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Effect of altering the cavity shape in infinitely periodic dipole cavities

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Abstract

Several current applications require the use of multi-cell superconducting dipole cavities. Iris shape and size are shown to be critical operational parameters. The effects of changes to the iris of an infinite periodic cavity, based on the FNAL CKM cavity, are presented, and discussed with relevance to the 9-cell ILC crab cavity. Changes to the resonant frequency of the cavity due to small parameter variations are studied, as is the effect of squashing the cavity.

1. Introduction

Dipole cavities are currently under investigation as crab cavities [1], time-slice diagnostics [2], and for creating short X-ray pulses in light sources [3]. Dipole cavities operate using the fundamental dipole mode of a cavity, where there is one azimuthal variation over 360 degrees. This mode is usually a transverse magnetic mode. This means that there is zero longitudinal electric field on axis, and the field increases linearly to the beam pipe radius. The longitudinal electric field is equal and opposite on opposing faces of the beam pipe, this creates a large surface current flow around the iris, creating a large magnetic field.

If we look at a transverse deflecting cavity, like the Fermi National laboratory CKM [4] and compare it to an accelerator cavity like the TESLA cavity, in Table 1 we can see that for the dipole mode the ratio of maximum magnetic field to maximum electric field is twice as large. As a consequence, the limit to the kick for a crab cavity is generally determined by the rf critical magnetic field and not by field emission.

Cavity type	mode	Frequency GHz	B_{max} mT	E_{max} MV/m
TESLA	TM010	1.3	105	50
CKM	TM110	3.9	80	18.5

Table 1 Comparison of the TESLA cavity and CKM cavity surface fields

For this reason it is better to optimise for low surface magnetic field compared to the deflecting voltage. For the dipole mode the maximum surface magnetic field is located at the iris, as can be seen in Figure 1.

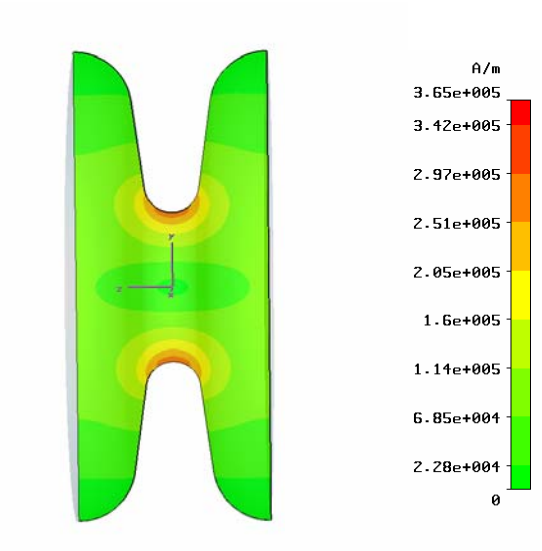

Figure 1 Magnetic field strength magnitude for a dipole mode.

For a multi-cell cavity, each cell must be half the free space wavelength in length in order to have the bunch enter each cell with the correct phase.

2. The FNAL CKM cavity

The FNAL CKM cavity [4] is a 13-cell superconducting dipole cavity operating at 3.9 GHz. This cavity operates using the TM_{110} π mode. The cavity dimensions are given in Table 2, and Figure 2.

Type C15a		mid-cell	trans-cup	end-cup
half cell length	g/2	19.2 mm	19.2 mm	18.6 mm
iris radius iris curvature	a r_i	15.0 mm 5.5 mm	15.0 mm 5.5 mm	18.0 mm 5.5 mm
equator radius equator curvature	b r_e	47.18 mm 11.41 mm	47.37 mm 11.41 mm	47.37 mm 11.41 mm

Table 2 Dimensions of the FNAL CKM cavity

The end-cell dimensions are slightly different from the mid-cell to ensure field flatness.

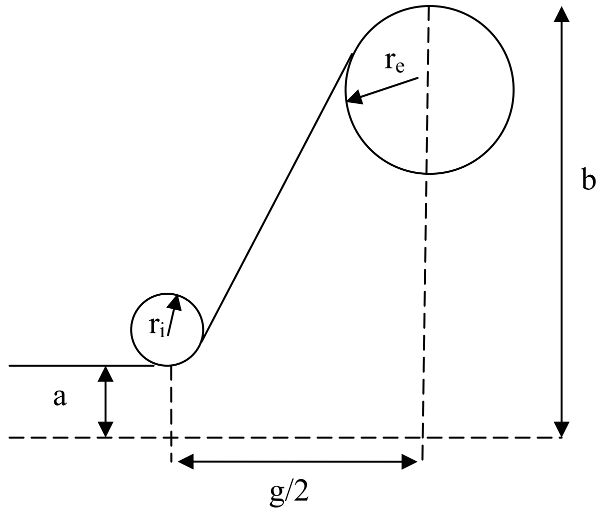

Figure 2 Schematic view of cavity shape.

