Design of the Fermilab Pre-Series Cold Mass for the HL-LHC Accelerator Upgrade Project

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Abstract—**As part of the U.S. contribution to the HL-LHC Accelerator Upgrade Project (AUP), Fermilab is designing and building cold masses suitable for use in the LHC interaction regions. The cold mass provides a vacuum-tight helium enclosure for the magnets. Two magnets are aligned both axially and in cross section at Fermilab based on survey and warm magnetic measurements. Bus work and instrumentation is added. A welded stainless steel vacuum-tight shell surrounds the two magnets, and the structure is prepared for insertion into the cryostat. This paper summarizes the design of the cold mass including alignment, bus work, weld details, and instrumentation.**

***Index Terms*—LMQXFA, Cold Mass, Bus, Expansion Loops, Quadrupole**

I. Introduction

THE LHC IR quadrupole (MQXF) is being supplied to CERN by a collaboration of US laboratories and CERN. The "inner triplets", surrounding the interaction region, consist of three quadrupoles located on each side of the beam collision point, called Q1, Q2 and Q3 [1]. Coils are fabricated at Fermilab and Brookhaven. The individual magnets are assembled at LBNL and tested at Brookhaven. After testing, the magnets are returned to Fermilab, where the cold mass and cryostat are added, and the complete assembly is tested. The Q1 and Q3 cold masses and cryostats are built and supplied by the US laboratories and are identical, while the Q2 is fabricated at CERN. Magnets used in Q1/Q3 and Q2 are nearly identical to each other.

A cross section of the complete Q1/Q3 assembly with cryostat is shown in Fig. 1. Main design parameters of the cold mass are shown in [1]. The assembly includes two magnets, (identical, but designated as Qa and Qb), built by key and bladder yoke assembly with aluminum shell [2]-[5]. The magnets are surrounded by a vacuum tight stainless steel shell to provide alignment and a helium enclosure. Bus work, expansion loops and instrumentation which exits at the "warm head" are enclosed within the stainless shell. The stainless shell and everything it contains is designated the "cold mass". Finally, the cryostat surrounds the cold mass, completing the cryo-assembly. The cryostat design was developed at CERN, and is identical to the design that is used for the Q2. This paper focuses on the cold mass design.

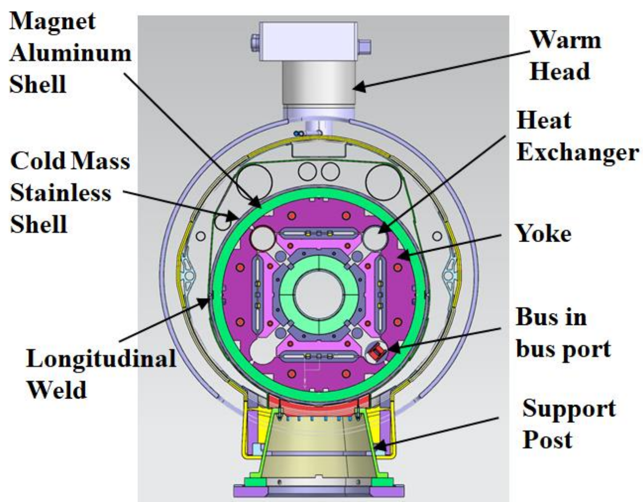

Fig. 1. Completed Cryo-assembly

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II. Magnet Alignment

The initial step is to align the two magnets for placement into the cold mass. They are positioned as shown in Fig. 2. The magnets are placed with the lead ends facing outward, and the non-lead ends facing each other. Physical and magnetic measurements are taken. The nominal distance between magnetic centers of the two magnets is 4806 mm. The two magnets must be aligned within +/- 5 mm of the specification in the ax-

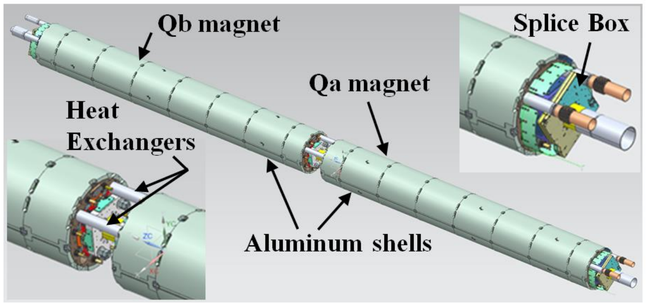

Fig. 2. Magnet alignment. Lead end of Qa shown at upper right. Interface of two non-lead ends shown at lower left.

