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ENGINEERING AND FABRICATION OF THE HIGH GRADIENT STRUCTURE FOR COMPACT ION THERAPY LINAC

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Abstract

RadiaBeam is fabricating a novel ultra-high gradient linear accelerator for the Advanced Compact Carbon Ion LINAC (ACCIL) project. The ACCIL is an Argonne National Laboratory (ANL) led project, in collaboration with RadiaBeam, designed to be capable of delivering sufficiently energized carbon ions and protons while maintaining a 50 m footprint. This is made possible by the development of S-Band 50 MV/m accelerating structures for particles with beta of 0.3 or higher. Such high gradient accelerating structures require particular care in their engineering details and fabrication process to limit the RF breakdown at the operating gradients. The details of fabrication and engineering design of the accelerating structure will be presented.

BACKGROUND

When it comes to cancer treatment, there are a wide variety of treatment options. Usable cancer treatment devices need to be able to successfully produce 200-250 MeV protons and/or 400-450 MeV/u carbon ions [1]. Currently, cyclotrons and synchrotrons are most commonly used to do this; however, their large footprint can make them very expensive to manufacture. Additionally, dose confinement of protons using these devices is less precise compared to carbon ion therapy [2]. ACCIL will be capable of producing 450 MeV/u $^{12}C^{6+}$ ions and 250 MeV protons while maintaining a small footprint. This is possible due to the development of an high gradient accelerating structure capable of providing 50 MV/m for particles with beta from 0.3 to 0.7 [3]. The novel structure will operate at the -1st harmonic and will produce 50 MV/m gradient at peak fields of <160 MV/m [4]. However, for the high gradient structure to successfully perform, particular care and attention to detail must be applied when producing and assembling the RF components of the structure.

ENGINEERING DESIGN

A 15 cell RF profile was designed, as shown in Fig. 1. A manufacturable accelerator structure was then designed around the vacuum profile with the intention of assembly through brazing. The final design consists of two coupler bodies, thirteen cells, and four cooling blocks as shown assembled in Fig. 2. Two cells are designed to bond to the couplers and one is a mirror cell used to ‘flip’ the mating features in the cell stack. The final mechanical design of the cells was driven by the RF and thermal designs, with acute consideration for the ease of assembly, handling, and tuning of the structure, along with generous vacuum pumping capabilities.

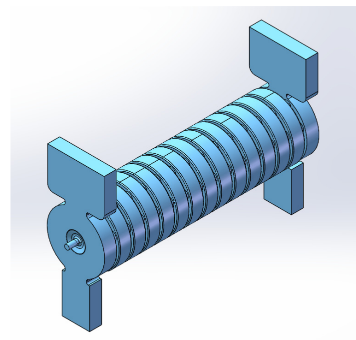

Figure 1: ACCIL high gradient structure RF profile.

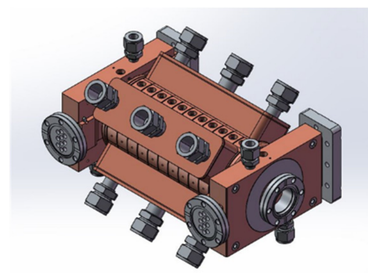

Figure 2: ACCIL high gradient structure assembly model.

The main cells have male and female mating features which are used to both align the cells with each other, and braze the cells together. The mirror cell has two male mating sides which are used in mating one of the main cells with the output coupling cell. Both of the coupling cells have female mating features used to either mate with the mirror cell or a main cell. Between cell and coupler mating features, a nominal gap of .0005” was preserved to both hold the RF profile to specification and allow braze alloy to flow. All but the mirror cells have tuning ports. These ports will house a custom tuning pin that will be used to manipulate the RF volume until the structure is tuned. Manipulation of RF volume is done through deformation of the thin wall that is at the base of the tuning pins. Finally, each main cell and coupler body was equipped with thermocouple holes. This feature is used to position a thermocouple during braze cycles to monitor the parts temperature without needing to contact the RF surfaces of the parts.

The couplers also had their profile designed after the RF profile that was developed, but a particular care was given to design the part such that certain tool ratios were followed. Namely, radii in the coupler bodies were selected such that the ratio between the diameter of the cutter used and the cut length did not exceed 1:3. This allows us to successful machine RF profiles that meet profile and finish

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requirements. Conductance holes were also integrated in the couplers to allow for better vacuum pumping capacity.

To successfully cool the high power structure, the cooling blocks shown in Fig. 3 were designed. Particular attention was given to preserving tuning pin access. The cooling blocks consist of one central inlet and two outlets that allow an even cooling gradient to develop across the cells. Cooling is also integrated into the couplers via machined cooling channels.

