Status of the 11T Dipole Project and Task Force Activities

F. Savary on behalf of WP11

With contributions from A. Ballarino, B. Bordini, L. Bottura, M. Daly, G. de Rijk, A. Devred, P. Ebermann, P. Ferracin, L. Fiscarelli, J. Fleiter, M. Giovannozzi, M. Guinchard, S. Izquierdo Bermudez, F. Lackner, C.H. Löffler, J.P. Meignan J.C. Perez, H. Prin, R. Principe, D. Ramos, J.L. Rudeiros Fernandez, A. Vande Craen, G. Willering, F.J. Wolf, S. Yammine

MDP – FCC – EuroCirCol Coordination Meeting 04 – CERN – 2018-03-07

Outline

- Part 1
  - Scope of WP11
- Part 2 – IP7
  - Update on the 11T dipole magnet development
  - Results from the models programme
  - Status of the prototype construction
  - Plan for series production
- Part 3 – IP2
  - Status of new connection cryostats for collimators
- Part 4
  - Summary

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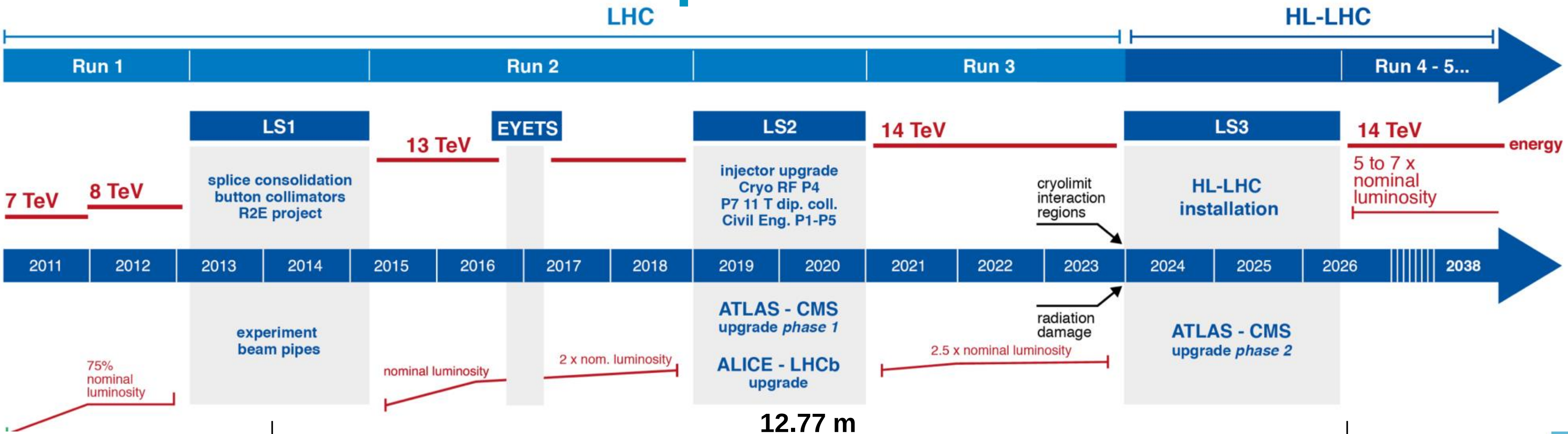
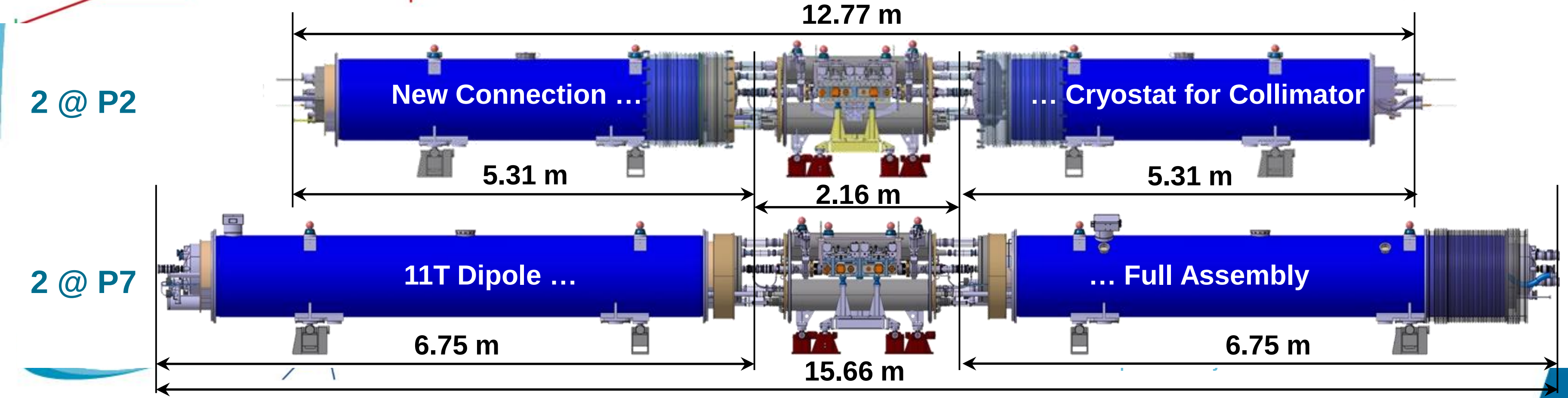
Scope of WP11





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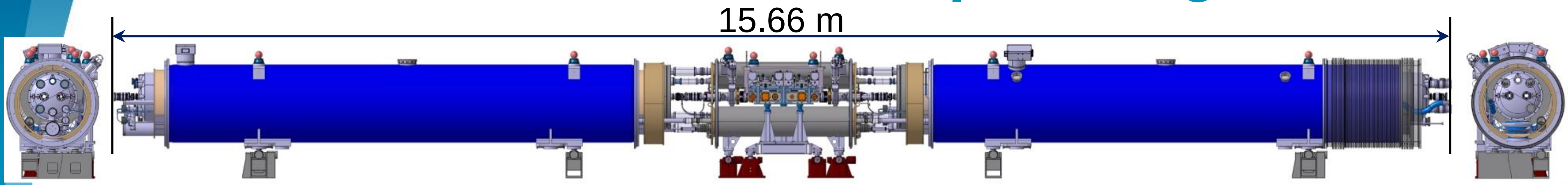
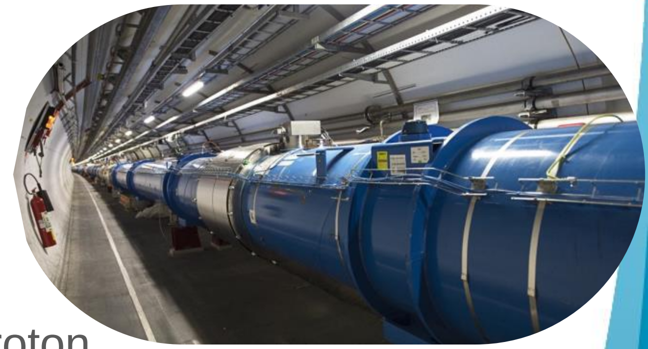
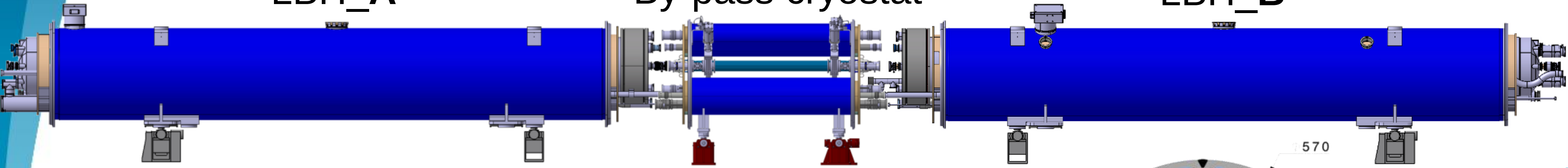
Motivation for an 11T dipole magnet

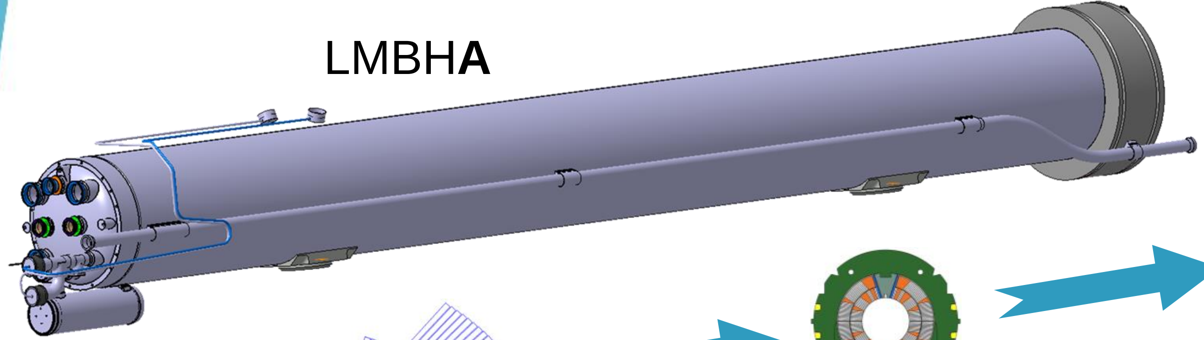


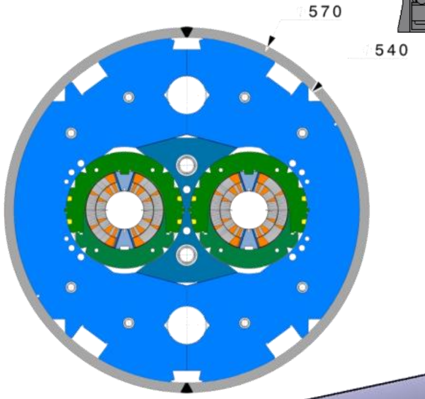


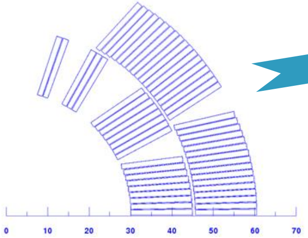
- The HL-LHC Project implies beams of larger intensity ➥ **additional collimators are needed** in order to **intercept and absorb higher beam losses** (dynamic heat loads on cryogenics and risk to quench superconducting magnets)
  - Two collimators, **one per beam, installed on either side of interaction point 7** (IP7) for both proton and heavy-ion collimation losses, in the Dispersion Suppressor region, MBA-B8L7 and MBB-B8R7 (half-cells C8L7 and C8R7)
- **Replace a standard Main Dipole by a pair of shorter 11 T Dipoles producing the same integrated field of 119 T·m at 11.85 kA**