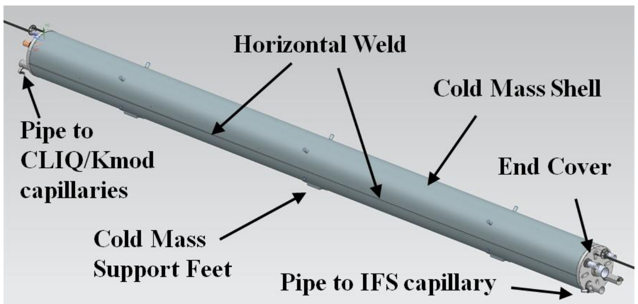

Fig. 3. Completed cold mass with stainless steel shell

ial direction, and within +/- 0.5 mm of the common magnetic axis in the horizontal and vertical directions. Horizontal, vertical and axial alignment is achieved by surveying fiducials on the magnets. The deviation of field angle of either the Qa or Qb from the common magnetic field angle [6] must be within +/- 2 mrad. This criteria is achieved by warm magnetic field measurements. After the magnets are aligned, heat exchangers are installed in the upper yoke ports. The heat exchangers are shown in Figs. 1 and 2.

III. Shell Welding

Cold mass shells are made of 316L low-cobalt content stainless steel. The top and bottom shells are connected by a horizontal MIG weld configured as shown in Figs. 3 and 4. The “tack blocks” shown in Figs. 4 and 5 provide an azimuthal and radial connection between the iron yoke of each magnet and the stainless steel cold mass shell. An important function of the tack blocks is to secure the position between the two magnets within the cold mass, ensuring that the longitudinal relationship between the Qa and the Qb magnets is maintained. One tack block is placed at each junction between magnet outer aluminum shells, and is located in an opening between them. Only the center tack block on each magnet is fixed longitudinally to both the magnet yoke and stainless steel shell. The rest are allowed (by the dovetail feature shown in Fig. 4) to float in the longitudinal direction when the assembly expands and contracts with cool-down and warm-up as well as with differential pressure. Finally, end covers are welded onto the ends, which can be seen in Fig. 3.

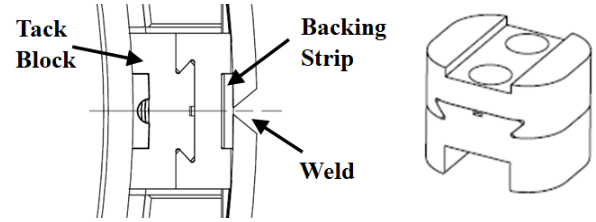

Fig. 4. Tack block details

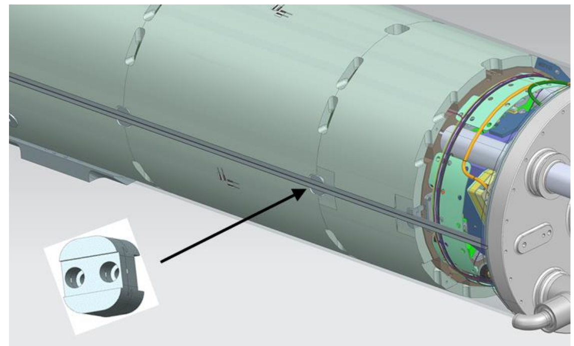

Fig. 5. Tack block position connecting magnet and cold mass. Tack blocks are placed at all interfaces between sections of the magnet outer aluminum tube. This illustration shows the tack block and backing strip installed on the magnet before the cold mass shell is added.

The shell must provide a vacuum tight enclosure and axial support during shipping. However, care must be taken to prevent excessive preload being applied to the magnet coils from the cold mass shell. According to the original specification, the cold mass shell must apply no more than 15 MPa of azimuthal preload to the coils, yet must be more than zero, to provide alignment between the two magnets within the cold mass. This was achieved by controlling the azimuthal length of the inside surface of the shell. Machining of the longitudinal edges of the shell is done after the forming process has been completed. Measurements are made after machining by pi tape and caliper and confirmed by metrology. Weld tests were done at room temperature, and shell welding was completed on a short model and tested at cryogenic temperatures to verify the design [7],[8].

