D2 design, short model manufacturing and test

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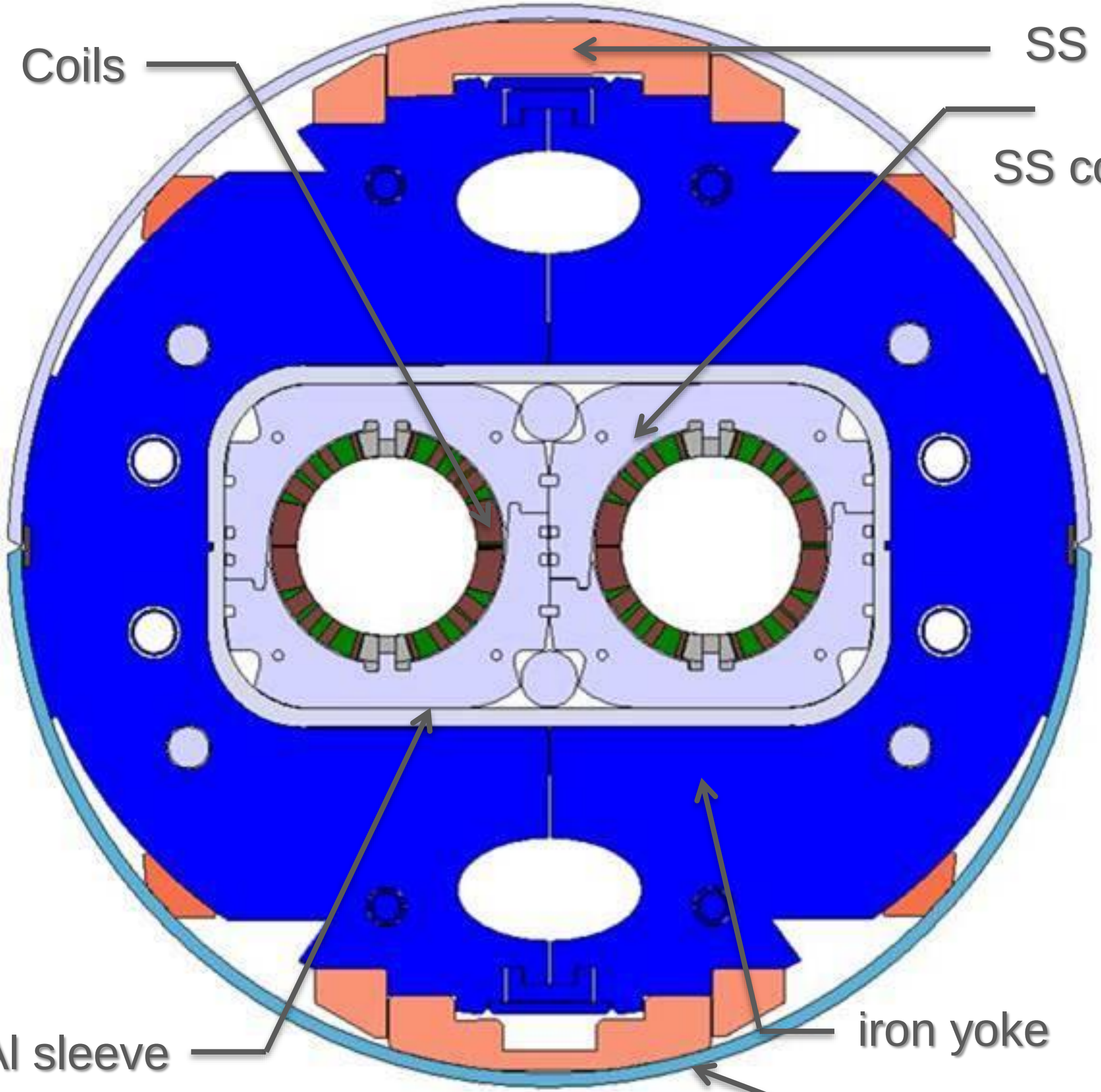
Outline

- Design of D2 magnet
- Short model (MBRDS1) construction at ASG Superconductors
- Short model (MBRDS1) test at CERN
- Prototype (MBRDP1): see P.Fabbricatore presentation

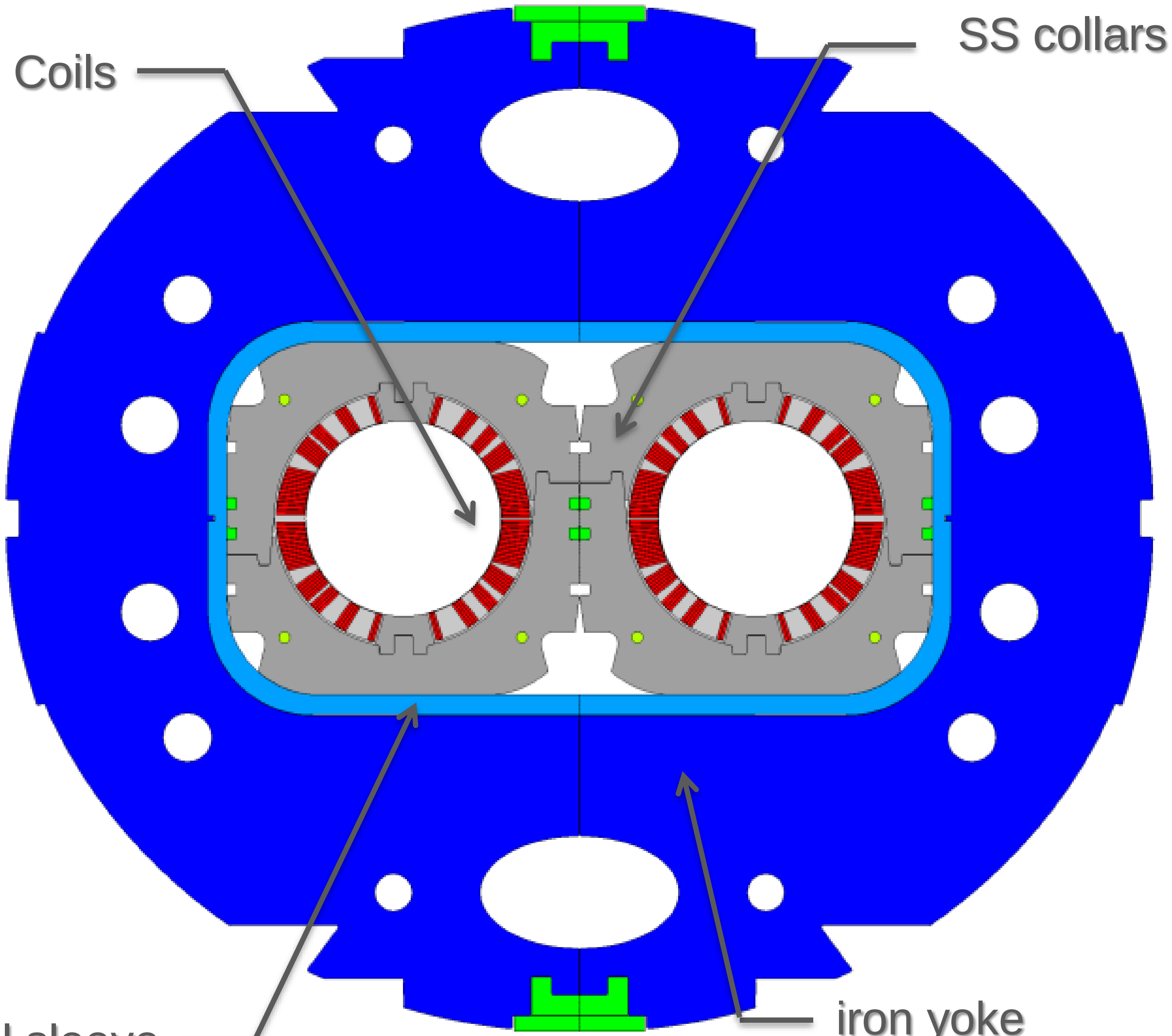
MBRDS1 design

The D2 prototype cross section



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
Magnet physical length	8.01 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

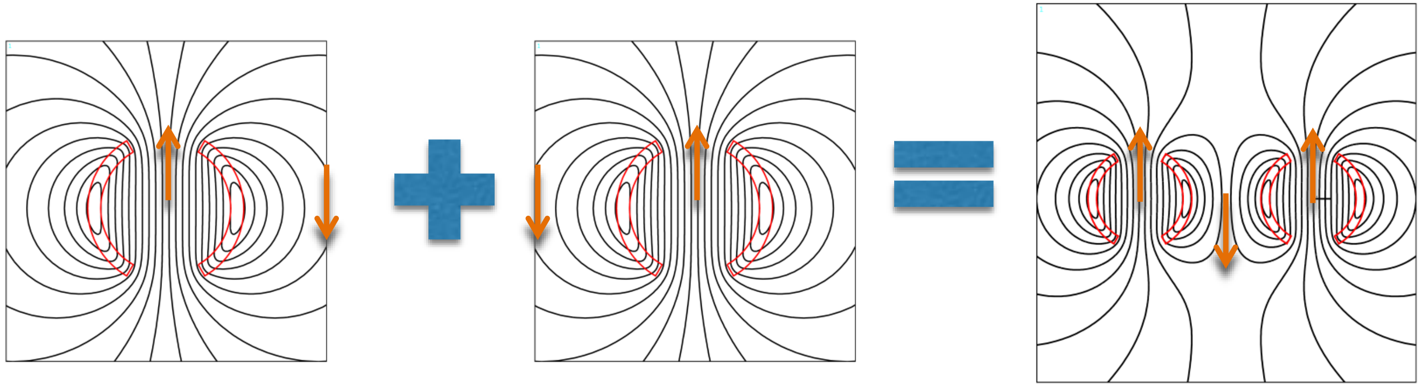
The D2 short model cross section



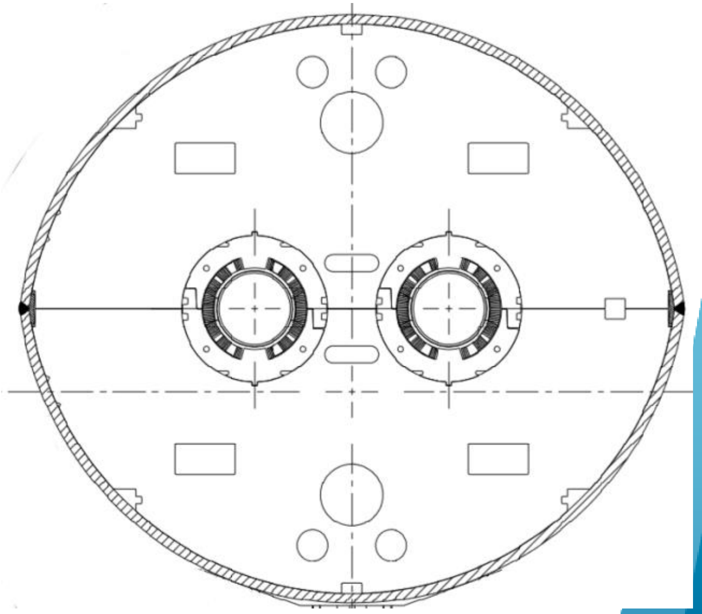
- The D2 short model scope of work does not includes magnet fillers and shell

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
Overall current density	479 A/mm^2
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

Electromagnetic model:

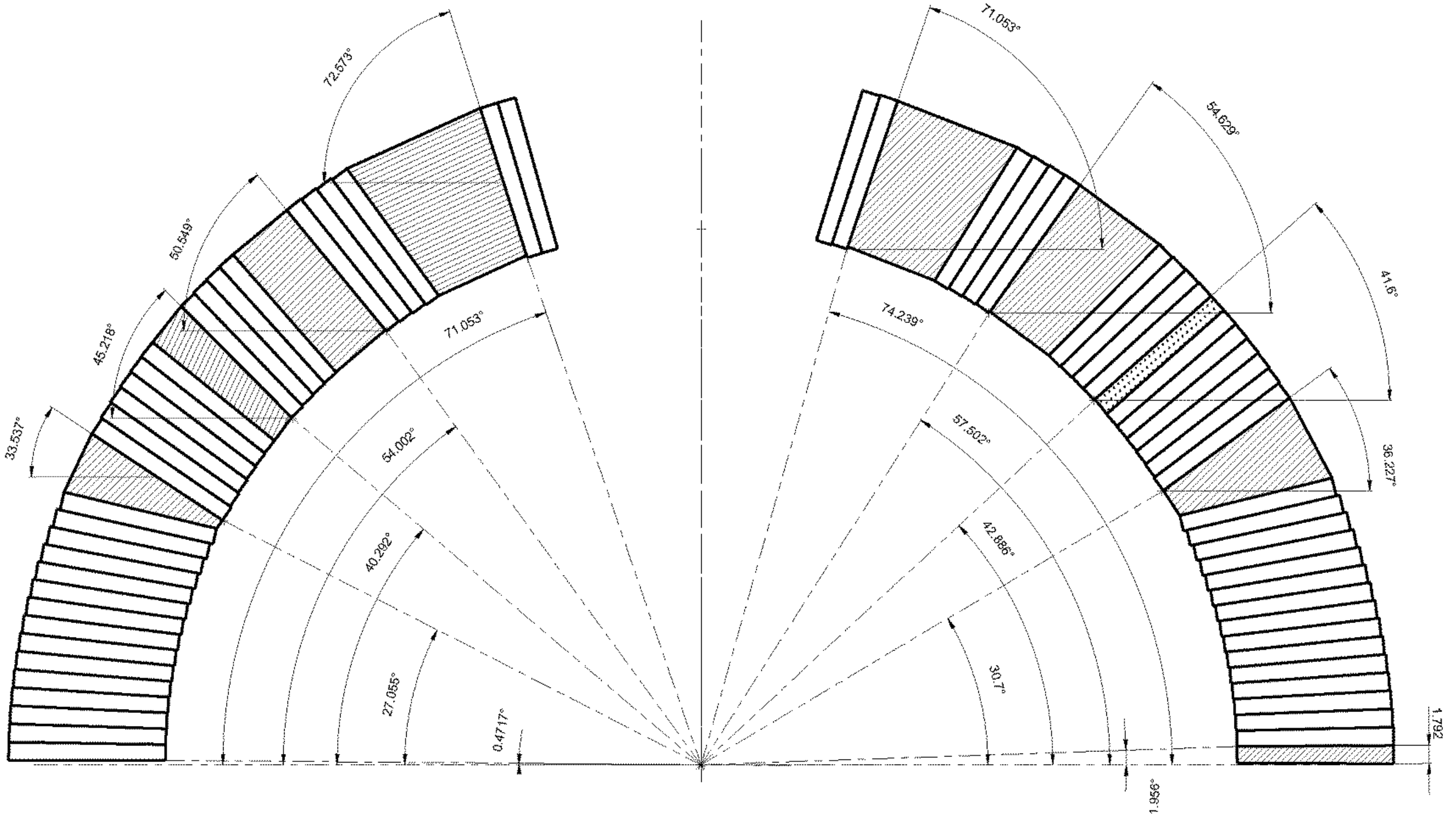


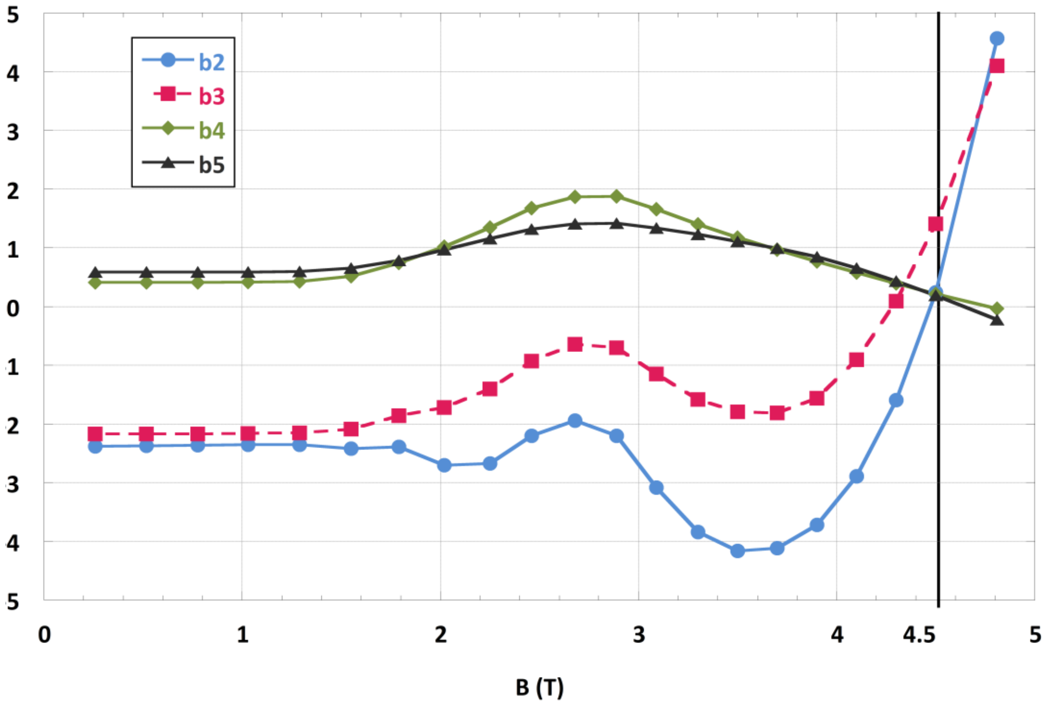
- in D2 magnet, magnetic fields in the two apertures are oriented in the same direction ➡ in the region between the two aperture the field adds up saturating the iron yoke (if any)
- the solution of LHC D2, to decouple the magnetic fields in the two apertures using iron yoke, is no more viable
- we decided to remove iron yoke between the aperture and tune the field quality via a-symmetric winding



