Status of D2 in INFN-Genova

A.Bersani, B.Caiffi, R.Cereseto, S.Farinon, F.Levi, D. Novelli, A.Pampaloni INFN – Genova
A.Foussat, E.Todesco – CERN

12th HL-LHC Collaboration Meeting, 19 - 22 September 2022

Outline

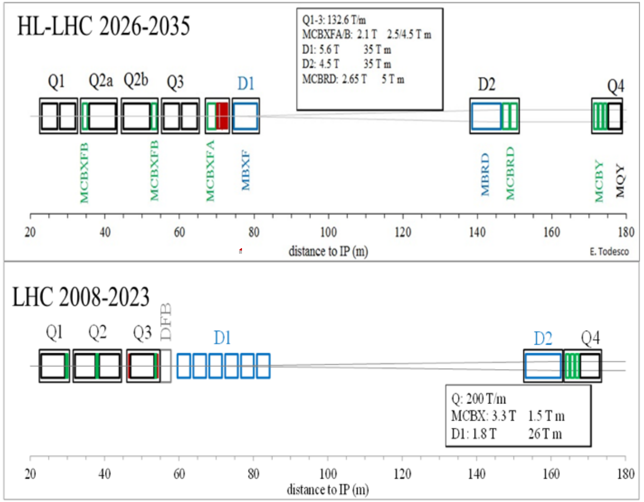
- CERN/INFN Agreements
- D2 magnet layout
- Prototype:
  - status
  - NCRs and mitigation strategies
- 3rd aperture activities
- Status and plan for the series magnets
- Overall schedule

CERN/INFN Agreements for D2

- KN 3083 Framework agreement
  - Addendum n.1 KE3084
    - D2 Short Model (MBRDS1) (1.6 m) and Prototype (MBRDP1) (8 m) construction
    - Short model tested at CERN in August 2020
    - Prototype completed and delivered to CERN in October 2021
    - Acceptance Test @ RT at CERN in the following weeks
    - Cold test ongoing (cool down started last Friday)
    - Prototype 3rd aperture re-assembled to test critical series magnet modifications
  - Addendum n.11 KE4417
    - D2 Series production of 6 units (4 units for installation and 2 units as spares)
    - Contract awarded to ASG Superconductors on March 2021
    - Engineering design completed, first coil fabricated and cured
    - Waiting for procurement of insulated wedges to start the production

D2 Layout and Function

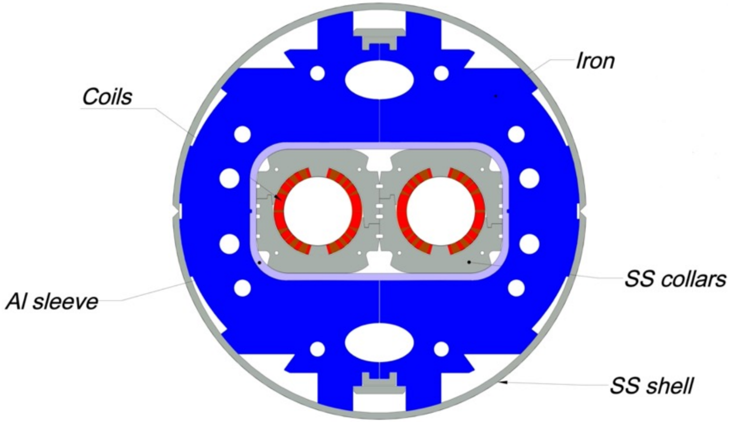
- The D2 dipole (MBRD, Main Bending Recombination Dipole) is placed in the D2 cold mass together with the orbit correctors around IP1 and IP5
- Main features:
  - same field direction in both apertures (used to bring beams to collision), apertures in series
  - 35 T m integrated field at 7 TeV
  - 37.6 T m integrated field at 7.5 TeV (ultimate field)
  - 2 apertures, 105 mm in diameter, 8010 mm total length



No. of magnets	No. of apertures	N. coils
4 Series	8	16
2 Spares	4	8
=6 Magnets	=12 apertures	=24 coils

D2 Cross Section

- Bore field: 4.5 T (4.8 T ultimate)
- Magnetic length: 7.8 m (8.01 m physical length)
- Challenges
  - Field quality optimisation based on asymmetric coils
  - Novel structure for the two apertures based on Al shells

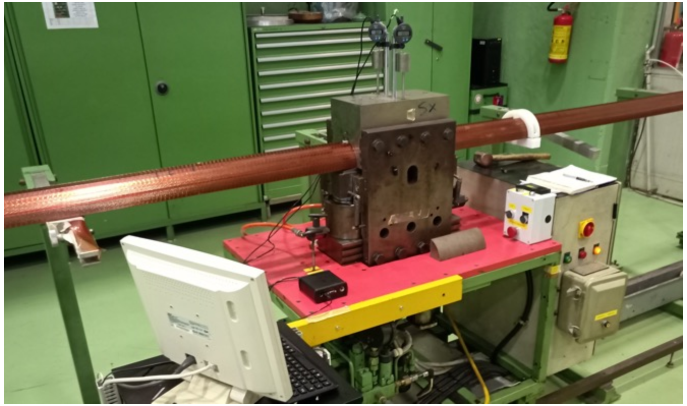


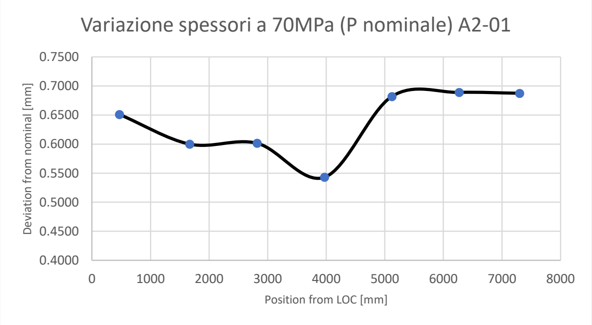
Main characteristics of the D2 dipole	
Bore magnetic field	4.5 T
Magnetic length	7.78 m
Peak field	5.26 T
Operating current	12.330 kA
Stored energy	2.26 MJ
Overall current density	478 A/mm^2
Aperture	105 mm
Operating temperature	1.9 K
Loadline fraction	67.5%
Multipole variation due to iron saturation	<10 units

