A HIGHLY EFFECTIVE DEFLECTING STRUCTURE*

C. Leemann and C. G. Yao
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue, Newport News, VA 23606

Abstract

A structure is presented that combines high transverse shunt impedance ($\approx$ 500 MΩ/m at 500 MHz) with outside dimensions that are small in relation to the desired mode's resonant frequency. The basic idea was to find a practical way to resonate a small gap, two conductor, $\lambda/4$ transmission line with a field pattern that is locally very close to a TEM dipole mode (apart from important and essential modifications at the gap end). Two possible applications stand out: use as an RF separator (discussed here) or use as a high sensitivity microwave beam position monitor.

Introduction

The basic structure, a 1/4 wavelength resonator, is shown in Figure 1.[1] Two rods are placed along the z direction, with gaps between the rods and the cavity wall on one side. The desired mode is a dipole mode, field patterns of which are shown in Figures 2 and 3. The gaps are essential to excite this mode.

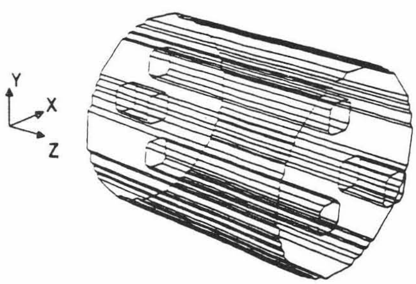

Figure 1. A 3-D picture of a 1/4 wavelength resonator.

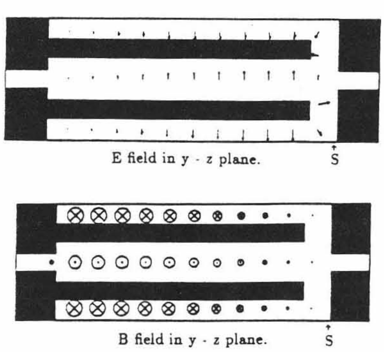

Figure 2. Field patterns in y - z plane.

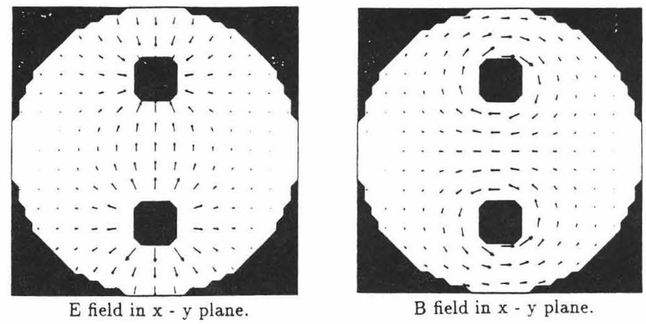

Figure 3. Field patterns in x - y plane.

The rods play an important role in two aspects. First, they cut down the outside cavity diameter. For example, the outside diameter of a disk loaded waveguide for a 500 MHz deflecting cavity is about 800 mm, but with the proposed cavity, it can be as small as 120 mm. It allows the effective RF separators used for bunch-to-bunch extractions at CEBAF to run at a frequency of 500 MHz, which will reduce emittance dilution caused by differential head-to-tail steering of RF separators. Second, they compress the field into the central region of the cavity, so that the fields in the central region of the cavity are very high which leads to very high transverse shunt impedance $R_\perp$. For example, for a square box deflecting cavity such as the CEBAF injector chopper, effective transverse shunt impedance $R_\perp \approx 6.8$ MΩ/m, and for a biperiodic structure of current CEBAF RF separator design $R_\perp \approx 15$ MΩ/m, but for the described structure the shunt impedance $R_\perp$ ranges from 200 to 500 MΩ/m depending on detailed choice of geometry.

Analytical Study

The cavity under study can be viewed approximately as a 1/4 wavelength transmission line, and is analyzed in this section following a discussion of Lambertson.[2] Its left end is short, and its right is open. Voltage and current distributions along z are, respectively:

$$V = V_0 \sin \frac{2\pi z}{\lambda} \tag{1}$$

$$I = \frac{V_0}{Z_c} \cos \frac{2\pi z}{\lambda} \tag{2}$$

where V_0 is a voltage across gaps. Z_c is characteristic impedance.

