MEASUREMENT OF FIELD ASYMMETRY IN ACCELERATING CAVITIES WITH WAVEGUIDE COUPLERS*

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Abstract.

A waveguide coupling aperture in one side of an accelerating structure cell produces a transverse asymmetry in the RF fields of the accelerating mode. The asymmetry results in a phase-dependent transverse kick delivered to electrons traversing the accelerating gap.

We describe a measurement of the transverse asymmetry of the longitudinal electric field having relative sensitivity of about 0.1%. We relate the measured quantity to the concomitant transverse shift in magnetic field pattern and the resulting transverse deflection shear imparted to the electron bunch, and present results of measurements on a model one-cell cavity for external Qs ranging from 800 to 18,000.

Motivation.

Recent interest in the use of overcoupled single cell accelerator cavities for high brightness linacs has prompted study of field asymmetries due to the coupling aperture. These produce transverse emittance growth in the form of an angular shear; i.e., a phase-dependent transverse kick giving a slightly different angle to the beginning and end of the bunch. Such an effect has been observed in travelling wave linac coupler cells [1-3].

Background.

Numerical studies at LANL have modeled accelerator cavities using the MAFIA 3-D family of codes in both frequency domain[4] and time domain[5]. These efforts revealed qualitatively that the asymmetry in the field has a predominantly dipole (TM110-like) spatial character; i.e., if the y-axis is directed towards the coupling aperture as in Fig. 1, there will be an x-directed component of magnetic field across the axis of the cavity.

Near the cavity axis the magnetic field of the TM110-like perturbation is roughly constant in space, whilst that of the unperturbed field is always in the azimuthal direction and is proportional in magnitude to the radius. The vector superposition of these fields results in a field which resembles the unperturbed field displaced by a small amount toward the coupling aperture. The size of this displacement constitutes one measure of distortion of the field.

Another measure of field distortion is the transverse gradient of the longitudinal electric field due to the perturbation, which can be seen in Fig. 1(b) to interfere constructively with the unperturbed field on the side of the cavity towards the coupling aperture, and destructively on the opposite side. By comparing the longitudinal electric field profiles (Fig. 2) along two paths on opposite sides of the beam aperture and normalizing with respect to the average field, one can determine the relative asymmetry.

* Work supported by USASDC/BMD under contract DASG60-87-0046.

Experimental approach.

Our experiment measures the latter of the manifestations of field distortion discussed above. The longitudinal component of electric field is mapped by measuring the change in resonant frequency of the cavity produced by a long metallic bead (in fact, a 1-in length of .072-in diameter hypodermic needle) threaded on a piece of dental floss stretched through the cavity. A stepping motor-driven lead screw pulls the needle through the cavity in accurately known steps. When the needle enters a region of electric field aligned in its direction, the resonant frequency of the cavity is lowered slightly by an amount proportional to the square of the electric field at the needle site[6]. The proportionality constant depends on the size and shape of the bead and on the stored energy in the cavity, but this constant does not need to be known in order to determine the relative asymmetry.

The resonant frequency of the cavity is measured by a vector network analyzer (Hewlett Packard model 8753A) which determines the frequency at which the reflected power from the cavity is exactly in phase with the forward power (resonance condition in an overcoupled cavity). The data is acquired by a computer which instructs the stepper motor to move the bead and interrogates the network analyzer after a suitable settling time.

Sources of experimental error.

The accuracy of the frequency determination is typically 200 Hz. At the gap center, the frequency shift is approximately 100 kHz for the needle we used. The relative uncertainty in field strength is half the relative uncertainty in frequency shift, or 0.1%. We expect the uncertainty in the difference of two field strengths to be 0.15%, which is consistent with the level of point-to-point fluctuations seen in the data. This noise can be averaged out by drawing a best fit straight line through the central data points. (See, for example, Fig. 2(c)).

Other errors arise in determining the asymmetry produced by a given coupling aperture; specifically, thermal drifts and alignment errors. The thermal coefficient of expansion of aluminum is on the order of 25 parts per million per degree Celsius. Thus, the resonant frequency of an isothermal 433 MHz cavity will decrease by about 11 kHz per degree Celsius increase in temperature. Our measurements are made in a room where the temperature is stabilized to approximately 1 degree Fahrenheit, and the thermal mass of the cavity is large enough to keep the observed thermal drift below a few kHz over the 15 minutes or so required to acquire a profile. Thermal drift can be checked for by returning the bead to its starting position in the field-free region inside the beam hole at intervals and measuring the unperturbed frequency, or by comparing the frequencies at the extreme ends of the profile, where the bead is well into the beam hole.

