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Status and challenges of the interaction region magnets for HL-LHC

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***Abstract*—About one hundred magnets of six different types shall be installed in the High Luminosity LHC (HL-LHC) in the years 2026-2028 at CERN. The magnets design, construction and test are based on CERN collaborations with institutes and industrial partners in USA, Spain, Italy, Japan and China. Three types of correctors are based on Nb–Ti technology and feature conductor peak fields in the 2 to 4 T range: for all of them the protoype phase has been successfully completed. The production is well advanced for the superferric correctors, and is starting for the canted cosine theta correctors and for the nested correctors. The separation and recombination Nb–Ti dipoles D1 and D2, with a 4.5-6 T bore field range, are both in the prototype phase after the completion of the short model program. The most challenging magnet, the Nb_3Sn quadrupole with conductor peak field above 11 T, is in the prototype phase at CERN and halfway through the production phase in the USA. In this paper we will give, for each type of magnet, an overview of the main achievements obtained so far and we will outline the technical points still needing validation from the prototype program.**

***Index Terms*—Superconducting magnets, accelerator magnets**

I. INTRODUCTION: HL-LHC MAGNETS AND REQUIREMENTS

THE HL-LHC project [1] aims at replacing the LHC interaction regions magnets around ATLAS and CMS with larger aperture magnets, allowing to reduce the beam size in the experiments, and thus increasing the luminosity. Six types of magnets are required: three main magnets and three correctors [2,3]. This flagship project of CERN is carried out in collaboration with 9 institutes in 6 states, has been approved in 2015 and will be commissioned in 2029. HL-LHC will install the first Nb_3Sn magnets in a hadron collider, namely the triplet quadrupoles built by US-AUP [4] and by CERN [5]. These magnets operate with a conductor peak field of 11.3 T [6], and are 4.2/7.2 m long, providing a significant step in scaling Nb_3Sn technology towards 15-m-long accelerator magnets as required for a possible Future Hadron Collider.

KEK and INFN-Genova provide the Nb-Ti based separation and recombination dipoles [7,8], and the three types of correctors are manufactured under the helm of CIEMAT, IHEP and INFN-LASA [9,10,11]. Each magnet type has to be produced in mini-series (6 to 50 magnets): this poses special challenges to the timeline of corrective actions. The salient parameters of the main HL-LHC magnets are given in Table I. In [2] we gave an extensive description of the design principles and of the results of short models and first prototypes. Here, we give an update of the status of the project, pointing out the main achievements in the past two years and the main challenges.

TABLE I
HL-LHC MAIN MAGNET PARAMETERS

Parameters	MQXFA	MQXFB	D1	D2
Technology	Nb_3Sn		Nb-Ti	Nb-Ti
Aperture (mm)	150		150	105
Field/gradient	132.2		5.6	4.5
Conductor peak field (T)	11.3		6.6	5.3
Prototypes	2	3	1	1
To be installed/spares	16/4	8/2	4/2	4/2
Magnetic length (m)	4.21	7.17	6.23	7.88
Nominal current (kA)	16.23		12.11	12.32
Overall j (A/mm^2)*	462		452	478
Loadline fraction**	0.78		0.77	0.68
Accumulated stress***	110		100	60

* Current density over insulated cable
**Ratio between nominal current and short sample current
***Peak accumulated stress in the midplane, analytical estimate

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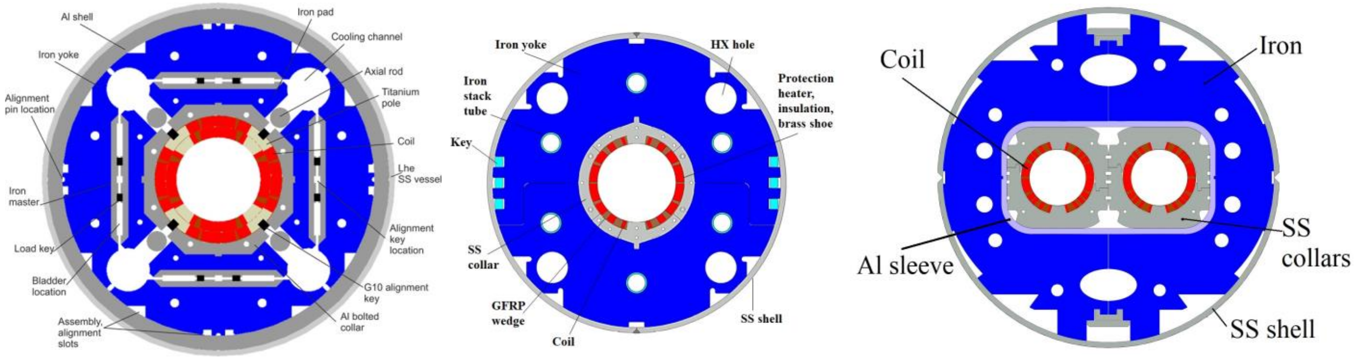

Fig. 1. Cross-section of the MQXF quadrupole, D1and D2

II. Outlook on requirements

The magnet nominal currents are defined for 7 TeV beam energy. The requirement on all Nb_3Sn magnets is to achieve 300 A higher than nominal current at 1.9 K. Nb_3Sn are also tested systematically at 4.5 K to verify the temperature margin. Note that when operating at ultimate luminosity the maximum temperature in the MQXF coil is 2.25 K [12]. Reaching ultimate current (corresponding to 7.5 TeV) is required for the Nb-Ti magnets (D1, D2 and correctors). For all magnet types there is no condition on the virgin training, i.e. on the number of quenches needed during the first powering. A maximum of three (one) quenches to reach nominal current is required for Nb_3Sn (Nb-Ti) main magnets after thermal cycle. A maximum of one quench is required to reach ultimate current for correctors after the first thermal cycle. Field quality requirements are set on the main magnets (MQXF, D1 and D2) only at 7 TeV, with integrated values of the order of few units for low order and one unit for high order multipoles.

