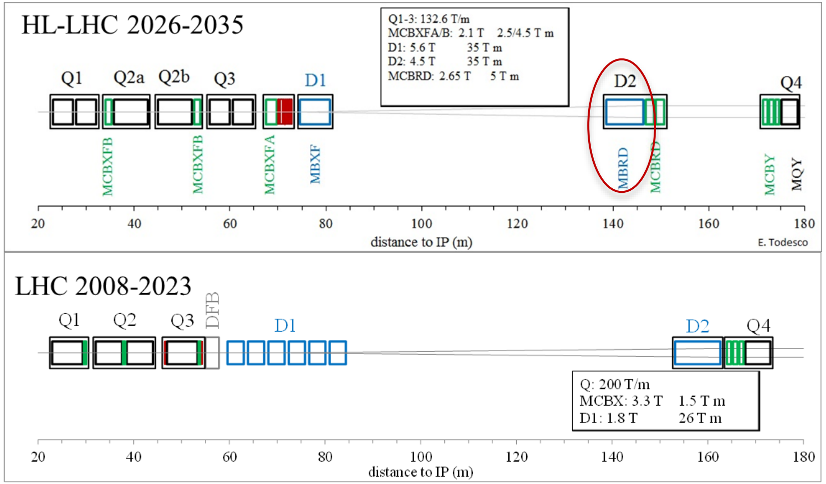
The MBRD dipoles for the luminosity upgrade at the LHC: from prototype tests to the series production

Stefania Farinon
A.Bersani, B.Caiffi, R.Cereseto, P.Fabbricatore, F.Levi, D.Novelli, A.Pampaloni (INFN)
E.Todesco, A.Foussat (CERN)
S.Angius, A.Barutti, N.Valle, A.Verardo (ASG)
On behalf of CERN-INFN WP3 Collaboration for D2 Construction for HL-LHC

D2 LAYOUT AND FUNCTION

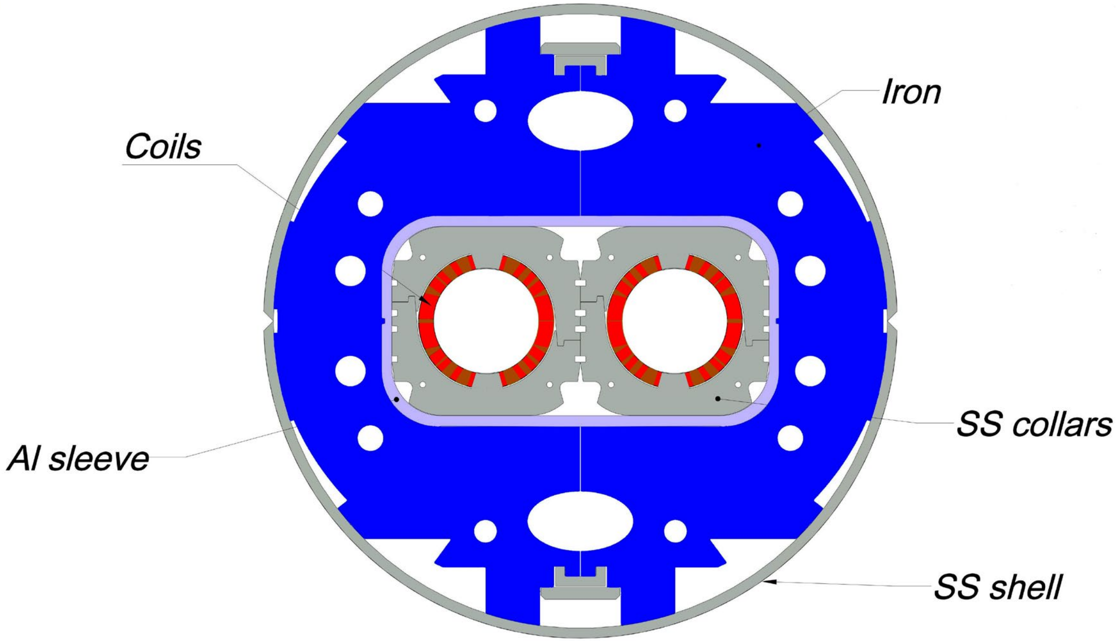
- The D2 dipole (MBRD, Main Bending Recombination Dipole) is placed in the D2 cold mass together with the orbit correctors around IP1 and IP5
- Main characteristics:
  - same field direction in both apertures (used to bring beams to collision), apertures in series
  - 35 T·m integrated field at 7 TeV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



- The CERN/INFN agreement includes the fabrication of a **short model**, a **prototype** and **4+2 spares magnets** of the HL-LHC recombination dipoles (MBRD)
- the contract has been awarded to

