scheme	Coil Temp. (K)	Shell Temp. (K)
1 strap	5.0532	8.8421
2 straps 2 sides	5.0183	8.6974
2 straps 1 side	4.9870	8.3832
4 straps	4.9515	8.1706



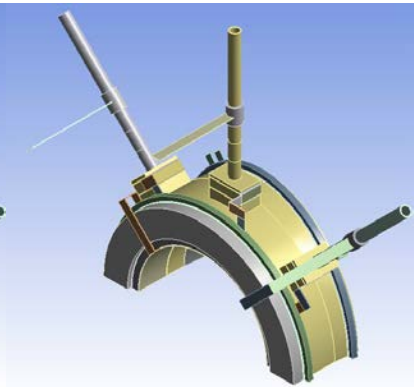
4 straps



2 straps fixed on 1 side



2 straps fixed on 2 sides



1 strap

Design – Splices R&D

- Rutherford to Rutherford
- Aluminum soldered joints
- Aluminum weld
- EM pulse joints
- Explosive joints
- Ultrasonic weld

Type	R (nOhm)	SC Degradation (%)
Rutherford-Rutherford #1	0.875	0
Rutherford-Rutherford #2	0.711	0
Rutherford-Rutherford #3	1.14	0
Rutherford-Rutherford #4	0.62	0
Soldered - SnPb	31.03	-
Soldered - SnAg	144.98	-
Soldered - SnZn	37.7	-
Ultrasonic welded #1	0.397	0
Ultrasonic welded #2	0.778	0
Ultrasonic sample #3	0.681	0
Standard welded #1	13.8	20
Standard welded #2	12	30

Improvements since CD-1

- Changes on the TSu nose that connects to PS due to the proton beam pipe.
- Change of the position of the Chimneys to accommodate the shield around the TS magnets.
- We removed the vertical supports located in the bottom of the magnet due to interference with the support feet.
- Trim power supplies included in TS

Value Engineering since CD-1

- TSu and TSd cryostat geometry nearly identical resulting in common parts, tooling, and assembly.
- TSu and TSd support feet positions identical resulting in common parts, tooling, support frames, and lifting fixtures.
- TSu and TSd axial and radial supports identical resulting in common parts, tooling, and assembly.
- Eliminated lower vertical supports resulting in lower cost, easier assembly, and easier cold mass alignment.

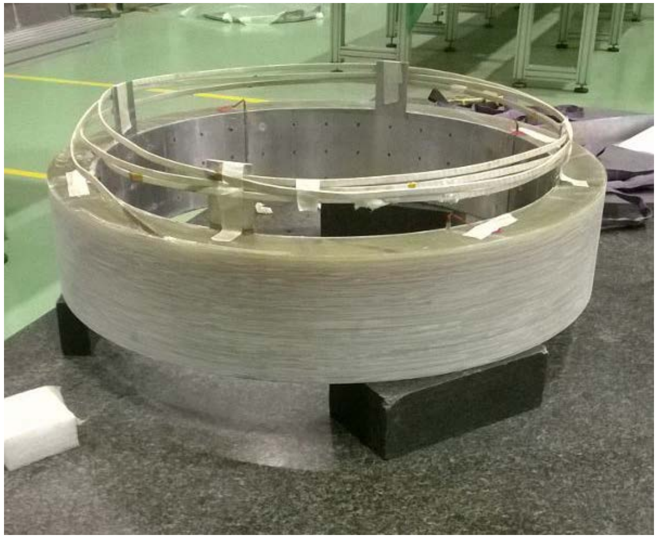
Downselects

- Forced flow was selected as the cooling scheme for TS (as opposed to thermo-syphoning).
- TS1 coils will be housed into a 2+1 coil modules (instead of a single 3-coils module)
- Coil modules will be fabricated in industry. Magnet assembly (cold mass and cryostat) will be done in-house.

CD3-b strategy

- The design of the complete magnet is still preliminary, but we have the details in hand to finish the coil module design.
- The design of coil modules is very advanced (~90% complete).
- Most of the design is based on the experience we had building the prototype.

Prototype



More details on G. Ambrosio's talk

Prototype

Prototype

Proprietary Information

Remaining work for the coil modules

- Finish all the drawings
  (90% of the design and 70% of the drawings are complete),
  -Drawings review

- Finish (Procurement) Technical Specifications,
  -Roberto Penco (Consultant).

