MCBRDP4 prototype
CERN D2 corrector production and test

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12nd HL-LHC Collaboration Meeting
https://indico.cern.ch/event/1161569

Uppsala University, Sweden, 21/09/2022

Outline

- Background
- MCBRD Magnets parameters
- MCBRDP4 production experience and feedback
- Cold test results
- Summary

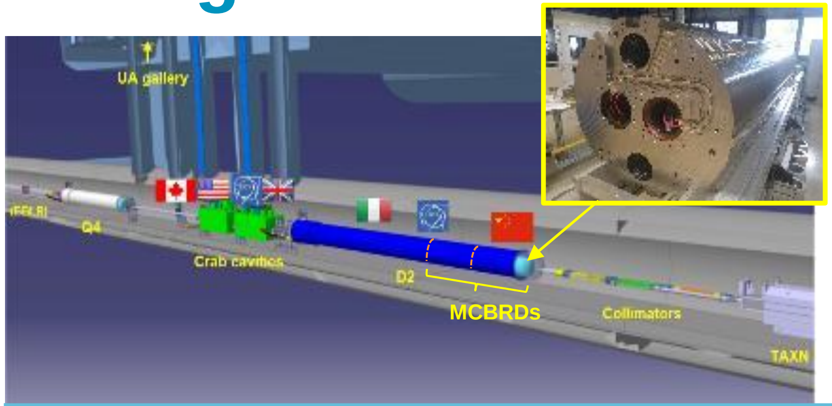
Background

Following decision in Oct.2021, **manufacturing of a fourth prototype MCBRDP4, series compliant,** at CERN, with the following scopes:

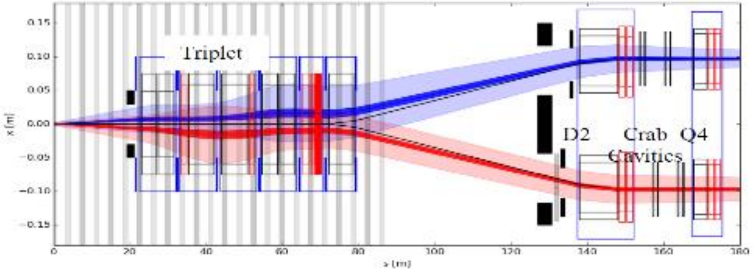
- Create an **additional contingency in the schedule**, leaving an adequate time to fully validate the magnets of the Chinese collaboration or to take mitigation actions if needed.
- To assess **training performances at 4.5 K wrt 1.9 K** to verify if the slow training is related to the *manufacturing quality, process or to the temperature* of the test;

HL-LHC MCBRD Magnets

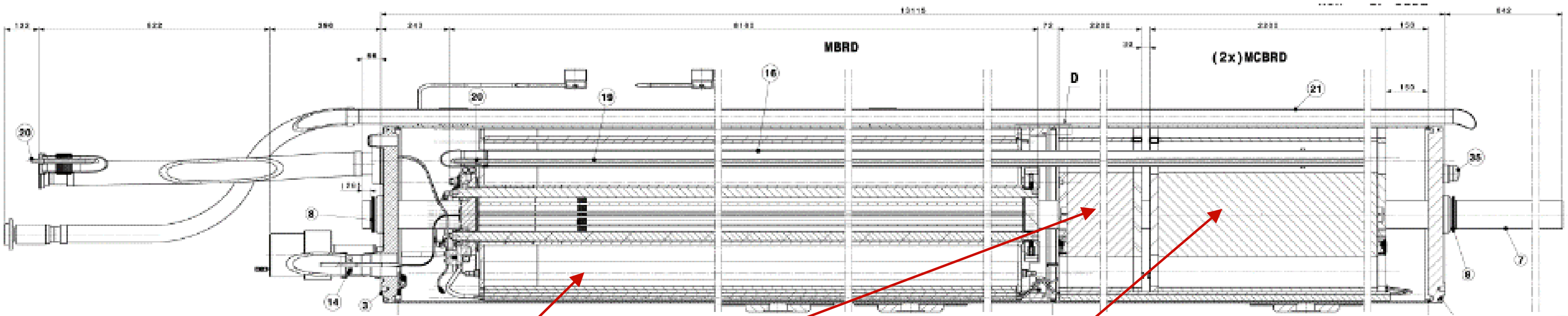
- MCBRD magnets as part of the HL-LHC WP3 **D2 orbit correctors (8 MCBRD units needed + 4 spares)**
- Based on Canted Cosine Theta (CCT) design
- **On going collaboration with IHEP-China on 12 MCBRDs series production**
- **Completed MCBRDP4 production @ CERN over 7 months, ended last 07/2022.**
- **Coming next CERN production of two series magnets MCBRD11,12 with IHEP components**



Parameters @ nominal current (7 TeV operation)	D2 MBRD	MCBRD
Material	Nb-Ti	**Nb-Ti**
# apertures	2	**2**
Distance between apertures [mm]	188	**188**
Aperture [mm]	105	**105**
Field [T]	4.50	**2.60**
Integrated field [T.m]	35	**5**
Nominal Current [kA]	12.328	**0.394**
Stored energy [MJ]	2.26	**0.143**



HL-LHC QBRD cryostated cold mass



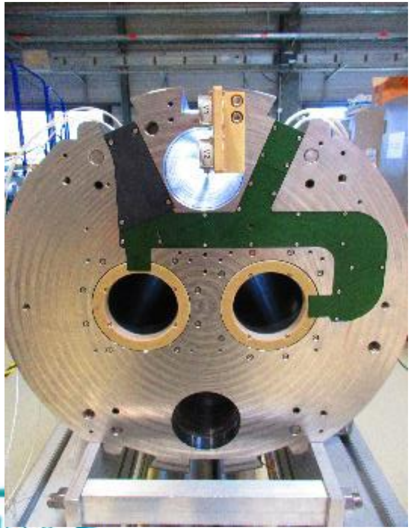

Prototype QBRD (07/2022)
Courtesy of Delio Duarte Ramos


Courtesy of Delio Duarte Ramos

Cryostat (QBRD) includes two double aperture MCBRDs orbit correctors. MCBRDP4 shall be part of spare series D2 corrector magnets.

MCBRDP4 dipole parameters

- MCBRDP4 2-in-1 magnet was built according to the series MCBRD magnet requirements. (EDMS 2051870)
- All components were manufactured and controlled by CERN (MSC, EN-MME).



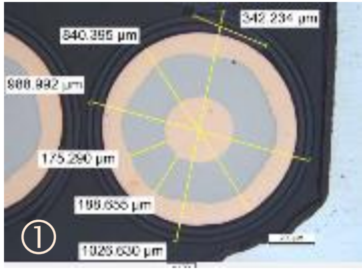
Parameter	Unit	Value
Aperture size	mm	105
Magnetic length	m	1.93
Nominal field	T	**2.59**
Nominal integrated field	T.m	**5.0**
Nominal current	A	**394**
Ultimate current	A	422
Short sample current at 1.9 K	A	767
Short sample current at 4.2 K	A	650
Loadline fraction at 1.9 K		51%
Strand diameter	mm	0.825
Cu/no_Cu	-	1.95
Strand critical current at 4 T	A	700
Nominal strand current density	A/mm^2	737
Nominal superconductor current density	A/mm^2	1695
Loadline fraction at 1.9 K		**51%**
Nominal differential inductance per aperture	mH	970
Nominal stored energy per aperture	kJ	74.9
CCT skew angle		30°
No. of turns per layer		365
Slot size in former (mm)		2.1 × 5.2
Number of CCT layers / Strands in channel		2 / 5 x 2

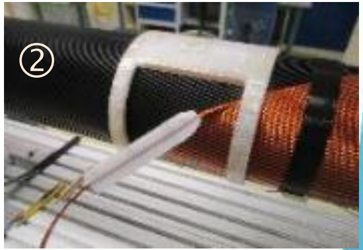
MCBRDP4 return on experience

- **MCBRDP4 has inherited from CERN P1-3 prototypes experience on processes optimization. Opportunity given to focus onto key manufacture items below:**
  - ✓ Manufacture tolerances crosscheck, CMM metrology and QC checks of components (Al-6082 formers, G10 insulating parts, SC wires) in support of each assembly step;
  - ✓ High voltage withstand enhanced level;
  - ✓ Winding dedicated tool;
  - ✓ Impregnation process control upgrade, additional diagnostics test;
  - ✓ Magnet dimensional checks during assembly;
- **Enhanced electrical insulation achieved in MCBRDP4 coils**, implementing conservative approach in manufacture and design option.