Prototype NCs: Coil Azimuthal Size

- Prototype coils exceed nominal azimuthal dimension by 0.64±0.05 mm on average
- For the series, a modified set of longitudinal spacers have been designed
- See dedicated presentation tomorrow

Coil	Min	Max	Average	
A-01	0.36	0.62	0.54	Spare coil
A1-02	0.55	0.8	0.7	Spare aperture
B1-02	0.55	0.72	0.66	Spare aperture
A1-01	0.54	0.71	0.64	aperture V1
B1-01	0.47	0.77	0.63	aperture V1
A2-01	0.54	0.69	0.64	aperture V2
B2-01	0.54	0.71	0.64	aperture V2

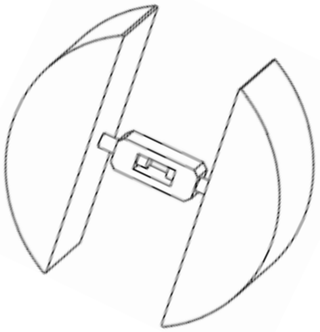


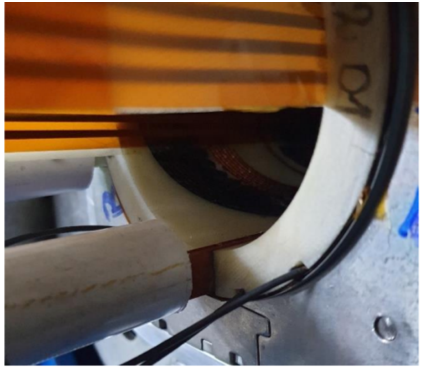


Prototype NCs: AP2 Leads Protrusion

NC EDMS **2618354**

- After collaring of AP02, the leads were found to protrude inside the bore, leaving a free diameter of 101.6 mm with respect to the nominal 105mm
- To mitigate this issue, a lead spring device will be used to ensure the correct position of the leads in the exits. This tool was already successfully tested in the 3° aperture of the prototype
- Furthermore, small protrusions corresponding to the electrical connections of the voltage taps decreased further the available free space – these are not foreseen in the series

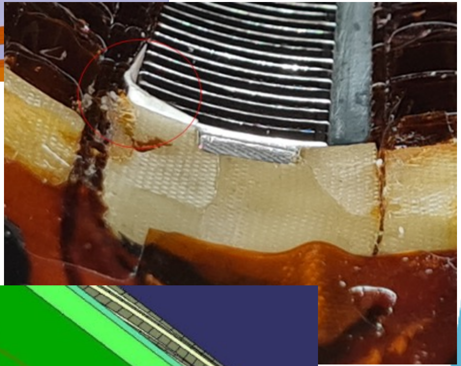


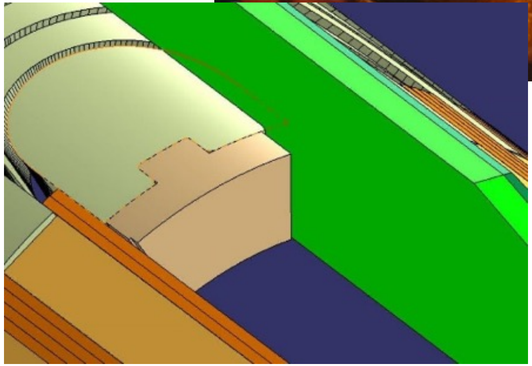


Prototype NCs: Coil B2-01 Ground Insulation

NC EDMS **2589433**

- An intermediate Hi-Pot test at 3.1 kV done during the assembly of AP1 and AP2 into the Al sleeve was not passed (sparks) . The maximum voltage with no spark and good insulation (> 10 GΩ) is 2.7 kV.
- The cause is the sharp edge of the shoe of the CPS too close to the conductor in the region of the first turn of the 5th block attached to the first G11 end spacer
- The failure was fixed by adding a NOMEX layer in the damaged region
- In the series magnet, a G10 insert will be placed between the pole end spacer and the pole collars to act as a mechanical and electrical intercept for the collar shoe: successfully tested in the 3rd aperture

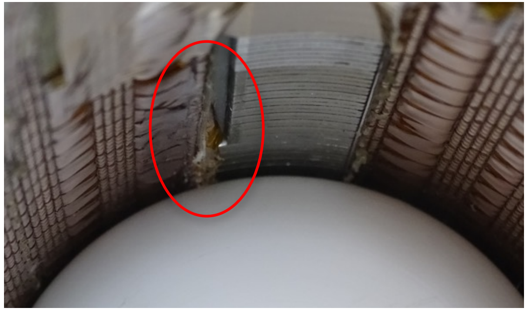


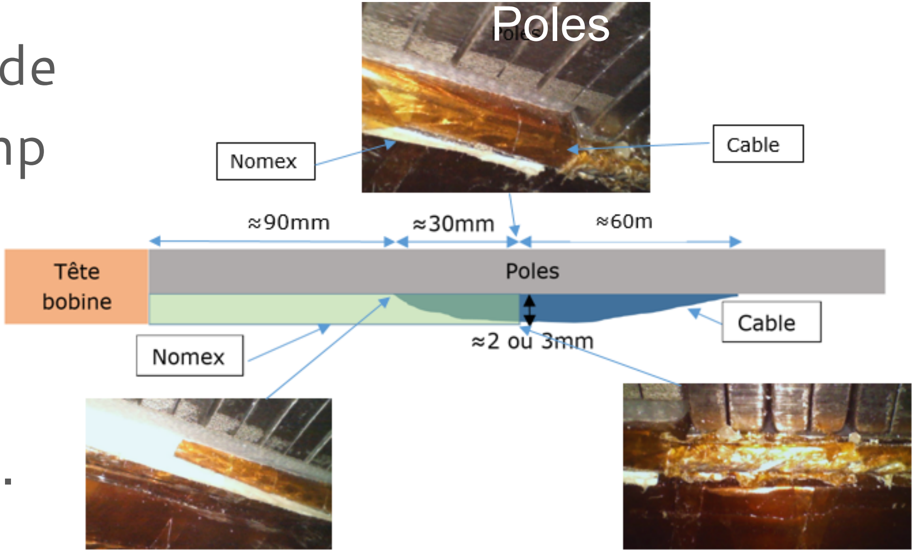


Prototype NCs : layer jump protrusion

EDMS NC 2715620

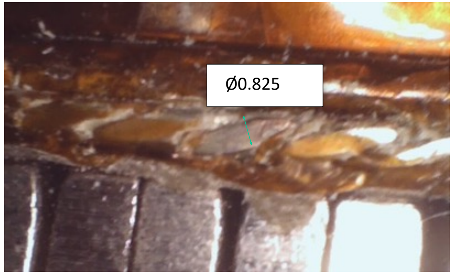
- During the cold bore insertion in V1 line, it was not possible to proceed because it got stuck on the connection side because both the layer jump and the NOMEX layer (introduced due to NCR 2521073/1.0) were protruding mm in the bore.

