MQXF Design Overview

P. Ferracin

on behalf of the MQXF team

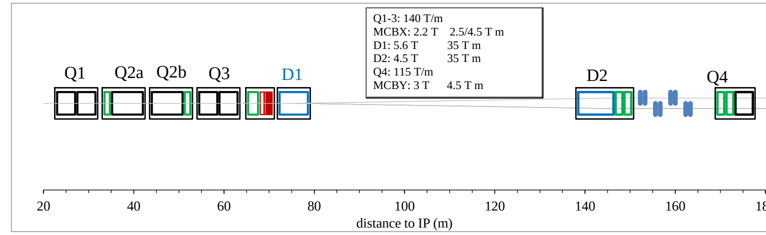
HL-LHC/LARP International Review of the MQXF Design
December 10-12, 2014
CERN

Outline

- Overview of MQXF project and design
- Strand and insulated cable
- Coil design, magnetic analysis, magnet parameters
- Support structure and mechanical analysis
- Quench protection

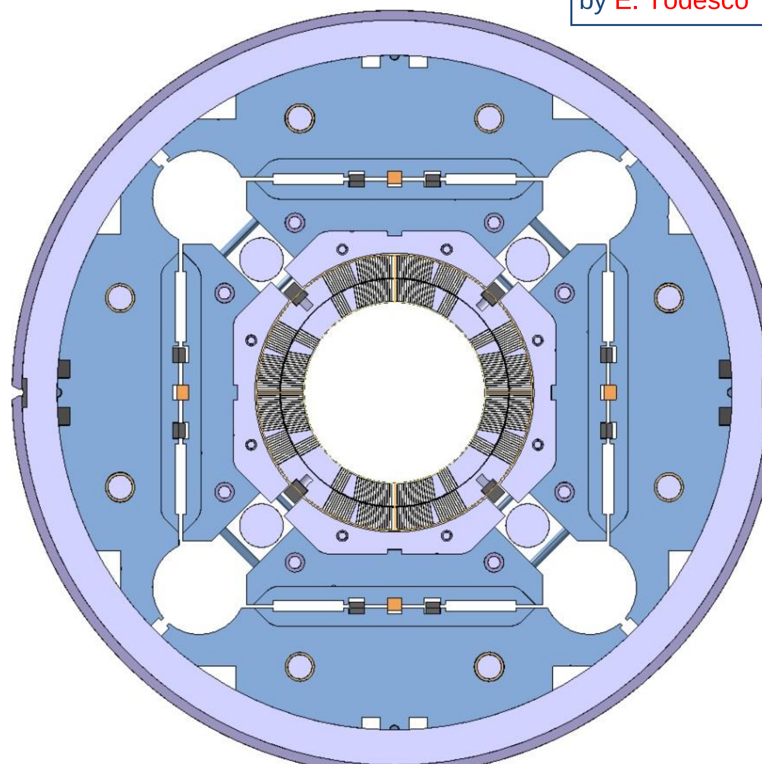
Overview of MQXF project

- Target: 140 T/m in 150 mm coil aperture
- To be installed in 2023 (*LS3*)



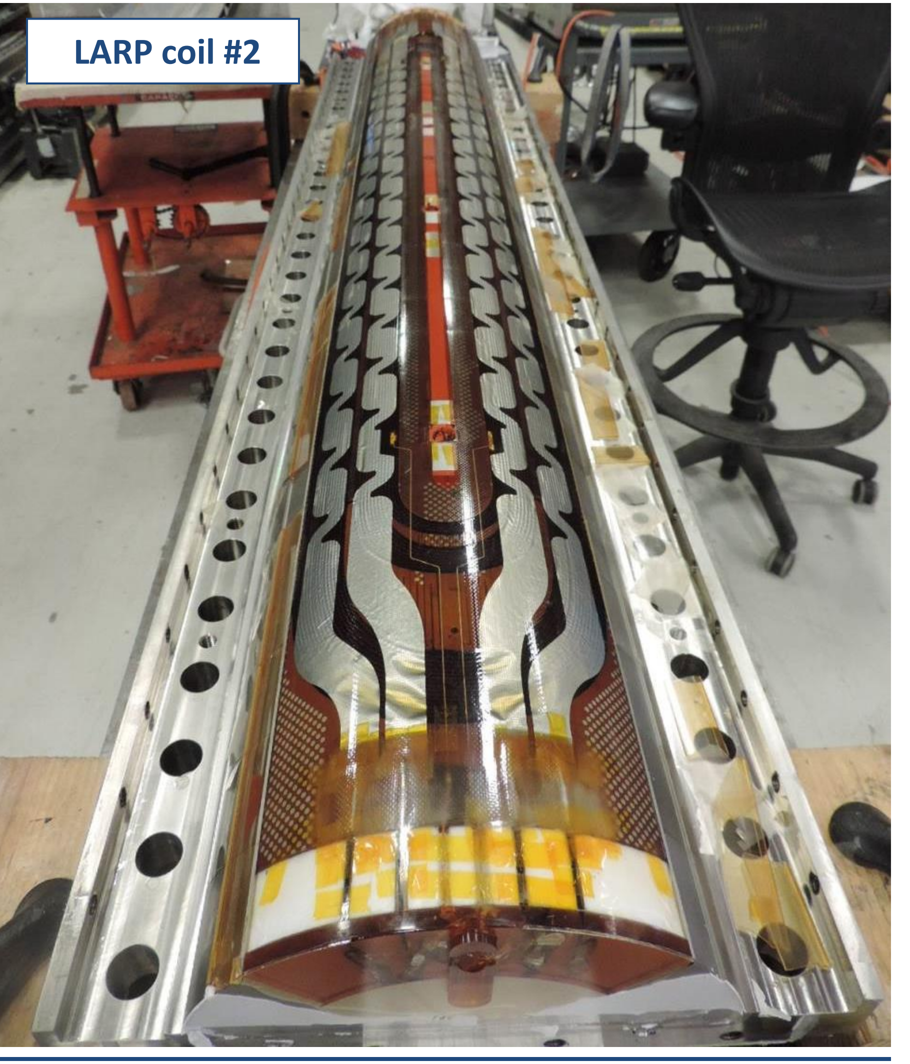
by E. Todesco

- Q1/Q3 (by US-HiLumi Project)
  - 2 magnets with 4.0 m of magnetic length within 1 cold mass
- Q2 (by CERN)
  - 1 magnet of 6.8 m within 1 cold mass, including MCBX (1.2 m)



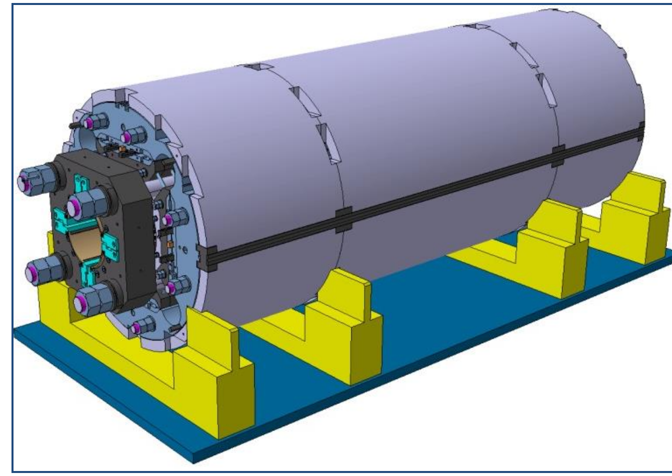
- Different lengths, same design
  - Identical short model magnets

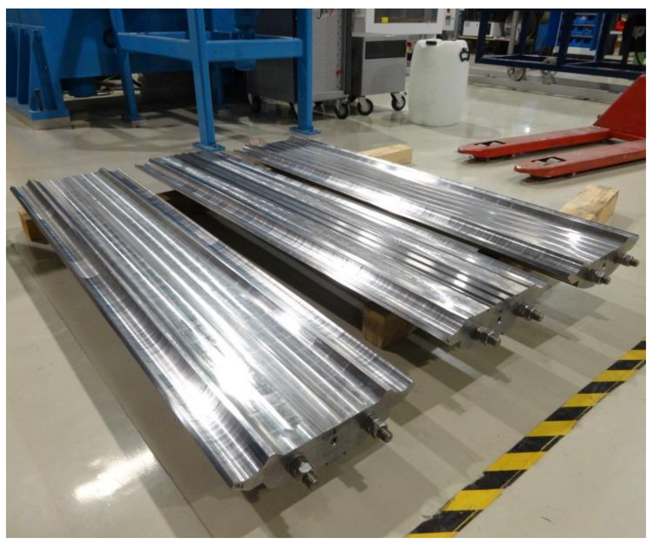
Integrated short model program
Exchangeable coils (almost identical)



Integrated short model program
2 identical support structures

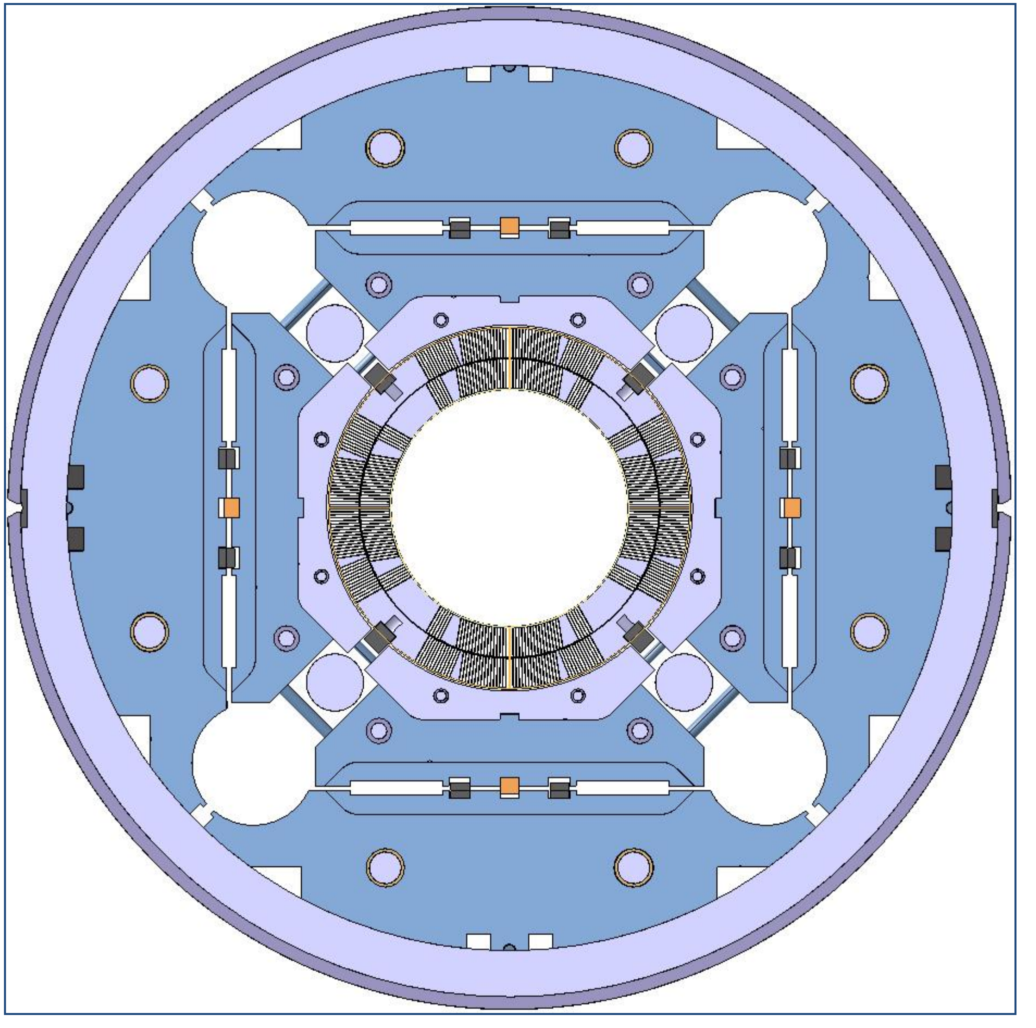
- One at CERN, one at LBNL
- Same CAD model and same fabrication companies





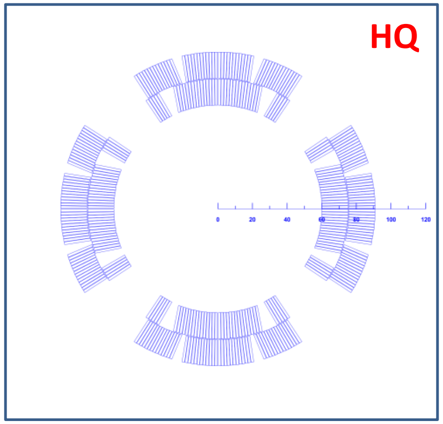
Overview of MQXF design

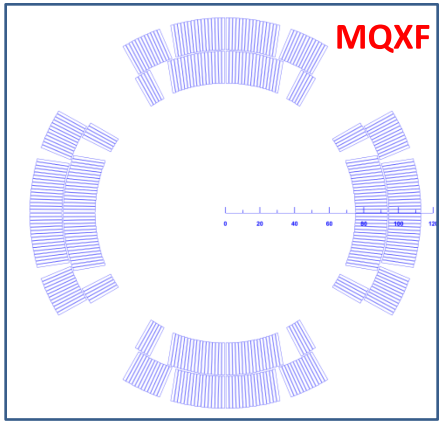
- OD: 630 m
- **Stainless steel shell**
  - 8 mm for LHe containment
- **Aluminum shell**
  - 29 mm thick
- **Iron yoke**
  - Gaps open
  - 4-fold symmetry
- **Iron master plates**
  - Bladder and keys
- **Iron pad**
- **Aluminum axial rods**
- **Aluminum bolted collars**
- **G10 pole key**
- **Ti alloy poles**



From LARP HQ to MQXF
Strand, cable and coil

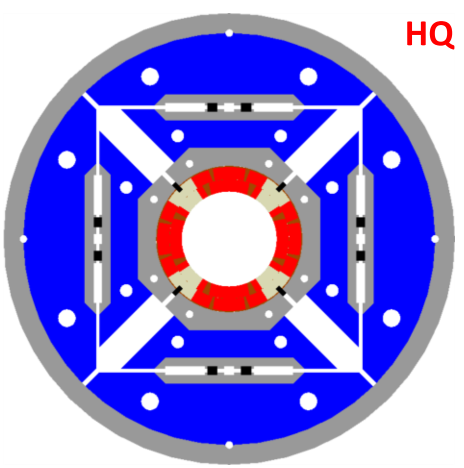
- The **aperture/cable width** is approximately maintained
  - Aperture from 120 mm to 150 mm
  - Cable from 15 to 18 mm width
  - Similar stress with +30% forces
- Same **coil lay-out**
  - 4-blocks, 2-layer with same angle
    - Optimized stress distribution
- **Strand** increased from 0.778 mm to 0.85 mm
  - Same filament size from 108/127 to 132/169
  - Maximum # of strands: 40
- **Lower $J_{overall}$** from quench protection
  - from 580 to 480 A/mm^2