ASG SUPERCONDUCTORS

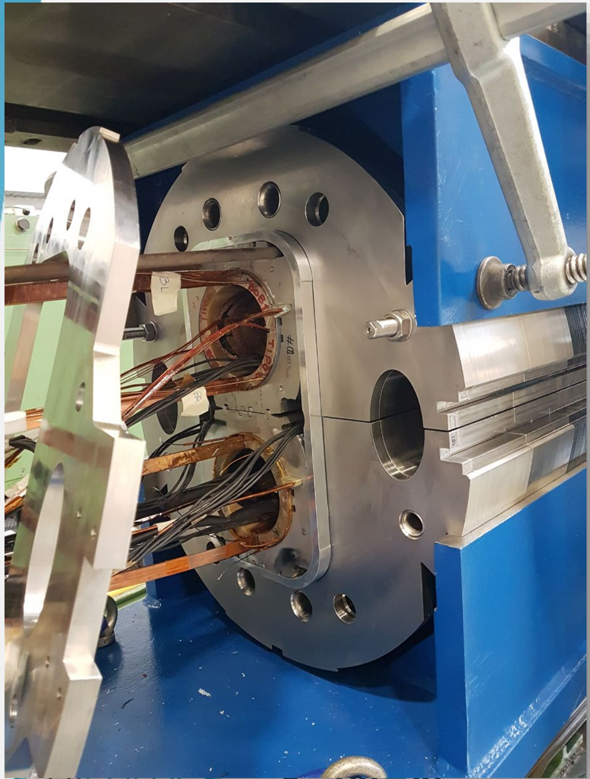
THE D2 CROSS SECTION

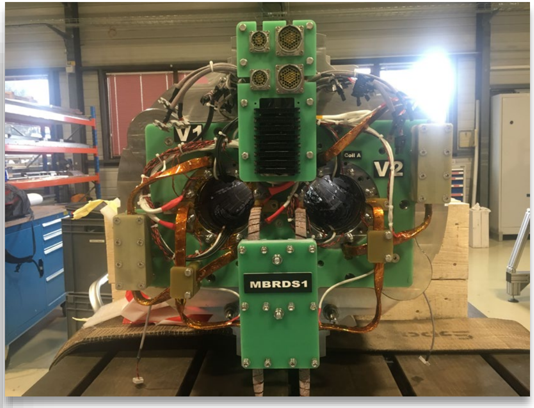


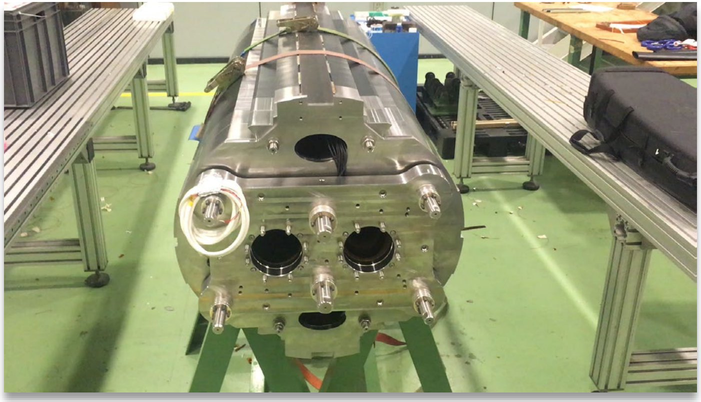
Main characteristics of the D2 dipole	
Bore magnetic field	4.5 T
Magnetic length	7.78 m
Peak field	5.26 T
Operating current	12.330 kA
Stored energy	2.26 MJ
Overall current density	478 A/mm^2
Magnet physical length	8.01 m
Aperture	105 mm
Beam separation at cold	188 mm
Operating temperature	1.9 K
Loadline fraction	67.5%
Multipole variation due to iron saturation	<10 units

THE SHORT MODEL (MBRDS1)

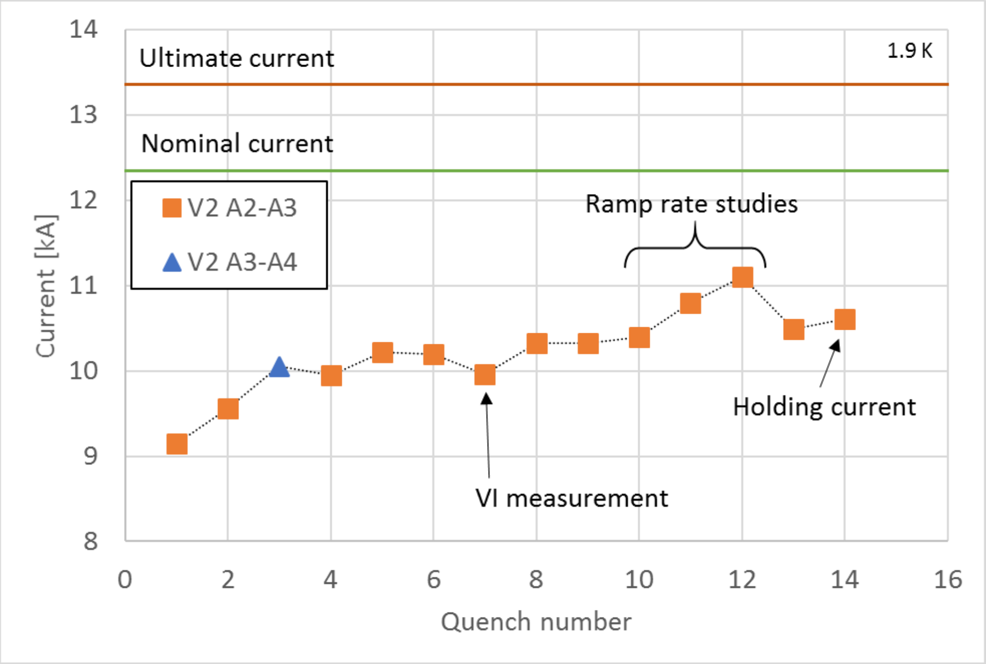
Short model completed and delivered to CERN on Jan. 17th 2019

