HiLumi
HL-LHC PROJECT

D2 azimuthal coil size

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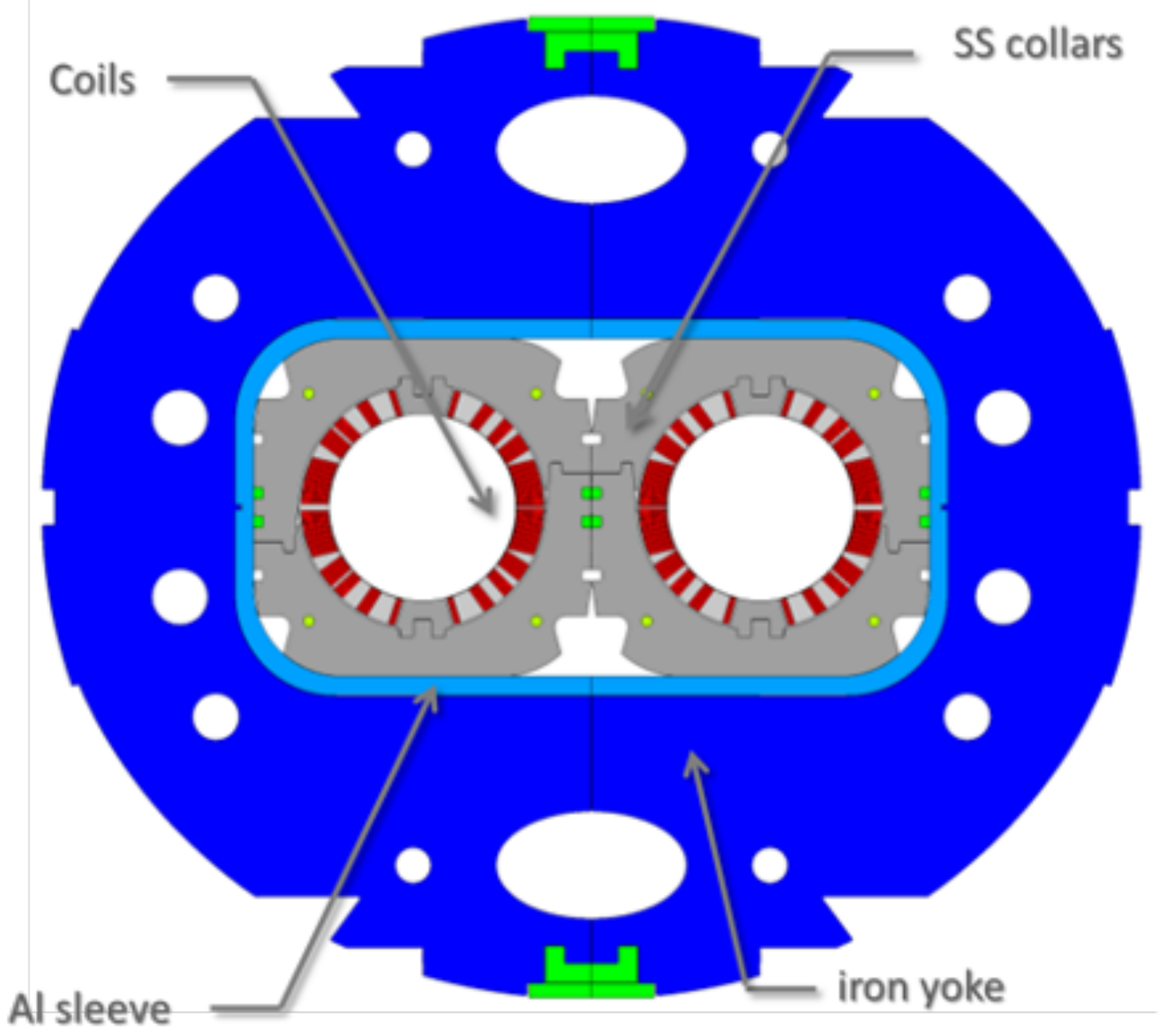
INFN GENOVA

OUTLOOK



- Short model overview
  - Construction
  - NCs
  - Cold tests at CERN
- Prototype overview:
  - Modifications wrt short model
  - New insulation scheme to mitigate excessive azimuthal coil size
  - Field quality
- Series overview:
  - Mitigation strategies implemented to improve field quality
  - Measurements of the first pre-series coil

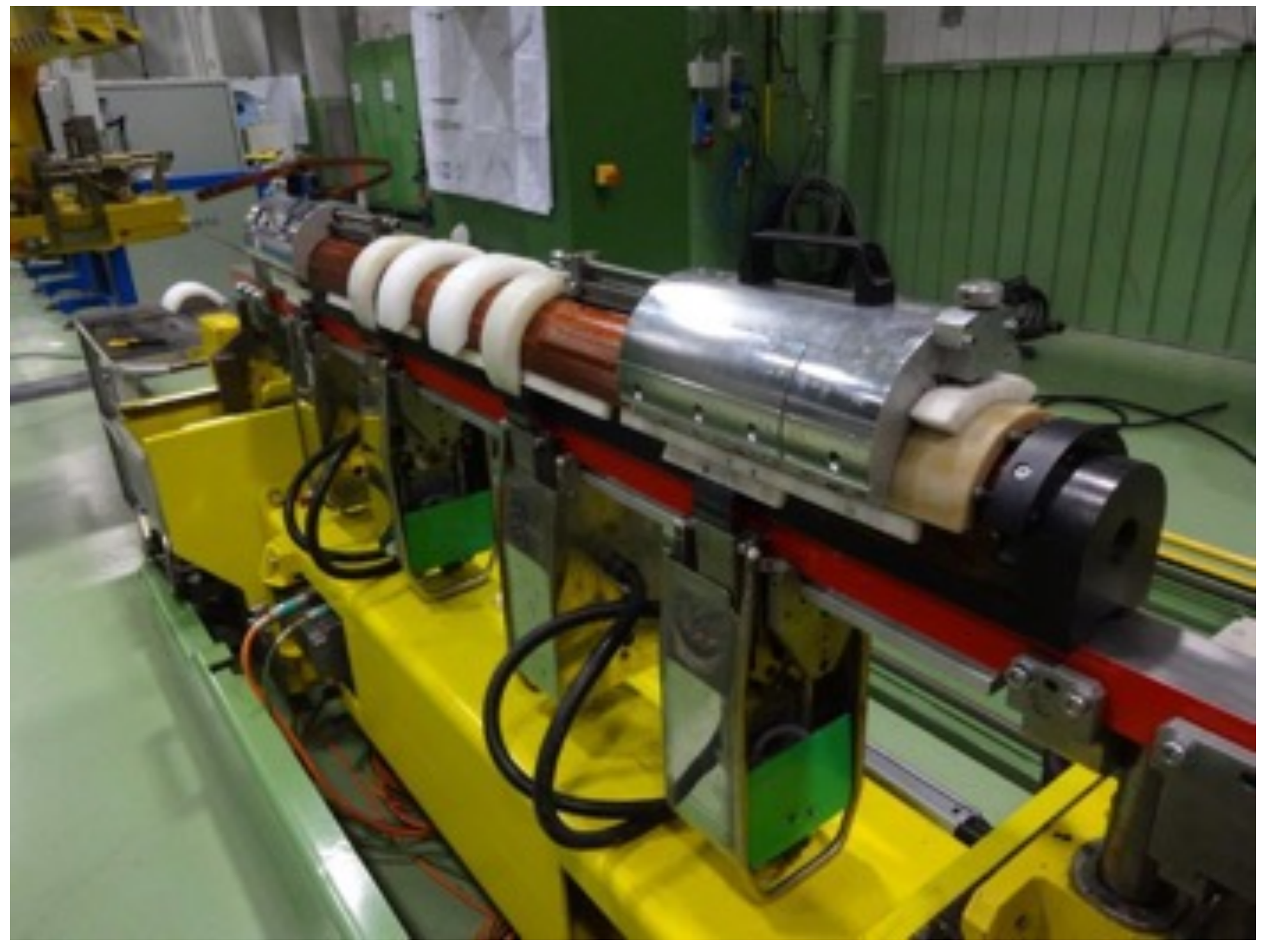
GENERAL DESIGN FEATURES

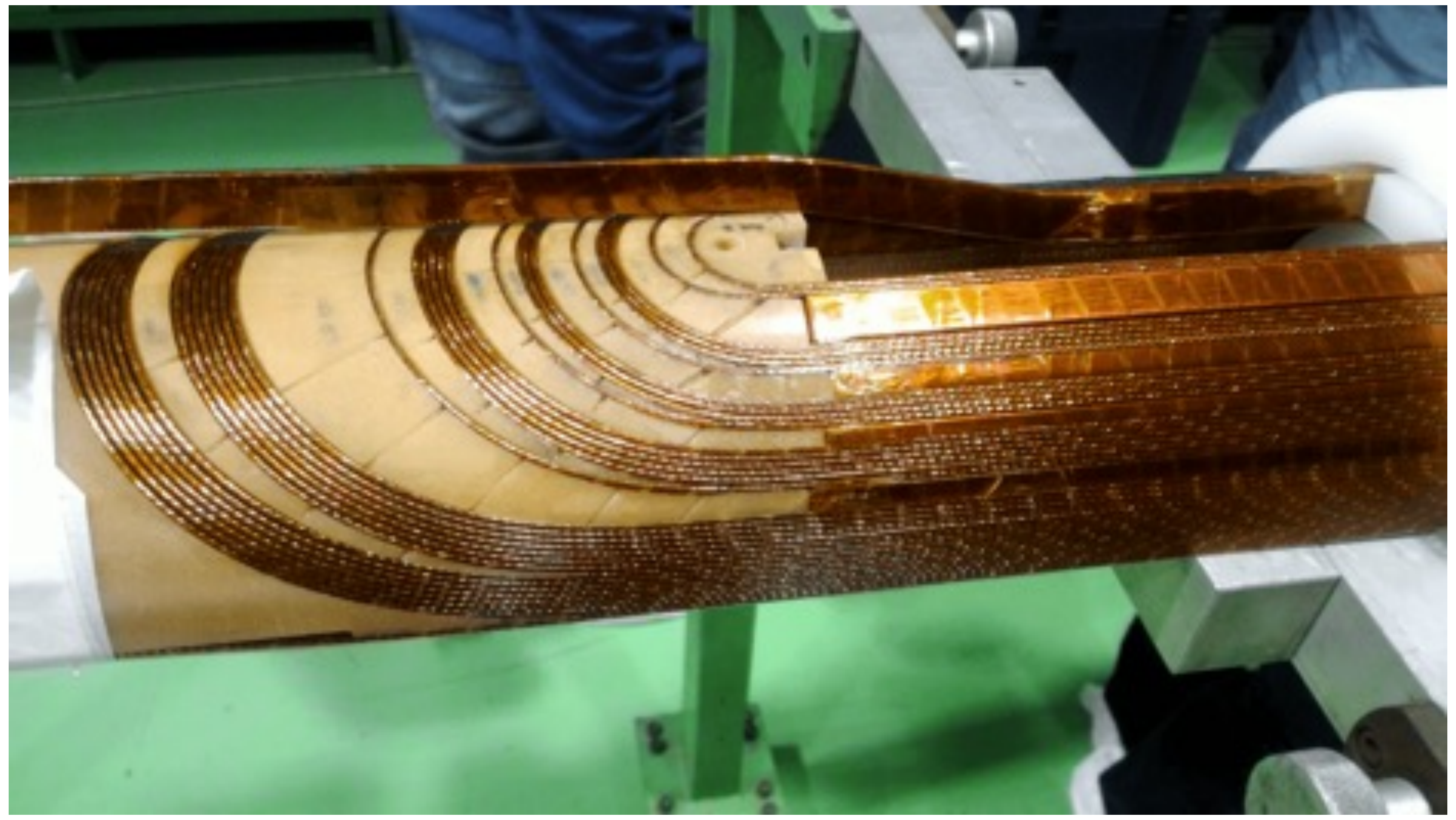
- D2 is a double aperture superconducting dipole with a 4.5 T bore field oriented in the same direction in the two apertures
- field quality is achieved by shaping the iron yoke and designing left/right a-symmetrical coils
- the apertures are individually collared to reduce the risk of the collaring operation itself and because the required hydraulic press is much smaller
- Al sleeves keep the repulsive Lorentz forces between the apertures and their shrinkage during cooling ensures the alignment of the apertures
- the iron yoke has no mechanical function, it is assembled under pressure to compensate for the lower thermal contraction coefficient
- the axial preload system is based on tie rods due to the fact that the cold mass includes also the orbit correctors
- the quench protection system is based on quench heater

