UPGRADING PROJECTS FOR THE PRINCETON UNIVERSITY AVF CYCLOTRON

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Summary

A design study for conversion of the Princeton University AVF cyclotron for external injection of ions is nearing completion. In this study, the cyclotron admittance phase space diagram was deduced from a beam orbit dynamics study. The beam transmission efficiency through the cyclotron was then studied by counting the number of particles which fall within this phase space. The study includes the injection of high charge state heavy ions and polarized ions. In parallel to the above, a series of upgrading programs have been planned for the existing modes of acceleration.

1. Introduction

The Princeton University cyclotron became operational in 1969. It is a constant orbit (210 turns), multi-particle, variable energy machine. A close copy of the Michigan State University's old K=50 cyclotron, the Princeton cyclotron has a three-sector, pseudo spiral-ridge magnetic field configuration. The accelerating system consists of two 134 degree dees, which can be operated in either push-pull or push-push modes over a frequency range of approximately 14 to 23.5 MHz, allowing for acceleration of particles in N=1, 2 and 4 modes. Maximum energies for typical particles are: 48 MeV protons, 29 MeV deuterons, 58 MeV alpha particles, 85 MeV $^{3}He^{++}$ ions, and 75 MeV $^{12}C^{4+}$ ions.

Lately, production of high charge-state light heavy ions as well as of polarized ions with reasonable beam currents is of interest for the program at this laboratory, but acceleration of these ions means that the ions have to be injected externally. The necessary space for such an injection scheme was provided in the Princeton cyclotron at the time of construction. Since 1984, we have carried out a feasibility study for converting the Princeton cyclotron to external injection of ions. This study includes the design of an axial injection system and of the accompanying N=1 and N=2 central regions. Our goal, in designing this new system, was to investigate the possibility of retaining all the existing features of the Princeton cyclotron as well as of producing a reasonable amount of beam current. During the execution of these studies, a particular emphasis has been placed on matching the beam emittance and the cyclotron acceptance, which was necessary in order to increase the beam transmission efficiency throughout the cyclotron central region. The first part of this paper describes the procedures and the results of these studies.

Another integral part of the upgrading program for the Princeton cyclotron is the improvement of the present facility with the internal injection scheme retained. The internal ion source can still provide a relatively intense beam for ions with charge number less than about 20. It was decided to maintain the internal injection method while the axial injection system would mainly be used for the acceleration of higher charge-state ions and the polarized ions. Up to the present, the Princeton cyclotron has been successful in producing beams of excellent quality and reasonable current for the N=1 mode of acceleration. For the N=2 mode of acceleration, however, the beam transmission and quality have been lower and poorer so that the need to enhance the performance of the N=2 central region became evident. It was therefore decided to launch an improvement project for the existing central region of the Princeton cyclotron as presented in detail in the second part of this paper.

2. The Axial Injection System and the New Central Region

The design study of the axial injection system was started in 1984. This study consists of the design of the axial injection system and the accompanying new N=1 and N=2 central regions. The design study of the axial injection system was completed in 1985, which includes a set of electrostatic quadrupole triplets, deflection channel, beam buncher, and electrostatic mirror.

Design of the new N=1 central region was also completed recently. Prior to the design of this new region, detailed beam orbit dynamics studies in the existing N=1 central region were carried out by utilizing a computer program which traces a beam trajectory both in and out of the median plane of the cyclotron. In this program, both the electric potential and the magnetic field are read as input data. The electric potential distribution inside the central region was calculated by employing a successive over-relaxation method. The magnetic field distribution for this cyclotron, however, was not available. We therfore substituted the Michigan State University (MSU) K50 cyclotron's measured magnetic field. The validity of this substitution was, in fact, confirmed by measuring the beam phase excursion and comparing the result with the calculated excursion which was obtained from the MSU magnetic field. By utilizing these calculated electric field and the measured magnetic field, the beam's radial and axial motion were studied. Subsequently, a new central region was designed in such a way that the beam's motion in the new N=1 central region would converge to an identical motion with the existing N=1 central region at large radii.

a. Calculation of the beam transmission efficiencies The core of the design study mentioned above was to calculate the total transmission efficiencies of various particles through the designed new injection system and accompanying new central region. In view of the Princeton cyclotron's single-turn extraction capability, we particularly focused our attention upon retaining such capability after injecting the ions externally. The single-turn extraction for the Princeton cyclotron can be achieved by placing a set of 0.5 mm width radial phase selection slits at the specific positions where the maximum displacements of a beam induced by the phase-dependent orbit centering error occur. These slits are expected to restrict the beam phase width to within ±2 degrees. In the new central region, the positions of the phase selection slits were obtained after detailed beam orbit calculations. We then constructed acceptance phase space diagrams at the starting plane of the injected beam (the starting plane was chosen to be a vertical plane that contains the effective point of injection) by tracing a number of representative particles' trajectories through these two slits in the central region.

A computer code INJECT was developed to trace particle trajectories along the axial injection system. In this code a DC beam from an ion source, with its beam properties (the electric charge, mass, injection energy and the energy spread, the emittance and its shape specified as initial parameters) enters the buncher and becomes a bunched beam. The buncher operates in the combined modes of the first and the second-harmonic RF. The bunched beam then passes through a drift space and enters the cyclotron magnetic field. The field values (including the fringe field) along the injection system are among the input data. For simplicity, this field was replaced by a step function type with no fringe field (this approximately represents the field for a low excitation). The beam is then reflected by 90 degree by an electrostatic mirror and reaches the injection plane inside the cyclotron. The beam transmission efficiency is computed by counting the number of particles that fall inside the phase space acceptance diagram which was previously computed.

