CORRECTION OF $\nu_r = 3/2$ RESONANCE IN THE TRIUMF CYCLOTRON

T. Planche, R. Baartman, Y.-N. Rao

TRIUMF, Vancouver, Canada

INTRODUCTION

The TRIUMF cyclotron is 6-fold symmetric and ideally its magnetic field will have only multiples of 6$^{\text{th}}$ harmonic. The third harmonic in the magnetic field gradient drives the $\nu_r = 3/2$ resonance. This results in a modulation of the current density versus radius observed after the resonance crossing 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. The 6-fold symmetry of this layout cannot provide a third harmonic of arbitrary phase. However, the outer two sets of harmonic correction coils (number 12 and 13) are azimuthally displaced. We use this fact to achieve a full correction of the resonance. This has the effect of reducing intensity fluctuations in the extracted beams, when there is beam sharing between two beamlines.

THIRD HARMONIC FIELD ERROR

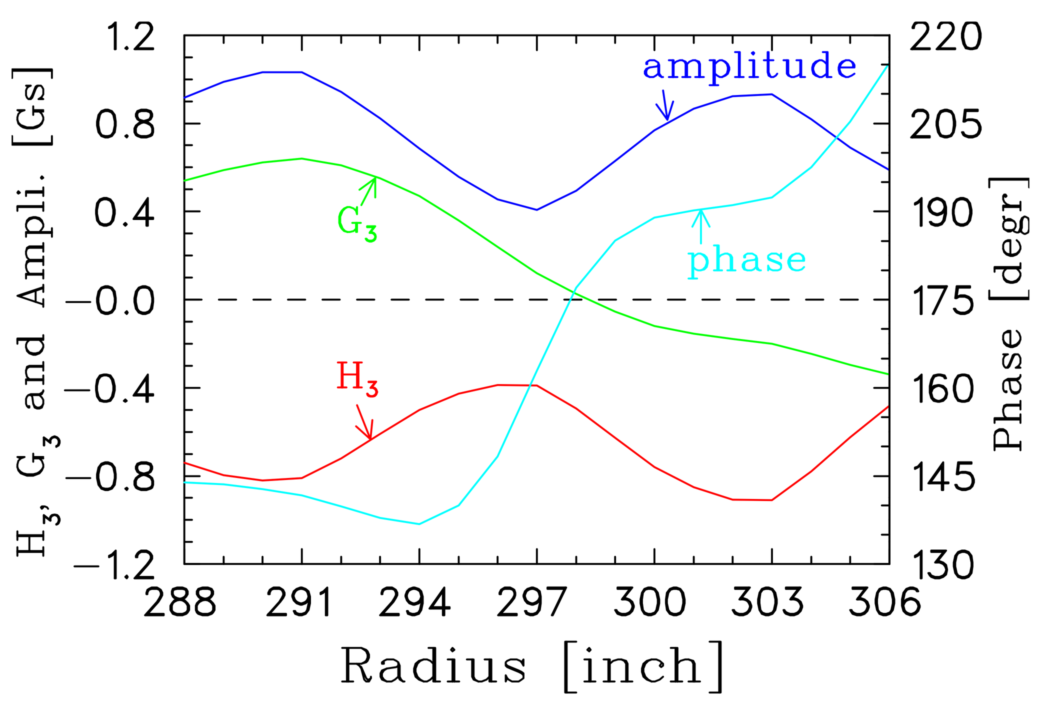

Figure 1: Fourier coefficients H_3 and G_3 of the third harmonic component in the base magnetic field, in a region of radius between 288 and 306 inch. Also shown is its amplitude and phase angle. The $\nu_r = 3/2$ resonance is driven primarily by the radial gradient of the third harmonic amplitude, which is ~ 0.1 G/inch.

DENSITY MODULATION

In (r, P_r) phase space, the beam particles occupy an ellipse. From one turn to the next, the particles move around the ellipse by an angle of $2\pi\nu_r$, but the ellipse orientation remains constant. This ellipse is called the "matched ellipse".

The third harmonic magnetic field gradient error causes perturbations away from this matched ellipse, but in the general case, the particle motion is out of step with this frequency and the perturbations average to zero. However, when ν_r is precisely $3/2$ (428 MeV), the perturbations accumulate and the initially matched ellipse becomes stretched. As the beam is accelerated away from the resonance, the ellipse, which is now mismatched: it no longer matches the "matched ellipse", and starts to rotate as a propeller. Such a rotation leads to a modulation of beam radial density.

