DESIGN OF SUPERCONDUCTING SPOKE CAVITIES FOR HIGH-VELOCITY APPLICATIONS

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Abstract
Superconducting spoke cavities have been designed and tested for particle velocities up to \( \beta_0 \approx 0.6 \) and are currently being designed for velocities up to \( \beta_0 = 1 \). We present the electromagnetic design for two-spoke cavities operating at 325 MHz for \( \beta_0 = 0.82 \) and \( \beta_0 = 1 \).

INTRODUCTION
Accelerating charged particles from \( \beta_0 = 0.6 \) to \( \beta_0 = 0.8 \) has typically been accomplished using elliptical cavities. Single and multiple-gap spoke cavities offer several advantages over their elliptical counterparts. The diameter of a spoke cavity is on the order of the half the rf wavelength, whereas the diameter of an elliptical cavity is twice that. This allows for either smaller physical dimensions at the same operating frequency or close to half the operating frequency for the same physical diameter. Since the BCS surface resistance is proportional to the square of the rf frequency, spoke cavities could allow for 4 K operation as well as a higher voltage gain over a wider range of velocities [1, 2]. We report here on the design of double-spoke 325 MHz cavities for \( \beta_0 = 0.82 \) and 1.

ELECTROMAGNETIC DESIGN
High surface fields in superconducting cavities can have detrimental effects on performance. If the surface magnetic field is too high, quenching can occur and if the surface electric field is too high, field emissions can be induced. When comparing the performance of cavities, we often refer to the normalized surface fields, \( E_p/E_{acc} \) and \( B_p/E_{acc} \), where \( E_p \) is the peak surface electric field, \( B_p \) is the peak surface magnetic field and \( E_{acc} \) is accelerating electric field which is defined here as

\[
E_{acc} = \frac{\Delta W(\beta_0)}{\beta_0^2 \cdot 90^\circ}
\]

where \( \Delta W(\beta_0) \) is the energy gain at the optimal velocity. Minimizing these fields is often the first step in cavity design, and the results of which are presented here.

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. All of the results presented are at a frequency of 325 MHz and \( \beta_0 = 0.82 \) and \( \beta_0 = 1 \).

Figure 1 shows the spoke parameters discussed here. 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.

Spoke Base
The magnetic field of the fundamental accelerating mode in a spoke cavity is more concentrated near the outer conductor’s surface and encircles the spokes. The size and shape of the spoke base region can thus have a strong effect on the peak surface magnetic field. The spokes run radially through the cavity, so changing the size of the base does have an effect in the beam-line region as well since the spoke tapers down to the center. In figure 3, the normalized magnetic field is shown as a function of the spoke base dimensions. The dimension is normalized to the rf wavelength corresponding to a frequency of 325 MHz. More detail on the optimization procedure can be found elsewhere [3].

For a longitudinal spoke base orientation, the length of the spoke base is changed beginning from cylindrical to a value at which the spoke is close enough to the outer wall.

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05 Cavity design
that the surface fields become very high. From figure 2, we see that there is a simple relation between the spoke base width and the normalized magnetic field for the longitudinal orientation. For the transverse spoke base orientation, again, we begin with a cylindrical shape and now increase the width until this dimension is close to the diameter of the cavity. From Fig. 2 and 3 we see that as we increase the width of the spoke base, both the normalized magnetic and electric fields continue to go down until they reach a constant value.

Figure 2: Normalized surface magnetic field as a function of the spoke base dimensions.

Figure 3: Normalized surface electric field as a function of the spoke base dimensions.

Figures 2 and 3 show similar trends, which is why we have chosen a transverse spoke orientation for the base.

**Spoke Aperture**

The electric field of the fundamental accelerating mode of a spoke cavity is of course concentrated at the accelerating gaps along the beam path. The shape and dimensions of the spoke aperture region thus have a great impact on the peak surface electric field. Figure 4 shows how the normalized electric field varies as a function of the spoke aperture dimensions. The variation was taken by fixing the transverse length of the aperture while increasing the longitudinal width. Figure 5 shows how both the normalized electric and magnetic fields change as the spoke aperture width to length ratio is varied.

![Normalized surface electric field as a function of spoke aperture dimensions.](image1)

Figure 4: Normalized surface electric field as a function of spoke aperture dimensions.

![Normalized surface electric and magnetic fields vs. the ratio of spoke aperture width to length.](image2)

Figure 5: Normalized surface electric and magnetic fields vs. the ratio of spoke aperture width to length.

**Spoke Separation**

In low-β structures made with several loading elements (multi-spoke, split-ring or twin-quarter-wave for example), the side gaps are approximately half the size of the central gap. We find that, as the β of the cavity is increased, the optimal size for the side gaps, i.e. the one that minimizes the surface fields, increases to become closer to the size of the central gaps.

The normalized surface electric and magnetic fields as a function of spoke separation are shown in figure 6. The dependence of the accelerating field profile on the spoke separation for three points in figure 6 are shown in Fig. 7. The overall accelerating voltage for the three cases are
comparable, so it would appear that there is some benefit to be had by not strictly balancing the fields in each cell. We choose to have the spoke separation slightly below $\beta_0 \lambda/2$ in order to reduce the peak surface electric and magnetic fields.

![Figure 6: Normalized surface magnetic and electric fields vs. the spoke separation distance.](image)

Figure 6: Normalized surface magnetic and electric fields vs. the spoke separation distance.

The physical dimensions are presented in table 1 and the rf properties we have simulated thus far for the 325 MHz, $\beta_0 = 0.82$ and $\beta_0 = 1$ are given in table 2.

![Figure 7: Longitudinal electric field profile of the fundamental accelerating mode for different spoke separation distances.](image)

Figure 7: Longitudinal electric field profile of the fundamental accelerating mode for different spoke separation distances.

<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>629</td>
<td>642</td>
<td>mm</td>
</tr>
<tr>
<td>Iris-to-iris length</td>
<td>956</td>
<td>1178</td>
<td>mm</td>
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<tr>
<td>Cavity length</td>
<td>1136</td>
<td>1370</td>
<td>mm</td>
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<tr>
<td>Aperture diameter</td>
<td>60</td>
<td>60</td>
<td>mm</td>
</tr>
</tbody>
</table>

CONCLUSION

The optimization for high-$\beta_0$ spoke cavities is ongoing. For both frequencies and values of beta we are optimizing, we find that transverse spoke base and aperture orientations seem to produce the lowest surface fields. Our results are promising and indicate the need for further research in this area, which we are pursuing.

REFERENCES