Status of D2 in INFN-Genova

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Outline

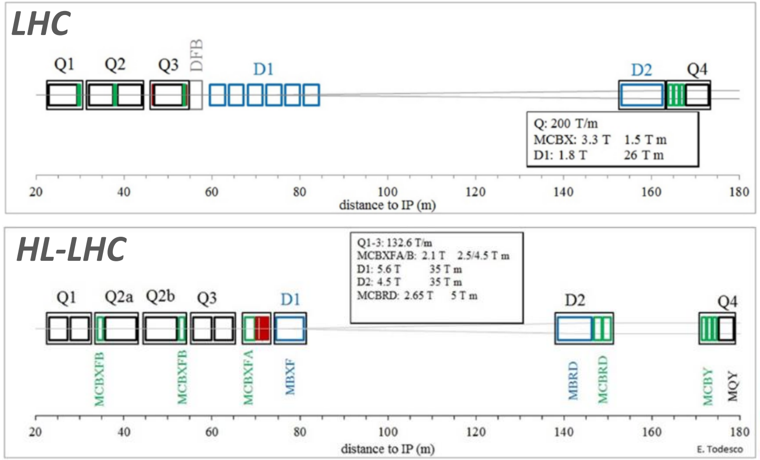
- CERN/INFN agreements
- D2 magnet layout
- Prototype test results:
  - Training
  - Protection scheme effectiveness
  - Magnetic measurements
  - Mechanical measurements
- From prototype to series:
  - Change of cross-section
- Status of the series magnets
- Overall schedule

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
    - Prototype tested at CERN from October 2022 to May 2023
    - Prototype 3rd aperture assembled to test critical series magnet modifications
  - *Addendum n.11 KE4417*
    - D2 Series production of 6 units (4 magnets for installation and 2 as spares)
    - Contract awarded to ASG Superconductors on March 2021
    - Engineering design completed
    - First magnet fabricated and tested @ RT at ASG Superconductors in July 2023

D2 Layout and Function

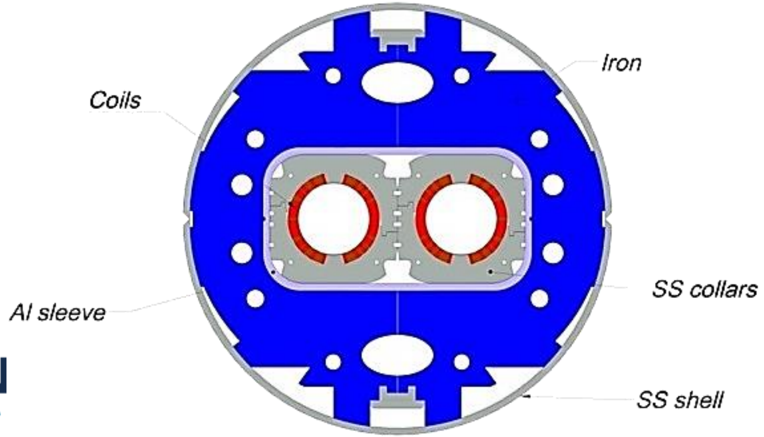
- The D2 dipole (MBRD, Main Bending Recombination Dipole) is placed in the D2 cold mass together with the orbit correctors around IP1 and IP5
- Main features:
  - Same field direction in both apertures connected in series (used to bring beams to collision)
  - $35\ T \cdot m$ integrated field at $7\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



# magnets	# apertures	# coils
4 series	8	16
2 spares	4	8
Total = 6	Total = 12	Total = 24

D2 Cross Section

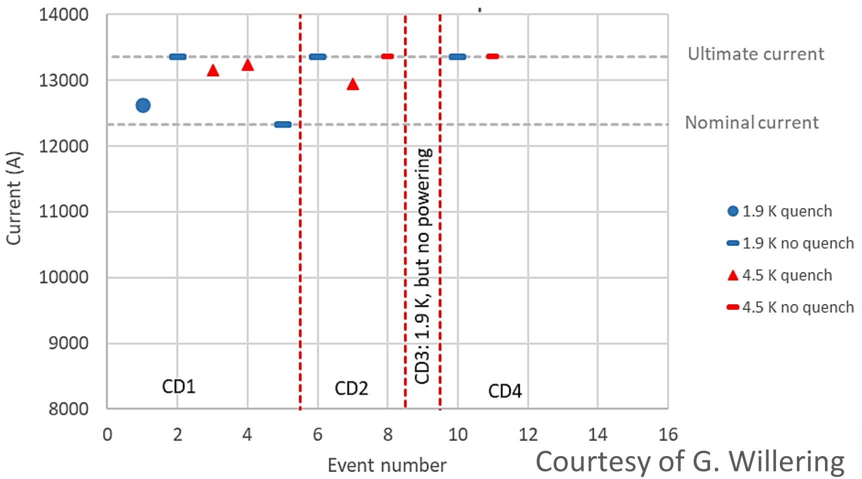
- Bore field: $4.5\ T$
- Magnetic length: $7.8\ m$ ($8.01\ m$ physical length)
- Challenges:
  - Field quality optimization based on asymmetric coils
  - Novel mechanical structure for the two apertures based on aluminum sleeves



Main characteristics of the D2 dipole	
Bore magnetic field	$4.5\ T$
Peak field	$5.3\ T$
Magnetic length	$7.78\ m$
Magnet physical length	$8.01\ m$
Operating current	$12.33\ kA$
Overall current density	$478\ A/mm^2$
Operating temperature	$1.9\ K$
Stored energy	$2.26\ MJ$
Aperture diameter	$105\ mm$
Beam separation @ cold	$188\ mm$
Loadline fraction	67.5%
Multipole variation due to iron saturation	< 10 units

