U.S. HL-LHC Accelerator Upgrade Project

MQXFS1d Shell Preparation

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Revision History

Revision	Date	Section No.	Revision Description
1.0	01/15/2017	All	Initial Draft
2.0	12/14/2017	All	Revised to match new weld results with new equipment

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1. Overview

Under the LARP program will be developed the Cold Mass and Cryostat design for the Hi-Lumi project. One of the essential elements for the cold mass is the proper design of the shell that will be holding the magnet straight (alignment) and it will be part of the pressure vessel. It is important to properly test the shell design to verify:

- Proper pre-load for the coil and shell
- Weld procedure
- Magnet performance degradation

MQXFS1d was chosen to be used to perform this essential test. In this document we describe the modification of the magnet that required to install the shell and the shell design itself. The shell preparation activities also described including the welding activities and strain gauge mounting plan.

2. Scope

MQXFS1d is a short prototype magnet that has been tested at Fermilab's Vertical Magnet Test Facility (VMTF) in Industrial Building 1. At the conclusion of the test, the short prototype was removed from VMTF and prepared for installing a stainless steel pressure vessel shell. To allow for welding and fastening of the stainless steel shell, the magnet required stainless steel tack bars to be fastened to the yoke in the openings between the aluminum shells. Stainless steel backing strips were then seated in the slots provided in the aluminum shell and matched in the stainless steel tack blocks. The backing strip needs to be welded to the stainless steel tack blocks and to provide an attachment surface, as well as a backing, for the full penetration stainless steel longitudinal seam weld of the pressure vessel shell.

The stainless steel shell design and weld procedures utilized have to minimize strain in the pressure vessel shell to avoid excessive pre-stress on the magnet that may affect performance as well as misalignment in production cold masses.

3. Cold Mass Modifications

To attach the stainless steel pressure vessel shell, stainless steel tack blocks are fastened directly to the iron yoke in openings through the aluminum shell sections to provide for seating and welding of the backing strip. The stainless steel backing strip provides a backing for welding the stainless steel shell and permanently affix the shell to the magnet (See figure 3.1).

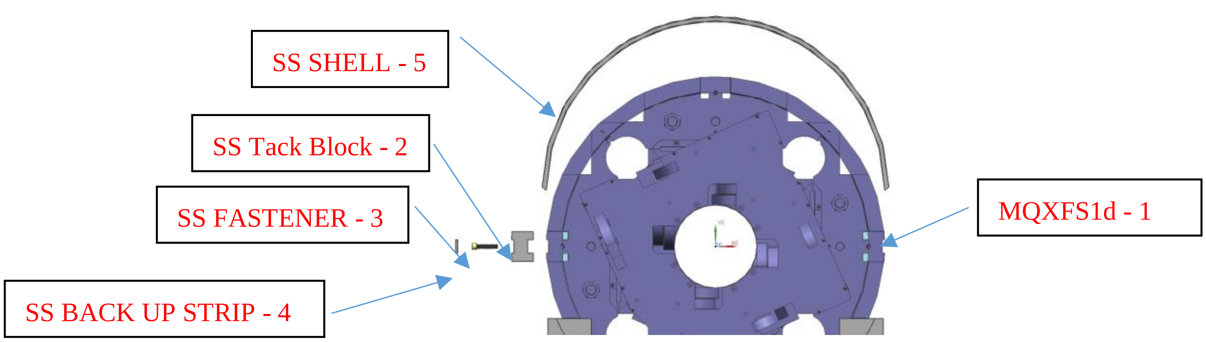


Figure 3.1 – Shell Attachment

MQXFS1d prior to its modifications had missing threaded holes (Figure 3.2) or guide pins (Figure 3.3) wedged in place preventing access to those threaded holes to fasten the tack block. These guide pins need to be cut/machined out to access the threaded holes or, if none exist, we needed to drill& tap a threaded hole in that location.

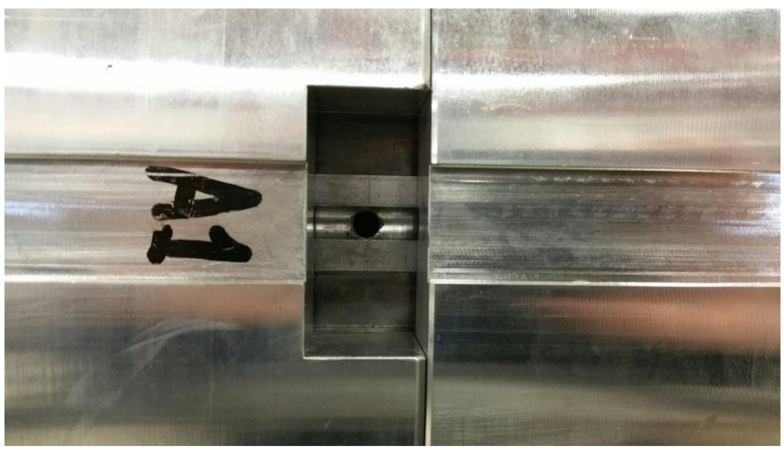


Figure 3.2 – Upper picture missing threaded hole, lower picture threaded hole machining completed.