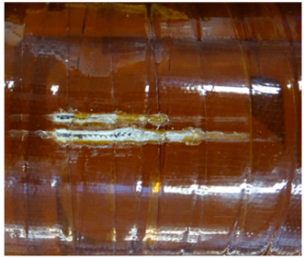


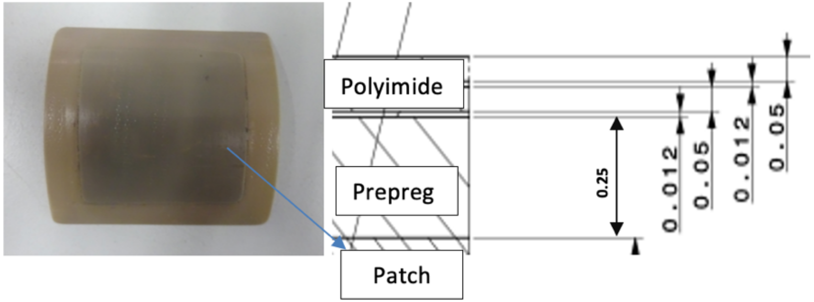


Prototype NCs : layer jump protrusion

- After the insertion trial, the cable insulation was damaged (bare cable visible on 60mm)
- The insulation was consolidated using the injection of Eccobond epoxy under a controlled applied pressure. Afterwards an electrical test was performed up to 750 V successfully with good insulation to ground of 5 GOhm (voltage lower than nominal)
- The cold bore tube insertion test was then performed on the prototype 3rd aperture with inner Kapton layer GI with the folded wing fixated to the bore via Kapton tape

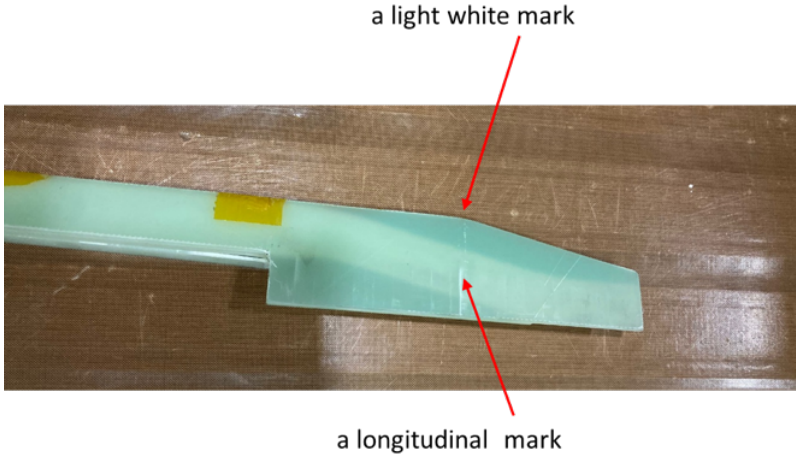


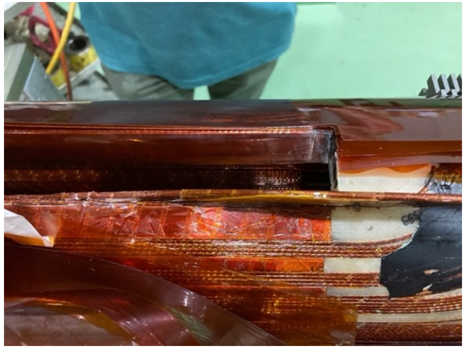


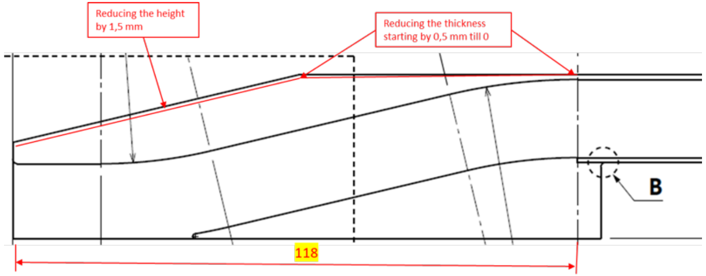


Prototype NCs : layer jump protrusion

- The root cause analysis was performed by ASG, finding that collars and G11 protection box were (marginally) in interference: the latter has been modified in the third aperture

