The HL-LHC Short model recombination D2 dipole: Cold test results and analysis

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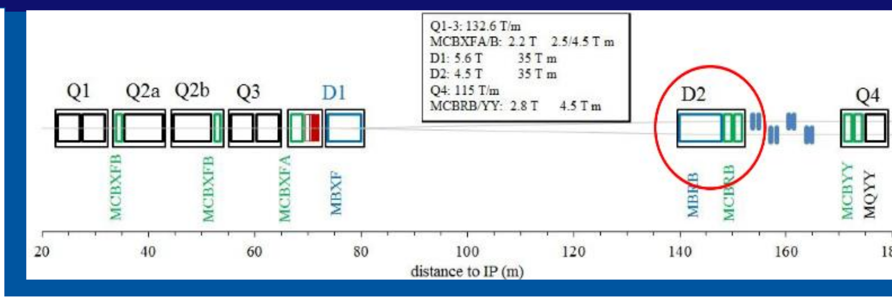
Abstract

The new **D2 recombination superconducting dipole** is a key two-in-one NbTi magnet with a 105 mm bore aperture for the high luminosity LHC accelerator upgrade project (HL-LHC) at CERN expected in operation from 2024. A short model MBRDS1 magnet of 1.6 m magnetic length has been designed by INFN (Genova), built by Ansaldo Superconductors Group, and



This model magnet features novel magnetic and mechanical design elements and future series of **six 8.5 m long full-length dipole magnets** shall be installed on both sides of ATLAS and CMS interaction points with an integral field of 35 T.m and 4.5 T bore magnetic field. This paper shall present the **first power test mechanical results including training, protection, and field quality.** Short model results will give a relevant feedback on the prototype construction and the series production.

Conclusions

The **first short model of HL-LHC D2 recombinaison dipole** has been constructed and tested at 1.9 K at CERN.

A **single aperture V1 test configuration allowed to reach successfully the ultimate current of 13357 A and to validate most of the mechanical structure and magnet electrical design operating margins.**

Some deviation on the mechanical instrumentation of poles, indicated a need to improve design. The **limitations of quench current observed in one aperture V2 at 10 kA were understood, related to local mechanical damage of several strands.**

The plan is to replace the faulty short model coil, to test in a twin aperture towards end 2019 and carry out the construction of the **prototype magnet fully integrated in a horizontal cold mass during Fall 2020** which will be tested at CERN.

Test program

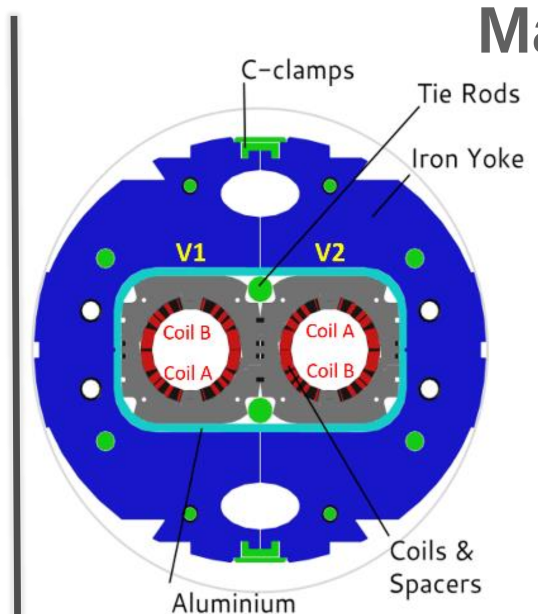
Short model test plan

- **Cold test at 1.9 K of first HL-LHC short model D2 large aperture NbTi dipole** (MBRDS1) aims at validating the design and manufacture processes of series.
- **Series 8.5 m long magnet, generating a field of 4.5 T in a 105 mm large aperture, an integrated field of 35 T.m with a stored energy of 2.26 MJ**
- Test station powered by 15 kA bipolar power supply, 40 mOhms dump resistor
- **nominal design current** of **12340 A at a peak field of 5.3 T, B_0 = 4.5 T** and a reserve ultimate current at 13357 A.
- **loadline fraction**: fnom = 66.8%, **B_{SS} = 7.42 T, I_{SS} = 18468 A, fult = 72.3%**