Main characteristics of the D2 dipole	
Bore magnetic field	4.5 T
Magnetic length	1.371 m
Peak field	5.26 T
Operating current	12.34 kA
Stored energy	2.28 MJ
Magnet physical length	1.6 m
Aperture	105 mm
Beam separation at cold	188 mm
Operating temperature	1.9 K
Loadline fraction	67.5%
Multipole variation due to iron saturation	<10 units

SHORT MODEL : COIL MANUFACTURING

- winding activity started on March 2018
- 1 practice pole (A01) and 3 standard poles (B01, A02 and B02) were successfully wound
- winding activity completed in June 2018
- the 4 poles passed all controls (coil resistance and inductance measurements, interturn insulation and ground insulation tests)





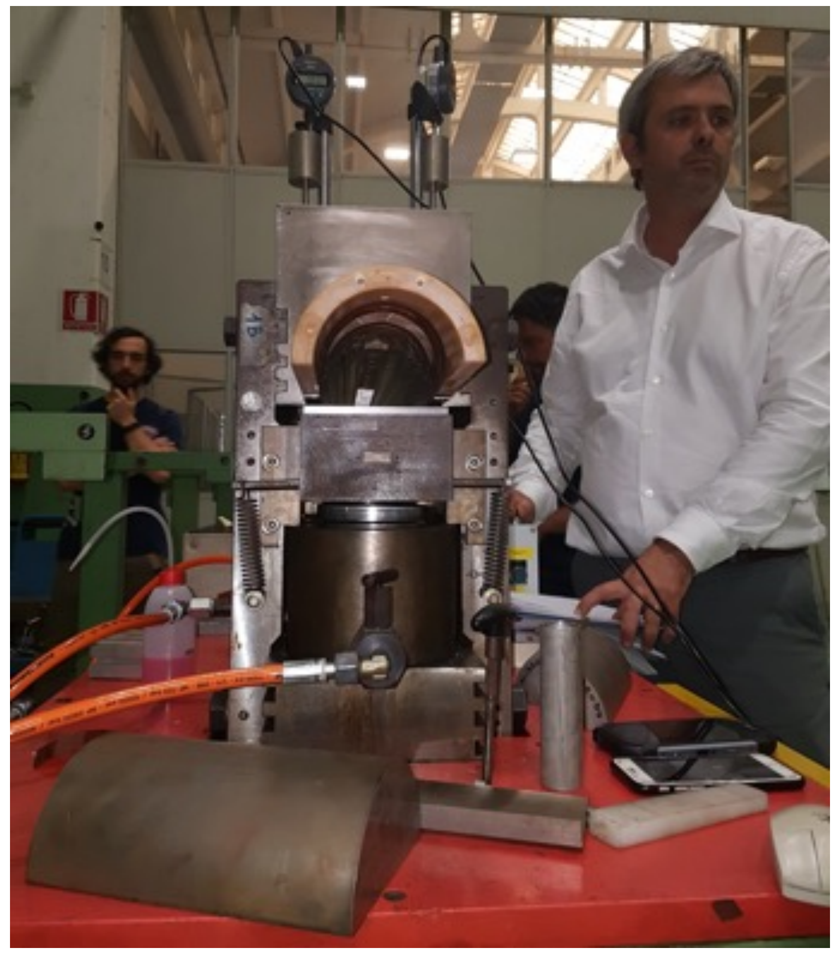
SHORT MODEL : COIL SIZE

- the cross section is designed at the operating pressure of 70 MPa
- pole dimension measurements at 70 MPa represent the deviation from a template with nominal dimensions
- due to an INFN/ASG misunderstanding that only became clear during prototype construction, the templates were ˜1 mm bigger than nominal (they included the nominal pole/midplane insulation thickness) so that all coil dimensions were underestimated by ˜1 mm

  this was the cause of most of the subsequent problems
- all 4 poles were considered acceptable even if bigger than specified, aware that this implied larger force for collaring and larger stress in the winding (˜10 MPa per 0.1 mm)

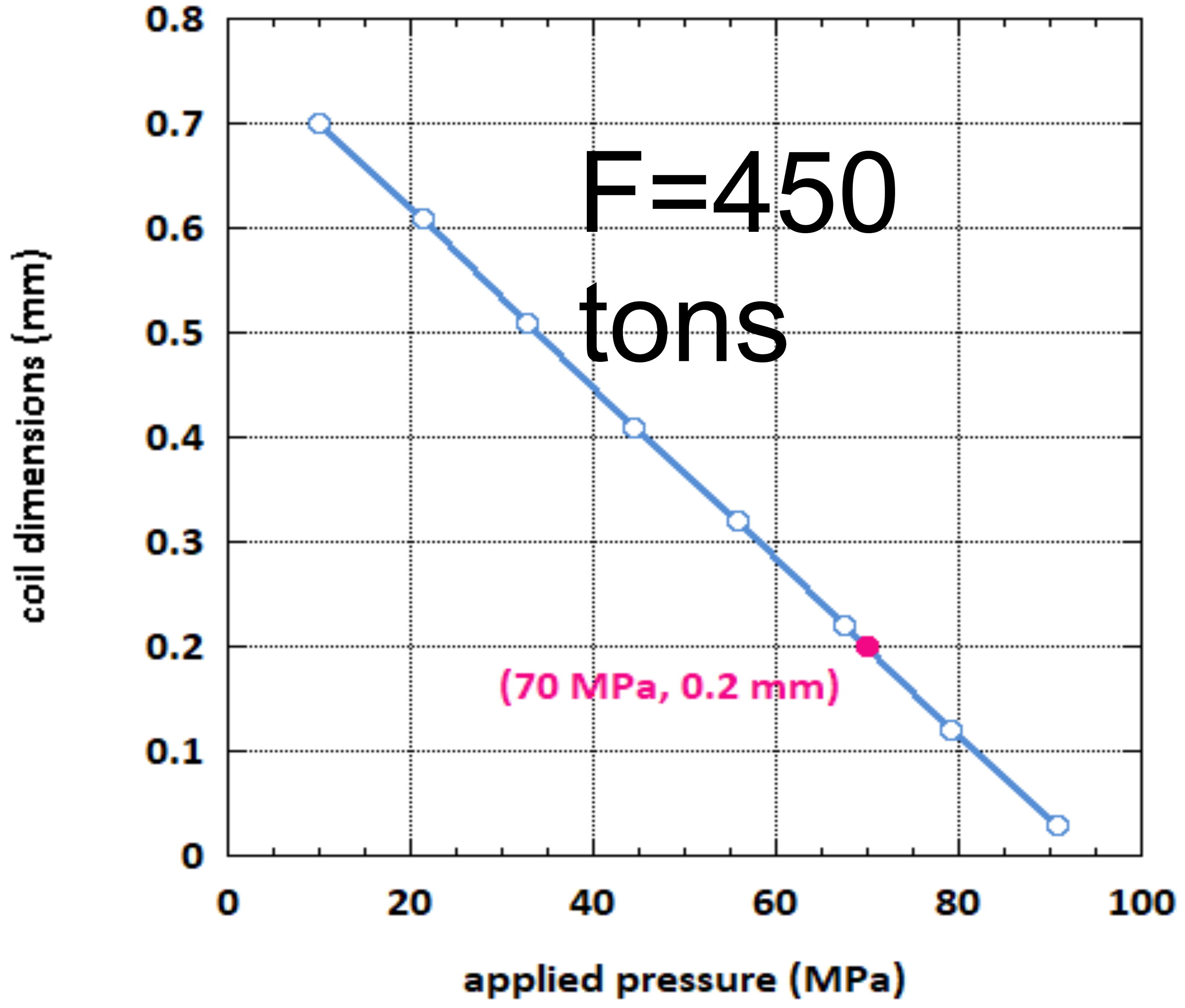
coil dimension excess wrt to nominal @ 70 MPa

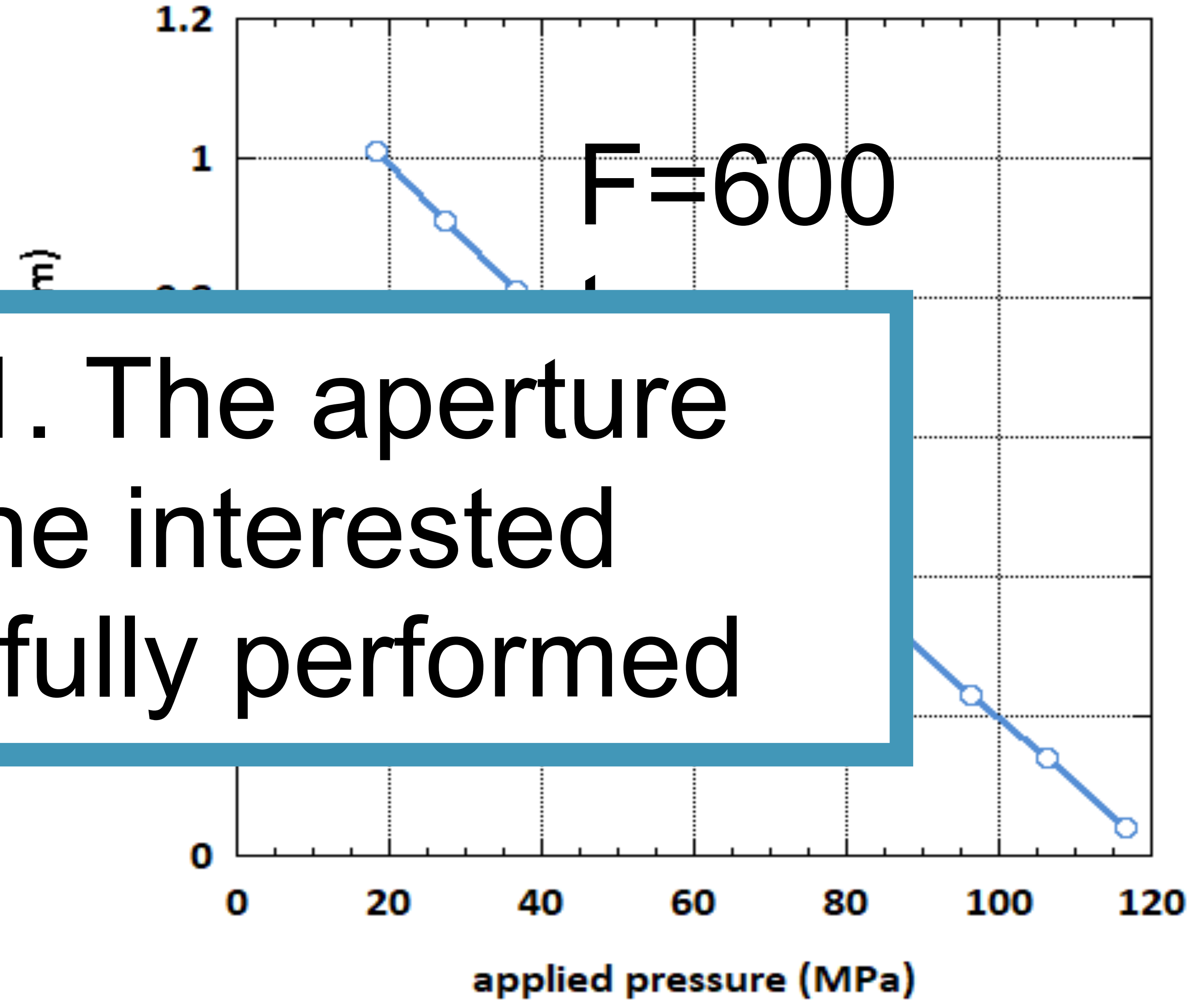
	AP1		AP2	
	A01	B02	A02	B01
connections side	0.11	0.37	0.37	0.32
Centre	0.26	0.36	0.39	0.34
non conn. side	0.15	0.33	0.31	0.27



