CORRECTION OF ν_r = 3/2 RESONANCE IN TRIUMF CYCLOTRON*

T. Planche†, Y.-N. Rao, R. Baartman
TRIUMF, Vancouver, Canada

Abstract

Imperfections in the TRIUMF cyclotron are a source of field errors which slightly violate the 6-fold symmetry of the ring. Among them, the third harmonic of the magnetic gradient errors drives the $\nu_r = 3/2$ resonance. This results in a modulation of the current density versus radius observed after the resonance crossing (428 MeV) all the way to the extraction (480 MeV). The cyclotron has sets of harmonic correction coils at different radii, each set constituted of 6 pairs of coils placed in a 6-fold symmetrical manner, and were designed to correct the first harmonic of the cyclotron magnetic field. The 6-fold symmetry of this layout cannot create a third harmonic of arbitrary phase, and so a single set of harmonic coils cannot provide a full correction of third harmonic errors driving the $\nu_r = 3/2$ resonance. However, the outermost two sets of harmonic correction coils (numbers 12 and 13) are azimuthally displaced. In this study, we use this fact to achieve a full correction of the resonance. We also present experimental measurements that demonstrate the full correction.

INTRODUCTION

The TRIUMF cyclotron accelerates H^- ions, which enables the use of charge exchange extraction. To extract beam to several high-energy (480 MeV) beam lines simultaneously, stripping foils are inserted at azimuths differing by 60°, at almost the same radius. Each foil takes part of the beam, converting H^- ions into protons for extraction. The fraction of beam taken by each foil depends on the radial density of the beam. Any fluctuation of the radial beam density in the region of a foil will cause variations of the current extracted to each individual beam line.

Such fluctuations are observed in the TRIUMF cyclotron, where variations of radial beam density in the high-energy region lead to undesirable fluctuations of the ratio between beam line 1A and 2A currents. The main source of these fluctuations is related to the crossing of an half-integer resonance.

MECHANISM DRIVING CURRENT INSTABILITIES

The horizontal tune crosses the half-integer value 3/2 around 428 MeV, as shown on Fig. 1. For reference, the relation between energy and average beam radius is also given in this figure. As discussed in [1], since the 6-fold symmetry of the TRIUMF cyclotron is imperfect, there exists in that region enough third harmonic field error to drive this resonance. After crossing the resonance the ellipse occupied by the beam in the horizontal phase becomes mismatched, and begins to rotate at the frequency $(\nu_r - 3/2)$ [2]. This precession of the horizontal phase space induces oscillations of the radial beam density, as shown in Fig. 2.

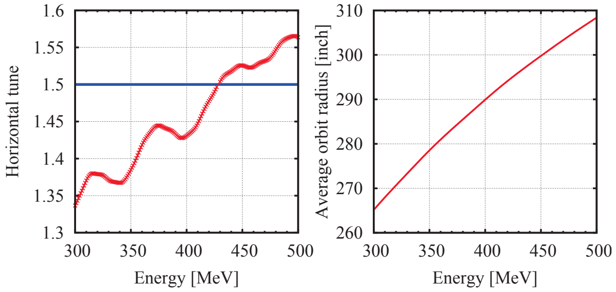

Figure 1: Left: horizontal tune variation with energy in the TRIUMF cyclotron. Right: average closed orbit position with energy. Results were obtained from simulation (using `CYCLOPS` [3]).

These oscillations could also be measured using one of the radially moving probe equipped with two diaphragms, shadowing each other, and displaced radially by 0.762 mm. Example of measurement results are presented in Fig. 3. One can see on this figure a current density modulation starting around 428 MeV (~296 inch) and propagating all the way to 480 MeV (~305 inch).

All other things being equal, these radial oscillations are purely static. Alone, they cannot be the cause of the fluctuation with time of the split ratio between extractions line 1A and 2A. But the number of these oscillations is function of the accelerating voltage, as one can see from the comparison of the two curves presented in Fig. 3. Fluctuations of the accelerating voltage affect the number of these oscillation. This is the source of the undesirable fluctuations of the beam density observed at the extraction radius.

In other words, the $\nu_r = 3/2$ resonance makes the split ratio between high-energy beam lines unnecessarily sensitive to the accelerating voltage. To get rid of this undesirable effect, one way is to correct the field harmonics driving this resonance.

