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# The 11 T Dipole for HL-LHC – Status and Plan

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***Abstract*— The upgrade of the LHC collimation system includes additional collimators in the LHC lattice. The longitudinal space for these collimators will be created by replacing some of the LHC main dipoles with shorter but stronger dipoles compatible with the LHC lattice and main systems. The project plan comprises the construction of two cryo-assemblies containing each two 11T dipoles of 5.5 m length for possible installation on either side of interaction point 2 of LHC in years 2018-2019 for ion operation, and the installation of two cryo-assemblies on either side of interaction point 7 of LHC in years 2023-2024 for proton operation. The development program conducted in conjunction between the Fermilab and CERN magnet groups is progressing well. The development activities carried out on the side of Fermilab were concluded in the middle of 2015 with the fabrication and test of a 1 m long two-in-one model and those on the CERN side are ramping up with the construction of 2 m long models and the preparation of the tooling for the fabrication of the first full-length prototype. The engineering design of the cryo-magnet is well advanced including the definition of the various interfaces, e.g. with the collimator, powering, protection, and vacuum systems. Several practice coils of 5.5 m length have been already fabricated. This paper describes the overall progress of the project, the final design of the cryo-magnet and the performance of the most recent models. The overall plan towards the fabrication of the series magnets for the two phases of the upgrade of the LHC collimation system is also presented.**

***Index Terms*—High Luminosity LHC Project, Accelerator Magnets, Superconducting Magnets, $Nb_3Sn$ 11 T Dipole**

## I. Introduction

COLLIMATORS are installed in the Large Hadron Collider (LHC) to safely intercept and absorb beam losses [1]. In order to cope with intensities that are larger than nominal, such as in the High Luminosity LHC (HL LHC) Project [2], including high-luminosity heavy-ion operation [3], [4], it is envisaged to install additional collimators [5], [6] in the Dispersion Suppressor (DS) region at the location of selected 14.3 m long, 8.3 T Nb-Ti LHC main bending dipoles (MB). This will be possible if these MBs are replaced by two shorter 11 T dipoles (MBH), symmetrically installed around the center of the replaced MB, thereby leaving space for warm collimators. These MBHs need to be compatible with the LHC lattice and main systems. They will be connected in series with the MBs, and shall produce an integrated field of 119 T·m at 11.85 kA [7], [8]. A joint Research & Development (R&D) program was started in October 2010 at FNAL and CERN with the goal of developing the necessary technology for the fabrication of a 5.5 m long two-in-one aperture $Nb_3Sn$ dipole prototype suitable for installation in the LHC.

## II. Project Development Status

The R&D program started with the design and construction of a single aperture demonstrator magnet of 2 m length, which constituted the foundations of the further development activities [9], [10]. Thereafter, the project has well progressed with the fabrication and test of 8 models aiming at demonstrating feasibility, studying conceptual and technological variants, and assessing compliance of key functional requirements like quench performance, protection, field quality, and persistent current effects. A list of the models made since the beginning of the project is given in Table I. The different cross sections are illustrated in Fig. 1 for the models made at Fermilab and in Fig. 2 for the models made at CERN. Although the final magnet will have a two-in-one structure like the MBs, single aperture models were made in order to maximize the overall effectiveness of the development activities. As the coils are individually collared, a single aperture model is good enough to test most of the features of a two-in-one magnet. It is planned to start testing a second two-in-one model in the end of 2015.

TABLE I
List of Models Fabricated and Tested at FERMILAB and at CERN

| Model ID | Type of cross section | Length [m] | Test period | Laboratory |
|---|---|---|---|---|
| MBHSP01 | Single aperture | 2 | Jun./Jul.12 | FNAL |
| MBHSP02 | Single aperture | 1 | Feb./Mar.13 | FNAL |
| MBHSM01 | Mirror assembly | 1 | Dec.13/Jan.14 | FNAL |
| MBHSP03 | Single aperture | 1 | May/Jun.14 | FNAL |
| MBHDP01 | Double aperture | 1 | Feb./Mar.15 | FNAL |
| MBHSM101 | Single coil | 2 | Jun./Jul.14 | CERN |
| MBHSP101 | Single aperture | 2 | Nov./Dec.14 | CERN |
| MBHSP102 | Single aperture | 2 | Jun./Jul.15 | CERN |
| MBHSP103 | Single aperture | 2 | Oct.15 | CERN |

The magnetic design of the coils is the same in the two laboratories, based on 2-layer and 6-block $Nb_3Sn$ coils,