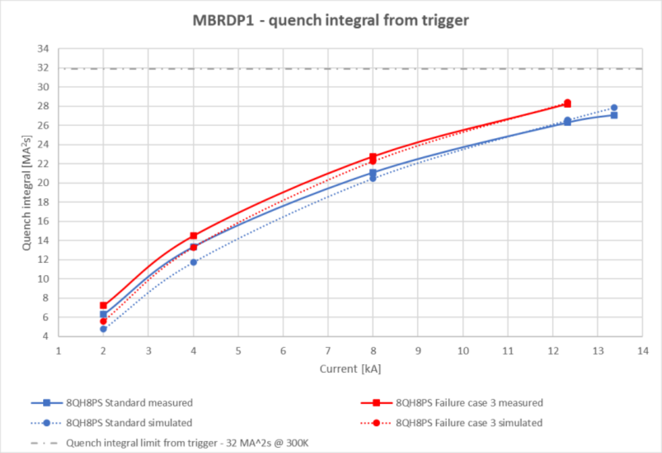
Prototype Test Results: Training

- First thermal cycle (CD1):
  - @ $1.9\ K$ reached nominal current without quench
  - @ $1.9\ K$ reached ultimate current in 1 quench
  - @ $4.5\ K$ quenched at 96% of SS limit
  - Ramp rate study were performed up to $200\ A/s$
- CD2:
  - @ $1.9\ K$ reached ultimate current without quench
  - @ $4.5\ K$ reached ultimate current in 1 quench
- CD4:
  - Reached ultimate current without quench at both $1.9\ K$ and $4.5\ K$



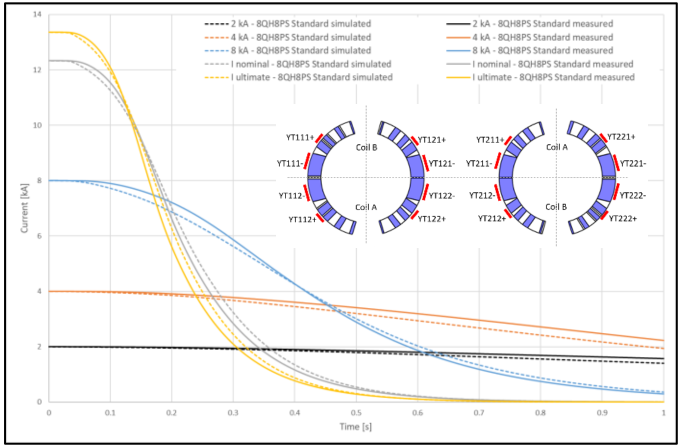
Courtesy of G. Willering

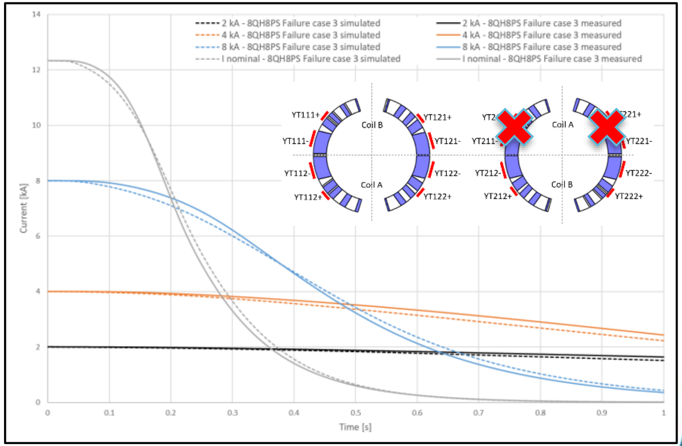
Prototype Test Results: Protection Scheme Effectiveness



The QI is given from the trigger; in a real quench one should add the time from quench start to trigger (e.g., for the quench at 1.9 K at 12.63 kA this was 23 ms or 3.7 MA^2s).

- The protection scheme used for D2 is based on 8 QHs, fed by 8 power supplies
- All the scenarios tested (including failure cases) are below the limit quench integral (QI) of 32 MA^2s corresponding to a 300 K hotspot
- The QI and the current decay measured are consistent with calculations
- The quench heaters fired $\sim$90 times ($\sim$33 with a current $\geq 8\ kA$)

