DESIGN OF HALF-REENTRANT SRF CAVITIES FOR HEAVY ION LINACS*

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Abstract

The Spallation Neutron Source (Oak Ridge), the proposed 8 GeV Proton Driver (Fermilab), and the proposed Rare Isotope Accelerator use multi-cell elliptical SRF cavities to provide much of the accelerating voltage. This makes the elliptical cavity segment the most expensive part of the linac. A new type of accelerating structure called a half-reentrant elliptical cavity can potentially improve upon existing elliptical designs by reducing the cryogenic load by as much as 40% for the same accelerating gradient. Alternatively, with the same peak surface magnetic field as traditional elliptical cavities, it is anticipated that half-reentrant designs could operate at up to 25% higher accelerating gradient. With a half-reentrant shape, liquids can drain easily during chemical etching and high pressure rinsing, which allows standard multi-cell processing techniques to be used. In this paper, electromagnetic designs are presented for three half-reentrant cell shapes suitable for an ion or proton linac ($\beta = 0.47$, 0.61 and 0.81, frequency = 805 MHz or 1.3 GHz). The mechanical designs for single-cell prototypes have also been completed.

INTRODUCTION

Multi-cell elliptical superconducting radio frequency (SRF) cavities are used to accelerate ions with velocities greater than about 40% of the speed of light. Reentrant [1, 2] or half-reentrant [3, 4] cavities have the potential to improve upon the performance of traditional elliptical cavities.

With a half-reentrant shape instead of a fully reentrant shape, liquids can still drain out easily during chemical etching and high pressure water rinsing, and there is no risk of trapped gas pockets in the acid or liquid after rinsing. The half-reentrant cavity is etched in one orientation and then rotated by 180° for high-pressure water rinsing. The fully reentrant cavity, on the other hand, has a trapped gas pocket and volume of liquid that is difficult to remove, which becomes more problematic for multi-cell structures.

Reentrant cavities have improved electromagnetic performance parameters relative to traditional non-reentrant elliptical cavities. Half-reentrant cavity designs can reach nearly the same parameters as fully reentrant cavities. A half-reentrant cavity for $\beta = v/c = 1$, suitable for the proposed ILC, has been designed and fabricated [5], with RF tests in progress [6]. In principle, this cavity should be capable of reaching accelerating gradients in excess of 50 MV/m. A gradient of 25 MV/m has been reached in initial tests before post-purification.

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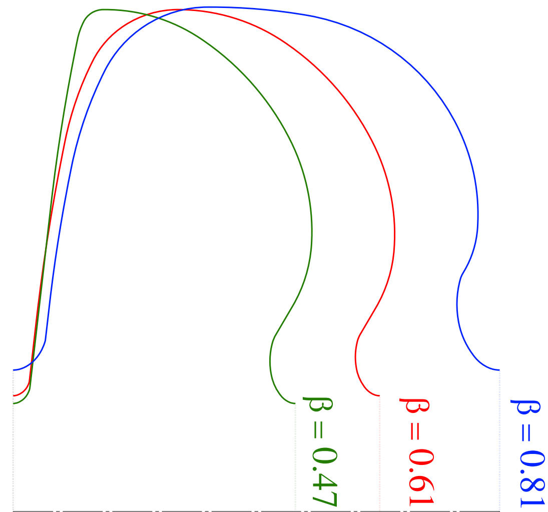

Figure 1. Cell shapes for reduced-β half-reentrant cavities.

Half-reentrant structures for velocities less than the speed of light can offer more significant gains than possible for $\beta = 1$ cavities because a larger fraction of the volume near the cavity's outer diameter is unused in the elliptical structure, but accessible for the inductive region of the reentrant and half-reentrant cavities. Figure 1 shows three reduced-β half-reentrant cell shapes.

Using 6-cell structures, three values of geometric β (0.47, 0.61 and 0.81), are needed to cover the range of velocities from about $\beta = 0.4$ to 1.0. The baseline elliptical cavities used for comparison are 805 MHz six-cell structures. The lowest-β cavity was developed by INFN-Milano, Jefferson Lab, and Michigan State University (MSU) for a heavy ion linac [7]; the last two cavities were developed for the Spallation Neutron Source (SNS) [8]. Figure 2 compares the half-reentrant and elliptical cell shapes.