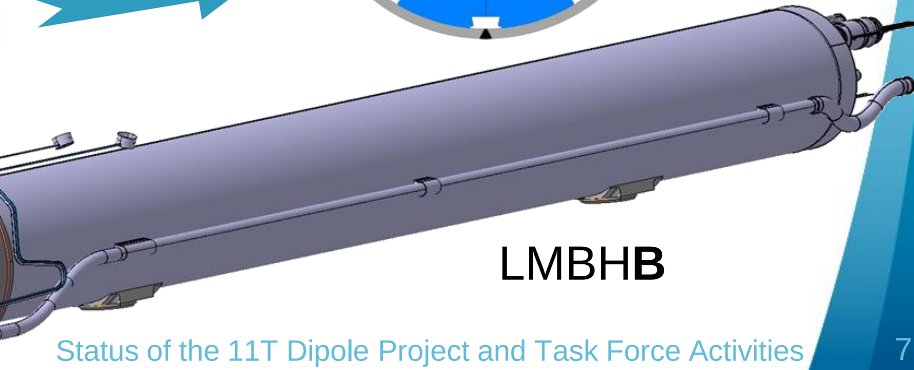
Design features, 1







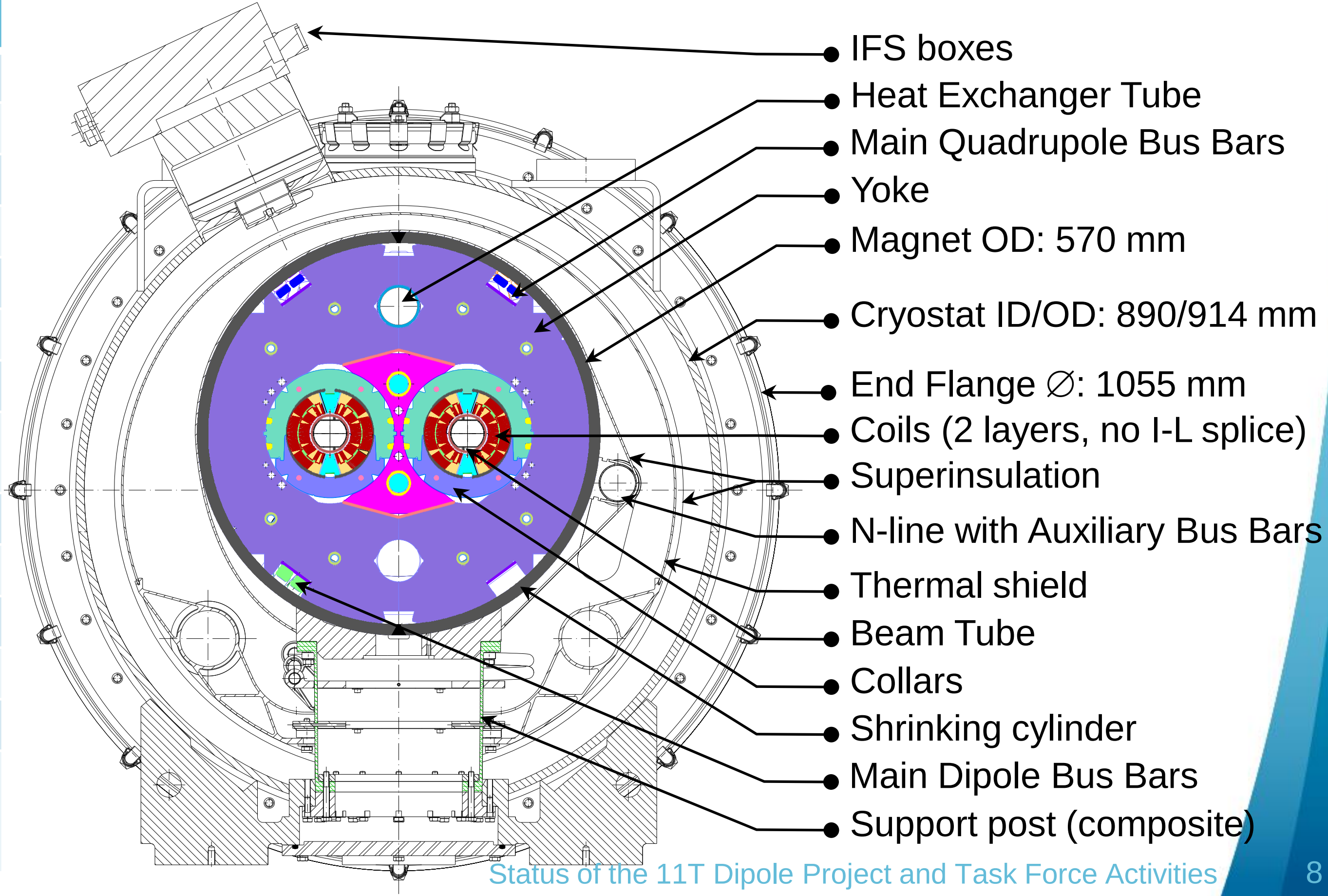




Courtesy
- *H. Prin*
- *D. Ramos*

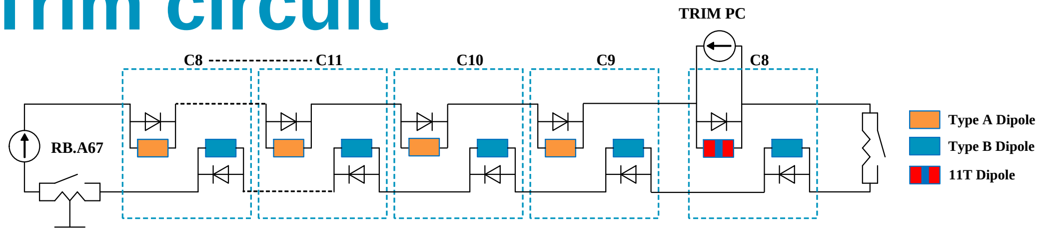
Design features, 2

Parameter	Value
Bore field @ I_{NOM}	11.23 T
Nominal current	11.85 kA
Operating T	1.9 K
Load line margin	20 %
Magnet aperture	60 mm
# turns (inner/outer)	56 (22/34)
Cable bare width	14.7 mm
Cable bare mid-thickness	1.25 mm
Keystone angle	0.79°
Strand diameter	0.7 mm
# strands per cable	40
Cu to non Cu ratio	1.15 ± 0.1
RRR after reaction	> 150
Minimum strand critical current, Ic (12T, 4.222 K)	438 A

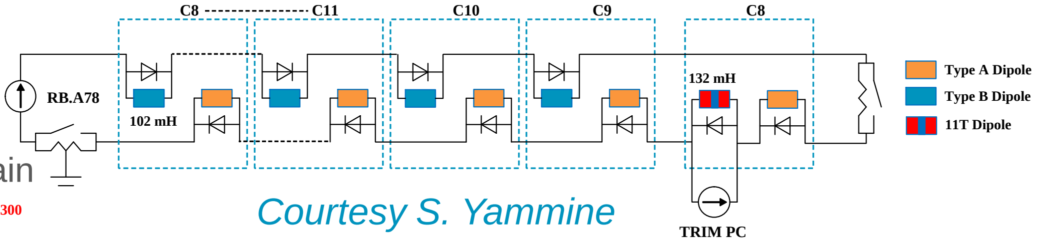


Trim circuit

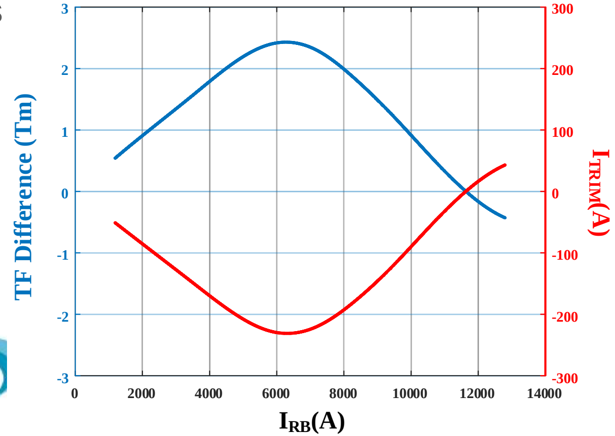
- The **11 T dipoles are powered in series with the main dipoles**
- The transfer function of the 11T dipole full-assembly (15 m long) is different from that of the MB magnet, it generates an orbit distortion at injection of about 2 mm (it can be up to 3 mm) [*R. De Maria, D. Gamba, M. Giovannozzi*]
- A trim current is needed to compensate for this
- Spool pieces will be installed, like in the main dipoles

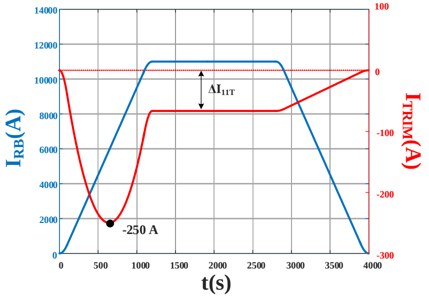


MB circuit configuration of HL-LHC with the 11T trim power converter (RB.A67 @ top, and RB.A78 @ bottom)

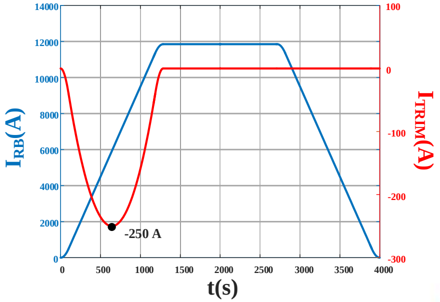


Courtesy S. Yammine





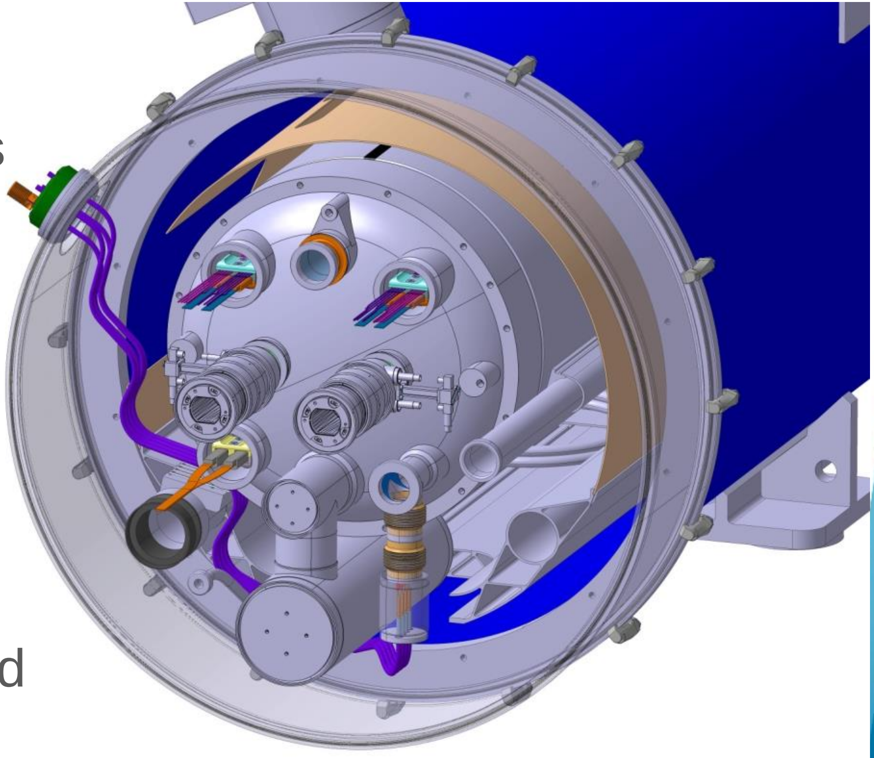
6.5 TeV, I_{RB} = 11 kA, ΔI_{11T} = -67 A



7 TeV, I_{RB} = 11.85 kA, ΔI_{11T} = 0 A

Trim current leads

- **Local powering**
- **Conduction-cooled** design as for the LHC 60 A and 120 A correctors (more than 2000 leads operational in the LHC)
- **One single thermal shield** (on the 20 K line)
- **Integration study** being completed
- **Leads tested** with the magnet before integration in the tunnel, and prototypes tested in SM18