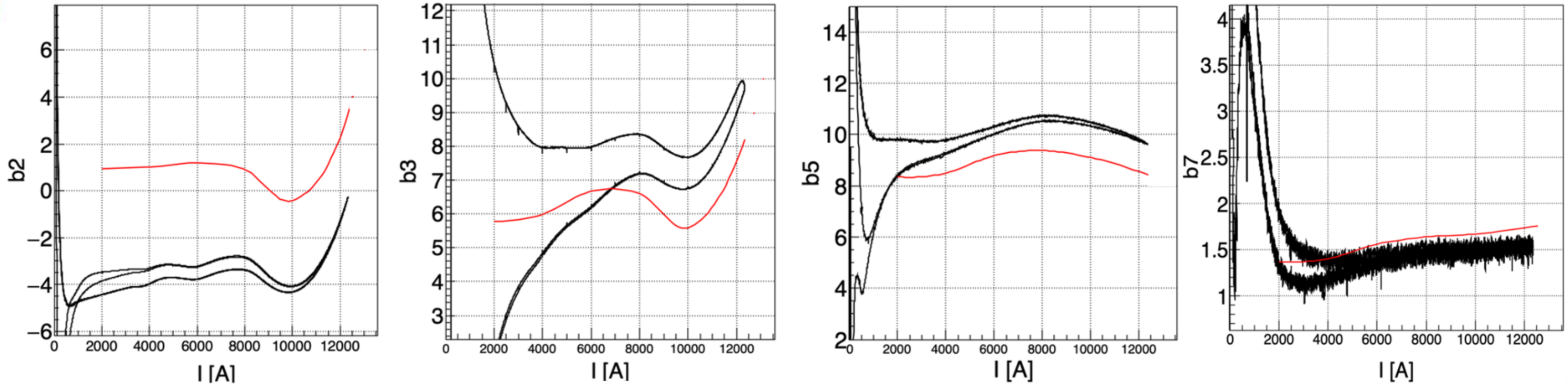




Courtesy of G. Willering

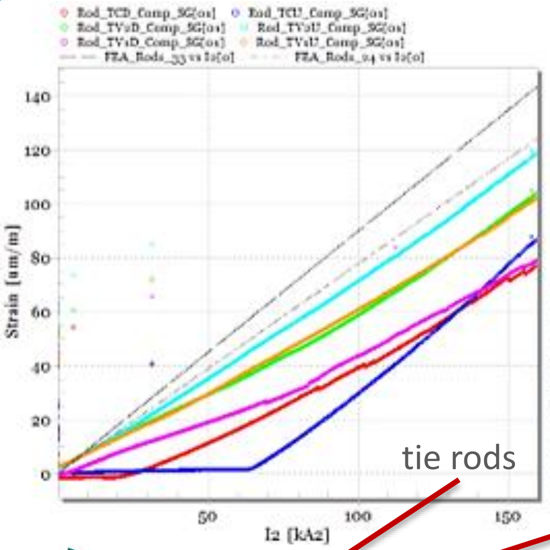
Prototype Test Results: Magnetic Measurements

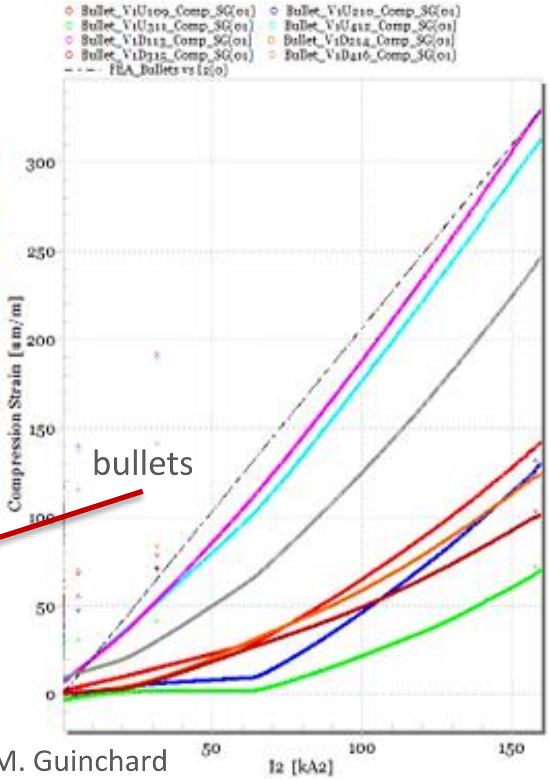
- The measured field quality is in fair agreement with the expected values:
  - Except for b_2, the measured integrated harmonics are in a range of about 1 $unit$ with our expectations
  - Harmonics components larger than b_7 are affected by noise because the mole radius is smaller than required (a new system is under developments at CERN for the series tests)

