HARMONICALLY RESONANT CAVITIES FOR HIGH BRIGHTNESS BEAMS*

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ABSTRACT

Several cavities of simple geometry that support two or more harmonic rf frequencies have been designed. The fields from these cavities are superimposed to form nonsinusoidal waveforms which have important applications in optimized bunchers, high brightness linacs, and storage rings. These cavities are compared in the areas of R/Q, peak surface electric and magnetic fields, and power dissipation. The issues of frequency tuning, rf drive and control, and loading of higher order modes are also addressed.

Introduction

Very high brightness electron guns have been designed and built [1], yet the beam brightness has always degraded one to two orders of magnitude as it passes through a linear accelerator. This degradation is mainly caused by the phase dependence of the longitudinal and transverse forces of the accelerating rf mode; but for intense beams, space charge effects and higher order modes (HOM's) also significantly contribute to the degradation. These problems can be reduced by the use of high gradient, harmonically resonant cavities. We superimpose the fields of a TM010-like fundamental mode with those of a harmonic mode to flat-top the cavity voltage gain versus phase. This leads to a greatly enhanced phase acceptance with no beam degradation. For example, using only a single frequency to accelerate the beam, a 5° bunch would yield a 0.1% energy spread. In contrast, a harmonically resonant cavity using a third harmonic mode with an optimized amplitude, can accept a 37° bunch and give the same 0.1% energy spread (Fig. 1).

Although a principal use of harmonically resonant cavities will be in an injector (where $\beta < 1$), the discussion in this paper will be limited to the case where $\beta = 1$. In the high energy regime, the principal cause of beam degradation is the phase dependence of the voltage gain. For harmonically resonant cavities, the voltage gain versus entry phase using an n^{th} harmonic (set to cancel $d^2V/d\phi^2$) is given by

$$V = V_0 (\cos \phi - (1/n^2) \cos n\phi) / (1 - 1/n^2)$$

where V_0 is the desired voltage gain through the cavity and ϕ is the entry phase of an electron. Our analysis has been done for $V_0 = 1$ MV per cavity, with a frequency of 1 GHz. The harmonic mode in a third harmonic cavity decelerates the beam by 0.125 MV while the fundamental accelerates the beam by 1.125 MV (Fig. 1). Bunching for high peak currents can then be performed in the high energy regime by employing a magnetic dispersion section.

Harmonically resonant cavities have been used for bunchers and proposed for accelerator structures at Los Alamos [2,3]. They used a TM010-like mode at 0.45 GHz as their fundamental and a TM020-like mode

Fig. 1 Flat-topping the energy gain versus phase with a third harmonic cavity optimized for a 37° bunch: this yields a 0.1% energy spread. The fundamental and the summed fields are normalized to the same energy gain.

Fig. 2 Electric field profiles of some of our harmonic modes.

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at 0.9 GHz as their second harmonic mode. The cavities are drawn to relative scale. Their cavities are inappropriate for acceleration at high beta because the achievable voltage gain per cell is small due to the short cell length and because the complex, sharp cornered geometry prevents high field levels. We have emphasized three important differences in our design: we have designed only smooth cavities capable of handling high fields; we have concentrated on third harmonic modes since these waste less than half the fundamental acceleration energy that a second harmonic wastes; and we have extended our study to include TM011-like and TM021-like modes that retain large harmonic R/Q values in a reasonably long cavity (Fig. 2). These changes will give us harmonically resonant cavities capable of achieving high acceleration gradients with relatively high efficiency.

Cavity Geometry

The general design for the cavities is shown in Fig. 3. The cavities are all smooth and of simple geometry. The outer surface was kept fully rounded to minimize the likelihood of one-point multipacting [4,5]. The beam pipe aperture was kept as large as is consistent with containing the harmonic mode, to help control undesired HOM's. The dimensions for three cavities are given in Table I. We have designed a third harmonic cavity using a TM021-like mode, a second harmonic cavity using a TM011-like mode and, for general interest, a second and third harmonic cavity using the TM020-like and TM030-like modes. A third harmonic cavity using the TM011-like mode was also designed, but was not included since it was inferior to our TM021-like third harmonic cavity. The computer code URMEL [6] was used to model the various cavity characteristics.

Fig. 3 Cavity Shape. Dimensions for three cavities given in Table I.