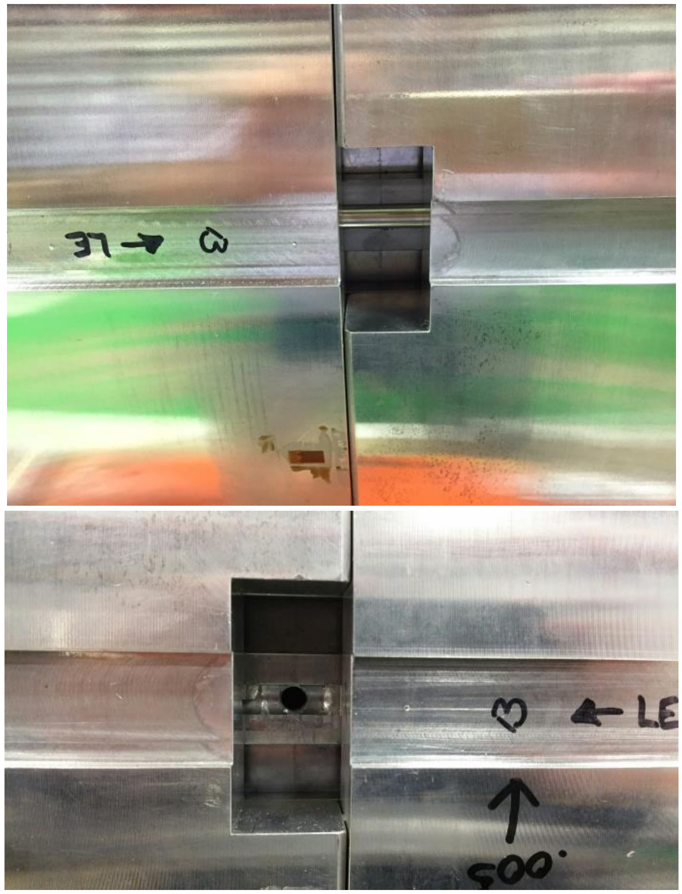


Figure 3.3 – Upper picture where Guide Pin needed to be removed. Lower picture Guide Pin removed.

For the MQXFS1d, three (3) guide pins needed removal and four (4) tapped holes were machined.

The MQXFS1d has 2 inch (52.5mm) thick stainless steel end plates with an OD of 23.819 in. (605mm) but also had two (2) raised surfaces for lifting lugs (See Figure 3.4) aligned perfectly with the slot feature for the backing strips. These raised surfaces would have interfered with an automated weld seam run-off. In order to continue and complete the shell seam welding with a single process and to extend the shell passed the magnet end plates for an additional 6 inch sample for radiographic testing, those details was partially removed. These features are still needed for handling the MQXFSc1 at VMTF as well as a mounting feature for the shipping fixture and therefore will be modified for shell fit up and welding.

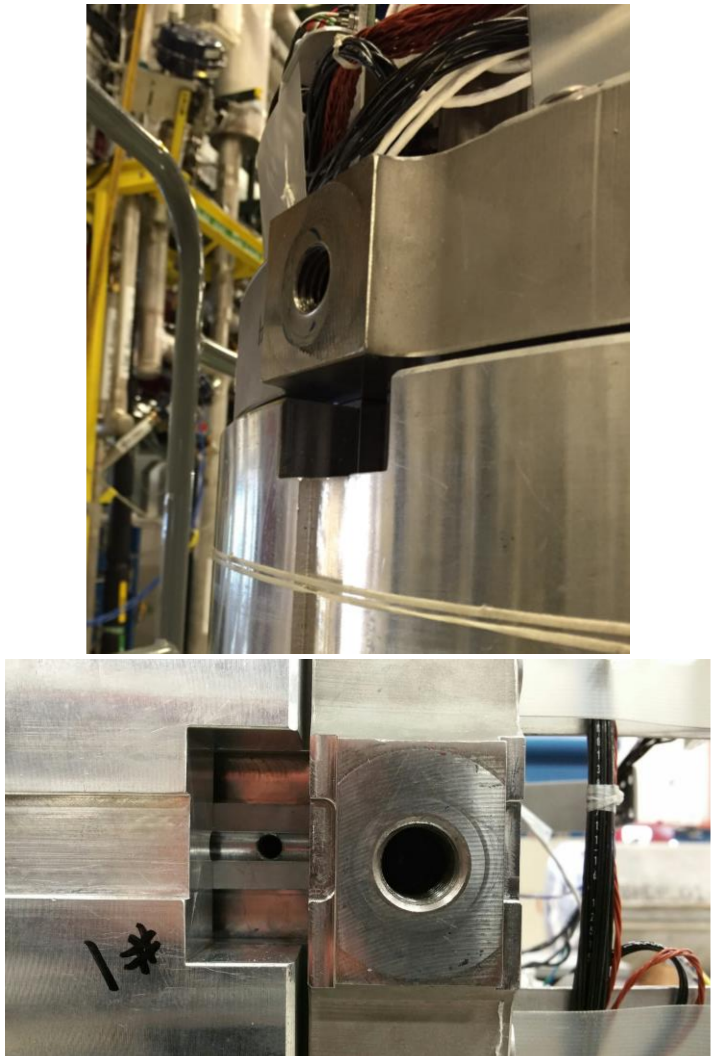


Figure 3.4 – Upper picture Raised Faces for Shackles before modification, lower picture after modification.