This cavity is slightly squashed after manufacture to separate the frequency of the two polarisations of the operating dipole mode; a change of 3mm in the diameter creates about an 8 MHz frequency splitting. This effect will be neglected in this study and only azimuthally symmetric cavities are considered.

3. The effect of altering the iris radius

The mid-cells of a multi-cell cavity can be analysed using an infinite periodic cavity in a Finite-Difference or Finite-Element code using a dumbbell shape, Figure 3, with a periodic boundary. In this case a periodic boundary of 180 degrees phase advance between cells was used.

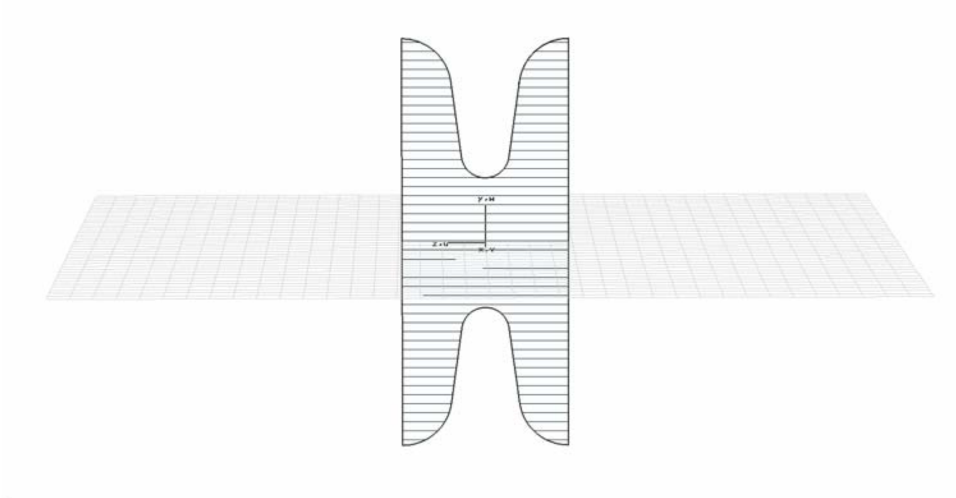

Figure 3 Schematic view of a dumbbell made from 2 half cell cavities

The FD code MicroWave Studio (MWS) was used to examine the effects of altering the iris size, using 170,000 mesh cells per dumbbell. The iris radius was varied from 1.0 cm to 1.7 cm and the equator radius was varied for each cavity to bring the resonant frequency to 3.9 GHz, shown in Figure 4.

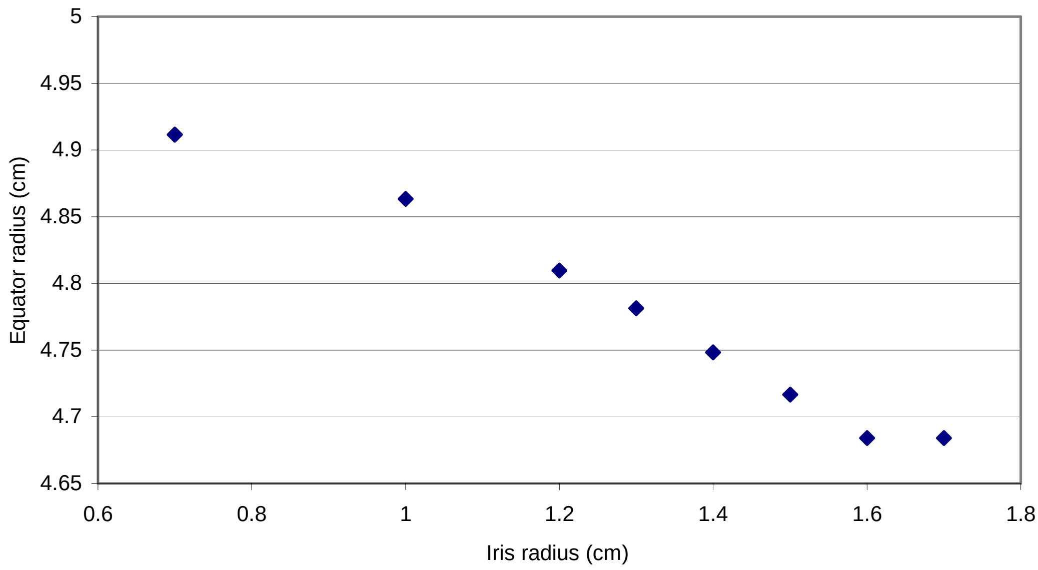

Figure 4 The relationship between iris and equator radius for a 3.9GHz cavity with iris curvature 0.55cm and equator curvature 1.141cm

As the iris radius was varied, the surface magnetic field and the longitudinal voltage 1 cm off-axis were calculated, where the longitudinal voltage is the integrated longitudinal electric field including the transit time factor. Note that the longitudinal electric field off axis is proportional to the transverse kick [5]. The ratio of the maximum surface magnetic field to the longitudinal voltage is shown in Figure 5.

