BEAM ACCELERATION BY A MULTICELL RF CAVITY STRUCTURE PROPOSED FOR AN IMPROVED YIELD IN HYDROFORMING*

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Abstract

We study the accelerating properties of a new multicell cavity structure with irises forming a rectangular aperture between the cavity cells. We are interested in this structure because, from a mechanical point of view, it may be possible to manufacture with high quality using a hydroforming process. RF analysis shows that the rectangular iris shape provides some asymmetric transverse focusing per half RF period, particularly for low beam energies. If the horizontal and vertical rectangular irises are interleaved, the net transverse focusing could be increased. Here we present studies of the acceleration and transport properties of these cavities by tracking particles using the ORBIT Code through time-dependent 3D cavity fields taken from CST MWS.

INTRODUCTION

A new multicell accelerating cavity structure with irises forming rectangular apertures between the cavity cells is being proposed in a paper at this conference [1]. In reference [1], the RF properties of such a structure are studied using 3D simulations with CST MWS to analyze the EM fields and the cavity parameters. We are interested in such structures because it may be possible to manufacture them with high yield using a hydroforming process. From the mechanical point of view, the rectangular iris may provide much improved structure quality using a hydroforming process since it can help to reduce the stress occurring within the sheet metal. The necking procedure can be easier because of the greater perimeter in the iris geometry. Peak electric and magnetic fields per accelerating gradient may increase however, compared to traditional TESLA type elliptical cavity structures. The rectangular iris shape provides asymmetric transverse forces per half RF period. If the horizontal and vertical rectangular irises are interleaved, it might be possible to obtain net transverse focusing.

In this paper, we study the accelerating properties of a multicell cavity with rectangular apertures using the time-dependent 3D particle tracker in the ORBIT Code [2]. The 3D time-dependent electromagnetic fields used in the tracking study are taken from the results of CST MWS calculations performed in Ref. [1]. The tracking calculations in the present work are carried out for a single cavity structure, similar to that of a TESLA type cavity, but additional structures are under study.

The structure that we consider here consists of nine half-wavelength cells, each of length 11.57 cm. The cavity is tuned for $\beta = 1$, namely, to accelerate most efficiently particles travelling at light speed. The corresponding cavity frequency is 1.296 GHz. The calculations in this paper assume that electrons are being accelerated. Figure 1 shows the cavity structure, and the alternating flattened horizontal and vertical irises are clearly seen.

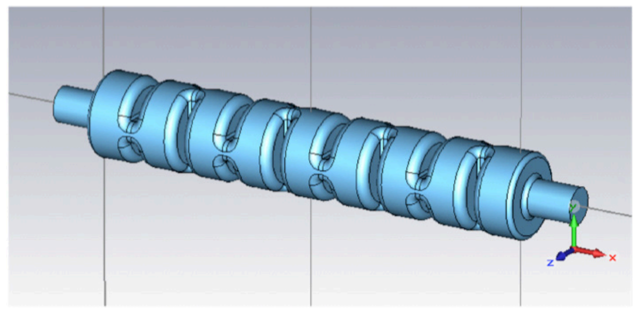

Figure 1: Cavity structure used in the present studies.

The calculations presented in this paper scale the field strengths calculated in Ref. [1] so that the peak accelerating gradients are between 20 MeV/m and 25 MeV/m. We now present the tracking results.

FIELDS AND PHASE DEPENDENCE

We begin our study of the accelerating properties of the rectangular iris cavity by observing its impact on a maximally accelerated energetic 1 GeV electron. Figure 2 shows the electric fields and magnetic fields seen by a maximally accelerated 1 GeV electron as it traverses the cavity. The transverse electric and magnetic fields in the figure are taken at 1 cm horizontal and vertical displacements from the cavity center, because they are zero on axis. The transverse fields increase linearly, (E_x and B_y) $\propto$ x and (E_y and B_x) $\propto$ y, for small transverse displacements, while the longitudinal fields vary as $E_z \propto$ constant and $B_z \propto xy$. A quick calculation shows that the focusing forces due to the transverse electric and magnetic fields are comparable in magnitude for electrons moving near the speed of light. The focusing effect of these forces decreases as the electron energy increases, and so they will be most observable on lower energy electrons, with energies below one GeV.

