Design of Half-Reentrant SRF Cavities

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Abstract

The shape of a TeSLA inner cell can be improved to lower the peak surface magnetic field at the expense of a higher peak surface electric field by making the cell reentrant. Such a single-cell cavity was designed and tested at Cornell, setting a world record accelerating gradient [1, 2]. However, the disadvantage to a cavity is that liquids become trapped in the reentrant portion when it is vertically hung during high-pressure rinsing. While this was overcome for Cornell's single-cell cavity by flipping it several times between high pressure rinse cycles, this may not be feasible for a multi-cell cavity. One solution to this problem is to make the cavity reentrant on only one side, leaving the opposite wall angle at six degrees for fluid drainage. This idea was first presented in 2004 [3]. Preliminary designs of two new half-reentrant (HR) inner cells have since been completed, one at a high cell-to-cell coupling of 2.1% (high-k$_{cc}$ HR) and the other at 1.5% (low-k_{cc} HR). The parameters of a HR cavity are comparable to a fully reentrant cavity, with the added benefit that a HR cavity can be easily cleaned with current technology.

CODES AND GEOMETRY

The code used to optimize the cell shape was Analyst [4], which calculates parameters within 2% of SUPERFISH. Table 1 compares the results of Analyst to SUPERFISH for the TeSLA inner cell geometry. Analyst was used because it allows periodic boundary conditions with a phase advance of 180° to be placed on the far left and right surfaces of Figure 1. Periodic boundary conditions are required for a HR cell because the electric field is not exactly perpendicular to the beam axis on those boundary surfaces as is the case with a symmetrical cell shape.

Table 1: Comparison of TeSLA inner cell parameters using Analyst versus SUPERFISH.

		SUPERFISH	Analyst
frequency	[MHz]	1301	1301
E_{peak}/E_{acc}	[-]	1.95	1.99
B_{peak}/E_{acc}	$[\frac{mT}{MV/m}]$	4.17	4.17
R/Q	[Ω]	113.3	113.5
G	[Ω]	271.2	270.9
k_{cc}	[%]	1.90	1.86

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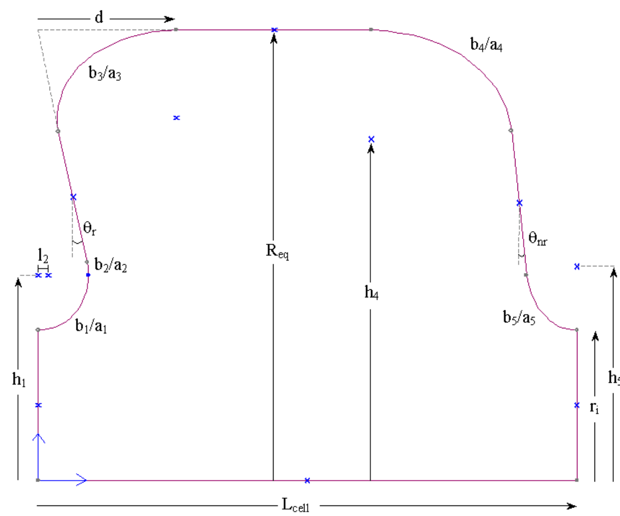

Figure 1: Half-reentrant inner cell geometry.

The geometry used for the HR shape is shown in Figure 1. The geometrical parameters in Figure 1 have been modified from the proposed shapes to make them clearly identifiable. The reentrant half of the cell consists of two ellipses in the iris region connected by a straight section to an ellipse in the high magnetic field region. The non-reentrant half consists of one ellipse in the iris region connected by a straight section to an ellipse in the high magnetic field region. In addition, there is a straight section along the top of the cell. Four conditions were placed on the cavity geometry: the length of the cell equals $\lambda/2$, the equatorial radius is set to maintain a frequency of 1300 MHz, the slope of the cavity wall must be continuous, and the non-reentrant wall angle (θ_{nr}) is 6°. With these four conditions, there are twelve remaining geometrical variables. If fluids are shown to easily drain from the non-reentrant wall, the wall angle could be reduced to less than 6° and improved cavity parameters would be expected.

