# Design Features:
# still to be determined and open questions

**P. Ferracin**

4th Joint HiLumi LHC-LARP Annual Meeting
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KEK, Tsukuba

# Outline

- Cable and coil design fine tuning
- Splicing
- Magnet length, axial support, and connection box
- Quench protection
- Support structure

# Extracts from MQXF conductor review close-outs

*Overall/schedule - 1*

- Design goals shall be conservative because $Nb_3Sn$ accelerator magnet technology is still not sufficiently matured and impregnated $Nb_3Sn$ coils operated at 1.9 K are prone to self-field instabilities
- Therefore: optimize margin by all means, such as: increasing length, revisiting Cu-to-non-Cu ratio, and so on.
- Make use of model/prototype phase for finalizing specifications essential for success, including of acceptance criteria

*Technical specs*

- Not complete at this time
  - Relationship of superconductor properties to magnet performance has not been clearly defined
- Add requirement on strand cleanliness and surface conditions (especially for bare copper strands)
- Clarify billet/unit length approval
- Benefit from model/prototype program to confirm that the following specs are correct:
  - strand $I_c$: 361 A at 4.2 K and 15 T
  - RRR: 150 on virgin strand/100 on extracted strand
- Address $R_a$ and $R_c$ on cable

# Extracts from MQXF conductor review close-outs

*RRP*

- Go ahead with 132/169 lower Sn content; final decision in one year concerning series production contract (back up being 108/127)

- Consider proposal to reduce keystone angle

*PIT*

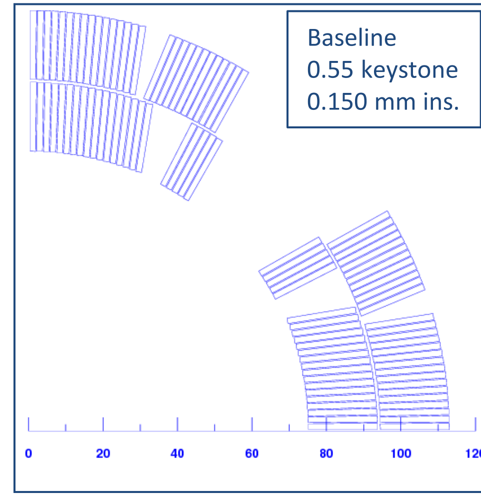
- Promote a substantive development program with BEAS to optimize strand properties and establish performance baseline for series production
- In the meantime, CERN should go ahead with RRP for model magnet production and should optimize phasing of strand/cable deliveries between RRP and PIT.
- Reduced keystone angle is a must.

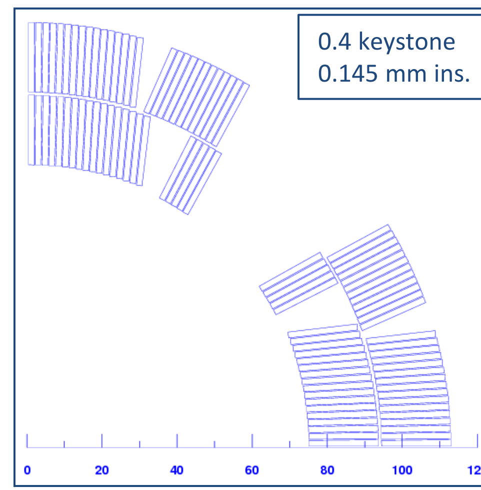
# Cable and coil design fine tuning

- Design parameters updates under consideration
  - **Cable geometry**
    - PIT cable to be updated and RRP fine tuning under consideration (from conductor review)
  - **Coil cross-section** changes to account for
    - Effect of mechanical deformation on field quality
    - Effect of 3D end effects on integrated field harmonics
    - Random/systematic errors
  - **Magnetic length**
    - Increase of margin (from conductor review) ?
  - **End spacers**

# Cable and coil design fine tuning (I)

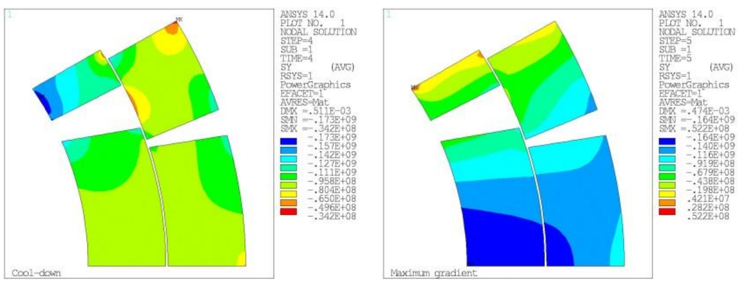
- For PIT, reduction of keystone angle from 0.55 to 0.4 deg., with same cable mid-thickness, under consideration
  - Thin/thick edge 0.025 mm thicker/thinner
  - Cross-section as close as possible to baseline
    - Still, new wedges, poles and spacers
      - 8-9 months from cable geometry definition to beginning of winding



# Cable and coil design fine tuning (II)

- Effect of mechanical deformation on field quality




AVERAGE DISPLACEMENT OF COIL-BLOCKS SIDES

| Layer | Block | $\Delta r_1$ | $\Delta r_2$ | $\Delta l_{\theta 1}$ | $\Delta l_{\theta 2}$ |
|---|---|---|---|---|---|
| | | mm | mm | mm | mm |
| Inner | Mid-plane | -0.290 | -0.351 | 0.000 | -0.047 |
| Inner | Pole | -0.315 | -0.367 | -0.043 | -0.044 |
| Outer | Mid-plane | -0.360 | -0.420 | 0.000 | -0.041 |
| Outer | Block | -0.370 | -0.433 | -0.043 | -0.050 |

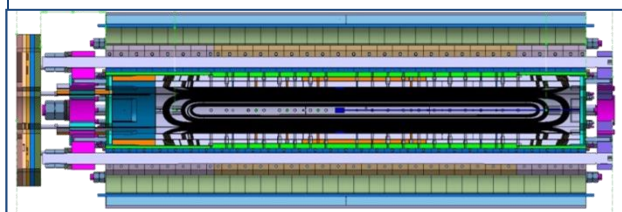
RESULTS OF NUMERICAL AND ANALYTICAL FIELD QUALITY ANALYSIS

| | Numerical | | | Analytical | | |
|---|---|---|---|---|---|---|
| | Undef. | Def. | Δ | Undef. | Def. | Δ |
| $b_6$ (units) | 0.26 | 1.01 | 0.75 | 4.50 | 5.36 | 0.86 |
| $b_{10}$ (units) | 0.22 | 0.20 | -0.02 | 2.10 | 2.16 | 0.06 |

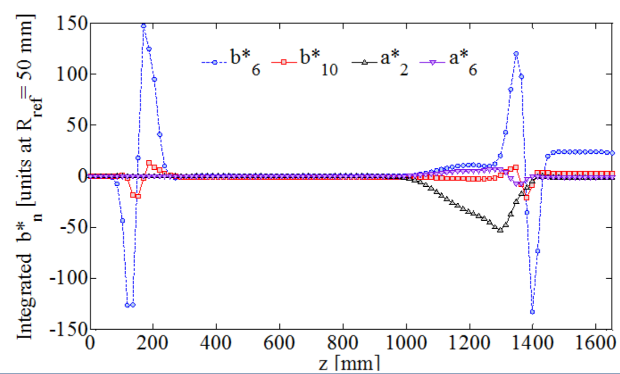
- Effect of 3D end effects on integrated field harmonics

INTEGRATED FIELD HARMONICS

| units at $R_{ref}$=50 mm | $\bar{b}_6$ | $\bar{b}_{10}$ | $\bar{a}_2$ | $\bar{a}_6$ |
|---|---|---|---|---|
| 2D | 0.3 | -0.4 | 0.0 | 0.0 |
| 3D-SQXF (1.2 m) | 9.1 | -0.5 | -8.9 | 0.6 |
| 3D-LARP-LQXF (4 m) | 2.9 | -0.4 | -2.7 | 0.2 |
| 3D-CERN-LQXF (6.8 m) | 1.9 | -0.4 | -1.6 | 0.1 |

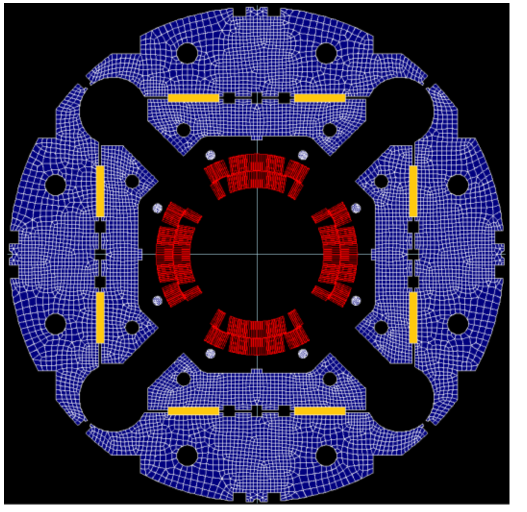


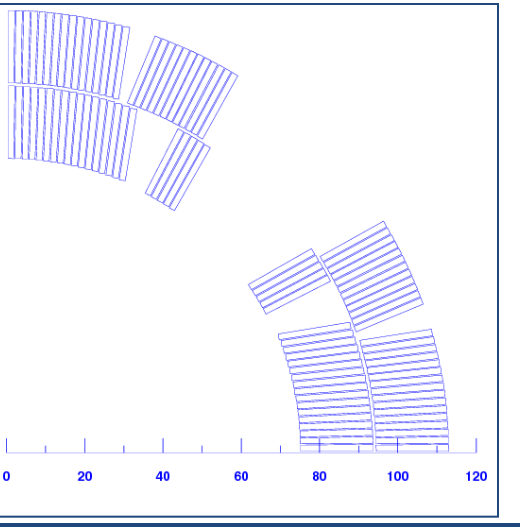
$$b^*_n(z) = \frac{\int_{z-\Delta z/2}^{z+\Delta z/2} B_n(z)dz}{B_2^{ss}\,\Delta z} \qquad (4)$$



# Cable and coil design fine tuning (III)

- How do we fine tune field quality during production?
  - Low order un-allowed harmonics
    - Magnetic shimming
  - Allowed harmonics
    - Fiberglass shim in pole and/or mid-plane included during winding curing?
    - With 0.100 mm shim → 4-5 μm reduction of space for expansion out of 70 μm
- And the $b_{14}$ (-0.67 units)?