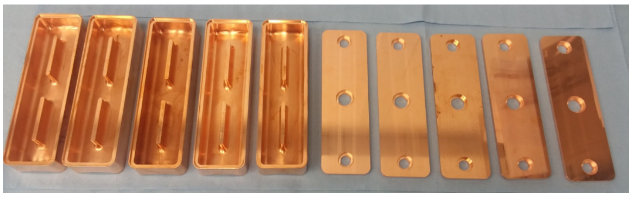

Figure 3: ACCIL structure cooling blocks.

PART FABRICATION

It was anticipated that cells and coupler bodies would be the most challenging components to machine. As such, we conducted a variety of tests to hone in machining practices and programs for manufacturing, with a particular focus on achieving an acceptable profile and surface finishes.

Figure 4 shows that the RF surface of our first test main cell was well out of specification. As we can see in the profile shown in Fig. 4, while one side has an even error to it across the flat, the other side does not. In fact, the error has a slope that increases as we get closer to the center axis of the part. This is largely due to the way the cell blanks were designed. In an attempt to minimize the differences between machining each cell and the amount of machine setups needed to turn the cells, a universal blank was designed to produce the like cells. This blank, shown in Fig. 5, uses a dovetail to get chucked into the CNC lathe-mill. The dovetail allows the part to successfully get chucked into the mill-lathe in such a fashion that the radial features of each cell can get machined without breaking the active machine setup. However, the downside to this feature is that the clamping pressure of the lathe-mill when holding onto the dovetail is not applied directly over the main cell wall. As a result of this, when the cell gets chucked, the cell outer diameter wall gets crushed since there is no supporting material where the pressure is applied. This in turn, results in the main cell wall bowing outwards. As the lathe runs its course, it cuts into the material more than needed as it gets closer to the center axis of the part, resulting in the sloped error observed. This error is not seen in the opposite side of the cell wall because when this profile gets machined, the cell is clamped over the main cell wall such that the dove tail can get machined off.

To address this, a stainless steel disk was made to fit in the universal cell blanks such that when the disk was fitted into the blank, it would rest in the same plane as the dovetail. This would allow the clamping pressure to be distributed across the disk, which in turn would reduce the bowing of the main cell wall. This, along with adjustments to the tool paths and feeds and speeds were done until an

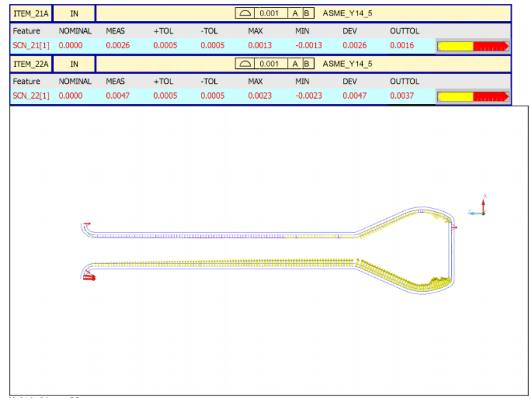

Figure 4: ACCIL structure cell #11 first test piece.

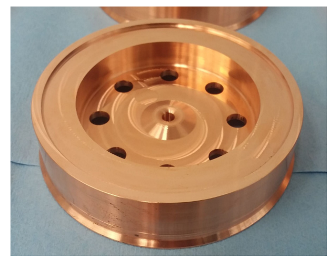

Figure 5: ACCIL structure main cell universal blank.

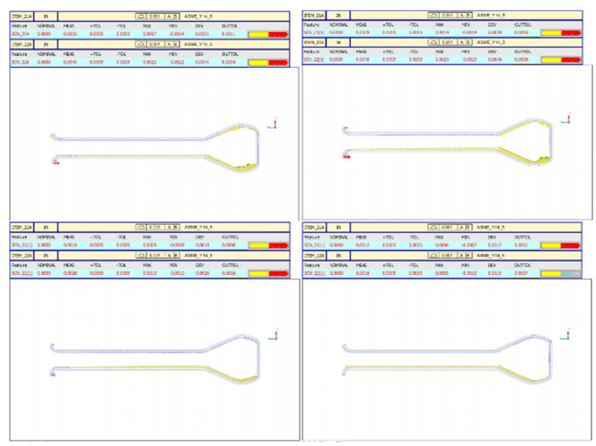

Figure 6: ACCIL cell #11 development progression. Final accepted surface finish Ra = 3-4 μin

acceptable part was produced. The progress of the tests can be seen in Fig. 6. Cell fabrication continues with the proofed procedure.