The increase in energy of a maximally accelerated 1 GeV electron is 12.4 MeV after it passes through the 1.23 m long cavity. This increase is independent of the initial electron energy for electrons travelling near the speed of light. In calculations below, we obtain this energy gain for an electron bunch at initial energies as low as a few MeV.

* ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

ISBN 978-3-95450-115-1

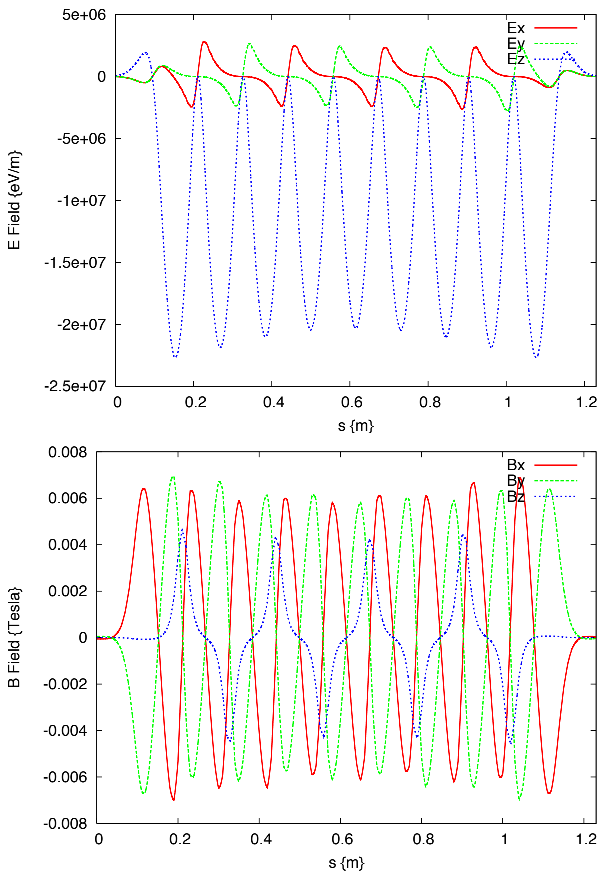

Figure 2: Electric fields (top) and magnetic fields (bottom) seen by a maximally accelerated 1 GeV electron as it traverses the cavity at 1 cm transverse horizontal and vertical displacements from the central axis.

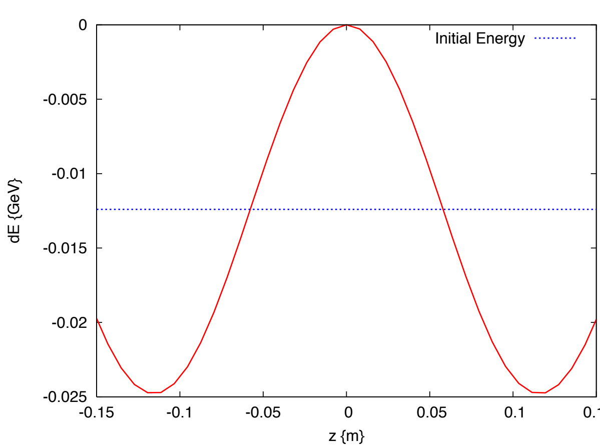

Figure 3: Energy relative to maximally accelerated electron for electrons longitudinally displaced by z from the maximum.