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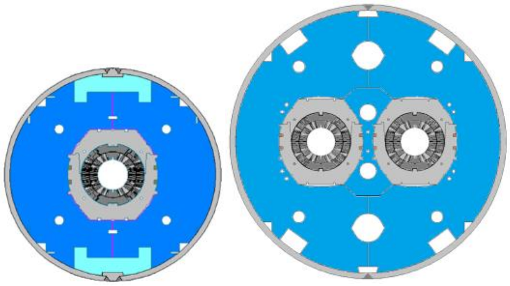

Fig. 1. Cross-section of the single aperture MBH – Yoke OD (left), and of the two-in-one aperture MBH (right), as per FNAL design.

keystoned Rutherford type cable made of 40 Restacked Rod Process (RRP) strands of 0.7 mm diameter [11]–[13]. There are 56 turns, of which 22 in the inner layer and 34 in the outer layer. An 11-mm-wide stainless steel core is embedded in the cable to reduce the effects of persistent currents, except for SP01 for which the cored cable was not yet developed. At Fermilab, the cable insulation is made of a double layer of 75 µm thick E-glass tape. At CERN, the cable insulation is composed of a Mica tape of 80 µm thickness shaped in the form of a "C" around the cable, and surrounded by a 70 µm thick braiding of S2-glass fiber. In both cases, the coil is impregnated, after reaction, with an epoxy resin system CTD-101K.

The mechanical structure comprises separate stainless steel collars for each aperture and a vertically split iron yoke, surrounded by a welded stainless steel outer shell. At Fermilab, the pole pieces make integral part of the coils, as they are impregnated together, whereas at CERN, the pole pieces are separated and put in place at the moment of the assembly of the

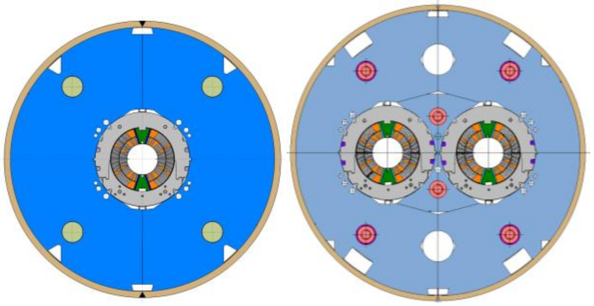

Fig. 2. Cross-section of the single aperture MBH (left), and of the two-in-one aperture MBH (right), as per CERN design.

coils with the collars, prior to collaring. In the first case, adjustments can be done with mid plane shims and variations of the number of ground insulation layers put onto the outer diameter of the coils. The latter solution allows more flexibility in terms of adjustment of the pre-stress with a pole shim to correct for example variations of the coil size throughout production and a top shim for finer tuning. The structure is made such that the coil is always in compression during powering till the ultimate magnetic flux density of 12 T. In the single aperture model of CERN (and of Fermilab), the azimuthal stress in the coil, after welding of the shells, is comprised between 90 (89) and 67 (59) MPa at the location of the pole and between 42 (49) and 78 (85) MPa in the mid plane. At cold and under ultimate current of 12.8 kA, these stresses are comprised between 15 (2) and 23 (23) MPa at the location of the pole and between 124 (124) and 114 (135) MPa in the mid plane. These numbers denote compression stresses.

## III. Quench Performance

The quench performance of the models made at Fermilab has already been reported extensively in recent publications for MBHSP01 [14], MBHSP02 [15], MBHSP03 [16], MBHSM01 [17], MBHDP02 [18], and for MBHSM001 [19]. The main results of the models SP02, SP03 and DP01, which was made with the collared coils of the two models SP02 and SP03, will be recalled here to provide a global picture and easier benchmarking with the other models made at CERN more recently.

The results of the quench performance tests of the models SP02, SP03, and of the model DP01 are illustrated in Fig. 3.

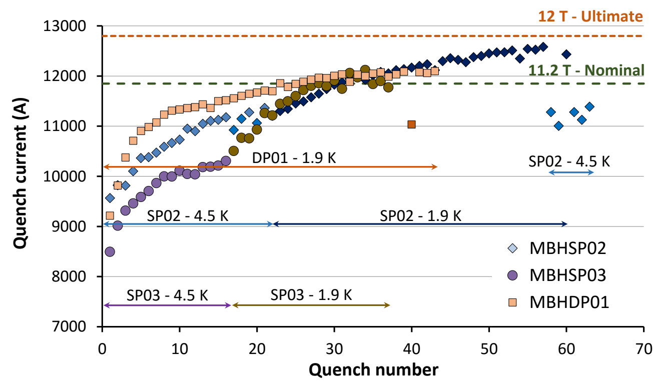


Fig. 3. Quench performance of models MBHSP02, MBHSP03, and MBHDP01 at Fermilab.

