D2-prototype cold mass *MTF: HCLMBRDP001-CR000001*

Test results end of Cool Down 4

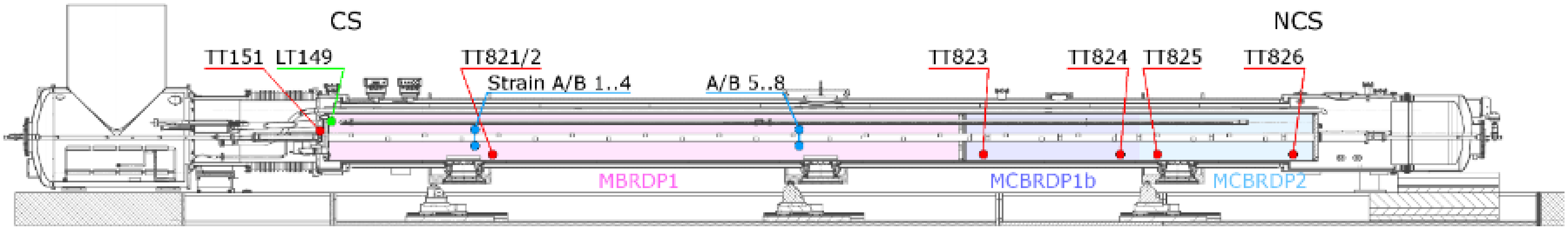
Gerard Willering
Franco Mangiarotti, Gaëlle Ninet
Many thanks to Raphaël Bouvier

Test plan: EDMS 2707482
Test results: EDMS 2821189

D2-prototype on the SM18 test bench

CFB

MRB



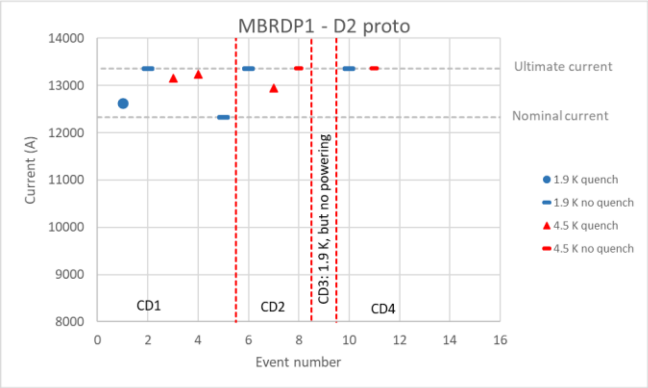
Three magnets are in the cold mass:

MBRDP1 – INFN + ASG
MCBRDP1b – CERN first prototype
MCBRDP2 – IHEP first prototype

Quench performance

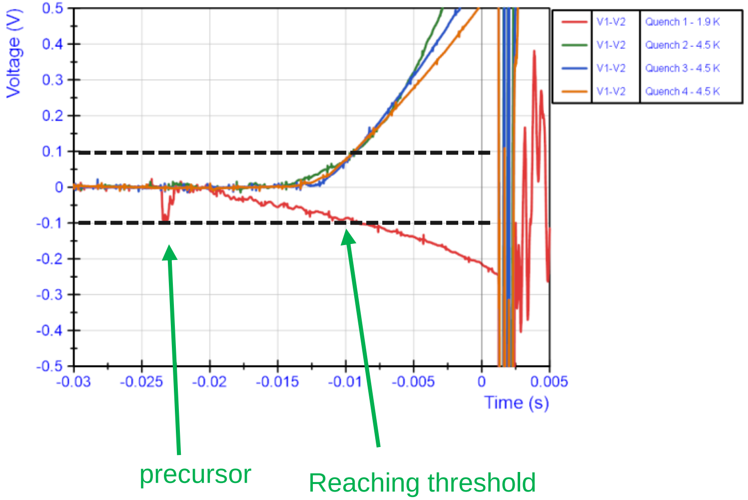
MBRDP1 magnet:
- 1 quench in 4 cool downs at 1.9 K above nominal current.
- 3 quenches in 4 cool downs at 4.5 K, all above nominal current.
- No powering in cool down 3
- No quench in cool down 4 up to ultimate at 1.9 K and 4.5 K

Good



Event in plot	CD	T (K)	Iq (kA)	RR (A/s)	Quenched coil	Voltage tap segment	Longitudinal location (quench antenna)
1	1	1.9	12.63	10	Aperture 2 lower coil	401-404	Head non-connection side
2	1	4.5	13.16	10	Aperture 1 lower coil	123-201 & 201-202	Head non-connection side
3	1	4.5	13.24	10	Aperture 1 upper coil	103-104	Straight
4	2	4.5	12.94	10	Aperture 1 upper coil	101-104	Head non-connection side

Voltage build up during quench



MBRDP1 magnet:

- One training quench with classical precursor at 1.9 K
- Three quenches without precursor at 4.5 K
- Quench detection threshold 100 mV with 10 ms validation time

Time to reach threshold is 13 ms in the 1.9 K quench, and about 3-5 ms in the 4.5 K qeunches.

(note: the time to reach threshold strongly depends on current, field in the quench location and temperature. For the quench integral at nominal current of 12.33 kA, every 10 ms accounts for 1.5 MA^2s).

MBRD test overview

	Period	I_QH > 50 A	I_QH > 50 A I_magnet > 8 kA	Comment
CD1	Oct 2022	20	8	Main dipole powering, start of protection studies
CD2	Oct-Nov 2022	49	20	Main dipole and correctors powering
CD3	Feb 2023	7	0	No powering, cryo-valve issue
CD4	April/May 2023	14	5	Tests completed, including full HV test.
Total		**~90**	**~33**	

In 4 cool downs the MBRD magnet quench heaters have been fired ~33 times while there was a current of ≥ 8 kA.
The total number of times the quench heaters were fired is about ~90.

Insulation test

MBRD
Coil-ground requirement: 2060 V (during first cool downs test voltage reduced to 1000 V because of insulation damage during magnet production)
QH-Coil requirement: 2300 V
Corrector magnet – ground: 1620 V

	Coil-Ground	**QH-Coil**	**MCBRDP1b-ground**	**MCBRDP2-ground**
CD 1	1000 V – OK	1000 V – OK	1620 V - OK	1620 V - OK
CD 2	1000 V – OK	1000 V – OK	1620 V – OK	1620 V, failed at 900 V and developed in low resistance short during warm up ~ 1.1 Ω
CD 3	1000 V – OK	1000 V – OK	1620 V – OK	~ 1.1 Ω short to ground.
CD 4	2060 V, failed above 1600 V followed by repetitive breakdowns at ~ 1200 V	2300 V - OK	1620 V - OK	~ 1.1 Ω short to ground. Localized to midpoint of one aperture where a CLIQ lead was connected. NC report, see EDMS 2812061

