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DEVELOPMENT OF SPOKE CAVITIES FOR HIGH-VELOCITY APPLICATIONS*

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Abstract

In response to recent interest in alternatives to TM-type cavities for low-frequency, high-velocity applications we have initiated a program for the development of multi-spoke superconducting cavities. We have completed the electromagnetic design for two-spoke cavities operating at 325, 352, 500, and 700 MHz with a design velocity of β_0 = 0.82 or β_0 = 1. We present the results of the optimization, higher order mode (HOM) analysis, multipacting analysis, and an initial analysis of multipole effects of the fundamental accelerating mode.

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

High surface fields in superconducting cavities are undesirable because of the detrimental effects on performance. Thus, the first goal in cavity design is to find a geometry which minimizes the surface fields.

During the minimization of the electric and magnetic surface fields, a point will be reached at which one field cannot be reduced without increasing the other. It is at this point that one must consider the current technical limits, and make some concessions in order to reach the expected limitations simultaneously. An example of a balanced cavity would be one that could reach a peak surface magnetic field of 80 mT while achieving a peak surface electric field of 40 MV/m, implying that a ratio of B_p/E_p = 2 would be desirable.

All the designs presented here are for high-velocity cavities and were done using CST MWS©. For β_0 = 0.82 cavities, which would be suitable for large machines, the most important optimization goal is likely to be minimizing 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.

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Table 1: Optimized Two-spoke Cavities, rf Properties

Parameter	Lower fields	Higher RRs	Units
Energy Gain at β_0	757	757	kV
R/Q	556	652	Ω
QR_s	171	175	Ω
(R/Q)*QR_s	95297	113905	Ω^2
E_p/E_{acc}	2.45	2.91	-
B_p/E_{acc}	5.11	6.0	$\frac{\text{mT}}{\text{(MV/m)}}$
B_p/E_p	2.09	2.06	$\frac{\text{mT}}{\text{(MV/m)}}$
Energy content	0.50	0.43	J
Power Dissipation	7.1	6.0	W

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

Table 1 lists the rf properties of 325 MHz, two-spoke cavities optimized for either lower surface fields or higher shunt impedance at β_0 = 0.82. A more detailed description of the design process and important cavity dimensions is given in [1]. It can be seen that the trade-offs to be made between shunt impedance and normalized fields are close to 20% in our case. The rf properties of the cavity we are fabricating lie between these values.

HIGHER ORDER MODE ANALYSIS

The types of higher order modes in a two-spoke cavity are accelerating, deflecting, hybrids and TE-type. The fundamental mode is the useful accelerating mode, which makes for a somewhat simpler mode damping scheme than in TM cavities. The separation between the fundamental mode and the nearest mode is typically several MHz, which can also be beneficial.

The detrimental effect of higher order modes are often characterized by the R/Q value of individual modes. For the accelerating modes, this values is easily calculated as

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

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 for the accelerating modes can be determined by inspection. Due to the symmetry of the cavity, the deflecting modes impart a momentum kick in both transverse directions for a single mode, and as such, the determination of R/Q is not as straightforward. For these deflecting modes, R/Q is determined by,

$$\left[\frac{R}{Q}\right]_{T,\,\phi_{max}} = \frac{\left|\int_{-\infty}^{\infty}\left[\left(\vec{E}_T(x(y), r=0) + i(\vec{v}_z \times \vec{B}_T)\right) e^{i\left(\frac{\omega z}{\beta c}+\phi\right)}\right] dz\right|^2}{\omega U} \tag{2}$$

where ϕ_{max} means that the integral in the numerator is maximized with respect to ϕ. The components of the electric and magnetic fields which are involved in a given transverse deflection do not necessarily have the same value of ϕ for which they will be maximized. We have automated the process of finding the values of ϕ_{max} by developing a MatLab© code which performs this task effectively. Figure 1 shows the R/Q values for modes up to about 1 GHz for one of the optimized cavities.

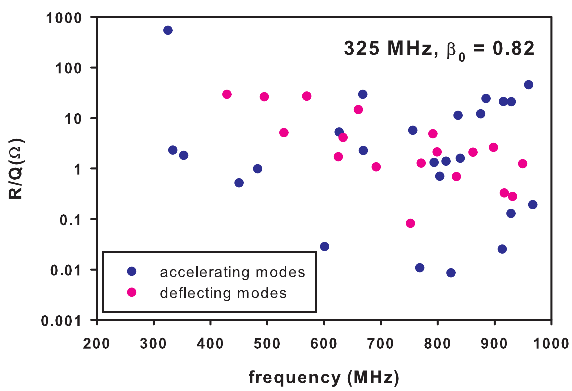

Figure 1: $[R/Q]$ values vs frequency for a 325 MHz, $\beta_0 =$ 0.82 cavity.