All strain gauges were removed from external surfaces of the aluminum shell to allow for the stainless steel shell to fit up firmly up against the aluminum shell. When gauges are relocated to the outside of the stainless steel shell, extreme care must be exercised to protect from damage when handling, inserting or removing from VMTF. Assuming the average ID of the VMTF Dewar is 25.69” and the theoretical diameter of the cold mass is 24.80”, we have an annular space of 0.44” or 11mm for strain gauge clearance.

4. Summary of the Welding Tests

For all samples measured, two (2) SA240 304L stainless steel plates, .3125 in. (8mm) thick were machined to 6 inches wide x 24 inches long. One (1) long edge of each plate was beveled to 37.5° with no land (sharp edge). The two plates were tack welded together with the bevels forming a 75° V-groove maintaining a root gap opening (spacing between weld seam edges). A 304 stainless steel, 1/8” thk. X 1” wide backing strip was used (See Figure 4.1). The overall width of the tacked plates were measured and recorded for three (3) indexed locations A, B, & C, before and after each weld pass as well as a measurement of the length.

In the original attempt to run samples with in-house older weld equipment, The root opening was set at 1/16" fixtured horizontally and clamped with c-clamps (See Figure 4.2 & Fig 4.5) to a stainless steel plate. The MIG torches were not water cooled and an older Millermatic 350P with an older style carriage.

To complete the cold mass welds, two (2) weld machines will be needed to simultaneously weld on both sides of the cold mass and avoid excessive distortion and thus 2 complete new systems were procured.

The latest trial samples were fixtured horizontally on a thick aluminum support plate. A pair of samples were bolted to the aluminum plate with minimum clearance holes and one sample was clamped. All three samples were welded in three (3) total passes (1 root & 2 cover passes) using GMAW procedure with a DC pulse mode (See Figure 4.3 & Figure 4.4) using a recently purchased pair of Miller Invision 450P power sources, Miller S-74 MPa Plus wire feeders, water cooled MIG torches and MPD 1000 Buggo carriages which utilize existing rails.

Trial Parameters and specific settings for sample welding (using old equipment) was as follows:`

Description	Original Test	Latest Test
Power source mode	Pulse / auto	Pulse / auto
Voltage (Variable)	22.6V	23V – 23.5V @
Current	NR	124A – 125A
Torch travel (Root)	8.75 IPM	12 IPM
Torch travel (2n pass)	10.50 IPM	12.75 IPM
Torch travel 3rd pass)	11.25 IPM	12.75 IPM
Wire Feed	350 IPM	400 IPM
Gas	90/10 Ar/CO2	98/2 Ar/CO2
Wire	0.035 Dia. 308LSi	0.035 Dia. 308LSi

Table 4.1 Sample Welding Parameters

Results from welding the stainless steel plate samples are listed below in table 4.1.

	Old Sample – Clamped Inches			**Sample 1 - bolted Inches**			**Sample 2 - Bolted Inches**			**Sample 3 - clamped Inches**		
	Start (A)	Middle (B)	End (C)	Start (A)	Middle (B)	End (C)	Start (A)	Middle (B)	End (C)	Start (A)	Middle (B)	End (C)
As Tacked	12.04	12.06	12.05	12.100	12.104	12.102	12.104	12.108	12.107	12.084	12.087	12.086
1st pass	11.970	12.00	12.026	12.084	12.083	12.083	12.086	12.085	12.088	12.065	12.067	12.067
2nd pass	*	*	*	12.073	12.074	12.074	12.073	12.071	12.078	12.052	12.056	12.057
3rd pass	11.965	11.960	12.00	12.062	12.064	12.066	12.063	12.065	12.070	12.040	12.046	12.048
Free State **	***	***	***	12.050 12.061	12.050 12.063	12.054 12.065	12.053 12.064	12.053 12.062	12.053 12.064	12.036 12.042	12.038 12.046	12.039 12.048

Table 4.2 – Welding Results

***No measurement recorded after second pass.**

**** After releasing the test sample from the fixture, plate sprung and deformed creating waviness. Measurement was recorded for plate width at both, across top edge of plate and across bottom edges of plate to determine variation.**