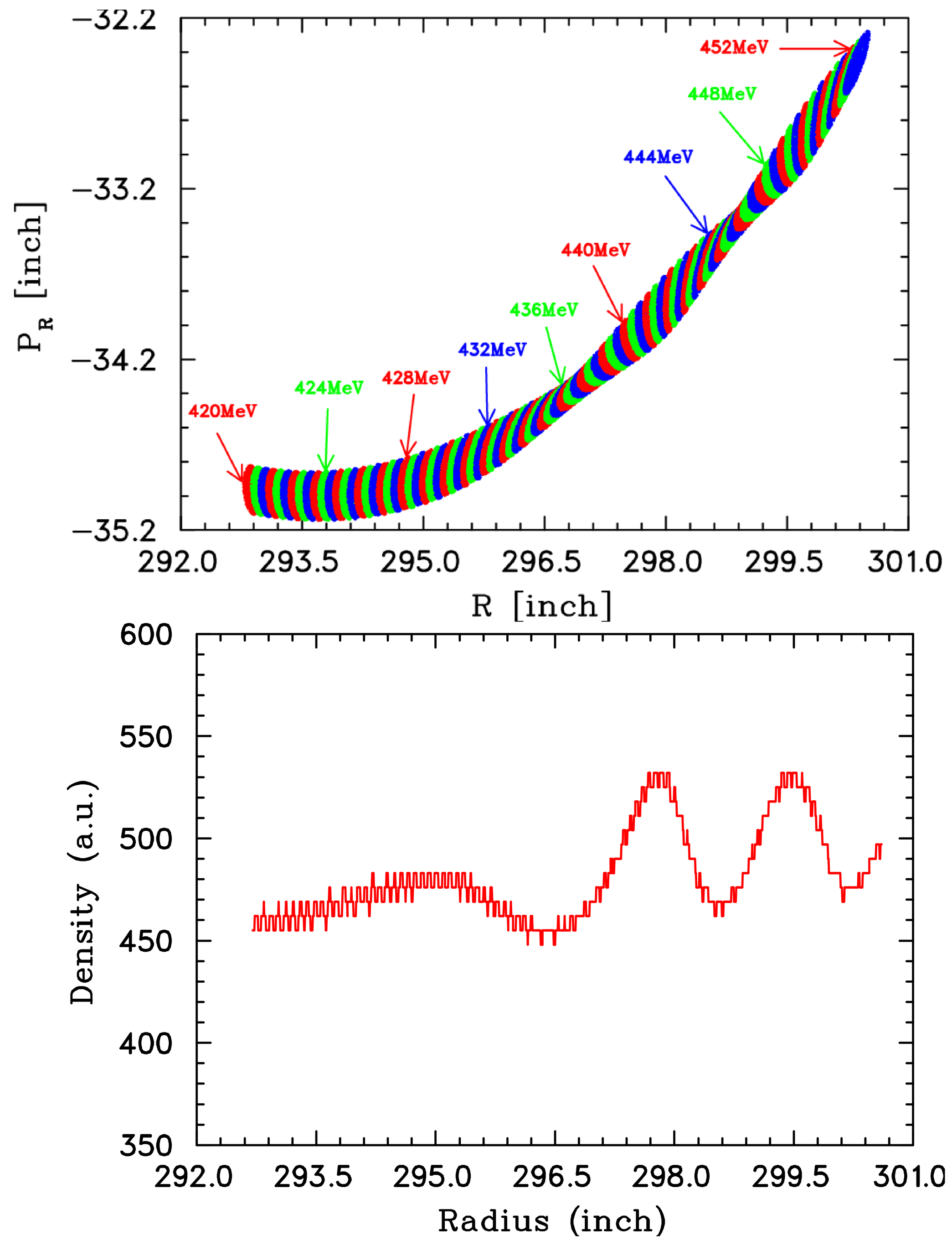

Figure 2: Simulation results. Top: turn-by-turn variation of the radial phase space passing through the $\nu_r = 3/2$ resonance. Clearly, one can see the rotation (precession) of the ellipse. Bottom: radial modulation of beam density, caused by the precession of radial ellipses. Here we only illustrate the first 2 periods of precession and modulation; in fact, the precession and density modulation persist to 480 MeV extraction.

The beam is extracted by placing a stripping foil at the radius corresponding to the desired beam energy. When beam is shared at one energy between two beam lines, the proportion received in each beamline (the "split ratio") depends sensitively on the radial density. Thus, when there are modulations in the radial density, small fluctuations in, for example, the rf accelerating voltage result in relatively and undesirably large fluctuations in the "split ratio".

RESONANCE CORRECTION

The TRIUMF cyclotron is equipped with 13 sets of harmonic correction coils; the outer-most two (numbers 12 and 13) can render the third harmonic field gradient in the energy region of the 3/2 resonance. However, with either set of coils, we cannot change the third harmonic phase angle except for a switch of $180°$, so cannot fully compensate the resonance. But, using these two coils in combination, we can change the phase angle. This is because these 2 sets of coils are displaced azimuthally; the displacement is only $11°$, but this is sufficient.

