6th HL-LHC Collaboration Meeting – Paris

11T Dipole Magnet for the DS Regions Around IP7 for the Upgrade of the LHC Collimation System

M. Barberan Marin, B. Bordini, L. Bottura, L. Fiscarelli, J. Fleiter, A. Foussat, L. Grand Clément, S. Izquierdo Bermudez, F. Lackner, C.H. Löffler, E.K. Nilsson, J.C. Perez, H. Prin, R. Principe, D. Ramos, L. Rossi, **F. Savary**, D. Smekens, G. Willering, S. Yammine, A.V. Zlobin

14-16 November 2016 Paris, Espace St Martin

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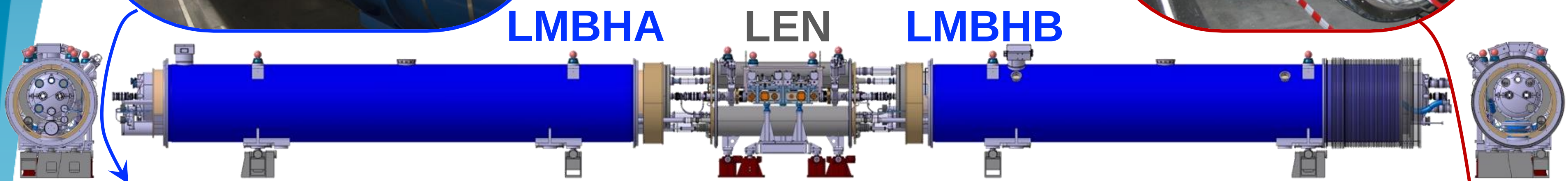
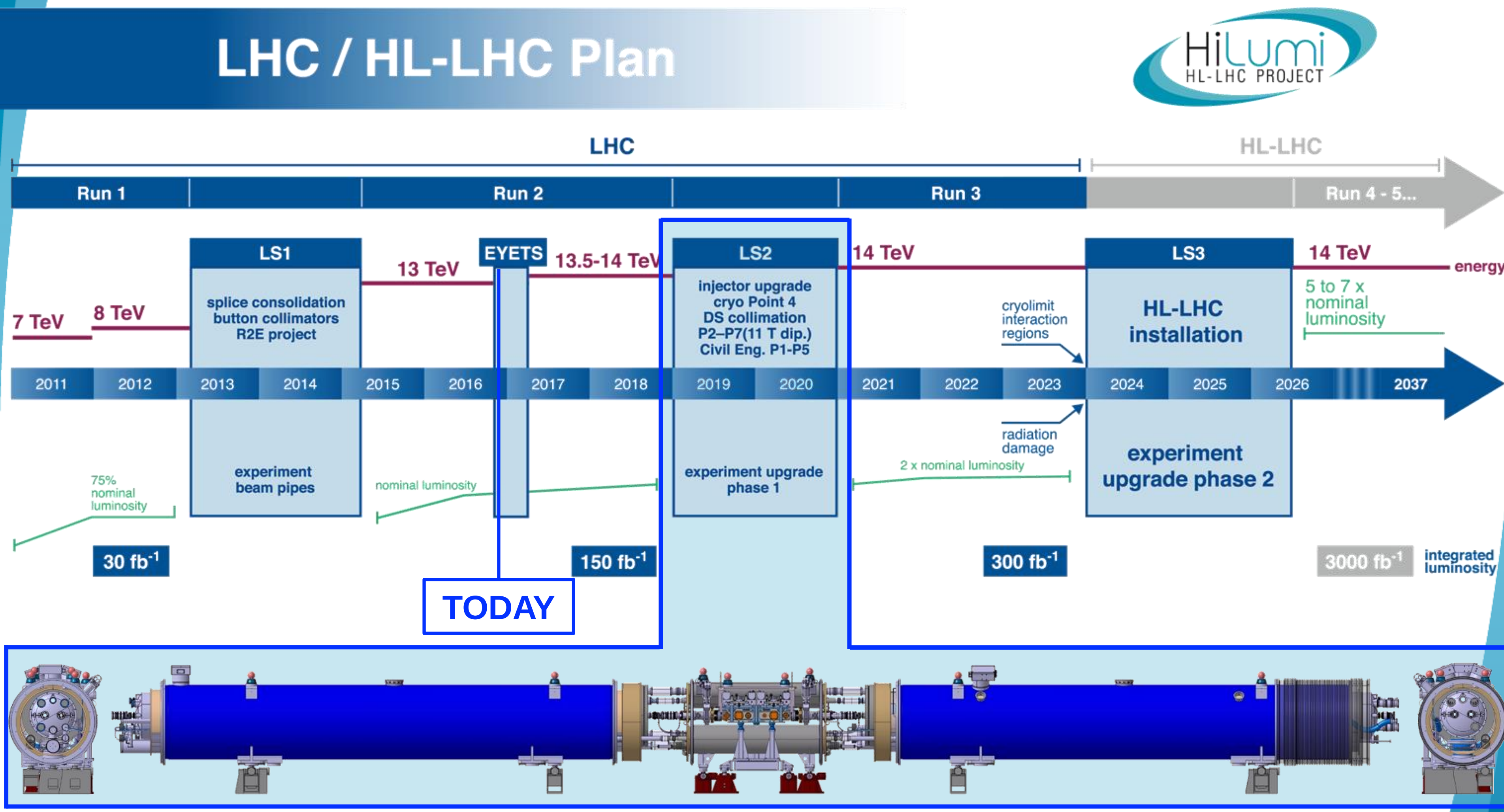
Scope of WP11



- **IP7**, for both proton and heavy-ion collimation losses
  - Design, fabricate, test, and install during **LS2**, around **IP7**, **two 11 T Dipole Full Assemblies** (replace the MBs MBA-B8L7 and MBB-B8R7)
  - Fabricate and test **one spare 11 T Dipole Full Assembly**
  - Plan **includes 14 magnet models**, and **2 full-length prototypes** (1 with RRP conductor, and 1 with PIT conductor)
- **IP2**, for heavy-ion secondary beams
  - Design, fabricate, test, and install during LS2, around IP2, two Connection Cryostat Full Assemblies, i.e. no 11 T Dipole magnet needed for this
  - Fabricate and test one spare Connection Cryostat Full Assembly
  - A Connection Cryostat Full Assembly contains two new connection cryostats, LEP, and one by-pass cryostat (LEN)