Electromagnetic model

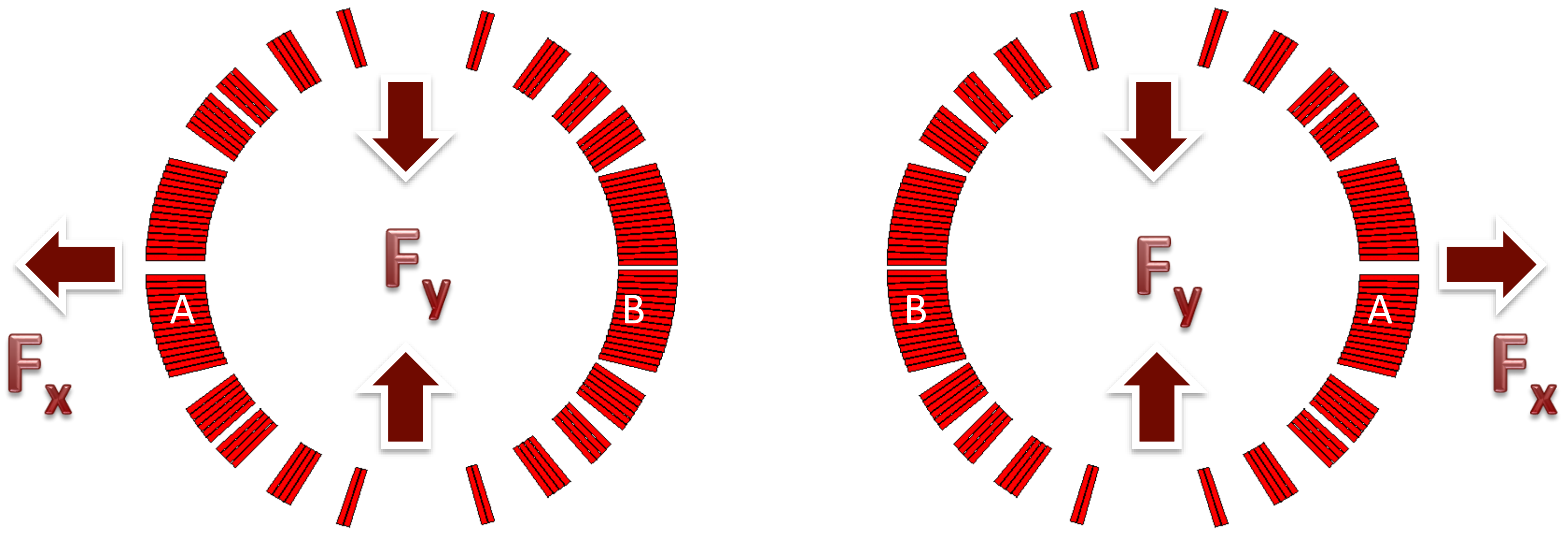
- both left and right branches of each coil are made by 5 blocks and 31 turns (15+6+4+4+2)





Lorentz forces at 4.5 T

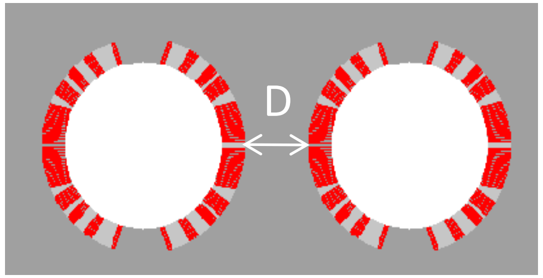
- F_x=196 kN/m and corresponds to the unbalance between the left and right part of each coil (F_{xA}=+1351 kN/m and F_{xB}=-1155 kN/m)
- Fy=-845 kN/m (F_{xA}=-433 kN/m and F_{xB}=-412 kN/m)



Mechanical design: considerations on collaring

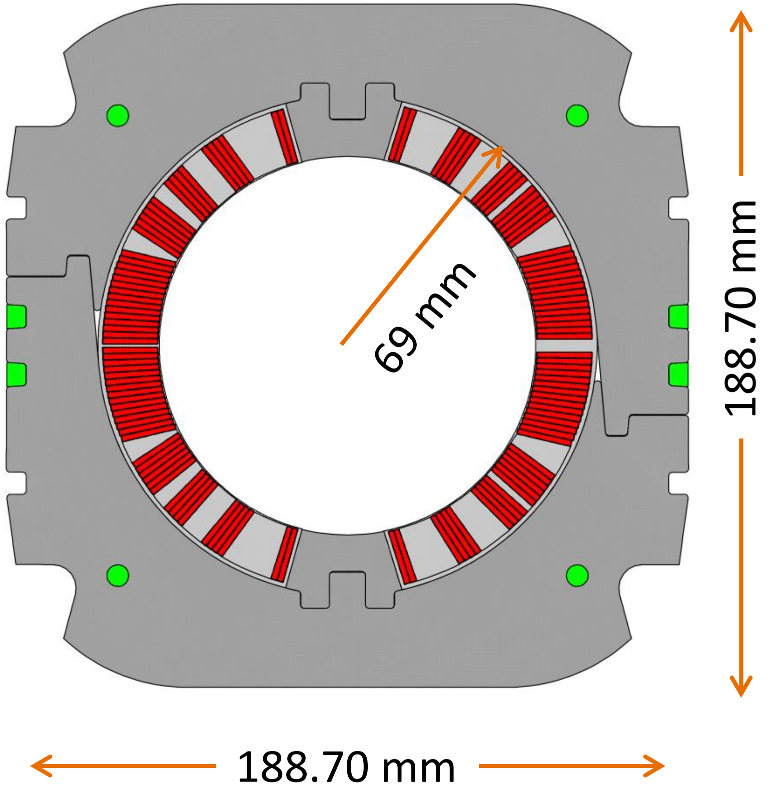
- to reduce the risks of the collaring operation we decided to
  - collar individually each aperture
  - design a fully symmetric collar

    ➡ the collar dimensions are determined by the (warm) distance D between the coils



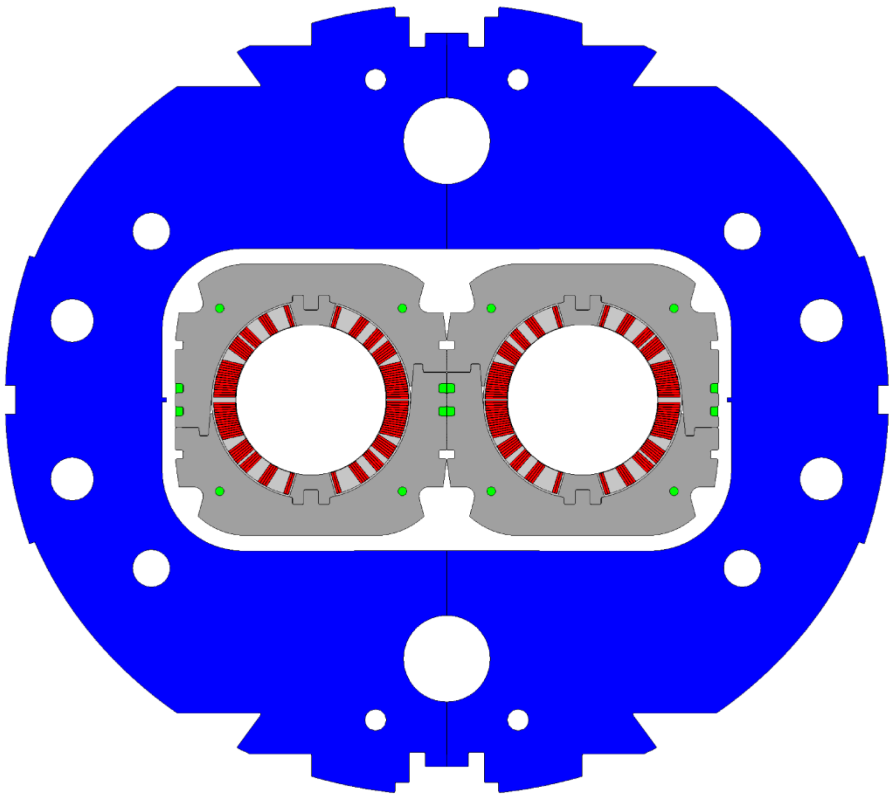
- the Lorentz forces being repulsive, we need a mechanical structure able to withstand them
- to preserve the field quality, we should avoid coils misalignments respect to one another and respect to the iron yoke
- the iron yoke being elliptical, it is preferable to give it no mechanical function
- we look for a solution where the collars have the main mechanical role, the iron yoke being almost a mere magnetic component

Mechanical design: collaring of a single aperture



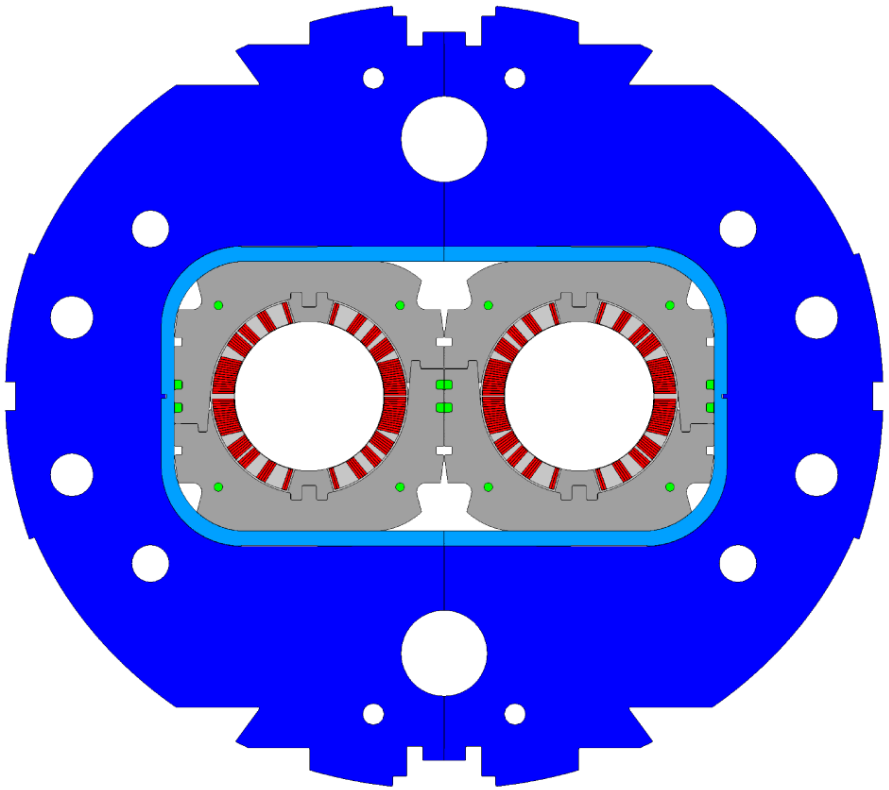
- to follow the iron yoke window, collars are squared
- the overall dimensions are 188.7×188.7 mm^2 (188.7 mm is the warm beam distance)
- the collar inner radius is 69 mm, so the thickness on the midplane is ~25 mm
- the nose is modular (this choice is not confirmed for the prototype)

Mechanical design: collared coils and iron yoke coupling



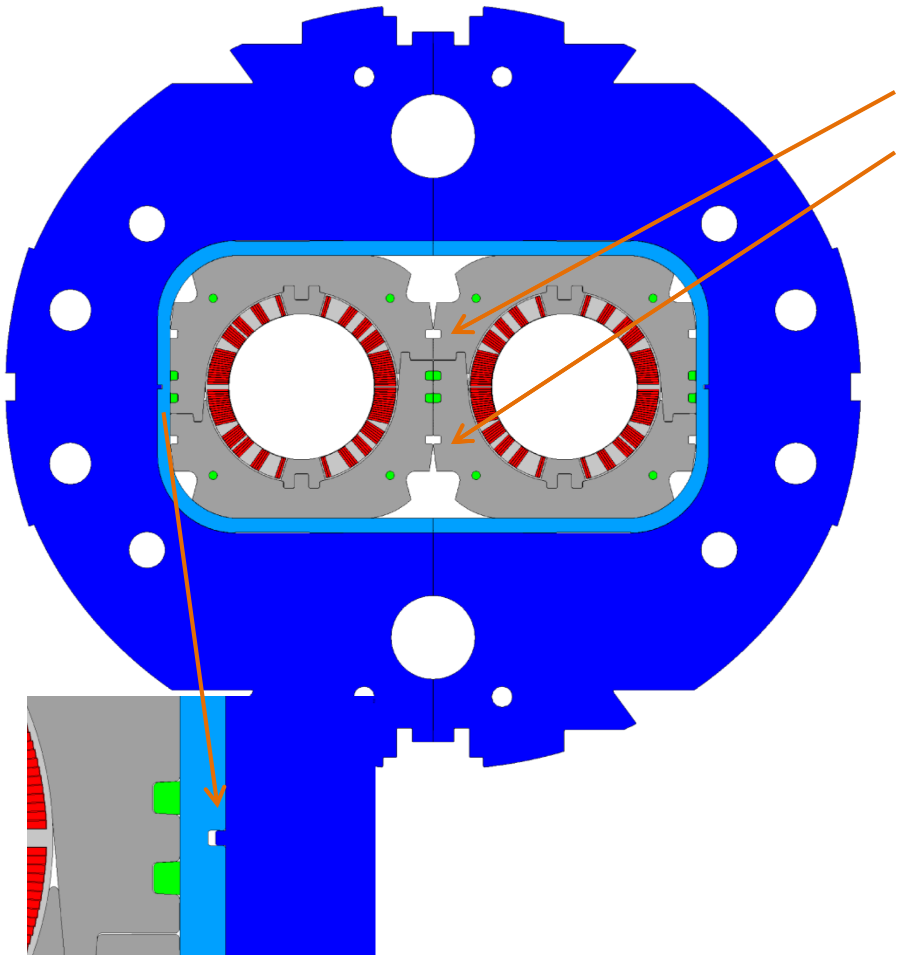
- once the collared coils are inside the iron yoke, there is a gap (9 mm thick on the midplane, and 10 mm thick axially)
- instead of simply filling this gap with inert materials, we decided to give it multiple mechanical functions

Mechanical design: aluminum alloy sleeve



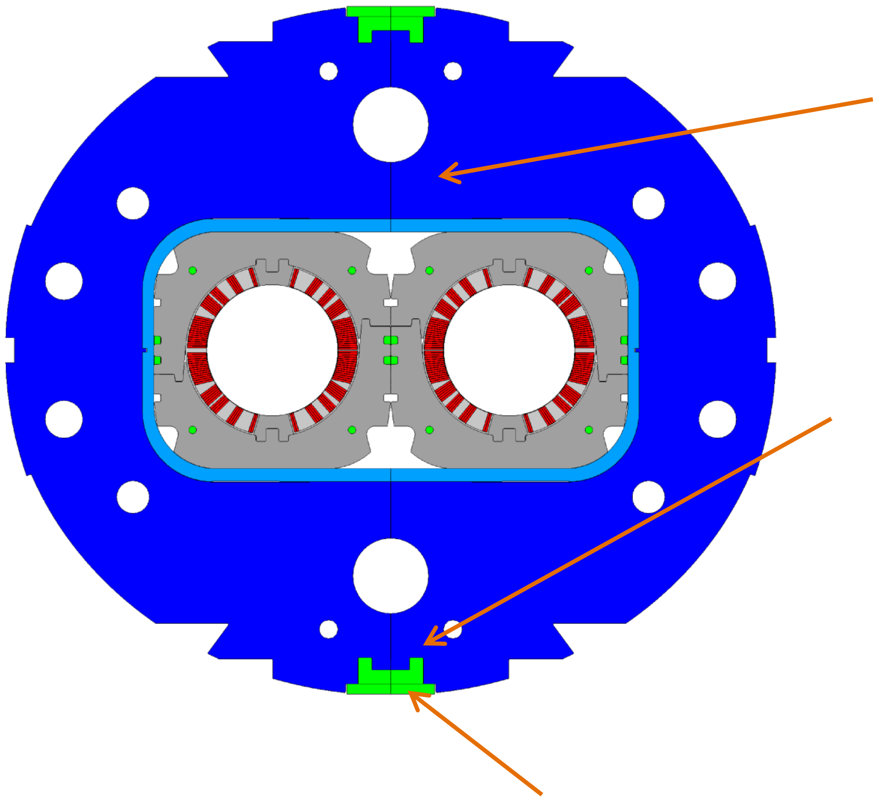
- to compensate the thermal contractions, the selected material is Al alloy ($\alpha_{Al\ alloy}$=4.3‰, α_{SS}=2.4‰, α_{iron}=1.8‰)
- the length of each Al alloy sleeves is 61 mm (to compensate longitudinal thermal contractions)
- to make the insertion possible, there is a warm gap 0.4 radially and 0.6 axially mm thick between collared coil and Al alloy sleeves (~closed at cold)
- this gap can be almost doubled by heating the sleeves