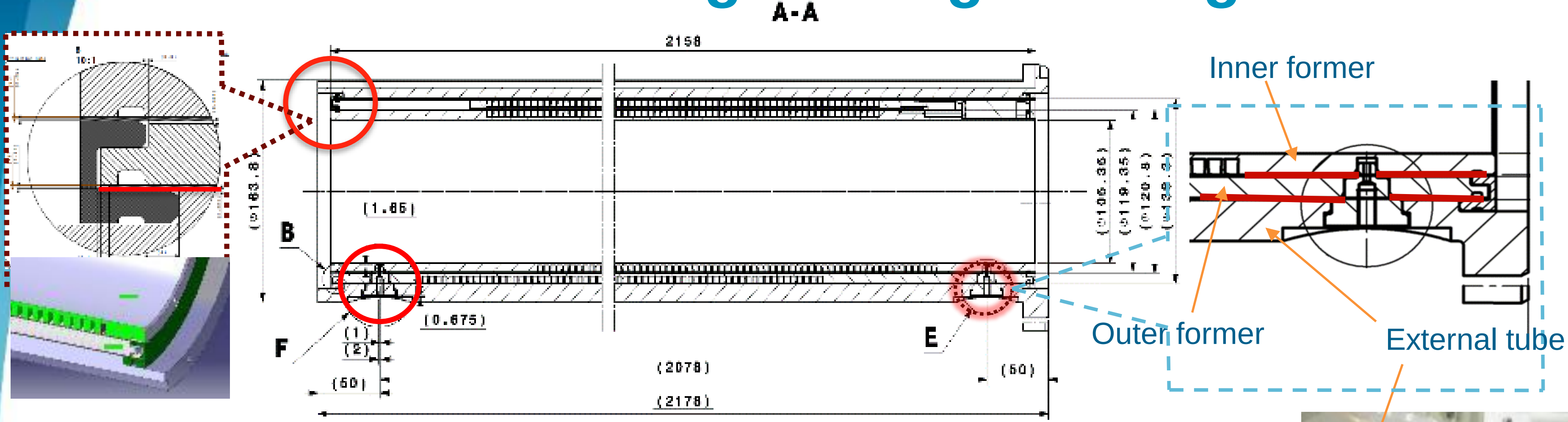
Feedback from winding

- Initial 10 km long SC NbTi insulated wire (∅ 0.98mm) had few defects, **electrically tested at 2 kV and repaired with polyimid tape**.
  - Alternative development of repair using cured liquid polyimide, under progress.
- **Multiple cleaning passes** of 20 unit lengths (UL ≈ 500 m each).
- Rounded grooves edges essential to keep **insulation integrity**.
- **Dedicated winding jig and better control of Fiber glass tension** to ease wires placement and ext. tube insertion.





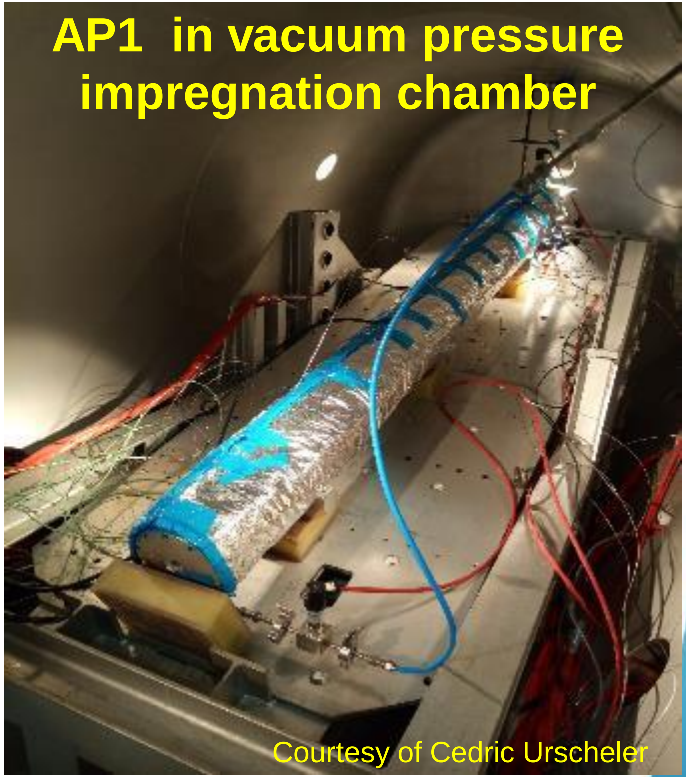
Feedback from High voltage management



- To reach minimum insulation resistance of **1 GΩ at 3.2 kV (30 s hold time) a 4 mm spark distance** shall be guaranteed between the outer former and external ground tube in case of any GI Kapton local interruption.
- Conservative electrical design following past CERN prototypes and IHEP series performances:
  - Improved cutting of Kapton GI, VPI resin parameters control, conservative 4 mm separation length.

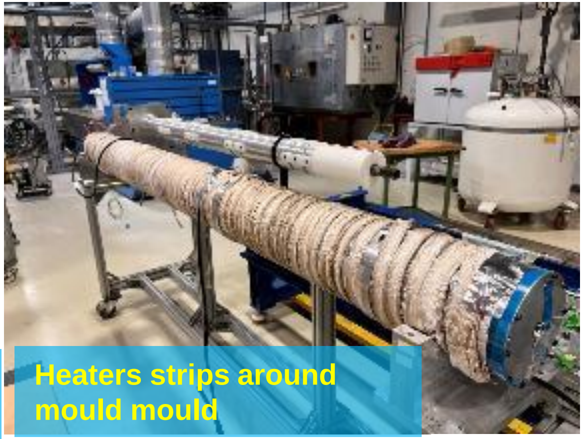
Vacuum pressure impregnation feedback

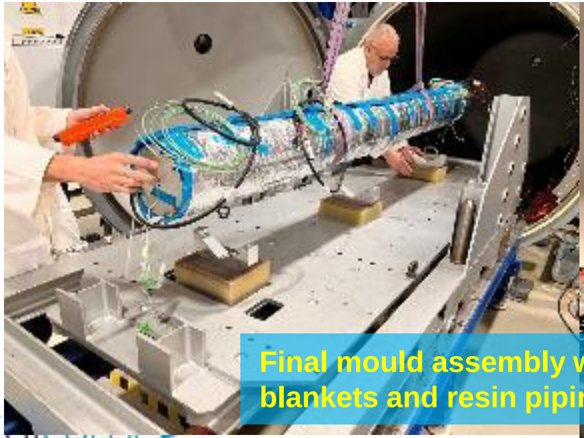
- MCBRDP4 followed the **standard CTD101K resin Pressure-Temperature VPI cycle.**
  - Curing under pressure (1.5 bar applied through N2): 110 °C for 6 h + 125 °C for 16 h
- ✓ Thermocouples **instrumentation was doubled** to confirm maximum thermal gradient in transient of 5 °C
- ✓ **Degazing of the mould** was enhanced at 110 °C for 6 h, then at 60 °C for 4 days and the resin at 60 – 70 °C
- ✓ Better control of inlet resin temperature at 60°C, **lower viscosity**
- ✓ *Control of **resin mould axial penetration time** (~ 50 mins) and total weight (2.5kg) through further **'milking' overhead pressure cycle**.*



MCBRDP4 VP Impregnation steps


Mould with sealed leads exits


Heaters strips around mould mould



Final mould assembly with insulating blankets and resin piping

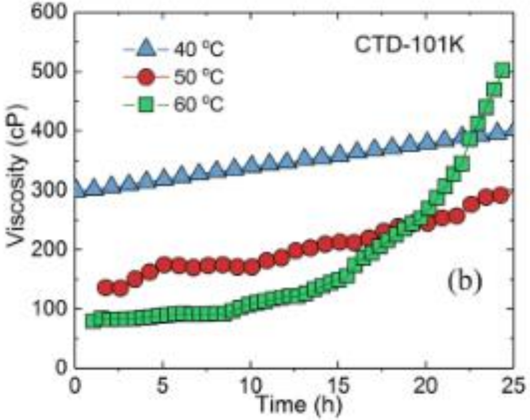


Fig.1 Viscosity measurement of CTD101K resin

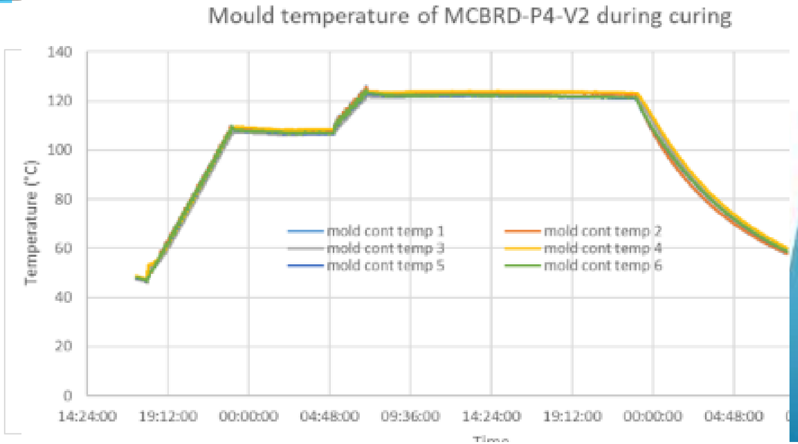


Fig.2 a) Milking pressure cycles on MCBRDP4, b) resin polymerization T cycle

New impregnation diagnostics

- Implementation on MCBRDP4 mould of new on-line **capacitance measurement between winding and Ground** during resin **filling and polymerization** cycle
  - Dynamic range up to 260 nF on MCBRD (Fig.1) showing effective filling time (~ 3h) at injection.
  - Influence on capacitance from pressure milking cycle. See reference similar measurement on 11T dipole in Fig.2