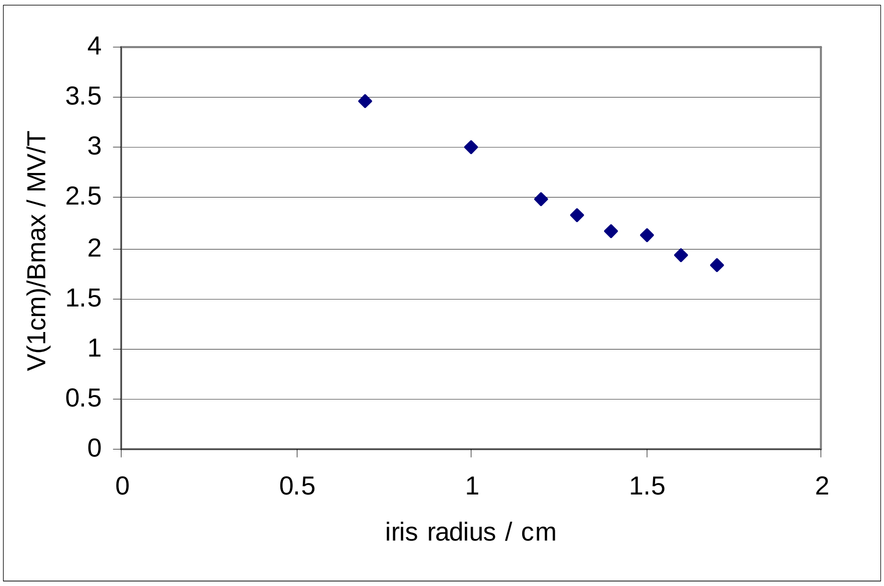

Figure 5 The longitudinal voltage offset from axis by 1 cm, normalised to the surface magnetic field versus iris radius for a 3.9 GHz cavity with iris curvature 0.55 cm and equator curvature 1.141 cm

Additionally, the geometric shunt impedance, R/Q, was calculated against iris radius, shown in Figure 6.

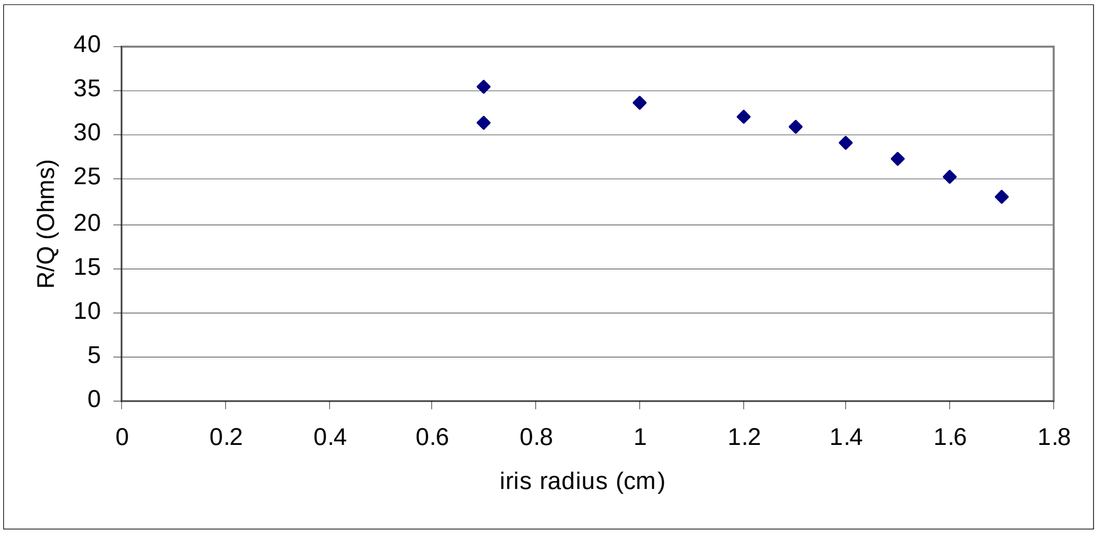

Figure 6 The geometric shunt impedance versus iris radius for a 3.9 GHz cavity with iris curvature 0.55 cm and equator curvature 1.141 cm

where the geometric shunt impedance is given as,

$$\frac{R}{Q} = \frac{|V_z|^2}{2\omega U}\left(\frac{c}{\omega r}\right)^2$$

For multi-cell cavities the π mode and (N-1) π / N mode, where N is the number of cells, will overlap slightly if the modes are close in frequency. This causes a potential problem in tuning the cavity for field flatness at room temperature when the modal bandwiths are large. The spacing between these modes should be at least 4 times their bandwidth when warm for ease of tuning.

