Status of the 11 T Nb_3Sn Dipole Project for the LHC

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***Abstract*—The planned upgrade of the LHC collimation system includes additional collimators in the LHC lattice. The longitudinal space for the collimators could be obtained by replacing some LHC main dipoles with shorter but stronger dipoles compatible with the LHC lattice and main systems. A joint development program with the goal of building a 5.5 m long two-in-one aperture Nb_3Sn dipole prototype suitable for installation in the LHC is being conducted by FNAL and CERN magnet groups. As part of the first phase of the program, 1 m long and 2 m long single aperture models are being built and tested, and the collared coils from these magnets will be assembled and tested in two-in-one configuration in both laboratories. In parallel with the short model magnet activities, the work has started on the production line in view of the scale-up to 5.5 m long prototype magnet. The development of the final cryo-assembly comprising two 5.5 m long 11T dipole cold masses and the warm collimator in the middle, fully compatible with the LHC main systems and the existing machine interfaces, has also started at CERN. This paper summarizes the progress made at CERN and FNAL towards the construction of 5.5 m long 11 T Nb_3Sn dipole prototype and the present status of the activities related to the integration of the 11 T dipole and collimator in the LHC.**

***Index Terms*— 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], [2]. In order to cope with intensities that are larger than nominal, such as in the High Luminosity LHC (HL LHC) Project [3], including high-luminosity heavy-ion operation [4], [5], it is envisaged to install additional collimators [6]-[8] in the Dispersion Suppressor (DS) in the middle 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 Tm at 11.85 kA [9], [10]. A joint 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.

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II. The Short Model Program

The design of the MBH is extensively described in [11], [12]. The short model program comprises two configurations, a single aperture, and a two-in-one aperture structure, in order to obtain a faster return on experience and testing with the single aperture before the collared coils are recovered to be assembled in a two-in-one structure. The design is based on 2 layer and 6 block Nb_3Sn coils, keystoned Rutherford type cable made of 40 Restacked Rod Process (RRP) strands of 0.7 mm diameter. There are 56 turns, of which 22 in the inner layer and 34 in the outer layer. 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. The short model program is meant to address a number of challenges for the project, e.g. the matching of the Transfer Function (TF) with that of the MBs, the persistent current and dynamic effects, the magnet protection, and the required accelerator quality level.

A. Model program at FNAL

The MBH cross-sections developed at FNAL are shown in Fig. 1 for the single aperture, and two-in-one aperture structures. The poles of the coils are integrated, i.e. potted with the coils.

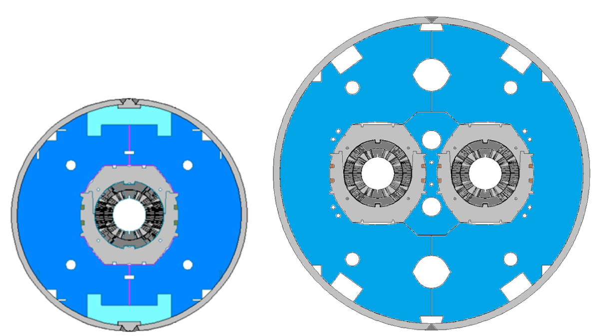

Fig. 1. Cross-section of the single aperture MBH (left), and of the two-in-one aperture MBH (right), as per FNAL design.

The development work carried out at FNAL covered the design and optimization of the strand and cable parameters, including the size of the sub-elements, the cable cross-section, the critical current degradation, the stainless steel (SS) core, and the cable RRR [13]-[15].

The fabrication and tests of the first 2-m-long single aperture demonstrator magnet (MBHSP01) was completed in June 2012. This demonstrator has reached 10.4 T at the LHC operating temperature, i.e. 1.9 K [16]. This test also revealed large conductor degradation in the coil that led to instabilities and spontaneous quenches during the current plateau, also for currents below 10 kA.

