SUPERCONDUCTING SINGLE-SPOKE CAVITIES FOR HIGH-VELOCITY APPLICATIONS*

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Abstract

The advantages offered by spoke cavities have been investigated for particle acceleration in the high-velocity regime. As part of these efforts, single-spoke cavities for particles at β_0 = 0.82 and 1 are being designed and built for proof-of-principle reasons. We report here on the electromagnetic properties, design optimization, multipacting analysis, higher order mode spectrum, and multipoleananlysis for a single-spoke cavity operating at 325 MHz.

INTRODUCTION

Single and multi-spoke cavities have attractive features and, in some applications, may offer some advantages over their TM counterparts. The relative compactness could prove beneficial for smaller machines where 2 K operation may not be feasible.

ELECTROMAGNETIC DESIGN

The first goal in cavity design is to find a geometry which minimizes the surface fields. In single- and multi-spoke cavities, the magnetic field is concentrated around the spoke base, thus increasing the area of the base helps to reduce the peak field. The electric field is concentrated around the beam line, and as such, a uniform distribution of fields around the spoke aperture as well as on the end caps gives the lowest field values.

The electromagnetic optimization was done using CST MWS©. The electric field of the fundamental accelerating mode is shown in figure 1.

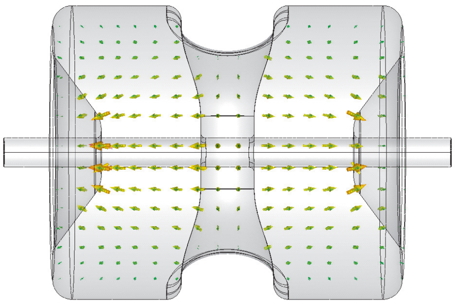

Figure 1: Electric field of the fundamental accelerating mode.

Here we present properties of a β_0 = 0.82 single-spoke (SS) cavity, which would be suitable for large machines. As such, the most important optimization goal was to minimize the surface fields. On the other hand, if we are optimizing a cavity intended to be used in a 4 K, small machine, the power dissipation may be more important. In the latter case, one should consider allowing for somewhat higher surface fields in order to obtain a higher shunt impedance.

Table 1: Optimized Single-spoke Cavity, rf Properties

Parameter	Value	Units
Energy Gain at β_0	757	kV
R/Q	449	Ω
QR_s	182	Ω
(R/Q)*QR_s	8.2×10^4	Ω^2
E_p/E_{acc}	3.6	-
B_p/E_{acc}	6.0	$\frac{\text{mT}}{\text{(MV/m)}}$
B_p/E_p	1.7	$\frac{\text{mT}}{\text{(MV/m)}}$
Energy content	0.61	J
Power Dissipation	0.48	W

At E_{acc} = 1 MV/m and reference length $\beta_0\lambda$
R_s = 68 nΩ

Table 1 lists the rf properties of a 325 MHz, β_0 = 0.82 SS cavity optimized for low surface fields. A more detailed description of the high-velocity multi-spoke cavity design process and important cavity dimensions is given in [1]. The same principles apply to the SS cavity.

HIGHER ORDER MODE ANALYSIS

The higher order mode spectrum of a single-spoke cavity is much simpler than that of a multi-spoke cavity. Both have accelerating modes as well as deflecting modes. In a two-spoke cavity, for example, there is a rotational symmetry involved in the deflecting mode fields [2], and as such, the determination of $[R/Q]$ is not as straight forward as in a single-spoke cavity. For an accelerating mode, $[R/Q]$ can be calculated as,

$$\left[\frac{R}{Q}\right] = \frac{\left|\int_{-\infty}^{\infty} \vec{E}_z(z, r = 0) e^{i\left(\frac{\omega z}{\beta c} + \phi\right)} dz\right|^2}{\omega U} \quad (1)$$

where ω is the angular frequency of the mode, βc is the particle velocity, U is the stored energy in the cavity, and ϕ is the phase, which can be determined by inspection for

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both accelerating and deflecting modes (unlike in the two-spoke cavity).

Due to the symmetry of the SS cavity, the deflecting modes impart a momentum kick in one of the transverse directions (x or y, in this case). For these deflecting modes, $[R/Q]$ is determined by,

$$\left[\frac{R}{Q}\right]_T = \frac{\left|\int_{-\infty}^{\infty}\left[\left(\vec{E}_T + i(\vec{v}_z \times \vec{B}_T)\right)e^{i\left(\frac{\omega z}{\beta c}+\phi\right)}\right]dz\right|^2}{\omega U} \tag{2}$$

where $\vec{E}_T$ is either the x or y component and $\vec{B}_T$ is then the y or x component. Figure 2 shows the $[R/Q]$ values for modes up to 1.5 GHz, although analysis was done to the cut-off frequency of 3 GHz for a 60 mm beam aperture.

