

Beam Dynamics Studies at the Gustaf Werner Cyclotron.

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Abstract

The beam dynamics of the Gustaf Werner cyclotron including the injection line from the external ion sources are being studied. Numerical calculations as well as the use of new instrumentation in the machine will increase the understanding of the beam behaviour under varying operational conditions. The GW-cyclotron is connected to an ECR-source for heavy ions and an ion source for polarized protons and deuterons, and it can be used both as an isochronous and synchronous cyclotron, which makes it highly flexible. The present instrumentation consisting of probes for measuring the current and turn separation in the cyclotron will be further developed. A phase probe, and a luminescent plate connected to a TV-monitor, have been installed. These tools will be incorporated in the routine adjustment of the cyclotron parameters.

1 INTRODUCTION

The transmission through the Gustaf Werner cyclotron when operated with externally injected beams has been lower than expected, especially for ions from the polarized ion source. At present, the transmission from the ECR ion source out to a radius of 500 mm in the cyclotron lies in the region 10-15%. The overall transmission for polarized protons to the cyclotron exit has been only 1%. In order to get a better understanding of what happens during injection and where particles are lost, a model for the axial injection system has been proposed and numerical calculations have been carried out.

Detailed measurements on the magnetic field distribution in the axial injection hole of the cyclotron were carried out in the summer of 1992 [1]. The resulting field maps have been used as a basis for a multipole expansion of the magnetic field in the hole [2]. The path tracking program ION_TRACKER [3] has been modified to include this multipole expansion, with the intent that it should be used for tracking calculations in the axial hole.

2 AXIAL INJECTION

Special problems arise when ions are injected from an external ion source. The ion optics elements in the injection line must be carefully matched to get the most efficient injection. The strong magnetic field gradients the ion beam encounters when it is about to enter the gap of the cyclotron magnet makes it difficult to align the beam for inflection into the median plane. Therefore it is desirable to get as good an understanding as possible of how the beam is modified by the magnetic and electric forces in the injection area and the central region of the cyclotron. Such knowledge would

suggest how the emittance of the beam must be to obtain the best transmission through the accelerator.

The first studies of axial injection were made at the Grenoble cyclotron by Pabot in the 1960's [4]. Pabot proposed a theoretical model for treating the inflection element, in his case a spiral inflector, and the ion motion in the central region of the cyclotron. His calculations were based upon simple geometrical and optical considerations, governed by basic electromagnetic theory. Pabot's work has been subject to further studies over the years and refinements of his thesis have been made by Belmont [5] and Root [6], [7].

To get a better idea of the axial injection in the Gustaf Werner cyclotron we have chosen to follow the scheme for calculations outlined by Pabot. Hence acceptances for the inflector and the first few turns in the cyclotron have been computed.

As a starting point for our calculations a six-dimensional phase space has been defined at the inflector entrance. The coordinate system used is closely connected to the coordinate system of TRANSPORT [8].

The injection system of the GW-cyclotron, from the last bending magnet down to the median plane, consists of a buncher, two solenoids and a spiral inflector. Guided by this, the problem has been divided into three parts:

- the spiral inflector
- the central region
- the axial hole

2.1 The spiral inflector

Under the assumption of a constant axial magnetic field Pabot derived a system of coupled differential equations that describe the motion of the ions near to the central trajectory inside a spiral inflector [4]. Root made some small adjustments to these equations [6] and stated them in the form:

$$\begin{cases} \alpha'' + 2\gamma' - 2k\beta' \cos \theta - 2\alpha = 0 \\ \beta'' + 2k(\alpha' \cos \theta + \gamma' \sin \theta) - 2k\alpha \sin \theta = 0 \\ \gamma'' - 2k\beta' \sin \theta - 2k\beta \cos \theta - 2\alpha' = 0 \end{cases} \quad (1)$$

(This is for the special case of "unslanted electrodes". For a more general treatment, allowing for a radial electric field component, proportional to the magnetic force along the trajectory, see Pabot [4] and Root [6].)

These equations have been solved numerically [9], using Euler's method for differential approximations. Special care has been taken when constructing the transfer matrices for the inflector as to incorporate the effect of changes between rotating and non-rotating reference coordinate systems. The hard edge approximation has been used at the electrode edges to compensate for the fringe fields.

