MEASUREMENT OF TURN STRUCTURE IN THE CENTRAL REGION OF TRIUMF CYCLOTRON*

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Abstract

To get the most out of the existing beam diagnostics in the TRIUMF cyclotron, we started in 2011 to develop new data processing and visualization tools. The main advantage of these Matlab©-based tools, compared with old VMS-based tools, is that they can benefit from a much larger library of modern data processing and visualization algorithms. This effort has already shown itself very useful to highlight essential features of the beam dynamics which remained unnoticed before. In this paper we present measurement results displaying beam dynamics processes taking place in the central region of the TRIUMF 500 MeV cyclotron.

INTRODUCTION

The TRIUMF 500 MeV cyclotron is equipped with five radially moving probes primarily dedicated to beam diagnosis. Among these five probes, two are low energy (LE) probes, covering the region between $R = 13.89$ and 161.5 inch (corresponding to $\sim 0.5 - 85$ MeV). These two probes move along identical rails placed 180° apart (see Fig. 1). The two LE probes have identical heads. They consist of five horizontal fingers, plus a large plate, which shields them from the beam except for the leading 0.075 inch (see Fig 2). The probe heads can take no more than about $0.5\,\mu$A, which requires that measurements are taken at very low duty cycle. Details concerning the design of the head can be found in this reference [1].

Measurement results presented in this paper have been chosen to highlight key features of the beam dynamics in the central region of the TRIUMF cyclotron.

PHASE-DEPENDENT DYNAMICS

The TRIUMF 500 MeV cyclotron accelerates H^- ions, and uses charge exchange extraction. No turn separation is required for extraction, which allows a very large phase acceptance (up to 60° [2]). The ion source produces a cw beam, which can be bunched by means of two rf cavities in the injection line. The first bunching cavity works at the same frequency that the cyclotron (first harmonic), which is the fifth harmonic of the revolution frequency; the second one works at twice this frequency to partially compensate the non-linearity of the first harmonic sine wave.

The azimuthal field variation is practically negligible in the central region, due to the fact that the injection radius (~ 11 inch) is smaller than the magnetic gap height (18 inch). Without azimuthal field variation, the sole source

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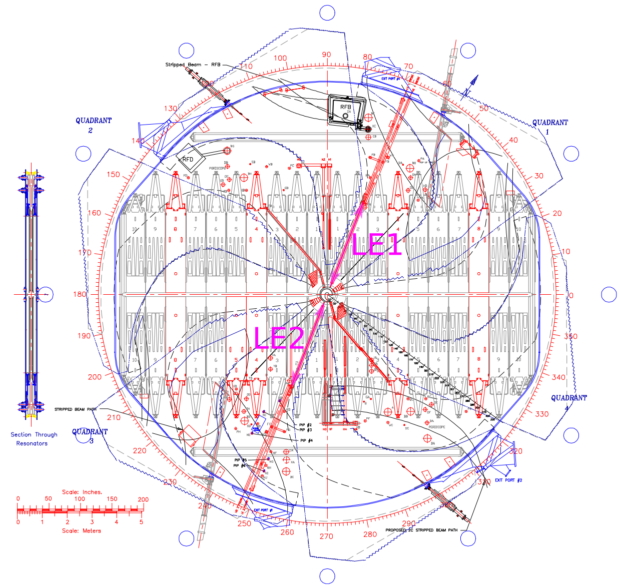

Figure 1: Schematic view of the TRIUMF cyclotron. The two low energy probes are indicated in magenta.

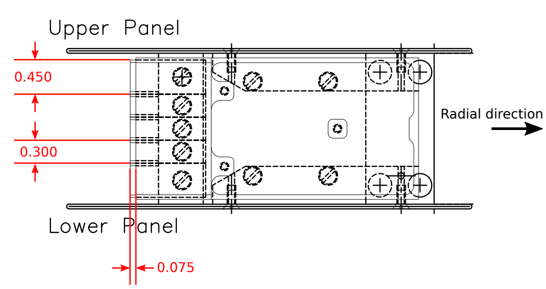

Figure 2: Schematic drawing of the low energy probe head. Dimensions are given in inch.

of vertical focusing is the rf gaps. This makes vertical focusing in the central region of TRIUMF cyclotron phase dependent.