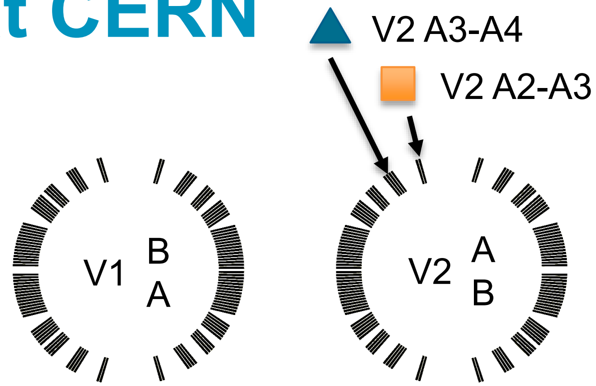






MBRDS1 magnet test at CERN

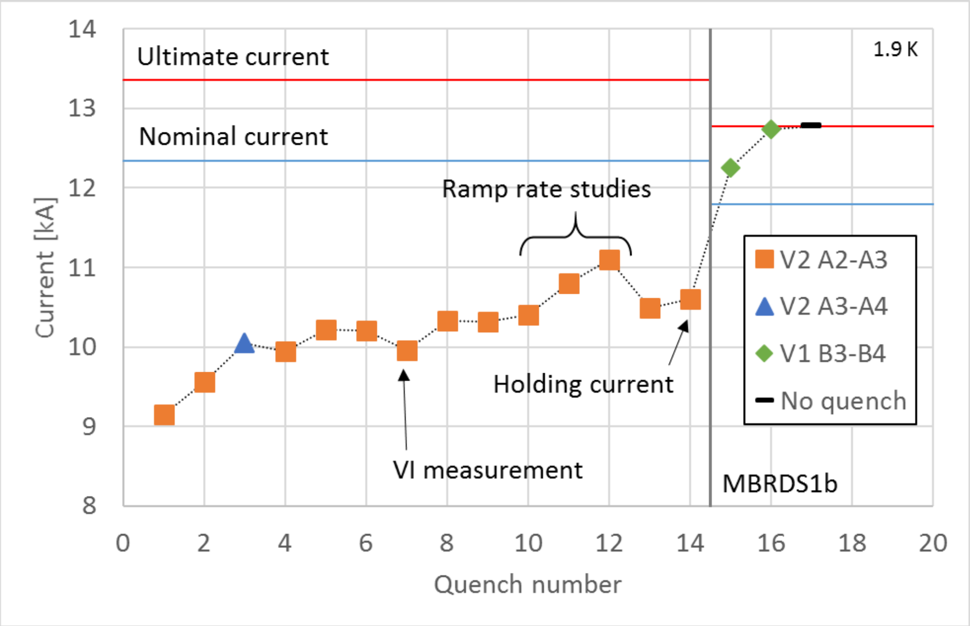


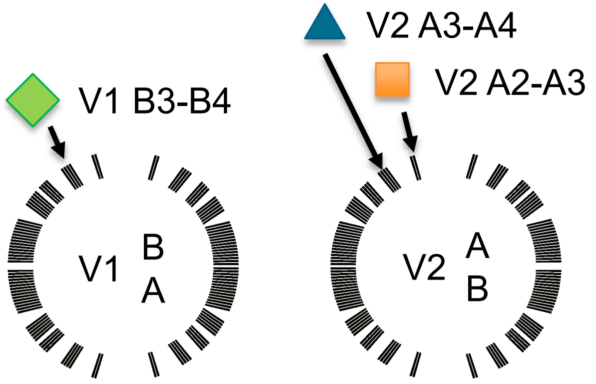


Courtesy of F.Mangiarotti

- all but one quench at the same position: V2 A2-A3. A training effect is seen, but this training-limiting position prompted us to make further investigations
- the conclusion was that the conductor in the fifth block of coil A in aperture V2 (the same with short repaired) was severely damaged (e.g. several wires broken)
- it was decided to disconnect the opening V2 and feed only the opening V1

MBRDS1b magnet test at CERN: aperture V2 disconnected





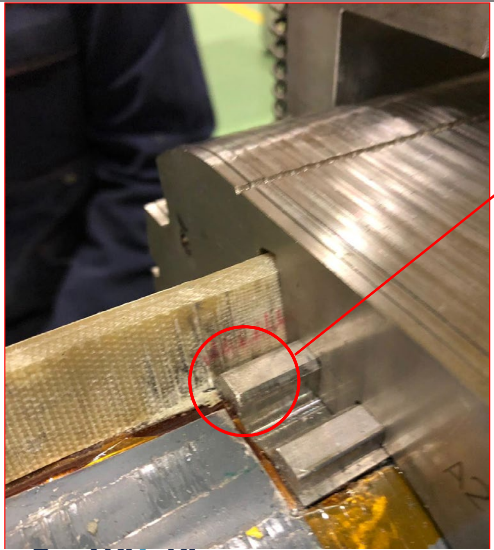
- MBRDS1b had two quenches until the final current.
- the magnet maintained the ultimate current for more than an hour without quench
- it also reached final current without quench at 400 A/s

- the main design choices were confirmed but we had to
  - figure out the problem in the A-coil of the V2 aperture
  - replace this coil
  - re-test the short model before the start of prototype winding

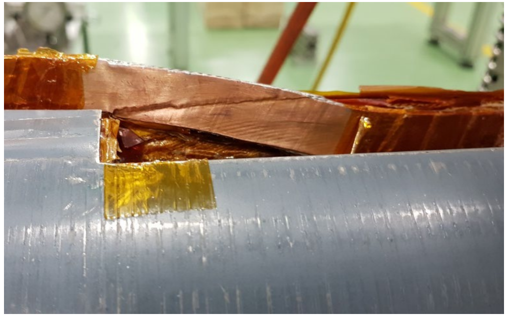
Courtesy of F.Mangiarotti

Disassembly of aperture V2

- the cause of the problem was clear: a corner of the collar pole entered the conductor and cut 20 wires out of 36
- the damaged aperture was replaced with a new one and the short model was re-assembled

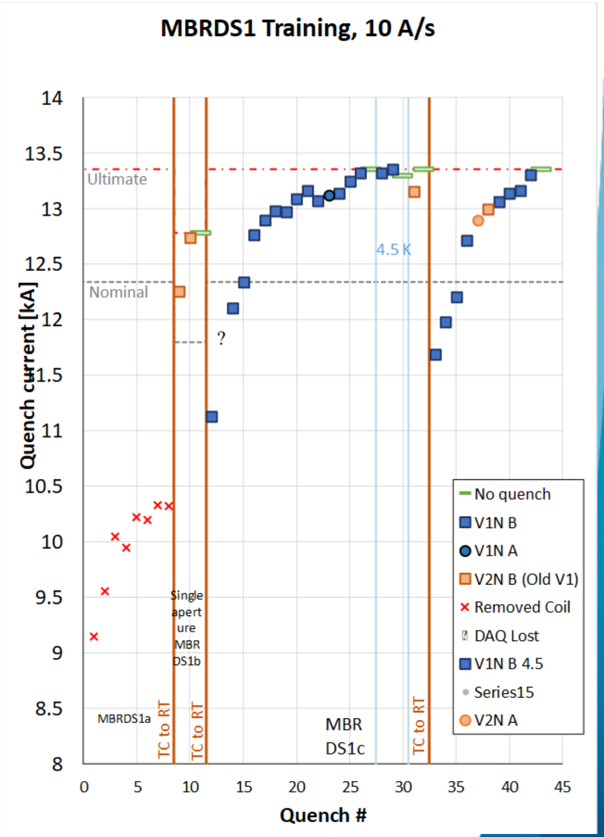


Here one can see that one edge of the pole is partially embedded in the G11 box.