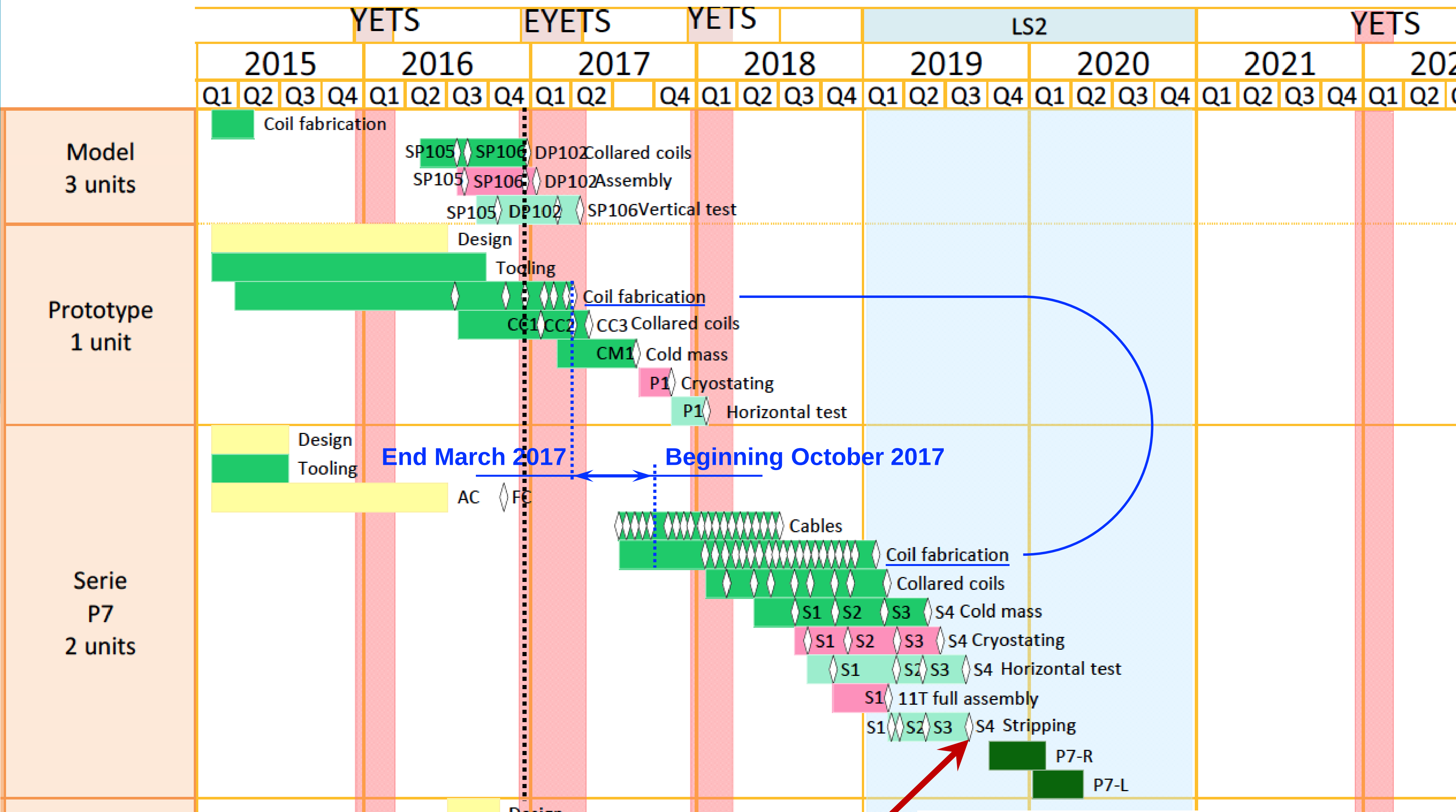
The 11T Dipole in the HL-LHC Timeline



A few numbers – 11T Dipole Full Ass^y for IP7

Item	LS2 (RRP) Cross-section 1	LS2 Spares (RRP – PIT) Cross-section 2	Total
COILS (including rework)			
• Model • Prototype • **Series**	• 18 (including 4 practice coils and 2 trial coils #110 - #201) • 8, including 1 rework, 1 Cu coil and 2 low grade Sc coils • **20 coils, including 4 rework**	• 10 (7 PIT, 3 RRP) • 7 (PIT) • **10, including 2 rework**	• 28 • 15 • **30**
COLLARED COILS			
• Model • Prototype • Series	• 7, including single coil assembly • 3, including 1 trial collaring with 2 low grade Sc coils • 8	• 4 (3 PIT, 1 RRP) • 2 (PIT) • 4 (PIT)	• 11 • 5 • 12
MAGNET MODEL OR COLD MASS (MBH)			
• Model • Prototype • **Series**	• 9 (1 single coil, 6 single aperture, 2 two-in-one) • 1 • **4**	• 5 (4 SP, 1 DP) • 1 (PIT) • **2**	• 14 • 2 • **6**
CRYOSTATING (LBH)			
• Prototype • Series	• 1 • 4	• 1 • 2	• 2 • 6
COLD TESTS			
• Model • Prototype • 11T Dipole Full Assembly • Series	• 9 (1 single coil, 6 single aperture, 2 two-in-one) • 1 • 1, with the prototype P001 and the first of series • 4	• 5 (4 SP, 1 DP) • 1 (PIT) • - • 2	• 14 • 2 • 1 • 6
11T DIPOLE FULL ASSEMBLY			
• **11T Dipole Full Assembly**	• **2**	• **1**	• **3**

Schedule X-Section 1



M. Barberan Marin et al.

11T Dipole for HiLumi LHC – Design features

LMBHB

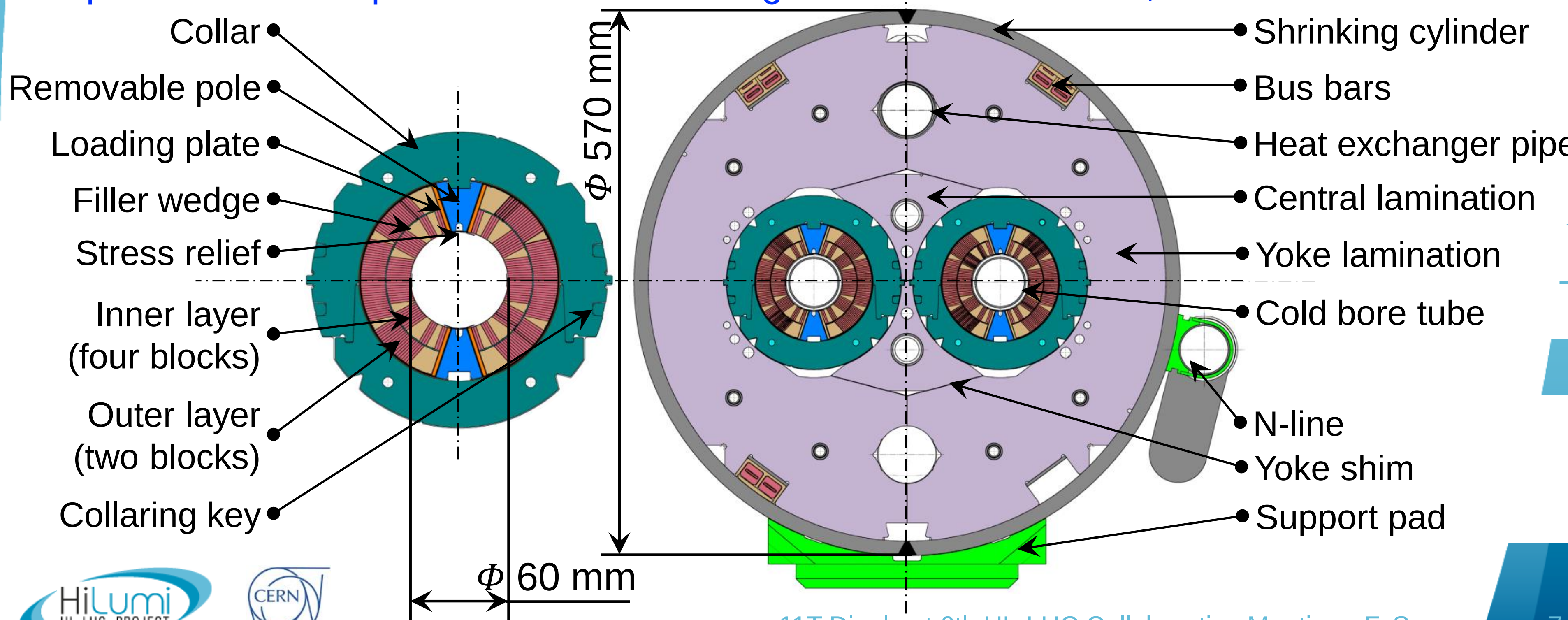
11T dipole **cryo-assembly**

11T dipole **cold mass assembly**

Like the LHC main dipole, the 11 T dipole has a **two-in-one** structure

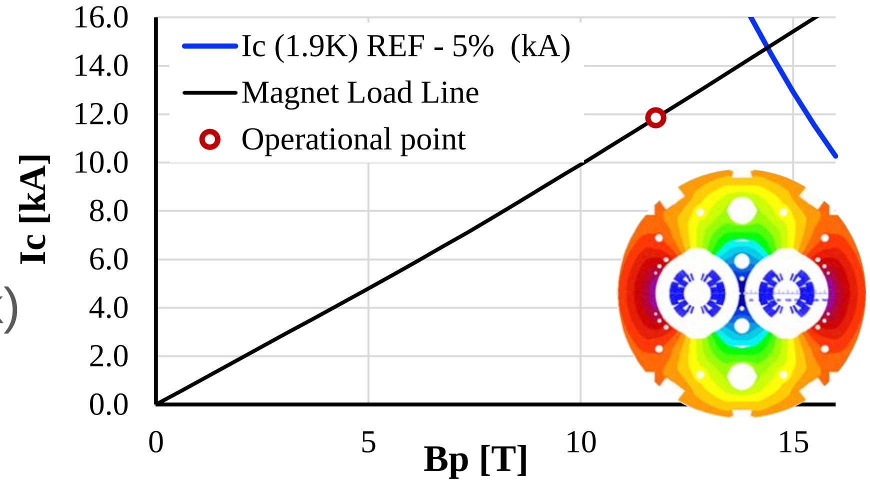
Cold mass length: 6.252 m, weight ≅ 8 t, **magnetic length = 5.307 m**

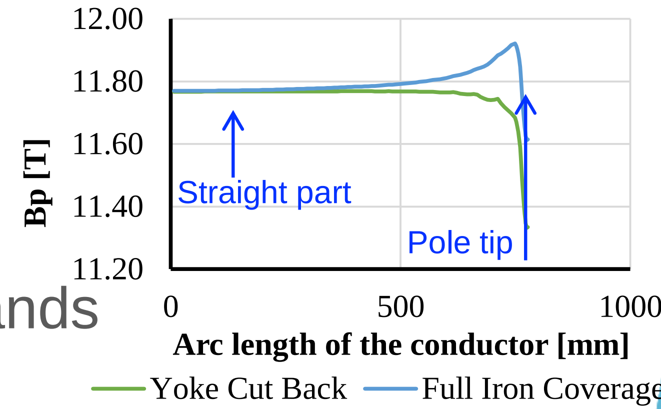
A pair of MBH will produce the same integrated field as the MB, **119 T·m at 11.85 kA**

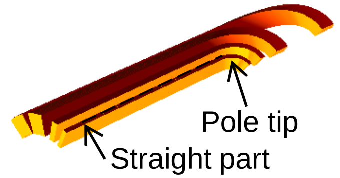


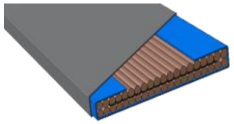
11T Dipole for HiLumi LHC – Design features

- Operational Conditions:
  - **T = 1.9 K**
  - **I_{op} = 11.85 kA – B = 11.23 T**
  - B_{peak} = 11.77 T (with cryostat, strand self-field, and yoke cutback)
  - **Load line margin ≅ 20 %** (operational point at 80.1% of Iss at 1.9 K with yoke cutback)
- Conductor, **Nb_3Sn**
  - **Strand *Φ* 0.700 ± 0.003**:
  - RRP 108/127, keystone angle 0.79°
  - PIT (with Nb barrier), keystone angle 0.50°
- Cable **mid-thickness 1.25 mm**, 40 strands
- Cable insulation:
  - **1 layer of Mica tape** of 80 μm thickness
  - **1 layer of S2-glass** of 75 μm thickness





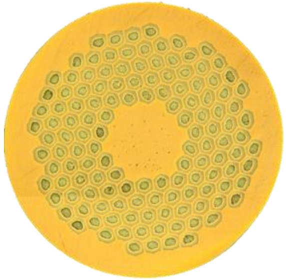




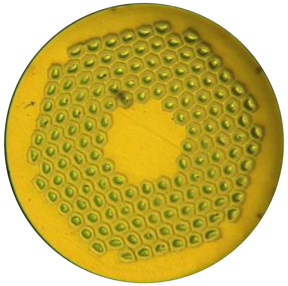
Conductor for Magnet Models
169 RRP Wire