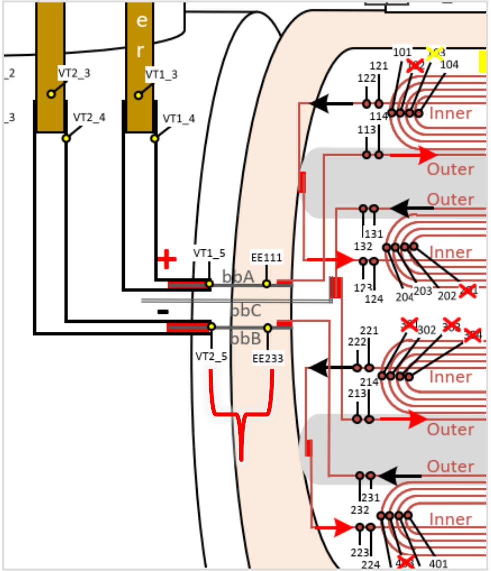
Not good
See next slide

Good

Good

Not good

Non-conformity localization during insulation test MBRD



Courtesy Gaëlle Ninet

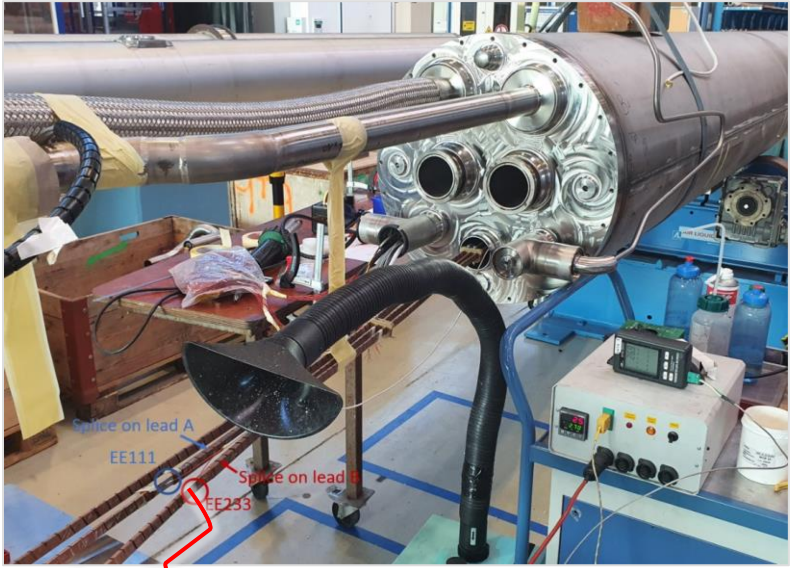


Photo before assembly, courtesy Hervé Prin and Ludovic Grand-Clement

NC report EDMS 2905472

The ELQA team (thanks to Giorgio D'Angelo and Jaromir Ludwin) performed localization tests and identified with high certainty that the breakdown occurs repetitively between EE233 and VT2_5.

The electrical localization suggests that the defect is on the busbar outside of the magnet.

This could not be confirmed yet, since the magnet is still connected and closed to the bench.

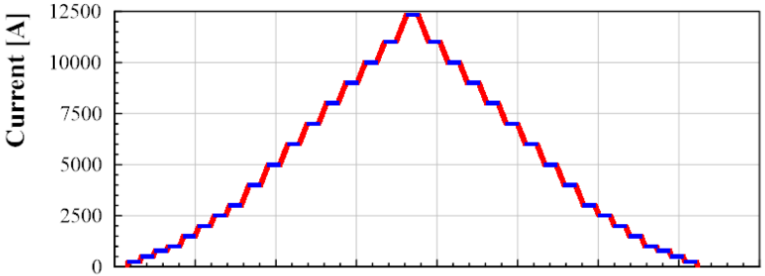
To be confirmed

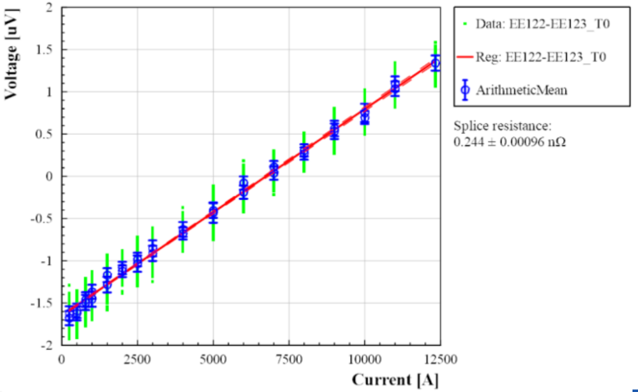
Splices MCBRD

EE111-EE113: 0.20 ± 0.02 nΩ (lead extension, made at CERN, will be desoldered for HLLHC installation)
EE122-EE123: 0.24 ± 0.02 nΩ (Interpole, made at ASG, will stay for HLLHC installation)
EE132-EE213: 0.64 ± 0.02 nΩ (Middle splice with 3rd lead. Current goes through 3 solderings, made at CERN, will be desoldered for installation)
EE222-EE223: 0.22 ± 0.02 nΩ (Interpole, made at ASG, will stay for HLLHC installation)
EE232-EE233: 0.30 ± 0.02 nΩ (lead extension, made at CERN, will be desoldered for HLLHC installation)

Good

All splices show linear behavior and fall in expected range up to nominal current.





Instrumentation wires

Category 1:

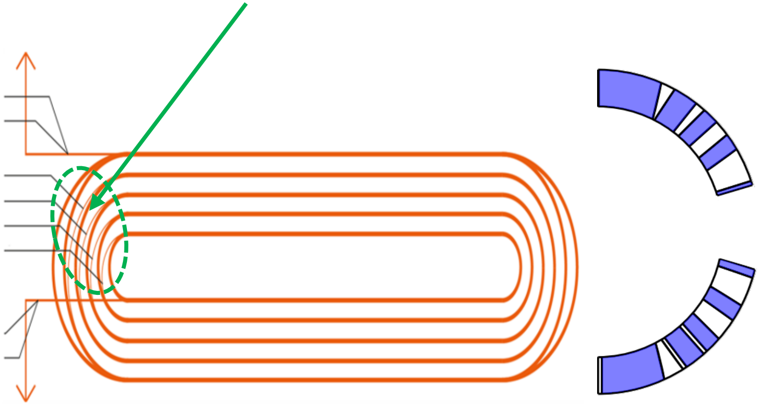
- Voltage taps for protection – HL-LHC scheme
- 4 per coil. All 16 voltage taps OK.

Category 2:

- Voltage taps for prototype magnet
- Not for HL-LHC series
- 4 per coil, lost 8 out of 16 voltage taps:

Lost before first cool down: EE102 and EE304
Lost during first cool down: EE301, EE402, EE403
Lost during powering CD1: EE103, EE201, EE303

Half of the additional voltage taps lost.



One could discuss the balance between risk and gain of the additional voltage taps.