Test of MBRDS1c

- the test of the new short model took place in August 2020:
  - *ultimate reached, even at 4.5 K*
  - loss of memory in one coil of one aperture, causing retraining after thermal cycle
    (V1NB coil has been subjected to 4 collaring operations, in the last of which the end spacers in the poles were damaged and repaired)
  - magnetic saturation measurements in line with models
  - quench heaters validated
-



Courtesy of F.Mangiarotti

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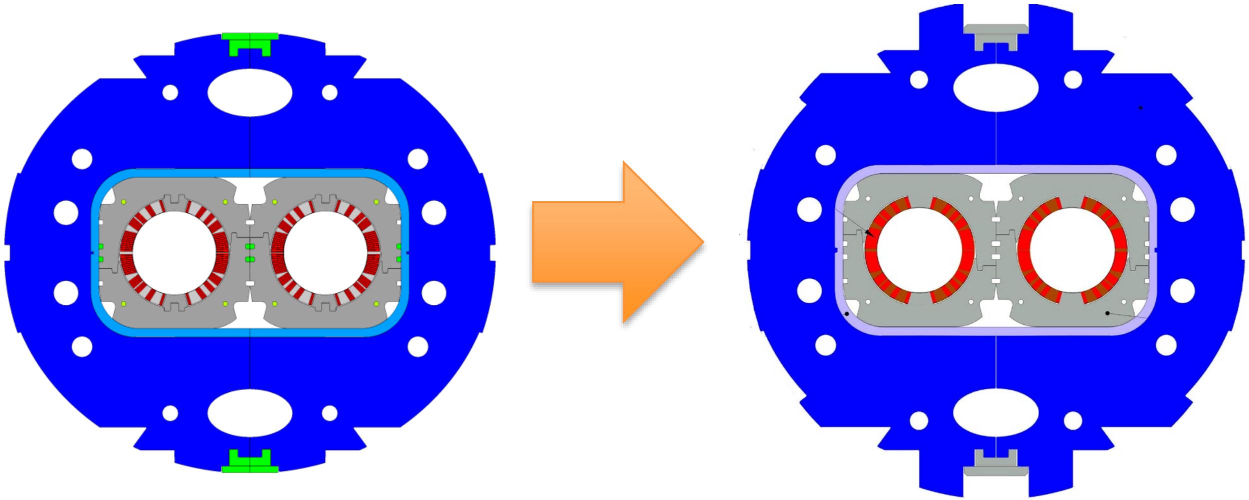
From Short Model (MBRDS1) to Prototype (MBRDP1)

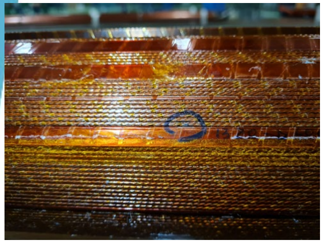


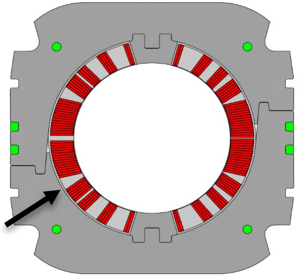
- Main modifications:
  - 1- Coils lay-out (for accounting effects on field quality of deformations and coil ends)
  - 2- Iron yoke (more circular for simplifying integration)
  - 3- Poles of collars (now integrated with collars)
  - 4- Conductor exits for avoid turn-to-turn shorts met with the short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

THE PROTOTYPE (MBRDP1)

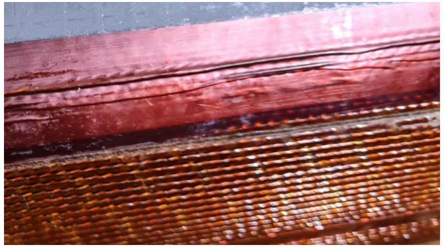
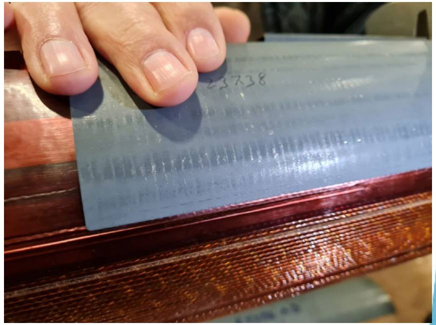
Issues in the prototype during construction

- 1. short QH to coil A1-01
  50 μm insulation added between coil and QHs

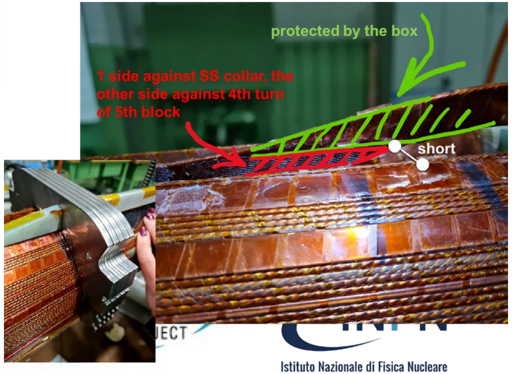


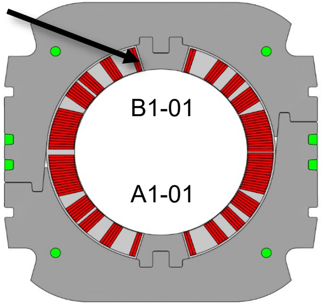


- 3. QH wrinkles in AP1
  SS sheath azimuthal split is moved to the non-active region of the QH

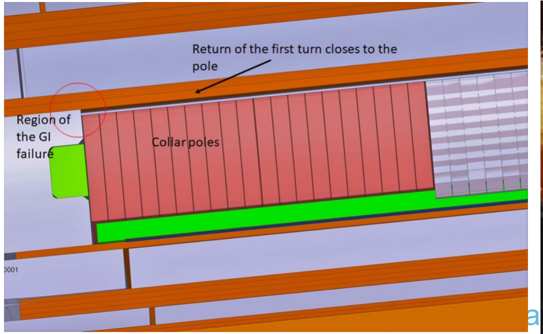



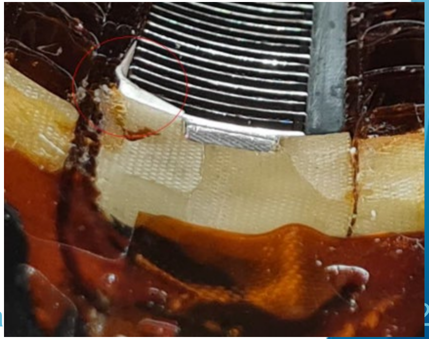
- 2. turn to turn short in coil B1-01
  a sheet of nomex added in the short location (0.18 mm)