FULL CORRECTION USING TWO SETS OF HARMONIC COILS

The cyclotron has sets of harmonic correction coils (HC) at different radii, 13 sets in total, each set constituted of 6 pairs of coils placed in a 6-fold symmetrical manner

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[†] http://trshare.triumf.ca/~tplanche/IPAC12nur32

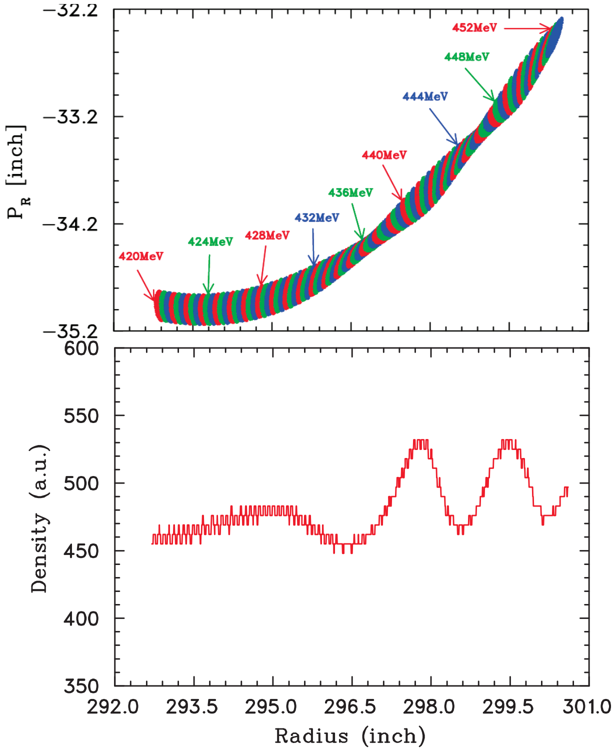

Figure 2: Simulation results. Top: turn-by-turn variation of the radial phase space passing through the $\nu_r = 3/2$ resonance. One can see the rotation (precession) of the ellipse. Bottom: induced radial modulation of beam density. Here we only illustrate the first 2 periods of precession and modulation; in fact, the precession and density modulation persist until extraction (see Fig. 6).

(see Fig. 4). Until recently, only one set of HC (#13) was used to correct the $\nu_r = 3/2$ resonance. Because the phase of the phase 3rd harmonic error does not match with the geometrical disposition of the coils, only a partial correction of the resonance had been achieved this way [1].

The resonance takes place, however, in a region where two sets of HC (number 12 and 13) have overlapping effects. In addition, these two sets of HC are azimuthally displaced (by about 11 degrees, see Fig. 4). It is therefore possible to take advantage of this azimuthal displacement to adjust the phase of the 3rd harmonic correction, and achieve a full correction of the resonance.

The scheme is as follows. We wish to create a third harmonic field of amplitude A and phase ϕ from coils which have fixed phase of zero and $\delta = 3 \times 11^\circ$ respectively, and amplitudes U and V respectively. Then by the sine law, we have (see Fig. 5)

$$\frac{U}{\sin(\delta+\phi)} = \frac{V}{\sin\phi} = \frac{A}{\sin\delta}. \tag{1}$$

Ideally, the desired field for arbitrary phase is most efficiently obtained if $\delta = \pi/2$. Since in fact $\delta = 33^\circ$, the coils act partly in opposition to each other and their strengths are a factor $\csc 33^\circ = 1.84$ higher than the ideal arrangement.

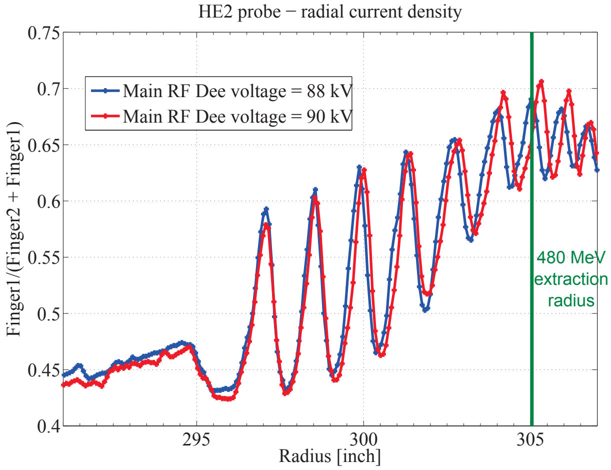

Figure 3: Radial variation of the current density measured with a high-energy equipped with differential fingers. The two curves present two measurements taken consecutively, with the main RF gap voltage set to 88 kV (blue) and 90 kV (red).

