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Automated Bead-Positioning System for Measuring Impedances of R-F Cavity Modes

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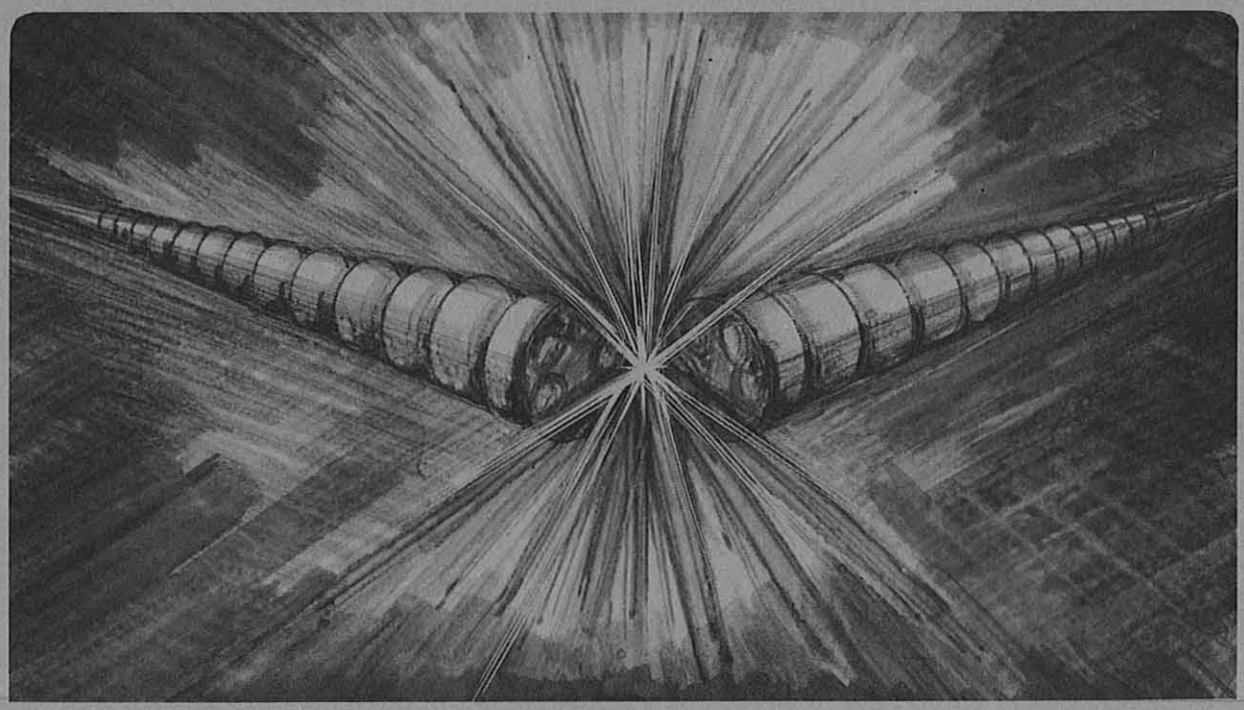

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Automated Bead-Positioning System For Measuring Impedances of R-F Cavity Modes*

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Abstract

We describe a fully automated bead puller system which uses stepping motors to position the bead, and an HP-8510 network analyzer to measure the resulting frequency shifts, both devices being under computer control. Longitudinal motion of the bead is used for measurement of cavity shunt impedance. In addition, azimuthal scans at fixed longitudinal position aid in determining the multipole character of higher-order modes. High sensitivity/accuracy is made possible by measuring phase shifts at the unperturbed resonant frequencies (rather than frequency shifts themselves), thereby permitting averaging factors of > 500 with only modest increases in data acquisition time. Sample measurements will be presented. A comprehensive analysis of the experimental results is presented in an accompanying paper [1].

I. INTRODUCTION

The longitudinal and transverse kicks which a beam of particles experiences, due to either externally imposed or self-generated fields, upon passing through any device in the accelerator can be parametrized in terms of the respective shunt impedances of that device [2]. Those impedances can be represented as integrals along the beam path involving the longitudinal or transverse fields. One of the most common methods for measuring the fields in a resonant device such as an R-F cavity is to make use of the fact that the introduction of a small perturbing object causes a shift in the resonant frequency which is proportional to the square of the local field [3]. Hence by moving such an object, frequently referred to generically as a "bead," along, say, the axis of the device, and measuring frequency shift as a function of position, one can determine the field values for the integrand of the impedance integral. Furthermore, by measuring the (longitudinal) impedance along a series of transversely displaced paths, we can, through the use of the Panofsky-Wenzel Theorem, determine the transverse shunt impedance as well [2,4].