To study the behavior of each individual phase we inject very short bunches, and follow their evolution with the LE probes. To achieve very short bunches, space charge is greatly reduced by inserting in the injection line, upstream of the bunchers, a pepper pot. This device reduces the charge by a factor ~ 50 without affecting the beam emittance. We set the amplitude of the first harmonic buncher to arrive at the injection gap with most of the particles gathered within a narrow phase window, as illustrated in Fig. 3 (a) and (b). After injection into the cyclotron and acceleration though the Dee gaps, the particle distribution as seen by the LE probes generally presents two peaks (see

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Fig. 3 (d)): the first one corresponding to the maximum of particle density; the second one coming from the fold over of the beam tail (viewed in radial projection), and making a handy marker of the position of on-crest particles.

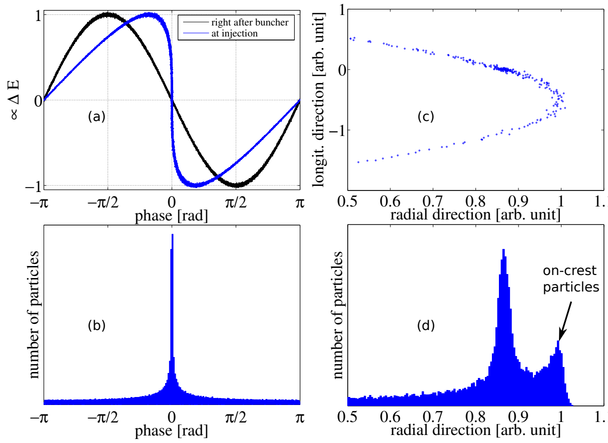

Figure 3: Macroparticle simulation of injection of short bunches: (a) longitudinal phase space right after the first harmonic buncher (black) and right before injection into the cyclotron (blue), in the absence of space charge; (b) phase distribution within the same beam before injection. The same particles, after crossing cyclotron acceleration gap, are show in 'top view' (c), and in radial projection (d).

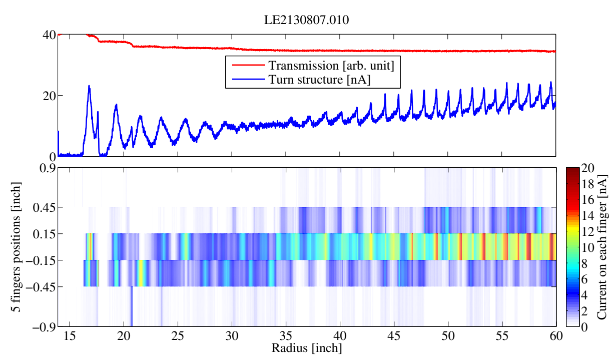

Figure 4: Measurement results from LE2 probe scan when injecting short bunches 30° off crest on the falling side of the rf wave. **Top**: the blue line shows beam current intercepted on the first 0.075 inch of the probe head; the red line shows the total current on the probe (arbitrary scale). **Bottom**: current read back on each of the five horizontal fingers.

A first set of measurement was taken moving the LE2 probe radially from $R = 13.89$ to 60 inch, while injecting a short bunch 30° off crest, on the falling side (*i.e.* vertically focusing side) of the rf wave. Results are shown in Fig. 4. The second turn is visible on the left of the plot (the first turn is out of the probe range). Its profile is very similar to what is described in Fig. 3, except that the low energy part of the profile is truncated; this is caused by particles being intercepted by the center post of the cyclotron. The bottom part of the plot shows a beam vertically well-focused, with no noticeable coherent vertical oscillation, and a beam small enough vertically to be seen on only one or two radial fingers at most radii.