MULTIPACTING ANALYSIS

When the internal surface of a rf cavity is exposed to the high fields maintained in a superconducting cavity, electrons (known as primary electrons) can be emitted from the metal. The trajectory of these electrons is determined by the electromagnetic fields, and in many cases, they will come in contact with another part of the surface with a certain amount of impact energy. If, for niobium, this energy falls within the range of $\sim$ 150 eV to 2000 eV, then additional electrons, known as secondary electrons, have a probability greater then 1 of being ejected, which is referred to as secondary emission yield (SEY) [2]. These electrons can even end up in resonant trajectories; at which point this multipacting process can generate a large amount of excess heat, thus leading to thermal breakdown.

Additionally, these secondary particles will absorb energy from the rf fields, thereby limiting the gradient which would otherwise be achievable in their absence. The SEY is not only material specific, but also depends of the condition of the surface [2]. 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.

In order to analyze the multipacting conditions in our optimized two-spoke cavities, the 3D parallel tracking code Track3P contained in the ACE3P code suite developed by SLAC was used [3]. In figure 2, we show some resonant electrons for field gradient levels from 0.5 MV/m to 10 MV/m in an optimized 325 MHz, β_0 = 0.82 cavity. The different areas identified as (a) - (c) correspond to each accelerating gap including half of one spoke or two spokes for areas (a) and (c) or (b), respectively. The impact energy is also shown.

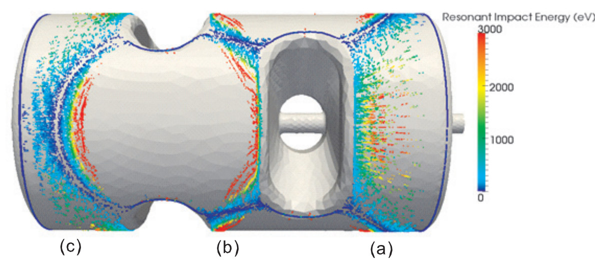

Figure 2: Resonant electrons and their energies for field levels from 0.5-10 MV. The labels (a), (b), and (c) refer to sections of the cavity.

The electrons colored blue-green, green, and yellow are the ones of concern, as they fall within the impact energy range for which secondary electrons are likely to be generated.

In figures 3-5, the resonant impact energies are shown for multipacting electrons of order 1-6. We can see that the resonant impacts occur at gradients, for the most part, of less than 2 MV/m.

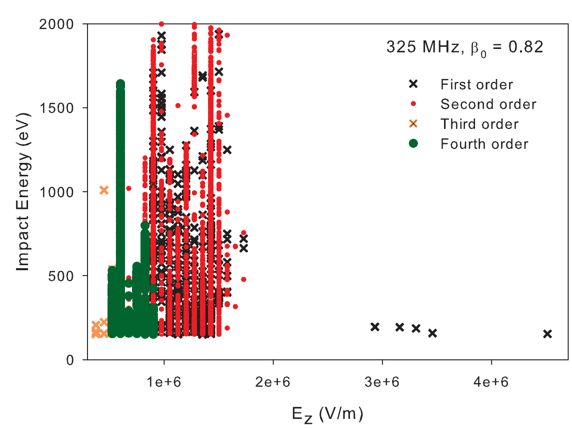

Figure 3: Resonant electrons in area (a) and their energies for field gradient levels from 0.5-10 MV/m.

Figures 3-5, show that there is an especially great deal of second order resonant electrons with energy falling in the

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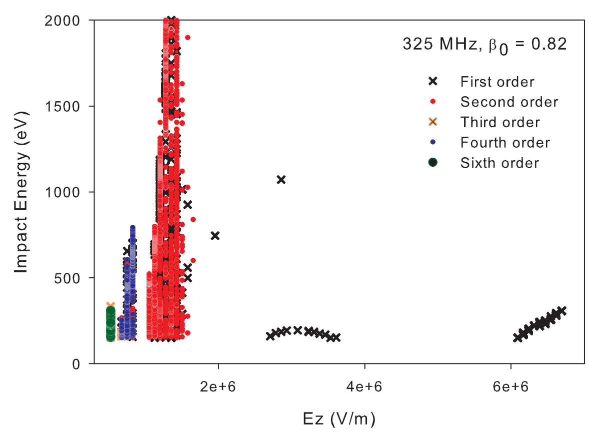

Figure 4: Resonant electrons in area (b) and their energies for field gradient levels from 0.5-10 MV/m.