Courtesy A. Ballarino

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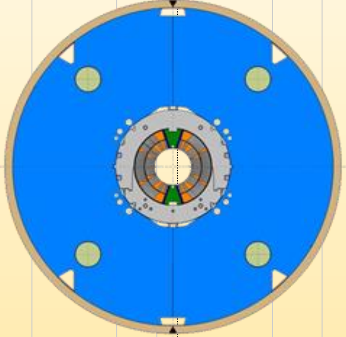
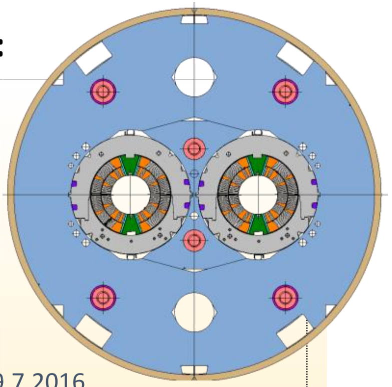
Timeline of magnet models cold testing

1 single practice coil model:
- MBHSM101

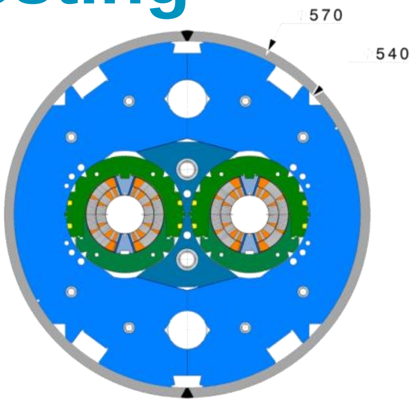
6 + 2 single aperture models:
- MBHSP101 to MBHSP106
- MBHSP107
- MBHSP108



2 two-in-one models:



MBHDP101



MBHDP102
same section as prototype and series

MBHSM101 02.06.2014 - 26.07.2014

MBHSP101 3.11.2014 - 19.12.2014

MBHSP102 4.5.2015 - 30.6.2015

MBHSP103 31.8.2015 - 30.10.2015

MBHDP101 1.12.2015 - 26.2.2016

MBHSP104 1.6.2016 - 29.7.2016

MBHSP105 1.11.2016 - 30.11.2016

MBHDP102 2.10.2017 - 31.10.2017

MBHSP106 1.12.2017 - 28.2.2018

MBHSP107 (series production cable/insulation scheme) 09.07.2018 - 03.08.2018

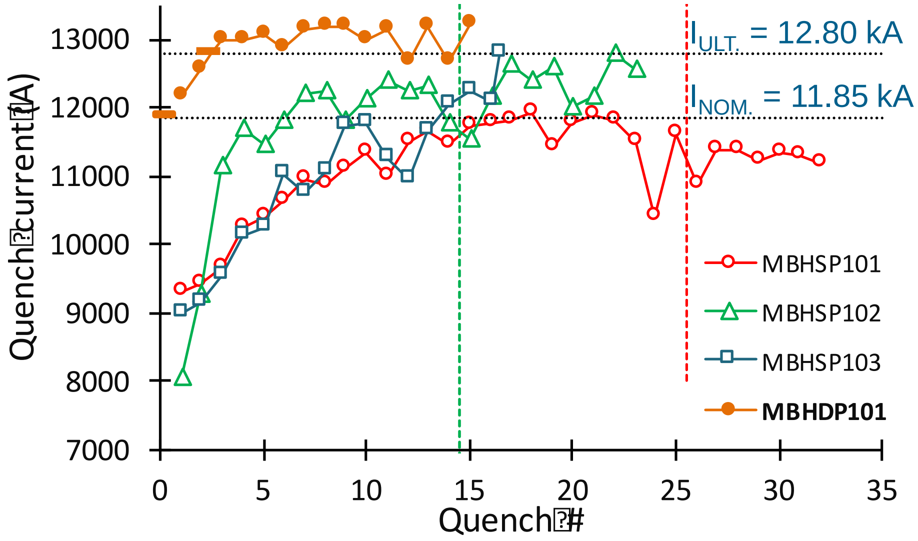
MBHSP108 (series production cable/insulation scheme) 16.08.2018 - 14.09.2018

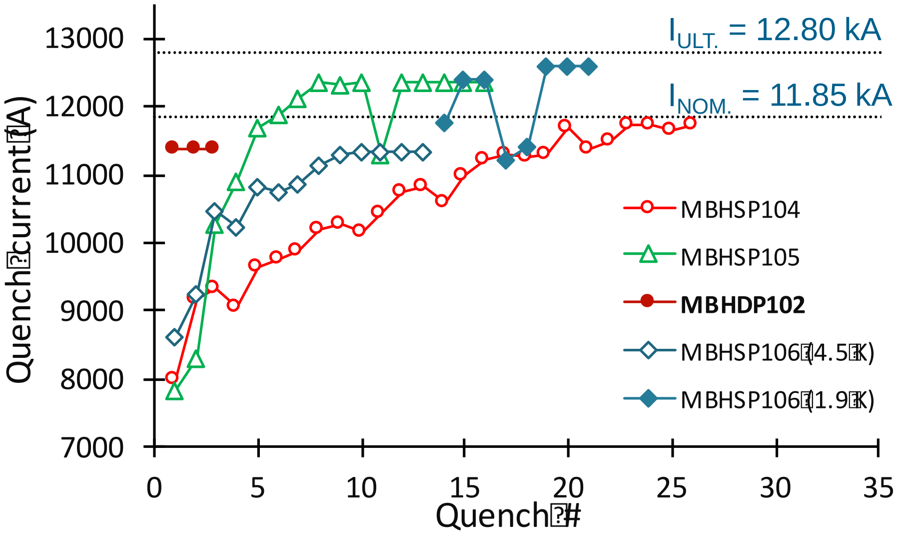
2014 2015 2016 2017 2018 **2018**

TODAY

Training performance @ 1.9K

MBHSM101 not shown, as it cannot be directly compared



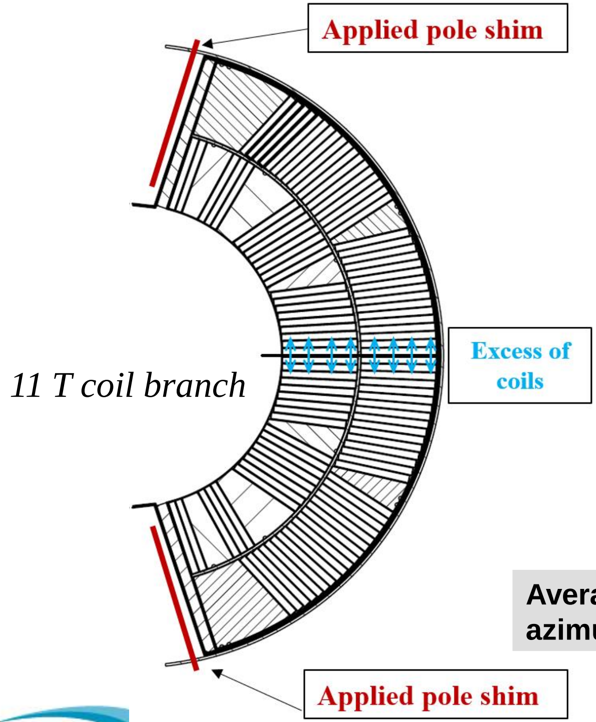


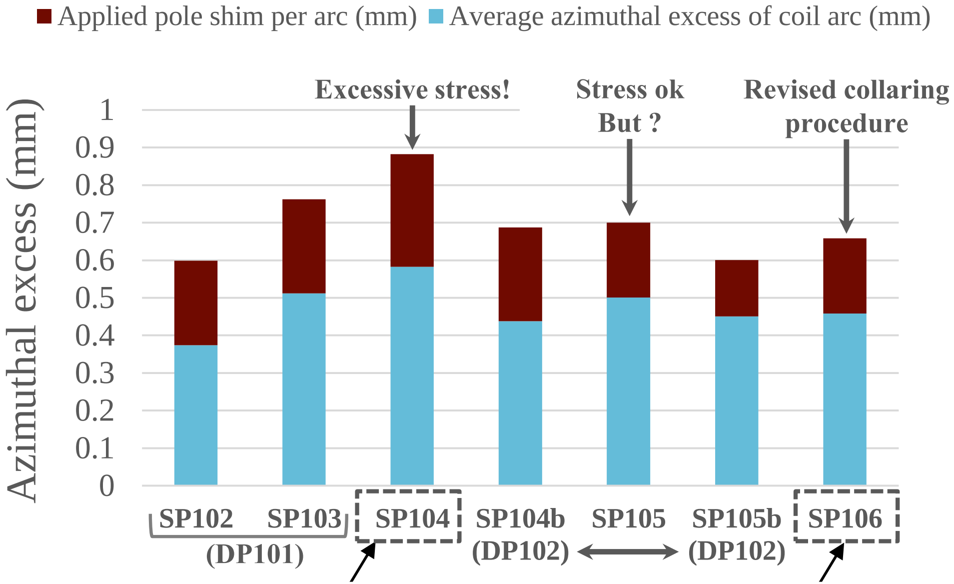
- Very good results on two single aperture models, SP102 & SP103, and first two-in-one DP101
- Limitations for the other models SP101, SP104, SP105, SP106, and second two-in-one DP102
- **Action:** understand the reason(s) for the limitations, and consolidate the manufacturing procedures, in particular the collaring operation, in order to guarantee sufficient operation margin

*Courtesy G. Willering, **see his presentation***

Shimming of magnet models

- The pre-stress depends on the sum of the **azimuthal oversize of the coils with the thickness of the pole shims** (… and also on the mechanical properties of the coil)

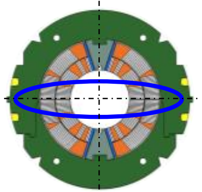




Average inner layer azimuthal stresses @ 12 T	SP104		SP106	
	Midplane turn	-147 MPa	Midplane turn	-127 MPa
	Pole turn	-29 MPa	Pole turn	-7 MPa

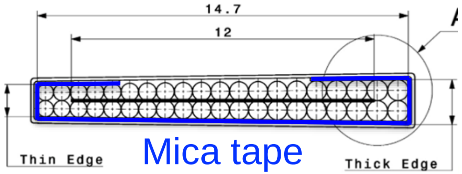
Courtesy C. Löffler, E. Nilsson

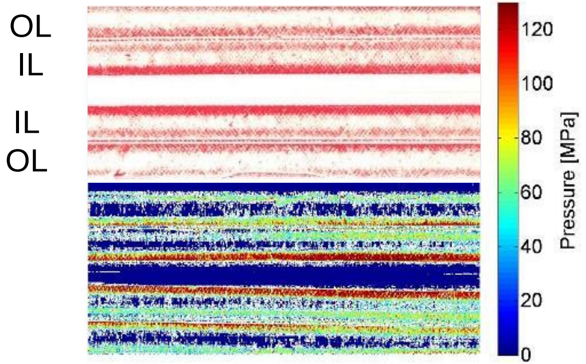
Locations of limitations – Hint 1



Model	Limit @ 1.9 K [kA] / Location	I/I_{ss} [%]	Limit @ 4.5 K [kA] / Location	I/I_{ss} [%]
SP101	11.9 / 107 / O1-O2 (head)	*82*	11.2 / 107 / O2-O3 (transition)	*86*
SP102	>12.8	*>88*	11.7 / 106 / layer jump	*90*
SP103	>12.8	*>90*	11.7 / 111 / layer jump	*92*
DP101	13.2 / mid-plane	*94*	-	*-*
SP104	12.3 / mid-plane	*85*	11.4 / mid-plane	*87*
SP105	12.4 / mid-plane	*84*	11.3 / mid-plane	*84*
DP102	11.4 / mid-plane	*80*	10.4 / mid-plane	*77*
SP106	12.6 / 1 location (straight part, close to lead end, in turns close to pole)	*85*	11.4 / 4 different locations	*84*

