TRIUMF

Canada's national laboratory for particle and nuclear physics

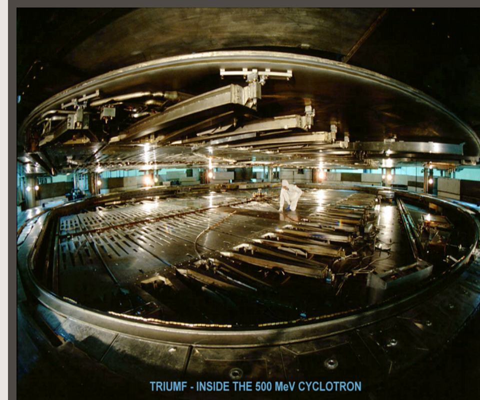
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

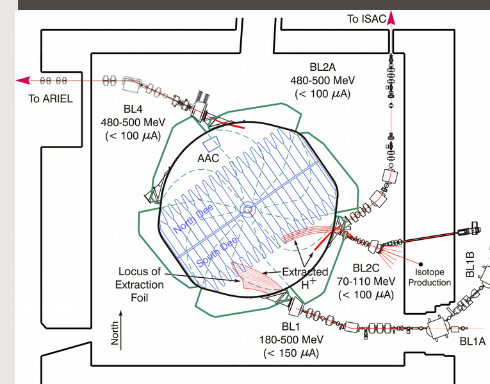
Correction of Coupling Resonance $\nu_r - \nu_z = 1$ in TRIUMF Cyclotron

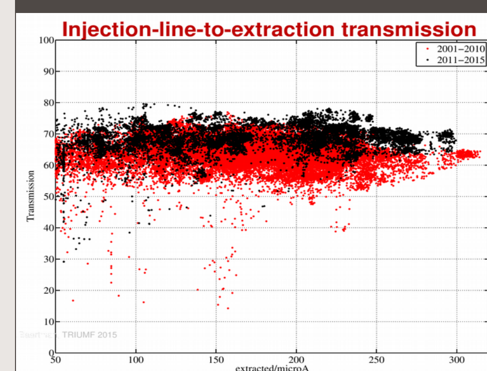
Y.-N. Rao, R. Baartman, T. Planche

40th European Cyclotron Progress Meeting

Sept. 20-23, 2017





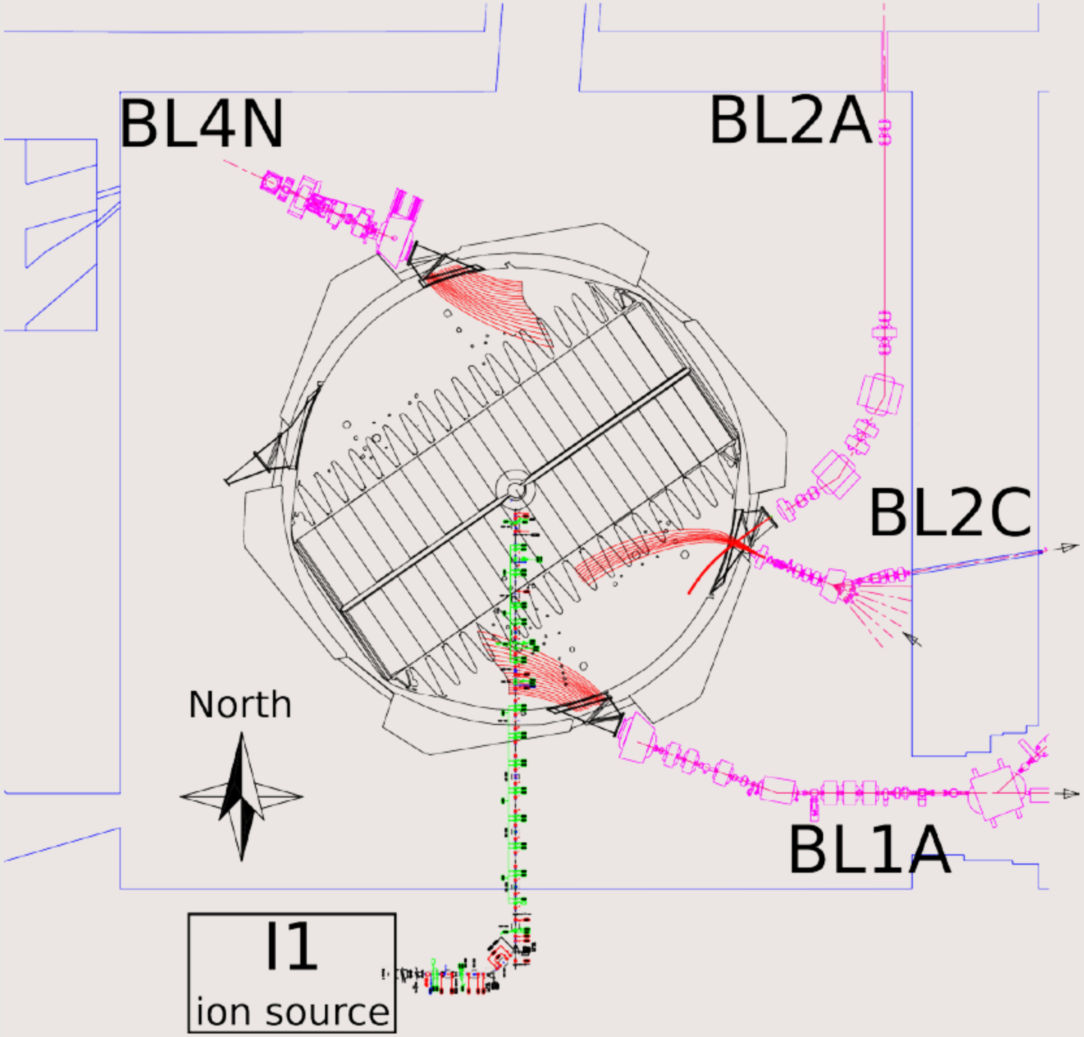


Outline

- Motivation
- Driving Term
- Historical Investigations
- Simulations and Measurements
- Summary

Motivation: Need Higher Intensity and Higher Stability Beam

Last decade routine operation: 220-270μA extracted

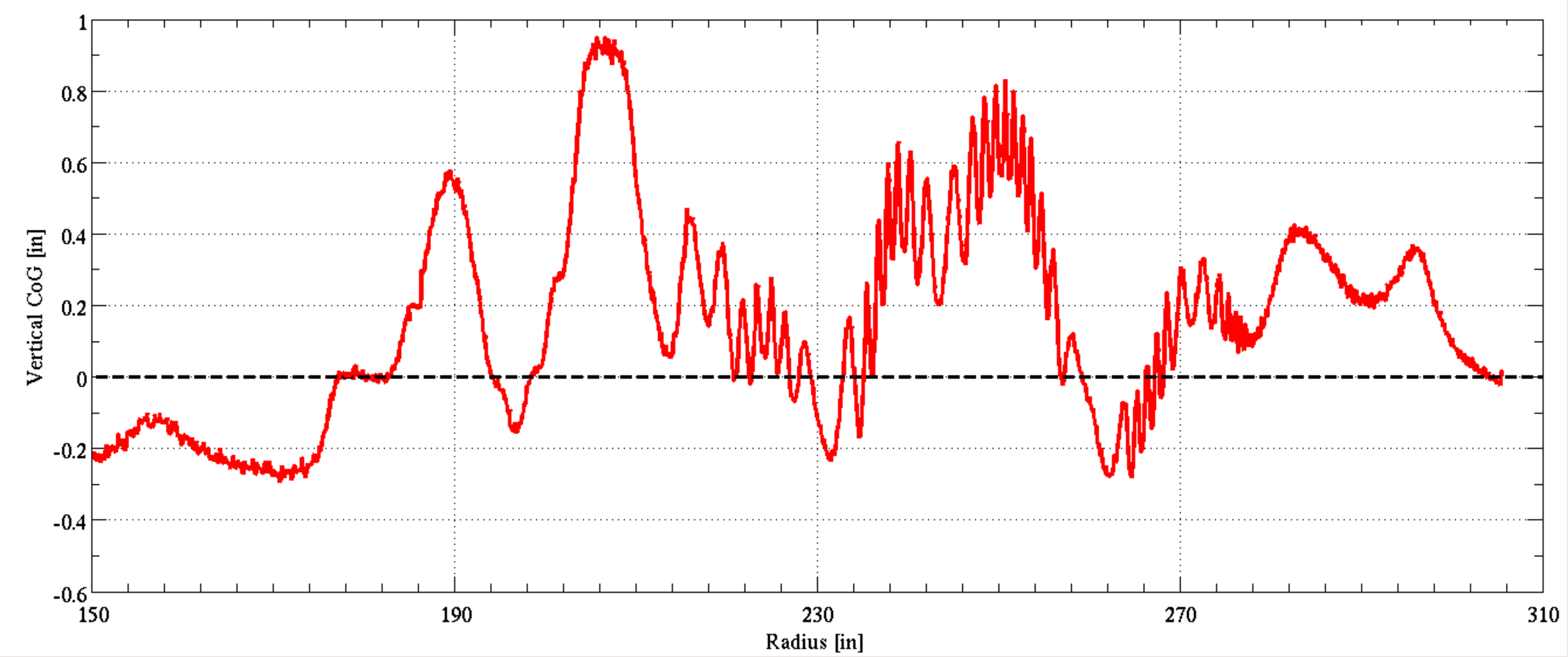


Future Requirements

- BL1A (100 – 150 μA)
  μSR experiments
- BL2A (70 – 100 μA)
  RIB production
- BL2C (70 – 100 μA)
  Sr production, Proton therapy, Proton Irradiation facility
- BL4N (70 – 100 μA)
  ARIEL
- Total (310 – 450 μA)
  with beam spills < 1.2% in the cyclotron and current instability within ±1% in the beam-lines.