To optimize the magnet design and the fabrication processes, improve quench performance and demonstrate performance reproducibility, a program of fabrication of eight 1-m-long coils was started at FNAL in the middle of 2012. The first two coils were made with cable RRP 150/169, and the other ones with RRP 108/127; in all cases, with an 11-mm-wide stainless steel core. The coil#6 was damaged during curing. The coils#5, #7, #9 and #10 were tested first in a single aperture configuration (MBHSP02 and MBHSP03) and then, will be in a two-in-one aperture configuration (MBHDP01) [17]. Coil#8 had more instrumentation, and was tested in a mirror configuration (MBHSM01) in order to study the effect of the coil pre-stress and to measure quench protection parameters [18]. The coils#11 and #12 will go in the second two-in-one aperture model.

The quench performance of these models is summarized in Fig. 2. All the models have shown long training, which seems typical for many Nb_3Sn magnets.

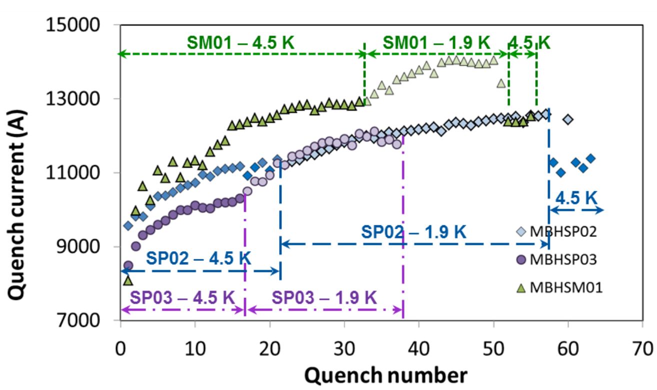

Fig. 2. Summary of MBH models trainings at FNAL.

Both models MBHSP02 and MBHSP03 were trained above the nominal field to 11.7 and 11.6 T respectively, which is ~97% of the ultimate field of 12 T, and corresponds to ~80% of the Short Sample Limit (SSL) at 1.9 K. The training of these models was stopped at that field level, and will continue in the two-in-one aperture configuration. The mirror assembly MBHSM01 reached ~100% of its SSL at 4.5 K, and ~97% of its SSL at 1.9 K. The large quench current degradation and the spontaneous quenches at current plateau observed in the first models MBHSP01 and MBHSP02 were eliminated in MBHSM01 and MBHSP03 thanks to the coil preload optimization.

Due to the large stored energy density, the quench protection of the MBH is challenging. It has been comprehensively studied at FNAL, including simulations [19], [20] and extensive measurements using the short models [21], [22], and the mirror assembly [23]. Thanks to the improved quench performance, quench protection studies in MBHSM01 were extended to currents up to 92% of the SSL. The efficiency of the quench heaters, the longitudinal and transverse quench propagation velocity, and the quench propagation from the outer to the inner layers of the coil were measured. Although standard quench heaters installed on the outer layer were sufficient to protect the short models, studies will continue to conclude whether this solution is fully safe for the final 5.5-m-long magnet, or if further measures are needed.

Field quality measurements provided important information on geometrical harmonics, coil magnetization, and iron saturation effects [17], [24], [25]. For example, Fig. 3 shows the variations of normal sextupole b_3 in the current cycles for MBHSP02 and MBHSP03. The persistent current effect seen at low currents in the TF (*B/I*) and b_3 is significant due to large D_{eff} of the order of 41 μm for RRP 108/127, and J_c of the Nb_3Sn strands used in these models. The iron saturation effect on the TF and b_3 starts at ~4 kA and is consistent with expectations [26] for the single aperture configuration, and quality of iron used. The ramp rate effect is small as expected for a cored cable. The measured b_3 decay at the LHC injection is large (4-7 units) and reproducible. The magnetic measurements show that all the higher order geometrical harmonics (n>3) are small, ~1 unit or less. The values and variation of lower order harmonics is large because of variations of the coil size and shims used for coil pre-stress. The large low order geometrical harmonics and the persistent current effect will be corrected for the final magnets.