III. The Nb_3Sn quadrupole magnets

A. Short model program

The MQXF design is described in [6]; six short model quadrupoles were built and tested [3]. Five of them reached ultimate current and beyond; only one (MQXFS3) failed to reach nominal current, with a reverse behaviour, i.e. higher currents reached for higher temperatures and higher ramp rates. Note that all short models used “virgin coils” with the exception of MQXFS6, reusing two coils from MQXFS5: a total of 25 coils were assembled in magnets and tested, with 18 of them reaching target performance, and 3 of them limiting the magnet performance.

The short model program proved the potential of this design for: (i) operation at ultimate current, (ii) no retraining to nominal current after thermal cycle, (iii) operation at nominal current at 4.5 K, implying a temperature margin larger than 2.6 K and (iv) good reproducibility (5 conforming magnets out of 6). Four magnets reached a conductor peak field 1.5 T above nominal powering (i.e., >12.8 T), with a record of 13.4 T in MQXFS4. The short magnet program successfully used two types of conductors (RRP, which is the project baseline [13], and PIT [14]).

The stainless steel shell integration around the magnet was validated in MQXFS1 and MQXFS7 [5]. A low preload experiment has been done on MQXFS6: the coil has been prestressed at a level corresponding to 50% of electromagnetic forces at nominal current, rather than 100% as in the baseline: the magnet reached ultimate current, but lost about 1 kA of margin, Fig. 2. Endurance tests were succesfully performed on several short models, see III.E.

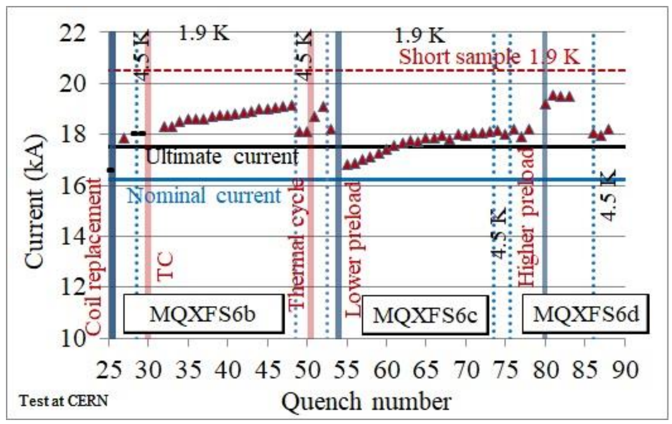

Fig. 2. Preload experiment in MQXFS6

B. MQXFA quench performance

Out of the 9 full-length magnets (including two prototypes) that have been completed, 8 have been tested in vertical configuration [4] and 6 have reached the required performance (03-06, 10, 11). A summary of the quench performance of the 6 conform magnets is given in Fig. 3.

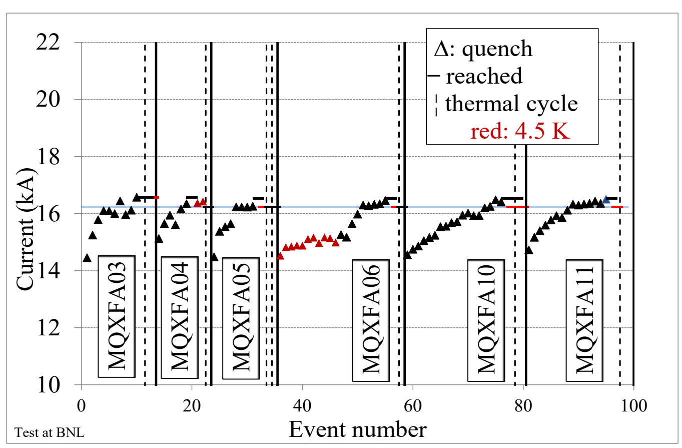

Fig. 3. Quench performance of MQXF03-06 and 10-11

The first prototype was powered up to 1 kA more than nominal current, and series magnets were powered up to nominal current plus 300 A. Power tests confirm the following short model features: (i) operation at nominal current plus 300 A, (ii) no retraining after thermal cycle, (iii) operation at nominal current at 4.5 K. Note that in MQXFA06 a virgin training at 4.5 K was performed; a very slow training rate was found, and the magnet eventually reached requirements at 1.9 K.

C. *MQXFA performance limitations*

The two prototypes failed to meet the requirements, with a good understanding of the reasons [3,4,15]; it should be noted that the first prototype reached 17 kA before electrical damage. However, a second assembly of the first prototype did not met the requirements, with a reverse behaviour similar to MQXFS3, and with a lack of understanding of the performance limitations. After the successful performance of four consecutive magnets, MQXFA03-06, MQXFA07 (see Fig. 4) and MQXFA08 failed to reach performance with a reverse behaviour, similar to what observed in MQXFS3 and MQXFAP1b. Analysis based on mechanical data and quench localization indicated an asymmetry in the assembled coil pack, producing during powering a local damage of the strands in the transition from the straight part to the end. This was confirmed by the metallography of the limiting coils [4,16], showing longitudinally broken filaments (see Fig. 5). The assembly procedure was reviewed to reduce the assembly asymmetries, pointing out also a negative side effect of procedure modifications induced by Covid-19 restrictions, and the performance of the next magnet MQXFA10 has been conforming.

