DESIGN STUDY FOR AXIAL INJECTION OF POLARIZED IONS INTO THE PRINCETON UNIVERSITY CYCLOTRON

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Abstract: A design study is in progress for an axial injection system for the Princeton University AVF cyclotron with particular emphasis on polarized beam such as $^3He^{++}$.

Introduction

To extend the capability of the Princeton University cyclotron [2] from an accelerator for unpolarized ions to polarized ions, it is necessary to convert the cyclotron for external injection of ions. Such a conversion necessitates a detailed study of beam optics in order to design the best system for the purpose and to determine the optimum injection parameters associated with it. The Princeton University (PU) cyclotron is noted for its excellent beam quality [2,3] and the axial injection system should retain this feature. It means, among other things, features such as a variable energy, constant orbit with a single turn extration capability for various types of ions, and first (n=1), second (n=2) and fourth (n=4) harmonic modes of acceleration of beam. Depolarization along the axial injection system was also studied to determine the type of focusing elements to be used for the proposed system. At the beginning the study was split into two parts. The first part is from the ion source to the electrostatic mirror in the cyclotron. The second part is the mirror and the central region. The studies were carried out in parallel and independently from each other. First order emittance-admittance matching of the two systems was possible by assuming that the injection system transports the beam without any distortion and that when the beam reaches the mirror it is focused so that the spread of the orbit centre of the beam is a minimum. It is therefore possible to design the accompanying central region of the cyclotron without a detailed knowledge of the injection system. In the following these two parts will be described.

The Axial Injection System

The first task to face in the design of an axial injection system is the choice of the types of beam focusing elements to be used for the system. For our purpose it is highly desirable for the lens to have, among other things, the smallest size (in radial dimension in particular) with the least disturbance for space charge neutralization. Out of the four types of focusing elements we considered (the einzel lens, the axial magnetic lens, the electrostatic and the magnetic quadrupoles) the einzel lens is by far the smallest. However, the lens has to be placed in a strong axial magnetic field arising from the cyclotron fringe field. In such a circumstance a serious instability in beam focusing would occur [5,6] under the expected vacuum condition and therefore the einzel lens was ruled out.

The axial magnetic lens is attractive from the space charge neutralization point of view and, in addition, can be made smaller than the quadrupoles. We studied an injection system based on these axial magnetic lenses. It, however, revealed that there may be a serious depolarization [7,8] and it was therefore reluctantly discarded.

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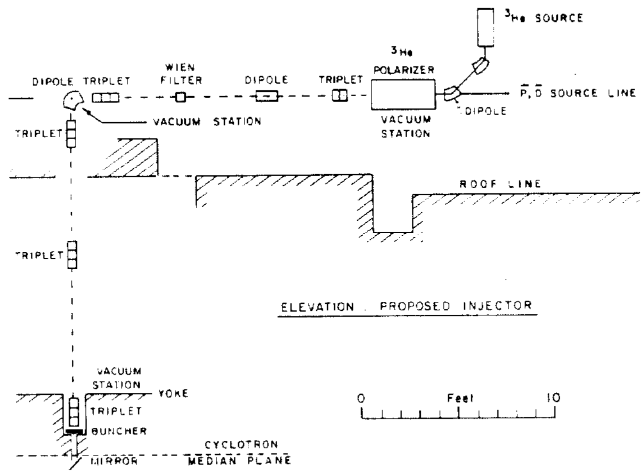

Fig. 1. Schematics of the proposed axial injection system - vertical view.