Mechanical design: aluminum alloy sleeve functions



- two small holes are used to align horizontally the coils at warm (no mechanical function)
- at cold the gap between Al alloy sleeves and collared coils closes. No movement of a coil with respect to the other is still possible
- a pin between iron an Al alloy sleeve keeps the vertical alignment

Mechanical design: iron yoke

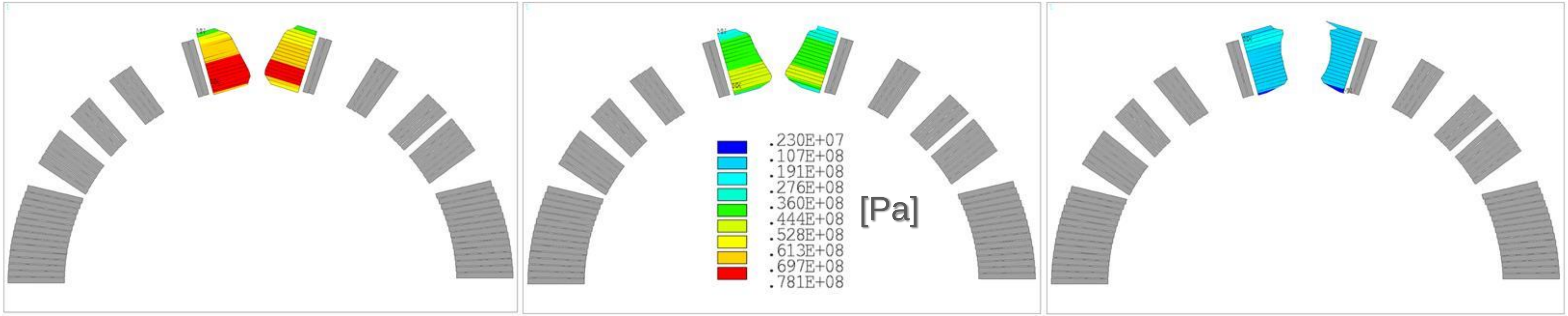


- the iron yoke has very limited mechanical function, it helps the Al sleeves in keeping the repulsive force between the aperture
- a 1.2 mm gap is closed at warm under pressure to allow the insertion of the C-clamps
- this mechanism ensures the horizontal alignment
- a continuous bar is then welded on the top of the C-clamps to give some longitudinal strength to the assembly

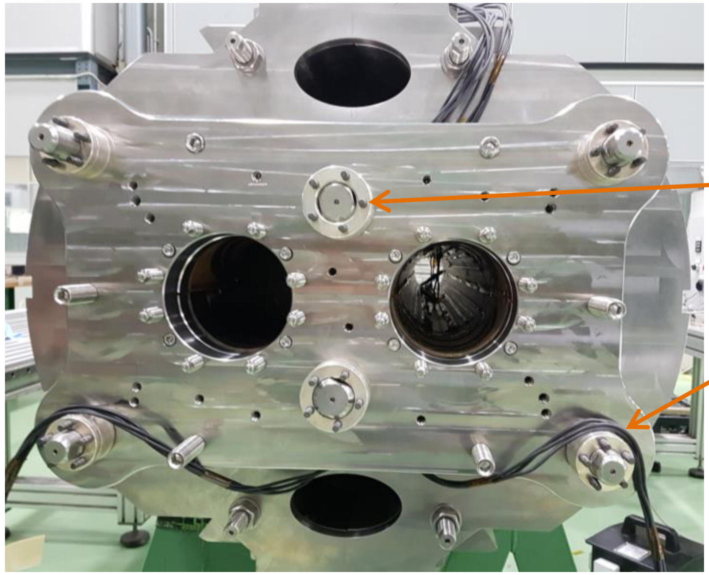
Resulting stress in winding

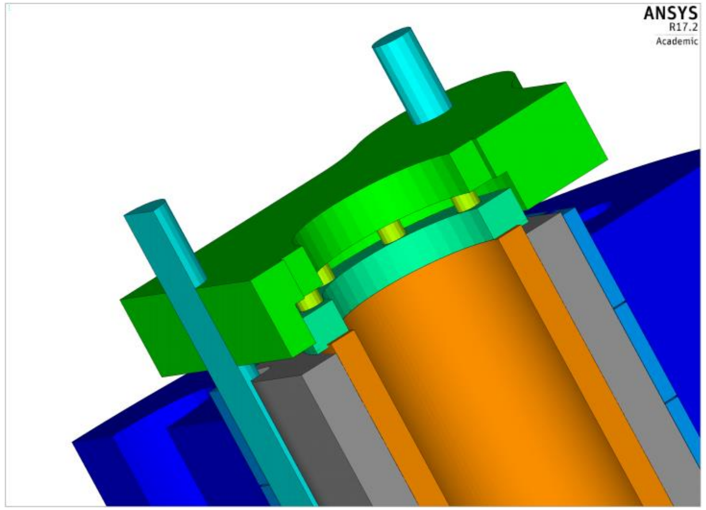
	$<\sigma_{eqv}>$ in conductors [Pa]	$<\sigma_\theta>$ in conductors [Pa]	$<\sigma_{eqv}>$ in windings [Pa]	$<\sigma_\theta>$ in windings [Pa]
collaring	86	-92	78	-82
collaring pressure relieved	74	-79	69	-72
yoke integration	75	-80	70	-73
cool-down	49	-49	44	-45
energization @ $I_{nominal}$	52	-53	43	-44
energization @ $I_{ultimate}$	53	-54	43	-45

assembly | cool down | energization @ $I_{ultimate}$



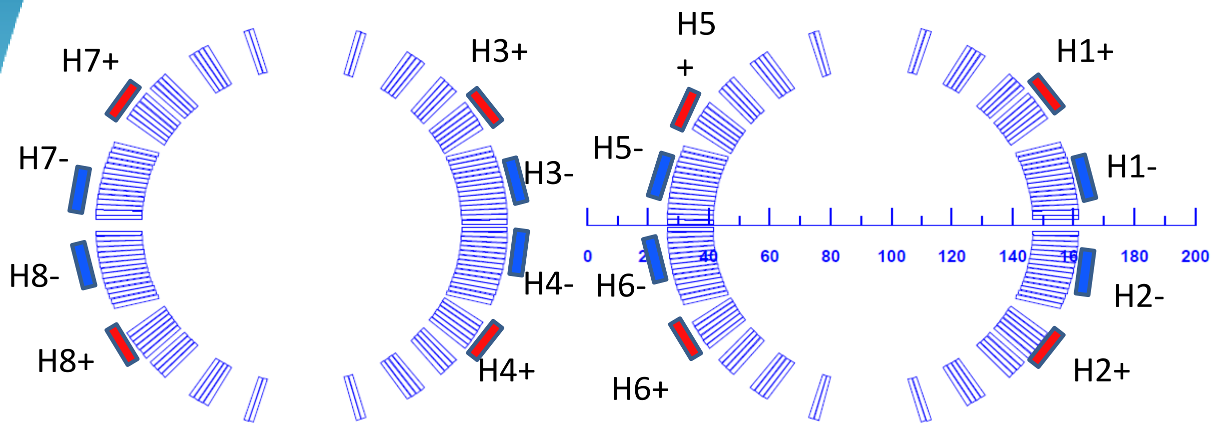
Mechanical concept: longitudinal preload

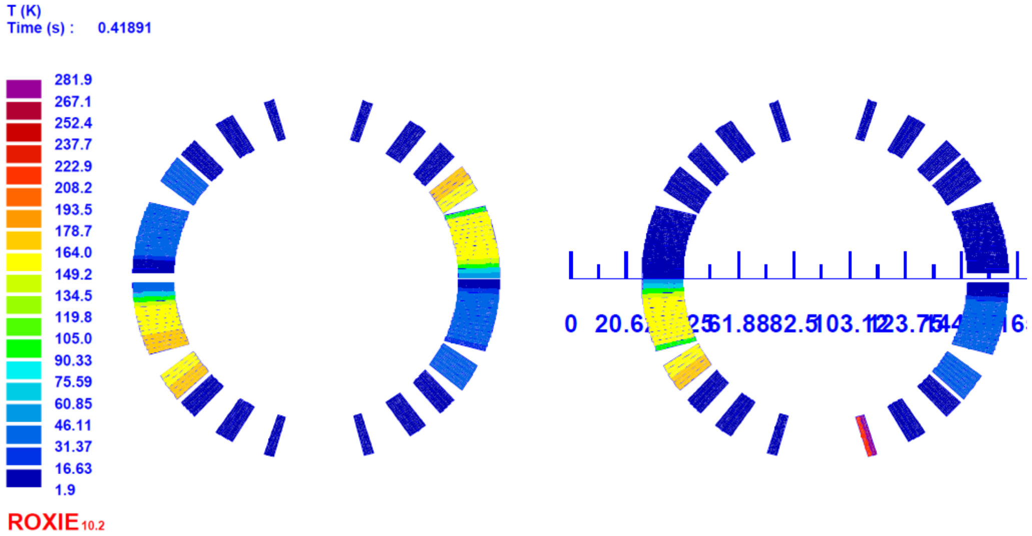


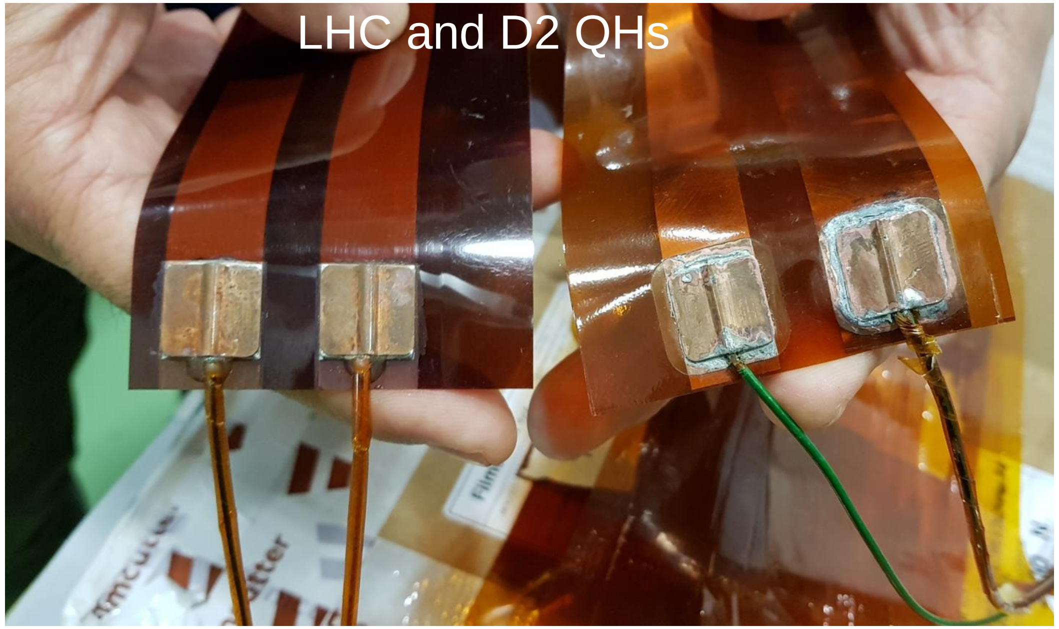


- longitudinal preload is supplied by 6 tie rods:
  - 2 central rods 33 mm in diameter
  - 4 side rods 24 mm in diameter
- the load is transferred to the coils through 16 bullet gauges per side acting on the end flange
- the total preload on the short model was 50% of the Lorentz force (125 kN) equally distributed on the ties rods

Quench protection with QHs





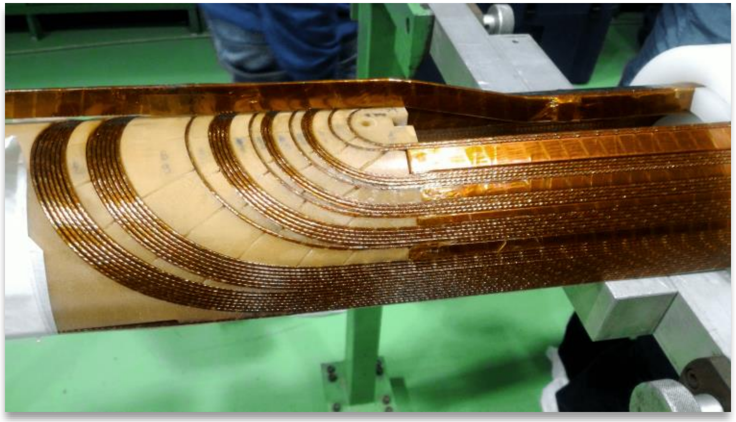


Operating mode	Max temp. (K) [<300 K]	Peak voltage to ground (V)	Peak turn-to turn voltage (V)
Standard Two circuits per aperture One circuit per coil working: 1,6,3,8→ All coils quench	**247**	**152**	**35**
Fail 1 One circuit fails (1) Three working : 6,3,8 → Three coils quench	**282**	**600**	**44**

MBRDS1 manufacturing at ASG

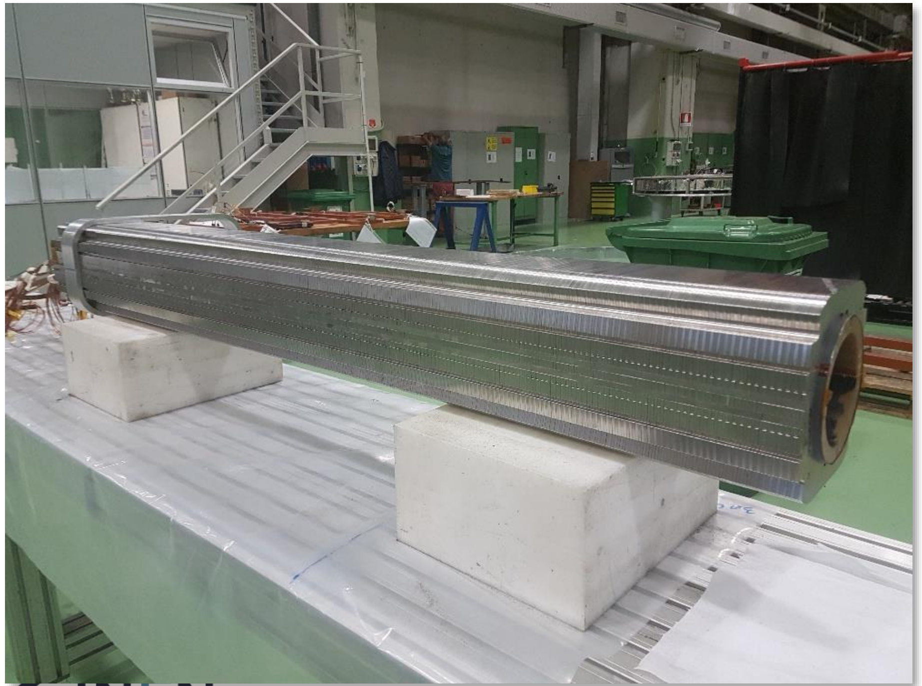
Winding activity

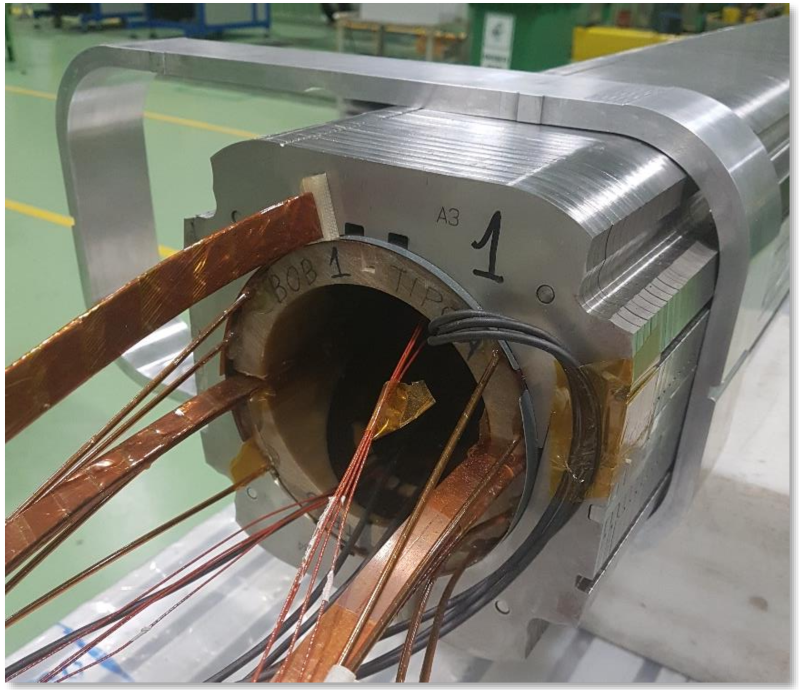
- Winding activity started on March 2018
- 1 practice pole (A01) and 3 standard poles (B01, A02 and B02) were successfully wound
- Winding activity was completed on June 2018
- The 4 poles passed all controls (coil resistance and inductance measurements, interturn insulation and ground insulation tests)