0.7 mm RRP	Value	
Quantity [km]	220	
n° billets	13	14
Layout	132/169	144/169 150/169
Average ***I_c***, *RMS* [A]	**431**, *24*	**456**, *24*
I_c **spec** [A]	**438**	
Average **RRR**, *RMS*	**185**, 64	**172**, 30
RRR spec	**150**	
Average ***J_c***, *RMS* [A/mm^2]	**2508**, *125*	**2408**, *146*
Average ***B_{c2}***, *RMS* [T]	**23.2**, *0.36*	**23.2**, *0.52*

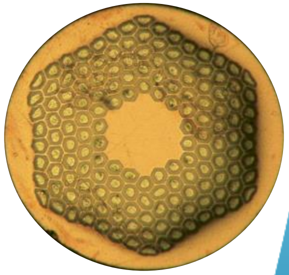
RRP 132/169



RRP 144/169



RRP 150/169



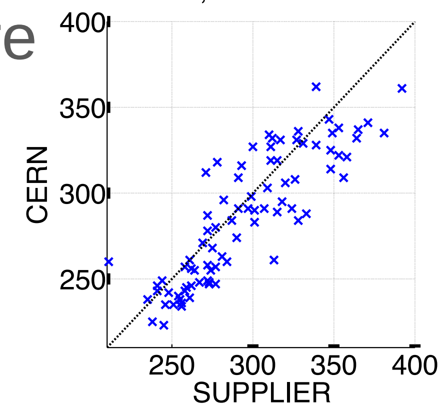
- At 12 T the average I_c of the 132/169 is about 1% lower then specification;
- The 144/169 and the 150/169 meet the I_c specs but the Cu content is insufficient

B. Bordini

Conductor for Series Magnets

108/127 RRP Wire

RRR, 0.70mm RRP



- Placed two contracts: 500 km and 200 km of wire
  - Received 320 km from first contract
    - Performance verified at CERN for 247 km
      - Cable for 3 coils have been produced at CERN
    - Satisfy specification with margin; in particular the RRR is significantly larger than that of the 169 RRP layout→ magnet stability
  - Remaining material from first contract by January 2017
  - First delivery from second contract by July 2017; all material by end 2017
- Bruker-EAS has identified a wire layout for the PIT conductor expected to meet the technical specification of the 11 T project
  - This PIT wire will be used to manufacture the two spare magnets

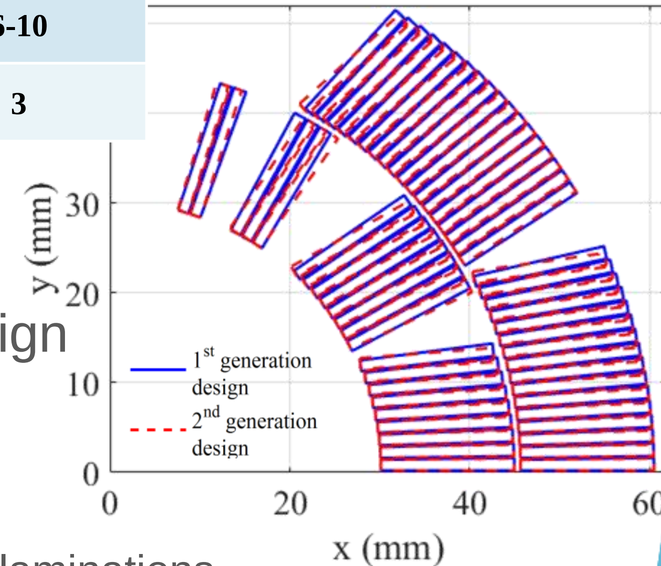
B. Bordini

X-section 2

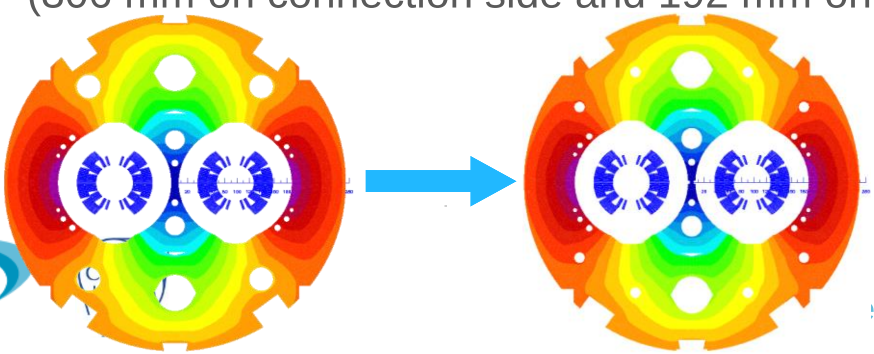
- Based on new cable geometry to guarantee **I_c degradation below 5 %** for both PIT and RRP conductors

	Bare mid- thickness (mm)	Bare width (mm)	Keystone angle (degree)	I_c degradation %
1st Gen. Design	1.250 (1.307)	14.70 (14.85)	**0.79** (0.81)	**6-10**
2nd Gen. Design	1.250 (1.288)	14.70 (14.85)	**0.50**	**3**

Cable geometry and measured critical current degradation.
Assumed dimensions after reaction in parentheses.



- Coil ends mechanically and magnetically optimized with few changes to previous design
- Iron yoke (also in X-section 1):
  - Outer diameter reduced from 550 to 540 mm
  - Assembly holes from one to two per quadrant
  - Yoke cutback implemented with non-magnetic yoke laminations (306 mm on connection side and 192 mm on non-connection side)



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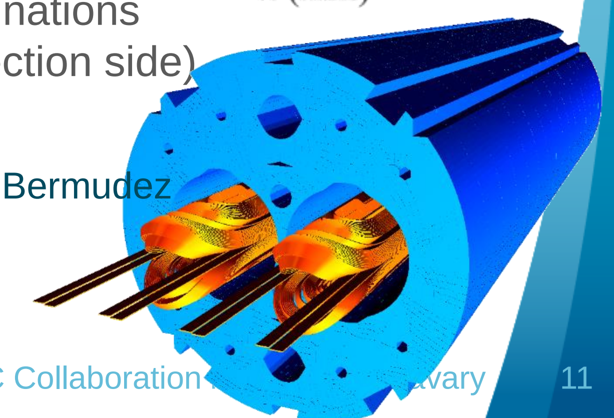
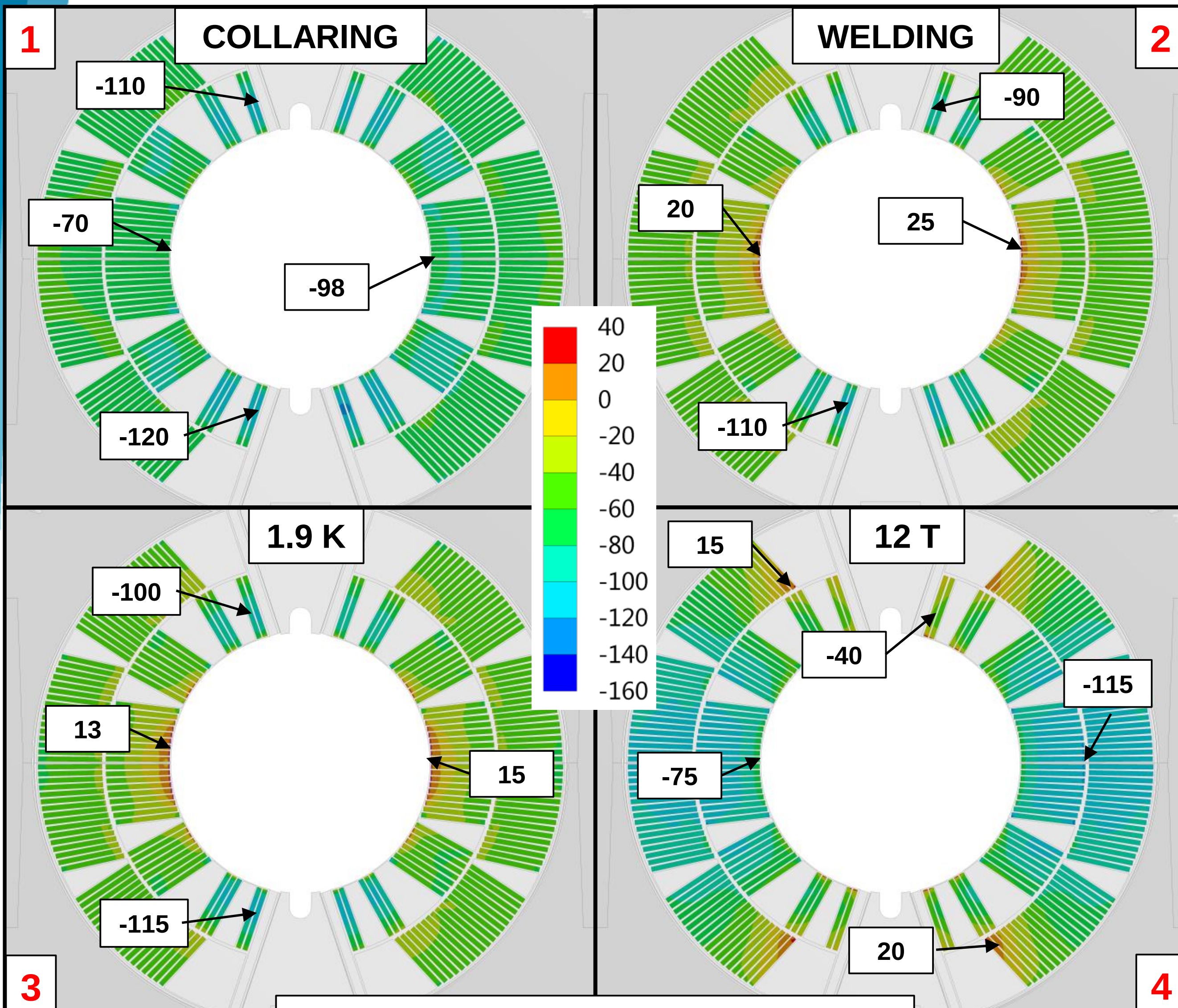
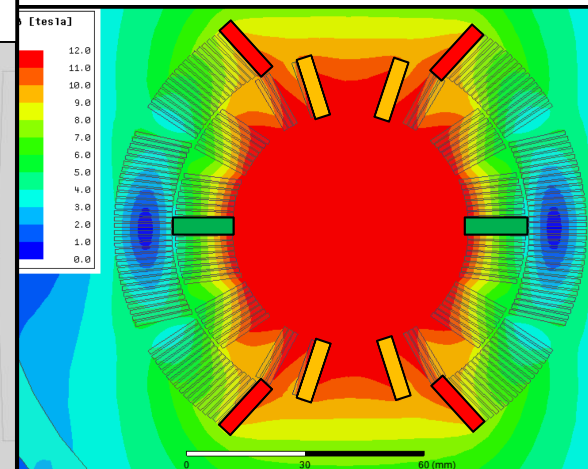
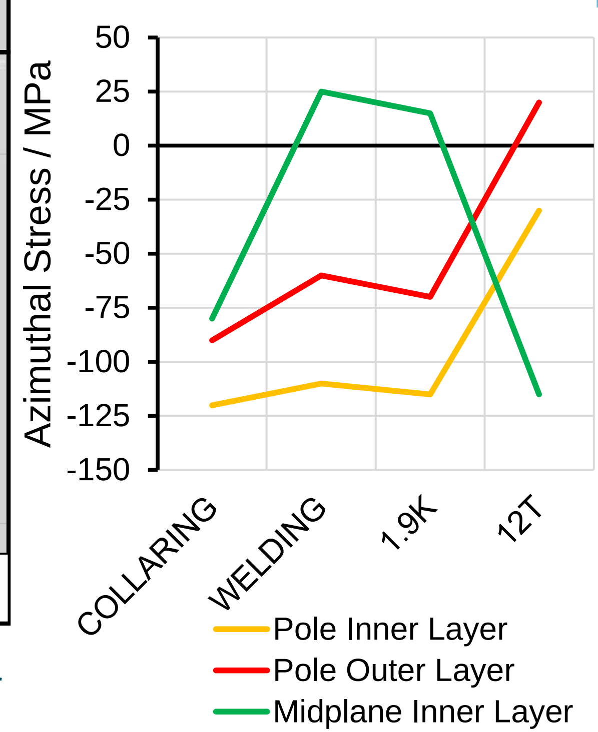
S. Izquierdo Bermudez
et al.