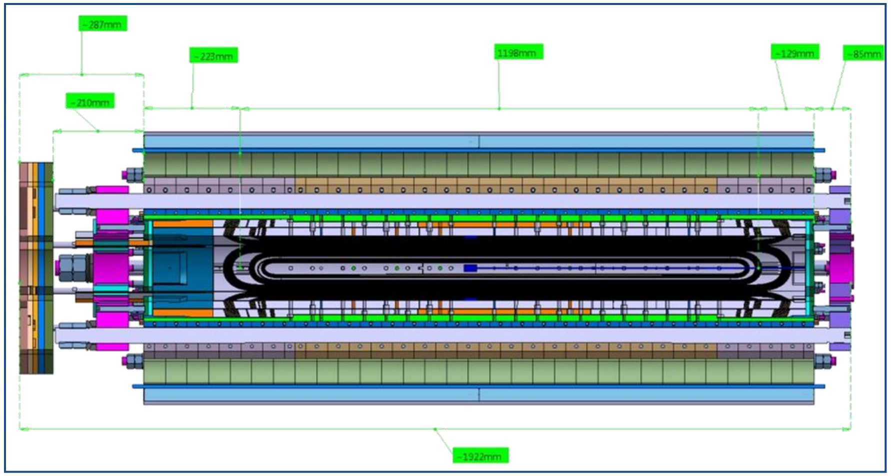




# Cable and coil design fine tuning (IV)

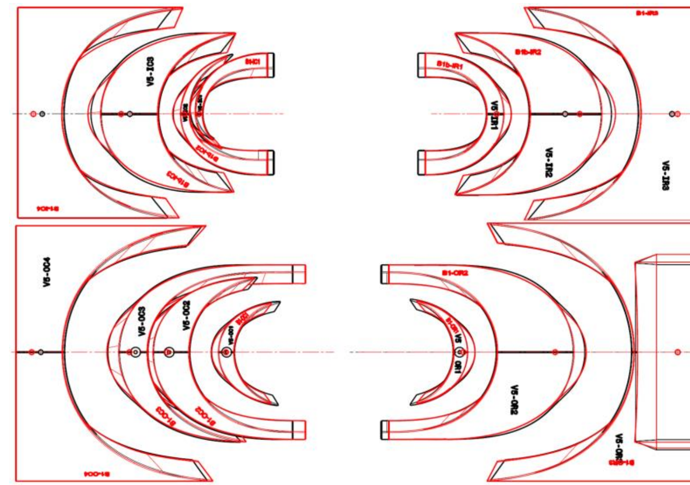
| | Short model | Q1/Q3 (half unit) | Q2 |
|---|---|---|---|
| Magnetic length [mm] at 293 K | 1198 | 4012 | 6820.5 |
| Magnetic length [mm] at 1.9 K | 1194.4 | 4000 | 6800 |
| “Good” field quality [m] | 0.5 | 3.3 | 6.1 |
| Coil physical length [mm] at 293 K | 1510 | 4324 | 7132.5 |
| Iron pad length [mm] at 293 K | 975 | 3789 | 6597.5 |
| Yoke length [mm] at 293 K | 1550 | 4364 | 7172.5 |

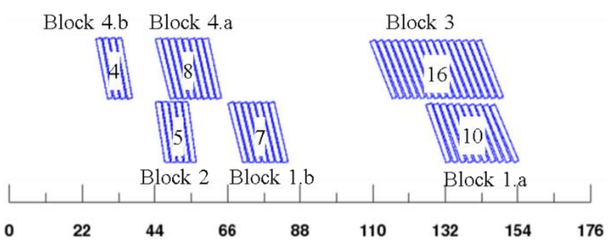
- Possible increase of magnetic length to increase margin
- Example
  - from 140 to 130 T/m → 7% decrease in $G_{nom}$
  - Coil length
    - +308 mm in Q1/Q3 (half unit)
    - +525 mm in Q2

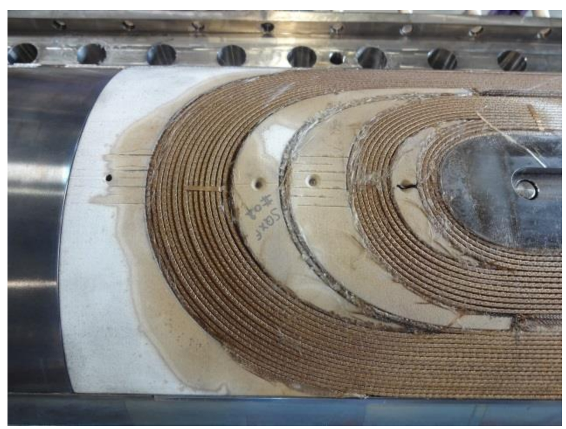


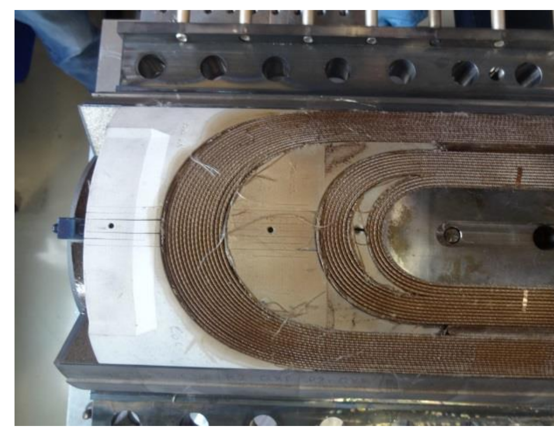
# Cable and coil design fine tuning (V)

- End spacers and end-shoes
  - Roxie and BEND designs
  - At the moment, no major issues observed by visual inspection
- Next steps: cut coils and magnet test

