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MICROWAVE MEASUREMENTS OF AZIMUTHAL ASYMMETRIES IN ACCELERATING FIELDS OF DISK-LOADED WAVEGUIDES*

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Summary

This paper presents microwave measurements of azimuthal asymmetries in the accelerating fields of the SLAC disk-loaded waveguide. These field asymmetries lead to RF phase-dependent beam steering which can be detrimental to operation of linear accelerators in general and of the SLAC Linear Collider in particular.

Introduction

The work presented here was motivated by two questions, the first one left over from an old unexplained observation in the SLAC linac, the second one prompted by a practical requirement of the SLAC Linear Collider (SLC). When the SLAC linac was being designed, it was understood that amplitude asymmetries in the accelerating field[1] which had been observed along the x-axis (see Fig. 1) of the input and output coupling cavities of the disk-loaded waveguide (DLWG) would lead to RF-dependent transverse beam deflection. As a result, the amplitude asymmetry was almost entirely corrected by a mechanical offset of the couplers. The phase asymmetry along the x-axis which was discovered after beginning of linac construction could not be corrected by a mechanical change within each section and it was compensated for by an alternation of the coupler orientation according to a scheme called (abab-baba). After the linac was put into operation, it was found that the coupler corrections had indeed been quite successful in compensating for field asymmetries along the x-axis of the couplers, but that other steering effects, both in x and in y, were apparent.[2] More recent measurements taken in 1980 showed that for a gradient of 7 MeV/m, several linac girders (consisting of four accelerator sections) produced RF transverse kicks in phase with acceleration (cosine-like, as will be seen below) of up to 15 keV/c, both in x and y. It was also discovered by using short RF and beam pulses that these effects were often caused by the main body of the sections and not necessarily by the couplers. Since these effects were too large to be explained by section or girder misalignment, it was thought that perhaps some internal misalignment or imperfection of the disks and cylinders in the DLWG which could not be seen from the outside might be causing the problem. Curiosity about this unresolved question was recently revived when the time came to select a SLAC 3.05 m - section for the first compressor section of the SLC.[3] In the compressor the electron and positron bunches which emerge from the damping rings are 4 or 5 times longer than in the linac and instead of riding close to the accelerating crest, must be centered 90° ahead of the crest. RF phase-dependent momentum kicks which are not corrected can lead to unacceptable emittance growth. Could microwave measurements on a section be used to detect amplitude and phase asymmetries, or at least to set an upper limit on their magnitude, thereby allowing to sort out an undesirable DLWG section before installation?

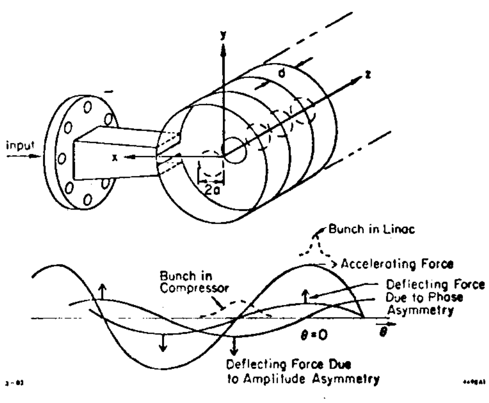

Fig. 1. Input of disk-loaded waveguide section showing coordinates and force components due to amplitude and phase asymmetries.

Transverse Momentum Kicks due to Accelerating Field Asymmetries

Referring to Fig. 1, the transverse momentum Δp imparted to an electron traveling at an angle θ with respect to the accelerating crest ($\theta = 0$) is given by:[1]

$$\Delta p = \frac{eE_z\lambda d}{2\pi c}\left(\frac{\Delta\phi}{2a}\ cos\theta + \frac{\Delta E}{2aE_z}\ sin\theta\right) \qquad (1)$$

where Δp can be in the x or y direction (or both) depending on the direction of the phase asymmetry $\Delta\phi$ or the amplitude asymmetry $\Delta E/E_z$ measured along x or y over a beam aperture $2a$; E_z is the axial accelerating field, d is the cavity length along which the asymmetries are measured and averaged, and λ is the wavelength. To illustrate the magnitude of the quantities involved, it might be pointed out that when the couplers were originally built, it is believed that the quantity $\Delta E/E_z$ along the x-axis over the beam aperture $2a$ was reduced to 0.1%. Thus, for example for $2a \sim 2.5$ cm, $\Delta E/2aE_z = 0.04/$meter, $d = 3.5$ cm, $\lambda = 10.5$ cm and $eE_z = 10$ MeV/m (the presently chosen accelerating gradient in the compressor), $\Delta p_x = 0.234\ sin\theta$ keV/m. Note that in the compressor, the bunch which has a σ_z of 6 mm or 20° is limited by a transverse beam clipping to a total length $4\sigma_z = 80°$ centered around $\theta = -90°$. Thus the transverse momentum imparted to the central electron is 0.234 keV/c whereas the extreme electrons receive momenta of 0.150 keV/c, both in the same direction. These quantities are extremely small and if necessary can be compensated for by a dc steering dipole. Conversely, a phase asymmetry or skewing of $\Delta\phi/2a = 1.2°/$cm along the x-axis in the input coupler leads to a transverse momentum $\Delta p_x = 12.2\ cos\theta$ keV/c which is equal to zero for the center of the bunch but has opposite values of ± 7.84 keV/c for the extreme electrons at $\pm 40°$ from the center. This effect would result in a transverse shearing of the bunch. Fortunately, to first order, it can be compensated for by a minor angular tilt $(2\Delta p_x/\Delta p_z)$ of the section.

