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Original Publication Citation

Delayen, J. R., DeSilva, S. U., & Hopper, C. S. (2011). *Design of superconducting spoke cavities for high-velocity applications* [Conference Paper]. 2011 Particle Accelerator Conference, New York, New York. https://accelconf.web.cern.ch/PAC2011/papers/tup100.pdf

DESIGN OF SUPERCONDUCTING SPOKE CAVITIES FOR HIGH-VELOCITY APPLICATIONS

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Abstract

Superconducting single- and multi-spoke cavities have been designed to-date for particle velocities from $\beta_0 \sim 0.15$ to $\beta_0 \sim 0.65$. Superconducting spoke cavities may also be of interest for higher-velocity, low-frequency applications, either for hadrons or electrons. We present the design of double-spoke cavities optimized for $\beta_0 = 0.82$ and $\beta_0 = 1$.

INTRODUCTION

Accelerating cavities intended to accelerate light particles or high-energy heavy particles above $\beta_0 = 0.6$ to $\beta_0 = 0.8$ have typically been of the elliptical type [1]. Single and multiple-gap spoke cavities offer several advantages over their elliptical counterparts. Since the diameter of the cavity is on the order of $\lambda/2$, the frequency is half that of an elliptical cavity for the same transverse dimension. The lower frequency allows for 4 K operation as well as a higher voltage gain over a wider range of velocities [2, 3]. We report here on the design of double-spoke 352 MHz cavities of $\beta_0 = 0.82$ and 1.

ELECTROMAGNETIC DESIGN

One of the major goals of the electromagnetic design is to minimize the normalized electric and magnetic fields, E_p/E_{acc} and B_p/E_{acc}, where is the peak surface electric field, B_p is the peak surface magnetic field and E_p is accelerating electric field which is defined here for a double-spoke cavity as

$$E_{acc} = \frac{\Delta W(\beta_0)}{\beta_0 \lambda} \tag{1}$$

where $\Delta W(\beta_0)$ is the energy gain at the optimal velocity.

Optimization of Peak Surface Fields

The cavity's radius and iris-to-iris length are approximately determined by the operating frequency and desired β_0. The peak surface fields, however, depend greatly on the shape and dimensions of both the spoke base and the spoke aperture region. While both areas of the spoke affect the peak electric and magnetic fields, the shape and dimension of the spoke base have more of an effect on the surface magnetic fields [4] while the spoke aperture region is more influential on the peak surface electric fields [5]. For the purposes of this paper, we discuss only the spoke base optimization. All of the results presented are at a frequency of 352 MHz and $\beta_0 = 0.82$ or $\beta_0 = 1$.

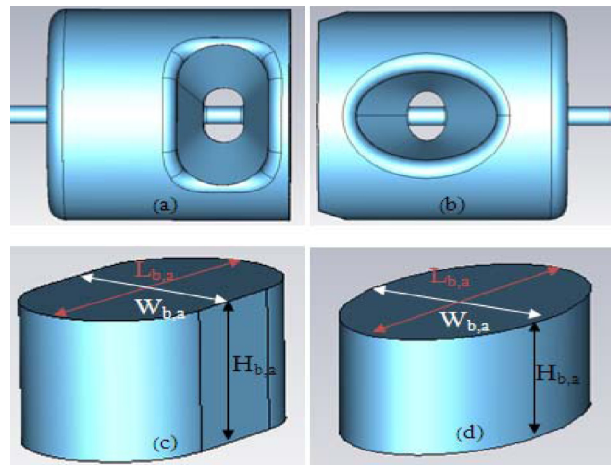

Figure 1: CST MWS view of half the cavity with a transverse racetrack design at the base and aperture (a) and longitudinal ellipse at the base and aperture (b). Racetrack part of spoke (c) and elliptical part of spoke (d). The dimensions of each carry a subscript a or b which refers to either the aperture or base.

For convenience, we will refer to the elongated dimension of the spoke (base or aperture, elliptical or racetrack) as either being longitudinal or transverse with respect to the beam line. Both the spoke base and aperture region have been investigated with the elliptical, cylindrical, and racetrack geometries. To determine the preferred shape and orientation of the spokes, we applied multiple approaches. First, 6 of the most important parameters as they relate to peak surface fields were identified. These are described in figure 1 as the length, width, and height of either the spoke base or aperture region. Fixing 5 of these parameters and adjusting the sixth to find the lowest peak surface fields achievable is one approach. Once this value is found, it can be fixed and another parameter can be varied until a new minimum is found. This second parameter can now be fixed and the first one can be adjusted once more just to ensure that this is in fact a minimum for both parameters. This process is repeated until all parameters are approximately optimized.

