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# VERTICAL BEAM MOTION IN THE AGOR CYCLOTRON

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## *Abstract*

Internal beam losses observed for the highest energy (190 MeV) proton beam accelerated with the AGOR-cyclotron has triggered a study of the vertical beam motion for various beams. The amplitude of the vertical motion increases strongly when approaching the vertical stability limit (E/A =200 Q/A MeV per nucleon). With increasing radius the beam gradually moves down out of the geometrical median plane by over five mm, eventually leading to internal beam losses.

It has been concluded that this is caused by a vertical alignment error of the main coils combined with the weak vertical focussing for the beams concerned. Moving the main coils 0.34 mm downward has significantly improved the situation. It can not be excluded that excitation of the $\nu_r - \nu_z = 1$ resonance plays a role for the highest energies.

## INTRODUCTION

The superconducting AGOR-cyclotron [1] accelerates ions of all elements to energies varying from 5 MeV per nucleon for heavy ions with a charge-to-mass ratio Q/A = 0.1 to 190 MeV for protons. The maximum attainable energy is determined by either the maximum magnetic field ($E_{max}/A = 600\ Q^2/A^2$ MeV per nucleon) or the loss of vertical stability ($E_{max}/A < 200$ Q/A MeV per nucleon).

For the highest energy (190 MeV) proton beam internal beam losses have been observed. The vacuumcover on the lower magnetpole has been found to be activated by these losses. This implies that the losses are caused by the beam centroid moving out of the median plane of the poles. The activation is localized at specific radii.

The measurements of the vertical beam motion presented show that this problem is not specific for the highest energy proton beam: vertical excursions occur for all beams. Their amplitude increases with increasing final energy, *i.e.* with reducing vertical focussing.

Possible causes and a (partial) remedy for this problem are described.

## VERTICAL STABILITY

The vertical focussing in an isochronous cyclotron is the balance between a focussing contribution from the azimuthal field variation and a defocussing contribution from the radially increasing field needed to maintain isochronism:

$$\nu_z^2(r) = \left[\Delta\nu_z^2(r)\right]_{AVF} + \left[1-\gamma^2(r)\right]_{ISO} \qquad (1).$$

The average magnetic field in the AGOR-cyclotron varies between 1.7 and 4.1 T. At these fields the iron poles providing the azimuthal field variation are fully saturated. Therefore the focussing contribution from the azimuthal field variation can be written as

$$\left[\Delta\nu_z^2(r)\right]_{AVF} = \frac{C(r)}{\gamma^2(r)-1}\frac{Q^2}{A^2} \qquad (2),$$

where $C(r)$ is determined by the geometry of the magnet poles.

## MAIN COIL ALIGNMENT

Close to the stability limit the small value of $\nu_z$ results not only in large coherent and incoherent betatron amplitudes but also in a strong sensitivity for perturbations of the midplane symmetry, such as misalignment between the main coils and the iron poles.

The scale of the changes in the location of the median surface, approximately defined by the $z$-value for which $B_r = 0$, caused by such misalignment is large compared to the scale of the betatron motion and therefore it is justified to assume that the beam adiabatically “follows” the median surface. A misalignment $\Delta z_{coil}$ between the main coils and the iron poles results in a approximate displacement of the beam with respect to the poles [2]

$$\Delta z_{beam}(r) = -\frac{r}{B_{z,coil}(r)}\frac{dB_{z,coil}(r)}{dr}\frac{1}{\nu_z^2(r)}\Delta z_{coil} \qquad (3)$$

The contribution of the iron poles to the average field does not depend on the radius in the area of interest. The field of the main coils thus increases at least as fast as necessary to retain isochronism. For the 190 MeV protons orbit calculations show that $\nu_z(r) \geq 0.1$. This results in a maximum magnification $\Delta z_{beam}(r) \approx 30\Delta z_{coil}$. As the vertical aperture of the beamchamber is 18 mm and the typical vertical beamsize is around 4 mm (full size), beam losses will occur for vertical alignment errors of the main coils with respect to the iron poles larger than 0.25 mm.

The assembly of the two pairs of main coils was aligned with respect to the iron poles by measuring the radial field of the main coils in the magnetic median plane of the iron poles at the radius corresponding to the middle of the main coils. These measurements were performed at central fields between 2 and 3.5 T. The magnetic median plane of the iron poles was determined by measuring the radial field inbetween the upper and lower poles at very low excitation of the main coils, where the field is essentially due to the iron. The measurements were performed at three azimuths 120° apart, allowing both offset and tilt of the mains coils to be determined.

