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Cyclotron Beam Development Shifts Summary on Measurements of Linear Coupling Resonance Correction and its Benefits

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Abstract: In this note we summarize the results of measurements that we took on the linear coupling resonance correction and its benefits on the circulating beam size and tank spill with and without utilizing the quadrant 2 vertical flag.

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1 2021-Sept-21

We began with cyclotron production tune and took HE2 scans to measure the effects of linear coupling resonance $\nu_r - \nu_z = 1$ on the circulating beam vertical size and transmission, with 2 different angular settings of quadrant 2 vertical flag (Q2VF) i.e. 19.0° and 30.6°. (In the production tune, the resonance crossing observed in the past at around 235″ i.e. around 224 MeV has been avoided by using trim coil 36 to create a local bump to the ν_z, so it's not an issue any more.) The 19.0° setting barely bit any circulating beam, while the 30.6° bit half amount. Therefore, for the 30.6° setting, the machine duty factor was increased by a factor of 2 to get the same average current arriving at $\sim 306''$ (~ 480 MeV). The results are shown in Fig. 1-6.

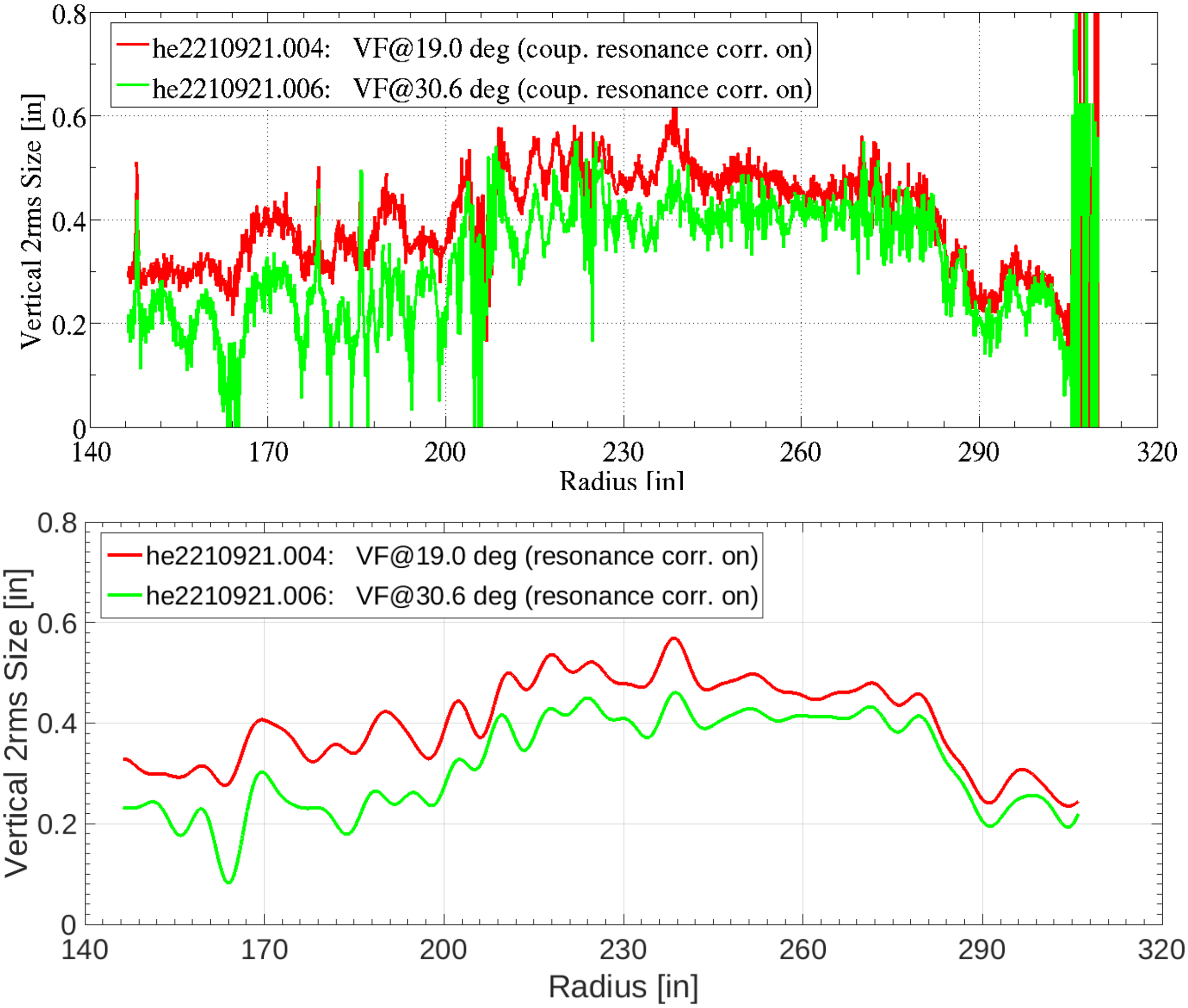

Figure 1: The vertical 2rms beam size, before (upper) and after (lower) smoothing, measured with 2 different angular settings of Q2VF in the presence of correction for the coupling resonance. Apparently, the larger angle of 30.6° makes a smaller beam size than the smaller angle of 19.0° over the entire high energy range up to 480 MeV extraction; the numerical values of beam sizes are over-estimated rather than accurate, though, due to the limitation of HE probe 7-finger configuration.

