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DESIGN OF A HIGH-GRADIENT S-BAND ANNULAR COUPLED STRUCTURE*

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Abstract

At Argonne, we have recently developed a conceptual design for a compact linear accelerator for ion beam therapy, named ACCIL. A linac-based ion-beam therapy facility offers many advantages over existing synchrotron based facilities. In addition to the reduced footprint, ACCIL offers more flexibility in beam tuning, including pulse-per-pulse energy and intensity modulation and fast switching between ion species. Essential to the compactness of the ACCIL linac are high-gradient structures for low to intermediate velocity ions, capable of accelerating fields of ~ 50 MV/m. For this purpose, we have designed an S-band annular-coupled structure (ACS). An ACS has the desired qualities of high electric field limit, high shunt-impedance, large area for magnetic coupling and good cooling capacity, making it a very promising candidate for high-gradient operations. We here present the optimized design for a β ~ 0.4 ACS.

INTRODUCTION

High-gradient R&D is well established for velocity-of-light electrons. Recently at the high-power RF Test Facility of the APS, we have demonstrated a gradient of 52 MV/m for a velocity-of-light S-band (2856 MHz) electron beam structure [1]. Such a high gradient is yet to be demonstrated for low velocity ions as R&D in this field started only recently. In the velocity range of β=v/c ~ 0.3, the accelerating cell is short and compact, making electric breakdowns and power dissipation a real challenge to reliably operate these high-gradient structures. R&D in this field is being pursued at CERN [2] and other European institutions, and most recently in the US. In collaboration with RadiaBeam through an SBIR project, we started the development of a β ~ 0.3 traveling-wave structure capable of delivering 50 MV/m [3]. This structure was designed to operate at the negative spatial harmonic which elongates the cell making it more suitable for β ~ 0.3. However, more development is needed to cover the whole β ~ 0.3-0.7 velocity range with the appropriate accelerating structures for the ACCIL linac [4]. Standing wave π/2-mode options such as the annular-coupled structure (ACS) are promising candidates for β ~ 0.4 and higher, capable of similar performance. Standing-wave structures are generally more desirable because they can be more compact and require less power in addition to being simpler to tune and operate. The ACS structure has been employed at lower gradients in the JPARC linac [5], but has not been investigated for high-gradient operation. Here, we developed an optimized design for a 2856 MHz β ~ 0.4 ACS structure. Along with the RF design, the tuning and cooling systems, as well as thermal analysis results and the proposed fabrication procedure are presented.

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RF DESIGN

The annular-coupled structure (ACS) is made of alternating accelerating and coupling cells. Coupling cells are annular rings surrounding accelerating cells. Magnetic coupling is ensured by windows cut between each coupling cell and two neighboring accelerating cells. Figure 1 shows the ACS geometry with 3 accelerating cells and two coupling cells.

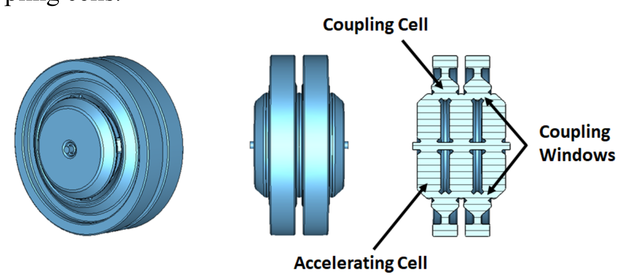

Figure 1: Geometry of an ACS structure with 3 accelerating cells and 2 coupling cells.

Following the RF design optimization of a single cell, a full cavity model with 15 accelerating cells and 14 coupling cells was built. The coupling window size was optimized to provide enough coupling to avoid higher order modes (HOMs) and stabilize the field for the main mode. The geometry of the end cells, especially the gap was adjusted to produce a flat field distribution along the structure. Figure 2 shows the electric field in the 15-cell cavity and the accelerating field along the structure. Table 1 lists the RF design parameters for the single cell and the coupled 15-cell structure. We clearly notice that the cell coupling significantly enhances the peak magnetic field and reduces the shunt impedance. While this is expected, further optimization of the coupling windows may be required to reduce the peak surface field. Two important criteria for pulsed high-gradient operations are also listed, these are the pulsed heating [6] and the modified Poynting vector [7]. While the latter is related to the voltage breakdown rate, the former has to do with the mechanical stability and lifetime of the structure.

