THE IMPROVEMENT PROGRAM FOR HIGHER INTENSITY AND BETTER QUALITY IN THE PRINCETON UNIVERSITY CYCLOTRON

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Abstract

A new design of the second harmonic central region for the Princeton cyclotron has been carried out. Extensive beam extraction studies based on the new design have also been performed. These studies suggest that modifications to the shape of the electrostatic deflector can lead to greater extraction efficiency. This result is consistent with the observed burn marks created by the beam in the present extraction region. Further improvements will also be introduced to increase the power dissipation that can be tolerated in the extraction septum.

Introduction

The Princeton University Cyclotron is a constant orbit, multi-particle and variable energy machine. It began operation in 1968 and is now showing signs of age. A proposal for NSF funding to upgrade the facility has been approved. The objective of the proposed modifications to the existing accelerator system is to provide beams of a wider variety, with substantial improvements in intensity and in energy resolution.

For this purpose, we plan to improve the reliability and stability of the aging power supply and diagnostic systems. To further increase the capability of the accelerator, we propose modifications to the central and extraction region to enhance the beam intensity by a significant amount for our lower energy beams. These modifications, combined with improvements in the rf ripple and the magnet power supply stability, will enable us to fully exploit the $\frac{1}{8000}$ energy resolution capability of our Q-3D magnetic spectometer. We also propose improvements to the accelerator and beam line vacuum systems, and a modest internal ion source development program to enable us to use low intensity beams up to ^{20}Ne. The set of improvements which we propose will provide a reliable, stable accelerator with unique properties, well matched to our future research objectives. This paper gives a brief description of the results of of our beam dynamics design studies for the Princeton University Cyclotron upgrading program.

A New Design of the Central Region for the N=2 Mode

The Princeton cyclotron was primarily designed to provide high energy resolution for light ion beams. Inherent to the design is the occurence of a radial beam spread as a function of the rf phase, producing high energy resolution by the use of slits at two internal points which define the radial size (and thus the rf phase width) of the beam. For the N=1 acceleration mode, this approach works very well. The first slit removes particles having both radial divergence and rf phase spread, while the second slit selects those particles whose rf phase spread falls within the desirable range(of less than $\pm 2^o$). Subsequent measurements of the beam phase-excursion(the phase history of the accelerated beam with respect to the accelerating rf field as a function of the radius of a beam) have confirmed that our theoretical analysis is reliable[1].

However, the single-turn extiaction of most N=2 beams has not been practical in our cyclotron. The difficulty is due in part to the fact that the N=2 beam requires twice as much RF time as the N=1 mode before reaching the extraction radius. Thus, each N=2 beam bunch along the acceleration orbit is much more sensitive to the cyclotron and beam parameters. The stability of the cyclotron magnetic field has to be a factor of two better for the N=2 mode to achieve the same result as in the N=1 mode.

A more serious difficulty with the N=2 mode is that the RF phase-dependent beam centering error for the existing central region may be too large. This was directly revealed by our beam dynamics study. This study indicates that, for a 28 MeV deuteron bunch with a ± 3 RF degree bunch length, the existing central region geometry for the N=2 mode induces an additional radial beam spread (arising from the phase-dependent centering error) of 10 mm at the first radial slit. Comparing with a corresponding value of only 2 mm for the N=1 mode, this radial spread of 10 mm is obviously too large making it impossible to properly select the RF phase of a beam, since the turn spacing in this area is only about 5 mm. With the additional spread which results from the beam emittance, the neighboring beam bunches already overlap at the position of the first slit. Accordingly, it is impossible to cleanly select a small phase group for single-turn extraction in the N=2 mode.

In an effert to try to overcome the above difficulties, a new design study for the central region has been carried out. The final geometry of a possible new central region is shown in Fig. 1. Also displayed in Fig. 1 is the radial trajectory of the reference particle for up to two orbit turns. For comparison, we also show in Fig. 1 the geometry of the present N=2 central region and the corresponding radial trajectory of the reference particle. The differences in the two designs lie in the location of the ion source and in the puller tilt angle, as well as in the position and dimension of the first half turn slit. By reducing tilted angle of the puller in the new design, we shift the initial RF phase of the particle by 10^o. This reduces the RF phase-dependent center spread of the beam. Our beam tracking in the newly designed central region indicates that the radial spread of the beam has been reduced to 4.5 mm, a half of the value in the present central region. A further reduction of the spread by making effort along the same direction is possible.