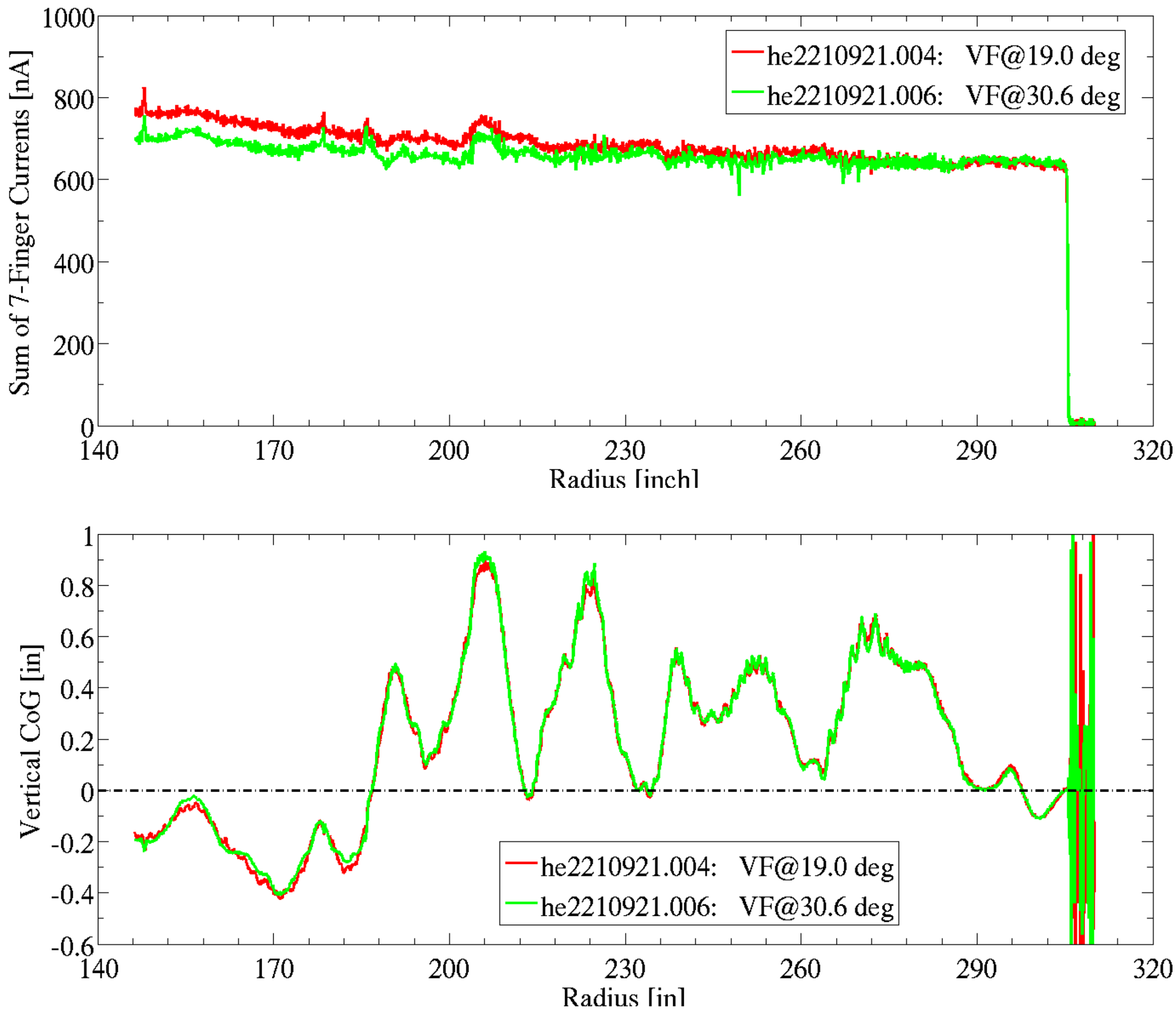

Figure 2: The beam transmission (upper) and vertical centre of gravity (lower), measured with 2 different angular settings of Q2VF in the presence of correction for the coupling resonance. Apparently, the larger angle of 30.6° makes a flatter transmission than the smaller angle of 19.0° over the entire high energy range up to 480 MeV extraction, implying less beam losses during acceleration. Whereas the two different angles barely change the vertical centre of gravity. This is because the flag bites the beam (from bottom) over a broad energy range from ~ 4.4 to ~ 8.0 MeV covering about 10 consecutive turns i.e. about 720° phase advance in the vertical phase space.

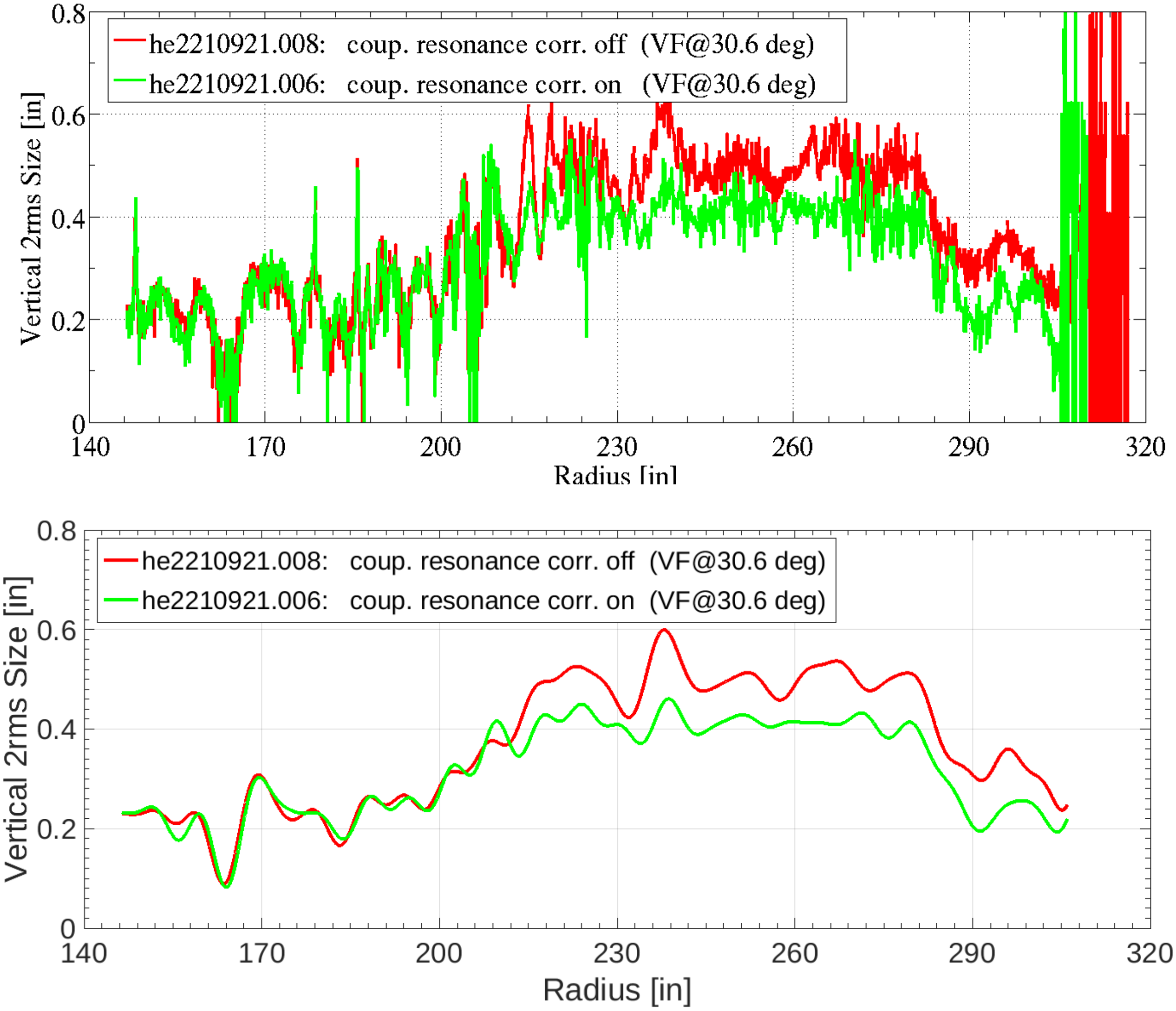

Figure 3: The vertical 2rms beam size, before (upper) and after (lower) smoothing, measured under the same angular setting of Q2VF with the correction on and correction off separately for the coupling resonance. Apparently, the correction-on makes a smaller beam size than the correction-off, starting from $\sim 215''$ (where the resonance is first encountered) up to $306''$ extraction.