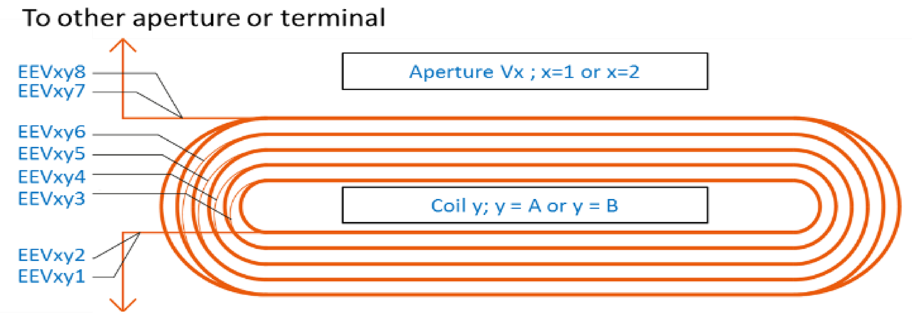
The initial double aperture test plan of the MBRDS1 double aperture magnet included as below, a final test of single V1 aperture after a thermal cycle to circumvent limitation issues appearing in the aperture V2.

- ❑ Training and ramp rate studies to ultimate current at 1.9 K;
- ❑ Mechanical response during cooling, energization
- ❑ Quench Protection scheme effectiveness;
- ❑ Splice resistance and Inductance measurements.
- ❑ Endurance test at ultimate current;

Magnet features



Magnetic Field	4.5 T
Magnetic length (m)	7.78
Peak field (T)	5.26
Operating current (kA)	12.34
Current density (A/mm2)	443
Beam separation at cold (mm)	188
Blocks number	5
Turn number/quadrant	31 (15+6+4+4+2)
Coil inner diameter (mm)	105
Margin on short sample limit load line (%)	38
Multipole variation due to iron saturation	< 10 (in 10-4 units)
Stored energy (MJ)	2.28



Design

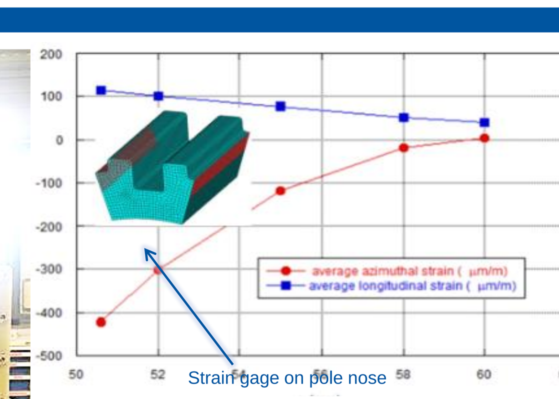


Fig. 2 Impact of the pole radial position of side contact pressure area onto the azimuthal & longitudinal strain reading on poles

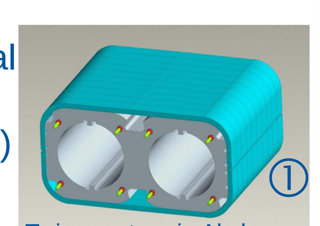
Results summary

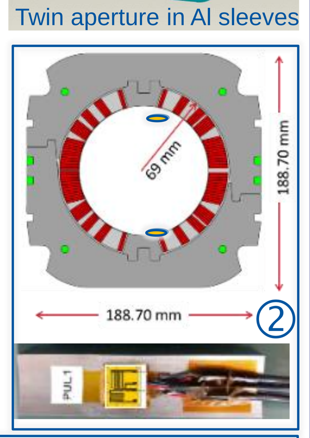
- Power test performed at 1.9K on D2 short model shown quench current limitations in one aperture V2 coil A at 10.2 kA in 5th block (A2-A3) with negative voltage precursor;
- A single aperture test configuration allowed to reach successfully the ultimate current at 12780 A only 2 quenches in coil B confirming the electrical and mechanical design parameters
- Mechanical instrumentation measurement of preloading structure followed expected loading line.
- Next plan is to replace the faulty short model coil, to test it towards end 2019, validating the field harmonics at cold and to carry out the construction of the prototype magnet fully integrated in a horizontal cold mass during fall 2020