SHORT MODEL : COLLARING

- collaring operations began in early August 2018
  - aperture #1: coil A01 and B02
    - collaring started on 2/8/18 and ended on 6/8/18
  - aperture #2: coil A02 and B01
    - collaring performed on 7/9/18
- the collar force was greater than the nominal one
  - for both apertures the required collaring force was around ***600 tons***
  - 2D FE analysis under nominal conditions (conductor parameters set by fitting stacking test measurements) predic
    to a to
    300×
    contribution of the ends)=***450 tons***

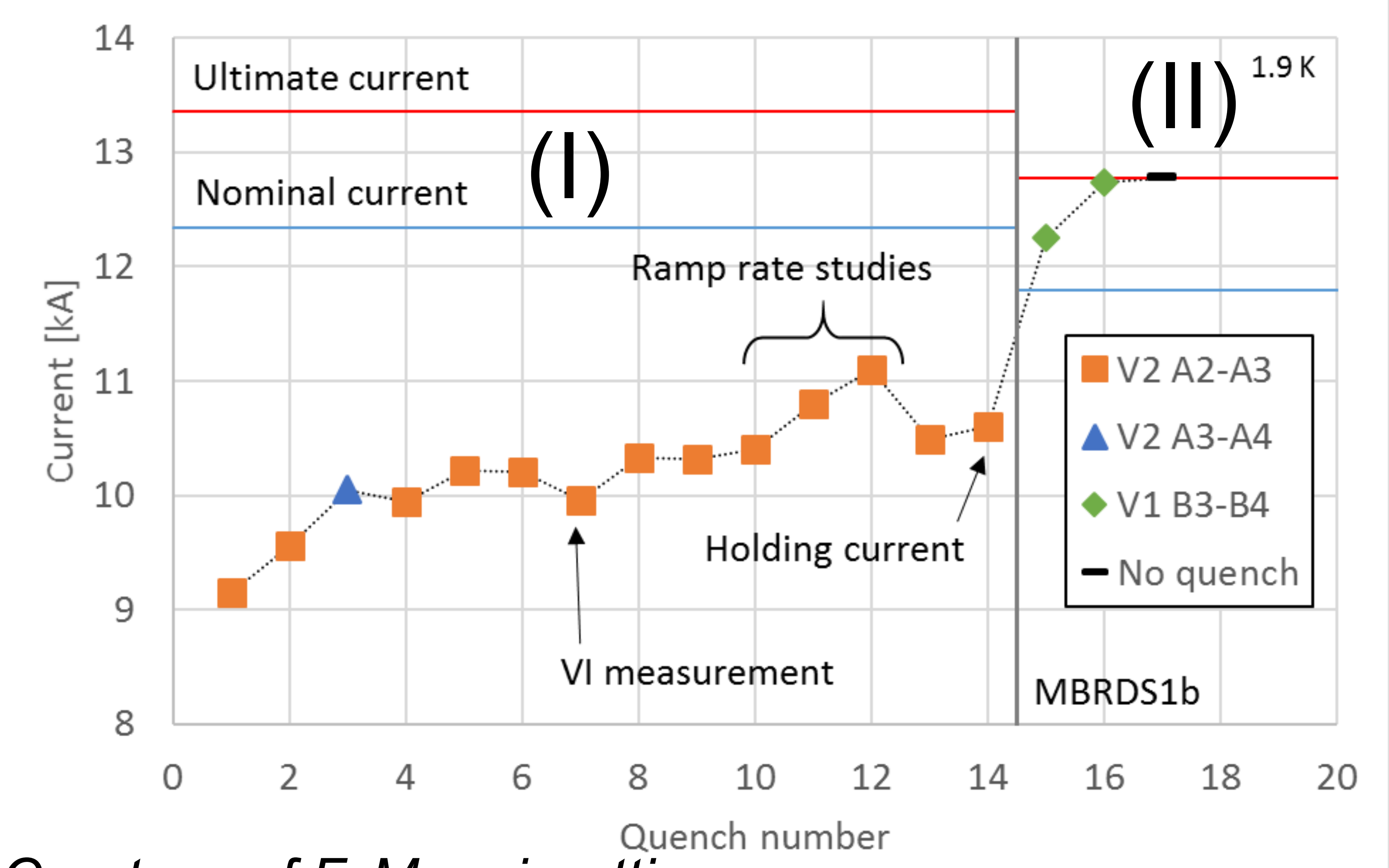




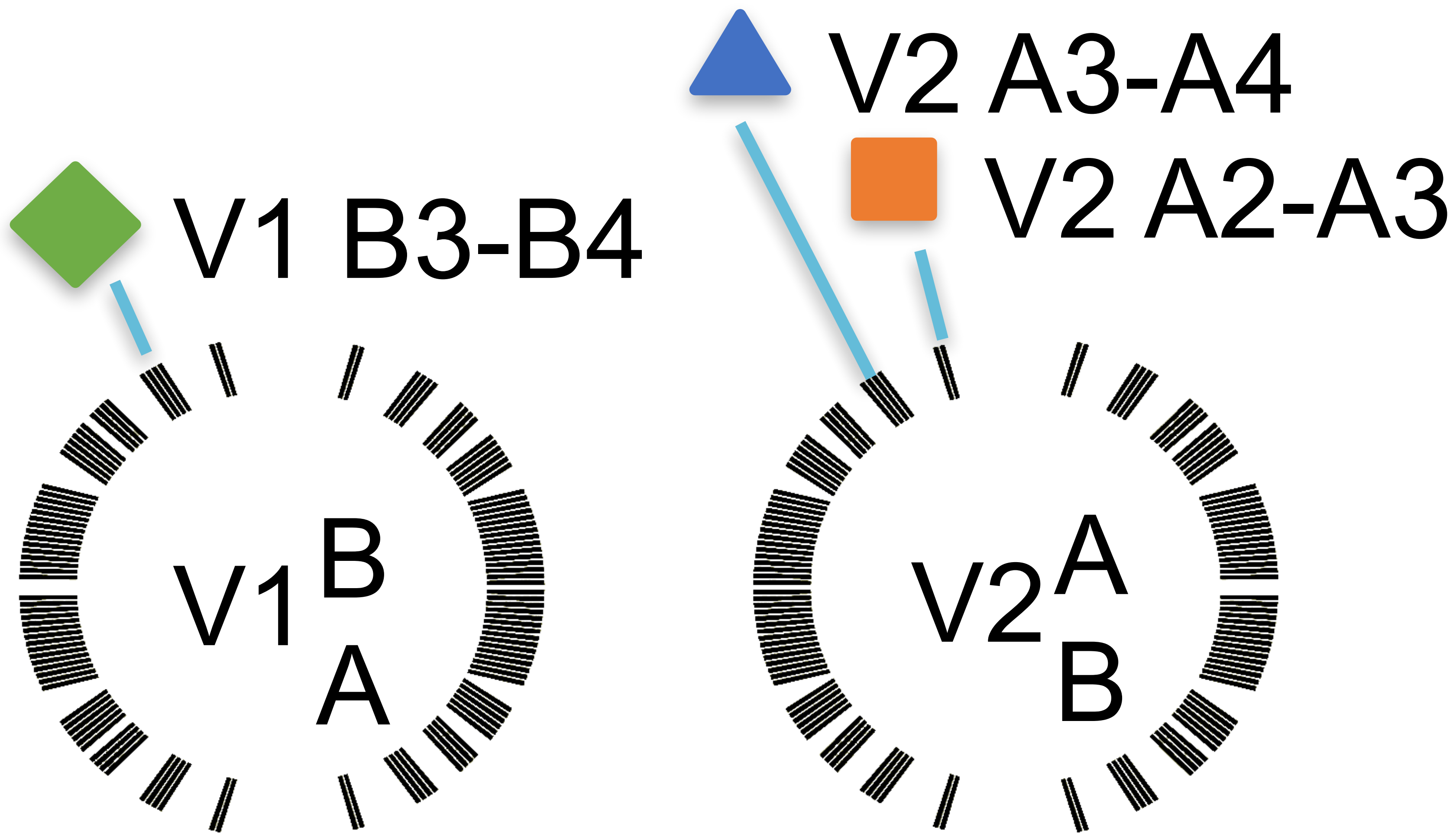
TBN: A short was found in the 5th block of A1-01. The aperture was disassembled, the insulation reinforced in the interested region and than a second collaring was successfully performed

SHORT MODEL : COLD TEST @ CERN

- The short model was completed and delivered to CERN on 17th January 2019



Courtesy of F. Mangiarotti



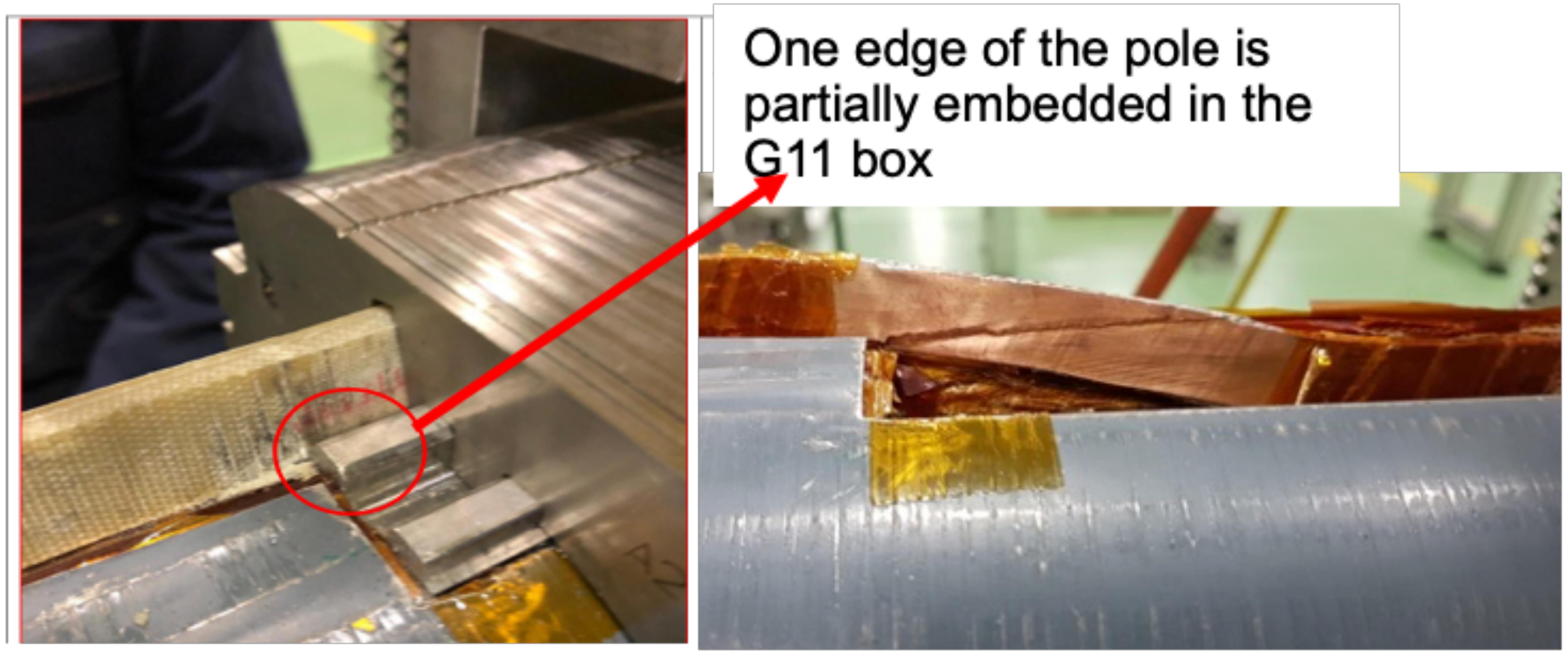
(I) all but one quench at the same position: V2 A2-A3. the conclusion was that the conductor in the fifth block of coil A in aperture V2 was severely damaged it was decided to disconnect V2 and feed only V1