- Complete the test of the TS Prototype at Fermilab
  -Warm magnetic measurement (stretched wire)
  -Finish the preparation of the test cryostat
  -Cold tests

Remaining work for the coil modules

~3 months of work (2 designers)

List of drawings that are <u>ready</u>:

- Coils w/Excel Chart
- Coils Spacers and Wedges
- Cooling Square Tubes

List of drawings that needs <u>update</u>:

- Module Assemblies (16)
- Housing Final Machining (16)
- Housing Weldment (16)
- Housings (16)

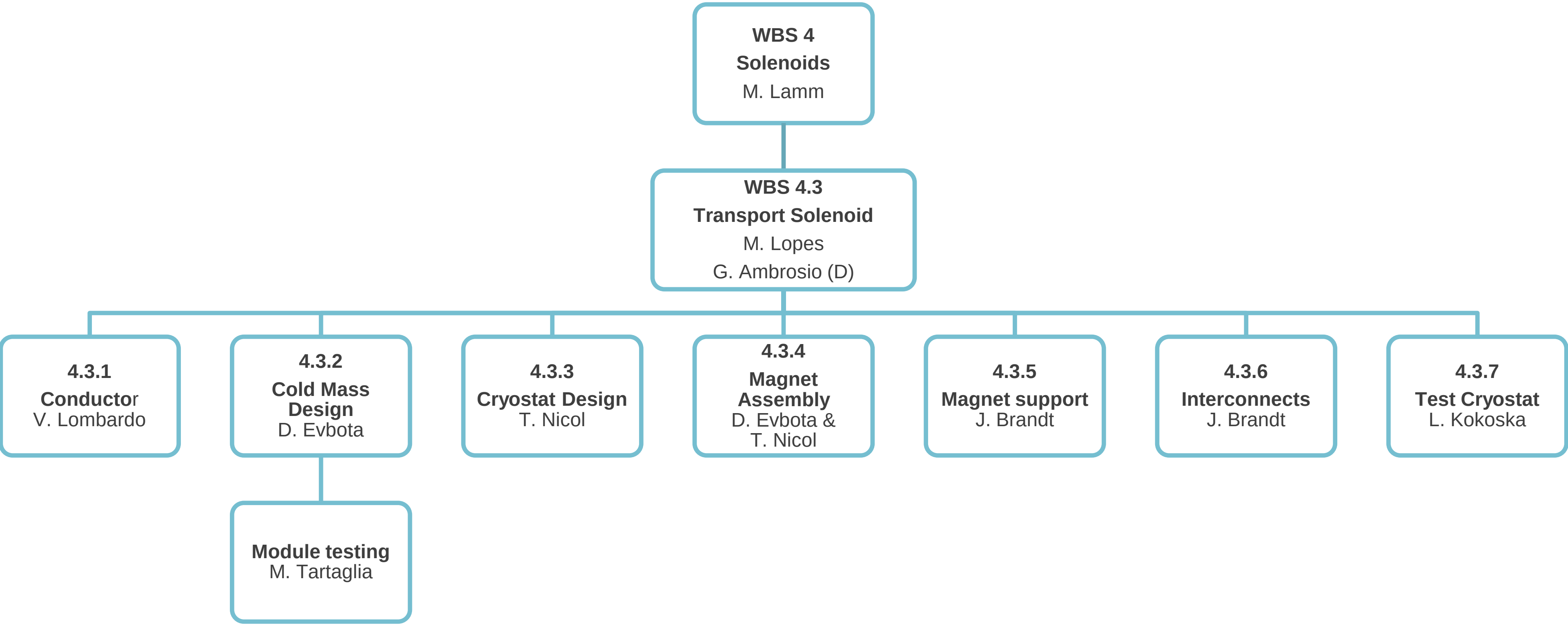
List of <u>remaining designing</u>:

- Splices Boxes (40)
- Update bolt holes end went holes for on all housings (16)
- Add hardware for TSu and TSd (8)
- For some module make room for new Lugs Support (24)
- Test assembly modules for TSu and TSd (40)
- Aluminum cooling sheets for global and test units cold mass assembly (80)
- Leads and splices routing for global and test units cold mass assembly (200)
- Support Splices (80)

List of <u>remaining drawings</u>:

- Splices boxes (80)
- Supports for leads (80)
- Supports for cooling tubes (40)
- Test units cold mass Assembly Modules for TSu and TSd (40)
- Global Cold Mass Assembly TSu and TSd (40)

Organizational Breakdown



Remaining work before CD3-c

- Finalize the design of the cryostat
  - -Thermal shield
  - -Support rods
    - >Prototype

- Finalize the tooling for the overall assembly (WBS 4.9)