Beam Instability

- But very small changes in the circulating beam orbit can result in large oscillations to the height of beam centre due to coupling resonance $\nu_r - \nu_z = 1$, causing beam loss in the cyclotron and even down to the beam-lines. Shown below is the HE probe measured result.



- If there were no radial-vertical coupling, then the vertical flag would be able to reduce vertical beam spill all the way to extraction. But we observe that it has hardly any such effect.

TRIUMF

What is the Resonance Driven by?

It's driven by an asymmetry in the median plane of the cyclotron due to presence of the first harmonic in the magnetic field Br component.

In action-angle variables, the Hamiltonian for the resonance is represented as

$$H = g_{11}\sqrt{2J_x}\sqrt{2J_z}\cos(\psi_x - \psi_z - \theta)$$

Using transformations from the action-angle variables to the normalized phase space coordinates

$$x = \sqrt{2J_x}\cos\psi_x \ , \quad x' = -\sqrt{2J_x}\sin\psi_x \ , \quad z = \sqrt{2J_z}\cos\psi_z \ , \quad z' = -\sqrt{2J_z}\sin\psi_z \ ,$$

we get

$$H = g_{11}(xz\cos\theta + x'z'\cos\theta - x'z\sin\theta + xz'\sin\theta)$$

In thin lens approximation, the orbit kicks are

$$\Delta x = \frac{\partial H}{\partial x'} = g_{11}(z\cos\theta - z\sin\theta) \ , \ \Delta x' = -\frac{\partial H}{\partial x} = -g_{11}(z\cos\theta + z'\sin\theta) \ ,$$

$$\Delta z = \frac{\partial H}{\partial z'} = g_{11}(x'\cos\theta + x\sin\theta) \ , \ \Delta z' = -\frac{\partial H}{\partial z} = -g_{11}(x\cos\theta - x'\sin\theta) \ .$$

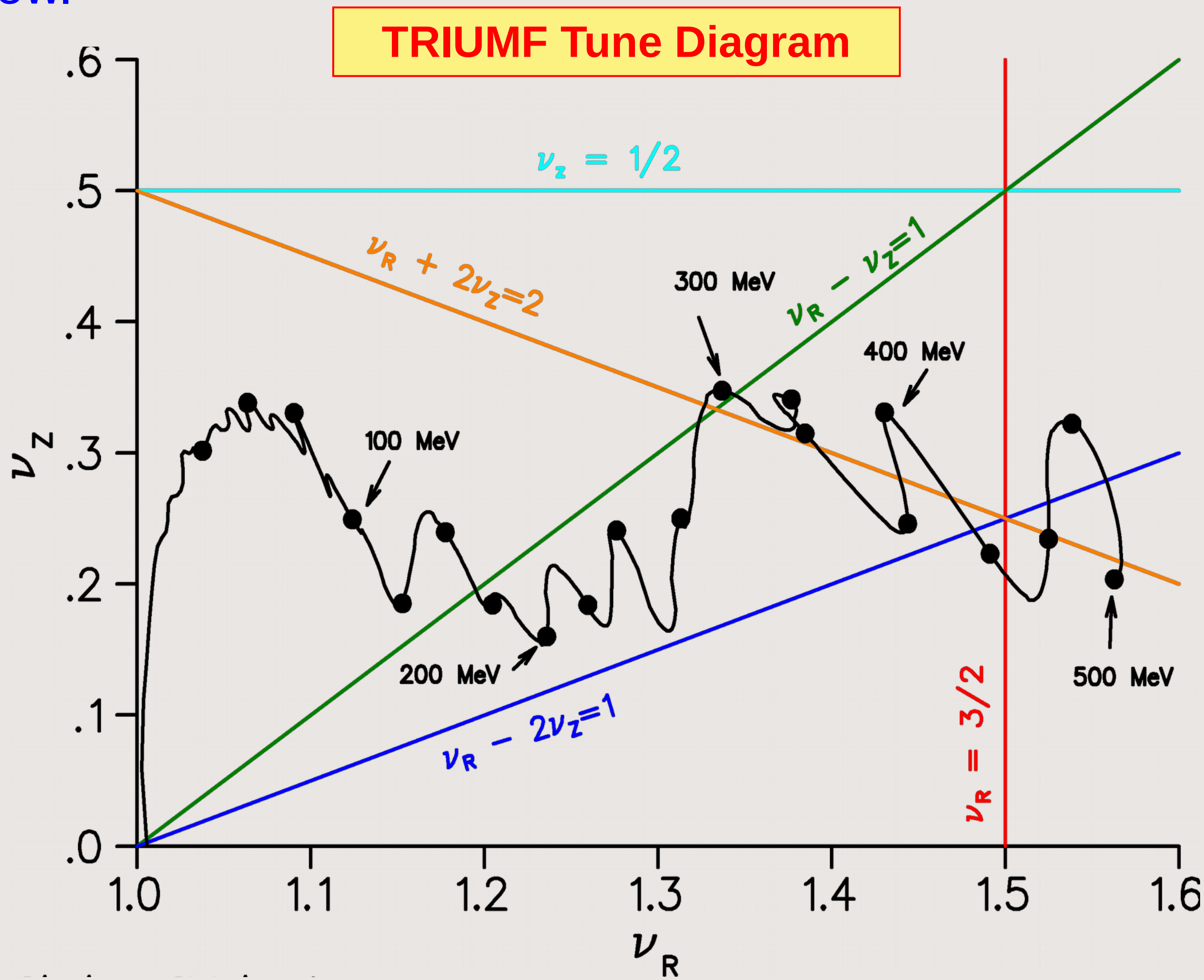
This means that the driving terms in the magnetic field are

$$B_x \sim (x\cos\theta - x'\sin\theta) \ , \quad B_z \sim (z\cos\theta + z'\sin\theta) \ ,$$

where the B_z component implies that one can use the first harmonic of B_z to centre the orbit radially to suppress the coupling. But this is not our objective here, because such a suppression is not a once-and-for-all solution; instead it depends on the amount of centring errors. Our goal is to apply the first harmonic of B_r (i.e. B_x) to correct the resonance permanently.

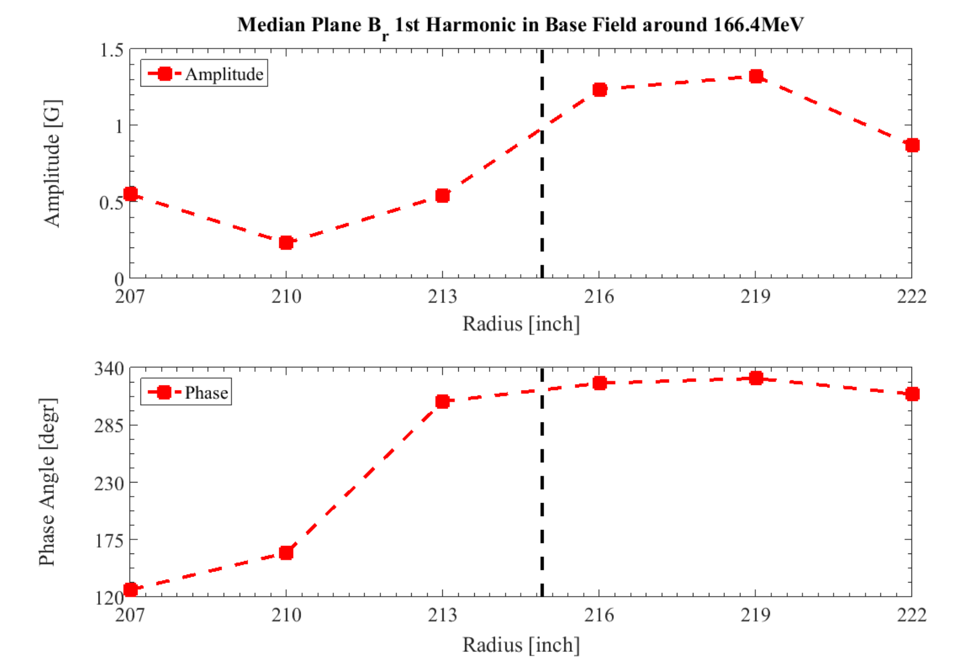
Resonance Crossing Twice

- In TRIUMF cyclotron, this resonance is encountered at ~166 MeV and ~291MeV twice, where $\nu_r \approx 1.20$, $\nu_z \approx 0.20$ and $\nu_r \approx 1.32$, $\nu_z \approx 0.32$ resp., as shown below.