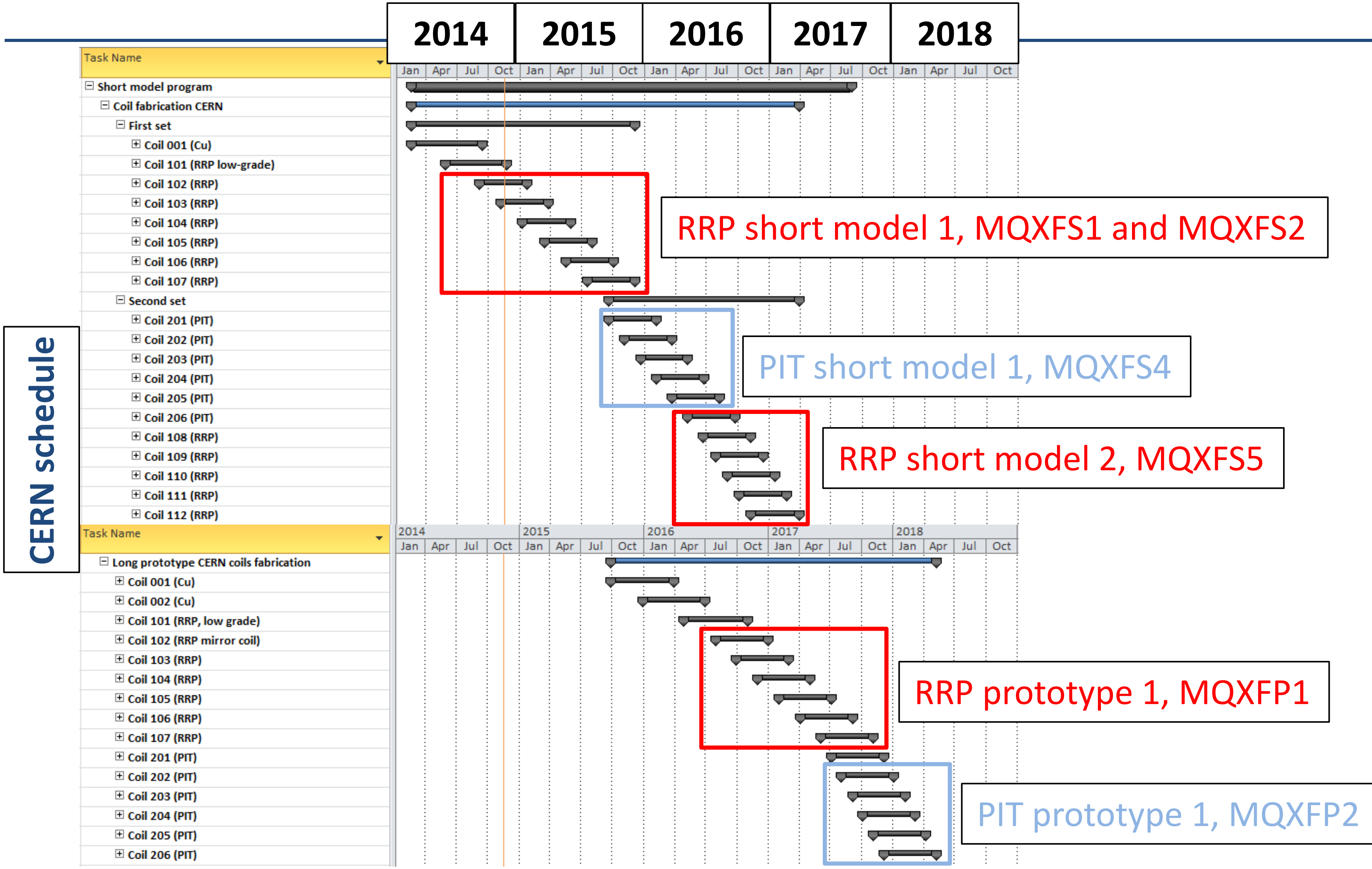




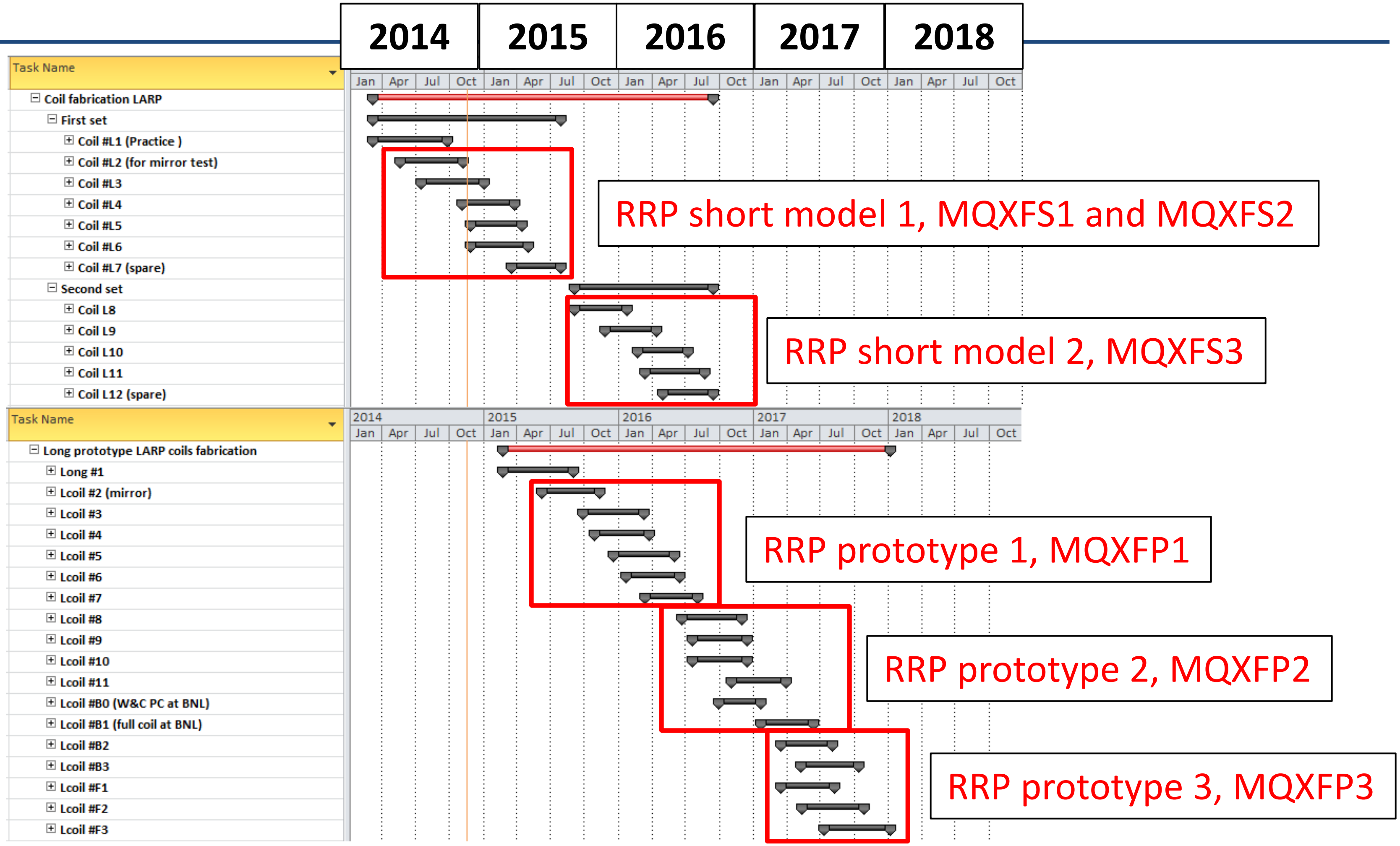


# Cable and coil design fine tuning: when?



# Cable and coil design fine tuning: when?

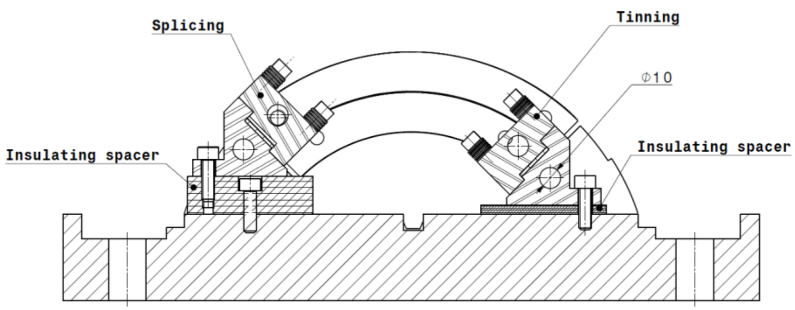
LARP schedule



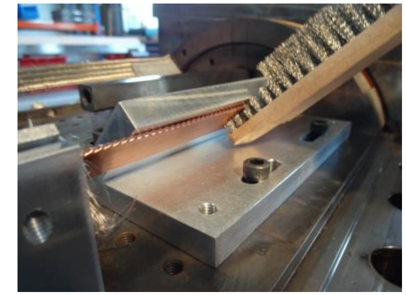
# Outline

- Cable and coil design fine tuning
- **Splicing**
- Magnet length, axial support, and connection box
- Quench protection
- Support structure

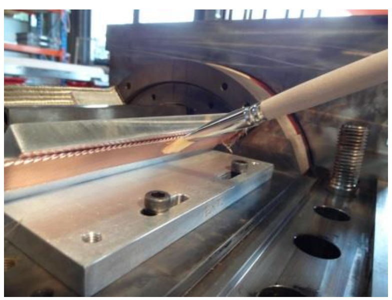
# Splice operation at CERN
# By J.C. Perez

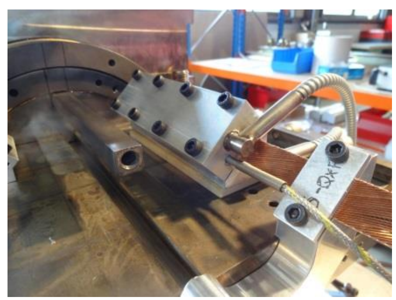



The same tooling is used for tinning and splicing using MOB 39 as flux and solder 96/4 Tin/Silver



The S2-Glass insulation is removed and the cable cleaned on both sides

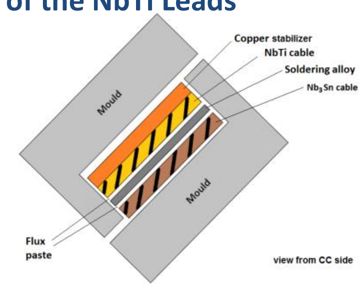




$Nb_3Sn$ cable tinning operation

Cutting of the $Nb_3Sn$ cable and splicing of the NbTi Leads

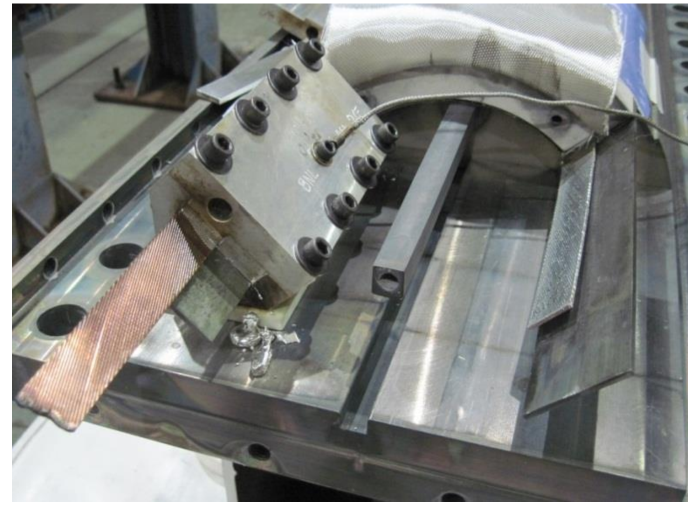
- $Nb_3Sn$ soldered to Nb-Ti and Cu stabilizer

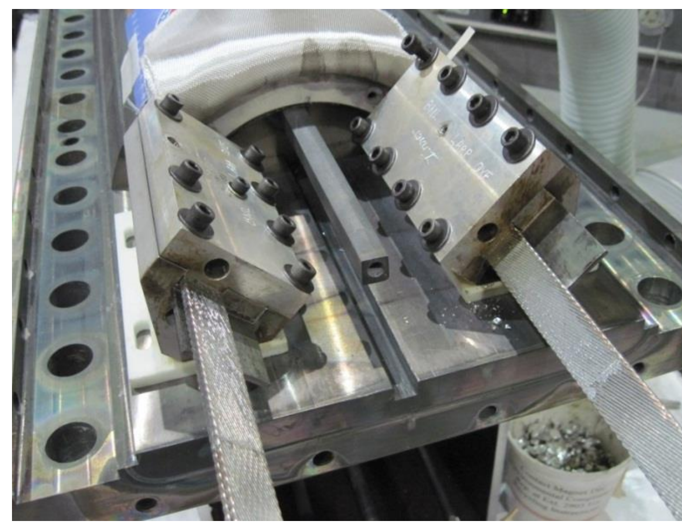


# Splice operation at BNL
# By J. Schmalzle

- Materials:
  - Double Nb-Ti extension lead.
  - Pre-assembled into pairs using separate fixture.
  - Solder - 96/4 Tin Silver ribbon.
  - Flux - MOB-39 (CERN approved).