Defining the frequency separation as df / f then

$$\frac{df}{f} = \frac{f_\pi - f_{N-1}}{f_\pi} = \frac{2}{Q_0}$$

hence for a Q_0 of 5000, this gives a tolerance of 0.4%. The frequency separation between the π mode and 8π / 9 mode have been calculated using MWS and results are shown in Figure 7.

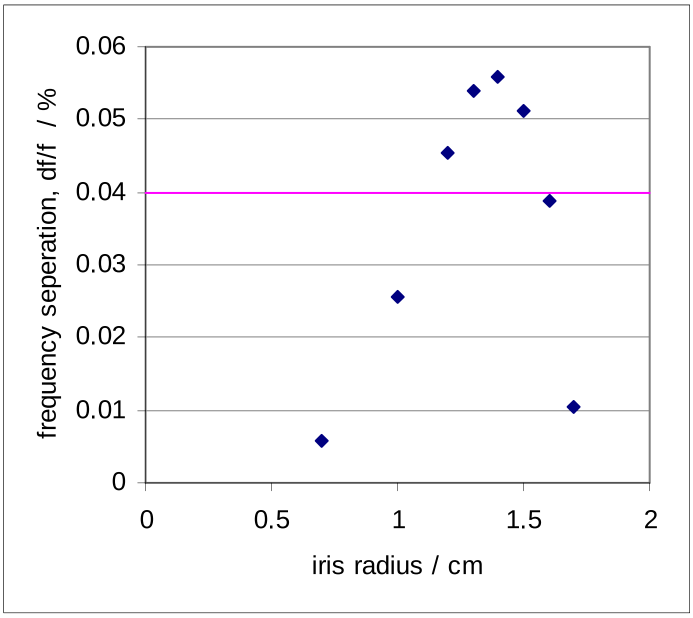

Figure 7 Frequency separations between the π mode and 8π / 9 mode versus iris radius for a 3.9 GHz cavity with iris curvature 0.55 cm and equator curvature 1.141 cm (the pink line is the tolerance for a 9 cell cavity)

A 9-cell cavity was chosen for this analysis as it corresponds to a recent proposal for the ILC crab cavity.

The variation in the cavities geometry factor, G ($G=QR_s$) was also studied, shown in Figure 8.

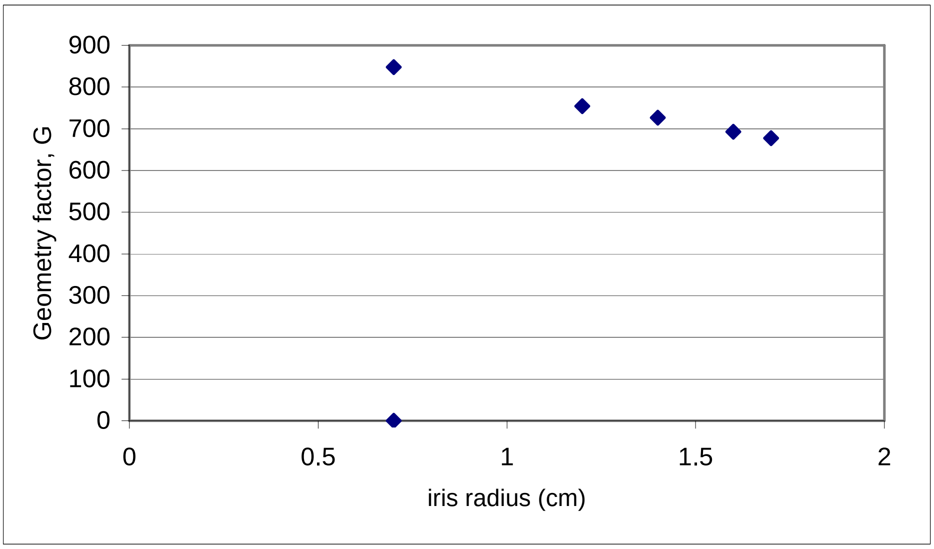

Figure 8 Geometry factor, G of a copper cavity versus iris radius for a 3.9 GHz cavity with iris curvature 0.55 cm and equator curvature 1.141 cm