***** After releasing plate sample from fixture, distortion was to great to consider a measurement.**

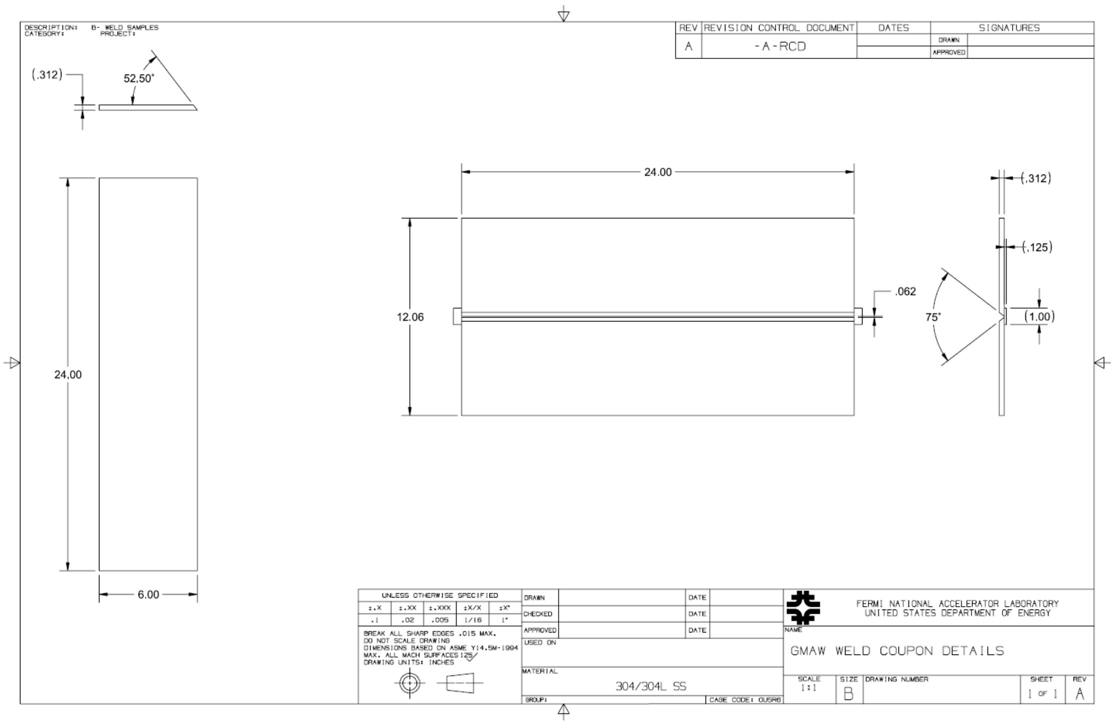


Figure 4.1 – Welding Sample

NOTE: Drawing above shows 1/16" root opening which has recently been revised to 3/32" for the latest samples using newer welding equipment.