- Procedure outline:
  - Remove saddle extensions.
  - Saddles remain in place.
  - Fold back interlayer insulation.
  - Remove cable insulation.
  - Clean leads with wire brush, alcohol.
  - Remove last few mandrel blocks.
  - Mid-plane shims stay in place, help support leads.
  - Pre-tin coil lead using lead solder fixture (with spacer).
  - Open fixture, clean, inspect and trim tinned lead.
  - Solder tinned lead to tinned extension pair using lead solder fixture (without spacer).

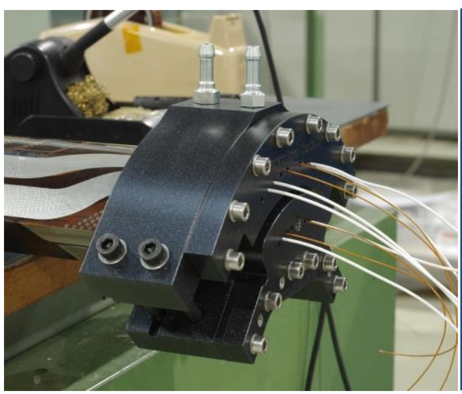


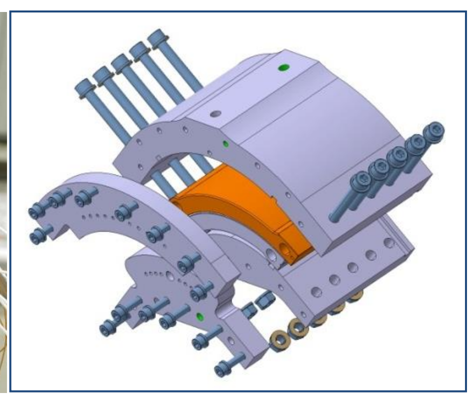


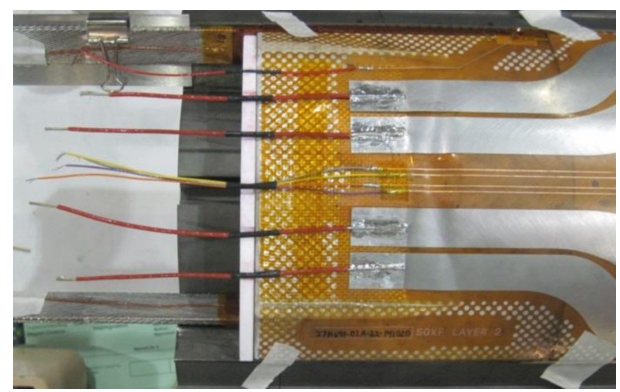
# Pre or Post-impregnation wire soldering

- LARP
  - Short wires soldered to trace before impregnation (~150 mm long wires).
  - Layers of fiberglass cloth added to fill wiring pocket.
  - Wires packed in Silicone putty.
    - Inside the impregnation fixture.
  - After impregnation, wires are extended by making an inline splice solder joint.

- CERN
  - After impregnation, instrumentation wires and Quench heaters powering leads are soldered to the trace
  - pockets filled using Eco-bond cured at room temperature