Microwave Measurements

In order to explore the extent of possible amplitude and phase asymmetries in the DLWG constant-gradient section to be selected for the SLC compressor (3.05 m long, 86 cavities), it was necessary to build a very accurate mechanical and RF setup which is shown in Fig. 2. The principle of the measurement

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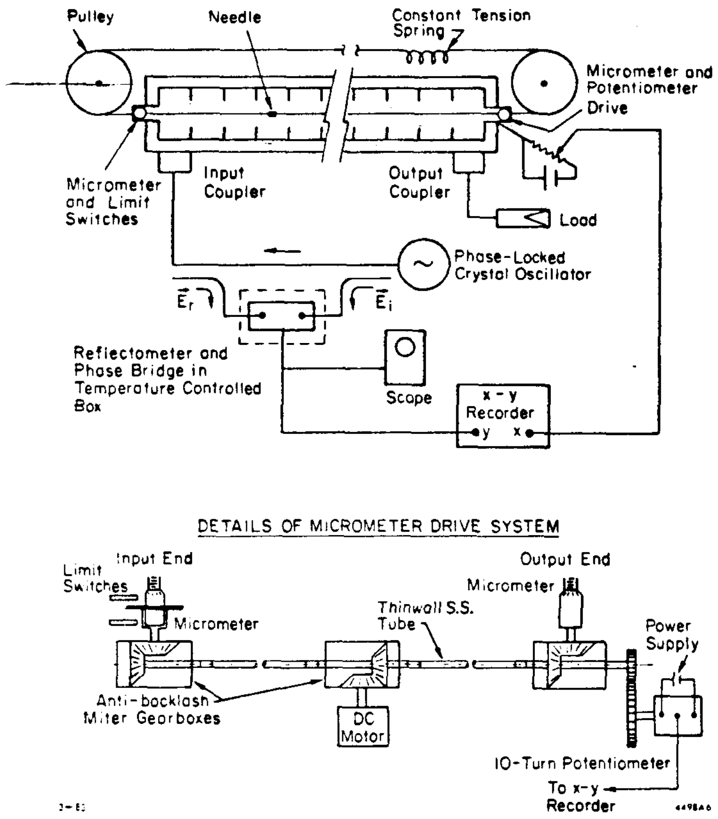

Fig. 2. Mechanical and RF measurement set-up.

is that if a small bead is placed inside an RF excited structure at coordinate (x, y, z), the perturbation causes a small amount of power to be reflected, whose amplitude $E_r(z)$ is shown in Fig. 3 and given by:

$$E_r(z) = K \, \frac{E^2(x, y, z)}{P(z)} \, E_i(z) \qquad (2)$$

where K is a constant which depends on the bead, $E(x, y, z)$ is the electric field at the bead, $P(z)$ is the forward power flowing

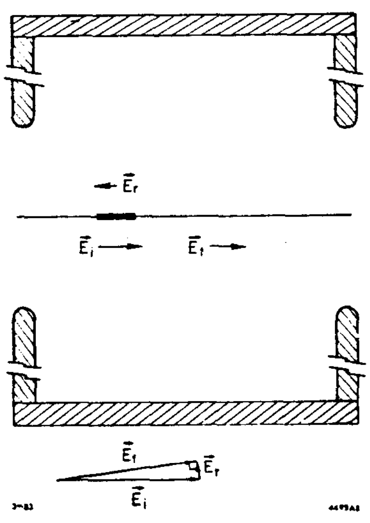

Fig. 3. Effect of bead perturbation showing vectorial relationship between incident ($\vec{E}_i$), reflected ($\vec{E}_r$) and transmitted ($\vec{E}_t$) waves.