Coil Stress in CERN 2-in-1 X-Section



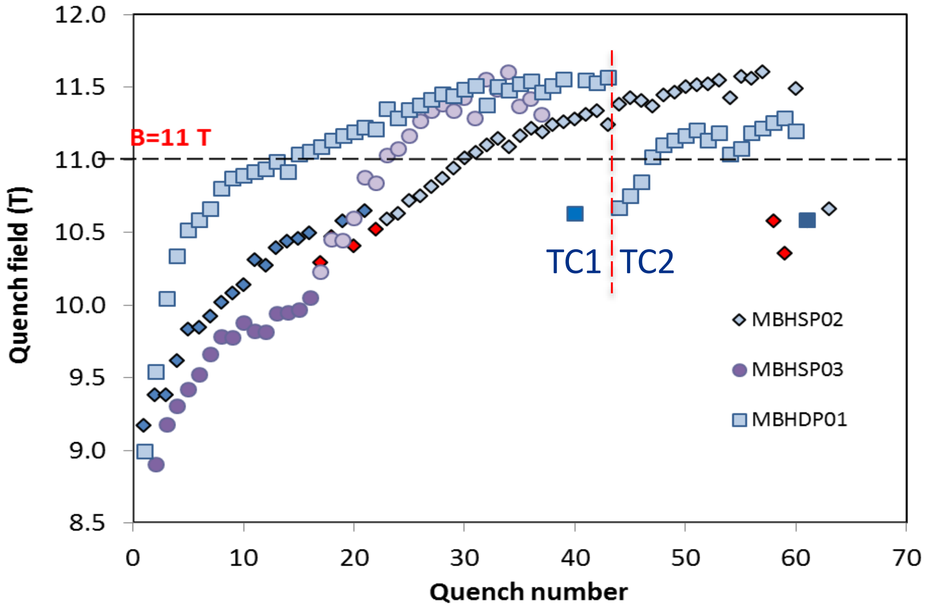




Azimuthal Stress / MPa
Min. if '-', Max if '+', on height of cable

Model Programme

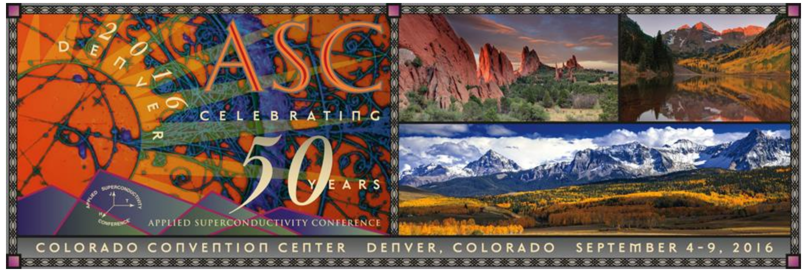
Model Programme at Fermilab



- MBHDP01 was re-tested, in "Thermal Cycle 2" or TC2
  - Magnet training memory
  - Quench protection study
  - Magnetic measurements

  } Goals
- Summary
  - Magnet re-training – effect of anti-cryostat and high MIITs quenches in TC1
  - Quench-back effect, observed in TC1, was confirmed
  - Magnetic measurement data are in a good agreement with the expectations and the data for single-aperture model MBHSP03

Publications

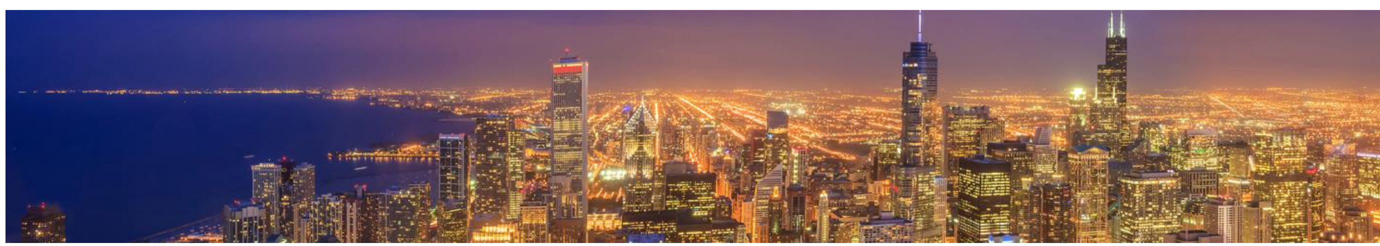


Quench Performance and Field Quality of the FNAL Twin-Aperture 11 T Nb_3Sn Dipole Model for LHC Upgrades

S. Stoynev, N. Andreev, G. Apollinari, B. Auchmann, E. Barzi, S. Izquierdo Bermudez, R. Bossert, G. Chlachidze, J. DiMarco, M. Karppinen, F. Nobrega, I. Novitski, L. Rossi, F. Savary, D. Smekens, T. Strauss, D. Turrioni, G. Velev, A.V. Zlobin

NAPAC2016

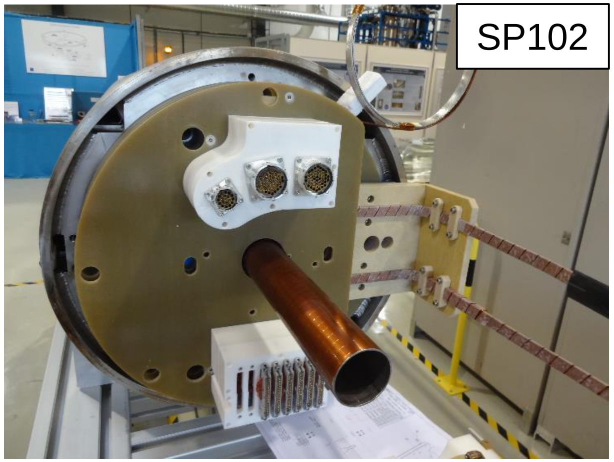
October 9 - 14, 2016
Chicago, IL U.S.A.