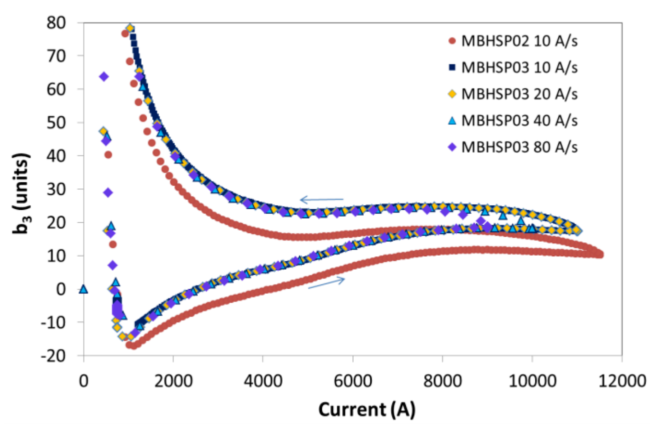

Fig. 3. Sextupole b_3 vs. magnet current.

Two collared coils MBHSP02 and MBHSP03 are being assembled in the first two-in-one aperture model. The collared coil of MBHSP03 was re-collared with slightly larger radial shims in order to increase the coil pre-stress. A two-in-one aperture mechanical model with instrumented collared coil blocks will validate the assembly conditions prior to assembly the model, which will be tested in October 2014.

B. Model program at CERN

The model program at CERN started, effectively, in the middle of 2011 on the basis of the technology developed at FNAL, with some variations such as the removable pole, which allows the adjustment of the coil pre-compression at the poles by appropriate shimming, and the mica insulation. After the fabrication of a few practice coils, it was decided to build a practice model of 2 m length made of a superconducting (SC) coil assembled with a copper coil. A comprehensive description of this practice model and of the results of the cold tests is given in [27]. This is actually the very first time that the CERN concept based on the use of removable poles and pole loading plates was tested. With the good results of this first model – a current of 11.85 kA reached after 5 training quenches, a field of 11 T reached in the coil ends after 16 quenches, and a maximum current of 16 kA reached at 1.9 K in the end of the training campaign, corresponding to a peak magnetic flux density of 12.9 T – CERN has demonstrated the validity of the coil winding including the removable pole concept, as well as the manufacturing procedures, and the tooling used.

The model program is currently continuing towards the goal of qualifying two types of cables, RRP 132/169 and PIT120, prior to launching procurement contracts for the cable needed for the full-length prototype magnets and the first units needed for the second long shutdown of LHC [5]. The memory will also be checked. The model program is summarized in Table I with a list of 2-m-long models to be produced in chronological order. The cross-section of the single aperture and two-in-one aperture models developed at CERN is shown in Fig. 4.

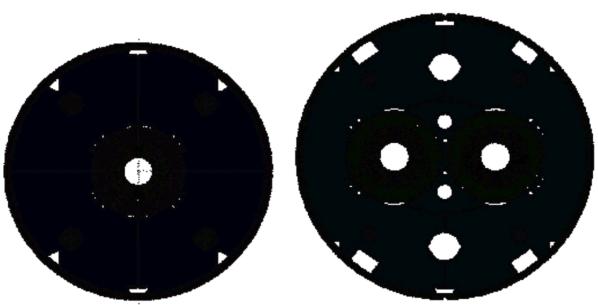

Fig. 4. Single aperture (left), and two-in-one aperture (right) model at CERN.

