RF PERTURBATION MEASUREMENTS IN LONG LINAC CAVITIES*

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The problem of assembling a series of unit cells into a long linac cavity resonant at the same frequency as the separate cells is a difficult problem for the designer and cannot be solved with an arbitrary accuracy. For this reason, all linacs are constructed with tuners to provide local variations in frequency or acceleration field. The adjustment of the tuners to eliminate the local variations of the fields is a necessary tune-up procedure. Because of the difficulty of reading, calibrating, interpreting, and relating magnetic pickup probe readings on the outer wall to the axial accelerating fields, a measurement of these fields directly is preferred. The usual method of measurement of the axial field is by the use of perturbation techniques.[1] In order to use the perturbation method in long linac cavities, special equipment has been developed to allow the small perturbations in the frequency to be accurately measured.

The equipment developed is an extension of the technique originally used at Argonne National Laboratory for measuring the axial accelerating fields in the 50 MeV linac injector.[2] The method makes use of an on-line digital computer for increased speed and accuracy in making the measurements. The equipment has been developed as an on-the-shelf item so that measurements can be made on short notice when different linac operating conditions are being investigated or when major changes have been made in the cavity and it is desirable to return to an earlier operating condition. At ANL this appeared particularly attractive since a CDC-924A computer was frequently available when the Zero Gradient Synchrotron was not in operation.

The equipment is shown in Fig. 1. The frequency perturbing bead is pulled along the axis of the cavity on a silk suture thread tightly stretched and at a constant tension. The pulleys are of a low friction type. A few ramps placed in the drift tube bore holes are sufficient to insure that the bead remain nearly on the linac axis so that negligible error will result from the sag in the thread. The thread is driven by a motor whose speed can be constantly increased to allow the bead to move through one linac cell each second. In the ANL linac a run can be taken in about two minutes. Readings of the perturbed cavity frequency are taken each millimeter along the axis as determined by the string-driven position marker which is a low inertia toothed wheel intercepting a light beam to a photo diode.

In the ANL linac the cavity is self-excited by amplifying the signal from a pickup loop close to one end of the cavity and by driving the main power amplifier connected to the normal cavity drive loop. The cavity frequency from another pickup loop is amplified and mixed with the 20th harmonic and the fundamental of a very stable crystal controlled 10 MHz oscillator to give a difference frequency of about 1 kHz. This difference frequency is used to generate well-determined period markers at the positive zero-crossing points. These are sent through a gate which is opened by a shaped pulse from the string-driven position marker. The first period marker through this gate then opens a second gate which couples the signal from a 10 MHz oscillator to a binary scaler. The end of one, two, four, or eight periods is signaled by the appropriate period marker, which closes both gates and thus terminates the 10 MHz signal to the scaler. The scaler output thus provides an accurate period measurement of the difference frequency, at millimeter intervals along the linac cavity, in computer compatible form.

The axial accelerating fields can be readily obtained from the information supplied to the computer. At each millimeter a number corresponding to the length of a period is transmitted to the computer. This period corresponds to the difference between the cavity frequency when the perturbation is at the i^{th} position, f_i, and the frequency of the crystal oscillator, f_o. Let this difference frequency be δf_{oi} obtained by taking the reciprocal of the period numbers. To find the frequency due to the perturbation an average of the δf_{oi}'s are taken while the perturbing bead is in the drift tube or outside

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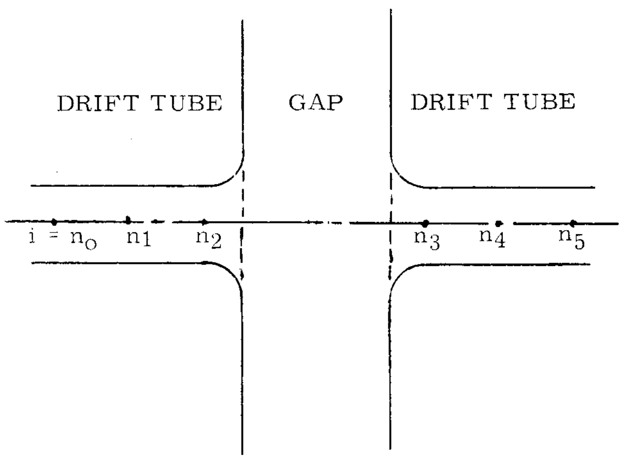
the cavity. The deviation from this average when the ball is in the gap corresponds to the perturbation in the frequency caused by the square of the electric field at the position of the ball. Suppose that from $i = n_o$ to n_1 there exists no field, from n_1 to n_2 corresponding to roughly three bore-hole radii to one bore-hole radius the field is too small to be measurable using these techniques, from n_2 to n_3 the field is appreciable extending through the gap, from n_3 to n_4 it is again too small to be measurable and then from n_4 to n_5 it is again zero. This repetitive nature along the axis of the linac can be illustrated as follows:



The averages, $\frac{1}{(n_1 - n_o)} \sum_{i=n_o}^{n_1} \delta f_{oi}$ and $\frac{1}{(n_5 - n_4)} \sum_{i=n_4}^{n_5} \delta f_{oi}$ allow the unperturbed difference-frequency base line to be determined and corrected for frequency drift when these averages are not the same. The δf_{oi} from n_2 to n_3 subtracted from the drift-corrected base line correspond to the perturbed frequencies, Δf_i. From the usual perturbation formula for a metal bead in the absence of magnetic field:[1]

$$\frac{\Delta f_i}{f_i} = \frac{k\,\delta V}{W} \quad \varepsilon_o\, E_i^2$$

where k is a constant close to 3/4, δV is the spherical bead volume, W is the stored energy in the cavity, and ε_o the free space dielectric constant, the electric field, E_i, at the position of the bead can be obtained. Except for the constant factor, the E_i values in the gap are the square roots of the Δf_i. These can be plotted to give the field shape throughout the gap. Figure 2 shows typical E_i plots for gaps number 1, 83, and 123. The square root causes fluctuations near the base line to appear large. This information is useful because numerical integration of these shapes allow transit-time information to be obtained.

For investigating linac performance, the integrals of the E_i over the m^{th} cell, or the average accelerating field, E_{om}, are required. These can be obtained as:

$$E_{om} = \frac{1}{L_m} \int_{n_1}^{n_4} E_i \, dz$$

where L_m is the length of the m^{th} cell.

Since the E_i values are not well determined from n_1 to n_2 and from n_3 to n_4, more consistent values of E_{om} are obtained if they are obtained from the integral:

$$E_{om} = \frac{\alpha_m}{L_m} \int_{n_2}^{n_3} E_i \, dz$$

where α_m is a correction factor which can be obtained from a field computational program[3] and amounts to about 1.06 for the first cell in the ANL linac and to about 1.02 for the 124th cell when the distance from n_2 to n_3 amounts to the gap length plus two bore-hole radii. In order to normalize these values it is convenient to calculate:

$$E_{om} = \frac{\dfrac{\alpha_m}{L_m} \displaystyle\int_{-G^m/2 - R_h^m}^{G^m/2 + R_h^m} E_i \, dz}{\dfrac{1}{L_T} \displaystyle\sum_{m=1}^{m=124} \int_{-G^m/2 - R_h^m}^{G^m/2 + R_h^m} E_i \, dz}$$

where L_T is the total length of the linac. When these values of E_{om} are plotted as a function of cell number or length, it is a simple thing to ascertain the degree of "flatness" of the linac cavity. Figure 3 shows two typical plots for the ANL linac; the top values were taken during a series of runs when the tuners were being adjusted to flatten the cavity, and the bottom values indicate a less favorable operating condition taken during runs on reflattening the cavity after a major change caused by adjusting the penetration into the cavity of the drive loop.

A ten drift-tube cavity was constructed to develop the equipment and procedures, and to determine the ball-size corrections without using valuable linac injector time. This cavity is shown in Fig. 4. The seven small bore-hole drift tubes, numbers 2 through 8, were borrowed from the Brookhaven 50 MeV linac, number 9 was borrowed from the display in the Argonne ZGS reception lobby, and numbers 1 and 10 were fabricated at MURA. The cavity and support were made at ANL and assembled at MURA.

Using this ten drift-tube cavity the fields could be measured quite accurately even for some distance inside the drift-tube bores. These measurements are useful for determining transit-time values for the gaps. The smaller volume of this cavity allowed measurable frequency shifts for perturbations as small as 1/8-in. metal balls so that errors due to ball size could be determined.