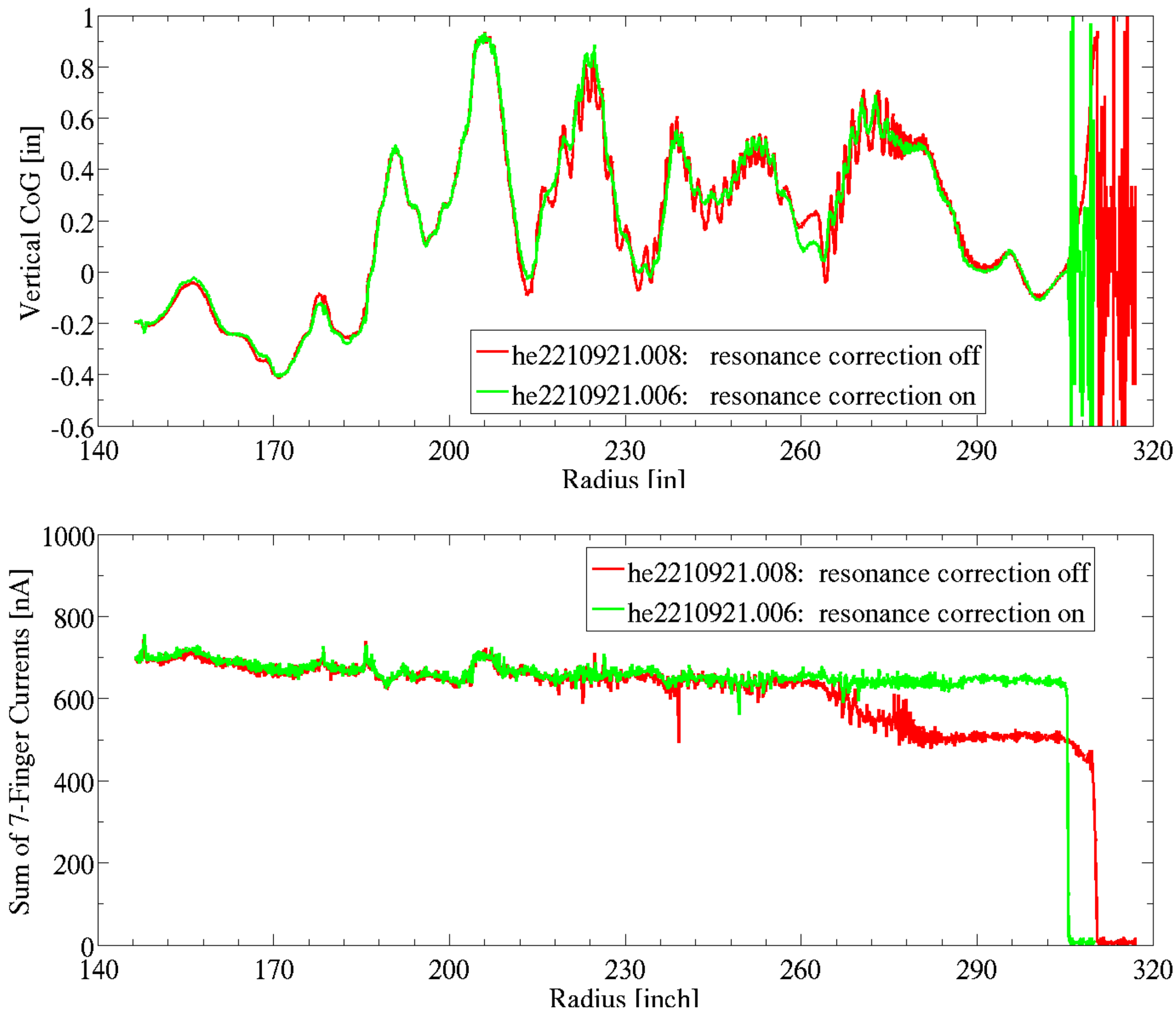

Figure 4: The vertical centre of gravity (upper) and beam transmission (lower), measured under the same angular setting 30.6° of Q2VF with the correction on and correction off separately for the coupling resonance. Apparently, the correction-on makes a smaller amplitude of oscillations in the vertical centre of gravity and also flatter transmission than the correction-off during the resonance crossing.

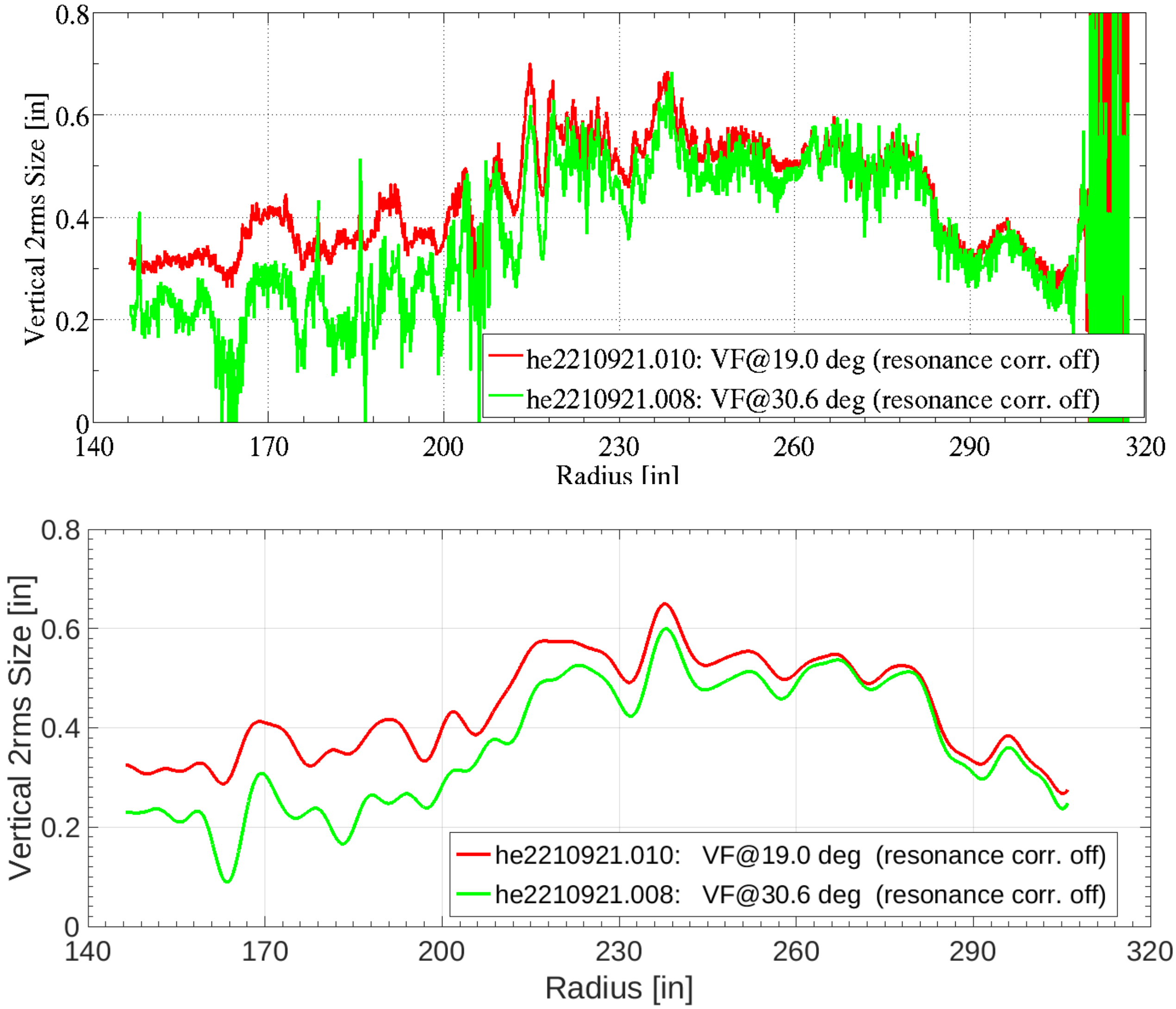

Figure 5: The vertical 2rms beam size, before (upper) and after (lower) smoothing, measured with 2 different angular settings of Q2VF in the absence of correction for the coupling resonance. The larger angle of 30.6° makes a smaller beam size than the smaller angle of 19.0°, but this observation is not as significant as in the presence of correction shown in Fig. 1 starting from 215″ onward.