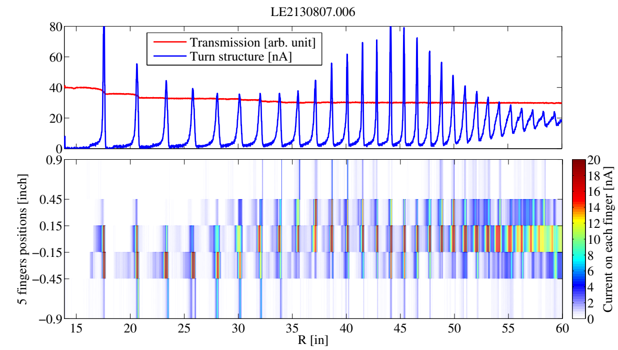

Figure 5: LE2 probe scan showing short bunches injected 10° off crest (falling side of the rf wave). (See caption of Fig. 4 for plot details.)

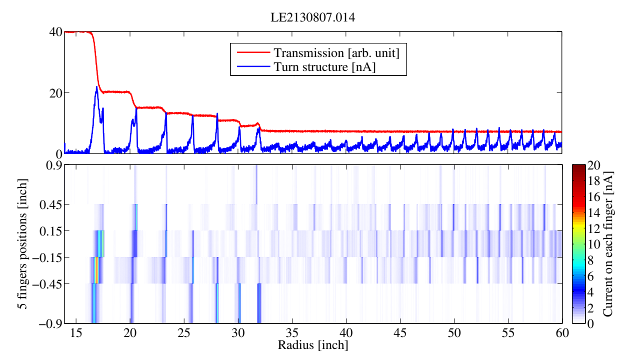

Figure 6: LE2 probe scan showing short bunches injected -10° off crest (rising side of the rf wave). (See caption of Fig. 4 for plot details.)

With bunches injected 10° off crest, still on the falling side of the rf wave (see Fig. 5), one can see that the vertical focusing is weaker: the beam is seen on three fingers or more at most radii; a coherent vertical oscillation is also visible, with about a full oscillation between turn #2 and turn #13. Once can also see that the radial beam density peaks around turn #16. This comes from the fact that the central region of TRIUMF cyclotron has been made slightly non-isochronous to move the beam from the falling side of the rf wave back on crest. Around turn #16 the short bunch injected 10° off crest is back on crest.

For bunches injected 10° off crest but on the rising side of the rf wave (see Fig. 6), most of the beam is lost vertically in about eight turns, due to the lack of vertical stability.

TURN STRUCTURE OF UNBUNCHED BEAM

An interesting exercise consists of turning off rf bunchers to inject an unbunched beam into the cyclotron. Two sets of data taken consecutively with the LE1 and LE2 probes are presented in Figs. 7 and 8, respectively. Peaks in radial density corresponding to the position of on-crest particles clearly seen on these plots are used to measure the effective Dee gap voltage. Bottom part of these two plots display a slightly different vertical steering on opposite sides of the cyclotron.

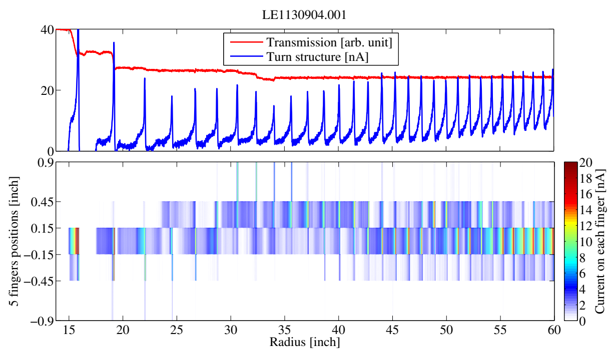

Figure 7: LE1 scan with bunchers off. (See caption of Fig. 4 for plot details.)