Calculations

A summary of cavity characteristics is given in Table II. We have included variables relating to achievable acceleration gradients for $\beta = 1$. The R/Q is a measure of the efficiency of the coupling between the fields and the beam. It is defined as V^2/PQ , where V is the voltage gain of the ideal electron, P is the power dissipated on the cavity

Table I

Dimensions for cavities at 1 GHz;
all distances in cm

Cavity Number	1	2	3
Harmonic Mode(s)	3rd TM021	2nd TM011	2nd/3rd TM020/TM030
R	13.1	13.1	14.5
L	11.9	13.0	6.6
r_1	4.0	4.8	0.8
r_2	1.0	1.0	0.6
b	3.2	4.0	3.1
θ	79.5°	79.5°	79.5°

walls, and Q is the cavity quality factor. E_{peak} and H_{peak} are the maximum electric and magnetic fields found in the cavity surface. The power dissipated on the cavity walls has been included for copper cavities at room temperature. For comparison, niobium at 4°K dissipates a factor of 10^5 less power. The maximum surface fields versus location are given for cavity #1 in Fig. 4.

Table II

Cavity Characteristics
assuming 1 MeV energy gain through 1 GHz cavity
with $\beta = 1$

Cavity Number	1	2	3
R/Q ₁	146.0	134.8	85.2
R/Q _{harm}	11.0	34.2	39.8/4.9
E_{peak} (MV/m)	14.2	17.8	42.4
H_{peak} (KA/m)	32.1	44.5	91.7
Power (MW)	0.4	0.6	3.0

Fig. 4 Maximum surface fields present on cavity #1. In all cases a 1 MV voltage gain is assumed through the cavity. See Fig. 3 for surface locations.

Cavities 2 and 3 have the advantage of wider phase acceptances due to the harmonics used. Nevertheless, using a second harmonic (cavity #2) to flat-top the rf for an accelerator cavity requires that 25% of the fundamental acceleration energy be dumped into the decelerating harmonic, while a third harmonic system (cavity #1) only wastes 11% of the energy. A second and third harmonic system (cavity #3) wastes a large 37% of the fundamental energy. Cavity #1 is clearly superior in power dissipation and peak surface fields due to its high fundamental R/Q and due to the lower harmonic field amplitude in a third harmonic cavity.

Tuning, rf System and HOM's

We abandoned the quest for independent tuning of the modes in favor of a simpler solution. The TM010-like fundamental mode has a concentration of magnetic field at the cavity equator (position A in Fig. 3), while its electric field is very weak there. Conversely, an antisymmetric harmonic mode has a strong electric field and a weak magnetic field at the equator. Thus, a tuning plunger located at the cavity equator will tune both the fundamental and the harmonic, but in opposite directions. A second tuning method is necessary to give us complete control over the two modes. A longitudinal compression or expansion of the cavity will shift the frequency of the anti-symmetric harmonic mode much more strongly than the fundamental, since the harmonic mode is much more sensitive to changes in cavity length than the fundamental mode. This compression tuner could tune the harmonic frequency to its proper value after the tuning plunger properly set the fundamental frequency.

The rf input couplers and monitors need to operate with a minimum of crosstalk between modes. The spatial mode characteristics of an antisymmetric harmonic mode could assist us in this endeavor. An azimuthal magnetic field probe for the fundamental mode and a radial electric field probe for the harmonic mode could prevent most of the crosstalk between the modes. The rf monitors require an exceptionally pure signal and thus it is likely that additional methods of rejecting the unwanted modes will be necessary. A waveguide attenuator could provide excellent rejection of the fundamental from the harmonic signal, while a resonant coupler could ensure the purity of our fundamental signal.

We need to be able to load the unwanted HOM's in the cavity without destroying the Q's of our operating modes. The plan most seriously being considered is to use our two input couplers as higher order mode couplers. By placing a major perturbation on the cavity equator it is possible to set the polarization of all of the dipole and quadrupole modes. Placing the input couplers on the cavity equator, symmetrically spaced 60° from the perturbation, would allow us to couple to all monopole, dipole and quadrupole modes. This method has the advantage of not having additional couplers which would load the Q of the desired modes, while still effectively loading all other important modes.

Summary and Conclusion

The choice between cavities depends on the particular application. In each case an antisymmetric harmonic mode is preferred for its usefulness in tuning and rf monitoring and, in accelerator cavities, for its potential in achieving high voltage gains. A third harmonic is preferred as an accelerator cavity for its efficiency, while a second harmonic is preferred as a buncher for its greater phase acceptance. Specifically, cavity #1 seems best suited to an accelerator cavity, cavity #2 to buncher applications, and cavity #3 appears to be too complicated for practical use.

Harmonically resonant cavities have the disadvantages of being more complicated, and somewhat less efficient, than single frequency cavities. Nevertheless, in those cases where a wider phase acceptance is deemed necessary, these cavities offer an easy solution. The ability of these cavities to accept large bunches with high field gradients in a single cell structure could be a powerful aid to achieving high brightness beams.

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