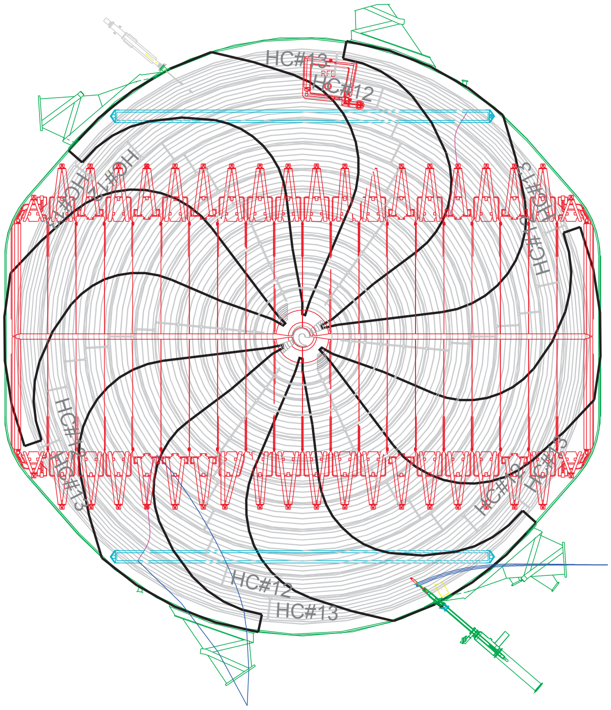

Figure 4: Cyclotron schematic layout. RF resonators are in red; trim and harmonic coils in gray.

The feasibility of the idea was first demonstrated using `COMA` [4] simulations. To achieve a full correction of the resonance, power supplies for HC #12 and #13 were upgraded to higher current. Full correction of the resonance was then demonstrated experimentally, by measuring the current density modulations using high-energy probe. Both simulation and experimental results are shown in Fig. 6.

Harmonic coil #12 was already used to correct the first

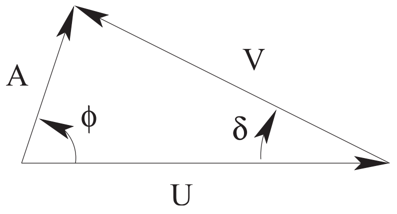

Figure 5: Vector diagram for harmonic coils U and V. The desired vector is $\vec{A} = \vec{U} + \vec{V}$.

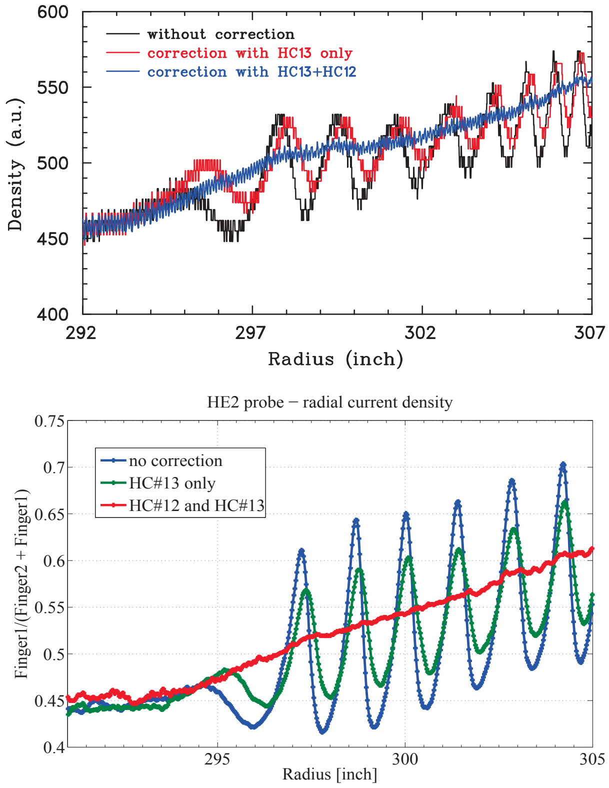

Figure 6: Current density radial modulation without correction, with correction using HC#13 only, and with correction using HC#12 and #13 in combination. Top: simulation result. Bottom: measured result, using the same apparatus than for measurements presented in Fig. 3. The full correction results in greatly reduced fluctuation.

harmonic error in the high-energy region. Since each pair of trim coils is controlled independently, we could superimpose the required third harmonic correction on top of the existing first harmonic correction. The control system of the cyclotron was upgraded to allow independent control of the first and third harmonic correction.

CONCLUSION

Full correction of the ν_r = 3/2 resonance is in use in the cyclotron since April 2012. This is expected to greatly improve the extracted current stability when beam is sent to beam line 1A and 2A simultaneously.

In the future, we plan to have the beam shared among three high-intensity 480 MeV extraction lines. Two of these beam lines will require a highly stabilized beam (fluctuations below 1%). The full correction of the ν_r = 3/2 resonance is a significant step toward this goal.

REFERENCES

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