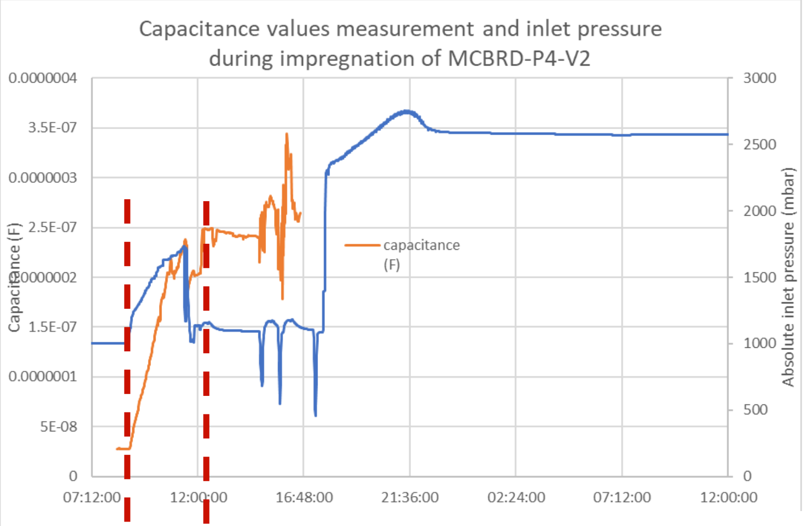


Fig.1. MCBRDP4 capacitance to GND vs. time

[IEEE Trans. Appl. Supercond. 28 (2018) 4003505]

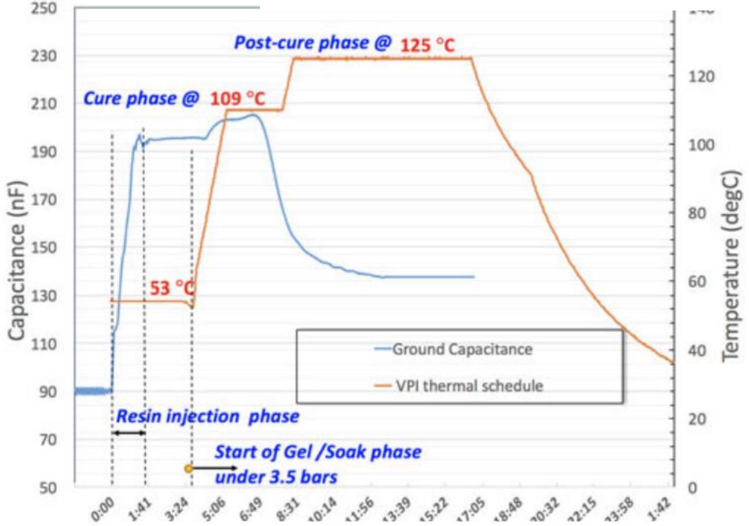


Fig.2 reference 11T capacitance record.

Electrical Hi-voltage insulation tests

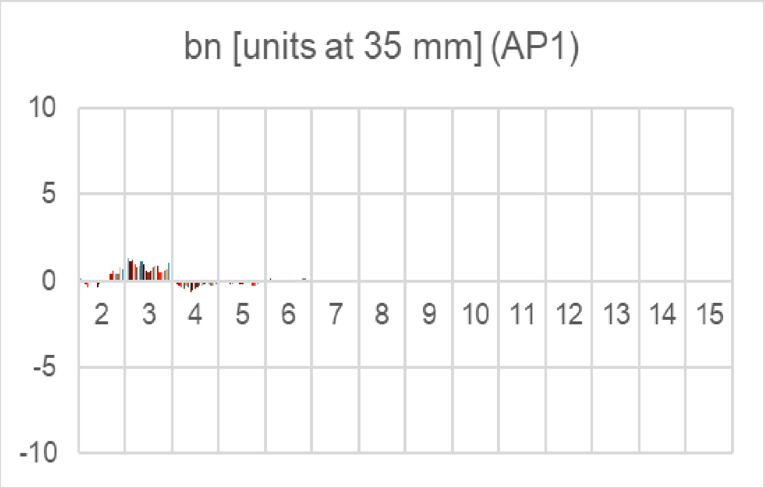
- MCBRDP4 **passed all manufacture QC Hi-pot acceptance tests** criteria at RT**. Final magnet insulation** Rins_GND > 100 GOhms.

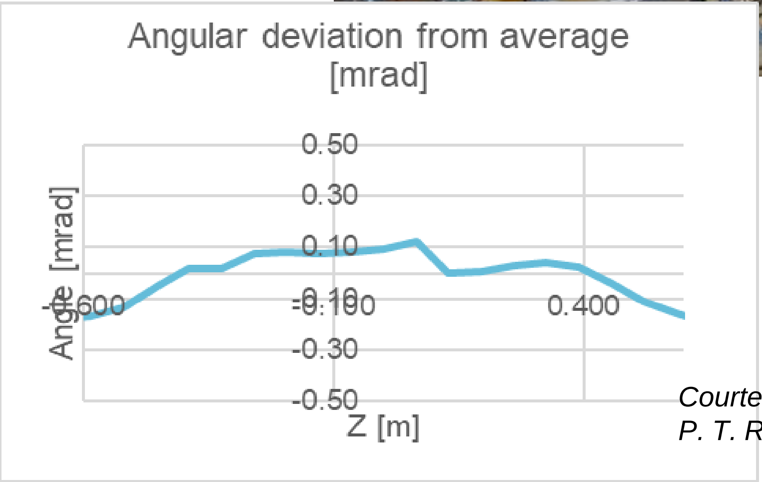
				Test name		Before impregnation	After impregnation	Final	
MCBRDSP4a Aperture V1	**Insulation resistance**			U[test]	time	measured	measured	measured	nominal
				[V]	[s]	[GΩ]	[GΩ]	[GΩ]	[GΩ]
	coil ---> former outer			500	30	X	X	X	>1
	inner former ---> ext. tube			1000	30	22.1	158.8	X	>1
	coil ---> former inner			1000	30	2.10	20.7	X	>1
	coil ---> ext. tube / ground			3250	30	X	138.4	139.5	>1
						All tubes= inner+Ext.			
MCBRDSP4a Aperture V2	**Insulation resistance**			U[test]	time	measured	measured	measured	nominal
				[V]	[s]	[GΩ]	[GΩ]	[GΩ]	[GΩ]
	coil ---> former outer			500	30	X	X	X	>1
	inner former ---> outer former			500	30	X	X	X	>1
	coil ---> inner former			1000	30	930MΩ	14.8	X	>1
	coil ---> ext. tube / ground			3250	30	X	121.9	106.7	>1

- At 1.9 K Liquid Helium temperature, the high voltage **1.6 kV withstand criteria was finally met on MCBRDP4** after some initial breakdowns located outside the magnet.
  - Residual coils to ground insulation respectively of 65 and 45 GOhm.

Magnetic measurement at ambient temperature

- **Similar levels of normal /skew harmonics (<1 unit)** and **field profile** on both **bare apertures** AP1 (Claret) and AP2 (Black)**.**
- Comparison made with others past apertures, with standard deviation up to 15th order multipole (see annex).





Courtesy of L Fiscarelli, P. T. Rogacki

Magnetic transfer function (TF)

- **Magnetic TF (Tm/kA) as expected,** slight effect seen from iron packing factor on slope. (Fig.1,2)
- Good field **alignment in magnet of both apertures within 1 mrad.** (Fig.3)

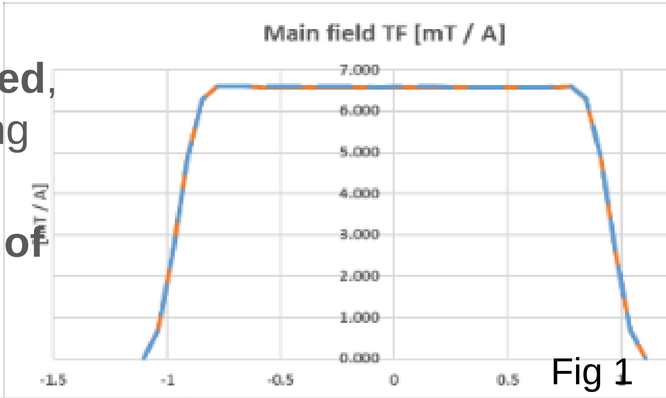
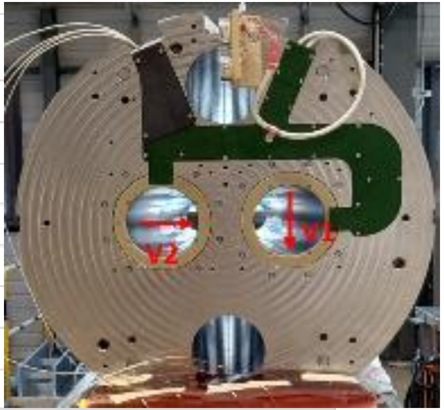