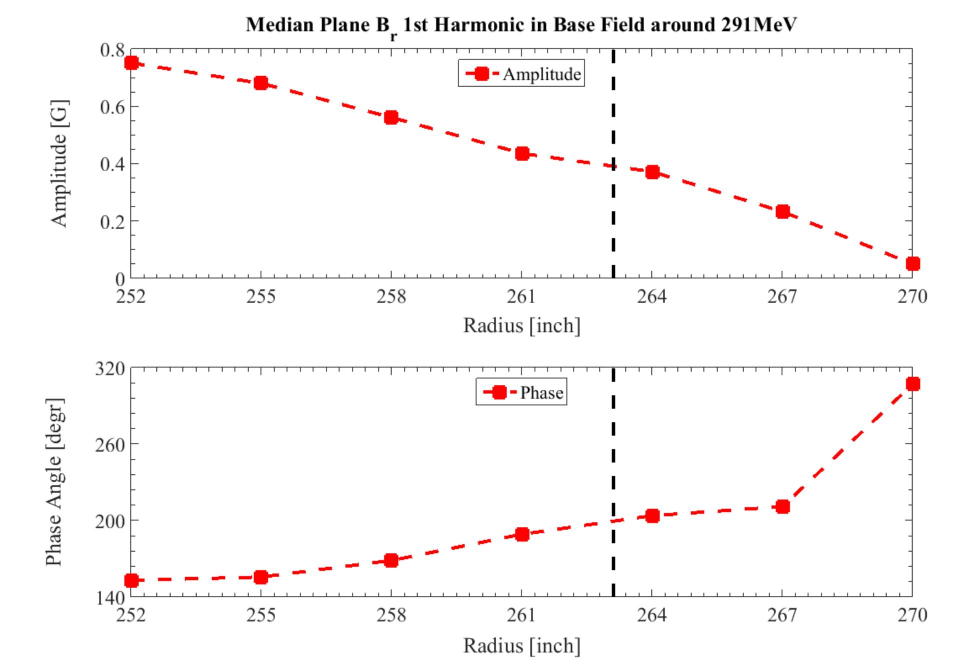


B_r 1st Harmonic Errors in Base Field

- At around 166 MeV



- At around 291 MeV



The ~0.5 G error is small but still large enough to excite the resonance.

Investigations in the History

- In 1970's, TRIUMF pioneers did investigations about the effect of a radial centring error on the beam height and on the beam loss. Also they attempted to power the harmonic coils to diminish the effect. But they did not seem to achieve it.

PROPERTIES OF THE TRIUMF CYCLOTRON BEAM

M.K. Craddock

Physics Department, University of British Columbia, Vancouver, Canada

E.W. Blackmore, G. Dutto, C.J. Kost, G.H. Mackenzie, J.R. Richardson,* L.W. Root and P. Schmor

TRIUMF, Vancouver, Canada

Abstract

8% of the 300 keV d.c. beam from the ion source can be transmitted to 500 MeV in the TRIUMF cyclotron, without using the buncher. The beam losses are entirely accounted for by the 40° phase acceptance at injection, 20% gas stripping and 6% Lorentz stripping; there are no significant losses due to orbit dynamic problems during 1500 turns of acceleration. The phase history, like ν_z^2, is in good agreement with predictions based on the magnetic field survey. The effect of the harmonic coils and injection parameters on beam quality has been investigated; they can be used, with a chopper, to reduce the energy resolution of the extracted beam to 0.9 MeV FWHM and the emittance for 90% of the beam to 4π mm.mrad horizontally and 11π mm.mrad vertically.

1. Introduction

In an earlier paper[1] we have described the initial operation of the TRIUMF cyclotron and the simultaneous extraction of two beams with energies variable from 183 to 525 MeV. At that time tuning operations had been aimed only at optimizing the beam transmission to full energy, without regard to the finer points of beam quality. The transmission through the central region was found to be about 10% of the d.c. beam supplied by the external ion source and injection system (ISIS).[2] This is consistent with values of about 40° for the phase acceptance, measured by varying the phase of a chopped beam from ISIS or by observing the shape of the magnet cyclotron resonance; the phase width of the extracted beam was also found to be about 40°. The transmission from 50 to 500 MeV was observed to be about 70%—the loss being only a little larger than that predicted theoretically for stripping H^- ions by the residual gas molecules at the observed pressure of 2.8×10^{-7} Torr. More recently the stripping losses caused by residual air and hydrogen have been measured directly, as described in the status report on TRIUMF appearing elsewhere in these proceedings.[3] The results indicate that at the present operating pressure of 3×10^{-7} Torr (indicated) the gas stripping loss should be 20%. Since an overall transmission to 500 MeV of 8% of the d.c. beam has been achieved (without bunching), it appears that there are no orbit dynamic problems giving rise to significant losses in intensity at intermediate energies. There is circumstancial evidence[3] of Lorentz stripping of the H^- ions at energies above 500 MeV, but up to that energy, where the integrated loss is expected theoretically to be 6%, the experimental evidence is inconclusive.

Although the cyclotron had not been tuned for beam quality initially, we were able to report in our earlier paper that the energy resolution of the extracted beam was no worse than 3 MeV. In the intervening months we have been able to measure the beam properties in more detail and begin tuning for better beam quality; this paper will describe this work. The energy resolution and emittance of the extracted beam have been improved. Some initial measurements of the phase history have been made, and, like the measurements of ν_z^2 reported earlier,[1] are in good agreement with the results of the magnetic field survey. Evidence for radial-vertical coupling in the outer region of the cyclotron is examined.

*on leave from UCLA

2. Diagnostics

The location of the diagnostic and extraction probes in the cyclotron is shown in Fig. 5 of the status report.[3] The low energy probes cover the radial range from the first turn to 145 in. (70 MeV) and the high energy probes extend from 142 in. to 315 in. (525 MeV). A schematic diagram of the probe heads is shown in Fig. 1. The low energy head consists of three horizontal fingers which provide vertical and radial information, together with a

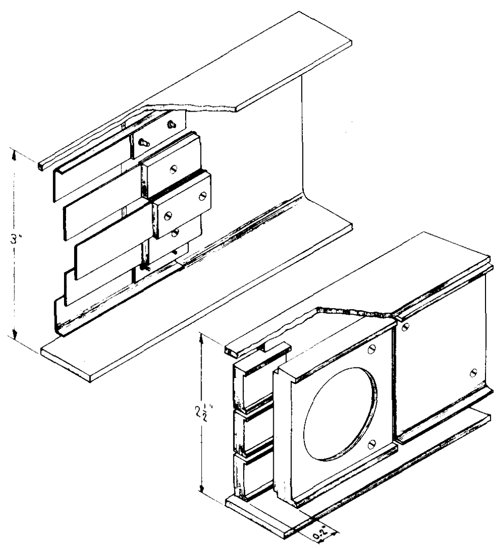


Fig. 1. (above) High energy probe head (below) Low energy probe head

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 240-244

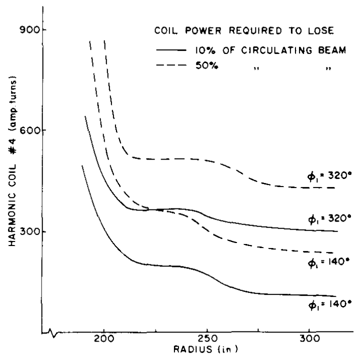


Fig. 3.

Sensitivity of the transmitted beam current to a centring error introduced by a set of first harmonic trim coils at 80 in. (20 MeV).

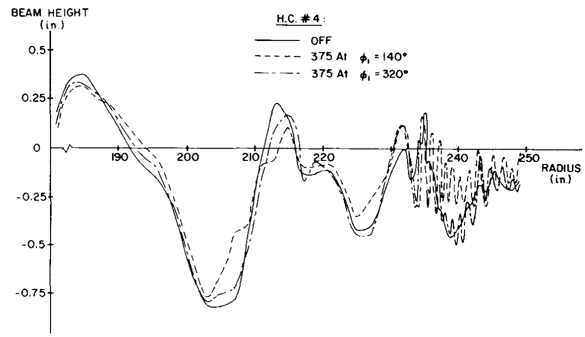


Fig. 4. Effect of a radial centring error on the height of the beam.

with the oscillations in phase illustrated in Fig. 2. We hope to be able to improve the resolution and accuracy of measurement (at present 1-2 μsec) by an order of magnitude in order to explore the possibilities of using the method for tuning purposes.

6. Radial Betatron Amplitudes

Harmonic coil set #4 alters the first harmonic component of the axial field between 15 and 23 MeV. Calculations show that 900 At introduce a change in radial amplitude of about 1 in. and in RF phase of about 10°, depending on the detailed history of a particle, and that this change persists to high energies. When the coil amplitude was increased above a threshold the current transmitted to full energy decreased, the decrease varying sinusoidally with the phase of the first harmonic perturbation. Fig. 3 shows how the coil amplitude required to lose 10% and 50% of the beam varies with radius for the most sensitive and least sensitive phase. Centring-dependent loss can occur at 200 and 250 in. radius; however, since a threshold of at least 50 At exists these loss modes do not reduce transmission for normal operation. Fig. 4 shows the height of the beam centre as a function of radius for these conditions; there is evidence of coupling between radial and vertical motion. This coupling may cause loss at 205 in. where the beam is low; however, the beam is vertically centred at 250 in. and there the loss may be phase related.