The quench performance tests at Fermilab usually start with training at 4.5 K in order to understand any possible limitation by the conductor itself, as the short sample limit is lower at that temperature. Also, there is a faster recovery of cryogenics and test conditions after a quench at that temperature. The model SP02 reached the nominal current at 1.9 K after 8 quenches, and the model SP03 after 11 quenches. These numbers are respectively 29 and 27 if one add the quenches at 4.5 K. Before integration in the two-in-one structure, the coils of the model SP03 were re-collared with slightly increased pre-stress by means of an additional 75 µm thick layer of polyimide insulation between the coils and the collars. The model DP01 was tested at 1.9 K only; it needed 22 quenches to reach nominal current. Expectedly, the two-in-one model was limited by the performance of the coils used in the single aperture models, especially by SP02 which had shown conductor degradation. A maximum magnetic flux density of 11.5 T was reached in the bore of the two-in-one structure.

The results of the quench performance of the models made at CERN are illustrated in Fig. 4. The quench performance tests at CERN start at 1.9 K because it is more representative of what happens in reality when the magnet is used in the accelerator. The first single aperture model, SP101, did not perform satisfactorily; it needed 17 quenches to reach nominal current, showed important detraining, and did not really exceed 11 T. It reached again nearly the nominal field at 1.9 K after a thermal cycle and after the tests carried out at 4.3 K. However, one of

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the two coils, coil 106, had only four quenches and was reused

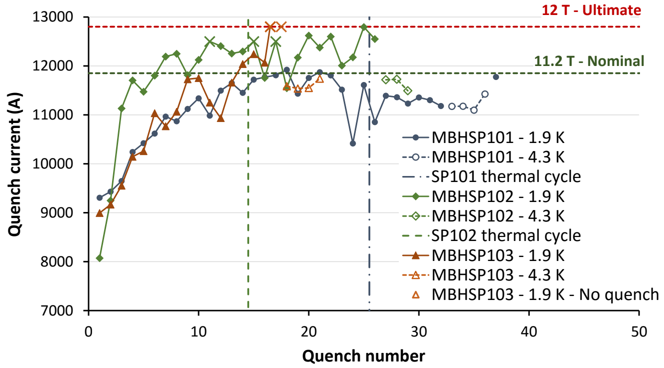


Fig. 4. Quench performance of models MBHSP001, MBHSP002 and MBHSP103 at CERN. Crosses on the graph mean no quench.

in the model SP102 in combination with a new coil, coil 108. The model SP102 needed only 6 quenches before exceeding nominal current and, even though a few detraining quenches were observed, this model reached the ultimate magnetic flux density, 12 T, after thermal cycle. Coil 108 turned out to be of excellent performance with only 4 quenches during the entire test campaign. This model was subject to current holding tests, one at 12.3 kA for 2.5 hours, and another one at 11.85 kA for 10 hours followed by a magnetic measurements cycle and a ramp to 12.5 kA, all without quench. The model SP103, which was made with two virgin coils, coil 109 and coil 111, performed also very well with 13 quenches before exceeding nominal current. Then, it reached 12 T after 3 additional quenches, where it remained stable during a one-hour plateau. During about 20 subsequent cycles to nominal current with ramp rates of up to 300 A/s and quench heater tests, the model SP103 did not quench anymore and reached again without retraining the ultimate magnetic flux density, and remained stable during a one-hour plateau.

## IV. Final Design

The baseline design of the 11 T dipole cryo-assembly and of the MBH cold mass assembly is presented here.

### *A. The cryo-assembly*

A detailed description of the integration of the 11 T dipole and collimators in the LHC is given in [20]. A standard arc MB cryostat will be replaced by a string of three independently installed and aligned cryo-assemblies: two of these will each house an MBH and a bypass cryostat will be installed between them. The bypass cryostat ensures the continuity of the cryogenic and electrical circuits and comprises cold to warm transitions on one of the two beam lines in order to create a room temperature vacuum sector for the collimator. The other beam line will be cold and will contain a beam screen, as in the arc. The total length of the cryo-assembly is 15.66 m. The length of the by-pass cryostat is 2.16 m for a room temperature beam vacuum sector of 1.23 m and an active length of the collimator jaws of 600 mm.