Fig 1



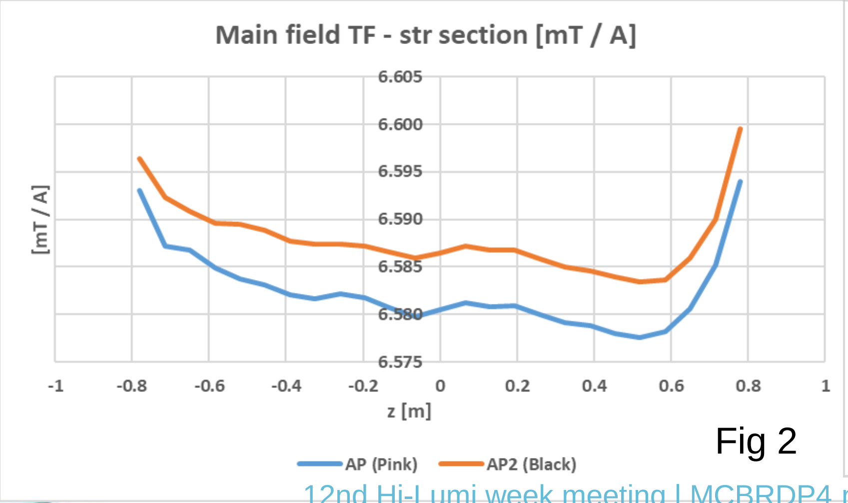


Fig 2

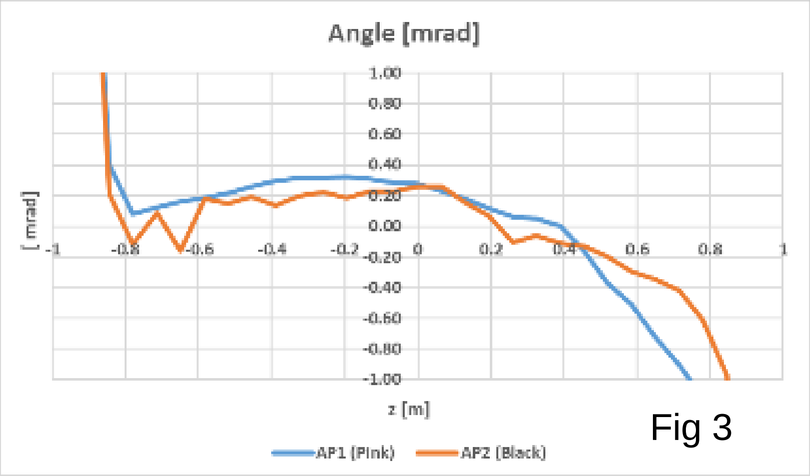


Fig 3

Magnetostatic model benchmarking

- Recent update at CERN to elaborate a reference MCBRD non linear magnetic Opera Simulia model with yoke ***Armco iron b-h*** non linear curve, and the ***304L SS keys***.
- Benchmark of integral allowed harmonics with SS keys. (acknowledgement to IHEP for sharing the initial FE model)

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Model size information
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Number of active elements : 1755154
Number of nodes           : 574975
Number of equations       : 300150
Number of non-zeros       : 2355598
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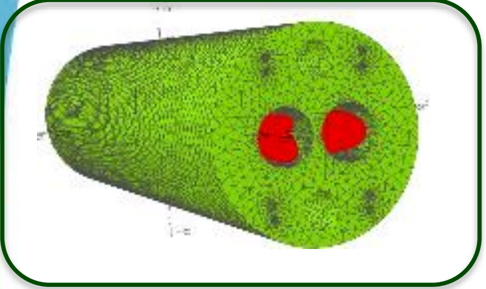
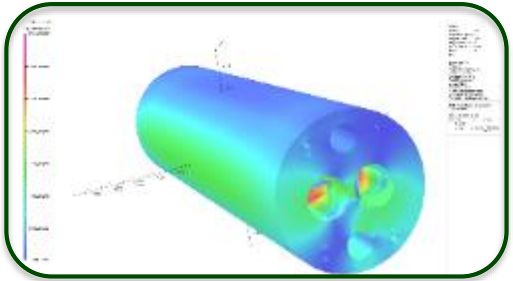
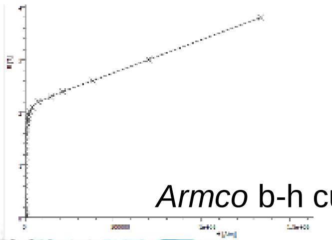
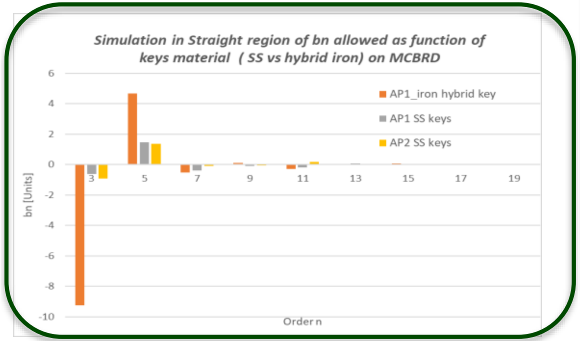
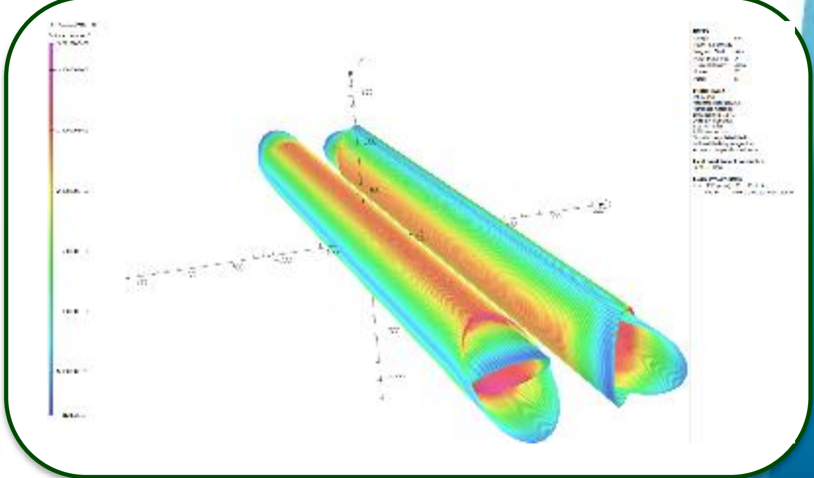






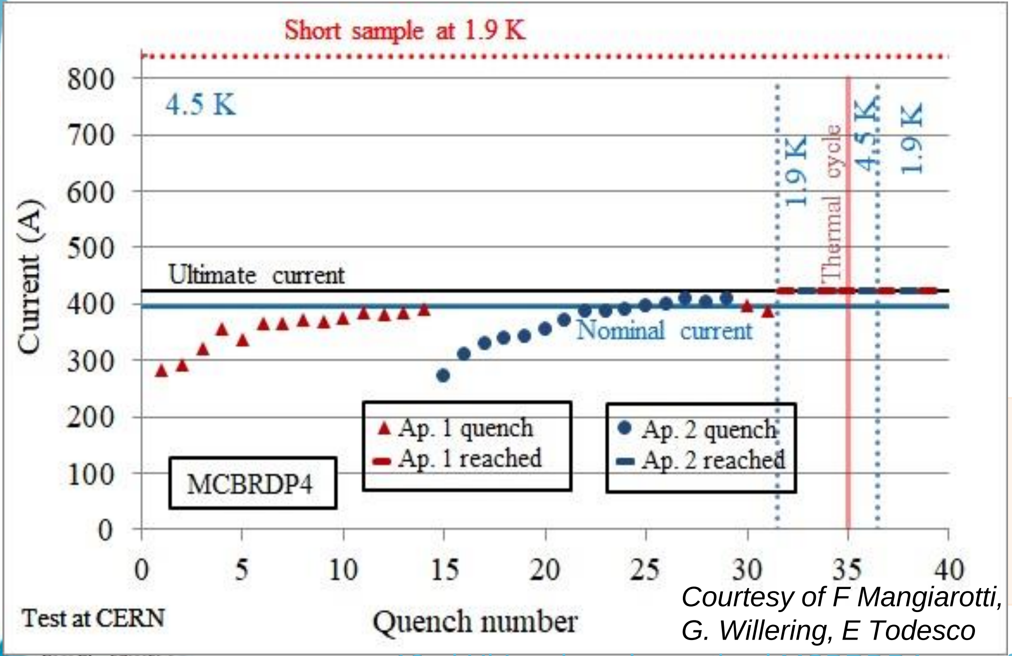
Armco b-h curve





MCBRDP4 COLD TEST : Training summary

- Powering to **394 A nominal @ 4.5 K** with 14 training quenches in apertures during CD1. (relatively fast training in comparison with magnets constructed so far)
- Powering at **422 A ultimate current @ 1.9 K** without any quenches, before & after second cool down CD2.



