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FABRICATION OF SPLIT-SECTION X-BAND STRUCTURE USING ELASTIC AVERAGING

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Abstract

Conventional accelerator structures are manufactured using axial stacks of cylindrical components which, when brazed together, form the accelerator cell structure. Splitting the accelerator structure into two sections along the beam axis allows for a significant reduction in part count and vacuum joint length. The resultant single and coplanar vacuum joint between the two split sections allows for joining techniques such as electron beam welding or brazing of the parts to form the accelerator vacuum envelope. High precision alignment of the two sections is achieved through an elastic averaging interface coupling where improved accuracy is derived from the averaging of errors over a large number of relatively compliant contacting members. The monoblock split sections allow for highly optimized cooling configurations with enhanced heat removal in high heat flux regions, reducing vacuum wall thermal stresses and enabling higher power operation. This paper describes the engineering and manufacturing of four generations of brazed and electron beam welded X-band accelerator structures at both 9.3 GHz and 11.4 GHz frequencies.

INTRODUCTION

Accelerators traditionally are constructed through axial stacking of individual cylindrical cell or half-cell piece parts. These structures require a minimum part count of n+1, where n is the number of accelerating cells. Cell geometry and RF coupling details only escalate this minimum part count, as in the case of structures with side RF coupling which requires 2n+1 parts. For X-band structures with cell counts in the dozens, this results in a large number of piece parts with many braze joints between individual cells. Each of these braze joints represents increased assembly complexity and increased vacuum joint failure risk.

An alternative approach involves the splitting of the structure into two parts along the beam axis to reduce the part count to two quasi-symmetrical pieces with a single co-planar vacuum joint. Key challenges of this method include the high shape accuracy required for the fabrication of the split section monoblocks, as dimensional accuracy needs to be preserved over the entire length of accelerating cells versus just for a single cell length. Positioning errors accumulate over the length of the entire structure whereas in the structure made of cylindrical parts it is independent of the structure length. The most significant challenge is the relative alignment of the two split sections [1]; high accelerating gradients and surface electric fields require very high alignment precision, a challenge exacerbated by the high process temperatures required for typical joining methods. Building upon recent advances in extending the application of ultra-high precision mechanical couplings to high temperature and high electric gradient vacuum applications [2], the sections were joined with an ultra-high precision alignment technique using an elastic averaging interface coupling.

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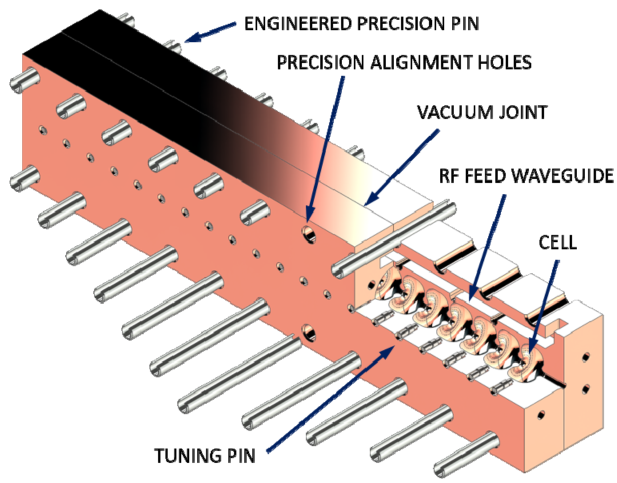

Figure 1: Cut-away view of split section accelerating structure showing the precision alignment features.

ELASTIC AVERAGING

The principle of elastic averaging states that the accuracy of an interface can be improved by averaging errors using controlled compliance between precision surfaces. The key to elastic averaging is to have a large number of features spread over a broad region that elastically deform when separate parts are forced into geometric compliance with each other. As the system is preloaded, the elastic properties of the material allow for the size and position error of each individual contact feature to be averaged out over the sum of the contact features throughout the solid body. Although the repeatability and accuracy obtained through elastic averaging may not be as high as in deterministic systems, elastic averaging design can allow for higher stiffness, lower local stress, and improved load robustness when compared to exact constraint designs. In a well-designed and preloaded elastically averaged coupling, the repeatability is approximately inversely proportional to the square root of the number of contact points [3].

The elastic averaging coupling is implemented in the accelerating structures through a large number of precision engineered compliant metal alloy pins which interface with the split sections through cylindrical alignment features machined throughout the structure (Figure 1).

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Figure 2: Pair of split monoblocks prior to assembly.

11.4 GHZ X-BAND STRUCTURES

Monoblock Fabrication

The split sections (Figure 2) are manufactured using ultra-precise machining operations. Metrology of the machined sections using a Zeiss scanning Coordinate Measurement Machine (CMM) allows for a detailed two and three dimensional contour mapping of the machining errors (Figure 3). Typical machining errors on the RF cell features were found to be 7 µm. The metrology results show the dependence of the shape error on the three dimensional gradient of the feature, demonstrating the potential for further process improvements by compensating for gradients in the machining process.