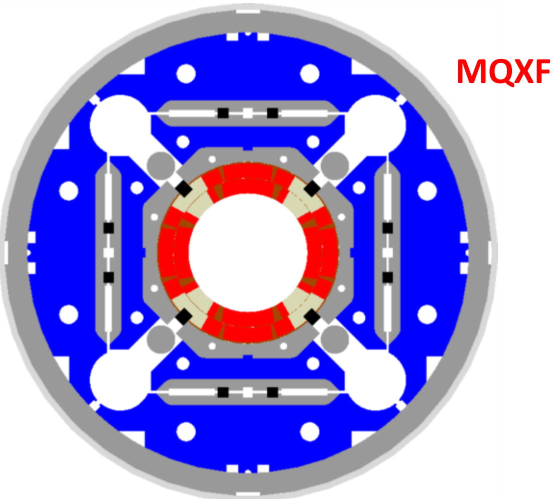




From LARP HQ to MQXF
Magnet design

- **Same structure concept**
  - Pre-load capabilities of HQ design qualified and successfully tested
- **Larger OD**: from 570 to 630 mm
- **Additional accelerator features**
  - Larger pole key for cooling holes
  - Cooling channels
  - Slots for assembly/alignment
  - LHe vessel and welding blocks and slots

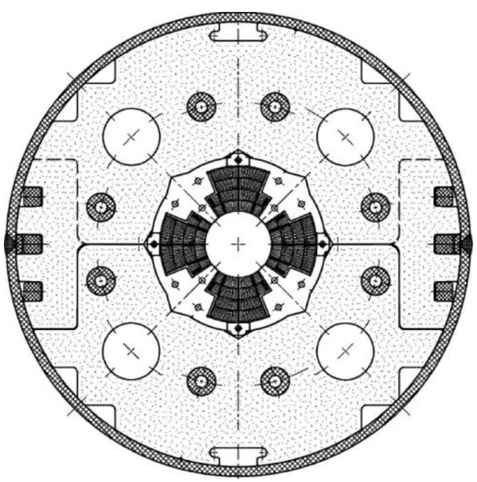




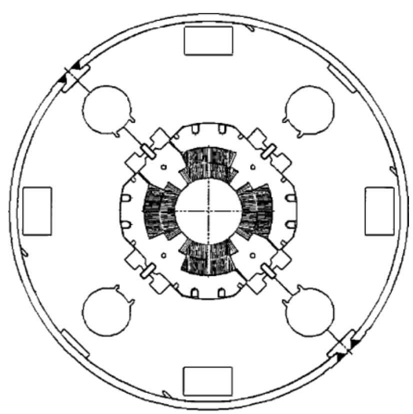
LHC low-β quadrupole support structures

- Cold mass OD from 490/420 in MQXA-B to 630 mm in MQXF
  - More than double the aperture
  - ~4 times the e.m. forces in straight section
  - ~6 times the e.m. forces in the ends

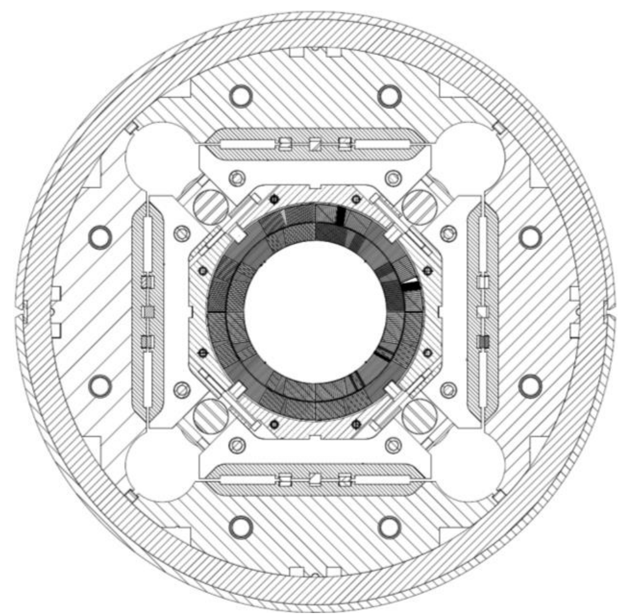
MQXA



MQXB



MQXF



In scale

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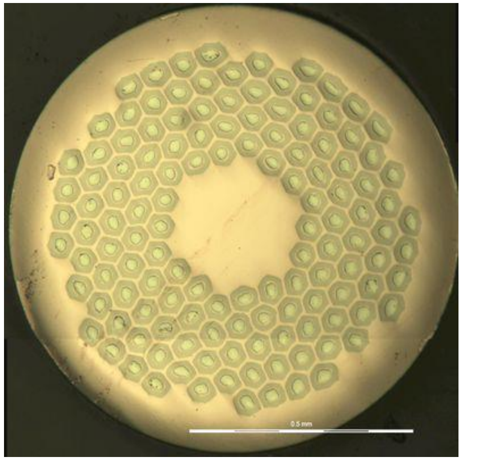
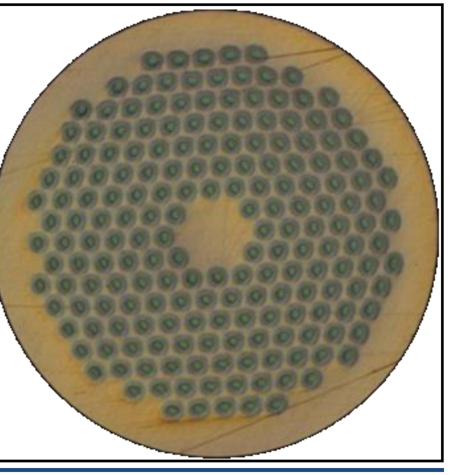
MQXF strand
(from CERN technical specification document)

- **0.85 mm** strand
- Filament size **<50 µm**
  - OST 132/169: 48-50 µm
  - Bruker PIT 192: 42 µm
- Cu/Sc: **1.2 ± 0.1** → 55% Cu
- Critical current at 4.2 K and 15 T
  - **361 A** at 15 T

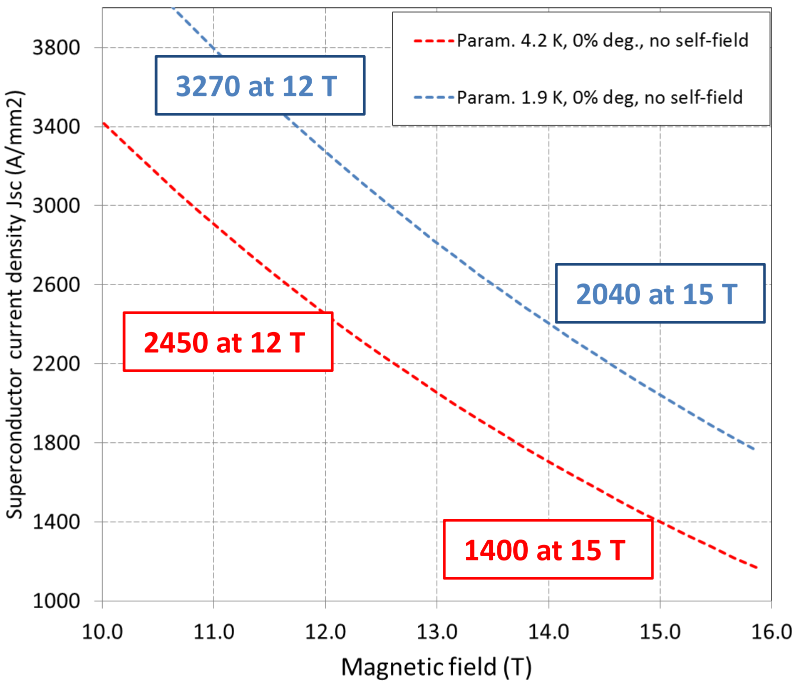
OST RRP strand, 132/169

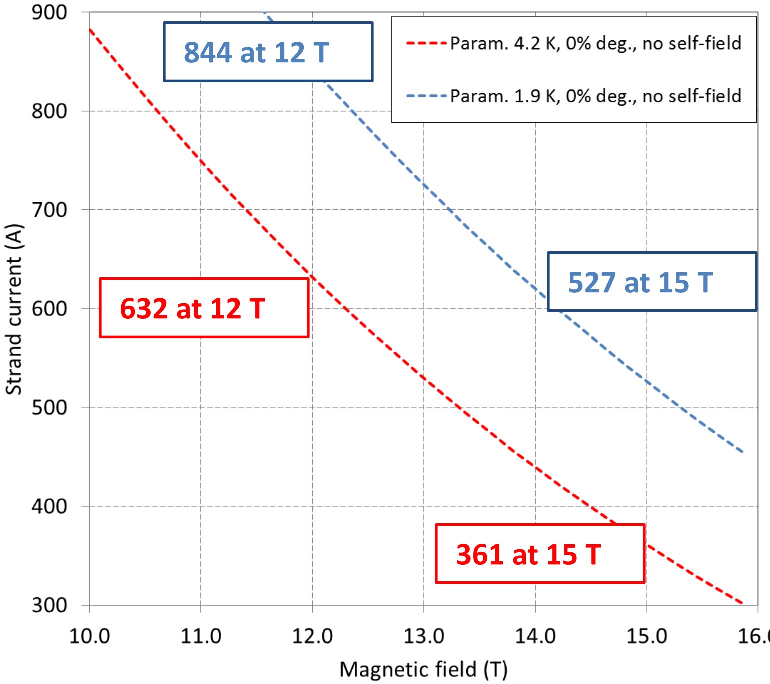


Bruker PIT strand, 192



Superconductor properties
Virgin strand, no self field correction





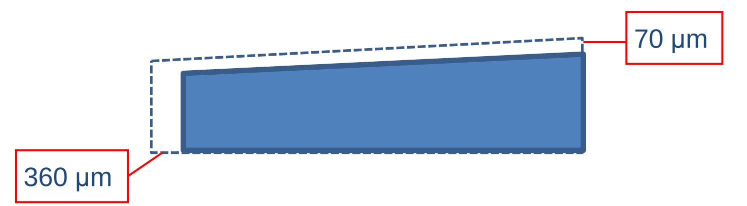
- Godeke's parameterization

Ca1*	41.24	T
Ca2* = 1034 x Ca1*	42642	T
eps_0,a	0.250%	
Bc2m*(0)	**31.50**	**T**
Tcm*	**15.34**	**K**
C*	**1541**	**TA**
p	0.5	
q	2	
Strain=	-0.20%	

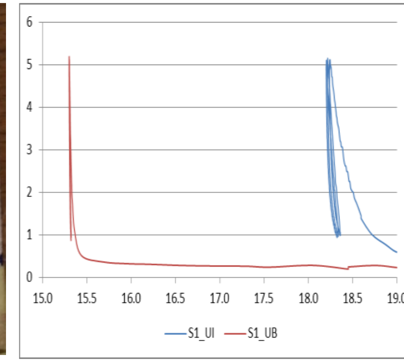
MQXF baseline cable

- 40-strand cable
- Mid – thickness after cabling
  - 1.525 +/- 0.010 mm
- Width after cabling
  - 18.150 +/- 0.050 mm
- Keystone angle
  - 0.55 +/- 0.10 deg.
- Pitch length
  - 109 mm
- SS core 12 mm x 25 μm thick

- Assumed expansion during reaction
  - 4.5% in thickness: ~70 μm, same keystone angle
  - 2% in width: ~360 μm
- Mid–thickness after reaction
  - 1.594 mm
- Width after reaction
  - 18.513 mm

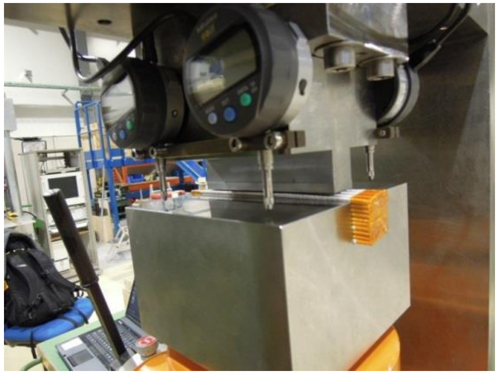


Cable insulation



- AGY S2-glass fibers 66 tex with 933 silane sizing
- 32 (CERN, CGP) or 48 (LARP, NEW) coils (bobbins)
  - Variables: # of yarn per coil and of picks/inch
- Target: ≤ 150 μm per side (145 ±5 μm) at 5 MPa, average 3 cycles

Sample	Ins. Cable thickness (mm)	Bare cable thick/ (mm)	Insulation thick. (mm)
001_1	1.822	1.530	146
001_2	1.823	1.531	146
001_3	1.821	1.530	146
101_1	1.817	1.531	143
101_3	1.816	1.531	143
102_1	1.821	1.531	145
102_2	1.819	1.531	144
102_3	1.823	1.531	146



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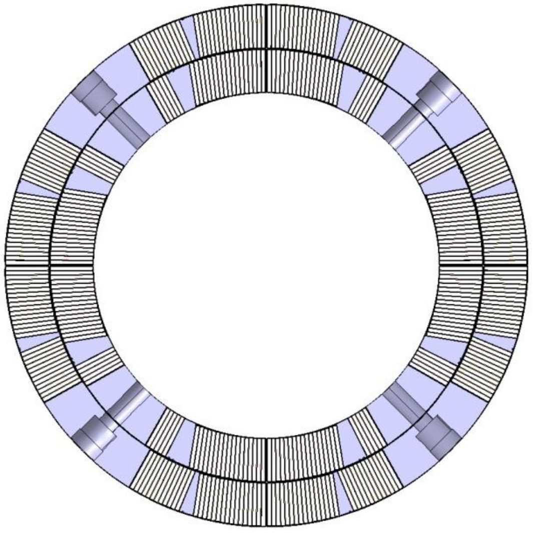
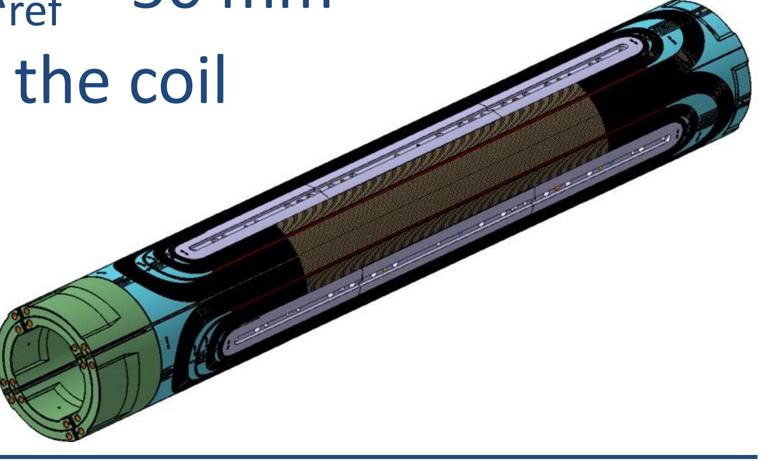
Coil design and magnetic analysis

See talk from S. Izquierdo Bermudez

- Two-layer – four-block design
  - similar to HQ
- Criteria for the selection
  - Maximize gradient and # of turns
  - Distribute e.m. forces and minimize stress
- Result: 22+28 = 50 turns
- All harmonics below 1 units at R_{ref} = 50 mm
- Winding pole impregnated with the coil
- Cooling holes in the pole
  - 8 mm Ø every 50 mm
- Splice extension 140 mm long