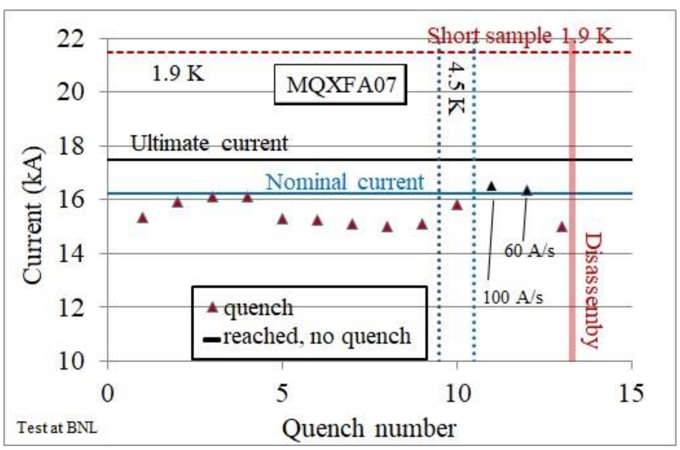

Fig. 4. Performance limitation of MQXFA07

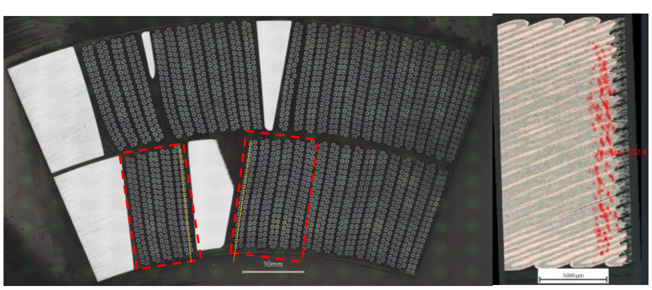

Fig. 5. Location of broken filaments in the limiting coil of MQXFA07

D. *MQXFB performance limitations*

The first two MQXFB full-length prototypes showed a performance limitation at 70% and 74% of short sample respectively, both at 1.9 K and at 4.5 K (see Fig. 6). Quench location was in the center of the magnet, inner layer pole turns, with a 20 m/s quench velocity indicating a local damage [5,17]. MQXFBP1 was disassembled and the metallography of the limiting coil showed presence of broken filaments in the strand at the corner of the pole inner turn (see Fig. 7), with several breakages along the magnet axis, close to the transition of the Ti poles (see [5,16] for a deeper discussion).

The third prototype reached nominal current plus 300 A, but at 4.5 K showed a limitation at 15.8 kA, just 500 A below nominal, with the same patterns of MQXFBP1 and MQXFBP2. The extrapolation of this quench provides a estimate of 2 K temperature margin. An outlook of the origins of this limitation and of the corrective actions is discussed in section II.F and in [5].

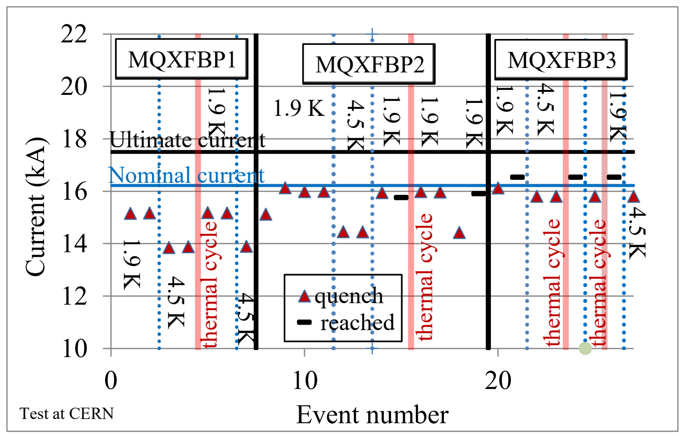

Fig. 6. Quench performance in MQXFBP1, MQXFBP2 and MQFBP3.

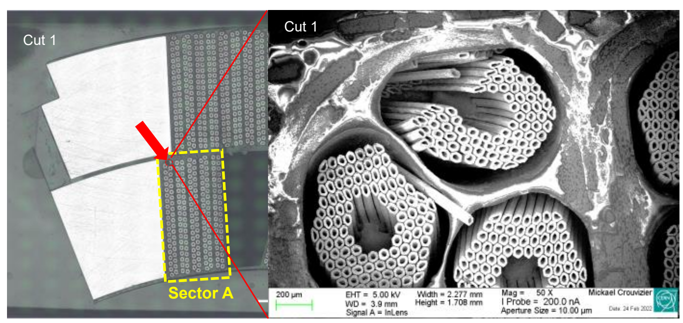

Fig. 7. Broken filaments in the limiting coil of MQXFBP1

E. *Endurance tests*

Endurance tests have been carried out to assess the reliability of the quadrupole magnets due to the stresses induced by thermal cycles (≤4 expected during in HL-LHC lifetime, excluding the first cool-down), quenches at nominal current (<50), and powering cycles (<10000). These tests acquired particular relevance after the results of the 11 T program, which was put on hold after a performance degradation observed after successive thermal cycles [18]. The first short model MQXFS1 went through five thermal cycles and 200 quenches, without evidence of degradation [3]. Short model MQXFS4 went through 7 thermal cycles at CERN, always reaching ultimate current at

1.9 K without retraining. MQXFS6 (see Fig. 2) went through a coil replacement and a change of preload, for a total of 6 thermal cycles, also showing no degradation.

MQXFA05 has been the first 4.2-m-long magnet to undergo an endurance test (see Fig. 8) involving 4 thermal cycles, 7 training quenches and 43 provoked quenches at nominal current. At the end of the test, the magnet reached the target current of 16.53 kA at 1.9 K and the nominal current of 16.23 kA at 4.5 K, showing no degradation [5]. Note that as for all the MQXFA magnets tested so far, results refer to a vertical test without the stainless steel shell which provides the LHe containment [5].