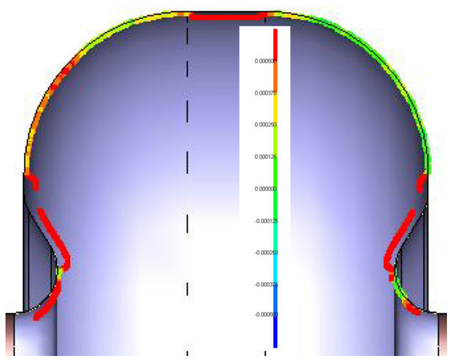

Figure 3: Scanning CMM inspection contour of a sample accelerating cell with deviation shown in inches. The maximum deviation is 7 µm.

Joining Methods

Brazing The primary fabrication method for joining the split section and providing a vacuum joint is high temperature brazing using a copper gold alloy. This technique was used to fabricate the first accelerating structure shown in Figure 4.

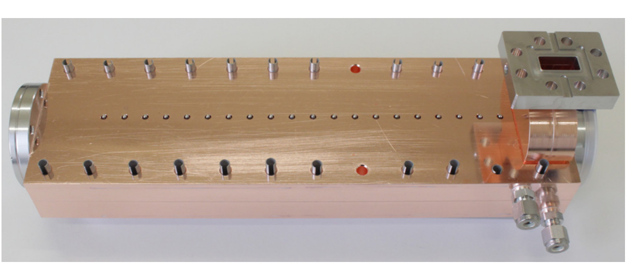

Figure 4: 11.4 GHz brazed 20 cell accelerating structure.

Electron Beam Welding An alternate method of joining the split sections is electron beam welding (EBW). The EBW process limits the heating of the copper base material to the welding zone of only a few millimeters, preserving the hard copper alloy properties. The ability to fabricate a structure with hard copper alloys, versus copper which has been annealed through a brazing process, provides a multitude of benefits. Hard copper has a finer grain structure; copper grain sizes are significantly enlarged through high temperature processing such as a braze cycle. Larger grain sizes with grain dislocations along the boundaries limit the obtainable electric gradients in an accelerating device. Additionally, elimination of the braze filler material has the potential to improve process control and enhance dimensional control.

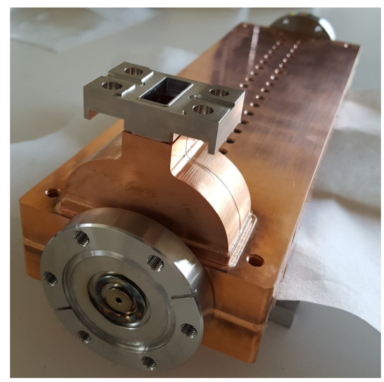

Figure 5: 11.4 GHz electron beam welded accelerating structure with 20 cells fabricated in hard copper alloy.

The electron beam welded structure (Figure 5) was fabricated from hard copper alloy monoblocks which were joined by electron beam welding. Frequency tuning capability was provided by incorporating thin wall regions into each RF cell which can be locally plastically deformed post assembly to fine tune the resonant frequency of each cell. The e-beam welded structure is in the process of being evaluated.

9.3 GHZ X-BAND STRUCTURES

A second set of structures operating at 9.3 GHz were developed and constructed; a 20 cell accelerating structure (Figure 6) and a 4.5 cell RF gun (Figure 9).

These structures included further refinements in the thermal management of the structures. Thermal Computational Fluid Dynamics (CFD) and mechanical Finite Element Analysis (FEA) optimizations were utilized to take advantage of the greater coolant layout flexibility in the monoblock compared to a conventional accelerator structure of axially stacked cups, where coolant routing is restricted by the large number of braze joints and the desire to avoid vacuum to water braze joint interfaces.

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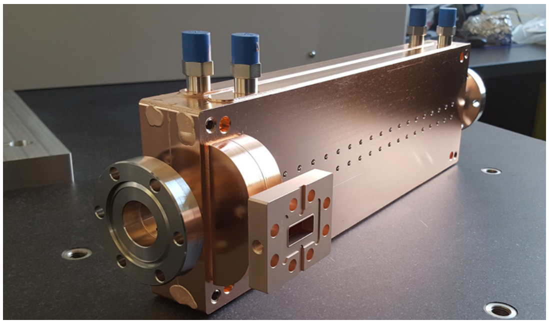

Figure 6: 9.3 GHz X-band brazed accelerating structure.

The thermal performance of the structures was optimized using ANSYS Fluent CFD analysis. The accelerating structure features a multitude of coolant channels perpendicular to the beam axis. These permit direct cooling of individual RF cells with minimal wall thickness between vacuum and wet wall, thereby reducing the structure temperature and gradients.