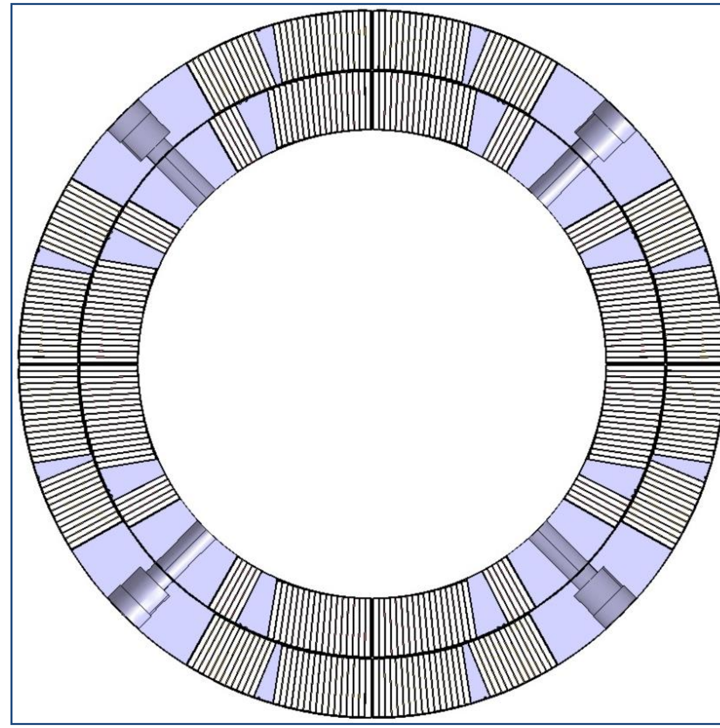




Coil insulation

See talk from M. Yu

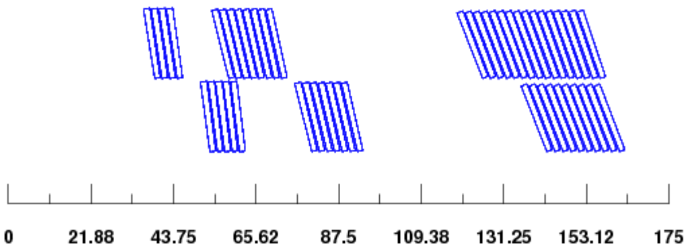
- 2 x 0.175 mm S2 glass around **winding pole**
- 0.125 mm S2 glass sleeve around **wedges**
- 0.5 mm S2 glass **inter-layer** insulation
- 0.125 S2 glass + 0.125 polymide **mid-plan shim** (per quadrant)
- 250 µm coating on **end parts** in red
- 175 µm S2 glass between **end parts and the cable**

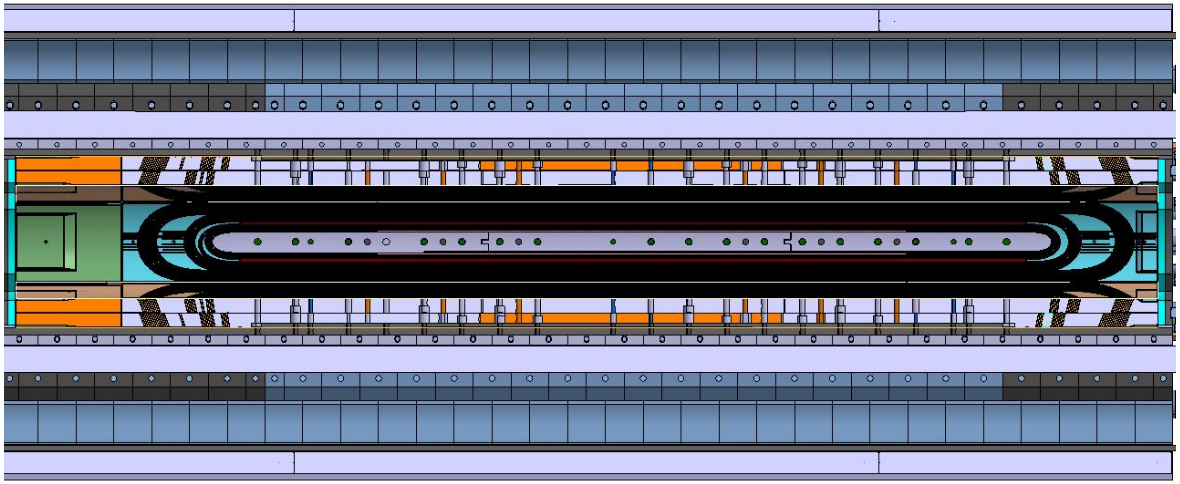


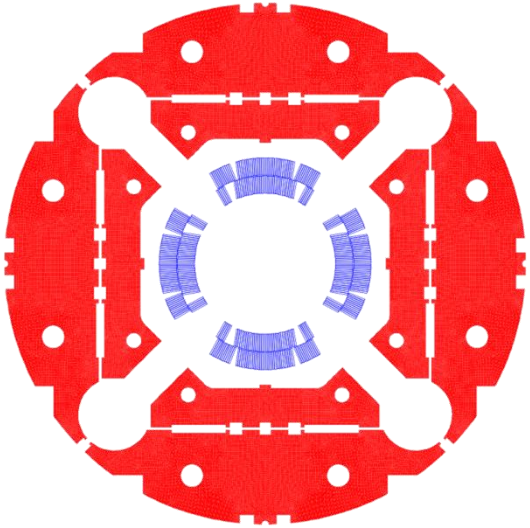
Coil design and magnetic analysis

See talk from S. Izquierdo Bermudez

- 6 blocks in the ends
  - Increase from 4 blocks in HQ
  - Minimized integrated harmonics in the RE
  - 1% lower peak field in the ends wrt straight section
    - Iron pad removed from the ends

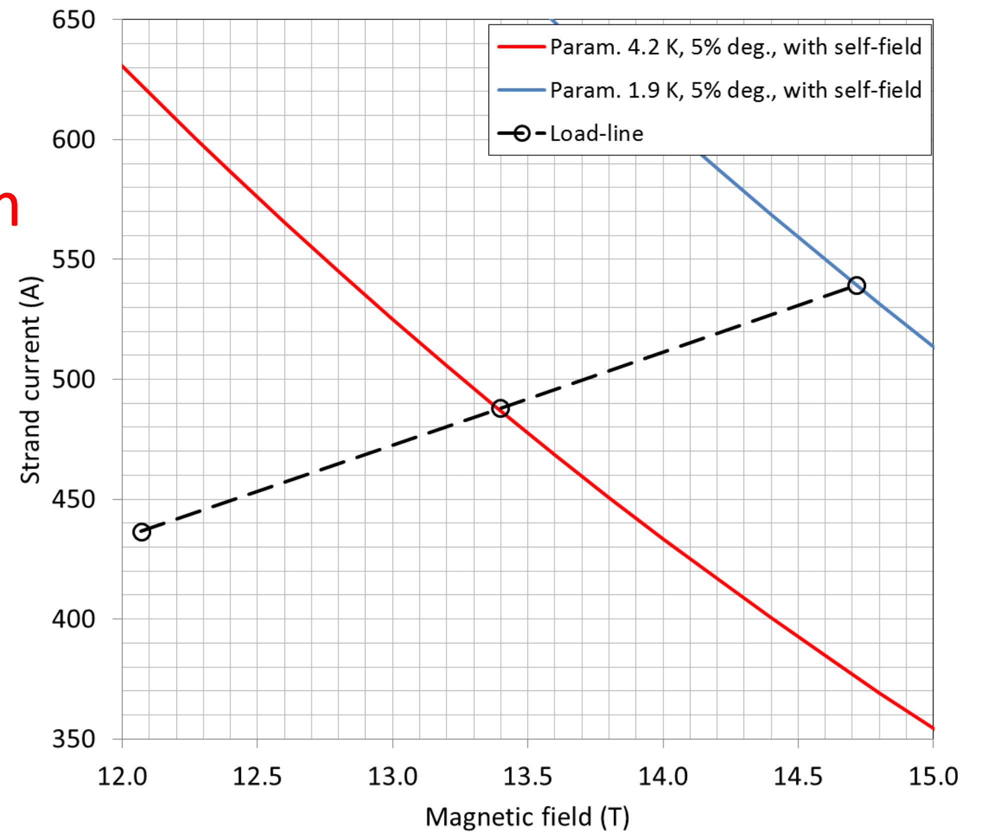






Magnet parameters

- Self field corr. (ITER barrel)
  - 0.429 T/kA
- 5% cabling degradation
- Operational grad.: 140 T/m
  - I_{op}: 17.5 kA
  - B_{peak_op}: 12.1 T
    - 81% of I_{ss} at 1.9 K
    - G_{ss}: 171 T/m
    - I_{ss}: 21.6 kA
    - B_{peak_ss}: 14.7 T
- Stored energy: 1.3 MJ/m
- Inductance: 8.2 mH/m



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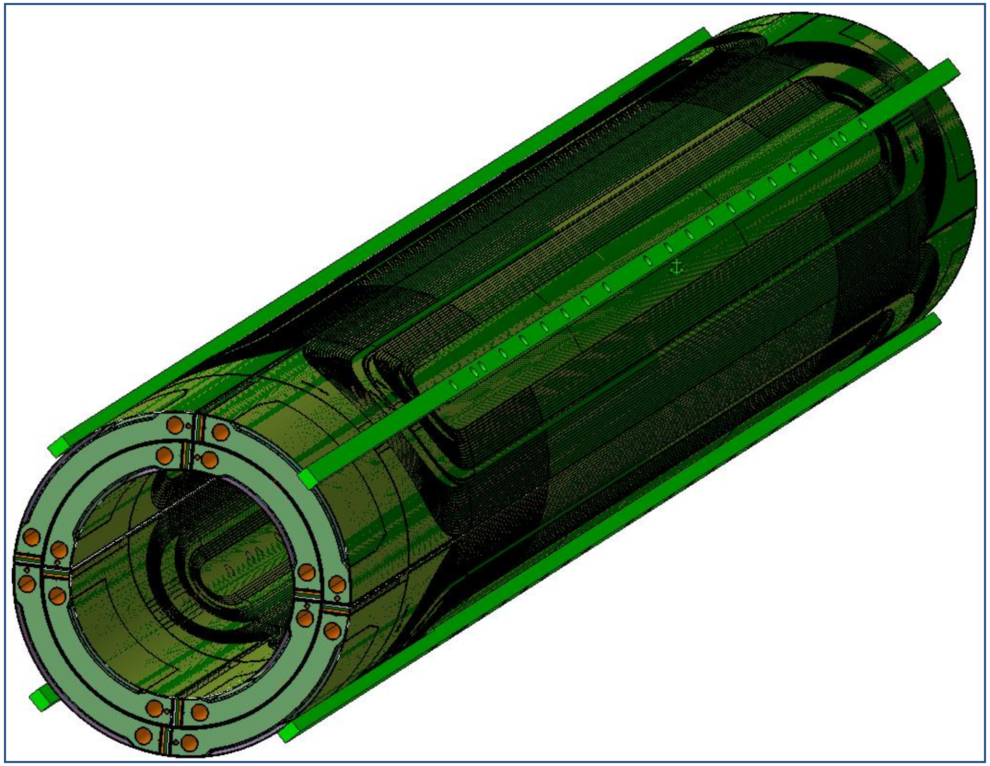
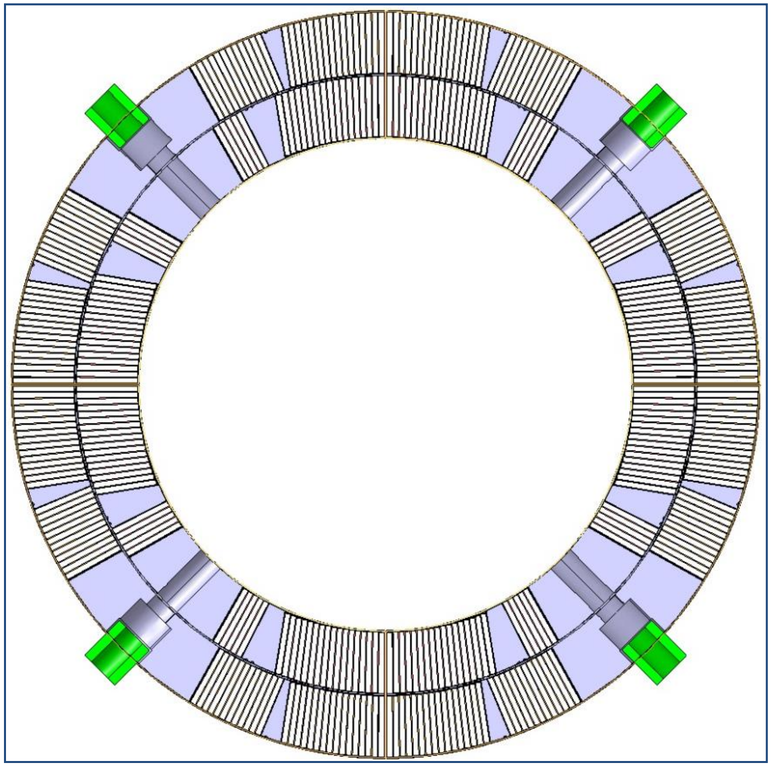
Coil and G10 pole key