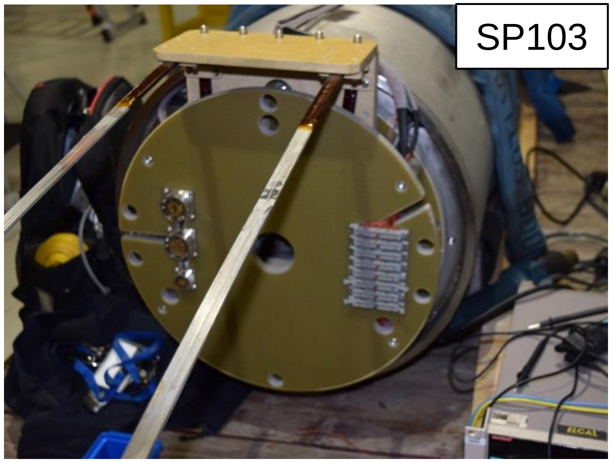


Field quality measurements in the FNAL twin-aperture 11 T dipole for LHC upgrades*

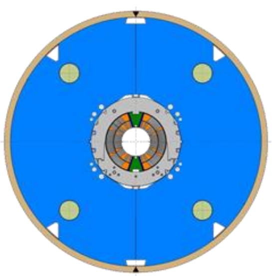
T. Strauss, G. Apollinari, E. Barzi, G. Chlachidze, J. Di Marco, F. Nobrega, I. Novitski, S. Stoynev, D. Turrioni, G. Velev, A.V. Zlobin (FNAL);
B. Auchmann, S. Izquierdo Bermudez, M. Karppinen, L. Rossi, F. Savary, D. Smekens (CERN)

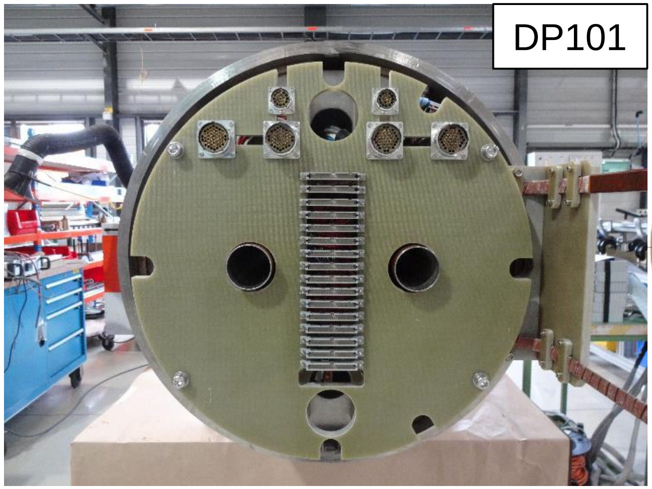
Model programme at CERN

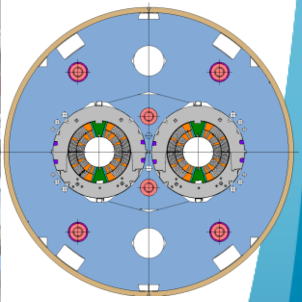




The 11T magnet models





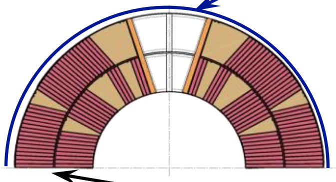


SP105, not shown

N. Bourcey, J.C. Perez

Model programme at CERN

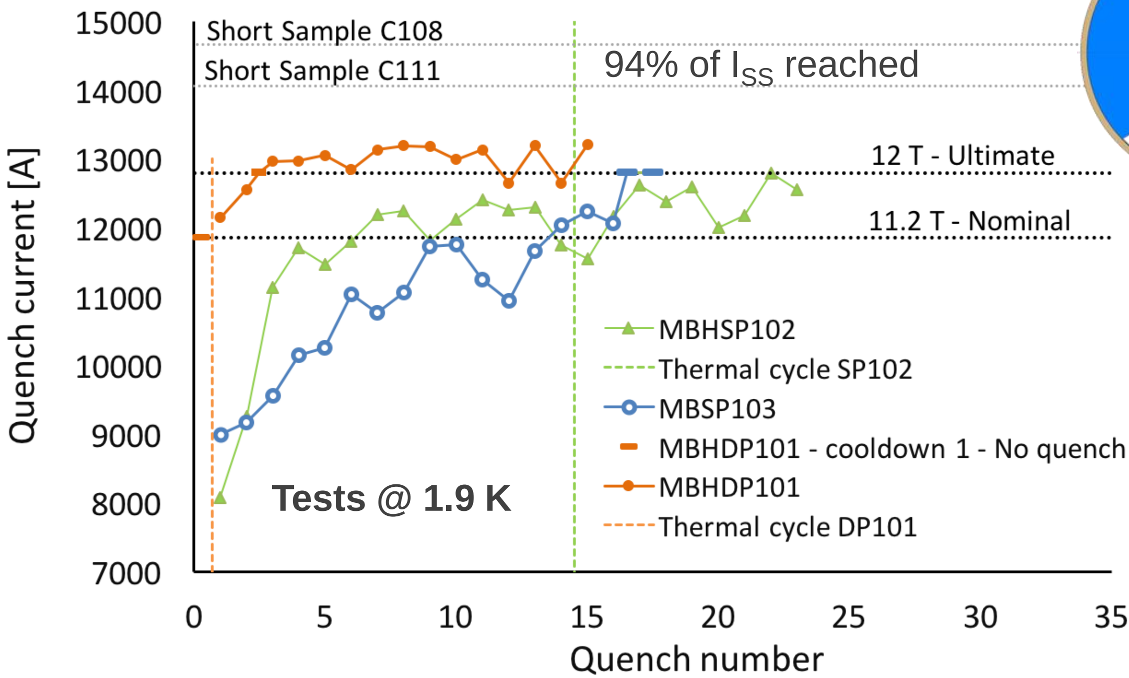
- Model SP105 is currently under test in SM18
  - **Quench heaters impregnated with the coils** for better efficiency and validation of the final design (full-length)
  - **Gelling and post-curing** after impregnation of the coils was done **under pressure ~3 bar**
- Model SP106 is under construction
  - **Interlayer quench heaters** are added
  - Complement the QH installed on the outside surface of the coil, should improve further the quench protection, and add redundancy
  - A development, not for production

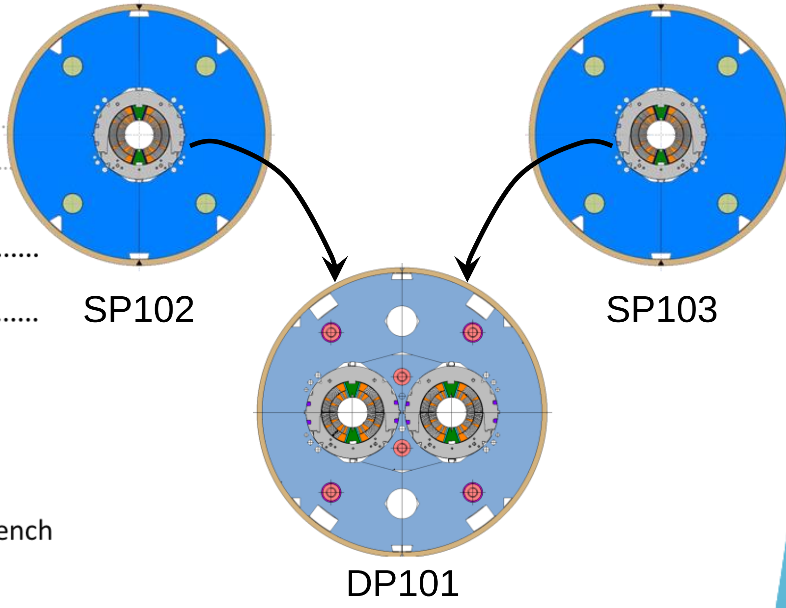


- To come as of next year: models with **PIT**, SP**2**01-**2**03, DP**2**01, and possibly one with RRP, SP107
  - **New cable geometry with reduced keystone angle** (0.79° to **0.50°**) in order to reduce critical current degradation due to cabling below 5%
  - Electro-magnetic and structural designs completed, 70% progress on 3D/2D CAD work

Quench performance, 1

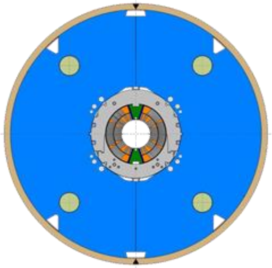
- Tests results of the **first Two-In-One at CERN, MBHDP101**, made of the collared coils of SP102 and SP103 (end 2015 + beginning of 2016)