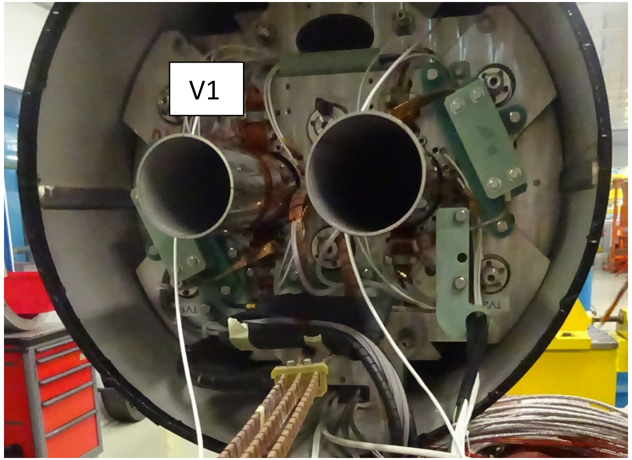
- 4. short to ground of coil B2-01
  repaired with Araldite XD 4447

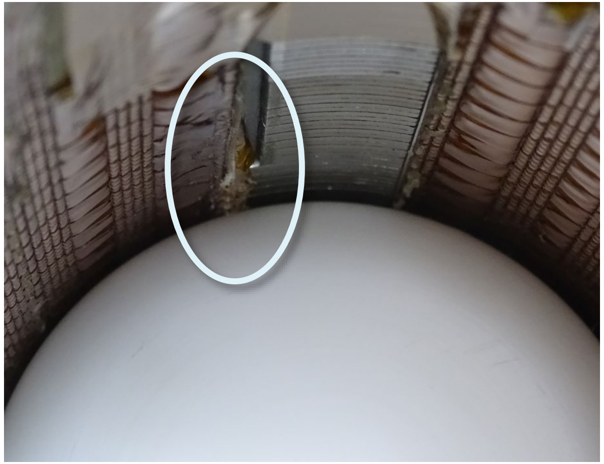




Issues in the prototype during BT insertion

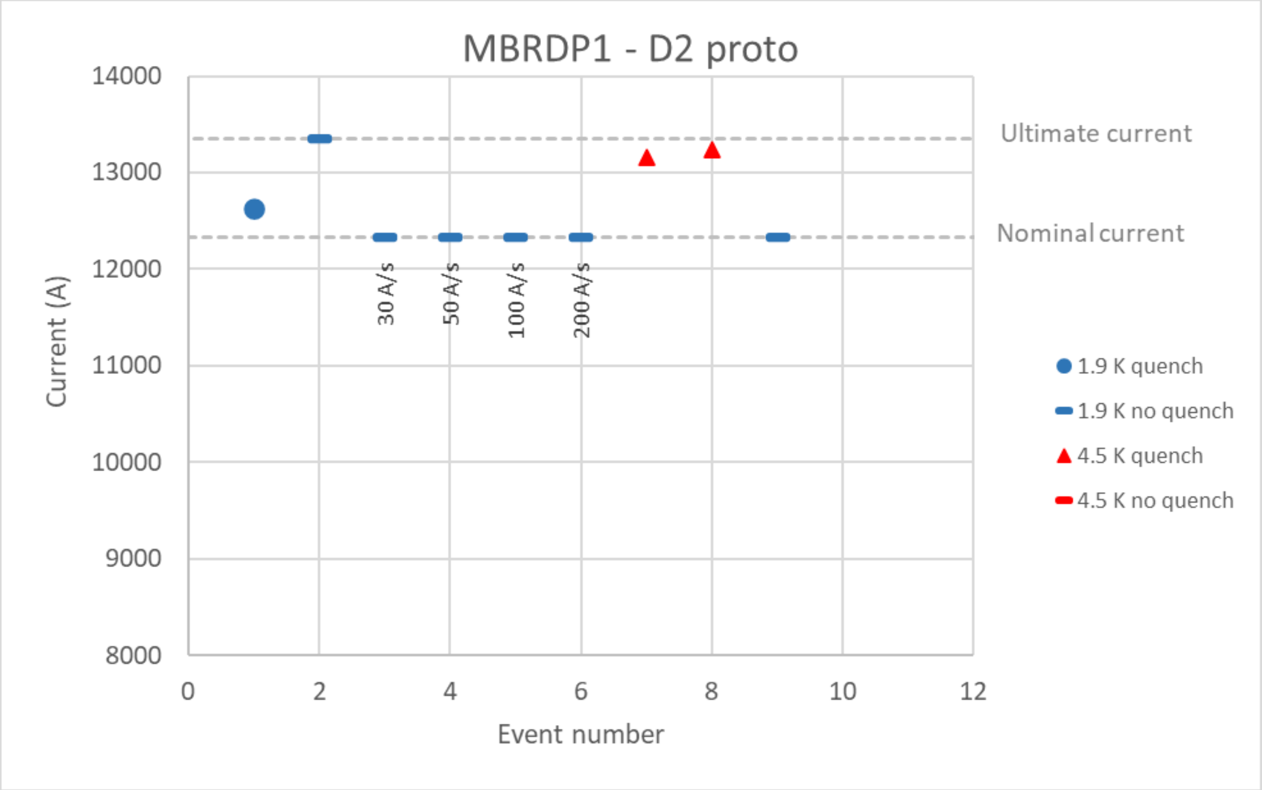
- While inserting the BT into the V1 line, it got stuck on the connection side.
- The pictures taken after the BT removal show a protrusion on coil B1 at the level of the layer jump and a damage in the insulation
- The insulation was repaired and the BM was reduced in diameter before final insertion