MBRD Protection studies

Long list of protection studies

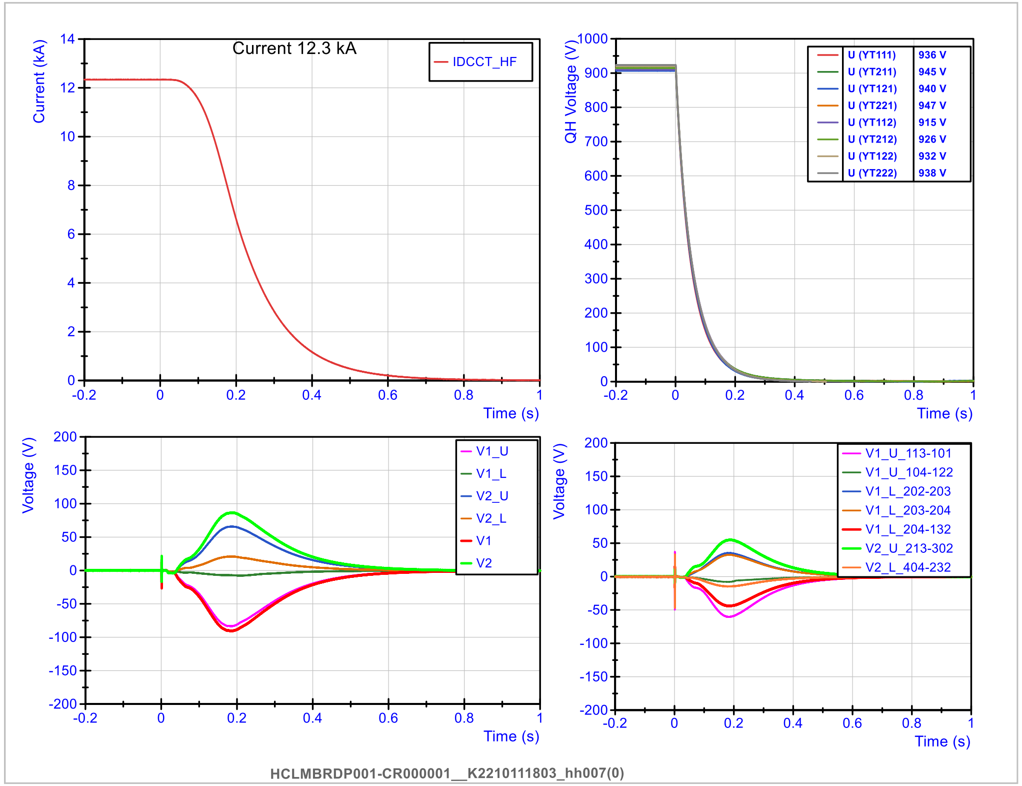
Quite time intensive, due to cryo recovery

44 tests done, data available.

Tests in red were not done, due to the change in baseline.

	Priority	Current [kA]	Trigger type	QH connected	V_QH [V]	R_QH [Ω]	Delay_QH [ms]	Notes
TO BE DONE FIRST								
8 QH 8QHPS characterization	1	2	Potaim	ALL QHs	900	7	0	8 QH 8QHPS Standard
	2	4	Potaim	ALL QHs	900	7	0	8 QH 8QHPS Standard
	1	8	Potaim	ALL QHs	900	7	0	8 QH 8QHPS Standard
	1	12.33	Potaim	ALL QHs	900	7	0	8 QH 8QHPS Standard
	1	13.36	Potaim	ALL QHs	900	7	0	8 QH 8QHPS Standard
4.5 K 8 QH			Potaim	ALL QHs	900	7	0	8 QH 8QHPS Standard
8QH 8QHPS characterization	1	2	Potaim	YT212, YT121, YT112, YT222,YT111,YT122	900	7	0	8 QH 8QHPS Failure 3
	2	4	Potaim	YT212, YT121, YT112, YT222,YT111,YT122	900	7	0	8 QH 8QHPS Failure 3
	1	8	Potaim	YT212, YT121, YT112, YT222,YT111,YT122	900	7	0	8 QH 8QHPS Failure 3
	1	12.33	Potaim	YT212, YT121, YT112, YT222,YT111,YT122	900	7	0	8 QH 8QHPS Failure 3
6 QH 6QHPS characterization	3	6	Potaim	YT212, YT121,YT112,YT222,YT111,YT221	900	7	0	6 QH 6QHPS Standard
	3	12.33	Potaim	YT212, YT121,YT112,YT222,YT111,YT221	900	7	0	6 QH 6QHPS Standard
6 QH 6QHPS characterization	3	6	Potaim	YT212, YT121, YT222,YT111	900	7	0	6 QH 6QHPS Failure 3
	3	12.33	Potaim	YT212, YT121, YT222,YT111	900	7	0	6 QH 6QHPS Failure 3
8 QH 4QHPS characterization	3	1.5	Potaim	(YT221,YT111) (YT211,YT112) (YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Standard
	3	4	Potaim	(YT221,YT111) (YT211,YT112) (YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Standard
	3	8	Potaim	(YT221,YT111) (YT211,YT112) (YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Standard
	3	10	Potaim	(YT221,YT111) (YT211,YT112) (YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Standard
	3	12.33	Potaim	(YT221,YT111) (YT211,YT112) (YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Standard
	3	13.36	Potaim	(YT221,YT111) (YT211,YT112) (YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Standard
8 QH 4QHPS characterization	3	2	Potaim	(YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Failure 3
	3	4	Potaim	(YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Failure 3
	3	8	Potaim	(YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Failure 3
	3	12.33	Potaim	(YT121,YT222) (YT122,YT212)	900	7	0	8 QH 4QHPS Failure 3
QH delay, low voltage (minimum QH energy) 8QH 8QHPS	2	1	YT221	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT221 at Vmin (in Ledet 200 V), the rest at 900V
	2	2	YT221	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT221 at Vmin (in Ledet 200 V), the rest at 900V
	2	3	YT221	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT221 at Vmin (in Ledet 200 V), the rest at 900V
QH delay, low voltage (minimum QH energy) 8QH 8QHPS	1	1	YT212	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT212 at Vmin (in Ledet 200 V), the rest at 900V
	1	2	YT212	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT212 at Vmin (in Ledet 200 V), the rest at 900V
	1	3	YT212	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT212 at Vmin (in Ledet 200 V), the rest at 900V
QH delay, low voltage (minimum QH energy) 8QH 8QHPS	1	1	YT111	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT111 at Vmin (in Ledet 200 V), the rest at 900V
	1	2	YT111	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT111 at Vmin (in Ledet 200 V), the rest at 900V
	1	3	YT111	~~All the other QHs~~ 6 quench heaters	200 900	7	0	YT111 at Vmin (in Ledet 200 V), the rest at 900V
QH delay 8QH 8QHPS	3	2	YT221	All the other QHs	450 900	7	0	YT221 at 450 V, the rest at 900V
	3	6	YT221	All the other QHs	450 900	7	0	YT221 at 450 V, the rest at 900V
	3	12.33	YT221	All the other QHs	450 900	7	0	YT221 at 450 V, the rest at 900V
QH delay 8QH 8QHPS	3	2	YT212	All the other QHs	450 900	7	0	YT212 at 450 V, the rest at 900V
	3	6	YT212	All the other QHs	450 900	7	0	YT212 at 450 V, the rest at 900V
	3	12.33	YT212	All the other QHs	450 900	7	0	YT212 at 450 V, the rest at 900V
QH delay 8QH 8QHPS	3	2	YT111	All the other QHs	450 900	7	0	YT111 at 450 V, the rest at 900V
	3	6	YT111	All the other QHs	450 900	7	0	YT111 at 450 V, the rest at 900V
	3	12.33	YT111	All the other QHs	450 900	7	0	YT111 at 450 V, the rest at 900V
QH delay 8QH 8QHPS	2	2	YT221	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT221 at 900 V, the rest at 900V
	2	6	YT221	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT221 at 900 V, the rest at 900V
	2	12.33	YT221	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT221 at 900 V, the rest at 900V
QH delay 8QH 8QHPS	1	2	YT212	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT212 at 900 V, the rest at 900V
	1	6	YT212	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT212 at 900 V, the rest at 900V
	1	12.33	YT212	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT212 at 900 V, the rest at 900V
QH delay 8QH 8QHPS	1	2	YT111	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT111 at 900 V, the rest at 900V
	1	6	YT111	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT111 at 900 V, the rest at 900V
	1	12.33	YT111	~~All the other QHs~~ 6 quench heaters	900 900	7	0	YT111 at 900 V, the rest at 900V
Do not do								
Baseline characterization (4QH, 4QHPS)	1	2	Potaim	YT212, YT121, YT112, YT221	900	7	0	4 QH 4QHPS Standard
	2	4	Potaim	YT212, YT121, YT112, YT221	900	7	0	4 QH 4QHPS Standard
	1	8	Potaim	YT212, YT121, YT112, YT221	900	7	0	4 QH 4QHPS Standard
	1	12.33	Potaim	YT212, YT121, YT112, YT221	900	7	0	4 QH 4QHPS Standard
	1	13.36	Potaim	YT212, YT121, YT112, YT221	900	7	0	4 QH 4QHPS Standard
Baseline characterization (4QH, 4QHPS)	1	2	Potaim	YT212, YT221	900	7	0	4 QH 4QHPS Failure 3
	2	4	Potaim	YT212, YT221	900	7	0	4 QH 4QHPS Failure 3
	1	8	Potaim	YT212, YT221	900	7	0	4 QH 4QHPS Failure 3
	1	12.33	Potaim	YT212, YT221	900	7	0	4 QH 4QHPS Failure 3