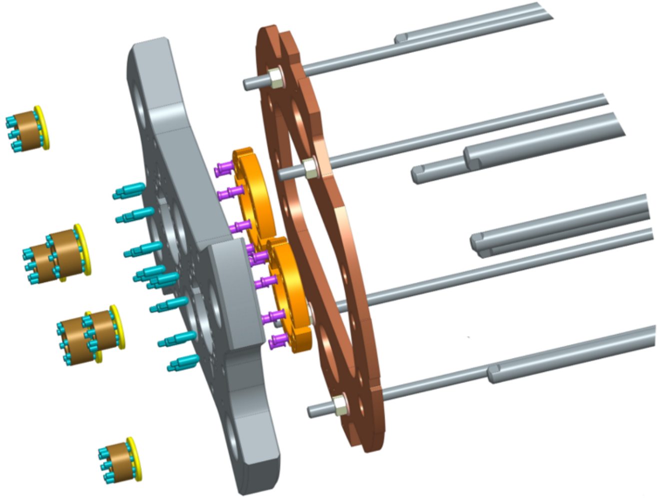






Prototype NCs: Axial Pre-stress Loss

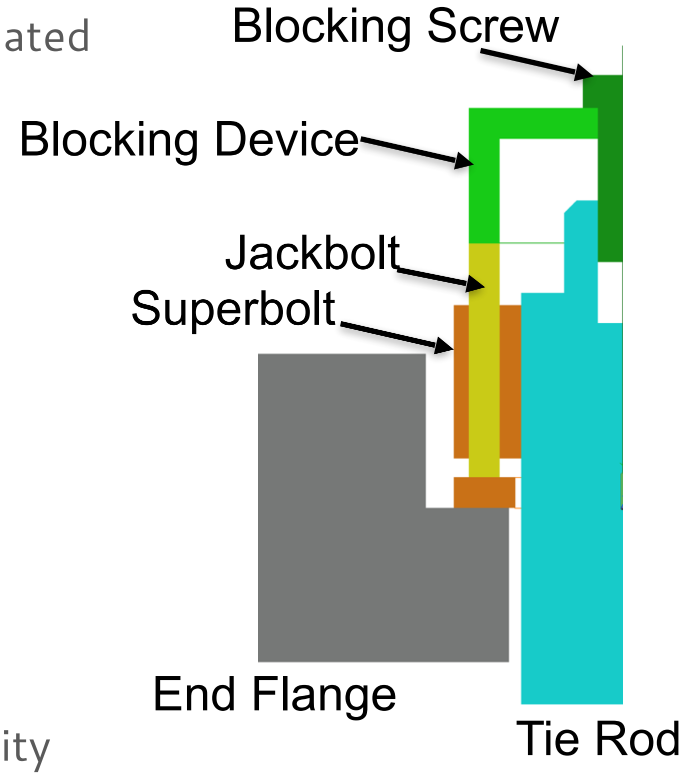
- Longitudinal tie rods are tightened via Nordlock Superbolts to avoid torque
- After delivery at CERN, a significant decrease of longitudinal pre-stress has been observed
- A new tightening has been performed at Bdg. 180 in March and bolts have been glued
- Afterwards no significant change has been observed (magnet handled several times)



- 5M Ishikawa analysis has been performed
- Most probable causes have been identified
- Internal friction release between coils and collars
- Unscrewing of jackbolts due to vibrations, tie rod bending and low applied torque (4Nm)

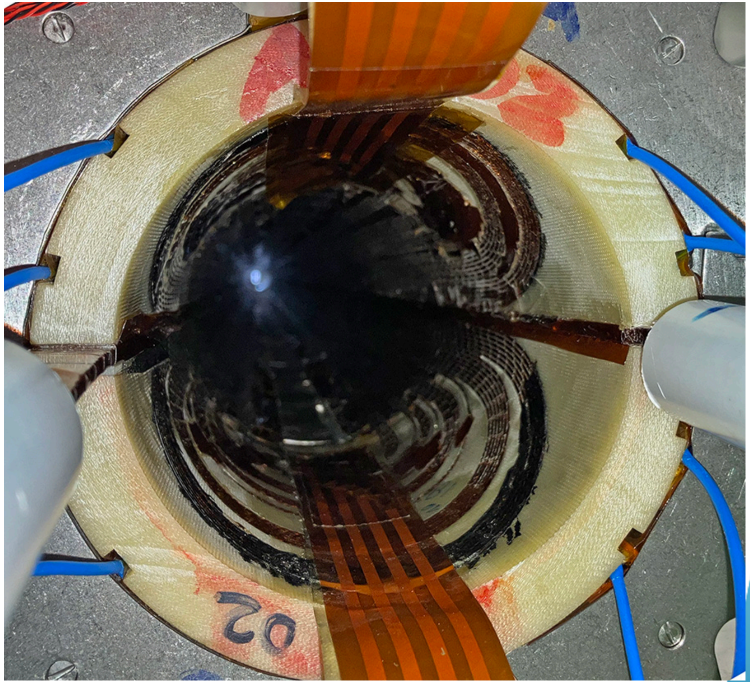
Prototype NCs: Axial Pre-stress Loss

- Several mitigation strategies have been investigated
  - Modification of the transport tool (done by ASG Superconductor)
  - Measurement of the actual properties of the Superbolts (ongoing)
  - Increase of the axial pre-load (to be investigated further
  - Final tightening at CERN (already discussed, no concern till now)
  - Screw blocking either mechanically, via welding or gluing
- Our suggestion is gluing, with Staycast or equivalent, after tightening, to ensure reversibility



Prototype: 3rd Aperture

- The third aperture foreseen by the prototype contract has been used to test some of the modifications designed for the series :
  - introduction of the folded GI layer, which in the prototype was cut at the edge of the collar nose (successfully tested during the beam tube insertions)
  - on the return end, introduction of a new end G11 nose piece (successfully tested)
  - introduction of a device adopted to keep the leads in the correct position during collaring (successfully tested)
  - insertion of a Nomex sheet to reinforce the insulation in the region of the layer jump (successfully tested)
  - use of an hybrid insulation scheme to test the field quality (successfully tested at RT)



Strategy for the Series

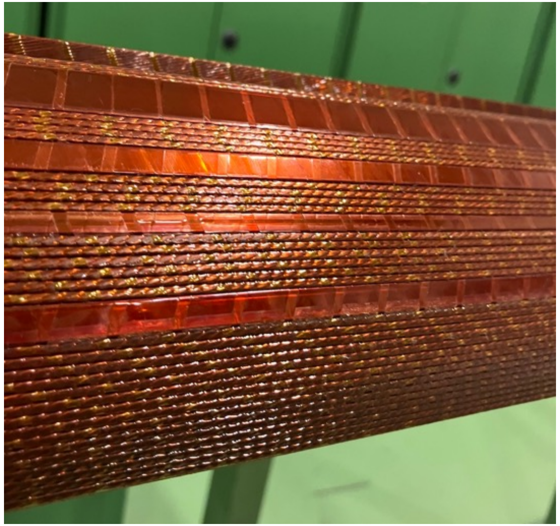
- Considering the issues on the prototype and the project update for the series
  - MBRD1 (DIP1) will be a pre-series magnet, followed by 5 series magnets MBRD2-MBRD6 (DIP2-DIP6)
  - MBRD1 will still be compliant with D2 requirements for use in the HL-LHC

