INFLUENCE OF THE RF MAGNETIC FIELD ON THE BEAM PHASE IN CYCLOTRONS

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Abstract

The integral along the particle orbit of the RF magnetic field generated by the accelerating cavities depends on the geometry of the cavities and the harmonic mode used for acceleration. This magnetic field may influence the beam phase profile in the machine as predicted for the COMET cyclotron at PSI [1]. Experimental verification of this effect is not feasible at PSI but has been attempted with the AGOR cyclotron. No conclusive evidence for the effect was seen.

INTRODUCTION

J.M. Schippers *et al.* [1] have reported on calculations of the influence of the beam phase of the time dependent magnetic field H(t), caused by the RF currents in the cavities. According to the calculations this field causes an additional phase slip of about 20 °RF at extraction radius in the 250 MeV proton therapy cyclotron developed by ACCEL Instruments GmbH and now installed at PSI.

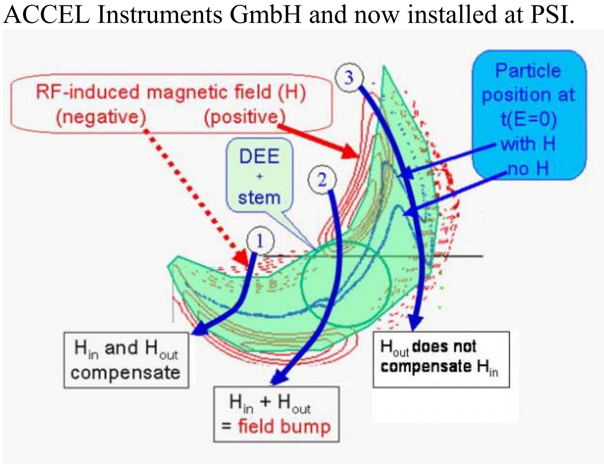

Figure 1: Calculations for the 250 MeV proton cyclotron COMET at PSI. Three particle tracks crossing the Dee and its H(t) field are indicated. The particle positions at t(E=0) with and without taking into account the H(t) field are shown [1].

The accuracy of measured fieldmaps and orbit calculations does not allow a direct experimental demonstration of this effect. In the AGOR cyclotron, which has a similar cavity geometry as the ACCEL cyclotron, the dependence of the RF-induced phase shift on the harmonic mode can be exploited to experimentally demonstrate the effect by accelerating a beam in the same magnetic field with different harmonic modes.

EQUIPMENT

The superconducting AGOR cyclotron is a multi-purpose research accelerator capable of accelerating light and heavy ions up to an energy of 190 MeV for protons 600 $(Q/A)^2$ MeV per nucleon. Three Dees deliver the RF accelerating field with a frequency between 24-60 MHz.

The accelerator operates in the 2^{nd}, 3^{rd} and 4^{th} harmonic mode. Change of harmonic mode normally requires the change of the inflector. Thirteen capacitive non-intercepting probes close to the azimuthal symmetry axis of a hill sector allow a non-intercepting measurement of the relative beam phase. A LabView based remote control system for these phase probes was recently implemented, allowing fast and convenient measurements.

At low currents a beam intensity modulation can be applied, improving the signal-to-background ratio of the measurement. In addition beam on/off measurements are used to determine the RF induced background.

At high enough currents, about 100 nA electrical or more, the relative beam phase can be measured without interrupting or modulating the beam. A more extensive description of the phase measurement system can be found in reference 2.

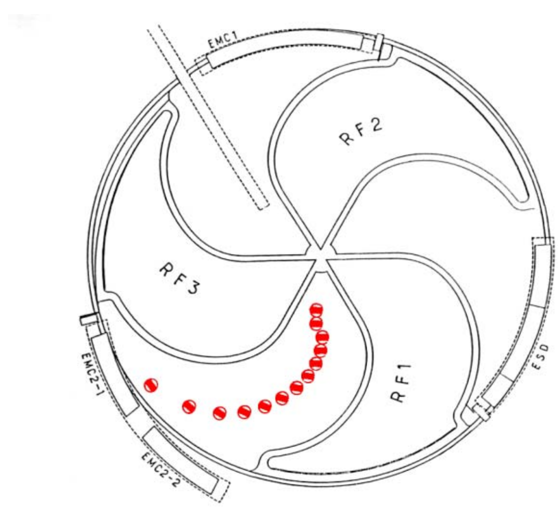

Figure 2: Location of the phase probes and extraction elements.

As can be see in figure 2, not all probes are placed on the centre line of the magnet pole face. This causes an offset of the measured phase depending on the location of the probe. The first two probes are corrected with a fixed, harmonic dependent, offset. The systematics for the offset of the probes at large radii is still under investigation, but plays no role in the currently reported results since only phase changes are measured.