ELECTROMAGNETIC DESIGN AND COMPARISON

Processing techniques have improved over the last several years, and this improvement is likely to continue. It is anticipated that higher peak surface electric fields (E_p) will be possible, but the peak surface magnetic field (B_p) will still be limited to about 200 mT due to the superconducting properties of niobium. Therefore, future designs can achieve a higher accelerating gradient (E_a) by decreasing B_p/E_a while allowing E_p/E_a to increase. In CW accelerators, the limit is generally not the peak magnetic field, but

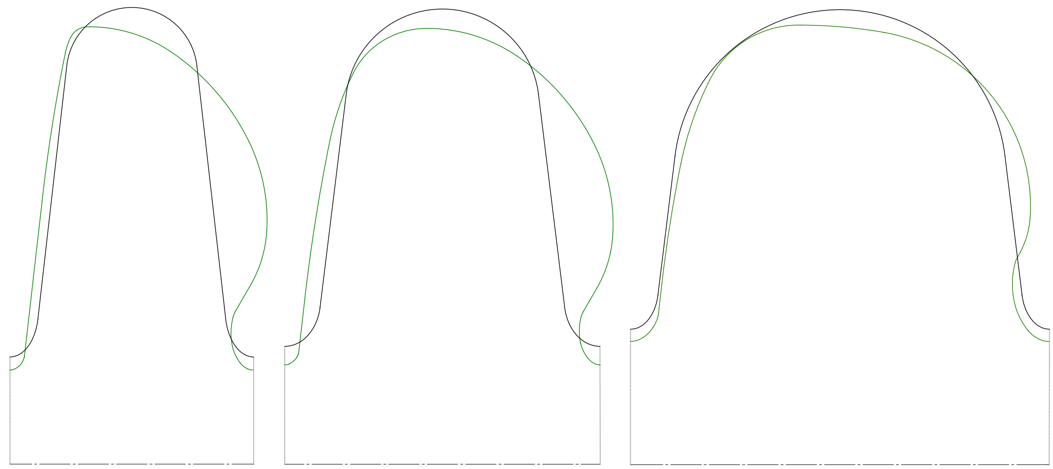

Figure 2. Comparison of cell shapes for non-reentrant cavities (RIA/SNS) and half-reentrant cavities. Left to right: $\beta = 0.47$, $\beta = 0.61$, and $\beta = 0.81$.

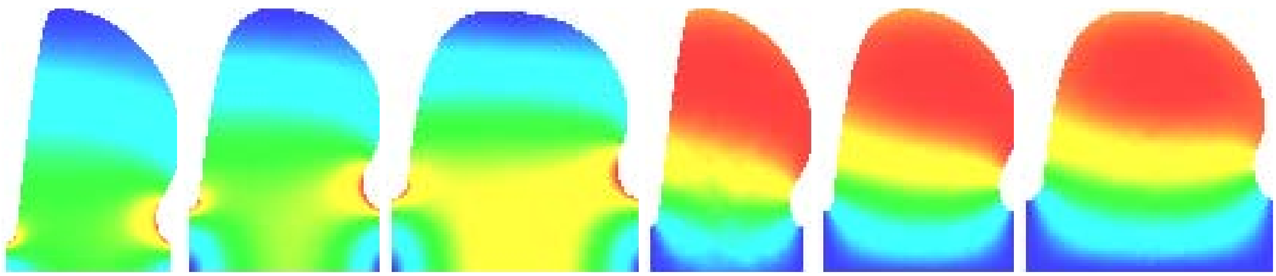

Figure 3. Electric (left) and magnetic (right) field maps for the half-reentrant cavities. Red indicates a large field magnitude and blue indicates a low field magnitude.

Table 1. Comparison of selected parameters for non-reentrant and half-reentrant (HR) cavities; E_a = accelerating gradient, E_p = peak surface field, B_p = peak surface magnetic field, R = shunt impedance (linac definition), Q = quality factor, G = geometry factor. Note that the cryogenic load is inversely proportional to $G \cdot R/Q$.

Type	RIA	HR	SNS/RIA	HR	SNS/RIA	HR	PD
geometrical $\beta = \beta_g$	0.47		0.61		0.81		
frequency (MHz)	805		805		805		1300
cell-to-cell coupling (%)	1.5		1.53		1.52		1.60
E_p/E_a	3.35	3.71	2.78	3.07	2.25	2.48	2.15
B_p/E_a [mT/(MV/m)]	6.47	4.74	5.43	4.39	4.58	4.04	4.58
R/Q per cell (Ω)	28.6	41.5	49.2	64.2	83.7	95.9	82.0
G (Ω)	136	166	176	204	227	243	226
$G \cdot R/Q$ (Ω^2)	3890	6900	8660	13100	19000	23300	18500
aperture (mm)	77.2	67.8	86.0	76.2	97.6	88.8	61.0

rather the cryogenic load, so the improved cryogenic performance of the advanced designs is the attractive feature.

The half-reentrant cavities were designed for the same geometric β values (0.47, 0.61 and 0.81) as the elliptical cavities. They have the same cell-to-cell coupling. Figure 3 shows the RF field distributions for each case. Table 1 gives the electromagnetic design parameters. The values for the SNS and RIA cavities are included for comparison, along with the parameters of a 1.3 GHz $\beta = 0.81$ seven-cell elliptical design [9]. The parameters given in Table 1 are for the case of a periodic structure (a multi-cell cavity in the limit in which the number of cells goes to infinity). The values were obtained from numerical calculations using SUPERFISH [10] and Analyst [11].