TUNER SYSTEM DESIGN

The design frequency for this cavity is 2856 MHz. Machining errors can be controlled down to 5 μm for certain dimensions like the inner cavity radius, while they can be up to 25 μm for other dimensions, especially after assem-

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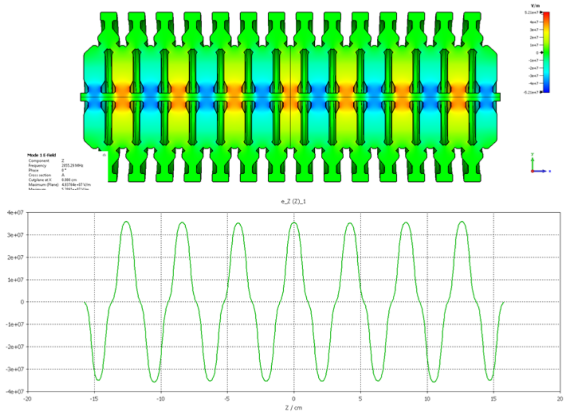

Figure 2: Electric field distribution in the 15-cell structure (top) and on-axis accelerating field profile (bottom).

Table 1: RF Design Parameters for a β ~ 0.4 ACS Structure

Parameter	Desired Value	Single Cell	15-Cell Cavity
Q-factor	10000	9640	8300
Shunt Impedance (ZT^2), MΩ/m	50	47.3	38.3
E_{peak}/E_{acc}	< 3	2.97	3.23
B_{peak}/E_{acc}, mT/(MV/m)	< 3	3.13	10.01
E_{peak} @ 50 MV/m, MV/m	150	148.5	161.6
B_{peak} @ 50 MV/m, mT	150	156.5	500.5
Pulse heating (1 µs), ΔT (°C)	< 50	11.0	34.6
Poynting S_{peak}, MW/mm^2	-	11.0	12.1
Modified Poynting S^c_{peak}, MW/mm^2	< 2.5	2.2	2.42

bly and brazing. Due to the high frequency and small features of the cavity, a tuning system is needed. Since this cavity is designed to operate at gradients of 50 MV/m or higher, a penetrating tuner may enhance the local field and lead to an increase of voltage breakdown rate. Therefore, we opted for a deformation tuner that slightly deforms the inner wall of the accelerating cell inward or outward to get the right frequency. In addition, the tuners will be used to flatten the longitudinal field along the structure. Based on sensitivity studies of frequency and field to the tuners, we decided to have two tuners per accelerating cell, rotated 90 deg from one cell to the next. This alternation allows enough space for the tuner assembly, and also counteracts any field asymmetry from the tuners. Figure 3 shows the tuners locations with respect to the coupling windows. They are located at 45 deg from the coupling windows, where the field sensitivity is higher.

Figure 4 shows the tuning system assembly originally designed as penetration tuner, and will be modified for deformation tuning. Figure 5 shows how the tuners were suc-

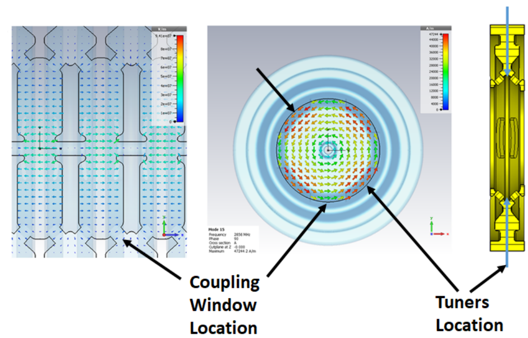

Figure 3: Tuners location with respect to coupling windows.

cessfully adjusted to compensate for field distortions due to randomly generated cell radius errors of up to 25 µm.

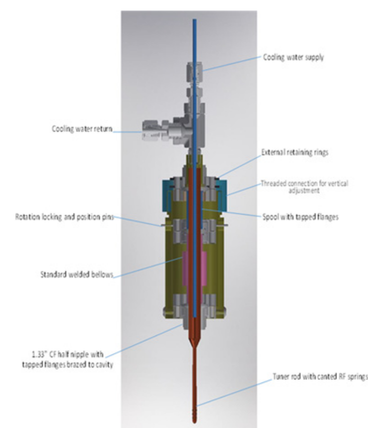

Figure 4: Tuner design and system assembly.

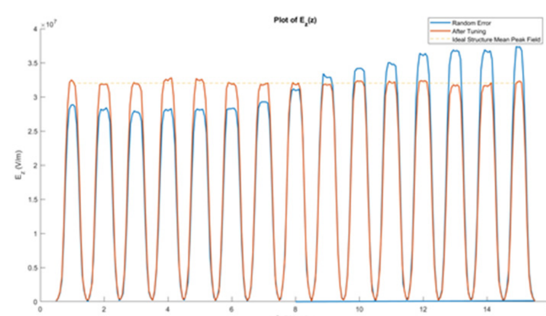

Figure 5: Longitudinal field profile (absolute value) along the structure including errors (blue) and after tuner adjustment for both frequency and flat field (red).