COMPARISON OF INNER CELLS

The inner cell geometry primarily determines the parameters of a multi-cell cavity. Table 2 lists the inner cell parameters for TeSLA [5], the reentrant cavity fabricated at Cornell [6], and a low-loss cavity designed for the CEBAF upgrade [7]. Table 3 lists the results from simulations of the two proposed HR inner cells and compares them to a proposed low-loss cavity for the International Linear Collider [8]. Figure 2 compares the geometry of the proposed

Table 2: Inner cell parameters for three existing cavity designs.

		TeSLA	Cornell Reentrant	CEBAF Low-Loss
frequency	[MHz]	1300	1300	1500
E_{peak}/E_{acc}	[-]	2.00	2.40	2.17
B_{peak}/E_{acc}	$[\frac{mT}{MV/m}]$	4.26	3.78	3.74
R/Q	$[\Omega]$	115	121	129
G	$[\Omega]$	270	280	280
$(R/Q)\cdot G$	$[\Omega^2]$	31050	33768	36103
k_{cc}	[%]	1.87	2.38	1.49
r_i	[cm]	3.5	3.5	2.65

Table 3: Parameters of the two proposed half-reentrant inner cells compared to the proposed Low Loss ILC geometry.

		High-k_{cc} HR	Low-k_{cc} HR	Low Loss ILC
frequency	[MHz]	1300	1300	1300
wall angle	[°]	6	6	0.165
E_{peak}/E_{acc}	[-]	2.40	2.38	2.36
B_{peak}/E_{acc}	$[\frac{mT}{MV/m}]$	3.78	3.60	3.61
R/Q	$[\Omega]$	123	135	134
G	$[\Omega]$	283	283	284
$(R/Q)\cdot G$	$[\Omega^2]$	34673	38021	37970
k_{cc}	[%]	2.09	1.51	1.52
r_i	[cm]	3.34	2.97	3.00

high-k_{cc} HR shape to a TeSLA inner cell.

B_{peak}/E_{acc} Ratio

There are two approaches to achieving higher accelerating gradients: using a material with a higher RF critical magnetic field than Nb to increase the theoretical maximum accelerating gradient, or improving the cell shape to lower B_{peak}/E_{acc}. The latter was done for the two proposed HR cells by making the cell reentrant on one side, thus increasing the inductance at the expense of E_{peak}/E_{acc}. B_{peak}/E_{acc} for the high-k_{cc} HR shape is the same as Cornell's reentrant cavity. The low-k_{cc} HR shape reduces B_{peak}/E_{acc} 15.5% below that of a TeSLA inner cell, making it comparable to the Low Loss ILC cavity. For the proposed low-k_{cc} HR shape, with a B_{peak} of 185 mT, an accelerating gradient of 51 MV/m is foreseeable.

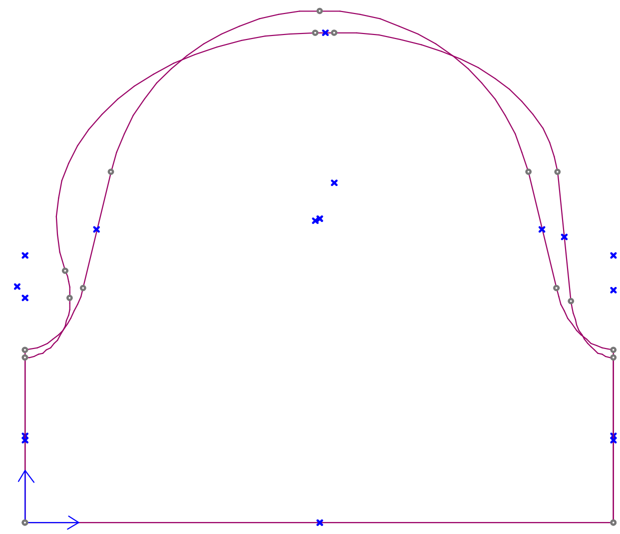

Figure 2: Comparison of proposed high-k HR shape to a TeSLA inner cell.

E_{peak}/E_{acc} Ratio

For both HR shapes, and reentrant shaped cavities in general, a lower B_{pk}/E_{acc} comes at the expense of a higher E_{peak}/E_{acc}. However, E_{peak}/E_{acc} must be kept tolerable for high-gradient cavities. For both of the proposed HR shapes, E_{peak}/E_{acc} was chosen to be no more than 2.40, as a world record of E_{acc} was already achieved with a cell designed with this value [2].

