VERTICAL PERTURBATION OF HIGH ENERGY PROTON BEAMS IN THE AGOR CYCLOTRON

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Abstract

Using a layered target on the radial probe, we have measured the vertical beam current distribution for several high energy proton beams ranging from 150 to 190 MeV. In particular, this allows us to measure the vertical centring of the beam. The 150 MeV beam, with high transmission (83 %) through the cyclotron, appears to be well-centred. The 190 MeV beam, with modest to poor transmission appears to be initially centred, then develops a strong vertical oscillation and finally remains several millimetres outside of the median plane. In this article these measurements are described, and possible causes of this behaviour are analysed.

1 NEW PROBE HEAD

Figure 1 shows a side view of our new radial probe head. It is made out of copper, and consists of a main piece, 16 mm high, a central piece, 6 mm high, and two copper spacer plates, each 1.5 mm thick. By putting the spacer plates in different positions, we can put the central piece in three different positions, labelled "top", "middle", and "bottom".

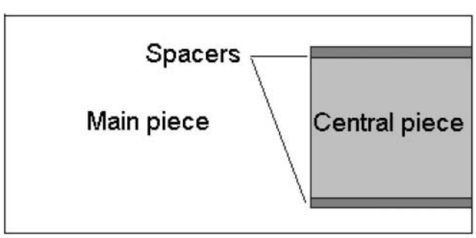

Figure 1: side view of the radial probe head

Current read-outs are connected to the central piece and the main piece. The latter is electrically connected to the spacers. Choosing z = 0 for the median plane, the central piece measures the current in the interval [-1.5 mm, 4.5 mm] (top), [-3 mm, 3 mm] (middle) or [-4.5 mm, 1.5 mm] (bottom). The main piece measures the current in the remainder of the interval [-8 mm, 8mm].

Measuring the beam current with the central piece in all three positions gives us an indication of the vertical current distribution in the cyclotron.

2 MEASUREMENTS

AGOR was tuned to produce a 190 MeV proton beam; the inflector height was adjusted for maximum extracted current, which meant that we had to put it 2 mm lower than its nominal position. Using this new probe head we could optimise the extracted beam current much more easily than before, reproducing the best-ever extraction efficiency (extraction of 40% of the injected beam) within hours.

Figure 2 shows a plot of the beam current falling on the central piece of the probe head in this configuration, for all three positions of the central piece.

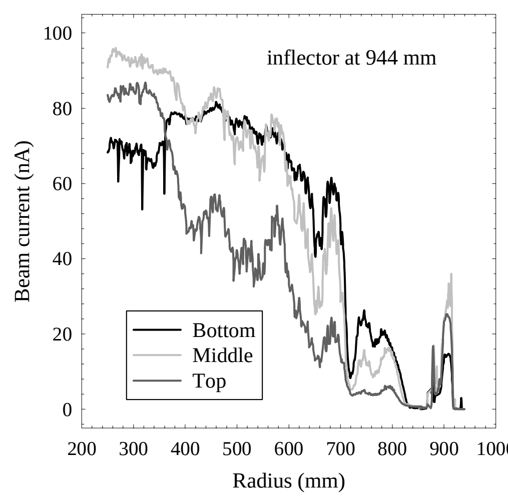

Figure 2: "central currents" in the three overlapping vertical regions.

We see that the "middle" current is highest at extraction around 900 mm, which must be the result of our optimising procedure with the inflector height. Obviously, beam arriving on the axis of the extraction channels will be extracted with the highest efficiency.

Secondly, we see some distinct features around 680 and 730 mm: the beam current locally decreased by factor two for the "middle" position. Some of this current is seen back on the main piece, (i.e. the beam either expands in the vertical direction, or it moves (coherently) away from the median plane), but most of it is lost in the cyclotron. At the abovementioned radii, and close to extraction, stripes and activation are observed on the vacuum chamber, indicating that the beam is lost by excessive vertical movement.

That the beam is moving away from the median plane, actually going underneath it, is seen by comparing the "top" and "bottom" beam current plots in figure 2. Also, the activation measured on the vacuum chamber of the lower pole is 10 times higher than on the upper pole.

This behaviour turns on as a function of beam energy with proton beams, from being hardly noticeable at 150 MeV (the beam stays essentially in the median plane) to being a nuisance at 190 MeV (focusing limit: 200 MeV).

The effect is also seen with deuteron/alpha beams, where it is absent at 50 MeV/A, but shows at 85 MeV/A (focusing limit: 100 MeV/A).

3 SOME THOUGHTS

3.1 Magnetic fields in AGOR

Figure 3 shows how the (azimuthally averaged) magnetic field is built up in the case of 150 and 190 MeV protons. There are three pairs of parallel curves, where the full lines belong to the 190 MeV and the dotted lines belong to the 150 MeV setting. Because the iron is almost saturated at 2 tesla, it cannot be seen on this scale that the "iron field" (dashed curve) consists of two parallel ones. Notice that coil 2 does hardly contribute at all.