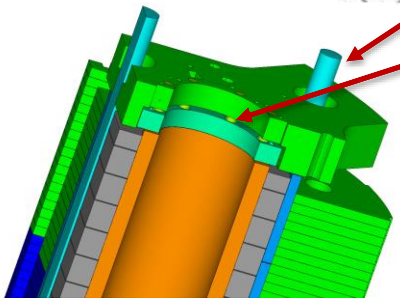


Courtesy of L. Fiscarelli

Prototype Test Results: Mechanical Measurements





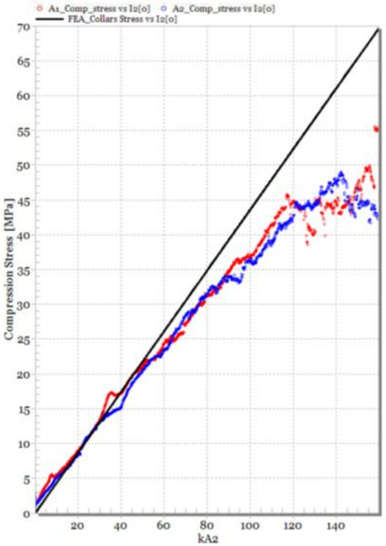


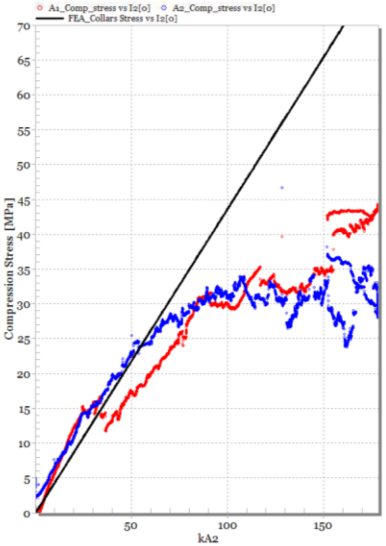
Courtesy of M. Guinchard

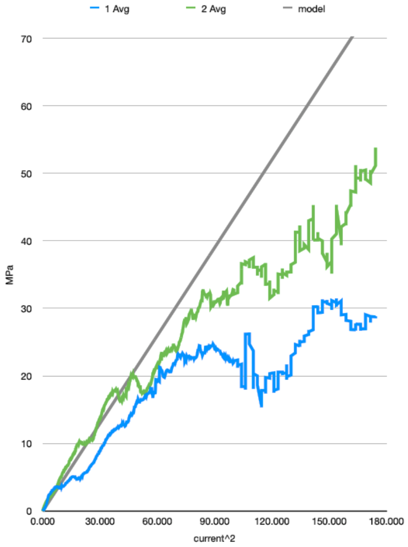
- The longitudinal pre-loading system is based on tie rods (2 M33 and 4 M24)
- The load is transferred to coils through 16 bullets
- The magnet is preloaded at half of the total Lorentz force ($256\ kN$)
- Mechanical measurements are slightly below FEA calculations
- A few tie rods and bullets are partially unloaded up to $7 - 8\ kA$
- The behaviour in the three cool downs is reproducible

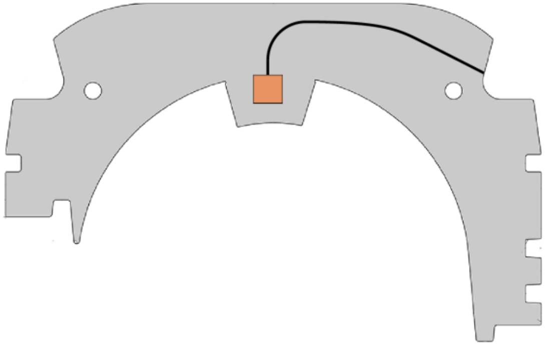
Prototype Test Results: Mechanical Measurements

- Several collars were instrumented with strain gauges in the pole
- A loss of pre-stress occurred between 1st and 2nd cool down
- No further reduction is evident between 2nd and 4th cool down





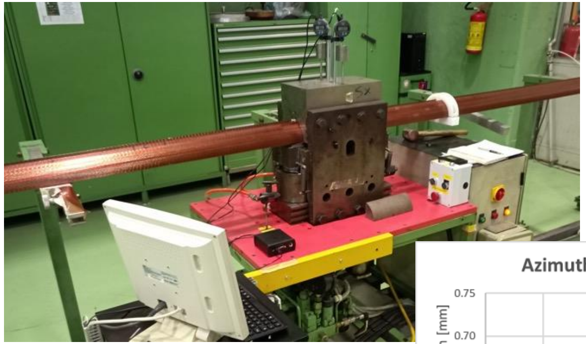


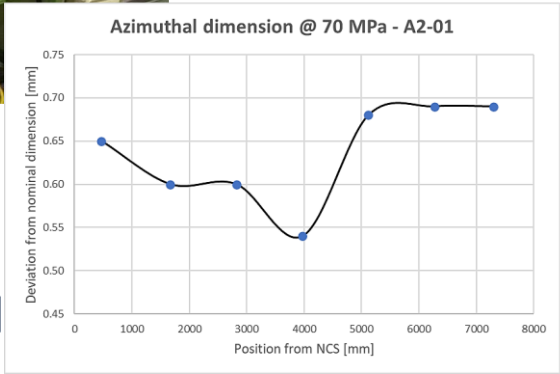


Courtesy of M. Guinchard

Prototype Coil Azimuthal Size

- Prototype coils exceed nominal azimuthal dimension by $0.64 \pm 0.05\ mm$ on average
- The dimensions are measured with a measuring press by applying several pressing cycles in 7 longitudinal points
- To keep the collaring pressure below reasonable values ($< 110\ MPa$), it was decided to reduce the azimuthal dimension of each coil by approximately $0.6\ mm$ by removing kapton layers from the insulation scheme, thus affecting the field quality