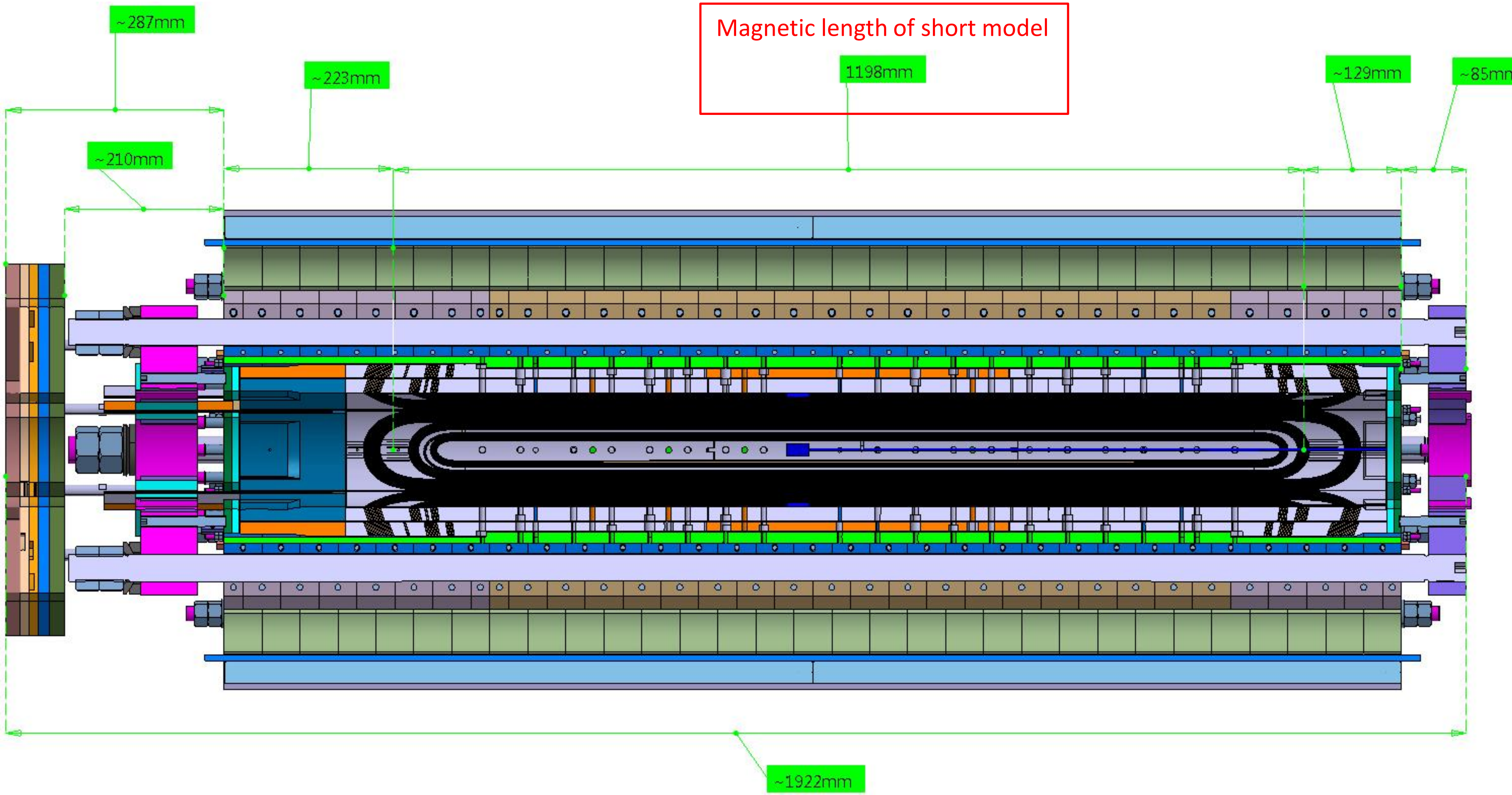




# Outline

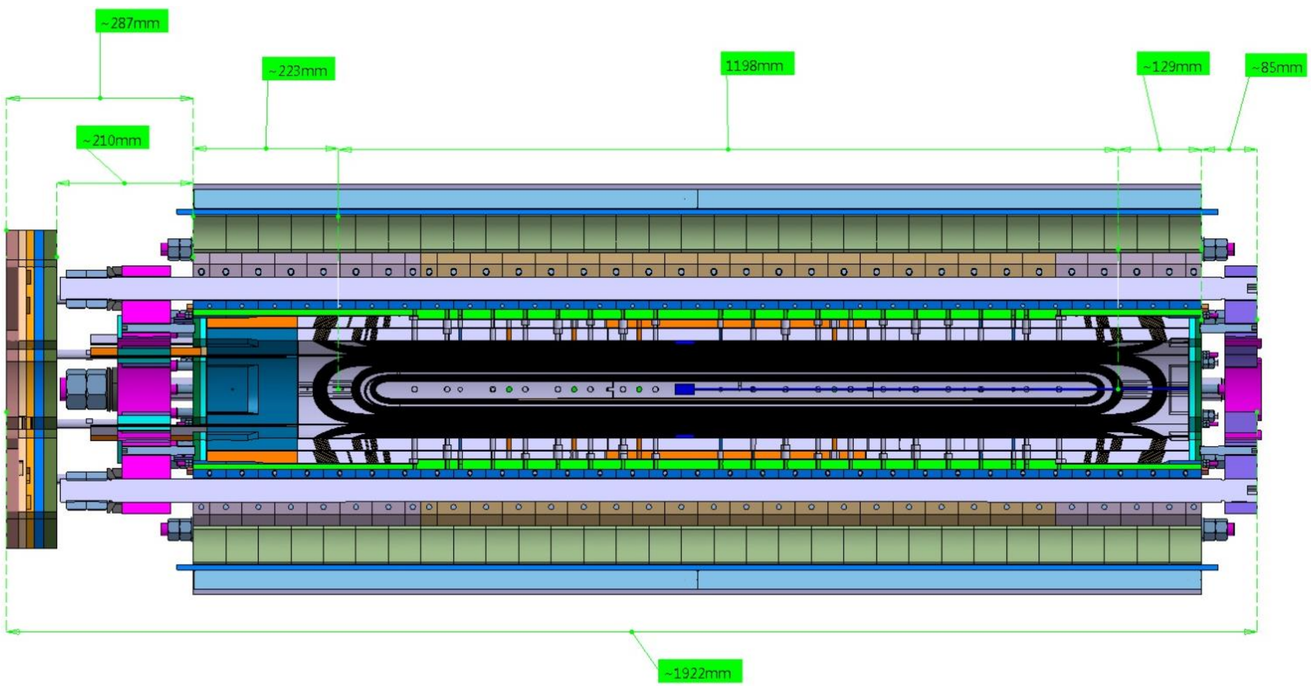
- Cable and coil design fine tuning
- Splicing
- **Magnet length, axial support, and connection box**
- Quench protection
- Support structure

# MQXF magnet design



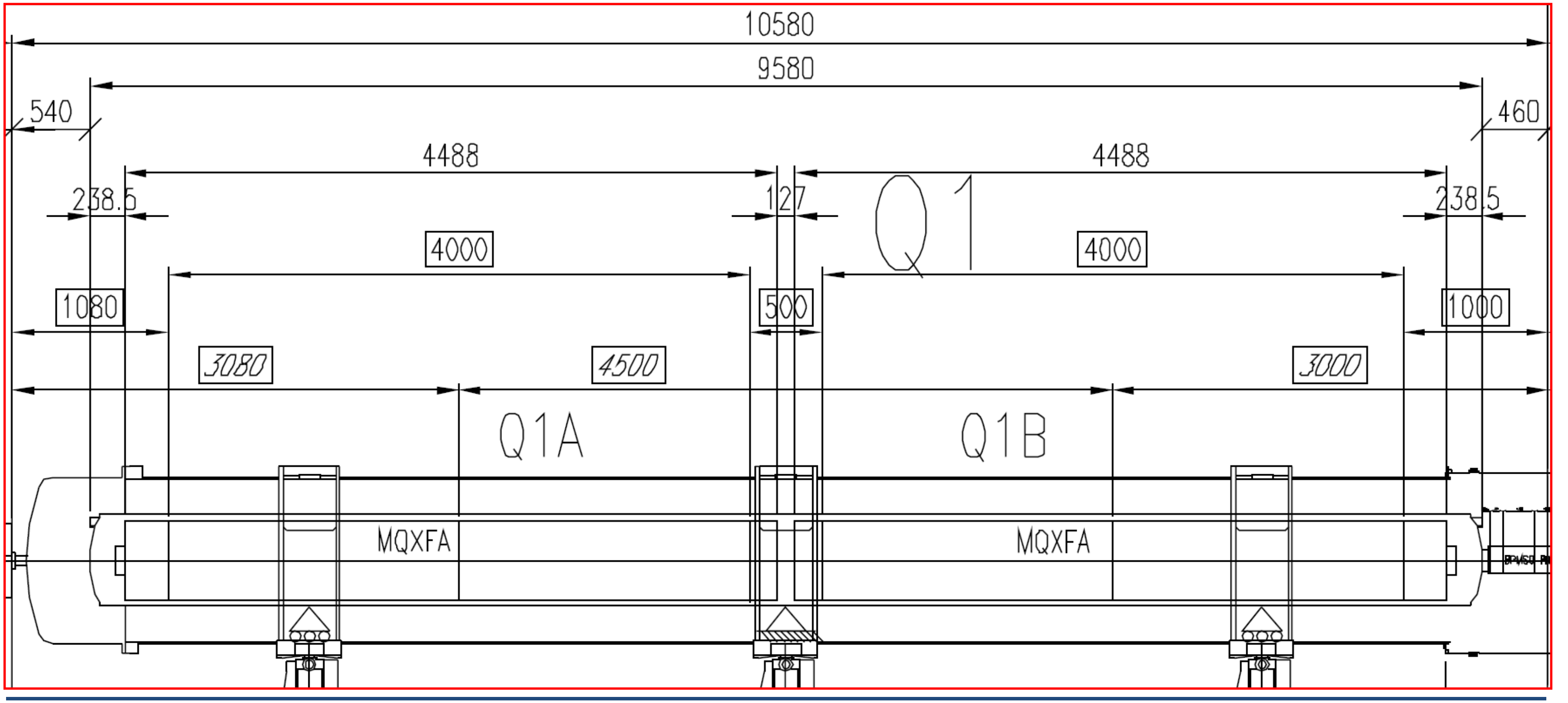
# MQXF magnet design

- From magnetic length to end of magnet (end-plate + connection box)
  - Connection side: **510 mm**
  - Non-connection side: **214 mm**



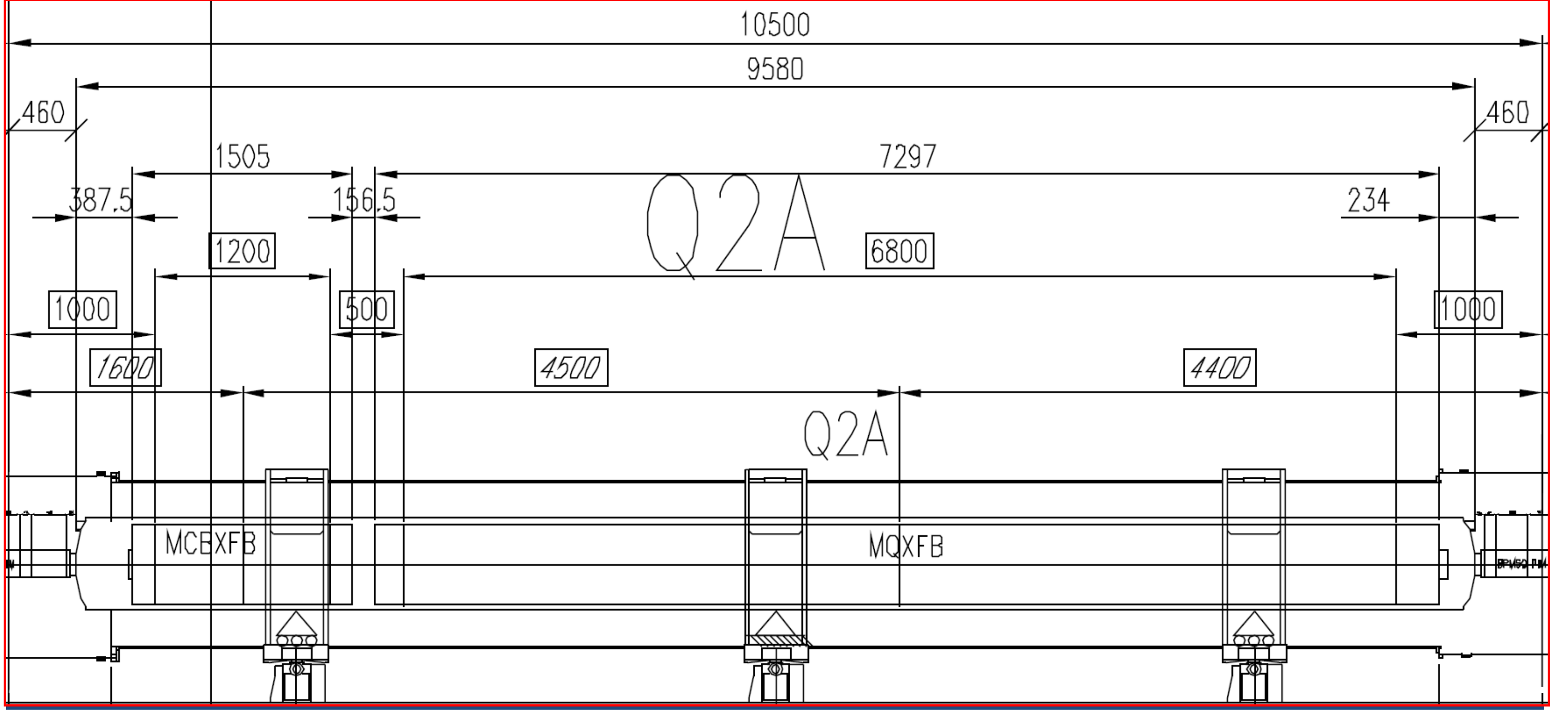
# Q1

- Connection side: from magnetic length to end of end-cover
  - **301.5+238.5=540 mm** (**510 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)