2.2 The central region

The behavior of the beam in the central region of the cyclotron is of special significance for the transmission, and hence for the acceptance of the cyclotron. Based upon Pabot's geometrical considerations [4], the calculations in the horizontal plane may be described as follows:

For each ion leaving the inflector, the centre and radius of curvature are determined at the inflector exit. The ions are then regarded as moving in circular paths across the dees and dummy-dees. Each time an ion travels across an accelerating gap its energy increases. Since the radius of rotation is proportional to and perpendicular to the velocity, there is a corresponding adjustment of the centre and radius of curvature to every increase in energy of the particle. If the relative increase in momentum is small, the dee gaps can be assigned transit time factors. The acceleration in the first gap is especially strong, so the calculation has to be carried out in a slightly different way: the gap can be decomposed into micro-gaps and the equation of motion is integrated analytically in each slice.

The vertical motion of the ions has been treated optically by Pabot [4]. The gaps between dees and dummy-dees constitute electrical lenses that have appreciable focusing effect on the ions in the central region where the relative gain in energy is large. Outside the gaps the predominant focusing force is magnetic. The transfer matrices for the dees/dummy-dees are rotation matrices containing the effect of the radial variation in the magnetic field through the field index n . The azimuthal variation of the magnetic field, usually described by the flutter parameter F , has a negligible effect in the central region of the cyclotron and has therefore been neglected.

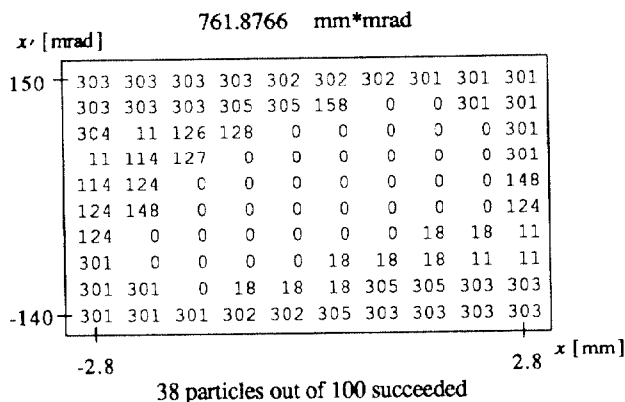


Figure 1: Acceptance area in the $x - x'$ plane (at top of spiral inflector).

Figure 1 is an example of an acceptance area in the $x - x'$ plane, calculated with a program package CYCLOTRON [9] that tracks particles through the spiral inflector and follows them during the first few turns in the cyclotron. The whole tracking volume has been coded with numbers which makes it easy to see where a specific particle is lost. Digit 0 corresponds to an accepted particle. The case shown is $^{12}\text{O}^{4+}$ injected at an energy of 40 keV. The ion frequency used is

6.25 MHz and the particles are accelerated on the second harmonic.

2.3 The Axial Hole

When the ions are injected from the external sources they have to pass through the fringe magnetic field in the axial hole in the cyclotron yoke. Because the field gradients are steep, especially upon entry in the median plane field, a strong focusing of the beam follows. To obtain a picture of how the field inside the hole affects the acceptances at the inflector entrance, tracking calculations have been performed using two versions of ION_TRACKER: the original version by Rinta-Nikkola [3] and a version that permits an azimuthally varying magnetic field.

The magnetic field measurements made in the injection hole of the GW-cyclotron [1], revealed a three-fold symmetry in the radial field component, at least a few decimetres up in the hole, reflecting the three sector symmetry of hills and valleys in the cyclotron median plane. This led us to believe that if the magnetic field was dissolved into its Fourier components there would be a significant contribution from the octupole term, that perhaps could affect the acceptance.

Starting with Maxwells equations for the region inside the hole, a multipole expansion of the magnetic field has been made which utilizes the measured field map. If the axial field is assumed to be approximately independent on both r and φ , (a cylindrical coordinate system (r, φ, Z) is defined for the hole with origin in the cyclotron median plane) the expression for the horizontal field component in the axial hole reads:

$$\bar{B}(r, \varphi) = \frac{c_0}{r_0} r + c_1 e^{i\varphi} + c_2 \frac{r}{r_0} e^{i2\varphi} + c_3 \frac{r^2}{r_0^2} e^{i3\varphi} \quad (2)$$

The quadrupole component can be neglected as the coefficient c_2 is very small for all Z -values (this is due to the three sector symmetry of the field). Terms of higher order than three are also negligible as long as $r \leq r_0$, the measuring radius. Equation (2) successfully reproduces the field in the hole.