The oscillations in height at 235 in. are thought to be related to passage through $\nu_r - \nu_z = 1$; this resonance also occurs at 210, 262 and 275 in. where similar oscillations have been seen. Interpretation is complicated by the fact that at large radial amplitudes the radius change/turn due to precession is greater than that due to energy gain. We are preparing experiments to measure more accurately the vertical width of the beam and to excite the resonance by asymmetrically powered harmonic coils.

7. Extracted Beam Quality

Energy Spread

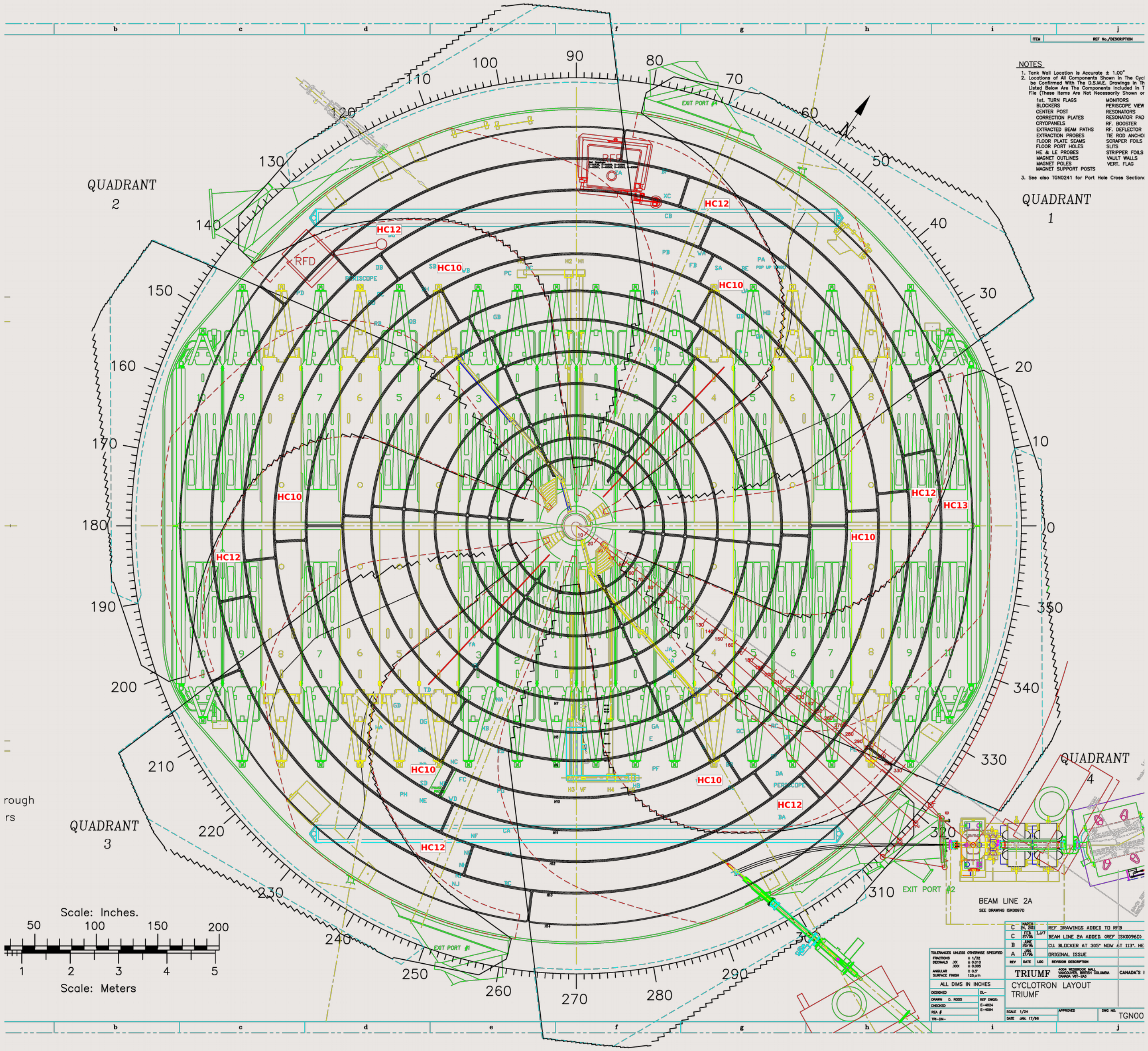
One of the beam lines has been designed to produce a double focus for both an achromatic or momentum dispersed mode of operation. At this focus is installed a gas-filled multi-wire chamber with 2 mm wire spacing in the horizontal (dispersion) plane. The beam optics calculations have been checked in the following manner.

At our extraction energies a change in the first harmonic component of the axial magnetic field moves the position of the equilibrium orbits in the vicinity horizontally, the beam following adiabatically. By powering a set of harmonic coils and choosing the appropriate phase for the first harmonic field produced, it is possible to displace the beam along the stripping foil radius or perpendicular to it, thus altering the energy or angle at which the extracted beam leaves the foil. If the foil is then moved radially the energy is again changed together with beam line object position. By measuring the position of the beam in the beam line during this sequence of operations, it is possible to obtain three elements of the horizontal transfer matrix. The predicted shift in equilibrium orbit was first checked by measuring the position of the shadow cast on one high energy probe by the other as a function of shadowing probe radius and first harmonic amplitude and phase. The technique was then used at 400 MeV for the dispersed mode of operation; the magnification R_{11} was found to be 0.86 ± 0.16, R_{12} was +0.3 ± 0.2 cm/mrad and the momentum dispersion -11.0 ± 1.5 cm/per cent. Calculated values were 0.75, 0.0 cm/mrad and -12.6 cm/per cent.[5]

Fig. 5 shows horizontal profiles measured at three different harmonic coil settings. The FWHM of the standard beam is 0.9 MeV and the width at

TRIUMF

Harmonic Coils

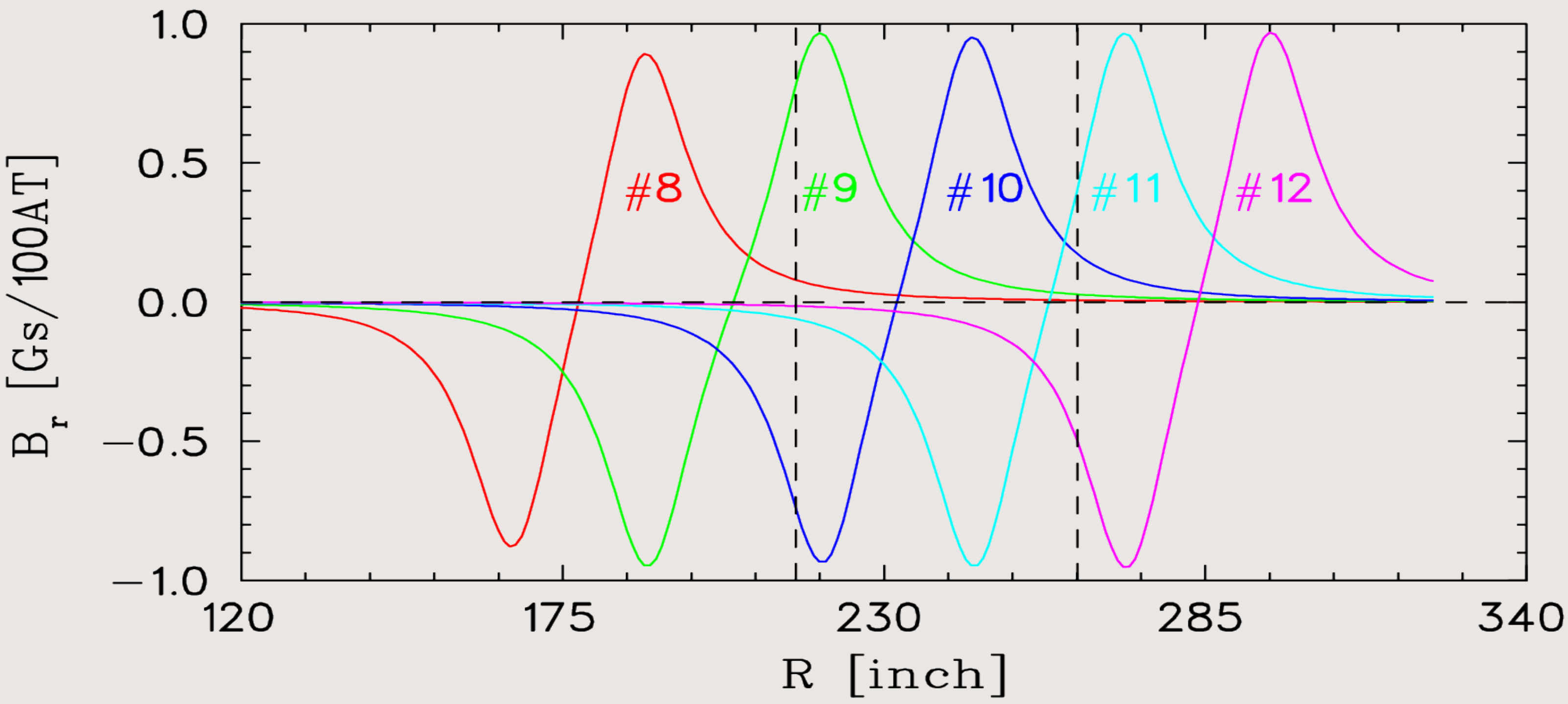


- We re-investigated this resonance, with a view to a correction for it by using the existing harmonic coils.