Collaring

- Collaring operations started at the beginning of August
- 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 in less than 2 hours





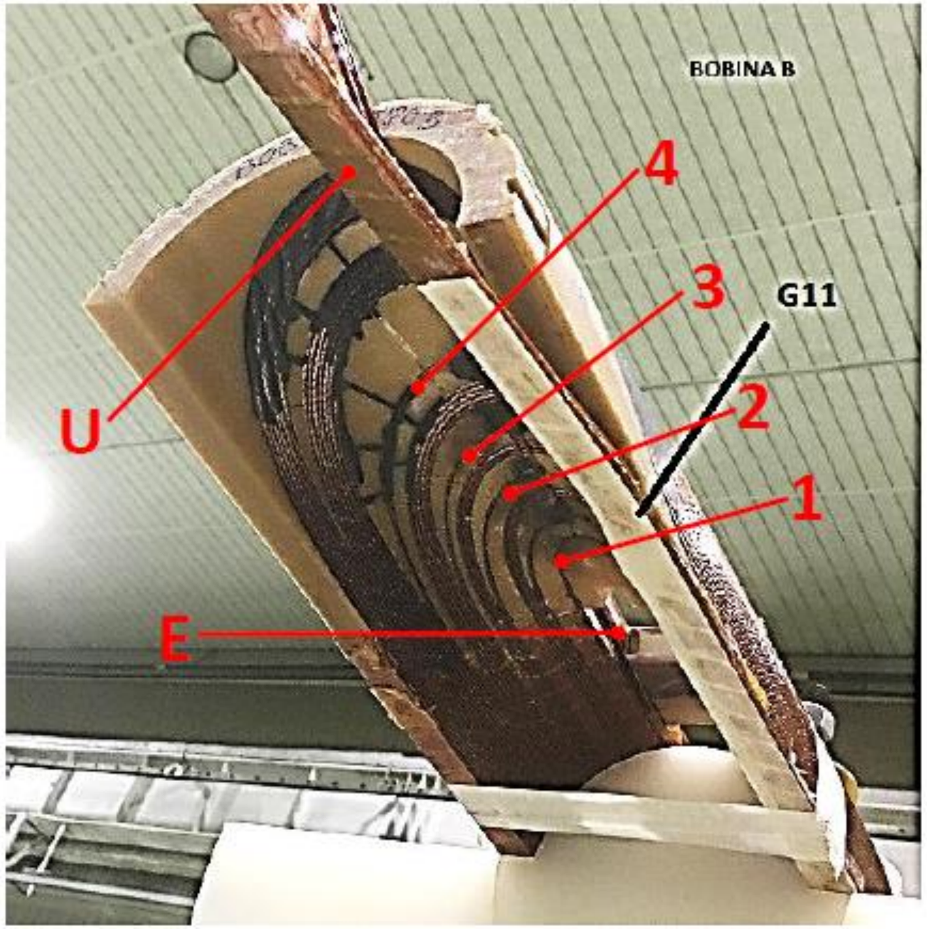
Non-conformity in aperture I:
refined electrical measurements

- Refined electrical measurements taking also advantages of the internal voltage taps:

VT id	A01 [mV]		A02 [mV]		B01 [mV]		B02 [mV]	
E\1	7,111	22,300	25,29	25,29	10,150	25,15	10,060	25,20
1\2	15,187				15,270		15,010	
2\3	15,827		15,900		15,880		15,650	
3\4	24,750		24,900		24,940		24,480	
4\U	70,900		71,400		71,600		71,000	
Somma	133,775		137,490		137,840		136,200	
Tot mis	133,7		137,3		137,3		136,7	

I=1.000A 0\+0.008

mV \ spira (media) 4,429032

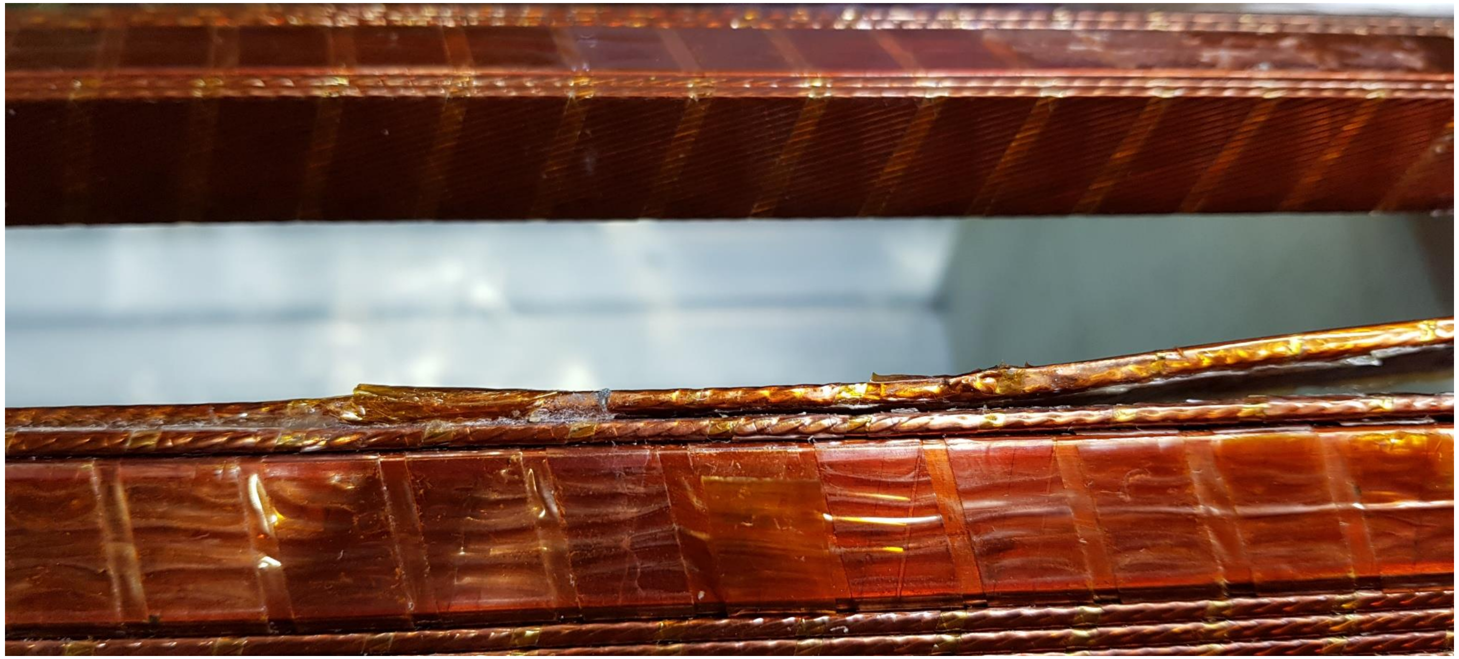


- about 3 mΩ missing at E/1confirmed the presence of a short in the 5th block
- a non-conformity was issued due to an evidence of short in coil A01

Re-collaring of aperture I

- Aperture I was de-collared, but no evidence of shorts could be found:

- ASG thought the reason could be a metallic chip, residue of the copper stabilizer soldering, lost after de-collaring



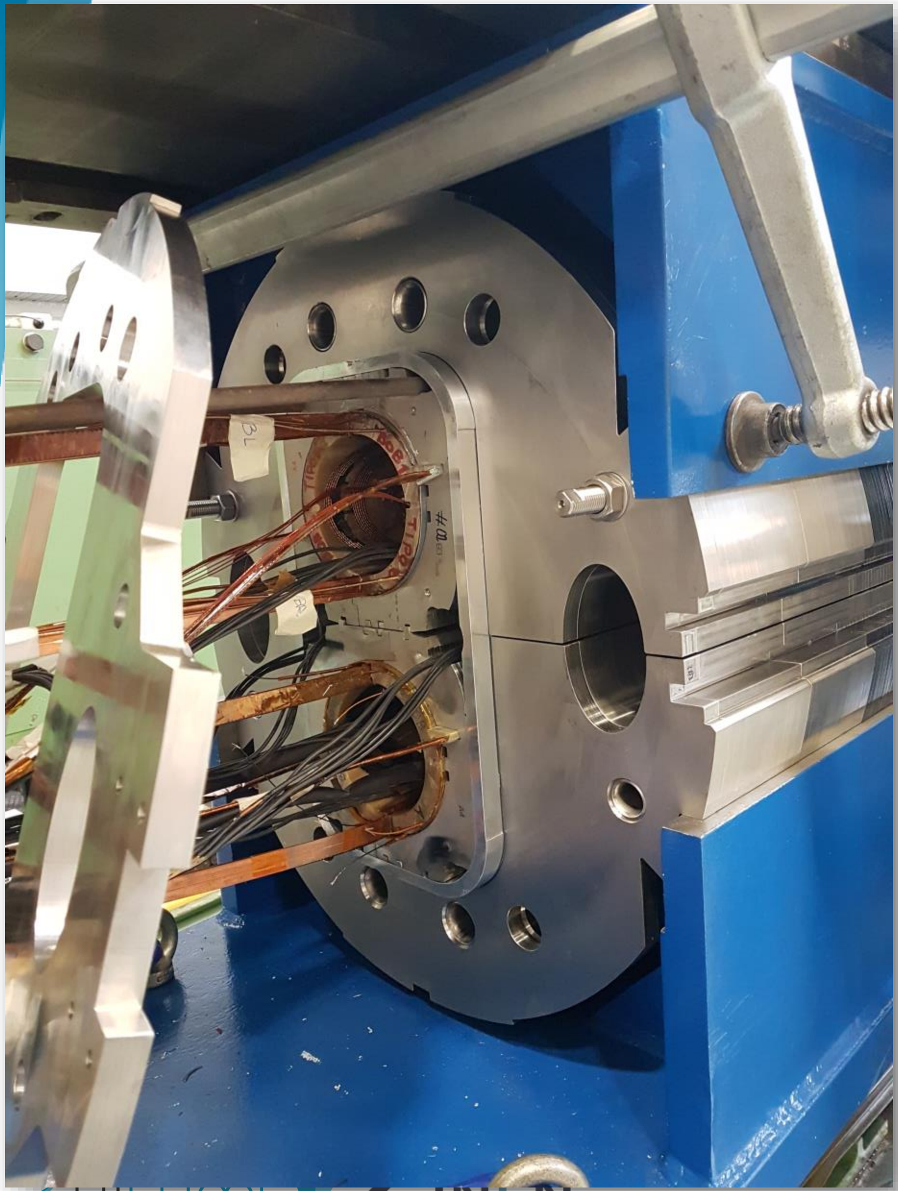
- To stay on the safe side, it was decided to unglue the two turns of the fifth block, then insulate, glue (with resin) and re-collar

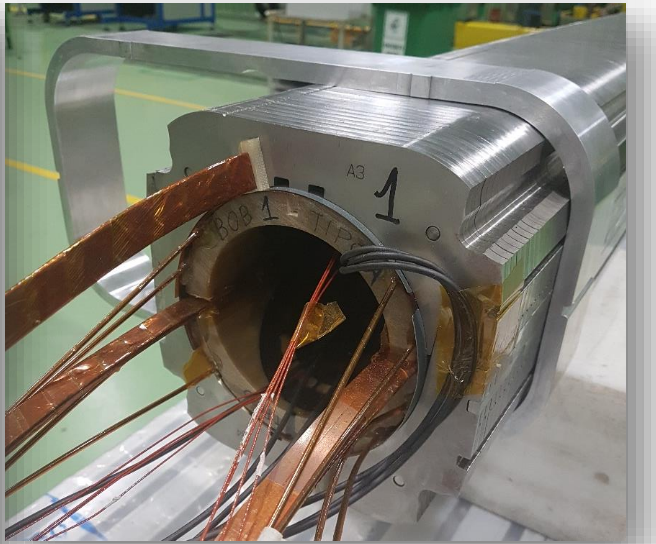
Field quality measurements of collared apertures

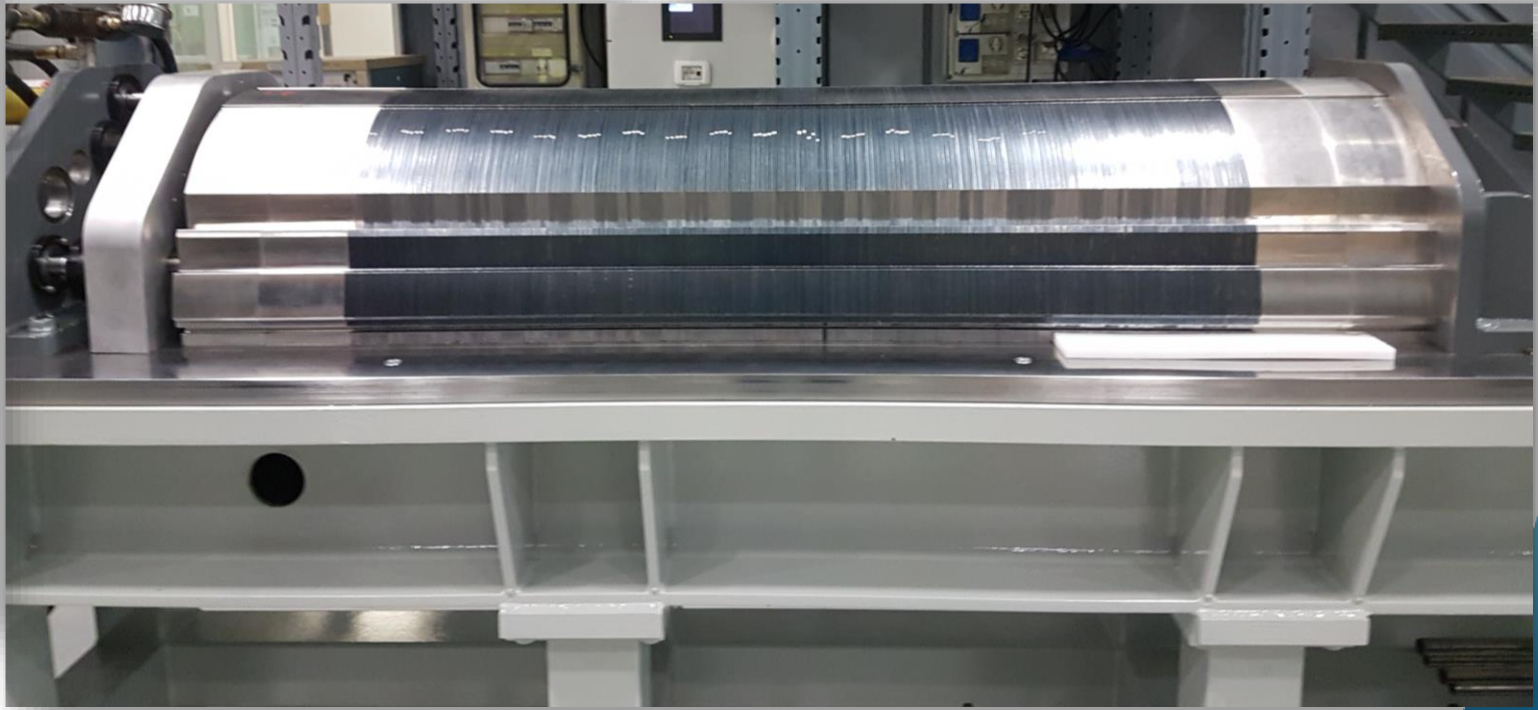
- Magnetic mesurements on single aperture, straight section @ 50A:

			b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	b15
I	**meas. @ 50 A**		-195	181	-35.0	6.7	-3.9	0.0	-1.0	0.8	0.0	-1.2	-1.1	-1.2	-0.8	-0.5
	simulations		-208	169	-37.2	0.7	-1.6	-0.1	-0.6	0.1	-0.1	-2.1	-1.9	-2.0	-1.0	-0.8
II	**meas. @ 50 A**		187	178	35.7	9.0	4.4	0.8	-0.8	0.5	0.0	-2.3	3.5	-1.7	1.7	-0.9
	simulations		208	169	36.8	0.7	1.9	-0.1	0.4	0.1	0.1	-2.1	1.9	-2.0	1.1	-0.8
		a1	**a2**	**a3**	**a4**	**a5**	**a6**	**a7**	**a8**	**a9**	**a10**	**a11**	**a12**	**a13**	**a14**	**a15**
I	**meas. @ 50 A**	0.0	-4.4	-0.6	0.8	2.5	0.5	1.5	0.0	0.0	0.0	0.3	0.4	0.5	1.0	0.5
	simulations	-1.9	0.2	-0.3	0.0	-0.1	-0.1	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
II	**meas. @ 50 A**	0.0	-6.0	-5.4	-1.2	0.9	1.5	1.7	0.6	-0.3	0.0	-1.8	0.1	0.1	0.2	0.5
	simulations	-1.1	0.1	0.2	0.0	0.0	-0.1	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0

