

US CONTRIBUTION TO THE HIGH LUMINOSITY LHC UPGRADE: FOCUSING QUADRUPOLES AND CRAB CAVITIES

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Abstract

In the early 2000's, the US High Energy Physics community contributing to the Large Hadron Collider (LHC) launched the LHC Accelerator R&D Program (LARP), a long-vision focused R&D program, intended contribute to a quick LHC commissioning and to bring the Nb₃Sn and other technologies to a maturity level that would allow applications in HEP machines [1-2]. Around 2015, the technologies developed by LARP, CERN and other institutions were mature enough to allow the spin-off of a major upgrade project to the LHC complex, the High Luminosity LHC (HL-LHC) [3]. This paper will focus on the US contribution to HL-LHC, namely the large-aperture low-β focusing Nb₃Sn quadrupoles and the Radio Frequency Dipole (RFD) Crab Cavities, located in close proximity to the ATLAS and CMS experiments.

This contribution, called the HL-LHC Accelerator Upgrade Project (HL-LHC AUP), focuses on production of these quadrupoles and cavities by sharing the work among a consortium of US Laboratories (FNAL, LBNL, BNL and SLAC) and Universities and in close connection with the CERN-led HL-LHC Collaboration. The collaboration achieved commonality of specifications and uniformity of performance. Final development of design, construction and first results from the prototypes are described to indicate the status of these critical components for HL-LHC.

INTRODUCTION

The LHC is a break-through machine. The 2012 observation of the Higgs boson, the simplest possible type of elementary particle (no spin, no charge, only mass) and yet the last “predicted” particle of the Standard Model to be observed, has shown once more that we do not have a clear understanding for what can explain the mass of the Higgs itself. The Higgs appears as a “lonely beast, unaccompanied by other particles” [4], which provides even more motivation to keep searching for hints of Beyond the Standard Model physics at the LHC. These searches rely on higher energy and higher luminosities.

The LHC is now operating at a center-of-mass energy of 13 TeV and is expected to reach the design energy of 14 TeV. The LHC also achieved a record instantaneous Luminosity of $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Over a period of two and a half years (2024 to 2026), an upgrade to the LHC called the High Luminosity LHC, will be installed to increase the instantaneous luminosity to $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (approximately three times higher than what is currently possible) and to increase the delivered integrated luminosity by a factor of ten.

In 2003, midway through the completion of the original US contribution to the LHC construction, it was recognized

that a focused development effort would have enabled the US accelerator community to be ready to construct the next generation of upgrades at the appropriate time. The LARP Program was established soon thereafter and funded at a level of approximately 10-12M\$/y since 2006. LARP coordinated the efforts of the four National Laboratories involved in HEP (Brookhaven, Fermi, Berkeley, and SLAC) with inclusion of Universities and effort from other national labs such as Jefferson Lab, to focus on the technology needed for the “next generation upgrade”.

HL-LHC AUP is enabled by this directed R&D effort. Thanks to the efforts of scientists supported by LARP, the contributions discussed in the following have been researched and developed to demonstrate their effectiveness in achieving the luminosity goal of HL-LHC. The inter-laboratory collaboration developed by LARP forms the backbone for the execution of HL-LHC AUP in the US.

HL-LHC FOCUSING QUADRUPOLES

The reduction of the transverse beam size by approximately a factor of two in the interaction points will be achieved in HL-LHC through the installation of new inner triplet, low-β insertion cryoassemblies (Q1, Q2a, Q2b and Q3) containing quadrupole magnets, called MQXF [5-9]. MQXF will feature a large aperture (150 mm), a higher peak field (11.4 T), and will use Nb₃Sn.

Requirements and Design

The Q1 and Q3 cryoassemblies of the final focusing string will utilize US magnets (MQXFA), while the magnets (MQXFB) built at CERN will be used in the Q2a and Q2b sections. The only difference between MQXFA and MQXFB is the magnetic length. The requirements for the MQXFA magnets are shown in Table 1.