Courtesy of F Mangiarotti, G. Willering, E Todesco

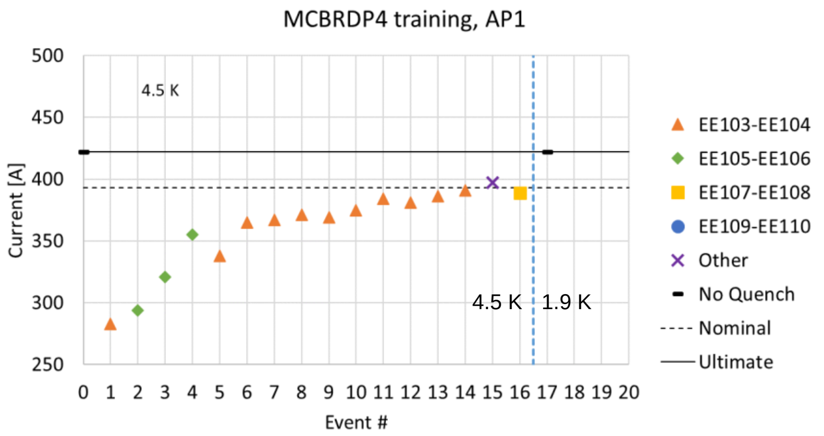
CD1 – 4.5 K single aperture - training quenches
CD1 – 1.9 K ultimate current single aperture - **No quench**
CD1 – 1.9 K ultimate current combined powering - **No quench**

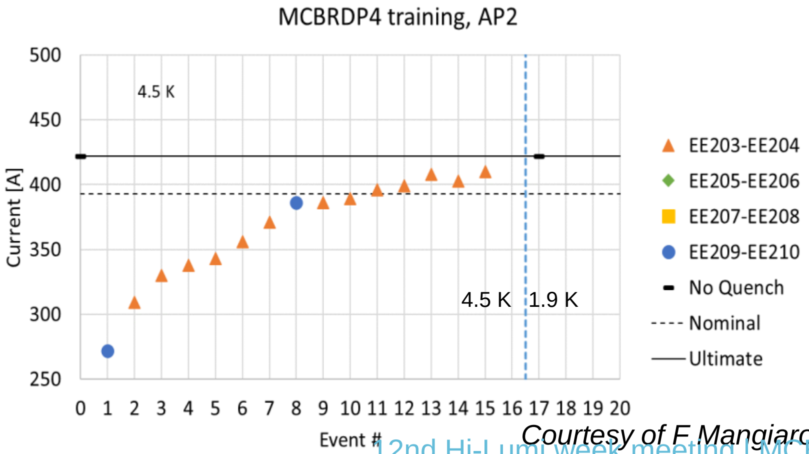
CD2 – 4.5 K ultimate current single aperture – **No quench**
CD2 – 1.9 K ultimate current single aperture - **No quench**
CD2 – 1.9 K ultimate current combined powering - **No quench**

Excellent results:

- After initial training at 4.5 K all cycles showed stable magnet performance, good memory at 1.9 K.

Single aperture training location

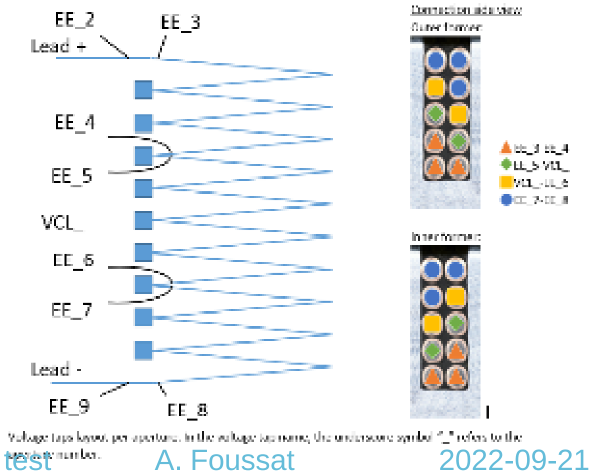




- First training <u>at 4.5 K with single apertures in yoke</u>: start at 280 and 270 A with **comparable training behavior on both coils**

Note : Most of training quenches occurred in bottom turns in the groove, (see orange triangles)

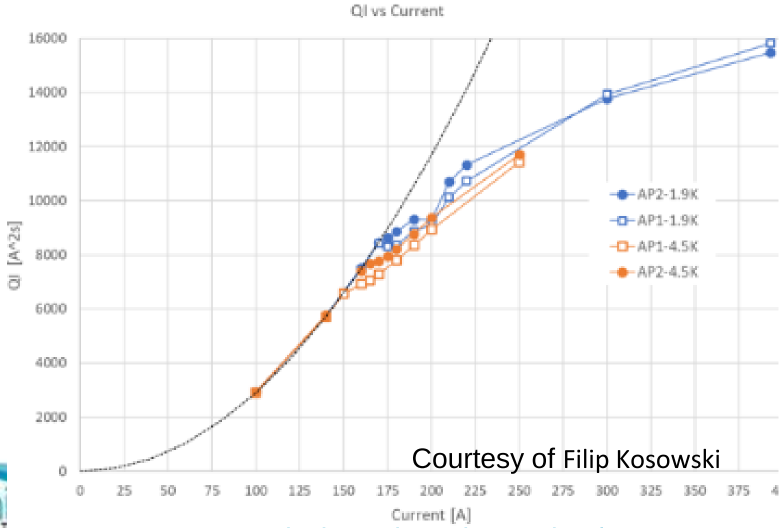
- No further quench at 1.9K to ultimate current.



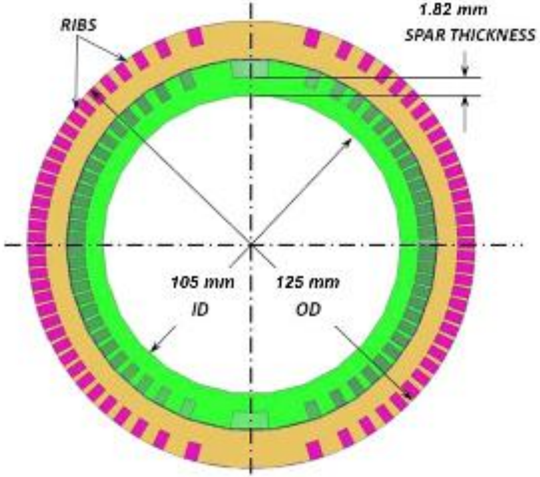
Courtesy of F Mangiarotti, G. Willering

Quench back vs. current

- Additional discharges performed on P4 for **quench back studies** in the 150-200 A current range showing a no-quench back to quench back regime transition in QI curve at both 4.5 K and 1.9 K.
- Next benchmarking of **CCT eddy current model using *Protect* package** by Mariusz Wostniak (TE-MPE).



Courtesy of Filip Kosowski



Cross section of MCBRD winding layers into Al 6082 formers

Magnet field quality at 1.9K– Integral

APERTURE 1					
Individual powering (positive-negative mean)			Difference from individual to combined powering		
AP1 at ±393A AP2 at 0A			AP1 at ±393A AP2 at ±393A		
	Unit	Value		Unit	Value
Norm. TF	Tm/kA	12.699	Norm. TF Δ*	units	-18
Norm. Int. Field	Tm	4.991	Norm. Int. Field Δ*	units	-18
n	**bn**	**an**	**n**	**Δbn****	**Δan****
2	**4.98**	3.16	2	**3.97**	±5.60
3	**-4.29**	0.14	3	**-3.41**	±1.90
4	-0.36	-0.15	4	0.34	±0.81
5	-1.74	0.23	5	-0.32	±0.34
6	0.14	0.05	6	-0.02	±0.12
7	0.36	-0.09	7	-0.02	±0.04
8	0.07	-0.03	8	-0.01	±0.00
9	0.02	-0.07	9	-0.01	±0.01
10	0.01	0.01	10	0.00	±0.00
11	0.01	-0.01	11	0.00	±0.00
12	-0.01	0.00	12	-0.01	±0.00
13	0.00	0.00	13	0.00	±0.00
14	0.00	0.00	14	0.00	±0.00
15	0.00	0.00	15	0.00	±0.00

APERTURE 2					
Individual powering (positive-negative mean)			Difference from individual to combined powering		
AP2 at ±393A AP1 at 0A			AP2 at ±393A AP1 at ±393A		
	Unit	Value		Unit	Value
Skew TF	Tm/kA	12.687	Skew TF Δ*	units	-12
Skew Int. Field	Tm	4.986	Skew Int. Field Δ*	units	-12
n	**bn**	**an**	**n**	**Δbn****	**Δan****
2	**-4.66**	-7.46	2	**±7.46**	-5.48
3	**0.05**	1.84	3	**±2.22**	-0.82
4	0.11	-0.18	4	±0.10	-0.17
5	0.02	-1.50	5	±0.14	-0.16
6	0.07	0.15	6	±0.05	-0.07
7	0.04	-0.31	7	±0.02	-0.01
8	-0.10	0.04	8	±0.01	0.00
9	0.01	-0.01	9	±0.01	0.01
10	0.01	0.01	10	±0.00	0.00
11	0.00	-0.01	11	±0.00	0.00
12	0.00	0.00	12	±0.00	0.00
13	0.00	0.00	13	±0.00	0.00
14	0.00	0.00	14	±0.00	0.00
15	0.00	0.00	15	±0.00	0.00