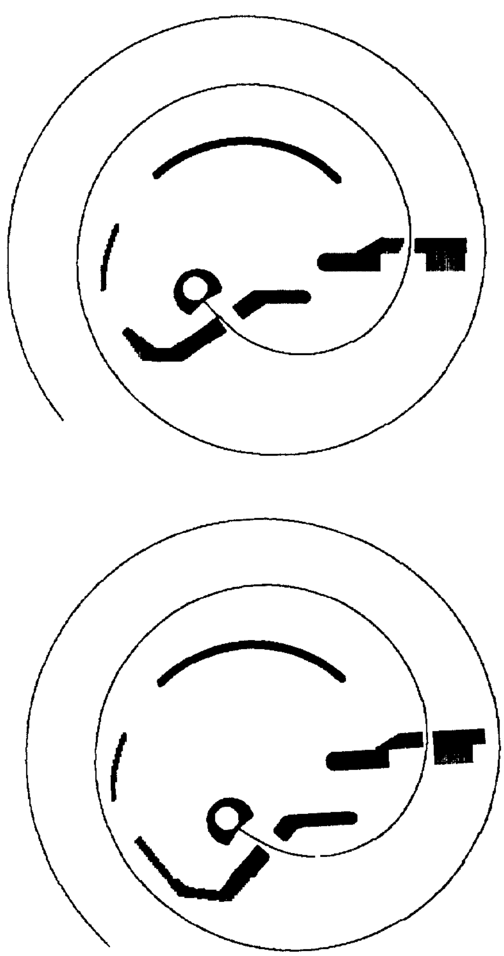

Fig. 1 The newly designed(top) and the present(bottom) $n=2$ central region geometries and the first two orbit turns of the reference particle.

Single-Turn Extraction of the Beam

In Princeton cyclotron the extraction of beam is achieved by means of precessional resonance[2]. Two sets of first harmonic coils are installed in proximity to the location of the radial unit resonance $\nu_r = 1$. The inner set centers the beam orbits to the geometric center of the cyclotron so as to reduce possible coherent oscillations. Then, the outer set (the bump field) causes an eccentric oscillation in the extraction region, so that an increased clearance of beam orbit can be obtained. Afterwards, first the electrostatic deflector and subsequently the magnetic channel both bend the beam out to the transmission line.

To obtain a clean single turn extraction of the beam, a feature which is always desirable in a cyclotron[3], most of the machine parameters have been optimized in our study. The amplitude of the precessional motion has been confined to within 2 mm after the optimization of the values of the strength and the azimuthal angle of the inner first harmonic field(It is 9 gauss and 240^o for the 28 MeV deuteron beam). The calculation of the beam trajectories long the radius indicates that at location of the electrostatic deflector, the turn separation has been increased from 3.5 mm to 8 mm after the installation of the bump field (of 1 gauss). In principle, the stronger the bump field, the wider the turn separation and this makes it easier for the beam to enter the electrostatic deflector. However, our study indicates that the existence of nonlinear coupling resonance in the extraction area places a practical limitation on the strength of the bump field. As a result of the coupling resonance $\nu_r - 2\nu_z = 0$, a large radial oscillation would cause an instability of the beam in its vertical motion, leading to the loss of some particles. Our calculations indicate that the beam would not blow up while crossing the coupling resonance region as long as we limit the value of the bump field to be between 1 to 1.5 gauss[4].

Through beam simulations in longitudinal phase space we obtain the final values of the radius and energy of particles as a function of their initial rf phase, as is shown in Fig. 2. This figure verifies that, when we use the newly designed central geometry, the desired single-turn extraction of the beam can be achieved with very good quality. According to our computation for a 20 MeV deuteron beam, the extracted single-turn beam at the entrance to the electrostatic deflector has an RF phase range of about 12^o and an energy spread of 60 keV. The relation between the energy resolution and the corresponding phase spread can be directly derived from Fig. 2 (the right figure) and can also approximately expressed as $\frac{\Delta E}{E} \approx \frac{1}{2}(\frac{\Delta \Phi_o}{2})^2$. For example, if the phase spread was limited to $\Delta\Phi_o = 1.6^o$ in the central region by the slits, then an extracted beam with an energy resolution of about 10^{-4} should be attained.