Table 1: MQXFA Coil and Magnet Parameters

Parameter	Unit	Value
Coil aperture diameter	mm	150
Magnet (LHe vessel) outer diameter	mm	630
No. turns in layer ½ (octant)		22/28
Operational temperature Top	K	1.9
Magnetic length (MQXFA)	m	4.20
Nominal gradient G _{nom}	T/m	132.6
Nominal current I _{nom}	kA	16.47
Nominal conductor peak field B _{op}	T	11.4
I _{nom} / I _{ss} at 1.9 K (for MQXFA)	%	77
Differential inductance at I _{nom}	mH/m	8.21
Stored energy at I _{nom} (MQXFA)	MJ	4.91
F _x / F _y (per octant) at I _{nom}	MN/m	+2.47/-3.5
F _θ layer1/layer2 (per octant)	MN/m	-1.84/-2.14
F _z (whole magnet) at I _{nom}	MN	1.17

The Nb₃Sn superconductor used in the US MQXFA magnets is the Rod-Restack Process (RRP®) 108/127 from Bruker [10]. Strand specifications are given in Table 2. An

example of Quality Control (QC) data from the ongoing procurement is shown in Fig. 1.

Magnet cables are assembled with 40 strands in a Ruthford configuration. With the transfer function for this magnet design, the nominal operation of MQXFA will be at 16.47 kA (i.e. 77% of the short sample critical current limit for the RRP[®] conductor). In addition, MQXFA magnets will be capable of reaching an ultimate current value of 17.9 kA, operating at 84% of the short sample limit.

Table 2: MQXFA Strand Specification

Parameter	Unit	Value
Strand Diameter	mm	0.85
Sub-element diameter	μm	≤55
Filament twist pitch	mm	19±3
Cu/SC		1.2±0.1
Residual Resistance Ratio		>150
I_c (12T, 4.2K), no self-field corr.	A	>632
I_c (15T, 4.2K), no self-field corr.	A	>331
No-Cu J_c (12T, 4.2K), no self-field corr.	A/mm ²	>2450
No-Cu J_c (15T, 4.2K), no self-field corr.	A/mm ²	>1280

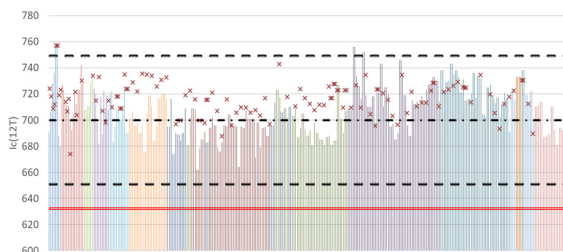


Figure 1: I_c vs. production spool for RRP[®] Nb₃Sn. Requirement (solid red line), average and $\pm 3\sigma$ are shown.

Coils are assembled using the winding, curing, reaction and impregnation technology [2,11-12]. A picture of a coil cross-section is shown in Fig. 2. Four coils are then assembled in a shell-based structure (Fig. 3) with a “bladder and key” concept to counteract nominal forces of +2.47/-3.48 MN/m (F_x/F_y) without overstressing the brittle Nb₃Sn conductor [13-14].

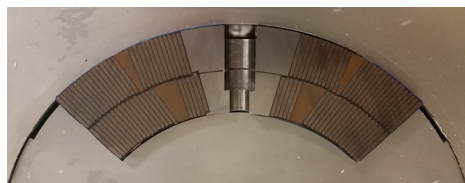


Figure 2: Cross-section and picture of a manufactured coil.

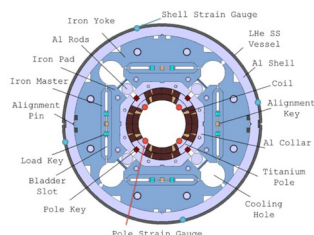


Figure 3: Schematics of MQXFA magnet assembly.

Two MQXFA magnets are then aligned and assembled in tandem in a cold mass Helium vessel structure, which

is inserted in a cryostat designed and provided by CERN (Fig. 4) [15].

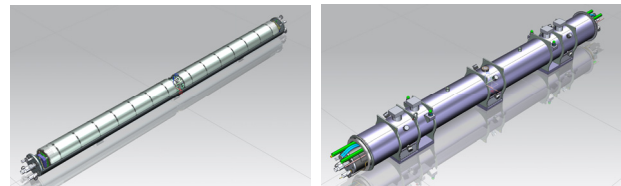


Figure 4: View of two MQXFA magnets aligned in a Cold Mass Structure (left) and final cryoassembly (right).

Lessons Learned from Models and Prototypes

A long series of short models for MQXF magnets have been constructed in parallel in the US and at CERN and are described in detail elsewhere [12]. Models have shown that:

- The technology allows achieving HL-LHC current and field quality performance with ~ 20 training quenches.
- Magnets preserve memory of their training.
- Loading of the magnets with the “bladder and key” concept maintains the magnet pre-stress in a safe region.
- Magnets can be protected during a quench.