At resonance, the stored energy in the cavity is:

$$U = \int_0^{\lambda/4} L I^2 \, dz \tag{3}$$

where $L = \frac{Z_c}{c}$ is the inductance per unit length and c is the velocity of light. Using equation (2) this becomes:

* This work was supported by the U.S. Department of Energy under contract DE-AC05-84ER40150.

$$U = \frac{V_0^2}{Z_e^c}\int_0^{\lambda/4} \cos^2\frac{2\pi z}{\lambda}\,dz = \frac{V_0^2}{8Z_c}\cdot\frac{\lambda}{c}\,. \tag{4}$$

The effective transverse shunt impedance $R_\perp$ is[3] (for $\beta = 1$):

$$R_\perp = \frac{Q}{\omega U}\left(\frac{\nabla_\perp V}{k}\right)^2 \tag{5}$$

where Q is quality factor, ω is angular frequency, and

$$k = \frac{2\pi}{\lambda}$$
$$V = \int_0^{\ell} E_z e^{jkz}dz$$
$$\nabla_\perp^2 V = 0.$$

Using equations (4) and (5), we find

$$\frac{R_\perp}{Q} = \frac{8Z_c}{\pi k^2}\left(\frac{\nabla_\perp V}{V_0}\right)^2. \tag{6}$$

Z_c and $\nabla_\perp V$ are obtained from 2-D calculations. V is the solution of the boundary value problem having $V = 0$ on the outer shell and $V = \pm V_0$ on the rod's surface of diameter d_0 and rod space d_c. We are interested in the area near the origin. It can be approximately treated as electrostatic problem of two parallel conducting cylinders. On the line joining the centers of two rods (x direction) we would have

$$V = \frac{V_0}{\ln\frac{b+a}{b-a}}\left[\ln(b-x) - \ln(b+x)\right] \tag{7}$$

where

$$b = \frac{1}{2}\sqrt{d_c^2 - d_0^2}\quad,\quad a = \frac{1}{2}(d_c - d_0).$$

From equation (7) we obtain

$$\left.\frac{dV}{dx}\right|_{x=0} = -\frac{2V_0}{b\ln\frac{b+a}{b-a}}\,.$$

Also, we have

$$Z_c = \frac{Z_0}{2\pi}\ln\frac{d_c}{d_0}\qquad (Z_0 = 120\,\pi\Omega) \tag{8}$$

where Z_0 is free space wave impedance. Using equations (7) and (8), we obtain

$$\frac{R_\perp}{Q} = \frac{1920}{\pi k^2}\,\frac{\ln\frac{d_c}{d_0}}{b^2\ln^2\frac{b+a}{b-a}} \tag{9}$$

and

$$\frac{R_\perp}{\ell Q} = \frac{7680}{\pi k^2\lambda}\,\frac{\ln\frac{d_c}{d_0}}{b^2\ln^2\frac{b+a}{b-a}}\,. \tag{10}$$

where $\ell = \lambda/4$.

It is interesting to see the $\frac{R_\perp}{\ell Q}$ dependence upon rod space d_c (as shown in Figure 4). When the two rods get closer to each other, the transverse shunt impedance rapidly inreases.

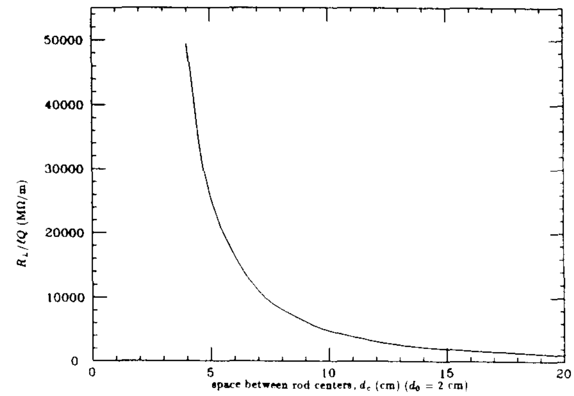

Figure 4. $R_\perp/\ell Q$ vs. d_c.

Numerical Study

We use MAFIA to calculate the properties of this type of cavity. The dimensions of the cavity under study are the following:

cavity length $l = 150$ mm

beam aperture $d_{in} = 20$ mm

rod diameter $d_0 = 20$ mm

Figure 5 shows the relationship between the frequency and gap width. As the gap gets larger, the frequencies of the modes go higher for all three modes.