Recent revised specifications from CERN require that the azimuthal coil pre-stress applied by the shell must be no more than 3.2 MPa. If this method is used, the inside length must be controlled to an accuracy of +/- 50 µm. Measurements of the shell can be taken to this accuracy, but consistently machining to this level of accuracy is problematic.

Consequently, for this design a shim may be introduced that mitigates the need for extreme accuracy of the shell. The cold mass shell azimuth is increased slightly, and shims are placed between the aluminum magnet shell and the stainless cold mass shell at assembly to achieve the accuracy required. The shell configuration on the magnet before and after welding is shown in cross section in Fig. 6. Based on measurements of the shell and magnet shape, shims are placed at top and bottom to achieve the desired preload. During welding, the stainless steel cold mass shell deforms to conform to the

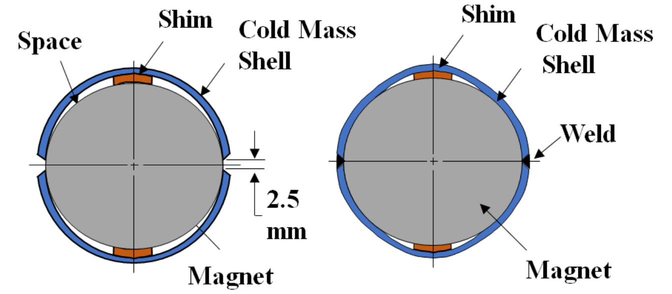

Fig. 6. Shell aligned on magnet before welding (left) and after welding (right). The space shown before welding is exaggerated for illustration. Typical shim thickness is approximately 1mm, with the space between shell and magnet outside diameter not larger than about 1mm thick before welding.

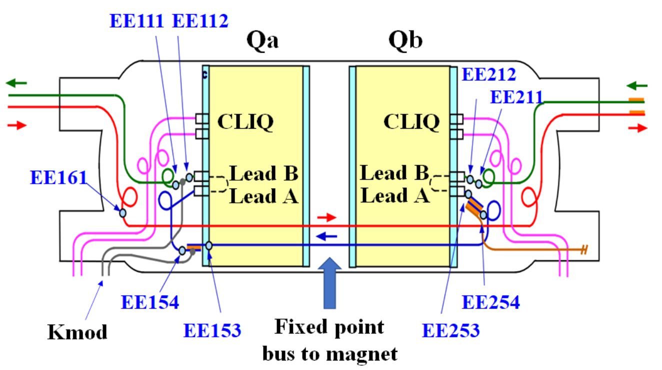

Fig. 7. Schematic of bus system. “B” lead is shown in green, “A” lead and local bus are shown in blue, through bus is shown in red, CLIQ leads are shown in pink, and Kmod leads are shown in grey. “EE” labels represent voltage taps added during cold mass assembly.

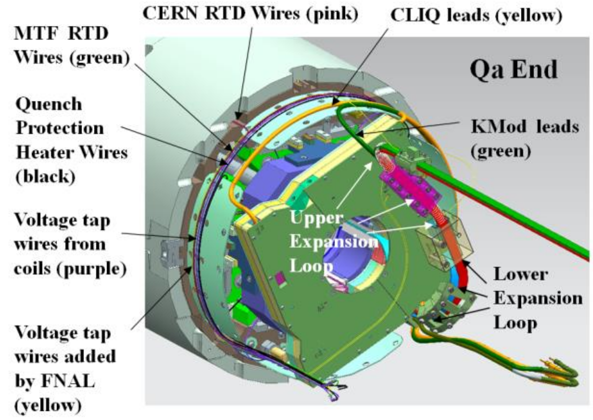

Fig. 8. Qa end of cold mass, showing bus, expansion loops and instrumentation wires.