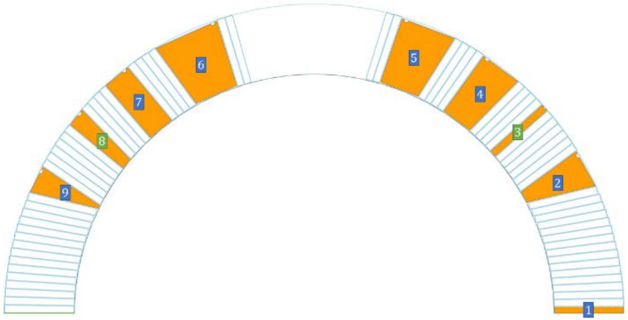


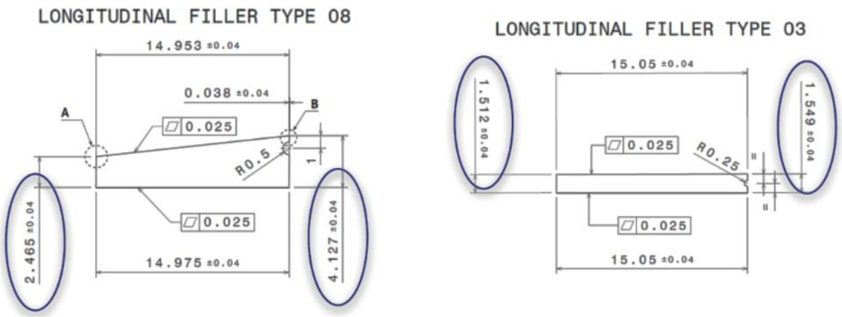


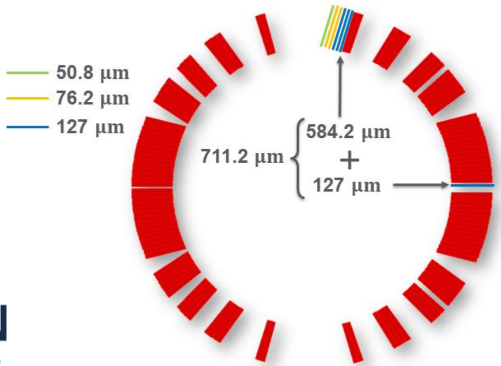
Coil	Min [mm]	Max [mm]	Avg [mm]	
A-01	0.36	0.62	0.54	Spare coil
A1-02	0.55	0.80	0.70	Spare aperture
B1-02	0.55	0.72	0.66	Spare aperture
A1-01	0.54	0.71	0.64	Aperture V1
B1-01	0.47	0.77	0.63	Aperture V1
A2-01	0.54	0.69	0.64	Aperture V2
B2-01	0.54	0.71	0.64	Aperture V2

Change of Cross-section

- For the series magnets, to address both field quality and coil size issues we proposed to modify by $0.3\,mm$ 2 longitudinal spacers out of 10 (type 8 and 3) and the insulation scheme → this mitigation strategy was partially tested with success in the prototype 3rd aperture.







The baseline insulation scheme of the series includes:

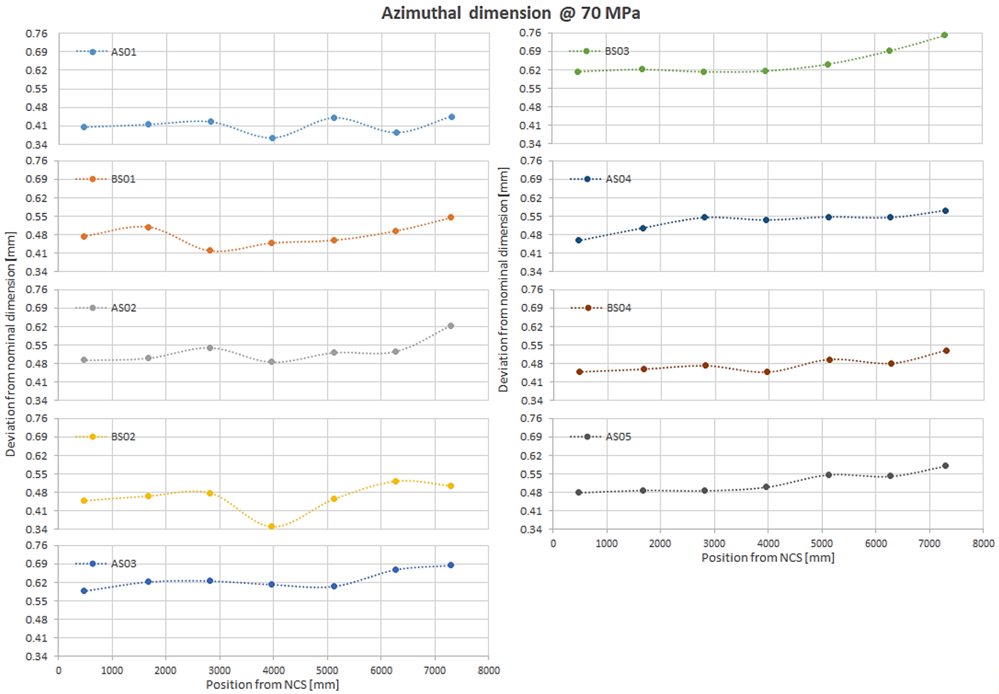
- On the pole
  - $1x50.8\ \mu m$ thick kapton sheet
  - $2x76.2\ \mu m$ thick kapton sheets
  - $3x127\ \mu m$ thick kapton sheets
- On the midplane
  - $1x127\ \mu m$ thick kapton sheet

Status of the Series Magnets

- MBRD1 (DIP1) fabrication has been completed at ASG Superconductors and the magnet has been measured at RT
- So far 13 coils have been wound, 9 of which have also been cured and measured (AS01, BS01, AS02 and BS02 were used for the construction of DIP1)
  - To address the different coil sizes, we studied a specific shimming plan to fulfil the field quality requirements

Oversize of the coils

Coil type	Min [mm]	Max [mm]	Avg [mm]
AS01	0.34	0.45	**0.41**
BS01	0.39	0.60	**0.48**
AS02	0.47	0.64	**0.53**
BS02	0.31	0.55	**0.46**
AS03	0.56	0.70	**0.63**
BS03	0.52	0.82	**0.65**
AS04	0.37	0.61	**0.53**
BS04	0.42	0.60	**0.48**
AS05	0.42	0.61	**0.52**



Status of the Series Magnets

- The cross-section change from prototype to series was effective according to RT magnetic measurements
- Our simulations show a consistent discrepancy of ~10 units in b_3 and ~5 units in b_5 that has not yet been understood and, therefore, needs to be carefully monitored and further studied
  - These discrepancies were also observed in the short model and in the prototype and are used as an offset to determine the expected field quality