Collaring tests with Fuji paper in the mid-plane have revealed peak stresses along the edges of the cable, not predicted by FEA

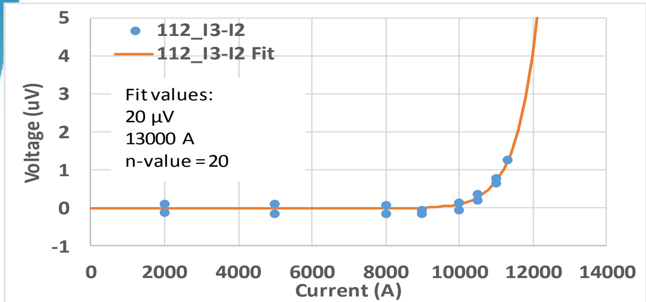




120 MPa stress gradient on the mid-plane in MBHSP105b

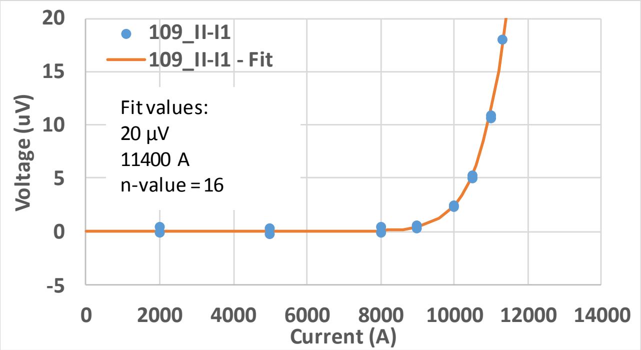
Courtesy G. Willering, S. Izquierdo Bermudez

V-I Curves in aperture 1 of MBHDP102 – Hint 2

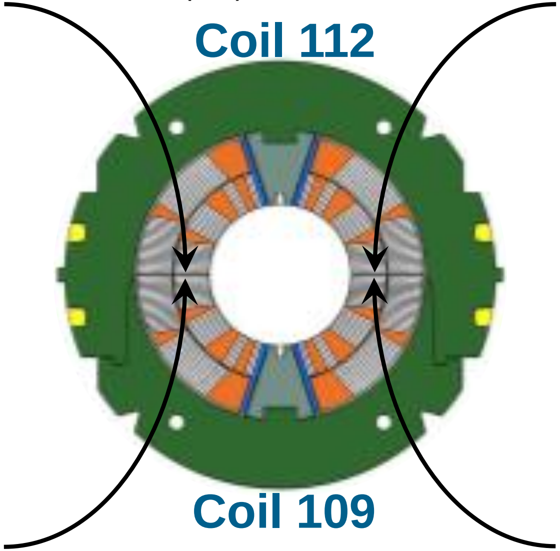


20 µV at 13000 A

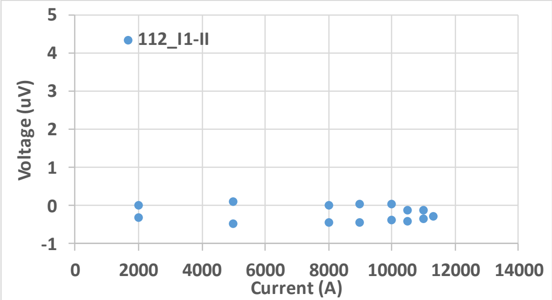
20 µV at 11400 A



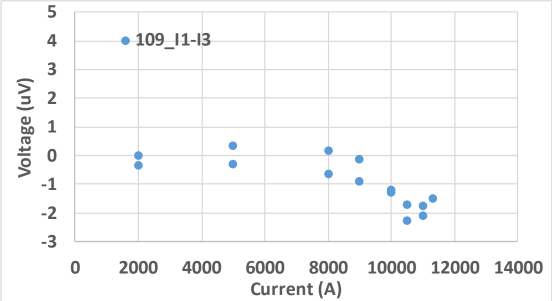
- Accurate superconducting to normal transition with a low n-value in 4 out of 8 midplane segments (2 in Ap. 1 and 2 in Ap. 2)



- No decay on current plateau
- **All this suggests possible (homogeneous) degradation of strands**



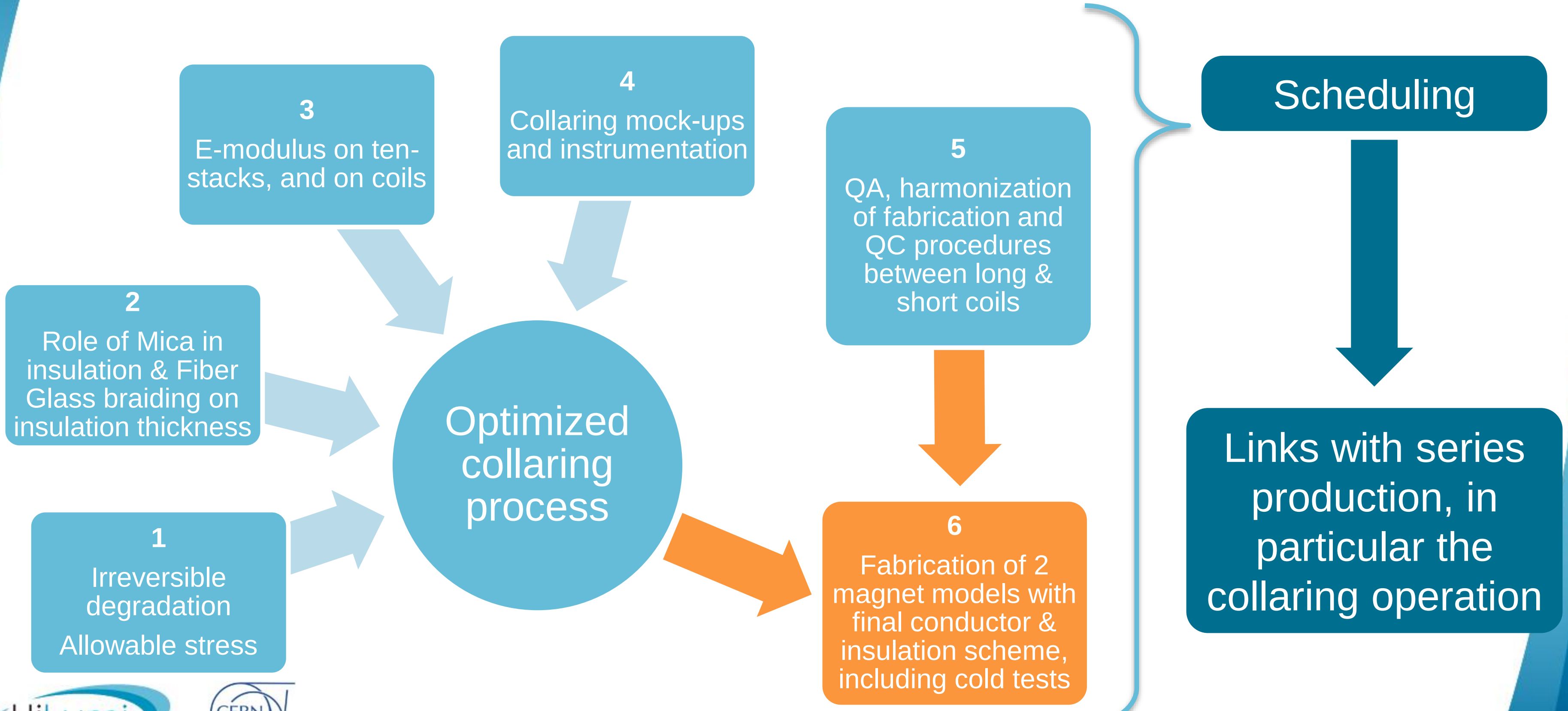
- No hysteresis between ramp up and ramp down
- Scales with temperature from 1.9 K to 4.3 K
- Reaches 1 hour stable 18 µV before/without quench



HiLumi HL-LHC PROJECT CERN

Courtesy G. Willering

Task Force on 11T Dipole Magnet



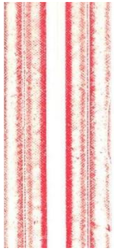
Task Force on 11T Dipole Magnet

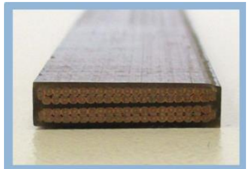
- Set up within the MSC Group
- Steering by L. Bottura, G. de Rijk, A. Devred, and F. Savary: to guide the task force and follow-up the activities (weekly meetings on Tuesday morning)
- 6 sub-tasks, as follows
  1. Irreversible degradation, allowable stress on impregnated cable
  2. Role of MICA in insulation and of Fiber Glass braiding on insulation thickness
  3. E-modulus on ten-stacks, and on coils
  4. Collaring kinematics, mechanics, instrumentation, and mock-ups
  5. Harmonization of fabrication and QC procedures between long & short coils
  6. Short models fabrication

  1. J. Fleiter and F. Lackner
  2. S. Izquierdo Bermudez
  3. S. Izquierdo Bermudez
  4. P. Ferracin
  5. F. Lackner & J.C. Perez
  6. J.C. Perez
- Support from EN-MME for mechanical instrumentation (M. Guinchard)
- Support from EN-ACE for scheduling (J.P. Meignan)
- Kick-off meeting on 10 November 2017
- Follow-up meetings every two weeks on Wednesday morning (https://indico.cern.ch/category/5095/)
- Extended meeting with external experts held on 10 January 2018 (https://indico.cern.ch/event/689859/)

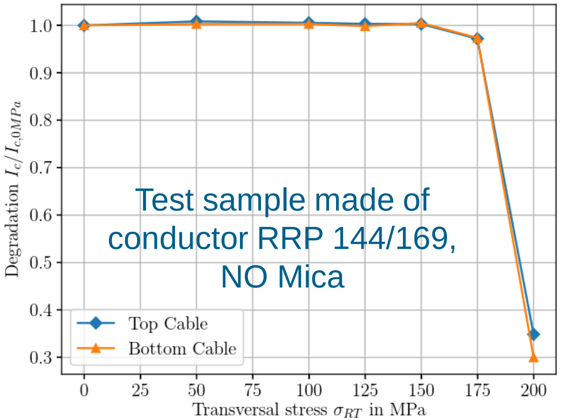
Task Force on 11T Dipole Magnet – Tasks 1 & 2

- Irreversible degradation on final cable with final insulation scheme
- 3 types of samples
  - No MICA
  - MICA 25 mm wide
  - MICA 31 mm wide