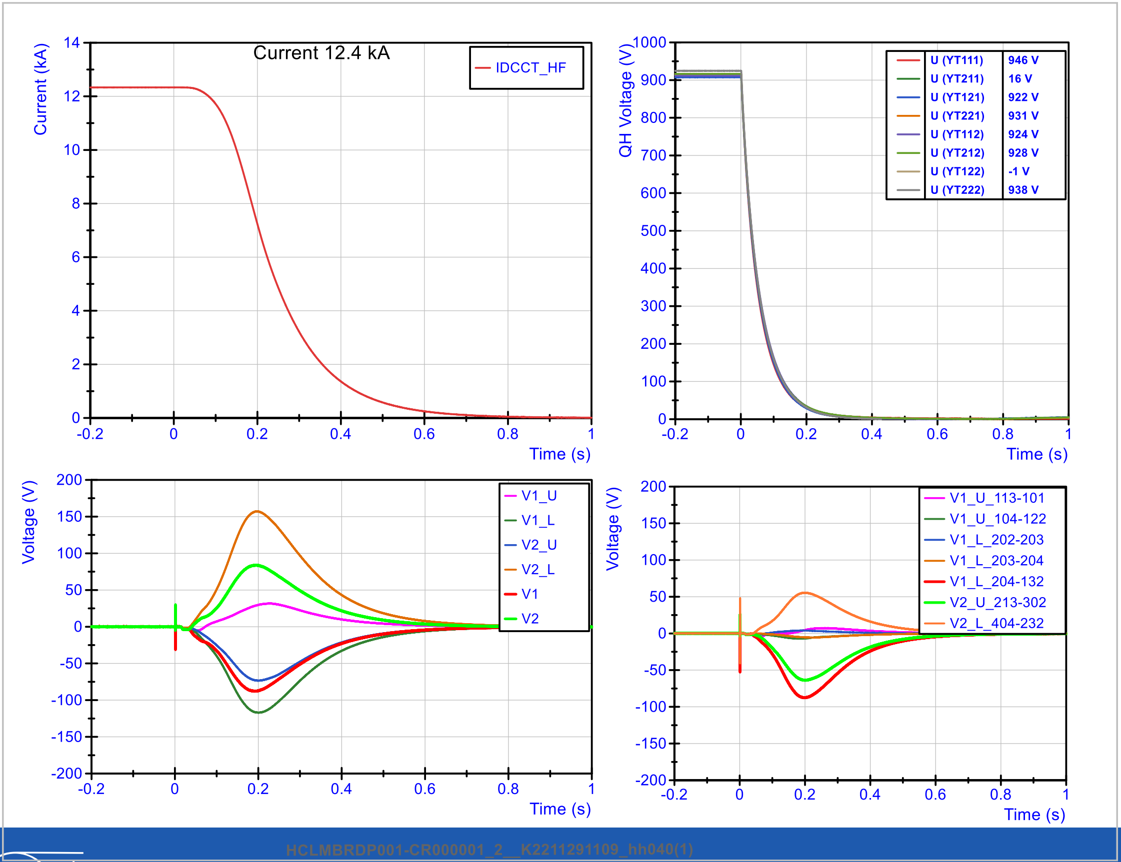
Nominal QH firing at nominal current - characteristic plots



8 quench heaters fired at t = 0 s
Baseline case.

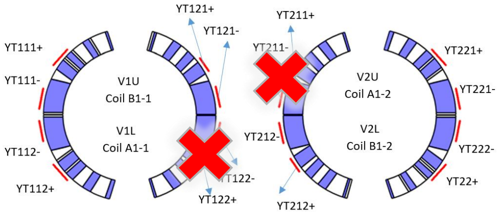
Some voltage imbalance between the coils of about 140 V between coil V2_U and V1_U.