II. DESCRIPTION OF APPARATUS

Figure 1 shows the bead puller together with a device under test, in this case the model B-Factory cavity described in Ref. 2. The test bead is mounted on a thin Kevlar string which runs longitudinally through the cavity. For most of our measurements, our "bead" consisted of a .040 in. diameter, 1 in. long stainless steel needle, which is almost exclusively sensitive to the longitudinal electric field. However, because analytic expressions for the form factors necessary to convert frequency shift to field strength are only derivable for a limited number of bead shapes (cylinders are

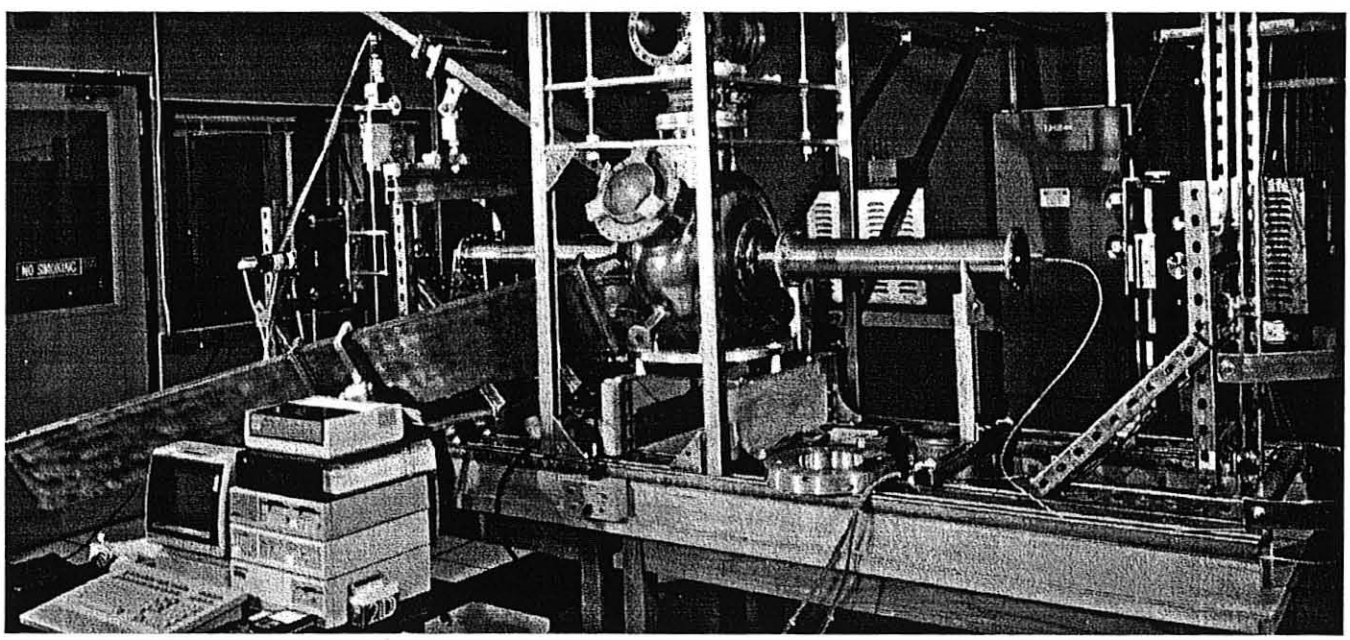

Fig.1 Bead Puller and Model B-Factory Cavity

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not among such shapes; small spheres are), it was necessary to "calibrate" the needle. This was done by first measuring the field in the TM_{010} mode (which is known to be almost perfectly longitudinal on the cavity axis) with a .375" diameter spherical alumina (99.5% purity) bead, remeasuring it with the needle, and normalizing the latter data to the former.

The needle was mounted on a .018" dia. Kevlar string; the bead, on a .023" one. In addition to its high tensile strength (50 lbs. for the former string, 80 lbs for the latter), Kevlar has the added advantage that after it is "run in" by making three or four full-length traverses, it shows negligible further elongation.