Al Alloy sleeves and iron yoke assembly







Short model warm magnetic measurements: normal components

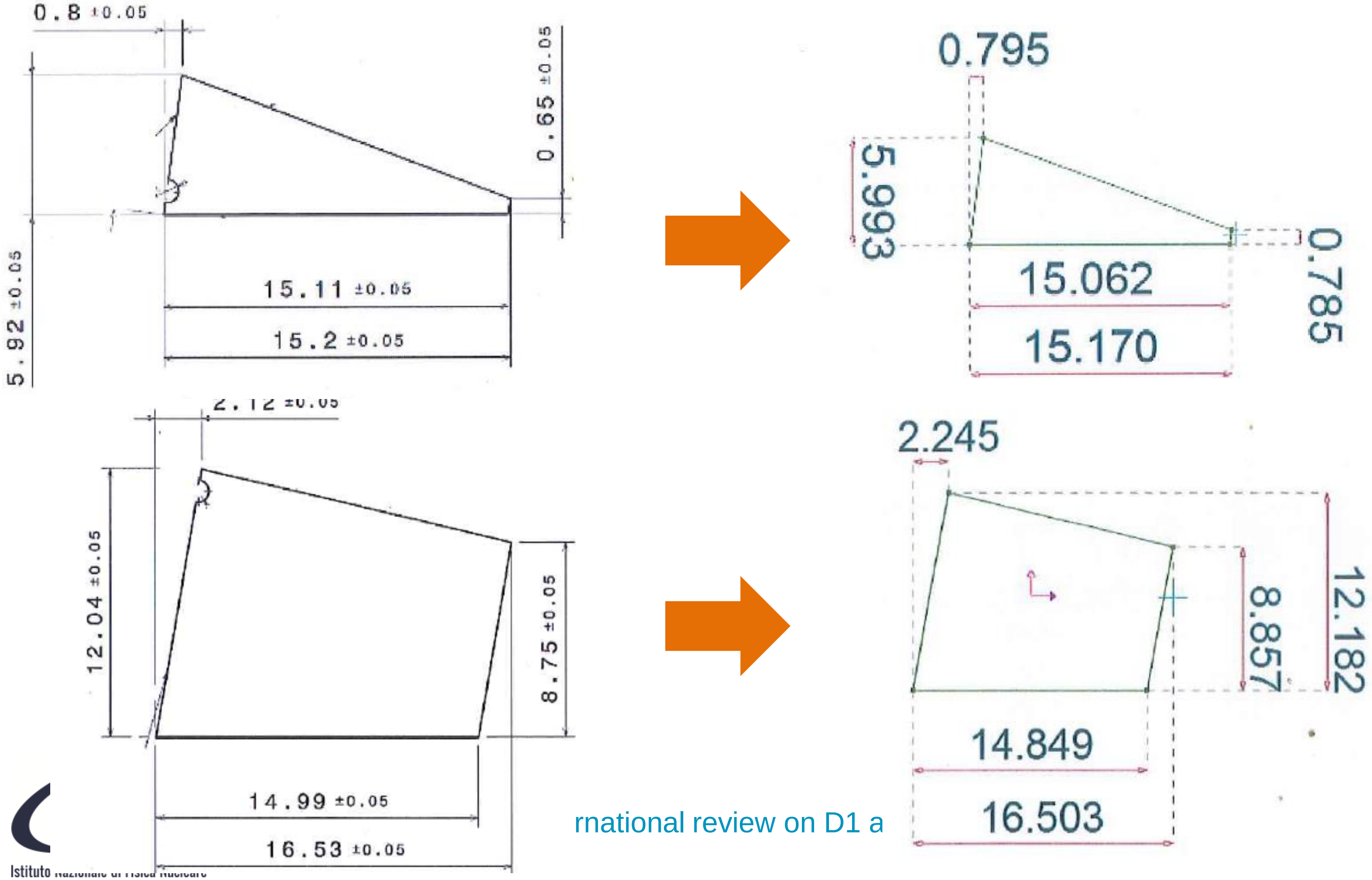
- main issues are related to b_2, b_3 and b_5
- coil end components are in good agreement with simulations

Aperture 1	LC	straight	LOC	Integrals	Integrals extrapolated to 8 m
C1 (gauss)	**105.4**	**207.6**	**101.2**		
b1	10000	10000	10000	10000	10000
b2	48.7	12.8	64.2	36.0	17.0
b3	17.2	9.2	17.2	13.5	9.9
b4	-7.5	2.1	-0.8	-1.3	1.5
b5	12.9	6.9	0.3	6.8	6.9
b6	-3.7	-1.7	-4.3	-2.9	-1.9
b7	-4.7	-0.3	-8.1	-3.6	-0.9
b8	-0.8	-0.7	-1.7	-1.0	-0.8
b9	-1.4	0.6	-2.8	-0.8	0.3
b10	0.0	0.0	0.0	0.0	0.0
b11	-1.4	-1.1	-1.7	-1.3	-1.1
b12	-0.7	-1.2	-0.6	-0.9	-1.2
b13	-0.7	-0.9	-0.8	-0.8	-0.9
b14	0.0	-0.6	-0.5	-0.4	-0.6
b15	0.0	-0.4	-0.5	-0.3	-0.4

Aperture 2	LC	straight	LOC	Integrals	Integrals extrapolated to 8 m
C1 (gauss)	**104.3**	**207.6**	**100.0**		
b1	10000	10000	10000	10000	10000
b2	-40.5	-9.4	-60.1	-31.0	-13.3
b3	17.7	10.0	17.0	13.9	10.7
b4	11.9	-0.4	2.9	3.8	0.4
b5	13.3	9.3	3.5	8.9	9.2
b6	5.9	1.7	1.4	2.7	1.9
b7	-3.2	0.0	-7.5	-2.8	-0.5
b8	0.8	-0.2	-0.5	0.0	-0.2
b9	-1.6	0.8	-2.8	-0.8	0.5
b10	0.0	0.0	0.0	0.0	0.0
b11	-1.1	-0.5	-0.2	-0.6	-0.5
b12	1.5	2.0	1.9	1.8	1.9
b13	-0.3	0.6	-0.3	0.1	0.5
b14	1.4	0.1	1.2	0.7	0.2
b15	0.1	0.4	-0.8	0.0	0.3

2D model including mechanical effects of “real” cross section

- the field quality is calculated starting from the conductor positions coming from a mechanical analysis where the worst “as built” wedges have been modeled



Normal components in the straight part compared to FE calculations

- Cu wedges out of tolerance accounts quite well for all variations except b_2
- running a special optimization using roxie, we verified that block layouts with large b_2 do exist with wedge variations within 200 μm
- we are still investigating other realistic source of b_2 deviation
- we need a confirmation of ASG magnetic measurements

		b2	b3	b4	b5	b6
I	**meas. @ 50 A**	12.8	9.2	2.1	7.0	-1.7
	2D nominal	-2.4	-2.2	0.4	0.6	0.0
	2D FEA mechanics	-2.6	0.8	0.7	2.7	-0.1
	2D FEA mechanics+real wedges	0.9	11.5	0.3	3.2	-1.0
II	**meas. @ 50 A**	-9.4	10.0	-0.4	9.3	1.7
	2D FEA nominal	2.4	-2.2	-0.4	0.6	0.0
	2D FEA mechanics	2.6	0.8	-0.7	2.7	0.1
	2D FEA mechanics+real wedges	-0.9	11.5	-0.3	3.2	1.0

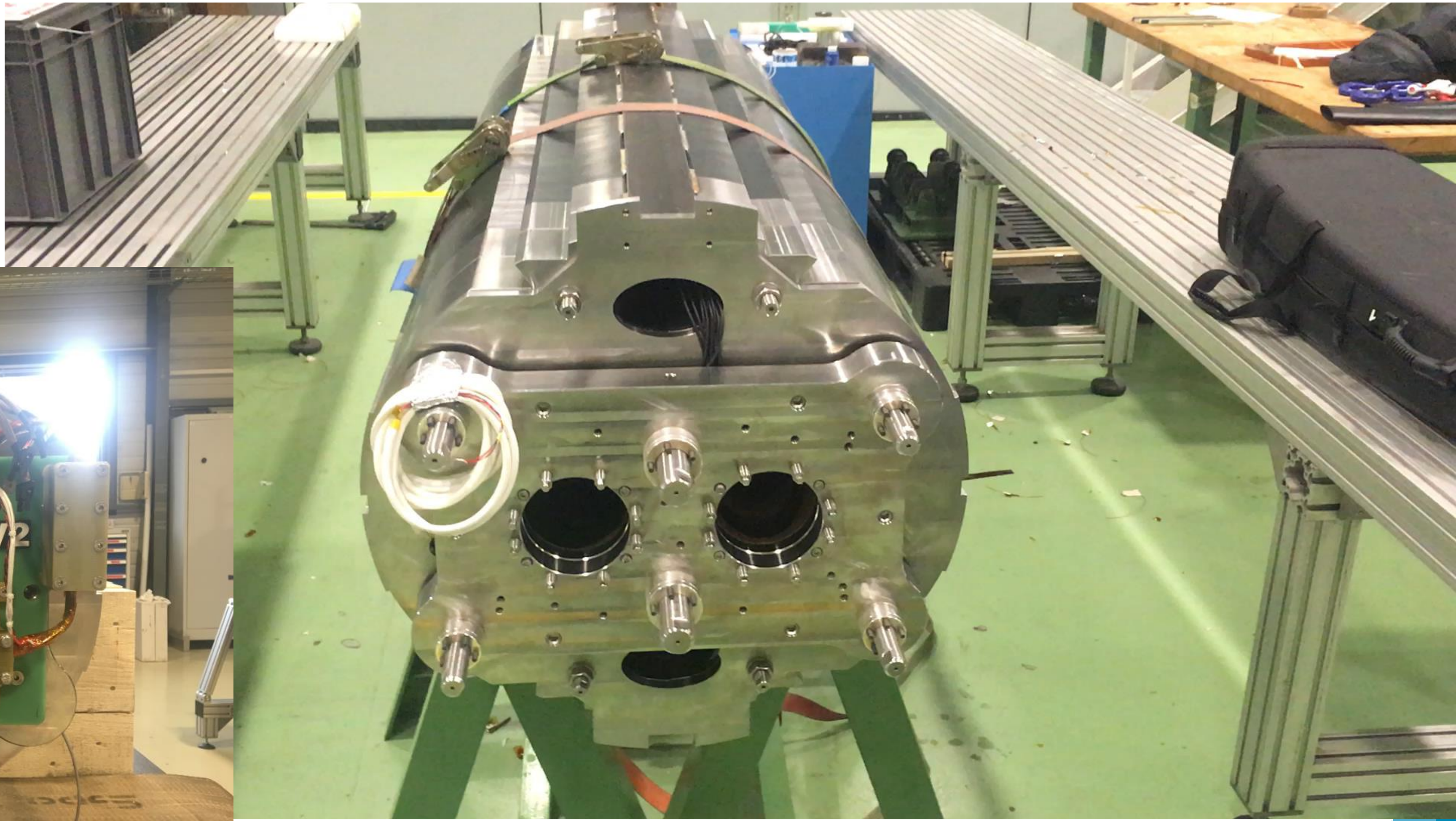
Short model warm magnetic measurements: skew components

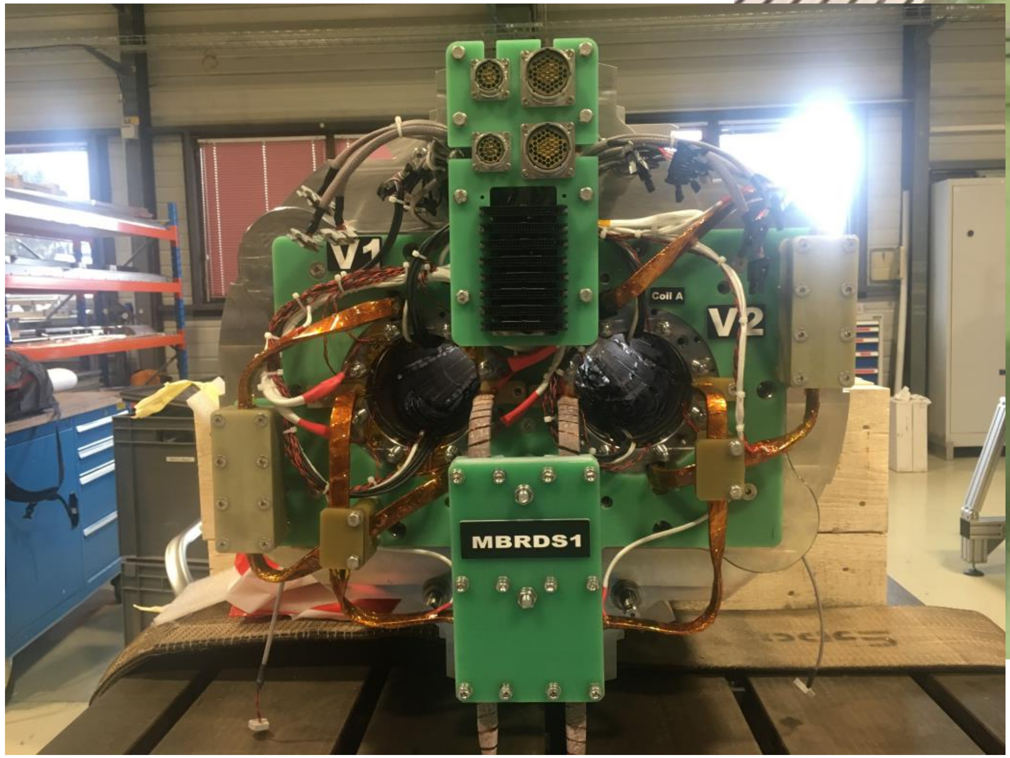
- large skew components on the connections side are possibly due to very long exits and wiring

Aperture 1	LC	straight	LOC	Integrals	Integrals extrapolated to 8 m
C1 (gauss)	105.4	207.6	101.2		
a1	2.0	0.9	3.1	1.8	1.1
a2	17.3	2.4	8.8	8.2	3.5
a3	-31.7	-2.4	1.6	-9.3	-3.6
a4	6.8	1.0	-0.1	2.3	1.2
a5	-4.2	1.7	1.4	0.0	1.4
a6	1.8	0.5	1.4	1.1	0.6
a7	-0.2	1.0	0.5	0.6	0.9
a8	1.3	0.0	0.0	0.4	0.1
a9	-1.2	0.1	-0.2	-0.3	0.0
a10	0.0	0.0	0.0	0.0	0.0
a11	-0.4	0.1	0.2	0.0	0.1
a12	-0.9	0.3	0.8	0.1	0.3
a13	-0.1	0.6	0.8	0.5	0.6
a14	0.7	1.0	1.2	1.0	1.0
a15	0.7	0.4	0.4	0.5	0.4

Aperture 2	LC	straight	LOC	Integrals	Integrals extrapolated to 8 m
C1 (gauss)	104.3	207.6	100.0		
a1	-1.1	-0.3	0.4	-0.3	-0.3
a2	8.9	4.0	-4.0	3.2	3.9
a3	-29.6	-1.8	3.1	-8.1	-3.0
a4	-2.0	-0.6	0.3	-0.7	-0.6
a5	-5.8	1.4	0.3	-0.8	1.0
a6	1.6	1.6	4.1	2.3	1.7
a7	-0.8	1.1	0.1	0.4	1.0
a8	0.4	0.1	1.0	0.4	0.2
a9	-1.3	-0.3	-0.4	-0.6	-0.3
a10	0.0	0.0	0.0	0.0	0.0
a11	-1.4	-0.4	-1.2	-0.9	-0.5
a12	0.0	0.3	1.1	0.4	0.3
a13	-0.9	-0.5	-0.1	-0.5	-0.5
a14	0.4	1.0	1.1	0.8	0.9
a15	0.3	0.5	0.5	0.5	0.5