6 out of 8 QH firing at nominal current - characteristic plots

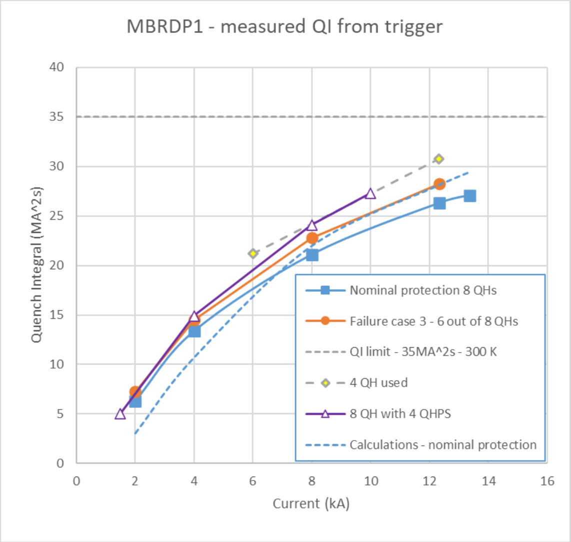


6 quench heaters fired at t = 0 s
Failure case scenario, with YT122 and YT211 not powered.

Higher voltage imbalance than in nominal protection case.

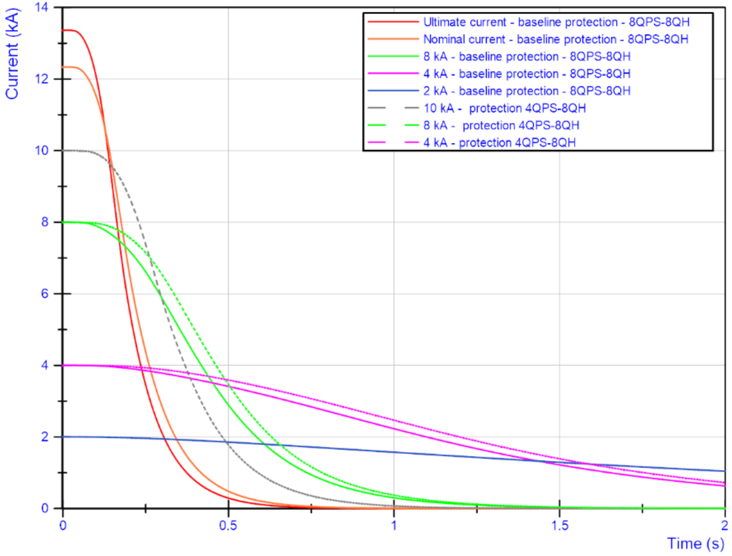


Quench integral

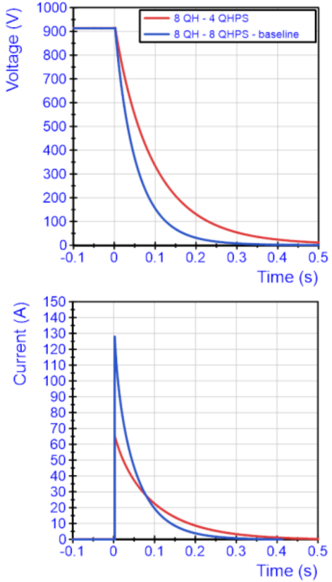


At nominal current, quench integral is lower in measurements than in simulations.

Note: the quench integral is given here from the trigger moment. In a real quench case one should add the time from quench start to trigger. For the quench at 1.9 K at 12.63 kA this was 23 ms or 3.7 MA^2s.

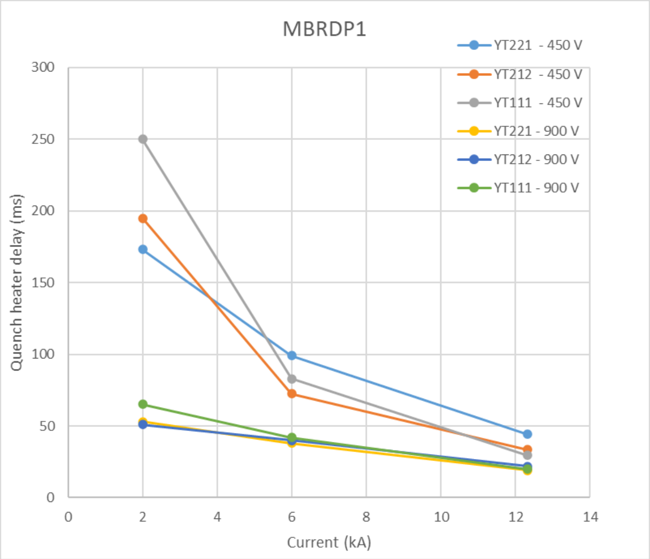


Comparison current decay between various discharges



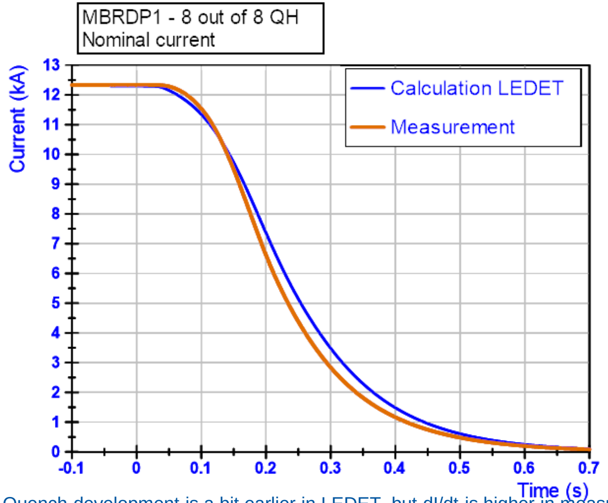
Comparison current in quench heaters between baseline and series connected heaters.

MBRD protection studies



Delay between QH firing and quench start.

Minimum Quench Energy studies showed that the quench heaters did not provoke a quench with 200 V discharge up to 3 kA. At 450 V the quench protection becomes effective.



Quench development is a bit earlier in LEDET, but dI/dt is higher in measurement.