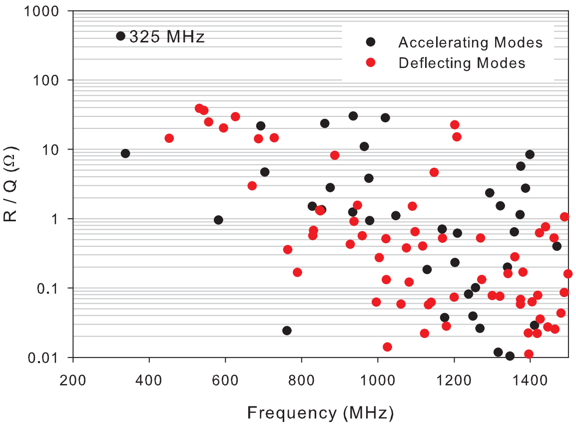


Figure 2: $[R/Q]$ values vs frequency for a 325 MHz, $\beta_0 = 0.82$ single-spoke cavity.

It is clear from figure 2, that at the design velocity of $\beta_0 = 0.82$, the fundamental mode has a much larger $[R/Q]$ value than any of the other modes. However, the large velocity acceptance of a spoke cavity requires that one consider the velocity dependence of the $[R/Q]$ values, especially for non-velocity-of-light cavities. We have previously found that for a two-spoke cavity, the beam coupling to the second accelerating mode can actually surpass that of the fundamental mode for low β [3]. This is not the case in a SS cavity because the first two modes are the π mode and the pillbox mode- which is equivalent to the first and third mode in a two-spoke cavity, where the coupling of the pillbox mode is also low. The β dependence of the first two modes are shown in figure 3

MULTIPACTING ANALYSIS

Electrons emitted from the internal surface of a rf cavity will interact with the electromagnetic fields present. The trajectories of these electron will often lead to their impacting the surface with a given amount of energy. For a well prepared niobium surface, if this energy falls within a range of roughly 150 eV to 1500 eV, then secondary electrons can be emitted [4]. This energy range is known as the secondary emission yield (SEY). The SEY is not only material specific, but also depends of the condition of the surface [5]. By improving the quality of the surface, the soft barriers on the gradient can be eliminated by processing and cleaning. On the other hand, hard barriers can only be overcome by changing the cavity geometry. These electrons can also be in resonant trajectories, at which point a cascade effect can begin, which can lead to thermal breakdown.

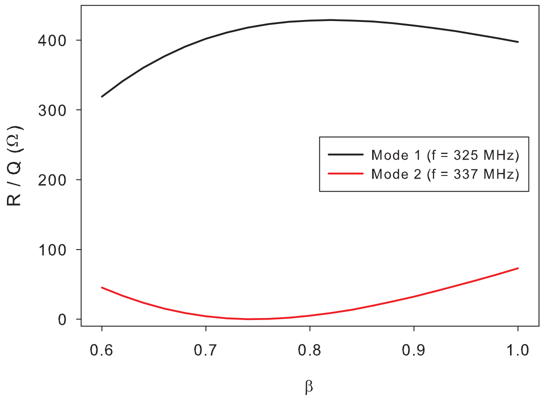


Figure 3: Dependence of $[R/Q]$ values on particle velocity for the first two modes in a single-spoke cavity.

In order to analyze the multipacting conditions in the cavity, the 3D parallel tracking code Track3P contained in the ACE3P code suite developed by SLAC was used [6]. In figure 4, we show some resonant electrons for field gradient levels from 100 kV/m to 10 MV/m in an optimized 325 MHz, $\beta_0 = 0.82$ cavity. The impact energy is also shown.

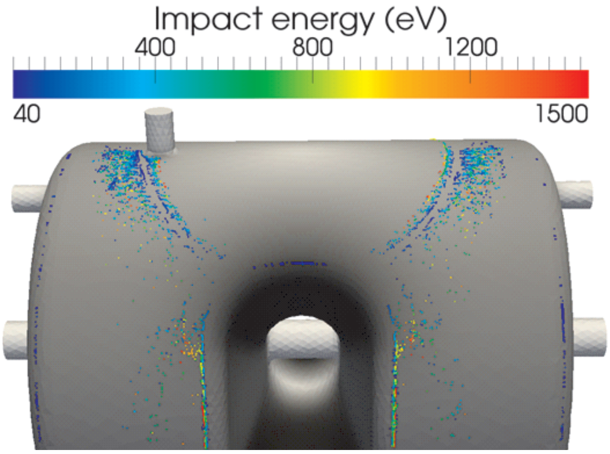


Figure 4: Resonant electron locations and energies for field levels between 0.1 - 10 MV/m.