See talk from R. Van Weelderen

- Cooling holes in the pole
  - 8 mm Ø every 50 mm

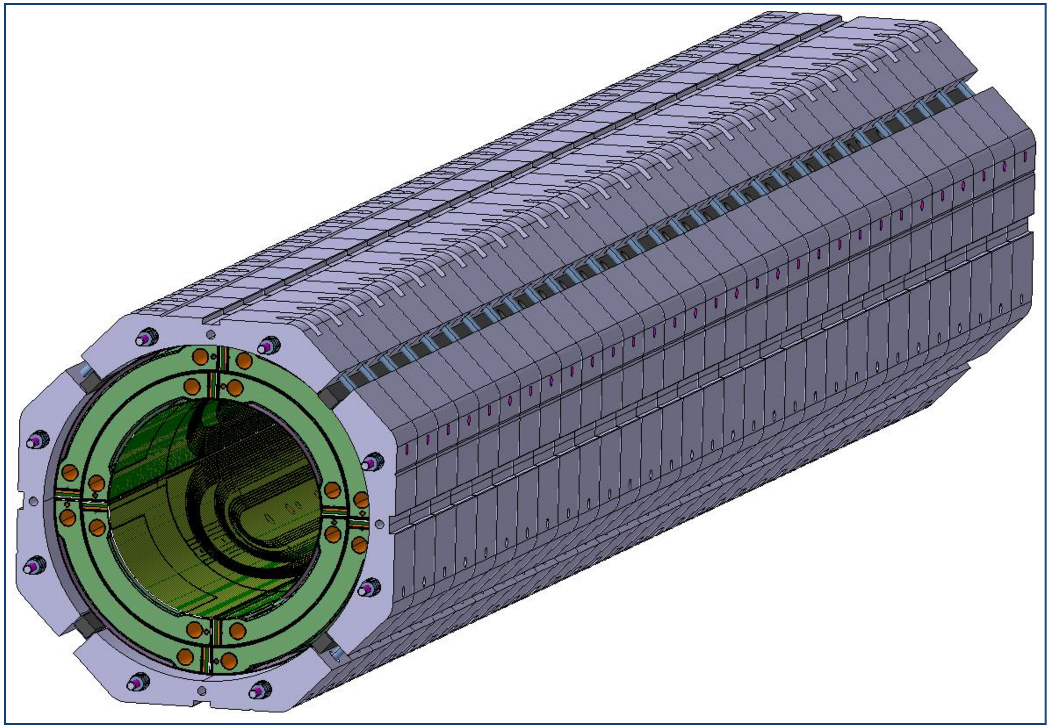


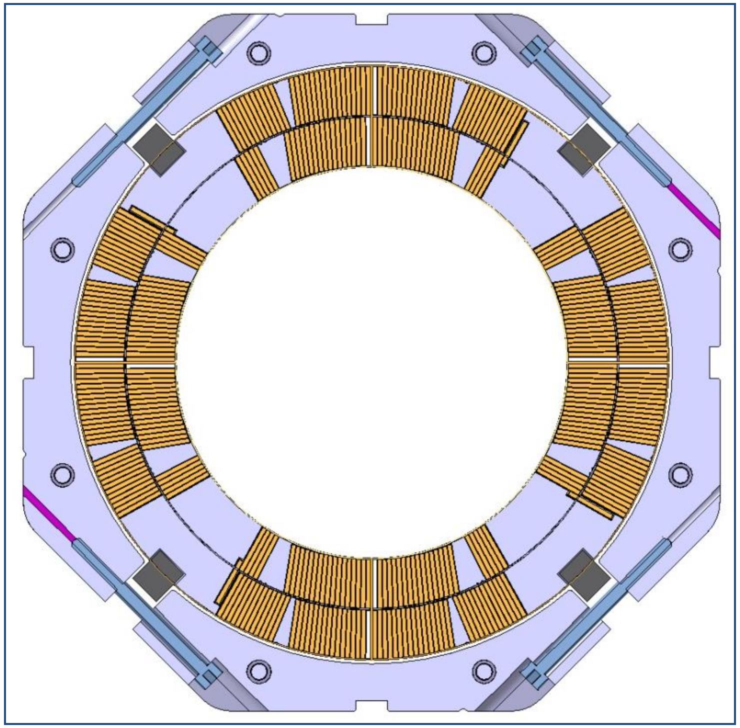


Aluminum bolted collars

See talk from P. Moyret on part fabrication

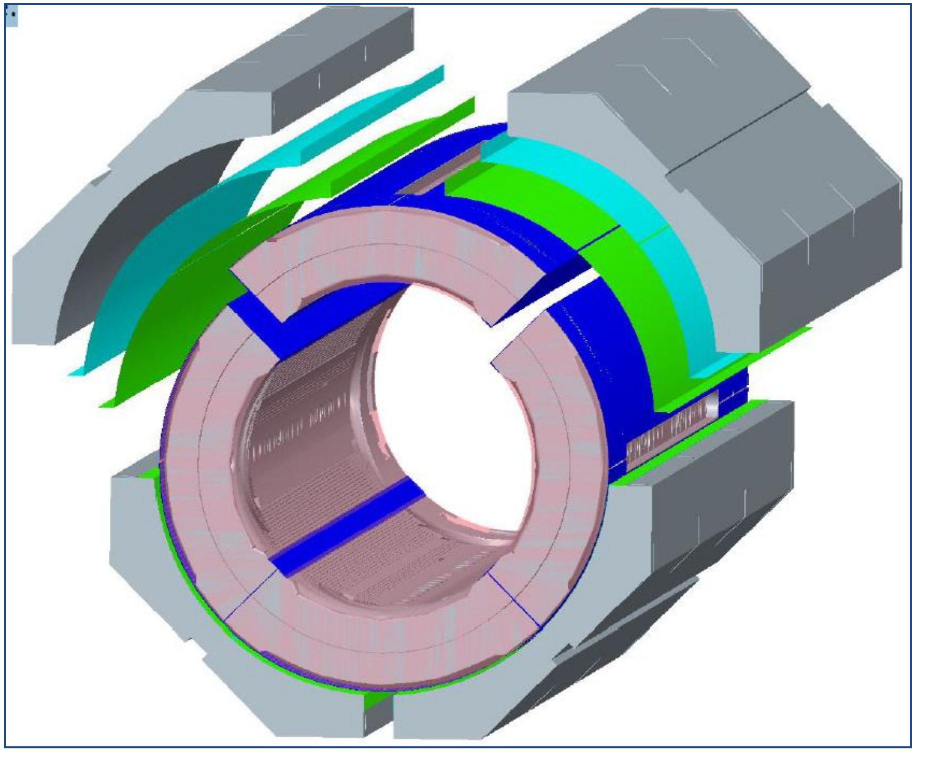
- 50 mm thick laminations
- Radial contact with coil and azimuthal contact with pole key (for alignment)
- No coil pre-load function
- 1.2 mm G10 shim used it to adjust radial contact between coil and collar





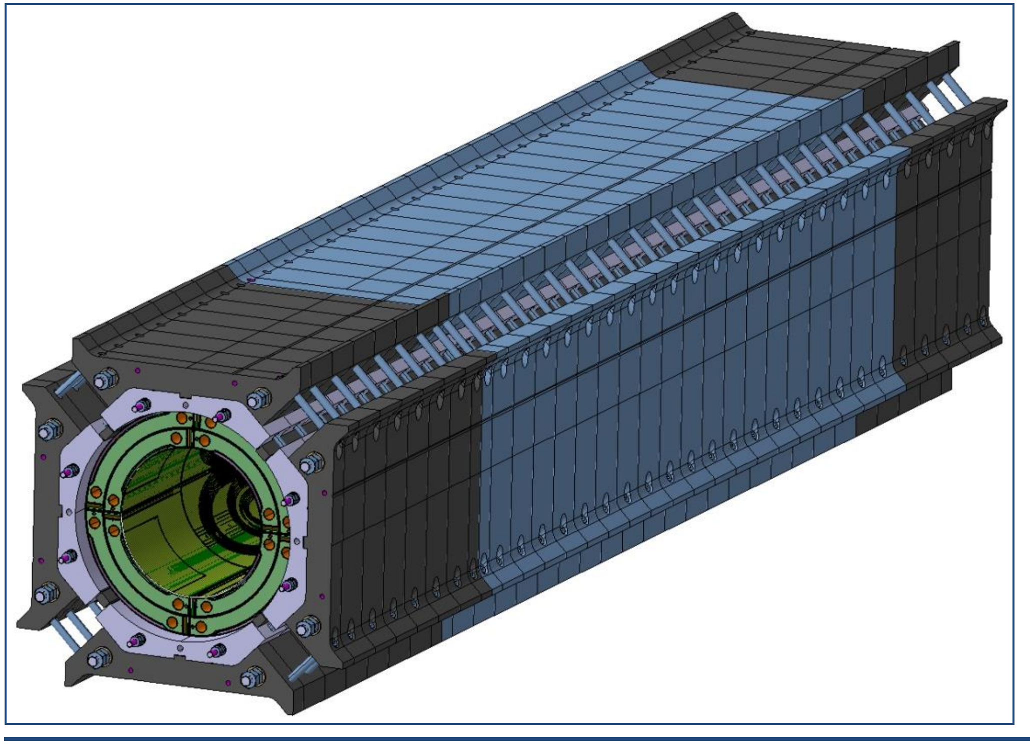
Ground insulation

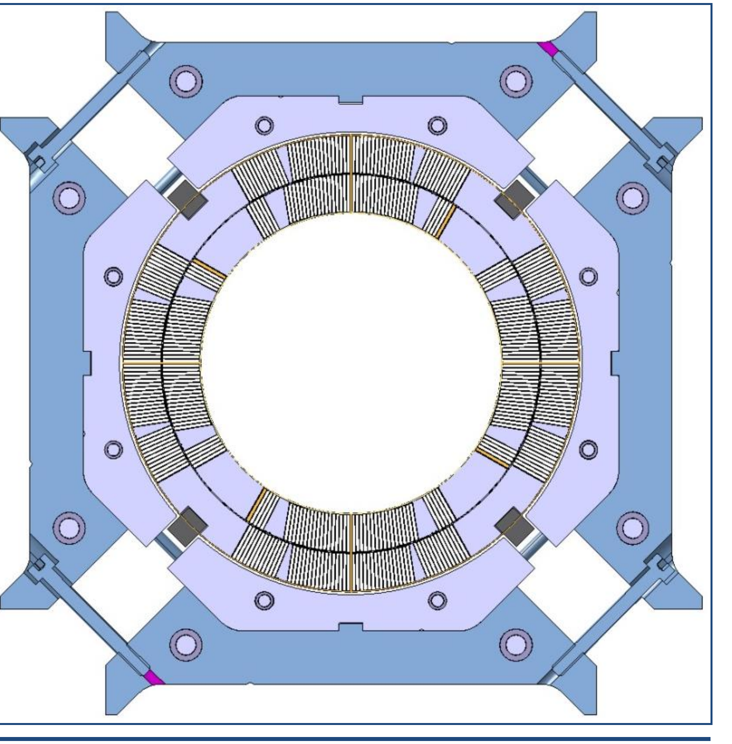
- Minimum 2 layers everywhere
- Minimum creep path
  - 7 mm
- Non-metallic pole key
- Seams staggered
- All pieces full length
- 1 layers on coil
- 2 layers on collars



Iron and stainless steel bolted pads
Coil-pack sub-assembly

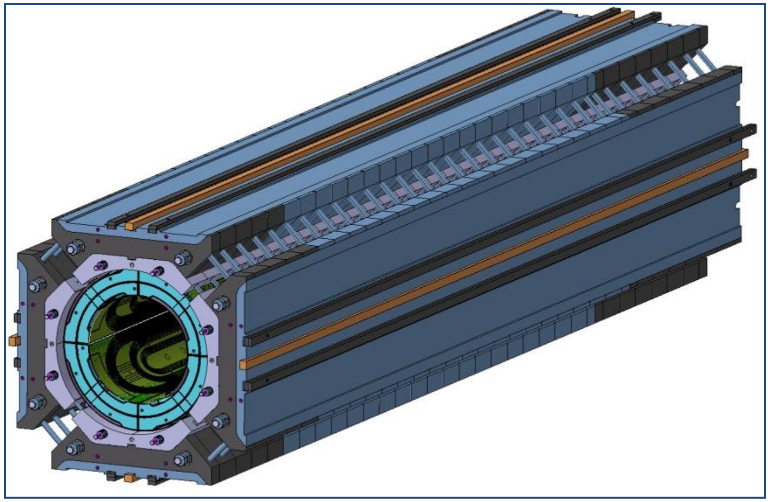
- 50 mm thick laminations
- Alignment with respect to collars
- Stainless steel laminations in the ends
- No coil pre-load function

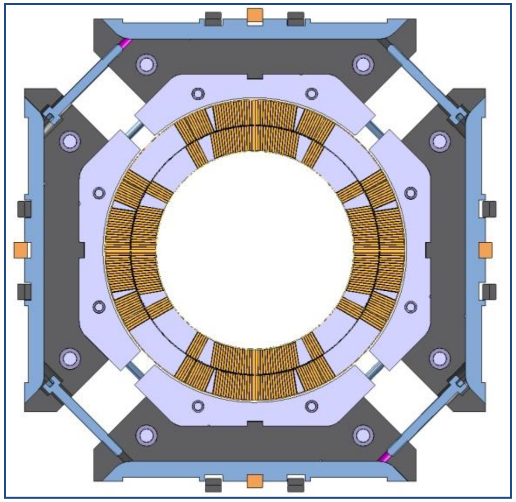




Iron masters and alignment-loading keys

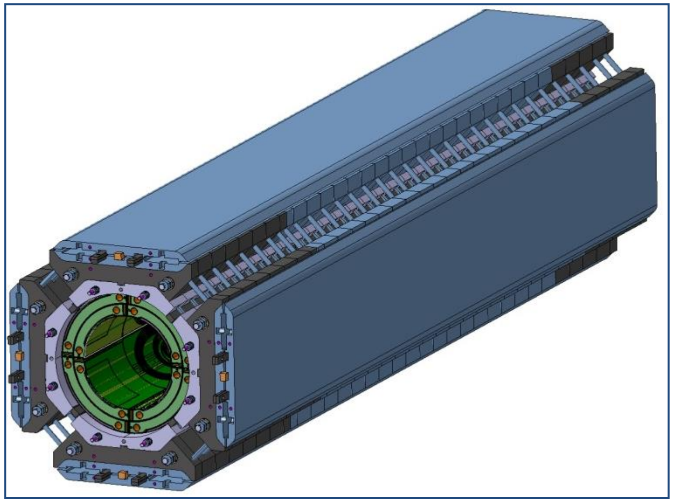
See talk from J.C. Perez and D. Cheng

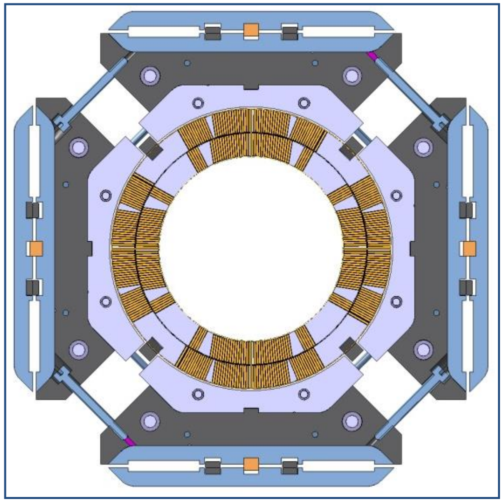




- Slots for
  - Bladders
  - Loading keys
  - Alignment keys
- Flat surface

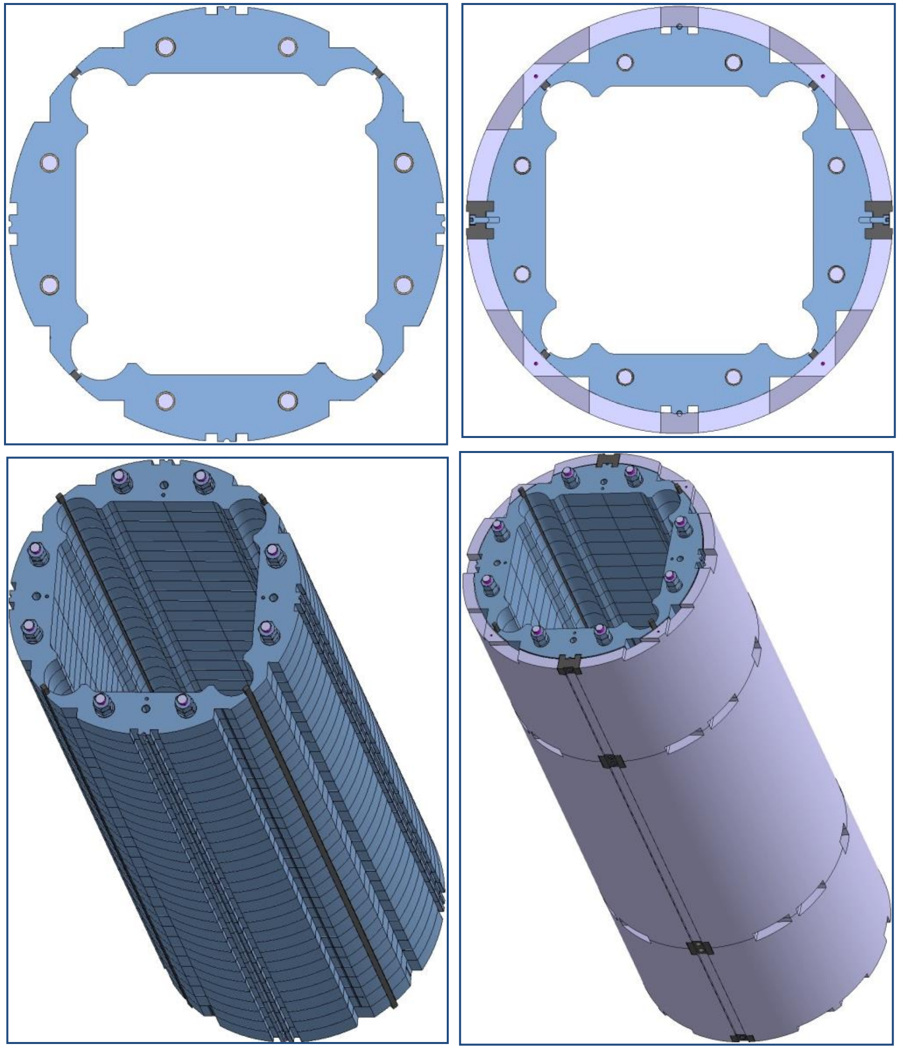
- Nested into features in the load pads (and yokes)