Such a computation revealed that for a typical unpolarized proton beam whose emittance is 16π mm mrad at 15 keV with a 20 eV energy spread, the transmission efficiency would be about 3%. Further calculation also indicated that the efficiency dropped down by 1/2 when the energy spread was increased to 100 eV. Allowing a loss due to a number of meshes along the axial injection system (e.g., meshes in the beam buncher and in the mirror), we expect the efficiency to be around 2% for a low intensity beam from the source. For a commercially available source of polarized protons (190π mm mrad emittance at 10 keV), the efficiency obtained was only 0.3%. For a polarized $^{3}\mathrm{He}^{++}$ beam of 26 keV with an emittance of 24π mm mrad and 100 eV energy spread, which correspond to typical parameters for the University of Birmingham source, the calculation predicted that the transmission efficiency was about 1%.

The calculations described above were based on a provision of obtaining a beam with extremely high energy resolution (0.04%), resulting in low transmission efficiencies. Since single-turn extraction of a beam in the Princeton cyclotron can be achieved for an accelerated beam bunch width of up to 6 RF degrees, we investigated the possibility of readjusting (increasing) the radial width of the phase selection slit in order to achieve ±3 degree beam phase width rather than ±2 degree width, thereby increasing the beam transmission while achieving a beam with reasonably high energy resolution. By the same procedure described above, the phase space acceptance diagrams for the range from −3 to +3 degrees were constructed at the beam injection plane. The result revealed that the transmission efficiencies did improve significantly. Thus, for the unpolarized proton beam whose parameters were quoted above, the efficiency was increased to about 3.6% (from 2%). And for the commercially available polarized proton beam the value obtained was 1.08% (from 0.3%), provided that the magnetic field of the ionizer of the atomic beam source is anti-parallel to the cyclotron magnetic field. The transmission efficiency for the beam from the Birmingham polarized $^{3}\mathrm{He}^{++}$ source was also calculated and predicted to be 7.2%. All those values listed above were obtained after taking into account a 60% loss of a beam due to a number of meshes along the axial injection system.

b. Design of the new N=2 central region The design study of the new N=2 central region is nearing completion. This study was also preceded by an investigation of the 28 MeV deuteron beam orbit dynamics in the existing N=2 central region. During this process, it was found that the existing system does not provide a well centered beam. A well centered beam for N=2 can be obtained only by redesigning the existing central region and, in fact, it is one of the proposed upgrading projects. This will be treated in the next part.

As with the case for the N=1 central region, the design study for N=2 central region started with finding the optimum radial positions for the two phase selection slits based on the orbit tracings of up to 35^{th} turn. However, it was found that, for N=2, the radial phase selection slits were too restrictive for the beam. To have a beam phase width of ±3 degrees, for instance, the radial gaps of the two slits have to be as large as 3.5 mm, which is totally unacceptable with the existing extraction system of the cyclotron for single turn extraction. Further investigation revealed that one half of the 3.5 mm radial spread for the ±3 degree beam bunch arises from energy spread of the particles within the bunch (the remaining half is attributable to the phase-dependent centering error), which is associated with the particle's phase excursion and may be eliminated by adjusting the phase excursion diagram. So far, no calculation has been carried out beyond this point. However, the first undertaking for further study will be to improve the phase excursion of the beam, as may be predicted by a computer program FIELDER, developed by the MSU group. Depending upon the outcome of this study, we might have to modify the geometry of the central region further.

3. Improvement Projects of the Existing Facility

The improvement projects for the present Princeton cyclotron facility include the enhancement of the performance of the existing N=2 central region, implementation of a heavy ion capability using an internal source, and improvements in the RF system.

The large dispersion problem as found for the new N=2 central region appears to be much more severe for the existing

N=2 central region. Moreover, the large off-centering problem also deteriorates the beam quality significantly. These effects in turn can explain the reason why it is so difficult to obtain a beam with good quality, with the present N=2 central region. In order to correct the above problems to some extent, we plan to investigate reducing the total number of orbital turns by one half to 105 turns from 210 turns by increasing the dee voltage by a factor of two together with redesigning the central region.

With this approach, the effect of any imperfection of the cyclotron field can be reduced significantly, and we anticipate a factor of two increase in the beam current. By increasing the dee voltage, we can also reduce the space charge repulsion which plays the most dominant role during the first half turn of orbit. Though this method does not use the phase selection slits (thereby employing the multi-turn extraction scheme), depending upon the outcome of the investigation we may expect the possibility of single-turn extraction with a set of selection slits.

In a long term plan it is conceived that high charge-state heavy ions and polarized ions will be provided by external sources in conjunction with the axial injection system, whereas those ions whose charge number is less than 20 will still be provided by an improved internal PIG source. The improved internal PIG source is expected to be larger than the existing one, thus requiring a modification to the existing top plug.

In order to maintain a reasonable degree of flexibility in switching between external and internal sources, it is planned to relocate our internal ion sources to the bottom of the cyclotron. The use of the larger plug caisson that we have obtained from the MSU K50 cyclotron can then be used. The only significant geometrical difference between the existing top-mounted probe-type source system and the bottom-mounted plug source system from MSU is that the probe system can be adjusted in position and exit-face angle, while the plug sources are fixed in position and angle. We are planning a staged installation that will preserve the ability to carry out our experimental program at each stage. The first such stage would be the preparation and installation of the lower plug and caisson system and preparation for it's use with internal sources.

Finally, we also plan to upgrade our RF system. The recent achievement of single-turn extraction with a 95% extraction efficiency revealed that the 5% loss of a beam during extraction mainly came from RF ripple. In order to reduce this ripple, thereby enhancing the performance of our RF system, we plan to improve filtering in the RF power supplies, and perhaps lower the bias on the output tubes. Replacement of the low power stages of the RF system is also envisioned. A planned control system for the cyclotron will also eliminate much of the noise that has been inherent in the present system.