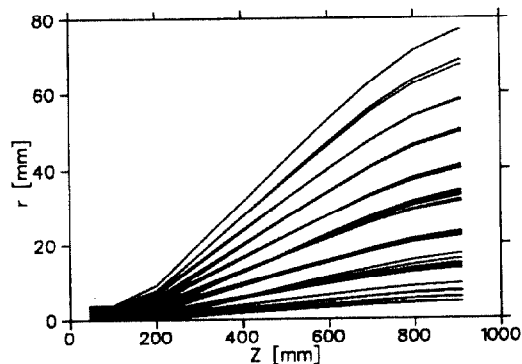


Figure 2: Particle trajectories in the axial hole. Tracking has been performed without solenoid fields.

The calculated acceptance at the top of the inflector has been transformed "backwards" through the axial hole [2] using both versions of ION_TRACKER. From the results, it has been concluded that the azimuthal field variations have a very

small influence on the acceptance. The results also show that, in order to fill the acceptance volume at the inflector entrance, a stronger focusing of the beam is needed in the last 100 cm of the hole down to the median plane. We are investigating the possibility of moving the present focusing elements (solenoids) or perhaps introduce additional ones to improve the transmission.

3 BUNCHING

To increase the intensity of accelerated, externally injected ions from the cyclotron, a bunching system has been installed in the injection beam line. The buncher has increased the cyclotron beam current by a factor of 3 to 5 for the ions tested so far. The buncher is positioned 2.65 m above the spiral inflector. It consists of three copper cylinders separated by accelerating gaps. The middle cylinder is connected to an rf amplifier and the outer cylinders are grounded. The buncher amplifier has so far been driven directly from a cyclotron rf pick-up via an adjustable delay and an adjustable attenuator.

4 PHASE PROBE

To obtain an effective way for tuning the precise isochronous magnetic field with the trim-coils, an on-line beam phase measuring system is planned to be installed in the cyclotron during 1994. Our design has many similarities with the system at the K130 cyclotron in Jyväskylä, Finland [10], and uses a set of capacitive probes to detect the phase information from the internal beam.

The beam signal is obtained from 11 electrostatic pick-up pairs, mounted symmetrically above and below the median plane of the cyclotron at radii mainly defined by the location of the trim-coils. Each probe consists of a copper plate and a coaxial vacuum feed-through leading to a beam and RF-shielded inner coaxial conductor. By adding the in phase signals from the upper and lower plate, a reduction of the RF-disturbances will be obtained. The phase information is extracted from a frequency component at twice the RF-frequency, reducing the undesired coupling of the fundamental frequency of the accelerating voltage to the phase probes. The added signals are first fed into a differential 16 to 1 multiplexer where one of the 11 pairs (or a test signal) is selected.

A phase reference signal, fixed in amplitude, is obtained from the accelerating system and, after frequency doubling, this signal is mixed with a local oscillator in a single-sideband (SSB) mixer. The upper sideband is then mixed with the comb-filtered and amplified probe signal from the multiplexer in a double-balanced mixer. As a result a fixed frequency signal is obtained carrying the information of the phase difference between the reference and the probe signal.

To eliminate undesired mixing products a narrow-band crystal filter will be installed before an amplifier and the detecting circuit. This I/Q -detector is formed by two analog multipliers where one is fed from the reference signal, with a phase lag of 90° (obtained with a length of coaxial cable). The resulting phase vector in rectangular coordinates, generated

from the output DC-signal, is then digitized for the control system.

5 INTERNAL TV-PROBE

In december 1993 an internal TV-probe for detection of low current beams was installed in the GW-cyclotron. The basic idea was borrowed from MSU, East Lansing, Michigan, [11] where similar equipment has been used to study internal beam dynamics. Our CCD camera is mounted inside a stainless steel tube facing a 4 cm^2 scintillator plate (doped aluminium oxide) at a distance of 2 m. The video signal received is processed with a digital frame grabber and a real time picture can be viewed on a TV-monitor. The scintillator plate can be moved from 100 mm radius out to full radius (1200 mm) in the cyclotron. Currents in the pA range can be detected for beam centering purposes, and it is possible to expose the scintillator to several nA without damage. Vertical oscillations as well as radial off-centering and turn separation can be observed. The TV-probe has turned out to be a valuable tool when searching for low current beams and hopefully it will help us to a better understanding of the internal beam dynamics in the cyclotron.

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