Prototype test: training

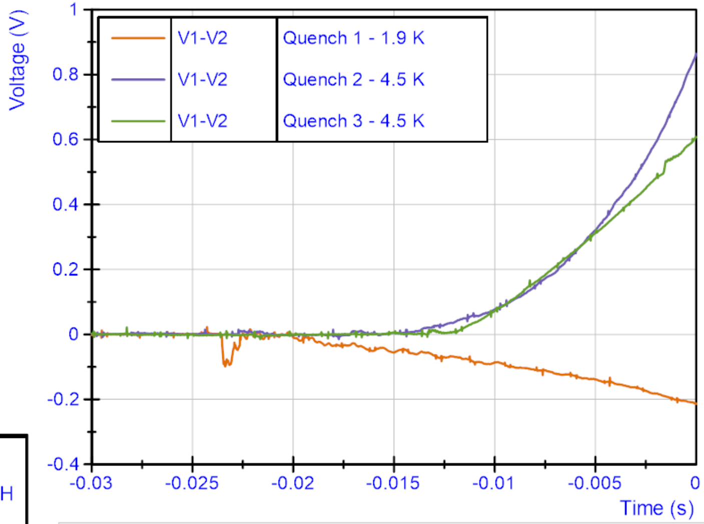
- in the first thermal cycle @ 1.9 the prototype:
  - reached nominal current without quenching
  - reached ultimate in 1 quench
- @ 4.5 K:
  - quenched @ 96% of SS limit
- no other natural quench occurred in the first test campaign

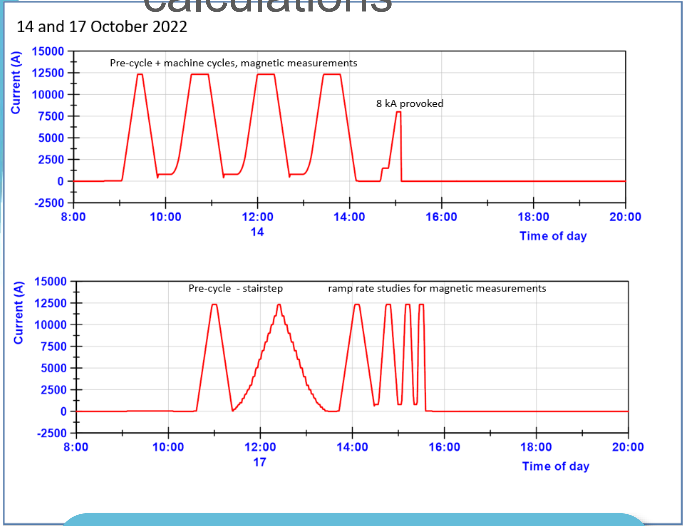


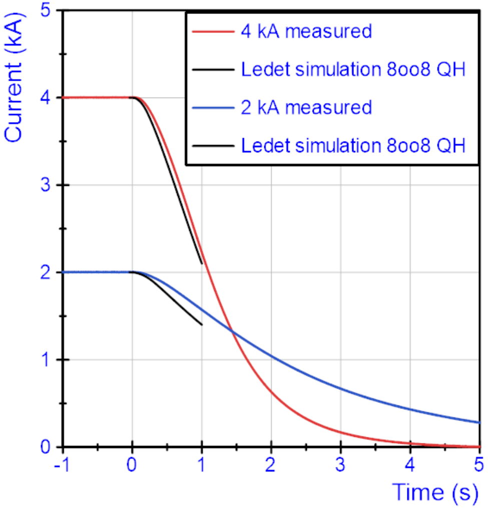
Courtesy of G.Willering

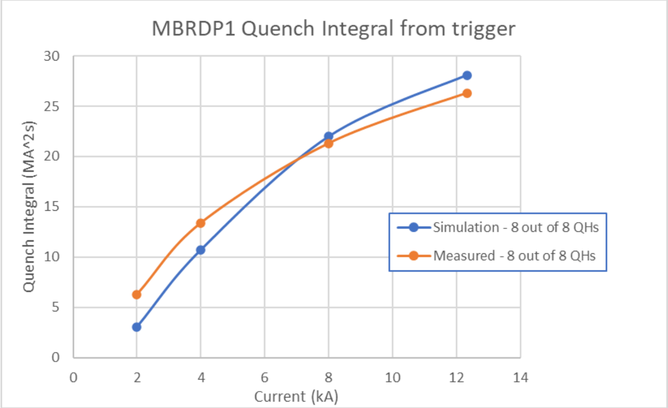
Prototype test: electrical measurements

- The differential voltage shows the clear precursor for the 1.9 K quench, while for 4.5 K quenches close to SS limit this was mostly absent
- the current decay after all QH fire and the quench integral are consistent with calculations



