REDESIGN OF A LOW ENERGY PROBE HEAD

Y.-N. Rao, G.H. Mackenzie, T. Ries, TRIUMF, Vancouver, Canada *

Abstract

The present situation of the low energy probe LE2 in TRIUMF cyclotron is that the thickness of the finger 5 is uniform over a radial length of 3.25 inch and its weight which amounts to ∼447 g is affecting its re-circulating ball mechanism and causing it to fall below the median plane over its range of movement. We therefore re-design it in order to reduce its weight. First, we made simulations and determined the optimum thickness of the probe head vs its radial length. These simulation results are found to be in good agreement with experimental measurements made. Finally, we calculated the temperature rise caused by the beam power dumped on the probe, and figured out the maximum current of beam that can be dumped on the finger.

INTRODUCTION

The low energy probe LE2 in TRIUMF cyclotron operates between 13.89 and 161.5 inch (∼0.5-85 MeV) and electrically has four copper fingers (1-4) arranged one above the other (see Fig. 1). These are shielded from the beam, apart from the leading ∼0.075 inch, by a copper block (finger 5) which, at present, has a uniform thickness of 0.5 inch in the beam direction, a length of 3.25 inch in the radial direction and a height of 1.875 inch in the vertical direction. Its weight amounts to ∼447 g. Such a weight is affecting the probe's re-circulating ball mechanism and causing the probe head fall below the median plane over its entire range.

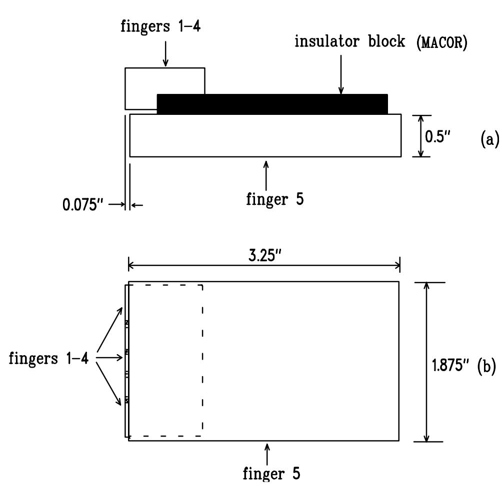

Figure 1: Schematic diagram showing the plan view (a) and front view (b) of LE2 fingers.

* TRIUMF receives funding via a contribution agreement through the National Research Council of Canada

Fingers 1-5 intercept beam at all energies ranging from ∼0.5 to ∼85 MeV and their thickness in the beam direction is determined by the range of the proton stopped in copper. The radial length of the finger 5 is determined by the largest radius gain per turn plus an allowance for the precessional radius gain and beam spot size. The minimum thickness at any point along its length is determined by the maximum beam energy incident at that point. Since the largest radius gains per turn occur at the lowest energies where the proton range in copper is much smaller than 1 mm, the thickness of the finger 5 can be chamfered from the front to the rear to reduce its weight.

For re-design of this finger 5, we first made analytical estimation on the radial length of finger 5 that can be hit by the beam at various energies. These were then checked by numerical simulations[1] using COMA[2], and compared with experimentally measured results. We ended up with a curve of thickness vs radial length in terms of a range-energy curve of proton in copper.

Also, we calculated the temperature rise caused by the beam power dumped on the probe, and eventually figured out the maximum beam current that can be dumped on the finger.

ANALYTICAL CALCULATION

The maximum possible turn to turn separation of a beam particle can be described by

$$\Delta r = \Delta r_c + 2(A_p + A_e)\sin(\pi(\nu_r - 1)) \qquad (1)$$

where

$$\Delta r_c = \frac{\gamma}{\gamma+1}\frac{\Delta E}{E}\frac{r}{\nu_r^2} \qquad (2)$$

is the radius gain per turn of a centered beam due to energy gain, γ is the relativistic factor, E is the kinetic energy of the beam, ΔE is the energy gain per turn, r is the average orbit radius, ν_r is the radial betatron oscillation frequency, A_p is the amplitude of a coherent oscillation of an off-centered beam, and

$$A_e = \sqrt{\frac{r\epsilon}{\nu_r}} \qquad (3)$$

is the amplitude of an incoherent oscillation with finite emittance ϵ.

Applying eqs.(1)-(3), we calculated the maximum radius gain per turn, assuming A_p=0.2 inch and a normalized emittance $\epsilon_n = 1.5\,\pi$mm-mrad. The results are shown in Fig. 2 for an energy range from 0.5 to 90 MeV.