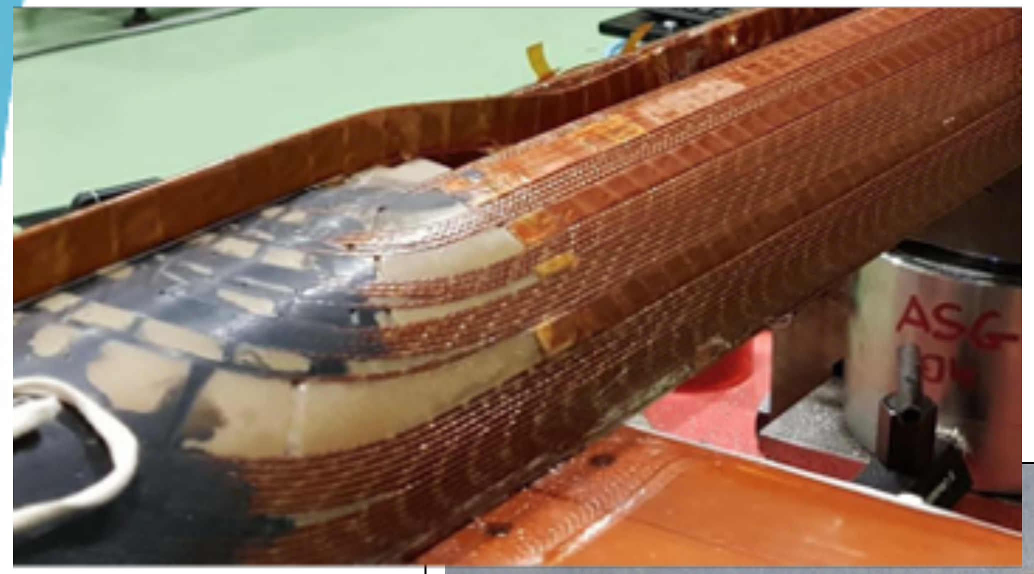
(II): V2 disconnected

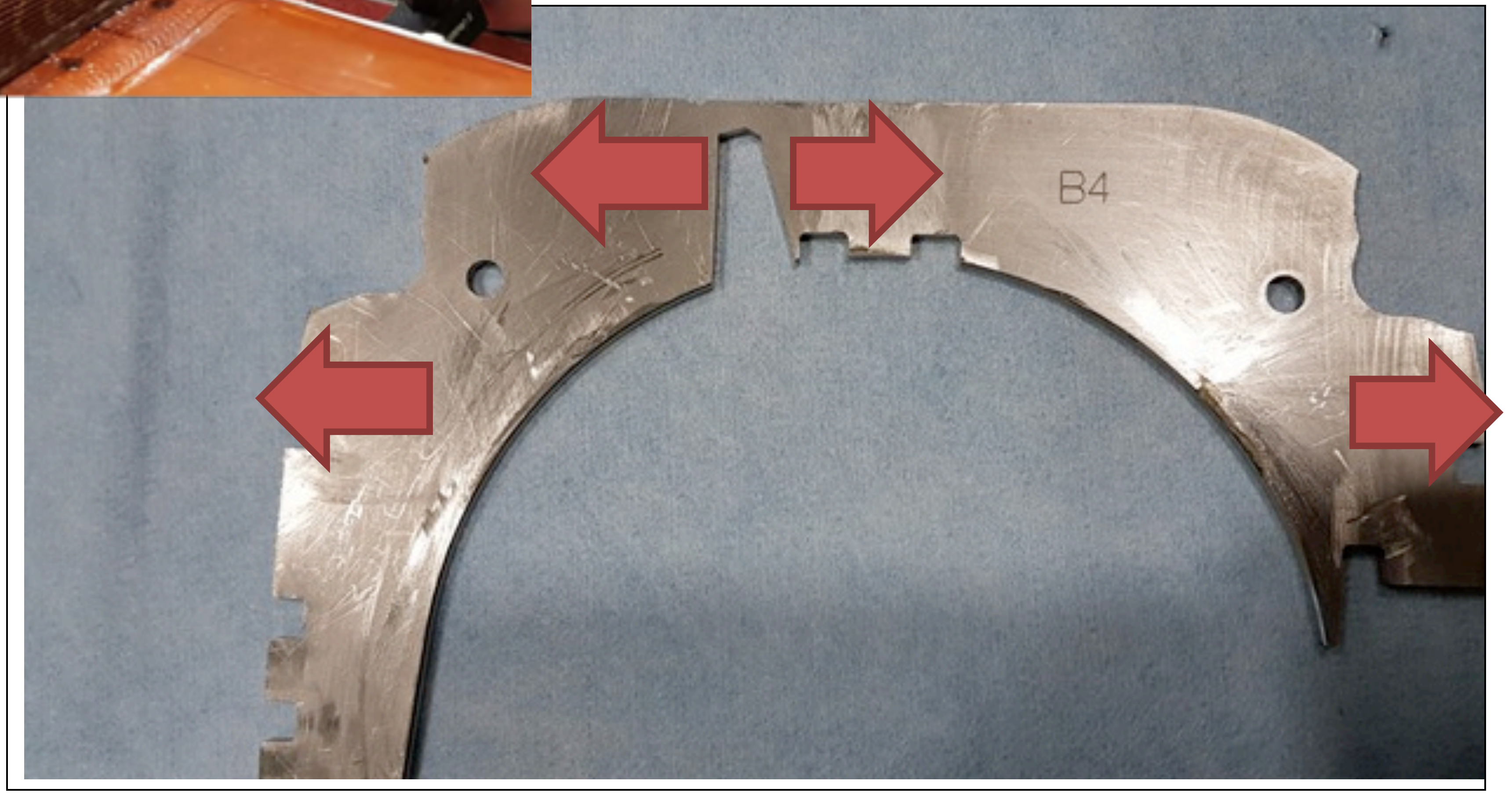
MBRDS1b had two quenches until the final current.
Ultimate current was maintained for more than an hour without quench
Ultimate current was reached also without quenches at 400 A/s

SHORT MODEL : CABLE DAMAGE ROOT CAUSE

- V2 was disassembled and visual inspected. The cable damage was due to a a corner of the collar pole entered the conductor and cut 20 wires out of 36.



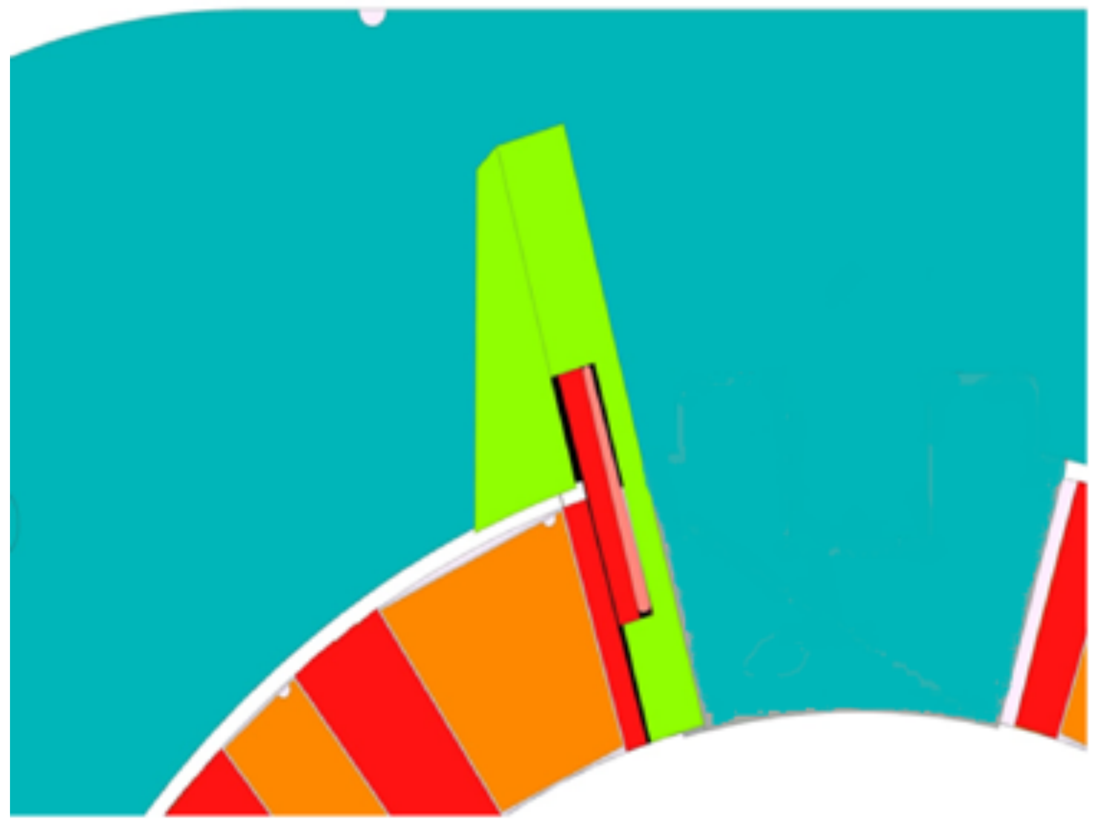




- ROOT CAUSES:
- The insulation in the layer jump region was too thick (it was reinforced after the first short circuit). This problem was worsened by the excessive size of the coil
- Because of the cut to allow the exit of the conductor, the collar deformed horizontally, and the cut is larger than a few tenths of a mm. This left space available for collar pole movements after first collaring