See discussion by Barbara Caiffi
All data is available for model validation

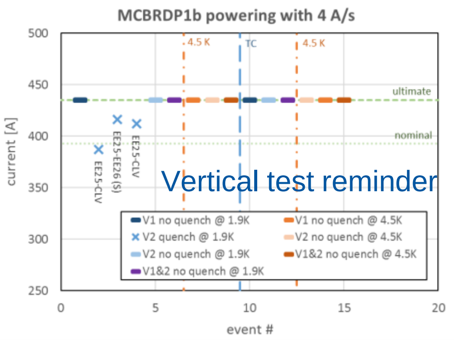
Protection studies are focused at providing a maximum amount of information to confirm baseline and failure case scenarios

MCBRDP1b Quench performance

MCBRDP1b magnet:

- No powering in CD1 and CD3
- No quenches to ultimate current in CD2 at 1.9 K
- No quenches to ultimate current in CD2 at 4.5 K
- No quenches to ultimate current in combined powering with the MBRDP1 magnet.
- No quenches in CD4 up to ultimate at 1.9 K

Good



MCBRDP2 magnet

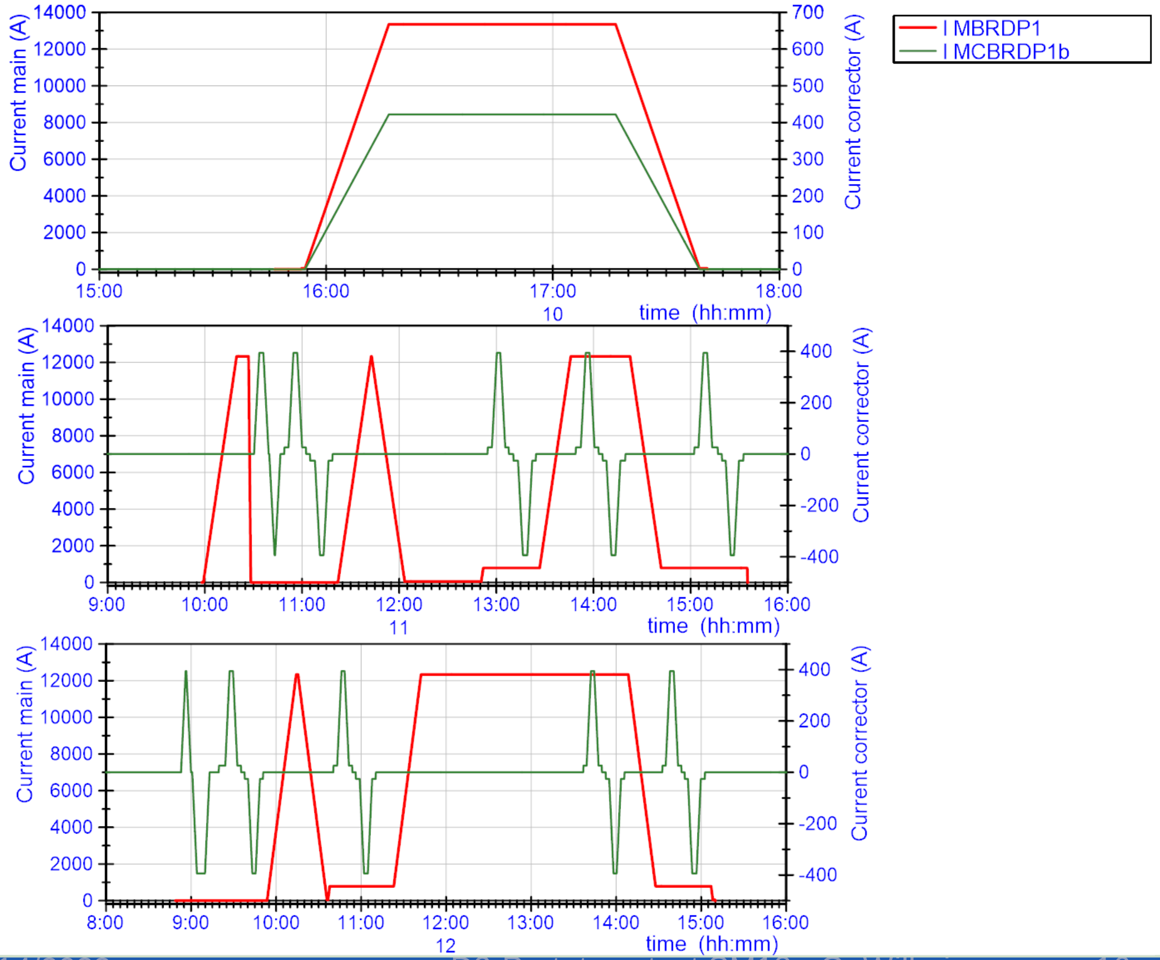
- No powering done due to short circuit to ground in CD2

Not tested

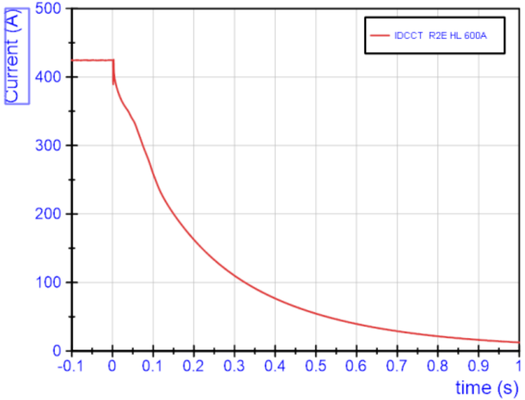
MCBRDP1b + MBRDP1 combined powering

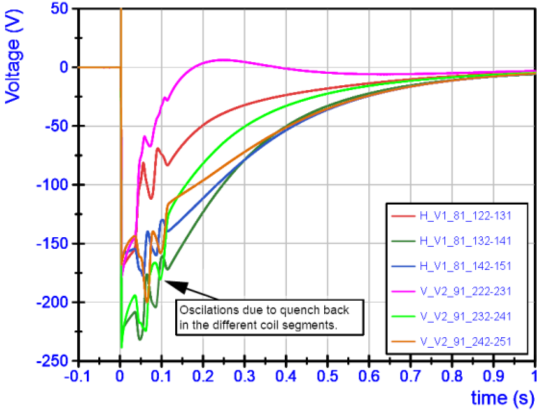
Combined powering to ultimate without quenches or surprises.

Magnetic measurement cycles done successfully at nominal current, see presentation by Lucio.



MCBRDP1b protection



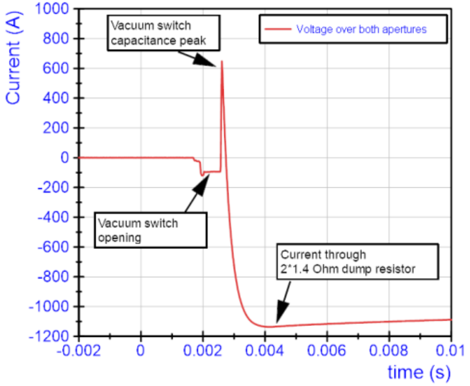


Test specific layout:

- 2 apertures powered in series.
- Two dump resistors with 1.4 Ohm each for the circuit (extraction voltage of ~1200 V)

Vacuum switches were used.

- All functioning as expected.
- This also is a test using new systems.