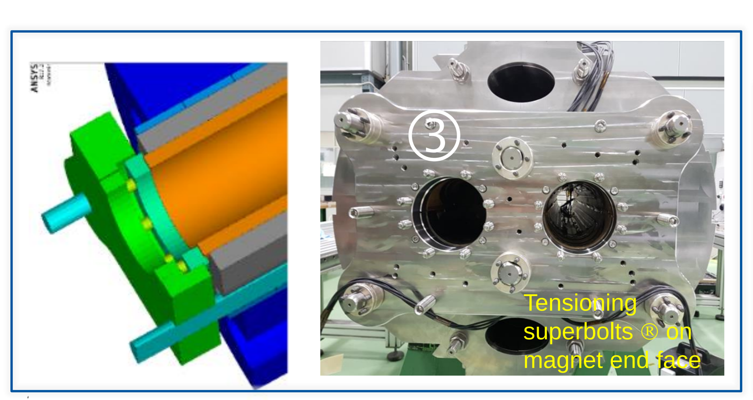
Mechanical measurements

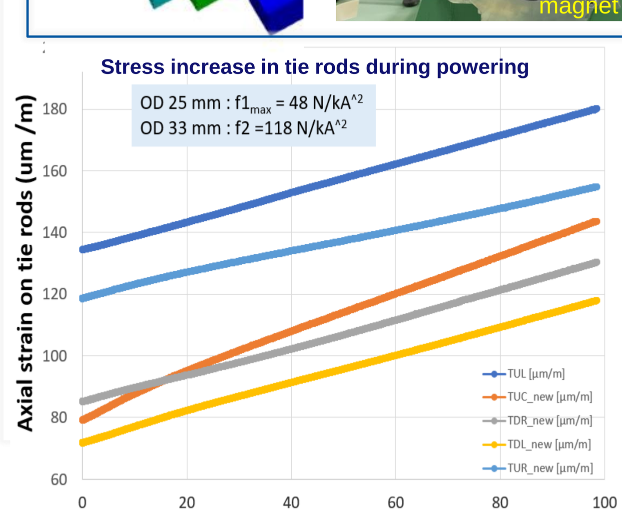
Mechanical Instrumentation

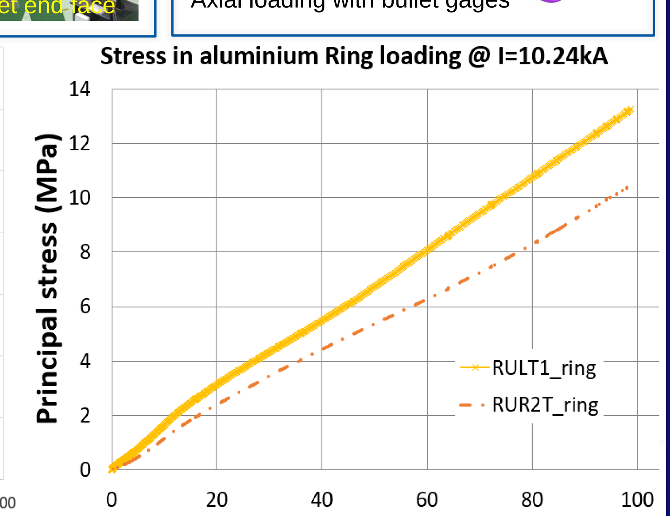
- Aluminium 6000-serie sleeves instrumented with uniaxial gages are initially prestressed at about 50 MPa in compression during yoking. Tensile loading of 13.5 Mpa (1)
- Inner 316LN collars detached pole nose were instrumented along six positions at inner bore surface with axial and azimuthal uniaxial strain gages to monitor the expected **average azimuthal pre-stress of 70 MPa** after collaring (2)
- Six Nitronic-50 tie rods preloaded with Superbolts® at 125 kN representing 50 % of axial Lorentz forces (3)
- 16 axial bullet gages equipped with 4 strain gauges in fulll bridge loaded at RT at 8 kN each (4).