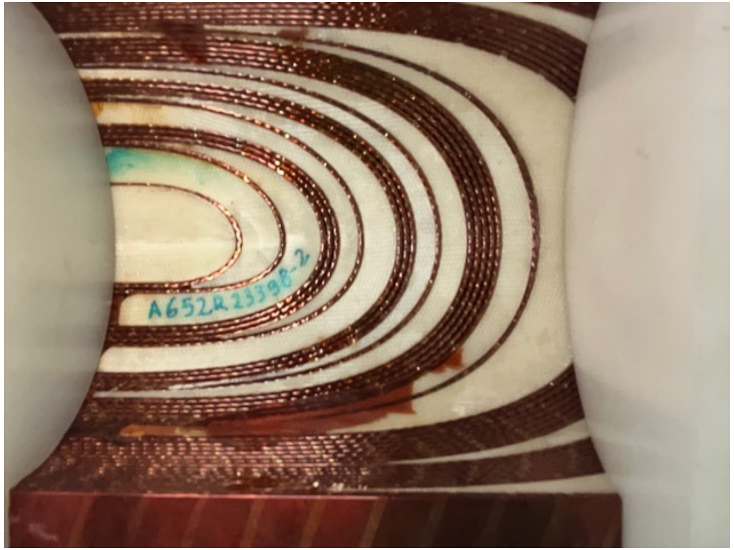
Therefore, the production of D2 magnets cannot be fully parallelised

- Our proposal for the series:
  - produce two coils and collar the first aperture as soon as components are available
  - fabricate and collar the second two coils; this second aperture will benefit from feedback (if any) from the fabrication of the first aperture and prototype testing
  - assemble the two pre-series apertures into the iron yoke and perform warm magnetic measurements (this will verify the effectiveness of field quality tuning for the series)
  - start the production of the 5 series magnets.

Series Magnets

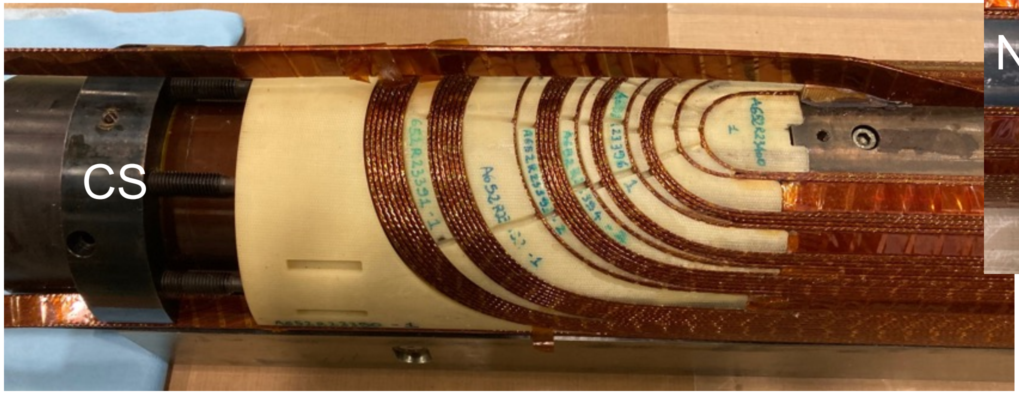
- A small production of the copper wedges type 2 and 8 (modified w.r.t. the prototype) was provided by LUVATA and used to produce the first coil of the pre-series magnet

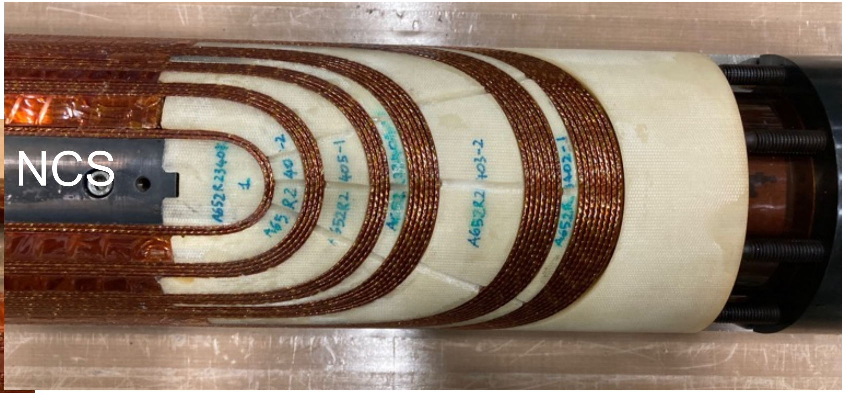




Series Magnets

- Coil AS-01 was wound and cured. The azimuthal dimension was measured and resulted to be 0.41 mm larger than nominal, about 0.23 mm smaller than the prototype coils (prototype coil size 0.64±0.05 mm)
- This results is expected considering the reduction of 0.3 mm in the thickness of wedges 2 and 8.





Series Magnets

- Iron yokes (raw material provided by CERN) already assembled in packs for the entire production
- SS collars (raw material provided by CERN) assembled in packs for the entire production


Collar packs

Half yoke assembly

Series Magnets

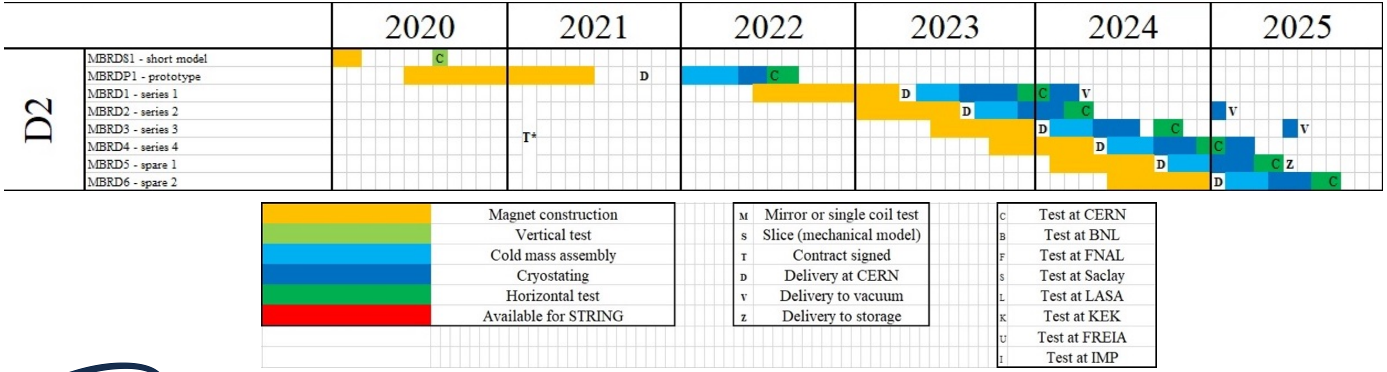
- G11 end spacers delivered from Resarm: some out of tolerances were found on inner diameter (repair is under evaluation)
- Remaining copper wedges from LUVATA were found to be out of spec (irregularities and bumps at the extremities, currently back at LUVATA)