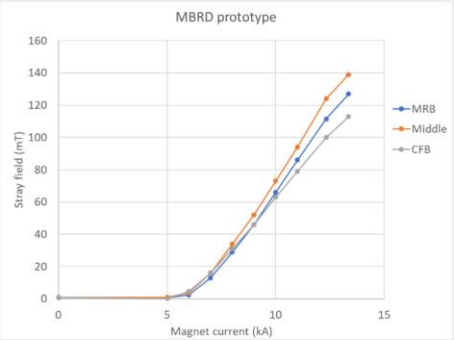
HCLMBRDP001-CR000001_2__K2211241016_gd019(0)

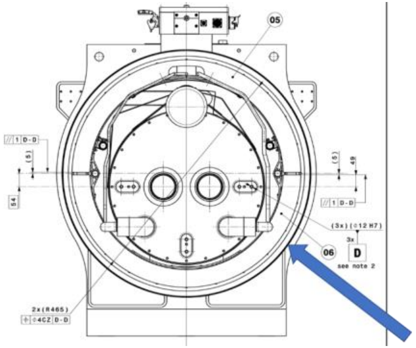
Good
Reference data is now available for new energy extraction system.

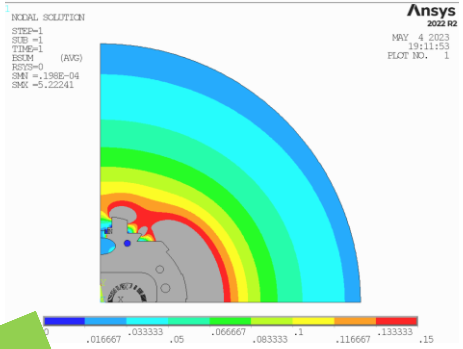
MBRDP1 stray field.

- Up to ~ 150 mT next to the magnet at ultimate current.
- Strong enough to lift a screwdriver
- Moving the signal cable from IFS box does not trigger the standard magnet protection, but in the test configuration it can trigger the bus bar protection.

Not a problem, but good to have reference data, also to follow safety rules.

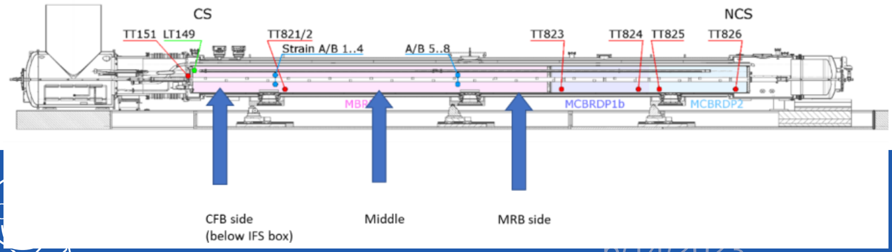






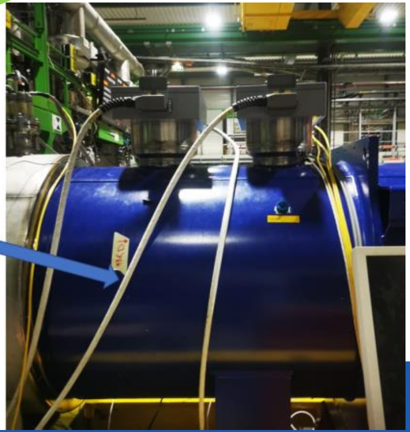
Field map courtesy Stefania Farinon

Good
Rough validation of calculations



150 mT (at ultimate current) at signal cable next to the cryostat.

For wire pairs in the moving cable there is no issue.



Summary

- MBRD powering performance very good.
- MBRD full insulation test had a break down outside the cold mass. To be investigated.
- Protection is OK. QI a bit lower than expected. Reference data available.
- Overall instrumentation and protection looks good.
- MCBRDP1b overall performance is good.
- MCBRDP2 was not powered due to insulation issue that was localized.

Overall test experience

First full HL-LHC assembly on the horizontal bench. This assembly and mainly its correctors required:

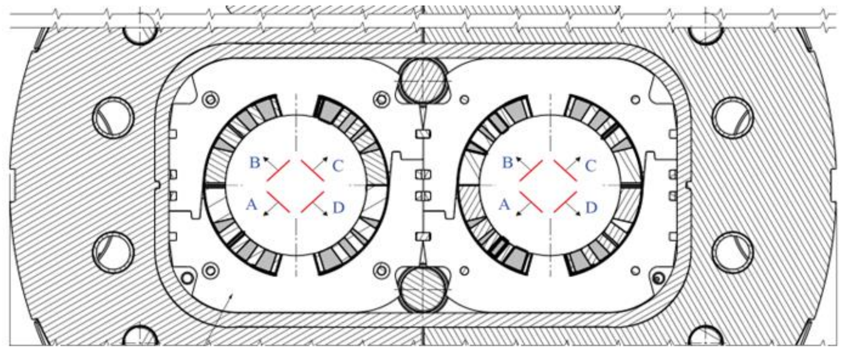
- Other power converters
- New Energy Extraction
- uQDS
- Lots of recabling
- Quench Antenna
- Mechanical measurements
- Magnetic measurements

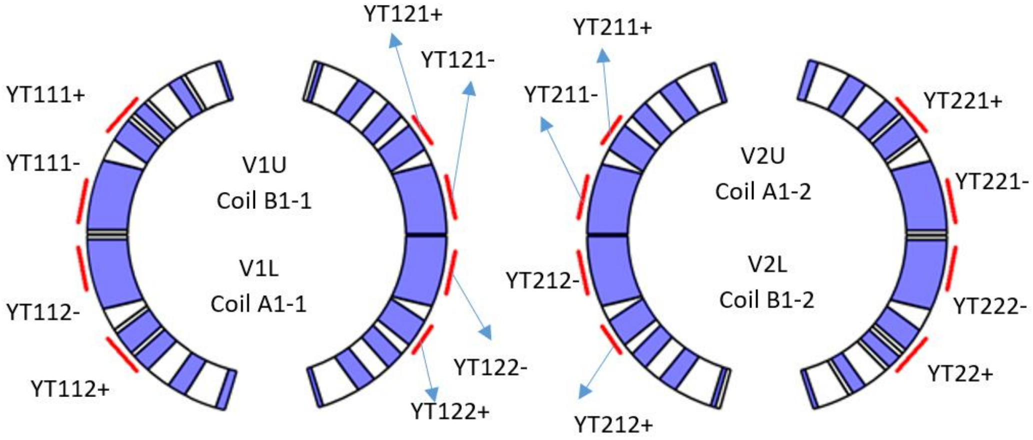
Test plan is rather demanding, since it requires lots of variations in quench heater configurations (safety system for the bench).

Many thanks to all involved for their support to make the test work
For MSC-TM: Gaëlle Ninet, Raphaël Bouvier, Adbelhay Azarkan, Bertrand Mouches, Olivier Ditsch, Lucio Fiscarelli et al.
For EPC: Frederic Daligault et al.
For MPE-MP Bozhidar Panev
For MPE-PE: Jens Steckert, Guzman Martin Garcia
For MM-MME: Michael Guinchard et al.
MSC-CMI and MSC-LMF for preparing the magnet and clarifying all questions
And many more.