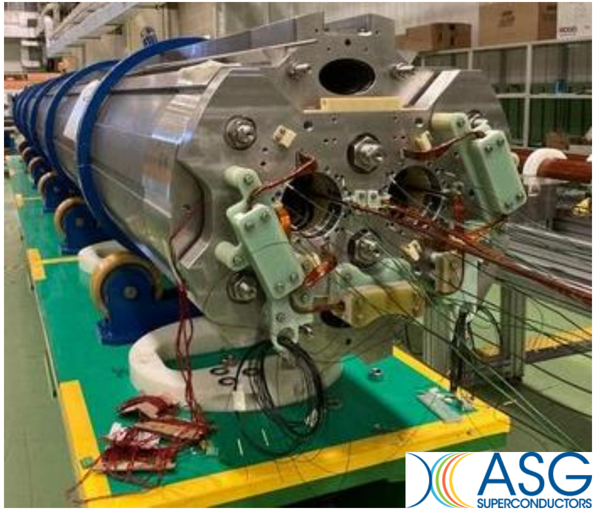
Double aperture with iron yoke at room temperature												
SIMULATIONS, EXPECTED & MEASUREMENTS												
	CENTER						INTEGRATED					
	AP01			AP02			AP01			AP02		
	SIMU	EXPE	MEAS	SIMU	EXPE	MEAS	SIMU	EXPE	MEAS	SIMU	EXPE	MEAS
b2	3.25	1.20	-1.27	-3.28	-1.23	1.32	-3.17	3.31	-5.19	3.22	-3.26	5.17
b3	-11.32	1.81	-1.84	-14.46	-1.33	1.35	-11.51	1.28	-3.26	-14.60	-1.81	-0.87
b4	-1.39	0.39	0.30	1.63	-0.15	2.08	-0.91	0.29	0.24	1.15	-0.05	1.66
b5	-0.43	4.78	4.90	-0.13	5.09	4.23	-1.53	3.63	4.01	-1.23	3.92	3.61
b6	-0.30	-2.03	1.32	0.30	2.02	0.45	-0.21	-2.00	1.33	0.20	1.99	0.32
b7	1.90	1.82	1.61	1.83	1.75	0.73	1.65	1.30	0.92	1.57	1.23	0.32

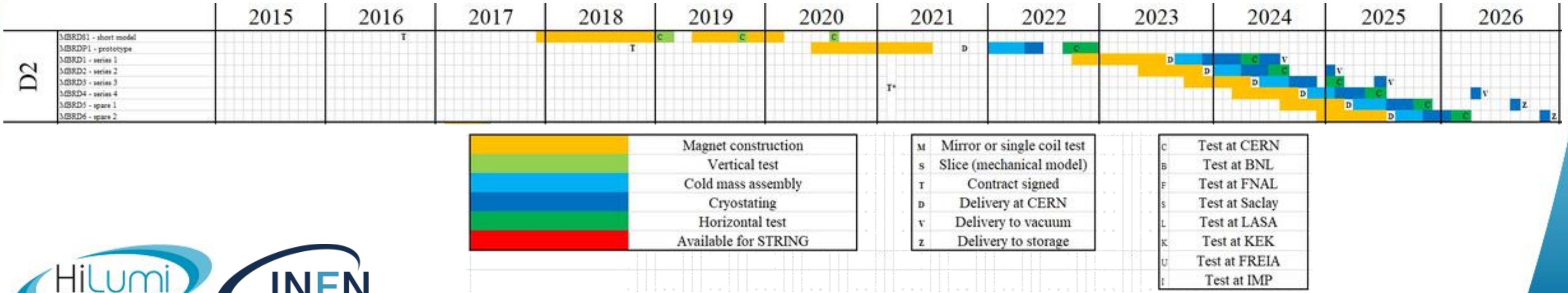
$$\Delta = Measurements_{PROTO}^{with\ iron\ @\ RT} - Simulations_{PROTO}^{with\ iron\ @\ RT}$$

$$EXPE = SIMU + \Delta$$

Overall Schedule

- The first series magnet (MBRD1) is completed and will be delivered to CERN in October
- Construction of the 6 series magnets is on schedule and is expected to be completed in mid-2025
- The plan for the series is aligned with the updated schedule
- The D2 series is not on the critical path





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Conclusion

- MBRD prototype was successfully tested in terms of training, protection scheme effectiveness, magnetic and mechanical measurements
  - In the fourth thermal cycle it reached ultimate current at both $1.9\ K$ and $4.5\ K$ without quench
  - The MIITs of all the scenarios tested are below the limit quench integral of $32\ MA^2s$ corresponding to a $300\ K$ hotspot
  - The measured field quality is in fair agreement with the simulation
- MBRD1 is completed and will be delivered to CERN in October 2023
- Production at ASG Superconductors is well organized and proceeding smoothly
  - 13 out of 24 coils have been fabricated