A ball-size correction arises because of the approximation of treating the field as uniform over the ball volume, δV, so that the frequency shift is just the simple ratio of $E_i^2\ \delta V/W$. If the field is not uniform over the ball volume (or if the image effect of the ball in the surface is appreciable), the value of the field at the center of the ball will only be an average over the ball volume. The correction may be determined by using successively smaller balls in the same field and hopefully extrapolating to zero ball size. The correction will be greatest where the fields have the highest gradients and where the balls are closest to the surface, which in this case is in the early linac gaps.

The field measured in gap 9 using four different size balls, where the largest is 15 times larger than the smallest, is shown in Fig. 5. The relative size of the balls with respect to the field is shown in the figure. A difficulty arises in measuring the field inside the bore hole for the smallest balls and it is difficult to make a comparison. At the peak of the field a definite difference in the measured fields of a few per cent is observed. In gap 1 similar differences were observed. However, since the intended use of this equipment was to measure the average field in each gap, the integral of these fields as a function of ball size is relevant.

Figure 6 shows the values of the integral of the field divided by the square root of the ball volume, $I/\sqrt{\delta V}$, plotted against the ball volume (or D^3) for gaps 1 and 2. The values are thus independent of the volume except for any ball-size correction that might be required in determining the integral. The plotted points are averages of two or three runs in these gaps for each ball size. The average of these runs does not show a ball-size correction to within $\pm$ 2 per cent. The bottom trace is the total integral for all nine gaps.

Although these data indicate that the ball-size correction is less than 2 per cent for balls as large as 3/8-in. used to measure the axial field in this geometry, another correction depending on ball size is relevant to long cavities. It is recognized that if the frequency of a single cell which is strongly coupled to many cells in a long linac cavity is perturbed as, for example, is the case when the end wall of a cavity is deflected, a change of amplitude of the field along the tank will result.[4] By virtue of the same effect, the change in frequency of the cell caused by the perturbing ball will result in a change in the field for a long linac. The error has been estimated by measuring the field in the 50 MeV ANL linac when a second perturbing ball is hung in gap 1 or gap 124. Figure 7 shows the results of the ratio of the average fields, E_{om}, taken with a 3/8-in. ball compared to five runs taken with a 5/16-in. ball. A definite trend for a value greater than one in the early gaps and less than one in the later gaps is seen. A small correction for this effect is reasonable.

A 3/8-in. perturbing ball is usually used to give a frequency shift at the maximum field of about 200 cycles in the ANL linac. The accuracy of the equipment and the stability of the system allows these frequency shifts to be related to average fields in the linac so that the relative accuracy of a single value is within 2 per cent. This is shown in Fig. 8, where the average deviation of a single value is compared with a five-run average. Except for an unexplained difficulty in the vicinity of cell 40, the average deviation is about 1 per cent in the short gaps decreasing to about 0.4 per cent in the larger gaps. If it is important to measure the relative axial field along the linac to a greater accuracy, the method is rapid enough to allow averages of several runs to be taken.

This equipment has been used to advantage in the ANL linac in tank flattening, in the calibration of the change in field resulting from endplate tuning, and for investigating different operating conditions. We have had an active program for some time attempting to compare the measured linac performance with the performance computed with particle dynamics programs such as the PARMILA program.[5] In these efforts, our greatest frustration results from an inadequate description of the linac, especially with regard to the fields in the linac. We now feel better about this situation, and in particular we have been able to arrive at a better set of transit-time values for the linac. In Fig. 9, the measured transit-time values are compared with the values originally used in the design of the linac to set up the drift-tube spacing. The difference is understandable on the basis of the measured field shapes, i.e., the larger discrepancy at low energy results from greater field penetration into the bore hole than expected in the original design and the larger discrepancy at higher energy results from the dip in the maximum field at the gap centers that is not well approximated by the square-field approximation. It should be stated that the measured fields alone are inadequate to give the fields at a distance into the bore hole, but for this purpose the field-computational program, MESSYMESH,[5] can be used to match the fields and extend them into this region. This difference in transit-time values means that the linac must be operated at higher gradient than the design value and for maximum acceptance must have the fields increased in the early gaps, i.e., tilted up. In Fig. 10, the ratio of the design transit time to the measured transit time, T_D/T_M, is plotted along the linac. The error in the structure resulting from this difference can be partially compensated by changing the field along the linac, so this ratio can also be interpreted as the change in the field, TILT, along the linac. Although a linac operating condition corresponding to this field distribution has not been attempted, particle dynamic studies using this distribution shows preferable beam properties, especially with regard to a mean output energy which is less sensitive to the rf level in the cavity.