Alignment errors may be of two types: skew alignment errors and position alignment errors. Skew errors arise when the path of the bead is not perfectly parallel to the axis of the cavity. This generally results in a field profile which is left-right asymmetrical. Especially sensitive is the region around the nose cones, where fields are intense and where the image of the bead in the metal wall of the cavity can have an effect. We accept only profiles which exhibit no obvious tilt, and use only that portion of the profile which represents the fields at the center of the gap in determining the asymmetry due to the coupling aperture.

Position alignment errors are the errors which limit the experimental sensitivity in the measurements reported here. These errors arise from failure to place the bead path at exactly the right distance from the axis. The concept of the measurement is to subtract the measured field along two paths which are identical displacements above and below the axis. The large, but symmetrical, TM010-like part of the field drops out, leaving the asymmetrical TM110-like perturbation. If the profiles are made at unequal displacements from the axis, the cancellation of the TM010-like part will be incomplete.

Analysis of URMEL results shows that the unperturbed fields have a radial gradient of about 0.2% per mm. We expect that the difference between upper and lower displacements is typically plus or minus half a millimeter, so we expect to see a spurious apparent asymmetry of plus or minus 0.1% which is actually due to asymmetrical positioning of the bead paths, rather than to real asymmetry in the cavity fields. The position error is more insidious than the others, because the spurious result is indistinguishable from an authentic field assymmetry in examining the data.

Interpretation in terms of field displacement.

From Maxwell's equations, we can deduce these relations between electric and magnetic field components: for the unperturbed field

$$E_z = -\frac{\lambda c}{2\pi}\frac{\partial B_x}{\partial y}$$

where λ is the free space wavelength, while for the dipole perturbation

$$\frac{\partial E_z}{\partial y} = \frac{2\pi c}{\lambda}\Delta B_x$$

where ΔB_x is the spatially uniform transverse magnetic field of the perturbation near the axis. Defining the relative asymmetry A

$$\frac{A}{h} = \frac{\partial E_z/\partial y}{E_z} = \frac{2(E_{up} - E_{dn})}{h(E_{up} + E_{dn})}$$

where E_{up} and E_{dn} are the square roots of the frequency shifts produced by pulling the bead along the upper and lower paths separated by vertical distance h (Fig. 2), we are able to write the expression for displacement Δy of the magnetic field pattern in terms of experimentally measurable quantities:

$$\Delta y = -\frac{\Delta B_x}{\partial B_x/\partial y} = \left(\frac{\lambda}{2\pi}\right)^2 \frac{\partial E_z/\partial y}{E_z} = \left(\frac{\lambda}{2\pi}\right)^2 \frac{A}{h}$$

Interpretation in terms of angular bunch shear.

The transverse kick imparted by the perturbation to a relativistic electron crossing the center of the gap at phase ϕ is

$$Py = e\cos(\phi)\int \Delta B_x \cos(2\pi z/\lambda)\,dz$$

$$= \frac{e}{\omega}\cos(\phi)\int (\partial E_z/\partial y)\cos(2\pi z/\lambda)\,dz$$

Assuming the asymmetry A is uniform across the gap (an admittedly crude assumption) we can factor it out of the integral, obtaining

$$Py = \frac{e}{\omega}\cos(\phi)\frac{A}{h}\int E_z \cos(2\pi z/\lambda)\,dz$$

$$= \frac{eV_a\cos(\phi)A}{\omega h} = \gamma mc\alpha$$

where V_a is the beam voltage gained in crossing the gap, and α is the angular kick.

To compute the angular shear on the bunch, we must find the derivative of α with respect to ϕ and multiply by the bunch phase duration $\delta\phi$.

$$\delta\alpha = -\frac{eV_a}{\gamma mc^2}\frac{\lambda A}{2\pi h}\sin(\phi)\,\delta\phi$$

Generally, the bunch arrives at the gap center near ϕ = 90 deg, so that the accelerating fields are maximized. The magnitude of the shear is then given simply by

$$\delta\alpha = \frac{eV_a}{\gamma mc^2}\frac{Ac}{h}\delta t$$

where δt is the time duration of the bunch.

Experimental Results.

We have made asymmetry measurement on our aluminum test cavity at a series of coupling aperture widths. The field profiles were measured along paths separated by 4.6 cm. The frequency, coupling aperture external Q, and relative asymmetry are tabulated in Table I, along with the implied field displacement Δy, and normalized angular shear $\gamma(d\alpha/dt)$ assuming a gain of 1 MeV/gap. Estimated experimental error is indicated.