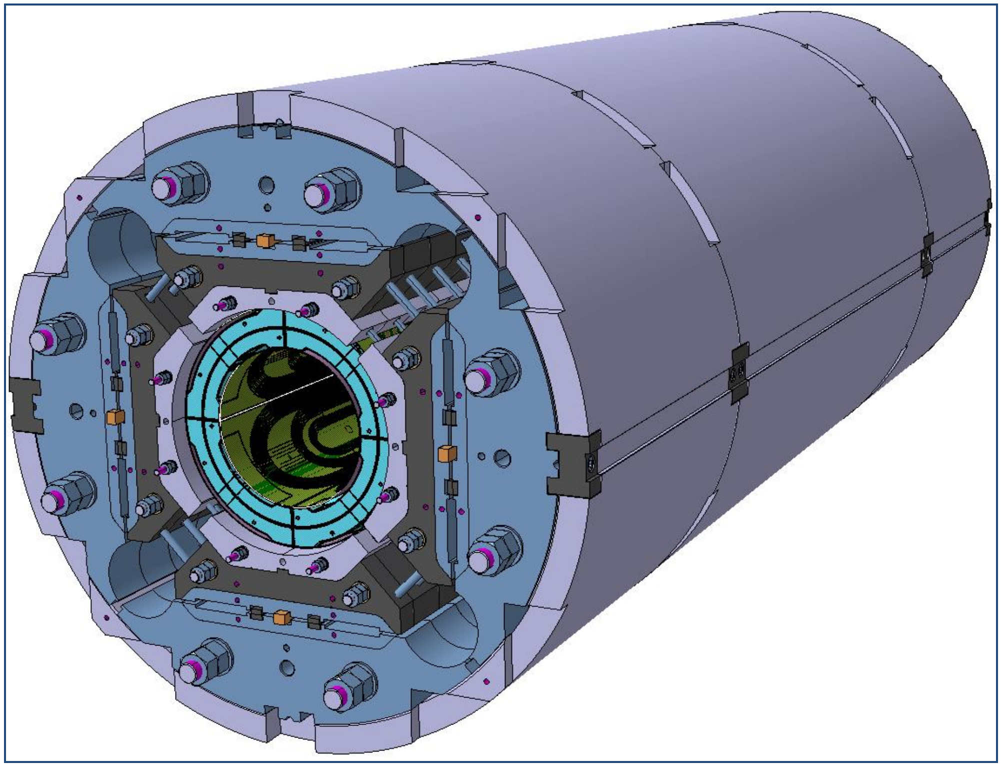
Yoke-shell sub-assembly

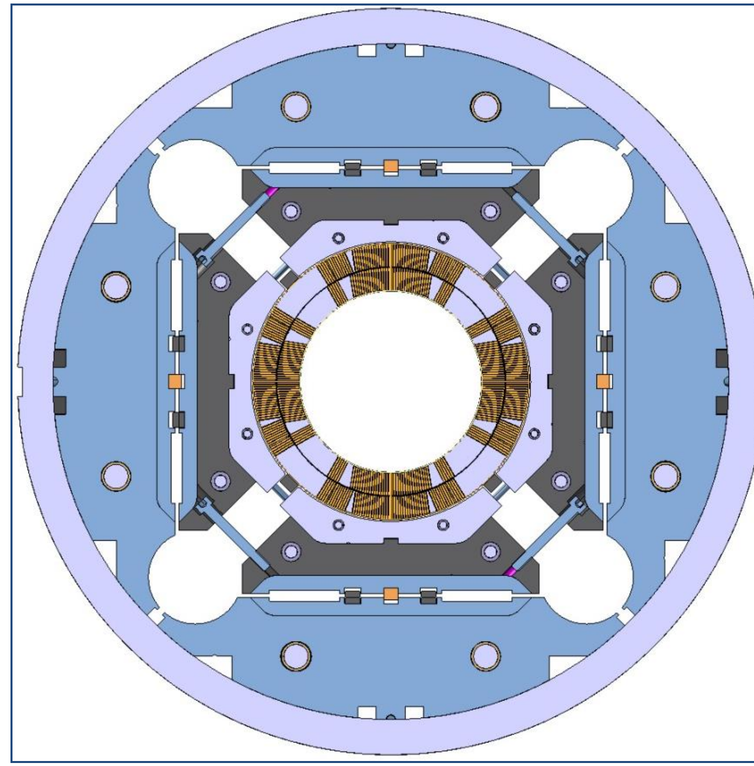
See talk from J.C. Perez and D. Cheng



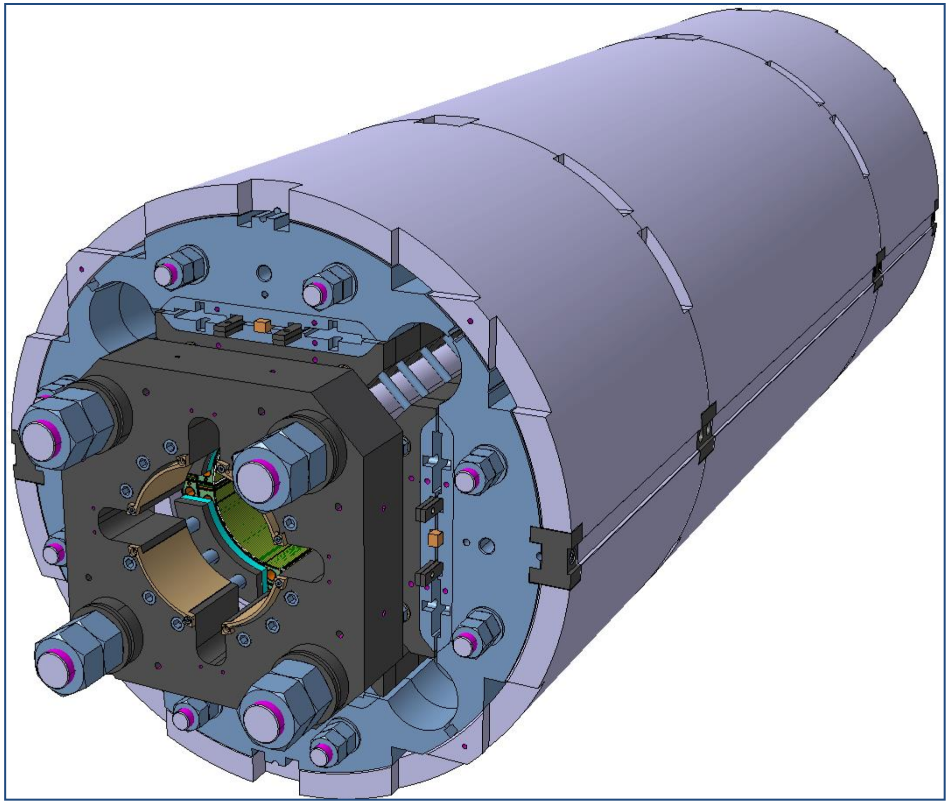
- 4 stacks of lamination assembled with ties rods
- Shell pre-load with temporary keys
- Tack-welding blocks bolted to the yoke
- Segmented shell with cut-outs for cold-mass assembly

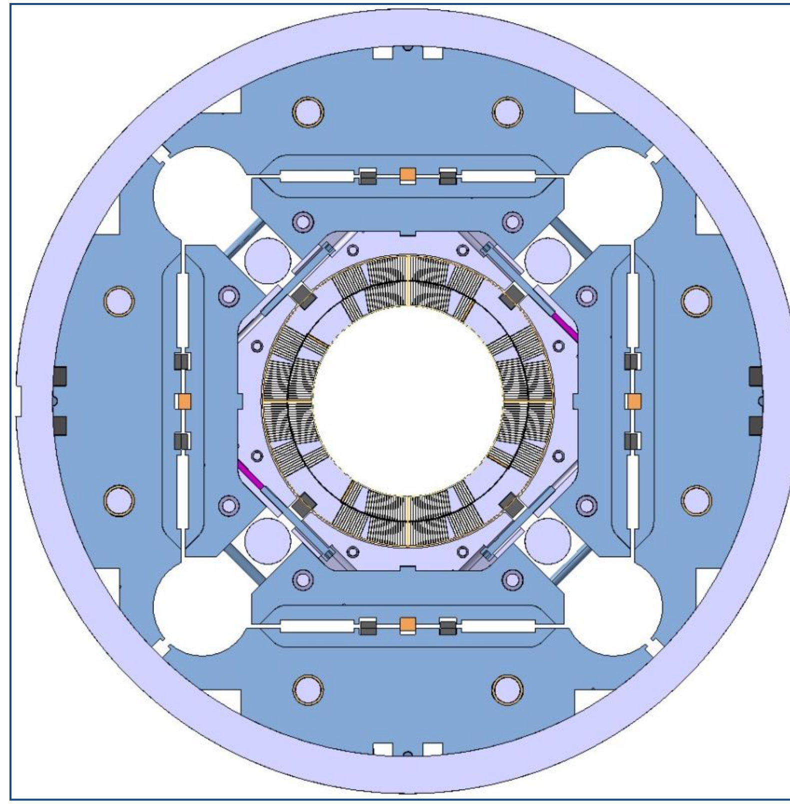
Coil-pack sub-assembly in shell-yoke-sub-assembly and pre-loading





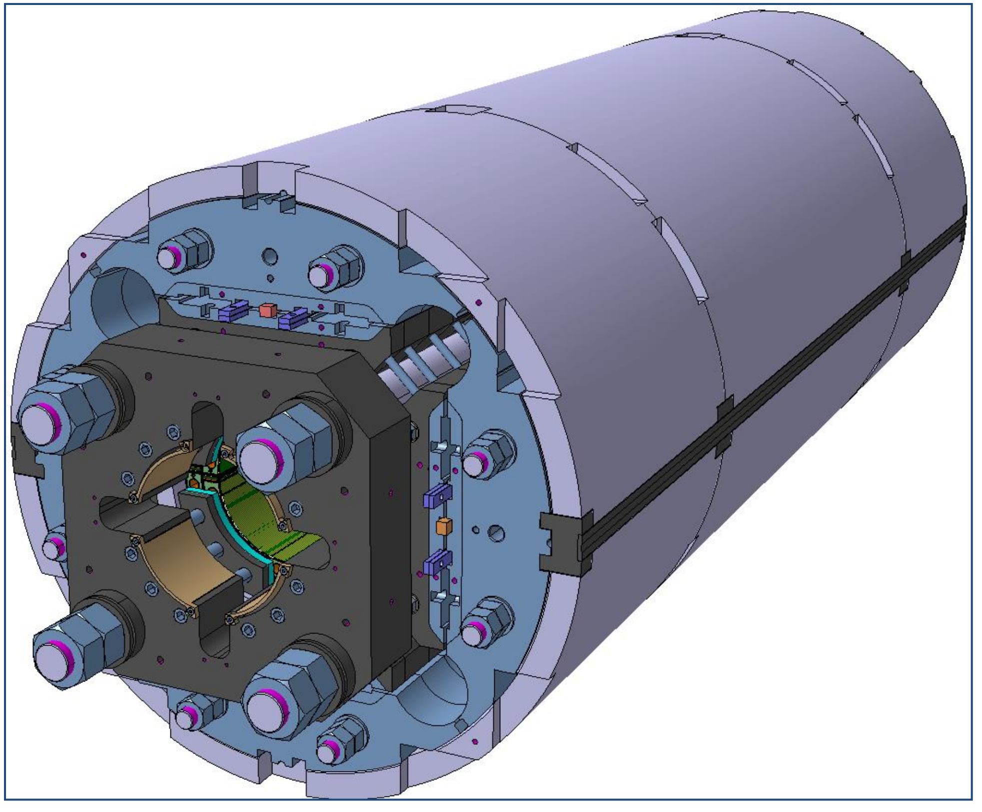
Aluminium axial rod insertion and assembly of end-plate

