A New Design of the University of Manitoba Cyclotron for D^- ion Acceleration and A Study for the Beam Extraction from the Princeton University AVF Cyclotron

by

YUNXIANG HUANG

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

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Synopsis

Two independent cyclotron upgrading projects are treated separately: a redesign of the University of Manitoba cyclotron for D^- ion acceleration and a study of the beam extraction from the Princeton University AVF cyclotron. These two projects are described in part 1 and part 2 of this thesis, respectively.

The first part includes an analysis of the magnetic field mapping data that was previously obtained from the University of Manitoba cyclotron, as well as systematic beam orbit dynamics study based on the improved magnetic field and the newly designed central dee-tips for D^- ion acceleration. These studies show that after the upgrade program is finished, it will be possible to obtain in the University of Manitoba cyclotron a D^- ion beam with substantial improvement in the available maximum energy, beam quality and transmission efficiency.

The second part of this thesis first describes the extensive modifications that were made in the computer program that was previously used. The modified program can now be used over the full energy range of an AVF cyclotron. Then the upgraded computer code is utilized to carry out simulative calculation for the reference particle and the beam in phase space, from the ion source through the electro-static deflector of the Princeton University AVF cyclotron. On the basis of these studies, all the parameters for the extraction system are optimized, and suggestions for further improvements are proposed.

Acknowledgements

Although only one name appears on the title page of this dissertation, a number of other people contributed to this work in very substantial ways, both technical and non-technical.

Most importantly, I shall always be extremely grateful to my advisor, Professor Saewoong Oh for his infinite encouragement and guidance. Professor Oh taught me very much about accelerator physics. He was a very thoughtful and very kind teacher and I have benefited greatly in very many ways by working with him during the past four years. Dr. Moohyun Yoon was extremely helpful, enthusiastic, as well as generous in sharing his knowledge. I am very grateful to Dr. Yoon for all his assistance and friendship.

For their constant and generous help during all the years of my stay at the University of Manitoba, I am grateful to all the members of the machine development group of the cyclotron laboratory: Professor J.S.C. McKee of the Director of the Cyclotron Laboratory, Mr. Irv Gusdal, Vladimir Drenchuk, Jim Anderson and their other colleagues. Dr. Tony Smith spent much time to introduce me to the VAX/750 computer; I would like to thank him deeply.

I was fortunate to have the chance to participate in the upgrading program of the Princeton University cyclotron. I am very grateful to Professor Frank Calaprice and Professor Arthur McDonald for providing me with this opportunity and for supporting me during my stay at the Princeton University. I also obtained a great deal of very valuable assistance from Dr. Richard Kouzes, who not only helped me to master the Data General MV 10000 Computer but also read carefully the second part of this thesis and suggested many improvements. Dr. Yitzhak Sharon spent a lot of time in reading the original manuscript of this thesis and in further improving my English. He also gave me other advice whenever it was needed. Therefore, I would like to thank him. The late Dr. William Moore, as well as Steve Kidner and Fred Loeser, have all been most helpful in familiarizing me with the intricacies of the Princeton cyclotron.

Finally, I wish to express my deepest and warmest gratitude to my wife, Shuzhen Li. While I was writing this thesis, she single-handedly took care of the entire housework and also assisted very greatly with the dissertation drawings and typing, in addition to her own research work in the Biochemistry Department of the Princeton University.

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Introduction

The principle of the cyclotron was proposed in 1930 by Ernest O. Lawrence of the University of California ([LAW30]). In 1932, Lawrence and Livingston in their paper described the first prototype model which produced a proton beam of over 1 MeV energy at the Berkeley Laboratory. This early success stimulated interest in many laboratories around the world, hence more cyclotrons were built during the next two decades.

However, the conventional cyclotron is limited in energy by contradictory requirements on the magnetic field. To provide beam stability (focusing) along the direction of the magnetic field (axial direction), the field must decrease with radius. But to keep the beam in phase with a constant frequency accelerating voltage on the dees, the field must increase with radius to compensate for the relativistic increase in the mass of particles.

The discovery of phase stability by Veksler and McMillan in 1945 allowed the phase requirements to be satisfied by modulating the frequency of the accelerating voltage. A magnetic field fall-off is introduced in this "synchrocyclotron" to provide axial focusing. This principle has been used to accelerate protons up to energies of 700 MeV at the University of California. Unfortunately, the duty cycle in this type of machine is only about 1% of that of the conventional fixed-frequency cyclotron.

An alternate solution to the energy limitation was proposed by Thomas in 1938 ([THO38]). He suggested that the phase requirement be satisfied by having the average magnetic field increase with radius. A new type of axial focusing would be provided by an azimuthally varying magnetic field (AVF). This would more than compensate for the defocusing due to the increasing average field. In the 1950's several "Thomas cyclotron" were built at Berkeley and Los Alamos. This demonstrated that for protons, the Thomas principle could be used to increase the energy of fixed-frequency cyclotrons from 20 MeV up to several hundred MeV. Another suggestion, made in 1955 by Kerst ([KER55]), was that spiral sectors of strong magnetic field would give more axial focusing than the straight sectors, and therefore a spiral-ridge cyclotron emerged.