- TRIUMF cyclotron has 13 sets of harmonic coils placed at different radii, covering full energy range; each set is composed of 6 pairs of coils installed in a 6-fold symmetrical manner azimuthally.

Harmonic Coils

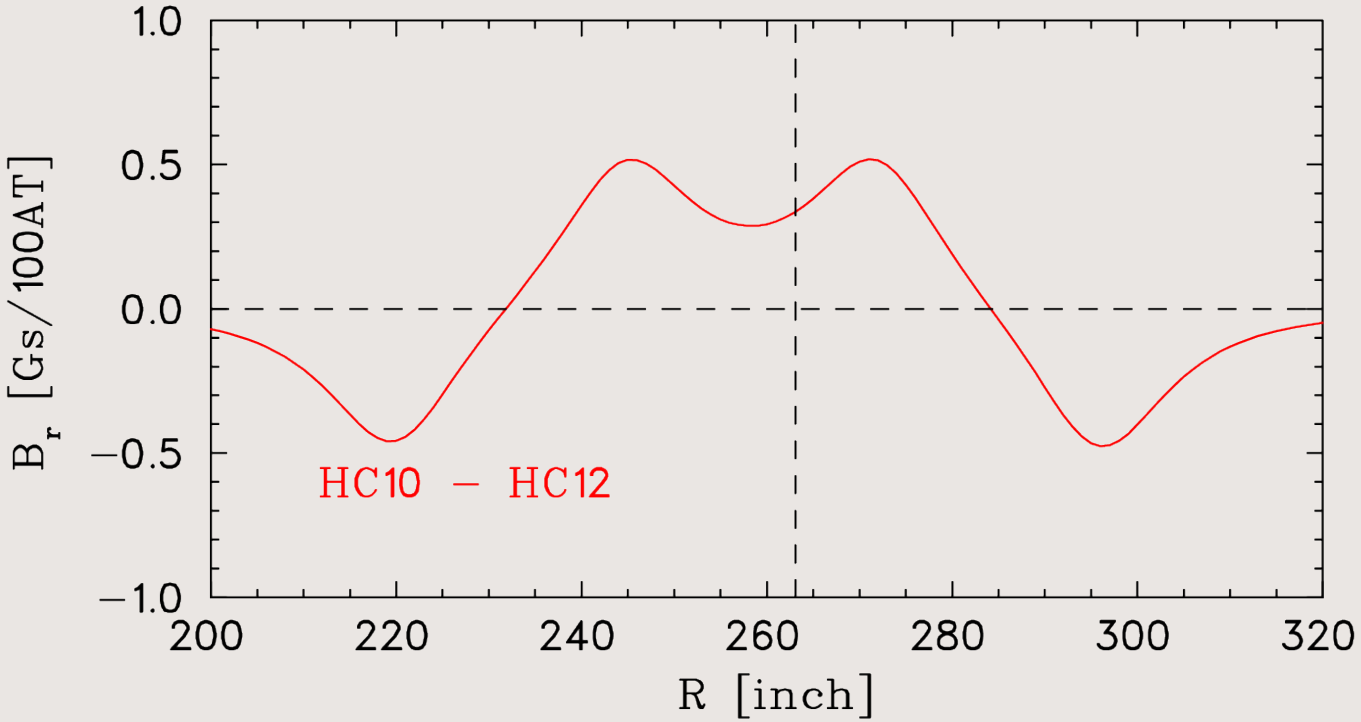
- B_r field shape due to the harmonic coils



- The B_r component on the geometrical median plane reaches a maximum at inner and outer radii of the coils while reverses the sign (i.e. direction), and becomes zero at nearly the coil centre.
- What matters to the coupling resonance correction is the strength of the B_r component itself, not its radial gradient.

Harmonic Coils

- We began with orbit simulations for the resonance correction. It turns out that by combining HC10 with HC12, we are able to correct the resonance which occurs at ~291 MeV.

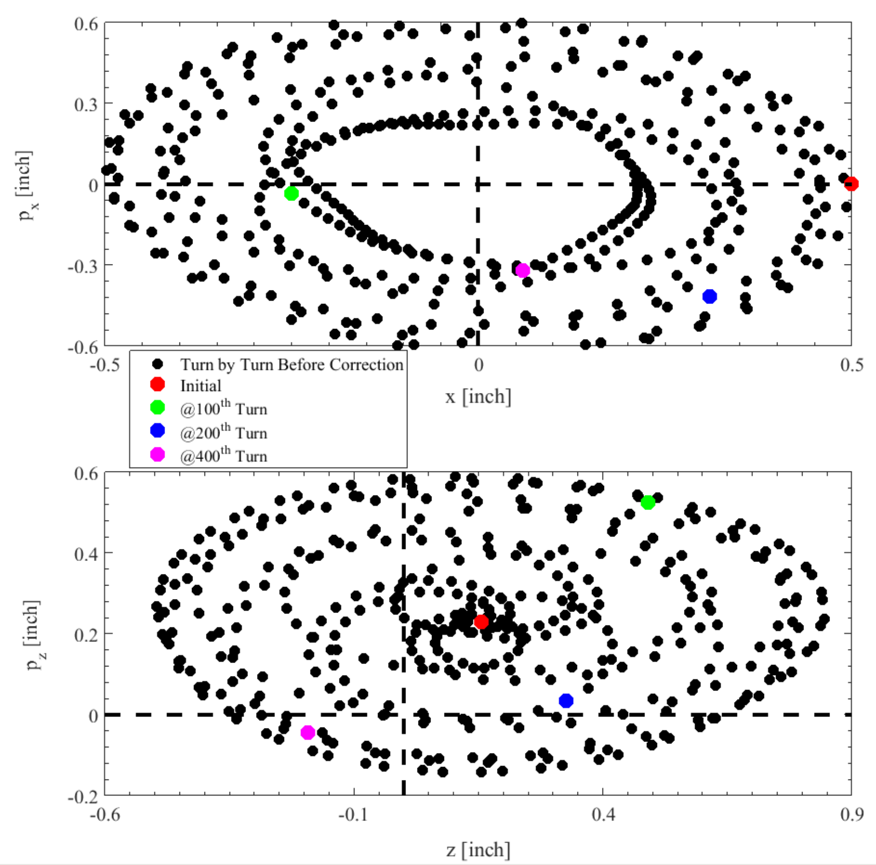


- But a single coil e.g. HC11 does not work out, though it is spaning the right radial range. This is because the field reverses direction and therefore cancels the effect.

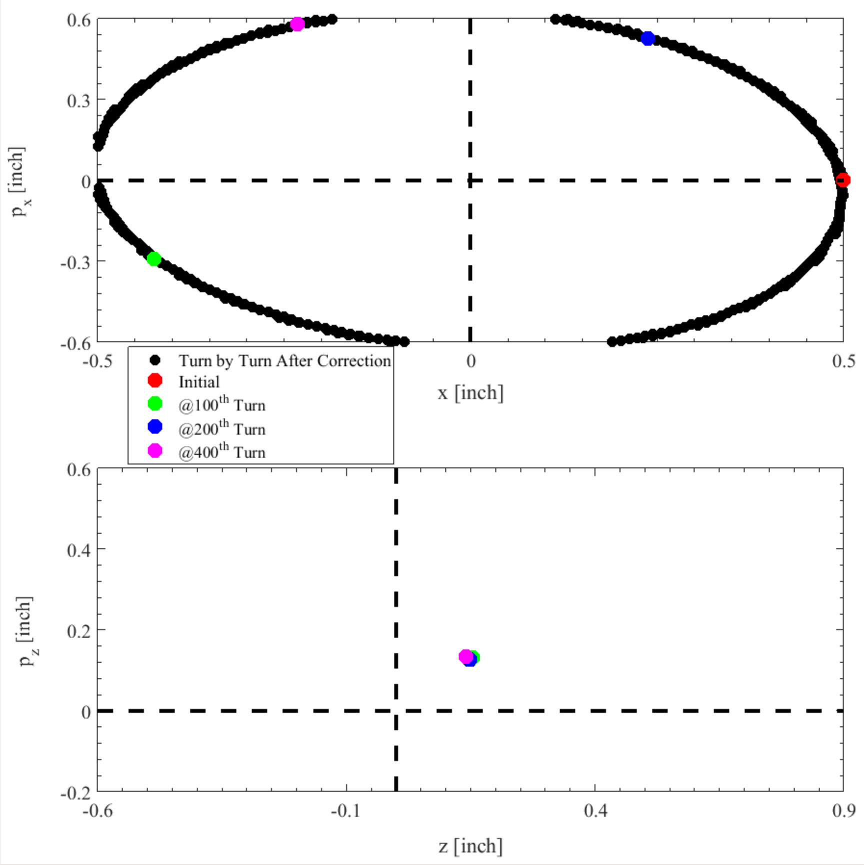
Static Orbit Simulations

- The simulations began with static orbit, i.e. without acceleration. At start, a single particle of 291 MeV was just sitting on its static equilibrium orbit (SEO) vertically while displaced from the SEO by 0.5'' radially. The particle's coordinates (x, p_x) and (z, p_z) were recorded turn by turn at the starting azimuth for a number of turns.