Shunt Impedance and Geometry Factor

A higher $(R/Q)\cdot G$ lowers the cavity losses for a given surface resistance and accelerating gradient:

$$P_{wall} = \frac{R_s(E_{acc}L_{cell})^2}{(R/Q)\cdot G}$$

Both HR shapes have excellent $(R/Q)\cdot G$ values. We see that for the high-kcc HR shape, $(R/Q)\cdot G$ is comparable to the reentrant cavity built at Cornell, and that $(R/Q)\cdot G$ for the low-k_{cc} HR shape is 5% higher than the low-loss cavity designed for the CEBAF upgrade, which was specifically optimized for $(R/Q)\cdot G$. Additionally, for constant RF power and voltage gain, a higher (R/Q) allows a smaller Q_{ext}, making the cell less susceptible to microphonics.

Cell-to-cell coupling

A measure of the sensitivity of the field profile of the accelerating mode to frequency errors of individual cells is $N^2/(\beta\cdot k_{cc})$, where a lower number is desirable. The values for the TeSLA shape, a nine-cell high-k_{cc} HR shape, and a nine-cell low-k_{cc} HR shape are 4330, 3880, and 5360, respectively. The lower value of the high-k_{cc} HR shape may allow a ten-cell cavity to be built with tolerable frequency errors. For some applications, a high cell number is not required, in which case a lower cell-to-cell coupling could be used, which would further improve the electromagnetic performance of the cell.

It is desirable to have a large aperture because wake fields decrease as the aperture increases. While the aperture for both the high-k_{cc} and low-k_{cc} HR shapes are smaller than that of TeSLA, the low-k_{cc} HR aperture radius is only 0.9 mm smaller than the low-loss design for the CEBAF upgrade, from which adequate dipole mode suppression was attained [7].

Electric and Magnetic Fields

The fields in the π-mode were calculated using Analyst, as shown in Figures 3 and 4 for the high-k_{cc} HR shape. Fields along the surface of the cell are shown in Figures 5 and 6. The dip in the magnetic field is 2.4% below the peak surface magnetic field, and the dip in the electric field is 3.3% below the peak surface electric field. Fine tuning of the HR shape could lower these values to 2%, which may further improve the cavity parameters by 1-2%. The fields could be further flattened by adding more geometrical variables, namely replacing every ellipse with a series of three arcs. The expected gain in cavity performance would be 1-2% [6]. Multipacting simulations still need to be done for the proposed HR cell shapes.

CONCLUSION

Two new HR cell shapes have been designed. Simulations show that electromagnetic parameters of the high-k_{cc} and low-k_{cc} HR shapes are comparable to a fully reentrant shape and the Low Loss ILC shape, respectively. However, the advantage of a multi-cell HR cavity to a fully reentrant cavity is that it can be readily cleaned with current technology. When compared to the Low Loss ILC shape, the low-k_{cc} shape has a 6° wall angle, which means the cavity can be more easily cleaned and therefore may reach higher gradients. The HR shape should also be beneficial for cavities designed for particle speeds less than the speed of light. Fabrication and testing of a single-cell HR cavity are planned to be completed by the end of this year.

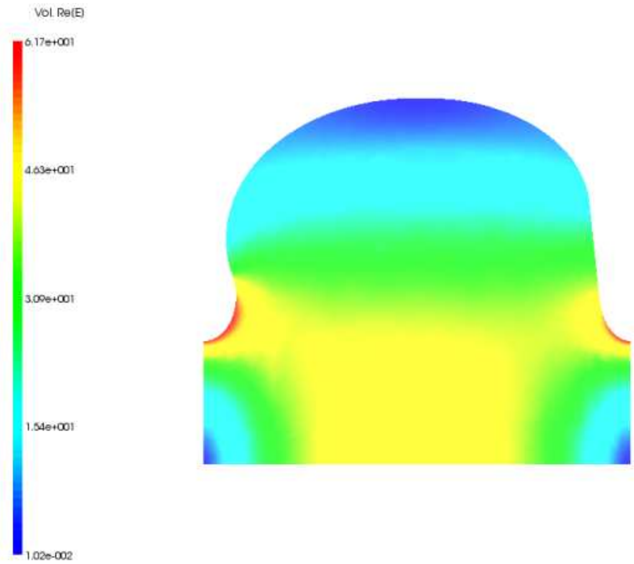

Figure 3: Electric fields of high-k_{cc} HR shape.