D2 short model completed

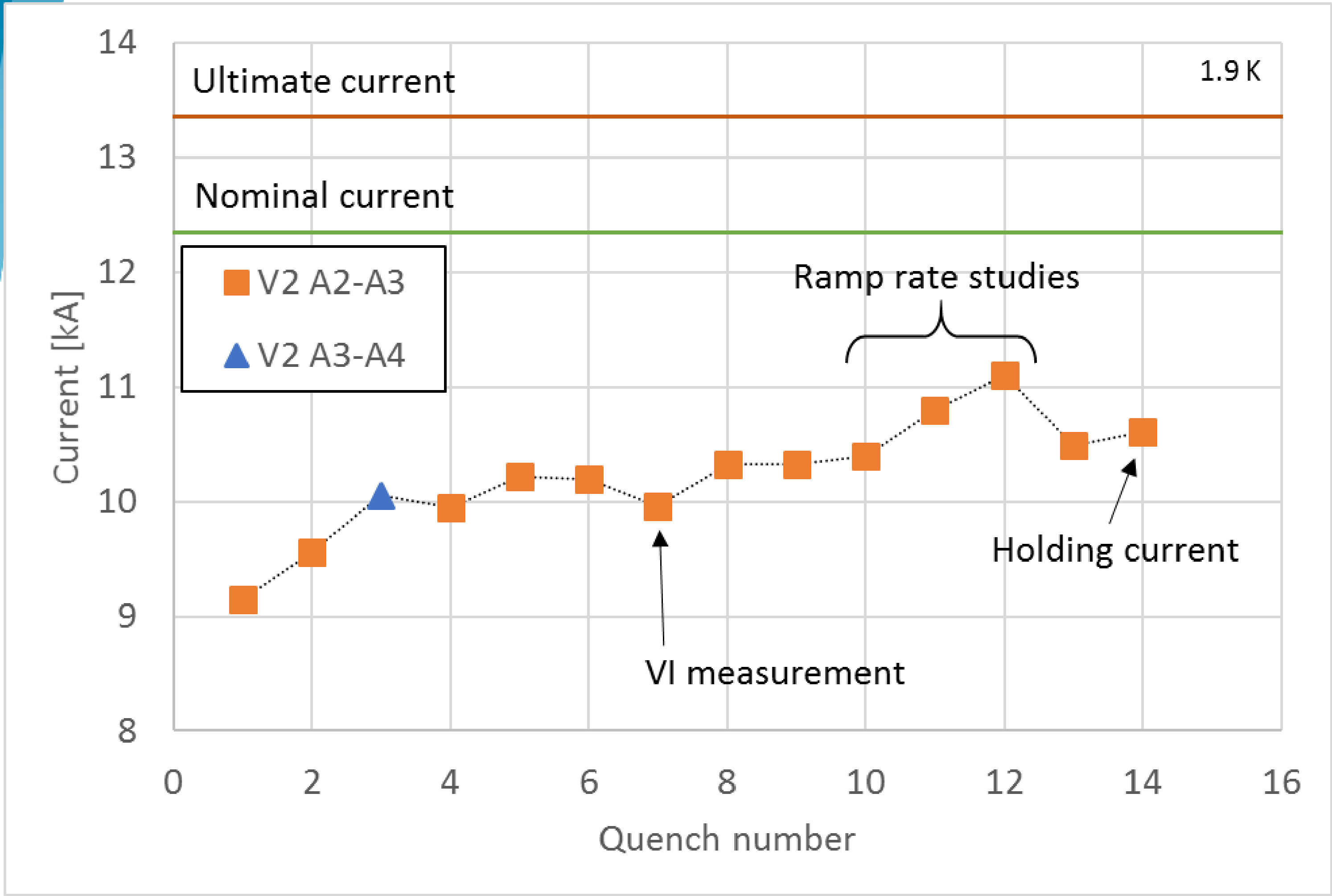


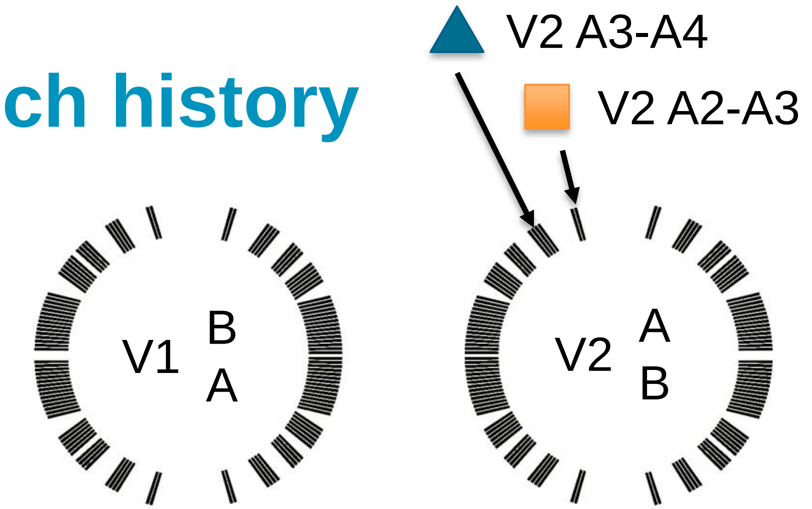


D2 short model delivered to CERN on Jan. 17th 2019

MBRDS1 test at CERN

Aperture fed in series quench history



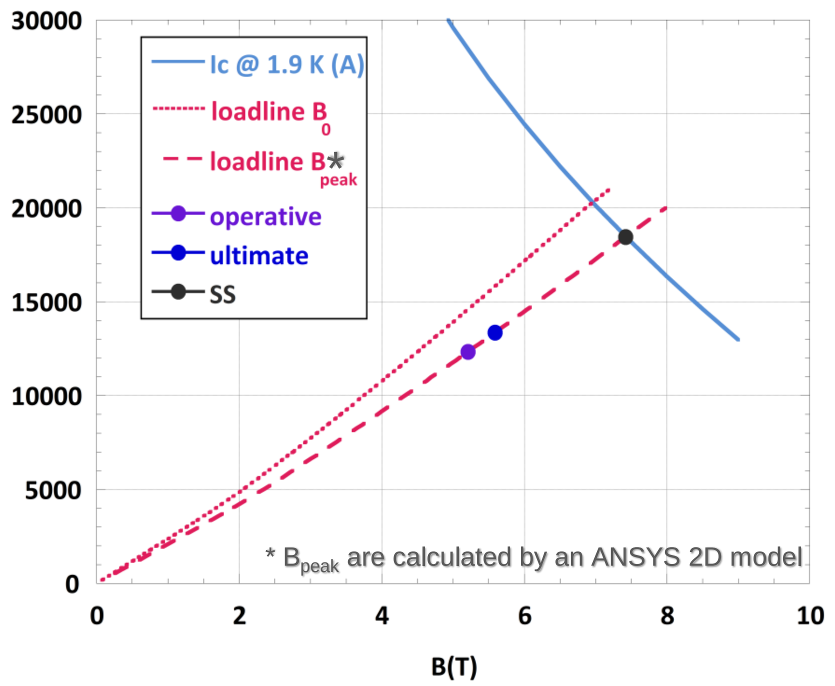


- all quenches but one in the same location: V2 A2-A3. A training effect is seen, but this location limiting the training prompted us to do further investigation
- the conclusion was that the conductor in the fifth block of coil A in aperture V2 (the same with short repaired) was seriously damaged (ex. several strands broken)
- it was decided to disconnect aperture V2 and feed aperture V1 only

Courtesy of F.Mangiarotti

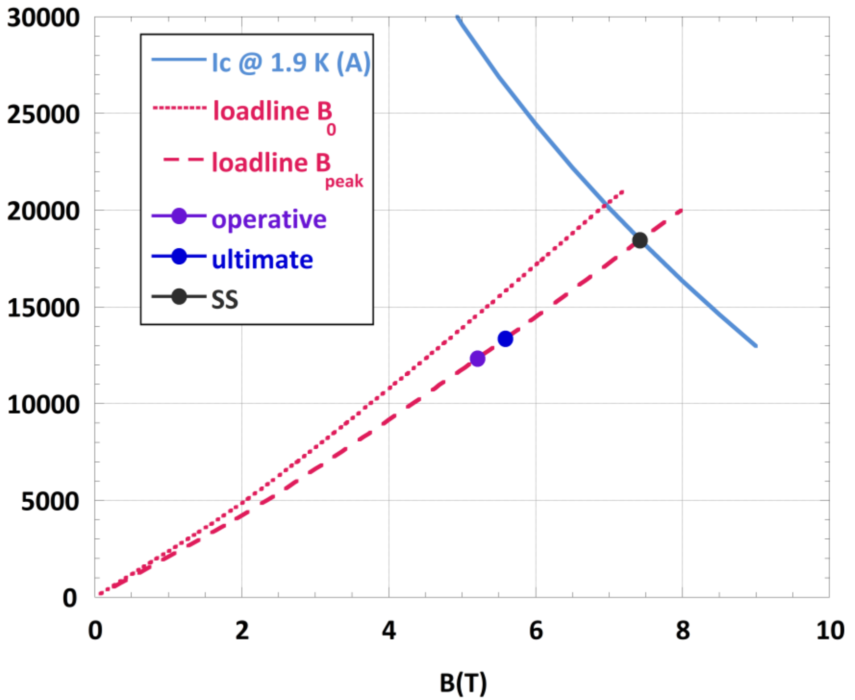
Nominal/ultimate current adjustment

- Double aperture fed in series:
  - I_{nom}=12340 A, B_0=4.5 T
  - I_{ult}=13357 A, $B_{0\ ult}$=4.82 T ($B_{0\ ult}=B_0\times70/75$)
  - B_{SS}=7.42 T, I_{SS}=18468 A
  - loadline fraction: f_{nom}=66.8%, f_{ult}=72.3%
- in D2 magnet, the two apertures cancel each other the magnetic field, so at the same current the main field of a single aperture is larger
  ➔ we decided to keep more or less the same margins
- mechanics was designed to work up to ultimate, so reaching ultimate of double aperture configuration (13357 A) in single aperture mode was not an option



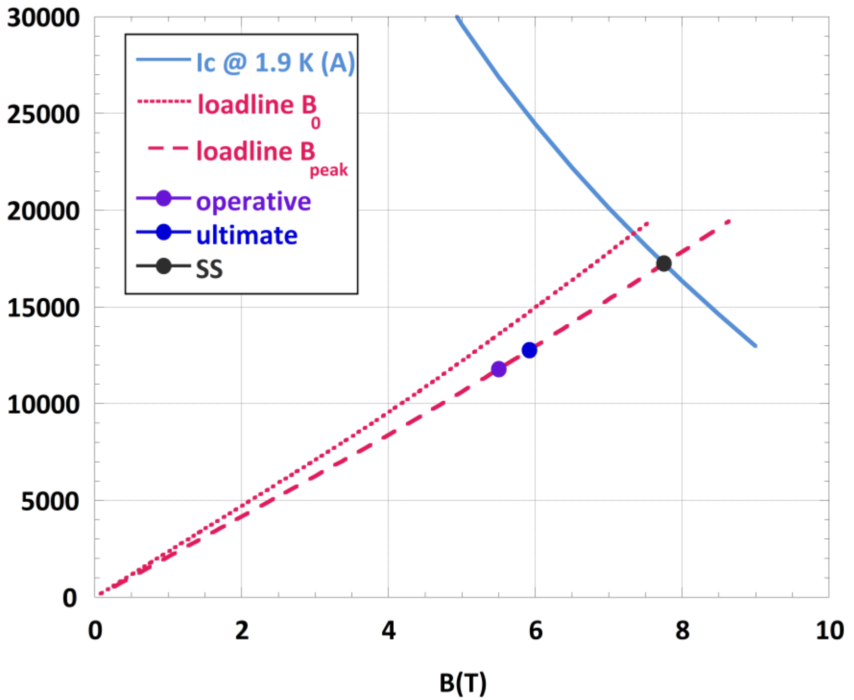
double aperture

- I_{nom}=12340 A, B_0=4.5 T
- I_{ult}=13357 A, $B_{0\ ult}$=4.82 T
- B_{SS}=7.42 T, I_{SS}=18468 A
- loadline fraction: f_{nom}=66.8%, f_{ult}=72.3%

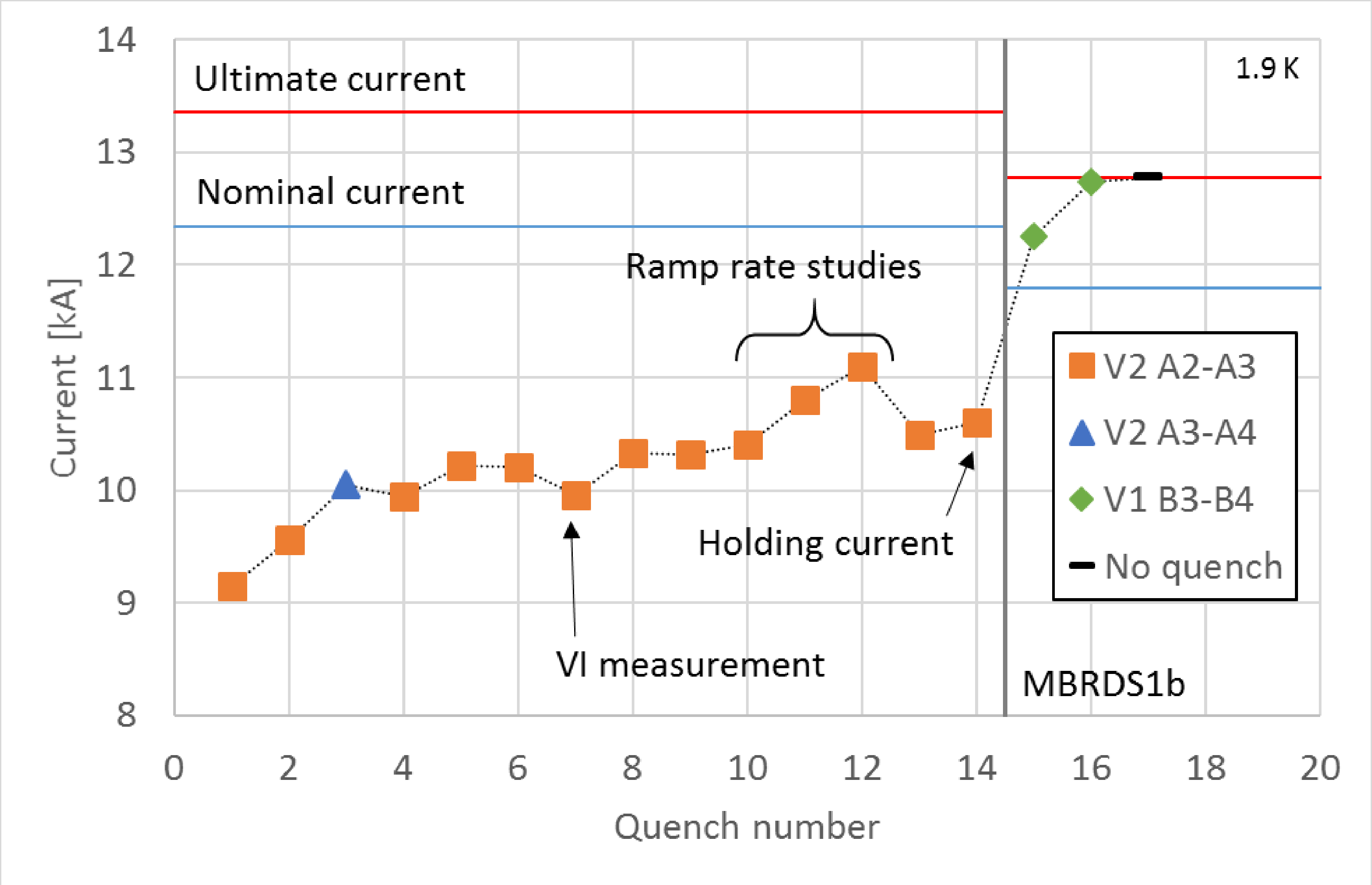


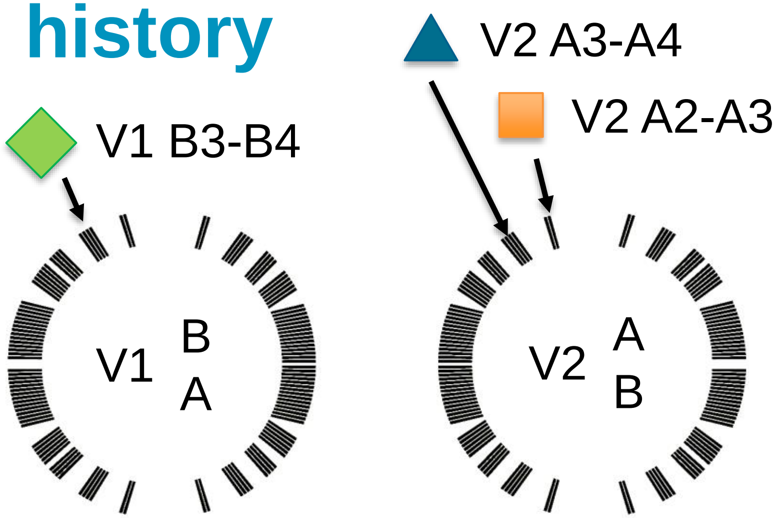
single aperture

- I_{nom}=11800 A, B_0=4.85 T
- I_{ult}=12780 A, $B_{0\ ult}$=5.21 T
- B_{SS}=7.75 T, I_{SS}=17243 A
- loadline fraction: f_{nom}=68.4%, f_{ult}=74.1%