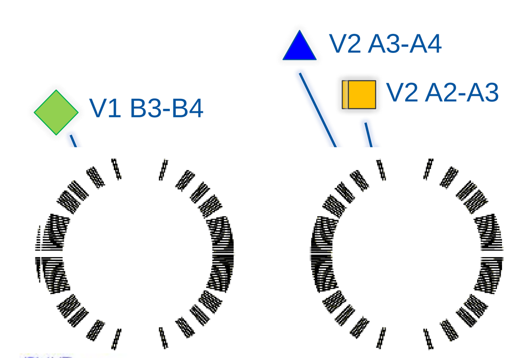
Electrical tests Results

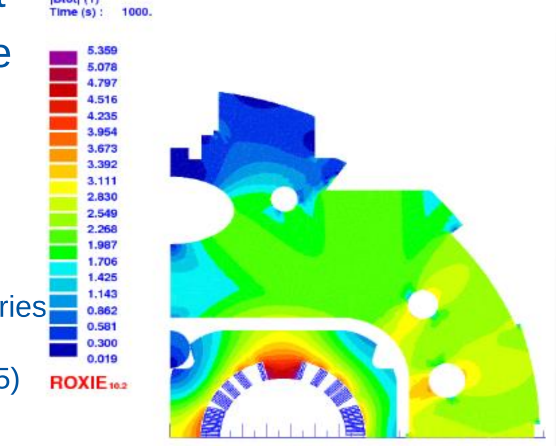
Training quench test

- **Double aperture MBRDS1a test** shown limitation in training current in aperture V2 * at 10.3 kA
- Refurbished **MBRDS1b single aperture** shown only two quenches up to ultimate current
- The MBRDS1b magnet held the ultimate current for more than one hour without quench.
- It also reached ultimate current without quench at 400 A/s

Operating point of 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_0×70/75)
- ❑ B_{SS}=7.42 T, I_{SS}=18468 A
- ❑ loadline fraction: f_{nom}=66.8%, f_{ult}=72.3%





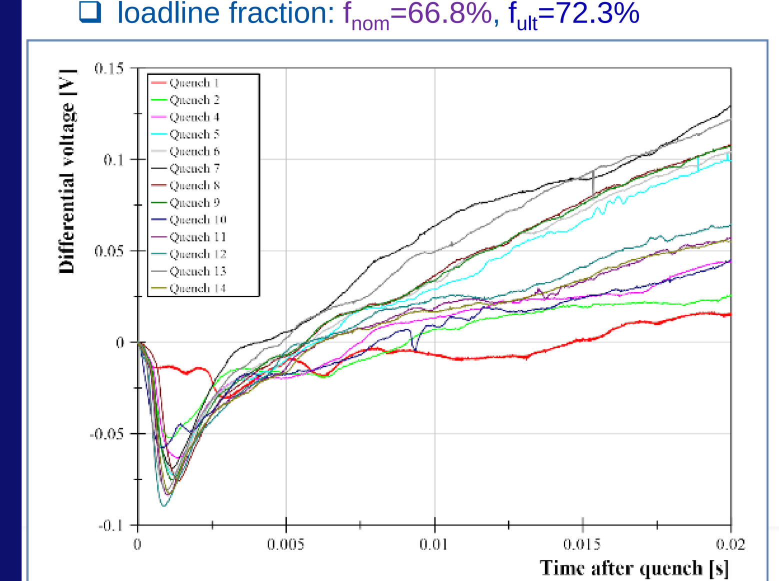
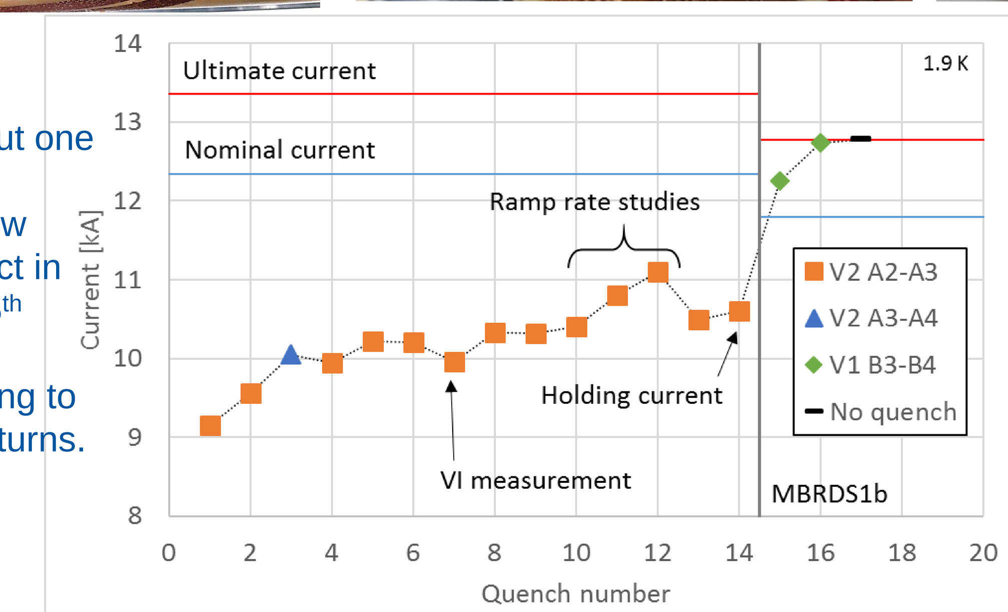


