Electromagnetic Field Measurements on a mm-wave Linear Accelerator*

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Abstract

Field strength measurements for the determination of the R/Q of a mm-wave, 50-MeV electron linear accelerator using perturbational techniques are described. The perturbation is achieved using optical fibers coated with a thin metallic film to form a hollow cylinder. The perturbational 'form factors' for such a geometry are approximated using several simple analytical expressions which are compared to a finite difference calculation as well as experimental results on a known cavity.

1 INTRODUCTION

Work is currently underway at the Advanced Photon Source (APS) at Argonne to develop a mm-wave, 50-MeV electron linear accelerator system [1]. Such a system can be used with a micro-undulator for the production of coherent, tunable wavelength synchrotron radiation. The proposed mm-wave electron linear accelerator is a double-sided, planar, muffin-tin structure. The structure under consideration is designed for 2 $\pi/3$ traveling wave operation at 120 GHz and is shown in Figure 1.

One important measure of the effectiveness of any accelerating scheme is the shunt impedance divided by the quality factor, R/Q. The value of R/Q is difficult to determine for more complex resonators such as the one under consideration here. Numerical simulation using three-dimensional computer codes such as MAFIA enable one to calculate R/Q. Experimental determination of R/Q is usually carried out using a perturbation technique to measure the accelerating electromagnetic fields. This is accomplished by measuring the resonant frequency shift of the cavity as a function of the position of a perturbing object in the cavity. The perturbing object may be dielectric or metallic and is usually a sphere, needle, or disk. Due to the size of the device at the operating frequency of 120 GHz, the measurement of the electromagnetic fields using conventional perturbating objects is difficult.

This paper describes field pattern measurements on the proposed mm-wave structure. The perturbing objects are optical fibers coated with an aluminum film to form a hollow cylinder with a given length. The major difficulty with such an approach is to evaluate the perturbational 'form factors' for such a geometry. Several analytical approximations are used to evaluate the form factors. These results are compared to a finite difference simulation using the URMEL code. Also, these theoretically determined form factors are compared to experimental values determined from measuring a known cavity.

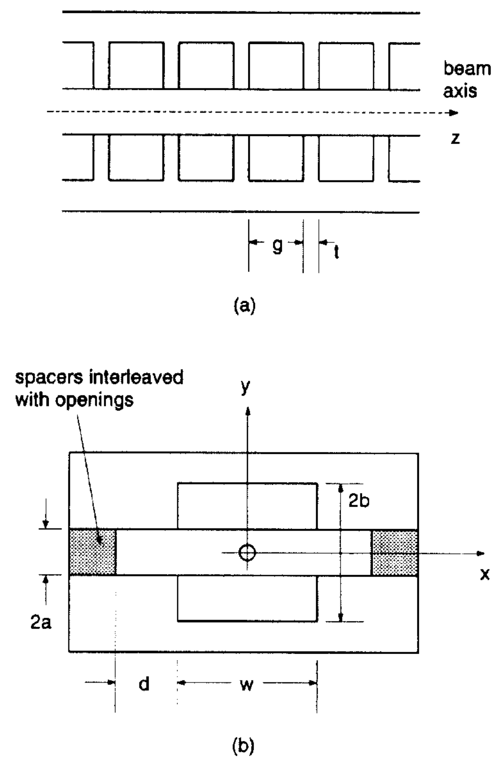

Figure 1: The 120-GHz double-sided muffin-tin structure.

2 GENERAL THEORY

The frequency shift of a resonant cavity due to the presence of a perturbing object was first formulated by Maier and Slater [2]. This frequency shift may be expressed as

$$\frac{\Delta f}{f_0} \approx -\frac{3\Delta V}{4U}\left[\epsilon_0\left(F_1\left|\vec{E}_{\|}\right|^2 + F_2\left|\vec{E}_{\perp}\right|^2\right) - \frac{\mu_0}{2}\left(F_3\left|\vec{H}_{\|}\right|^2 + F_4\left|\vec{H}_{\perp}\right|^2\right)\right] \quad (1)$$

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.

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Figure 2: The optical fiber bead.

where f_0 is the unperturbed resonant frequency, $\Delta f = f_0 - f$, ΔV is the volume of the perturbing object, U is the stored energy of the cavity, $\vec{E}_{\parallel}$ ($\vec{E}_{\perp}$) and $\vec{H}_{\parallel}$ ($\vec{H}_{\perp}$) are the electric and magnetic fields parallel (perpendicular) to the perturbing object axis, and the F_i are the perturbation form factors which depend on the material, size, and shape of the perturbing object (bead).

In principle, the bead may be of any size or shape and may be metallic or dielectric. However, the form factors can be exactly determined only for simple geometrical shapes. The form factors for general ellipsoids of revolution have been determined in [2]. Typically, conducting spheres, needles, and disks are used.