Tooling for coil assembly rotation


AL sleeves assembly bench

Planning

- The plan for the series is aligned with the updated schedule
- Procurement of unmodified components is finished and packs of SS collars and iron yokes are already assembled for the entire production
- The bottle-neck is the procurement of the copper wedges, the delivery date has not been officialised yet
- The D2 series is not on the critical path



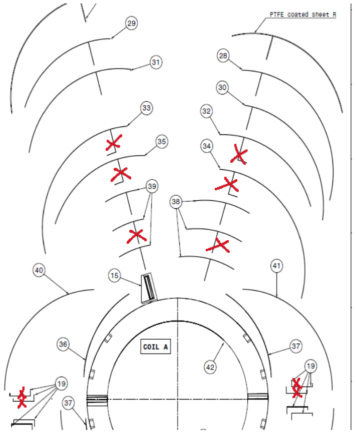
Conclusion

- The D2 prototype was delivered in October 2021 and is currently in SM18 for the cold test.
- All the non-conformities raised were addressed with solutions that will be implemented in the magnets of the series. Part of the mitigation solutions were already tested successfully in the prototype 3rd aperture
- The series magnet production had started: the first coil of the pre-series magnet has been wound, cured and measured, finding an azimuthal size 0.4 mm larger than nominal, in agreement with what was expected
- The first series magnet will be assembled (as soon as the copper wedges will be delivered) and tested. If the magnetic measurements will be compliant with the foreseen performance, the full production will be completed

backup slides

Prototype NCs: Coil Azimuthal Size

- To keep the collaring pressure below reasonable values (<110 MPa) it was decided to reduce the azimuthal dimension of each coil of 0.6 mm, by removing two polyimide layers in the midplane and three polyimide layers in the pole for a total of 584 μm
- This affect the field quality, which is now different from nominal
- From warm magnetic measurements performed at ASG, we derived the expected field quality @ nominal current:



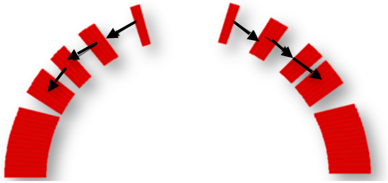
AP01	warm, I=18 A (calculated)	cold, Inom (calculated)	diff.	warm, I=18 A (measured)	cold, Inom (expected)
b2	-2.4	-5.6	-3.2	-2.9	-6.1
b3	-5.2	-4.9	0.3	7.6	7.9
b4	1.7	1.8	0.1	-0.4	-0.3
b5	6.1	6.3	0.2	11.3	11.5
b6	-0.2	-0.1	0.1	-1.5	-1.4
b7	2.1	2.5	0.4	1.7	2.1
b8	-0.9	-1.0	-0.1	-2.4	-2.5
b9	1.2	1.4	0.2	0.6	0.8
b10	-0.1	-0.1	0.0	0.0	0.0

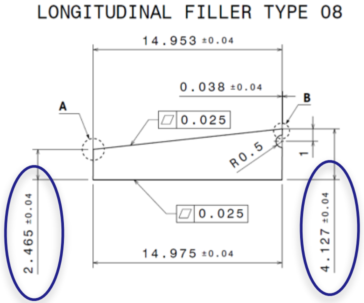
AP02	warm, I=18 A (calculated)	cold, Inom (calculated)	diff.	warm, I=18 A (measured)	cold, Inom (expected)
b2	2.4	5.6	3.2	-3.1	0.2
b3	-5.2	-4.9	0.3	8.6	8.9
b4	-1.7	-1.8	-0.1	-0.5	-0.6
b5	6.1	6.3	0.2	11.4	11.6
b6	0.2	0.1	-0.1	1.4	1.3
b7	2.1	2.5	0.4	2.3	2.7
b8	0.9	1.0	0.1	0.3	0.4
b9	1.2	1.4	0.2	0.8	1.0
b10	0.1	0.1	0.0	-0.7	-0.7

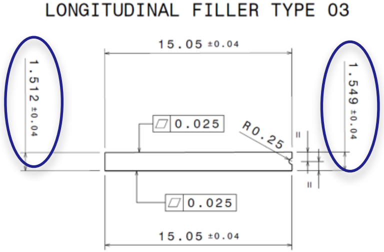
- b3 and b5 don't fulfil requirements of field quality and mitigations actions are foreseen for the series

Prototype NCs: Coil Azimuthal Size

- To address both field quality and coil size issues, for the series we proposed to modify by 0.3 mm 2 wedges out of ten







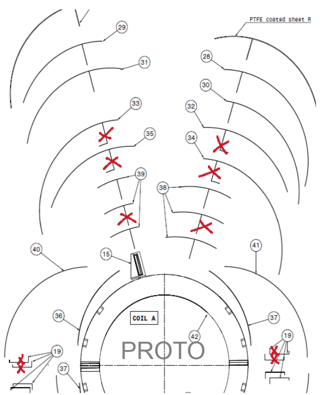
- Field quality is fine tuned restoring a 127 μm thick U shaped Kapton layer on the midplane
- The proposed change satisfactorily corrects b3 and b5 and has minor influence on the other harmonics

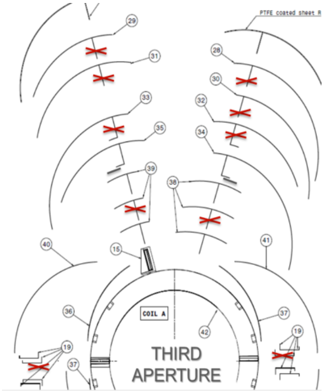
AP01	warm prototype (calculated)	cold series, Inom (calculated)	diff.	warm prototype (measured)	cold series, Inom (expected)
b2	-2.4	-6.7	-4.3	-2.9	-7.2
b3	-5.2	-15.5	-10.2	7.6	-2.7
b4	1.7	1.4	-0.3	-0.4	-0.7
b5	6.1	-3.5	-9.6	11.3	1.7
b6	-0.2	0.5	0.8	-1.5	-0.7
b7	2.1	1.5	-0.5	1.7	1.2
b8	-0.9	-1.0	-0.1	-2.4	-2.5
b9	1.2	1.4	0.2	0.6	0.9
b10	-0.1	-0.2	-0.1	0.0	-0.1