- Finalize the magnet support feet

- Finalize the magnet interconnects

Quality Assurance

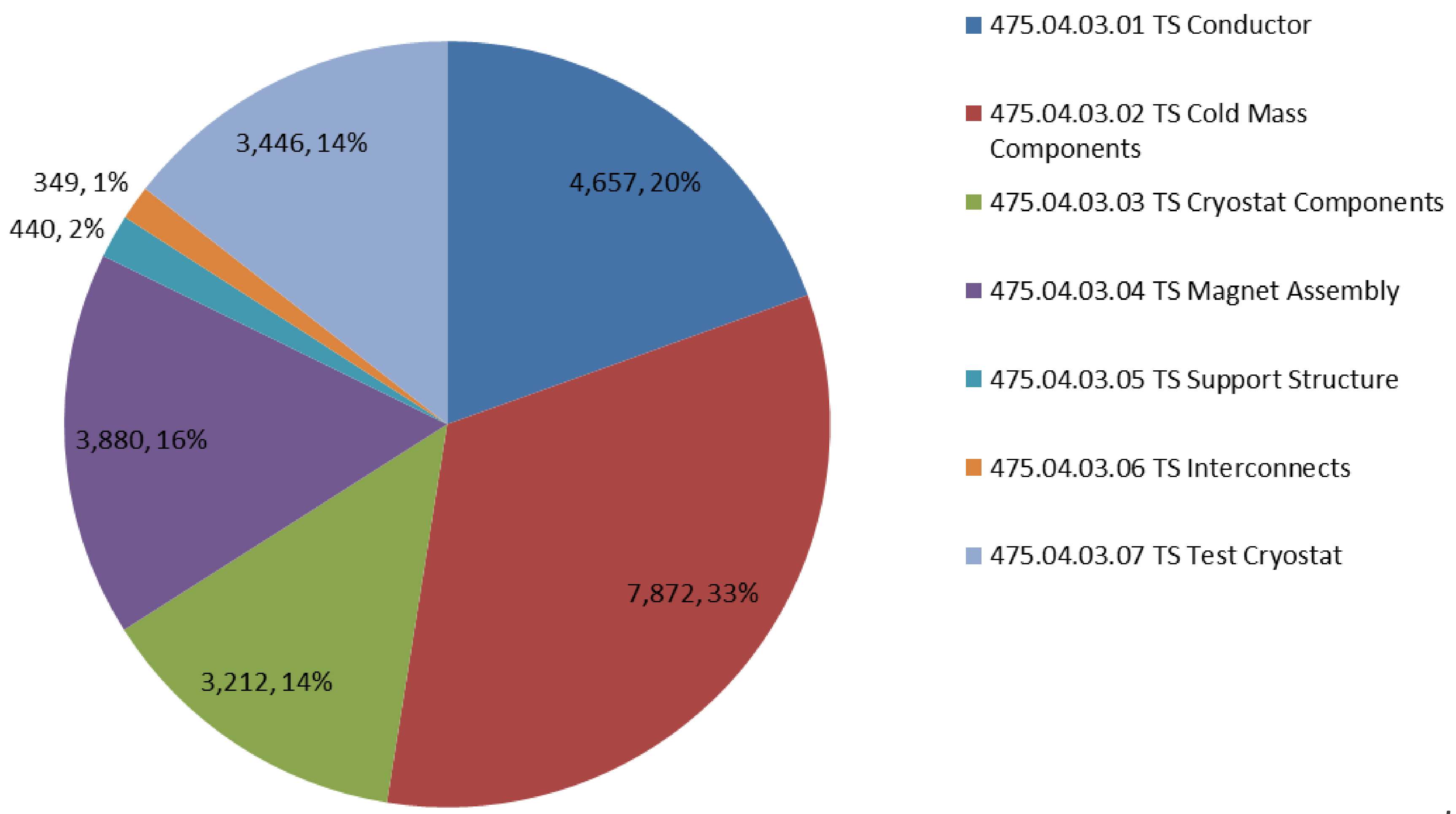
- Vendors must provide Preliminary QAP as part of bid package
- Vendor's QAP will include tests requested by Fermilab
- Hold points in fabrication at major milestones
- Regularly scheduled meetings to discuss fabrication status/issues. Regular visits to the vendor.
- Use of traveler system at the vendor and at Fermilab
- Acceptance tests upon delivery at Fermilab:
  - Electrical tests
  - Mechanical surveys
  - Magnetic measurements
  - Cold tests of coils and splices
- Monthly EVMS-style reporting

ES&H

- Common to large superconducting magnet systems
  - Cryogenic fluids
  - Large stored energy (13 MJ)
  - High currents (up to 2 kA)
  - Large voltages during quench (up to 600 V)
  - ODH
  - Mechanical forces (up to 130 Tons of axial force)
  - Stray magnetic fields
  - Use of chemicals (Sodium hydroxide)
  - Radiation