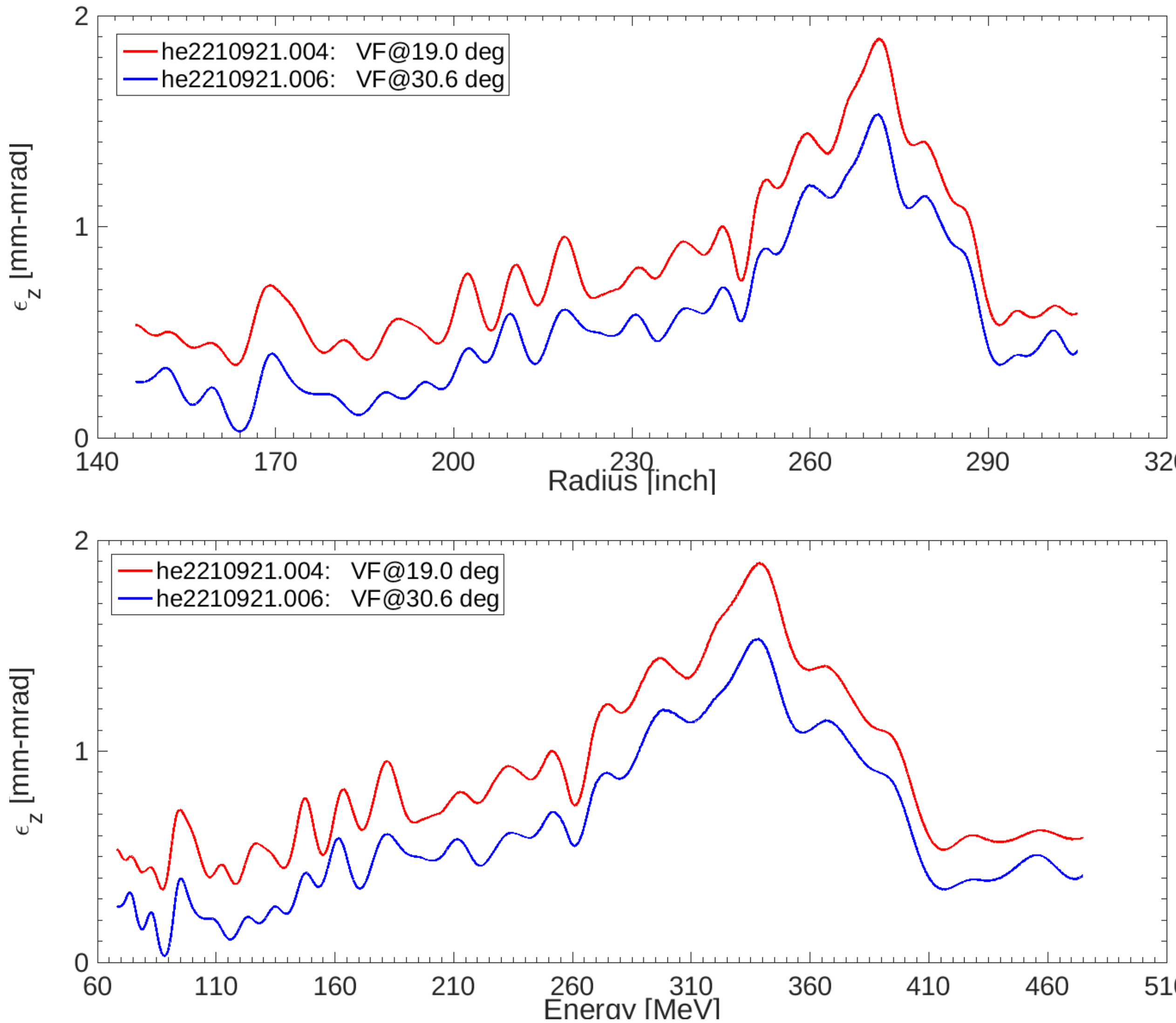

Figure 6: The vertical emittance (rms, normalized) versus radius (upper) and energy (lower) in the presence of correction for the coupling resonance, evaluated from Fig. 1 using the beta function calculated theoretically along the HE2 travel path. The normalized emittance appears to be oscillating rather than constant. This is believed to be an artifact due to the limitation of 7-finger configuration. Nevertheless, there is a sharp increase at $260 - 320$ MeV. This is perhaps caused by a Walkingshaw type of resonance $\nu_r + 2\nu_z = 2$.

2 2021-Oct-12

We started with cyclotron production tune and took HE2 scans to check the correction of linear coupling resonance $\nu_r - \nu_z = 1$ to see if it was working as expected. To that end, a coherent radial centring error ($\sim 0.3''$) of the beam orbit was introduced intentionally by either changing the centre region electrostatic deflector's high voltage setting from the production value, or by detuning the amplitude or phase angle of HC#2 first harmonic in B_z from the production settings. These production settings had been reasonably well tuned to minimize the machine spill. The results are shown in Fig.7−9.

The nominal correction for the coupling resonance did function, but did not function as efficiently as before (see Reference [1]); still there was a significant drop of transmission at $\sim 215''$ where the resonance is first time encountered. This implied that the correction amplitude was not large enough for a full correction. So, we attempted to increase the correction amplitude by 12% and then 36% from the nominal value. These increases did help with the transmission, shown in Fig. 10. Still, it wanted further increased amplitude, but we could not go higher because at this point one of the power supplies for the correction harmonic coils was already maxed out. This is strange; for some reason we can't reproduce the results of full correction that we achieved before [1]. **It seems to imply that the driving of the coupling resonance has somehow become much stronger**. Maybe the cyclotron magnetic field was not fully reproduced as the machine was just restarted from the mini-shutdown.

We also tried to elevate the beam vertical centre of gravity at around $215''$ by using trim coils 32 and 33 in B_r. The beam did want to be elevated to gain the transmission, shown in Fig. 11.

In addition, Fig. 12 shows the coherent oscillation vertical CoG versus radius (and energy) for the scan #12, detailed in the 320 MeV region. This scan was taken under the condition that the correction was turned off for the coupling resonance and the deflector's setting was detuned intentionally to create a coherent radial oscillation starting from centre region. Notice the fast oscillation drops to zero between ∼295 and ∼305 MeV, reappears from 310 MeV and persists to 380 MeV. The oscillation exhibits about 1 period per 5 MeV from 320 to 340 MeV, meaning an oscillation frequency of $(1/5) \times 0.31 = 0.06$ as the energy gain is $\sim 0.087 \times 4 \times \cos 25^\circ = 0.31$ MeV/turn. This is not the vertical tune of the machine, which is large, around 0.30 in this region. Instead, this is actually measuring the $\nu_r - \nu_z - 1$. See Fig. 13. Note that the measurement is taken only at a single azimuth so can't tell the difference between integers.

3 2021-Nov-02

We began with the production tune of cyclotron to measure the tank spill as a function of Q2VF angular setting, with the correction on and off separately for the linear coupling resonance. This measurement was taken under a high intensity beam of 100 μA extracted down to BL1A. At low intensity ($< 1\,\mu$A), the tank spill read-back appears noisy and not very meaningful. Fig. 13 shows the raw data, recorded with `Xstrip`.

Fig. 14 gives the data processing results, showing the tank spill (relative to the total extracted current), the VF collimated amount of beam, and the VF collimation efficiency as a function of VF angle setting. Fig. 15 shows the tank spill (relative value) versus the VF collimated amount of beam. Clearly, the correction-on helps to reduce the tank spill.

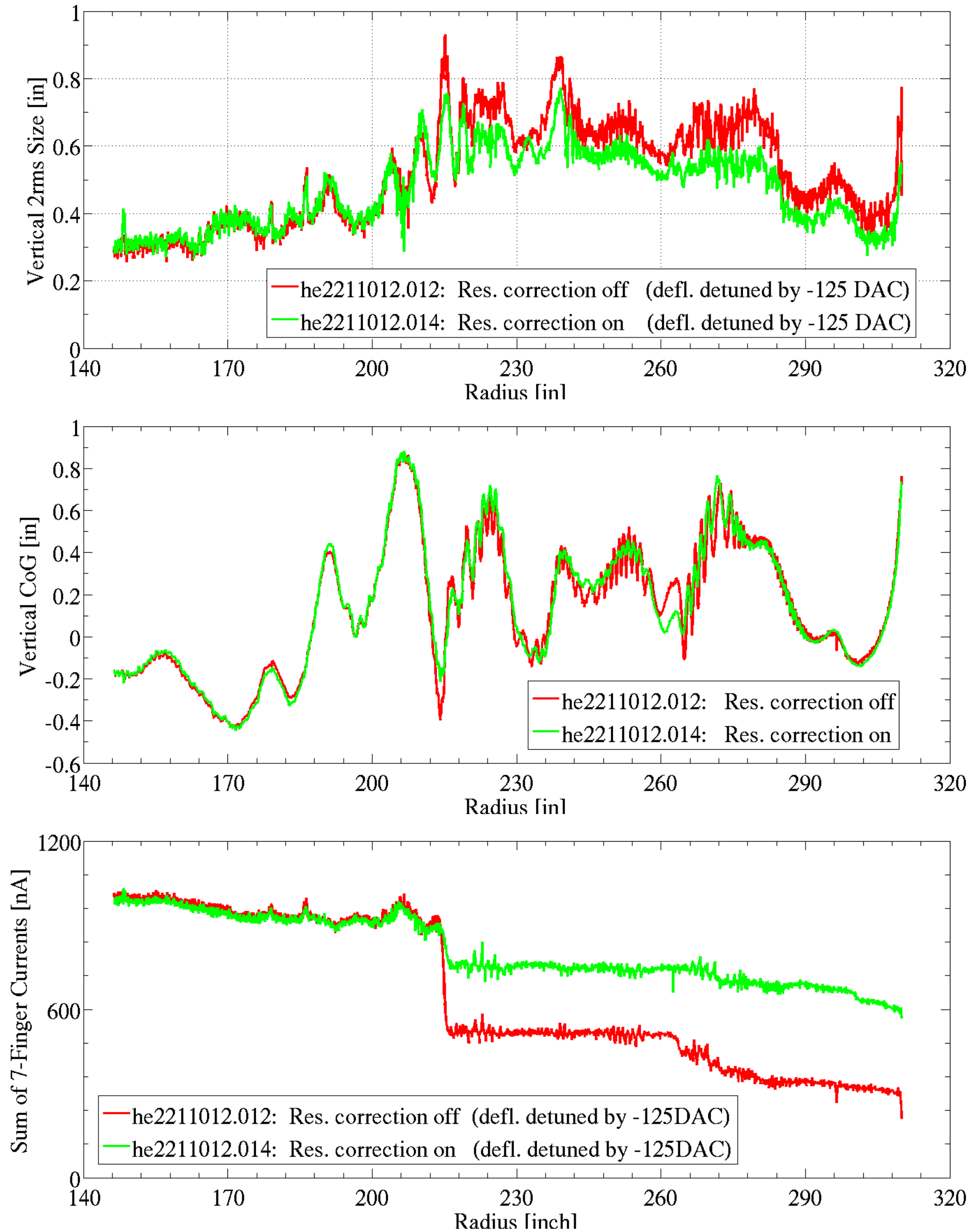

Figure 7: The vertical 2rms beam size (top), vertical centre of gravity (middle), and transmission (bottom), measured under the condition of correction on and off separately as well as the deflector's setting detuned by $-125\,\mathrm{DAC}$. Clearly, in comparison with the correction off, the correction on makes a smaller beam size, smaller amplitude of oscillation in the vertical centre of gravity, and less beam losses during the resonance crossing.

