HIGH-CURRENT SRF CAVITY DESIGN

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Abstract

For high current applications, it is desirable for the cavity shape to have a low longitudinal loss factor and to have a high beam-breakup threshold current. This paper briefly describes three different cavities designed for this purpose: a six-cell elliptical cavity for particles traveling at the speed of light, a two-cell elliptical cavity for subluminal particle speeds, and a single cell cavity which uses the TM012 mode for acceleration. SUPERFISH simulations predict the peak fields in both of the elliptical cavities will not exceed the TeSLA values by more than 10% but both will have 28.7% larger apertures. The elliptical designs assume the bunch frequency equals the accelerating mode frequency. The beam pipe radius is chosen so that the cutoff frequency is less than twice that of the accelerating mode. Hence all of the monopole and dipole higher-order modes (HOMs) that can be driven by the beam have low loaded Q values. This simplifies the problem of HOM damping. The TM012 cavity is predicted to have much higher peak fields than a π-mode elliptical cavity, but offers potential advantages from its simplified shape; it is essentially a circular waveguide with curved end plates. This basic shape results in easier fabrication and simplified tuning.

INTRODUCTION

Superconducting technology is especially suited for applications requiring high average beam currents. High current means approximately 200 mA to 500 mA for synchrotron light sources such as Diamond, SOLEIL, and the Canadian Light Source. Electron cooling for RHICII will require 200 mA, with future projects such as eRHIC requiring 300 mA - 600 mA [1], while JLab's high power FEL is being developed for up to 1000 mA. The recent design of an "Ampere Class" cavity [2] demonstrates the challenge of designing a cavity for the latter two projects. The cavity must simultaneously have a low longitudinal loss factor and sufficiently damped higher order modes (HOMs). The bunch frequency is less than the cavity accelerating mode frequency for all cases mentioned above.

A different approach to reach high average beam currents is to set the bunch frequency equal to the cavity accelerating mode frequency, ν_o. When bunches are recirculated back into a cavity in a storage ring or energy recovery linac (ERL), a single high-Q HOM can cause multipass/multibunch instabilities and limit the available beam current. These instabilities may be avoided if the beam pipe radius is large enough so that the cutoff frequencies of the TM01 and TE11 mode are lower than $2\nu_o$. In this case, any monopole or dipole HOM that could be excited by the beam can propogate along the beam pipe and damped.

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The multipass, multibunch beam breakup threshold current for ERLs can be approximated by the following expression [3],

$$I_{th} = \frac{-2p_r c}{e(R/Q)_m Q_m k_m M_{12}}$$

where p_r is the momentum of the recirculating beam, $(R/Q)_m$ is the shunt impedance for a particular HOM, $k_m = \omega_m/c$ is the HOM wavenumber, and M_{12} is the transfer matrix element for the recirculation path in the (x, x') space. Low-frequency HOMs are preferable since it tends to raise the threshold current, but higher frequencies are possible if the dangerous HOMs are strongly damped. In this way a smaller, high-frequency cavity with simplified damping may be possible by filling every RF bucket and allowing any dangerous HOMs to propogate down the beam pipe.

A higher bunch frequency has the additional advantage of requiring a lower bunch charge to achieve a given design current. The wake amplitude will generally be lower since the magnitude of the wake for a given mode is proportional to the bunch charge. The lower bunch charge also makes it easier to use a superconducting photocathode as a source of electrons. This paper describes two elliptical cavity shapes designed for these concepts, with only modest increases in peak fields when compared to the TeSLA Test Facility cell shape [4].

A cavity consisting of a single cell using the TM012 mode for acceleration is also considered as an alternative to conventional elliptical designs [5]. Higher peak fields and trapped lower/higher order modes are the main shortcomings of the TM012 cavity, but the simple shape offers some potential advantages. These include easier fabrication, easier tuning, and a lower beam impedance by eliminating the radial variations (hills and valleys) of multicell cavities. All RF calculations were done using SUPERFISH [6].

