IMPROVEMENT OF THE CURRENT STABILITY FROM THE TRIUMF CYCLOTRON*

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Abstract

The $\nu_r = 3/2$ resonance, driven by the third harmonic of the magnetic gradient errors, causes modulation of the radial beam density in the TRIUMF cyclotron. Since extraction is by H^- stripping, this modulation induces unwanted fluctuations of the current split between the two high-energy beam lines. To compensate field imperfections, 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. 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 are azimuthally displaced. We took advantage of this fact to achieve a full correction of the resonance. This greatly reduces rapid fluctuations of the beam current in the high-energy beam lines.

An active feedback system has also been implemented to compensate for the slow fluctuations (~ 1 minute range and above). This feedback acts on the amplitude of the first harmonic B_z correction produced by the outermost set of harmonic coils. A proper choice of the phase of this first harmonic correction allows us to affect the split ratio, without changing the energy of the extracted beams.

INTRODUCTION

A large part of the results presented in this paper have already been reported in the proceedings of an earlier conference [1].

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 beam current split between beam line 1A and 2A. The main source of these fluctuations is related to the crossing of the 3/2 half-integer resonance.

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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 [2], 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 $(\nu_r - 3/2)$ [3]. This precession of the horizontal phase space induces oscillations of the radial beam density, as shown in Fig. 2.

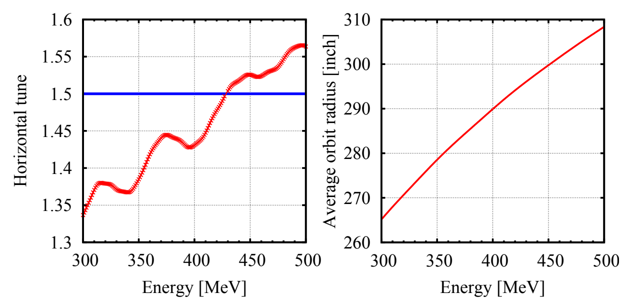

Figure 1: Left: horizontal tune variation with energy in the TRIUMF cyclotron. Right: average closed orbit position with energy. Results were obtained from simulation (using `CYCLOPS` [4]).

These oscillations could also be measured using one of the radially moving probes equipped with two diaphragms, shadowing each other, and displaced radially by 0.762 mm. Examples 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).

If all cyclotron parameters are fixed, these radial oscillations are fixed in radius and so they cannot be the cause of the fluctuation with time of the split ratio between extraction lines 1A and 2A. But as is clear from Fig. 3, even a slight fluctuation in rf voltage can cause a large change in radial density at the location of the foil, making the split ratio between high-energy beam lines unnecessarily sensitive to the accelerating voltage. To stabilize the energy gain per turn to the required level ($\ll 0.1\%$) is very difficult since the TRIUMF resonator system is itself mechanically unstable, suffering 5 Hz oscillations driven by turbulence in the cooling water. Thus, to get rid of the fluctuations in extracted current, it is necessary to correct the field harmonics driving the $3/2$ resonance.

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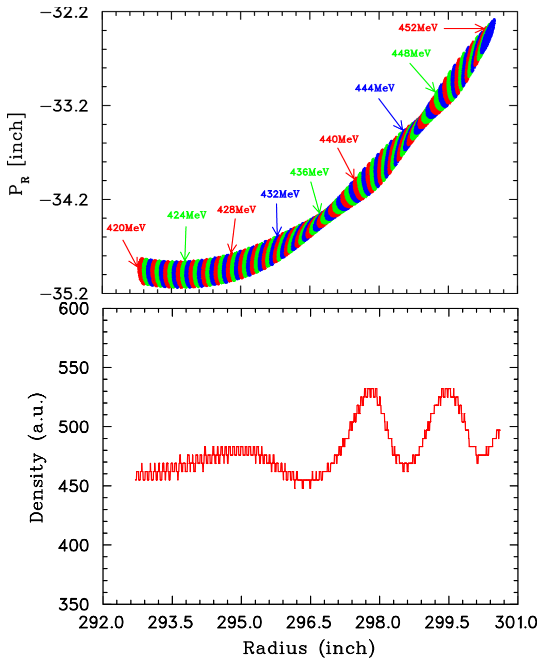

Figure 2: Simulation results. Top: turn-by-turn variation of the radial phase space passing through the $\nu_r = 3/2$ resonance. One can see the rotation (precession) of the ellipse. Bottom: induced radial modulation of beam density. Here we only illustrate the first 2 periods of precession and modulation;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