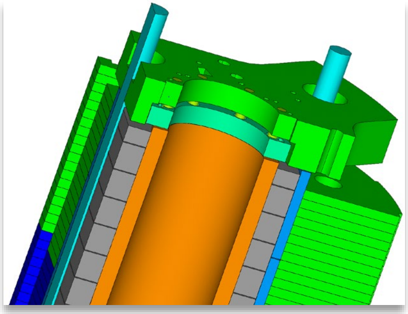




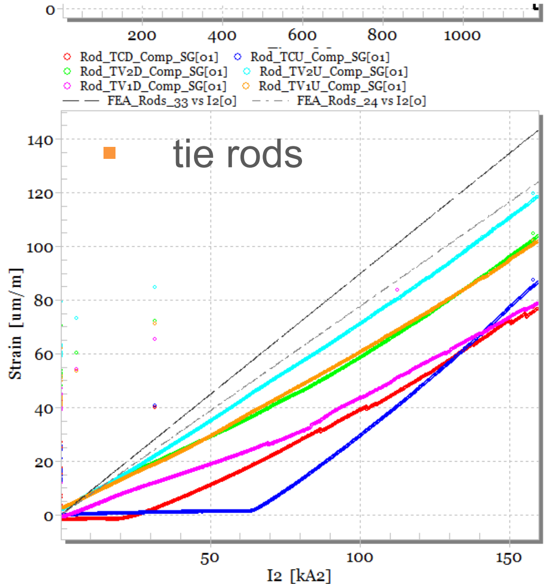


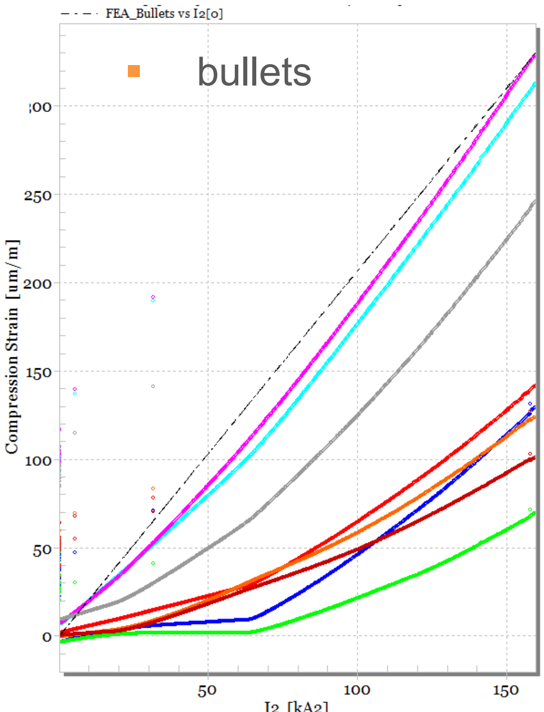
Courtesy of G.Willering

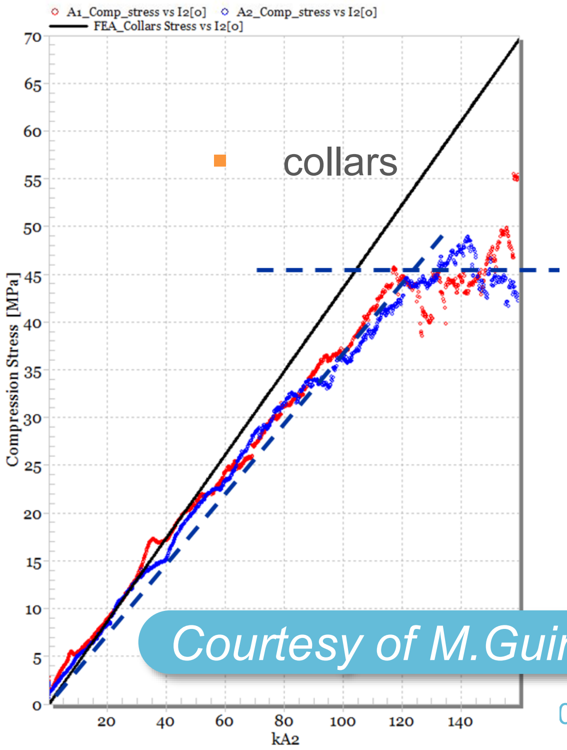
Prototype test: mechanical measurements



- mechanical measurements are consistent with FEA calculation
- the kink in collars meas. is close to nominal current
- tie rods and bulllets are partially unloaded up to 7-8 kA







Courtesy of M.Guinchard

Prototype test: field quality

- measured field quality is in line with expectation
- integrated harmonics at low current:

AP01	expected	measured		AP02	expected	measured
b2	0.06	-1.19		b2	-7.01	-3.1
b3	5.98	6.58		b3	6.73	5.2
b4	-0.65	-1.89		b4	-0.12	0.85
b5	10.80	10.54		b5	10.73	9.58
b6	-1.61	0.58		b6	1.32	-1.48
b7	1.29	2.6		b7	1.71	1.18
b8	-2.52	1.19		b8	0.49	1.65

- we need more time to process all the measured data

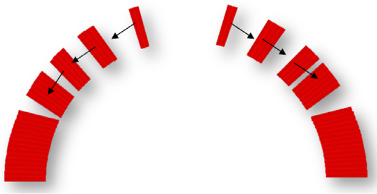
Courtesy of L.Fiscarelli (measurements)

Courtesy of B.Caiffi, F.Levi, A.Pampaloni (calculations)

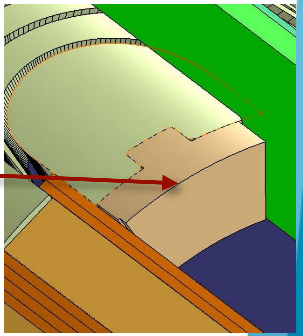
THE SERIES (MBRD1-MBRD6)

The series magnets

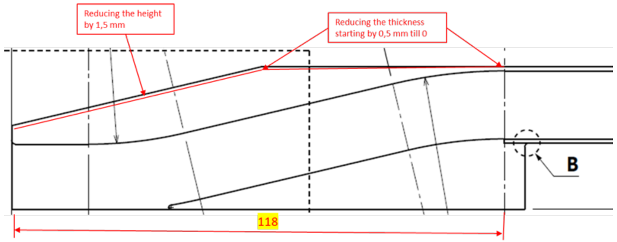
- Several changes were approved to account for the problems with the prototype.
- Among them:
  - fine tuning of field quality and compensation for coil excessive size: modification of wedges 3 and 8



- Blocks 3-4-5 (from miplane) shifted downward by 0.3 mm
- Coils 0.3 mm smaller → +0.3 mm kapton insulation in the pole
- 2 wedges out of 10 modified



  - on return end, introduction of a new end G11 nose piece with the aim to intercept the collar shoe preventing any possible contact with the turns
  - new design of the G11 layer jump box to prevent layer jump protrusion in the inner bore



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The series magnet production @ ASG

- Given the accepted changes from prototype to series:
  - the MBRD1 magnet will be a pre-series magnet, followed by 5 series magnets MBRD2-MBRD6
  - the pre-series magnet will have all the characteristics complying with D2 requirements for use in the HL-LHC
- MBRD1 fabrication has started: the first coil magnet has been wound, cured, and measured
- ASG is awaiting delivery of Cu-insulated wedges and G11 end spacers to resume fabrication of MBRD1
- all other components and equipment are ready
- Series construction is expected to be completed by the end of 2024