* Relative difference in units **to nominal value in individual powering**

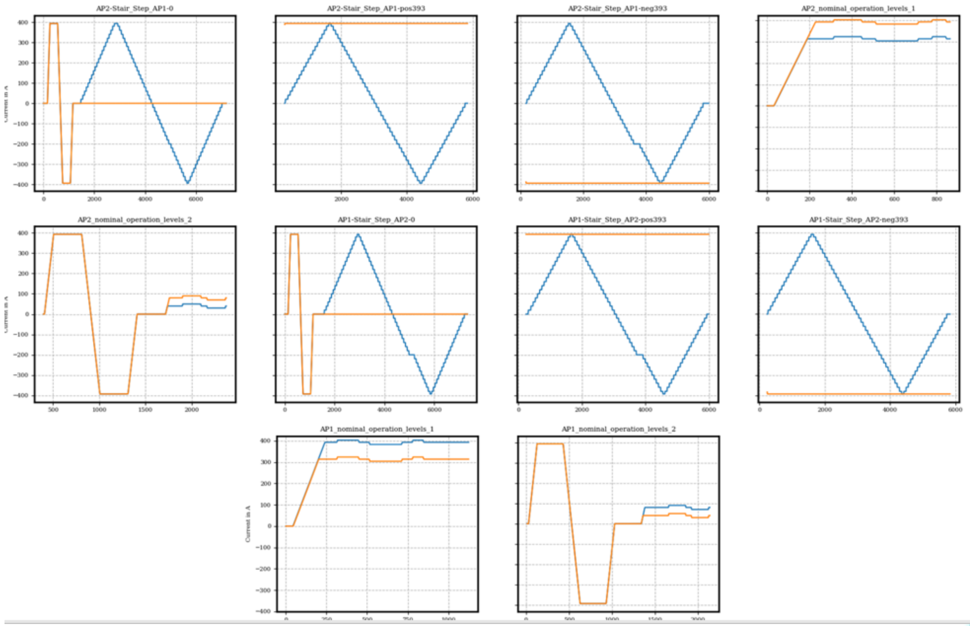
** Difference in units between individual and combined powering - the '±' indicates that the sign of the difference is dependent on the powering quadrant.

MCBRDP4 met multipoles criteria at cold.

Courtesy of L Fischarelli, P. T. Rogacki

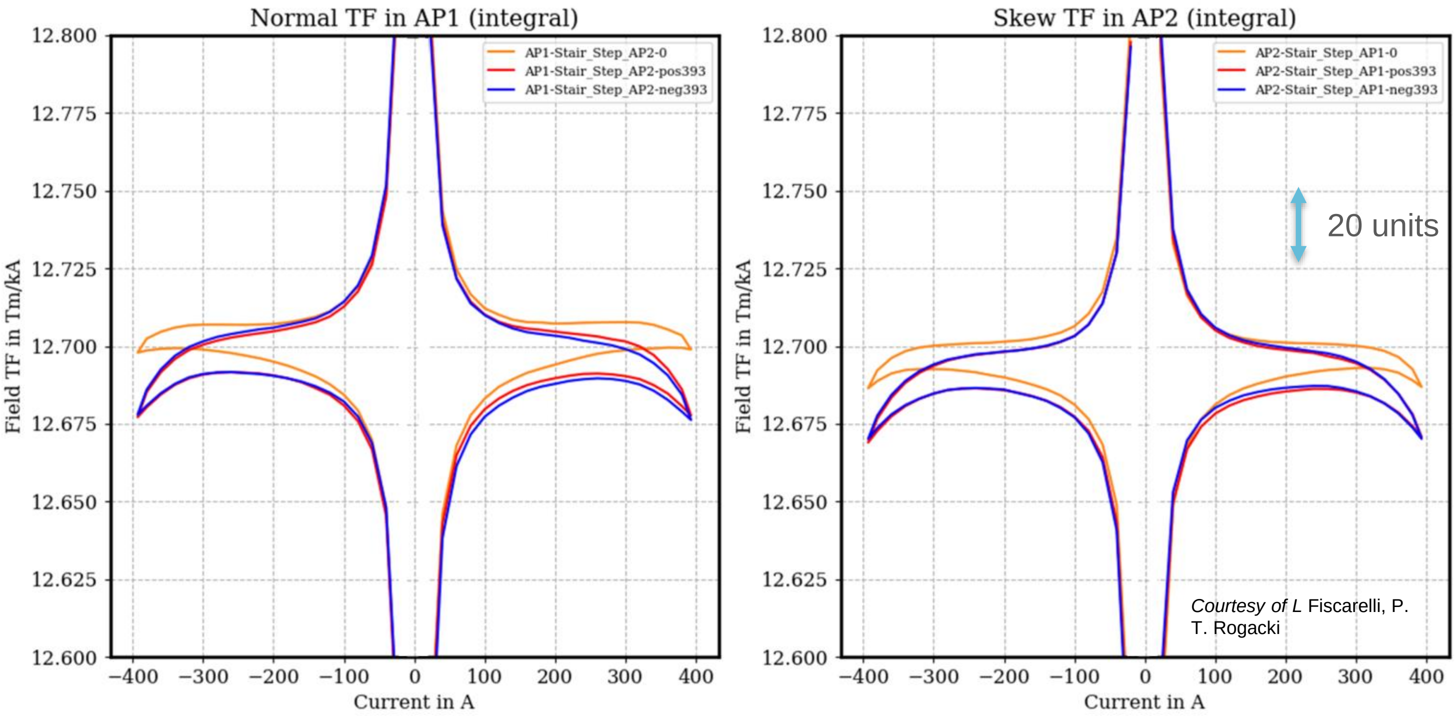
Stability & power plateaus

- At 1.9 K powering **to ultimate current in all quadrants** was performed for 3.5 hours per quadrant (++, --, +-, -+).
- **Extensive number of powering cycles performed. Magnet was stable, including the magnetic measurement cycles.**



Courtesy of L Fiscarelli, P. T. Rogacki

Magnetic transfer function @ 1.9K



Courtesy of L Fiscarelli, P. T. Rogacki

Individual powering saturation: < 0.1%
Combined powering saturation: -0.15%

Warm TF: EDMS 1185245/
Cold TF: EDMS 2779805/

Summary

- **MCBRDP4 magnet cold test was completed successfully last August 2022. It featured best training performances at both 4.5 K and 1.9 K including compliant electrical insulation levels.**
  - Maximum number of **14 training quenches at 4.5 K, no further quenches to ultimate current at 1.9K.**
- MCBRDP4 apertures and magnet assembly were carried out at CERN in SMT lab, **passing all main QC tests** (*dimensional, electrical Hi pot insulation test levels, RT & cold magnetic measurement)*
  - *integral normal multipole < 2 units in single aperture, main field strength of MCBRDP4 as expected*
  - *b_3 and a_3 within 10 units in magnet for all nominal powering combinations*
  - **electrical joint resistances verified at 7-8 nOhms** at 1.9K.
- Upgrade of manufacture processes controls, new diagnostics as valuable insights in knowledge on CCTs. Further updates of MCBRD magnetic model done.

Overall, MCBRDP4 constitutes an excellent reference baseline for design, the series manufacture and CCT magnet performances.

Acknowledgements to all contributors

MCBRDP4 apertures and magnet assembly at 927 (SMT)

MCBRDP4 in SM18 cryostat insert

Thanks to H. Felice, E. Todesco and G. Kirby for steady support to the project

Thanks for your attention

Back up slides

Canted Cosinus Theta (CCT) features

- Although much is known on the benefits and cons of CCT coils (economical construction way in 3-5 T range SC magnets, stress managed magnet, nearly perfect cos-theta coils, field errors superposition ability, least field efficiency), the P4 has been focusing on the manufacture QC details.

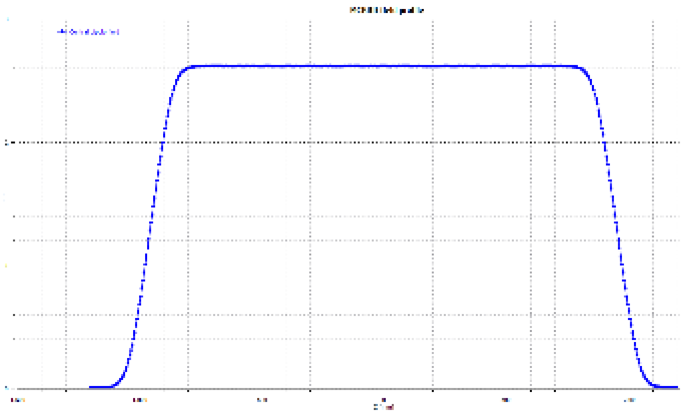


Fig.1 MCBRD Central dipole bore field profile

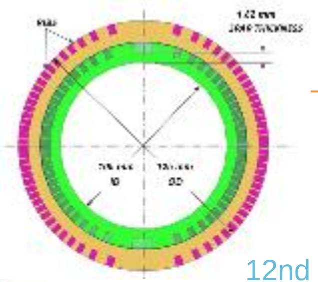
PATH

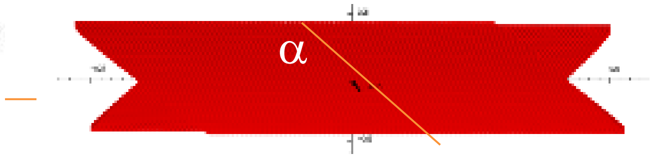
$$\vec{x} = \vec{e}_x R_0 \cos(\theta) + \vec{e}_y R_0 \sin(\theta) + \vec{e}_z \left[\frac{R_0 \sin(n\theta)}{n \tan(\alpha)} + \frac{\omega\theta}{2\pi} \right]$$

STRENGTH

$$B_n = \left[\frac{r_0}{R_0} \right]^{n-1} \frac{\mu_0 I_0 \cot(\alpha)}{2\omega}$$