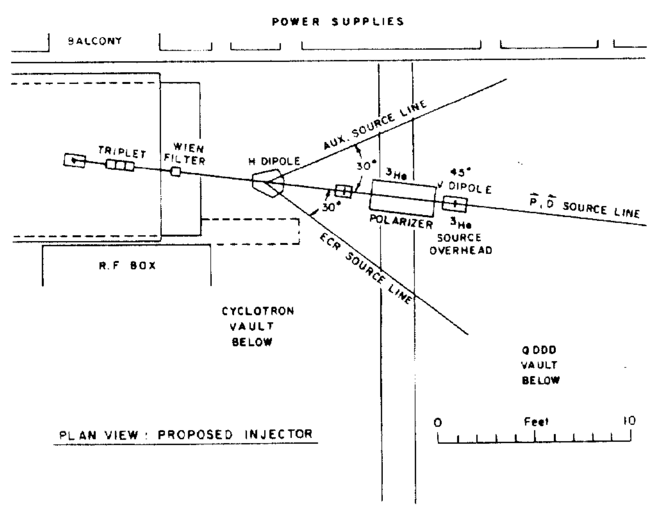

Fig. 2. Schematics of the proposed axial injection system - plane view.

Magnetic quadrupoles can also depolarize beam although not as seriously as an axial magnetic lens. We in the end settled with the electric quadrupoles as the basic focusing elements for the system.

Figs. 1 and 2 are the schematics of the axial injection system. Discussions are in progress concerning the installation of the Birmingham (U.K.) polarized $^3He^{++}$source in a location as shown by the figure. Provision has also been made for future installation of a polarized proton and deuteron source and an ECR source. The injection system is designed [7] to transport beams up to 180mm mrad in x- and 230 mm mrad in y-plane for a lower beam inection energy (corresponding to lower beam extraction energy from the cyclotron). For higher injection energy (matching higher extraction energy) the cyclotron leakage

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magnetic field along the injection axis increases rapidly and the additional focusing from this leakage field begins to increase the admittance of the system. From this a 30mm mrad will be accepted by the cyclotron for a single turn extraction mode. The optics is such that when a beam with axial symmetry enters the cyclotron field the envelope forms a uniform column of diameter d, which for an ideal injection system is given by:

$$d = 4\{A/(\pi B)*(2mV/e)^{\frac{1}{2}}\}^{\frac{1}{2}}$$

In the above, A is the phase space area in meter-radian, B is the magnetic field in Tesla, m and e are the mass and charge of the ion respectively, V is the beam energy in eV, and d is in meter. For a 15 keV proton beam (for which B=1.33T) with 30mm-mrad phase space area this yields d=1mm. When deflected 90° by an ideal impulse mirror this beam will have a cyclotron orbit center spread of 0.5mm.

The injection axis is displaced from the cyclotron geometrical centre by ∿2cm. This, combined with the central region bump field, will make the flux line curved. The magnetic field inside the cyclotron pole tip gap is, however, uniform within 5% along the axial injection axis and therefore the beam properties are expected to be affected little by the curved nature of the flux lines, except for changes in the overall beam trajectory.

The Central Region

The Princeton University (PU) cyclotron is designed to accept a beam of 0.5mm radial width with a ∿2°RF phase window [2] when operated with an internal ion source. This was achieved by a radial slit having a 0,5mm gap placed at 180° in azimuth at the first turn. This design presumes the additional restriction of the phase acceptance by two optional radial slits located approximately at the 18th and 28th turn respectively. Thus it is expected that with a proper design it may be possible to successfully accelerate the previously quoted beam of 30mm m-radian. The study for the central region of the cyclotron was therefore aimed at designing dee-tips which will put as much of this beam inside the six dimensional acceptance phase space volume of the cyclotron which is known to be accepted with an internal ion source. This was done by the following steps:

1. The RF field for the existing geometry (with the internal ion source) was computed by a relaxation calculation. Then the motion of particles was studied for the above geometry with the corresponding cyclotron magnetic field. From this study the reference particle was established. (Refer to [3,4] for the definition of the reference particle.)
2. A geometry for the dee-tip (the replacement piece in place of the puller) and the central region was assumed and the RF electric field is computed by the relaxation method. (We used the quasistatic approximation for the RF field.)
3. The orbits were traced for a set of particles with different initial starting parameters under the RF accelerating field obtained from the above. The reference particle for this particular geometry was included among these trajectories.
4. The convergence of the trajectory of this reference particle towards the corresponding trajectory for the existing geometry is studied at a sufficiently large radius where the difference between the two cases becomes negligible. Based on this study the geometry of the dee-tip and the central region was modified.