Acknowledgments

Many people have contributed to this effort. We especially appreciate the early suggestions of Dr. P. V. Livdahl at ANL who provided the early incentive and pointed out the usefulness of the measurements. The ANL linac group assisted in the construction, development, and operation of the equipment and made available, at the expense of other priority projects, time for the measurements on the linac. We are also grateful for the assistance of the computer group under the direction of Dr. L. Lewis who undertook all the programming and interconnecting of the ANL CDC-924A computer. Without the able assistance of Mr. J. A. Hughes, MURA, who took responsibility for most of the transporting, setting up, and trouble shooting of the equipment, the accomplishments would have been considerably reduced.

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DISCUSSION

D. E. YOUNG, MURA

HUBBARD, Berkeley: Have you had a chance to get any recent measurements with beam on for your corrected field distribution?

YOUNG: We have not been able to do any more work on the linac, but we would like to set up this field and measure the beam properties to see how well these check with the computer program. This has been a long-range program with our group, and we are anxious to do this, but we have not had a chance to do it as yet.

SLUYTERS, BNL: Have you also done off-axis measurements and off-axis transit time calculations?

YOUNG: No, we have not done an off-axis transit time calculation. The measurement here was taken on-axis, and in order to get a sizeable perturbation, we are required to use a 3/8-in. ball to get a 200-cycle shift in the 200 megacycles. A 3/8-in. ball will just go through a 1/2-in. bore hole in the early drift tubes of the tank, so we can't really measure the field off-axis with any accuracy.

SLUYTERS: My first question is based on measurements made on drift-tube shapes in an electrolytic tank at CERN. As soon as you suggest how to set the tuner in a linac, then I think the final settings with beam will be quite different from the ones you calculate, because the transit times for off-axis particles are not the same as for on-axis particles, etc.

YOUNG: What we've really been trying to do is to compare the performance of the linac against what we would claim from the particle dynamics program. We have done this by using the field distribution that is currently obtained from measured values. However, there are many variables that need to be controlled before even qualitative agreement can be achieved. So, we cannot say what an optimum distribution should be.

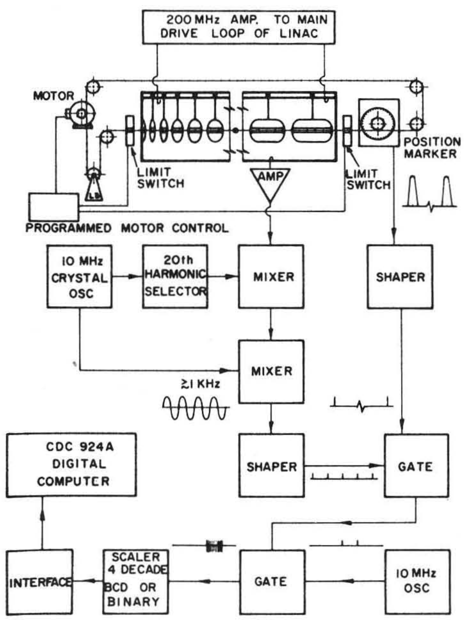


Fig. 1. Block diagram showing equipment used to digitally measure accelerating fields in the linac using perturbation techniques.

Fig. 2. A computer plot (shown at right) of actual measured fields at mm intervals along the axis for gaps 1, 83, and 123.

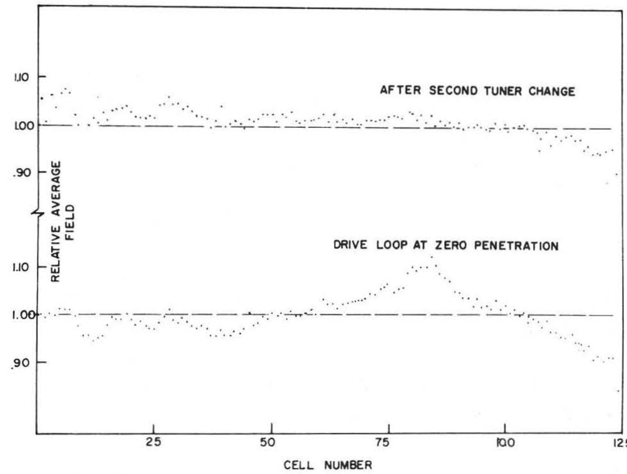


Fig. 3. Two typical plots of average accelerating fields for each cell along the linac.