Ref Dissertation by Brouwer 2015





MAIN REQUIREMENTS

- Ultimate **integral field of 5.4 T.m** has to be reached
  - **Positive and negative powering**, any combination of aperture 1 and aperture 2 field as operation at flat top.
  - **Virgin training: no requirement.** Training after thermal cycle: **1 quench to nominal**
- **Magnet length** has to fit within the 2.2 m (D2 cold mass)
- Magnet size as to fit within the **614 mm diameter** (D2 cold mass)
- The magnet shall fulfill **the electrical HL test requirements** during assembly and at 1.9 K (EDMS 2363906)
  - 3.2 kV at RT to GND 1.6kV in LHe, 330 V at RT post cold test (1GOhms min or 10 μAmax leakage),
- ***Field quality***
  - Field harmonics have to be **smaller than 0.1% of main component (10 units)** at Rref = 35 mm at nominal field in any aperture
  - No requirement on saturation of main component (we measure and use in the HL-LHC field model)
- ***Cooling:*** no heat exchanger, direct conduction
  - Free X-sectional area of 200 cm2 and stacking factor lower than 98%

Winding improvements

- 2 layers of fiberglass (amino silane E-glass, thickness 0.09 mm)
  - *1 layer overlapped at 45%*
  - *1 contiguous layer*
- 2 polyimide sheets, 125 µm thick.
- ***Better position of wires during winding using dedicated jigs. (fig.1)***
- ***Improved fiber E-glass tape with controlled applied tension to keep homogenous insertion gap (~0.2 mm) (fig.2)***

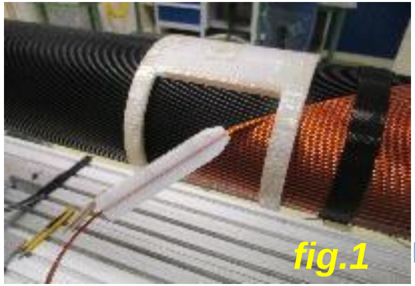


fig.1

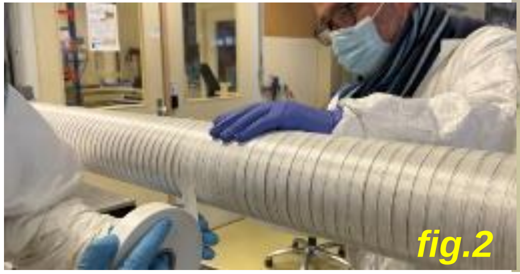
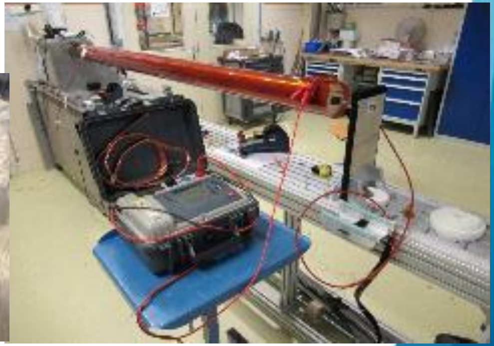
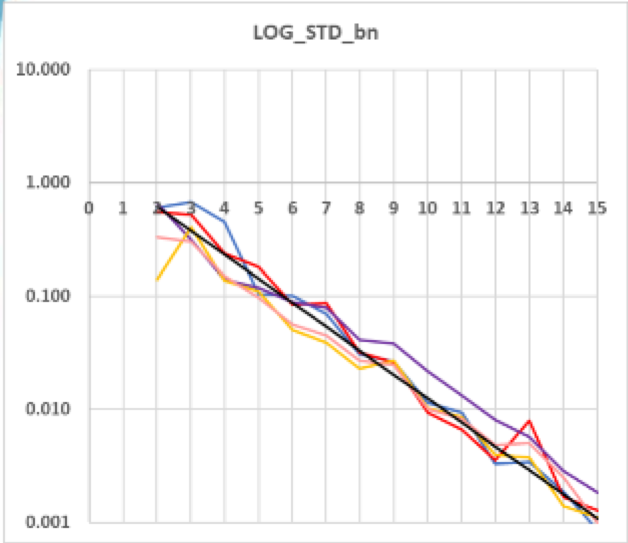


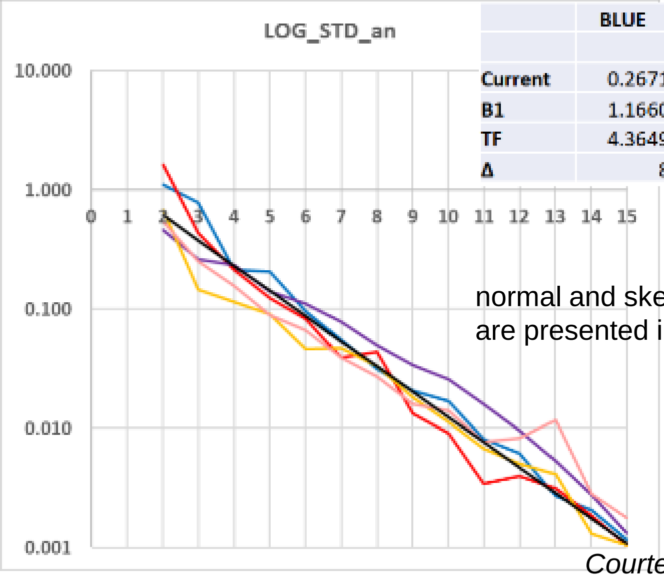
fig.2



Comparison between past CCT apertures

- Normal and skew components of same order (up to n=15) have a similar linear spread (within a few percent) : measurements are then **coming from the magnet construction tolerances and not due to measurement errors.**
- **No clear differences among manufactured apertures.**





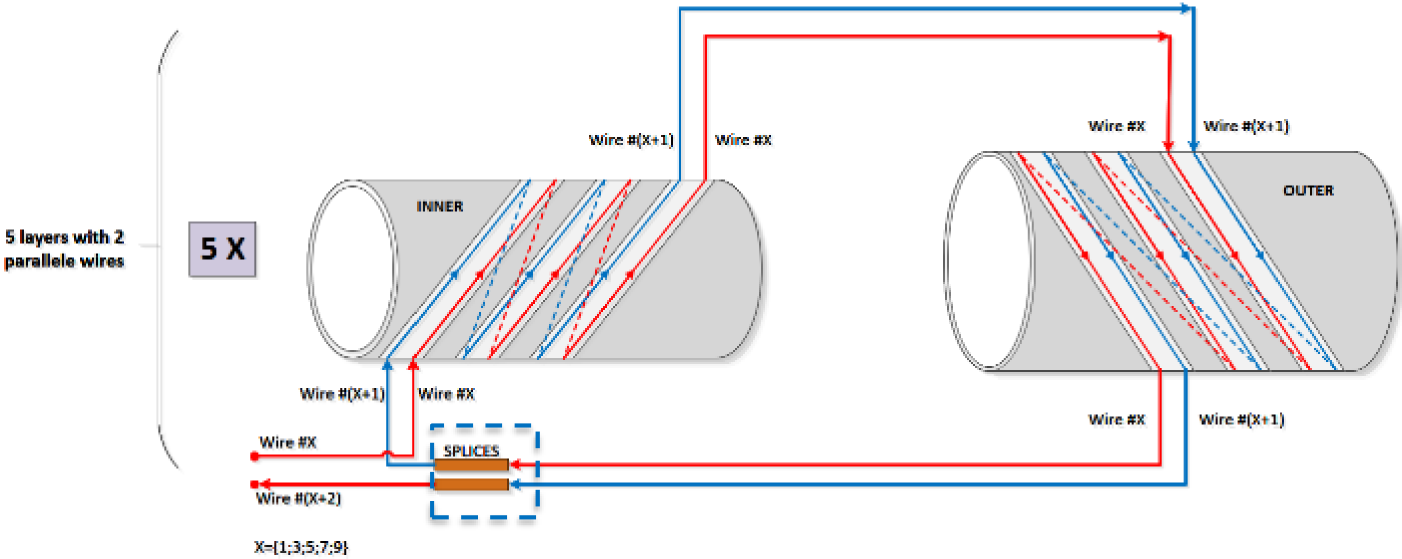
	BLUE	RED	VIOLET	GOLD	PINK	
Current	0.2671	0.2674	0.2673	0.2471	0.2473	A
B1	1.1660	1.1676	1.1656	1.0772	1.0769	mT
TF	4.3649	4.3669	4.3611	4.3594	4.3539	mT / A
Δ	8	13	0	-4	-17	units