EXPERIMENTAL METHOD

Beams with a frequency of 24-30 MHz at h=2 can be accelerated at all three harmonics. Figure 3 shows the acceleration voltage for such a case. The effective voltage at the location of the acceleration gap is the same for all three frequencies, but the gradient differs.

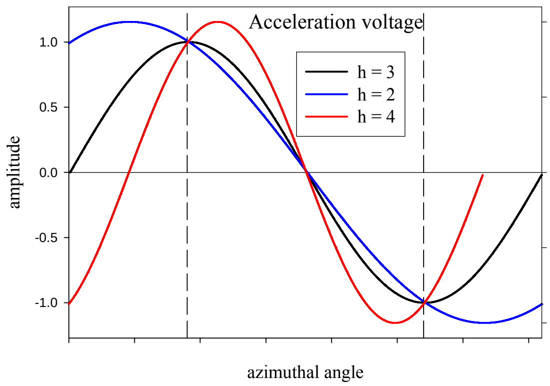

Figure 3: Acceleration voltage for different harmonic modes. The dashed lines indicate the position of the two acceleration gaps of one cavity.

When particles are crossing the acceleration gap for h=2 and 4 currents flow in the Dee, inducing a magnetic field as indicated in figure 4. In 2nd and 4th harmonic the accelerating voltage is of similar amplitude but opposite gradient. The current therefore flows in opposite direction and thus the RF induced phase slip is expected to have a opposite sign, with the amplitude for h=4 being twice that of h=2. In 3rd harmonic acceleration takes place on the top of the RF wave when no current is flowing and thus the RF magnetic field experienced by the particles will be nearly zero.

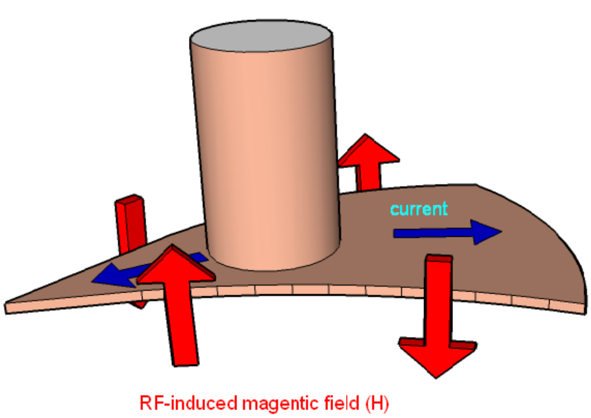

Figure 4: The direction of the RF induced magnetic field for current flowing into the Dee.

By making a precise measurement of the phase profile of a beam at all three harmonics, for exactly the same magnetic field, the phase shift caused by the RF-induced magnetic field can be measured.

PRELIMINARY MEASUREMENTS

Preliminary tests were done with a 34 MeV/A deuterium beam, to see if we could measure the predicted effect. Initial measurement at h=3 was done with an internal beam current of about 20 nA. Measurement with h=2 were done after switching the inflector, which in retrospect invalidated the results since it could not be ascertained that the magnetic field reproduced accurately.

The measured phase of probe 1 was set to zero. The phase profiles for h=2 and h=3 were subtracted and the resulting phase difference is shown in figure 5. As can be seen in the figure, the phases for the first few probes were very similar, after which a phase slip of about 15 degrees slowly built up, which could be due to thermal effects.

In a second experiment both the h=3 and h=4 beam were injected with the h=3 inflector. First the h=3 measurement was done, after which the frequency was changed and the beam was optimized. The resulting relative phase measurement is also presented in figure 5. The measurement at probe 3 seems anomalous. The general trend of the difference measurement is the same as for the previous experiment, but has the same sign, contrary to the prediction made in reference 1.

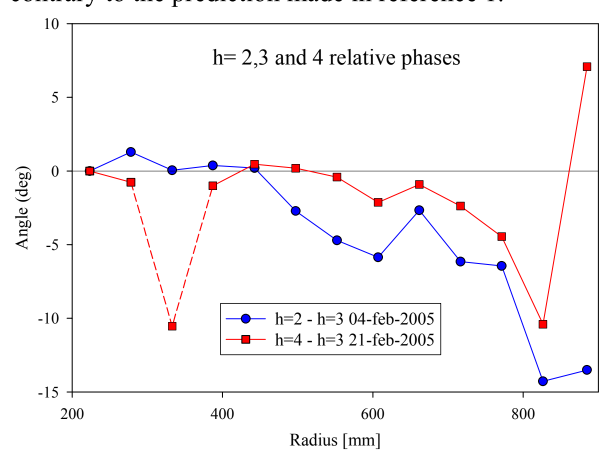

Figure 5: Phase difference measurements for a 34 MeV/A deuterium beam at h = 2 and 4 compared to h = 3 measurements immediately preceding it. The phase of probe 1 is set to zero.

Possible explanation for the observed phase change is a slow change in temperature of the magnet. The h = 3 were not repeated after the h = 2 and 4 measurements, so there is no way to verify this hypothesis.