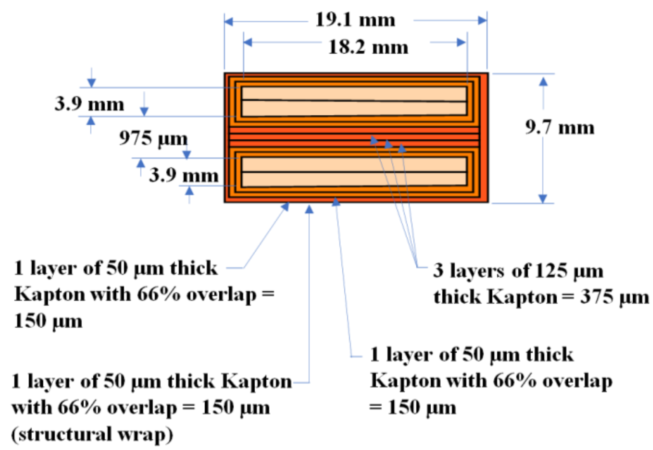

Fig. 9. Cross section of bus with insulation. The through bus is on top with the local bus beneath. The “structural wrap”, which surrounds both busses, described in the text, is used to withstand the opposing forces of the through bus and the local bus.

shape of the aluminum magnet shell, providing the correct preload as well as some friction between shell and magnet. Allowing the shell to be shimmed and deform into shape allows the accuracy requirement for the stainless shells to be reduced to +/- 500 µm, a value that is easier to achieve.

After the horizontal shell weld and electrical work is complete, end plates and pipes for instrumentation and leads are welded to the cold mass ends.

IV. Bus and Expansion Loops

A pictorial representation of the position of the magnet leads, busses and splices is shown in Fig. 7. The bus work is identical whether the cold mass is a Q1 or a Q3. One magnet lead (lead B in green) extends to the next cold mass in the triplet. The other lead (lead A in blue) is spliced to the “local bus” on the magnet at the other end of the cold mass. A “through bus” (in red) passes through all magnets as the return lead. Expansion loops on each end of the cold mass allow movement between separate cold masses as well as movements between the various parts within a cold mass during cooldown and warmup. There are two loops on each end, the “upper loop” and the “lower loop” as shown in Fig. 8. The Qa end is shown. A similar but not identical configuration is used on the Qb end. The upper loop is required to withstand +/- 18 mm of axial displacement while the lower loop requires +/- 7 mm. Calculations which describe the axial displacement needed for each loop are shown in [9]. A special lead connects to the lower loop on the Qb end [10], which allows the magnets to be tested separately after being inserted into the cryostat. This lead will be capped and insulated after testing at Fermilab and is not used in operation in the LHC.

The cold mass implements a full length (10 meter long) bus as shown in Fig. 9, with the through bus on top and the local bus beneath. Layers of polyimide insulation provide electrical insulation between the busses. Mechanical support for the busses is provided by a combination of a “structural wrap” of polyimide, and enclosure in a G-11 housing as shown in Figs. 9 and 10. This design is similar to that done on the MQXB cold masses [11],[12]. It is inserted into the magnet at assembly through a port in the magnet yoke as shown in Fig. 10. Spring loaded aluminum retaining clips hold the bus structure into place but still allow the bus to slide axially within the bus port.

The bus is made of NbTi cable, rectangular, without keystone angle. Cable specifications are shown in [13]. Maxi-

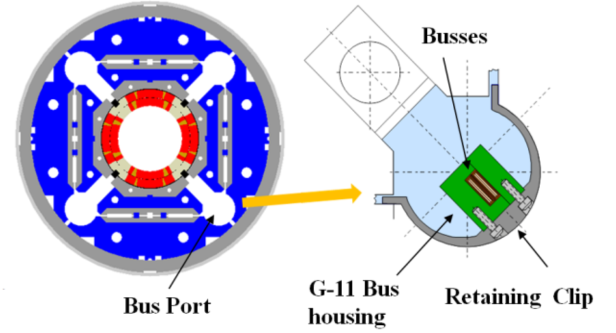

Fig. 10. Cross section of bus assembly shown as installed at right, with the bus port within the magnet shown at left.

mum repulsive force between bus cables within the body is 7500 N/m. A complete discussion of the forces on the bus cable within the cold mass is described in [14].