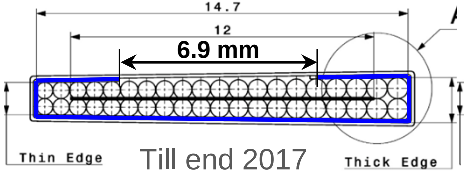




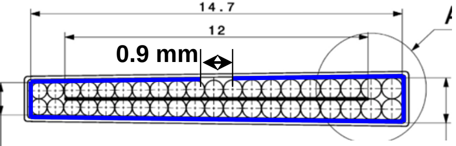
Specimen cross section (15.6 x 3.8) mm²



- Role of MICA, as stress concentrator



Till end 2017



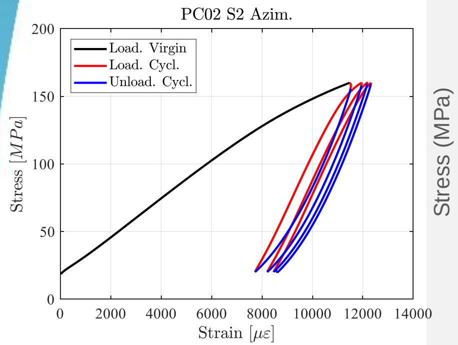
New insulation scheme

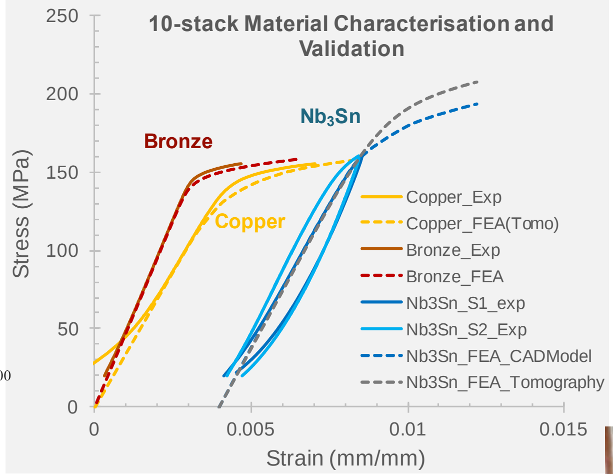
- Optimization of Fiber Glass braiding parameters to reduce thickness of insulation

Parameter	All coils till end 2017	New models & Series production
Cable width, mm	14.7	14.7
Cable thickness, mm	1.25	1.25
Mica width, mm	25	**31**
Gap, mm	6.9	0.9
Gap/cable width, %	50	6
Gap/cable thickness, --	5.5	0.7
Insulation thickness @ 5 MPa	135	**100**

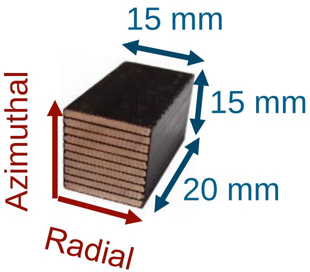
Task Force on 11T Dipole Magnet – Task 3

- E-modulus on ten-stacks
  - Compression in azimuthal direction

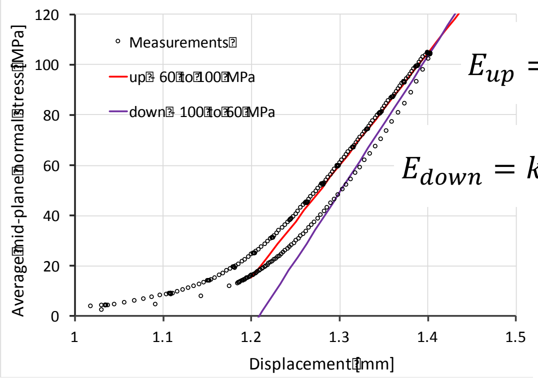




Material	E (GPa)
Resin	3,8
Bronze	118
Copper	109
Fibre/Mica/Resin	11
Nb_3Sn filaments	140
Nb_3Sn/Cu (1:1) composite strand	123
Nb_3Sn 10-stack	36 ± 5

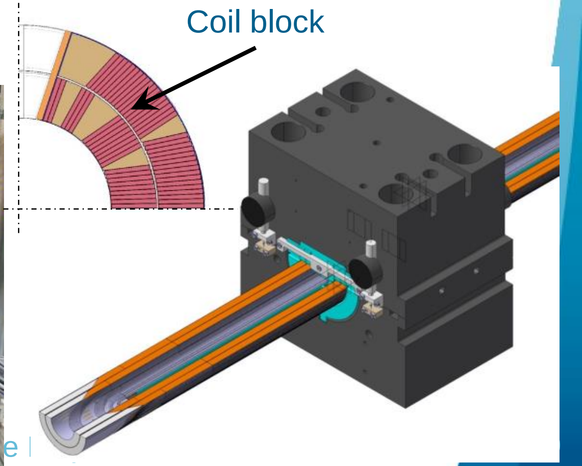


- E-modulus on full coil cross-section



$$E_{up} = k_{up} \frac{l^n_{COIL}}{w_{coil}} = 27\ GPa$$

$$E_{down} = k_{down} \frac{l^n_{COIL}}{w_{coil}} = 33\ GPa$$

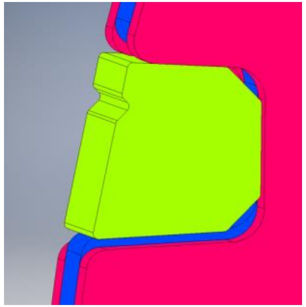


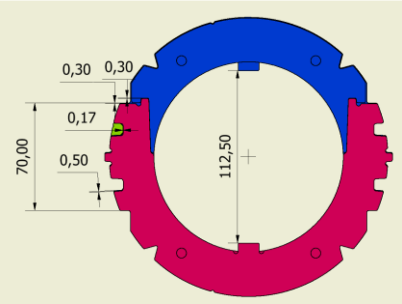
Task Force on 11T Dipole Magnet – Task 4

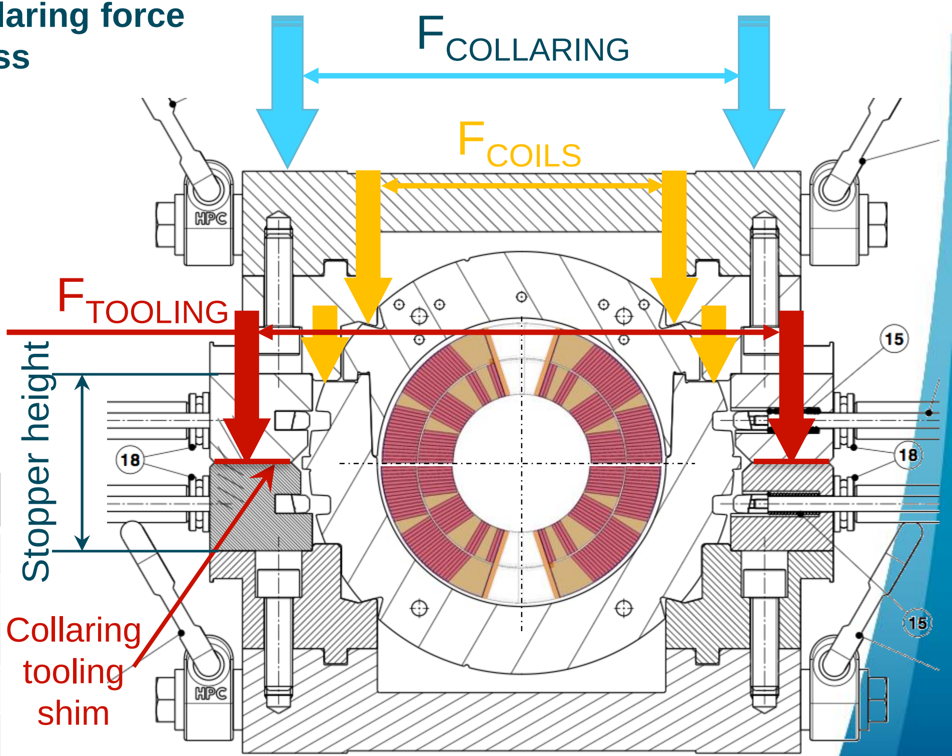
Collaring procedure

- **Stopper height,** or collaring tooling shim, and **$F_{COLLARING}$** such that:
  - **Keys** can be **inserted** successfully **at minimum collaring force**
  - **Coil stress at full collaring force < allowable stress** (w.r.t. irreversible degradation)
  - **Spring back as small as possible**

$$F_{COLLARING} = F_{COILS} + F_{TOOLING}$$



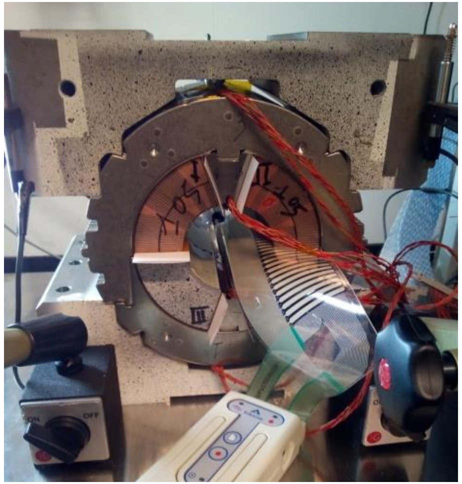


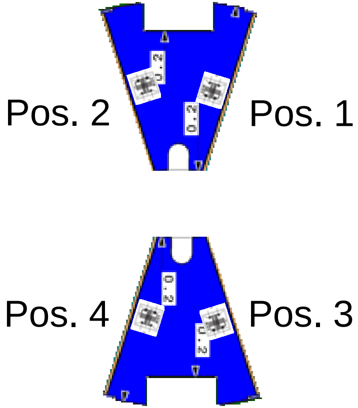


SP Model	Collaring tooling shim	Stopper height	Key clearance
	0 μm	69.7 mm	+300 μm
	100 μm	69.8 mm	+200 μm
	200 μm	69.9 mm	+100 μm
	300 μm	70.0 mm	0
101,102,103	400 μm	70.1 mm	-100 μm
104,105,106	150 μm	69.85 mm	+150 μm

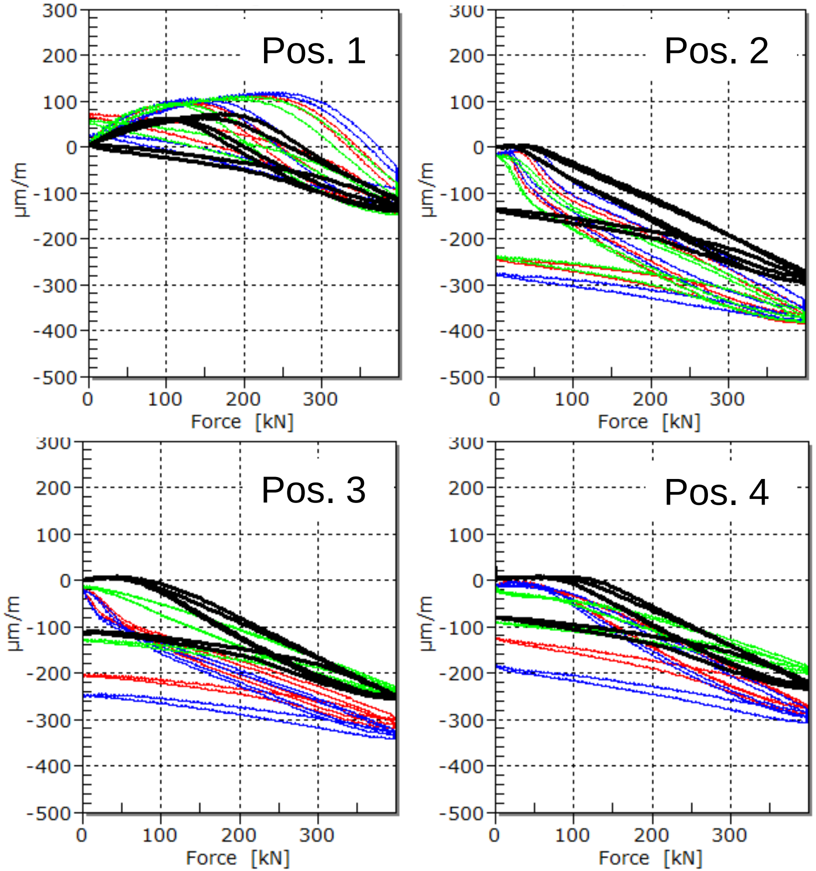
Task Force on 11T Dipole Magnet – Task 4