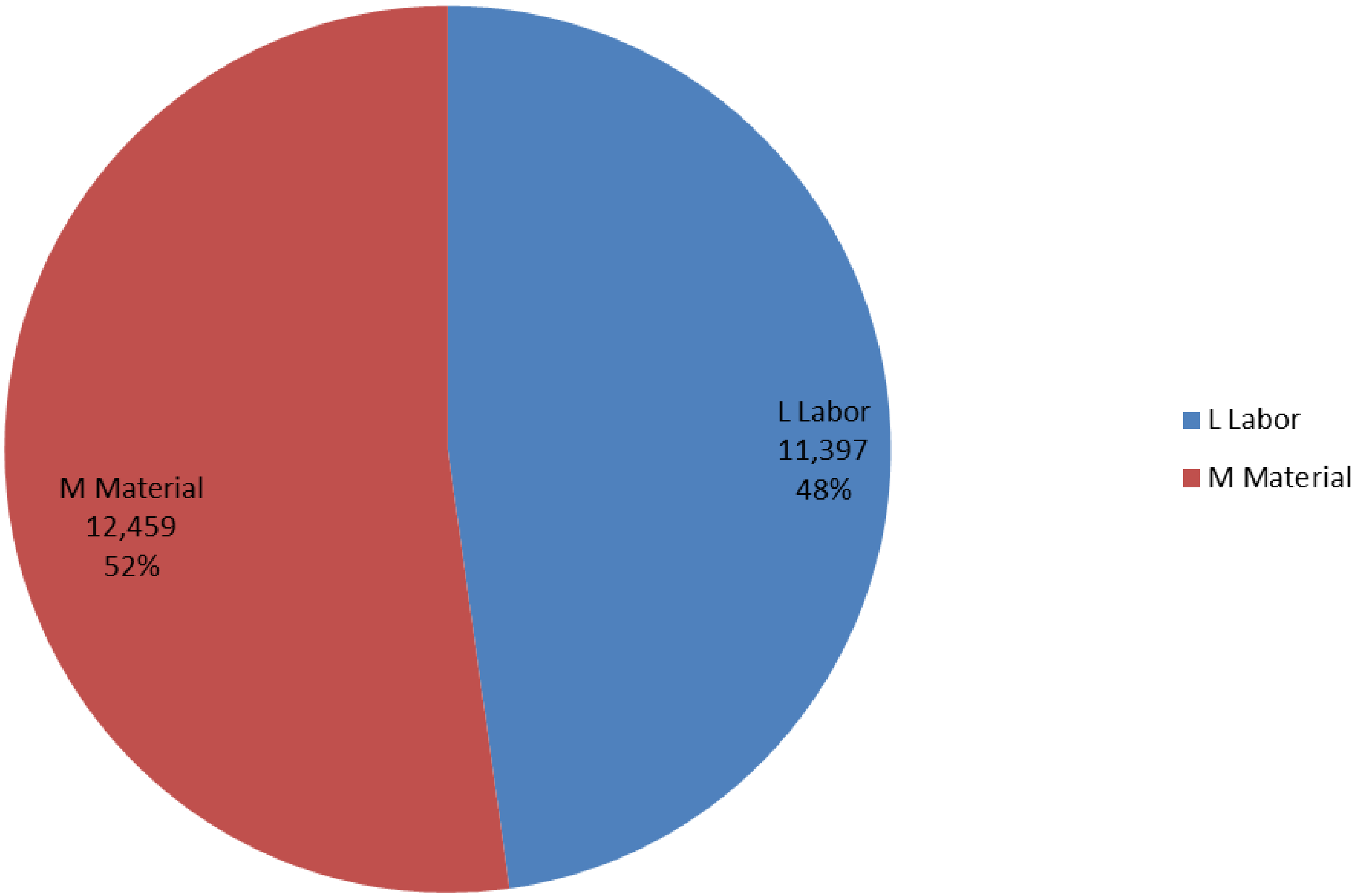
All of these are covered in the Mu2e Hazard Analysis