The process from 2 to 4 was repeated until we reached a satisfactory geometry for the central region. The study of the beam vertical motion (in the linear approximation) is in progress for various electrode geometries for the exit from the mirror and the entrance to the dee-tip. So far the study has been carried out for n=1 mode of RF.
The computer model central region is shown in Fig. 3. A refined beam optics matching between the injection system and the central region will then follow.

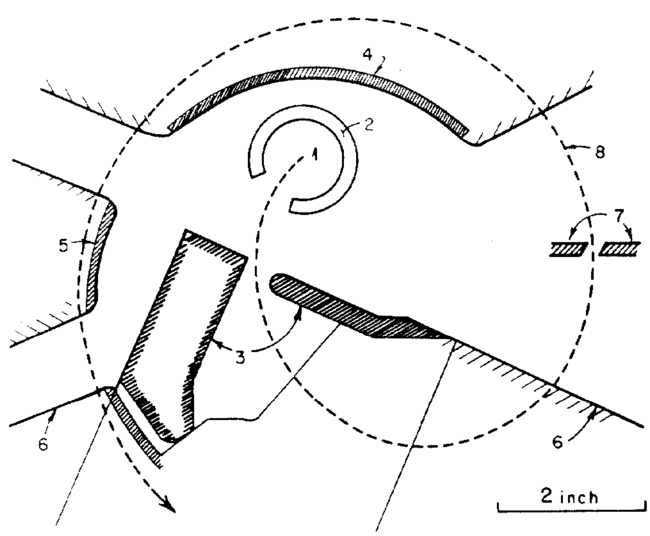

Fig. 3. The computer model central region geometry for n=1. 1:mirror, 2:RF shield, 3:dee-tips, 4:dee, 5:dummy dee, 6:dee, 7:radial slit, 8: reference particle trajectory.

The Beam Buncher

As was mentioned earlier the RF phase acceptance is very small and therefore the available beam current from the cyclotron will be exceedingly small unless an efficient beam buncher is incorporated in the injection system. A University of Manitoba type beam buncher [9] is placed in the injection system as shown in Fig. 1. This is a combined first- and second-harmonic beam buncher having three accelerating gaps. A total of six surfaces (each of them is made up of stretched parallel copper wires) define a uniform buncher electric field across each gap. The buncher has 85% transparency, limited by RF heating of the wires, and effectively compresses a polarized $^3He^{++}$ dc beam (with 80eV energy spread at 25keV) of ±45° RF width to ∿7°, which is considerably wider than the desired width of 4°. Of this 7°, 2.8° arises from the non-ideal buncher wave form and the remaining 4.2° from the combination of the beam energy spread (this effect gets worse at lower injection energy), the marginal ray (the axial velocity is slower), the dispersion by the mirror (mainly the additional beam energy spread of 400eV induced by the buncher) and the finite phase space area of the beam (30 mm m-rad.) [7,8].

For the polarized proton beam which has less energy spread (∿20eV) the bunching efficiency is expected to improve by 50% over the $^3He^{++}$ beam. A buncher enhancement factor of 10 to 15 is expected at higher injection energy, but drops down considerably for lower injection energy.

The space charge effect arising from the highly compressed bunched beam may debunch it seriously in the future when a very high current polarized proton source is incorporated with the system. For polarized He^{++} beam such a problem is unforseeable at present.

It is noticed that the buncher is the last element in the beam transport system leading to the mirror. Study showed that the placement of any focusing element downstream of the buncher will seriously deteriorate the compression. Resonating the buncher with a quarter-wave tuned line will permit locating it away from the variable elements in its tuning cavity.

Conclusion

The axial injection scheme for the Princeton University AVF cyclotron (K=50) is expected to provide polarized proton, deuteron and $^3He^{++}$ of a modest beam current. Its low energy spread ($\lesssim$0.1%), small phase space area ($\sim$1mm m-rad. for 30MeV proton beam, for instance), combined with the variable energy capability, is expected to provide a useful tool for nuclear structure study.

More detailed studies will be published in the near future.

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