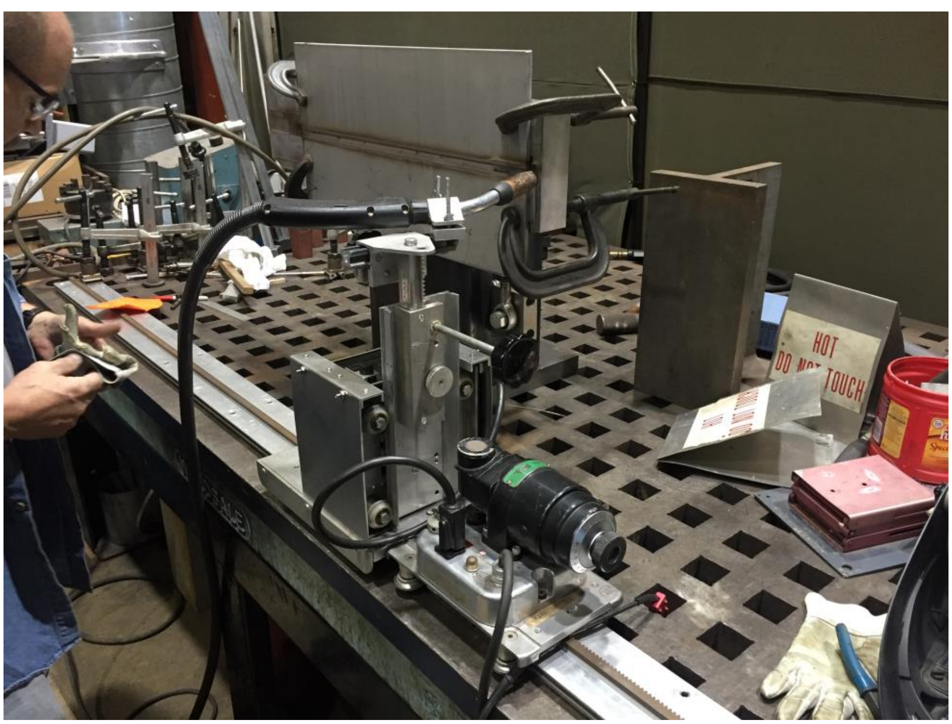


Figure 4.2 – Old Welding Sample set up

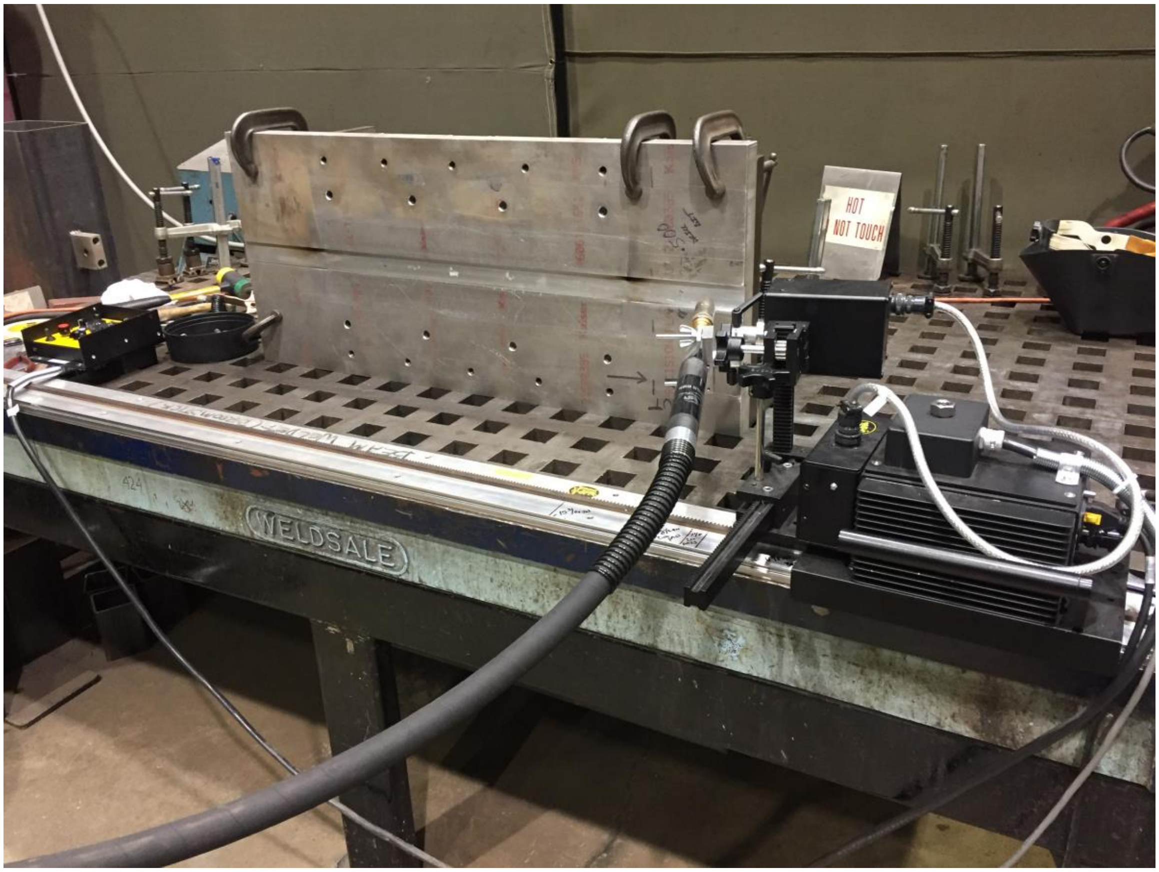


Figure 4.3 – New Welding Sample set up

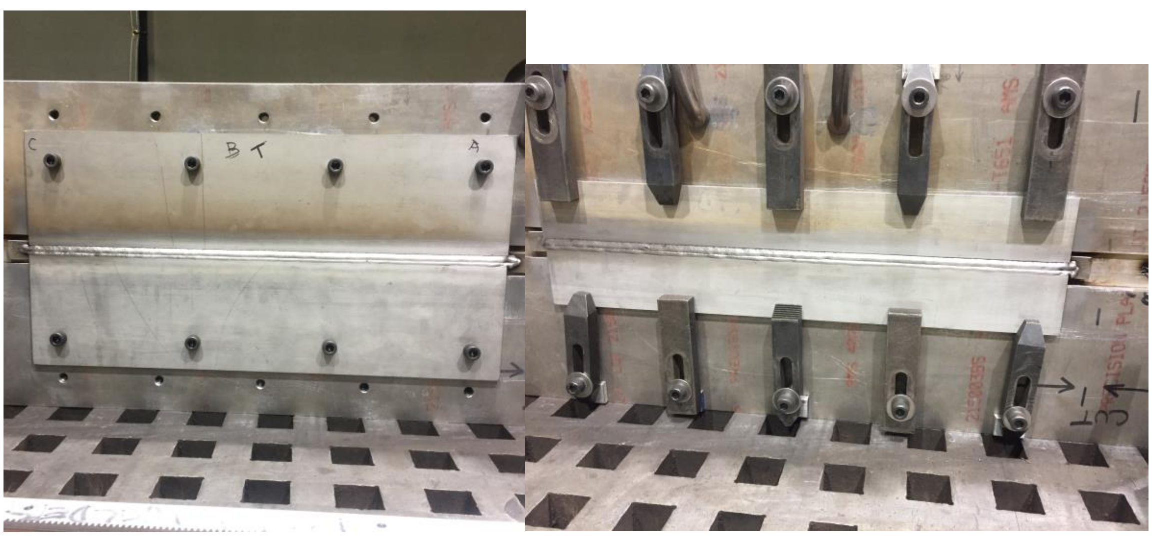


Figure 4.4 – Completed New Welding Samples

Figure 4.5 – Completed Original Welding Sample

5. Shell Design

5.1. Stress Requirements on the Shell

There is no minimum pre-stress requirement for the stainless steel shell. A zero pre-stress is acceptable although there is somewhat of a preference that the stainless steel skin is snug with no gaps between the shells but also completely welded and attached to the magnet via the longitudinal weld seam backing strip. On the other hand, an excessive pre-stress of the stainless steel shell can cause misalignment issues for the cold mass, affect the magnet performance or even damage coils. As analyzed by Heng Pen at LBNL and Giorgio Vallone at CERN, the coil stress increases by ~ 3.2 MPa for every 0.1mm of weld shrinkage in the shell. Thus, our goal is to maintain a very minimal contact, if any, between the shell and magnet to avoid any additional stress to the coil transferred from the shell.