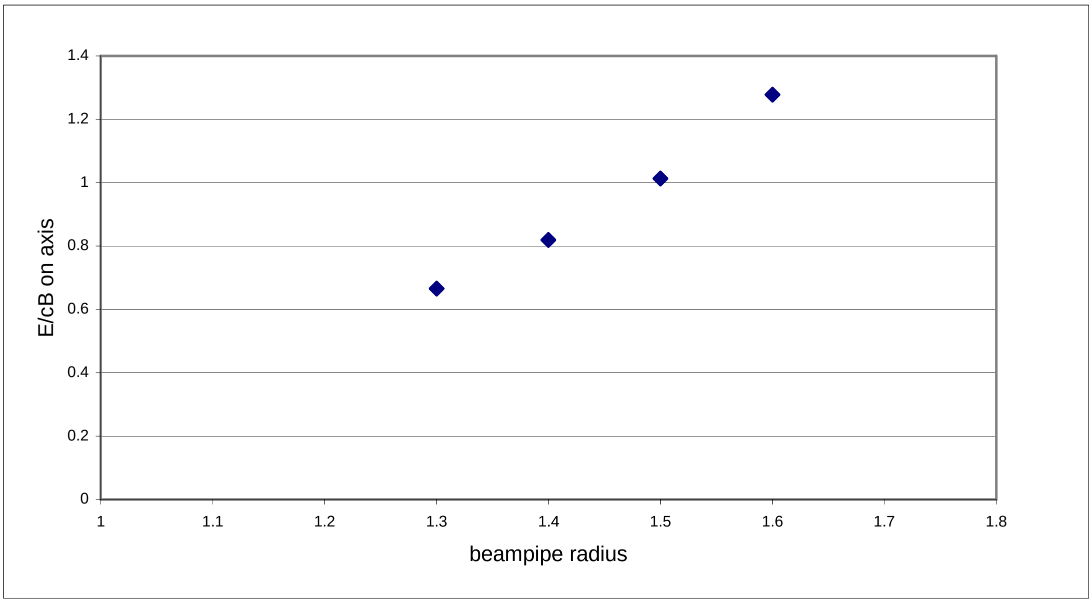

Figure 9 Ratio of the peak Electric field on axis to the peak magnetic field on axis divided by c versus the beam pipe radius.

In a multi-cell dipole cavity, the kick is provided by both the transverse electric and magnetic fields on axis. The proportion each component contributes to the kick varies with the iris radius. The ratio of the peak fields are shown in Figure 9.

It should also be noted that the HOM wake-fields will also decrease as the iris radius is increased and that the iris must be of sufficient size for the beam to clear the cavity. Hence for the ILC crab cavity an iris radius of 1.4-1.5 cm seems a good range.

4. The effect of altering the iris curvature

The effect of changing the radius of curvature of the iris is shown in figure 9. An iris radius of 1.4 cm was chosen for the study to differ slightly from the FNAL study. The equator radius was again varied to keep the resonant frequency at 3.9 GHz.

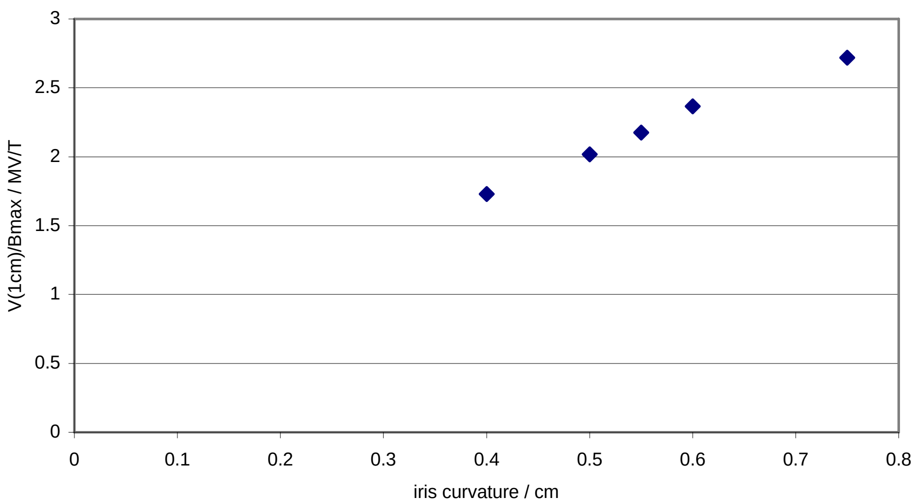

Figure 10 The longitudinal voltage offset from axis by 1cm and normalised to the surface magnetic field versus iris curvature for a 3.9 GHz cavity with iris radius 1.4 cm and Equator Curvature 1.141 cm

Figure 10 shows that a large iris curvature gives more transverse kick for a defined maximum surface magnetic field. Additional computations showed that the geometric shunt impedance, frequency separation and cavity Q factor did not vary greatly with variations in iris curvature; hence, increasing the iris curvature is desirable. The constraint on the curvature is that the slope of the flat section in figure 2 typically needs to be more than 7^{o} for ease of draining acid from the cavity during etching, although this problem can be overcome [5].