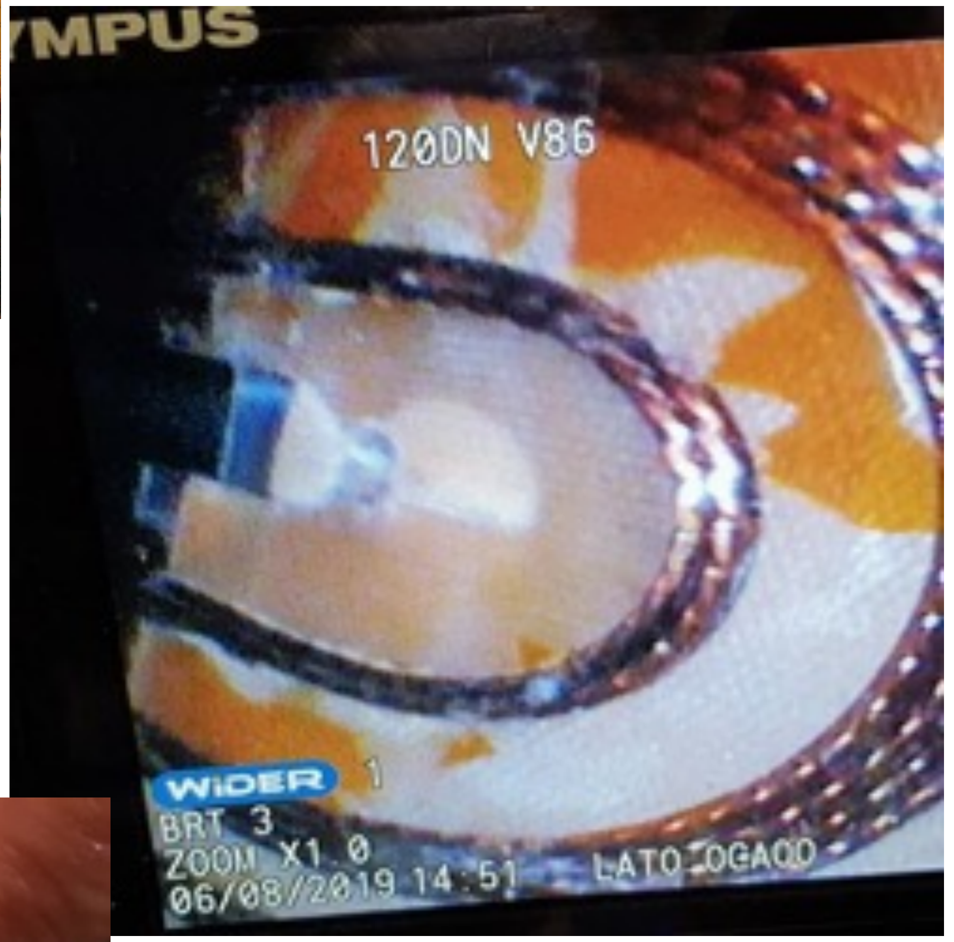
SHORT MODEL : CORRECTIVE ACTIONS

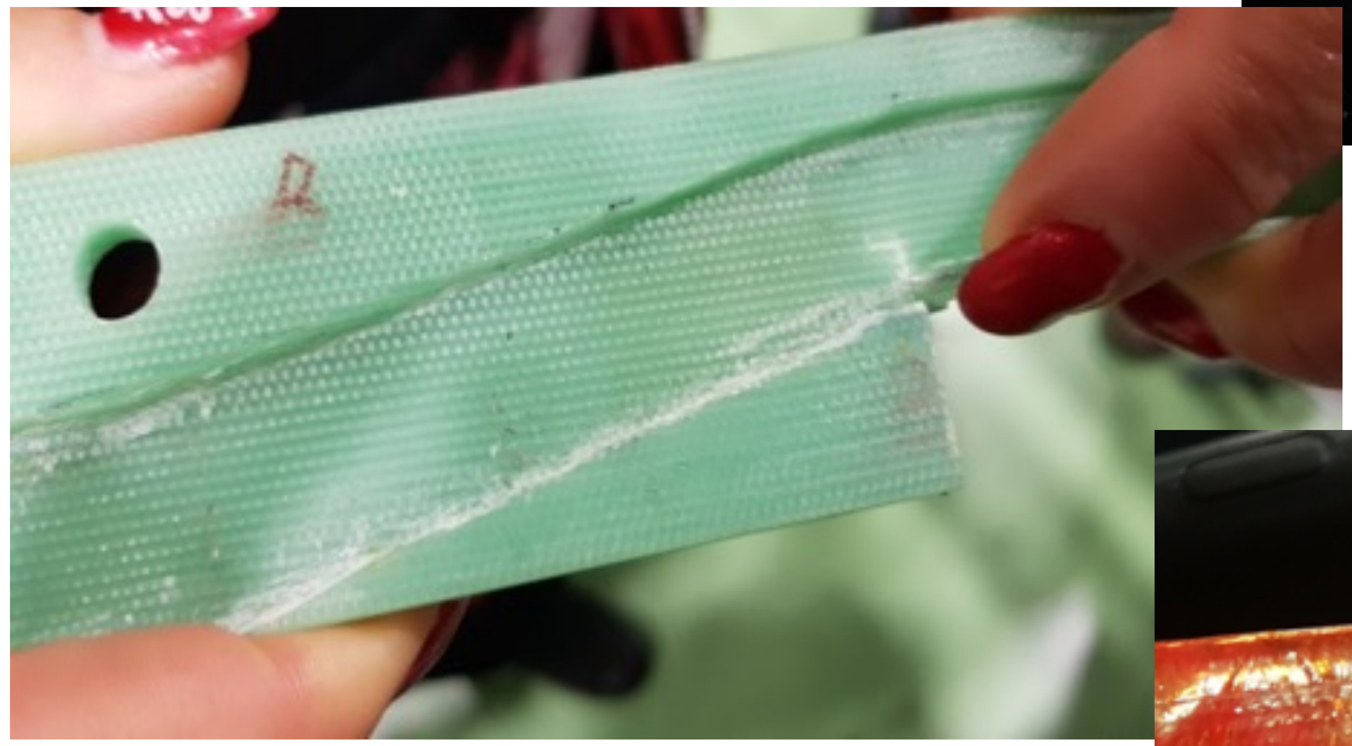
- Based on what was observed on the short model, the following actions were taken for the ***prototype***:
  - the collars were modified to include poles, made by fine blanking.
  - The insulation thickness of the exit conductor must be carefully controlled in order not to be too thick.
  - The cut in the collar was reduced as much as possible to increase the stiffness of the collar in this region.

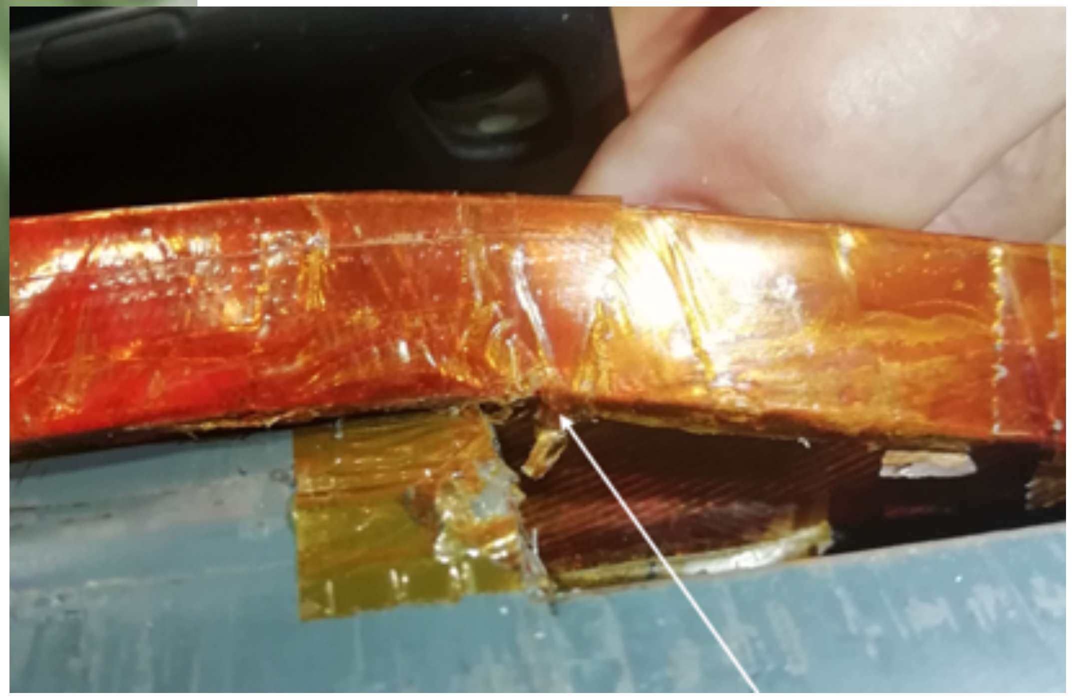


- Regarding the ***short model***:
  - the collars in the LC side of the Aperture V2 were changed to include noses in the collars (as it will be in the prototype) so as to verify this solution before it was applied in the prototype.
  - a new coil type A was wound and a new aperture V2 assembled