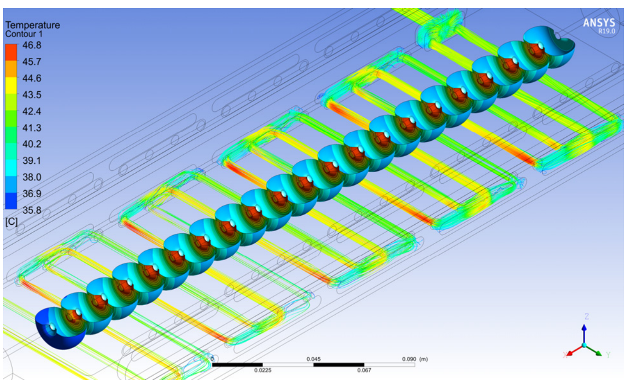

Figure 7: Temperature (°C) of the accelerating cells with 30 °C coolant inlet temperature. Maximum average temperature is 46.8 °C and maximum pulsed temperature is 49.3 °C. Streamlines show the relative coolant velocity in the fluid cooling channels.

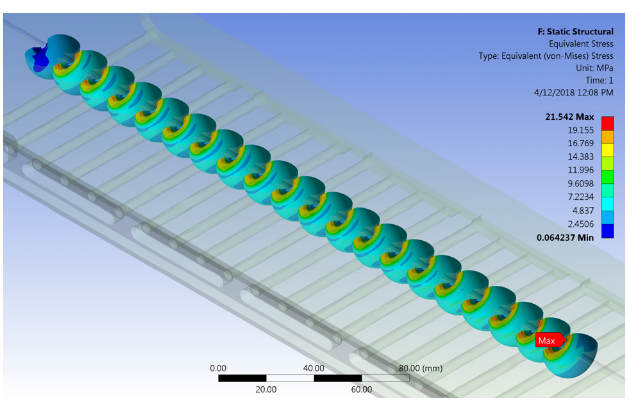

Figure 8: Von-Mises Stress (MPa) on the cell walls with 2.5 kW average power loading. Maximum stress is 21.5 MPa.

With a coolant inlet temperature of 30 °C and an average power loading of 2.5 kW, the simulation of the gun structure reaches a maximum temperature of 46.8 °C (Figure 7). Due to the highly optimized cooling configuration the temperature distribution across the cells remains fairly uniform with a maximum variation of approximately 11 °C. The results of the thermal analysis were used to perform a 3D ANSYS Mechanical stress analysis; the peak stress is 21.5 MPa at the first iris (Figure 8). The effect of the pulse RF heating of the cell structure was investigated with a 3D ANSYS Mechanical thermal and stress analyses. The peak pulse surface heating is 49.3 °C, resulting in a peak stress of 25.8 MPa. The average and peak stresses are well below the 40 MPa elastic limit of annealed copper, limiting electric gradient reducing grain growth, and plastic deformation of the cell surfaces over the operational life time.

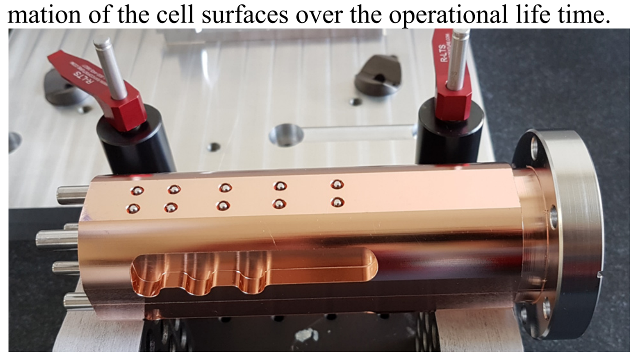

Figure 9: 9.3 GHz RF gun 4.5 cell structure.

The RF gun structure (Figure 9) was designed with a similarly optimized thermal design [4]. The open bore geometry on the downstream side of the RF gun structure allows for post-braze mechanical CMM inspection of key internal RF cell features, including the irises and cathode surface. An extended reach measurement stylus on a Zeiss scanning CMM was utilized to for direct mechanical evaluation of the alignment precision between the two split sections. The measurements showed an RMS alignment precision of 5 µm between the two sections in the assembled braze structure.

CONCLUSION

A range of X-band accelerating structures at 11.4 and 9.3 GHz have been fabricated from monoblock split sections utilizing the elastic averaging method for high precision alignment between halves. The measured RMS alignment accuracy of the interior RF cell features of the assembled structures was better than 5 µm. This alignment precision exceeded the high precision machining cell shape tolerances. In addition to providing ultra-high precision alignment the monoblock construction allows for highly optimized cooling configurations with enhanced heat removal in high heat flux regions. These enhancements reduce operating temperatures and vacuum wall thermal stresses, thus enabling high electrical gradient and higher power operation. The developed technology provides significant overall accelerating structures cost reductions, due to the reductions in part count and braze joints.

The 11.4 GHz accelerating structures are being operated at SLAC National Accelerator Laboratory [5] and the 9.3 GHz structures will be used to produce electron beam for the ASU Compact X-ray Light Source [6].

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