Before Correction

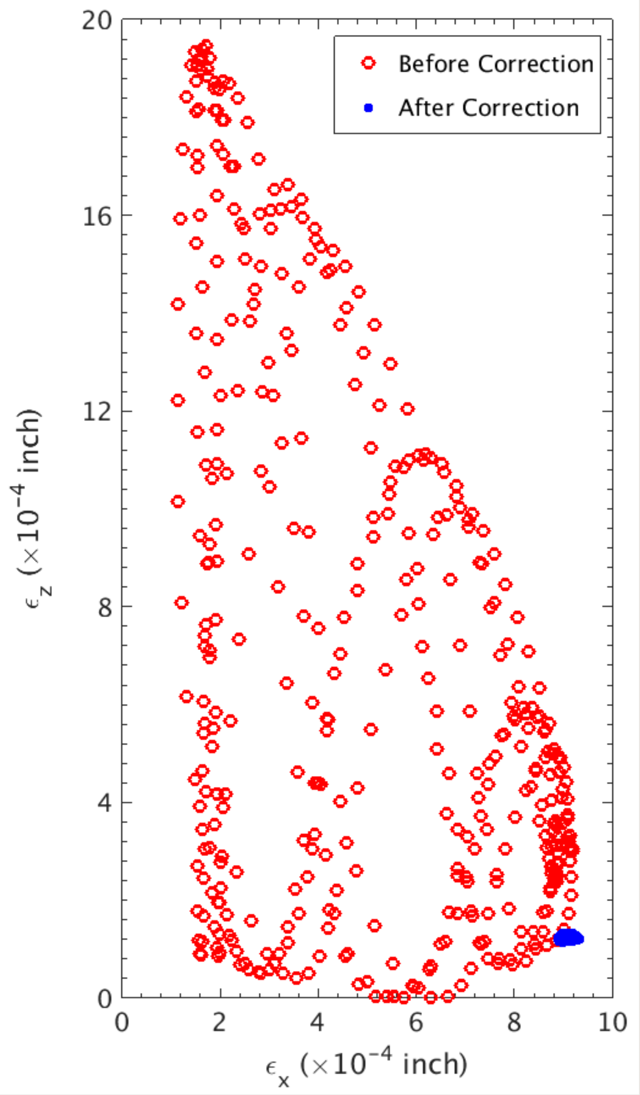


After Correction



Static Orbit Simulations

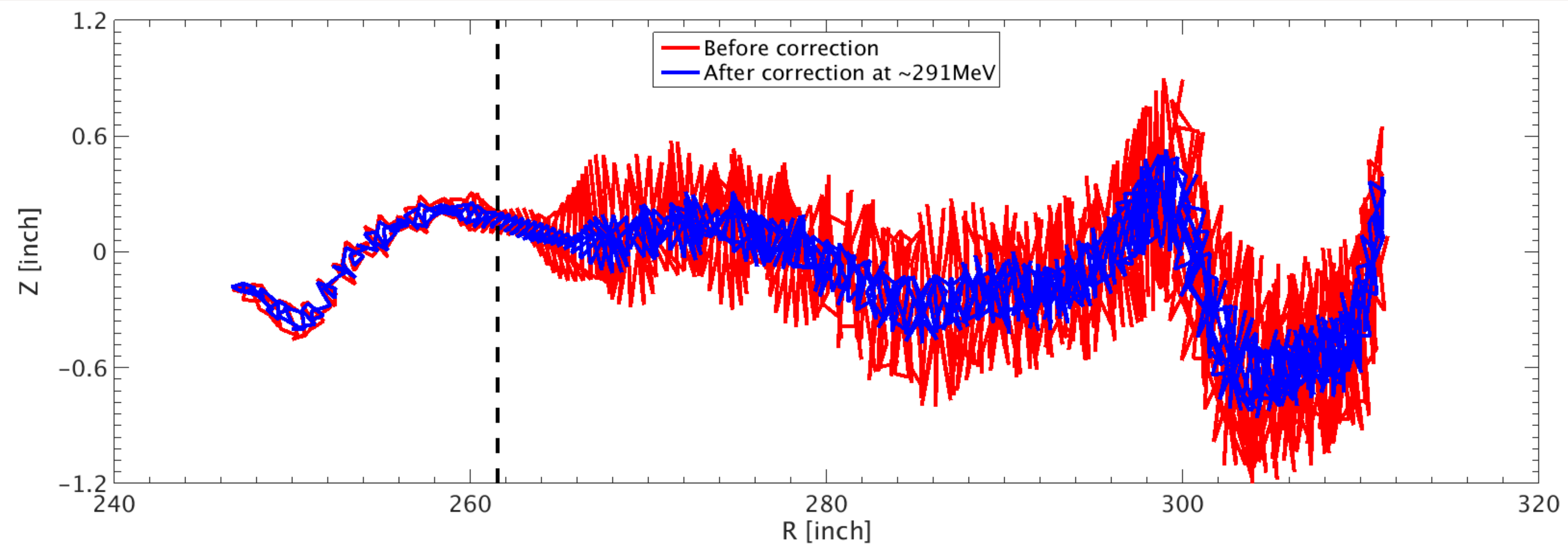
- In the action space (Jx, Jz):



TRIUMF

Accelerated Orbit Simulations

- And then, an accelerated orbit was simulated, starting at 250 MeV, far enough from the resonance energy of 291 MeV. Similarly, at start, the particle was just sitting on its static equilibrium orbit (SEO) vertically while displaced from the SEO by +0.5'' or -0.5'' radially. The particle's coordinates (x, p_x) and (z, p_z) were recorded turn by turn at the starting azimuth for a number of turns until it gets to 500MeV extraction.

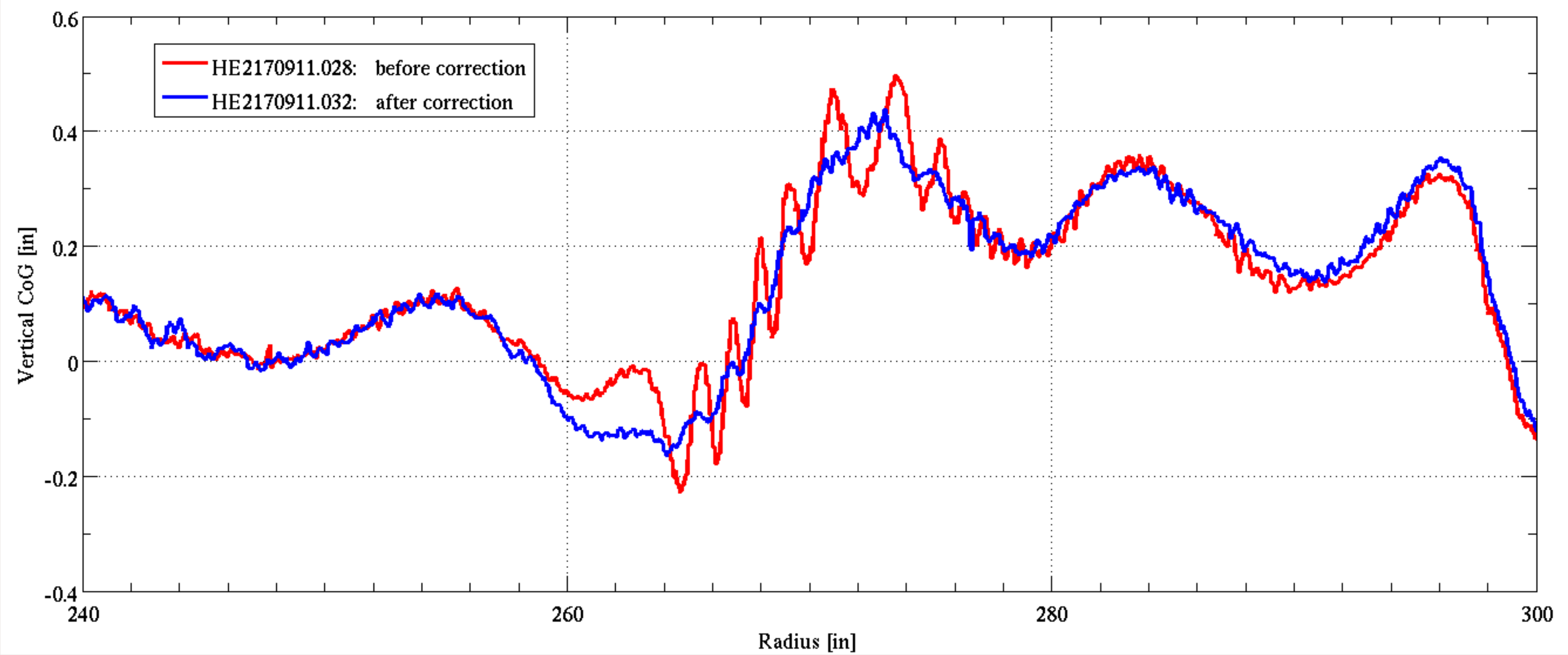


- The residual oscillations, even showing up before 260 inch, is probably due to the other higher order resonance.