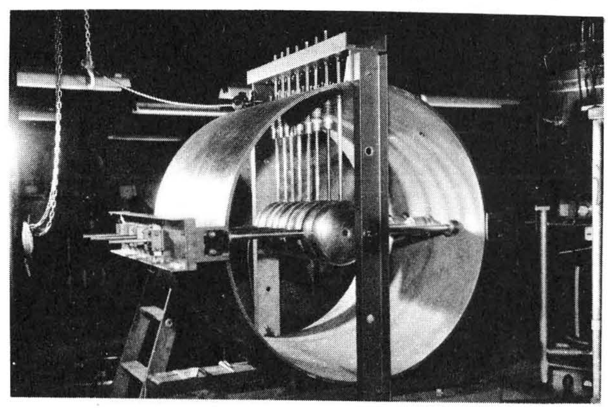
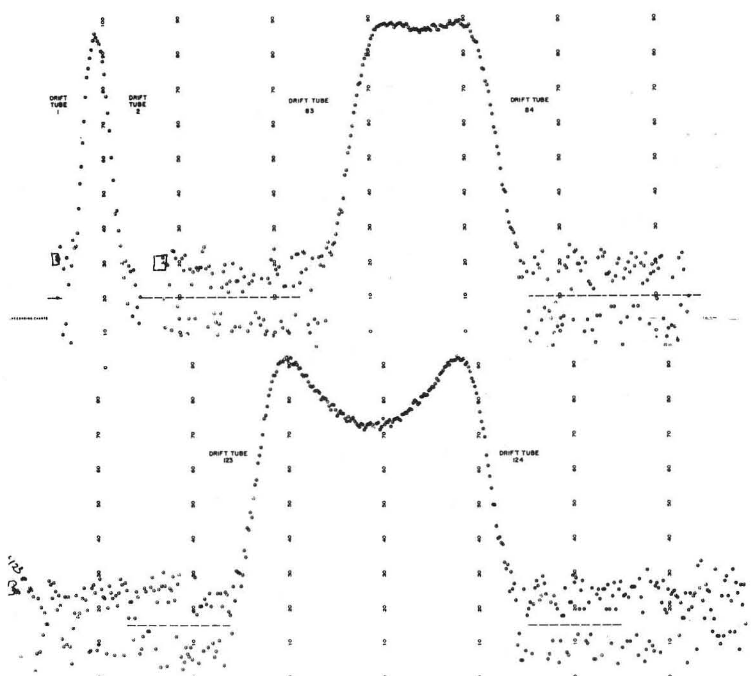


Fig. 4. Ten drift-tube test cavity.



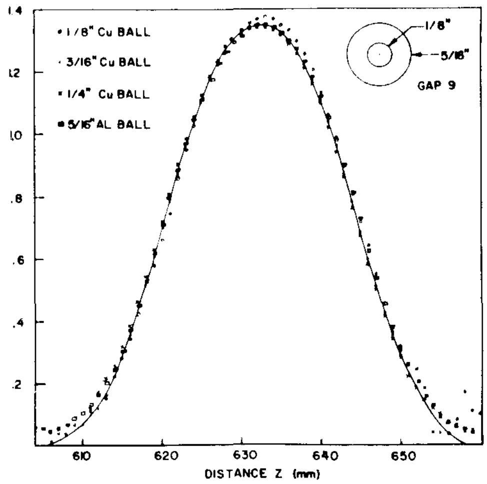


Fig. 5. Field distribution in gap 9 as measured with four different ball sizes.

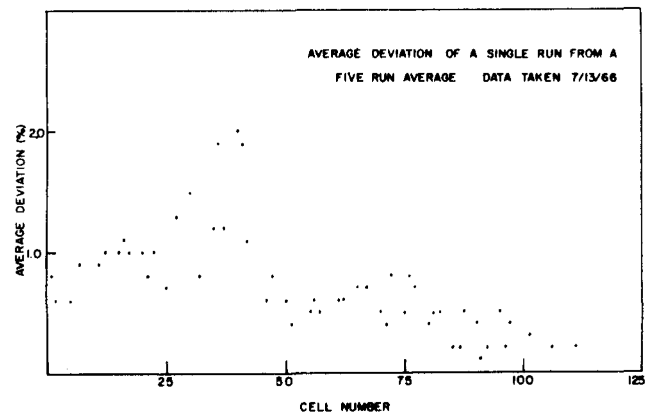


Fig. 8. Relative accuracy of measurements as determined by average deviation for values in single determination from 5-run average.