The 7.17-m-long magnet MQXFBP2 went through 50 quenches during the powering tests needed to better assess the performance limitations, and one thermal cycle, without showing signs of degradation of the observed performance limitation. The third prototype MQXFBP3 went through two thermal cycles, also confirming the absence of degradation of the limitation. All MQXFB magnets were tested horizontally, in the stainless steel shell.

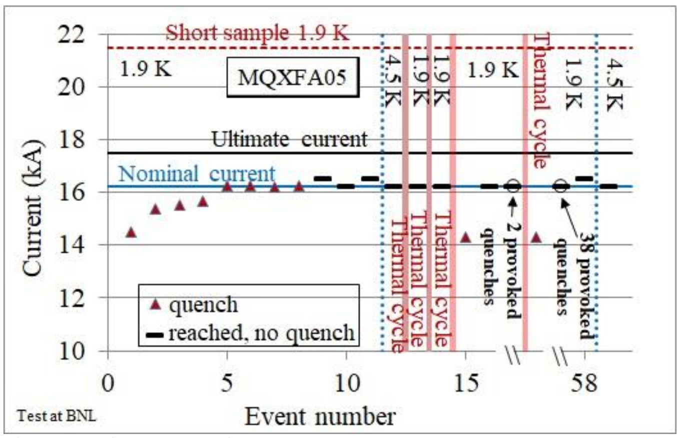

Fig. 8. Endurance test of MQXFA05.

F. *Coil fabrication, magnet and cold mass assembly*

After the test of MQXFBP2 in April 2021, three possible sources of performance limitation were identified: (i) issues in the coil manufacturing (ii) an excess of preload in the magnet assembly (iii) an issue related to the integration of the magnet in the LHe vessel. The three were addressed in reverse order, as described in the following paragraphs.

Integration in LHe vessel: MQXFB was the first magnet based on a bladder and key structure to be integrated in a stainless steel shell, used as LHe vessel; in fact, the development of the LARP magnets was based on tests in vertical cryostats. The first two MQXFB prototypes were integrated in the LHe vessel with a mechanical coupling present also at 1.9 K. MQXFBP3 included revised welding procedures, guaranteeing no mechanical interference of the magnet with the LHe vesssel at 1.9 K, and also in the initial phases of the cool-down. This change required the inclusion of a fixed point to anchor the magnet to the LHe vessel to avoid movements under the pressure waves induced during operation. The AUP first cold mass, integrating MQXFA03 and MQXFA04, also implemented this change; tested is expected in late 2022.

Peak stress during assembly: the MQXF target preload at 1.9 K was set in the short model program at 110 MPa, to have the coils under compression up to nominal current. To fulfil this condition, a 80±8 MPa target at room temperature was set for MQXFA, with a specified maximum peak stress <110 MPa during loading at room temperature; this strategy was used for the 11 magnets assembled until now. The three prototypes of MQXFB achieved the same preload targets at 1.9 K with a higher peak stress during assembly (up to 140 MPa), as did most of the short models [5]. A new procedure, implemented in MQXFB02, allowed to achieve the loading targets at 1.9 K with a peak stress lower than 80 MPa: this is a significant step in the scaling of bladder and key structures towards 15-m-long magnets. The magnet will be tested at the end of 2022. AUP is considering weather using this revised assembly procedure.

Coil manufacturing: After the performance limitation seen in MQXFBP1 and MQXFBP2, in April 2021 the coil production has been put on hold to review all data, and take corrective actions if needed. Back then, the first series magnet MQXFB01 (later renamed MQXFBP3) was already assembled, and the coils of the second MQXFB02 were ready for magnet assembly: one third of the MQXFB coils were produced, putting the project in a fragile situation. The result of 18 months of extensive analysis of coil manufacturing are treated in [5]. Here we point out to the main findings: (i) the presence of broken filaments (but with much less intensity than in the limiting coil of MQXFBP1) also in one coil that was not assembled and never tested, (ii) an azimuthal coil size systematically ~0.2 mm larger in the central part of the coil, where the quenches of the prototypes are observed (not seen in AUP coils, where the spread of coil size is ±0.1 mm and there are no systematic patterns along the magnet length), (iii) a ~2 mm upward movement of the coil pole when opening the reaction mould (~0.7 mm measured in AUP coils). At the moment of writing, we cannot state if the presence of broken filaments takes place only during coil manufacturing, or if it was produced or enhanced by the coupling with the LHe vessel and/or an excess of preload. Efforts are ongoing to address and cure this feature of MQXFB coils.

G. *Protection and flux jumps*

Due to the higher efficiency of coil design, the protection of the triplet poses a special challenge with respect to previous magnets based on Nb-Ti: the energy density in the coil (stored energy divided by the volume of the insulated coil) is of about 0.1 J/mm^3, versus 0.05 J/mm^3 in the main LHC dipoles. This requires the ability of quenching the whole coil within 50 ms, rather than 100-200 ms as in the main LHC dipoles [3].

Initial studies for the protection of a two-layer Nb_3Sn quadrupole showed that outer layer quench heaters were not enough to guarantee protection in case of failures. In 2015, a novel protection system based on Coupling Losses Induced Quench (CLIQ) [18] was proposed at CERN and has been adopted as a baseline of HL-LHC in 2017. CLIQ and outer layer quench heaters guarantee a maximum hotspot temperature of 270 K.