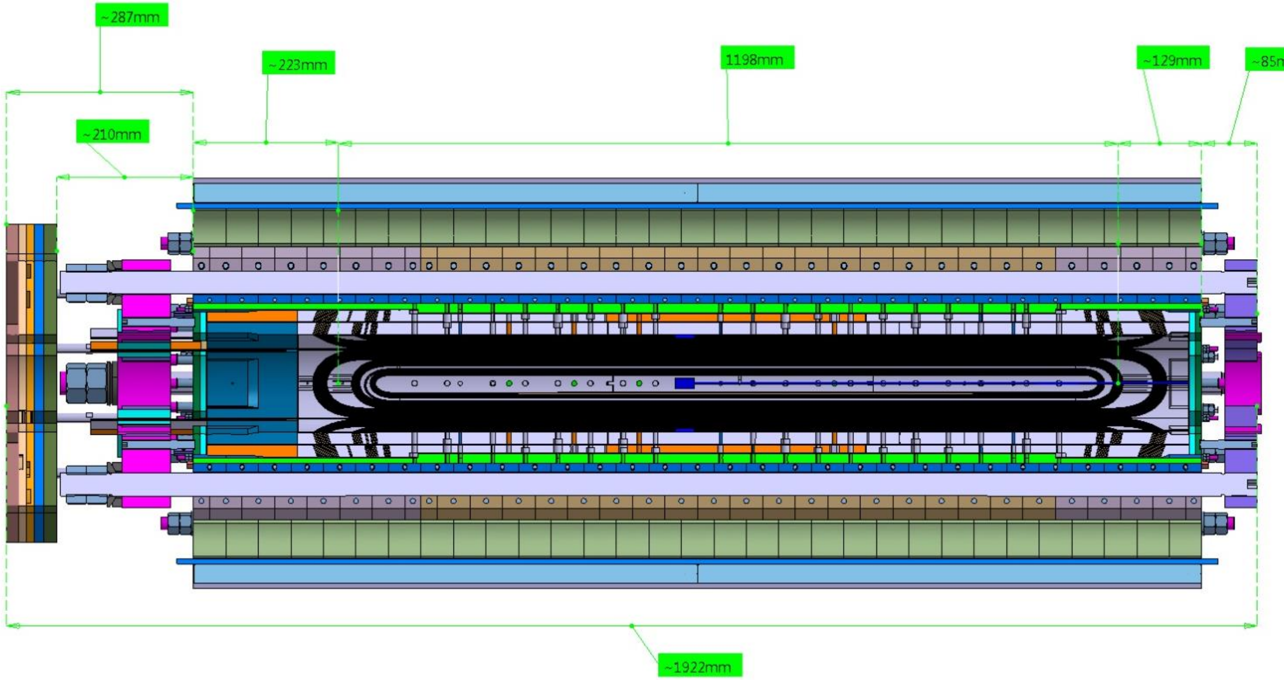
# Q2

- Connection side: from magnetic length to end of end-cover
  - **325+234=559 mm** (**510 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)



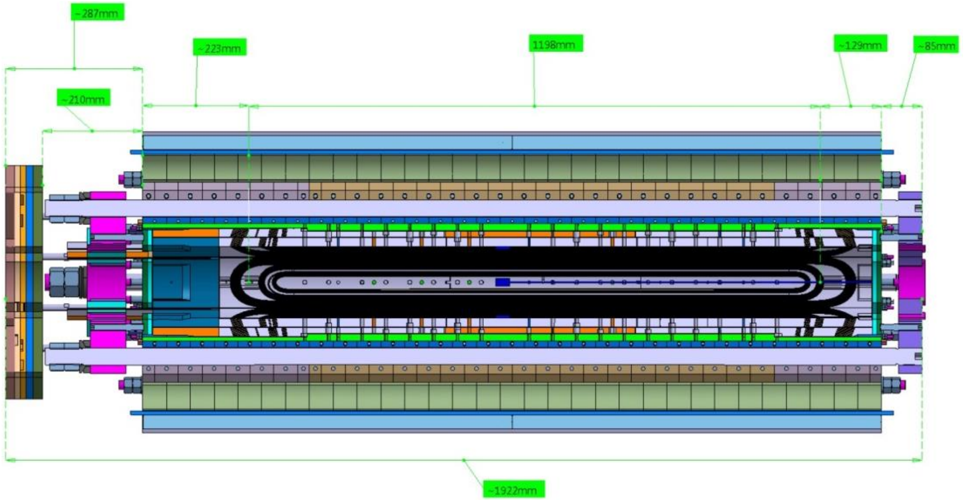
# Minimum distance between Q1a and Q1b magnetic lengths

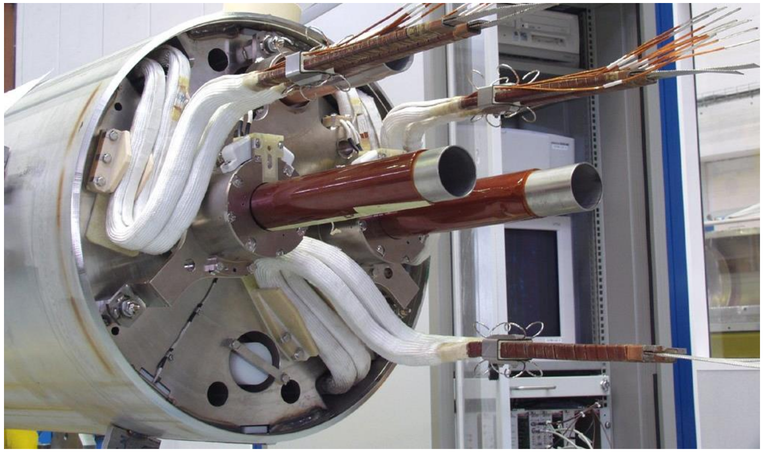
- From magnetic length to end of magnet (end-plate + connection box)
  - Non-connection side: **220 mm**
  - Minimum distance: ~ **440 mm**
- The 500 mm distance between the magnetic lengths is compatible with the present design of the MQXF magnet.



# Q1-Q2-Q3 connection side

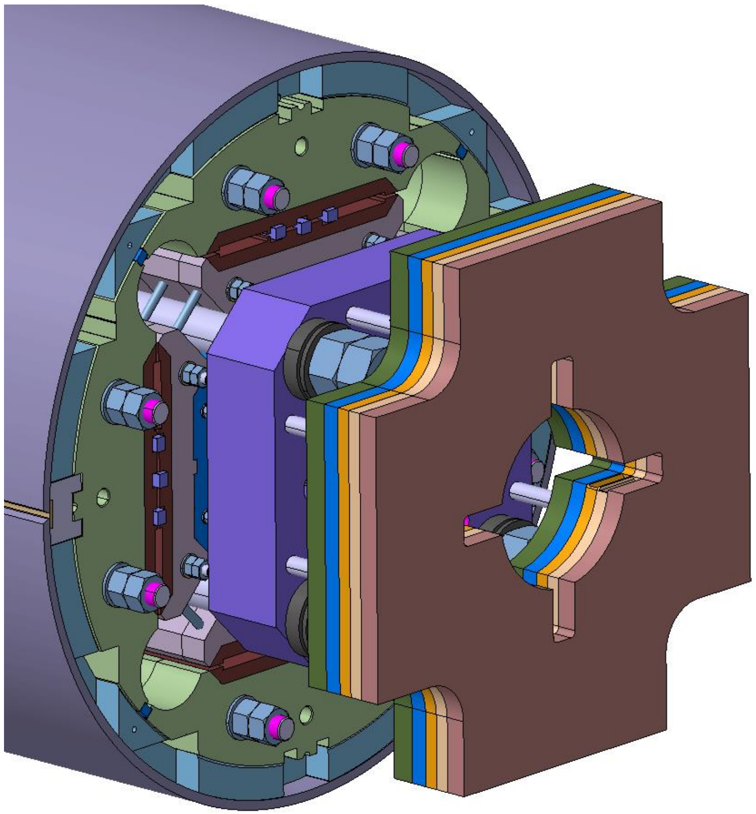
- From magnetic length to end-cover
  - **559 mm in current lay-out**
    - **510 mm** magnetic to end of magnet in short model
    - Lyra and end-cover
  - **Additional ~200 mm → 759 mm**
- TBD
  - bus-bars inside or outside cold mass
  - More compact LE end plate
  - Nuts on the RE?