References

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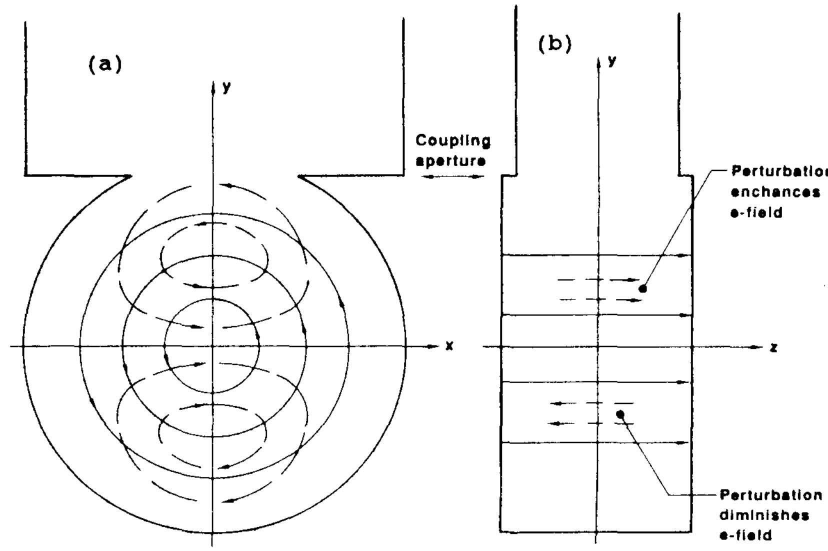
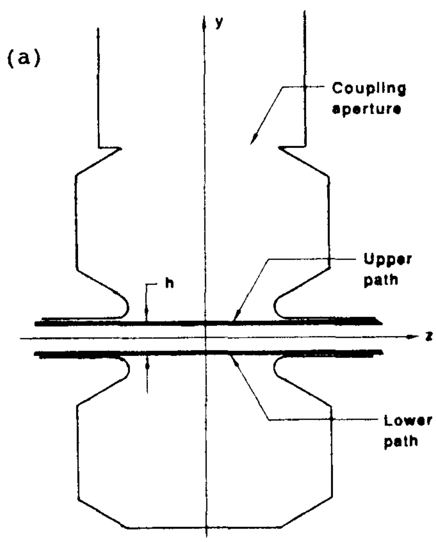


Figure 1. (a) Unperturbed magnetic fields (solid lines) and perturbation (dashed lines) in a cavity with a side coupling aperture. (b) Electric fields of the same mode.



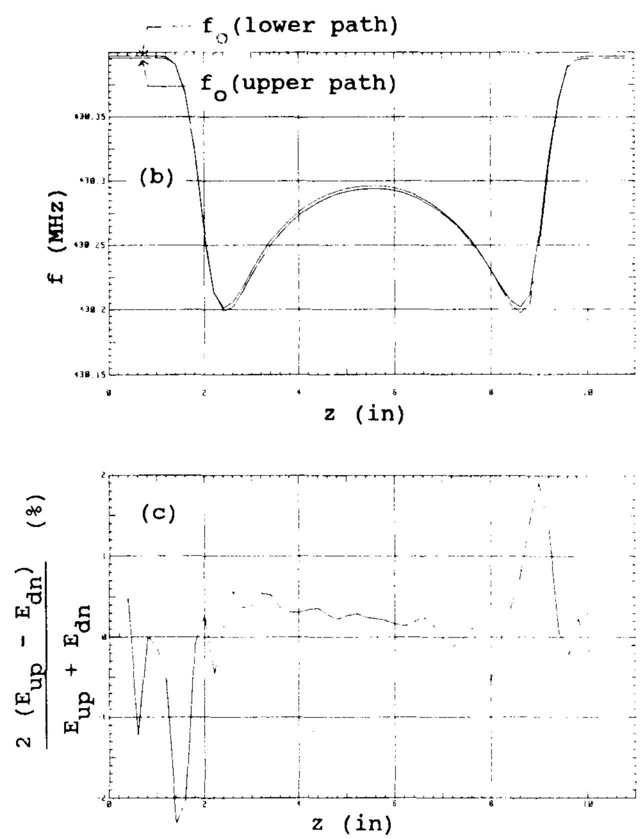


Figure 2. (a) Schematic section of cavity showing paths along which longitudinal E-field profiles are taken. (b) Frequency traces for the two paths. (c) Normalized difference of the sqare roots of the traces in (a).

Coupling Aperture (in)	f (MHz)	Ext. Q	Asymmetry A (%)	Shift Δ_y (mm)	Normalized Shear $\gamma(d\alpha/dt)$ (mrad/ps)
3.0	431.6	18700	.15+/-.1	.4+/-.25	.02+/-.01
3.5	431.4	9200	.15 "	.4 "	.02 "
3.8	431.2	6000	.20 "	.5 "	.03 "
4.0	431.0	5000	.22 "	.6 "	.03 "
4.8	430.4	2300	.35 "	.9 "	.04 "
6.0	429.1	760	.50 "	1.3 "	.06 "

Table I. Measured asymmetry and implied field shift and bunch shear.