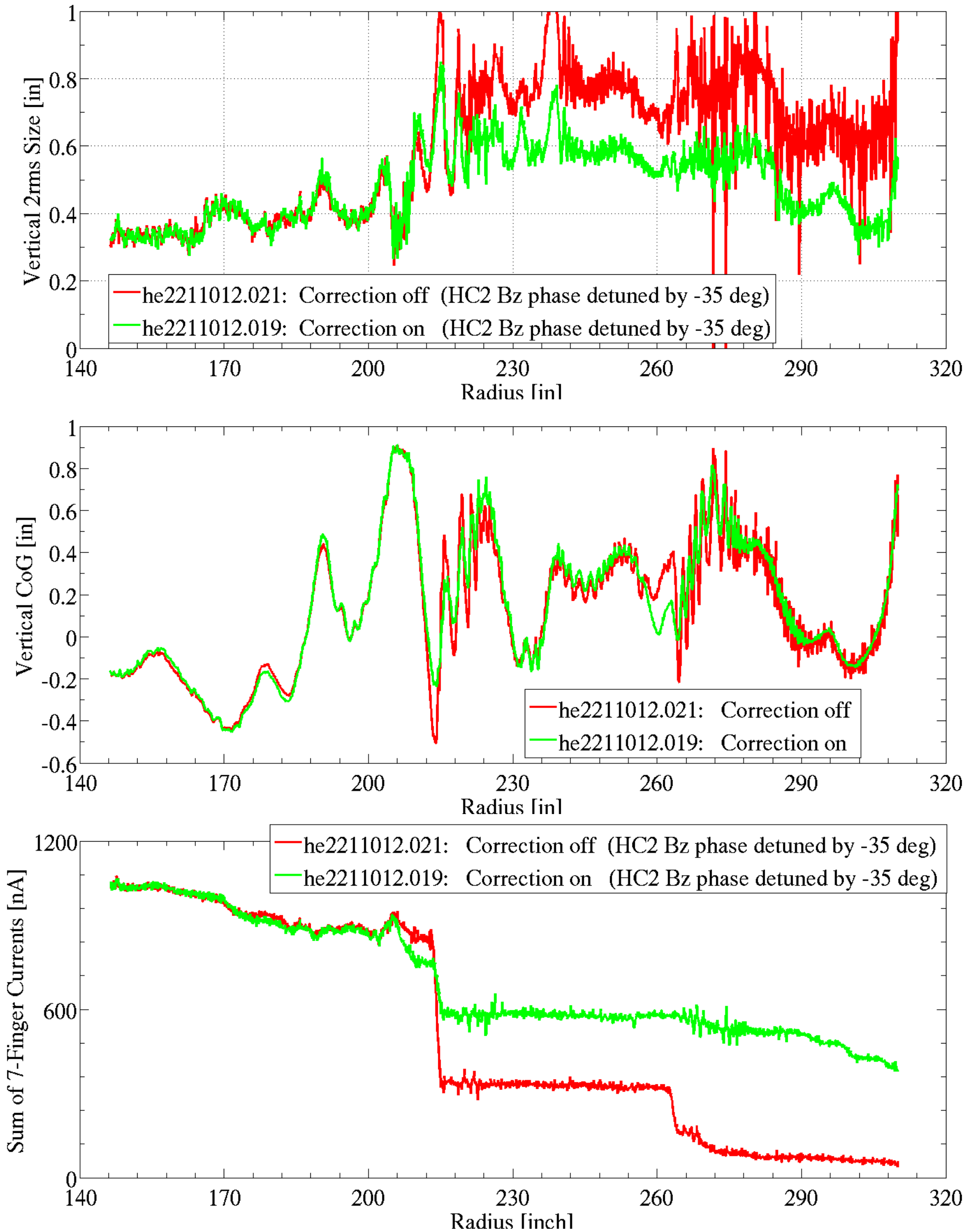

Figure 8: The vertical 2rms beam size (top), vertical centre of gravity (middle), and transmission (bottom), measured under the condition of correction on and off separately as well as the HC2 B_z first harmonic phase angle detuned by $-35°$. Clearly, in comparison with the correction off, the correction on makes a smaller beam size, smaller amplitude of oscillation in the vertical centre of gravity, and less beam losses during the resonance crossing.

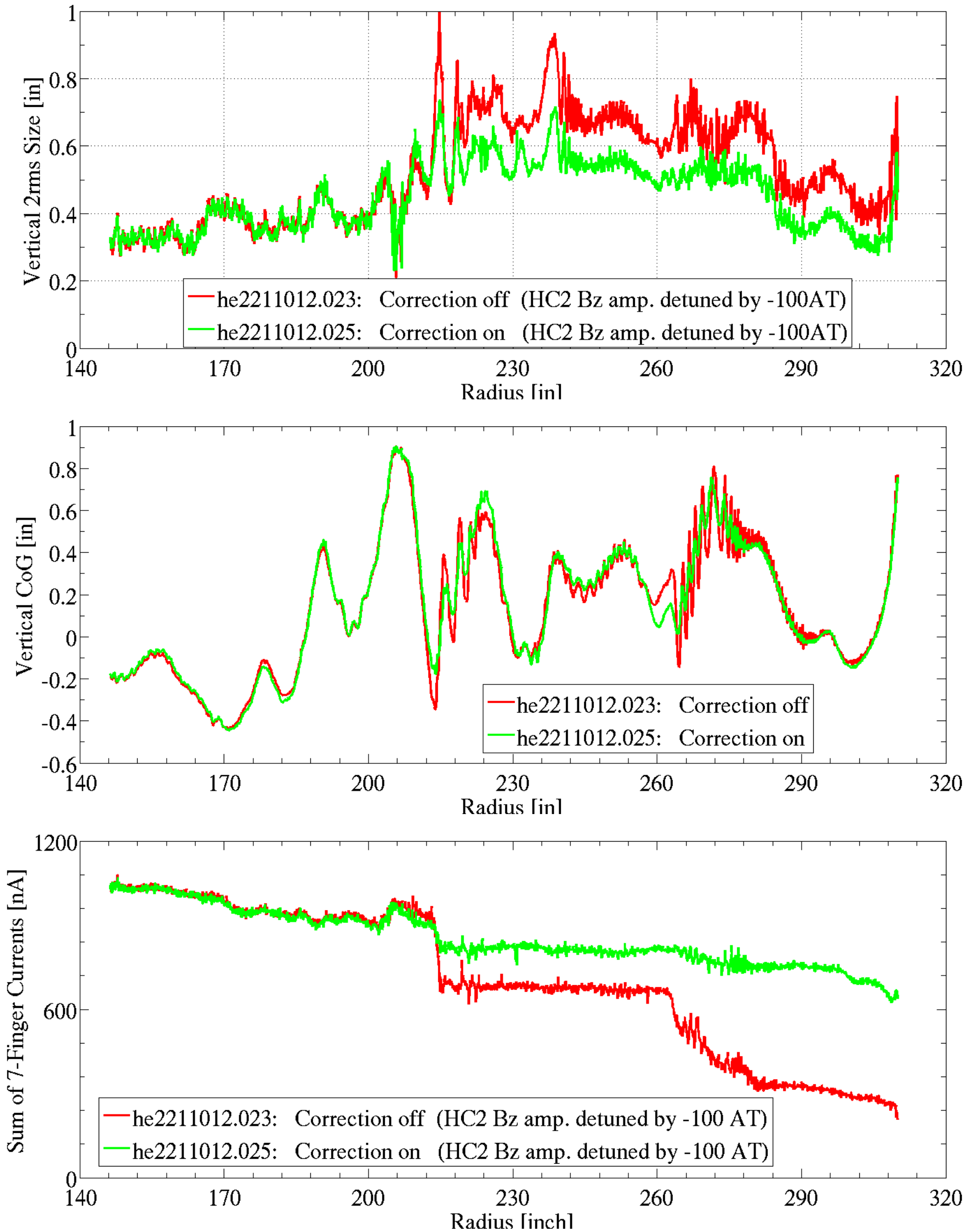

Figure 9: The vertical 2rms beam size (top), vertical centre of gravity (middle), and transmission (bottom), measured under the condition of correction on and off separately as well as the HC2 B_z first harmonic amplitude detuned by $-100\,\mathrm{DAC}$. Clearly, in comparison with the correction off, the correction on makes a smaller beam size, smaller amplitude of oscillation in the vertical centre of gravity, and less beam losses during the resonance crossing.