Aperture V1 (MBRDS1b) quench history





- MBRDS1b has two quenches up to ultimate current
- The magnet held the ultimate current for more than one hour without quench.
- It also reached ultimate current without quench at 400 A/s

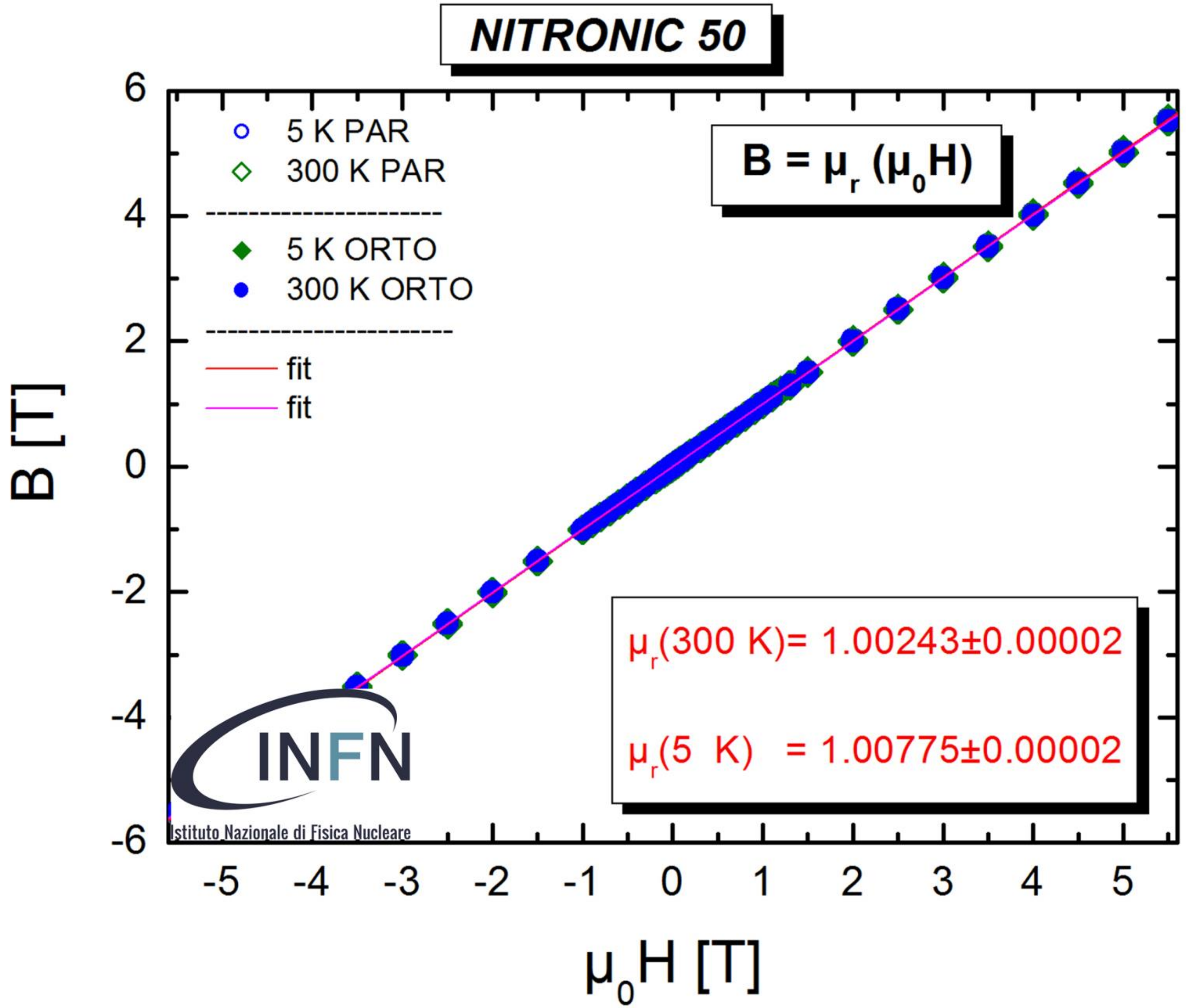
Courtesy of F.Mangiarotti

Conclusions

- The Short Model (MBRDS1) has been delivered to CERN on Jan. 17th and tested last month
  - aperture V2 exhibited a major damage (possible broken strands)
  - aperture V1, individually fed, performed very well reaching ultimate current in 2 quenches, confirming most of our mechanical choices
- Due to planning MBRDS1b will not be retested before the SM18 shutdown. Warm magnetic measurements will be performed soon (to check and validate ASG measurements)
- CERN decided not to give priority to cold magnetic measurements, so we have a fundamental piece of information presently missing for the prototype final design

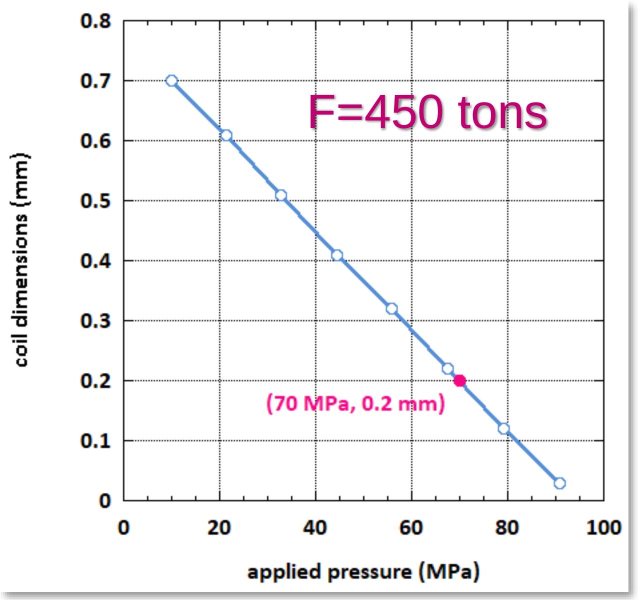
Thank you for your attention

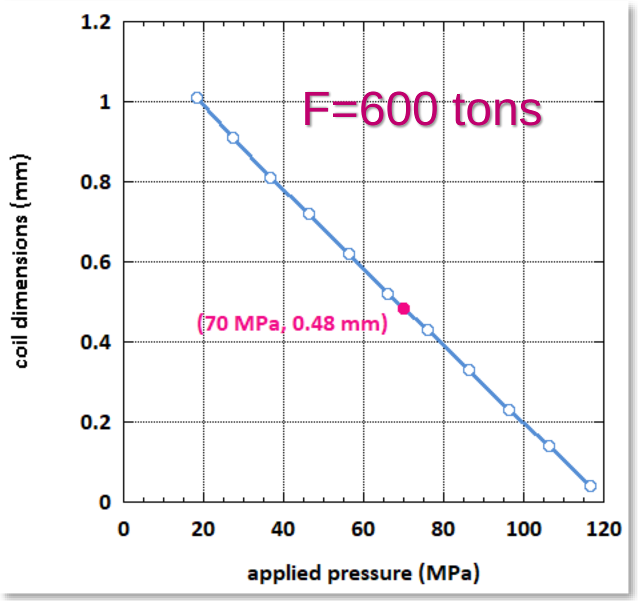
Nitronic 50 magnetic properties



Collaring [2/3]

- for both apertures the force needed for collaring was around **600 tons**
- 2D FE analysis in nominal conditions (conductor parameters set by fitting stacking test measurements) foresee a collaring force around 300 tons/m, corresponding to a total of: 300×1.2 (lenght of straight section)+100 (estimated contribution of the ends)=**450 tons**
- 2D FE analysis is compatible with a collaring force of 600 tons if the coils are 0.48 mm bigger than nominal @ 70 MPa (measured coil dimensions @ 70 MPa were 0.3–0.4 mm larger than nominal)





Non-conformity in aperture I: electrical resistance measurements and surge tests

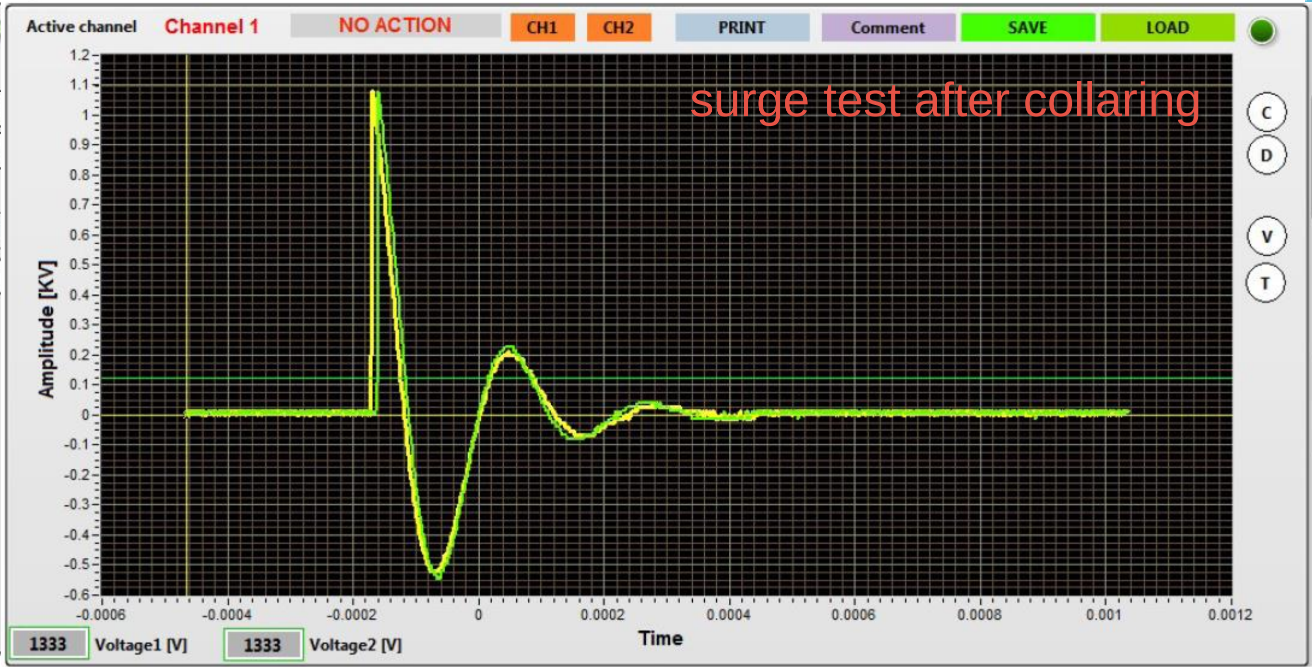
electrical resistance **before** collaring

	I (A)	V (V)	R (mΩ)	Temp(°C)	R @ 20°C (mΩ)	$R_{nominal}$ @ 20°C (mΩ)*
A01	9.97	1.373	137.7	23.3	135.9	132.4*
B02	9.95	1.372	137.8	23.3	136.0	132.4*

electrical resistance **after** collaring

	I (A)	V (V)	R (mΩ)	Temp(°C)	R @ 20°C (mΩ)	$R_{nominal}$ @ 20°C (mΩ)*
A01	10.0	1.348	134.8	22.5	133.5**	132.4*
B02	10.0	1.363	136.3	22.5	135	132.4*

*electrical exits not included



Non-conformity in aperture I: magnetic measurements of collared apertures

- Magnetic mesurements on single aperture, straight section:

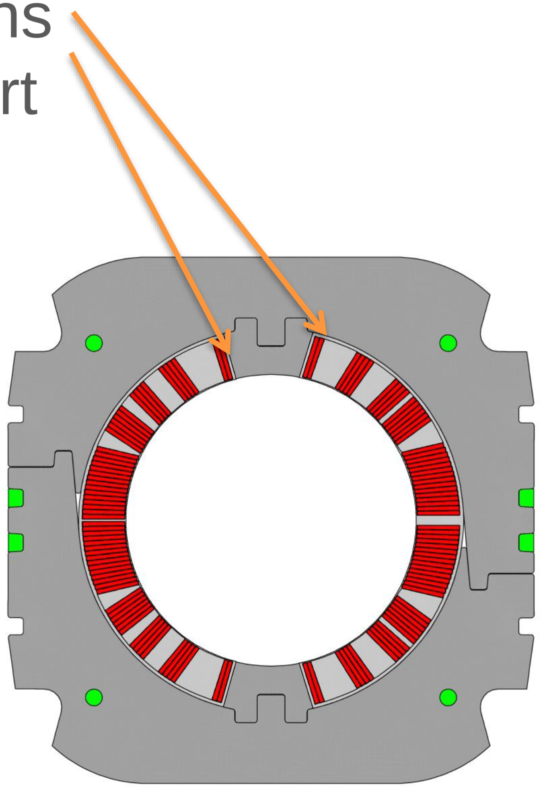
			b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	b15
I	**meas. @ 20 A**		-200	**224**	-35.3	**-8.0**	-2.9	**8.0**	-2.1	-1.4	0.0	-0.3	-0.4	-0.4	-0.2	-0. 7
	simulations		-208	**169**	-37.2	**0.7**	-1.6	**-0.05**	-0.6	0.1	-0.09	-2.1	-1.9	-2.0	-1.0	-0.8
II	**meas. @ 20 A**		187	184	36.4	7.6	4.4	1.4	-0.9	0.3	0.0	-1.5	3.4	-1.0	1.7	-0.8
	meas. @ 100 A		198	182	36.3	8.6	4.0	0.8	-0.07	1.1	0.0	-1.5	2.2	-1.6	1.4	-0.06
	simulations		208	169	36.8	0.7	1.9	-0.05	0.4	0.1	0.1	-2.1	1.9	-2.0	1.1	-0.8

		a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15
I	**meas. @ 20 A**	0.6	**41.3**	-1.5	**-27.3**	2.4	**12.4**	0.9	-3.3	-0.2	0.0	-0.8	-0.3	0.4	1.0	0.9
	simulations	-1.9	**0.2**	-0.3	**-0.01**	-0.07	**-0.05**	-0.1	-0.04	-0.07	-0.02	-0.02	0.0	0.002	0.002	-0.003
II	**meas. @ 20 A**	-1.8	-4.1	-6.5	-4. 7	0.8	3.3	2.2	0.2	-0.7	0.00	-1.9	0.5	-0.3	1.14	0.9
	meas. @ 100 A	3.0	3.0	-3.3	-0.7	1.1	1.6	1.2	0.3	-0.2	0.00	-0.5	0.4	-0.3	0.6	0.08
	simulations	-1.1	0.1	0.2	0.03	-0.04	-0.05	-0.1	-0.04	-0.06	-0.01	-0.02	-0.002	0.0003	0.003	0.003