SHORT MODEL FINALIZATION

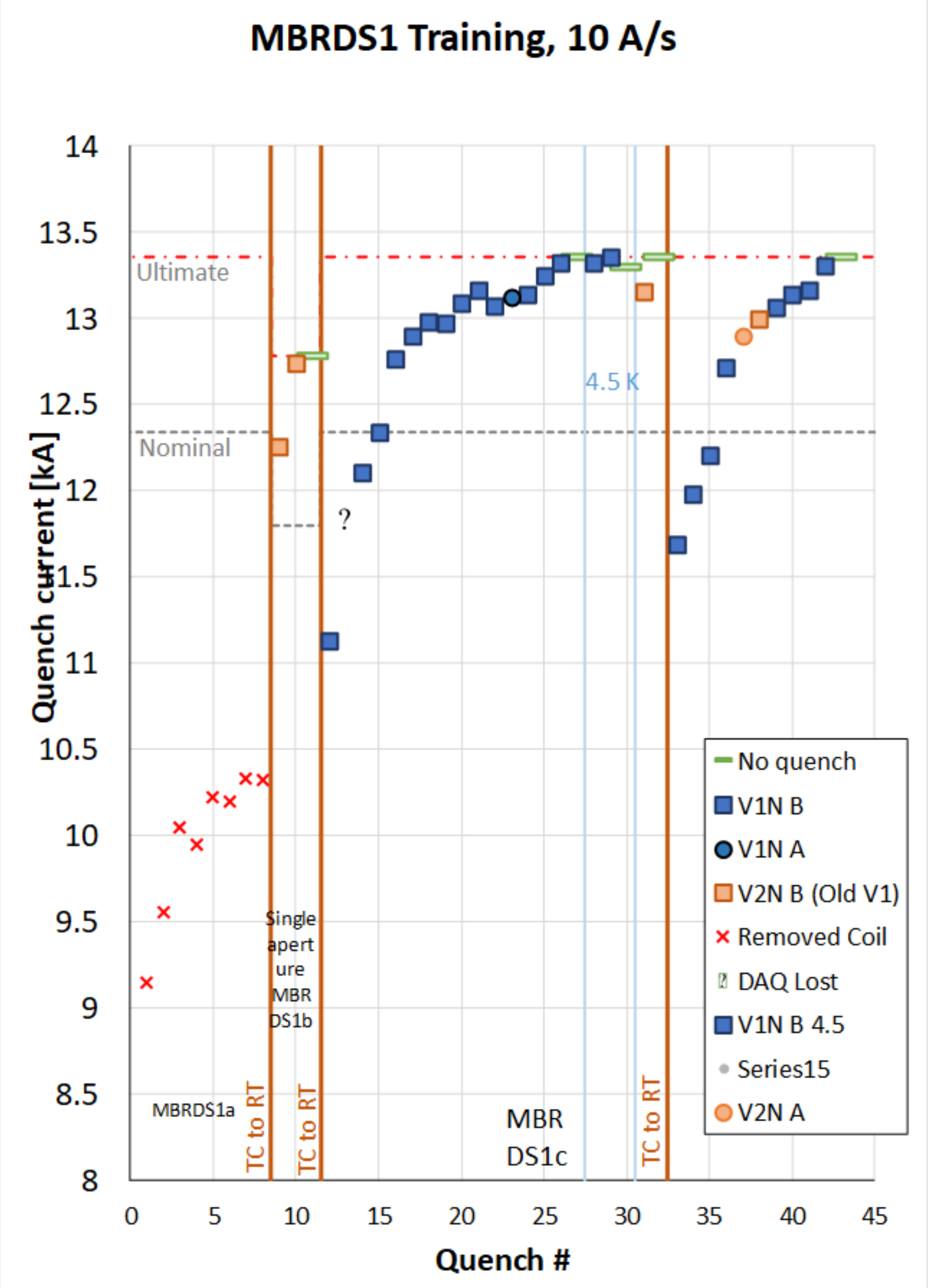






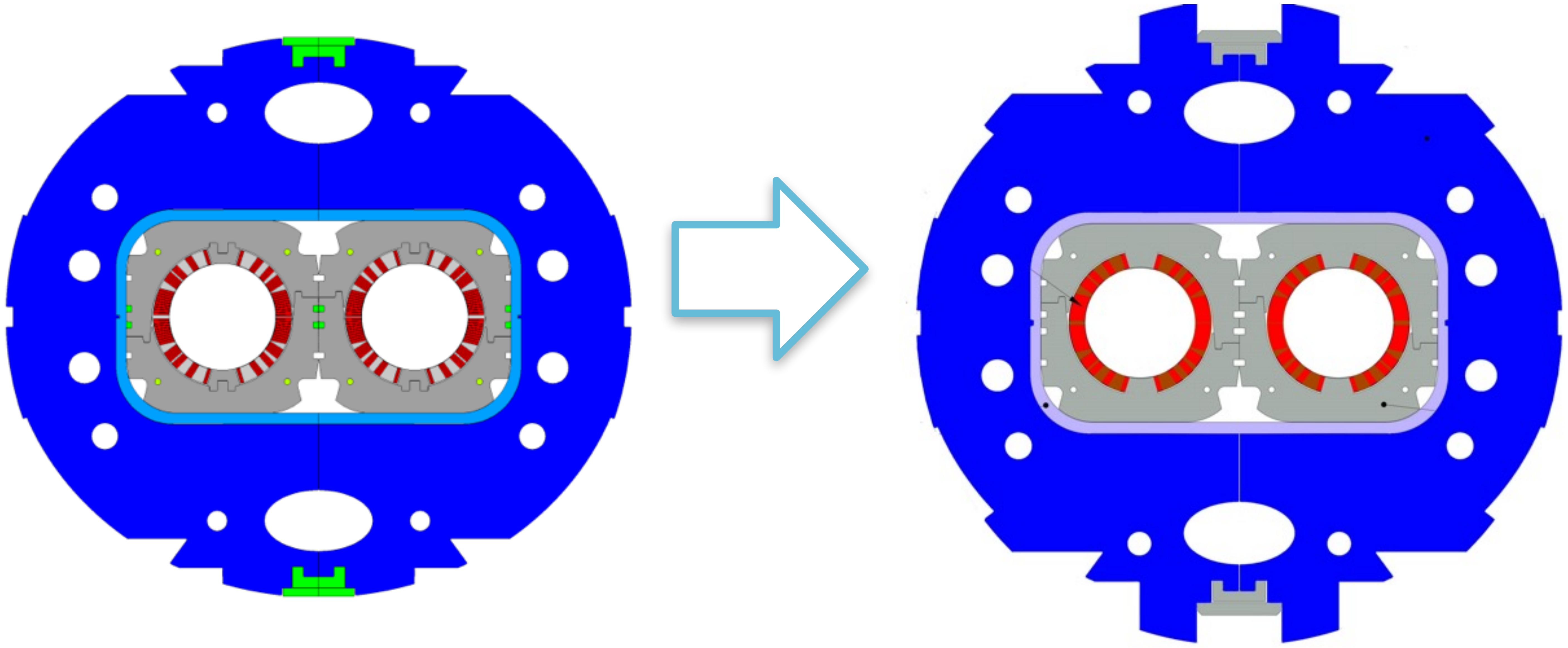
- After the new collaring, two new issues were found:
  - delamination of the end spacer in the pole at the connection side → repaired with charged stycast
  - short circuit in the 5th block of coil B of V2 due to:
    - excessive pressure (more than 120 MPa) during collaring caused by the size of the coils (new A coil 1.43 mm larger than nominal)
    - use of the nominal 200 μm mid-plane insulation for each coil (previously it was 50 microns by mistake)
    - G11 box not protecting the conductor exit enough

SHORT MODEL: SECOND COLD TEST @ CERN



- A 2nd cold test was performed in August 2020:
  - ultimate current reached, even at 4.5 K
  - loss of memory in one coil of one aperture, causing retraining after thermal cycle
  - magnetic saturation measurements in line with models
  - quench heaters validated
- The evidence of a weak coil (V1NB) causing retraining after thermal cycling triggered the decision to disassemble the short model at CERN and have a visual inspection of the four coils to better understand the problems:
  - the inspection could not find any clear indication of weakness in the V1NB coil
  - V1NB coil has been subjected to 4 collaring operations, in the last of which the end spacers in the poles were damaged and repaired

FROM SHORT MODEL (MBRDS1) TO PROTOTYPE (MBRDP1)



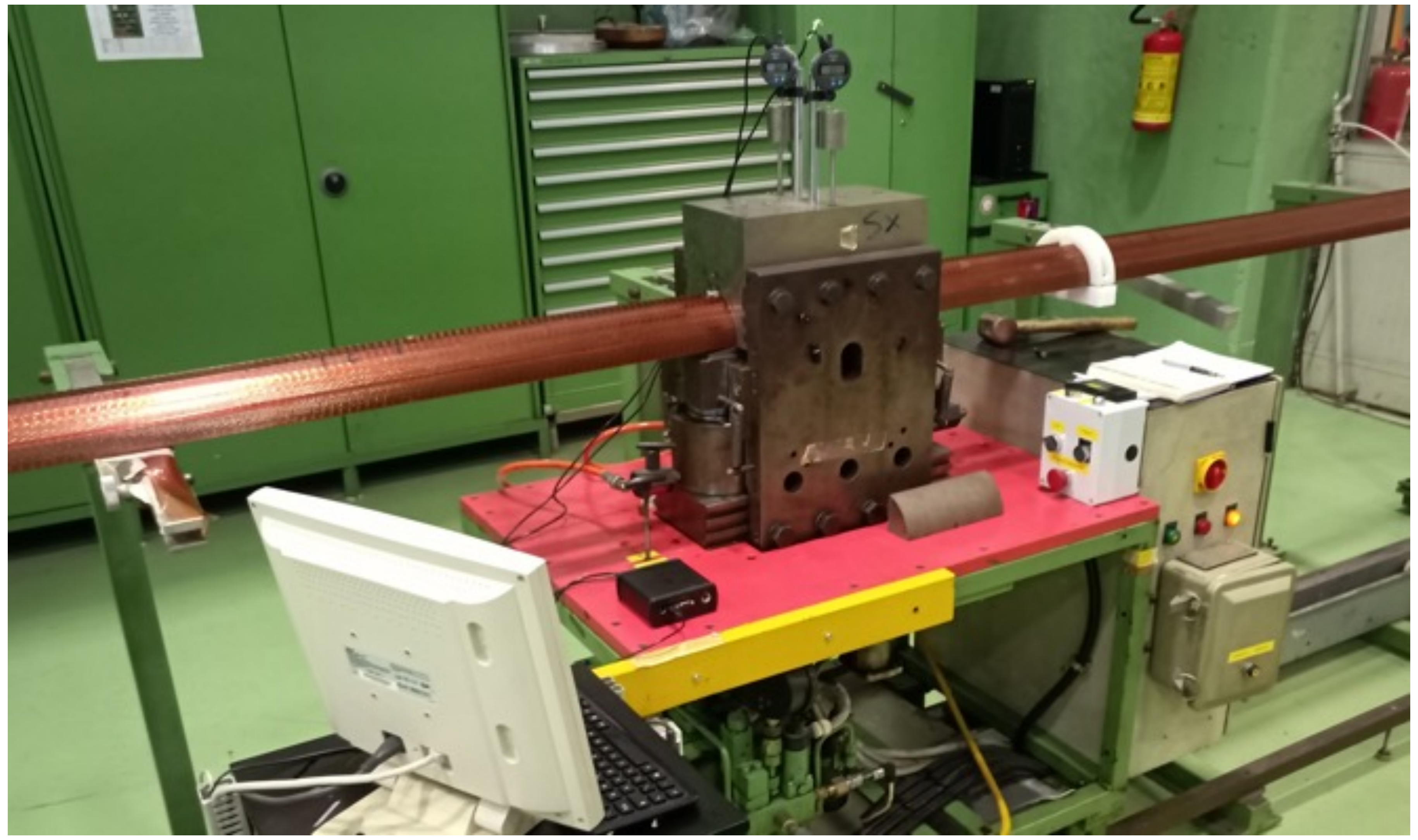
- Main modifications:

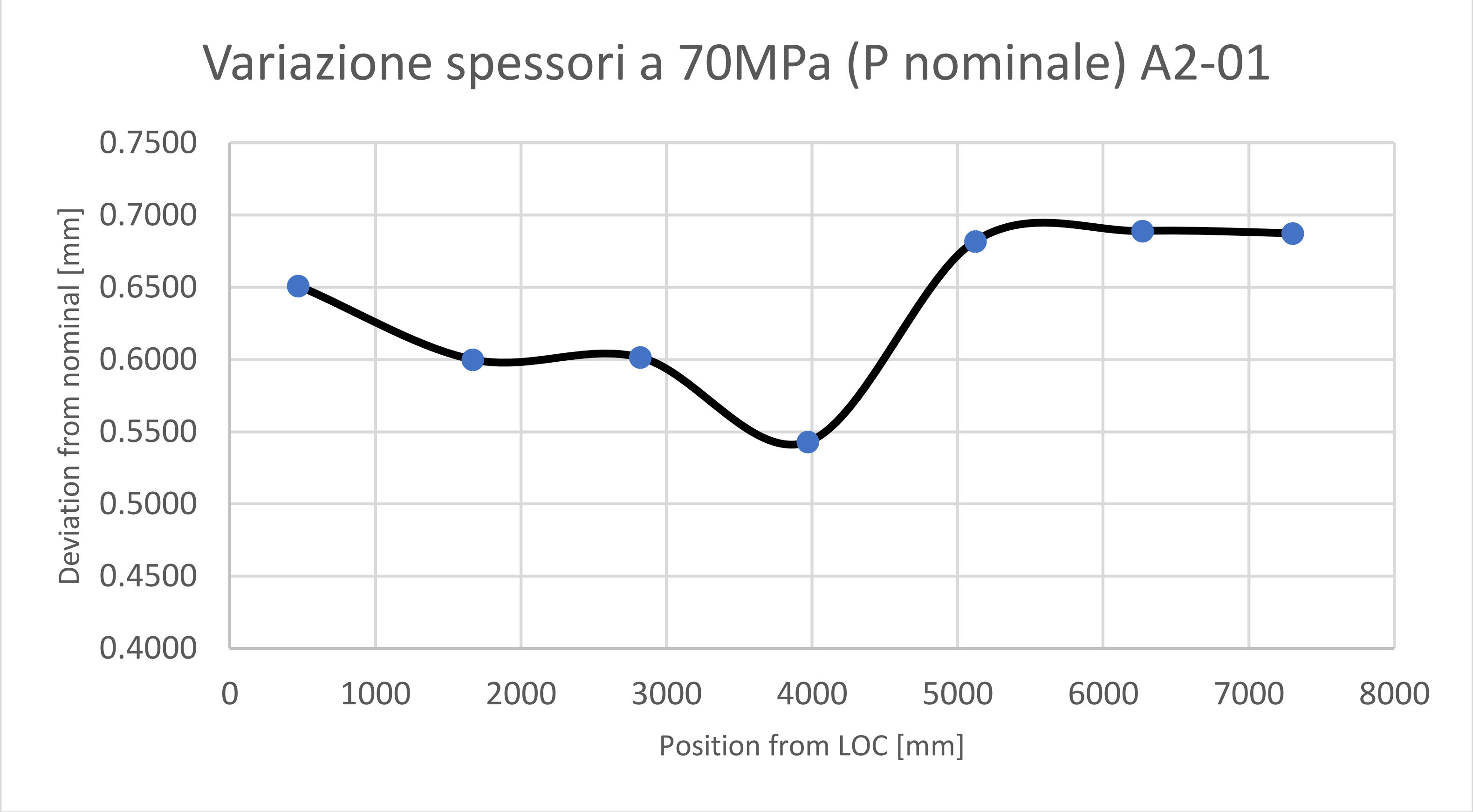
1. Coils layout (for accounting effects on field quality of deformations and coil ends)
2. Iron yoke (more circular for simplifying integration)
3. Poles of collars (now integrated with collars)
4. Conductor exits to avoid turn-to-turn shorts met with the short model
5. Collars in the connection side (for reinforcing the collars in this region)

