AN AXIAL INJECTION SYSTEM FOR THE ORIC

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Abstract

An axial injection system has been designed for injection of high intensity beams of H^-, D^-, and He^{++} into the Oak Ridge Isochronous Cyclotron (ORIC). The device consists of two high-voltage platforms, two external ion sources, a double-drift-tube beam bunching system, a spiral inflector and integrated beam analysis diagnostics and focusing elements. With the axial injection system, it is expected that more than 100 µA of high quality, primary light ion beams will be extracted from the ORIC using either the existing septum extraction system for He^{++} beams or a foil stripping extraction system for extracting either H^+ or D^+ beams. In addition, beam scattering and the consequent internal activation problems, endemic with the present short lifetime internal Penning discharge source along with the down times attributable to its maintenance will be dramatically reduced.

1 INTRODUCTION

The ORIC is the driver accelerator for producing radioactive isotopes for the Holifield Radioactive Ion Beam Facility (HRIBF) [1]. Extracted beam intensities from the ORIC are limited by the internal cold-cathode Penning discharge source due to beam scattering from residual gas in the vacuum system that also leads to serious activation of internal components. The internal source also has a very short lifetime, particularly, for generation of He^{++} beams because of the brute force method used for producing these ions. Consequently, source maintenance accounts for a major part of the ORIC down time. The maximum deliverable beam-on-target intensities from the ORIC range between 10 and 20 µA; however, in practice, the beams are further limited to <10 µA by the power handling capabilities of ISOL targets. An axial injection system with two external ion sources (a multi-cusp, filter-field source for H^- and D^- generation and an ECR ion source for He^{++} generation) have been conceptually designed as a potential upgrade for the ORIC. The injection system consists of two 60-kV platforms, a double-drift beam bunching system and a spiral inflector [2]. When implemented, the axial injection system will be capable of injecting >100 µA beams of H^-, D^-, or He^{++} into the ORIC.

A top view of the injection system is shown schematically in Fig. 1. Since the injection system must transport space-charge-dominated, high-intensity beams, the injection energy will be as high as practically achievable (limited by the voltage holding capability spiral inflector). Where possible, all beam manipulation devices will be magnetic in order to avoid serious space-charge blow-up effects. The beam bunching system consists of a beam chopper and buncher designed to efficiently inject beam into the cyclotron while reducing stray beam scattering and the consequent activation problems. Since the magnetic field inside the cyclotron yoke increases from nearly zero at the entrance to the yoke to more than one Tesla at the central field region of the cyclotron, the action of the field on injected particles behaves like a strong magnetic mirror, which would reflect most of the injected beams without the action of a strong beam-focusing lens during injection. To solve this problem, a magnetic solenoid was designed for installation inside the yoke to compensate for the strong mirror effect to ensure high-efficiency injection into the ORIC.
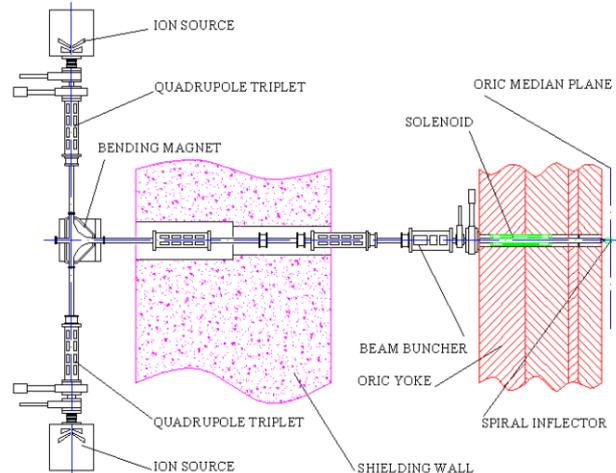
Fig. 1. Layout of the injection system for the ORIC.

2 SPIRAL INFLECTOR

An electrostatic mirror [3] is the simplest device for axial injection of beams into a cyclotron. However, for the present injection system, a spiral inflector has higher beam transmission efficiency - up to 100% - compared to a typical efficiency of ~65% for an electrostatic mirror. Although a mirror is smaller in dimension, it requires a very high voltage for operation. For example, an electrostatic mirror must operate at a voltage of more than 25 kV in order to inject 50-keV proton beams into the gyration plane of a cyclotron, while only ~10 kV is required for a properly designed spiral inflector. This reduction will reduce sparking and reliability problems associated with high-voltage breakdown and shorting.

In a spiral inflector, the central beam trajectory is generally used as the first-step in the design. A spiral inflector consists of a pair of coaxial, spirally twisted electrostatic deflection plates submerged in a strong magnetic field. Consequently, the beam trajectories are

more complicated due to the actions of both fields on particles during transit through the device. In order to simplify the problem for computing the position coordinates of beam trajectories, the fringe fields at the entrance and exit of the spiral are usually ignored and the transverse electric field within a spiral inflector through which the beam passes is assumed to be uniformly distributed so that the central trajectory of the beam can be expressed analytically. Fig. 2 shows the two meshed electrodes of a spiral inflector simulated with the 3D finite element code ANSYS [4]. Unfortunately, fringe fields at the entrance to an inflector and the twisted electrode structure of the inflection system have significant affects on the electric-field distribution and consequently, the trajectories of injected beams within the device deviate considerably from those derived by analytical means [2].
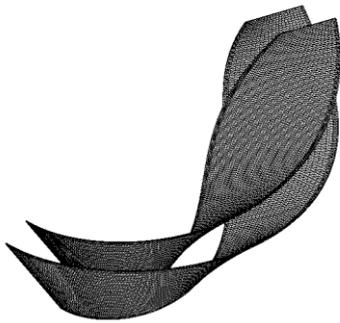
Fig. 2. Meshed electrodes of a spiral inflector.

It is a common practice to design a spiral inflector with a large gap size, nearly twice the dimension of the beam envelope [5], to deflect the beam into the central field region of the cyclotron and to tolerate shifts in beam trajectories inside the inflector. However, the large gap scenario is not desirable for injection of high-energy beams that require a higher operating electrode voltage for the spiral inflector. The problem cannot be solved simply by increasing the bending path length, since shifts in beam trajectories within a spiral inflector also increase with increasing bending path length. Efforts have been made to reduce the trajectory shift problem by using a smaller bending radius and by modifying the shape of the electrodes at the entrance to the inflector [6]. However, the approach cannot eliminate the problem, and it compromises the maximum voltage that can be used for operating the inflector.

In numerical electric field analyses and beam trajectory simulation studies, ploys are sought that reduce or even eliminate completely, beam shift problems while permitting operation of the inflector at electrode voltages commensurate with efficient injection into the central region of the cyclotron. By rotating the electrodes at entrance to the inflector or reshaping the inflector appropriately, the beam-path shift problem can be significantly reduced. