Status of cold mass activities at CERN (all HL-LHC WP3)

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14th HL-LHC Collaboration Meeting, Genoa (Italy), 7-10 October 2024

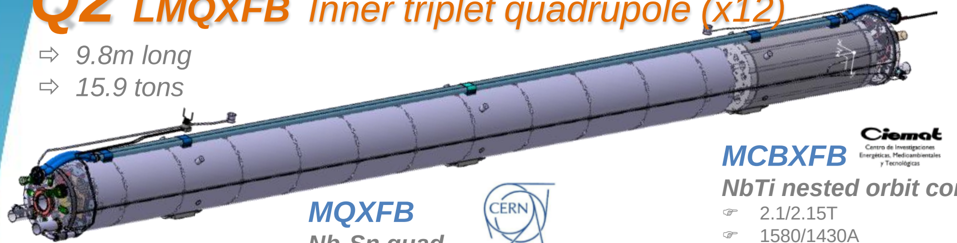
Outline

- The 4 types of HL-LHC cold masses assembled at CERN:
  - Q2: LMQXFB
  - CP: LMCXF
  - D2: LMBRD
  - Q10: LMQMT
- Findings, Non-Conformities, Mitigations and Improvements
- Alignment
- Tooling development
- Production status
- Summary

HL-LHC CERN cold masses: 4 types

Q2 LMQXFB *Inner triplet quadrupole (x12)*

- ⇨ *9.8m long*
- ⇨ *15.9 tons*



MCBXFB

NbTi nested orbit corrector

- 2.1/2.15T
- 1580/1430A
- 1.2m magnetic length

MQXFB

Nb_3Sn quad

- 132.6T/m
- 16230A
- 7.2m magnetic length

CP LMCXF *Corrector package (x5)*

- ⇨ *6.2m long*
- ⇨ *9 tons*

9 NbTi superferric HO correctors

- 1.5 to 3.6T
- 184 to 174A
- 99 to 401mm magnetic length

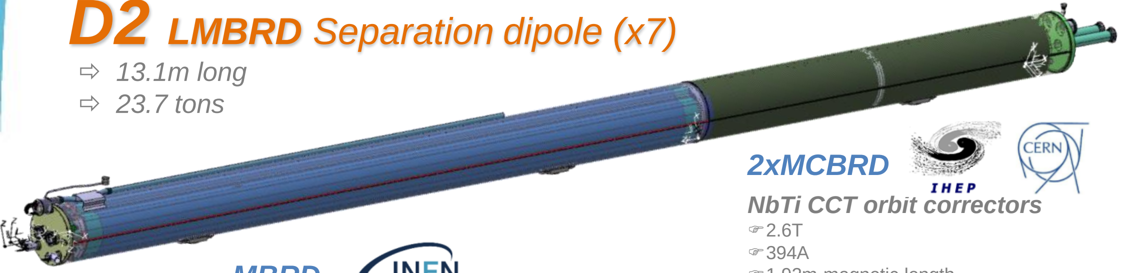
MCBXFA

NbTi nested orbit corrector

- 2.1/2.15T
- 1580/1430A
- 2.2m magnetic length

D2 LMBRD *Separation dipole (x7)*

- ⇨ *13.1m long*
- ⇨ *23.7 tons*



2xMCBRD

NbTi CCT orbit correctors

- 2.6T
- 394A
- 1.92m magnetic length

MBRD

NbTi separation dipole

- 4.5T
- 12328A
- 7.8m magnetic length

Q10 LMQMT *DS quadrupole with MS (x4)*

- ⇨ *6.6m long*
- ⇨ *8.1 tons*

MSCBB

Combined NbTi sextupole and orbit corrector

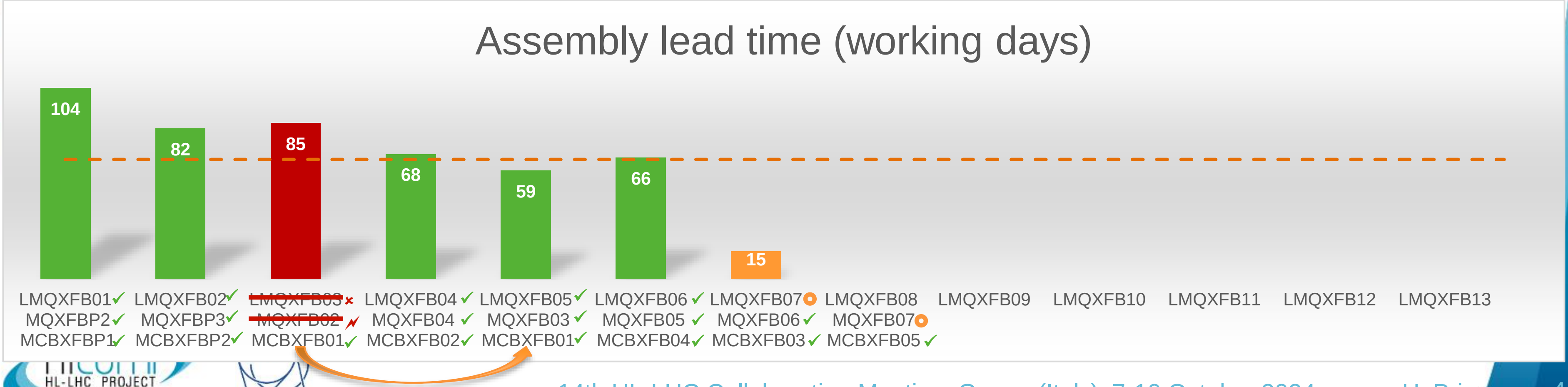
MQML

NbTi quad used in the MS and DS in LHC

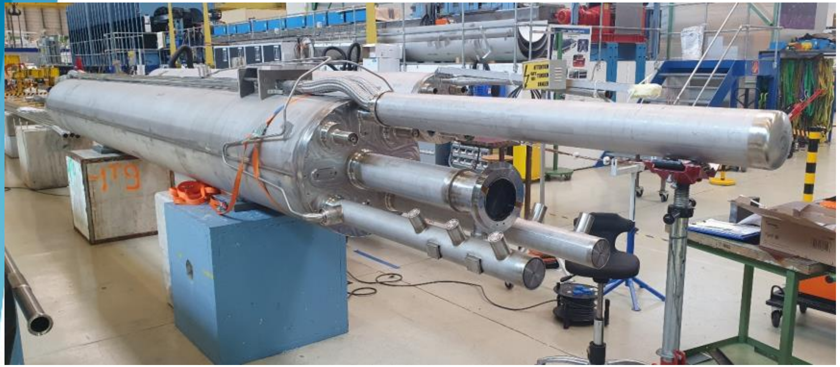
- 200T/m
- 5390A
- 4.8m magnetic length

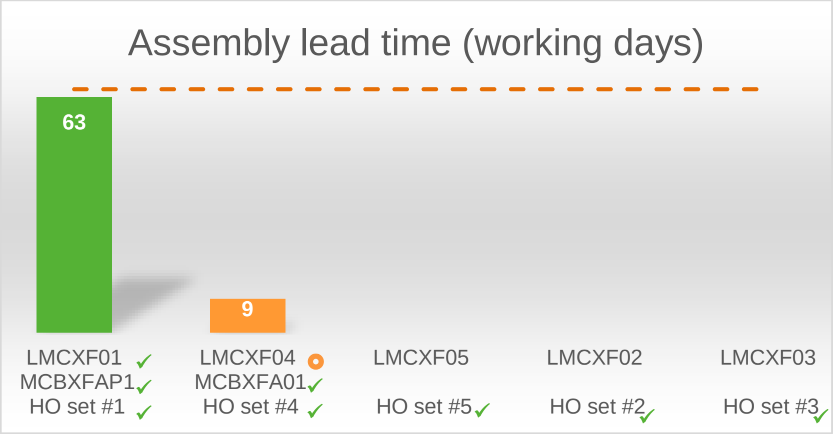
Q2 LMQXFB Cold Mass

- 12 to be delivered (2 prototype, 8 series, 2 spares).
- Most populated type of all HL-LHC cold masses.
- Nominal assembly duration was estimated to 13 weeks (65 WD).
- LMQXFB03 had to be disassembled (see next slides)

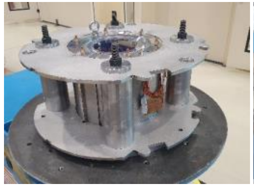


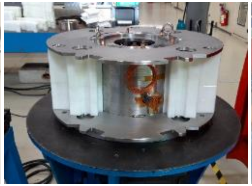
CP LMCXF Cold Mass





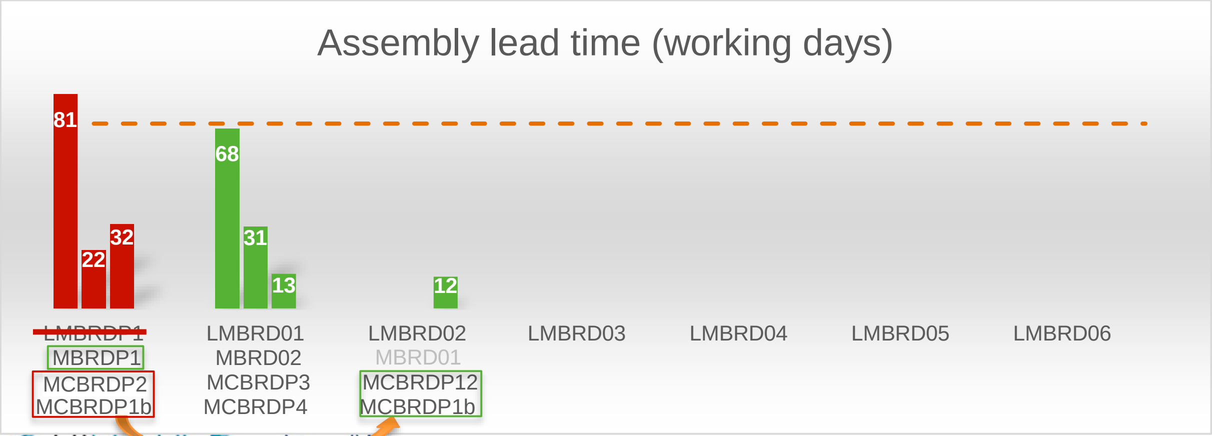
- 5 to be delivered (no prototype, 4 series, 1 spares, 1 set of spare magnets not assembled in a cold mass).
- Equipped with the largest number of magnets (10) and electrical circuits (11 in total).
- The HO correctors are powered by conduction cooled leads through the vacuum vessel in between the cold mass and the cryostat.
- Nominal assembly duration was estimated to 13 weeks (65 WD) once all the High Order corrector magnets have been prepared.
- All HO corrector magnets were delivered in 2023 (54 in total).
- The 6 sets of HO corrector magnets are ready but at least 2 magnets need consolidation on the leads that were damaged or broken during preparation.

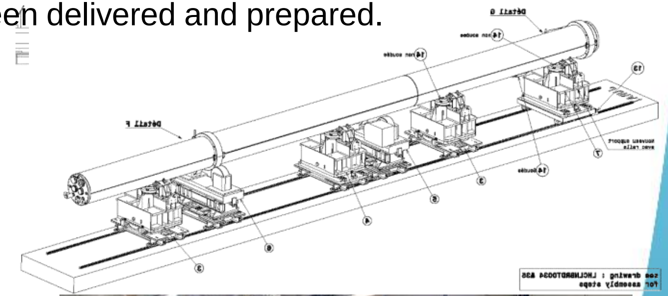




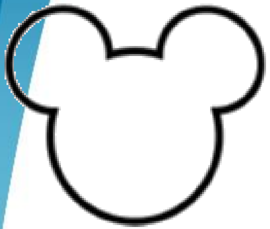
D2 LMBRD Cold Mass

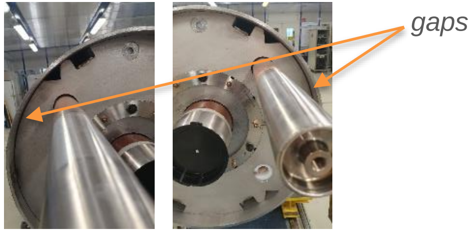
- 7 to be delivered (1 prototype, 4 series, 2 spares).
- Longest and heavyset of all HL-LHC cold masses.
- 2 butt welded cylinders: one containing the MBRD separation dipole, the second housing the MCBRD CCT orbit correctors.
- Nominal assembly duration was estimated to 14 weeks (70 WD) once magnets have been delivered and prepared.

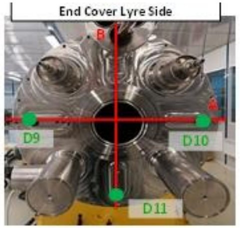


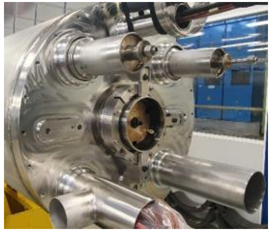


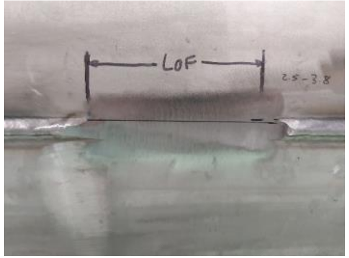
Welding Findings and Non-Conformities,







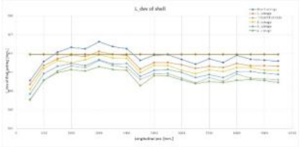


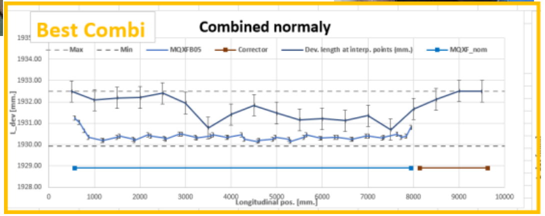


- ***Mickey's ears":*** Due to the shells additional developed length introduced to prevent any extra pre-stress in the MQXFB coils and the deformation induced during welding, the shape of the outer vessel is not perfectly circular. Gaps up to 1mm were observed at 2 and 10 o'clock.
  - ⇨ Complications during the welding of end covers and the butt welding of the D2 cylinders.
  - ⇨ Alignment non-conformities to balance the thickness in X and Z (NCR LHC-LMQXF-QN-0003, LHC-LMQXFBS-QN-0017, LHC-LMQXFB-QN-0007).
  - ⇨ Cold bore tube extremities are following the end cover misalignment despite bending. Efforts to bring it into tolerances makes the flare welding to the end cover difficult sometime.

- ***Welding defects*** on the longitudinal joins (NCR LHC-LMQXFB-QN-0001)
  - ⇨ Undercut and lack of fusion were locally observed, root causes being misalignment during tack-up and welding parameters.

Welding Mitigations and Improvements

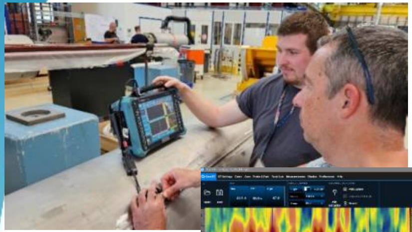


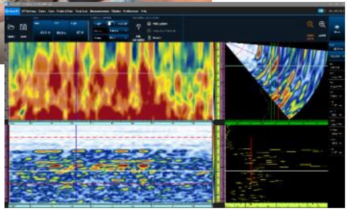


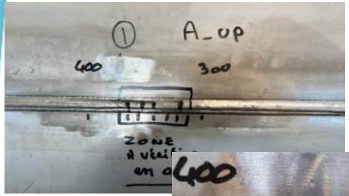
- *“Mickey’s ears”* moderation of the issues caused by excessive additional developed length:
  - The shells are measured, paired, the upper shell is then milled with a machine developed in house, so that the total developed length is fine tuned to comply with the MQXFB measurement (for D2 and CP cold masses, yoke theoretical developed length is used).
  - A calibrated tack up shimming was developed as well as tooling to assist tack up gaps between the shell and the backing strip.
  - Systematic welding shrinkage measurements are conducted and reported for each cold mass.

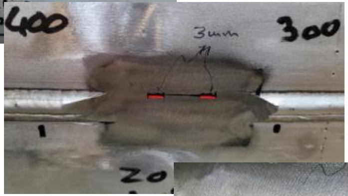
- ***Welding defect*** improvements:
  - The old welding posts dating from the LHC dipole production were replaced.
  - A shell compression tool was developed for the tack up to limit the gap between the shell and the backing strip. A 0.5mm limit was implemented for QA inspections.
  - Systematic inter-pass grinding is implemented to remove known default features:
    - Undercut from the first TIG pass (feature propagating inter-pass LOF).
    - Removal of oxides and slag between the MIG passes (reduction in possibility of inclusions).
  - A derogation request for the finished weld profile, agreed with CERN welding experts, was submitted and is being written by HSE.
  - During summer, MIG welding chariots and related hardware as well as software was upgraded to improve repeatability and quality.

Welding Improvements





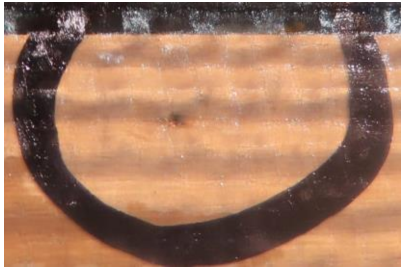


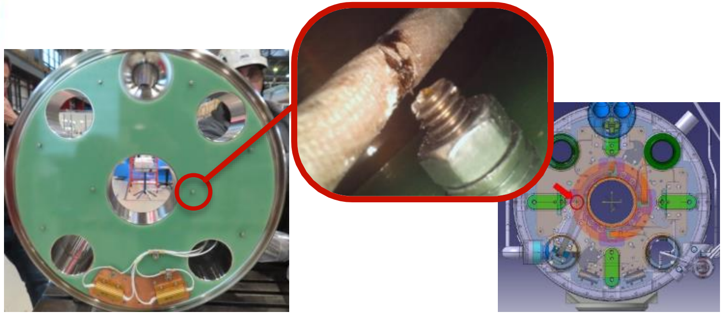


- *Calibration sample plates for PAUT inspection were produced. They enable precision detection of the defaults.*
- *Continuous exchanges with the NDT inspectors to collect the additional signals, behaviors and inject them in the review catalogue and enhance the learning process.*
- *Processes followed to correct a welding defect or to clarify doubts after a PAUT examination:*
  - ⇨ *The area is marked along the longitudinal length.*
  - ⇨ *Surface is ground to remove the protruding weld bead.*
  - ⇨ *The section is then tested using a UT probe perpendicular to the helium vessel surface, this confirms or not the presence of defects and clarifies with precision the longitudinal localization and its depth.*
  - ⇨ *Material on top of the area of concern is ground down to the specified distance. The designated longitudinal location is correlated with the tack up locations according to their references and the gap measurements between the shells and the backing strip recorded by QA.*
  - ⇨ *Repairs are conducted, in general with a a first 'hot' run without filler followed by filling runs, then inspection is repeated to confirm conformity.*

  - ⇨ *A systematic debriefing with the welding expert, the inspector and the welders is conducted to train for identification of defaults and their repairs.*

Other Findings, Issues and Non-Conformities

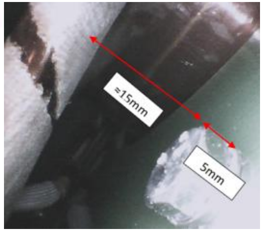


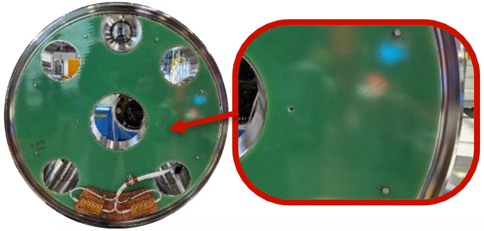


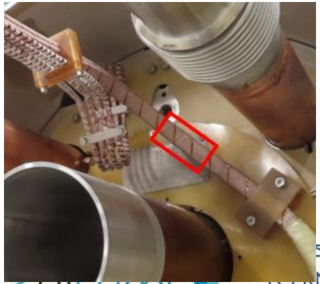
- ***High voltage tests*** (NCR LHC-MQXFBS-QN-0017): During the final electrical test before pressure test, a short circuit occurred between a quench heater and the coil. The operator followed the series production procedure and applied 2kV. Actually, MQXFB02 already saw the helium during the cold test of the cold mass LMQXFBT05 therefore the maximal allowable voltage should have been 450V. The LMQXFB03 cold mass had to be disassembled, as well as the magnet, to dismount pole HCMQXFBC08-CR000124.

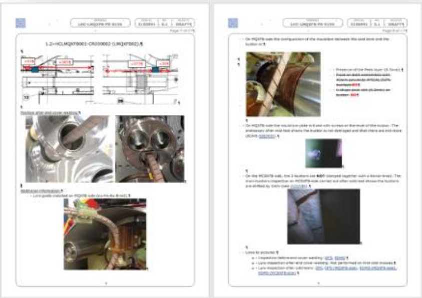
- ***Issues with the Busbars***:
  - Busbar short to ground (NCR LHC-LMQXF-QN-0004): During powering test the power converter connected to the main circuit (MQXFB) detected an elevated ground current. Upon performing electrical insulation tests, a short to ground was found. The investigations driven with the endoscope pointed out a proximity between the lead A and a stud that fixes the insulation plate inside the end cover.
  - Shift and lyres (NCR LHC-LMQXFB-QN-0008, LHC-LMQXFB-QN-0009): The visual inspection carried out after cold tests revealed that 2 busbars had shifted radially in relation to each other.
  - Spacer (NCR LHC-LMQXFB-QN-0007): The spacer on the MCBXFB side was placed at 35mm from the tube's extremity instead of 20mm nominal.

Other Mitigations and Improvements





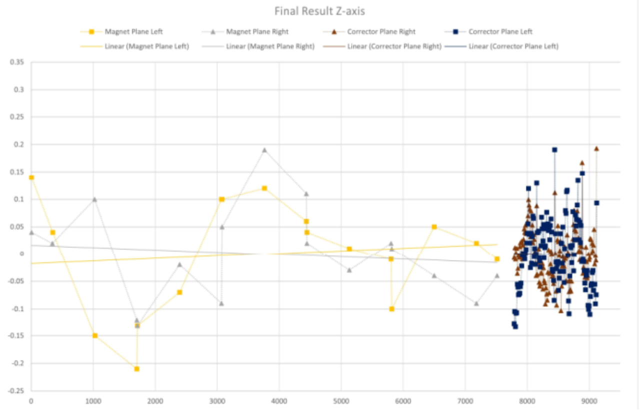


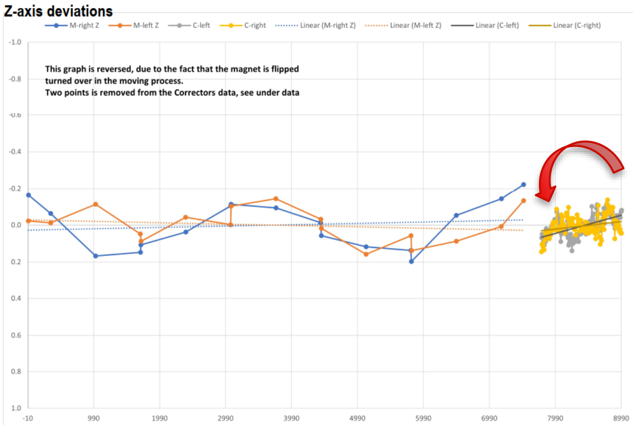


- ***High voltage tests*** mitigation to prevent the wrong voltage application during electrical tests: QA team identify each component (both manufactured in LMF or delivered to LMF) with panels that indicate if the component saw helium or not and the persons to contact to get information. Test sheets are associated to the coils/magnets/cold masses accordingly. The person responsible for the electrical tests must give a green light before each electrical test. This green light is formalized in the MIP.

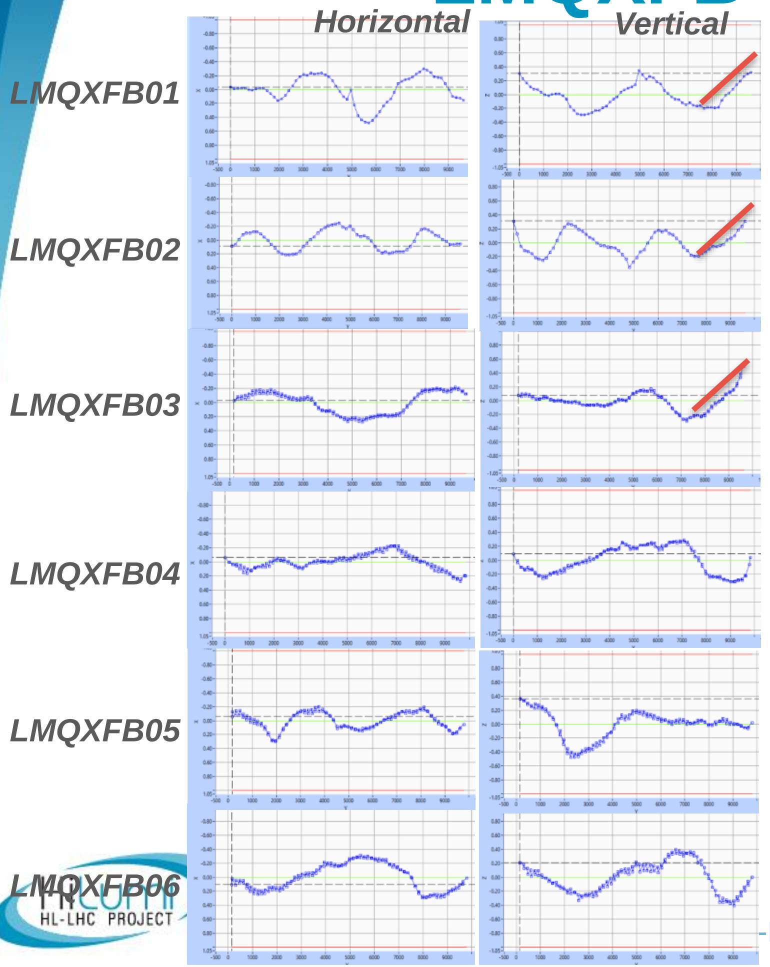
- ***Issues with the Busbars***:
  - On the second cold mass, the studs were replaced by threaded holes and screws, this was before the non-conformity was found. Endoscopic inspection showed that the bus was not damaged after cold test and the minimum distance with the expansion loop is more than 15mm compressed or extended. The fixation screws located on the internal radius were suppressed starting from the third Q2 cold mass.
  - The busses are now kept in place by a Kevlar wire braided. This Kevlar is maintained on both extremities by 2 fiberglass rings impregnated with Araldite 2011. This braiding is performed on the straight part of the lyra to avoid its stiffening.
  - Spacer situations installed on the first assemblies are summarized in LHC-LMQXFB-FR-0156 so that their positions during the interconnection activities in the string or the tunnel are well known to give the correct precompression. Standard positions were agreed during a meeting with US-LARP for the next cold masses.

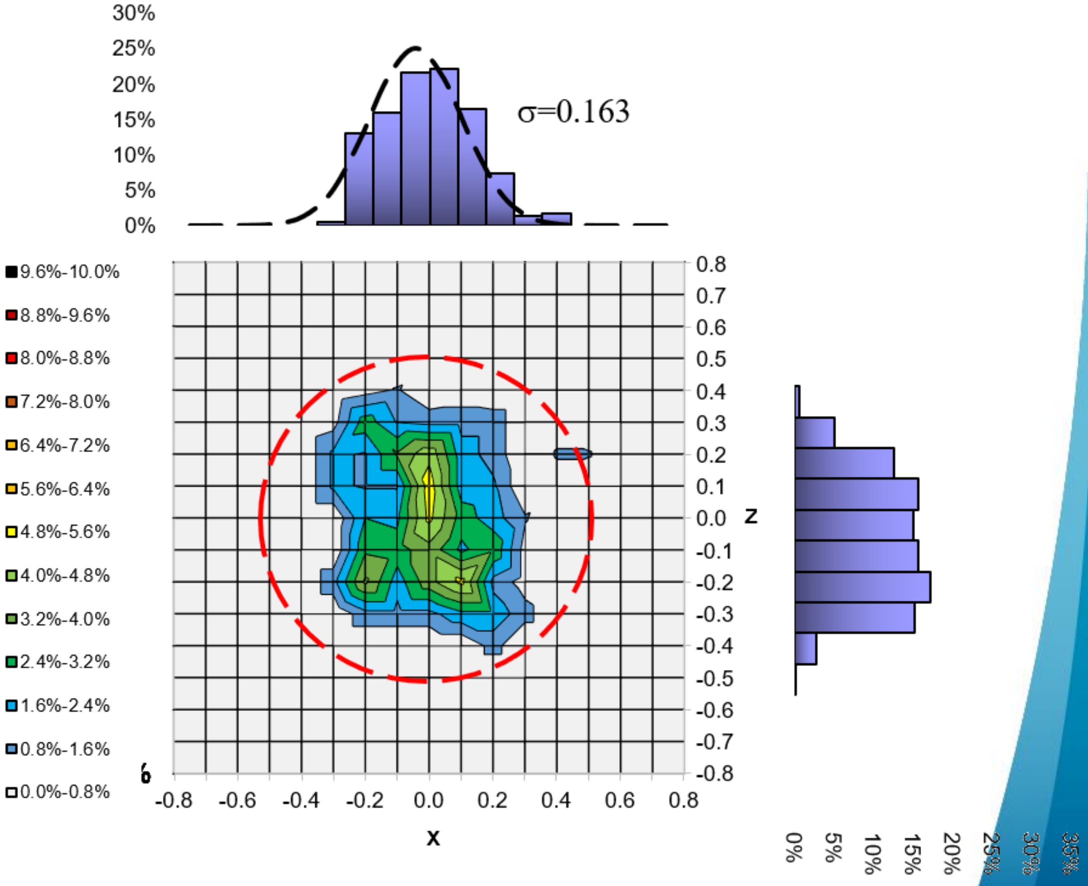
LMQXFB Q2 Cold Masses Alignment



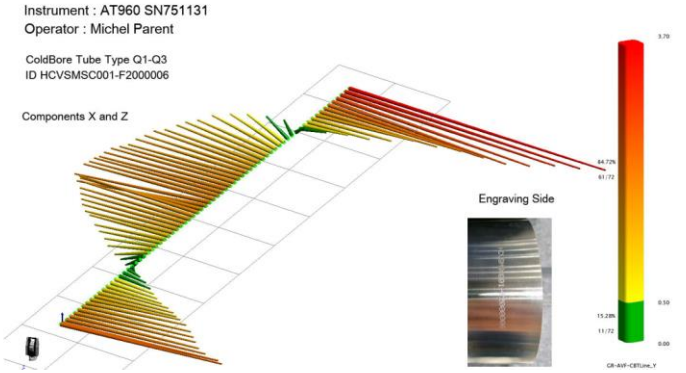


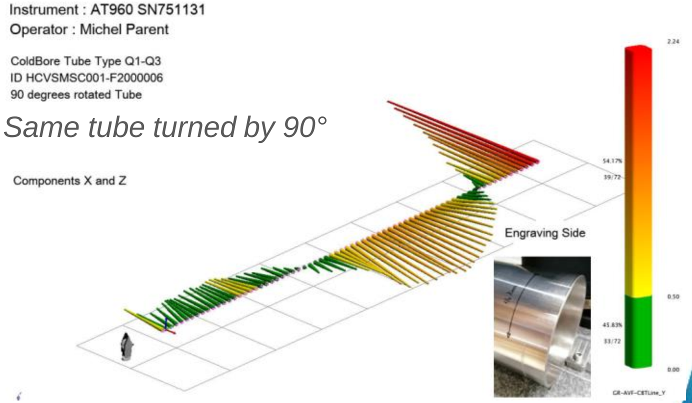
LMQXFB Q2 CBT Alignment





Beam Pipe Orientation Optimization



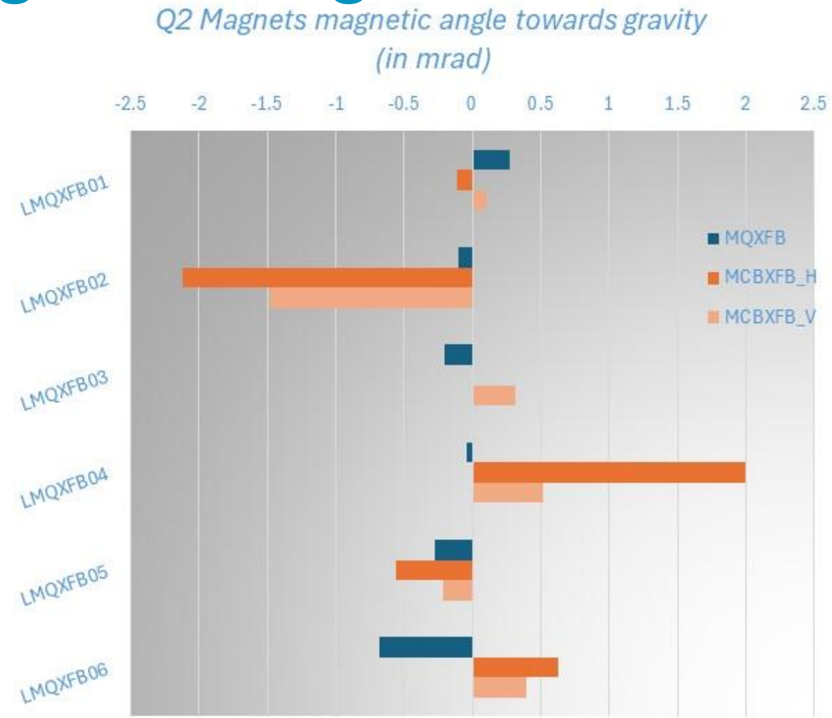


Same tube turned by 90°

LMQXFB Q2 Magnetic Alignment

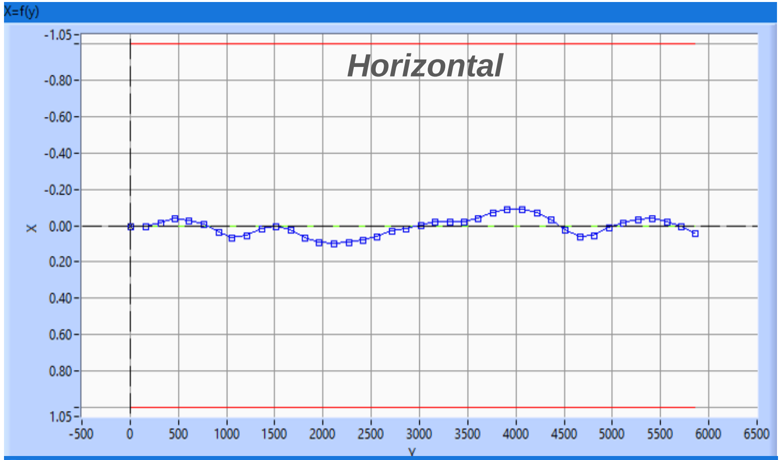
	MQXFB	MCBXFB_H	MCBXFB_V
LMQXFB01	0.27	-0.11	0.10
LMQXFB02	-0.10	-2.12	-1.48
LMQXFB03	-0.20	0.00	0.31
LMQXFB04	-0.04	2.00	0.52
LMQXFB05	-0.28	-0.56	-0.21
LMQXFB06	-0.68	0.63	0.39

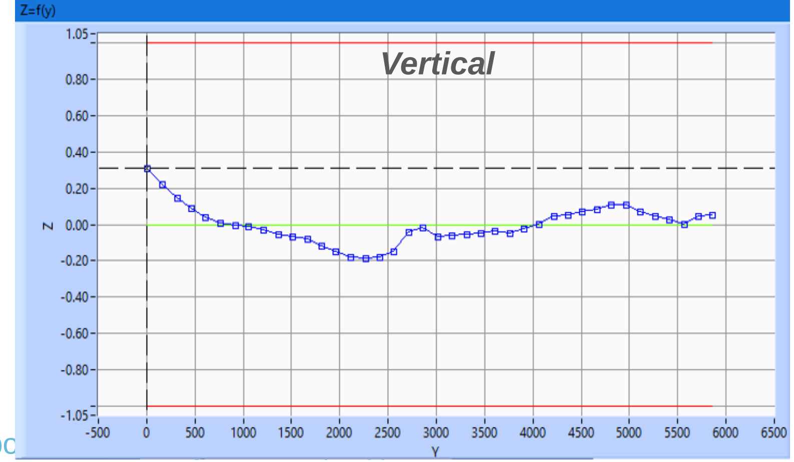
Courtesy of M. Pentella



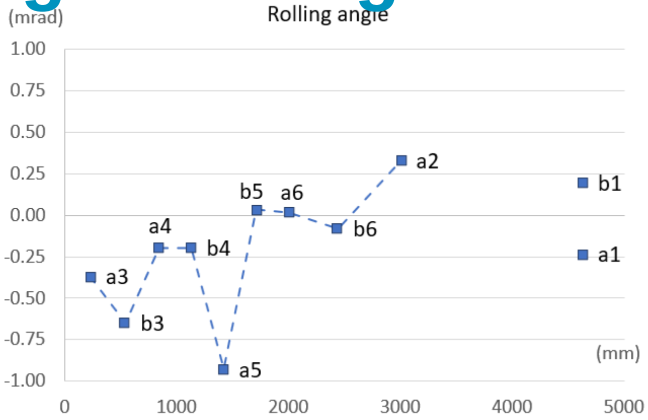
- ⇨ *Excellent correlation between the MQXFB magnetic axis and the yoke geometry.*
- ⇨ *The quadrupole geometry can be used to orient the cold mass tilt towards gravity better than within ±1 mrad.*

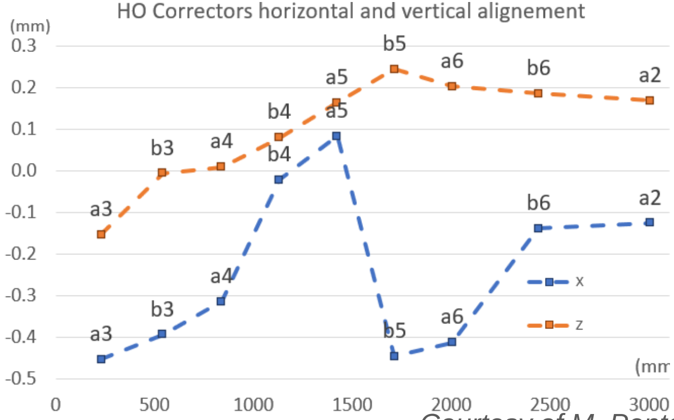
LMCXF01 CP CBT Alignment





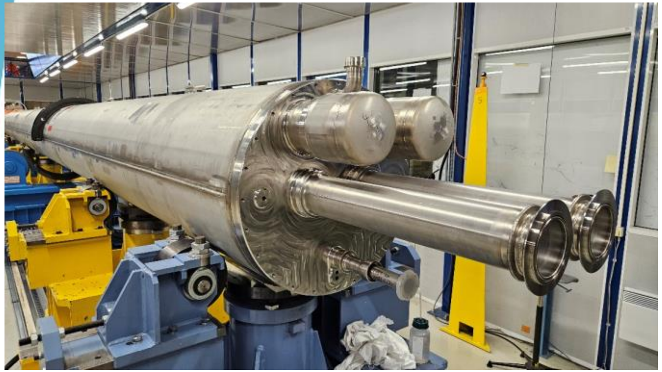
LMCXF01 Correctors Magnetic Alignment

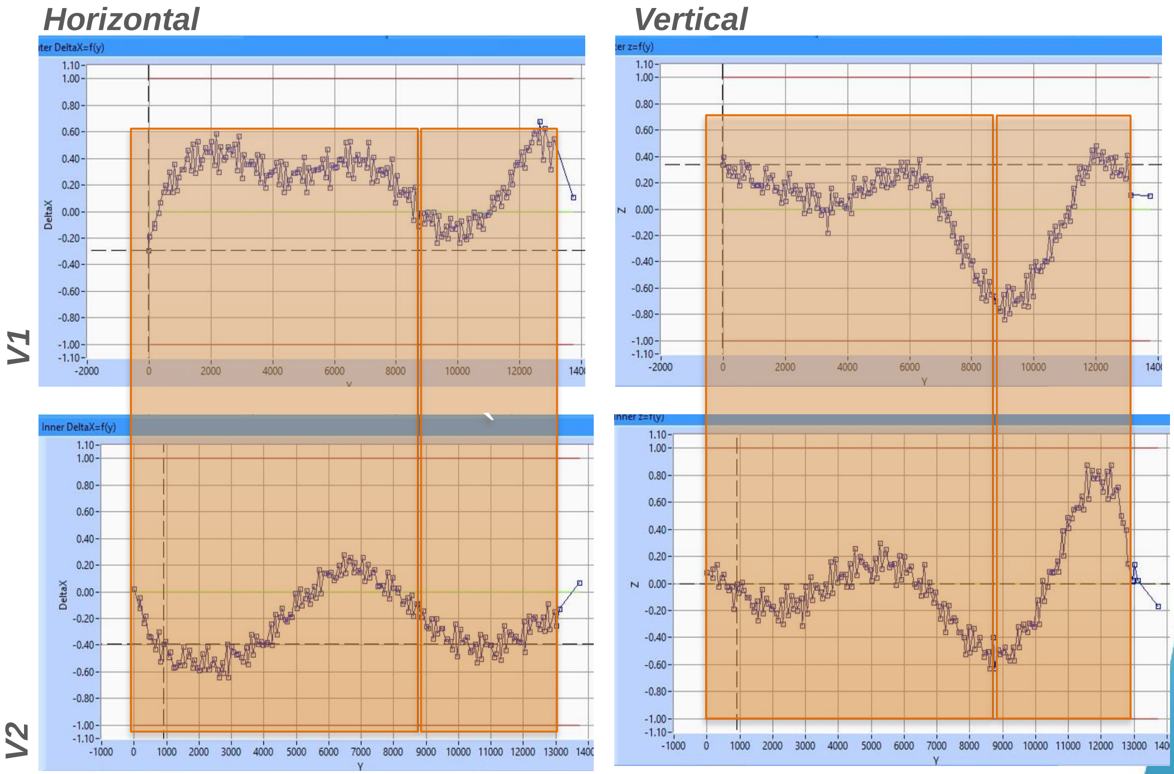




Courtesy of M. Pentella

LMBRD01 Cold Bore Tube Alignment



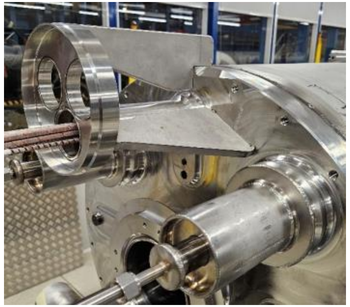


Tooling Developments

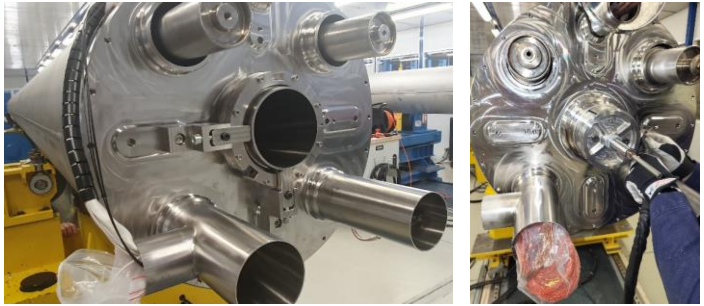
X lines positioning and welding copper rings

IFS capillary bending

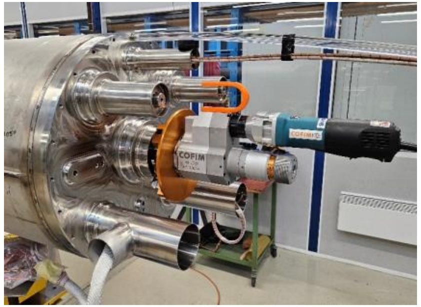
Welding shrinkage probe



The triple flange reinforcement ribs alignment



V line alignment and gas protection system preventing cbt deformations

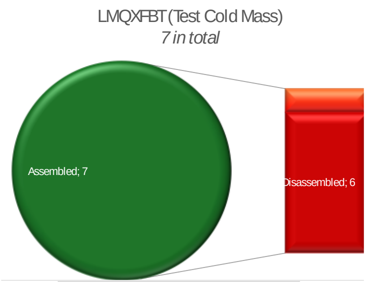


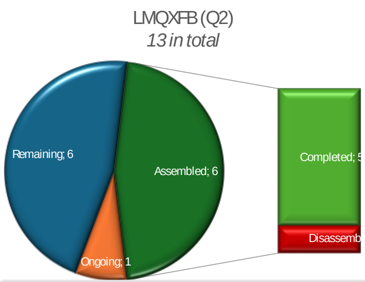
V line cutting and chamfering

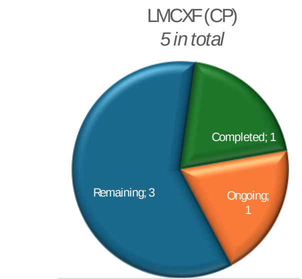
Chain hoists to adjust accurately the load for each cable when handling the cold masses replacing tensioners left/right

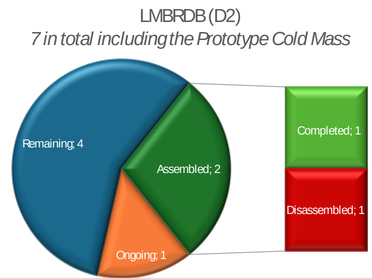
Production Status

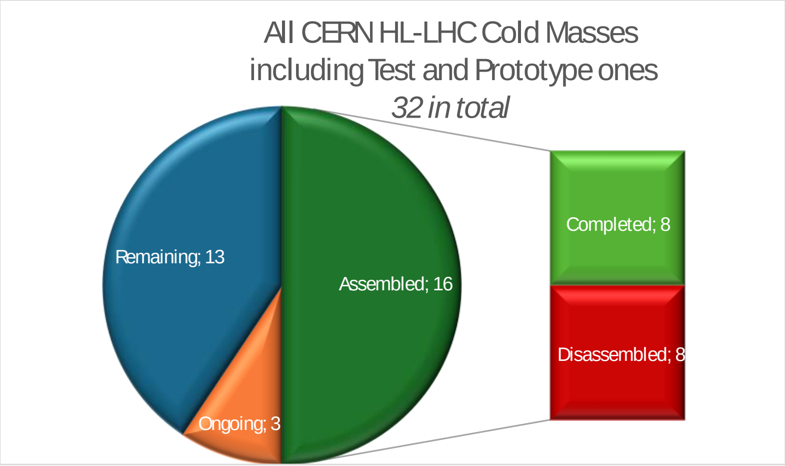
	Total	Assembled	Accepted	Ongoing	Disassembled
LMQXFBT (MQXFB test)	7	7	7		6
LMQXFB (Q2)	13	6	5	1	1
LMCXF (CP)	5	1	1	1	0
LMBRD (D2)	7	2	2	1	1
Total	32	16	8	3	8
Total without test and proto	25	8	7	3	1

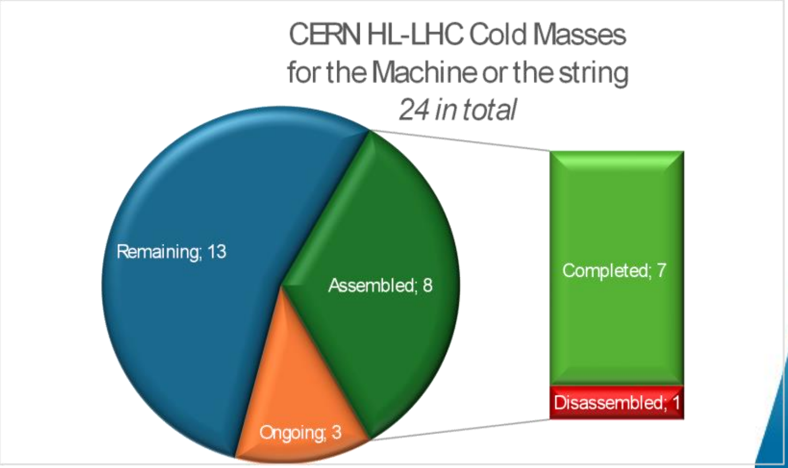












On-going cold masses

LMQXFB07 (Q2)

MQXFB06 - MCBXFB03

Longitudinal welding was completed last week, the PAUT revealed two 6mm zones with minor defects that were repaired (see slide 9).
Extremities were cut, the cylinder was transferred inside the finishing zone where it is tilted according to gravity.

LMCXF04 (CP)

MCBXFA01 - HO set #4

The lower shell was installed and aligned on the press conveyor and aligned inside the cradles.
Magnets were prepared and are being aligned inside the shell.

LMBRD02 (D2)

MBRD01 - MCBRDP12-MCBRDP1b

The two orbit correctors cylinder was welded two weeks ago. Extra length in extremities were cut and the welding preparation will be machined.
The separation dipole is expected to be delivered and inspected before continuing the work with the second cylinder.

Summary

- *CERN cold masses design has been completed. It has been validated by the production of prototypes and at least one series cold mass for each type (except the Q10, not presented in this talk).*
- *All components were delivered except for few bellows that equip the heat exchangers.*
- *The production is following the magnet deliveries which is, today, the parameter that dictates the sequence and the schedule.*
- *The assembly process is being refined continuously; improvements are retrofitted in the procedures that are regularly updated.*
- *The rate of production has reached its nominal and conforms to initial forecasts. Experience showed that the tooling setup for the cold masses production in the CERN Large Magnet Facility is compatible with 3 to 4 assemblies in parallel if the sequencing is well organized.*

Spare slides

Q10 with MS LMQMT Cold Mass

- Following the lack of performance of the first MQML magnet observed cold test, it was decided not to start the cold mass production before all the necessary magnets have been fully qualified.
- 2 out of 5 MQML were cold tested and one is presently under test conditions.
- 4 MSCBB magnets need to be cold tested.
- Nominal assembly duration was estimated to 15 weeks (65 WD) once magnets have been delivered.
- Busbar production started, one set has been completed.

- Tooling for the MQM IR cold mass production needs to be refurbished, the last cold mass of assembled that type was completed in July 2012 before being installed in Q5R8 during the LS1.