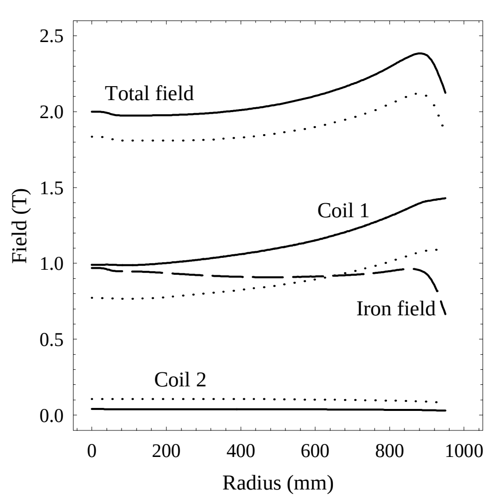

Figure 3: the magnetic field caused by the main coils and the iron, for 150 (dotted curves) and 190 MeV protons (full curves).

Similar curves can be made for 50 and 85 MeV/A deuterons, the only difference being that coils 1 and 2 have about equal contributions to the central field.

3.2 Positioning of the main coils

Figure 4 shows that our cryostat consists of two connected halves, with enough room left for (radial) access to the space between the poles and coils. Therefore, measurements could be carried out to ensure that the magnet coils were properly aligned.

This was done right after AGOR was built up in Groningen. Hall probes were used, blocking out unwanted vector components of the magnetic field by rotating the probe 180 degrees around the appropriate axis, and adding the two signals.

In this way, both the radial and the axial alignment of the coils were shown to be off by not more than 0.1 mm at 2.5 T [1].

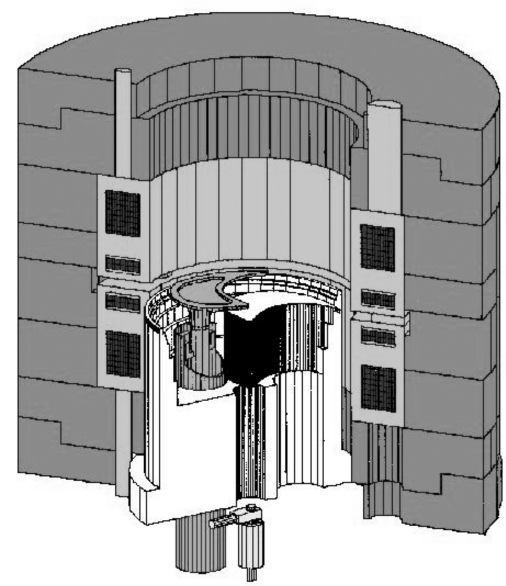

Figure 4: an exploded view of AGOR, showing the cryostat with the magnet coils, and the magnet yoke. Coil 1 is located close to the median plane, coil 2 at a larger distance.

3.3 Resonance

Another possible source of beam loss which is worth investigating is that it is caused by a resonance. This type of beam loss would explain the continuous build up of the effect as a function of beam energy. Because of our observations, this resonance should cause vertical beam movement; the most promising candidate seems to be the ν_r - ν_z =1 coupling resonance.

To excite this mode, a first harmonic midplane asymmetry has to be present. Possible sources of such a distortion could be a non-symmetric distribution of the iron in the poles, or a non-symmetric field generated by the trim coils.

Figure 5 shows the behaviour of ν_r and ν_z as a function of radius. The point ν_r - ν_z = 1 is passed several times. For 150 MeV protons, the ν_r - ν_z curve stays well below unity, as is the case with 50 MeV/A deuterium. Also, the ν_r - ν_z curve of the 85 MeV/A deuterium beam stays below unity, albeit less pronounced than is the case for 50 MeV/A.

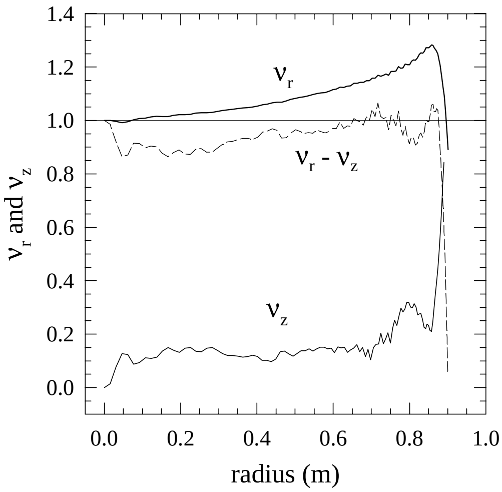

Figure 5: ν_r and ν_z for the 190 MeV proton beam, as function of radius.

4 CONCLUSIONS

From the field curves for 150 and 190 MeV protons it seems unlikely that the coils are misaligned. The fields are too similar to explain the effect that the vertical beam movements are present at 190, and absent at 150 MeV.

Also the fact that the coil positions have been measured 6 years ago and found to be correct does add to our confidence that we have no problem of misalignment.

The observation that the resonance is crossed several times for the 190 MeV beam, but not for the 150 MeV beam is an interesting one. The abovementioned radii (r = 680 and 730 mm) are compatible with the $\nu_r - \nu_z = 1$ points found in the calculations.

A puzzling point is that these calculations do not show crossing of the $\nu_r - \nu_z = 1$ resonance with the 85 MeV/A deuteron beam, while for the 85 MeV/A the vertical movement is observed.

Although a case is building for the hypothesis that the losses are caused by a resonance, presumably $\nu_r - \nu_z = 1$, the evidence is too inconclusive yet to lead to a conviction.

ACKNOWLEDGEMENTS

This work has been supported by the Rijks Universiteit Groningen (R*u*G)and by the European Union through the Large-Scale Facility program LIFE under contract number ERBFMGE-CT98-0125.

It has been performed as part of the research programme of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM), with support of the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek" (NWO).

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