In figure 5, the resonant impact energies are shown for multipacting electrons of order 1-4. We can see that the resonant impacts occur at gradients, for the most part, of less than 3 MV/m.

There are possible multipacting barriers present in the

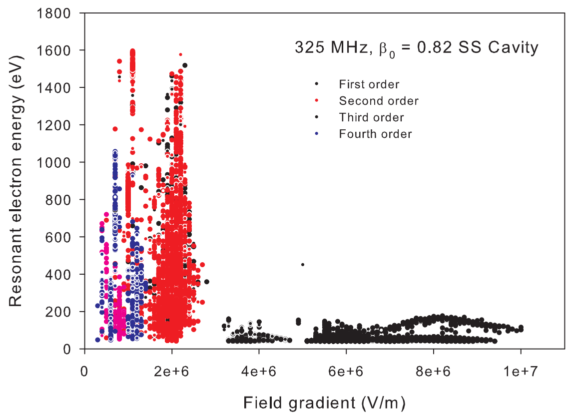
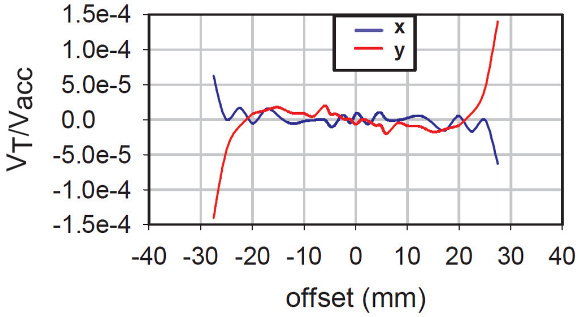


Figure 5: Dependence of resonant electron energy on electric field gradient.

simulations. Those below 3 MV/m, are mostly second, third and fourth order multipactors. Those between 3 and 10 MV/m, are made up of first order, mostly two-point multipactors. While this is of concern, most of them are below 100 eV, at the intended operating gradient of 10 MV/m (or V_{acc} = 7.6 MV). As we reported in [7], Niowave has already fabricated and tested a 700 MHz, β_0 = 1 two-spoke cavity of our design, which showed a similar potential for hard barriers, but found none.



Multipole Components	
b2	-0.88 mT
b4	327 mT/m^2
b6	1.9e5 mT/m^4

Figure 6: Dependence of transverse voltage on offset from beam axis (top) and the first 3 multipole components, normalized to 1 MV.

MULTIPOLE EFFECTS

It is important to notice that the geometry of this cavity results in a very uniform field within the aperture region, as evidenced by negligible higher order multipole components. Figure 6 shows a plot of the transverse voltage in both x and y directions (normalized to the accelerating voltage), as a function of transverse offset from the design beamline. From a multipolar expansion of the field in the vicinity of the beam axis, we include the first three multipole components that result in rf-kicks in a transverse direction expressed in the conventional notation for magnetic multipoles. The method we used to calculate these components have been defined previously [8].

CURRENT STATUS

Presently, Niowave is fabricating this 325 MHz, β_0 = 0.82 single-spoke cavity. Many of the parts have now been machined and welded (see figure 7). Complete assembly will be done at Niowave, along with bulk BCP and HPR. The cavity will then be brought to Jefferson Lab for further processing and testing at both 4.2 K and 2 K.

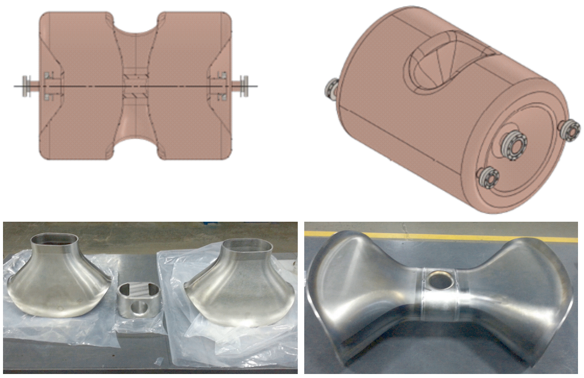


Figure 7: Single-spoke cavity with cleaning ports (top), spoke parts (bottom left), and welded spoke (bottom right).

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