0-7803-8859-3/05/$20.00

NUMERICAL SIMULATIONS

COMA was run to check the estimation result above-mentioned. We ran a centered beam of 30 MeV with a matched emittance of 5.9 πmm-mrad (corresponding to a normalized emittance of 1.5 πmm-mrad) and 36° phase width backwards to the injection gap, and then fit an enclosing ellipse to the X-P_x and Z-P_z phase spaces at the injection gap, keeping the normalized emittance identical to that at 30 MeV. This beam (with a phase width of 36°) was accelerated outward to 90 MeV, and the LE2 probe scan was simulated starting from a radius 13.890 inch to plot out the maximum hit distance from the probe tip as a function of the energy of the particle with that maximum hit distance. The result is shown in Fig. 2, together with a result obtained from starting at 30 MeV with finite emittances and a displacement of 0.2 inch which account for a precession. Also shown is the analytical result. The analytical result appears to be in good agreement with the simulated result from starting at 30 MeV where the R-ϕ coupling is much weaker. However, the simulation result from starting at the injection gap shows a further out hit distance. The reason for this is that the R-ϕ coupling causes a large distortion of the radial emittance (especially for particles with a large positive phase angle) and also the orbit became off-centered.

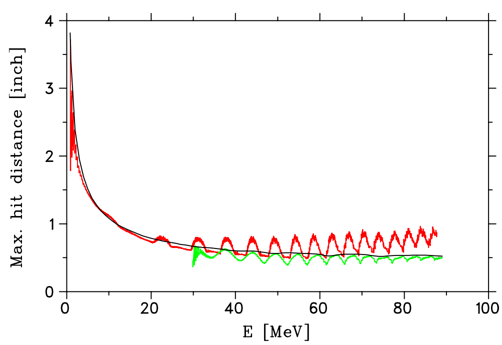

Figure 2: Calculated maximum hit distance of beam from the probe tip as a function of the energy. Red: result from starting at injection gap; Green: result from starting at 30 MeV with finite emittance and a displacement of 0.2 inch at start; Black: analytical result.

MEASUREMENTS

Experimental measurements were performed in TRIUMF cyclotron to compare with the simulation results. The bunchers in the injection beam line were turned off and the slits were fully open so that a poor quality beam could be accepted with a maximum phase width into the cyclotron.

At inner radii (<30 inch), there exists clearly successive turn structure. Therefore, the measurement was pretty straightforward; LE2 itself can investigate the turn separation. Fig. 3 shows the measured turn structure in a radial region from 13.89 to 29.98 inch, where, on each turn, the maximum hit distance from the probe tip is indicated. The RF voltage amplitude was ∼91 kV.

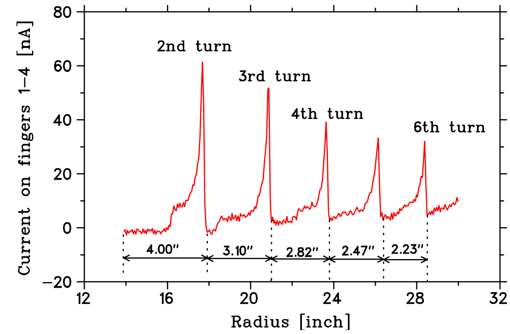

Figure 3: Measured differential (summation over fingers 1-4) scan of successive turns of beam using probe LE2.

At larger radii, there is no well-defined turn separation for the beam with a broad phase width. The distribution of the beam on the probe head was therefore investigated by using a shadow measurement. We park LE2 at a fixed radius R, and then move LE1 (180° apart from LE2) in a radial region from $(R - 2.0)$ to $(R + 2.0)$ inch (because the maximum turn separation is known to be no more than 4.0 inch). In such a way, LE1 moves across the paths of the orbits intersecting LE2. The beam currents on LE1 and LE2 are recorded as a function of LE1's position. The measurement was repeated 3 times by jogging LE2 at $\sim \frac{1}{3}$ of the local turn separation so as to find out the maximum width of the radial shadow.

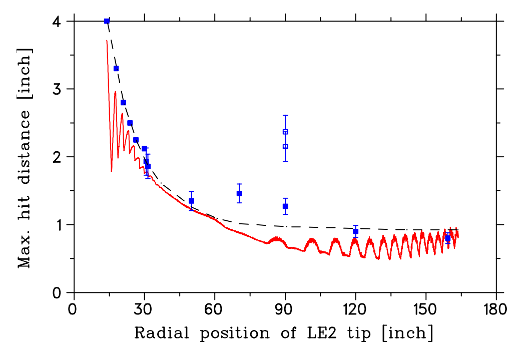

Figure 4: A comparison of the measured (filled squares: HC4 off; open squares: HC4 excited) and the simulated (solid line, from Fig. 2) results of the maximum hit distance vs LE2 tip radius. The dash line is a fit through the filled squares.

Fig. 4 plots the measured and simulated (from Fig. 2) results of the maximum hit distance vs the radial position of LE2 tip. We can see that they are in good agreement except that at 70 and 90 inch the measured hit distances extend further out. This could be because of a strong stretching in the radial phase space arised from the R-ϕ coupling. Although the beam at these two radii hits further than 1.0 inch, their projected ranges in the finger are both below $\frac{1}{16}$ inch. We therefore fit a smooth curve through these measured data points (see the dash line in Fig. 4). Then, using a range-energy curve of protons in copper (see Fig. 5), we eventually achieve the thickness of finger 5 vs its radial distance from the tip. This is shown in Fig. 5. In practice, it would be easier to machine it in a step shape (see the dash line in Fig. 5, or see Fig. 7). The maximum distance from the probe tip that is hit by an 85 MeV beam is 0.93 inch. We could make finger 5 slightly (∼10%) longer, namely 1.0 inch. Thus the inner 0.075 inch of fingers 1-4 and the first 1.0 inch of finger 5 must be slightly (20%) thicker than the range (0.41 inch) of an 85 MeV proton, for example 0.5 inch.