Other approaches included fixing 4 of the 6 parameters discussed here while varying the other two simultaneously, as well as using the 'Optimization' feature in CST Microwave Studio (MWS). Figure 2 shows B_p/E_{acc} vs. E_p/E_{acc} for many combinations of racetrack and

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Part of this work was done in collaboration with and supported by Niowave Inc. under the DOE STTR Phase I program.
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elliptical spoke base and aperture regions. These designs were obtained during the optimization process, meaning that as the different spoke parameters were varied, the peak fields were plotted. The straight lines in figure 2 represent different ratios of B_p/E_p, which are measures of the balance of the design with respect of the technological limitations on the performance of superconducting cavities. We can see that depending on the particular expected achievable peak fields (*e.g.* 80 mT and 35 MV/m for B_p/E_p = 2.3), the choice of cavity parameters may be different. At this time, we have chosen to further investigate a design which falls low on the line representing B_p/E_p = 2.3 (as indicated in figure 2).

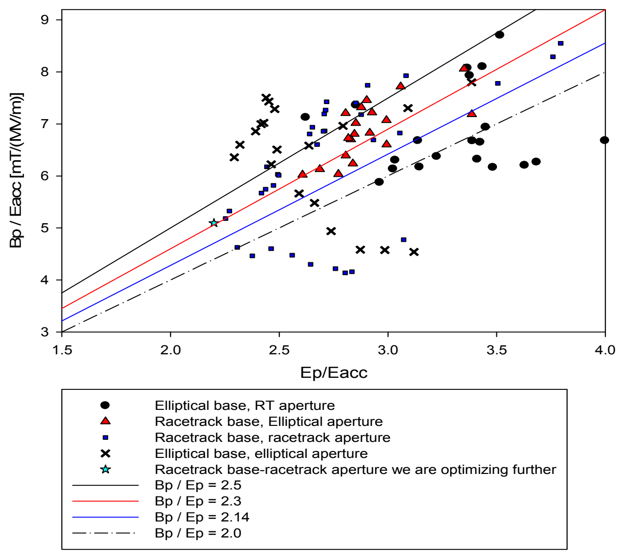

Figure 2: Normalized surface magnetic field vs. electric field for many different racetrack and elliptical base parameters.

Table 1 summarizes the spoke shape combinations and the associated peak fields after an initial optimization has been performed.

In figure 3, the normalized peak magnetic field is plotted as a function of W_b/L_b. The longest dimension of the spoke base being in the longitudinal direction with respect to the beam line is represented in figure 3 when W_b/L_b is greater than 1. This ratio being less than 1 represents what is referred to here as a transverse spoke orientation. A ratio of 1 indicates a cylindrical spoke base.

The data presented in figure 3 was acquired by fixing the spoke base height, H_b, and either the width, W_b or the length, L_b, depending on if the base is oriented longitudinally or transversely. All of these data also has been taken with the spoke aperture region oriented in the transverse direction because other optimization processes found this gives the lowest E_p/E_{acc}, which is consistent with what has been found previously [4, 5].

Another interesting observation from figure 3 is that it appears that the transverse racetrack spoke base orientation provides lower peak surface magnetic fields than that of the longitudinal one. The difference is less pronounced with the elliptical spoke base. This is also apparent in figure 2 which shows that the lowest fields simulated (both electric and magnetic) have the racetrack geometry for both the base and aperture region, both of which are oriented in the transverse direction.

Table 1: Peak Surface Fields for Various Combinations of Racetrack and Elliptical Spokes

Spoke base	**Spoke aperture region**	**Ep/Eacc**	**Bp/Eacc** mT/(MV/m)
		2.35	5.42
		2.49	5.56
		2.96	5.87
		2.61	6.02

Based on these findings, cavities with the transverse racetrack geometry for both the base and aperture being further optimized. Figures 4 and 5 show how normalized magnetic and electric fields change as the spoke base length (as a ratio of rf wavelength) is varied. In figure 4, B_p/E_{acc} continues to decrease as the base length gets larger; however there is a significant loss in accelerating voltage.

Tables 2 and 3 contain the physical dimensions and rf characteristics we have been able to simulate to date.

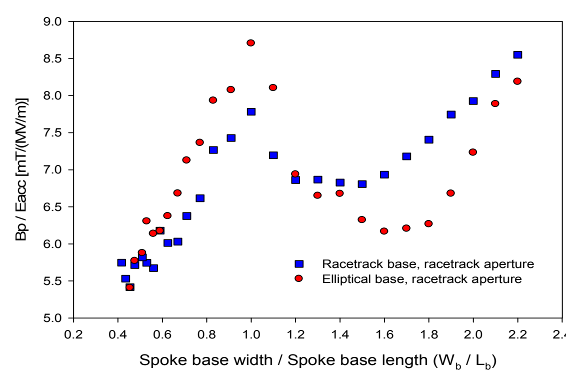

Figure 3: Normalized surface magnetic field vs. W_b/L_b.