5. Equator curvature

An investigation into the effect of changing the curvature of the equator was conducted. It was found that varying the equator curvature between 0.1 cm and 1.4 cm produces only a 10% variation in the ratio of the longitudinal voltage at an offset to the maximum surface magnetic field for a cavity with iris radius of 0.5cm and iris curvature of 0.55 cm, as shown in Figure 11.

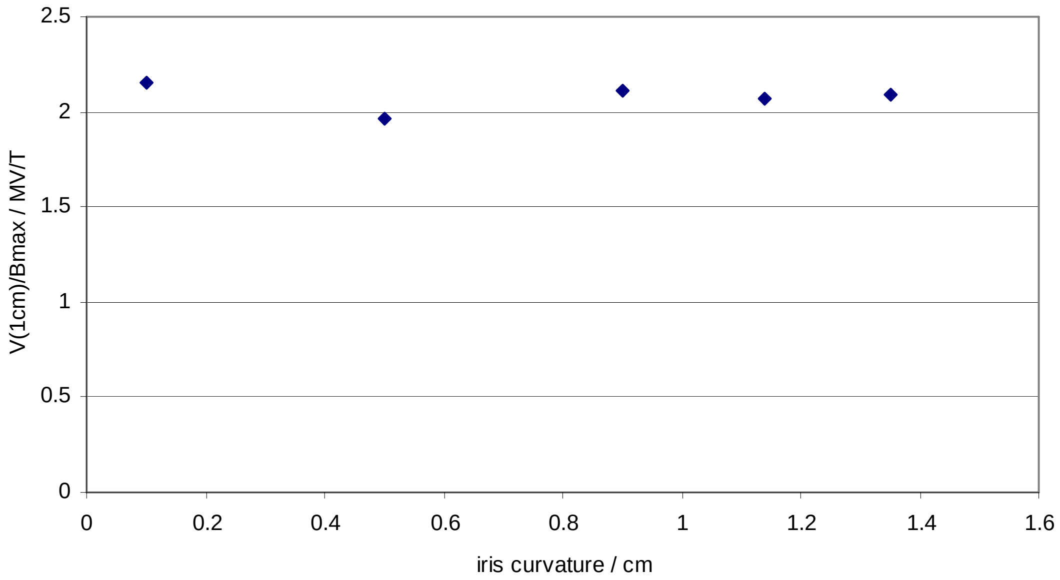

Figure 11 The longitudinal voltage offset from axis by 1cm and normalised to the surface magnetic field versus equator curvature for a 3.9 GHz cavity with iris radius 1.5 cm and iris Curvature 0.55 cm

The peak in the longitudinal voltage at an offset to magnetic field ratio was found to be relatively flat between 0.6 cm and 1.2 cm.

6. Effect of mechanical tolerances on the CKM cavity

The effect of mechanical tolerances was studied by varying each of the cavity parameters by ± 0.5mm and noting the frequency gradient.

Varying the cavity equator radius was found to be the most sensitive parameter, producing a frequency gradient of -80.6 MHz/mm, as seen if figure 12. This means that a 100 μm error in the equator radius would produce an 8.06 MHz frequency error, which is about 2.5 times the bunch repetition frequency in the ILC. Varying the iris radius produced a frequency gradient of -25.8 MHz/mm and varying the iris and equator curvatures produced frequency gradients of -23.1 MHz/mm and -23.2 MHz/mm, respectively. Varying the cavity length was found to alter the frequency by 17.4 MHz/mm.