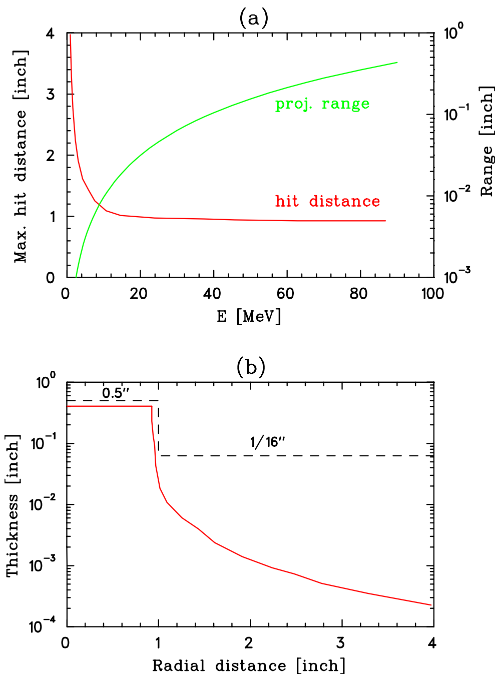

Figure 5: Max. hit distance and projected range in copper vs the energy of proton (a), and thickness of finger 5 vs the distance from the probe tip (b). The dash line suggests a step shape for easier machining.

THERMAL CALCULATIONS

High temperature materials, connectors etc. were used in the design of the probe. The MACOR insulator may set the limiting temperature. This retains its mechanical and electrical properties to 1000 °C in air but evolves fluorine compounds in vacuum at temperatures above 600 °C. The Engineering Group felt that the maximum local temperature should not exceed 350 °C.

The result of 3-D ALGOR heat transfer simulation for the step-shaped geometry showed that, to yield a maximum temperature of 350 °C, the maximum allowable beam power is 36 W, and this corresponds to a maximum allowable beam current of ∼420 nA at maximum energy 84.5 MeV, see Fig. 6.

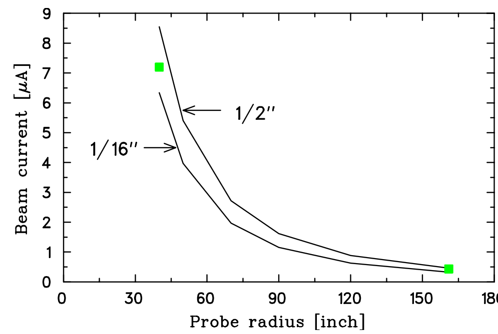

Figure 6: 1-D WAERME[3] calculated beam current to yield a maximum temperature of 350 °C at several radii. The plate thickness was assumed to be uniform and either $\frac{1}{16}$ or 0.5 inch; copper emissivity was 0.4. Filled squares: results from 3-D ALGOR calculations where the finger thickness used is a step-shape as is shown in Fig. 7.

CONCLUSIONS

Based on the beam dynamics considerations, the shape and dimensions of LE2 finger 5 have been determined. As sketched in Fig. 7, the finger 5 can be manufactured in a step shape so that its weight can be reduced from the current 447 g to 190 g. For such a proposed finger geometry, the thermal calculation results show that one should restrict beam power on the probe head to 36 W, namely ∼420 nA average current at the maximum energy 84.5 MeV, or 500 nA at 70 MeV, or 5 μA at energies below 10 MeV. The maximum temperature reached on the finger would be lower than 330° $\pm$ 33%.

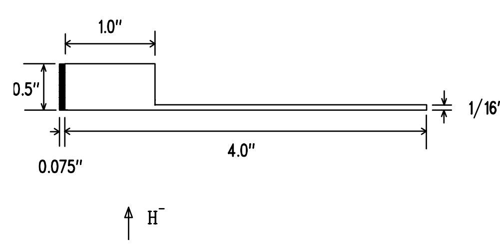

Figure 7: Plan view of the proposed step-shaped finger 5 and its thickness. The leading portion 0.075 inch represents fingers 1-4.

REFERENCES

[1] Y.-N. Rao, G.H. Mackenzie, T. Ries, “Calculations on LE2 probe head thickness and experimental measurements”, TRI-DN-04-8, August 18, 2004.

[2] C.J. Kost and G.H. Mackenzie, “COMA - A LINEAR MOTION CODE FOR CYCLOTRON”, Proc. of IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975, p.1922-1925.

[3] L. Rezzonico and M. Zach,“WAERME - A Heat Transfer Code in One Dimension and Time”,TRI-DN-96-10, June 1996.

 0-7803-8859-3/05/$20.00 ©2005 IEEE