THANKS FOR YOUR ATTENTION
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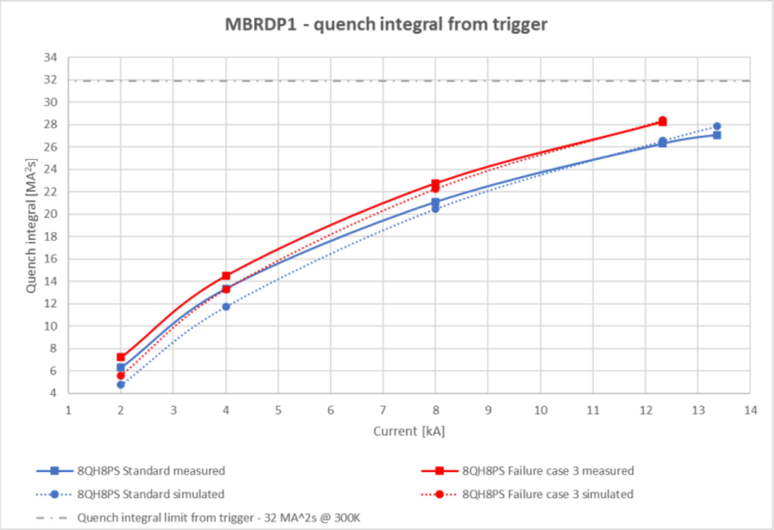
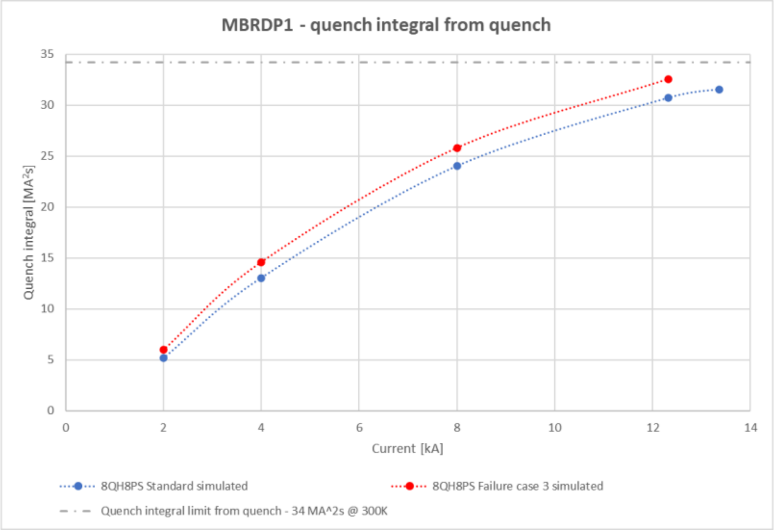
Prototype test results: protection scheme effectiveness



Note: the quench integral is given from the trigger moment; in a real quench one should add the time from quench start to trigger (e. g. for the quench at $1.9\ K$ at $12.63\ kA$ this was $23\ ms$ or $3.7\ MA^2s$).



Note: the quench integral simulated is given from the quench moment.

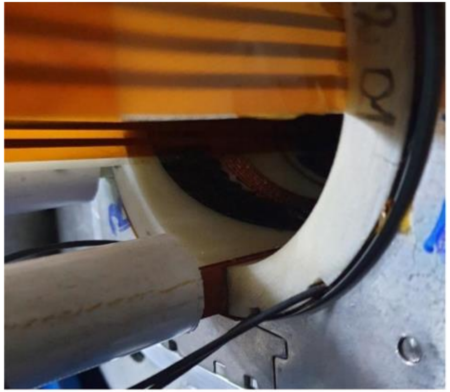
- The quench integral and the current decay measured are consistent with calculations
- During tests, the quench heaters fired about 90 times (~ 33 times with a current $\geq 8\ kA$)

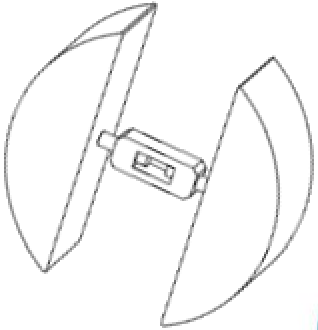
Courtesy of G. Willering

Prototype NCs: AP02 Leads Protrusion

NC EDMS 2618354 – noncritical, level 3

- After collaring of AP02, the leads were found to protrude into the bore leaving a free diameter of $101.6\ mm$ compared to the nominal diameter of $105\ mm$.
- 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 prototype 3rd aperture.
- Moreover, the small protrusions corresponding to the electrical connections of the voltage taps further reduce the free space available in the bore – these voltage taps are not foreseen in the series.