SIX-CELL ELLIPTICAL

The six-cell cavity was designed for accelerating particles close to the speed of light. The cavity shape is shown in Figure 1. The cavity wall is tilted by 6° from the vertical. The parameters of the π-mode for the entire six-cell cavity are shown in Table 1. The shunt impedance is defined by the relation $R = \frac{V^2}{P}$ where V is the cavity voltage and P is the dissipated power. The cell-to-cell coupling is calculated using the following formula,

$$k_{cc} = 2\frac{f_\pi - f_0}{f_\pi + f_0}$$

where f_π and f_0 are the frequencies of the π-mode and 0-mode respectively. Figure 1 shows the magnitude of the

Table 1. Figures of merit for each cavity scaled to 1.500 GHz.

Cavity	6-Cell	2-Cell	TeSLA[4]	Ampere Class[2]
E_p/E_a	2.19	2.16	2.00	2.00
B_p/E_a	4.68 $\frac{mT}{(\frac{MV}{m})}$	4.59 $\frac{mT}{(\frac{MV}{m})}$	4.26 $\frac{mT}{(\frac{MV}{m})}$	5.8 $\frac{mT}{(\frac{MV}{m})}$
β_{geom}	1.0	0.805	1.0	1.0
R/Q	535 Ω	165 Ω	1036 Ω	404 Ω
Geometry Factor	275 Ω	228 Ω	270 Ω	225 Ω
Cell-to-Cell Coupling	3.9 %	2.8 %	1.9 %	3 %
Frequency	1.500 GHz	1.500 GHz	1.500 GHz	1.500 GHz
Beam tube radius	3.9 cm	3.9 cm	3.0 cm	4.0 cm

axial component of the electric field on axis with a corresponding field unflatness of 2.7%. Figure 2 shows the variation of both the electric and magnetic field on the surface of three of the cells. The larger cell-to-cell coupling of the six-cell cavity also makes it plausible to increase the number of cells, since the sensitivity of a cavity mode to perturbations is proportional to N^2/k_{cc}. Here N is the number of cells per cavity and k_{cc} is the cell-to-cell coupling. A thirteen-cell cavity with 3.9% coupling would have the same sensitivity as a nine-cell TeSLA cavity. For an accelerating mode frequency of 1.5 GHz, the beam tube radius would be 3.9 cm with TE11 and TM01 cutoff frequencies of 2.252 GHz and 2.942 GHz respectively.

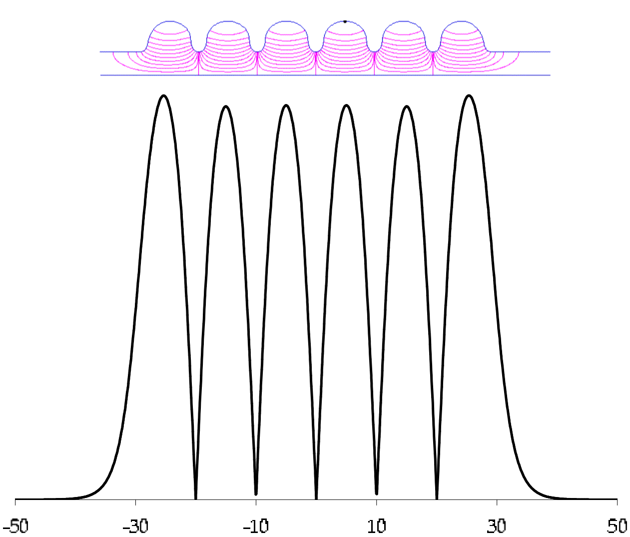

Figure 1. Six-cell electric field lines and amplitude of axial electric field.

TWO-CELL CAVITY

The six-cell cavity can only offer marginal voltage gains for electron velocities less than approximately 80% the speed of light, as can be seen in the transit time curve of Figure 3 in which a constant velocity approximation was used. The first step in designing a cavity for accelerating slow electrons was to simply form a two-cell cavity using the end cell geometry of the six-cell design. However, the evanescent field extending into the beam pipe effectively lengthened the wavelength of the resulting accelerating mode. To shorten the wavelength to a level comparable to that of the original six-cell cavity, the cell length was shortened to a geometric β of 0.805. Figure 4 shows the final shape, with the surface fields on one of the two cells shown in Figure 5.