TABLE I
MODEL PROGRAM AT CERN

Identification	Single / Two-in-One	Type of cable
MBHSM101 (single coil)	1-in-1	Cu – RRP 108/127
MBHSP101	1-in-1	RRP 108/127
MBHSP102	1-in-1	RRP 132/169
MBHSP103	1-in-1	PIT120
MBHDP101	2-in-1	RRP 108/127 – RRP 132/169
MBHDP102	2-in-1	RRP 108/127 – PIT120
MBHSP104	1-in-1	RRP 132/169
MBHDP103	2-in-1	RRP 132/169 – RRP 132/169
MBHSP105	1-in-1	PIT120
MBHDP104	2-in-1	PIT120 – PIT120

Except for MBHSM101 for which the table indicates the type of cable for Coil 1 and for Coil 2, the table indicates the type of cable for both coils in case of a single aperture model (SP), and the type of cable for Aperture 1 and for Aperture 2 in case of a two-in-one aperture model (DP).

III. THE PROTOTYPE PHASE

Although the model programs currently going on at both FNAL and CERN are not yet completed, and development work is still needed, e.g., for the design and fabrication technology of quench heaters, the preparation of the tooling necessary to produce full-length two-in-one aperture prototypes at CERN has already started.

A first dummy coil was wound with copper cable, and used to test the binder curing tooling, a reaction furnace of 6.5 m of effective length is on its way to CERN from the supplier, and a vacuum impregnation system of 10.5 m of effective length shall be delivered in March 2015, completing the installation of the major tooling for the fabrication of the coils.

Two prototypes will be fabricated, one with cable RRP 132/169, and one with cable PIT120. The cross section will be derived from the one developed for the short models. The main parameters of the MBH are given in Table II.

TABLE II
MAIN PARAMETERS OF THE 11 T DIPOLE MAGNET FOR LHC

Parameter description	Value
Nominal magnetic flux density @ the center of the bore, @ 1.9 K, @ 81% of I_{max} on the load line	11.25 T at 11.85 kA
Ultimate magnetic flux density	12 T
Bore diameter	60 mm
Number of turns, inner/outer layer	22 / 34
Non insulated cable width / mid-thickness	14.70 mm / 1.25 mm
Keystone angle	0.79°
Magnetic length	5.307 m

It is expected that the first prototype will be tested by middle of 2016, and the second by the end of 2016. In order to anticipate technology transfer to industry that will take part in the production and to take into account the industrial constraints at an early stage of the engineering work, CERN has placed industrial service contracts with four companies well known in the field of SC magnets fabrication. Personnel from these companies are gradually integrated into the CERN teams.

IV. INTEGRATION OF THE MBH IN THE LHC LATTICE

A. MBH and collimation integration

The first integration studies to install collimators in the DS regions started in 2010. The approach to create the required space for collimators involved changing the position of several magnets in the continuous 1.9 K cryostat combined with modifications of existing connection cryostats, powering feed boxes and cryogenic transfer lines.

A 4.5-m-long cryostat comprising all the necessary temperature transitions, fluid and electrical circuits and ensuring their continuity throughout the machine was designed along with a specific collimator [28].

With respect to the approach based on moving the DS magnets, the solution based on MBHs reduces the amount and impact of the necessary modifications to the LHC, as only one

MB must be replaced per collimator with no further changes to adjacent equipment. The string of cryostats replacing one MB consists of three independently installed and aligned cryo-assemblies: two of them housing the 5.5-m-long MBH, and one connection cryostat installed in-between, which creates a room temperature vacuum sector for the 800 mm active length collimator. This layout is schematically represented in Fig. 5. Given the existing scheme of supports and compensation of thermal contractions on the main powering bus bars along the LHC arcs, positioning the connection cryostat in the middle was found to result in the most compact layout in terms of length. This new design of connection cryostat creates the space for the collimator and its vacuum sector, as well as provides continuity of the cryogenics and powering circuits and includes the cold to warm transitions on the beam lines, all within demanding integration constraints.

On the transverse plane the designs of the collimator and of the connection cryostat are driven by the position of the two-phase superfluid helium heat exchanger, which must be kept levelled along the string of magnets, combined with the space taken by the RF-shielded gate valves sectorizing the beam vacuum lines. All the other cryogenic lines passing through the connection cryostat must be placed further away from the beam lines with respect to their standard position in the LHC, but respecting these two constraints. Various concepts of connection cryostat were studied in detail, allowing independent alignment and minimizing work in-situ. Because of the short distance between the heat exchanger pipe and the beam lines, a specific collimator design is required. The collimator will have its supports anchored directly to the floor so that its precise alignment will be decoupled from the cryostats and, therefore, deformations resulting from pumping down of the insulation vacuum.