Positioning of the bead is accomplished by means of a set of Lintech TWIN RAIL® tables which are driven by Compumotor SX 57-102 stepping motors under the control of Model SX programmable controllers. The Lintech tables use an Acme thread lead screw so that in the event of loss of stepping motor power, even the vertically mounted tables retain their position.

Longitudinal (z-)motion is controlled by the long table shown at the far (left hand) end of the cavity; the geometry is shown schematically in Fig. 2. The total table travel is roughly 60 cm, but this can be multiplied with the use of a block and tackle arrangement; the present setup employs a multiplication factor of three, making it possible to measure devices nearly two meters long. Use of an 8 lb. counterweight is sufficient to maintain the vertical position of a bead of mass up to 7 gm. to within 1 mm over its entire distance of travel.

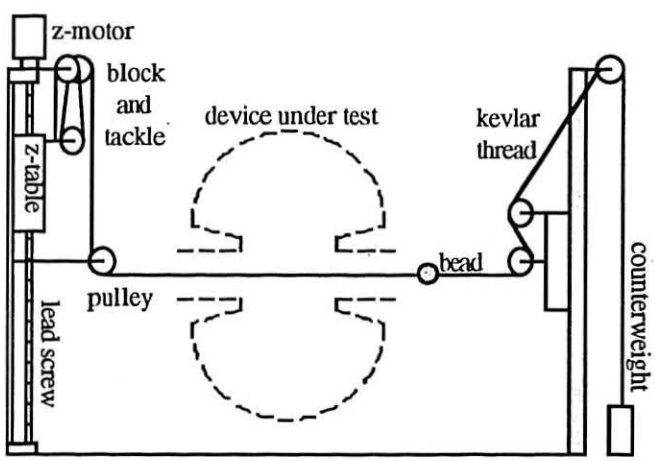

Fig. 2. Schematic Representation of Longitudinal Drive

Transverse bead position is determined by a pair of x,y tables at either end of the apparatus, on one of which the z-drive (table and pulleys) is mounted (see Fig. 1). Both x-table motors are driven by a common controller, as are both y-table motors. The range of travel in both transverse planes is ±8cm. Each set of tables is mounted on its own modular frame; in the present experiment, both table frames are mounted on a common bed which also supports the cavity. However, the modular construction also permits transporting the apparatus to measure cavities "in the field" or on their own support stands.

The table motion and controller settings can be directed from a Hewlett-Packard (HP) 216 computer via an RS-232 serial link. (A hand controller can also be used to adjust table position.) The same computer is also used to control (via the GP-IB) the frequency measurements, as well as to compute the beam impedances from the measurement data.

Measurement of the (shift of the) cavity resonant frequency is done using an HP 8510 network analyzer. In the present setup, we employ two probes, one to excite the cavity, and one to detect the excitation, and determine the resonant frequency from S_{21}. For high-Q modes, one can measure frequency shifts directly. However, for low-Q modes it is much more advantageous to measure the phase shifts at the unperturbed resonant frequency.

A similar measurement technique has been recently reported by the Chalk River group in their measurements of the longitudinal fields of the accelerating modes of RF cavities and RFQ's [5]. Our method differs from theirs in several significant ways. First, instead of measuring "on the fly," we bring the probe to a stop during the measurement, which permits signal averaging at each point,[1] thereby making possible accurate determination of phase shifts as small as even a few tenths of a degree. Secondly, use of the HP 8510 analyzer in the single-frequency (CW) mode makes it possible to use an averaging factor of up to 128 at as little as 1 second per point, or as high as 4096, at less than 2 sec per point, enabling us to do a 100 point scan in less than two minutes.[2] In addition, the 3-dimensional motion capability permits us to do not only transverse scans (for measuring transverse impedance), but to take angular distributions to facilitate mode identification.

III. RESULTS AND ANALYSIS

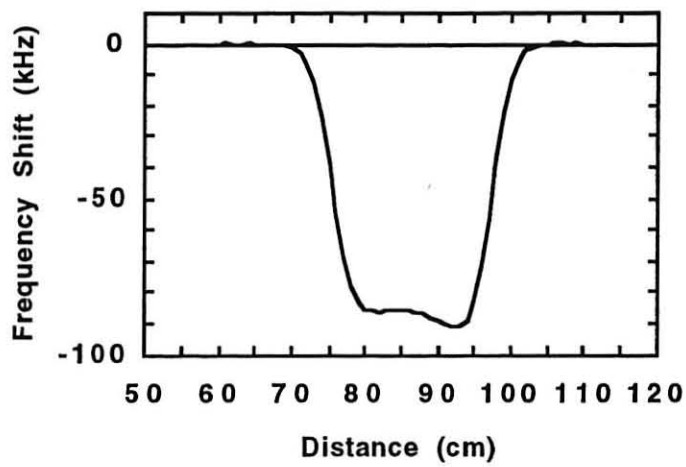

Fig. 3 Frequency shift *vs* position for fundamental mode of the B-factory model cavity.