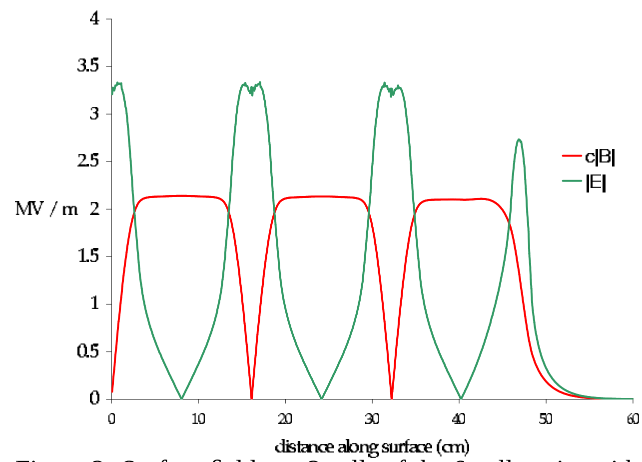

Figure 2. Surface fields on 3 cells of the 6-cell cavity with a total stored energy of 0.0381 J. The distance along the surface of the cavity is measured by starting at the middle iris of the cavity and moving to the right along the surface of the three cells.

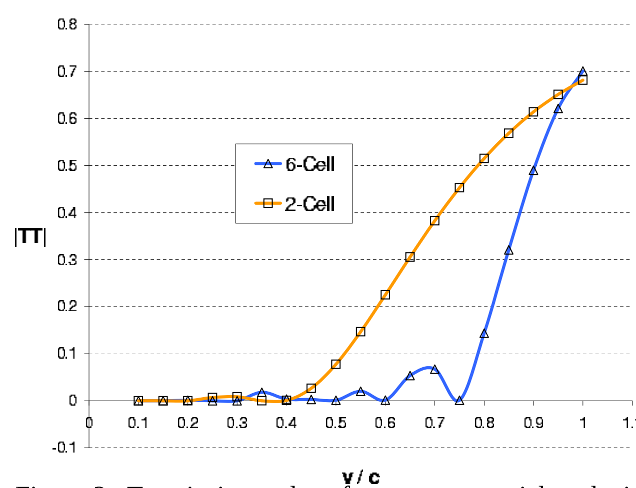

Figure 3. Transit time values for constant particle velocities.

The transit time curve of the final two-cell design shows improved performance down to 50% the speed of light (see

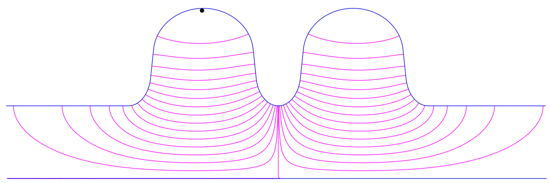

Figure 4. π-mode electric field lines of the two-cell cavity.

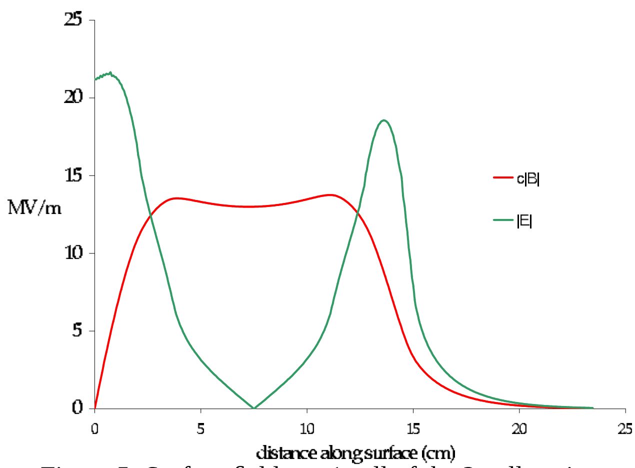

Figure 5. Surface fields on 1 cell of the 2-cell cavity.

Figure 3). The figures of merit are shown in Table 1.

TM012 CAVITY

The basic concept of this design is to reproduce the TM010, π-mode electric field pattern of a multicell elliptical cavity using a higher order TM01p mode of a larger, single-cell cavity. The electric field pattern for the TM012 mode is shown in Figure 6. One advantage of using a single cell cavity is the relative ease of tuning, since the mode separation is large. A single-cell cavity made from bulk niobium would be easier to build and have fewer welds compared to a multicell elliptical cavity. Also, the shape is more amenable to hydroforming and thin film deposition. Finally, lower loss factors are achieved by eliminating reflections from the radially varying surface of a muticell cavity.