5.2. Tolerance Calculations Based on Weld Test results

From our weld sample tests, we have determined that in both conditions, bolted or clamped, we will see a weld shrinkage of approximately 0.05" (1.3mm) per weld. To confirm our results, CERN had similar results of 1.3 mm during their sample welding of a short shell to an aluminum dummy magnet (no coils). Assuming that we will be consistently shrinking at that same rate for every weld seam, we will add 1mm or .039" of developed length to each half shell to compensate for the total weld shrinkage between 2 welds.

The calculated half shell developed length is as follows:
MQXFS1 aluminum shell measurements:
Sect. 1 =614.679 mm (24.200")
Sect. 2 = 614.685 mm (24.200")
Sect. 3 = 614.607 mm (24.197")

Avg. Dia. = 614.657 mm (24.199")

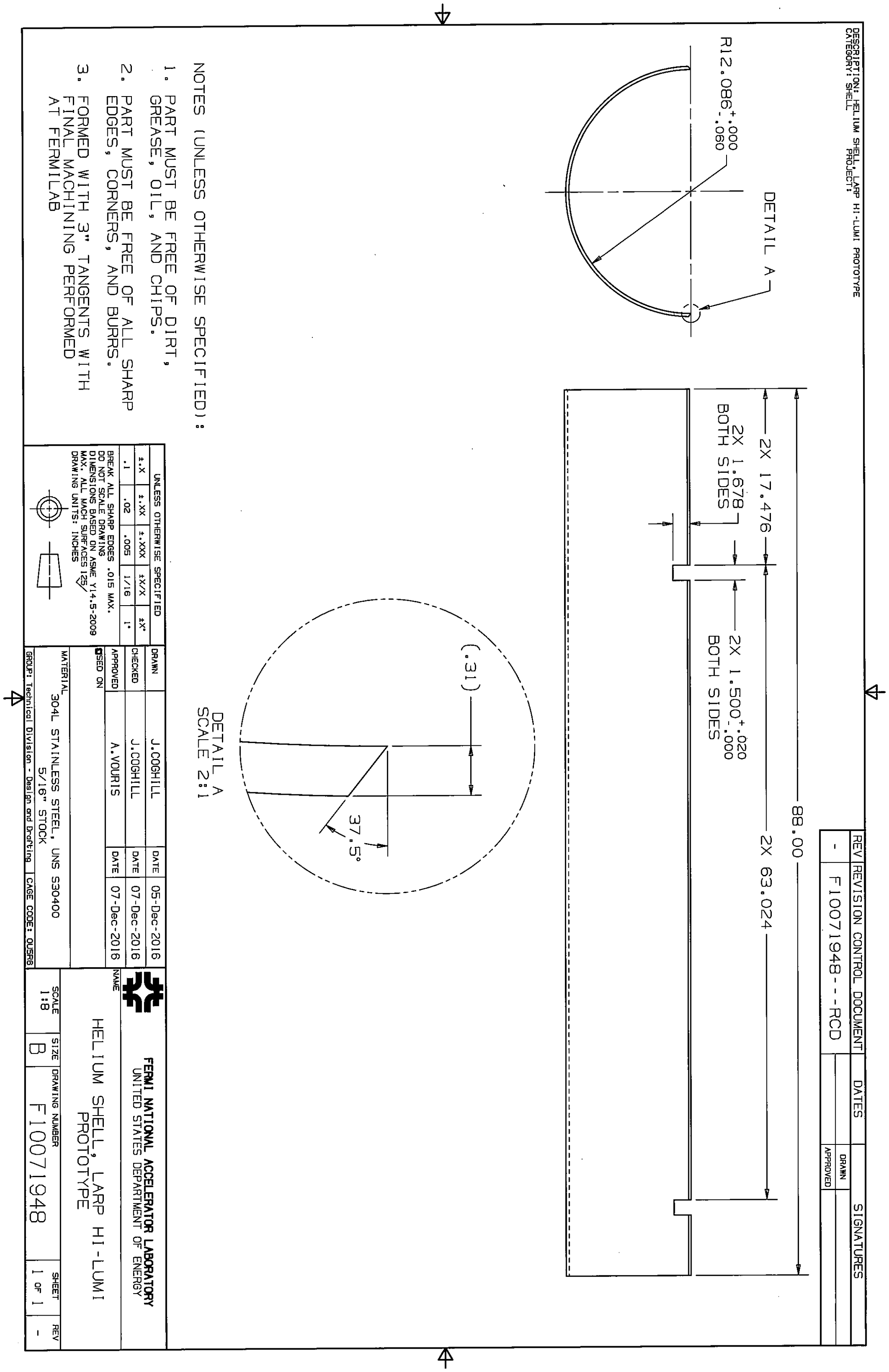
Dev. Length = Circ. – root opening (x 2) + weld shrinkage of 1 mm per weld (x2)