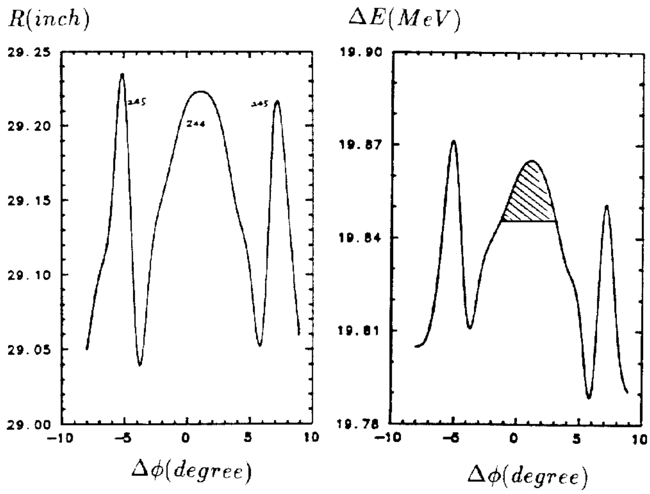

Fig. 2 Final radius R (inch) and energy E (MeV) for orbits of a 20 MeV deuteron beam entering the electrostatic channel on turn 244 and 245 vs. initial phase $\Delta\phi_0$ (degree); septum is located at R = 29 inches. The shaded area in the right figure denotes the portiion which has an energy spread $\Delta E = 20$ keV.

An Improved Design of the Electrostatic Deflector

A major limitation on obtaining high currents from Princeton cyclotron is the power dissipated in the extraction region. We are therefore considering modifications to the extraction system to achieve better extraction efficiency and allow higher power dissipation.

During the past decade, the Princeton cyclotron group has been employing an electrostatic deflector with a constant channel width for the extraction of beams of all different species. However, our beam orbit dynamics calculations reveal that the beam spreads out extensively while it passes through the electrostatic channel whose length is about 1 meter. Our computer simulation of a beam in radial phase space indicates that the beam initially has a radial width of 1.6 mm at the beginning of the channel. This radial width subsequently incerases gradually along the beam trace until it becomes about 3 mm when the beam reaches the tail of the channel. By considering the emittance of an actual beam in longitudinal phase space, which is a predominant cause of the beam's radial spread, it is obvious that some part of beam would get lost by hitting the wall of a channel of 5 mm wide at its tail part. Our calculations of beam orbits in the extraction region have also revealed that the configuration of the existing electrostatic channel may not be optimal for the passage of the beam. These calculations agree with observations on used deflectors, where we have noticed scars burned into the middle of the septum and into the tail of the shoes. Therefore, we are considering a new channel whose width gradually increases along the beam trace, and whose configuration should accomodate the actual beam trace very well. To provide maximum flexibility, the new electrostatic deflector could be adjustable radially. At present, our technical group has tested a new type of deflector which is wider at its tail part. The extracted beam current was increased by up to 50% for some beam species.

We are also considering a redesign of the septum, to increase the allowable power dissipation and protect the deflector electrode, by adding a grounded, water-cooled "shadow" electrode just upstream from the shoe. As in most cyclotrons, the limitation on the amount of beam that can be extracted from our cyclotron is usually set by the power dissipation in the extraction system. Examination of plates that have failed because of excessive beam reveals that they typically have cracked without showing signs of melting. This indicates that thermal stress is the limitation, rather than the more fundamental problem of reaching the melting point of the tungsten. To remove the conduction limit imposed by the large free height of the present septum, we propose to replace the front septum plate with a two-piece design that features a tungsten tip plate that reproduces our present geometry over the central one inch section of the septum but which is carried in a much thicker (0.060 to 0.080 inch) holder for better thermal conduction.

Measurement using high-current beams in the present N=2 mode indicates that extraction ratios are generally 30% to 35%. In the past, much better extraction efficiency has been obtained. The suggested improvements to the machine stability and to the higher power dissipation in the extraction system will allow for significant improvements in beam intensity in the N=2 mode.

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