V. Instrumentation

Quench protection heaters and voltage taps are installed on each magnet when it is initially fabricated at LBNL and are routed to the warm head at cold mass assembly. The cold mass is also instrumented with additional voltage taps for quench detection, temperature sensors and warmup heaters. All instrumentation is routed out of the cold mass through the instrumentation port to the IFS capillary, then to the warm head where the wires are terminated into connectors.

In addition to 16 strip heaters per magnet (4 per coil), a system based on coupling loss induced quench (CLIQ) is used for additional protection [15], and these leads need to be routed to the warm head. Two CLIQ leads, each consisting of 30 A non-superconducting copper cable, extend from the lead end of each magnet. They are shown in pink in Fig. 7 and yellow in Fig. 8. Two Kmod (trim) leads are attached to the power leads on the Qa end only as shown in grey in Fig. 7 and in green in Fig. 8 and are also routed to the warm head. They consist of non-superconducting copper cable and are identical to the CLIQ leads. Both CLIQ and Kmod leads are wrapped around "connector skirts" before exiting the cold mass.

VI. CLIQ and Kmod Capillaries

Instrumentation wires are carried from the cold mass body to the exterior of the cryostat (through the "warm heads") by thin "capillary tubes", 14 mm outside diameter, which are formed at assembly to a design developed at CERN [16]. All instrumentation wires are by design full length so no splices should be made between the cold mass and the warm head. The IFS capillary tube assembly is shown in Fig. 11. Similar capillary tubes (except formed before installation) are used to extend the CLIQ and K-mod leads from the cold mass to the exterior of the cryostat.

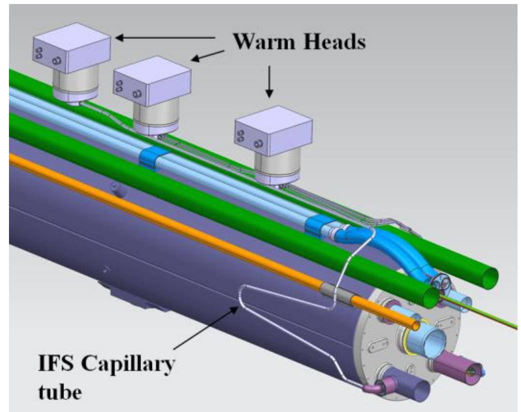

Fig. 11. Routing path of instrumentation wires. Wires are routed though the IFS Capillary and terminated to connectors at the warm head. CLIQ and Kmod wires are routed through separate capillaries on the other side of the cold mass to separate warm heads.

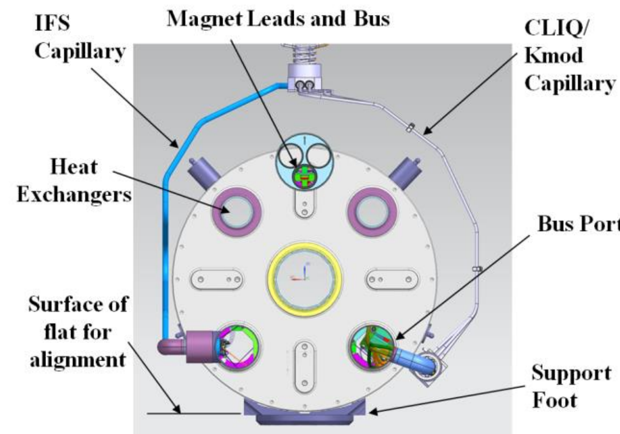

Fig. 12. Model of end view of cold mass showing support foot and capillaries.

VII. Cold mass supports

The Q1/Q3 cold mass is supported by the cryostat through support feet in three places, as shown in Fig. 3 and in cross section in Figs. 1 and 12. The supports are made of 316/316L stainless steel, are welded onto the cold mass shell, and are aligned to meet the specified angular tolerances of coplanarity within 0.5 mm for 3 distinct flats shown in Fig. 12 (see also datum "C" in [17]) as well as a true position of 2 mm with respect to the cold mass centerline for other features. In addition to operating conditions, the support feet must also meet structural loads during shipping.

VIII. Conclusion

The MQXF cold mass design is established. The design has been validated by previous tests to establish shell welding parameters at room temperature [7],[8] as well as bus tests at cryogenic temperatures on a short model [18]. Also, an almost identical bus design was used in the MQXB cold masses [11],[12].

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