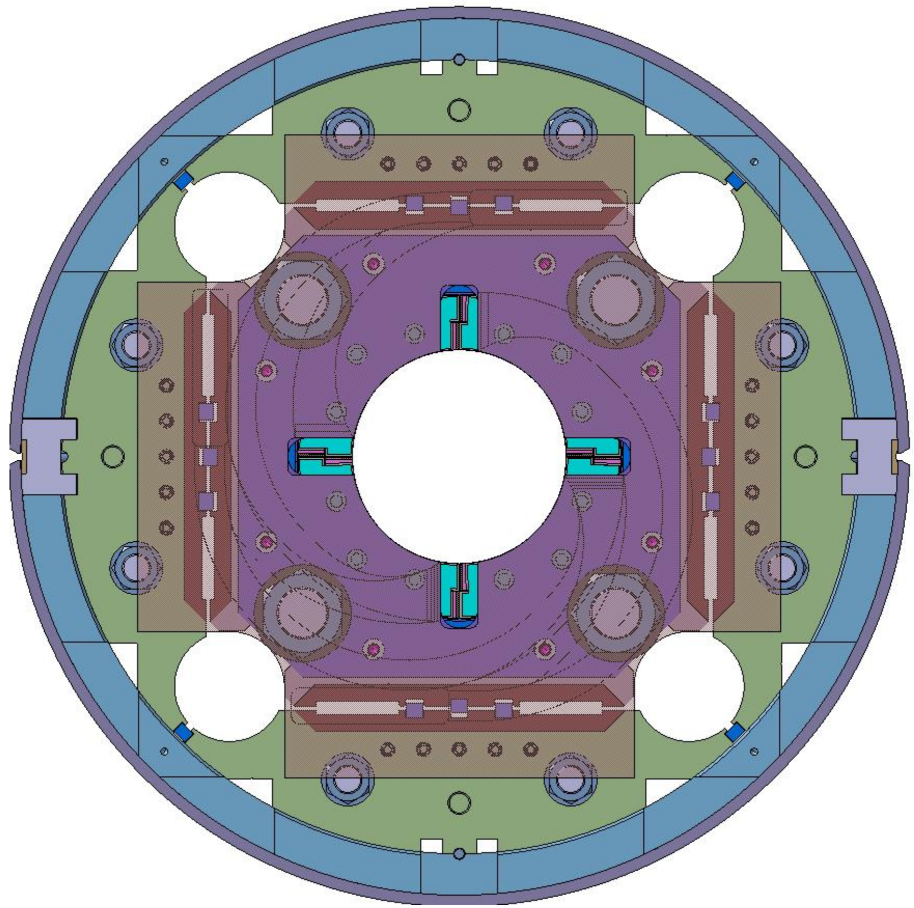


# Connection box
# First iteration

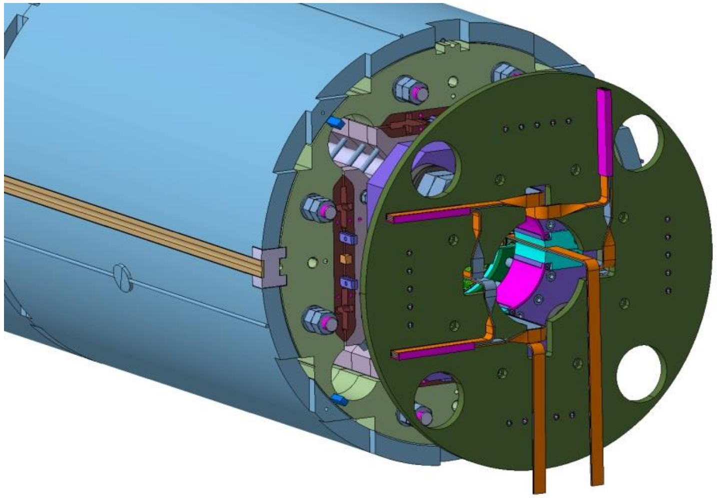
- Top and bottom support plate
- Instrumentation plate
- 2 plates for connections

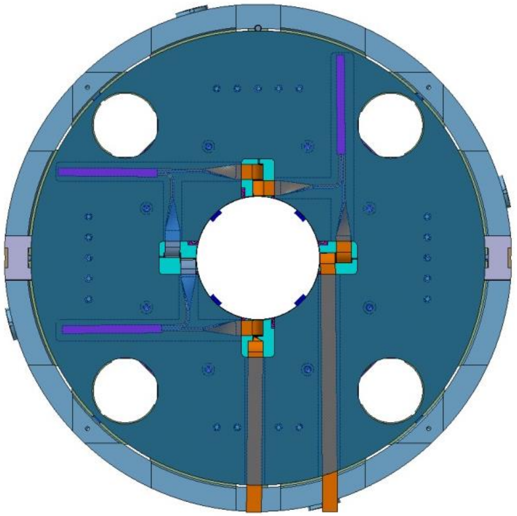


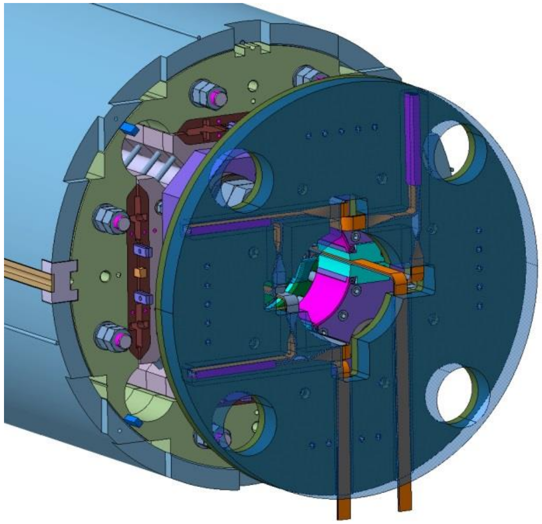


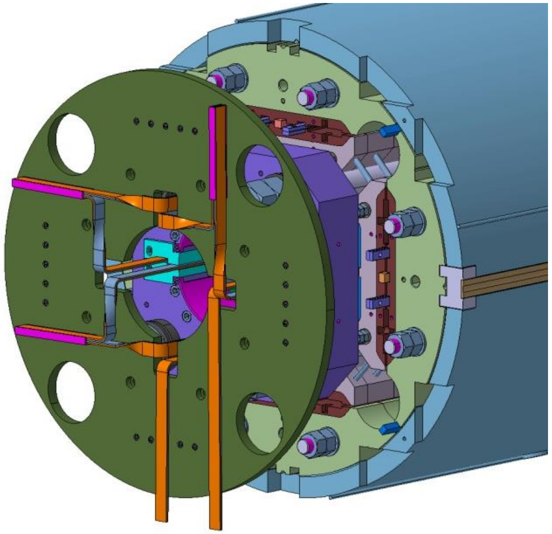
# Connection box
# Second iteration

- Both easy-way and hard-way bent cables
- More compacted option under investigation









# Outline

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- **Quench protection**
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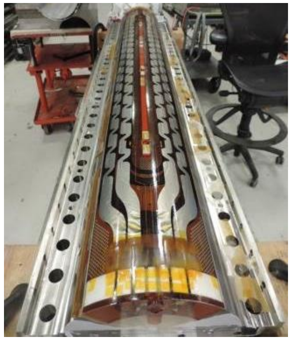
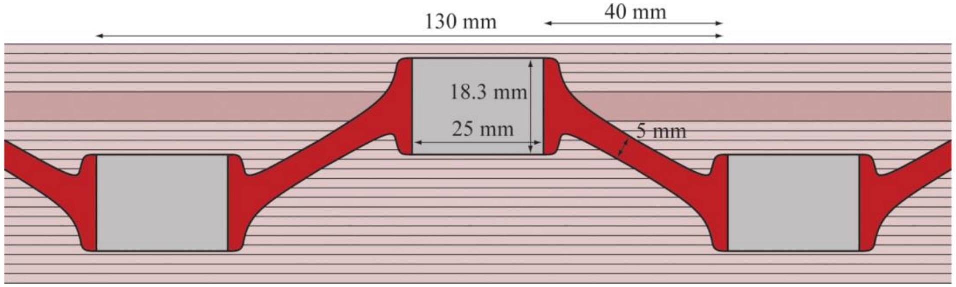
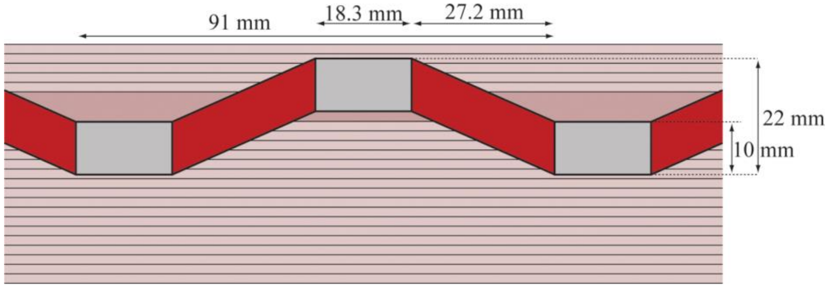
# Quench protection baseline scenario

- Protection studied in the case of 2 magnets in series (16 m) protected by one dump resistor (48 mΩ, 800 V maximum voltage)
  - Voltage threshold: 100 mV
  - Cu/Non-Cu: 1.2
  - Validation time: 10 ms
  - Protection heaters on the outer and on the inner layer
- **Hot spot T** with 1.2 Cu/Non-Cu ratio: **~263 K**
- Negligible effect of ~6-7 K from RRR (100-200) and Cu/non-Cu ratio (1.1 to 1.2)





# Inner layer quench heaters vs. CLIQ (I)

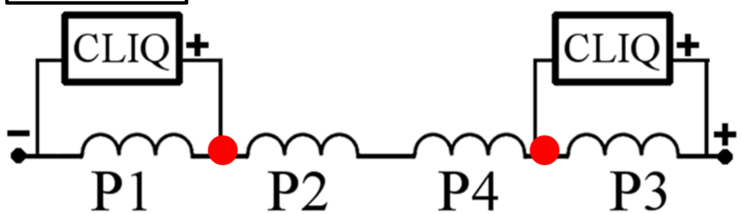
- Perforated polyimide
  - 18% of stainless steel
  - 32% of holes, 1 mm diameter
  - 50% polyimide 0.05 mm thick