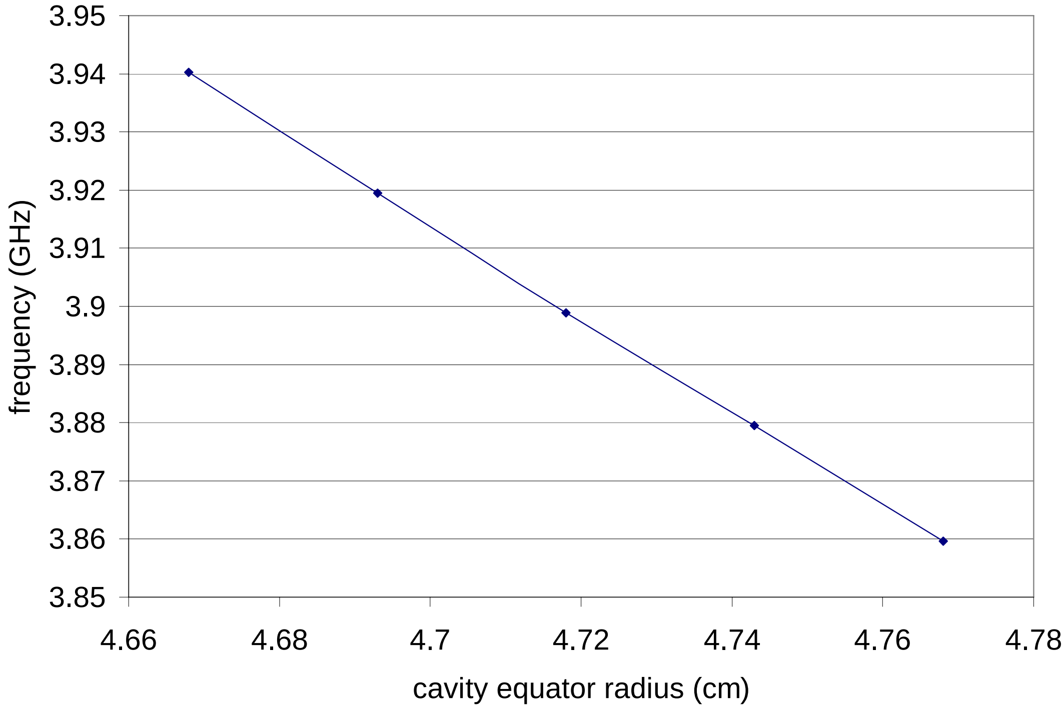

Figure 12 The variation in frequency with respect to equator radius.

The frequency gradient of varying the cavity equator was checked using a 2D MAFIA simulation with 9100 mesh cells. The MAFIA simulation gave a gradient of -77.45 MHz/mm with an uncertainty of 0.88 MHz/mm.

7. The effect of transversely squashing the CKM cavity

In order to separate the frequencies of the two polarisations of the fundamental dipole mode, the CKM cavity will be slightly squashed transversely. The effect on frequency, voltage, ohmic Q and R/Q of squashing an infinitely periodic mid-cell was studied in Microwave Studio. First the fundamental dipole mode was investigated; Figure 13 shows the effect on the frequencies of the two polarisations by indenting the equator in the transverse direction.

The frequency gradient of the unwanted vertical polarisation as a function of squashing, close to the proposed 1.5 mm radius indent was found to be 12.1 MHz/mm. The cavity gradient to peak surface magnetic field ratio, geometry factor and R/Q were not found to vary by more that 5%.

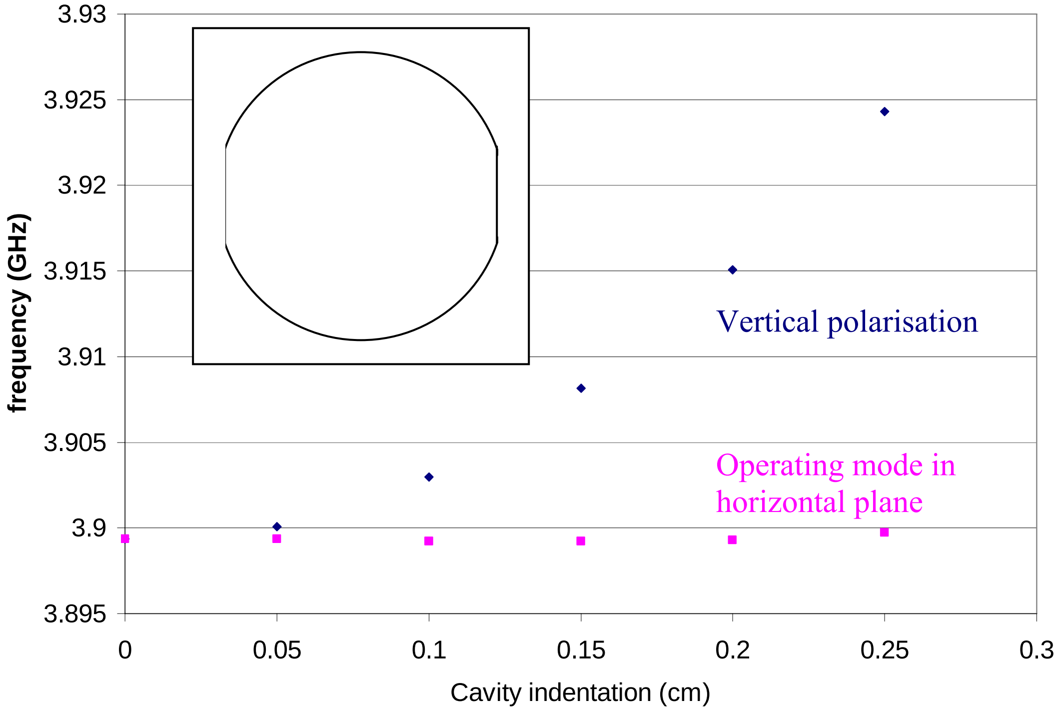

Figure 13 The separation in the frequencies of the two polarisations of the fundamental dipole mode as a function of the depth of the indent, shown in the insert.