We now consider the phase dependence of the acceleration for energetic on-axis electrons. We start with a string of 1 GeV electrons separated in longitudinal coordinate z with the cavity phased to provide maximum acceleration of electrons at $z = 0$. Figure 3 shows the energy of the electrons as they exit the cavity, compared to that of the maximally accelerated electron, as a function of the distance ahead or behind the maximally accelerated electron. The result is just a sinusoid of amplitude 12.4 MeV and shifted down that amount, namely, the energy gain of the maximally accelerated electron. This shift corresponds to zero acceleration. The wavelength of the sinusoid is 231 mm, which corresponds to the cavity frequency of 1.296 GHz. In a linear accelerator, we would choose to accelerate energetic electrons maximally, because longitudinal focusing is not a problem there. Figure 3 suggests that in order to achieve good acceleration of the entire bunch, we should choose the bunch length to be no more than a few millimeters. In the bunched beam acceleration studies below, we choose a bunch length of 5 mm.

ENERGY AND TRANSVERSE BEHAVIOR

In order to examine the accelerating properties of the rectangular iris cavity over a range of energies, we create a simple periodic FODO lattice with cavities placed centrally between the quadrupole magnets. We set the quadrupole lengths to 0.5 m and the periodic FODO cell length to 5.0 m. We set the quadrupole strengths equal and opposite such that the maximum and minimum Twiss parameter values at the quadrupole centers in the absence of acceleration are $\beta_{max} = 11.48$ m and $\beta_{min} = 6.43$ m. Also with no acceleration, the tune, or phase advance is 34° per cell. The accelerating properties of the cavities, rather than the lattice design, are our emphasis here.

To study the accelerating properties of a bunch in this lattice, we choose a KV transverse distribution with an initial RMS emittance of 0.3 mm-mradian in both the horizontal and vertical planes. We match the distribution to the lattice with no acceleration, so that the maximum and minimum transverse beam radii in each plane are 3.71 mm and 2.78 mm, respectively. Although this is not crucial to our study, we initialize the bunch with a uniform energy distribution having a small spread of ±0.15 MeV. As stated above, the initial bunch length is taken to be 5.0 mm. We examine the acceleration of the bunch for different values initial energy. In all cases, we phase the cavities to provide maximum acceleration at the bunch center.

Starting at a low kinetic energy of 1 MeV, corresponding to electrons with $\gamma = 2.96$ and $\beta = v/c = 0.941$, we find that the distribution debunches longitudinally after passing through a single cavity and that there is also some transverse spreading. The longitudinal spreading is accompanied by an increase in the energy spread to about 1 MeV. This is not too surprising because we are tracking a bunch with $\beta = 0.941$ in a $\beta = 1$ cavity. At an initial kinetic energy of 3 MeV, corresponding to electrons with $\gamma = 6.87$ and $\beta = 0.989$, there is only a very slight longitudinal debunching and increased energy spread. The transverse distribution is altered by the electric and magnetic fields of the cavities, which at this energy have a much greater effect than the

ISBN 978-3-95450-115-1

FODO quadrupole focusing fields. However, the distribution spreads only slightly in the transverse direction, so that the beam as a whole is accelerated and contained.

We repeated the tracking of our particle distribution through cavities with higher and higher initial beam kinetic energies, specifically, 10 MeV ($\gamma = 20.6$, $\beta = 0.999$) and 30 MeV ($\gamma = 59.7$, $\beta \approx 1$). In both these cases there was no longitudinal debunching and there was uniform acceleration of the entire bunch. In both transverse directions, the beam was compressed due to the effect of the transverse cavity fields, the acceleration, and the FODO quadrupoles. The effect of the transverse cavity fields compared with that of the FODO quadrupole magnets decreases with beam energy. Based on the magnitude of the transverse cavity fields shown in Fig. 2, we would expect them to dominate the FODO quadrupoles in determining the transverse dynamics up to $\gamma \sim 1000$, or 500 MeV (for protons, the corresponding energy would be about 150 MeV). However, the transverse cavity fields seen by the beam oscillate rapidly, so their observed effect on the beam diminishes more quickly. By the time $\gamma = 400$, or at energy 200 MeV, the quadrupole focusing dominates the transverse beam behavior.