Since the 1950's, the advent of the relativistic cyclotron gave an impetus to build new cyclotrons in many laboratories around the world. The University of Manitoba cyclotron and the Princeton University cyclotron (whose upgrading studies form the two main constituents of this thesis) were built in the early and in the late 1960's, respectively. From then until the present time, they have been continuously devoted to fundamental subatomic physics investigations.

In the two decades that have passed since these two cyclotrons were built, there has been a significant advance in cyclotron technology, progress that was in part due to the appearance of solid-state electronic devices and the emergence of powerful computers. The solid-state based instrumentation made it possible to carry out precise mappings and analyses of the cyclotron magnetic field. The powerful new generation of computers enabled one to calculate the RF electric field distribution inside a cyclotron and then to trace particle trajectories from the ion source to the extraction radius, under the influence of this calculated electric field and the measured magnetic field. The accuracy of these calculations is much better than what could be obtained at the time when these first-generation AVF cyclotrons became operational.

In a separate development, nuclear physics experiments became more and more sophisticated during the same time span, resulting in a need for beams of higher intensity and better quality. In response to this demand, together with the availability of enormously more advanced cyclotron technology in the 1980's, many laboratories around the world began to embark upon ambitious upgrading programs for their cyclotrons.

The University of Manitoba Cyclotron Laboratory was no exception. In fact, members of the machine development group at this laboratory started investigating the possibility of such an upgrading as early as 1976, when they carried out exploratory magnetic field mappings. Later, in 1982, more elaborate field mappings [DER83] based on computer-aided technology were performed with much higher precision. The result was quite encouraging; it convinced them that a substantial improvement in beam quality would be achieved by upgrading the cyclotron. This finally led to a decision to initiate an extensive and intensive improvement program for the cyclotron, a project which was started in 1984. The author was engaged in design studies for a new central region of the cyclotron for the acceleration of D^- ions, and in a beam dynamic investigation based on this new central region geometry.

The Princeton University AVF Cyclotron Laboratory also turned its attention to the type of improvements described earlier. A proposal to upgrade the facility has been submitted to the National Science Foundation. The objective of the modifications to the existing accelerator system is to provide beams of a wider variety, with substantial improvements in intensity and energy resolution.

For this purpose, a design of a new central region of the accelerator has been developed by Professor Oh and Dr. Yoon. The design, coupled with a new design study of the extraction system as well as improvements to the power supply system and the use of a higher dee voltage, is expected to enhance beam intensity by about a factor of four. This also enables single turn extraction to be accomplished, providing the excellent energy resolution and brightness needed for high resolution experiments.

The initial beam dynamics study by Professor Oh and Dr. Yoon was limited to the central region. The author's task was to extend the above study to the full energy range of the accelerator and to carry out a redesign investigation of the beam extraction system.

This thesis consists of two independent parts under the following headings:

(1) A redesign of the University of Manitoba cyclotron for the acceleration of D^- ions, and,

(2) A study of beam extraction from the Princeton University AVF cyclotron.

The first part begins with a brief historical background of the University of Manitoba cyclotron is presented. Then the magnetic field analysis before and after the upgrading program is given. It is then followed by comprehensive investigations of the particle dynamics of the D^- ions in the newly designed central region based on the improved magnetic field. This part contains an introduction to the electric field distribution calculation, determinations of some important engineering parameters, an inspection of the beam stability in both radial and axial motions, and finally a computer simulation study of positive beam extraction from the cyclotron. This part concludes with a presentation of the expected improvement in performance of the cyclotron for the acceleration of D^- ions after the upgrade.

The second part of this thesis deals with the upgrading program of the Princeton University cyclotron. It starts with an introduction to the Princeton University cyclotron, followed by a description of the modifications of the old computer programs. These modifications were necessary for the project. Considerable amount of space in connection with the new design, is devoted to the discussion of the investigation of the beam extraction system. Finally, a summary is given in which optimized values of important parameters for the extraction system are presented and some possible future improvements are also suggested.

Part I

A New Design

of

the University of Manitoba Cyclotron

for D^- Ion Acceleration

Chapter 1

Historical Background

The University of Manitoba cyclotron is a four-sector, spiral-ridge, variable energy machine, which was originally designed to accelerate an H^- beam whose energy could range from 20 to 50 MeV [STA62]. The unique feature of this cyclotron is the method that is employed in it for trimming the magnetic field. Here, unlike other machines, the field is trimmed by individually controlling the permeability of 64 blocks of Invar alloy ([PIC40], [BUR65], [BUR66]). These blocks are placed, eight at a time, sandwiched between each hill piece and the corresponding pole piece (8 blocks/hill piece $\times$ 2 hill pieces/hill $\times$ 4 hills). The radial profile of the magnetic field can be shaped by adjusting the temperatures of the Invar blocks (which are arranged underneath each hill piece, successively, in eight radial positions along the radius of the cyclotron.)

