Design of Superconducting Spoke Cavities for High-Velocity Applications

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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 \( \beta_0 = 1 \).

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

\[
E_{acc} = \frac{\Delta W(\beta_0)}{\beta_0 \lambda}
\]

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 \( \beta_0 \). 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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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).

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

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

<table>
<thead>
<tr>
<th>Spoke base</th>
<th>Spoke aperture region</th>
<th>$Ep/Eacc$</th>
<th>$Bp/Eacc$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliptical base</td>
<td>RT aperture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racetrack base</td>
<td>Elliptical aperture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racetrack base</td>
<td>Racetrack aperture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elliptical base</td>
<td>elliptical aperture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racetrack base</td>
<td>racetrack aperture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racetrack base-racetrack aperture</td>
<td>we are optimizing further</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
**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 $\beta$ and not simply for $\beta_0$.

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].

![Graph](image)

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

**Table 2: Physical Dimensions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\beta_0 = 0.82$</th>
<th>$\beta_0 = 1.0$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity diameter</td>
<td>584.4</td>
<td>588</td>
<td>mm</td>
</tr>
<tr>
<td>Iris-to-iris length</td>
<td>877</td>
<td>1072</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity length</td>
<td>1057</td>
<td>1252</td>
<td>mm</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>50</td>
<td>50</td>
<td>mm</td>
</tr>
</tbody>
</table>

**Table 3: RF Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\beta_0 = 0.82$</th>
<th>$\beta_0 = 1.0$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of 0 mode</td>
<td>352</td>
<td>352</td>
<td>MHz</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>545</td>
<td>670</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Geometrical factor</td>
<td>172</td>
<td>184</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>$E_p / E_{acc}$</td>
<td>2.20</td>
<td>2.20</td>
<td></td>
</tr>
<tr>
<td>$B_p / E_{acc}$</td>
<td>5.09</td>
<td>5.56</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$B_p / E_p$</td>
<td>2.31</td>
<td>2.53</td>
<td>mT/(MV/m)</td>
</tr>
</tbody>
</table>

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

**CONCLUSION**

The optimization and HOM analysis for high-$\beta_0$ spoke cavities is ongoing. Our results are promising and indicate the need for further research in this area, which we are pursuing.

**REFERENCES**