As a final study, we track the test bunch through 50 FODO cells, or 100 cavities, with an initial kinetic energy of 50 MeV (total energy of 50.511 MeV). The results are shown in Figure 4. The longitudinal distribution shows no debunching as the bunch is accelerated to 1.29 GeV over 250 m, although the energy spread increases to 3 MeV due to the smaller acceleration of the ends of the bunch. The beam size decreases in transverse phase space as the bunch is accelerated in such a way that the normalized transverse emittances are constant. Figure 4 shows that most of the small variation in the normalized emittances occurs within the first 200 MeV of acceleration, where the influence of the transverse fields in the cavities is strongest. We repeated the calculation with the FODO quadrupoles turned off, and found that the transverse cavity fields provided a net focusing effect in the horizontal direction, but a defocusing effect vertically that caused the beam to be lost at about 500 MeV.

In summary, the multicell cavity with rectangular apertures is capable of accelerating electron bunches at energies above a few MeV. The rectangular apertures lead to additional transverse electromagnetic fields that give rise to additional transverse forces. These are most significant for electrons having energies below about 200 MeV. However, an electron bunch with an initial energy of 50 MeV was successfully accelerated to high energy.

Future studies will focus on the accelerating properties of other variants of rectangular aperture cavities and on lattice optimization.

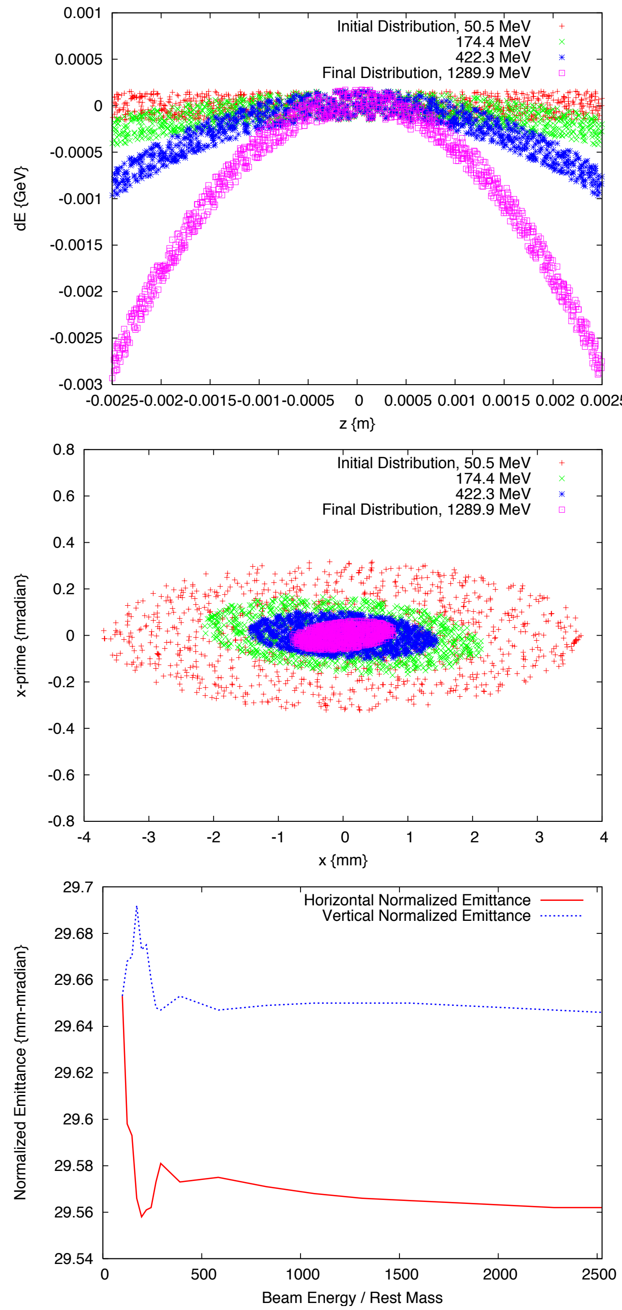

Figure 4. Longitudinal distributions (top), transverse horizontal distributions (middle), and normalized transverse emittances (bottom) versus energy.

REFERENCES

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ISBN 978-3-95450-115-1