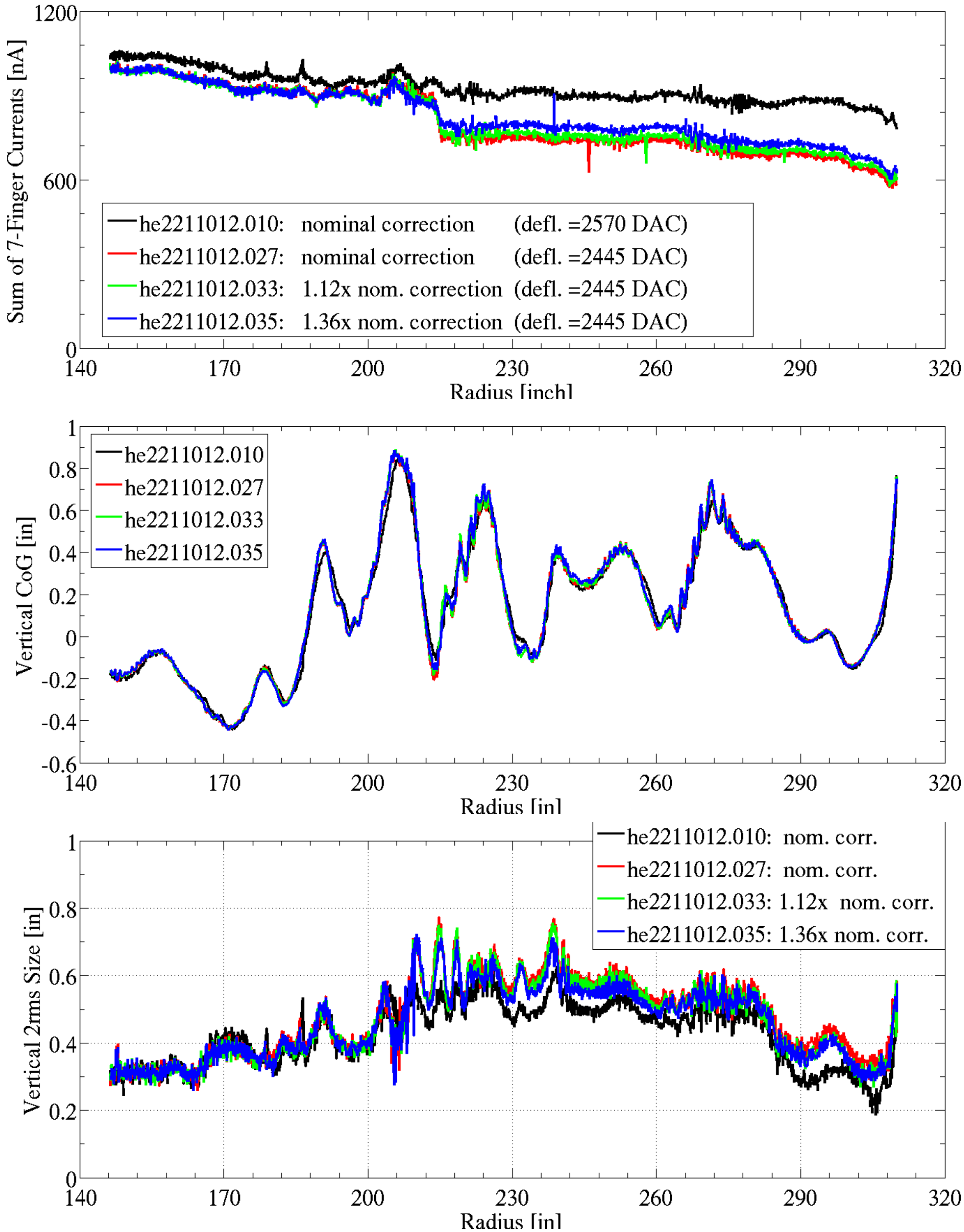

Figure 10: The transmission (top), vertical centre of gravity (middle), and 2rms beam size (bottom), measured under nominal correction amplitude, 12% and 36% stronger correction amplitudes. It's seen that the stronger corrections do help with the transmission.

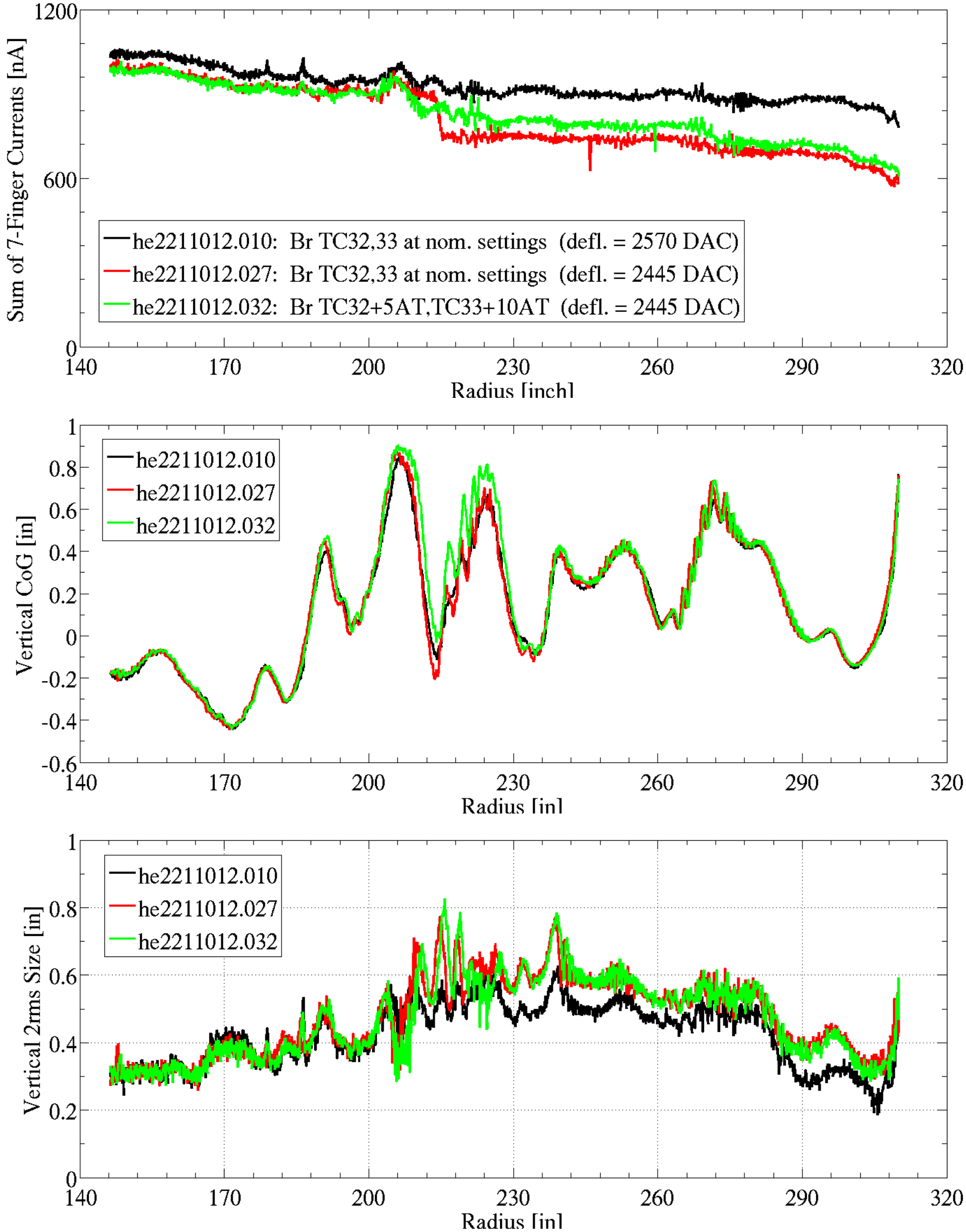

Figure 11: The transmission (top), vertical centre of gravity (middle), and vertical 2rms beam size (bottom), measured under nominal settings of trim coils and larger settings for the trim coils 32 plus 33 in B_r. It's seen that the elevating the beam position at around 215″ helps to gain the transmission.