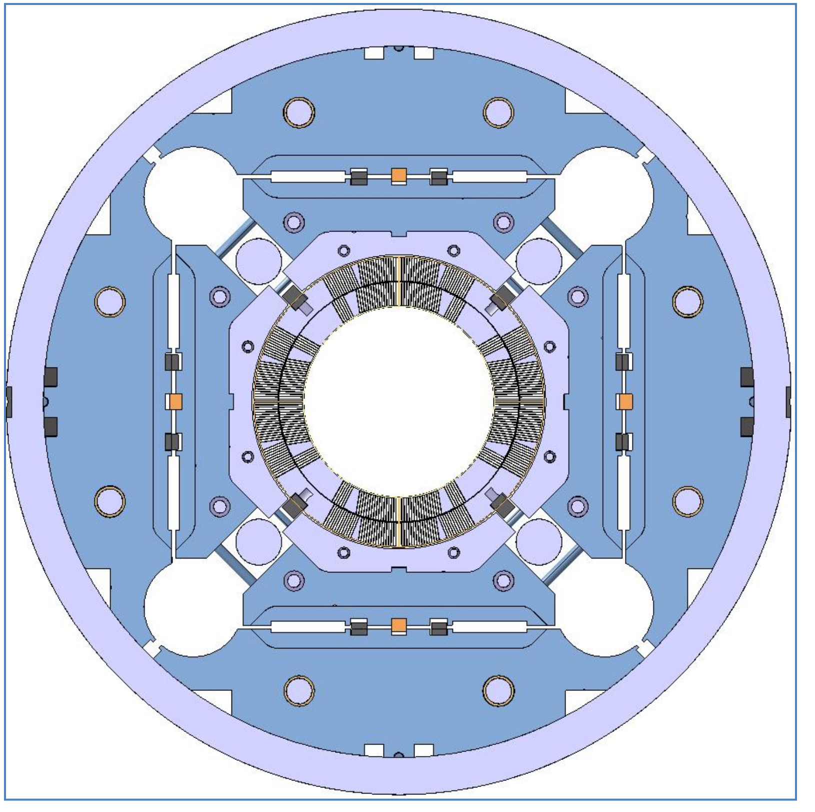




Backing-strip

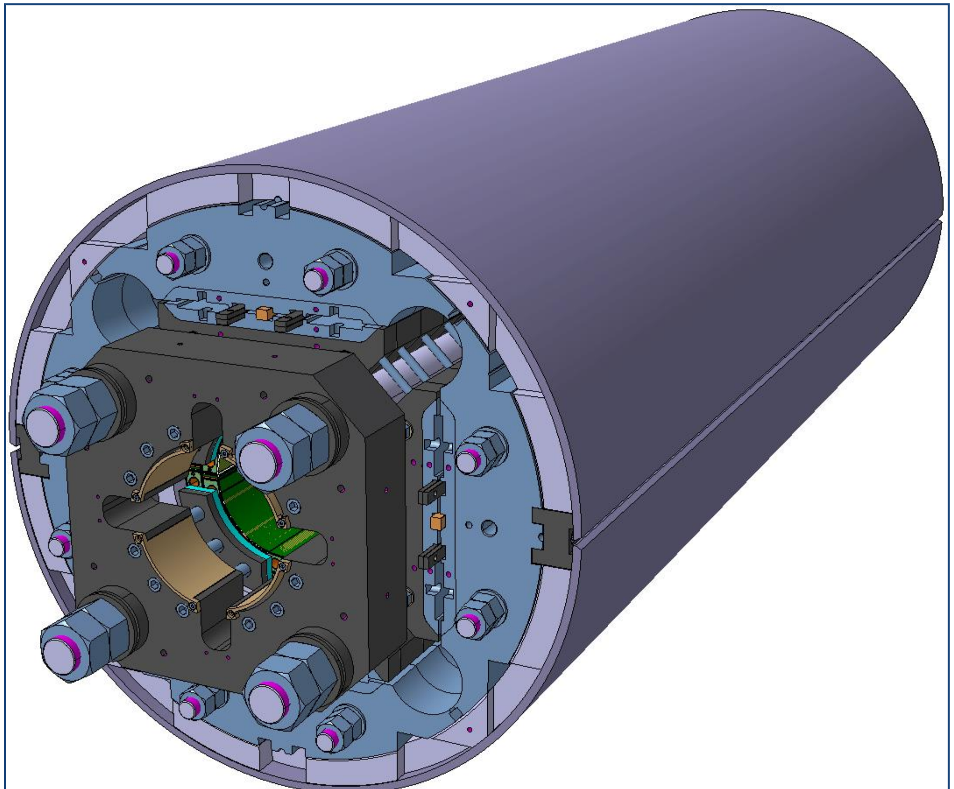
See talk from H. Prin

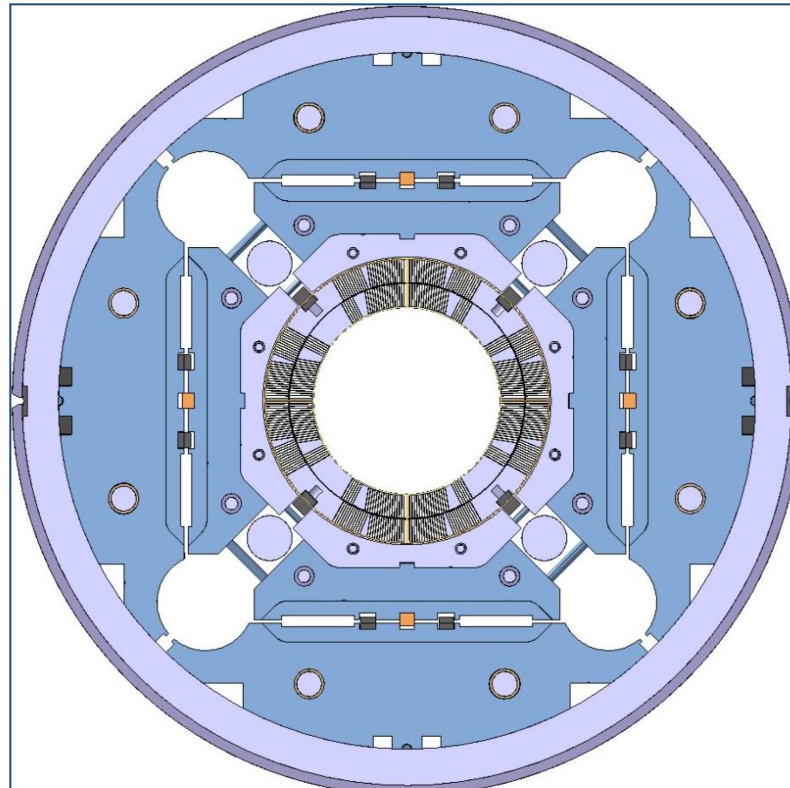




Welded LHe vessel (stainless steel shell)

See talk from H. Prin

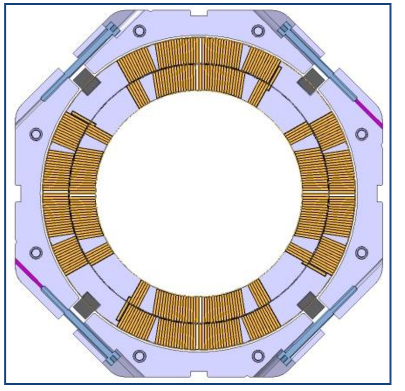


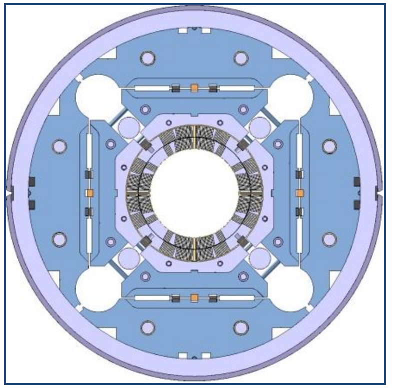


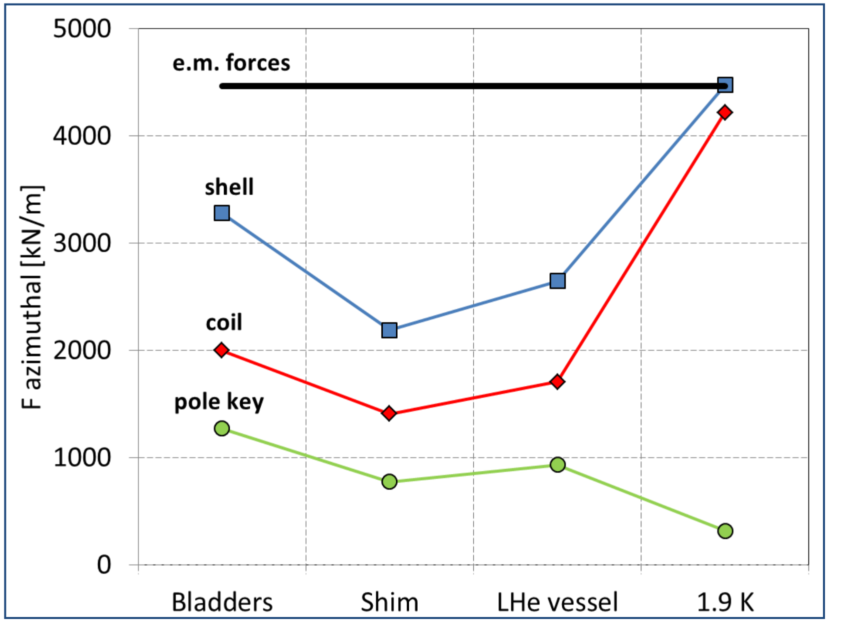
Pre-loading sequence

See talk from M. Juchno

- Target:
  - Coil pre-load = e.m. force
- Room temperature
  - **40 MPa bladder pressure**
    - Overshoot to insert shim
  - **~30%** of force on collars
  - Marginal impact of vessel
  - Coil peak stress **<100 MPa**
- 1.9 K
  - 0.4 mm coil radial displ.
  - Minimum force on collars
  - Vessel still in contact
  - Coil peak stress **~175 MPa**



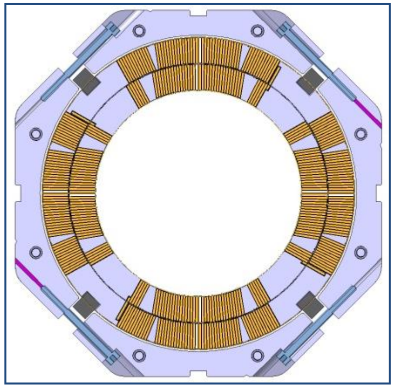


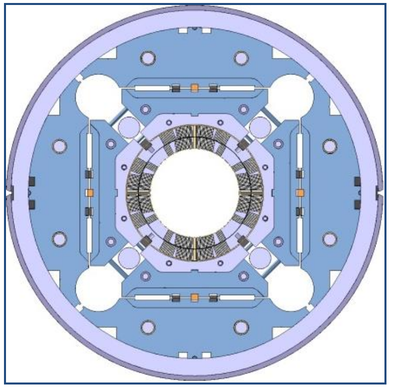


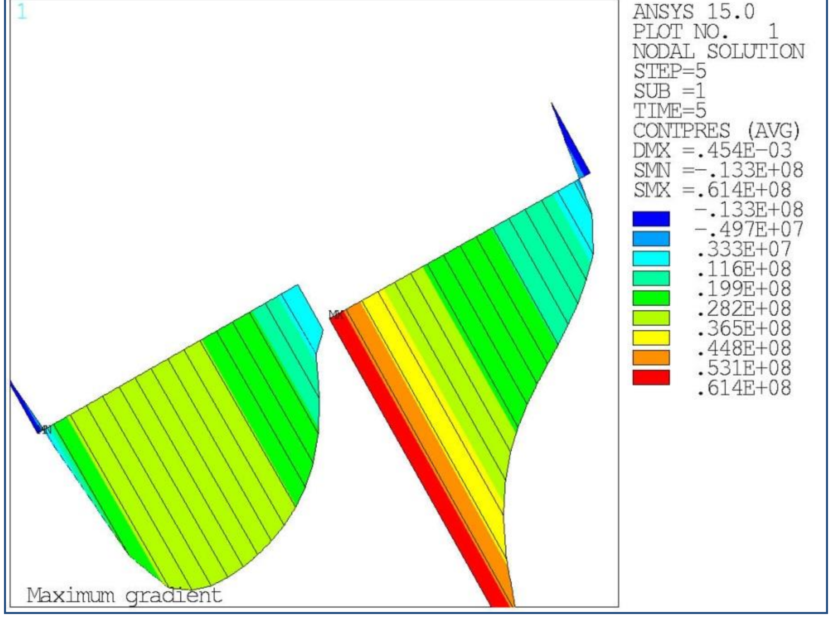
Excitation to 140 T/m

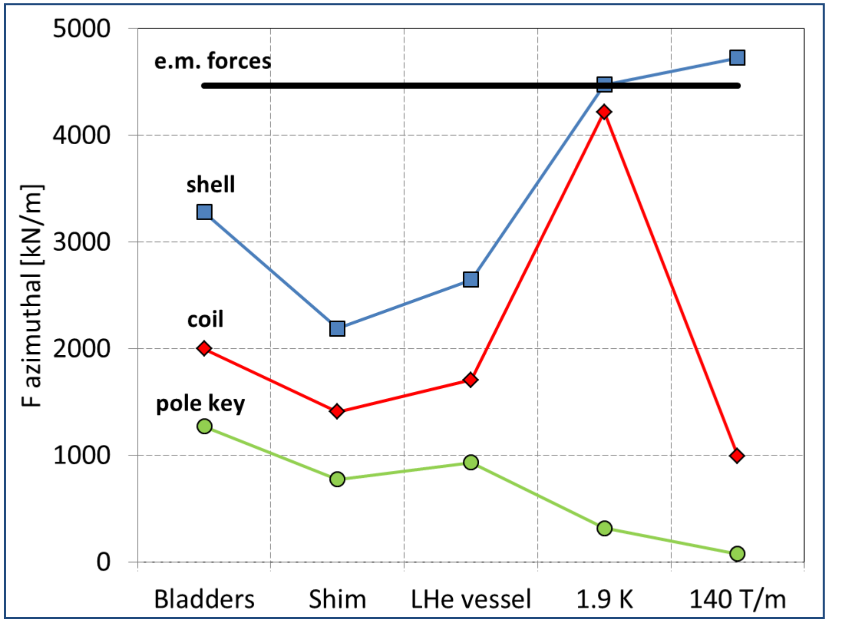
See talk from M. Juchno

- Coil under pressure
  - Capability to pre-load to 155 T/m
- Coil peak stress **~140 MPa**
- Structure rigidity
  - ~0.045 mm on the mid-plane
    - No impact on field quality







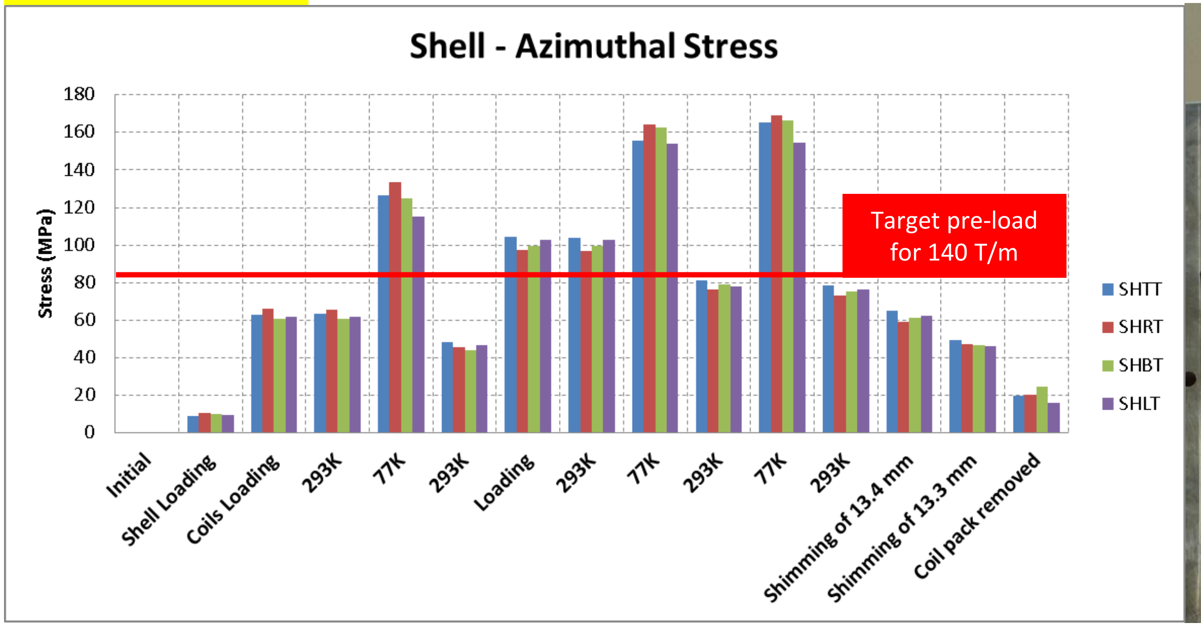


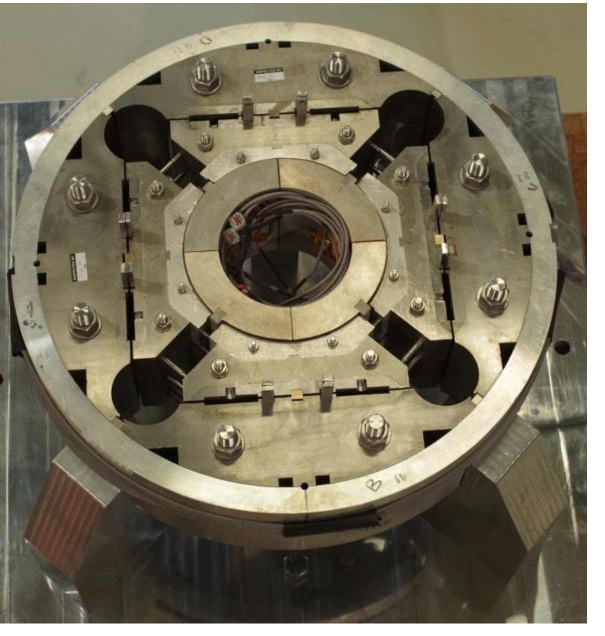
Loading of 150 mm mock-up

See talk from J.C. Perez

- Shell target pre-load for 140 T/m passed
  - All bladders pressurized at the same time
- ~10 MPa variation among shell gauges