In 1976, D^- ions were also successfully accelerated and extracted from the Manitoba cyclotron. Polarized D^- ions were subsequently successfully accelerated in 1980. However, deuteron beams were rarely accelerated after that time, due to low beam intensity and beam instability. In addition, the maximum D^- ion beam energy that was reached was only 19 MeV. From the existing cyclotron design parameters, on the other hand, one expected to achieve variable- energy deuteron extraction with up to 23 MeV. The main problem here was the loss of vertical focusing in some regions of the cyclotron, and the isochronism was also poor. In addition, there were some other problems which also contributed to fluctuations in the beam current that was available from the cyclotron. These problems included, among others, very small energy gain per turn, dee movements due to a mechanical backlash, RF heating of the dee system, etc. These problems are described in detail in ref. ([HUA84]), ([CDG83]), ([BRU82]).

The above facts, plus the specific problems which were related to the acceleration of H^- ions ([MYT86]), led us to believe that the upgrading of the Manitoba cyclotron was an urgent task. Additionally, as time passed, the nuclear physics experiments became more and more sophisticated, requiring beams of increasingly higher quality and versatility. Hence, the need to upgrade the cyclotron performance to meet the above demands became acute. Consequently, two exploratory studies were carried out in 1976 and 1982. Based on the above, major upgradings were carried out in 1984, as is described in detail by Dr. Yoon in his Ph.D dissertation([MYT86]).

Prior to the 1984 upgrading program, the D^- ions were injected at 5.5 KeV and then accelerated by application of 14.24 MHz rf to a pair of diametrically placed dees which was operated in the push-pull mode at a peak voltage of 14.5 KV. These parameter values, however, were by no means the optimum values, having been chosen to keep the D^- ions in the same trajectory as the H^- ions. Until the completion of the 1984 major upgrading program, this was the only option available for accelerating D^- ions.

An extensive upgrading of the cyclotron in 1984 totally changed the cyclotron parameters for D^- ion acceleration. The main features were:

1. The presence of two separate dee-tips in the central regions; one for H^- ions and another for D^- ions. These were built to be mechanically interchangeable

without too much inconvenience. It was not possible to compromise the central region design so that one central region geometry would serve for both modes of operation, and still maintain the required beam quality.

2. The dee frequency was changed from 14.24 MHz in a push-pull mode to about 30.50 MHz in a push-push mode. The change in frequency, coupled with an improved magnetic field, was expected to increase the available maximum energy of the deuteron beam to 27 MeV from 19 MeV.

3. The D^- ion injection energy was increased to about 15 keV(from 5.5 keV) and the dee voltage to 40 kV(from 14.5 kV). These changes, together with the change to an RF push-push mode, greatly increased the energy gain of the D^- ions, resulting in much better beam stability, beam reproducibility and transmission efficiency.

The construction of the new dee-tips and the new central region for D^- ions was started in-house in 1984, during an intensive major cyclotron upgrading project. The design was based on the data that was obtained during the exploratory cyclotron magnetic field mapping program which was carried out in 1982. During the 1984 field mapping and shimming program, however, the magnetic field of the cyclotron underwent an extensive reshaping([GUS84]). The cyclotron flutter field was effectively extended inward, towards the center of the cyclotron, to improve the vertical focusing in this region. This extension, however, resulted in the radial broadening of the bump magnetic field of the cyclotron.

To take this broadening effect into account, and to investigate the effectiveness of the parameter changes, the dee-tips and central region were redesigned and the beam orbit dynamics were restudied.

The first part of this thesis (chapters 1-5) describes the author's work within the context of the upgrading project of the University of Manitoba cyclotron. This work involved the analyses of the field mapping data, the redesign studies for a new central region for the D^- ion acceleration, and a detailed study of the beam orbit dynamics.

Chapter 2

The Magnetic Field for the Acceleration of D^- Ions

2.1 The magnetic field mapping method

In the University of Manitoba cyclotron, to measure and improve the magnetic field distribution, field mapping programs were carried out in 1976,1982 and 1984. In the last mapping program, a "flip coil" (which consisted of an assembly of 52 coils, equally spaced along the radius of the cyclotron), was utilized. As the coils were moved along the azimuthal direction on the median plane and flipped, the current induced in them flowed to chopper-stablized integrators. A digital voltmeter measured the individual integrated voltages through the multiplexer. All the data and control signals passed through interfaces onto a LSI-11/23 microcomputer. Once a mapping had been started, this computer controlled all the measuring events and recorded the field measurements at uniform intervals of azimuth angle. The resulting raw field values were transferred to the VAX-11/750 computer for analysis.