Full-scale prototypes have been tested only in the US so far with equipment and materials inherited from LARP.

The first MQXFA prototype (MQXFAP1), was tested at BNL in August 2017. The magnet was trained to a current of 17.4 kA, when an electrical short between a coil and ground forced us to stop the test. The mechanism leading to the short between the quench heaters and the coils in MQXFAP1 was caused by repeated tests at high voltage (~ 2.5 kV) between quench heaters and coils [16]. The Electrical Design Criteria for HL-LHC IT Magnets [17], developed after the MQXFAP1 test, requires significantly lower values and the test procedure for these magnets is being revised.

The second prototype (MQXFAP2) was tested at BNL in September 2018. The magnet reached a current of 15 kA followed by detrainning quenches. Upon warm-up and inspection, one of the shells - designed and built under the LARP program - was found to be fractured (Fig. 5). The fracture was the result of a non-conforming sharp corner. The non-conforming part was accepted for use according to LARP procedures, which didn’t account properly for stress-concentration points.

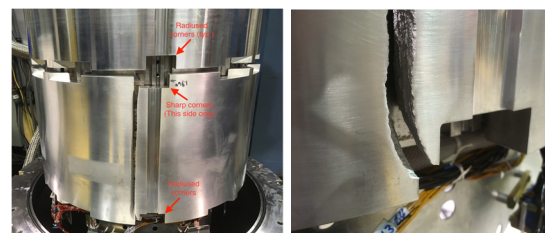


Figure 5: Pictures of fractured shell in MQXFAP2.

AUP has performed an optimization of the MQXFA shell design, based on Finite Element Analysis and advanced failure assessment diagram (FAD), which, contrary to

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LARP procedures, includes large radii at all cut-out corners and tighter QC procedures. These changes will be implemented in all future MQXFA magnets and are expected to prevent any fracture development in the future [18].

HL-LHC CRAB CAVITIES

The two counter-rotating beams in the LHC are separated in different vacuum chambers and brought into collision with a crossing angle at the interaction point. This angle introduces a luminosity reduction which for HL-LHC can be as large as 70% compared to head-on collisions [19]. To recover the loss, an elegant scheme using RF deflectors (Fig. 6) on either side of the collision point was first proposed and used for electrons [20, 21, 22]. An additional benefit of this scheme is the ability to level luminosity during a store.



Figure 6: Schematic of bunch crossing with and without crab cavities.

Two types of RF deflectors, or crab cavities, are envisioned: Double Quarter Wave cavities built by CERN [23], deflecting the beam in the vertical direction (ATLAS) and already tested in the SPS [24, 25] and Radio Frequency Dipole (RFD) cavities, deflecting the beam in the horizontal direction (CMS) and built by AUP.

Requirements and Design

Table 3 shows the requirements for the RFD cavities.

Table 3: RFD Crab Cavities Parameters

Parameter	Unit	Value
Nominal Resonance frequency	MHz	400.790
Nominal Deflecting Voltage	MV	3.4
Peak Surface Electric Field at V_{Nom}	MV/m	≤ 40
Peak Surface Magnetic Field at V_{Nom}	mT	≤ 70
Dynamic Heat Load Per Cavity	W	≤ 10
Quality Factor at 2 K and V_{Nom}		$> 3.9 \cdot 10^9$
Residual Resistance	n Ω	27
dF/dp (Sensitivity to LHe pressure)	Hz/mbar	≤ 150
Lorentz Force Detuning Coefficient	Hz/MV ²	≤ 865
Electrical Axis Deviation	mm	≤ 0.7
HOM Filters Power Leakage at f_{Nom}	W	≤ 1.5
Operating temperature	K	2
Maximum LHe Pressure	bar	1.8
Tuning Range (at 2K)	kHz	> 300

The RFD design is a compact design with reduced peak surface fields and high shunt impedance. One advantageous RF property of the RFD design is that the cavity does not have a lower order mode, which normally is present in an elliptical-shaped dipole deflecting cavity.

Lessons Learned from Models and Prototypes

Figure 7 (Left) shows one of the two prototype RFD cavities built during LARP and inherited by AUP. Thanks to these prototypes, high-pressure rinsing, chemical etching,

and cleanroom activities were validated in US laboratories (FNAL, ANL and JLAB).