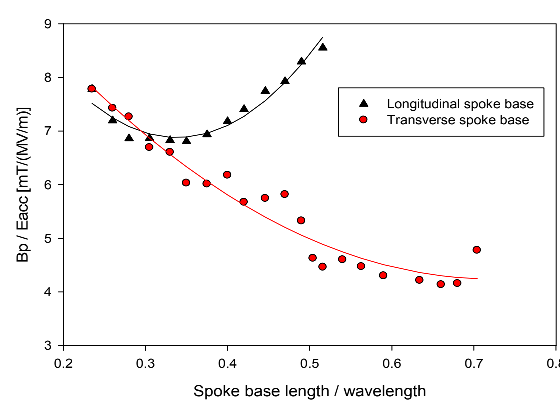

Figure 4: Normalized surface magnetic field vs. the ratio of spoke base length to cavity diameter.

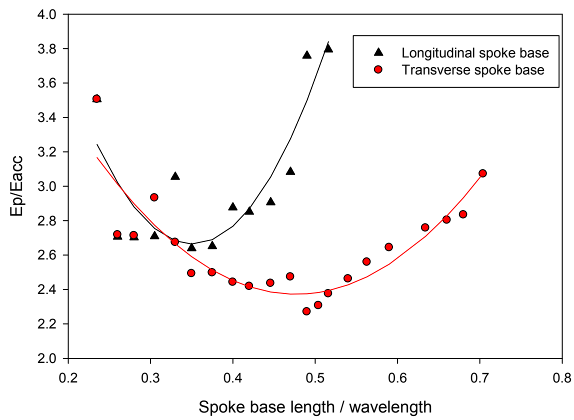

Figure 5: Normalized surface electric field vs. the ratio of spoke aperture length to cavity diameter.

Table 2: Physical Dimensions

Parameter	$\beta_0 = 0.82$	$\beta_0 = 1.0$	Units
Cavity diameter	584.4	588	mm
Iris-to-iris length	877	1072	mm
Cavity length	1057	1252	mm
Aperture diameter	50	50	mm

Table 3: RF Parameters

Parameter	$\beta_0 = 0.82$	$\beta_0 = 1.0$	Units
Frequency of 0 mode	352	352	MHz
R/Q	545	670	Ω
Geometrical factor	172	184	Ω
E_p / E_{acc}	2.20	2.20	
B_p / E_{acc}	5.09	5.56	mT/(MV/m)
B_p / E_p	2.31	2.53	mT/(MV/m)

At E_{acc} = 1 MV/m and reference length = $\beta_0\lambda$

HIGHER-ORDER MODE ANALYSIS

An initial analysis of the higher-order modes (HOM's) is currently underway. The fact that the spokes destroy the cylindrical symmetry and are perpendicular allows for a more complex HOM spectrum than in a cavity with a high degree of symmetry. In a multi-spoke cavity there can be multiple components of both *E* and *H* along the direction of beam propagation. Some modes, for example the 2nd and 3rd HOM's of the two-spoke cavity, are accelerating modes. Other modes, such as the 4th mode, are deflecting modes where both the electric and magnetic fields are in the transverse direction. These modes, however, can contain different components of the electric field and magnetic field in various positions along the beam line. Additionally, since these cavities are intended for the acceleration of particles of different velocities, for each mode the *R/Q* needs to be calculated as a function of β and not simply for β_0.

Table 4 is a summary of the modes analyzed thus far. The *R/Q* calculations for each of these modes are in progress.

This analysis confirms the fact that, in a multi-spoke cavity, the fundamental accelerating mode is the lowest frequency mode and is well separated from the nearest HOM [6].

Table 4: Cavity Modes

Mode type	Frequency (MHz)
Accelerating	352.0, 358.9, 378.5, 500.7, 527.4, 663.4*, 685.6, 713.8, 719.2
Deflecting	478.0*, 529.7*, 573.3*, 615.0*, 663.7, 672.7, 677.1*, 702.3, 709.3*, 729.0*

*indicates degenerate modes

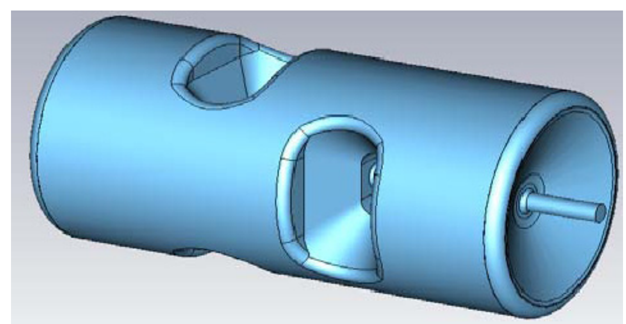

Figure 6: 352 MHz, β_0 =1, double-spoke cavity.

CONCLUSION

The optimization and HOM analysis for high-β_0 spoke cavities is ongoing. Our results are promising and indicate the need for further research in this area, which we are pursuing.

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