After that, the fields were Fourier-analyzed to sort out their intrinsic harmonic components. The resulting magnetic field in the median plane(z=0) of the cyclotron can be expanded as

$$B_z(r,\theta) = B_0(r) + \sum_{n=1}^{\infty}(A_n(r)\cos(nN\theta) + B_n(r)\sin(nN\theta)) \quad , \qquad (2.1)$$

where $B_0(r)$ is the average field at radius r, and N is the number of magnet sectors. Here, $A_n(r)$ and $B_n(r)$ represent the amplitude of the n^{th} harmonic components of the magnetic field.

Note that components attributable to the field imperfection have been omitted in eq.(2.1) because the field mappings were performed only over one complete sector of the cyclotron. This automatically eliminated any possibility of recovering the imperfection field components from the measurements.

The analysis was carried out by using the code MAPANL which was developed at the University of Manitoba (henceforth denoted by U. of M.) cyclotron laboratory. The basic algorithm of MAPANL was introduced in the work of Gordon and Welton ([GOR59], [WEL59]), who developed methods to find the equilibrium orbit and to calculate ν, ν_r, ν_z, *etc.* as functions of the energy. With the particle energy as an input, the program integrates the equations of motion over one magnetic field period(90°), using the azimuthal angle(θ) as the independent variable. Since the equilibrium orbit, by definition, is smoothly closed upon itself, the initial values of r and p_r are the same as the final values of these variables along the equilibrium orbit. The determination of an equilibrium orbit then reduces to the determination of the initial values of r and p_r.

The radial equations of motion are integrated numerically, to obtain r and p_r through a process of successive iterations and to determine the transfer matrices over one period. Once r and p_r have been found, all the equations, including the axial equations, are subsequently integrated. Then the knowledge of transfer matrices for the radial and axial motions enables us to calculate ν_r and ν_z by using the following two relations ([LIV61]):

$$\nu_r = \frac{1}{\theta_0}\cos^{-1}\left(\frac{J_{11}+J_{22}}{2}\right), \qquad \nu_z = \frac{1}{\theta_0}\cos^{-1}\left(\frac{K_{11}+K_{22}}{2}\right) \quad . \tag{2.2}$$

Here, θ_0 is 2π divided by the number of sectors; J_{ij}, K_{ij} are the corresponding elements of the radial and axial transfer matrices, respectively. From the above equations, it is apparent that the motion stays bounded if $J_{11}, J_{22}, K_{11}, K_{22}$ are real and if the absolute value of the trace of each of the transfer matrices is less than two.

The revolution frequencies, ν_r and ν_z, can be easily evaluated after all the integrations over one period have been carried out with respect to the independent variable θ. The time t is also integrated as a function of θ. Several references ([GOR59], [WEL59]) provide the explicit forms of the equations of motion as well as more details about the computational procedures.

By repeating the above procedures for different input energies, one can obtain curves of ν, ν_z and ν_r, as functions of r.

These three curves were then investigated to obtain improved shapes and locations for shims to be placed inside the cyclotron. On the basis of these three curves, we could also choose a better set of temperature settings for the Invar blocks for the succeeding mapping. The shims, after being machined, were placed in the indicated position inside the cyclotron for the next set of field mappings.

2.2 Analysis of the mapping data

Figs. 2.1, 2.2 and 2.3 show the field properties before the upgrade of the magnetic field. These figures provide the D^- particle's revolution frequency (ν) as well as the axial (ν_z) and radial (ν_r) focusing frequencies. Each of these frequencies, (the three most important characteristics of the cyclotron magnetic field), is plotted as a function of the radius of the D^- ion beam.

Ideally, ν should be a constant all along the radius, so that the isochronism in the acceleration of the D^- ions can be maintained. However, Fig. 2.1 indicates that it fluctuates considerably.

A particularly conspicuous fluctuation is seen to occur at a radius of approximately 10 cm. This fluctuation is caused by a premature termination of the central bump magnetic field. Such a bump pulls the flux from the surrounding area, and therefore tends to leave a shadow just outside the bump.