Measurements with HE Probe

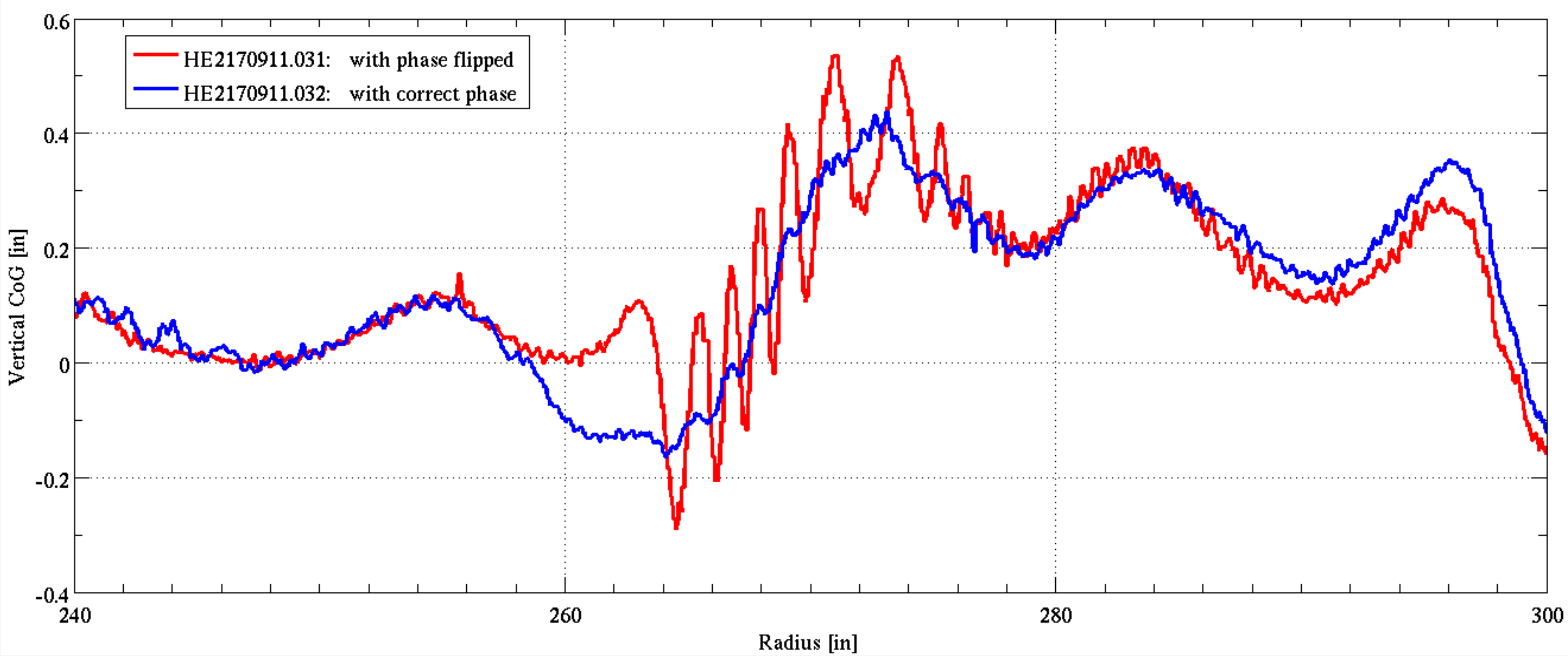
- For the measurements, a coherent radial centring error of beam orbit was introduced by detuning the deflector's high voltage from the production setting, or by detuning the amplitude and/or phase of Bz first harmonic coil #2 from the production settings. These production settings were usually well tuned to minimize the machine spills.

Deflector's voltage was detuned by 9%



Measurements with HE Probe

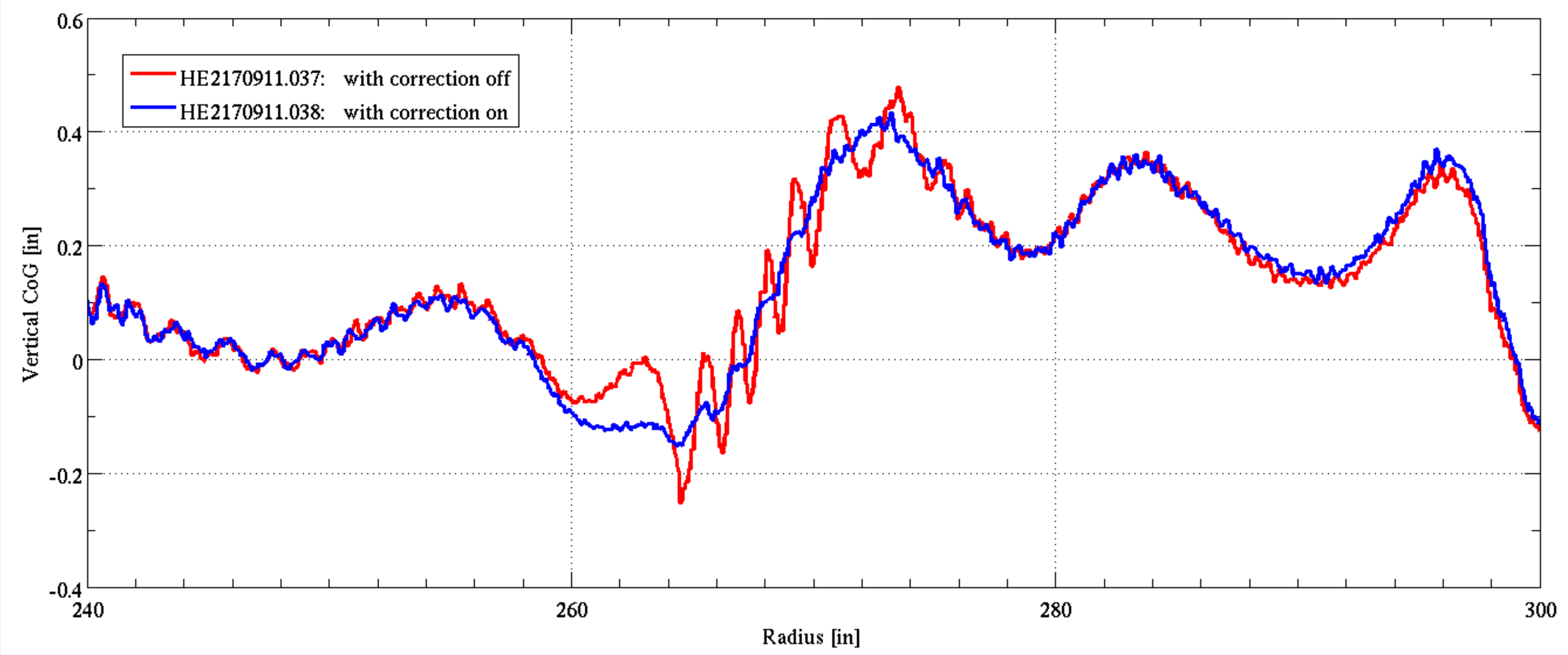
Deflector's voltage was detuned by 9%



- Apparently, the flipped phase manifests the correct phase.