across the structure at z and E_i is the incident wave amplitude which is proportional to $\sqrt{P(z)}$. The reflection coefficient at the bead is then $\rho(z) = E_r(z)/E_i(z)$. The reflection coefficient which is measured at the input of the section is $\rho(0) = E_r(0)/E_i(0)$. For an attenuation per unit length α, it is easily shown that

$$\rho(0) = K \, \frac{E^2(x, y, z)}{P(z) e^{2\alpha z}} = K \, \frac{E^2(x, y, z)}{P(0)} \qquad (3)$$

This is an interesting result because it shows that for a constant-gradient structure where for any integer n, $\hat{E}(x, y, z) = \hat{E}(x, y, z \pm nd)$, $\rho(0)$ is independent of which cavity the bead is in and only depends on x and y. Assuming that $E_i(0)$ is constant, the square root of $E_r(0)$ measured in the reflected arm of the reflectometer is then proportional to $E(x, y, z)$.

Given the vectorial relationship between $\vec{E}_r$, $\vec{E}_i$ and $\vec{E}_t$ (the transmitted wave) shown in Fig. 3, as long as $\vec{E}_r$ remains small, the angle between $\vec{E}_i$ and $\vec{E}_r$ is very close to 90^o and to first order does not change. Thus, a measurement of the phase change of $\vec{E}_r$ with respect to $\vec{E}_i(0)$ at the phase bridge is also a measurement of the phase change of $E_i(z)$. The phase bridge shown in Fig. 2 which uses a double-balanced mixer was insensitive to amplitude variations. Accurate phase measurements were made by reading a calibrated precision phase shifter which was used to zero the bridge output after each bead movement.

Each of the 86 cavities of the compressor section was scanned with the bead. Amplitude and phase variations were plotted by hand for a few cavities (see Fig. 4) but phase variations were recorded for every single cavity by means of an x-y recorder (see Fig. 5). The points in Fig. 4 were obtained for a grid of 12 points per cavity in each plane (x and y) as shown (z=0, ±d/4, ±d/2, x and y = 0, ±0.5 cm). The amplitude plots show the effect of the space harmonics.[4] As is well known, these are collinear and all in phase in the center of the

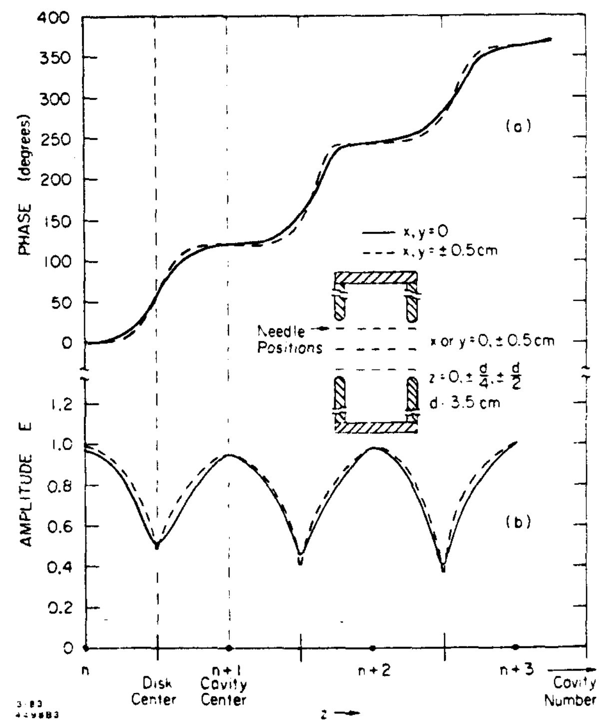

Fig. 4. Phase and amplitude variations as plotted in successive cavities at various x,y and z coordinates.

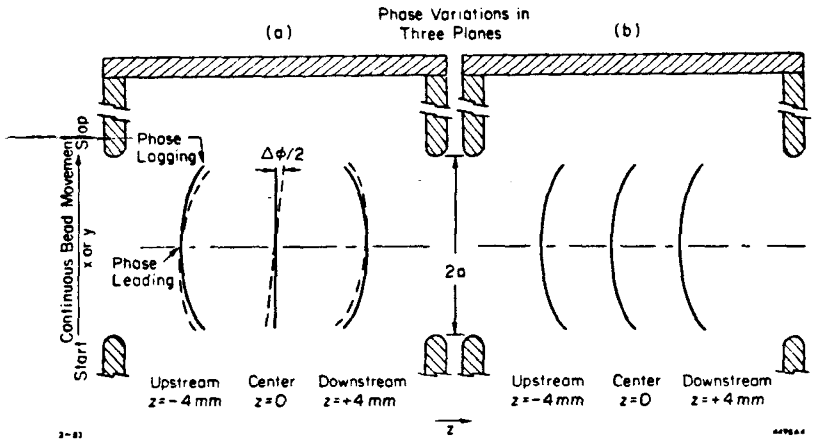

Fig. 5. Phase variations in transverse planes of early (a) and late (b) cavities showing change in phase "bowing." The continuous lines, which represent a phase variation of about 1^o between center (x = y = 0) and disk edge (x or y = a) at $z = \pm 4$ *mm*, are symmetrical with respect to the z-axis. The dashed lines are "skewed" and give a net asymmetry $\Delta\phi$.