The MBH cryostats and cold masses will follow the same design principles as the standard MB, with the exception that the diameter of the cold mass extremities facing the collimator must be locally increased in order to accommodate bus bar flexible elements and to allow straight routing of the bus bar lines across the connection cryostat.

The interconnects between the MBH cold masses and the connection cryostats are shorter than nominal but designed with standard LHC interconnect components for most of the parts, thus capitalizing on proven design and assembly methods.

B. Beam dynamics studies

The characteristics of the MBH have several implications for the operation of the LHC, which need to be mitigated with appropriate measures. First, the MBH was not designed to be fabricated in a bent shape because of the brittleness of Nb_3Sn after reaction, and second, although the aperture of the MBH is 60 mm for historical reason, it will be equipped with the same cold bore tube and beam screen as the present curved dipole to facilitate integration. Therefore, the mechanical aperture available to the beam is reduced by at least half the value of the sagitta, i.e. about 0.8 mm. To mitigate this, the two 5.5 m long straight cold masses 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 LHC. This will minimize the aperture loss, and also feed-down effects.

Aperture restrictions are critical at injection energy when the beam is large, as well as at collision energy, when debris trajectories have large excursions in the experimental areas. First results [29] show that the use of the nominal beam screen, although reducing the aperture, would not introduce new aperture bottlenecks. Nevertheless, a refined assessment is needed once the review of the beam tolerances used for aperture margin calculations has been completed [30].

Since the MBHs will be powered in series with the MBs, any difference of TF between the two classes of dipoles will induce a deformation of the beam closed orbit. Such a deformation will need to be corrected either by dedicated trim power converters applied to MBHs, or by means of the standard orbit correctors in the LHC lattice [12], [31]. The correction of the TF with a trim circuit is currently the preferred option as it would allow keeping the operation margin of the orbit correctors. As far as the field quality is concerned, persistent current effects are expected to be stronger than in MBs, e.g. ~20 units for b_3 at nominal current, leading to strong components that may affect the long term stability of particle dynamics at injection energy [32]. A review of the need for local spool pieces will be carried out in the near future.

V. Conclusions

The development of the MBH for the upcoming upgrade of the LHC collimation system has well advanced with the completion of several models at FNAL, and a practice model at CERN, which have shown promising performance. While the production of the short magnets continues in the two laboratories in order to learn further on the performance parameters and to refine the design, the preparation of the tooling for the long MBH has started at CERN with a plan to test the first prototype in the end of 2016. A conceptual design of integration satisfying all operation and installation requirements is available.

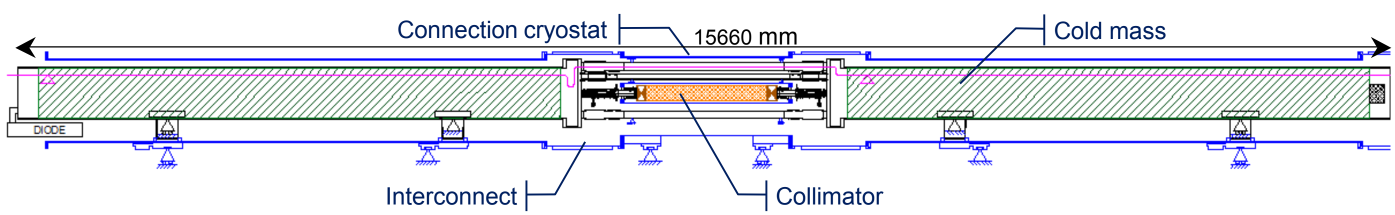

Fig. 5. Integration layout of the collimator and two MBH magnets.

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