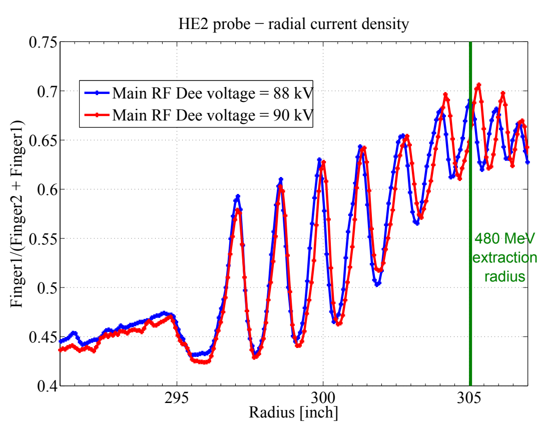

Figure 3: Radial variation of the current density measured with a probe equipped with differential fingers. The two curves present two measurements taken consecutively, with the main RF gap voltage set to 88 kV (blue) and 90 kV (red).

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

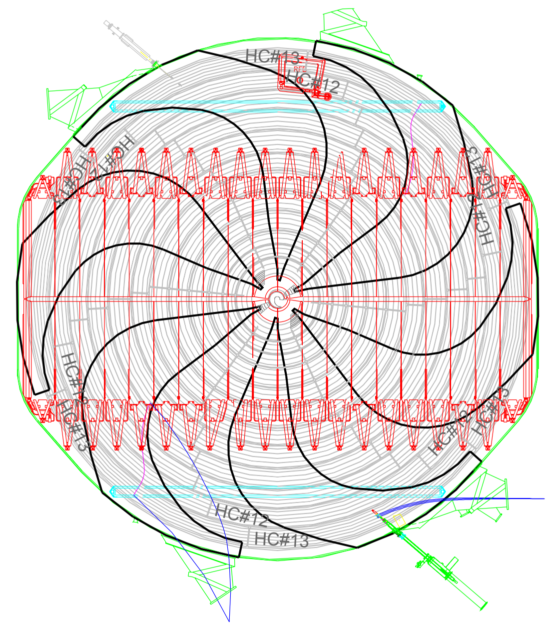

Figure 4: Cyclotron schematic layout. RF resonators are in red; trim and harmonic coils in gray.

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

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 third 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 $\delta = 3 \times 11°$ respectively, and amplitudes U and V respectively. Then by the sine law, we have (see Fig. 5)

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

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

FEEDBACK LOOPS

Two feedback loops are now working together to regulate the beam current into the high-energy beam lines. The first one had been implemented in 2008, before the 3/2 resonance had been corrected fully. It acts on the duty cycle to regulate beam line 2A current. While stabilizing the current in 2A, this system amplifies the fluctuation in beam line

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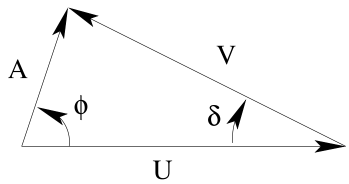

Figure 5: Vector diagram for harmonic coils U and V. The desired vector is $\vec{A} = \vec{U} + \vec{V}$.

1A [6]. To stabilize the current in both high-energy beam lines simultaneously, we implemented a second feedback loop, which stabilized the current split by acting on the first harmonic of the vertical field component (B_z) produced by the outer set of harmonics coils (HC#13).

The first harmonic B_z correction produces locally a horizontal shift of the equilibrium orbits. The direction of this shift is linked to phase of the correction. If the phase is such that the orbits are moved along the bisector of the angle formed by the two extraction foils and the center of the cyclotron, the field correction affects the energy of the extracted beams, but not the current split between beam lines. On Fig. 7 it corresponds to the phases where the three curves cross each other ($\sim 25°(180°)$). If the phase is 90° apart, the field correction affects the split ratio without affecting the energy of the extracted beams. This is the phase the feedback regulation loop is working at. Details about the feedback loop algorithm can in found in Ref. [7].

CONCLUSION

The progress made over the past two years to improve the beam stability in high-energy beam lines are shown in Fig. 6. In 2011, 2A current was maintained constant by a first feedback loop, but 1A current was fluctuating substantially. In 2012, after the correction of the $\nu_r = 3/2$ resonance, the current in beam line 1A was greatly stabilized, with only long-term drift observed. Since 2013, the implementation of the second feedback allowed similar level of current stability in the two high-energy beam lines.