### *B. The 11 T dipole cold mass assembly*

There will be 2 types of cold mass per cryo-assembly, one to be installed on the left-hand side of the collimator, and one to be installed on the right-hand side. For the full-length magnet, a few modifications were made to the design described above for the models. The outer diameter of the yoke was reduced by 10 mm in order to facilitate the integration of the cold mass assembly with the cryostat and to increase the level of compatibility with the existing MBs, thus avoiding reengineering a number of challenging interfaces.

A cutback was introduced at the extremities of the yoke assembly to move the peak field away from the transition region between the straight part of the coils and the ends. The cutback consists in replacing a number of low-carbon steel laminations by others made of non-magnetic steel. This will move the peak field in the straight part, which is mechanically more robust. A longitudinal section of the MBH to be installed on the left-hand side of the collimator is shown in Fig. 5.

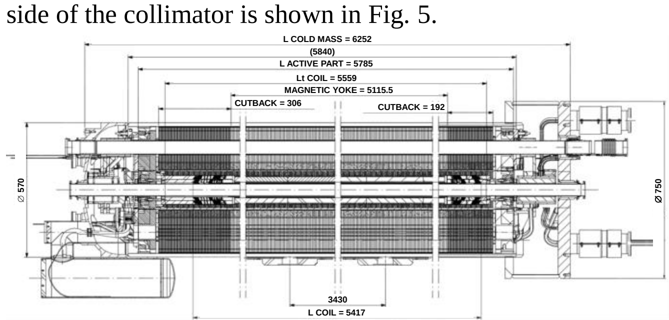


Fig. 5. Longitudinal section of the MBH on the left-hand side of the collimator.

Unlike the MB, which is curved in the horizontal plane, the MBH will be straight because of the brittleness of $Nb_3Sn$ after reaction. It will be equipped with the same cold bore tube and beam screen as the present MB, to facilitate integration. To mitigate for the corresponding reduction of mechanical aperture, the two MBHs of a cryo-assembly will be assembled with an angle of 2.55 mrad relative to each other, and shifted by 0.8 mm towards the center of the accelerator.

### *C. Powering and protection*

The two MBH's of a cryo-assembly will be connected in series as shown in Fig. 6. There will be two powering directions depending on the direction of circulation of the beam at the location of installation. Fig. 6 shows one of these cases. A cold by-pass diode will be used for the two MBH's.

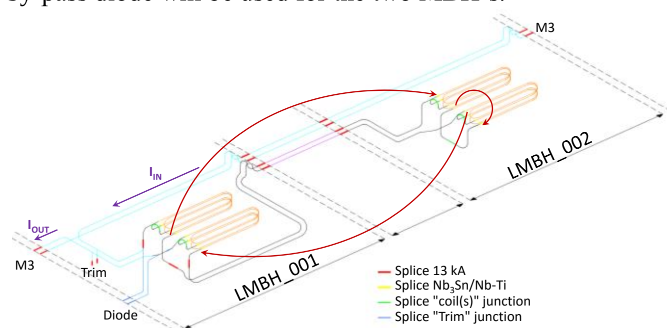


Fig. 6. Powering scheme of the MBH's of a cryo-assembly. LMBH_001 is the MBH on the left-hand side of the collimator and LMBH_002 is the MBH on the right-hand side of the collimator.

To avoid deformation of the beam closed orbit, the integrated transfer function of a pair of MBHs shall be identical to that of the MB. However, this is not possible across the entire range of current during ramping up to nominal, as shown in Fig. 7. The design is such that a pair of MBHs provides the same integrated field of 119 T·m as an MB at the nominal current of 11.85 kA. Because it has more turns, the MBH is stronger than the MB at lower currents, with a peak difference in integrated field around 6.5 kA. This will be mitigated by adding a dedicated trim power converter.

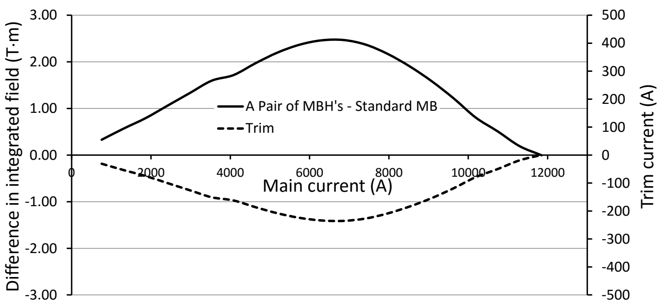


Fig. 7. The solid line shows the difference in integrated field between a pair of MBHs and an MB, both delivering 119 T·m at 11.85 kA. The dotted line shows the trim current needed to correct the difference at currents below 11.85 kA.