A departure from isochronism results in a phase oscillation of the particles during acceleration. Let us now utilize the following notation: we define ϕ to be the phase of a particle with respect to the RF voltage, N the turn number, ω_{RF} the angular oscillation frequency of the electric field, $\omega(E)$ the particle's revolution frequency at the energy E, h the integral harmonic ratio. We also let E_1 denote the maximum energy gain per turn [which is a function of the charge number, the total number of dees, the dee voltage, the harmonic mode, and the dee angle that depends on the turn number]. One can then formulate the expressions for the phase change per turn and for the energy gain per turn as,

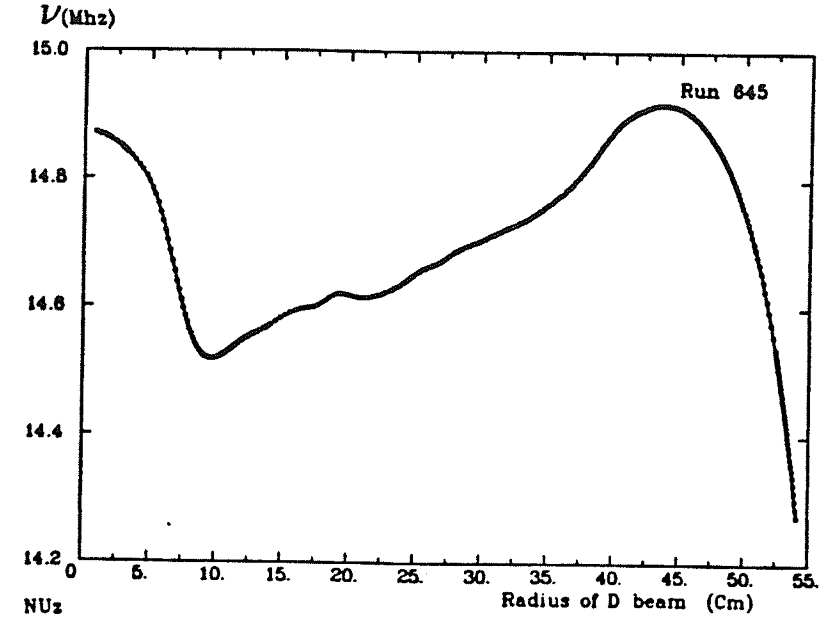
$$\frac{d\phi(E)}{dN} = 2\pi\left(\frac{\omega_{RF}}{\omega(E)} - h\right) \qquad and \qquad \frac{dE}{dN} = E_1 \cos\phi(E) \quad . \tag{2.3}$$

From these equations, it is straightforward to derive a formula for the phase oscillation as a function of energy. The result is given by

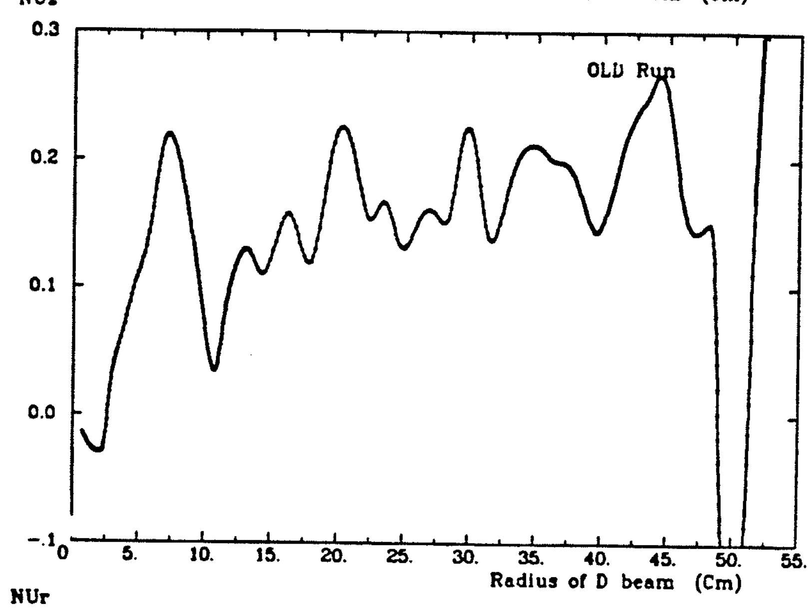
$$\sin\phi(E) = \sin\phi_0 + \frac{2\pi h}{E_1}\int_{E_i}^{E}\left(\frac{\omega_{RF}}{h\omega(E)} - 1\right) dE \quad , \tag{2.4}$$

where ϕ_0 and E_i, respectively, are the RF phase and the beam energy at the center