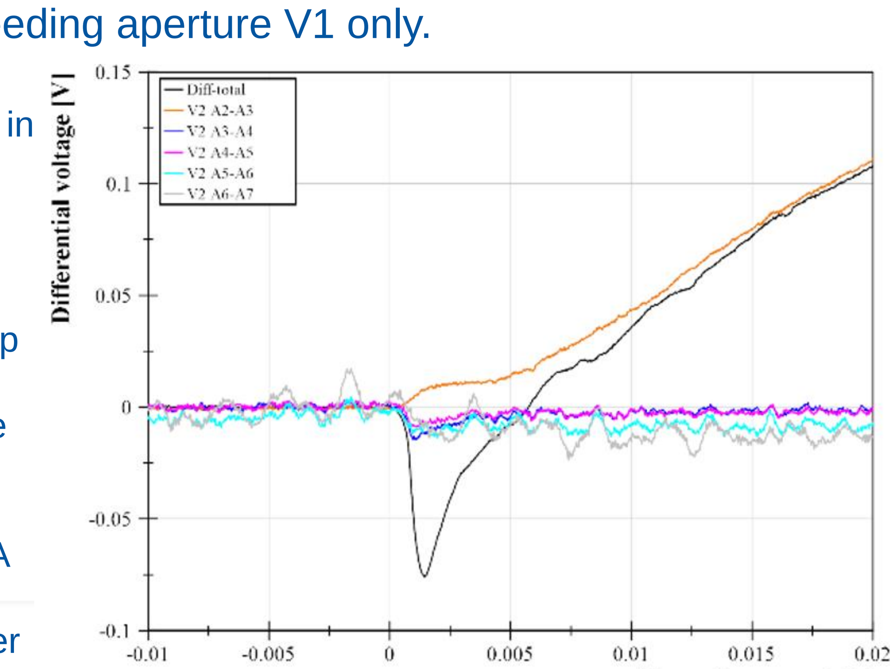
Fig. 1 After the quench, the quenching differential voltage of segment V2 A2-A3 jumps up, while the other coil segments voltage go down.

Fig.3 All quenches but one in the same location show training effect in V2 A2-A3 (5th block) corresponding to first 2 polar turns.



- Post mortem autopsy of aperture V2 coil A show exit conductor in 5th block edge line (repaired block with inter turn short) damaged with up to 20 strand sheared cut due to local overthickness of Kapton re-insulation and detachable nose. It was decided to disconnect aperture V2 and persue test campaign by feeding aperture V1 only.

Fig. 4 Quench starts in A2-A3 5th block. Differential voltage between Coils A - B showing negative inductive voltage loop due to current redistribution into the local cable defect. In all non-quenching segments of coil V2A the voltage after the quench starts is lower than before.