Like cell development, the coupler bodies also required some feature prototyping. The main feature that needed to be proven out were the surface profile and finish of the iris in the coupler bodies. Test pieces of this feature were machined and inspected until a satisfactory profile and surface finish was produced as we can see in Fig. 7. To achieve the final acceptable profile and finish, machining tools, tool paths, and feeds and speeds were modified and recorded. With the proven process parameters, final coupler body manufacturing continued and successfully produced the desired parts shown in Fig. 8.

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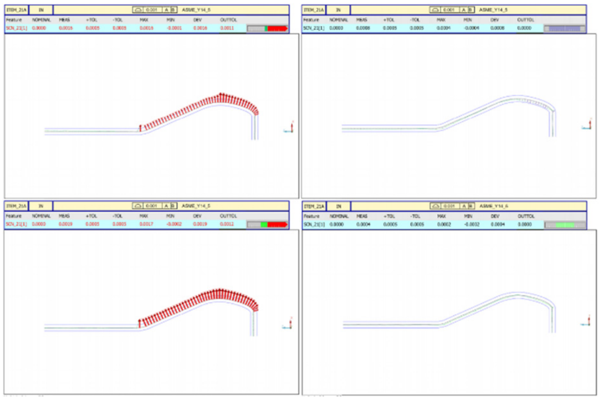

Figure 7: ACCIL Coupler Iris Development progression. Final accepted surface finish Ra = 6-8 µin.

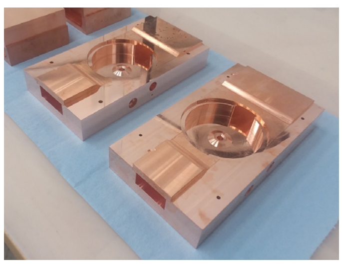

Figure 8: ACCIL final input and output couplers with cover.

ASSEMBLY

As parts continue to get produced, assembly of the components can begin. The final structure will be vacuum brazed together in steps that will utilize 25% Au – 75% Cu, 35% Au – 65% Cu, and 50% Au – 50% Cu alloys. It is important to limit the thermal cycles that the RF surfaces experience to minimize erosion at the joints and deterioration on the actual RF surfaces. Furthermore, four brazing thermal cycles are the most any RF surface will experience as the system gets brazed together. Said surfaces will be found in the couplers. The couplers have already gone through their first stage of brazing shown in Fig. 9. These parts are now undergoing dry machining in preparation for the remaining brazing operation. It is important to note that prior to going through a first braze operation, all components are subjected to a Citronox based cleaning, with the exception of RF facing components that are finished with a modified version of the SLAC C01 etching formulary. Once cleaned or brazed, components are bagged and stored in dry nitrogen gas to protect parts from oxidation. All components are handled with gloves from the start of machining to protect critical surfaces from oils. Parts are always securely transported in heavy duty cases to protect parts from potential collisions.

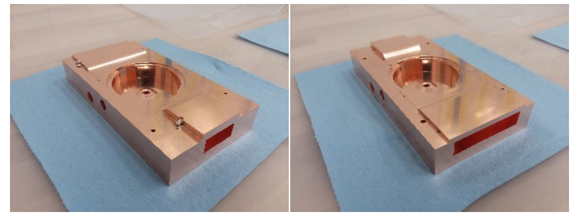

Figure 9: ACCIL brazed input and output couplers.

FUTURE WORK

Cell fabrication has proven to be the bottle neck in the manufacturing of this structure. Cell fabrication is estimated to be completed by the time of this publication, and brazing of the structure is expected to be completed by October 2019. Once the brazing operations have been completed and vacuum hermeticity validated, the structure will be tuned on a purpose built test stand. The cell tuning will be performed through manual bi-directional manipulation via integrated tuning pins. To understand how much each cell needs to be manipulated, bead pull measurements will be conducted. The bead pull measurement allows allow us sample the field inside the structure cells via changes in resonance frequencies or phase shifts due to small perturbations generated by the bead [4]. Depending on the changes observed, the cell radial volume is adjusted until the cell is in phase. The process is repeated for each cell until the entire structure is in resonance.

CONCLUSION

The development of a high gradient structure requires a lot of attention to detail and proofing out. Care must be implemented to both achieve acceptable RF surfaces and profiles, and maintain those surfaces and profiles through assembly. Cell fabrication continues with the coupling and mirror cells. Once these components are completed, brazing of the structure can continue. Currently, the couplers have undergone their first braze cycles and are being machined in preparation for their next brazing operation. Once the structure is full brazed and hermetic, it will go on to get tuned before getting shipped to ANL for high power testing.

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