Cost Distribution



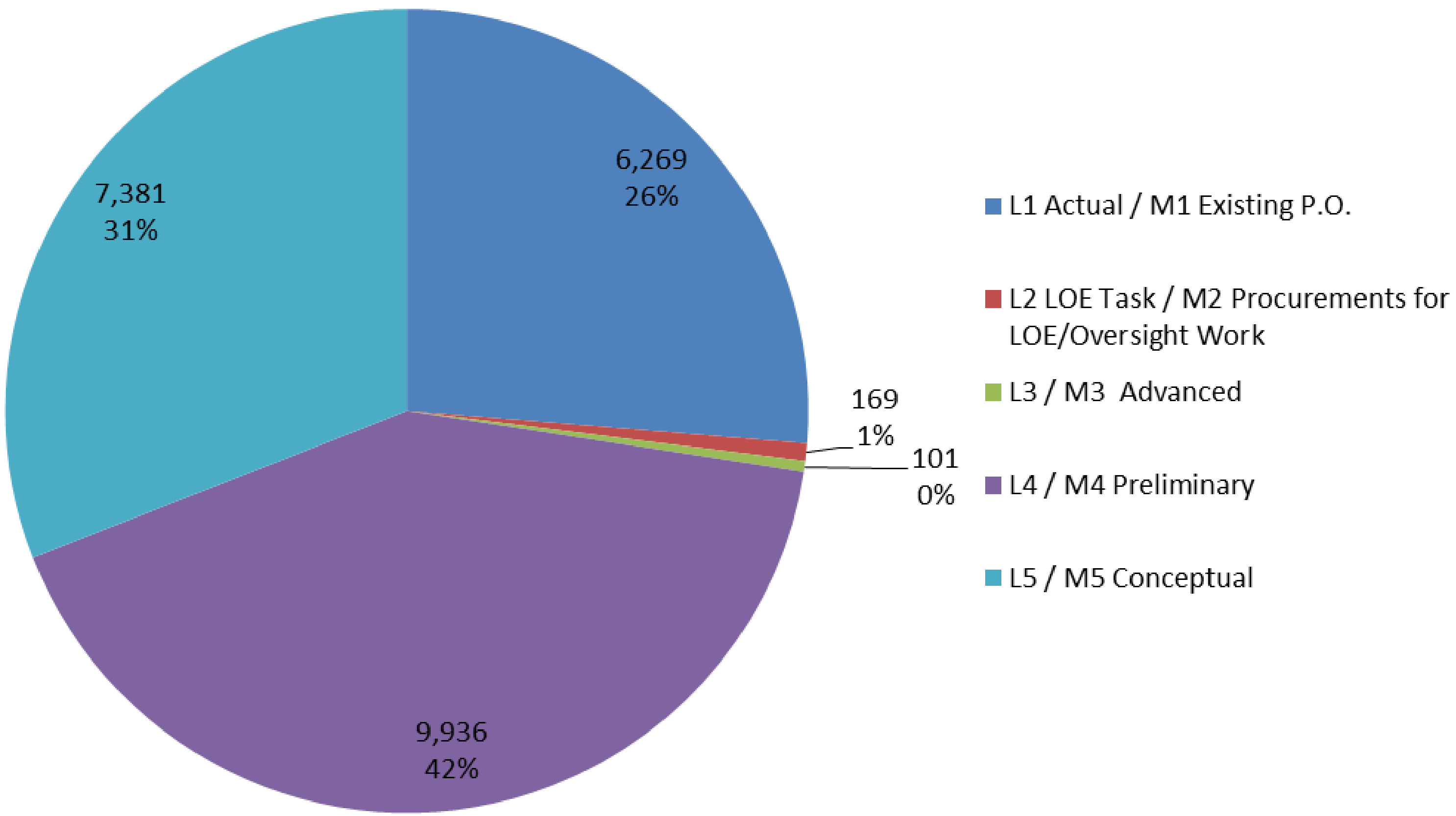
AY k$

Cost Distribution by Resource Type



AY k$

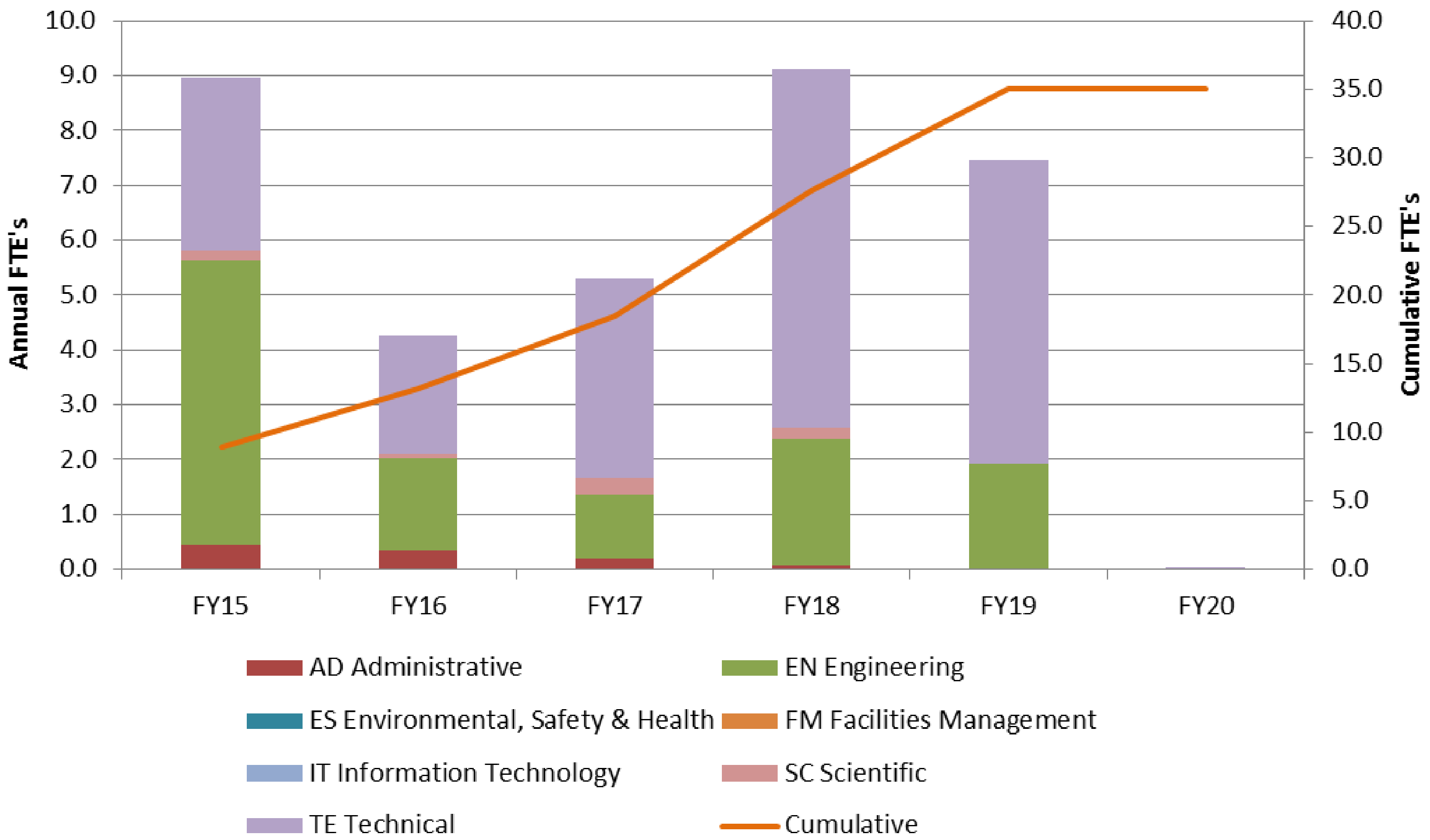
Quality of Estimate



69% of the cost is preliminary or better

AY k$

Labor Resources



All the resources for FY15 are identified by name

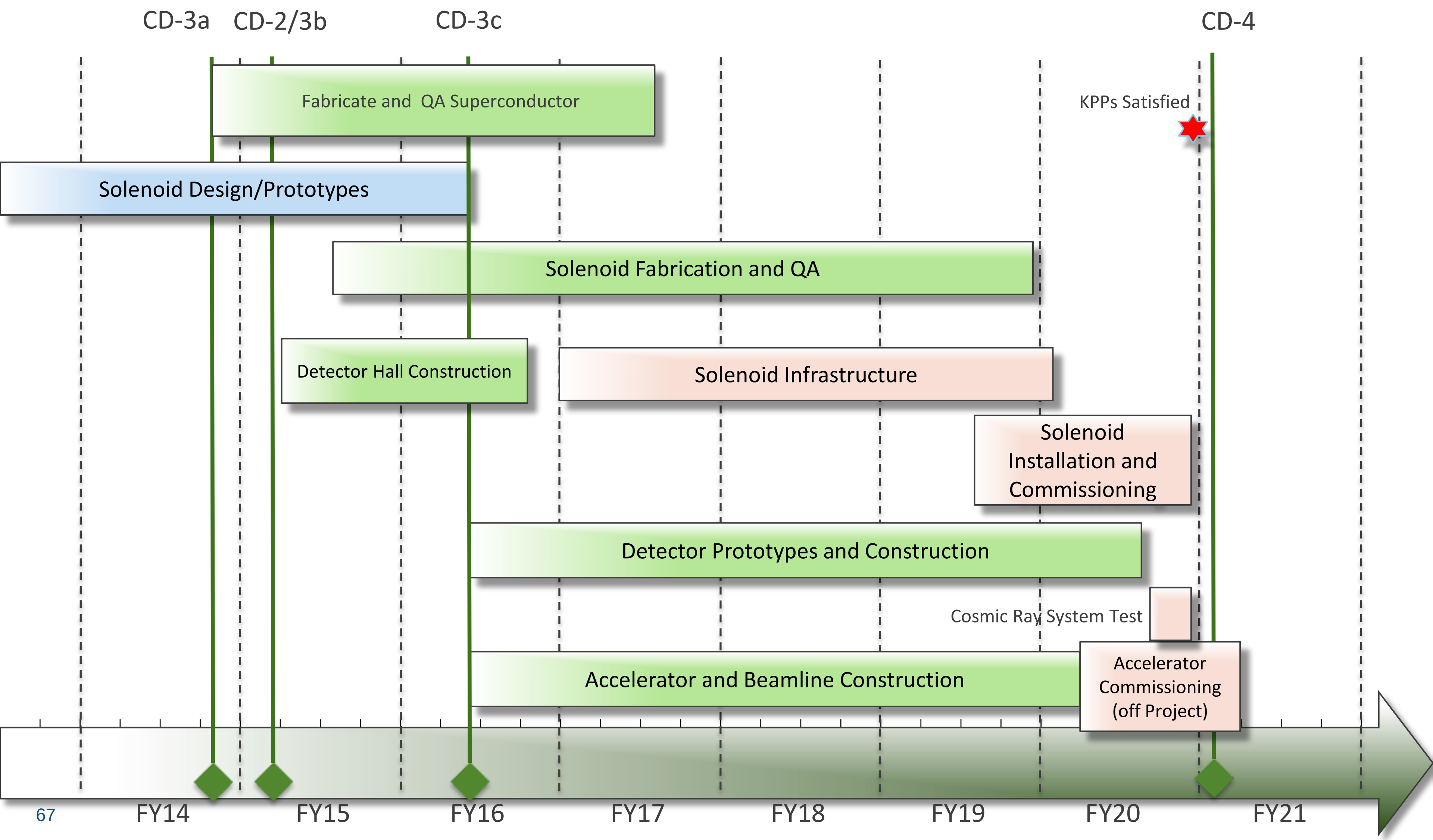
Cost Table

	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency on (on remaining budget)	Total Cost
475.04.03 Transport Solenoids						
475.04.03.01 TS Conductor	2,684	1,973	4,657	289	10%	4,946
475.04.03.02 TS Cold Mass Components	6,125	1,747	7,872	3,717	51%	11,589
475.04.03.03 TS Cryostat Components	2,187	1,025	3,212	1,491	46%	4,703
475.04.03.04 TS Magnet Assembly	492	3,387	3,880	1,552	40%	5,431
475.04.03.05 TS Support Structure	166	274	440	161	46%	600
475.04.03.06 TS Interconnects	142	207	349	123	41%	473
475.04.03.07 TS Test Cryostat	661	2,785	3,446	497	48%	3,943