AP02	warm prototype (calculated)	cold series, Inom (calculated)	diff.	warm prototype (measured)	cold series, Inom (expected)
b2	2.4	6.7	4.3	-3.1	1.3
b3	-5.2	-15.5	-10.2	8.6	-1.7
b4	-1.7	-1.4	0.3	-0.5	-0.2
b5	6.1	-3.5	-9.6	11.4	1.8
b6	0.2	-0.5	-0.8	1.4	0.7
b7	2.1	1.5	-0.5	2.3	1.7
b8	0.9	1.0	0.1	0.3	0.3
b9	1.2	1.4	0.2	0.8	1.1
b10	0.1	0.2	0.1	-0.7	-0.5

Prototype NCs: Coil Azimuthal Size

- This mitigation solution was partially tested on the 3° aperture (same insulations scheme in the midplane foreseen for the series, but using the prototype wedges)
- A 127 μm thick U shaped Kapton layer was restored on the midplane
- The field quality measured on the 3° aperture is in agreement with what we expected





	single aperture (calculated)	single aperture 1 (mis)	single aperture 2 (mis)	diff1	diff2	3rd aperture (calculated – new insulation scheme)	expected	expected	measured
b2	213.7	209.6	-212.8	-4.0	0.9	-214.4	-210.3	-213.5	-207.3
b3	165.6	176.8	179.5	11.2	13.9	150.6	161.8	164.6	162.9
b4	35.5	37.9	-35.6	2.5	-0.1	-35.0	-37.5	-35.1	-35.2
b5	6.1	10.6	11.3	4.5	5.3	2.8	7.3	8.0	8.5
b6	2.3	3.6	-3.2	1.3	-0.9	-2.3	-3.6	-3.2	-3.4
b7	3.1	2.2	3.3	-0.9	0.2	1.4	0.6	1.7	1.2
b8	1.3	0.9	-2.3	-0.4	-1.0	-1.3	-0.8	-2.3	-2.1
b9	1.5	1.3	1.6	-0.2	0.0	1.0	0.8	1.0	1.2
b10	0.1	-0.3	0.5	-0.4	0.6	-0.2	0.3	0.4	-0.4

Prototype NCs: Coil Azimuthal Size

	single aperture (calculated)	single aperture 1 (mis)	single aperture 2 (mis)	diff1	diff2	3rd aperture (calculated – new insulation scheme)	expected	expected	measured
b2	213.7	209.6	-212.8	-4.0	0.9	-214.4	-210.3	-213.5	-207.3
b3	165.6	176.8	179.5	11.2	13.9	150.6	161.8	164.6	162.9
b4	35.5	37.9	-35.6	2.5	-0.1	-35.0	-37.5	-35.1	-35.2
b5	6.1	10.6	11.3	4.5	5.3	2.8	7.3	8.0	8.5
b6	2.3	3.6	-3.2	1.3	-0.9	-2.3	-3.6	-3.2	-3.4
b7	3.1	2.2	3.3	-0.9	0.2	1.4	0.6	1.7	1.2
b8	1.3	0.9	-2.3	-0.4	-1.0	-1.3	-0.8	-2.3	-2.1
b9	1.5	1.3	1.6	-0.2	0.0	1.0	0.8	1.0	1.2
b10	0.1	-0.3	0.5	-0.4	0.6	-0.2	0.3	0.4	-0.4

- To be noted that b5 variation from the single aperture configuration to the yoked double aperture configuration @RT is within 1 unit. The same behaviour was observed in the short model, including the yoked double aperture configuration @Inom.

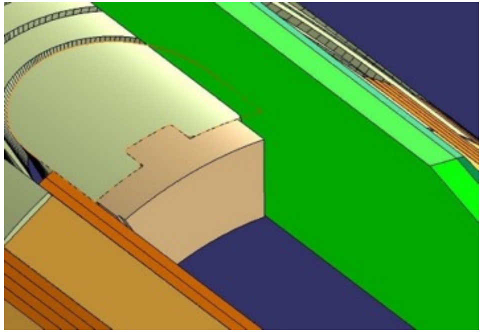
PROTOTYPE

b5	Single Aperture RT	Yokes Double Aperture RT (measured @ ASG)	Yoked Double Aperture RT (measured @ CERN)
V01	10.6	11.3	9.5
V02	11.3	11.4	10.1

SHORT MODEL

b5	Single Aperture RT	Yoked Double Aperture RT	Yoked Double Aperture @ I_{nom}
V1N	9.01	9.43	9.57
V2N	6.75	6.97	N.A.

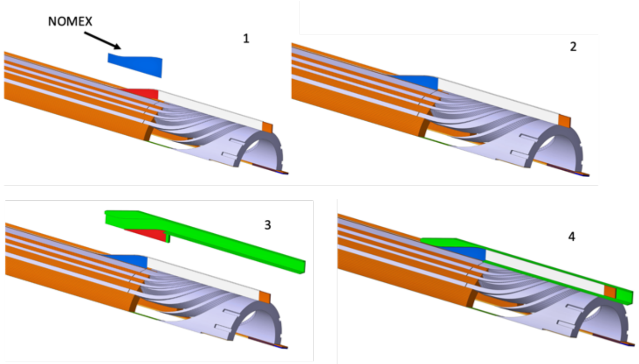
- modification of wedges 3 and 8 for fine-tuning of field quality and compensation of excessive coil size
- reintroduction of the folded GI layer, which in the prototype was cut at the edge of the collar nose (already successfully tested on the third aperture)
- azimuthal division of the collar shoes moved to the area between the QH active strips, Teflon coating added on both sides of the collar shoes (?)
- on the return end, introduction of a new end G11 nose piece with the aim of intercepting the collar shoe preventing any possible contact with the turns (already successfully tested on the third aperture)
- a lead spreading device adopted to keep the leads in the correct position during collaring (already successfully tested on the third aperture)
- insertion of a Nomex sheet to reinforce the insulation in the region of the layer jump (already successfully tested on the third aperture)
- Superbolt moved to the non-connecting side, stiffening of the end plates as much as possible
- Transport under temporary loading conditions, final loading of the longitudinal system at CERN
- Use an expandable mandrel on the first 1 m during collaring preventing layer jump protrusion into the aperture
- New system for locking the Superbolts screws (see AB presentation)