Results of the frequency measurements of the fundamental mode are shown in Fig. 3., where we have plotted the

[1] Signal averaging is essential for measuring the fields of the strongly damped modes, as well as for accurately determining the small transverse gradients of the longitudinal modes.

[2] There is also a 2-3 minute measuring "overhead" which includes a recording of the full spectrum at the start and end of each run, as well as a one-half second settling time between the end of the bead movement and the start of the measurement.

frequency shift, proportional to the *square* of the electric field, as a function of longitudinal position. The larger distances correspond to the side of the cavity containing the higher-order mode (HOM) dampers; the longitudinal asymmetry introduced by the dampers is clearly evident.

To compensate for possible short-term temperature drifts, we measure the phase shift at a field-free point at the start and end of the scan, record the times of these measurements as well as the times at which the first and last points of the actual scan are taken, and assume a linear variation; the data in Figs. 3 and 4 reflect this drift correction. Despite being deliberately overcoupled to the input waveguide, the cavity still has a relatively high Q of roughly 1800, so that a relatively modest averaging factor of 256 sufficed. We note that there appears to be a difficulty in reproducing the measured value of RT^2/Q to better than ±1-2% which appears to be unrelated to the signal-to-noise problem which averaging addresses, and presents a problem in measuring the transverse gradients needed to obtain the transverse impedances. The present suspicion is that it is due to short-term temperature fluctuations; the problem is being studied further.

RT^2/Q can be obtained from the dielectric bead data using

$$\frac{RT^2}{Q} = \frac{c^2}{\pi r^2}\frac{\varepsilon+2}{\varepsilon-1}\frac{1}{f^2}\left[\int_{path}\sqrt{\Delta f}\, e^{ikz}\, dz\right]^2 \qquad (1)$$

Eq. 1 has been adapted from Ref. 4; to evaluate the quantity in brackets one breaks the integral into sine and cosine parts, then squares and sums the two parts. As stated above, we then repeated the measurements using the metal needle, set the "epsilon factor" equal to unity (it is 1.353 for the alumina bead), and replaced the $c^2/\pi r^2$ with an empirical constant. Overall, including the epsilon factor, we find that the needle gives phase shifts roughly 50% greater than those obtained using the bead.

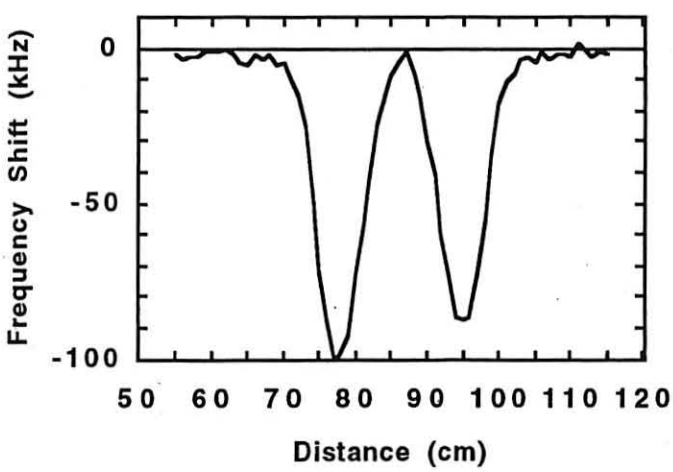

Fig. 4 Frequency shift *vs* position for TM_{011} mode of the B-factory model cavity.

The advantages of the HP 8510 in CW mode are clearly illustrated in the frequency measurements for the TM_{011} mode, shown in Fig. 4. This is one of the most troublesome HOM's in the undamped cavity, and the dampers' efficacy in reducing its Q-value by over three orders of magnitude to a value of 28 reduces the resulting perturbed phase shifts to a maximum value of 0.4 degrees! Nonetheless, by employing an averaging factor of 4096, we were able to obtain the data in Fig. 4 in less than two minutes.

IV. ACKNOWLEDGEMENTS

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