The protection of the 11 T dipole is challenging because of a high stored energy density, a large engineering current density, a high temperature margin, and a low copper to non-copper ratio. These parameters are given in Table II with those of the MB for comparison.

TABLE II
KEY PARAMETERS FOR THE MAGNET PROTECTION

| Symbol | Quantity | MB (Nb-Ti) | MBH ($Nb_3Sn$) |
|---|---|---|---|
| $e_m$ | Stored energy density at $I_{nom}$ | 60 MJ/m$^3$ | 130 MJ/m$^3$ |
| $J_{op}$ | Engineering current density | 500 A/mm$^2$ | 790 A/mm$^2$ |
| $T$ | Temperature margin | 1.8-6.5 K | 4.5-14.5 K |
| | Copper to non-copper ratio | 1.6-1.7 inner layer<br>1.9-2.0 outer layer | 1.15 ± 0.10 |

Protection studies for the 11 T dipole are extensively described in [21], where it is reported that the hot spot temperature in the coil shall not exceed 350 K. This has been taken as design criteria for the MBH, and more generally for all the $Nb_3Sn$ magnets for HL-LHC [22]. To achieve this, quench heaters will be installed on the outer surface of the outer layer of the coil. In the original design, the heaters are glued on the coil after impregnation, implying a layer of impregnated fiber glass between the coil and the heater. Experimental tests reported in [20] have shown that the hot spot temperature may increase by 45 K per 0.1 mm additional thickness of impregnated fiber glass between the coil and the heater. It is therefore planned to have the heaters impregnated with the coil to increase their efficiency by reducing their reaction delay.

There will be 2 quench heater circuits per coil (i.e. per pole) meaning a total of 8 quench heater circuits per MBH and 16 quench heater circuits per cryo-assembly. The heaters are made of a stainless steel strip of 25 μm thickness glued on a polyimide foil of 50 μm thickness. In order to reduce the electrical resistance of the heaters, which is needed to limit the voltage across them to ± 450 V, copper plating of 5 μm is applied on the stainless steel strips.

## V. Plan towards Prototyping and Production

In addition to the models listed in Table I, 3 additional single aperture models are in the plan, the first to understand better the repeatability of the manufacturing conditions and performance indicators, the second to confirm the performance of impregnated quench heaters and the third to test inter-layer quench heaters, which are under study to bring redundancy into the system.

It is foreseen to produce a full length MBH prototype and two cryo-assemblies, using conductor type RRP. One of these two cry-assemblies shall be ready by the end of 2018.

For LS3, which is scheduled to start in the beginning of 2024 with a duration of 2.5 years, it is foreseen to produce a full-length MBH prototype, this time with conductor type Powder-In-Tube (PIT), and four cryo-assemblies for which the choice of the conductor will depend on the outcome of a tendering process. These cryo-assemblies shall be ready by the end of 2023. Depending on whether the first two cryo-assemblies made by the end of 2018 are used prior to LS3, or not, two additional cryo-assemblies may be produced as spare units.

The prototypes will be built at the CERN Large Magnet Facility where the installation and commissioning of the major tooling is well advanced. The 6.5 m long reaction furnace is operational. A first practice coil made of copper was reacted in the beginning of October 2015, and two other practice coils made of $Nb_3Sn$ conductor are ready for reaction. The commissioning of the impregnation system will be finished in the middle of November 2015. Production strategies for the series magnets are under study, including for the production of the other types of magnets needed for HL-LHC, e.g. new $Nb_3Sn$ quadrupoles for the inner triplets.

## VI. Conclusion

The development of an 11 T dipole for HL-LHC is well advanced. Nine models were manufactured and tested at Fermilab and CERN, and more models are under construction at CERN. The quench performance of the last two models, MBHSP102 and MBHSP103, meets expectations. Holding current tests at nominal and ultimate current have demonstrated stability, with margin, in operation conditions. There is good progress with the installation and commissioning at CERN of the tooling for the fabrication of full-length coils. There are good indications that the magnet can be protected with quench heaters, on the condition they are in tight contact with the coils.

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