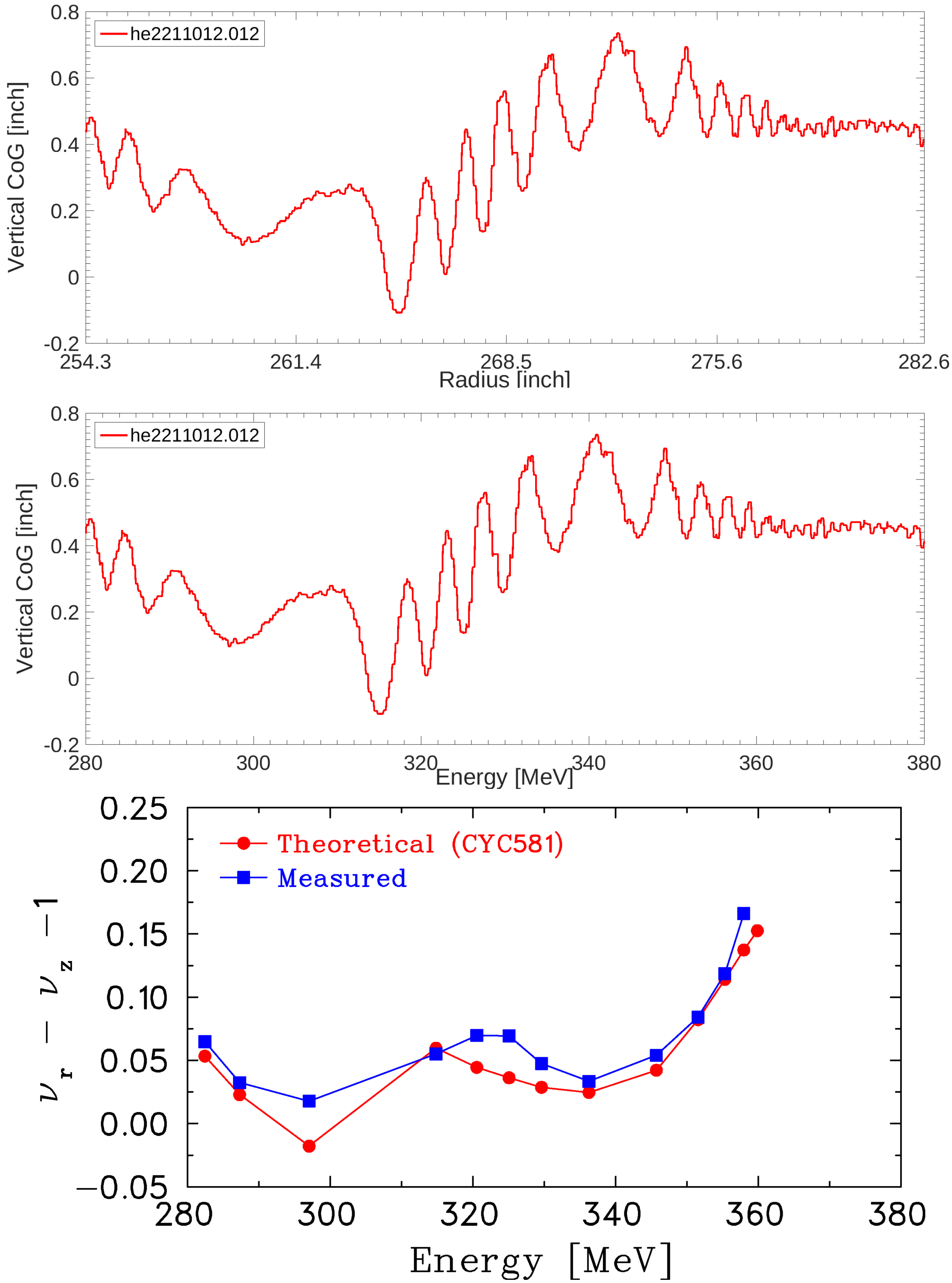

Figure 12: The vertical centre of gravity of the scan #12 versus radius (top) and energy (middle), detailed in the 320 MeV region. The fast oscillations reveal the frequency $\nu_r - \nu_z - 1$ vs. energy (bottom).

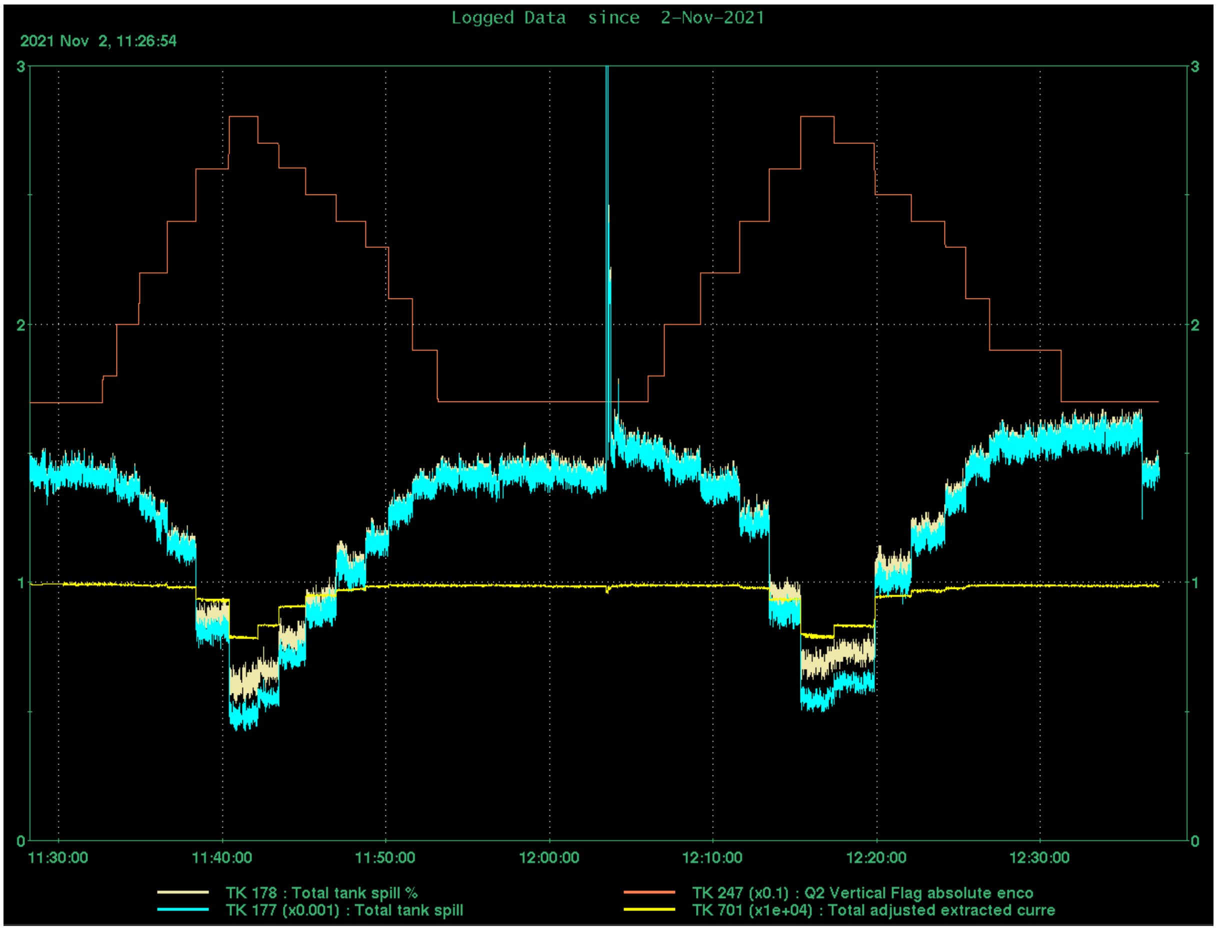

Figure 13: The `Xstrip` logged raw data of Q2VF angle setting, the total tank spill (absolute value and relative value), and the total adjusted extracted current, as a function of time. As the independent variable, the Q2VF was changed in steps. The first half log i.e. from 11:30 to ∼12:03 was with the coupling resonance correction on, while the second half i.e. from 12:04 to ∼12:37 was with the correction off. The last bit of step down in the tank spill was with the correction turned back on.