Non-conformity in aperture I: comparison with the simulation of a short circuit

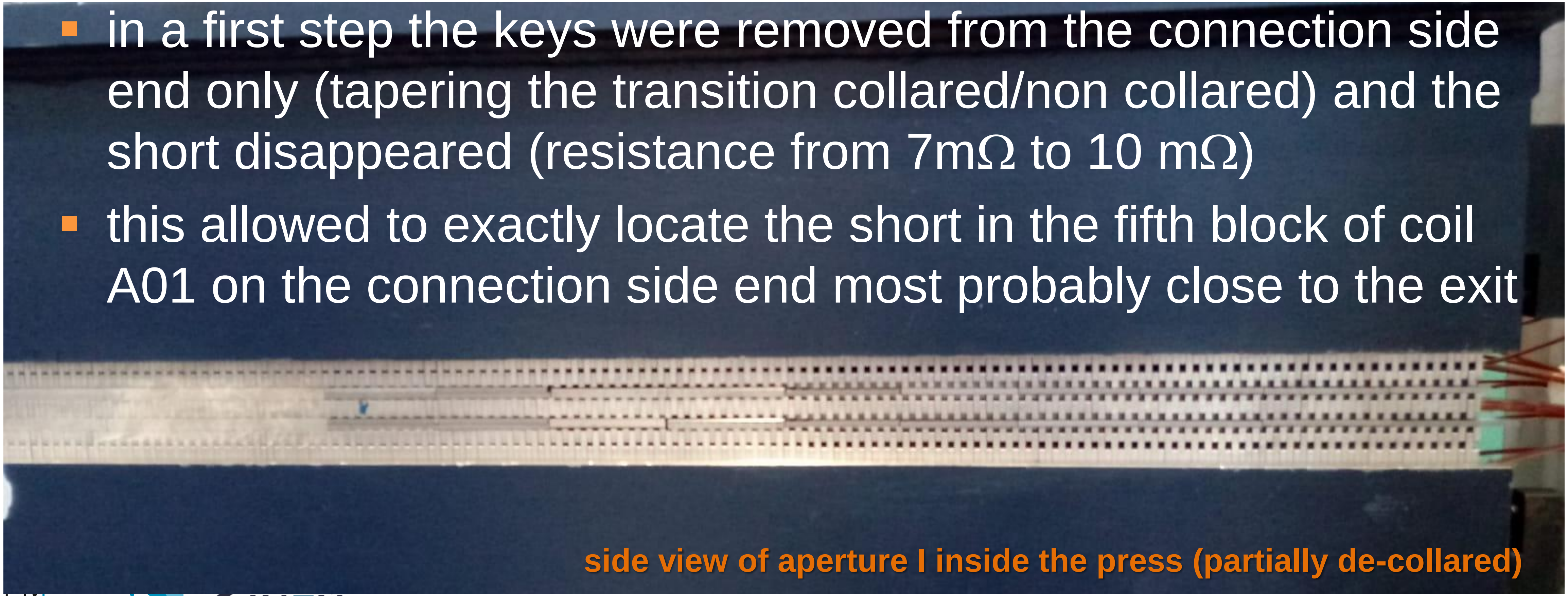
- Roxie simulation with a reduced current in the two turns of the fifth block of the upper pole (simulation of a short circuit accounts for large a_n even and b_n odd)

			b2	b3	b4	b5	b6
I	**measurements**		-200	**224**	-35.3	**-8.0**	-2.9
	simulations		-208	**169**	-37.2	**0.7**	-1.6
	simulations with short circuit		-209	**203**	-39.3	**-15.2**	-0.9
		a1	a2	a3	a4	a5	a6
I	**measurements**	0.6	**41.3**	-1.5	**-27.3**	2.4	**12.4**
	simulations	-1.9	**0.2**	-0.3	**-0.01**	-0.07	**-0.05**
	simulations with short circuit	0.6	**36.9**	-1.8	**-22.0**	1.5	**8.8**



De-collaring of aperture I [1/3]

- the first aperture was de-collared with continuous monitoring of the resistance E\1 (4 wire contacts)
- in a first step the keys were removed from the connection side end only (tapering the transition collared/non collared) and the short disappeared (resistance from 7mΩ to 10 mΩ)
- this allowed to exactly locate the short in the fifth block of coil A01 on the connection side end most probably close to the exit



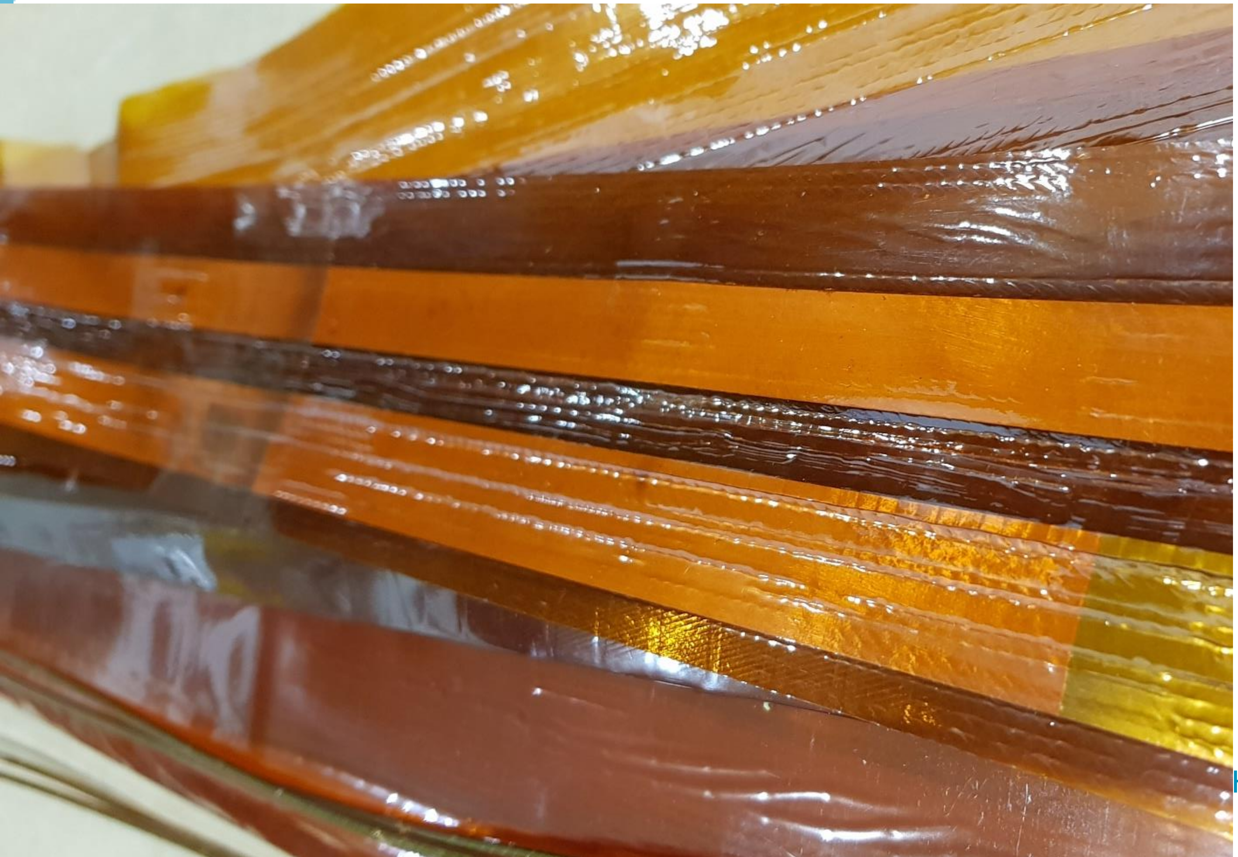
side view of aperture I inside the press (partially de-collared)

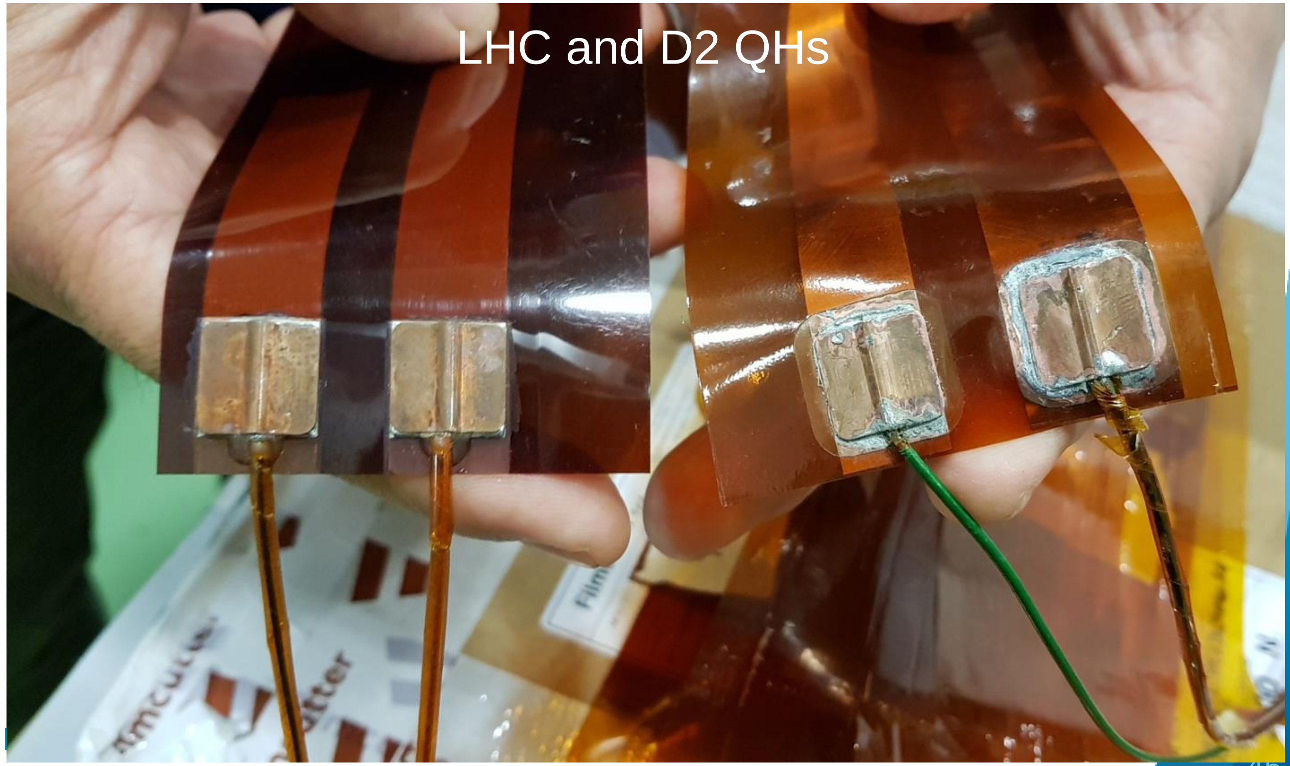
Re-collaring of aperture I [1/3]

- Coil protection and ground insulation sheets were not damaged by collaring and could be re-used

Re-collaring of aperture I [2/3]

- instead, quench heaters were visibly affected by collaring
- since we have no spare, we decided to replace them with the quench heaters of LHC (exactly the same dimensions...)
- the lack of the QHs on one of the coils did not preclude the test



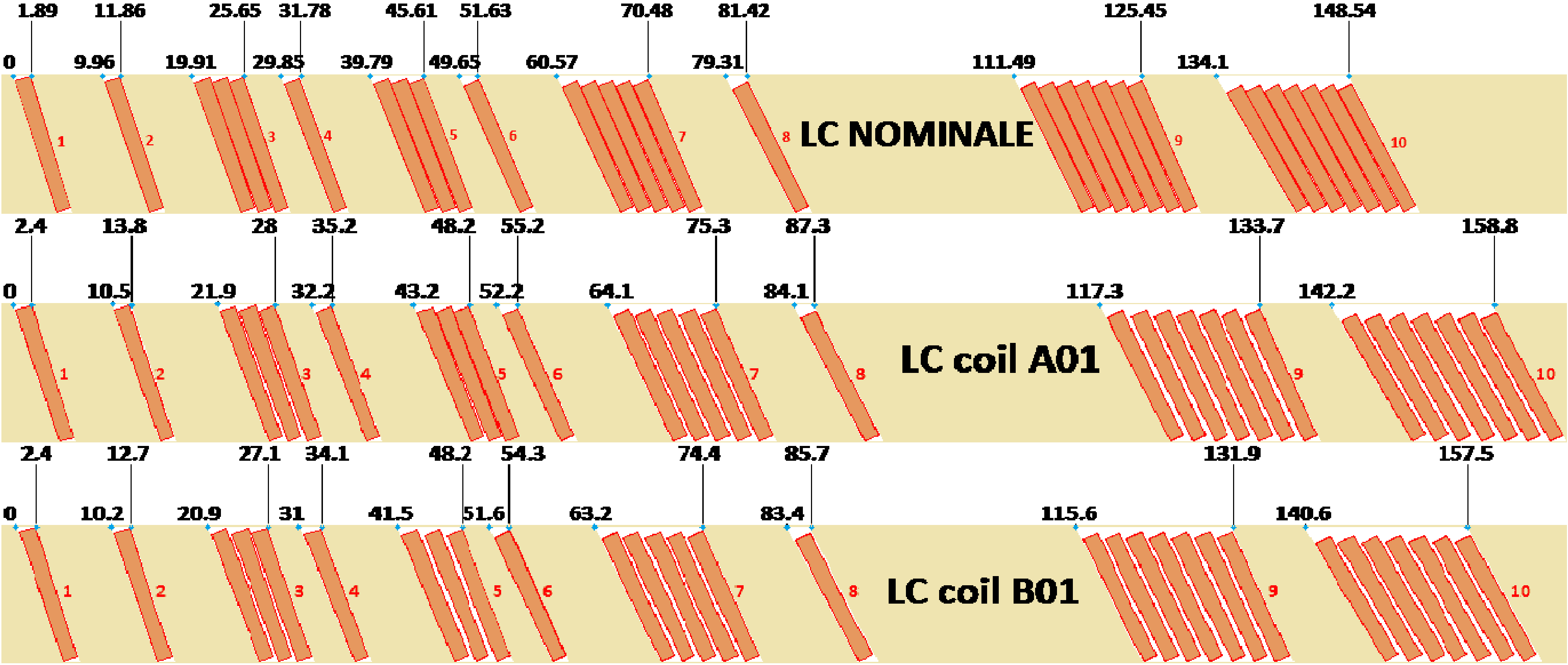


Re-collaring of aperture I [2/2]

- Aperture I was finally re-collared on October 10th
- The operation was been successfully completed in 45 min, continuously monitoring the resistance of the fifth block, which remained unchanged during the whole process.
- Electrical resistance and surge test are ok (phase displacement disappeared)

	I (A)	**V** (V)	**R** (mΩ)	**Temp**(°C)	**R @ 20°C** (mΩ)	**$R_{nominal}$ @ 20°C** (mΩ)*
A01	10.0	1.370	137	22.9	135.4	132.4
B02	10.0	1.368	136.8	22.9	135.3	132.4

3D model with real coil end dimensions



Normal and skew components in the coil ends compared to FE calculations

Aperture 1	LC meas.	3D nominal	3D real	LOC meas.	3D nominal	3D real
C1 (gauss)	**105.36**	**107.00**	**99.86**	**101.15**	**97.00**	**97.43**
b1	10000	10000	10000	10000	10000	10000
b2	48.69	95.51	96.33	64.21	51.20	56.69
b3	17.22	2.15	17.79	17.24	2.00	19.96
b4	-7.51	-7.40	-7.49	-0.80	-2.35	-2.80
b5	12.94	-11.72	-9.63	0.28	-5.75	-2.76
b6	-3.68	-1.29	-1.39	-4.29	1.51	-1.76
b7	-4.70	-5.33	-4.95	-8.12	-7.78	-7.80
b8	-0.83	-0.78	-0.82	-1.74	-0.90	-0.95
b9	-1.35	-3.22	-3.29	-2.75	-3.47	-3.45
a1	1.96	-46.10	-47.47	3.06	-0.15	-0.05
a2	17.32	-17.29	-13.36	8.81	0.19	2.18
a3	-31.69	0.35	-0.31	1.64	0.28	0.28
a4	6.81	6.50	7.77	-0.09	0.00	0.75
a5	-4.22	-1.52	-1.57	1.43	-0.09	-0.12
a6	1.80	-1.84	-1.48	1.36	-0.06	0.01
a7	-0.16	-0.08	-0.10	0.49	-0.15	-0.15
a8	1.33	0.29	0.36	-0.04	0.04	-0.02
a9	-1.15	0.31	0.33	-0.20	-0.09	-0.08

Aperture 2	LC meas.	3D nominal	3D real	LOC meas.	3D nominal	3D real
C1 (gauss)	**104.28**	**107.00**	**100.10**	**99.98**	**97.00**	**97.63**
b1	10000	10000	10000	10000	10000	10000
b2	-40.51	-95.52	-94.89	-60.09	-51.28	-55.61
b3	17.70	2.18	21.46	16.97	2.02	22.21
b4	11.90	7.41	7.78	2.88	2.35	2.91
b5	13.31	-11.73	-8.88	3.53	-5.75	-1.93
b6	5.88	1.30	1.48	1.38	1.53	1.79
b7	-3.17	-5.35	-4.78	-7.46	-7.80	-7.58
b8	0.84	0.79	0.84	-0.51	0.91	0.97
b9	-1.58	-3.24	-3.27	-2.76	-3.47	-3.44
a1	-1.07	-46.15	-47.90	0.41	-1.21	-1.37
a2	8.88	17.30	15.51	-4.04	0.19	0.75
a3	-29.64	0.36	-0.63	3.09	-0.29	-0.36
a4	-1.99	-6.52	-6.05	0.35	0.00	0.63
a5	-5.79	-1.54	-1.61	0.33	0.09	0.10
a6	1.64	1.83	2.11	4.07	-0.07	0.04
a7	-0.77	-0.09	-0.11	0.11	0.15	0.16
a8	0.36	-0.31	-0.29	0.98	-0.05	-0.05
a9	-1.25	0.32	0.32	-0.42	0.08	0.07