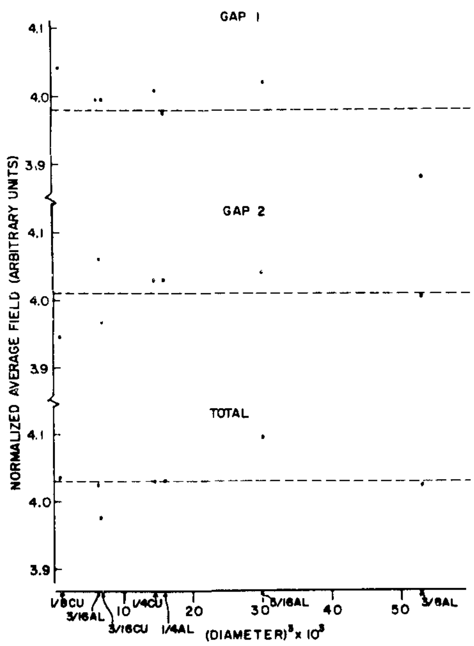


Fig. 6. Integrated fields normalized to unit ball volume vs ball (diameter)^3 to determine effect of ball size on measurements for gaps 1 and 2, and total of 9 gaps.

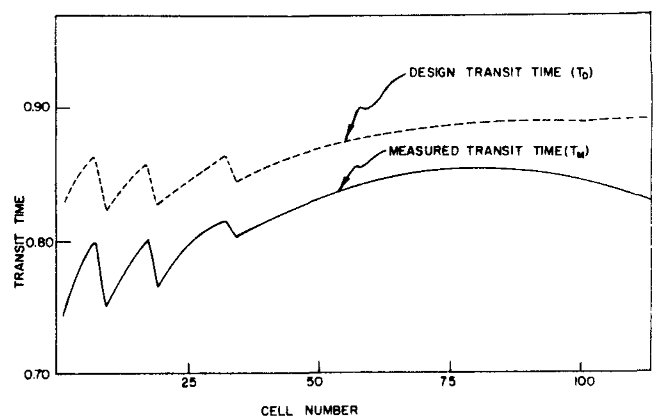


Fig. 9. Plot of design transit times and measured transit times in the ANL 50 MeV linac.

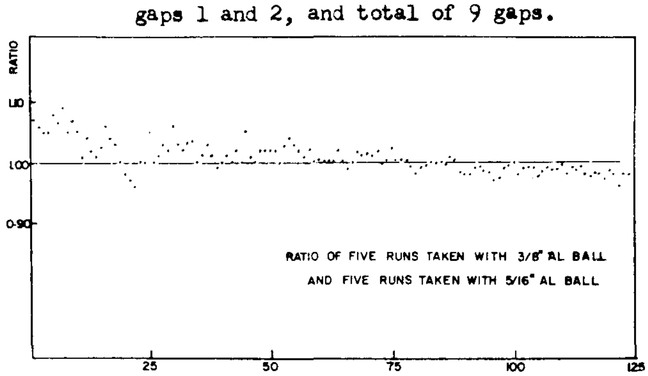


Fig. 7. Effect on tank tilt caused by using two different ball sizes.

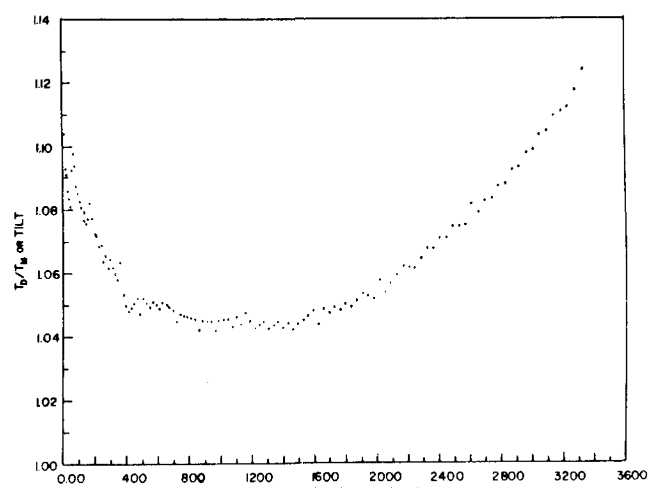


Fig. 10. Ratio of design transit time to measured transit time in the ANL 50 MeV linac.