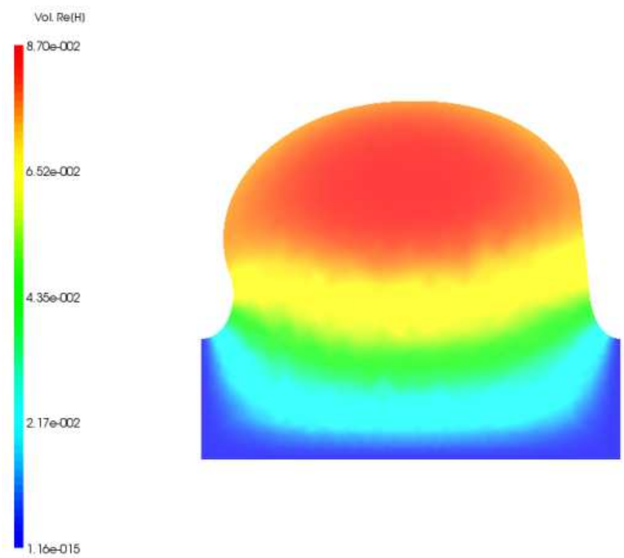

Figure 4: Magnetic fields of high-k_{cc} HR shape.

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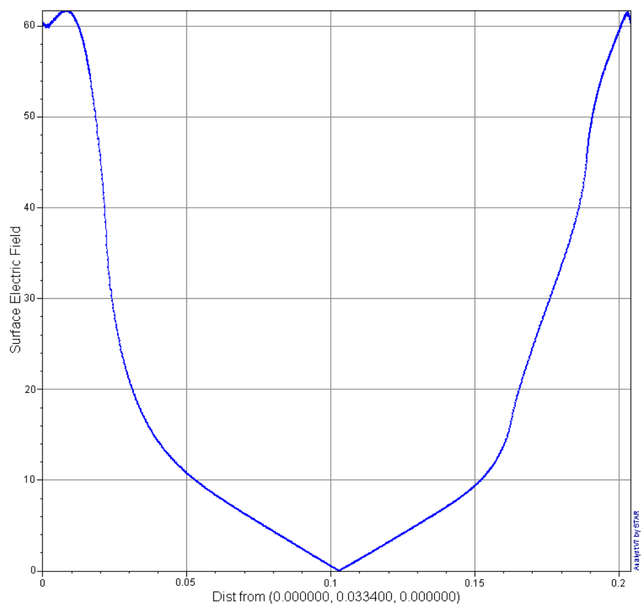

Figure 5: Surface electric field for high-k_{cc} HR shape.

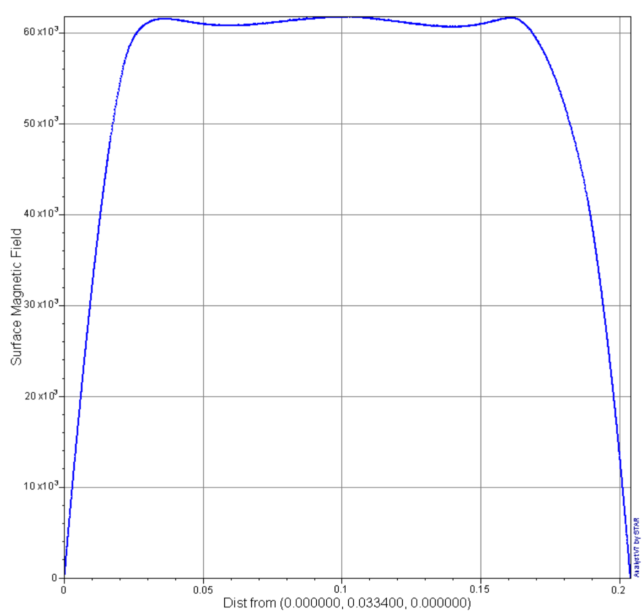

Figure 6: Surface magnetic field for high-k_{cc} HR shape.