



The 11T Dipole Prototype Construction and Preparation for Testing, and The Connection Cryostats

F. Savary on behalf of WP11

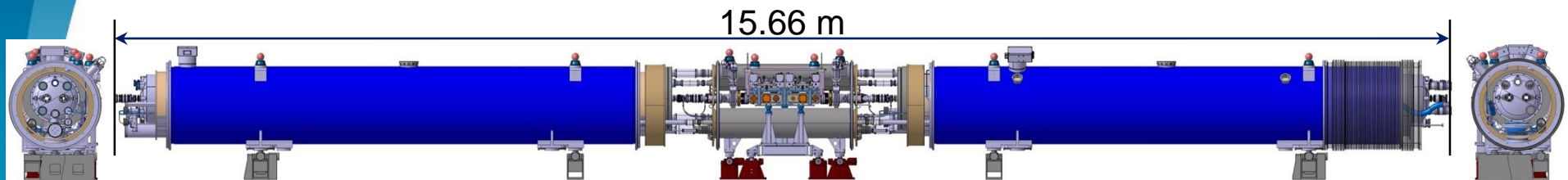
<https://indico.cern.ch/event/647714/>



Outlook

- Introduction and master plan
- The 11T dipole full assembly
- Design feature of the prototype
- Main magnet parameters
- Cable performance requirements
- Coil characteristics
- Main manufacturing steps
- Collaring tooling & process
- Progress on the prototype construction
- Training of short models
- Connection cryostats for IP2

Introduction

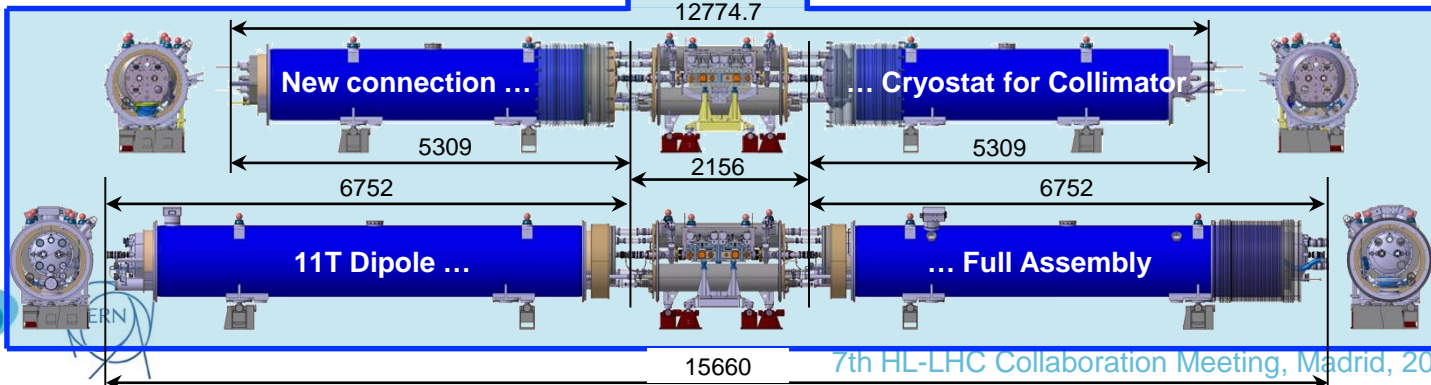
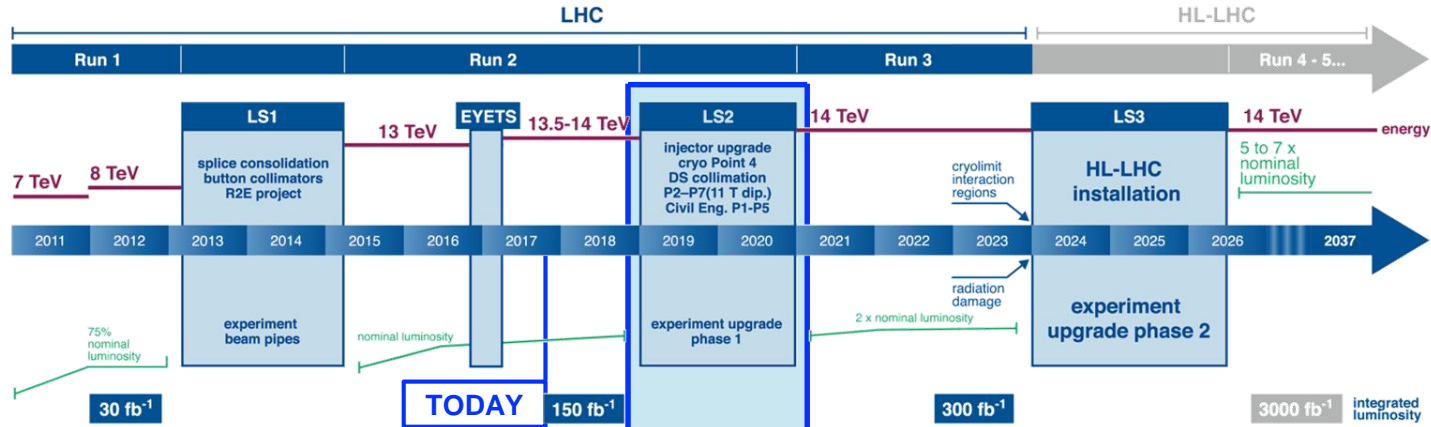


- The HL-LHC Project implies beams of larger intensity → **additional collimators are needed** in order to **intercept and absorb higher beam losses** (dynamic heat loads on cryogenics and risk to quench superconducting magnets)
 - Two collimators, **one per beam, installed on either side of interaction point 7 (IP7)** for both proton and heavy-ion collimation losses, in the Dispersion Suppressor region
- **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**

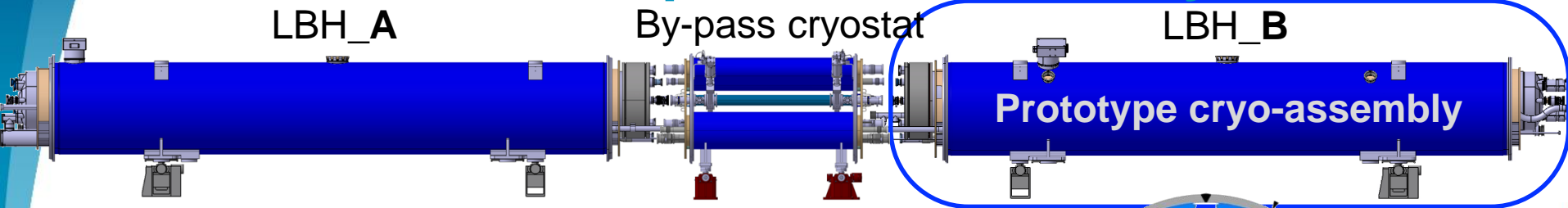


Masterplan of WP11

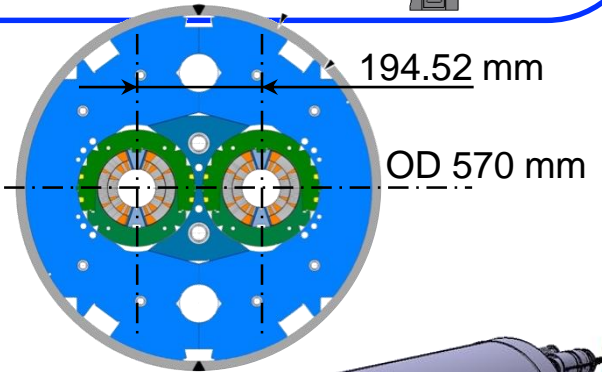
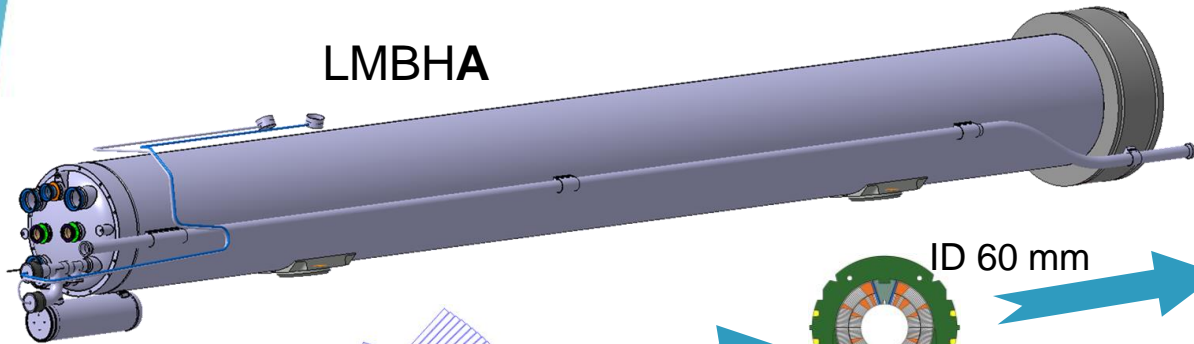
LHC / HL-LHC Plan



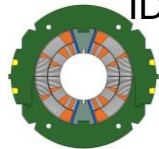
The 11T Dipole Full Assembly



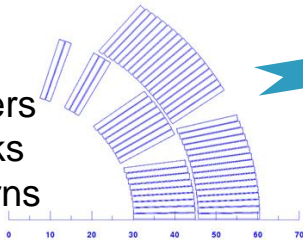
LMBHA



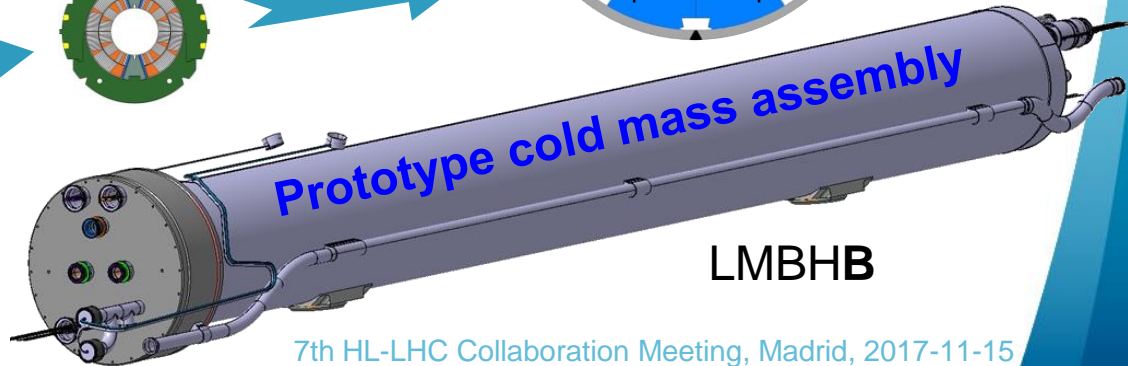
ID 60 mm



- 2 layers
- 6 bloks
- 56 turns



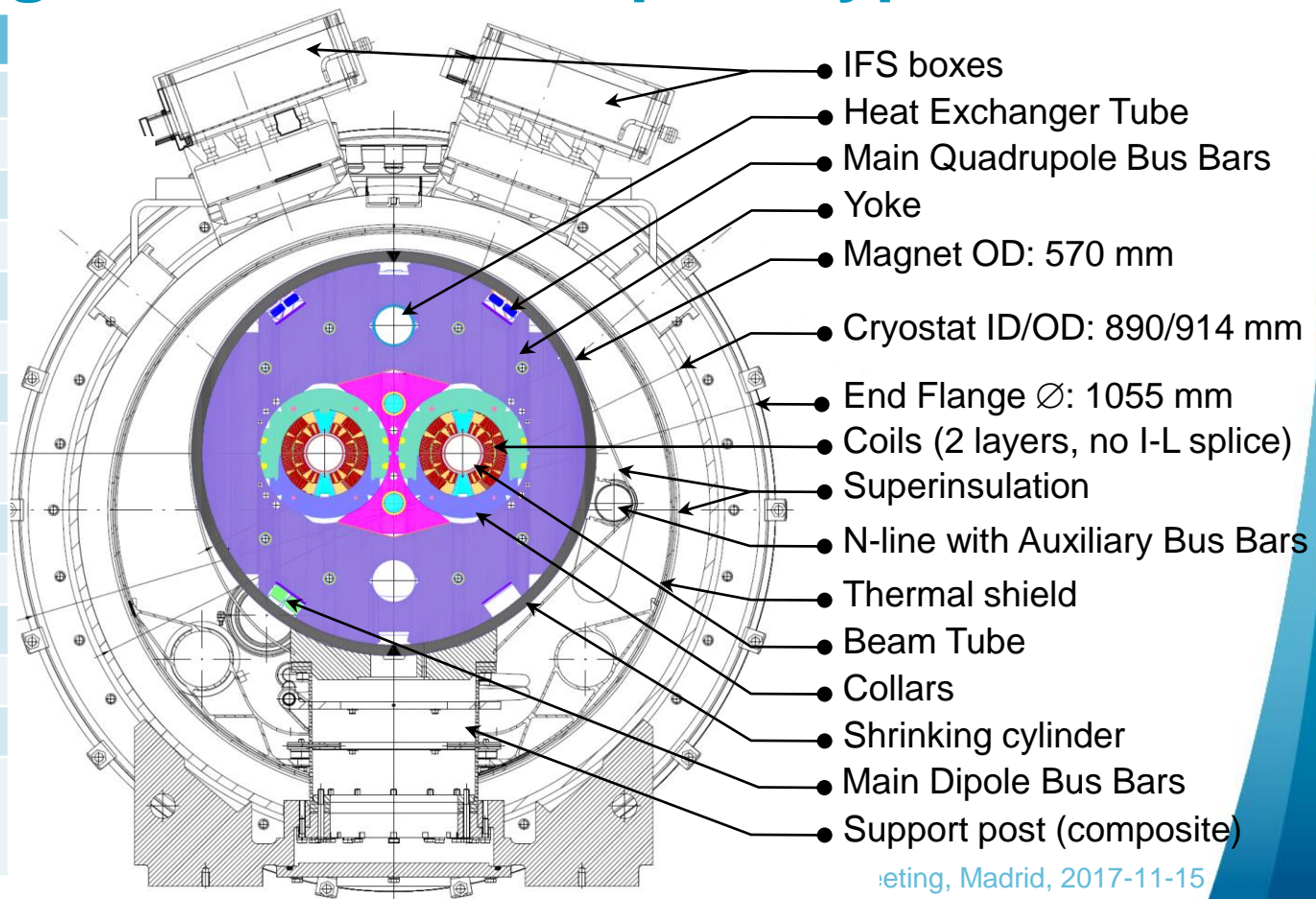
Prototype cold mass assembly



LMBHB

Design features of the prototype

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, I_c (12T, 4.222 K)	438 A



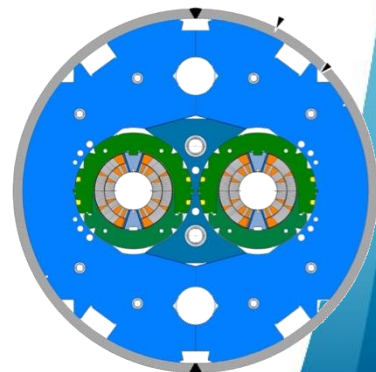
Magnet main parameters

Parameter	Value	Unit
Aperture	60	mm
Distance between apertures at RT / 1.9 K	194.52 / 194.00	mm
Magnetic length	5.307	m
Coil length	5.415	m
Magnet length, between end plates	5.799	m
Cold mass assembly length	6.252	m
Cold mass assembly outside diameter	570	mm
Operating temperature	1.9	K
Nominal operation current	11.85	kA
Bore field @ nominal current	11.23	T
Peak field @ nominal current (without strand self-field and without cryostat)	11.59	T
Stored energy/m at I_{nom}	0.9663	MJ/m
Differential inductance/m at I_{nom}	11.97	mH/m
Cable bare width before reaction	mm	14.7
Cable bare mid-thickness before reaction	mm	1.25
Keystone angle	Degree	0.79
Strand diameter	0.700 ± 0.003	mm
Number of strands per cable	40	-
Cable insulation thickness per side azimuthal, free status / @ 30 MPa	0.150/0.110	mm

Magnetic measurements at RT have shown that the coils have to be made longer by 40 mm to get the right magnetic length

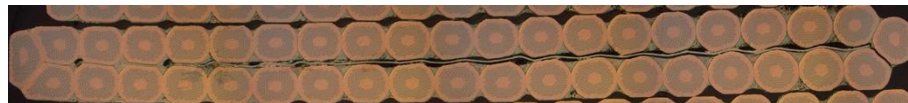


Braiding optimized for thickness of 100 μm @ 5 MPa for series production



Cabling Specs - Cable Performance

Parameter	Value
Number of strands	40
Strand diameter (mm)	0.7
Width (mm)	14.7
Mid-thickness (mm)	1.25
Thick/thin edge (mm)	1.149/1.351
Keystone angle (degree)	0.79
Transposition pitch (mm)	100
Packing factor (%)	87.3
Compaction thin/thick edge (%)	17.95/3.48
Core material	AISI 316L
Core width (mm)	12
Core thickness (μm)	25



RRP cable

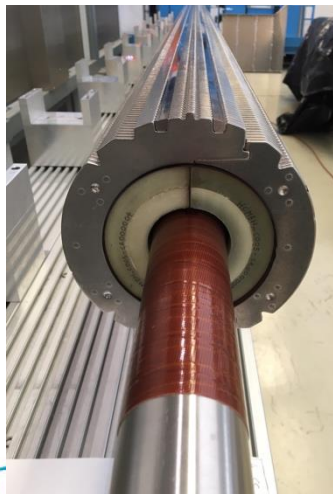
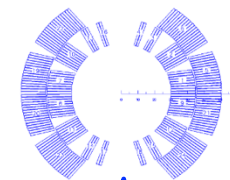
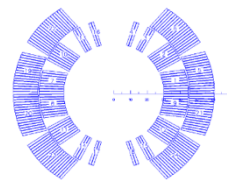
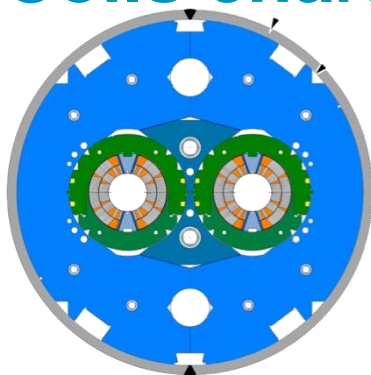
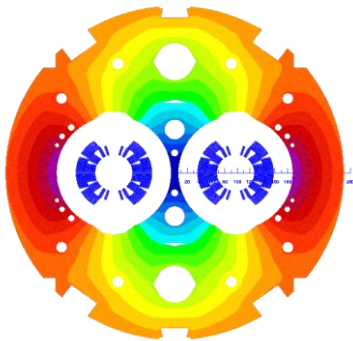
Courtesy A. Bonasia

Cable performance requirements

- I_c degradation lower than 5 %
- RRR of extracted strands above 100

Courtesy B. Bordini

Coils characteristics



Development conductor

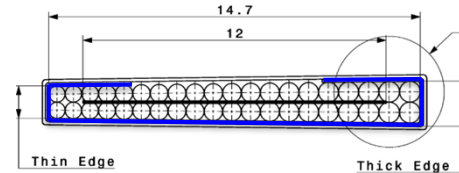
Final conductor

Parameter / 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

Main manufacturing steps, 1

■ Cable insulation and braiding

- 25 mm wide, and 80 μm thick Mica tape rolled around the cable in a C-shaped profile, and a 70 μm thick layer of S2-glass braided over the Mica layer



■ Winding and binder curing

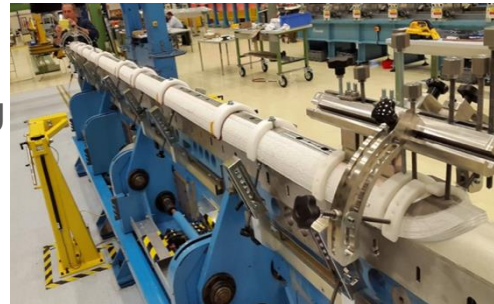
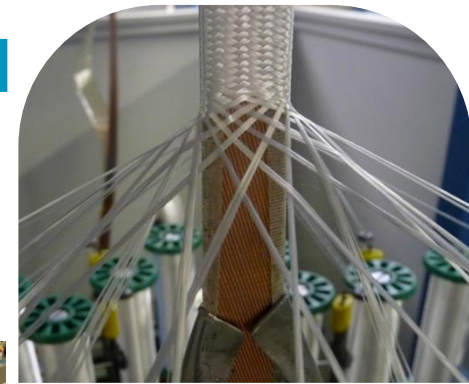
- A ceramic binder is applied after winding to glue the turns together, and avoid the coil dislocation during subsequent steps

■ Reaction and splicing

- In a reaction fixture, under Ar atmosphere, 150 hours including 3 plateaus at 210, 400, and 650°C

■ Impregnation

- Resin system CTD101K, processed @ 60°C under vacuum, then pressurized to 3.5 bar before gelling @ 110°C and curing @ 125°C



Main manufacturing steps, 2

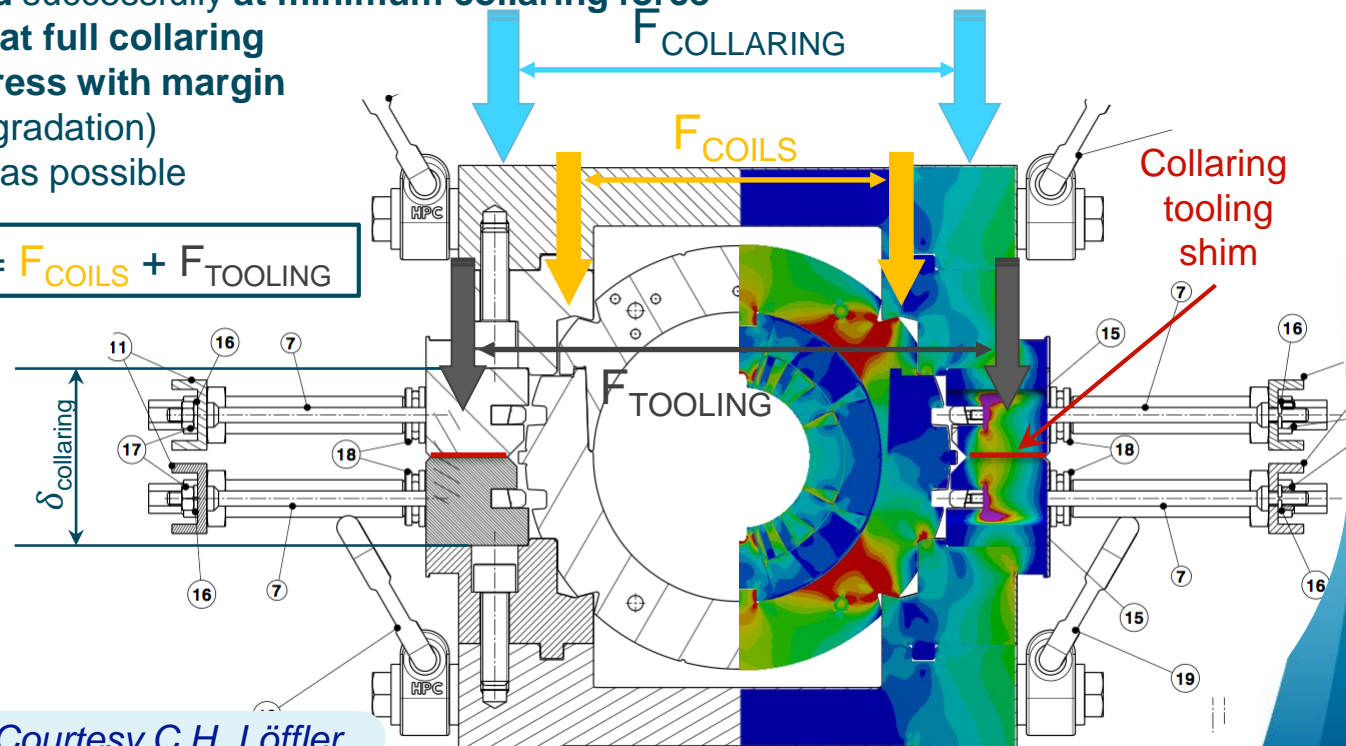
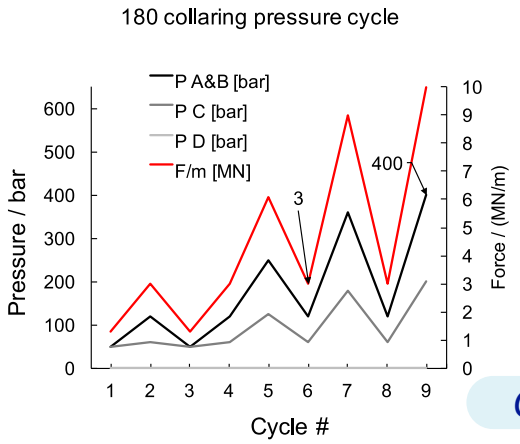
- Coil pairing and assembly
 - With ground insulation, collaring shims, removable pole, cold bore tube, coil protection sheet, and collar packs
- Collaring
 - $F = 10 \text{ MN/m}$ (of which 50-60 % are taken by the coils)
 - Local stress in coils up to 150 MPa, and probably higher due to the Mica tape
- Yoking, and welding of the 15 mm thick shrinking cylinder made of 316LN
 - TIG welding, 13-15 passes and tensile stresses of the order of 220 MPa
- Cold mass finishing
 - Spool pieces, electrical joints, V-taps, instrumentation feed thru system, end covers, N-line, supports, ...



Collaring tooling & process

- $\delta_{\text{collaring}}$ = size of the tooling, corresponding to the closure of the tooling on collaring tooling shims
- **Thickness of collaring tooling shim**, and $F_{\text{COLLARING}}$ are determined such that:
 - **Keys** can be **inserted** successfully at **minimum collaring force**
 - **Stress at mid-plane at full collaring force** < **allowable stress with margin** (w.r.t. irreversible degradation)
 - Spring back as small as possible

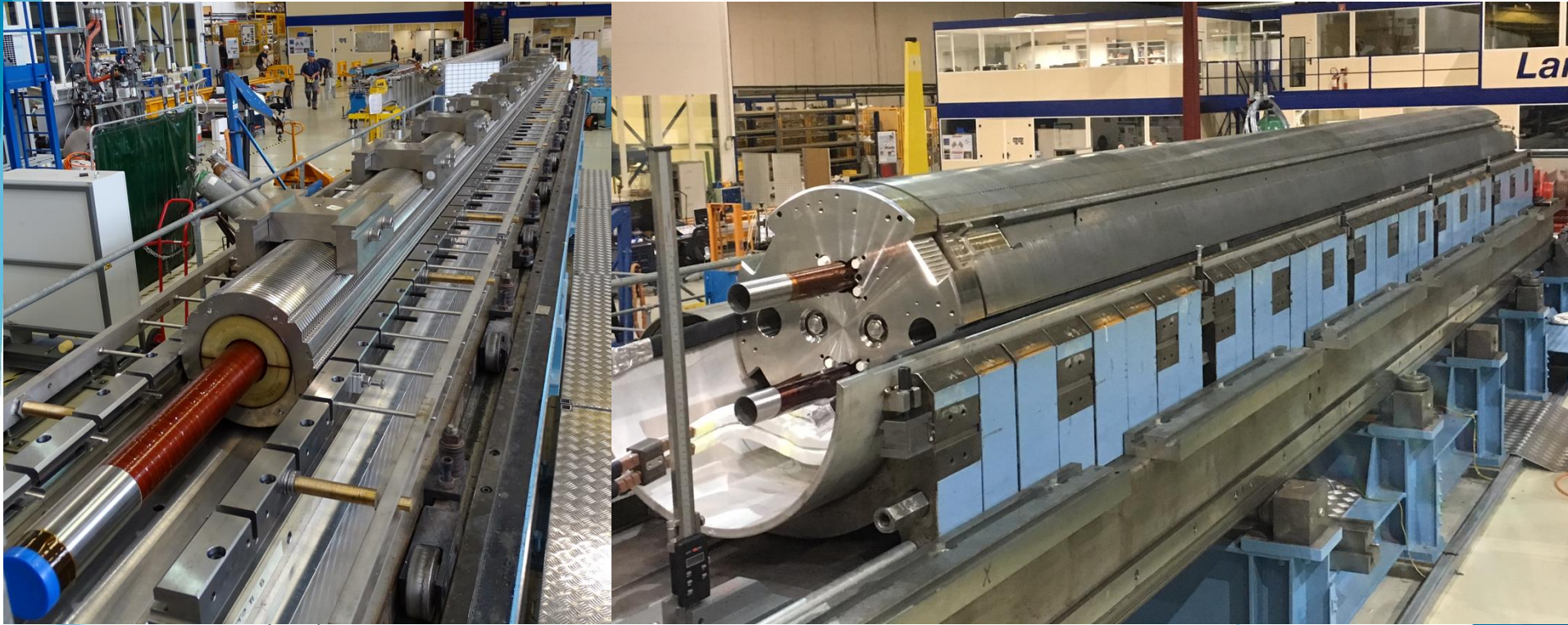
$$F_{\text{COLLARING}} = F_{\text{COILS}} + F_{\text{TOOLING}}$$



Courtesy C.H. Löffler

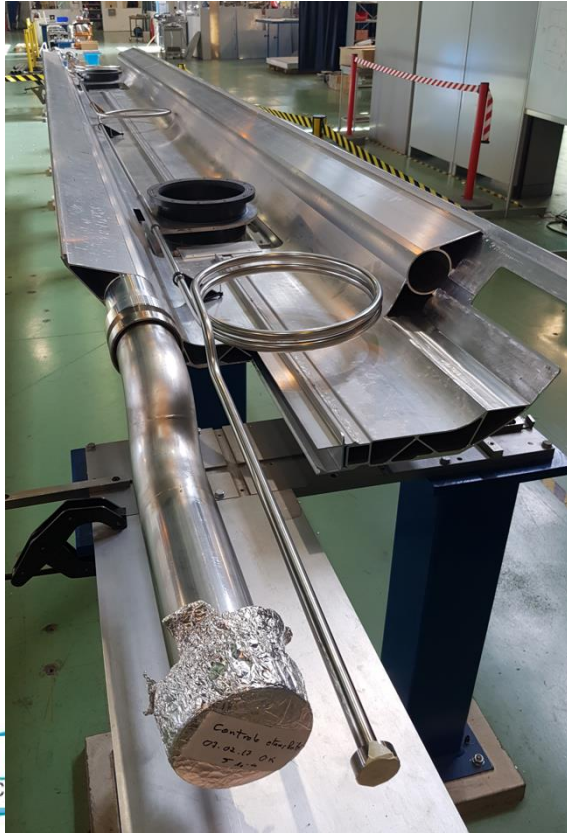
Progress on the Prototype construction, LMBHB

- The collared coils assemblies are ready, and assembled in the yoke
- The cryostating and the cold tests are planned in the beginning of 2018



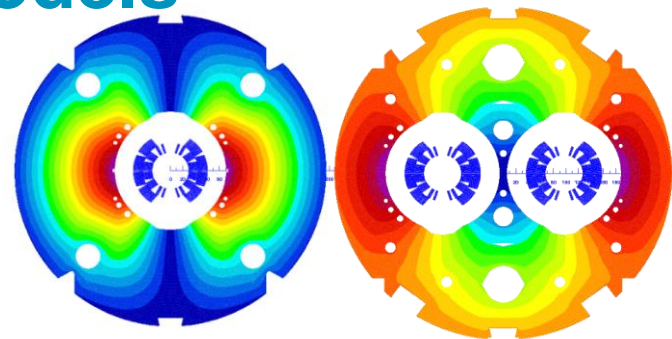
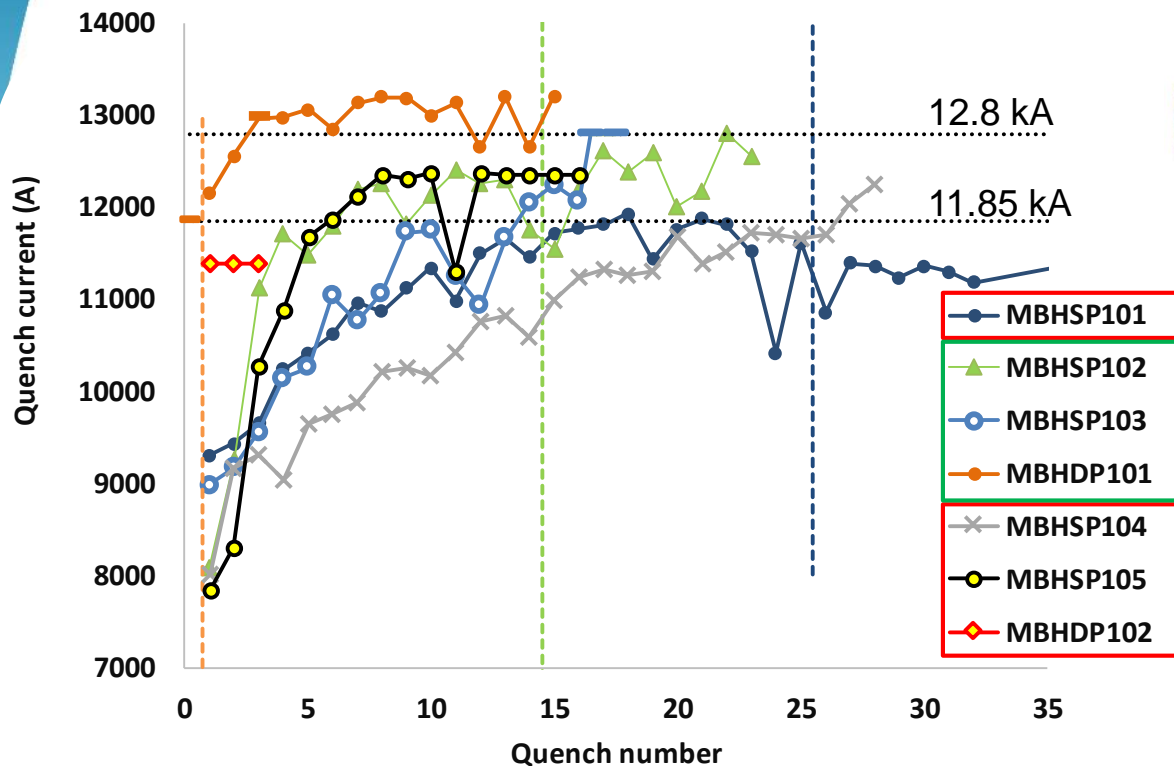
Progress on the Prototype construction

- The bottom tray and the main cryostat



Images by courtesy of M. Struik

Training of short models



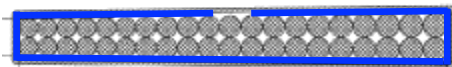
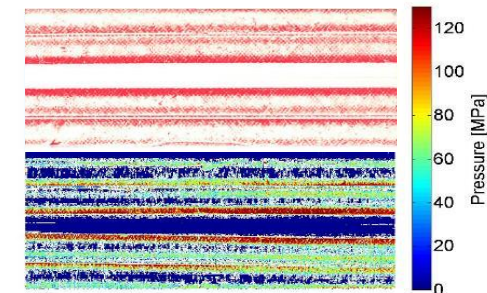
- The last models, MBHSP104 and MBHSP105, exhibit limitation due to conductor degradation in the mid-plane (due to excessive stress)
- Re-collared with 15 MPa lower pre-stress, and put together in a two-in-one structure MBHDP102, which did not perform better

Observations, and actions

- Peak stresses are observed with Fuji paper along the edges of the cable in the mid-plane, higher on the side of the thin edge, and on the inner layer

S. Izquierdo Bermudez et al. in MSC-MDT

- The use of Mica for the cable insulation of the coils, in addition to impregnated fiberglass, is a necessary feature
- The Mica tape will be made wider to reduce peak stresses
- In addition:
 - The thickness of the cable insulation, so far **110 μm @ 30 MPa** (not 100 μm as wanted) will be reduced to **100 μm @ 5 MPa**, thanks to optimized braiding parameters
 - The collaring procedure will be optimized further based on:
 - E-modulus measurements on ten-stacks
 - E-modulus measurements on full coil cross-sections (see Workshop on Nb₃Sn Rutherford cable characterization for accelerator magnets, talk by Jose Luis Rudeiros Fernandez)
 - Collaring tests on a fully representative and instrumented collared coils assembly
 - Measurements at cold of the irreversible degradation due to stress applied at room temperature on final cable with final insulation scheme



Task Force
being set up
within TE-MSC

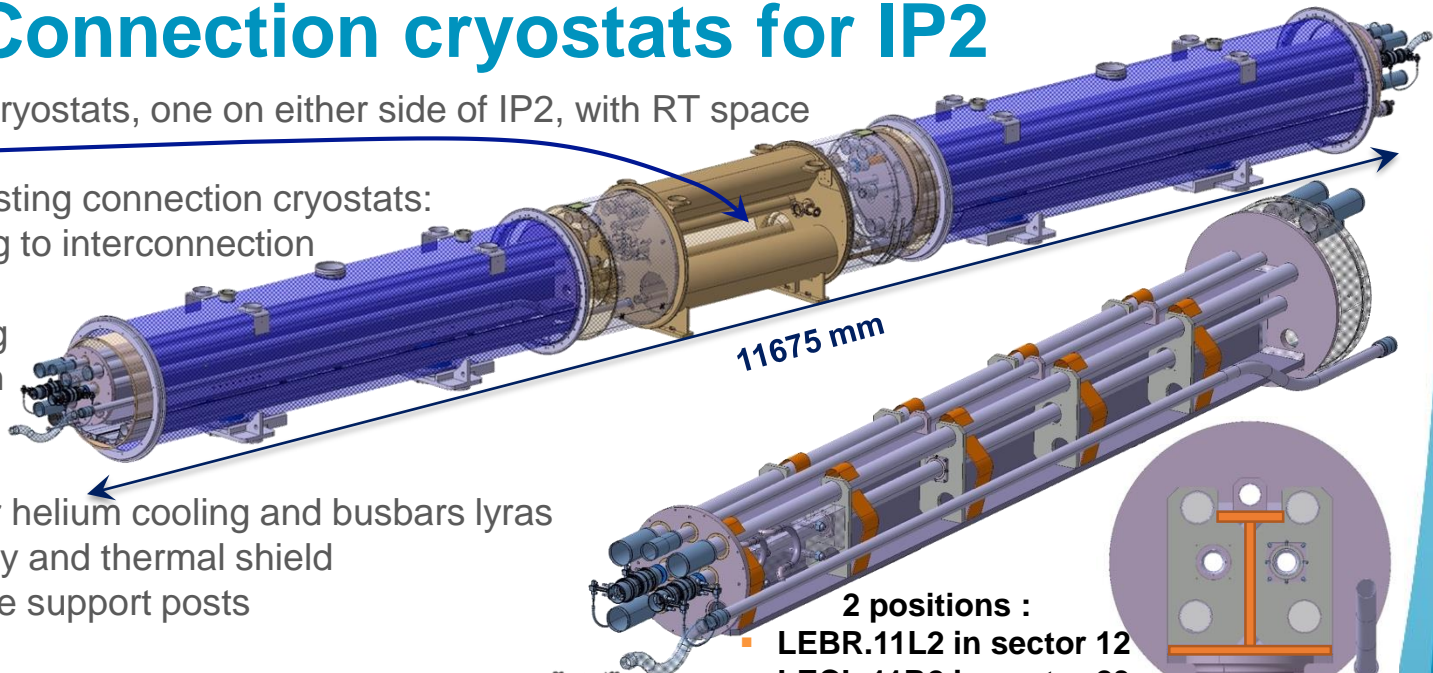


Two additional models made of RRP conductor will be made to demonstrate effectiveness of the modifications

7th HL-LHC Collaboration Meeting, Madrid, 2017-11-15

Connection cryostats for IP2

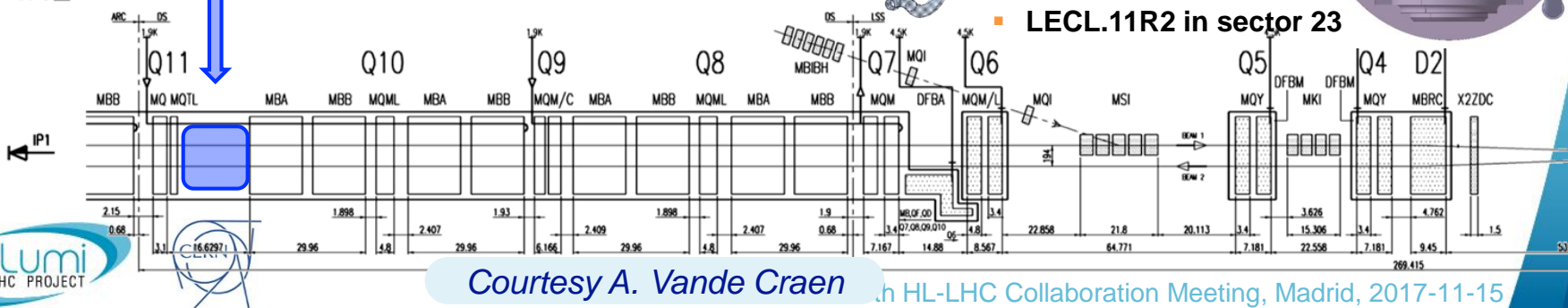
- 2 special connection cryostats, one on either side of IP2, with RT space for collimator
- Re-use concept of existing connection cryostats:
 - Pipes corresponding to interconnection cryogenic lines
 - Cold mass providing mechanical strength and overall stability of the assembly
 - Shuffling module for 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

IR2



Courtesy A. Vande Craen

HL-LHC Collaboration Meeting, Madrid, 2017-11-15

Status

- The design is finished. It has been reviewed in May this year (<https://indico.cern.ch/event/630930/>)
- The fabrication of the components for the 6 units (4 to be installed + 2 spares) is ongoing
 - Some of them were delivered to CERN
 - A first set of plates composing the mechanical structure was received
- The assembly of the first unit should start in December



Summary

- The construction of the 11T dipole prototype is coming to an end, after a long process of tooling design and construction, and the careful development of manufacturing procedures
- The prototype will be cryostated and tested in the beginning of next year
- The results of the cold tests of the last magnet models and the recent study of the stress distribution in the mid plane of the coils trigger the need of further optimization. The cause for the limited performance is identified, and actions are being launched to cure it
- The construction of the new connection cryostats for collimators is progressing according to plan



Thank you for your attention