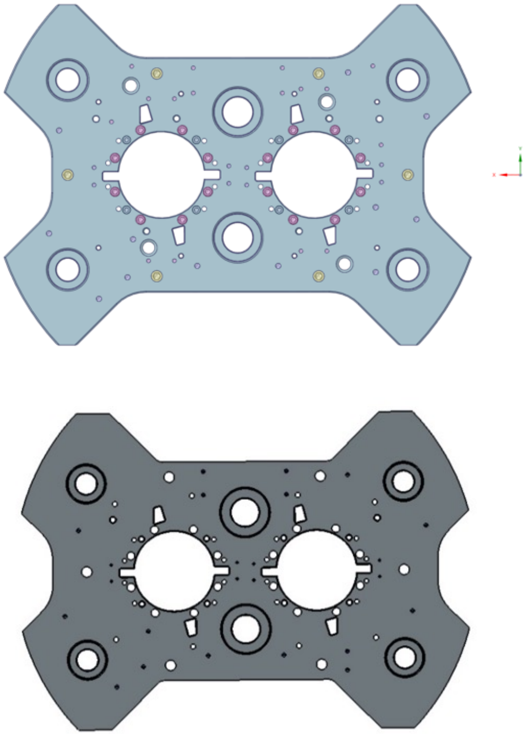


End G11 nose piece intercepting the collar shoe (4)

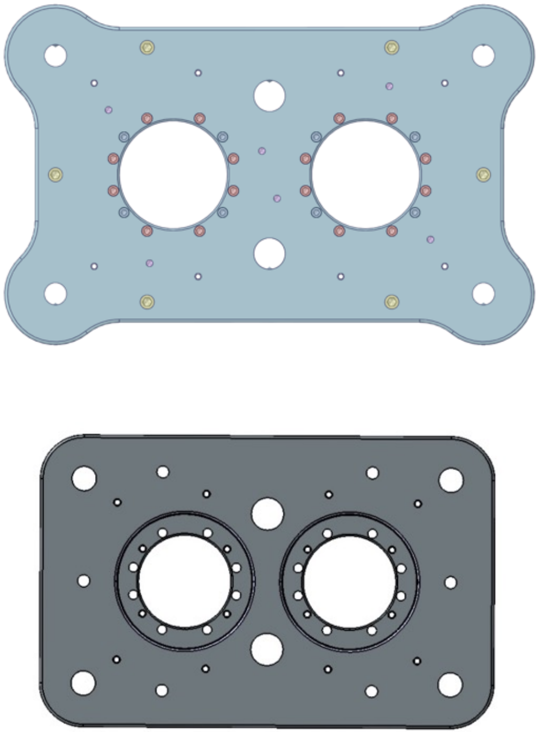
Lead spring device

NOMEX sheet to reinforce the insulation in the layer jump region

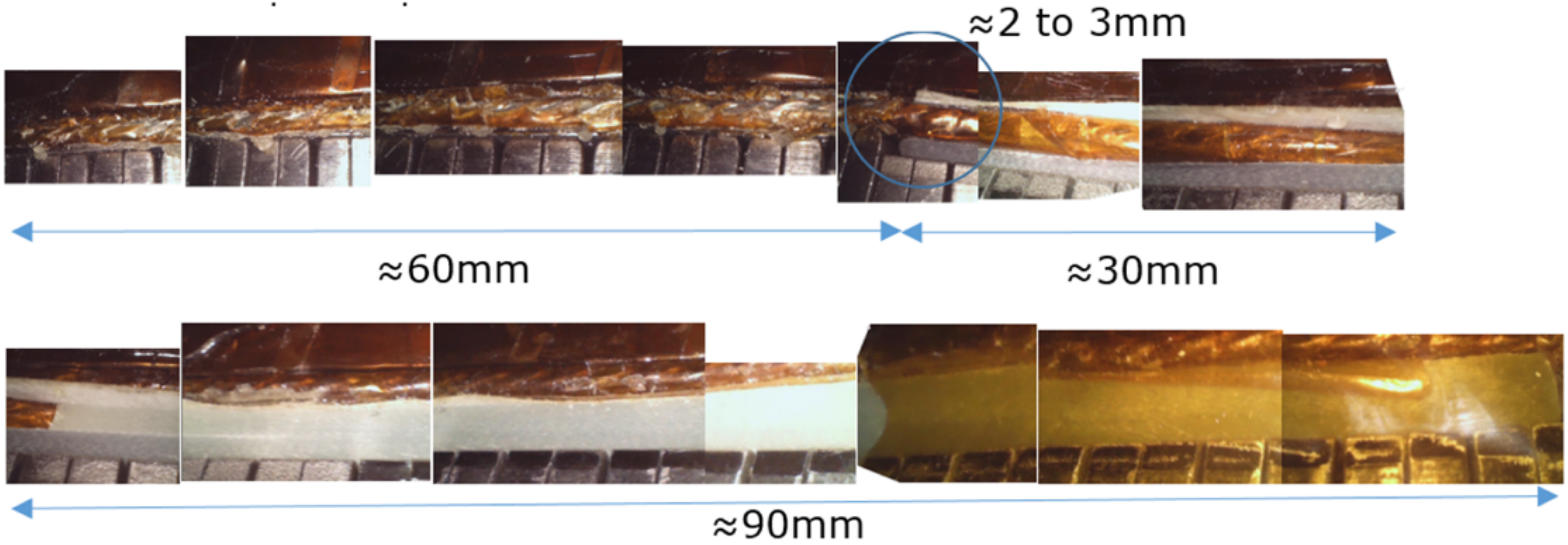




MBRD connection side



MBRD non connection side


≈2 to 3mm
≈60mm
≈30mm
≈90mm

- ASG will need to guarantee no protrusion inside the bore diameter of the first jumper turn using a collapsible mandrel in this area during collaring (similarly to the use of CBT tube for LHC dipole) and to implement a systematic dimensional jig check. This solution should be tested beforehand.
- The Nomex layer used as a repair material in situ once collared pack formed by ASG having edge facing CBT is a too hard material with sharp edges and should not be used unless its placement is precisely controlled.
- The precise inspection of the jumper layer cable should be performed on the existing trial spare Aperture AP03.
- Electrical test : This is reinforcing the importance that ASG implement a solution of folded Ground insulation layer to prevent from this risk.
- All the procedures will be updated to implement the correctives actions.