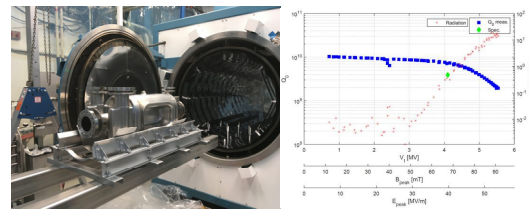


Figure 7: (Left) RFD-LARP-001 before thermal treatment at FNAL. (Right) RFD-LARP-002 test results with HOM.

Two RFD cavities were fabricated by Niowave Inc. The design was carried out by Old Dominion University in collaboration with SLAC. Final welds, chemistry and cold tests were done at Jefferson Lab. Figure 7 (Right) shows the result of the cold test at JLAB of RFD-LARP-002 with HOMs dampers. These LARP crab cavities had the main goal of providing a cost-effective roadmap to demonstrate feasibility and working principles of this type of SRF cavity [26-27].

Both LARP cavities achieved a deflecting voltage greater than 4.1 MV and $Q_0 > 10^{10}$, exceeding the design specifications with and without HOM dampers installed. Multipacting was observed and processed away during cold tests without issues. It was observed that once multipacting was processed, it did not come back within the same test. In 2018-2019 a design change was necessary to address HOM impedance requirements and to implement lessons learned from the SPS beam tests carried out at CERN on the DQW crab cavity [24-25]. RFD cavity prototypes for HL-LHC are being built at this time by the US to lead the way for the production of the cavities planned for tunnel installation.

US CONTRIBUTIONS TO HL-LHC

The HL-LHC AUP Project is a formally approved Project tasked with the delivery of 10 MQXFA Cryomodules and 10 Dressed RFD cavities to CERN.

The project is supported by the US Department of Energy- Office of Science, is managed from the Fermi National Accelerator Laboratory, Batavia, IL and was baselined (i.e. approved scope, cost and schedule) in Feb. 2019.

The 10 Q1/Q3 MQXFA cryomodules will be delivered between 2022 and 2025. The 10 RFD Crab Cavities will be delivered between 2022 and 2024. Acceptance criteria for the US deliverables have been negotiated with CERN and documented appropriately.

AUP is now in the pre-series execution phase (~20%), with final approval for full execution (balance of ~80%) expected by 2021.