However, there are considerable obstacles in using a TM01p mode for acceleration. The peak magnetic fields can be many times that of multicell cavities. The geometric β is greater than unity and a particle will experience a phase slip within the cell, resulting in a lower shunt impedance. Also, there are a number of trapped modes below the accelerating mode. All of these problems worsen as p increases and therefore limits use to relatively small values of p. TM012 was chosen as the accelerating mode, which provides an active length of approximately $3\lambda/2$. The purpose here is to compare the TM012 cavity with an established structure to understand under which conditions the advantages may begin to outweigh the disadvantages.

The higher peak magnetic fields in the TM012 cavity precludes high gradient applications, but not high current applications. If the bunches are repeatedly fed back to the same cavity, then a modest accelerating gradient may be acceptable. High current storage rings such as Diamond, SOLEIL, and the Canadian Light Source require voltage gains between 2 MV to 5 MV. As an example, consider the Nb/Cu, single-cell SOLEIL cavity [7], designed for an average beam current of 500 mA. The TM012 cavity was rescaled so that the accelerating mode frequency matched that of the SOLEIL cavity (353 MHz). The predicted field levels and loss factors are shown in Table 2, assuming a voltage gain of 2 MV and a bunch length of 5 mm for both cavities. ABCI [8] was used to calculate the longitudinal loss factor. Note that while the TM012 cavity has a lower shunt impedance and a lower loss factor it also has a 31% larger beam pipe radius. The geometry factor, G, for the SOLEIL cavity would need to be 291 Ω for the product $(R/Q)G$ to be equal for both designs. Since elliptical cells typically have values of G between 225 Ω and 280 Ω, less power is expected to be dissipated in the accelerating mode of the TM012 cavity. Combining this with the lower loss factor of the TM012 cavity leads to less dynamic losses overall.

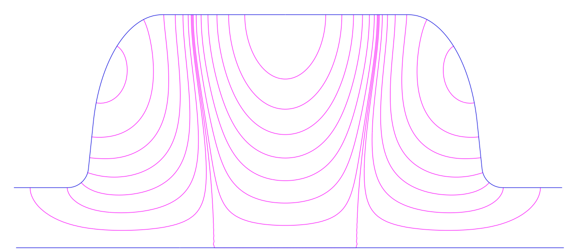

Figure 6. Electric field lines for the TM012 cavity.

Table 2. Figures of merit and field levels for the TM012 cavity as compared to SOLEIL.

	SOLEIL	TM012
E_p/E_a	2	3.06
B_p/E_a	$4.5\ \frac{mT}{(\frac{MV}{m})}$	$8.40\ \frac{mT}{(\frac{MV}{m})}$
$k_{\|\|}$	0.75 V/ pC	0.37 V/ pC
R/Q	90 Ω	55 Ω
Geometry Factor		476 Ω
Cavity length	42.5 cm	122.7 cm
Beam pipe radius	13.0 cm	17.0 cm
Voltage	2.0 MV	2.0 MV
E_p	9.42 MV/ m	4.99 MV/ m
B_p	21.2 mT	13.69 mT

The TM012 cavity shares some of the advantages of existing single-cell cavities since the TM012 cavity also has large separation between the accelerating mode and higher order modes. The additional length of the TM012 cavity results in lower gradients, and therefore lower peak fields, while providing the same voltage as a conventional single-cell cavity. This allows the beam tube radius to be larger, leading to lower longitudinal loss factors and higher attainable beam currents. While the lower-order modes prevent the TM012 cavity from ever being "HOM free", damping of the lower-order modes is not different, in principle, from lower-order mode damping in crab cavities [9, 10].

SUMMARY

Smaller, higher-frequency cavities for accelerating 100's mA of beam current for an ERL are envisioned with every RF bucket filled. This has the advantages of reducing the bunch charge and simplifying HOM damping by ensuring that all dangerous HOMs are above cutoff. Two elliptical cavity designs for this purpose are presented which provide low peak fields and high cell-to-cell coupling. The beam pipe radius is large enough for any HOM with a frequency at or above twice the accelerating mode frequency to propogate out of the cavity. A single-cell cavity operating in a higher order TM01p mode can provide useful voltage gain and a low loss factor, but the issue of adequate parasitic mode damping must still be addressed.

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