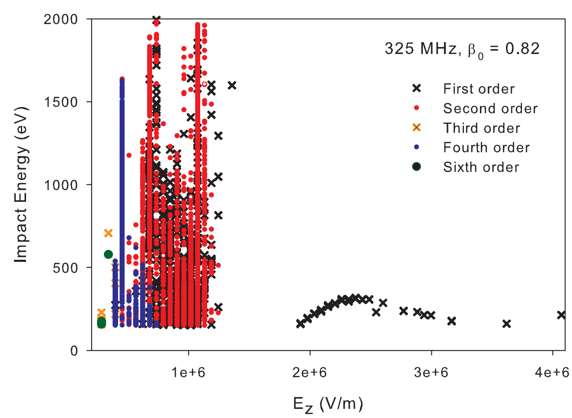

Figure 5: Resonant electrons in area (c) and their energies for field gradient levels from 0.5-10 MV/m.

SEY range. While this is of concern, some of these resonant electrons can be eliminated by slightly changing the geometry, specifically the rounding at the spoke base. Improved cavity cleaning techniques will likely be beneficial in reducing the resonant electrons, at least those closer to the lower limit of the SEY condition. However, this will not negate the problem altogether, therefore we are pursuing other methods for dealing with this possible challenge.

MULTIPOLE EFFECTS

In order to understand the beam dynamics in our two-spoke cavities, we need to identify the multipole expansion of the accelerating mode to understand any nonlinear effects. As a preliminary step, we have analyzed the off-axis fields, and present in Figure 6 a plot of transverse voltages along the beamline as a function of transverse offset from EM simulation field data.

The particles appear to have an effective transverse voltage at the beamline (null offset), but this apparent offset is an artifact of the simulation software, which does not render perfectly symmetric geometries for these cavities. While the effects of the asymmetry are negligible for the large accelerating voltages, they accumulate and are very noticeable for the small transverse voltages that exist off-axis. Nevertheless, we can gleam some qualitative information from this initial study. If we ignore this offset, it can be seen that any off-axis particles will experience a transverse voltage along the direction of off-axis displacement; the fields seem to be focusing particles displaced along one transverse direction (y), while defocusing along the other transverse direction (x). This is typical of quadrupole field behavior. We also see that the strength of this quadrupole field in terms of the resulting transverse voltages is very small, less than 1% of the accelerating voltage. We see little evidence in this plot of significant higher order multipole components. Further analysis is underway.

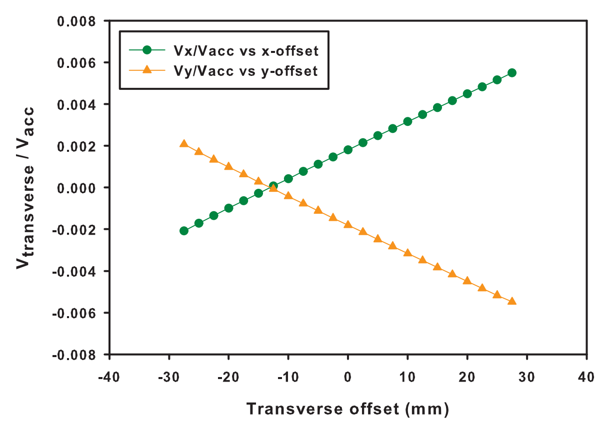

Figure 6: Transverse voltage at the beamline as a function of transverse offset.

CURRENT STATUS

With the electromagnetic optimization, HOM and multipacting analysis complete, a full mechanical analysis of the 325 MHz, $\beta_0 = 0.82$ cavity is underway. Some areas which are most susceptible to deformation have been identified and solutions have been simulated giving encouraging results. Fabrication of this cavity will begin in the coming months.

ACKNOWLEDGMENT

We would like to thank Michael Moore for his contributions in analyzing the higher order modes.

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