Magnetic & Electrical measurements

- Warm magnetic measurement repeated at CERN with a 130 mm long probe.
- **Discrepancy between multipoles measurement results and simulations by about 10 units on b2, b3, b5 normal field harmonics.** (Table 1)
- Main harmonics deviation assigned to out of tolerance OFE Cu wedges.

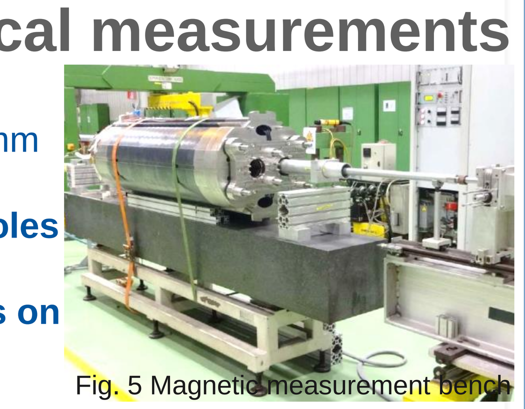


Fig. 5 Magnetic measurement bench

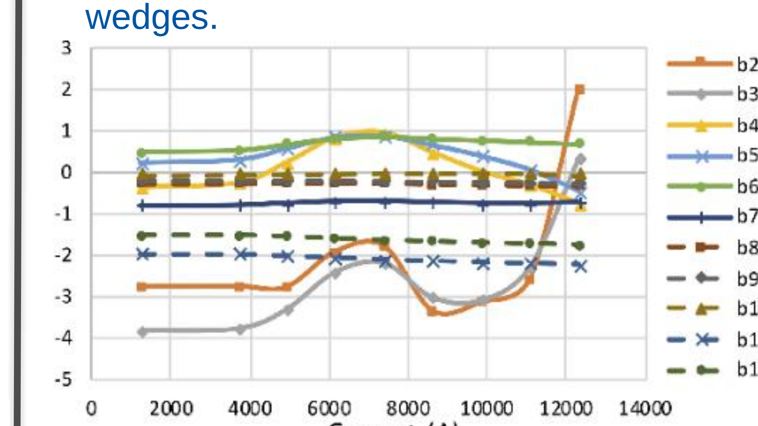


Fig.6 Expected normal field harmonics as function of current

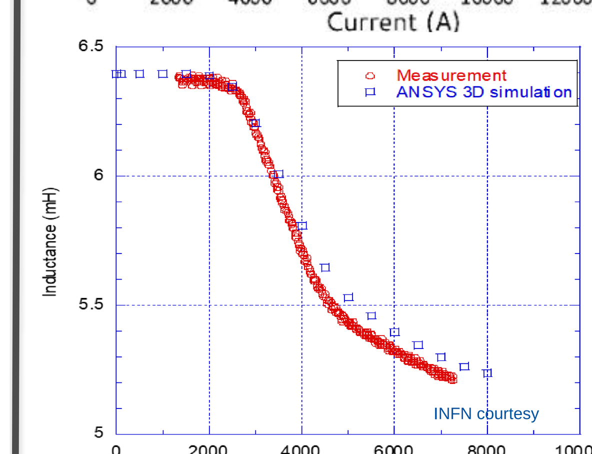


Fig.7 Fitting of dynamic inductance measurement with simulation of the double aperture magnet during powering.

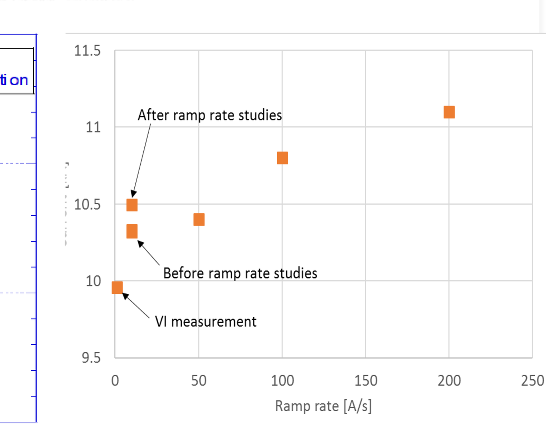


Fig. 8 Ramp rate dependency of the quench current with atypical behavior (higher current at higher ramp rate)