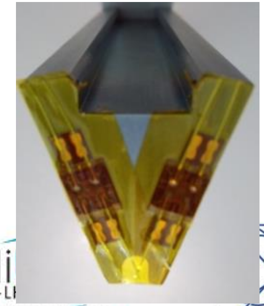
Collaring mock-up

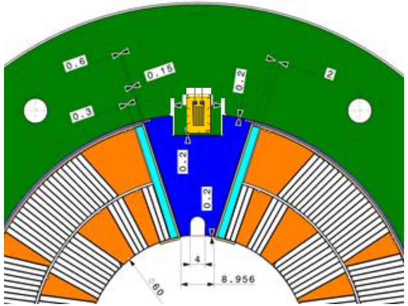




Azimuthal strain seen by the gauges glued on the X-section of the pole piece during collaring







Outline

- Part 1
  - Scope of WP11
- Part 2 – IP7
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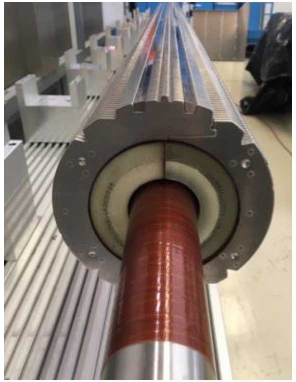
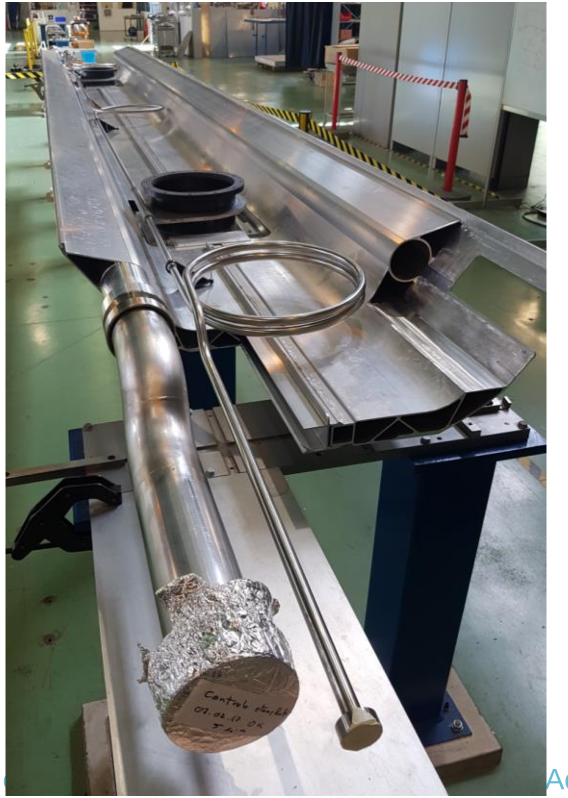
Status of the prototype construction – Cold mass

Coil ID	CR4	CR5	CR6	CR7
Strand type RRP	132/169 & 150/169	150/169 & 144/169	108/127	108/127
Cu/Sc, average	1.18	1.06	1.14	1.15
RRR, average	250.6	168.0	293.6	297.0
Critical current, I_c [A] (12 T, 4.222 K), average	404.6	451.6	449.0	460.7
Mid-thickness [mm]	1.2512	1.2486	1.2502	1.2495
Width [mm]	14.710	14.701	14.694	14.694
Keystone angle [°]	0.80	0.81	0.79	0.79



Status of the prototype construction - Cryostat

- The cold mass assembly will be finished by the end of March
- The assembly with the cryostat will be completed by the end of April
- **Cold testing will start in May**



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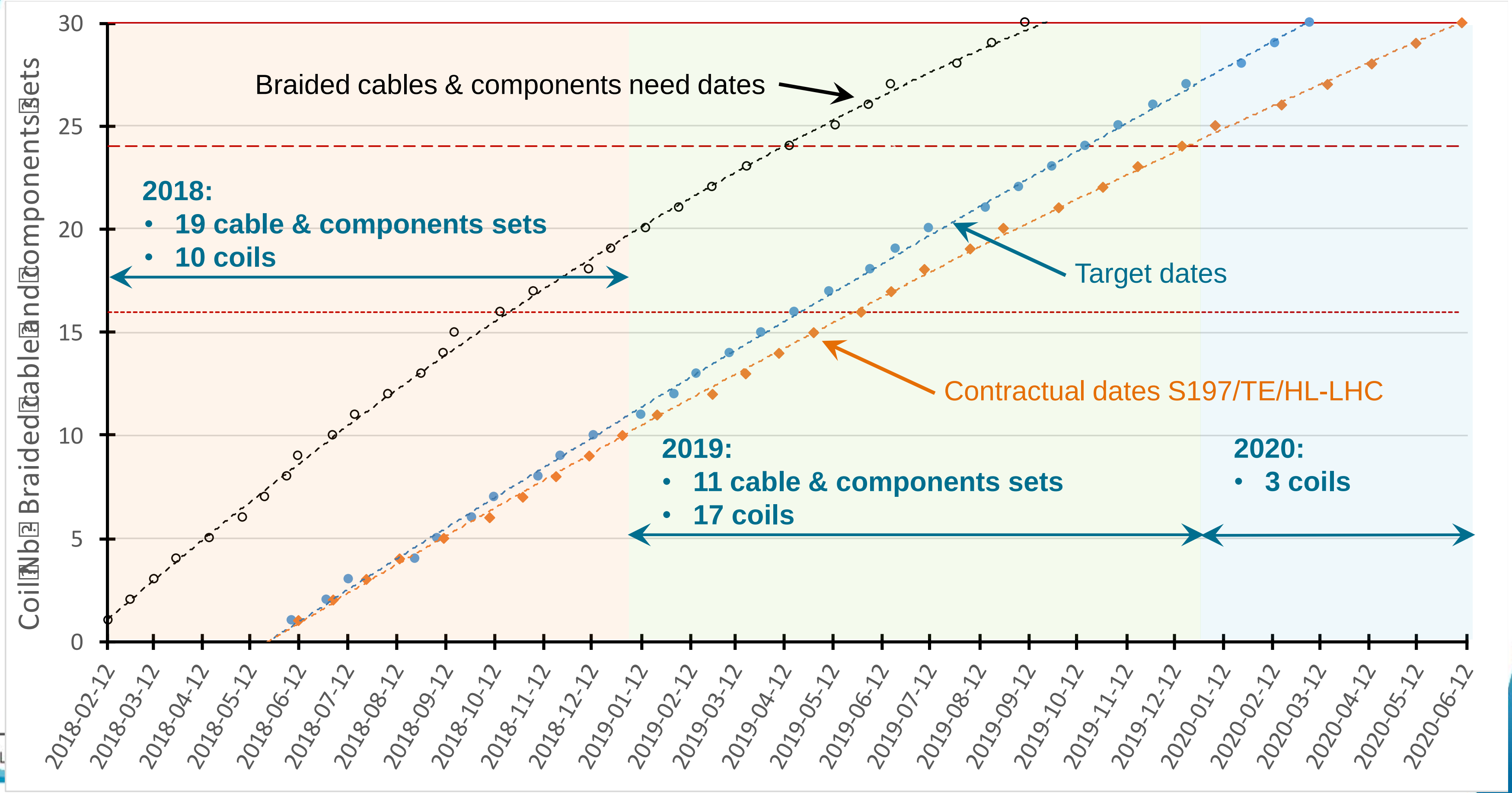
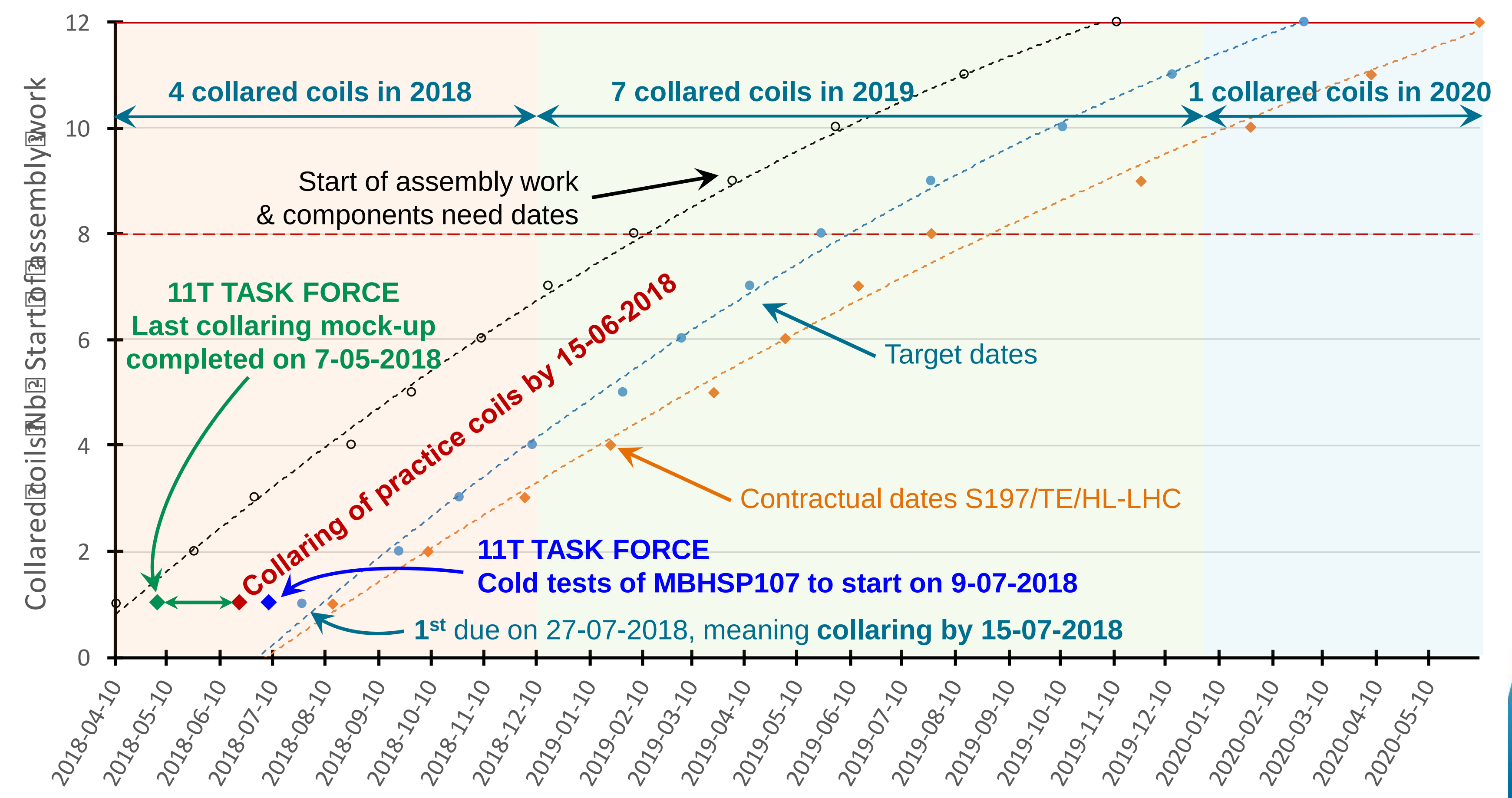
Plan for series production

- A **service contract** was placed with Alstom Power Services SA (now part of General Electric) for the production of the coils and collared coils: **S197/TE/HL-LHC**
  - Manpower only. However, performance obligation is on the contractor side who shall provide good workmanship
  - Work will be carried out @ CERN in bldg.180, the Large Magnet Facility
  - Infrastructure, tooling, components, manufacturing and inspection procedures provided by CERN
- The cold masses, cryostating, cold testing, stripping operations, and connections in the tunnel will be done by the MSC crew
- There are also other contributions by other groups/departments for quench heater power supplies, quench protection system, beam screen and sector valves, fiducialisation, transport to tunnel, alignment in tunnel, installation of trim power supplies and warm cables

Coils production plan (30 coils)



Collared coils production plan (12 collared coils)



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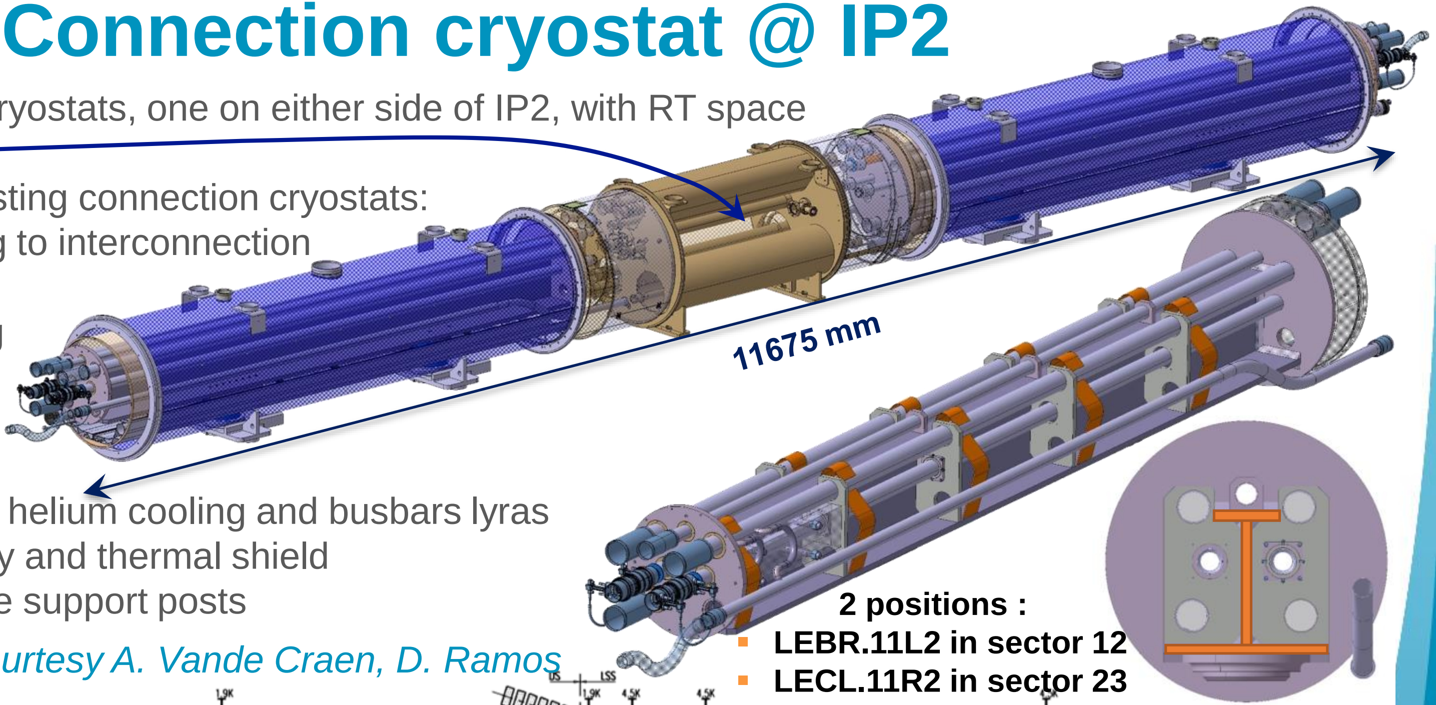
Connection cryostat @ IP2

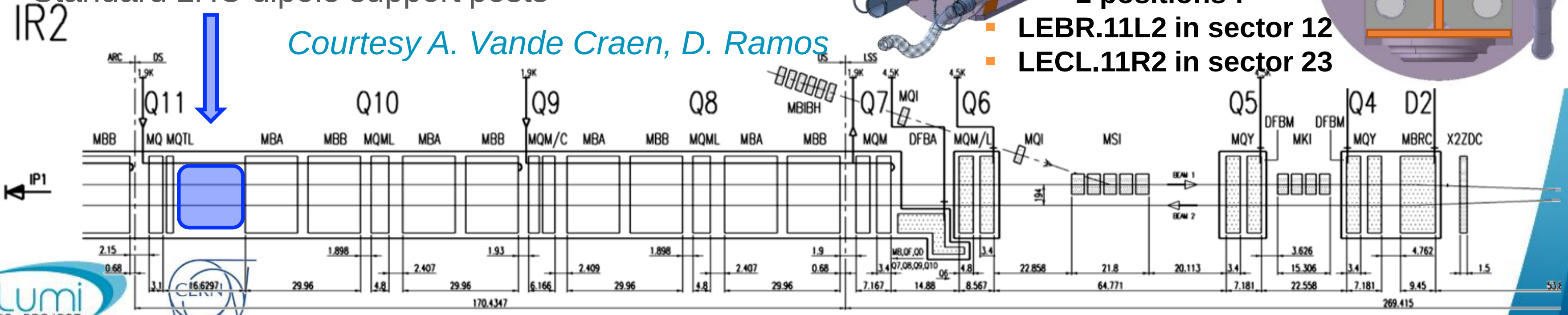
- 2 special connection cryostats, one on either side of IP2, with RT space for collimator
- Re-use concept of existing connection cryostats:
  - Pipes corresponding to interconnection cryogenic lines
  - Cold mass providing mechanical strength and overall stability of the assembly
  - Shuffling module for helium cooling and busbars lyras
  - Standard bottom tray and thermal shield
  - Standard LHC dipole support posts



2 positions :

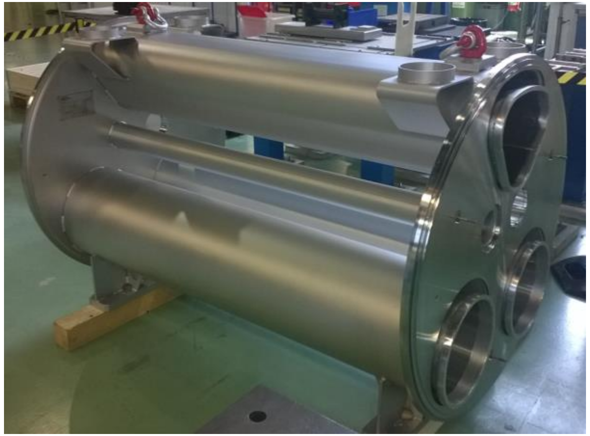
- **LEBR.11L2 in sector 12**
- **LECL.11R2 in sector 23**

Courtesy A. Vande Craen, D. Ramos



Status

- The design was reviewed in May 2017, and is finished
  - Internal review of IR2 LEP cryostats (WP11/WP5): https://indico.cern.ch/event/630930/overview
- The fabrication of the components for the 6 units (4 to be installed + 2 spares) is ongoing
  - Some of them were delivered to CERN
  - First cold mass assembly, by-pass cryostat, and cryostat, are finished



Courtesy G. Barlow, A. Vande Craen

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Summary

- The design of 11T dipole full assembly, and of the connection cryostats for collimators, is completed
- Nine 11T dipole models were built, and tested at CERN. Performance is generally good
- Field errors are within expectations
- Limitations were observed in some models due to excessive stress in the coils with impact on conductor performance. There are indications that the cable insulation system plays an important role. It has been reviewed, and optimized
- A Task Force was set-up in order to refine the understanding of the magnet behavior, and improve the collaring process
- Two additional models will be built in order to show evidence that performance can be reached with adequate margin
- The schedule of the Task Force allows timely provision of input for the series production of the collared coils
- The production of the 11T dipole magnets, and of the connection cryostats for collimators, is compatible with the LS2 installation schedule requirements

Thank you for your attention

Contributors to WP11 at FNAL (in the early stages of the magnet developement):

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Contributors to WP11 at CERN:

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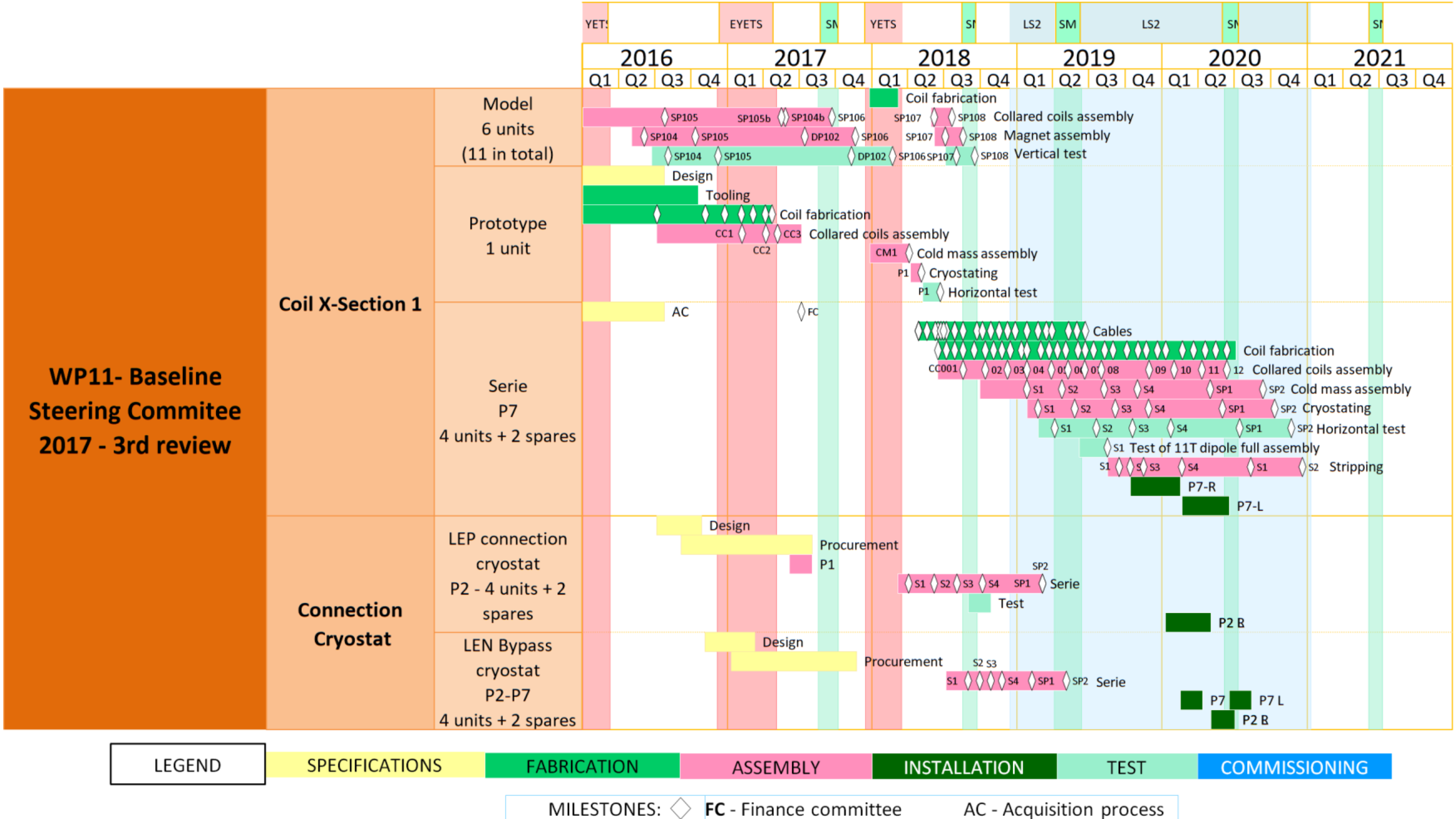
Contributors to WP11 from Industry:

E. Cavana (ASG Superconductors), T. Genestier (GE – Alstom), V. Letellier (GE – Alstom), Z. Melhem (Oxford Instruments), P. Revilak (BNG)

Spare slides

Master plan – Updated after PSM of Dec. 2017

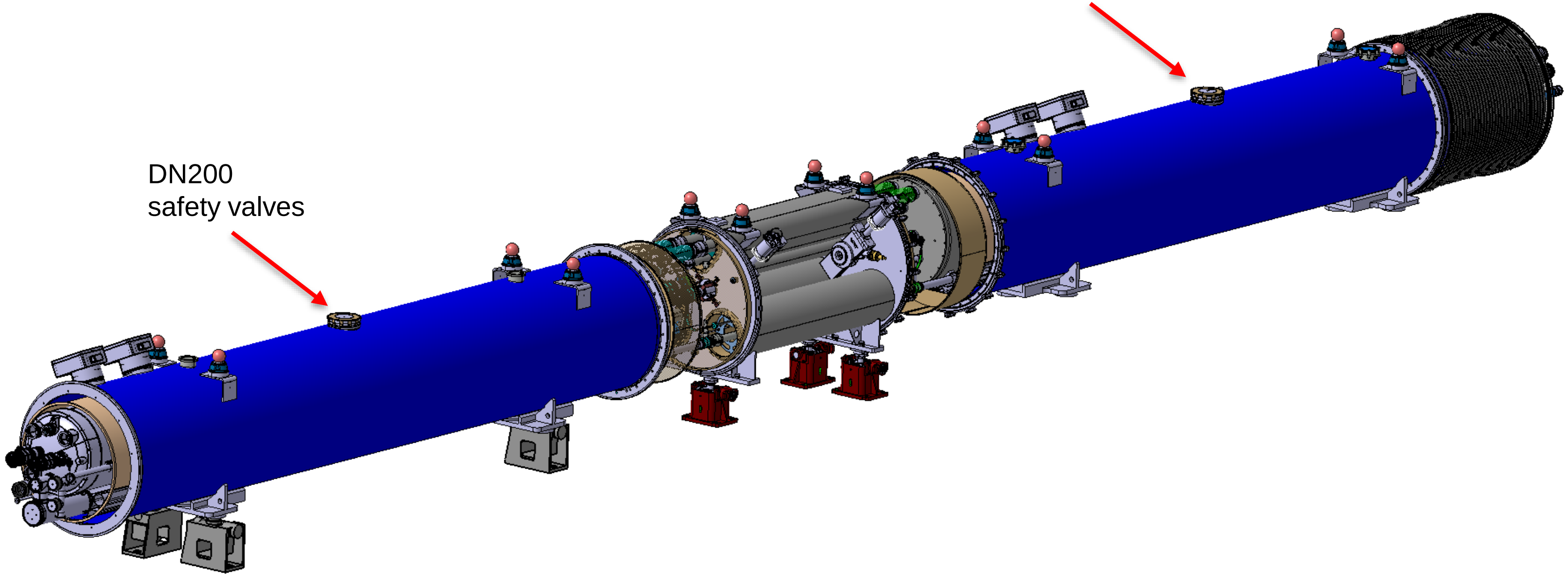


P7: 11T+TCLD Integration

7. DN200 He release

Under study, TBC

Pending action: a study is being carried out



Courtesy M. Gonzalez de la Aleja and integration team

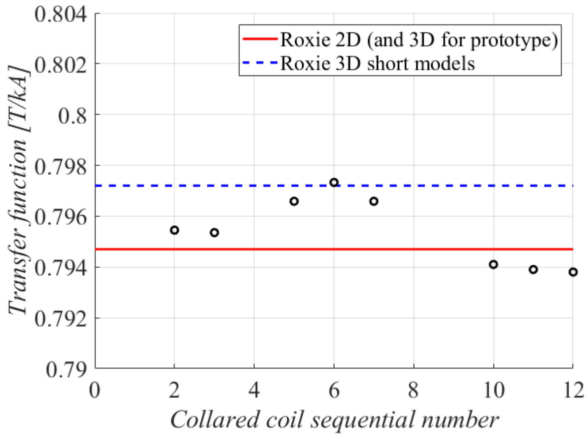
Transfer function and integral field

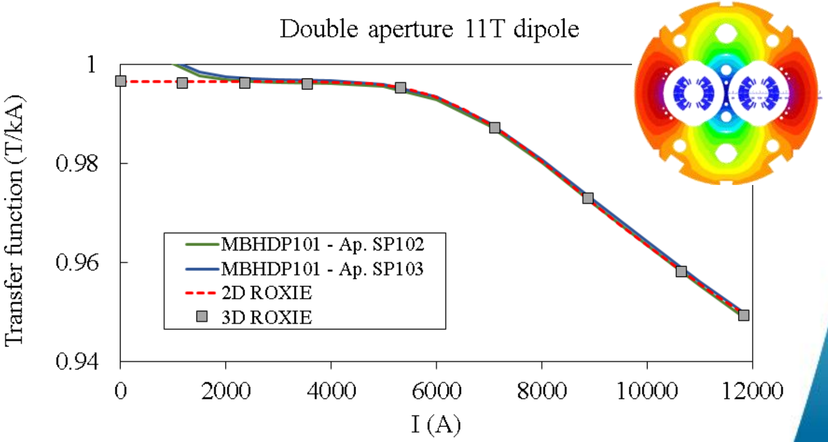
At room temperature:

- The **transfer function in the straight part of the collared coils is within 10 units** of the expected value for the 2-m long models and the full-length prototype
- The **transfer function of the complete magnet** exhibits **larger discrepancy**, of the order of 25 units
- **The integral field** of the prototype cold mass **within 10 units the expected value** (accurate measurements of the integral field are not available for the 2-m long models)

At 1.9 K

- The measured field in the straight part is within 10 units the expected value for all current levels



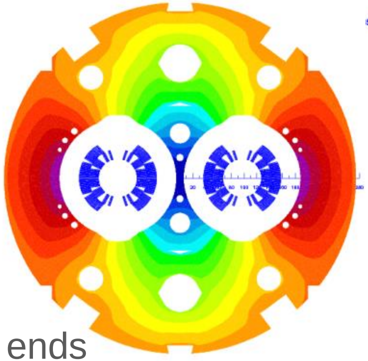


Courtesy
- *L. Fiscarelli*
- *S. Izquierdo Bermudez*

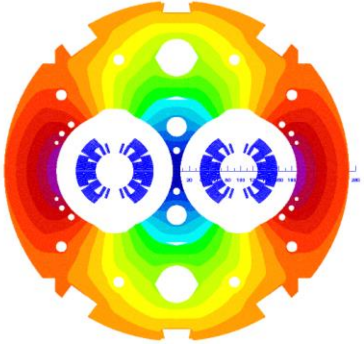
Design evolution, and adjustment of coil length

- **Required integral field:** 119.2 Tm at 11.85 kA
- **Design evolutions after the first** two-in-one 2-m long model (MBHDP101):
  - Outer radius of yoke laminations reduced from 275 mm to 270 mm (to be compatible with the tooling of the LHC main dipole)
  - Iron yoke laminations at the magnet extremities replaced by non-magnetic steel laminations (**cut-back**) in order to decrease the peak field in the coil ends

MBHDP101



MBHDP102 – Prototype – Series



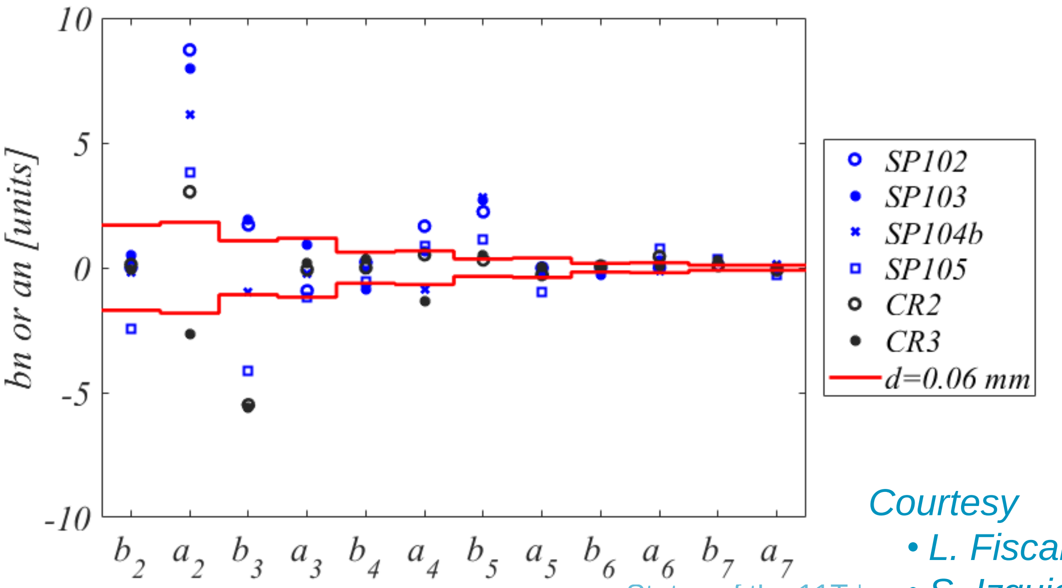
- Due to time constraints, and the lack of experience on the dimensional changes of the coil during the reaction process (5.5 m long coils made of Nb_3Sn were produced for the first time), the **length of the coils for the prototype were not modified straightaway after the above mentioned design evolutions**
- Based on the magnetic measurements carried out on the prototype collared coils and the second two-in-one 2-m long model (MBHDP102), **the physical length of the coil was increased by 40 mm** to achieve the required integral field

Courtesy
- *L. Fiscarelli*
- *S. Izquierdo Bermudez*

Geometric field errors

- The non-allowed harmonics in the prototype collared coils (CR02, CR03) are within expected random components, except *a_2*
- The measured *b_3* (allowed harmonic) is outside the expected range

Geometric field errors measured in the collared coils assemblies at room temperature



Courtesy
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