3 OPTICAL FIBER BEAD

For the formula in Eq. 1 to be valid, the perturbing object must be a small fraction of a wavelength. Typical sphere or needle dimensions which give good results are on the order of 1/50 λ or smaller. This corresponds to a 50μm diameter sphere for the proposed 120-GHz accelerating structure. Due to the difficulty in fabricating such an object, alternative perturbing objects were investigated.

The perturbing object used was an optical fiber coated with a thin conducting coating to form a hollow cylinder as shown in Figure 2. The cylinder was formed by masking the fiber with a hollow capillary tube and sputtering an aluminum film onto the fiber through a slot cut into the capillary. This method gives one precise control over the dimensions and shape of the perturbing object.

4 FORM FACTORS

4.1 *Analytical Approximations*

A crude approximation for the form factor of a hollow cylinder may be obtained by approximating the cylinder with an ellipsoid having the same length and diameter of the cylinder. Making this approximation allows one to use the exact analytical results in [2].

The perturbation due to an infinitely thin hollow cylinder was solved in [3] by the method of moments. The infinite linear system was solved by truncating it to a reasonable number of unknowns and extrapolating the results to an infinite system by assuming a polynomial dependence on the number of unknowns. The following simple expression was used to approximate the form factor

$$F_1 = \frac{4}{9}\left(\frac{l}{a}\right)^2 \ln\left[\left(\frac{2}{3\pi}\frac{l}{a}\right) + \sqrt{\left(\frac{2}{3\pi}\frac{l}{a}\right)^2 + 1}\right]^{-1} \quad (2)$$

where l and a are the length and diameter of the cylinder. This expression should be very accurate for small and large aspect ratios (defined as l/a).

4.2 *Numerical Approximations*

The form factors for a cylinder of finite length may also be found using numerical techniques. Due to the cylindrical symmetry of the problem, the URMEL code was used to calculate the frequency shift of the TM_{010} mode of a pillbox cavity due to beads of various sizes on the cavity axis. The form factor, F_1, is then given by

$$F_1 = -\frac{\Delta f}{f}\,\frac{4\,J_1^2(p_{01})}{3}\,\frac{V}{\Delta V} \quad (3)$$

where J_1 is a Bessel function of the first kind and V is the volume of the cavity. It was assumed that the magnetic fields and perpendicular electric fields were negligible.

4.3 *Measured Form Factors*

In principle, the form factor for any shape bead may be determined by measuring the change in frequency due to the bead in a known cavity. The form factor may then be determined from equation 1. This approach was used to measure the form factors of various hollow cylindrical beads. The fundamental TM_{010} mode of a 352-MHz pillbox cavity was used to determine the frequency shift. Care was taken to isolate the cavity from vibrations and temperature variations. A network analyzer monitored the phase of the transmitted signal at the resonant frequency as the bead was pulled through the cavity. The change in phase was related to the frequency shift of the cavity by

$$\frac{\Delta\omega}{\omega} \approx \frac{\tan\Delta\phi}{2Q_l} \quad (4)$$

where Q_l is the loaded Q of the cavity.

4.4 *Form Factor Results*

The various methods for determining the form factors for the proposed optical fiber bead were compared. Measured results were compared to both the analytical expressions and the numerical simulations. For ease of measurement, the optical fiber bead was simulated using small diameter ($\approx$ 1 to 3 mm) copper tubing on a 0.4mm nylon thread. This would be equivalent to a bead 30 to 90 μm in diameter at 120 GHz. The results are shown in Table 1. The URMEL results do not have the same aspect ratios as the measured beads due to mesh limitations. The errors in the measured results are the standard deviation of five separate measurements on the same bead. Some of the results are plotted in Figure 3.

As one would expect, the crude ellipsoidal approximation does not accurately predict the form factors. The results calculated from Eq. 2 are consistently smaller ($\approx$ 4 to 9 %) than the measured results. This is consistent with the expected errors given in [3] for this range of aspect ratios. The URMEL simulations appear to be quite accurate (within $\approx$ 5 %) but are consistently higher. This discrepancy may be due to the fact that solid cylindrical beads were used in the URMEL simulations. Simulating hollow cylindrical beads tends to slightly decrease the form

Table 1: Form factor measurements and calculations.