Next the effect on the frequencies of a significant higher order mode(HOM) in the 5th dipole passband, is shown in Figure 14. The mode with the highest R/Q in this band has a phase advance of 20 degrees, and this mode was chosen for study.

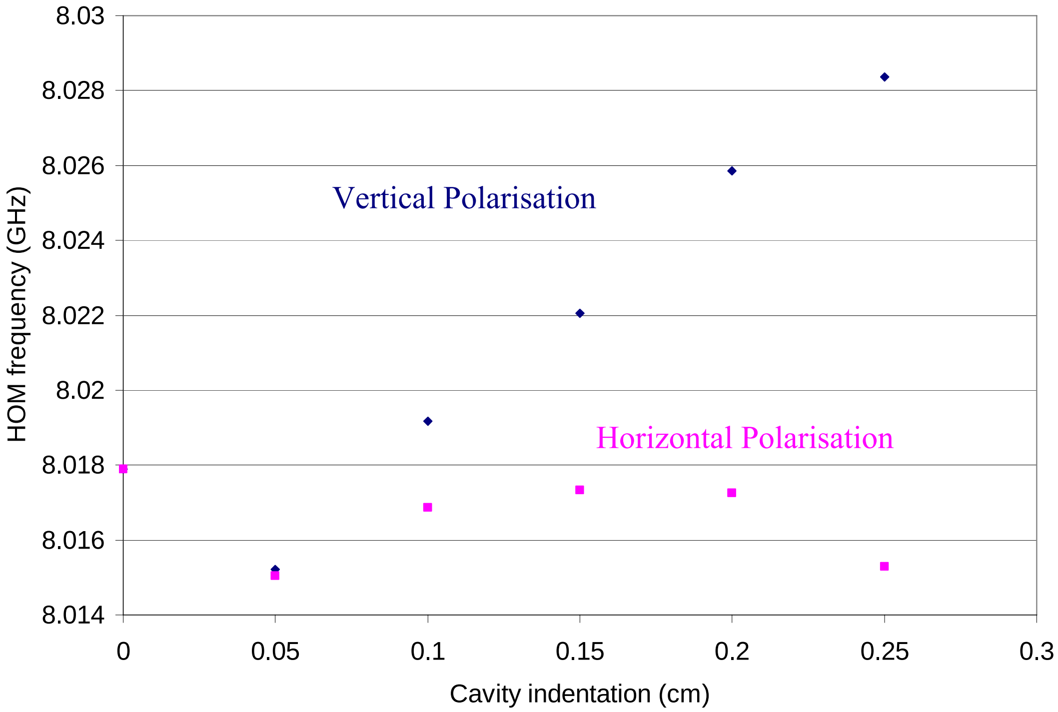

Figure 14 The separation in the frequencies of the two polarisations of the π/9 mode in the 5th dipole passband.

The frequency gradient of the two polarisations of the HOM were found to be 0.38 MHz/mm and 6.69 MHz/mm in the vertical and horizontal planes, respectively.

Lastly the fundamental monopole mode, known as the lower order mode, LOM, was simulated. The frequency gradient of the LOM mode close to the proposed 1.5 mm indent was found to be 4.67 MHz/mm.

8. Conclusions

The study of cavity parameters in this paper shows that the parameters used for the CKM cavity are sufficient for the ILC crab cavity. A moderately better design could have a slightly larger iris curvature and slightly smaller equator curvature. Another alternative could be to slightly reduce the iris radius, however for the ILC a beam clearance of 1.5 cm is preferred.

The study of small parameter variations shows that the cavity is sensitive to mechanical tolerances. The most sensitive parameter is the equator radius which has a frequency gradient of -80.6 MHz/mm for the operating mode. The squashing of the cavity is not a well controlled process; hence this is likely to be a major source of frequency deviations. The most problematic higher order mode is the opposite polarisation of the operating dipole mode. The frequency of this mode was found to vary at 12.1 MHz/mm as the cavity indents are varied. Frequency errors close to the ILC bunch repetition frequency of ~3 MHz are expected.

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