Grand Total	12,459	11,397	23,856	7,830	41%	31,686

Major Milestones

Activity Name	Date	Milestone Description
T5 - PO issued for TS production conductor	7/11/2014	PO issued for TS production conductor
T5 - Design of TS Cold Mass completed	11/3/2014	Design and documentation are ready to prepare for bid package.
T5 - Technical Readiness Review for module fabrication bid package Completed	11/11/2014	Technical Readiness Review for module fabrication bid package Completed
T5 - PO issued for TS module fabrication	4/16/2015	PO issued for module fabrication
T5 - PO issued to Perform TS production conductor acceptance tests	5/7/2015	PO issued to Perform TS production conductor acceptance tests
T5 - Final design of TS interconnects complete	7/24/2015	Design and documentation are ready to prepare for CD-3.
T5 - Final Design of TS Cryostat Complete	11/2/2015	Design and documentation are ready to prepare for CD-3.
T5 - TS Support Structure Final design complete	11/2/2015	Design and documentation are ready to prepare for CD-3.
T5 - Solenoids receives CD-3c approval	2/23/2016	Line Item PED funds released by DOE.
T5 - Vendor for TS interconnect components Fabrication selected	3/2/2018	Vendor for TS interconnect components Fabrication selected
T5 - PO issued for TS interconnect components Fabrication	4/30/2018	PO issued for TS interconnect components Fabrication
T5 - Building ready for Solenoid installation	8/7/2018	Mu2e Experimental Hall is complete and ready for installation of Mu2e solenoid system and components.
T5 - Solenoid system installation complete and ready for cooldown	4/9/2020	Solenoid system and supporting equipment is installed and magnets are ready to be cooled down to 4.5 K.
T5 - On Project Solenoid Commissioning complete	9/29/2020	Key Performance Parameter: Solenoid system has been cooled down and powered and demonstrated to run at nominal field strength.