The scheme is as follows. We wish to create a third harmonic field of amplitude A and phase ϕ from coils (U and V) 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

$$\frac{U}{\sin(\delta - \phi)} = \frac{V}{\sin\phi} = \frac{A}{\sin\delta} \qquad (1)$$

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. Consequently, we have recently upgraded the power supplies for harmonic coils 12 and 13 to higher current. The results are shown below.

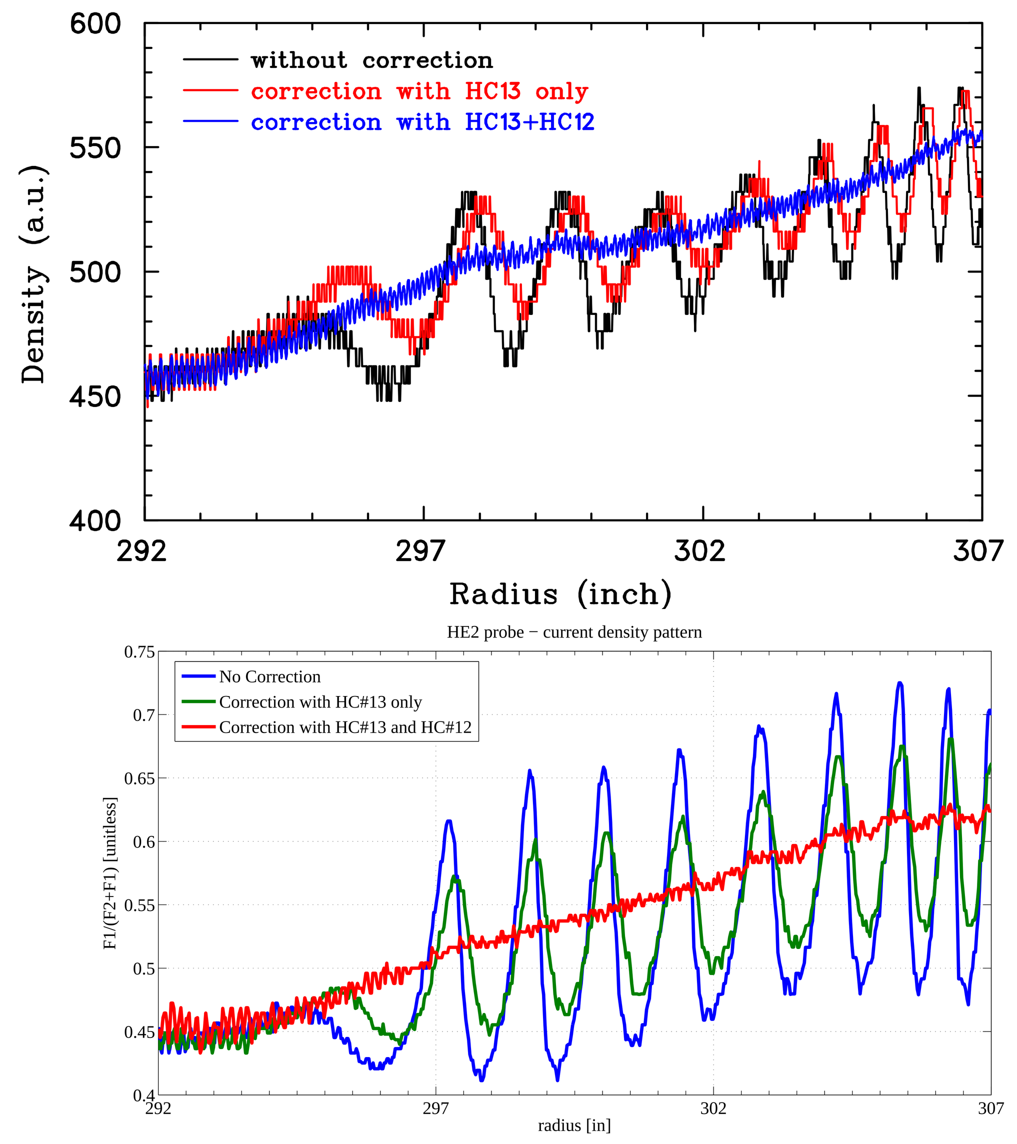

Figure 3: Current density radial modulation without correction, with correction using HC#13 only, and with correction using HC#12 and #13 in combination. Top: simulation result. Bottom: measured result. Clearly, the full correction results in greatly reduced density modulation.