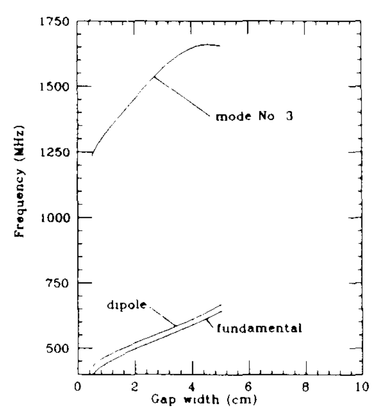

Figure 5. Frequency vs. gap width.

As gap width is decreased, Q goes down. Since this is a 1/4 wavelength resonator, it is expected that the frequency of the mode strongly depends on the rod length (or gap width) rather than the outside diameter of the cavity.

In some applications only one single cavity need be used. However, to make this type of cavity useful for the CEBAF RF separators that require a very strong deflection effect, it may be desirable to find a way to couple them together.

The field patterns in Figure 2 show that the electric field is perpendicular to the plane S and the magnetic field is very weak in the region close to the plane S. If the two 1/4 wavelength cells are put together facing each other as shown in Figure 6, and the plane S is taken away to form a 1/2 wavelength cavity (π mode), the field pattern will almost be unaffected, and its performances (frequency, $R_\perp$, etc.) will remain the same as a single 1/4 wavelength cell. Furthermore, we are able to couple several of these cavities together through slots in the webs to constitute a structure. This is a structure with magnetic coupling. It has a backward wave property. An increase in slot size will enlarge the separation of the modes.

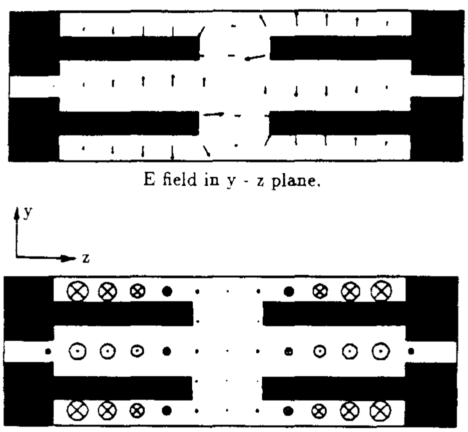

Figure 6. Field patterns in a half-wavelength cavity.

After careful optimization of cavity geometry the effective transverse shunt impedance $R_\perp$ over the whole structure, which is 60 cm long and operated at 500 MHz, is around 500 MΩ/m. The Q value of the structure is ≈ 10000. If this structure is used as an RF separator for the highest energy (5 GeV), the required RF power is:

$$p = \frac{(5\ \text{GeV} \times 10^{-4} \times 1.16)^2}{R_\perp L} = 1.1\ \text{kW}.$$

By comparison, the current design RF separator for the highest energy is $\approx$ 3 m long and requires 10 kW of RF power.

It can be seen from the field pattern that a large part of power dissipation is on the surface of the rods and the web, and special attention should be paid to cooling these parts of the structure.

Figure 7 shows the field uniformity in the central region of the structure. As can be seen the fields in the central region are more uniform with bigger rods. The phase space distortion caused by the deflecting structure is less than 1% if the beam size is about 1 mm in diameter. On the one hand, the field pattern is sextupole-like; any phase space distortion caused by the structure may presumably be corrected by a sextupole magnet placed with an appropriate phase advance downstream of the separator. On the other hand, field aberration could be minimized by choosing the proper shape of the rods.

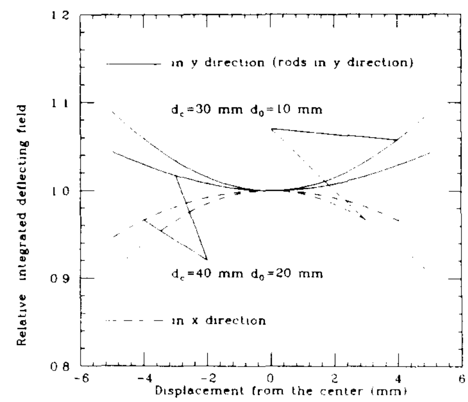

Figure 7. Field uniformity in central region.

Acknowledgement

We wish to thank R. Miller at SLAC, G. Lambertson at LBL, and W. Barry for valuable discussions.

References

1. C. Leemann, C. G. Yao, CEBAF TN-90-217, April 25, 1990.
2. G. Lambertson, Short Note to Ref. 1, August 6, 1990.
3. W. K. H. Panofsky, et. al., R.S.I. 1956, **27**, No. 11, p. 967.