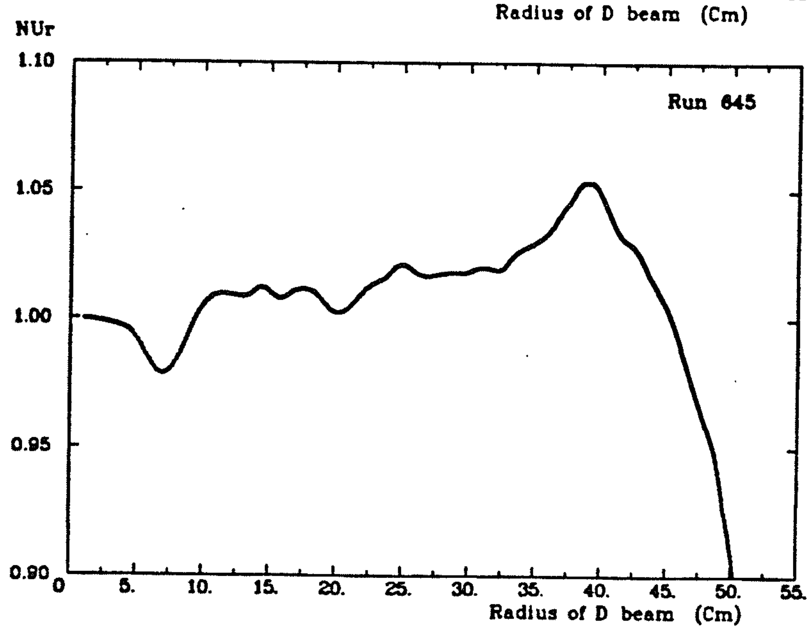
Figs. 2.1, 2.2, 2.3 Results of the magnetic field mapping that was carried out before 1984. For each plot, the horizontal axis denotes the radius of D^- ion in centimeters, and the vertical axis represents the D^- ion's revolution frequency (fig. 2.1), axial focusing frequency (fig. 2.2) and radial focusing frequency (fig. 2.3) in figs. 2.1, 2.2, and 2.3, respectively.



ν(Mhz)
15.0
14.8
14.6
14.4
14.2
Run 645
0
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
55.
Radius of D beam (Cm)



NUz
0.3
0.2
0.1
0.0
-.1
OLD Run
0
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
55.
Radius of D beam (Cm)



NUr
1.10
1.05
1.00
0.95
0.90
Run 645
0
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
55.
Radius of D beam (Cm)

of the first gap (between the mirror and the dee-tips in the case of the U of M cyclotron).

We now apply the above equation to fig. 2.1 and substitute the following values: ϕ_0=+8°, h=1, $\omega_{RF}=2\pi \times 14.24$ MHz, E_i=5.5 keV and E_1 ranging from 25 keV to 48 keV, depending on the turn number. The result that we obtain is shown in fig. 2.4.

From this figure, we notice that the phase excursion keeps increasing along the radius. The figure indicates that when the particle's energy reaches 19 MeV (r=40 cm), the phase has already become −80°. Therefore, with the field configuration that leads to fig. 2.4, it is no longer possible to accelerate a D^- particle with an energy that is higher than 20 MeV. Moreover, these large phase excursions cause the beam to undergo a great number of turns to reach 19 MeV, and the turn separation in this energy region is, in fact, almost unrecognizable. It is therefore expected that there will be a large spread in the number of turns among the particles extracted from the cyclotron. This kind of spread may lead to a deterioration in beam quality (*e.g.*, to a large energy spread or to a large beam center spread, *etc.*).

Let us now turn our attention to the axial motion, Fig. 2.2. A large dip is seen to fall to zero at r= 48 cm and then for larger radii, ν_z acquires an imaginary value, indicating that the axial motion experiences a defocusing force. The axial displacement, z, when ν_z varies adiabatically, is given by [LIV61](assume no acceleration):

$$z = \frac{const}{\sqrt{\nu_z B_0}} e^{\pm i \int \nu_z \omega dt} \quad , \tag{2.5}$$

where B_0 ($=\omega M/q$) is the average magnetic field, and ω is the cyclotron angular frequency. This expression indicates that the motion in the z direction grows exponentially when ν_z is imaginary with a growth rate $(\Delta z/\Delta r)$ that is proportional to $\pm i\nu_z$, where $i = \sqrt{-1}$. Therefore, most of the ions are expected to be lost in passing through this region, by hitting the dee structures. Even for those that are not lost, many will have a large oscillation amplitude.

Fig. 2.2 shows that there is a large defocusing effect between r=48 and 51 cm. This effect was eventually traced to the presence of a large magnetic shim placed at the leading edge of each valley at this radius and further outward(It turned out that the presence of this shim affected the shape of the spiral so much that the sense of the direction of the spiral reversed in this region). The sudden rise in ν_r, starting at r=48 cm in fig. 2.3, results from the effect of this shim. This is the most serious imperfection of the U of M cyclotron that had to be corrected.

The above two effects, the defect in the axial focusing and the serious phase excursion, were together sufficient to prevent the D^- ion beam from reaching energies above 19 MeV instead of achieving the intended design goal of 22.5 MeV.

It is now therefore clear that the magnetic field in the U of M cyclotron had serious imperfections before 1984. These problems could be corrected only by reoptimizing the cyclotron field through a series of field mapping and shimming programs, and such a project was started in November 1983.