Aspect Ratio	Measured Results	Results of [3]	Ellipsoidal Approx.	URMEL Results
1.25	–	2.65	1.21	3.43
2.50	–	5.46	2.47	6.52
2.98	6.80 ± 0.04	6.62	3.04	–
3.23	7.50 ± 0.07	7.24	3.36	–
3.75	–	8.57	4.06	10.06
4.00	9.51 ± 0.04	9.23	4.42	–
4.96	12.80 ± 0.09	11.91	5.91	–
5.00	–	12.03	5.97	13.89
5.85	16.00 ± 0.10	14.59	7.44	–
6.25	–	15.86	8.17	18.39
7.00	20.23 ± 0.12	18.35	9.63	–
7.50	–	20.09	10.66	23.21
8.00	24.07 ± 0.11	21.89	11.73	–
8.96	27.51 ± 0.19	25.51	13.90	–
10.05	32.77 ± 0.12	29.90	16.56	–
11.06	37.72 ± 0.28	34.22	19.19	–
12.09	42.97 ± 0.22	38.87	22.05	–
12.50	–	40.79	23.23	46.93
12.76	45.73 ± 0.89	42.03	24.00	–

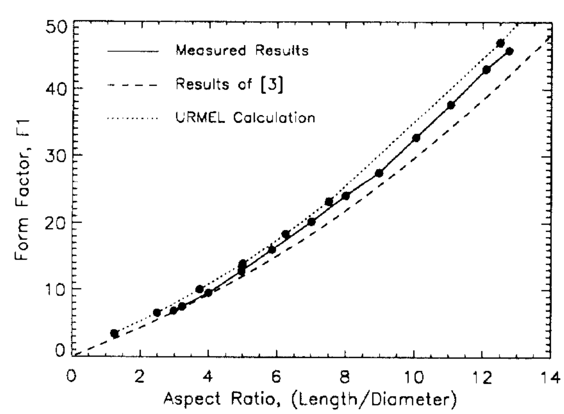

Figure 3: The form factor results.

factor by decreasing the effective length of the bead due to penetration of the fields in the hollow metallic waveguide of the bead. The diameter of the bead gives a very high cutoff frequency which makes this effect small especially at higher aspect ratios. It should also be noted that the URMEL simulations did not include the effect of the dielectric fiber.

5 SCALE MODEL RESULTS

A hollow cylindrical bead was fabricated on an 80μm optical fiber by sputtering an aluminum film through a shadow mask. The resultant bead was used to measure the field patterns on a 12-GHz model of the proposed mm-wave linear accelerator. The model consisted of five full cells with two half cells at the ends. A typical phase measurement (which is proportional to the magnitude of the electric field) for the $2\pi/3$ mode is shown in Figure 4. The result is similar to the expected field patterns for this mode. The discrepancies are mainly due to the large cell-to-cell dimensional variations in our scale model. The form factors for the bead could not be determined theoretically due to imperfections in the fabrication process which resulted in a bead which was not a cylinder (sputtering coverage was not 360^0) and which had an irregular length. These fabrication difficulties are currently being solved.

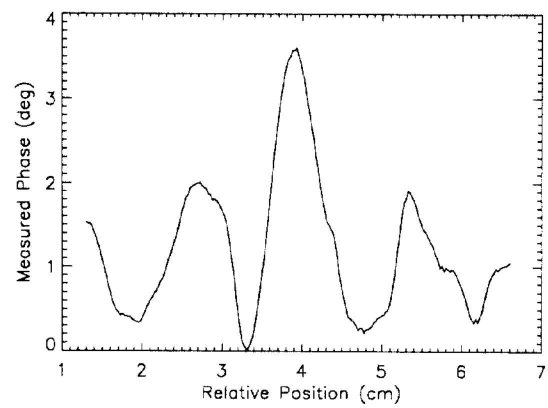

Figure 4: Scale model bead pull results.

6 CONCLUSIONS

A method for the measurement of the field strength and R/Q of mm-wave accelerating structures using hollow cylindrical perturbing objects fabricated on optical fibers was described. Various techniques for analytically predicting the form factors of such a perturbing object were evaluated and compared to experimentally determined form factors. The feasibility of using such a perturbing object on high frequency structures was tested by fabricating an aluminum bead on an 80μm optical fiber and using it to evaluate the field patterns of the accelerating modes in a 12-GHz structure.

7 REFERENCES

[1] A. Nassiri, R.L. Kustom, F.E. Mills, Y.W. Kang, A.D. Feinerman, H. Henke, P.J. Matthews, T.L. Willke, D. Grudzien, J. Song, and D. Horan, "A 50 MeV mm-wave Electron Linear Accelerator System for Production of Tunable Short Wavelength Synchrotron Radiation," in IEEE Int. Electron Device Meeting Proc., pp. 111-120, Washington, D.C., USA, December 1993.

[2] L.C. Maier and J.C. Slater, "Field Strength Measurements in Resonant Cavities," Journ. Appl. Physics, vol. 23, pp. 68–77, January, 1952.

[3] F. Caspers and G. Dome "Precise Perturbation Measurements of Resonant Cavities and Higher Order Mode Identification," CERN SPS/85-46, Geneva, Switzerland, November, 1985.