Failure scenarios (failure of two quench heater circuits, or of one quench heater circuit and CLIQ) guarantee a maximum hotspot of 350 K; these conditions have been experimentally proven during the tests of several short models: Long MQXFB prototypes are tested in the nominal configuration, i.e., without dump resistor; moreover in some special cases protection without CLIQ was successfully used, validating the one failure scenario. So far, MQXFA magnets have been tested vertical always with a 50 mΩ dump resistor; validation of the nominal protection scheme will be done during horizontal test.

Flux jumps are a new challenge introduced by the use of Nb_3Sn. They provoke voltage spikes that can be well above the usual detection thresholds (100 mV) in the intermediate range of currents. Even though the experience on short models proved that flux jumps can be bypassed via the use of current dependent thresholds, special concern was on the behaviour of longer magnets. Experience on the three 7-m-long MQXFB prototypes show that in the more difficult range, i.e. 3 to 8 kA, protection can be ensured by two thresholds, a short one of 300 mV for 50 ms, together with a long one of 400 mV for 30 ms. At nominal current, and in general above 12 kA, the thresholds used are 100 mV for 5 ms, and 150 mV for 3 ms.

H. Field quality

A +4 units correction of b_6 was successfully carried out in after MQXFA03 and MQXFBP1, via removal of a 0.125 mm shim from the midplane and the addition on the pole. The MQXFA magnets built with the same cross-section (after MQXFA03) have a maximum spread of 0.5% on the integrated gradient, in line with the requirements. The three MQXFB prototypes build so far have an integrated transfer function within a range of 20 units, also in line with requirements. Integral values of the non-allowed multipoles are in line with the requirements for MQXFB; for MQXFA non-zero systematic values for even skew multipoles are observed, above the acceptance ranges (see Fig. 9). Magnetic shimming has been used in half of the magnets to reduce non allowed multipoles.

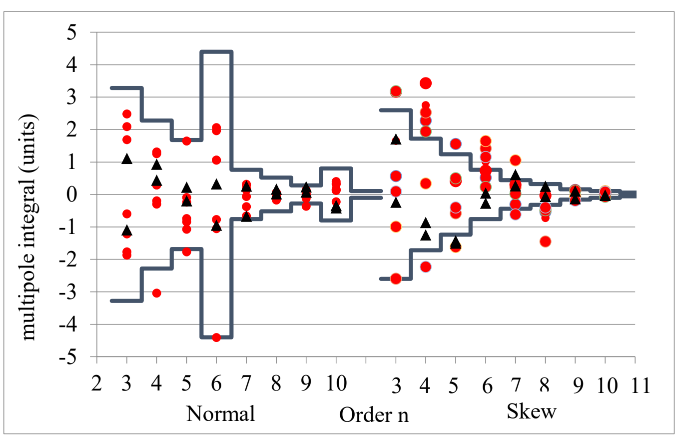

Fig. 9. Integral multipoles of 7 MQXFA (dots) and 2 MQXFB (triangles) versus requirements (line).

IV. THE SEPARATION DIPOLE D1

The separation dipole D1 provides a nominal field of 5.6 T over a 6.23 m length, with a single layer coil based on the LHC main dipole outer layer cable (see Fig. 1 and Table I). The main challenge of this magnet is the 100 MPa midplane stress created by the accumulation of electromagnetic forces [3,7]; this value is close to the midplane stress in MQXF, or in the 11 T HL-LHC dipole [3];. A full preload for nominal current is provided by a mechanical structure based on horizontally split iron, similar to what developed for MQXA or for the combined function magnets of J-PARC [20].

A short model program based on three 1.5-m-long magnets was used to validate the design principles [7]. A full size prototype was manufactured in Hitachi and tested vertically at KEK: it reached nominal current with 3 quenches, but the training was stopped due to time constraints in the test station (see Fig. 10).

After the thermal cycle, three quenches were needed to reach nominal current, possibly due to an insufficient level of training in the virgin cycle. In the second cycle, the magnet reached 800 A above nominal current [20]; training was then stopped due to limits related to the test station. A test station upgrade is ongoing, to allow training series magnets up to ultimate current. Production of the coils for the series magnet started in summer 2022, with the completion of four coils at the moment of writing. The series magnet will include a third fine tuning of field quality to further reduce the systematic values of b_3 and b_5 from 5 units to about zero [21].

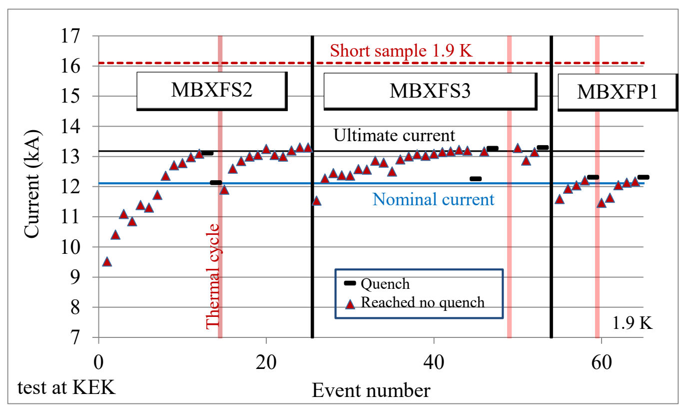

Fig. 10. Power test of short models MBXFS2 and MBXFS3 and prototype MBXFP1 (different magnets separated by black lines), all data at 1.9 K.

V. THE RECOMBINATION DIPOLE D2

The recombination dipole D2 provides a nominal field of 4.5 T over a 7.9 m length, with a single layer coil based on the LHC main dipole outer layer cable as for the D1 (see Table I and Fig. 1). Magnet manufacturing has been assigned to ASG, followed-up by INFN-Genova, where a 3-m-long magnet with similar parameters for SIS-300 was manufactured in 2015 [22]. The main challenge of D2 is the magnetic cross-talk between the two apertures, requiring a ~1 mm left-right asymmetry in the coil geometry to compensate for this effect [3,8,23].