2.3 The improvement of the magnetic field after upgrade

The results of the 1984 field mapping for the D^- ions are depicted in fig. 2.5, 2.6 and 2.7. These graphs indicate that the serious shortcomings of the field, as mentioned earlier, have now disappeared. The improvement in the isochronism can

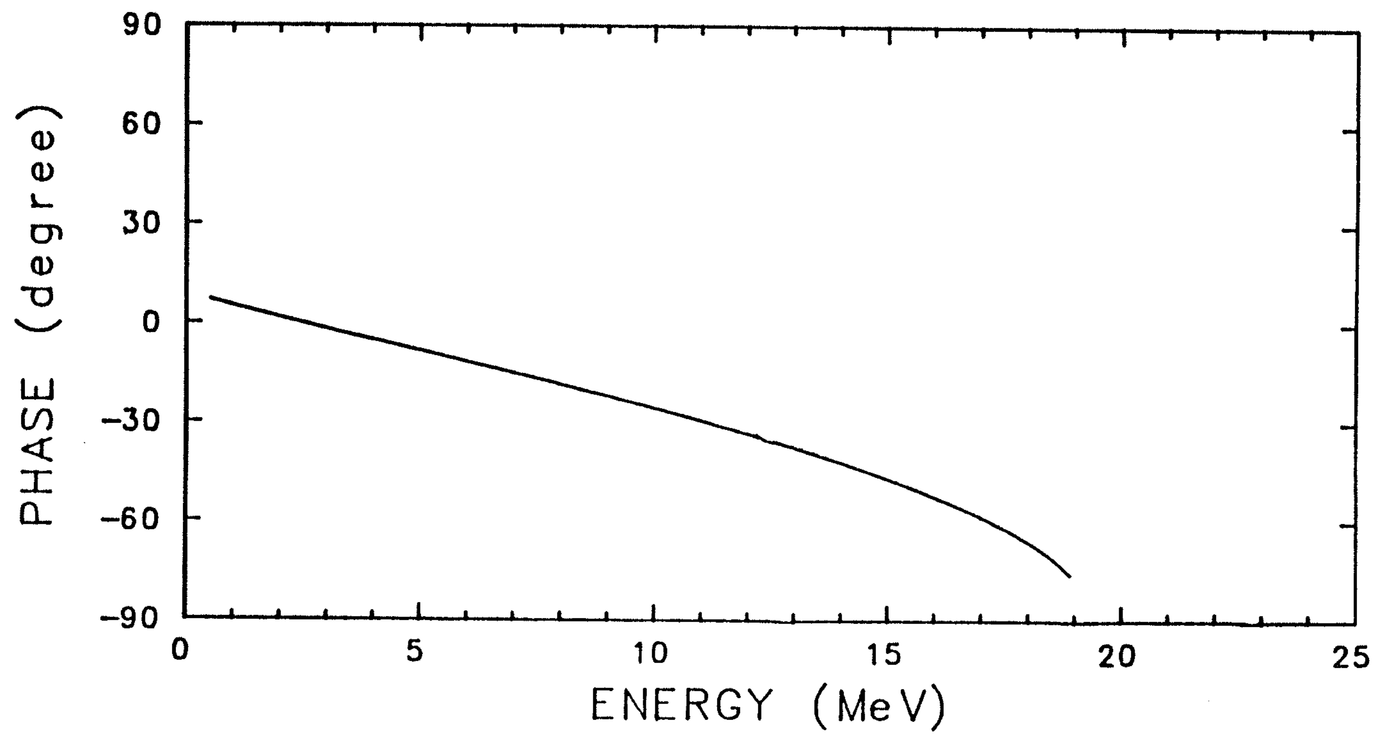


Fig. 2.4 The phase excursion of the D^- particle as a function of the energy(up to 19 MeV) for a typical magnetic field that was measured before the 1984 updrade.