The results of Table 1 are displayed graphically in Figure 4, which shows the difference in selected performance parameters between the half-reentrant and elliptical cavities. At the expense of a small ($\sim$ 10%) increase in peak electric field (squares) and a modest aperture reduction (circles), the reduction in peak magnetic field (diamonds) and cryogenic load (triangles), is a significant benefit, especially at the lower velocities.

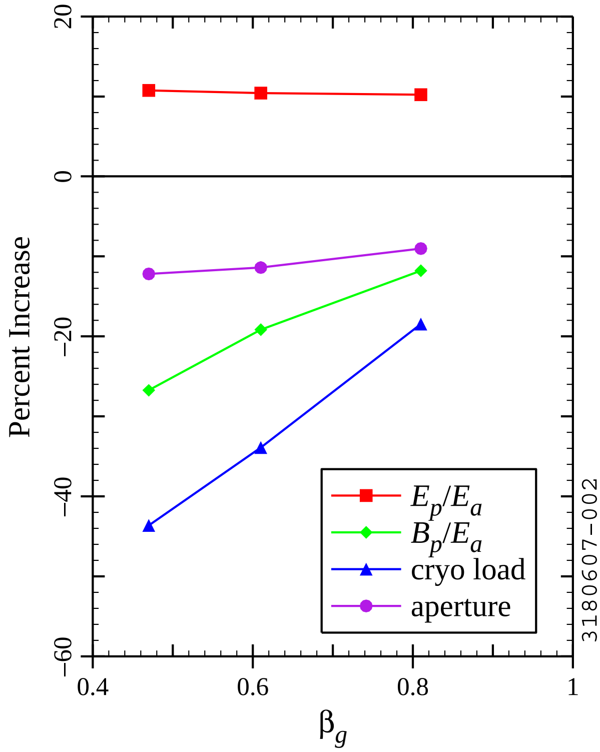

Figure 4. Figures of merit for half-reentrant cavities relative to elliptical cavities (SNS/RIA) as a function of geometrical β.

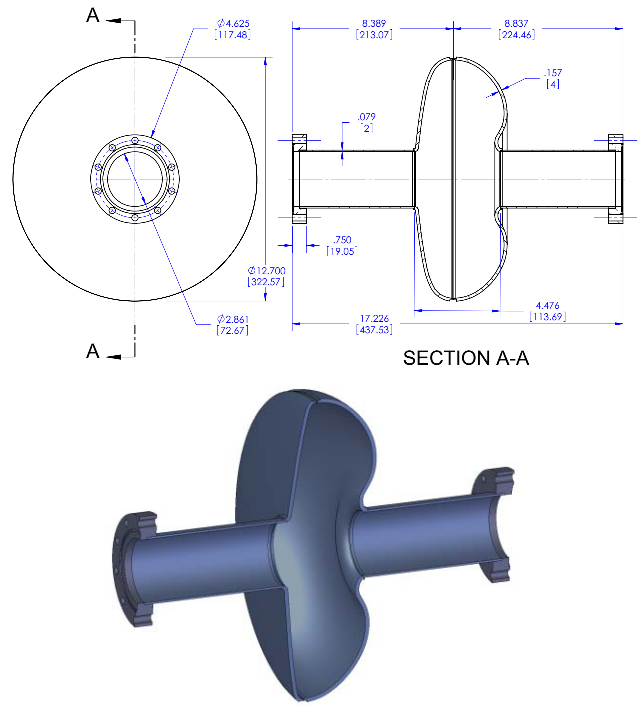

Figure 5. Two-view drawing (top) and isometric sectional view (bottom) of the 805 MHz $\beta = 0.61$ single cell prototype.

SINGLE-CELL MECHANICAL DESIGNS

Mechanical designs for single-cell prototypes of half-reentrant $\beta = 0.47$, 0.61, and 0.81 cavities have been completed. Figure 5 shows the $\beta = 0.61$ case. The cavities would be fabricated from 3–4 mm thick niobium and scale inversely with frequency for 1.3 GHz cavities.

CONCLUSION

The half-reentrant design offers the possibility of significantly higher accelerating gradient or significantly lower cryogenic load relative to traditional multi-cell elliptical cavities, while still allowing for effective surface preparation via traditional etching and high-pressure rinsing. There are additional performance advantages at lower velocities, which offers the possibility of using multi-cell elliptical cavities for lower velocities such as $\beta = 0.3$ to 0.4. Fabrication and testing of single-cell $\beta = 0.47$, 0.61 and 0.81 half-reentrant cavities is pending support.

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