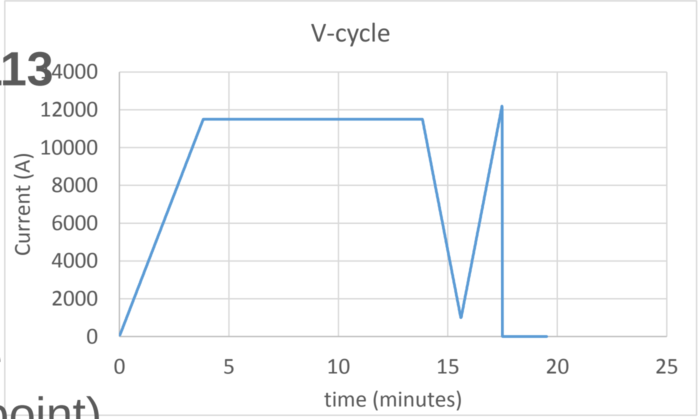


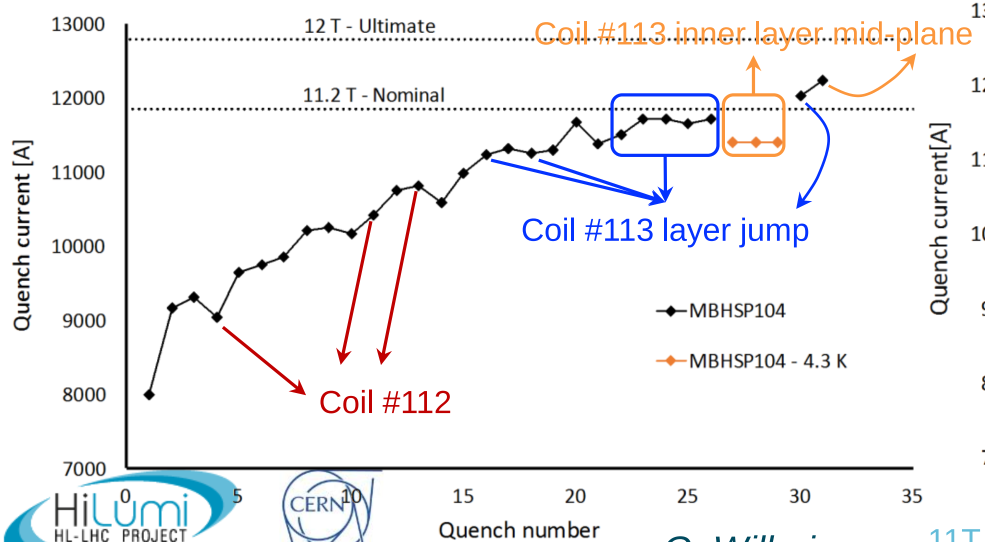
G. Willering

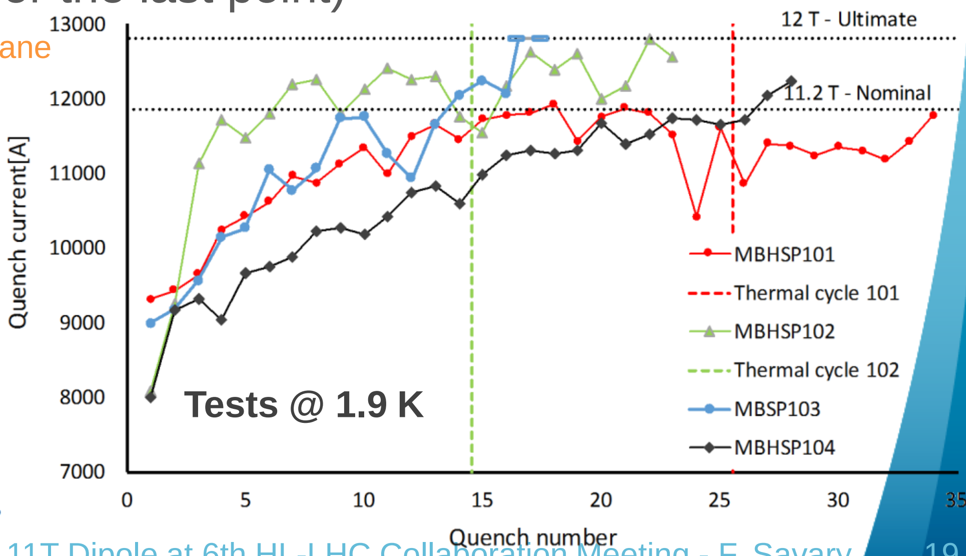
Quench performance, 2



- Model **SP104** (June-July 2016)
  - Fast training of coil #112 with only 3 quenches
  - **Slow training of coil #113 with 17 quenches up to 11.7 kA**
  - Limited at 11.7 kA at nominal ramp rate
  - **Midplane limited at 4.3 K at 11.4 kA in coil 113**
  - $I_{max.}$ reached = 12.24 kA, 88% of I_{SS} @ 1.9 K
  - Holding current test @ 12 kA failed after 62 minutes, quench at layer jump of coil #113
  - **V-shaped pre-cycles** trigger current redistribution, which **allowed overcoming the limitation @ the layer jump** (like for the last point)

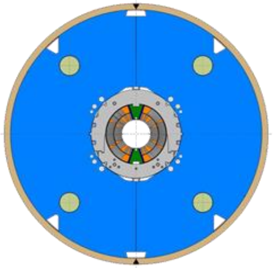




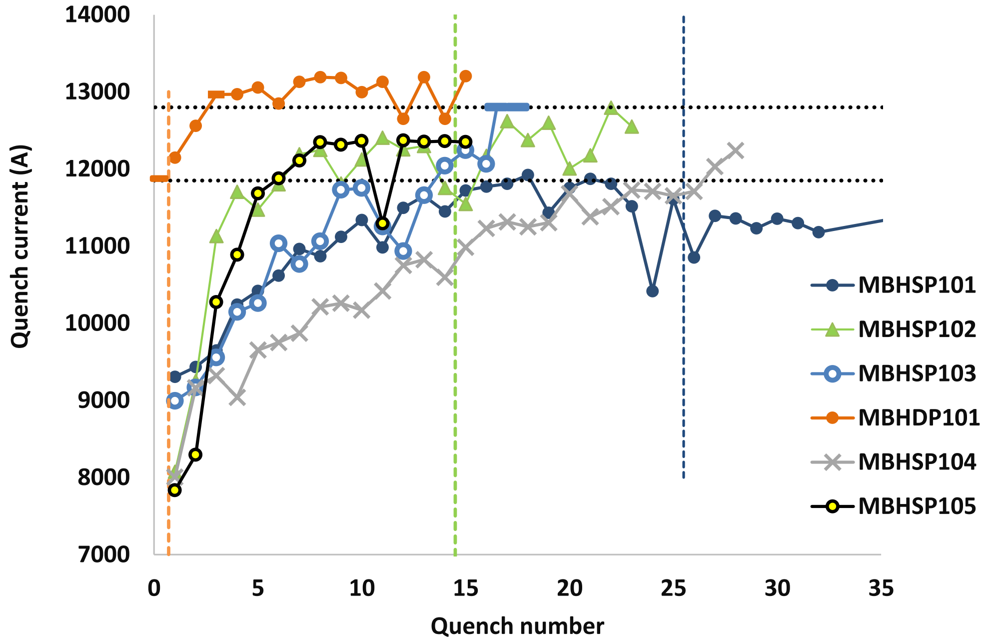


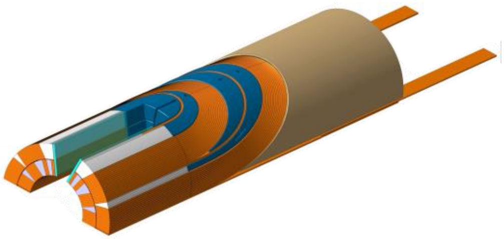
G. Willering

Quench performance, 3



- Model **SP105**, coils #114 and #115 (Nov. 2016 – ongoing)
  - Fastest training so far with only 5 quenches to nominal current
  - Detraining in coil #114 @ layer jump and adjacent turns
  - Last quenches were all in the midplane at 12.3 kA in both coils simultaneous
  - Tests are ongoing with protection studies, quench integral, magnetic measurements, ramp rate dependency



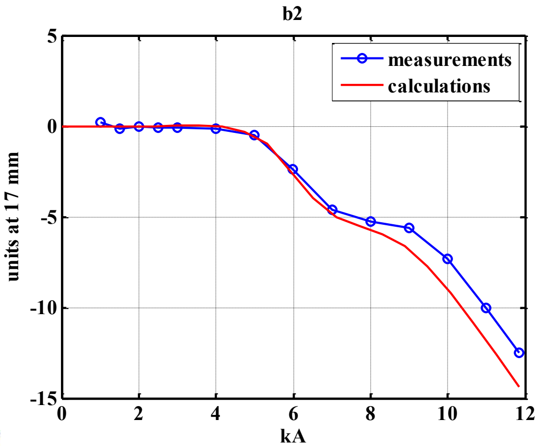


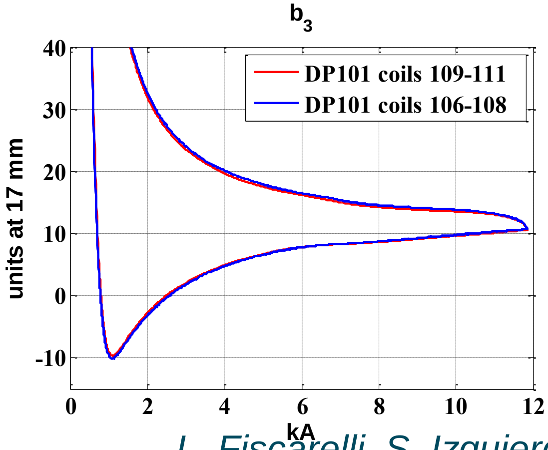
G. Willering

Field quality 1: systematic

- Magnetic measurements on short models show:
  - TF as designed → trimming ok
  - Iron saturation effects as expected on
    - TF
    - Affected multipoles (b_2)
- Persistent current effects on b_3 show a total variation, from injection to nominal, in the order of 20 units
- Systematic field errors mainly due to coil shimming

Average results from 3 magnets		
n	b_n	a_n
2	-0.5	5.1
3	8.0	-0.6
4	-0.3	0.9
5	1.4	-0.4
6	0.0	0.3
7	0.3	-0.1
8	0.0	0.1
9	0.8	0.0
10	0.0	0.0



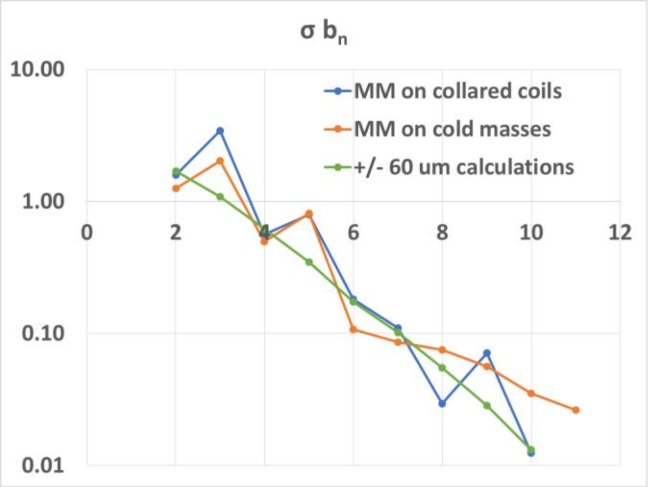


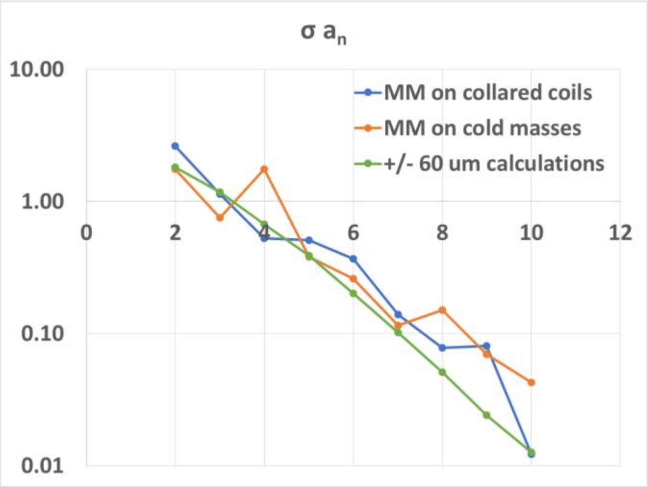
L. Fiscarelli, S. Izquierdo Bermudez

Field quality 2: random

- Random components on multipoles
  - Precision of cable positioning under control
  - Measured standard deviation is in line with simulations of random block displacements of ± 60 μm

std on 3 magnets		
n	b_n	a_n
2	1.26	1.77
3	2.02	0.76
4	0.49	1.76
5	0.81	0.38
6	0.11	0.26
7	0.09	0.11
8	0.08	0.15
9	0.06	0.07
10	0.04	0.04