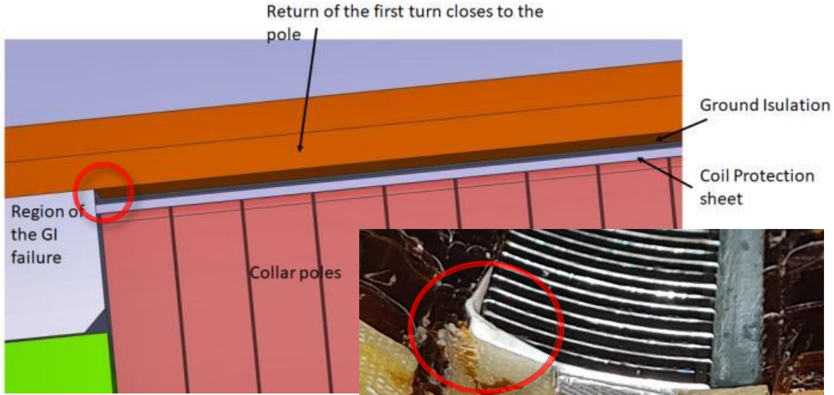


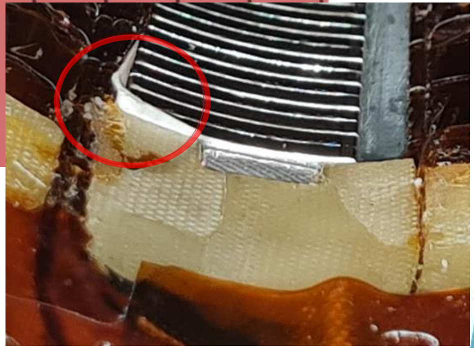


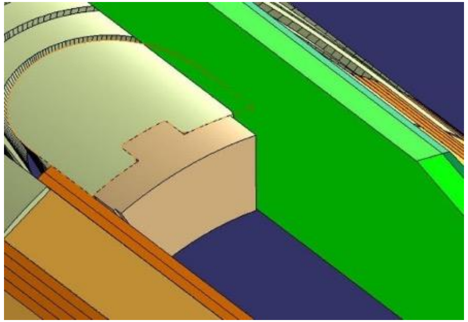
Prototype NCs: Coil B2-01 of AP02 Ground Insulation

NC EDMS 2589433 – noncritical, level 3

- An intermediate Hi-Pot test at $3.1\ kV$ done during the assembly of AP01 and AP02 into the Al sleeves was not passed (sparks). The maximum voltage with no spark and good insulation ($> 10G\Omega$) is $2.7\ kV$.
- The cause is the sharp edge of the Coil Protection Sheet (CPS) shoe 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 mechanical and electrical intercept for the collar shoe → successfully tested in the prototype 3rd aperture.



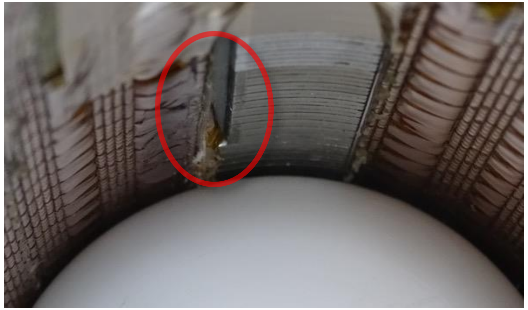


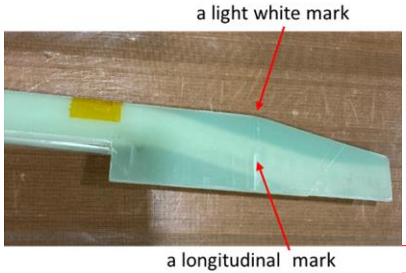


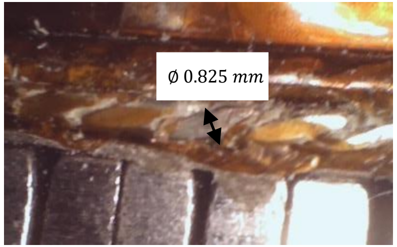
Prototype NCs: Layer Jump Protrusion

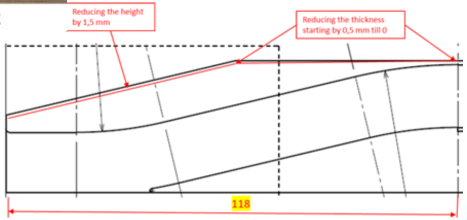
EDMS NC 2715620 – critical, level 4

- During the cold bore insertion, it was not possible to proceed because it got stuck on the connection side because both the layer jump and the NOMEX layer were protruding $\sim 2\,mm$ in the bore.
- After the insertion trial, the cable insulation was damaged → the insulation was consolidated using the injection of Eccobond epoxy under a controlled applied pressure afterwards successfully passed the electrical tests.
- 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 prototype 3rd aperture.



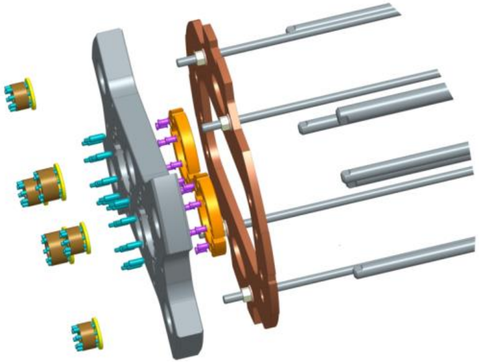






Prototype NCs: Axial Pre-stress Loss

- 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 CERN and bolts have been glued → afterwards no significant change has been observed.
- 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.



- Several mitigation strategies have been investigated:
  - Modification of transport tool
  - Measurement of the actual properties of the Superbolts
  - Increase of the axial pre-load
  - Final tightening at CERN
  - Screw blocking either mechanically, via welding or gluing.
- Our suggestion is gluing, with Staycast or equivalent, after tightening to ensure reversibility.

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Strategy for the Series Magnets

- 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 from MBRD2 to MBRD6 (**DIP2 – DIP6**)
  - MBRD1 will still be compliant with D2 requirements for use in the HL-LHC

    ⇒ **The production of the D2 series magnets cannot be fully parallelized**
- Our strategy for the series production:
  - Produce two coils and collar the first pre-series aperture (**hold point on coil fabrication**)
  - If the collaring of the first aperture is successfully done, release the hold point on coil fabrication
  - Produce and collar the second two coils (**hold point on the aperture fabrication**)
  - Assemble the two pre-series apertures into the iron yoke and perform warm magnetic measurements
  - If the warm magnetic measurements are in line with expectations, release the hold point on aperture fabrication
  - Start the production of the 5 series magnets