The radial fieldcomponent was measured with two calibrated Hall-sensors, mounted on a copper pendulum 10 mm above and below the geometrical median plane of the iron poles. To cancel crosstalk from the vertical field component, which is about 100 times stronger than the radial one, the difference of readings taken at two orientations of the Hall-sensors, differing by a rotation of 180° around the vertical axis, was used. The vertical coil position error then follows from the sum and difference between the readings on the upper and lower Hall-sensors. From the measurements made during the position adjustment process it was concluded that the sensitivity of the measurement is about 0.05 mm. This method is not very sensitive to systematic errors in the calibration, since most of these will cancel out in the differential measurement. The optimum position of the coils achieved corresponded to a measured vertical coil misalignment varying between -0.09 mm at 2.5 T and +0.15 mm at 4.0 T [1].

## PROBLEM ANALYSIS

Internal beam losses have been reported for the the Texas A&M K500 superconducting cyclotron [2], which is a machine similar to the AGOR-cyclotron, and the CYCLONE235 cyclotron [3], which accelerates 235 MeV protons exclusively. In the CYCLONE235 cyclotron it was concluded that the beam losses were caused by passing the $\nu_r$ - $\nu_z$ = 1 resonance. For the Texas A&M cyclotron it was found to be due to a vertical misalignment of several mm between the main coils and the iron poles.

### $\nu_r$ - $\nu_z$ = 1 resonance crossing

In view of the procedure followed in aligning the main coils and the iron poles a significant misalignment between the main coils and the iron was considered very unlikely. The strong localization of the beam losses, the fact that they were observed for the 190 MeV proton beam only and the calculated betatron frequencies suggested crossing the $\nu_r$ - $\nu_z$ = 1 resonance as a possible cause of the losses. This resonance is excited by *e.g.* a tilt of the main coils with respect to the iron poles or a defect in a hill sector on one magnet pole.

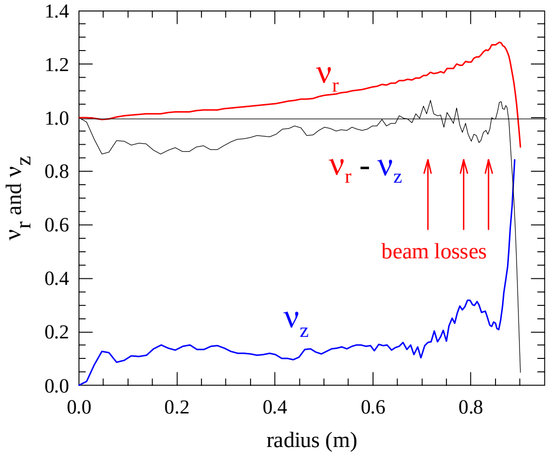

Figure 1: Betatron frequencies for 190 MeV proton beam and location of beam losses

In figure 1 the betatron frequencies $\nu_r$ and $\nu_z$ and their difference are plotted for the 190 MeV proton beam, showing that the measured locations of the beam losses observed by activation, indicated by arrows, correspond with the region where the resonance is crossed several times. The accuracy of the locations of the beam losses is about 10 mm due to the inaccuracy in translating their physical position in the machine into the average orbital radius used as the ordinate in the figure.

Calculations show that the $\nu_r$ - $\nu_z$ = 1 resonance is only crossed for beams very close to the stability limit, such as the 190 MeV proton beam. This is in agreement with the fact that for other beams no internal beam losses have been observed.

### *Coil position error*

In order to gain a better understanding of the beam losses measurements of the vertical beam position were made for the 190 MeV proton beam and the 170 MeV deuteron beam, which is also close to the stability limit. For the deuteron beam no internal beam losses have been observed and the $\nu_r$ - $\nu_z$ = 1 resonance is not crossed.

The measurements were made with a radial probe consisting of five layers of 3 mm each, thus covering almost the whole gap. The current is measured separately for each layer. The beam position is then given by

$$z_{beam} = \sum_{i=1}^{5} I_i z_i \Big/ \sum_{i=1}^{5} I_i \qquad (4),$$

where $z_i$ corresponds to the middle of each layer. The probehead is vertically centered in the beam gap to better than 0.5 mm by its support on the vacuumcover of the lower magnet pole.

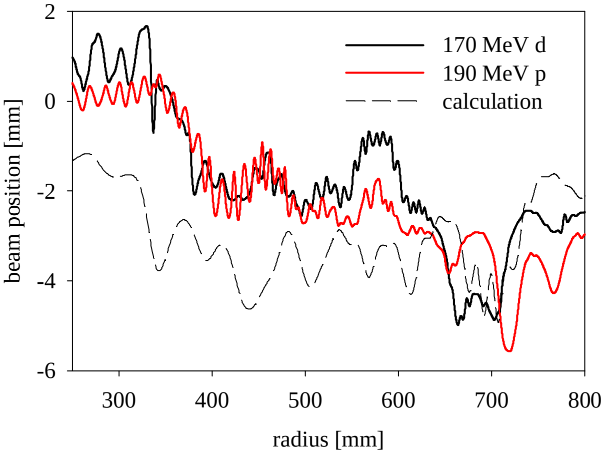

Figure 2: Beam position for 190 MeV proton beam and 170 MeV deuteron beam before corrections. The dashed line is a calculation, using equation 3, of the beam position caused by an overall misalignment of 0.5 mm.