Prototype NCs: Coil Azimuthal Size

- Prototype coils exceed nominal azimuthal dimension by 0.64±0.05 mm on average
- The dimensions are measured with a measuring press by applying several pressing cycles in 7 longitudinal points

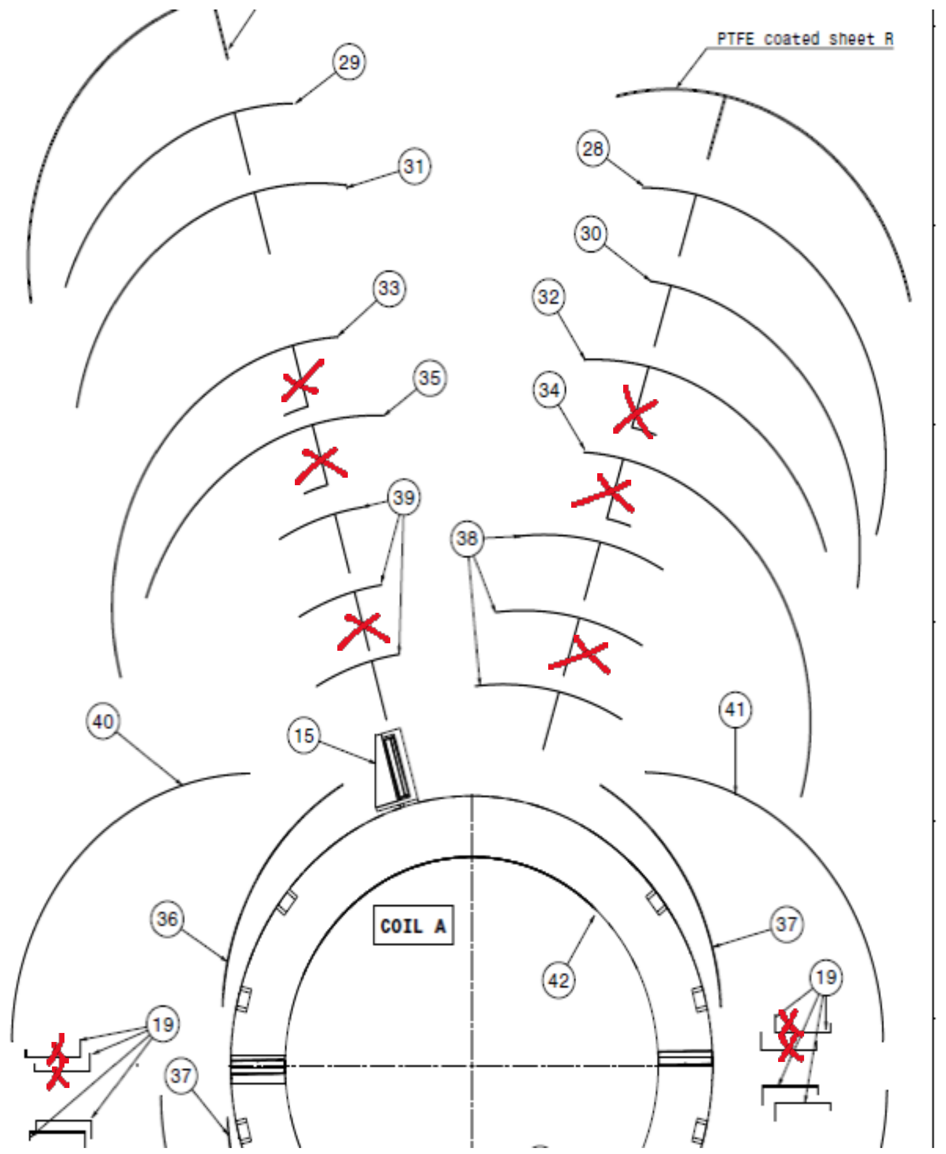
Coil	Min	Max	Average	
A-01	0.36	0.62	0.54	Spare coil
A1-02	0.55	0.8	0.7	Spare aperture
B1-02	0.55	0.72	0.66	Spare aperture
A1-01	0.54	0.71	0.64	aperture V1
B1-01	0.47	0.77	0.63	aperture V1
A2-01	0.54	0.69	0.64	aperture V2
B2-01	0.54	0.71	0.64	aperture V2





Prototype NCs: 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:



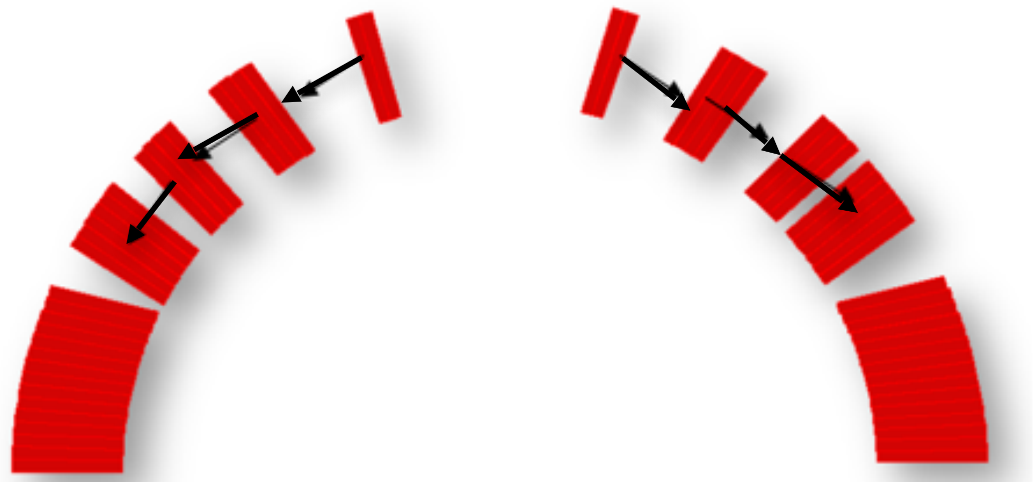
AP01	warm, I=18 A (calculated)	cold, Inom (calculated)	diff.	warm, I=18 A (measured)	cold, Inom (expected)
b2	-2.4	-5.6	-3.2	-2.9	-6.1
b3	-5.2	-4.9	0.3	7.6	7.9
b4	1.7	1.8	0.1	-0.4	-0.3
b5	6.1	6.3	0.2	11.3	11.5
b6	-0.2	-0.1	0.1	-1.5	-1.4
b7	2.1	2.5	0.4	1.7	2.1
b8	-0.9	-1.0	-0.1	-2.4	-2.5
b9	1.2	1.4	0.2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

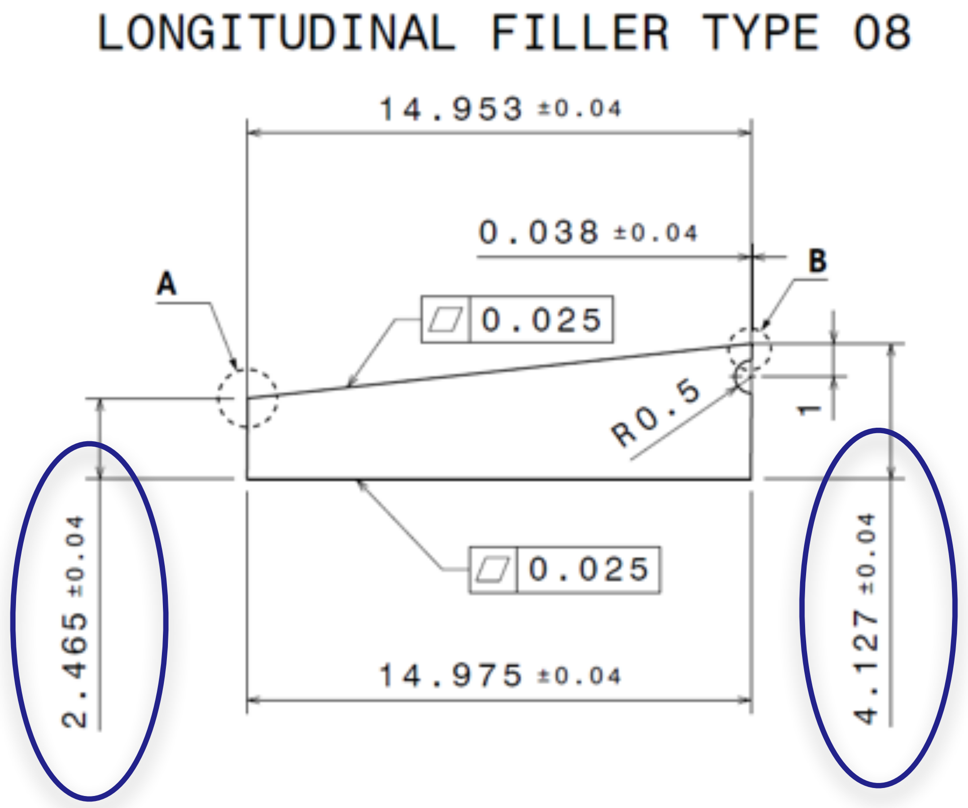
AP02	warm, I=18 A (calculated)	cold, Inom (calculated)	diff.	warm, I=18 A (measured)	cold, Inom (expected)
b2	2.4	5.6	3.2	-3.1	0.2
b3	-5.2	-4.9	0.3	8.6	8.9
b4	-1.7	-1.8	-0.1	-0.5	-0.6
b5	6.1	6.3	0.2	11.4	11.6
b6	0.2	0.1	-0.1	1.4	1.3
b7	2.1	2.5	0.4	2.3	2.7
b8	0.9	1.0	0.1	0.3	0.4
b9	1.2	1.4	0.2	0.8	1.0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

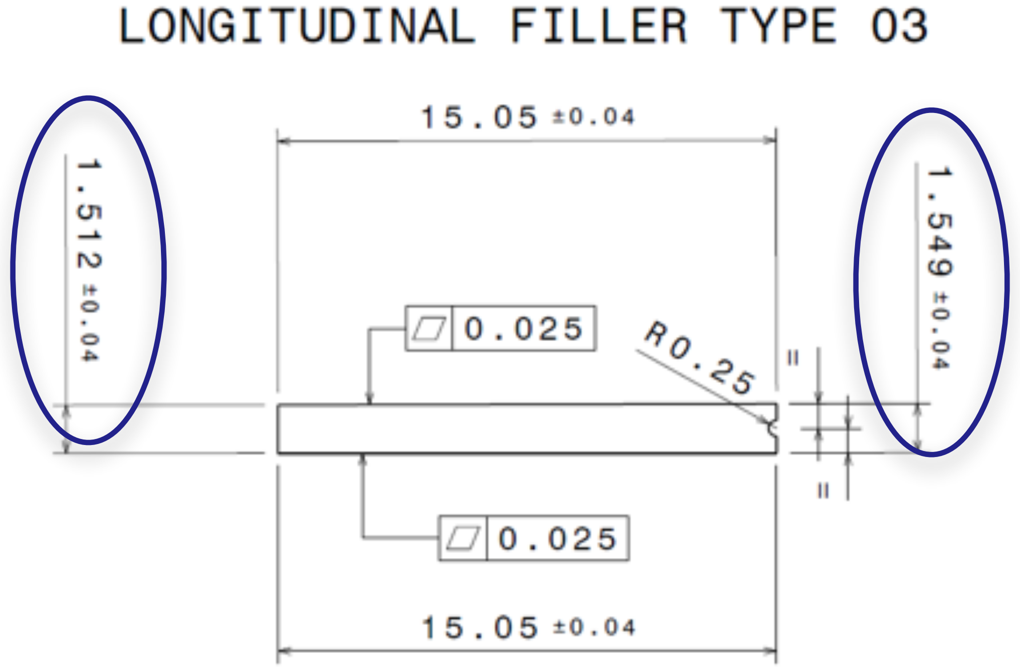
- b3 and b5 don’t fulfil requirements of field quality and mitigations actions are foreseen for the series

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







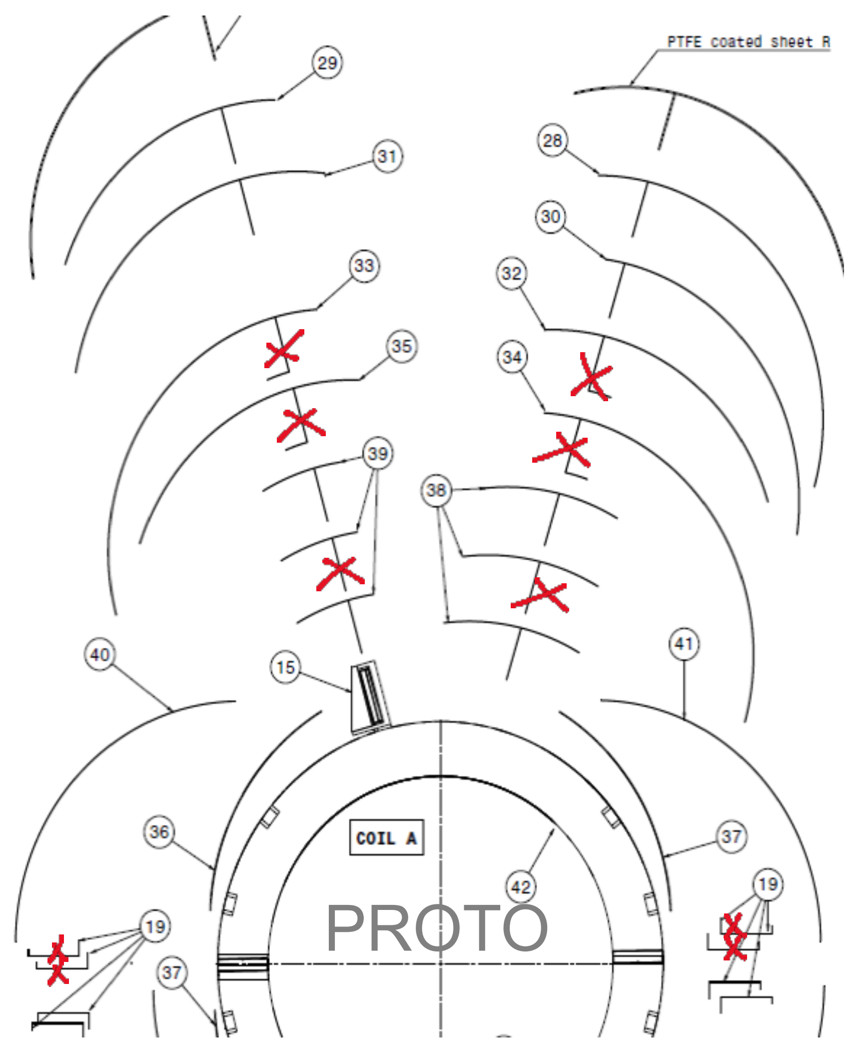
- Field quality is fine tuned restoring a 127 μm thick U shaped Kapton layer on the midplane
- The proposed change satisfactorily corrects b3 and b5 and has minor influence on the other harmonics

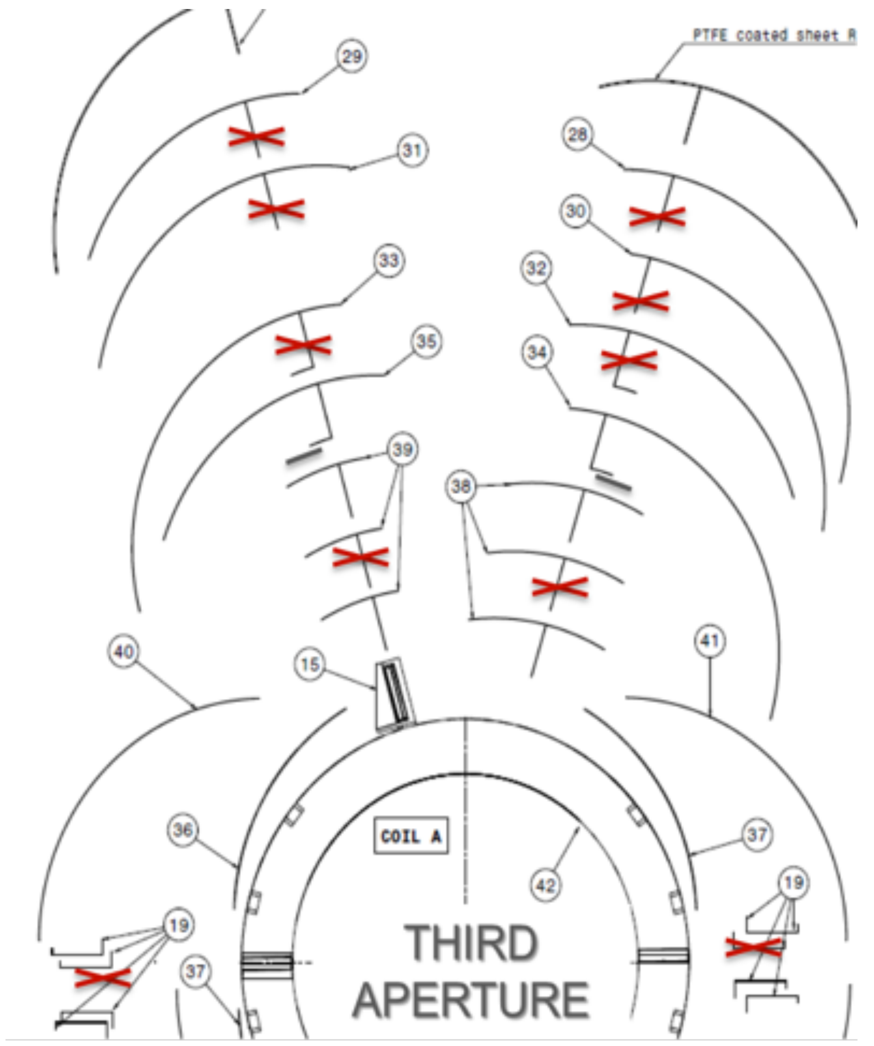
AP01	warm prototype (calculated)	cold series, Inom (calculated)	diff.	warm prototype (measured)	cold series, Inom (expected)
b2	-2.4	-6.7	-4.3	-2.9	-7.2
b3	-5.2	-15.5	-10.2	7.6	-2.7
b4	1.7	1.4	-0.3	-0.4	-0.7
b5	6.1	-3.5	-9.6	11.3	1.7
b6	-0.2	0.5	0.8	-1.5	-0.7
b7	2.1	1.5	-0.5	1.7	1.2
b8	-0.9	-1.0	-0.1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

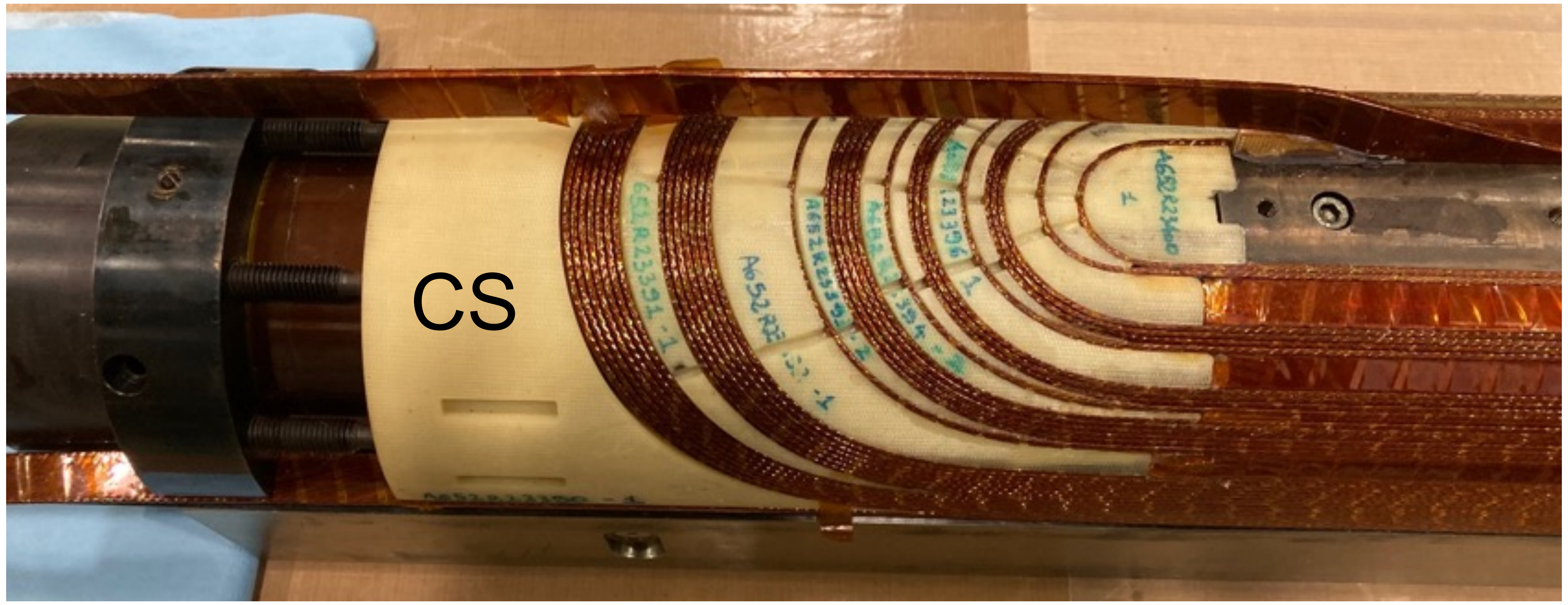
PROTOTYPE

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.

PRE-SERIES MAGNET: COIL AS-01



- A small production of the copper wedges type 2 and 8 (modified wrt prototype) was provided by LUVATA and used to produce the first coil of the pre-series magnet
- Coil AS-01 was wound and cured. The azimuthal dimension was measured and resulted to be 0.41 mm larger than nominal, about 0.24 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.
- 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

SUMMARY (I)

- The CERN/INFN agreement includes the fabrication of a short model, a prototype, 1 pre-series and 4+1 series magnets of the HL-LHC recombination dipoles
- The short model experienced few failures due to short circuits: because of one short, the first cold test at CERN was performed feeding only one of the 2 apertures and the subsequent inspection shown severe damages to the cable in the exit region.
- After the repairing, a second cold test was performed: both nominal and ultimate current were reached (even at 4.5 K),but still one coil shown loss of memory during the retraining.
- During the prototype construction, a misinterpretation of the azimuthal coil size was understood, leading to the awareness that the short model coil sizes were about 1.4 mm larger azimuthally than nominal. This could explain the failures during the short model tests.
- Corrective action were taken and implemented in the prototype (reduction of the midplane insulation and pole insulation thickness, usage of collar+poles system instead of removable poles, etc..)

SUMMARY (II)

- The prototype coils were still 0.6 mm larger than nominal (azimuthally) on average. To avoid excessive stress during collaring, the insulation scheme was modified by removing 0.6 mm of Kapton layers (both from the midplane and from the pole) The field quality was compromised by the change in the insulation scheme
- To improve the field quality and restore partially the Kapton insulation layers , the coil layout was optimised in view of the series, by modifying 2 wedges out of 10
- An intermediate insulation scheme configuration was successfully tested in the prototype 3rd aperture, showing a field quality in agreement with expectations
- The first coil of the pre-series magnet was found about 0.4 mm larger than nominal (so 0.25 mm smaller than the prototype), in agreement with what was expected with the new coil cross section
- 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

THANKS FOR YOUR ATTENTION