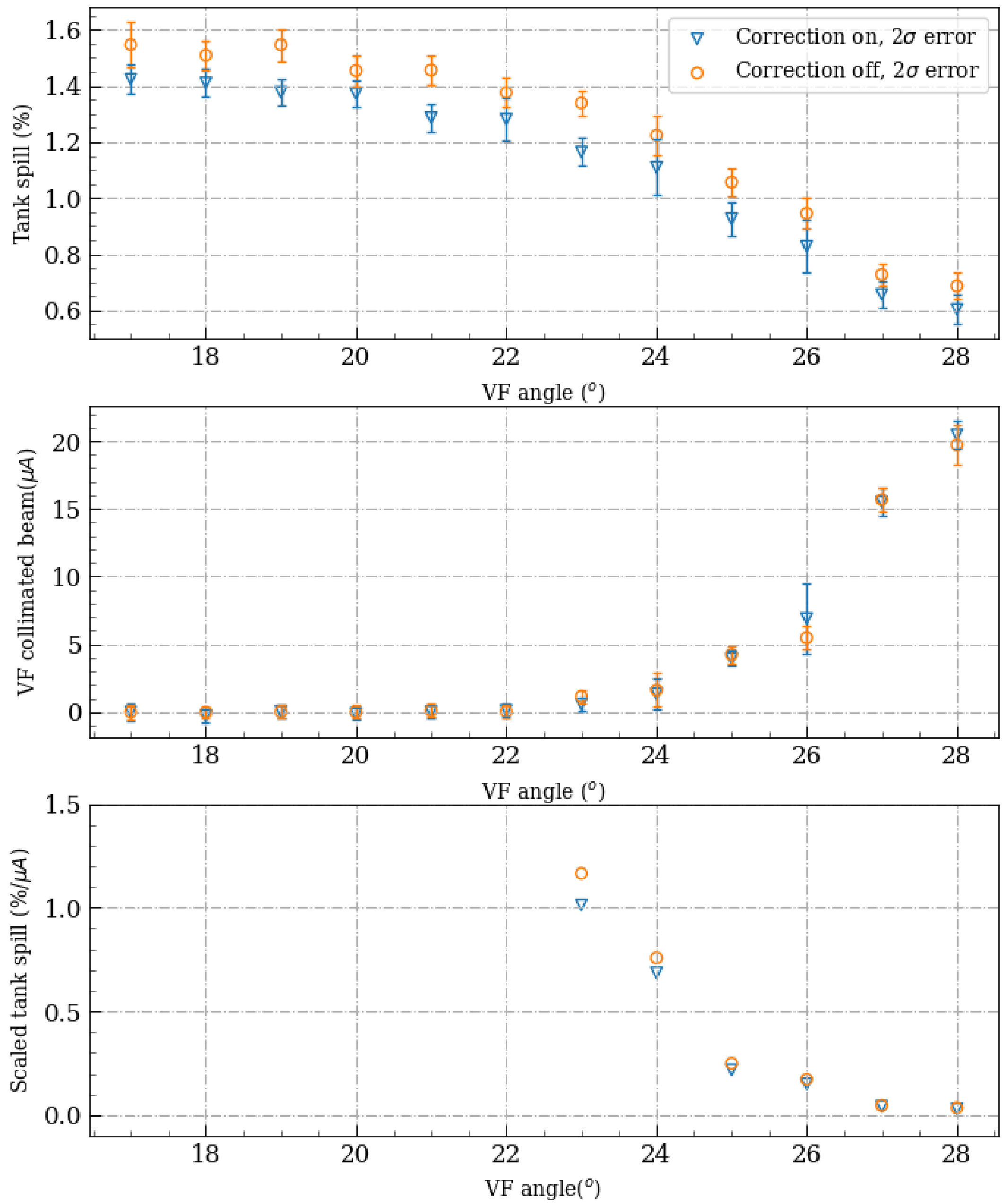

Figure 14: The tank spill (top) relative to the total extracted current, the VF collimated amount of beam (middle), and the scaled tank spill (bottom) as a function of its angle setting. The bottom graph, obtained from the top graph data divided by the middle graph data, shows that cutting a little (to 23°) cuts the halo that arises from the coupling resonance, but cutting a lot (above 23°) mostly cuts beam that is not going to end up on spill monitors.

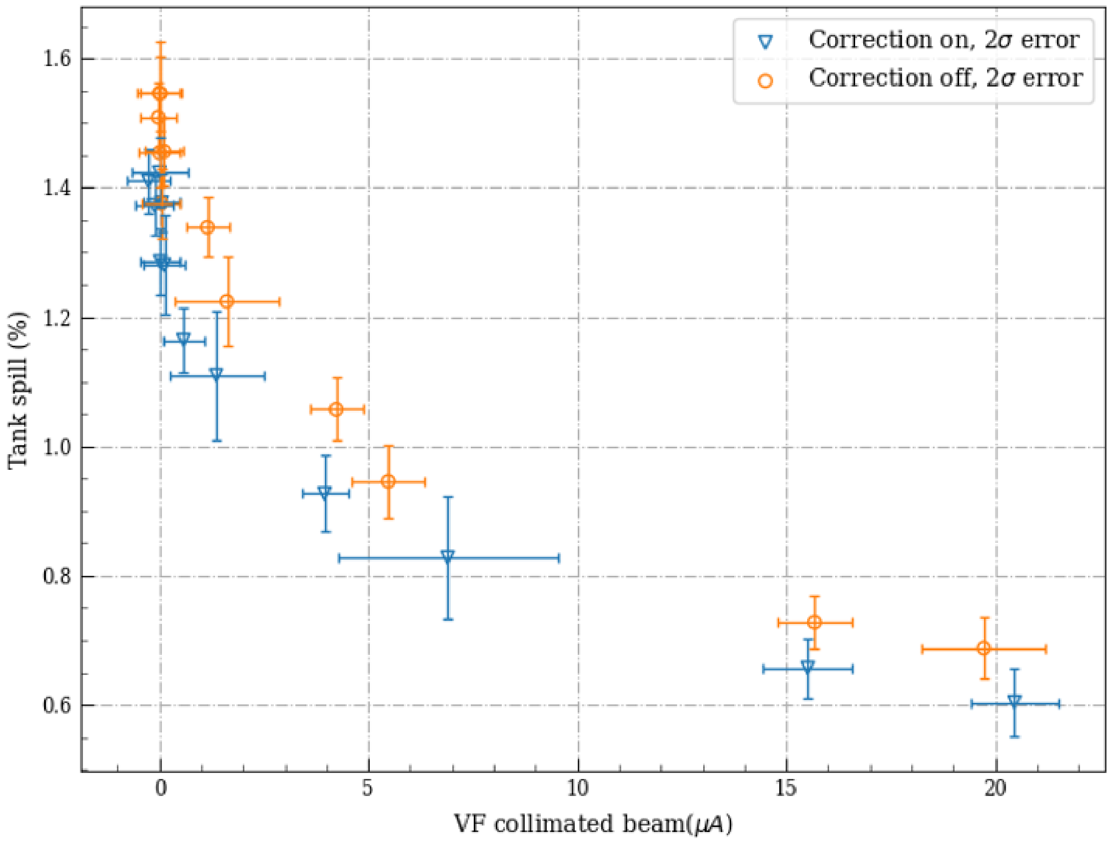

Figure 15: The tank spill (relative to the total extracted current) vs. the amount of beam collimated out by the VF, with the correction on and off separately for the coupling resonance.

4 Conclusions

The measurement results show that the correction for the linear coupling resonance did function but did not function as efficiently as before. For some reason we can't reproduce the results of full correction that we achieved before. This seems to imply that the driving of the resonance has somehow become much stronger. One of explanations for this is that the cyclotron magnetic field was not fully reproduced as the machine was just restarted from the mini-shutdown. Nevertheless, the correction helps to reduce the tank spill. The Q2VF can further reduce the tank spill, depending on the amount of beam it collimates out.

5 Acknowledgment

Useful discussions with cyclotron beam development team are appreciated.

References

[1] Y.-N. Rao, *Correction of Coupling Resonance* $\nu_r - \nu_z = 1$, TRIUMF Beam Physics Note, TRI-BN-19-27, Jun.18, 2019.