Collar packs

Half yoke assembly


Tooling for coil assembly rotation


AL sleeves assembly bench

D2 series production

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Collar packs

Half yoke assembly


Tooling for coil assembly rotation


AL sleeves assembly bench

THANKS FOR THE ATTENTION

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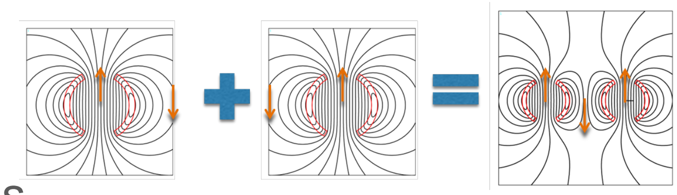
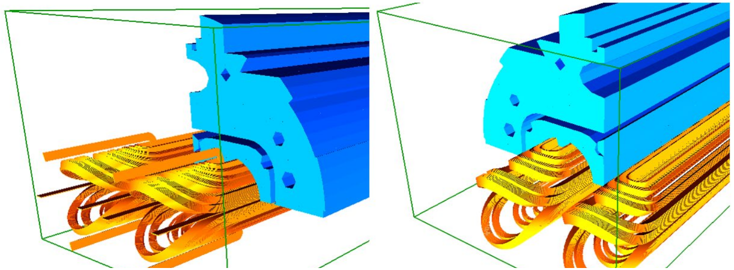
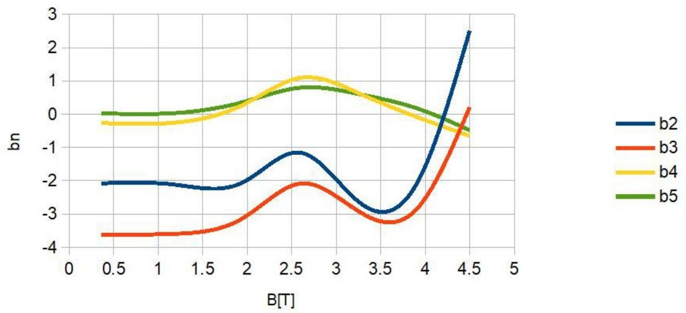
SPARES

ELECTROMAGNETIC MODEL

- LHC dipole outer layer cable is re-used
- The huge cross-talk due to the field being oriented in the same directions in both apertures, is compensated for by asymmetrical coils (no iron between the apertures)
- Single coil has b2 and b3 of order of 200 units – compensation required within 98%
- Iron yoke features (rectangular window, elliptical outer shape, holes position) help to correct the field quality







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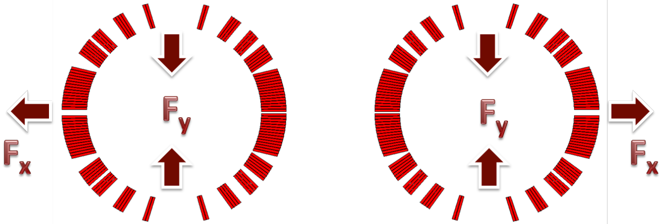
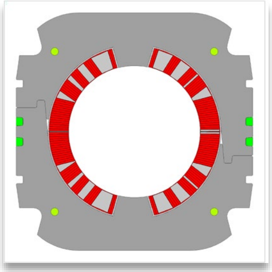
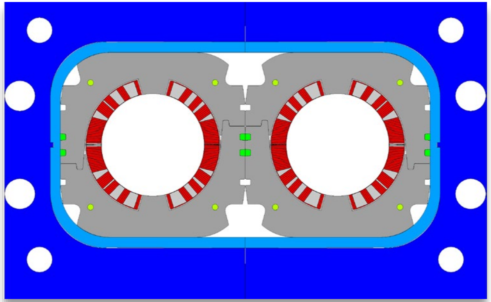
MECHANICAL MODEL

- Fx=193 kN/m and corresponds to the unbalance between the left and right part of each coil (FxA=+1352 kN/m and FxB=-1159 kN/m)
  Fy=-848 kN/m (FxA=-433 kN/m and FxB=-415 kN/m)
- Within each aperture, azimuthal and radial Lorentz forces are kept by collars
- Collars are designed to have a residual preload of 50 MPa at nominal current
- The unbalance between the left and right side of each coil (with consequent mutual repulsion of the two apertures) is kept by the Al alloy sleeves
- Al alloy sleeves are designed with warm gaps which shrink and close at cold

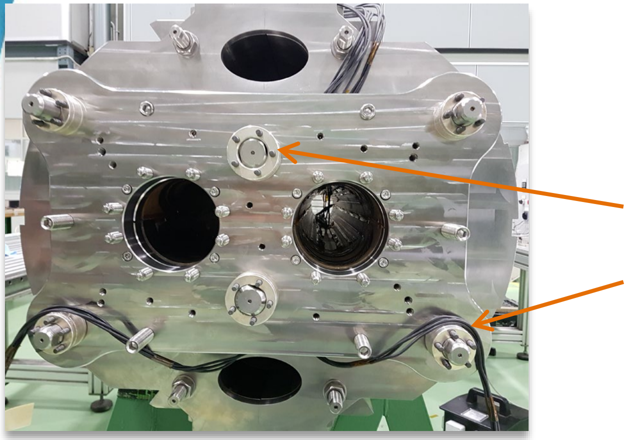
LORENTZ FORCES SCHEME

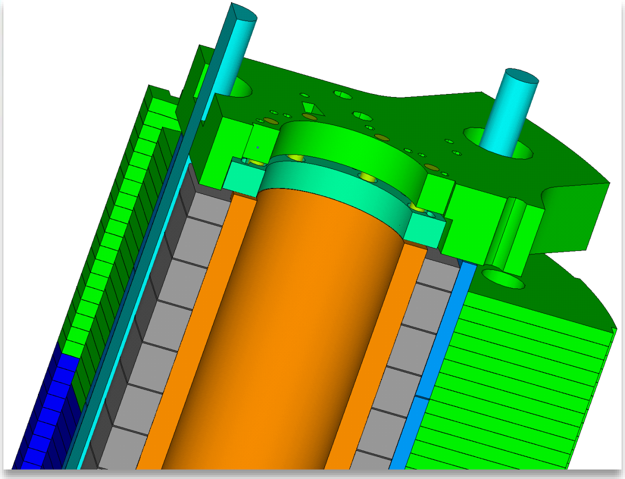






AXIAL PRELOADING SYSTEM





- 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, connecting the coils to the end flange
- the total preload is 50% of the Lorentz force (125 kN), equally loading the tie rods