normal and skew harmonics are presented in LOG scale

Courtesy of L Fiscarelli, P. T. Rogacki

Fig. 1 Standard deviation in Normal , skew Terms at the Max. Field

Inter layers series splicing, V-taps



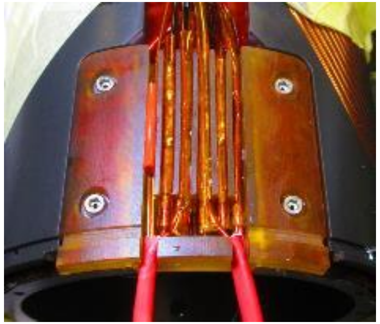
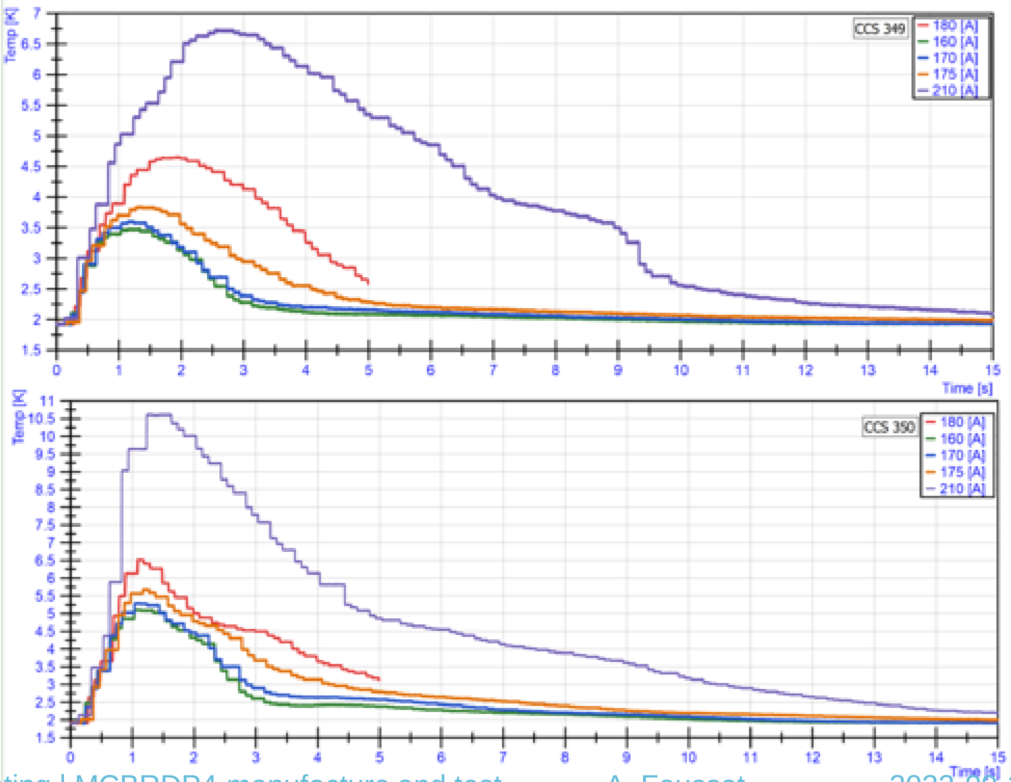


Fig.1 Series splicing terminal connection box

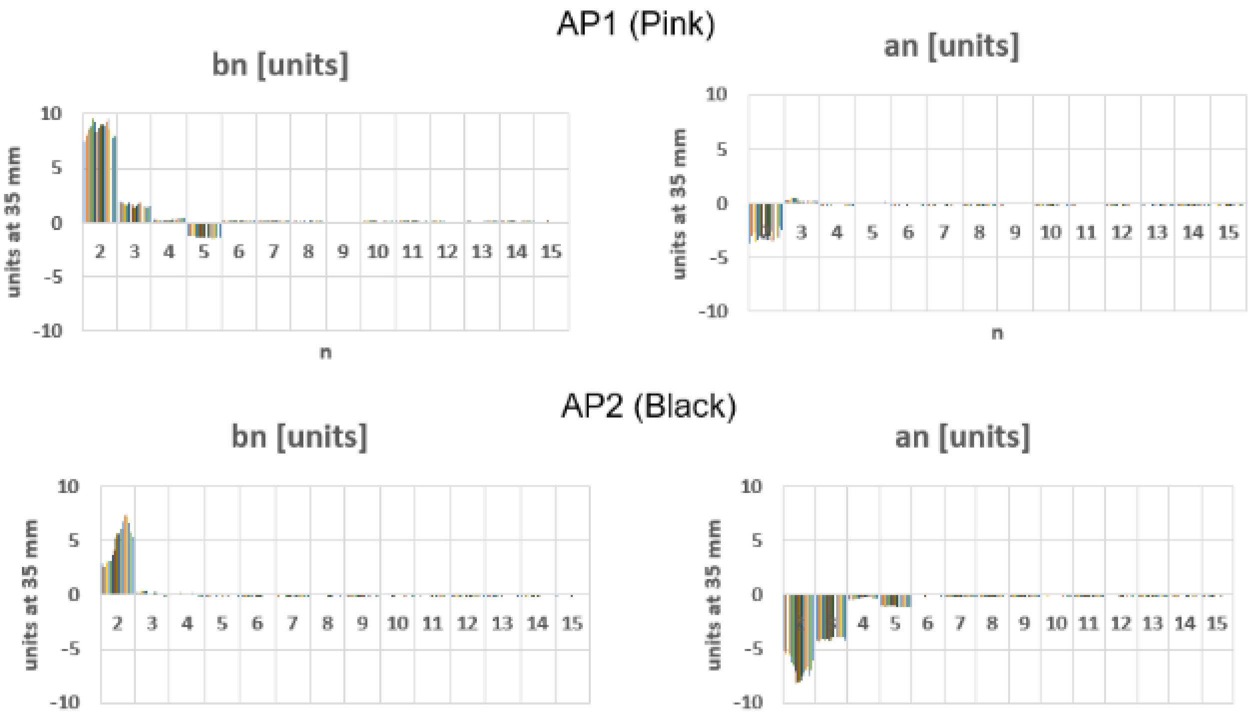
- Layout of 10 wires in series laid in two layers spliced in the connection box
  - Includes 10 voltage taps wires and **9 SC wires joint splices** (Crimped, Sn96Ag4 soldered then polyimide insulated)
  - **Joint electrical resistances verified at 7-8 nOhms** at 1.9K.

CCS T sensors

- Temperature rise monitoring due to quench back in Al6082 formers during quench event

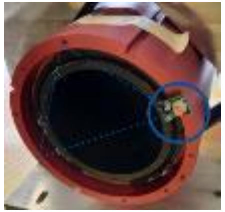


Harmonics in the magnet straight section



Acoustic emission trials

- First outcomes of acoustic activities during current ramp up/down, quench event triggering and frequency spectrum signature on CCTs (Fig1-3). Post analysis under progress. Further development needed and characterization tests of in-layers quench initiation localisation



3 AE piezosensors, 300 kHz BW based on LBNL (M. Marchevesky) design and installed on one Aperture AP1

Courtesy of Daniel Molnar

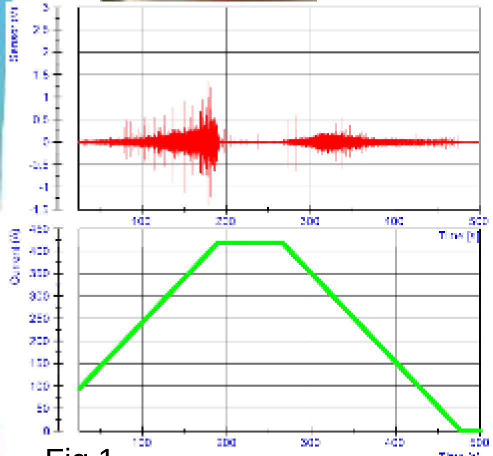


Fig.1

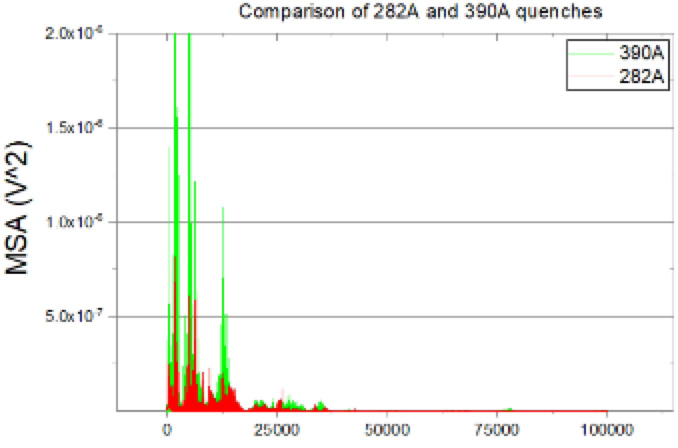


Fig.2

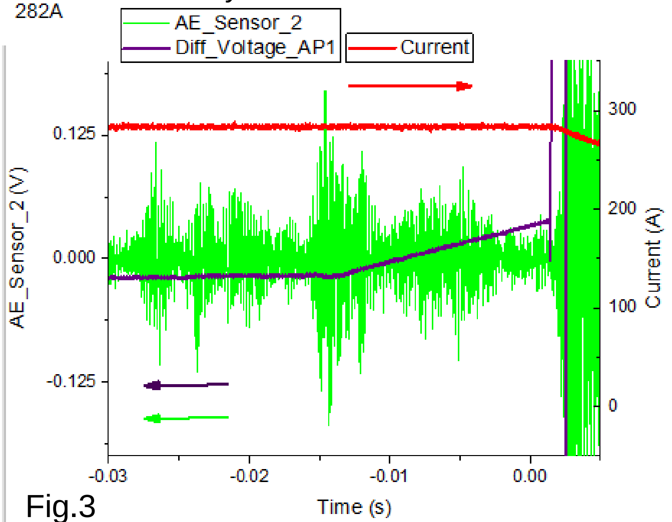


Fig.3