Schedule

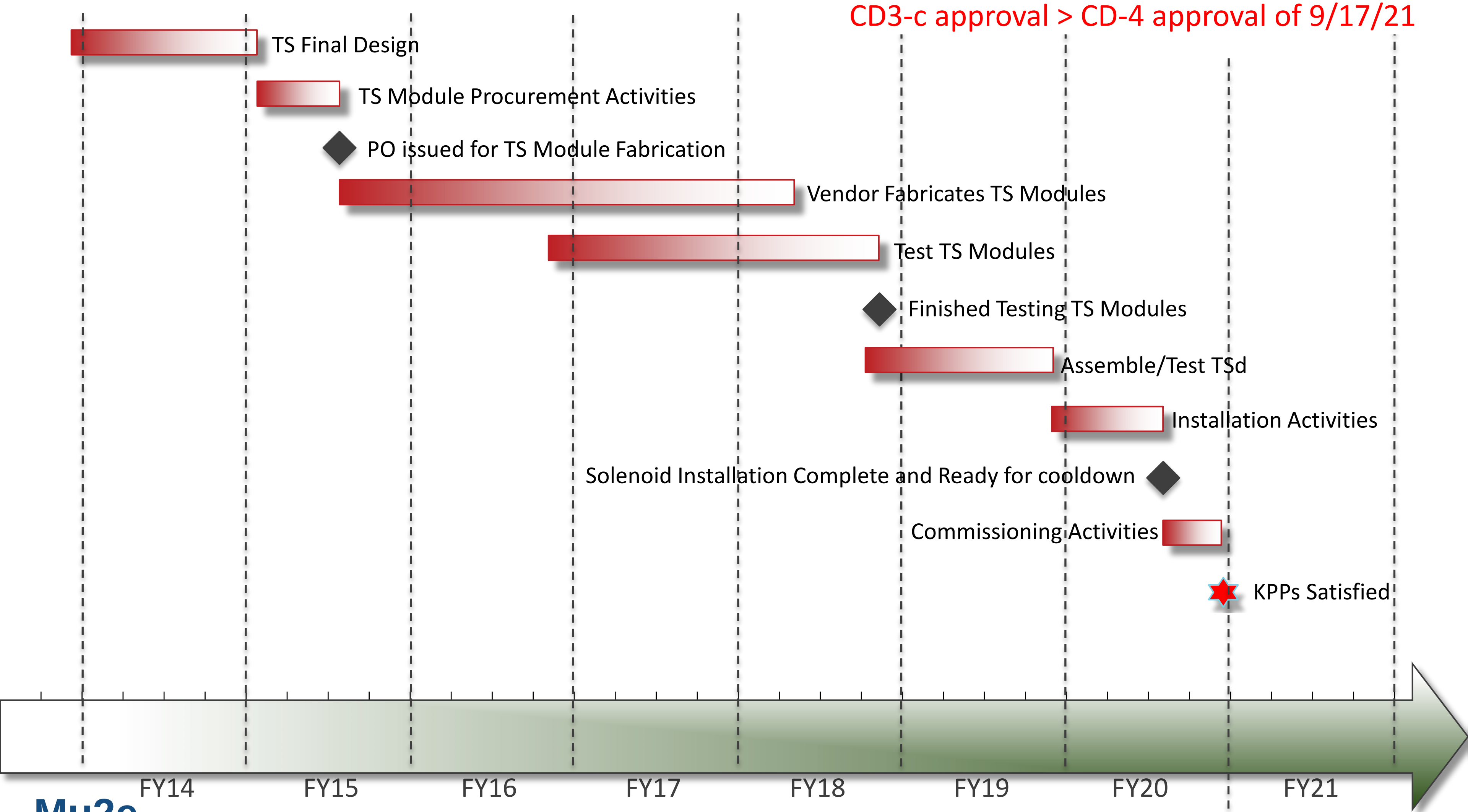


CD-3a
CD-2/3b
CD-3c
CD-4
Fabricate and QA Superconductor
KPPs Satisfied
Solenoid Design/Prototypes
Solenoid Fabrication and QA
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Detector Prototypes and Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Critical Path

CD3-b approval > CD-4 approval of 11/09/20

CD3-c approval > CD-4 approval of 9/17/21



Summary

- The TS conductor performed really well and the PO was placed (July14).
- The solenoid magnetic design meets the requirements for the experiments and tolerances are well understood.
- Cost and Schedule understood.
- We believe we are ready for CD2 project baseline
- The coil modules design is very advanced (90% of the design and 70% of the drawings are complete) and they are based on the experience we are having with the prototype.
- We believe we are ready for CD3-b for the coil modules in order to avoid a major delay in the project (~1 year).