A double aperture short model was first developed: the most critical element was the region with the cable exit on the coil pole, where iterations on the design were required. The model reached ultimate current, but showed a long retraining of one aperture, possibly related to an issue to the cable exit (see Fig. 11). The full size prototype reached nominal current without quench, and ultimate current with one quench. At 4.5 K, the magnet reached ~95% of short sample current.

The asymmetric coil of D2 proved to comply with the stringent field quality requirements: in particular, the 200 units present in the single aperture are reduced to few units after assembly of the two apertures in the yoke (see Table II, where the limited precision of the measurements is related to the use of a mole conceived for LHC dipoles, with a 40 mm diameter). This proof of principle can be of special interest for a combined function dipole for FCC or for HE-LHC [24], where the cell quadrupole is spread over the length of the dipoles, as a b_2 of ~200 units.

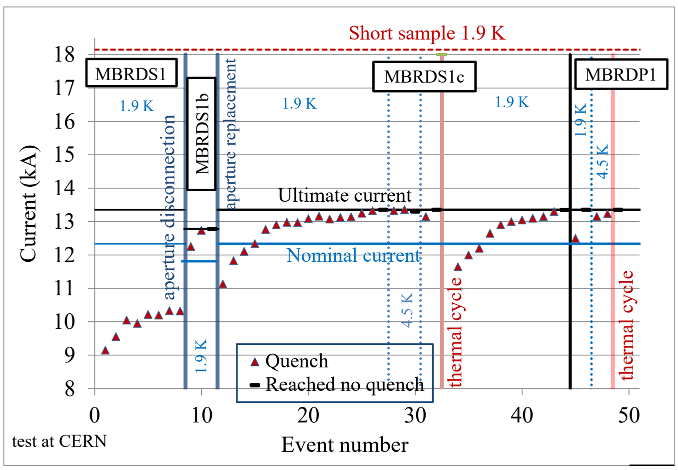

Fig. 11. Power test of D2 short model and D2 prototype.

TABLE II
D2 PROTOTYPE INTEGRAL FIELD HARMONICS AT R_{REF}=35 MM AT NOMINAL CURRENT

	Ap.1	Ap.2		Ap.1	Ap.2
b2	-0.3	-2.4	a2	5.7	1.1
b3	9.7	11.0	a3	4.6	1.5
b4	-0.1	-0.8	a4	-0.9	-0.6
b5	9.6	10.1	a5	2.3	1.0
b6	-1.5	1.4	a6	-0.4	-0.3
b7	1.5	2.2	a7	1.8	0.0

VI. THE NESTED CORRECTORS

Three orbit correctors placed close to the triplet quadrupoles provide up to 2.1 T dipolar field both in horizontal and vertical direction, giving rise to a torque of 140 kN·m/m. [3,9,25]. Two versions are needed: a 1.5-m-long magnet to be installed in each cold mass of the Q2a/b magnets, and a 2.5-m-long magnet in the corrector package cold mass. The design relies on a nested collared structure, where the outer collars are locked, in the straight part, on the inner collars; coils are made by two layers of 4.5-mm-width Nb-Ti cable. This design provides a stress-managed magnet that allows to independently preload each dipole up to the level required by the electromagnetic forces (see Fig. 12). The stainless steel collars provide a 40 MPa preload at 1.9 K, required to keep the coil under compression in all conditions of powering. To achieve this target, due to the large loss of preload during cool-down, up to 120 MPa peak stress during collaring has to be reached.

The first two prototypes of the short nested corrector MCBXFB were built at CIEMAT and assembled at CERN. Both magnets reached nominal current in both planes simultaneously, with order of 50 quenches, but the same amount of training was needed each time the torque sign was changed. An iteration on the design was made, namely a reduction of the length of the inner dipole to reduce the torque in the ends where the mechanical lock is not available, and an extension of the legs of the end spacers inside the straight part [25]. Changes were implemented on a third magnet, also made at CIEMAT and assembled at CERN; the magnet reached the whole operational space and required no retraining after thermal cycle, independently of the sign of the torque.

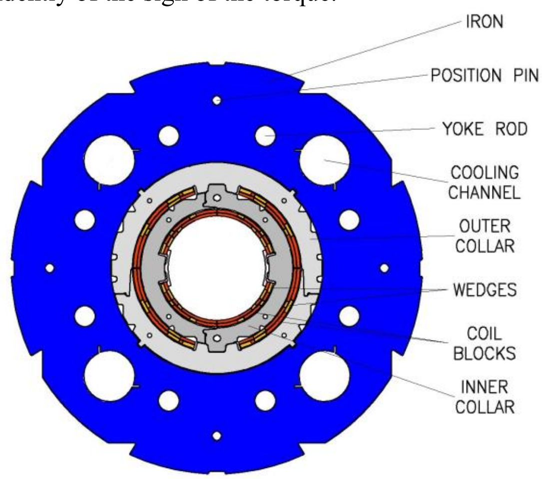

Fig. 12. Cross-section of the MCBXF nested corrector.

The contract for industrial production of 11 “short” and 6 “long” nested correctors was assigned to Elytt: the first coils of the inner short dipole were retrofitted to the second prototype, which thanks to this modification reached the performance requirements. This additional test allowed to validate the first coils industrially produced, and to verify the reproducibility of the performance following the design change.