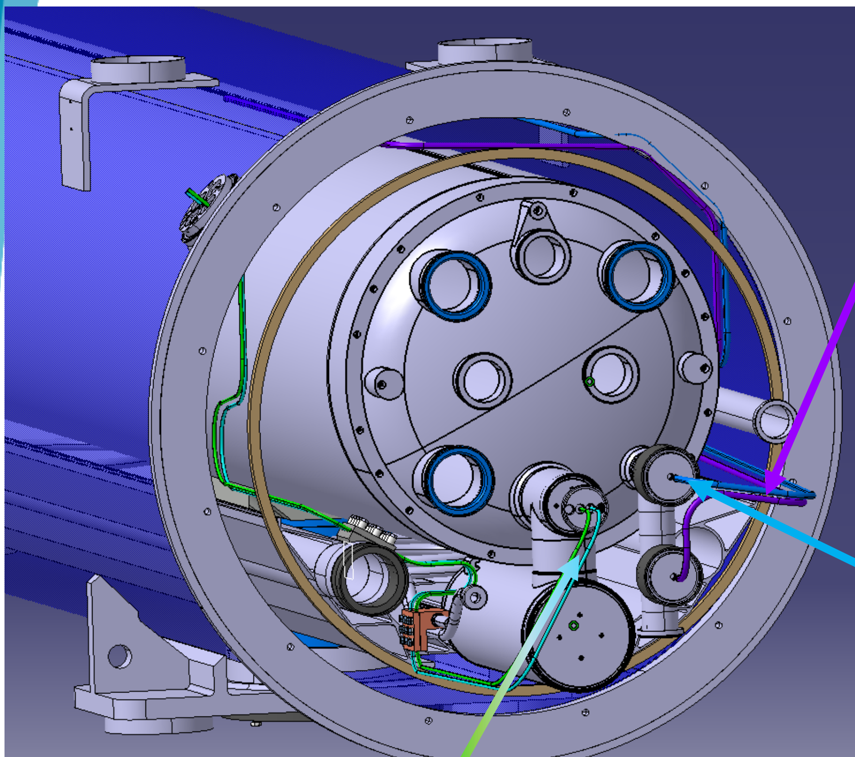


L. Fiscarelli, S. Izquierdo Bermudez

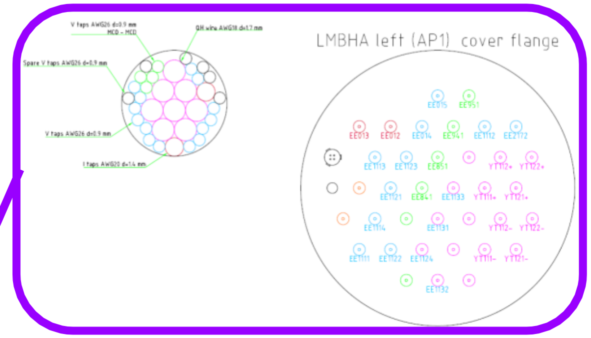
Full Length 11T Magnet

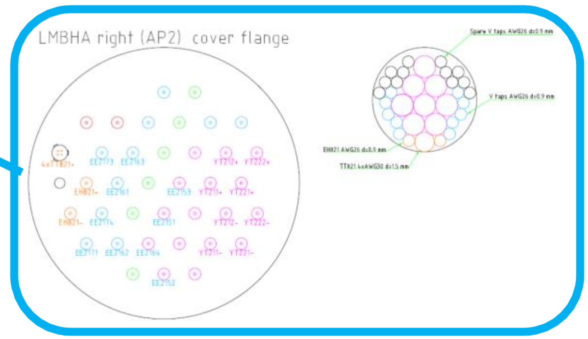
Instrumentation

One instrumentation capillary and cover flange <u>per aperture</u> for routing: V-Taps, quench heater, diode, and cryogenic instrumentation wiring



Conduction cooled trim cables routing (study on-going)





LMBHA (cold mass up-stream)

LMBHA (1)

- V-Taps AWG26 18 +6 spares
- I-Taps AWG20 2
- QH AWG18 8

LMBHA (2)

- V-Taps AWG26 10 +12 spares
- I-Taps AWG20 2
- QH AWG18 8
- TT821 AWG30 4
- EH821 AWG26 2

LMBHB (cold mass down-stream)

LMBHB (1)

- V-Taps AWG26 10 +18 spares
- QH AWG18 8

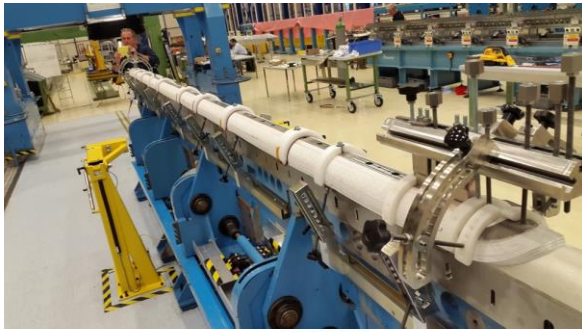
LMBHB (2)

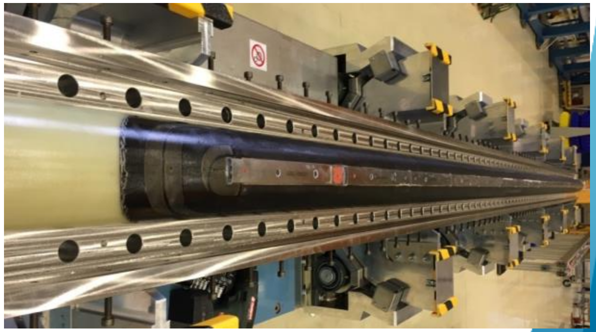
- V-Taps AWG26 8 +14 spares
- QH AWG18 8
- TT821 AWG30 4
- EH821 AWG26 2

L. Grand Clement, H. Prin

Work progress on the prototype

- Most tooling available and operational, non-exhaustive list:
  - Coil impregnation system, 3 short coils and 2 long coils were impregnated
  - Ground insulation forming tooling operational, insulation formed and assembled on the practice coil made of copper cable and 1st low grade coil
  - Assembly and rotation benches available and operational
  - Collaring tooling just received, metrology and assembly on-going
  - Welding press revamping close to completion (control system, hydraulics, and welding equipment), should be ready by the end of the year





Work progress on the prototype – Plan for series

For series production: procurement process recently initiated, aiming at placing a contract for the assembling activities of the collared coils, to be carried out in the CERN Large Magnet Facility (coil winding to start Oct.17)

Cold mass envelope compliance

- **Approved** structural analysis report (EDMS 1711518) on ***conformity of the cold mass envelope*** **to the requirements** of the ***European Pressure Equipment Directive*** *2014/68/EU per new European harmonised standard EN 13445* (Unfired Pressure Vessels)

CERN
CH-1211 Geneva 23
Switzerland

EDMS NO.	REV.	VALIDITY
1711518	1.0	RELEASED

REFERENCE
LHC-LMBH-ES-0002

Date: 2016-11-08

HL-LHC / WP11 – Engineering Specification

Structural analysis of
LMBH DS 11T Dipole magnet cold mass

ABSTRACT:

The HiLumi LMBH 11T dispersion dipole cold mass (DS 11T) must safely withstand the internal helium pressure in all operating conditions, including under the electromagnetic loads. This report presents the stress analysis performed to demonstrate the conformity of the cold mass vessel to the safety requirements of the European Pressure Equipment Directive 2014/68/EU according to the new European harmonised standard EN 13445 (Unfired Pressure Vessels). The low cycle fatigue requirement and choice of filler metal are also addressed to check the margins against leak before break criteria, and justify the minimum toughness requirements at ambient and 1.9K temperature.