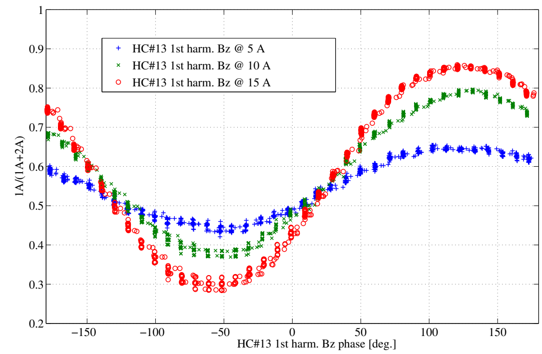

Figure 7: Measured split ratio between high-energy beam lines (1A and 2A) when scanning the phase of HC#13 first harmonic B_z field correction from -180° to +180°. Three sets of measurements were taken with different current flowing into HC#13 are shown here.

REFERENCES

[1] T. Planche, Y.-N. Rao, R. Baartman, "Correction of ν_r = 3/2 Resonance in TRIUMF Cyclotro", Proc. of IPAC'12 Conf., New Orleans, USA, May 2012, MOPPD023, p. 415.

[2] Y.-N. Rao, R. Baartman, G. Dutto, L. Root, "Studies of the ν_r = 3/2 Resonance in the TRIUMF Cyclotron", Proc. of PAC'09 Conf., Vancouver, Canada, May 2009, TH6PFP09, p. 3940.

[3] R. Baartman, G.H. MacKenzie, and M.M. Gordon, "Amplitude growth from the rapid traversal of a half-integer resonance", Proc. of 10th Int. Conf. on Cyclotrons and their Applications, East Lansing, USA, April 1984, p. 40, `http://cdsweb.cern.ch/record/152883`

[4] M.M. Gordon, Part. Accel. 16, 39 (1984).

[5] C.J. Kost, 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.

[6] I. Bylinskii *et al.*, "TRIUMF Cyclotron Beam Quality Improvement", Proc. of PAC'11 Conf., New York, USA, October 2011, WEP231, p. 1921.

[7] J.J. Pon *et al.*,"Stabilizing the Beam Current Split Ratio in TRIUMF's 500 MeV Cyclotron with High-Level, Closed-Loop Feedback Software", To be published in Proc. of ICALEPCS 2013 Conf., San Francisco, USA, October 2013.

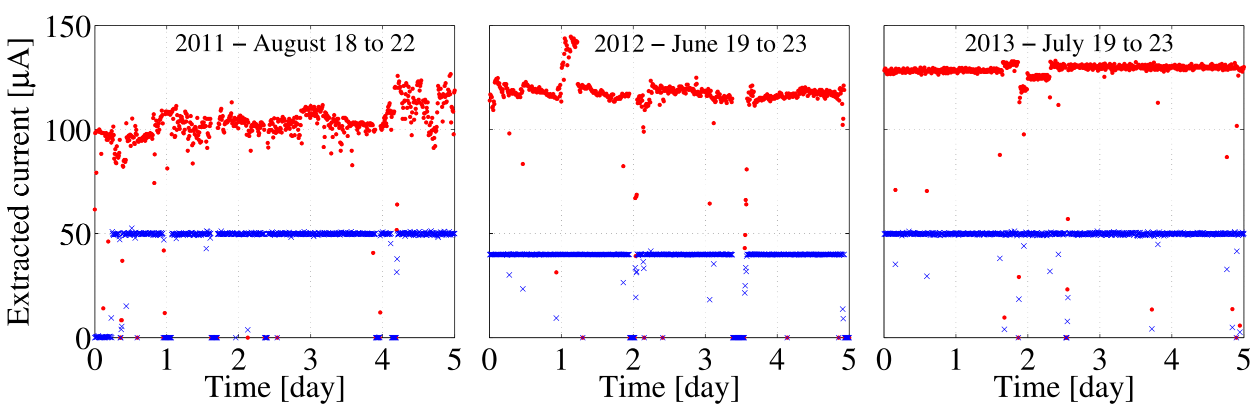

Figure 6: Gradual improvement of current stability in the high-energy beam lines since 2011. Red dots: BL1A current. Blue crosses: BL2A current. Each plot corresponds to five consecutive days of beam delivery.