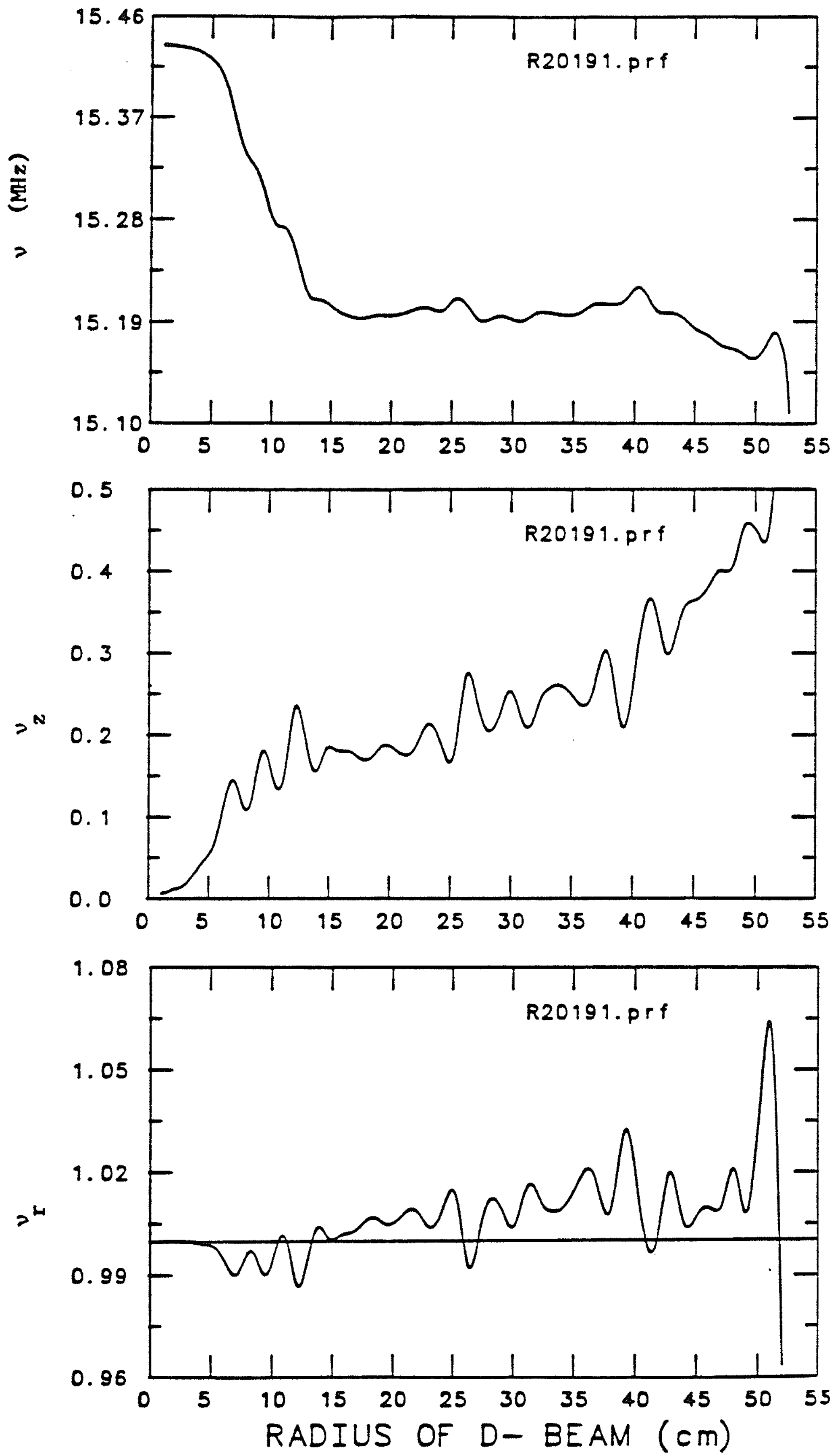
be clearly seen by comparing fig. 2.5 with fig. 2.1. The width of the fluctuations in ν, between 13 and 40 cm, is now within 30 kHz(60 kHz with the second-harmonic mode of acceleration).

The axial focusing frequency, ν_z, has also improved significantly, as can be seen by comparing fig. 2.6 with fig. 2.2. To obtain these results, the Invar temperatures were set at T_1=40, T_2=50, T_3=154, T_4=95, T_5=230, T_6=105, T_7=180, T_8=230 °C, (the main magnet current set at 3350 A), as well as placing three sets of shims in the valley. The first set of shims, a very large one, extends from the 40 cm radius to the outer edge of pole-tips, and is placed on the trailing edge of the valley. The second set of shims is of medium size, and is centered around the 20 cm radius. The third set is a small one, and is located at a radius of approximately 8 cm. This last set of shims was introduced in order to reduce the slope of ν in this region and to extend the central bump field further out, while at the same time improving the behaviors of ν_z in this region.

An improvement in axial focusing can also be seen clearly from fig. 2.6. The disappearances of the axial focusing at radii of 10 and 48 cm (see fig. 2.2) have clearly been corrected. Furthermore, ν_z is now seen to increase smoothly throughout the entire region.

The radial contour maps of the new magnetic field in the median plane of the cyclotron for the D^- ions are depicted in figs. 2.8.

Figs. 2.5, 2.6, 2.7 Results of the magnetic field mapping that was carried out in 1984. For each plot, the horizontal axis denotes the radius of D^- ion in centimeters, and the vertical axis represents the D^- ion's revolution frequency (fig. 2.5), axial focusing frequency (fig. 2.6) and radial focusing frequency (fig. 2.7).


R20191.prf
ν (MHz)
15.46
15.37
15.28
15.19
15.10
0 5 10 15 20 25 30 35 40 45 50 55
R20191.prf
ν z
0.5
0.4
0.3
0.2
0.1
0.0
0 5 10 15 20 25 30 35 40 45 50 55
R20191.prf
ν r
1.08
1.05
1.02
0.99
0.96
0 5 10 15 20 25 30 35 40 45 50 55
RADIUS OF D- BEAM (cm)