# Inner layer quench heaters vs. CLIQ (II)
# CLIQ to be validated in HQ03 and MQXFS

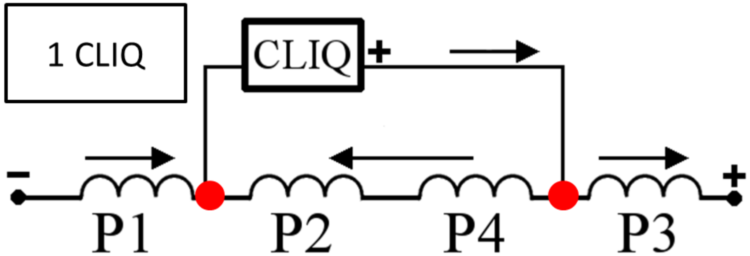
Electrical order for the poles of a quadrupole which optimizes 1-CLIQ and 2-CLIQ configuration: **P1-P2-P4-P3**

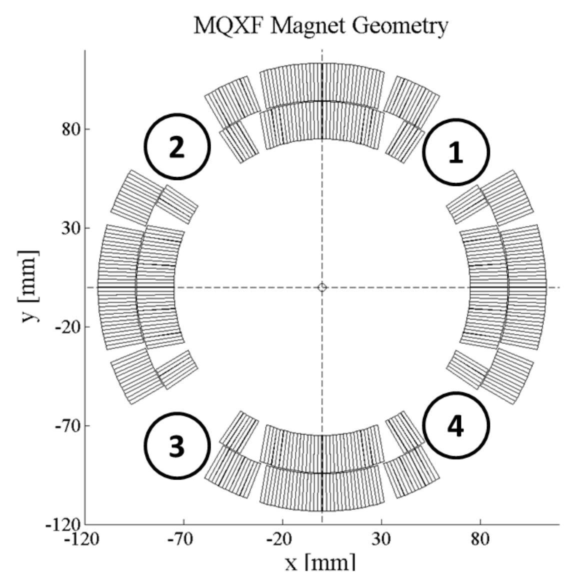
**2** internal CLIQ terminals with 10 mm^2 of copper
(about 1.5 MIIt deposited in each of them)

2 CLIQ



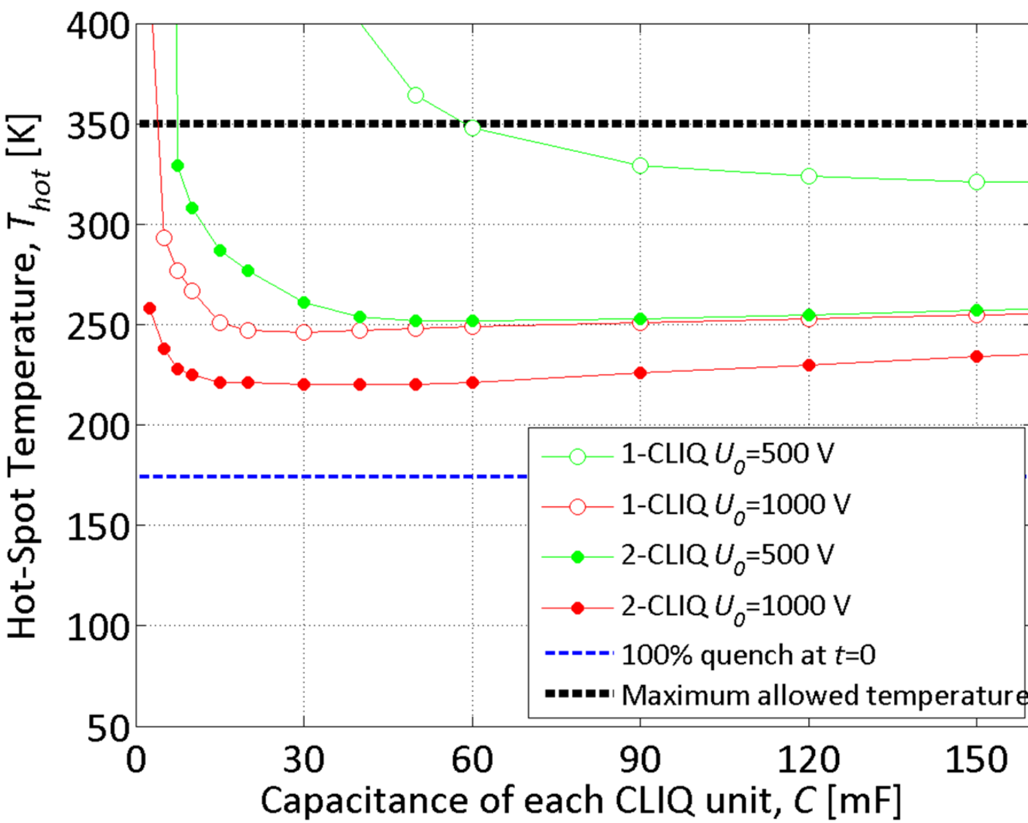

1 CLIQ



# Inner layer quench heaters vs. CLIQ (II)
# CLIQ to be validated in HQ03 and MQXFS

**Simulation results – $I_0$ = 17.3 kA ($I_{nom}$)**




**MQXF**

Magnetic Length 6.8 m
Self-inductance 70 mH
Nominal current 17.3 kA

Quadrupole magnet for the **LHC high luminosity upgrade** (US-LARP collaboration)

For each studied configuration a minimum capacitance is needed to protect the magnet

As expected performance of 2-CLIQ-500 V similar to 1-CLIQ-1 kV

Assumptions: no QH; no EE; RRR=140; 10 ms detection time

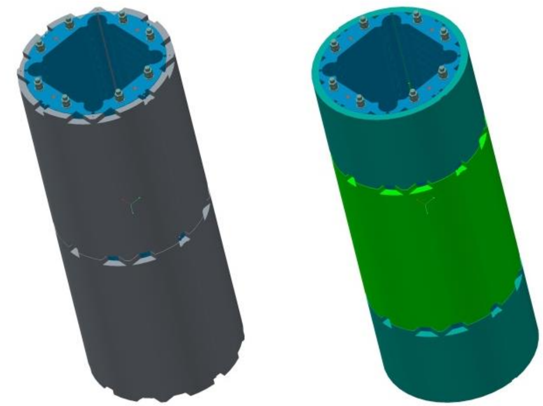
Protecting a Full-Scale Nb3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System 11 August 2014 1

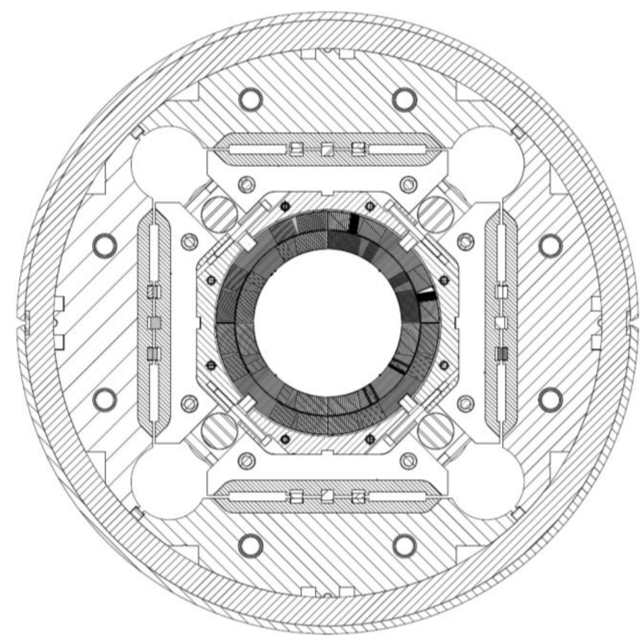
# Outline

- Cable and coil design fine tuning
- Splicing and soldering of instrumentation wires
- Magnet length, axial support, and connection box
- Quench protection
- **Support structure**

# Support structure modification

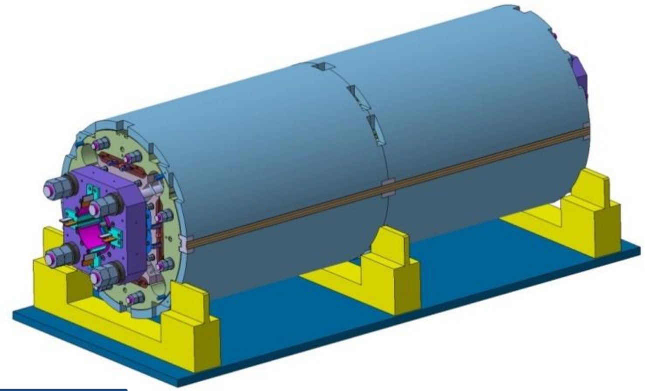
- Shell segments
  - From ½ + ½
  - to ¼ + ½ + ¼
- Laminated structure?
  - No issues for yokes
  - Impact on assembly for collar and pads
  - Cost
- Still under consideration
  - Reduction of parts (master incorporated into the pads)





# Support structure
# TBDs

- LHe containment
  - Dimensions of SS shell, tack welding blocks and backing strip



Aluminium Plate

Longitudinal groove for gas protection (second trial)

Stainless steel samples to be welded

Stainless steel backing strip (first trail)

# Support structure
# TBDs

- Cold bore tube and beam screen
  - Current baseline scenario
    - Insertion of cold bore tube in cold mass without beam screen
      - Features in coil poles to guide and support are needed
    - Insertion of beam screen after cold testing, before installation