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A. Foussat. J.L. Rudeiros Fernandez

Structural analysis of welds

- **Elastic structural analysis of linearized stresses components** in new 11T dipole cold mass weld geometry for normal operation and test load conditions **- OK**
- **Gross elasto-plastic** assessment **- OK**
- **Fracture toughness critical value** versus **Leak before break criterion** - **Compliant**
- **Linear Fracture Mechanics crack growth rate and low cycle fatigue analysis**, in line with filler metal material properties (AISI 1.4453). **- Compliant**

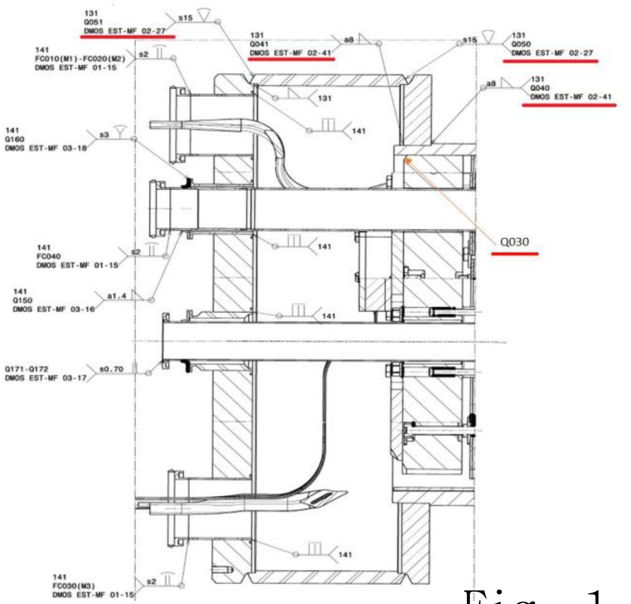

Fig .1

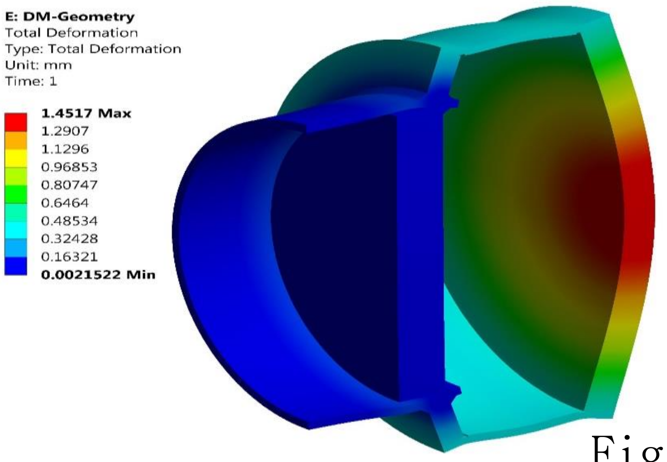

Fig .2

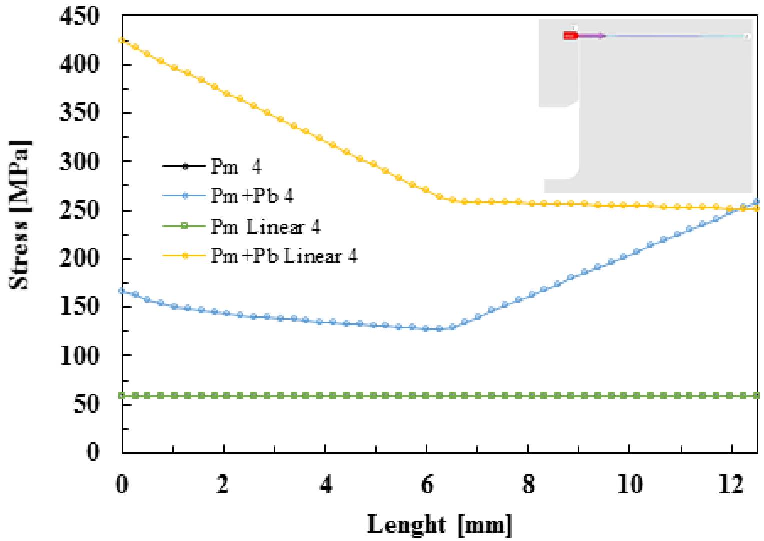

Fig .3

A. Foussat. J.L. Rudeiros Fernandez

Work progress on the cryostat

- 11T Prototype
  - **Vacuum vessel**: final machining at the contractor, leak test planned on 16th November, delivery expected 12th December
  - **Bottom tray**: machining done, all parts available, welding in December
- Bypass cryostat prototype
  - Order placed for the vacuum vessel, delivery in April 2016
  - Price enquiries on going for all other components
- Assembly and QA
  - Adaptations of cryostating designed, work starting in Dec.
  - Procedures for 11T cryostat done
  - Procedures for bypass cryostat on-going

D. Ramos

Summary

- The **successful tests of the two-in-one model MBHDP101 demonstrate feasibility of the upgrade of the LHC collimation system with 11 T dipoles for IP7 of LHC**
- A lot of **attention** is **required throughout the manufacturing process** (recall low performance of SP104)
- Most of the tooling needed for the fabrication of the 11 T dipole is available and operational in the Large Magnet Facility @ CERN, in particular the reaction furnace and impregnation system have been successfully commissioned
- The **construction of the first full length prototype is surely the next major milestone**. The performance tests are planned in winter 2017
- The **production schedule** is **a challenge**

Thank you for your attention

Acknowledgements

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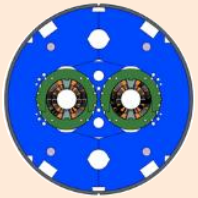
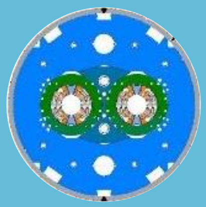
Spare slides

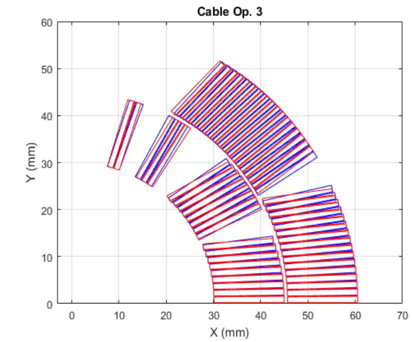
Magnet models X-section 1

Coil #	Single aperture	Note	Test results	Double aperture
106 108	MBHSP102	Second single aperture magnet. Coil 106 from SP101	Reached ultimate current	MBHDP101 First 2 in 1 magnet Outer shell Ø 580 mm Reached ultimate current 
109 111	MBHSP103	Third single aperture magnet	Reached ultimate current	
112 113	New collared coil assembly with coils #112 & #tbd	single aperture collared coil to be assembled with already tested coils	Not cold tested	MBHDP102 Second 2 in 1 magnet Outer shell Ø 570 mm Cold powering tests Q1-2017 
114 115	MBHSP105	Fifth single aperture magnet Impregnated QH traces, Multiple injection points & pressurized curing	Test ongoing Q4-2016	
116 117	MBHSP106	Sixth single aperture magnet Impregnated QH traces, Inter Layer QH, Multiple injection points & pressurized curing	To be assembled Q1-2017 and tested Q2-2017	

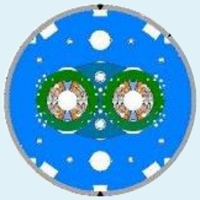
N. Bourcey, J.C. Perez

Magnet models X-section 2

Keystone angle 0.50 deg.



- A new cable geometry is required for PIT in order to reduce critical current degradation during cabling

Coil #	Single aperture	Note	Remarks	Double aperture
202 203	MBHSP201	First single aperture magnet with PIT conductor & new X-section Spot Heaters integration for high MIIts tests	Coil winding scheduled to start Q1-2017 Cold powering tests Q2-2017	MBHDP201 Third 2 in 1 magnet First double aperture with PIT Outer shell Ø 570 mm Cold powering tests Q4_2017 
204 205	Reproducibility MBHSP202	Second single aperture magnet with PIT conductor & new X-section Spot Heaters integration for high MIIts tests	Coil winding scheduled to start Q2-2017	
206 207	MBHSP203	Third single aperture magnet with PIT conductor & new X-section	Coil winding scheduled to start Q3-2017	
118 119	MBHSP107	First single aperture magnet with RRP conductor & new X-section	Coil winding schedule TBD	

N. Bourcey, J.C. Perez

Linear Fatigue Crack growth rate analysis and fracture assessment

- Cross check of **minimal critical fracture toughness K_{IC}** of weld metal at 4K vs. critical crack size
- **Fatigue crack growth rate assessment** across shell closure weld against initial embedded crack dimensions.
- Outcome of minimum acceptable embedded defect size compatible with the **ISO 5817 quality level B and UT quality inspection procedure per ISO 17640** (> 5 mm²)

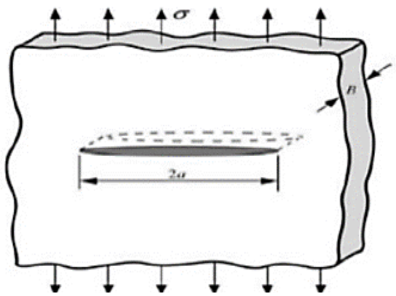


Fig .1

$$\frac{da}{dN} = C(\Delta K_1{}^m - \Delta K_{th}{}^m)$$

Where a is the crack size in mm,
ΔK_1 the variation of stress intensity factor in MPa√m,
N the number of cycles,
ΔK_{th} is the threshold of stress factor intensity range

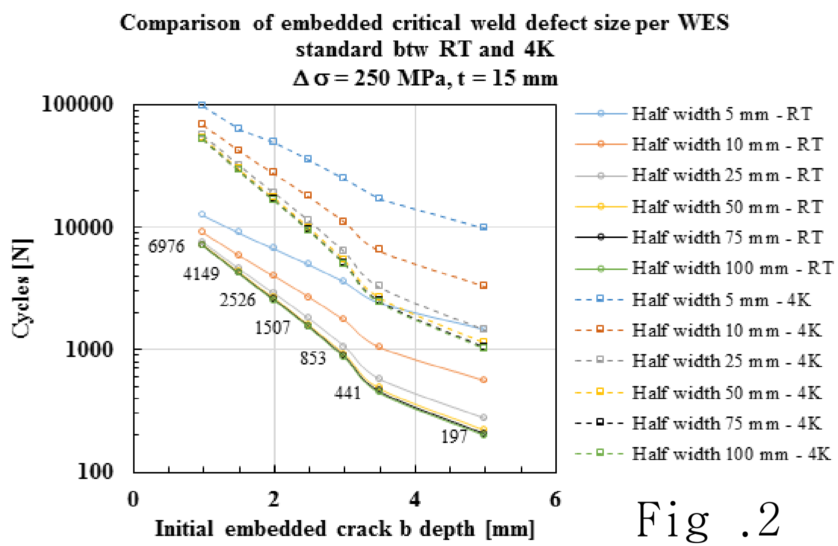


Fig .2

A. Foussat. J.L. Rudeiros Fernandez