VII. THE CANTED COSINE THETA CORRECTOR

The orbit correctors installed in the D2 cold mass are double aperture magnets, with 105 mm aperture as D2, 2.8 T nominal field over 1.8 m, giving 5 T m integrated field. Two correctors are needed for D2, bending the protons in horizontal and vertical direction. The magnet is based on a canted cosine theta design [3,26,27], with a winding of ten 0.825-mm diameter strands in a groove machined in a Al former. The magnet operates at 50% of the short sample current, a wide margin as for all the HL-LHC corrector magnets. The design was developed at CERN, where three double aperture prototypes were manufactured and successfully tested. The 12 magnets required for installation and spares are in-kind contribution of China steered by IHEP, Beijing. A short model was independently developed by IHEP in WST, and a double aperture prototype with the same design as CERN was successful built by WST and tested in IMP, China. All prototypes reach ultimate current with few quenches per aperture, with the exception of one aperture built at CERN, requiring about 30 quenches. All prototypes, including the slow trainer aperture, showed no retraining after thermal cycle.

Production was awarded to BAMA in 2020. The first two series magnets were affected by a long training (see Fig. 13, where the training of each aperture is shown, coils CB02 to CB06); this problem has been cured by reducing the size of the groove of the former and by improving the impregnation procedures (coil CB09 in Fig. 13).

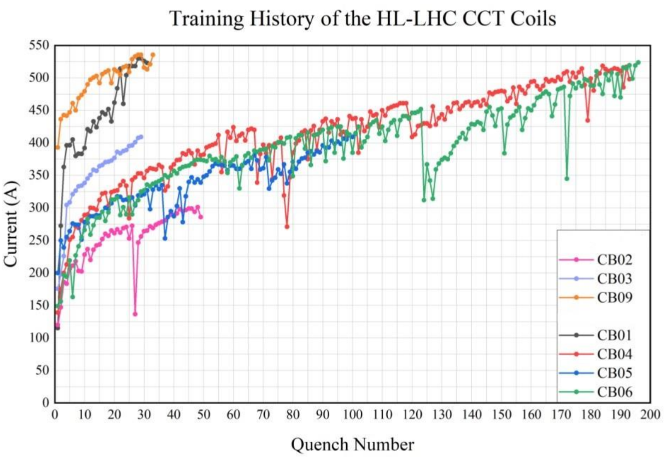

Fig. 13. Training of individual series coils tested in IMP.

VIII. The high order correctors

High order correctors are superferric magnets, with Nb-Ti windings providing the field shaped by the iron poles: coil peak field is in the 2-3 T range [3,28]. Production of the high order correctors has been completed at the end of 2021. Two thirds of the magnets have been accepted after power test in LASA at 4.5 K. The test of the last batch will take place at the end of 2022. All magnets met requirements with few quenches in virgin conditions, with the exception of the skew quadrupoles that needed order of 30 quenches to reach ultimate current. However, retraining requirements were met in all cases. An iteration has been done on the design of the connector PCB (encapsulation to improve insulation) and on the mechanical assembly procedures of the coils in the yoke (supports of the coil that were found to be loose after cool-down in a few magnets).

INFN-LASA also developed, in the framework of the HL-LHC project, an alternative design based on round coil superferric magnet [29] (see Fig. 14). This design, first proposed in the 60's [30] and then further developed in the 10's [31], was not retained for HL-LHC due to its 50% lower efficiency, that would have required a 3 m longer corrector package, to be compensated by 5% stronger D1 and D2. The attractiveness of this option relies on having the same round coil for all correctors, the shape of the field being given by the iron; moreover, the lower curvature radius allows using MgB_2 conductor. A first prototype module was manufactured in LASA in 2018, and a second one (needed to cancel the transverse field) was completed in 2022. Both modules had quenches at 230 A, i.e. 50% above the operational current of 149 A, and reached 70% of the short sample current [32], with a peak field on the conductor of 1.8 T.

Fig. 12. The round coil superferric magnet based on MgB_2 coil: single module (left) and double module tested in 2022 (right).

IX. Conclusion

The six types of HL-LHC interaction region magnets are completing the prototype phase, or advancing in the production. Half of the Nb_3Sn quadrupoles built in the US (MQXFA) have been completed: the quadrupoles reached the performance requirements with wide margins and absence of retraining; endurance tests were successfully concluded on a full length magnet. The main present challenge is the performance reproducibility: two magnets failed to reach requirements, but the issue has been identified and corrective actions proved to be effective. Integration of the two magnets in LHe vessel has not yet been proved.

For the longer quadrupole MQXFB, manufactured at CERN, the three prototypes showed the same performance limitation, at increasing values of current; the third prototype was be able to operate at nominal current. The phenomenology of this limitation has been clarified, and efforts are ongoing to eliminate or mitigate this issue. MQXFB allowed validating for the first time the integration of a magnet based on Al rings structure in a LHe vessel, and the protection strategy based on CLIQ and quench heaters. Field quality is in line with requirements and does not pose significant issues.

After the successful conclusion of the short model phase, a prototype of the D1 magnet has been built and vertical test has given positive results, which need to be confirmed in the horizontal test of the cold mass. The D2 prototype has reached the performance requirements, showing that the issues seen in the short model have been correctly addressed. Both D1 and D2 went through iterations to center the narrow acceptance range for b_3 and b_5. The first D1 and D2 series magnets, whose coils have already been completed, will confirm the validity of these iterations, particularly challenging due to the short series.

Two nested correctors proved to reach the performance requirements, after one iteration on the design carried out on the prototypes. The third D2 correctors produced in the industry also reached performance after an iteration on design and procedures. The high order corrector production is completed and acceptance tests are ongoing smoothly.