cavity (z = 0) and alternately in phase and 180^o out of phase at the disk edge ($z = \pm d/2$). The resulting field variations are on the order of 3 to 1 as shown. The amplitude measurements as a function of x and y were reliable to an accuracy of 1% for x and y = ±0.5 cm, giving an equivalent upper limit to $\Delta E/2aE_z$ of 1/m, or $\Delta p_{max} \leq 5.85$ keV/c per cavity for the compressor. Since the amplitude measurements were very time-consuming and earlier beam measurements on the accelerator had not shown any systematic sinθ-like steering effects [see Eq. (1)], only a few cavities were scanned carefully.

The phase measurements were made much more systematically in each cavity because, indeed, most of the past beam-steering observations had been cosθ-like. Figure 4 shows the 120^o phase advance per cavity characteristic of the $2\pi/3$ mode used at SLAC. Note the difference between the plots for x and y = 0 and those for x and y = ±0.5 cm. This difference can be better understood by looking at the solid line phase variations (leading on-axis and lagging off-axis) shown in Fig. 5(a) which exhibit "phase bowing" as one approaches the disk radius where the phase is more nearly stationary. In the first 70 or so cavities, the phase bowing exhibited mirror symmetry with respect to the z = 0 plane of the cavity. In the last few cavities, however, it assumed a shape like in Fig. 5(b). This gradual flip-over seemed to be related to the thickness and dielectric constant of the string and is briefly discussed below. The uncertainty introduced by this observation was eliminated by turning the structure around, thereby switching input and output. Then the downstream cavity patterns looked again as in Fig. 5(a). The transverse phase asymmetry was measured by examining each of three planes per cavity (z = 0, z = ±0.4 cm) and seeing whether there was any average phase skewing over the beam aperture as indicated schematically by the dashed phase lines. The input coupler was found to have a phase skewing of 1.2^o/cm and the output coupler of -0.6^o/cm. All other cavities seemed to be symmetrical to at least $0.05^o - 0.1^o$/cm, which was the limit of accuracy to which the measurements could be made. A phase skewing of 0.1^o/cm represents a maximum Δp at the $2\sigma_z$ edge of the beam in the compressor of ±0.65 keV/c. Assuming that these asymmetries of $\leq 0.1^o$/cm are random in sign and therefore <u>not</u> additive (i.e. they average out to zero net transverse momentum), one would have to assume that a section with such characteristics is acceptable for the compressor. The transverse momentum kicks on the order of 5-15 keV/c produced by a number of SLAC linac girders and observed on the beam along both x and y axes would have to be explained by non-random mechanical effects or some other phenomenon.

Experimental Conditions

A few of the stringent experimental conditions which made these tests possible are discussed below:

(a) The entire DLWG-rectangular waveguide set-up had to be temperature stabilized to within $\pm 0.1^oC$ at 28^oC and purged constantly with dry Nitrogen at the same temperature.

(b) After considerable experimentation, the best bead turned out to be a hollow hypodermic needle (I.D. = 0.15 mm, O.D. = 0.3 mm, length = 7.3 mm) which, when in the center of the cavity, introduced a reflection coefficient $\rho(0) = 0.08$ (VSWR = 1.17). The best string had an O.D. of 0.13 mm. The reflection introduced by its presence was about 0.02. This reflection (together with all other imperfections of the section) was matched out externally to a $\rho(0) = 0.005$ before the needle was introduced into the section. A thicker string was used at first but turned out to already produce the effect shown in Fig. 5(b) when the needle was half-way through the section. Although this effect is not well understood, it is suspected that it has to do with the local $\rho(z)$ which, toward the output of the section, is 3.12 times larger than at $z = 0$, i.e. 0.25, due to attenuation. When $\rho(z)$ reaches this magnitude, the perturbation measurement loses its validity.

(c) The positioning of the needle in x and y was made repeatable to 0.05 mm. This was verified with a boroscope. The drive mechanism shown in Fig. 2 consisted of a motor and three anti-backlash gears which drove the string by means of two parallel micrometers, one at each end of the section. The micrometers tracked to within 10 microns of each other. The effect of the catenary of the string was minimized by only sweeping it in the horizontal plane. The section was rotated by 90^o to scan the section in the other plane. The z-coordinate of the needle was checked frequently by driving it to one end or the other of the section. The center of each cavity (z = 0) was located by searching the plane for maximum $\rho(0)$.

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