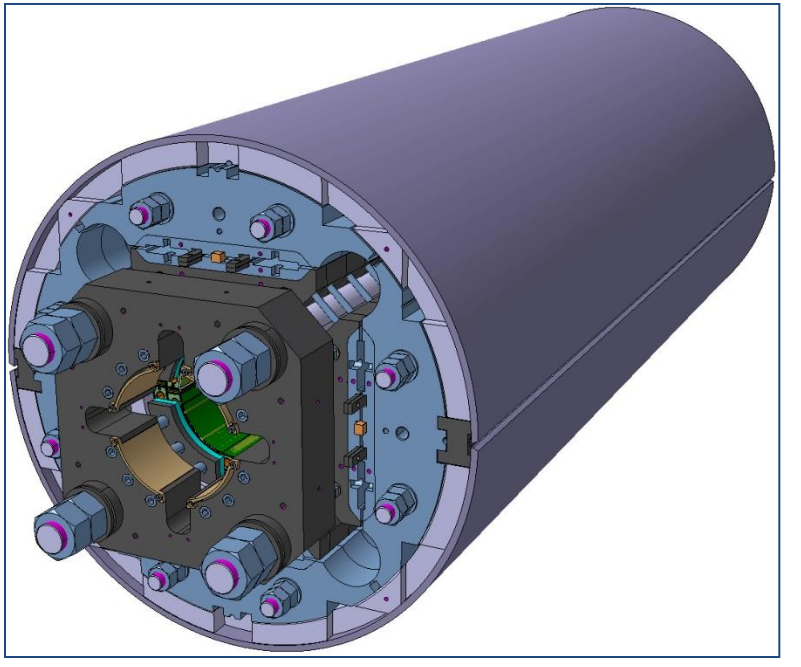
Data from EN/MME

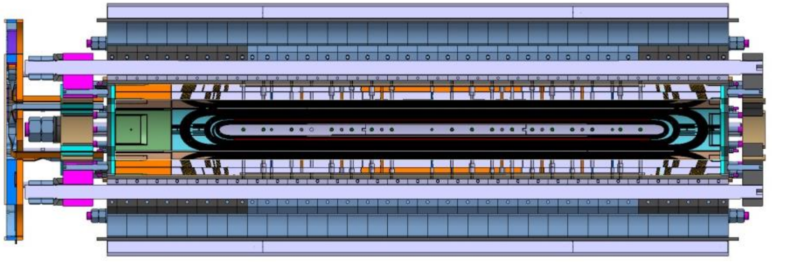




Axial loading

- Same loading principle as azimuthal loading
  - Coil pre-load = e.m. force
    - From "open gap yoke" to "free aluminum rods"
  - Pre-load to maintain pressure coil – end-parts
- Rigidity
  - ~100 μm rod elongation
    - In LQ, +10 microstrain →
      - 33 micron over 3.3 m length



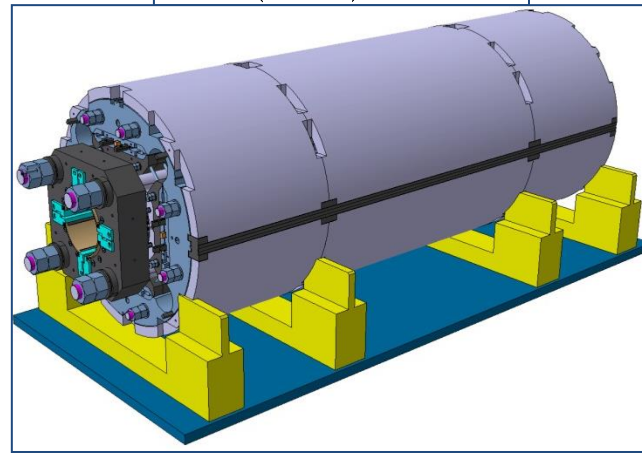


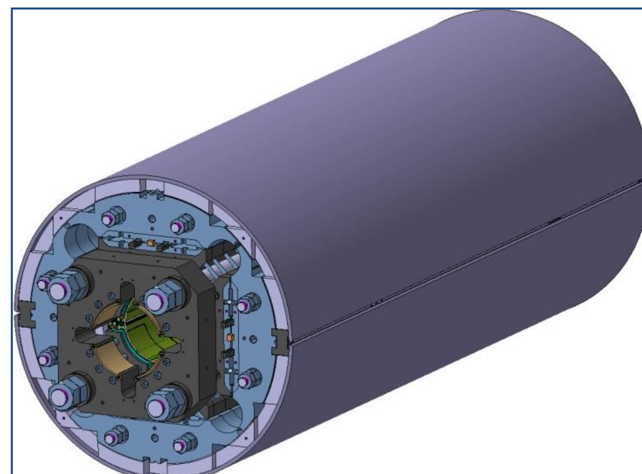
Shell segmentation and LHe vessel (I)

See talk from M. Juchno

- In case of full length aluminum shell
  - High ε_z and σ_z due to friction and high thermal contraction
    - Risk of ratcheting
  - Variation of shell axial ε_z due to friction
    - Large coil stress σ_ϑ variation
- Aluminum shell in 0.755 m segments
  - LQ/HQ shell axial stress levels
  - Coil azimuthal stress variation ±10 MPa
- Optimization of shell segments for long model in progress

$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z)$$



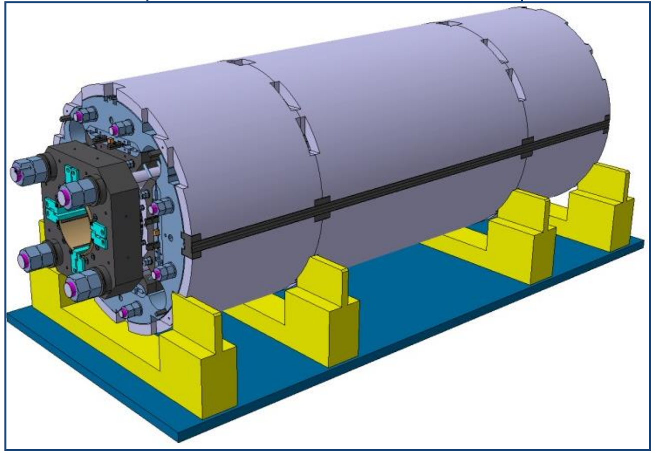


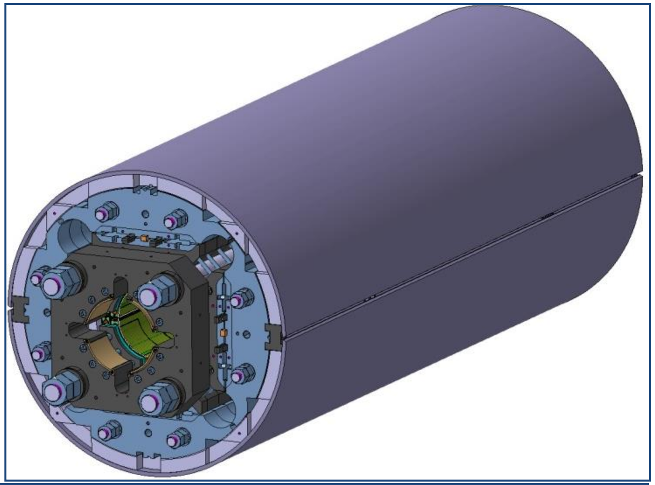
Shell segmentation and LHe vessel (II)

See talk from H. Prin

- Shell cut-outs to align magnet under press during tack welding process
  - Optimization of welding blocks and backing strips in progress
- Stainless steel shell welded with 50-100 MPa tension
  - Still in contact after cool-down (~20 MPa)

$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z)$$





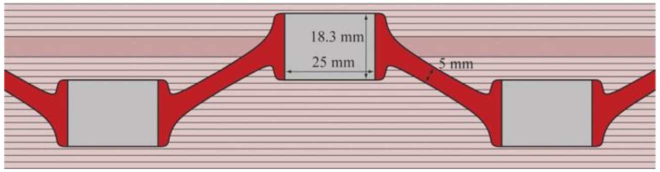
Outline

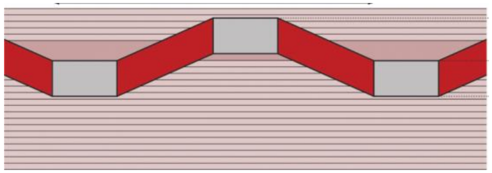
- Overview of MQXF project and design
- Strand and insulated cable
- Coil design, magnetic analysis, magnet parameters
- Support structure and mechanical analysis
- **Quench protection**

Quench protection

See talk from G. Ambrosio

- Inner and outer layer trace impregnated with the coil
- Cu plating (~10 µm) on 25 mm ss
- Perforated 50 µm polymide layer and minimum covered area
  - Different designs to be tested
- **Hot spot T: ~290 K**
  - 330 K with only out layer heaters
- CLIQ under study and test for redundancy



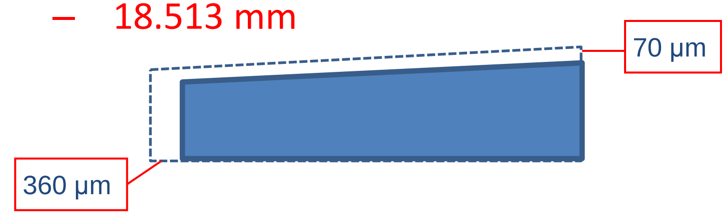


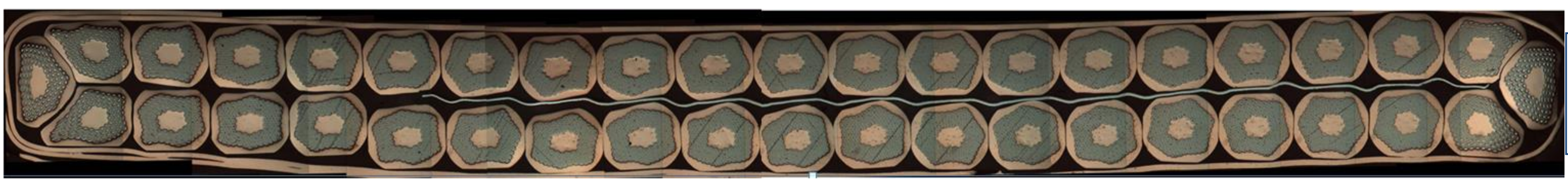
Appendix

MQXF baseline cable

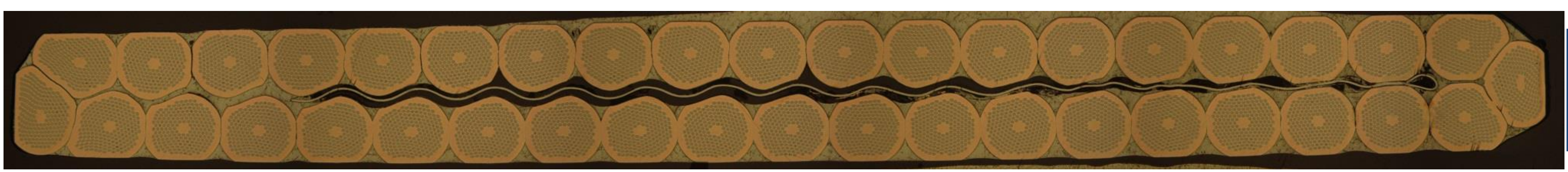
- 40-strand cable
- Mid – thickness after cabling
  - 1.525 +/- 0.010 mm
  - Thin/thick edge: 1.438 /1.612 mm
- Width after cabling
  - 18.150 +/- 0.050 mm
- Keystone angle
  - 0.55 +/- 0.10 deg.
- Pitch length
  - 109 mm
- SS core 12 mm wide and 25 µm thick

- Assumed expansion during reaction
  - 4.5% in thickness: ~70 µm, same keystone angle
  - 2% in width: ~360 µm
- Mid – thickness after reaction
  - 1.594 mm
  - Thin/thick edge: 1.505/1.682 mm
- Width after reaction
  - 18.513 mm





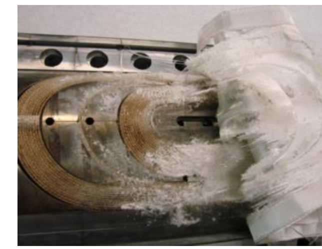
RRP cable



PIT cable

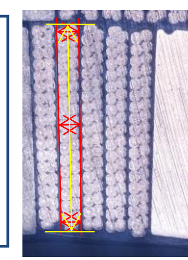
Dimensional changes during heat treatment

- Unconfined cables and strands (RRP) at LBNL
  - axial contraction: 0.1 to 0.3 %
  - thickness increase: 1.5 to 4 %
  - width increase: 1.5 to 2 %



- Data on PIT strands and cables (FRESCA2)
  - larger axial contraction, comparable cross-section increase
- In HQ01, only 1-2% space for expansion left in design
  - Clear signs of over compressed and degraded coils

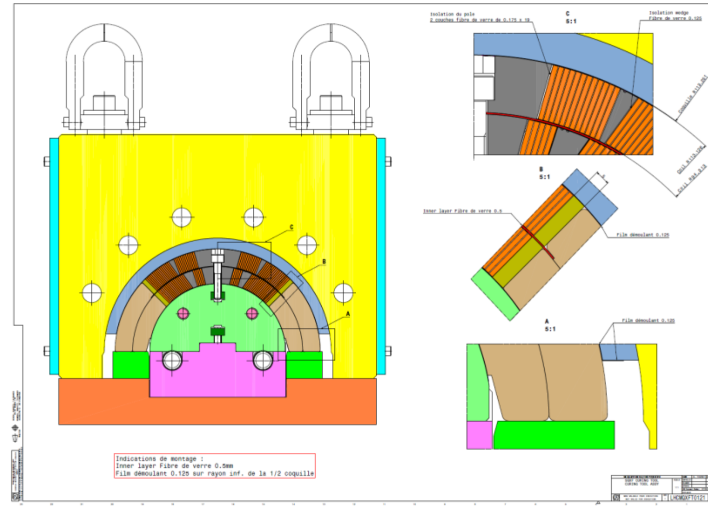
- So in HQ02, reduction of strand diameter (0.8 → 0.778 mm)
  - Thickness: 4.5%, from 29 μm (HQ01) to 65 μm (HQ02)
  - Width: 2%
  - Very good HQ02 quench performance