REFERENCES

[1] O. Bruning, et al, “High Luminosity Large Hadron Collider – Technical Design Report” CERN 2020-010

[2] E. Todesco, et al., "A first baseline for the magnets in the high luminosity LHC insertion regions" IEEE Trans. Appl. Supercond. 24 (2014) 4003305

[3] E. Todesco, et al., “The HL-LHC interaction region magnets towards series production”, *Supercond. Sci. Technol.* **34** (2021) 053001

[4] G. Ambrosio, et al., “Challenges and Lessons Learned from fabrication, test and analysis of 10 MQXFA Low Beta Quadrupoles for HL-LHC” *IEEE. Trans. Appl. Supercond.* **23** (2023) to be published.

[5] S. Izquierdo Bermudez, et al., “Status of the MQXFB Nb3Sn quadrupoles for HL-LHC “ *IEEE. Trans. Appl. Supercond.* **33** (2023) to be published.

[6] P. Ferracin, et al., “Development of MQXF: the Nb3Sn low-beta quadrupole for the HiLumi LHC” *IEEE. Trans. Appl. Supercond.* **26** (2016) 4000207.

[7] M. Sugano, et al., "Development of 2 m model magnet of the beam separation dipole with new iron cross-section for the high luminosity LHC upgrade" *IEEE Trans. Appl. Supercond.* **29** (2019) 4003607

[8] S. Farinon, et al., "The design of superconducting separation dipoles D2 for the High Luminosity Upgrade of LHC" *IEEE Trans. Appl. Supercond.* **26** (2016) 4001504

[9] C. Martins, et al., “First short orbit nested corrector magnet for HL-LHC produced in the industry” *IEEE. Trans. Appl. Supercond.* **33** (2023) to be published.

[10] G. Kirby, et al., "Hi-Lumi LHC twin aperture orbit correctors magnet system optimisation" *IEEE Trans. Appl. Supercond.* **27** (2017) 4002805

[11] M. Statera, et al., “Experience on Series Production of the HL-LHC Superferric High Order Corrector Magnets” *IEEE. Trans. Appl. Supercond.* **23** (2023) to be published.

[12] P. Borges de Sousa, et al., “Numerical assessment of the inhomogeneous temperature field and the quality of heat extraction of Nb_3Sn impregnated magnets for the High Luminosity upgrade of the LHC” *IEEE. Trans. Appl. Supercond.* **33** (2023) to be published.

[13] L. Cooley, “Challenges and Opportunities to Assure Future Manufacturing of Magnet Conductors” *IEEE. Trans. Appl. Supercond.* **33** (2023) to be published.

[14] B. Bordini, et al., “The bundle-barrier PIT wire developed for the HiLumi project” *IEEE. Trans. Appl. Supercond.* **27** (2017) 6000706.

[15] J. Muratore, et al., "Test results of the first two full-length prototype quadrupole magnets for the LHC Hi-Lumi upgrade" *IEEE Trans. Appl. Supercond.* **30** (2020) 4004205

[16] S. Sgobba, et al., “Advanced Examination of Nb3Sn Coils and Conductors for the LHC luminosity upgrade: Computed Tomography and Materialographic Analyses” *IEEE. Trans. Appl. Supercond.* **33** (2023) to be published.

[17] F. Mangiarotti, et al., “Power test of the first two HL-LHC insertion quadrupole magnets built at CERN” ” *IEEE. Trans. Appl. Supercond.* **32** (2022) 4003305.

[18] G. Willering, private communication.

[19] E. Ravaioli, et al., "New coupling loss induced quench protection system for superconducting accelerator magnets" *IEEE Trans. Appl. Supercond.* **24** (2014) 0500905

[20] T. Ogitsu, et al., "Superconducting combined function magnet system for J-PARC neutrino experiment" *IEEE Trans. Appl. Supercond.* **15** (2005) 1175-1180

[21] K. Suzuki, et al., "Magnetic field design of a full-scale prototype of the HL.LHC beam separation dipole with geometrical and iron-saturation corrections" *IEEE Trans. Appl. Supercond.* **30** (2020) 4002706

[22] M. Sorbi, et al. 2008 IEEE Transactions on Applied Superconductivity **18** 138-141

[23] S. Farinon, et al., “ The MBRD dipoles for the High Luminosity LHC: from the prototype tests to the beginning of the series production” *IEEE. Trans. Appl. Supercond.* **23** (2023) to be published.

[24] M. Giovannozzi, et al. “Combined-function optics for circular high-energy hadron colliders” *Eur. Phys. J. Plus* **137** (2022) 361

[25] F. Toral, et al., “Experience on Series Production of the HL-LHC Superferric High Order Corrector Magnets” *IEEE. Trans. Appl. Supercond.* **23** (2023) to be published.

[26] D. I. Mayer and R. Flasck “A new configuration for a dipole magnet for use in high energy physics applications” *Nucl. Instrum. Meth.* **80** (1970) 339

[27] G. Kirby, et al., "Hi-Lumi LHC twin aperture orbit correctors magnet system optimisation" *IEEE Trans. Appl. Supercond.* **27** (2017) 4002805

[28] P. Fabbricatore, et al., “Development of a curved fast ramped dipole for FAIR SIS300” *IEEE Trans. Appl. Supercond.* **18** (2008) 232-235

[29] S. Mariotto, et al. “Study of a sextupole round coil superferric magnet prototype at LASA” *IEEE Trans. Appl. Supercond.* **28** (2018) 4003305

[30] I. F. Malyshev, U. S. Patent 1698 890/26-25, Oct. 12 1973

[31] V. Kashikhin “A novel design of iron dominated superconducting multipole magnets with circular coils” *IEEE Trans. Appl. Supercond.* **20** (2010) 196-200

[32] S. Mariotto, “Performances of the first full-length module prototype of the MgB2 round coil superferric magnet at LASA” *IEEE. Trans. Appl. Supercond.* **33** (2023) to be published.