Measurements with HE Probe

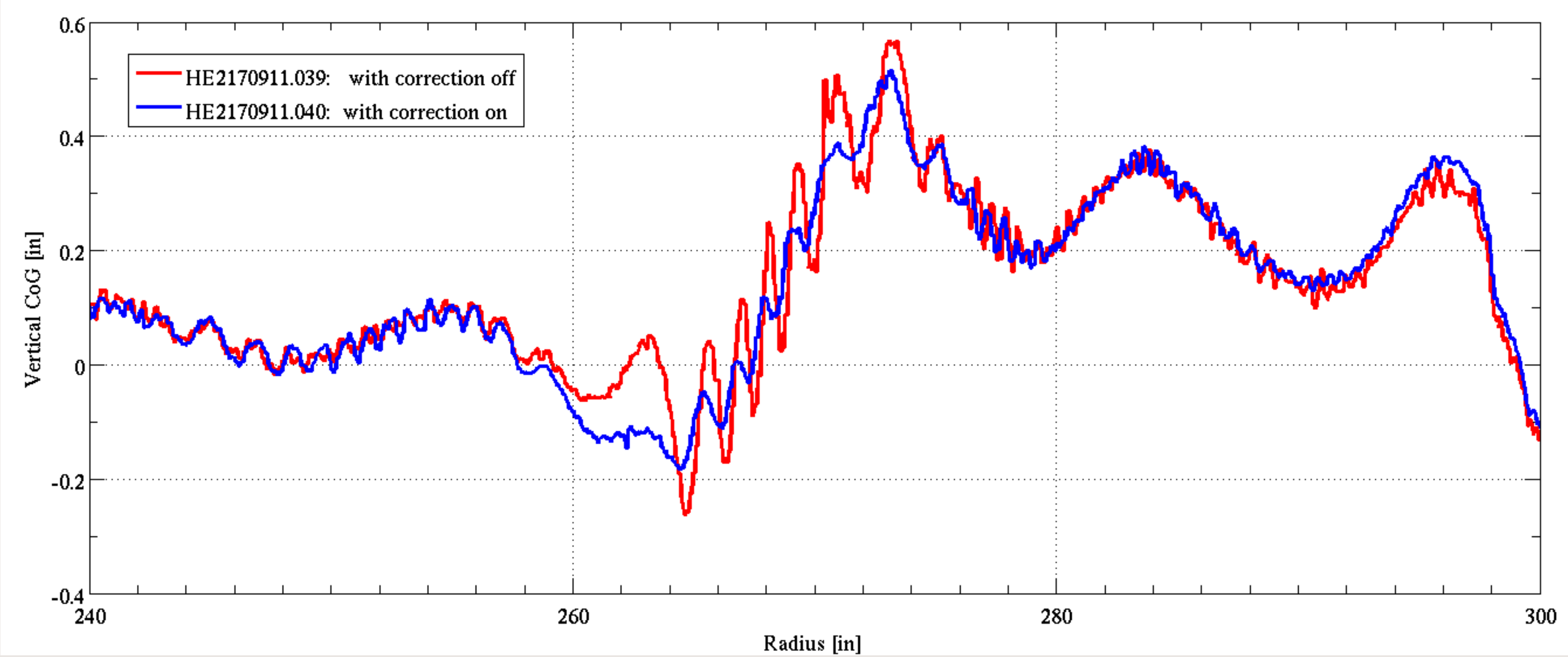
Bz 1st HC#2 phase detuned by 30^{o}



TRIUMF

Measurements with HE Probe

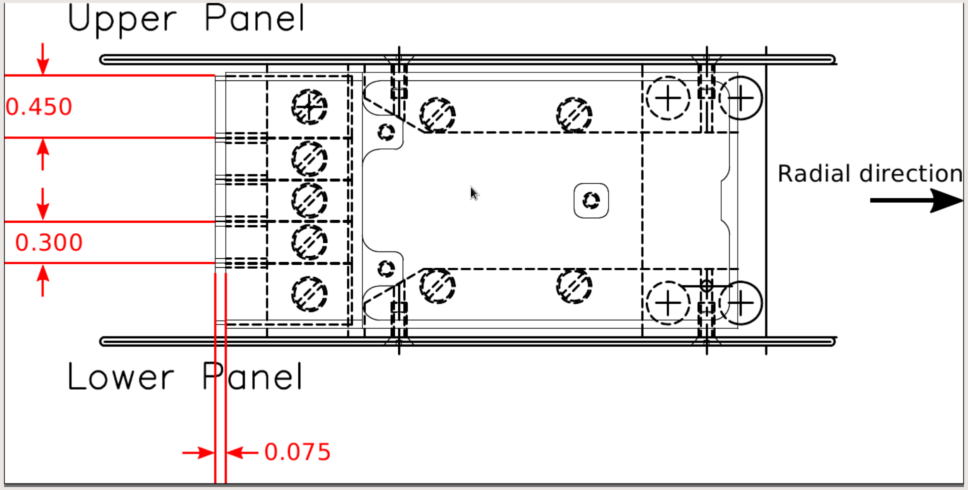
Bz 1st HC#2 amplitude detuned by 200AT

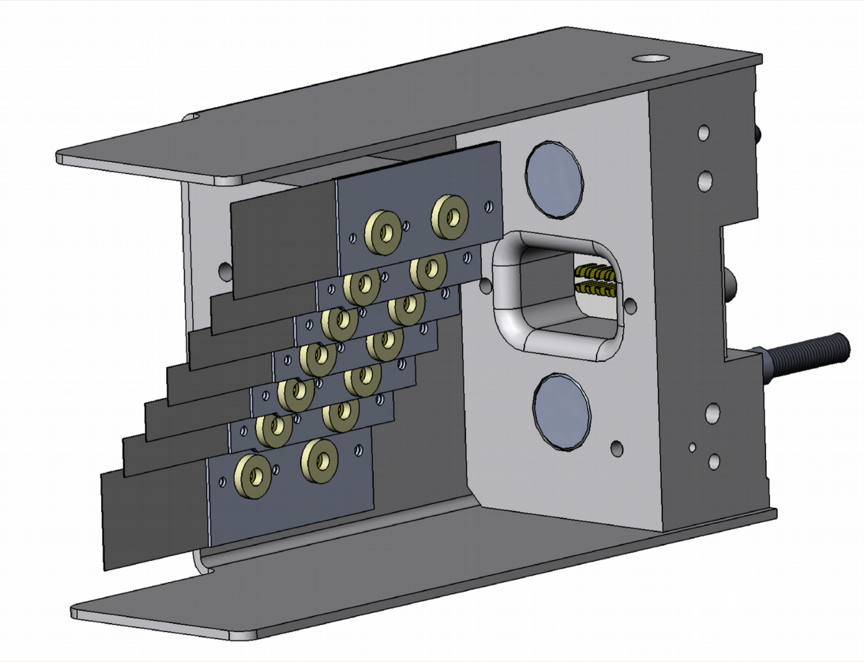


- These indicate that the correction made works for the other arbitrary centring errors. This is exactly the goal we want to achieve.

TRIUMF HE Probe

- The existing low energy (LE) and high energy (HE) probes in the cyclotron CAN measure the beam vertical centre-of-gravity and radial density.



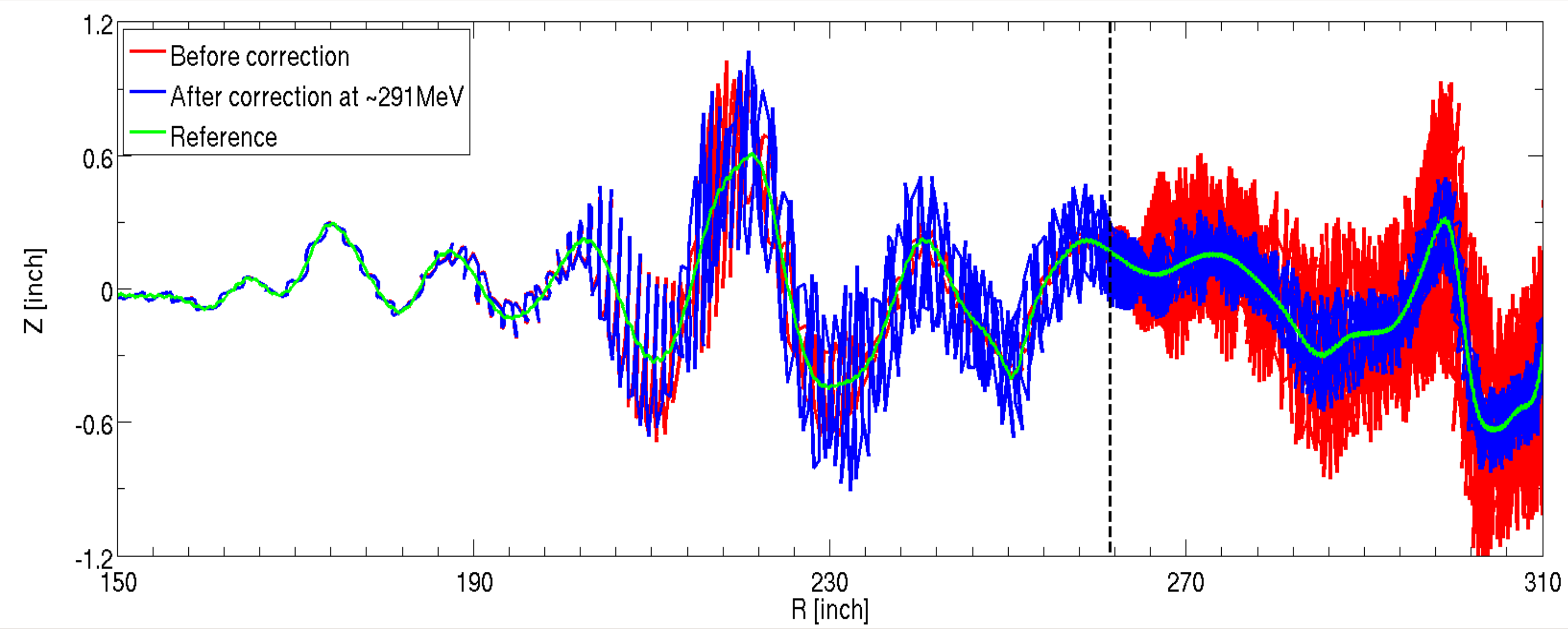


- But can't measure longitudinal density distributions of bunches in the cyclotron.

TRIUMF

Summary

- We demonstrated that we've found a solution to correct the 2nd crossing of the coupling resonance using the existing harmonic coils #10 and #12 in combination.
- Next, we shall expect to correct the 1st crossing. As a result of these corrections, the machine spills can be further reduced.



Thank you!

Merci