= 24.199" π – (2x) .094" + (2x) .045" – 0.020" = 75.904"

75.904/2 = 37.952 per half shell (see Appendix A for detailed calculation)

Both half shells will be measured from top dead center to distribute an equal amount of developed length on both sides of the center line.

5.3. Design Drawings of the Shell

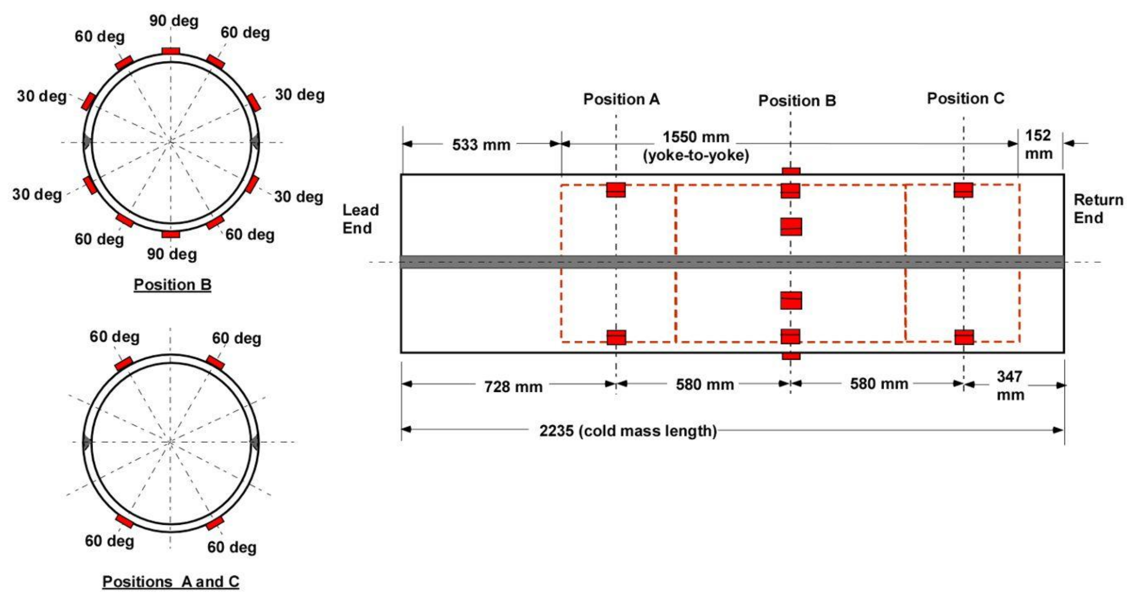


6. Shell Instrumentation to Monitor Stress Development

Clamps for rotating the cold mass will be placed at the junction between shell sections. Stations will be placed at the middle of each aluminum shell section so that they do not interfere with placement of the clamps. There are stations at 30, 60 and 90 degrees at the middle, and only at 60 degrees near the ends. We will attempt to infer the 30 and 90 at the ends from the combination of the others. The Figure below is a schematic to identify strain gauge positions.

The traditional method of shell gauge application is to use single elements (quarter bridges) placed so the active direction is azimuthal, and add one or two temperature compensators (single elements on stainless steel plates that do not undergo stress). Most gauges in this application will be quarter bridges as described about, but full bridges will be used at a few selected locations to attempt to assess whether bending or longitudinal strain is affecting the readings. The full bridges will be placed at the 60 degree angle in quadrants 1 and 3 at positions A, B and C. Two temperature compensators will be used, one placed near each end of the cold mass.

QXF Cold Mass Weld Test Strain Gauge Station Positions



7. Shell Fabrication and Installation onto the Magnet

Modifications of the shell began on MQXFS1d after testing was completed at VMTF and removed from the test dewar. The following steps need to be followed to install the He pressure shell:

- Step 1 – remove all external sensors, wires, instrumentation and/or strain gauges that will interfere with shell installation or inhibit the interface between the MQXF aluminum shell OD and the stainless shell pressure vessel ID.

Fig. 7.1 External instrumentation, wiring & gauges that were on MQXFS1d were removed.