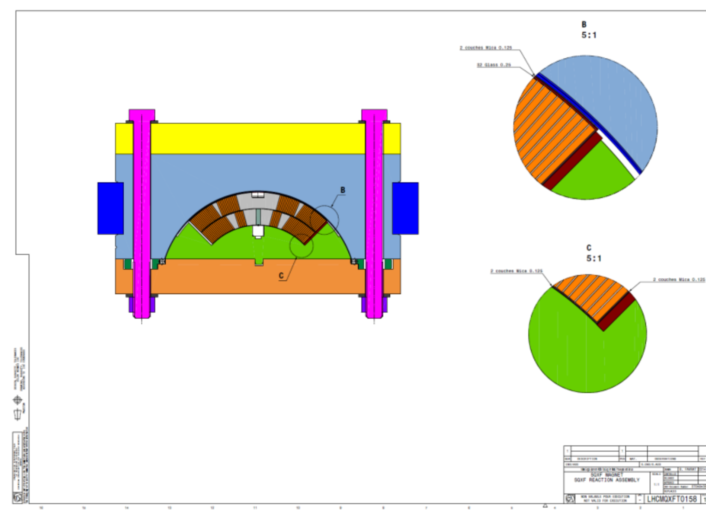


- Same assumptions used for MQXF
  - No signs of over-compression in first coils
  - Work in progress: Ten stack measurements at CERN and MQXF LARP coil 1 cross-section measurements at LBNL

Tooling design

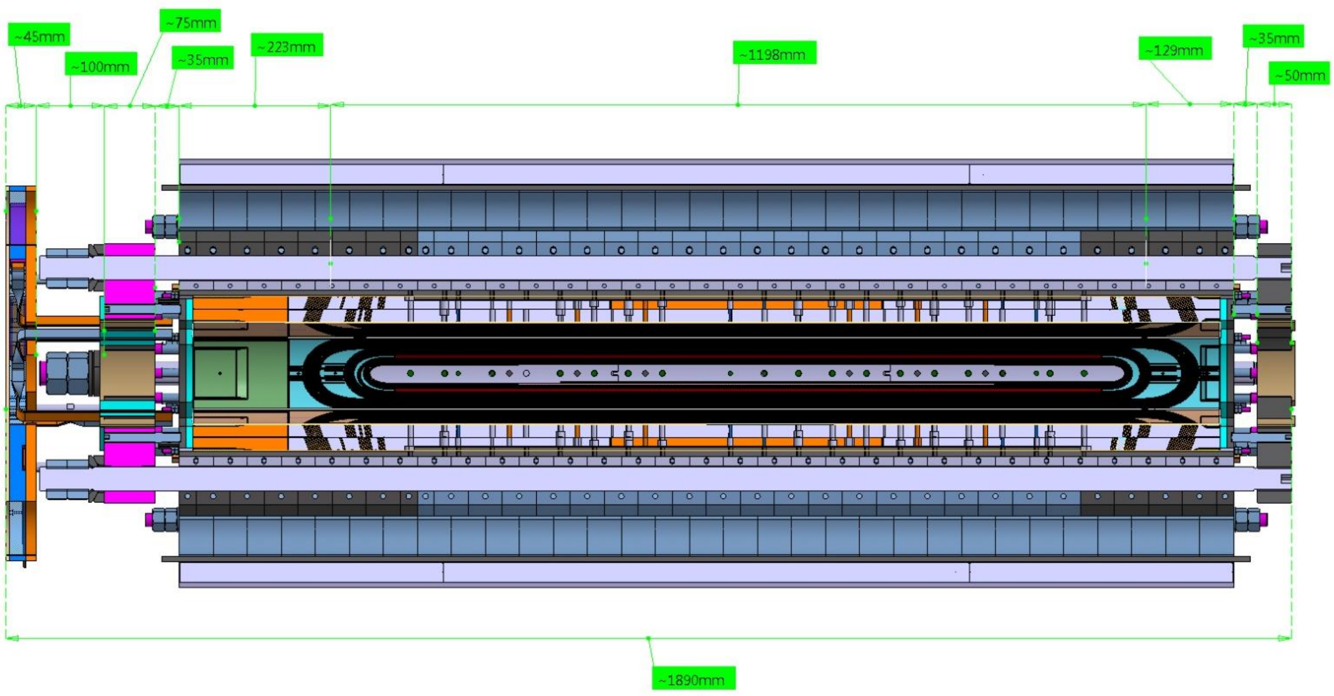
- Cable dimension after reaction and 150 μm thick insulation
- Coil cured in larger cavity
- Coil closed in reaction fixture in larger cavity
- Coil after reaction and during impregnation in nominal cavity
    - Theoretical pressure ~5 MPa





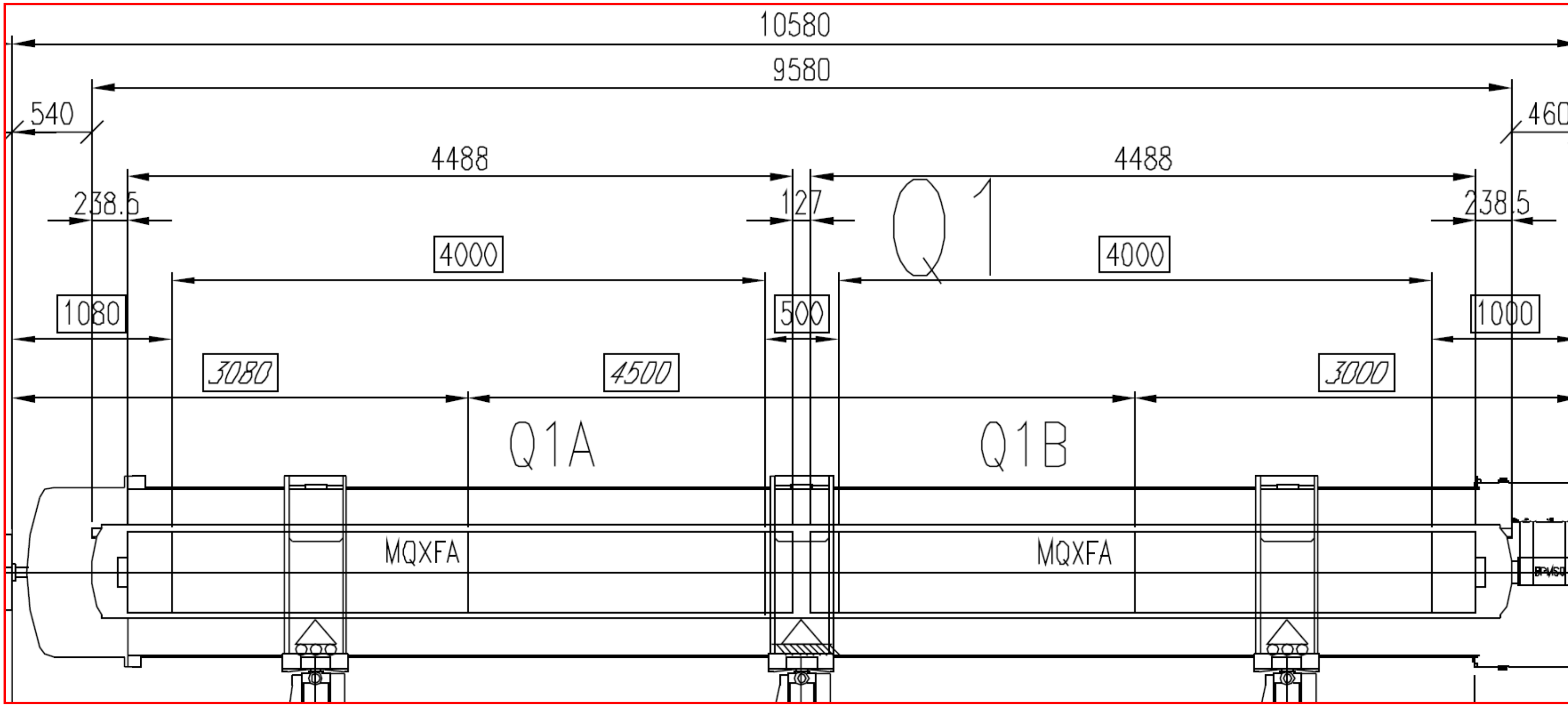
MQXF length

- From magnetic length to end of magnet (end-plate + connection box)
  - Connection side: **478 mm**
  - Non-connection side: **214 mm**



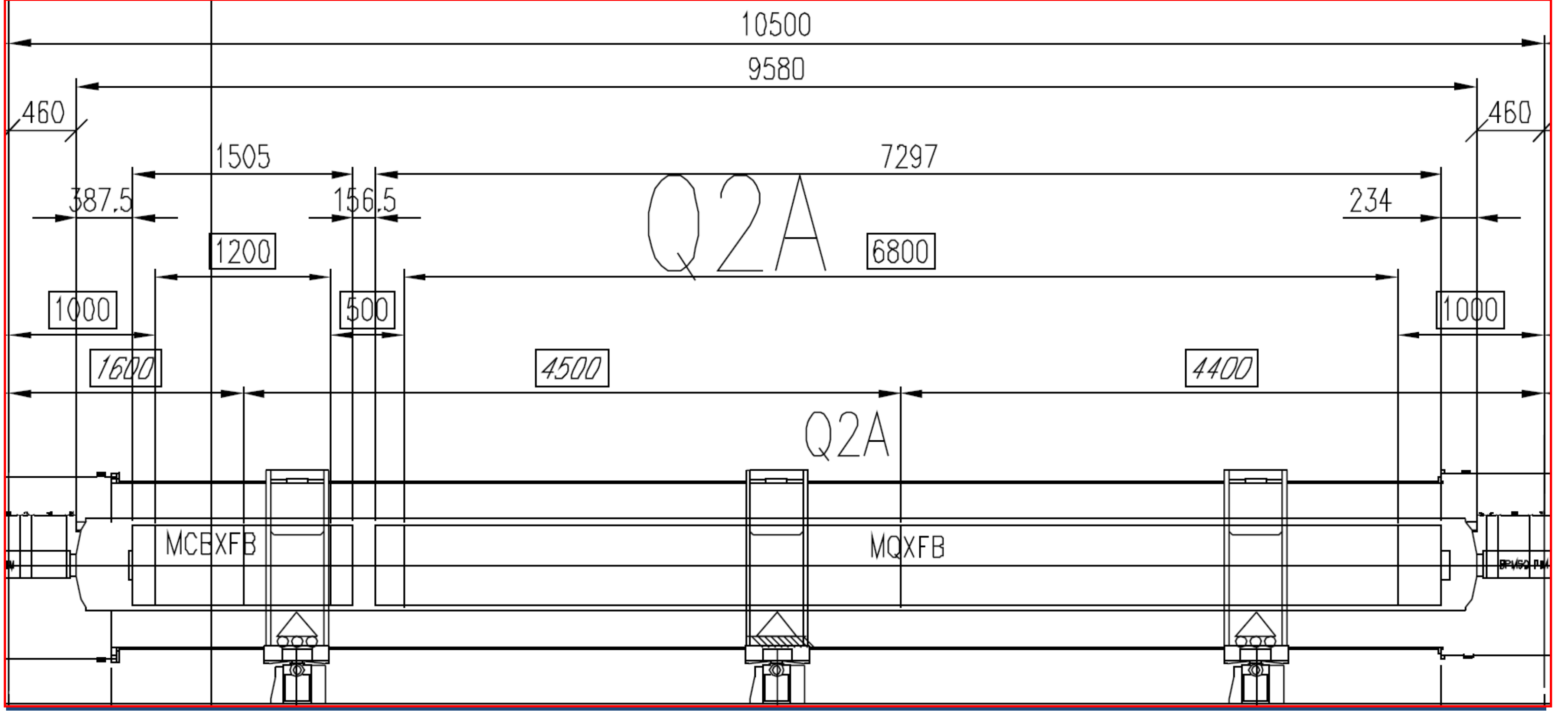
Q1

- Connection side: from magnetic length to end of end-cover
  - **301.5+238.5=540 mm** (**478 mm** magnetic to end of magnet in MQXF)
- Non-connection side: from magnetic length to Q1a-Q1b "middle point"
  - **186.5+63.5=250 mm** (**214 mm** magnetic to end of magnet in MQXF)



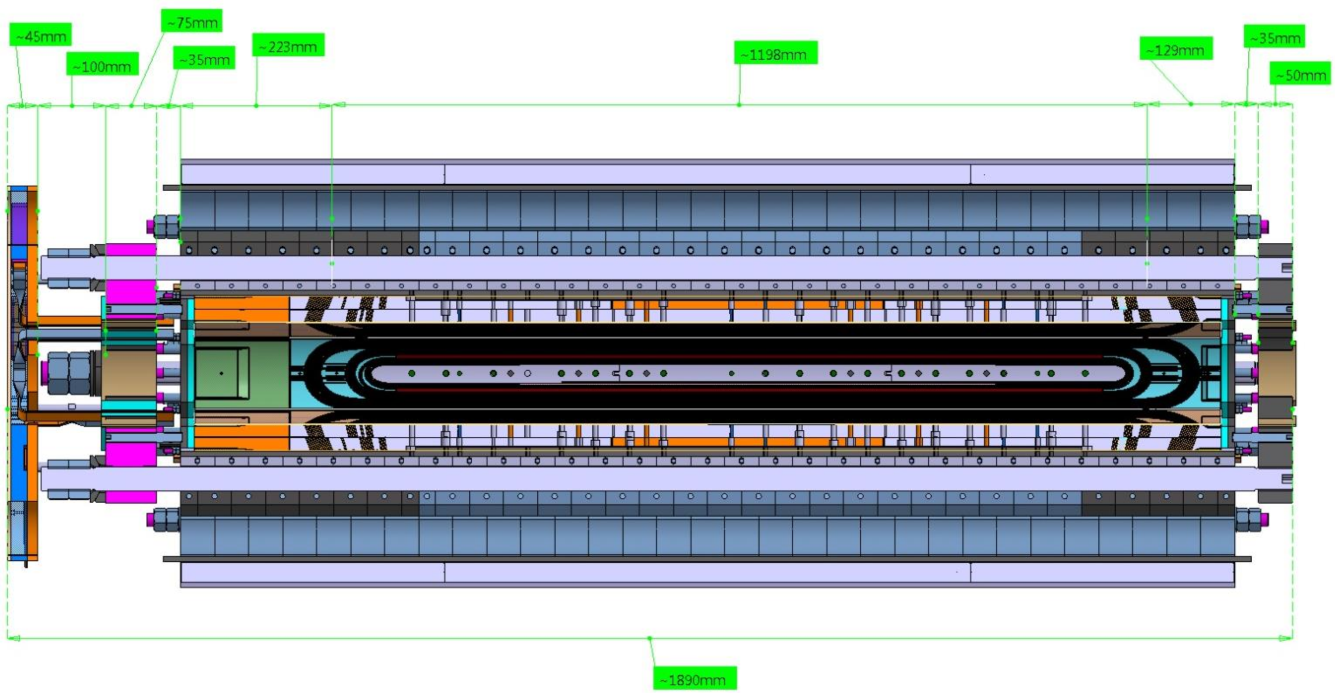
Q2

- Connection side: from magnetic length to end of end-cover
  - **325+234=559 mm** (**478 mm** magnetic to end of magnet in MQXF)
- Non-connection side: from magnetic length to Q1a-Q1b “middle point”
  - **172+78=250 mm** (**214 mm** magnetic to end of magnet in MQXF)



Minimum distance between Q1a and Q1b magnetic lengths

- From magnetic length to end of magnet (end-plate + connection box)
  - Non-connection side: **214 mm**
  - Minimum distance: 214+214+22 (?) = ~ 450 mm



CERN connection box