COOLING DESIGN AND THERMAL ANALYSIS

Based on power loss calculations using CST, the average power dissipation for 50 MV/m accelerating field is ~ 2.5 kW. Figure 6 shows the power loss distribution on the cavity surface for 1/8 of the geometry with peak losses on the coupling windows. A water cooling system was designed to properly carry out the lost power and cool the structure. The cooling channel design is shown in Fig. 7, and the re-

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sults of the thermal analysis assuming a typical 4-bar pressure drop are shown in Fig. 8 with a maximum temperature increase of 18 C.

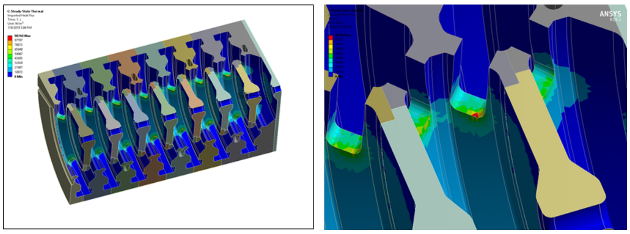

Figure 6: Loss distribution for 2.5 kW average power.

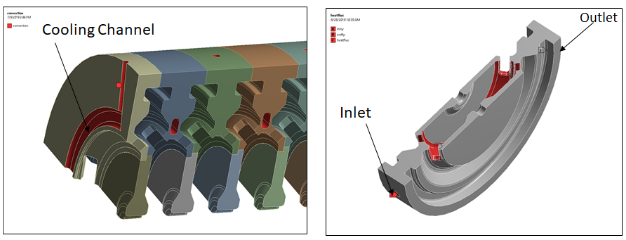

Figure 7: Cooling system design showing the cooling channels inlet and outlet.

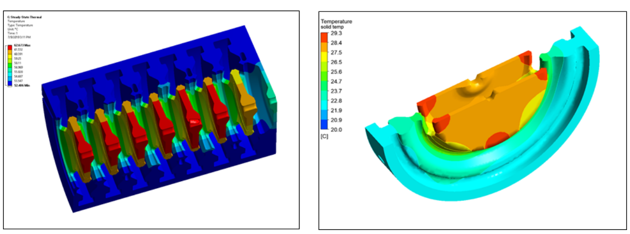

Figure 8: Temperature distribution assuming 4-bar pressure drop, the maximum temperature gradient is ~ 18 C.

FABRICATION PROCEDURE

The proposed fabrication procedure for the ACS cavity is shown in Fig. 9. The structure is split in the middle of the coupling cell with two disks closing the accelerating cell. Following the machining of individual cells and disks, the 15-cell cavity will be assembled by properly stacking the building blocks and brazed.

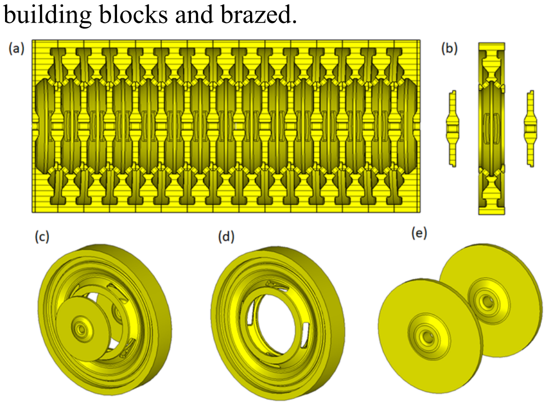

Figure 9: Fabrication procedure. (a) and (b) shows how the cavity is split into cells and disks. (c), (d) and (e) show how a single cell is built of a ring and two disks.

Figure 10 is a photo of a single cell where the body is 3D printed from white plastic and the disks 3D printed from transparent plastic. The photo also shows one tuner assembly and the inlets and outlets of the cooling channels.

Figure 10: Photo of a 3D-printed single cell with one tuner assembly and inlets and outlets of cooling channels.

SUMMARY

A design for a 2856 MHz $\beta \sim 0.4$ ACS structure has been developed for high-gradient operation as part of the compact carbon linac ACCIL. Following rf coupler design and full engineering analysis, a prototype of the cavity will be built and high-power tested at the APS high-power test facility at Argonne.

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