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REFERENCES

- [1] S. J. Strait *et al.*, "Towards a new LHC interaction region design for a luminosity upgrade" in *Proc. 20th Particle Accelerator Conf. (PAC 2003)*, Portland, OR, USA, May 2003, Paper MOPA006, pp. 42-44
- [2] S. A. Gourlay *et al.*, "Magnet R&D for the US LHC accelerator research program", *IEEE Trans. Appl. Supercond.*, vol. 16, no.2, pp. 324-327, Jun 2006
- [3] "The High Luminosity Large Hadron Collider", edited by O. Bruning and L. Rossi, *World Scientific*, Oct. 2015
- [4] N. Arkani-Hamed, "In it for the long haul", Opinion interview in *CERN Courier*, Mar./Apr. 2019
- [5] E. Todesco *et al.*, "Design studies for the low- β quadrupoles for the LHC luminosity upgrade," *IEEE Trans. Appl. Supercond.*, vol. 23 no. 3, pp. 4002405, Jun. 2013, doi:10.1109/TASC.2013.2248314
- [6] E. Todesco, *et al.*, "A first baseline for the magnets in the high luminosity LHC insertion regions," *IEEE Trans. Appl. Supercond.*, vol. 24 no. 3, pp. 4003305, Jun 2014, doi:10.1109/TASC.2013.2288603
- [7] P. Ferracin *et al.*, "Magnet design of the 150 mm aperture low- β quadrupoles for the High Luminosity LHC," *IEEE Trans. Appl. Supercond.*, vol. 24 no. 3, pp. 4002306, Jun. 2014, doi:10.1109/TASC.2013.2284970
- [8] P. Ferracin *et al.*, "Development of MQXF: The Nb₃Sn low- β quadrupole for the HL-LHC", *IEEE Trans. Appl. Supercond.*, vol. 26 no. 4, pp. 4000207, Jun. 2016, doi:10.1109/TASC.2015.2510508.
- [9] E. Todesco *et al.*, "Progress on HL-LHC Nb₃Sn Magnets", *IEEE Trans. Appl. Supercond.*, vol. 28 no. 4, pp. 4008809, Jun. 2018, doi:10.1109/TASC.2018.2830703.
- [10] L. D. Cooley *et al.*, "Conductor specification and validation for High-Luminosity LHC quadrupole magnets" *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 6000505, Jun. 2017, doi:10.1109/TASC.2017.2648738.
- [11] A. V. Zlobin *et al.*, "Development of Nb₃Sn 11T single aperture demonstrator dipole for the LHC upgrade" in *Proc. 2011 Particle Accelerator Conf. (PAC 2011)*, New York, NY, May 2011, doi:10.1109/TASC.2012.2236138.
- [12] P. Ferracin *et al.*, "The HL-LHC low- β quadrupole magnet MQXF: from short models to long prototypes", *IEEE Trans. Appl. Supercond.*, doi:10.1109/TASC.2019.2895908.
- [13] H. Pan *et al.*, "Assembly tests of the first Nb₃Sn low- β quadrupole short model for the HL- LHC upgrade" *IEEE Trans. Appl. Supercond.*, vol. 26, pp. 4001705, Jun. 2016, doi:10.1109/TASC.2016.2516584.
- [14] H. Pan *et al.*, "Mechanical Design Studies of the MQXF Long Model Quadrupole for the HiLumi LHC" *IEEE Trans. Appl. Supercond.*, vol. 27, pp. 4004105, Jun. 2017, doi:10.1109/TASC.2016.2642169.
- [15] D. Ramos *et al.*, "Conceptual design of the cryostat for the new high luminosity (HL-LHC) triplet magnets", in *2017 Cryogenic Engineering Conference and International Cryogenic Materials Conference*, Madison, WI, USA, Jul. 2011, doi:10.1088/1757-899X/278/1/012175.
- [16] V. Marinuzzi *et al.*, "Analysis of the short-to-ground event in the LARP-AUP MQXFAP1 magnet and its implication on the production and tests of the series magnets", <http://1ss.fnal.gov/archive/2018/pub/fermilab-pub-18-580-td.pdf>
- [17] F. Menendez Camara, F. Rodriguez Mateos, "Electrical Design Criteria for the HL-LHC Inner Triplet Magnets" CERN EDMS No. 1963398; US-HiLumi-doc-879.
- [18] H. Pan *et al.*, "Failure assessment for MQXF magnet support structure with a graded approach", *IEEE Trans. Appl. Supercond.*, vol. 29 no. 5, Aug. 2019, doi:10.1109/TASC.2019.29081132.
- [19] A. Piwinski, *Nucl. Inst. Meth.* 81, 199 (1970)
- [20] R. Palmer "Energy scaling, crab crossing and the pair problem", SLAC-PUB-4707, 1988.
- [21] K. Oide, K. Yokoya "The crab crossing scheme for storage-ring colliders" SLAC-PUB-4832, 1989.
- [22] Y. Funakoshi "Operational Experience with Crab Cavities at KEKB", (2014), <http://arxiv.org/pdf/1410.4036>
- [23] R. Calaga "Crab cavities for the High-Luminosity LHC", in *Proc. of the 18th International Conference on RF Superconductivity (SRF2017)*, Lanzhou, China, Jul. 2017, doi:10.18429/JACoW-SRF2017-THXA03.
- [24] R. Calaga *et al.*, "First machine development results with HL-LHC Crab Cavities inside the SPS", presented at the 10th Int. Particle Accelerator Conference (IPAC19), Melbourne, Australia, May 2019, this conference.
- [25] R. Calaga "First Crabbing of Proton Beam", presented at the TESLA Technology Collaboration Meeting (TTC 2019), Vancouver, CA, Feb. 2019
- [26] S. De Silva *et al.*, "Design and Prototyping of a 400 MHz RF-dipole Crabbing Cavity for the LHC High-Luminosity Upgrade", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, doi:10.18429/JACoW-IPAC2015-WEPWI036.
- [27] S. De Silva *et al.*, "RF Test of RF-Dipole Prototype Crabbing Cavity for LHC High Luminosity Upgrade", in *Proc. of the 18th International Conference on RF Superconductivity (SRF2017)*, Lanzhou, China, Jul. 2017, doi:10.18429/JACoW-SRF2017-TUPB054.