The measurements for both beams before correction, displayed in figure 2, show the same overall pattern: the beam is progressively leaving the median plane until a minimum at a radius of about 720 mm, whereafter the beam to some extent moves back towards the median plane. The minima and maxima in the beam position occur for both beams at the same radii.

From these measurements it was concluded that a vertical misalignment between the main coils and the iron poles exists. The comparison of the data with Equation 3 shows qualitative agreement for a misalignment of about 0.5 mm, the detailed features of measurement and calculation do not match. This is only partly explained by artefacts in the calculation and the presence of a coherent vertical betatron oscillation.

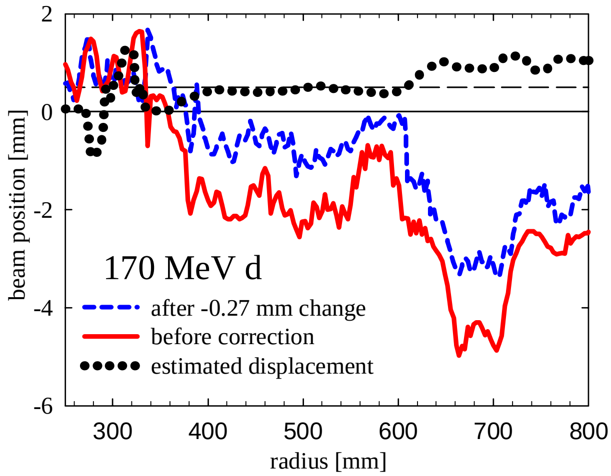

Figure 3: Beam position for 170 MeV deuteron beam before (solid line) and after (dashed line) 1$^{st}$ corrections. From the measured change in actual beam position a $\Delta z_{coil}$ can be determined (dotted line), which agrees with the initial estimate (horizontal long dashes), but shows an unexpected radial dependence.

To verify this interpretation the main coils were lowered by 0.34 mm in a few steps. After an initial displacement of 0.27 mm the beam had come closer to the median plane and the actual coil displacement could be estimated from a comparison between the two measured beam profiles (see Fig. 3). An additional step of 0.07 mm was then made. No further corrections were made, since problems started to occur at smaller radii, around 330 mm. Measurements were performed on the 180 MeV energy deuteron beam, which could not previously be extracted, which indicated that further displacement of the coils would cause large beamlosses.

Measurements of the beam position after each step show a decrease in the amplitude of the vertical motion of the beam, as is illustrated for the 190 MeV proton beam in Fig. 4, where the initial beam position and the measurements after lowering the coils by 0.27 and 0.34 mm respectively are displayed.

## CONCLUSION

During the commissioning of the AGOR-cyclotron the main coils were aligned with respect to the iron poles using magnetic measurements. From the measurements it was deduced that the sensitivity of the measurement system is about 0.05 mm. Changes in main coil position due to deformation of the magnet yoke under the magnetic forces were measured by to be smaller than 0.15 mm.

However, measurements of the vertical beam position made after observing internal beam losses indicate that a vertical alignment error of about 0.5 mm subsisted. This conclusion is corroborated by the smaller amplitude of the vertical motion after changing the main coil position. From a re-analysis of the alignment procedure it has been concluded that the only plausible explanation for this discrepancy is a 1.5 mrad tilt of the arm carrying the pendulum with the Hall-probes.

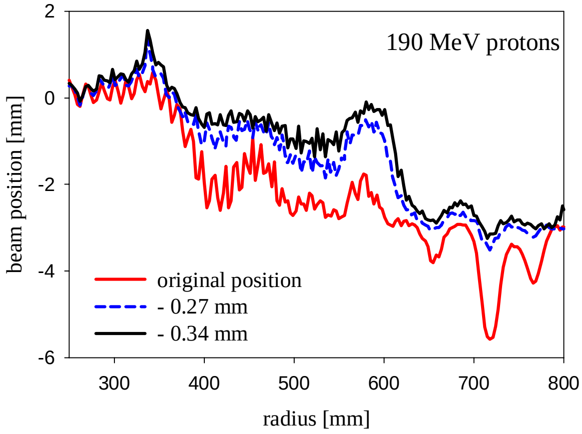

Figure 4: Beam position for 190 MeV proton beam for three different locations of the main coils.

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## REFERENCES

[1] H. W. Schreuder for the AGOR team, Proc. XIVth Int. Conf. on Cyclotrons and their Applications, Capetown (South Africa), eds. J.C. Cornell , p. 6 (World Scientific, Singapore, 1996)
[2] D.P. May and G. Mouchaty, Proc. Int. Conf. Cyclotrons and Applications, Vancouver (Canada), 1992, eds. G. Dutto and M.K. Craddock p 439 (World Scientific, Singapore, 1992)
[3] D. Vandeplassche, private communication.