IMPROVEMENTS

Over the past two years several improvements have been made that make a more precise measurement of the effect possible. Hence the issue was revisited in two more recent experiments.

Magnet Temperature

Since we have no way to actively control the magnet temperature, we decided to perform these sensitive measurements after the magnet yoke had time enough to reach thermal equilibrium. Since the amount of power dissipated in the correction coils is the main cause of temperature variations, it is important to compare measurements where these coils have been at the same setting for at least 24 hours.

High beam current

Based on experience with the phase measurement system it became clear that beam currents significantly higher than 20 nA were needed to get a good signal-to-background ratio. The choice of deuterium for the beam severely limited the available current so we switched to a molecular hydrogen beam (H_2^+)

Furthermore, a program was started to increase the beam intensities of heavy ion beams, which are needed for the TRIμP experiments [3].

The advantage of the higher beam intensities is that measurements can be performed without interrupting the beam. Intensity modulation and beam-off measurements are not needed. The buncher is not required to get sufficiently high currents. In this way excellent signal-to-background ratio and very reproducible results are obtained.

Automated beam phase measurement system.

In the winter of 2006 the phase measurement system was fully automated and provided with a LabView user interface, allowing fast and convenient measurements from the cyclotron control room with immediate processing and display of the data.

RECENT MEASUREMENTS

A recent measurement was performed with a 40 MeV/A H_2-molecular ion beam. The whole experiment was done using the h=3 inflector without making any changes to the magnetic field or injection. This experiment was not successful, since no beam could be accelerated at h=4 because a too high acceleration voltage was needed. Repeated measurements at h=3 showed a change in relative phase up to 10 degrees near extraction, indicating that the magnet was not sufficiently stable.

A final experiment was performed using a high intensity 23.3 MeV/A $^{20}Ne^{6+}$ beam. This experiment was performed at the end of a 3-day experiment, at which point the magnetic field can be considered stable and the magnet settings optimized for highest extraction efficiency. All measurements were done with the h=3 inflector and an internal beam current of several hundred nA, which gives a good signal-to-background ratio without beam intensity modulation. Background measurements (beam-off) were done to eliminate possible RF induced systematic effects. The h=2 measurements were performed with a frequency of 23.606 MHz, below the nominal range of our RF system and the lowest frequency used up to now.

Three sets of h=3 data with about 3 hours in between showed minimal variation, see figure 6, giving confidence that the magnetic field was indeed stable. The beam was not extracted, therefore the outermost probe 13 is excluded from analysis. Although phase changes up to 10 degrees are observed, the trend and magnitude do not correspond to predictions in reference 1.

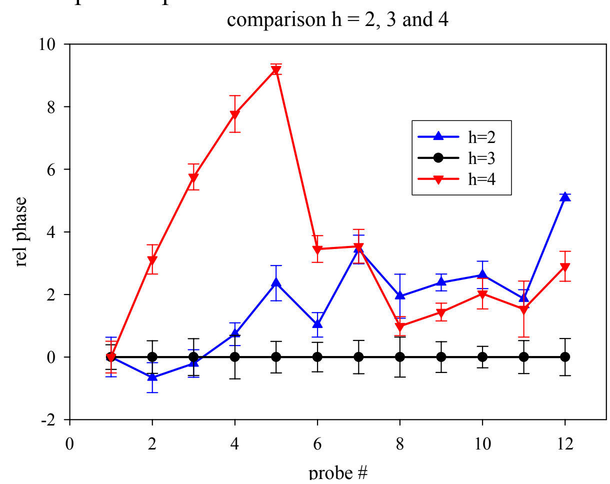

Figure 6: Relative phase shifts between measurements at h=2, 3 and 4 for a 23.3 MeV/A $^{20}Ne^{6+}$ beam, corresponding to an RF frequency of h*11.803 MHz. Error bars for h=3 represent the variance of the three data sets. Due to time constraints only one set of measurements was performed for both h=2 and h=4.

CONCLUSIONS AND OUTLOOK

A reliable and reproducible beam phase measurement without beam modulation is possible with a low energy (23.3-40 MeV/A) high intensity (>200 nA) beam. For best results it is important that the magnet is in thermal equilibrium.

In a series of experiments performed at h=2, 3 and 4 we have attempted to measure the effect of an RF induced magnetic field on the beam phase predicted by Schippers et al. [1]. A sub-degree sensitivity was achieved, but no conclusive evidence was found for this effect, possibly because the RF fields used in our experiments were smaller.

REFERENCES

[1] J.M. Schippers, D.C. George and V. Vrankovic, Proc. ICCA 2004, p. 435

[2] S. Brandenburg, T.W. Nijboer and W.K. van Asselt, Proc. DIPAC 2003, PT12

[3] S. Brandenburg *et al.*, "High Intensity operation of the AGOR cyclotron for RIB-production", these proceedings