- Step 2 – Wrap/protect/package magnet with plastic prior to sending MQXFS1d to Village Machine Shop for modifications per Section 3 above. All seams and openings shall be sealed with putty or plastic to prevent dirt, cutting fluids, lubricants or shavings from getting trapped in the MQXF Assembly. Once everything is sealed and confirmed by an engineer, machining can proceed to:
  - Remove guide pins – 3 each.
  - Drill & tap holes – 4 each.
  - Mill slots to allow for backing strip mounting beyond magnet ends and into stainless steel end plates.

- Step 3 - Set up work station at IB3: Weld table with rollers (see figure 7.2 below)

Fig. 7.2 MQXFS1 Magnet in cold mass weld station

- Step 4 – Shell Fit up
  - Install tack blocks with fasteners
  - Install both backing strips and weld in place to tack blocks
  - Fit & tack 6” wide 5/16” thk shims to MQXFS1C bottom half – spaced to align with rollers (The shims will adjust magnet center and allow a balanced 360 degree roll).
  - Fit and tack weld upper half shell on top side of magnet. The stainless steel shell shall be fit to allow 0.02” gap between magnet aluminum shell and stainless ID at 90 degrees away from seem. This will allow a root gap opening (3/32” total between shell edges). Note: use clamp fixture to draw shell onto magnet.
  - Roll 180 degrees, remove 6” wide spacers and install lower shell – similarly as done with top half (allowing 0.02” gap at 90 degrees from seam and a total gap of 1/16” at the weld seam).
- Step 5 – Install strain gauges to stainless steel shell per Section 6 (Prior to welding).

- Step 6 – Complete GMAW welding
  - Utilize two welders, start GMAW welding per written weld procedure on both seams simultaneously from same end (3 passes – 1 root & 2 covers).
    - Step 7 – Visually inspect shell welding and analyze strain gauge results.
      - Step 8 – Proceed with testing: He leak test, NDT (RT), etc.

Fig. 7.3 Weld equipment

8. References

1. Heng Pan's calculation; December 15th, 2017 presentation
2. Miller Invision 450P Power source, manual
3. Miller S-74 MPa plus wire feeder, manual
4. Buggo MPD1000 carriage system, manual

9. Appendix A – Calculation details of Shell Weld Preparation

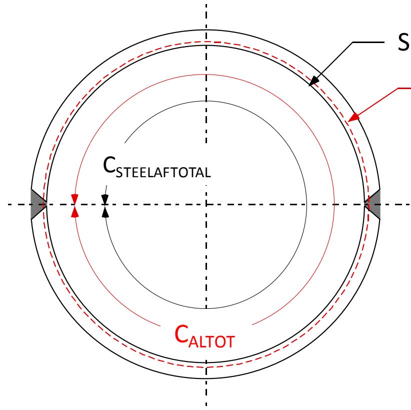


Fig. A.1

- C_{ALTOT} =Total Circumference of Outside surface of Aluminum shell
- $C_{STEELAFTOT}$ = Total Circumference of Inner surface of Steel shell after welding
- Measured dia. of Aluminum Shell O.D. = 614.657 mm = 24.199 in.
- *Criteria to achieve correct tightness after welding*: $C_{STEELAFTOT} = C_{ALTOT}$ - .020 in.
- C_{ALTOT} = 24.199 in. x ∏ = 76.023 in.
- $C_{STEELBEFTOT} = C_{STEELAFTOT}$ + Total Shrinkage during welding
- Total shrinkage during welding = .090 in. (over entire azimuth) = .045 in. per side.
- Therefore, $C_{STEELBEFTOT}$ = 76.023 in. -.020 in. + .090 in. = 76.093 in.
- And the inside diameter of the steel before welding is 76.093/ ∏ =24.221 in.

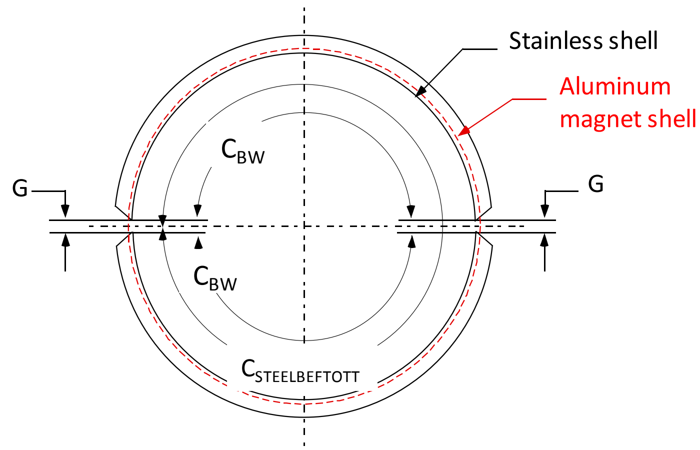


Fig. A.2

- C_{BW} = Circumference of inside of steel shell half before welding
- G = Gap size before welding per side = .094 in.
- $C_{STEELBEFTOT} = C_{BW} + C_{BW} + G + G$
- Therefore, $C_{BW} = (C_{STEELBEFTOT} - 2G)/2$
- Therefore, C_{BW} = (76.093 in. – .188 in.)/2 = 37.952 in.

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