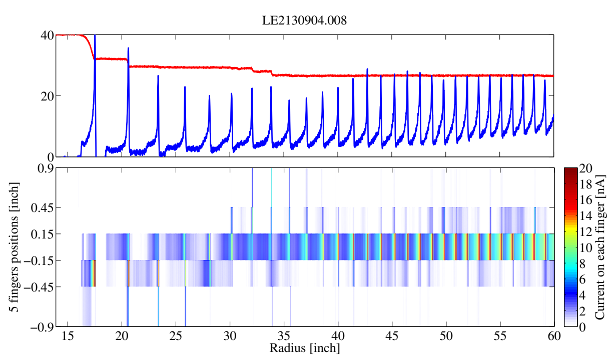

Figure 8: LE2 scan with bunchers off. (See caption of Fig. 4 for plot details.)

OPERATIONAL CONDITIONS

Machine preparation for high-current requires minimization of horizontal and vertical coherent oscillation, and fine adjustment of the first and second harmonic bunchers' phase and amplitude to maximize transmission and minimize spill. The instantaneous current injected into the cyclotron can be modulated by changing the opening of four pairs of emittance-defining slits, placed in the injection line, upstream of the bunchers, 90° phase advance apart.

The two sets of measurements presented here were taken on different days, when the machine was tuned for standard high-current delivery, but with a different amount of current injected into the machine. The measurement presented in Fig. 9 was taken at equivalent extracted current of 210 μA. The measurement presented in Fig. 10 was taken at equivalent extracted current of $\sim$ 290 μA.

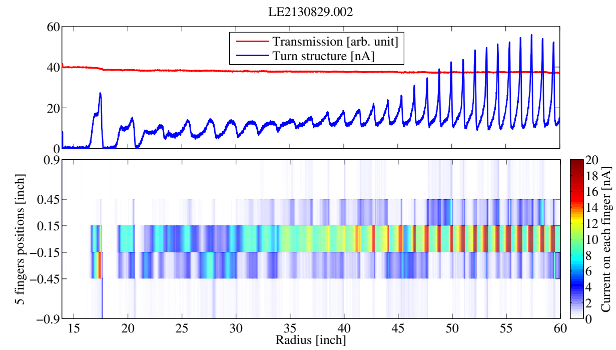

Figure 9: LE2 scan at normal 210 μA operating conditions. (See caption of Fig. 4 for plot details.)

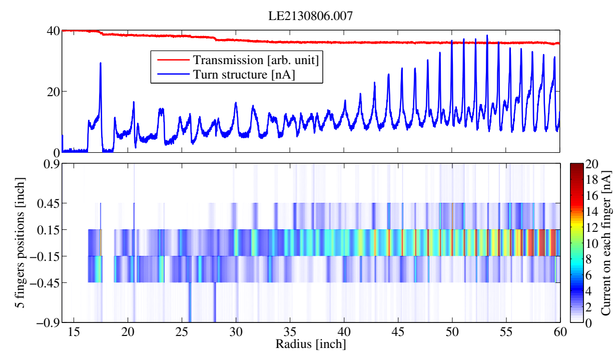

Figure 10: LE2 scan at normal $\sim$ 290 μA operating conditions. (See caption of Fig. 4 for plot details.)

The more complicated turn structure observed with higher charge per bunch is presumably a consequence of the space charge driven vortex motion[3]. Detailed simulations need to be carried out to verify that what we are observing is actually caused by this effect. Nevertheless, the sharp peaks in radial density seen on the low energy side of turns #3 and #4 (Fig. 10) seem to indicate that the bunch tail is bent by space charge forces. The peak in radial density seen around turn #28 in Fig. 9, and around turn #23 in Fig. 10 could correspond to a 180° rotation of the beam core. Again, this reading needs to be compared with simulations results.

REFERENCES

[1] Y.-N. Rao, G.H. Mackenzie, T. Ries, "Redesign of a Low Energy Probe Head", Proc. of PAC'05 Conf., Knoxville, USA, May 2005, WPAE008, p. 1105.

[2] J.R. Richardson et al., "Production of Simultaneous, Variable Energy Beams from the TRIUMF Cyclotron", Proc. of PAC75 Conf., p. 1402.

[3] R.A Baartman, "Review of Space Charge Effects in Cyclotrons", these proceedings, Proc. of Cyclotrons'13 Conf., Vancouver, Canada, Sep 2013, WE2PB01.