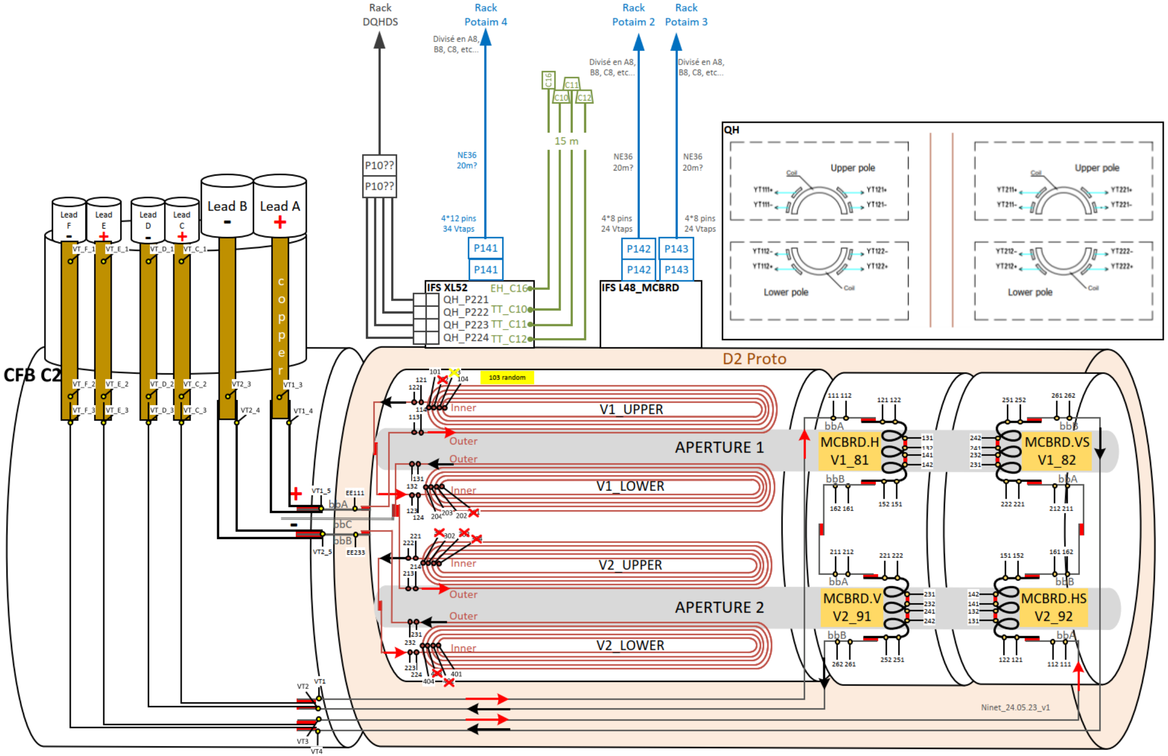
And of course thanks to all from the magnet project that always gave the input and for the nice collaboration.

Image from:
LHCMBRDP0002-vAB





D2 Proto



Courtesy Gaëlle Ninet

Option 1: Local Quench Antenna for D2 proto

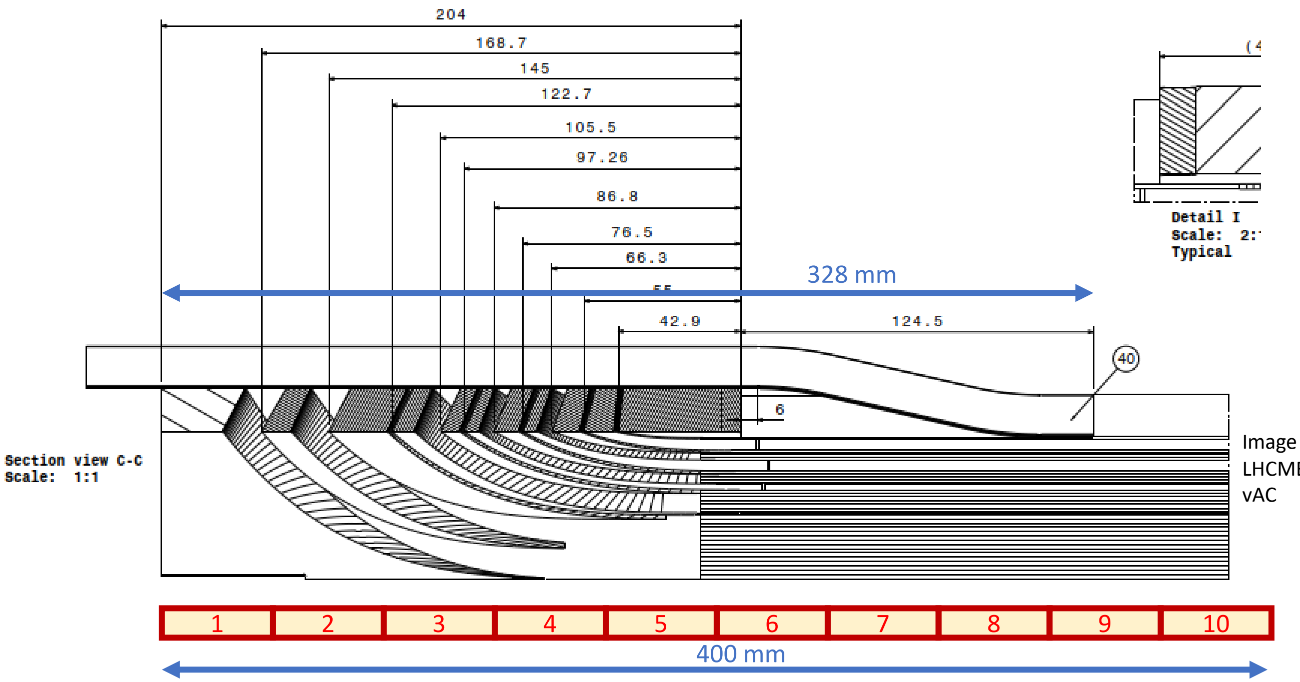


Image from:
LHCMBRDC0054-vAC

Four “Local Quench Antenna shafts” with 10 segments of 40 mm each

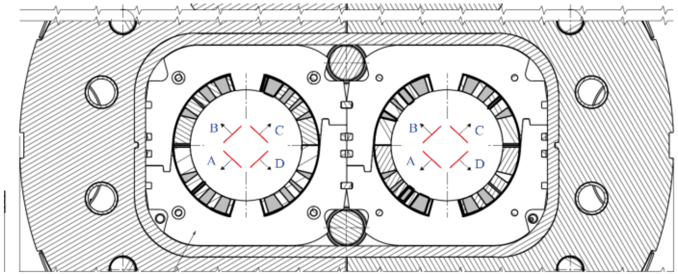


Image from:
LHCMBRDP0002-vAB

Quench Antenna for D2 proto – Measurements during the only quench at 1.9 K.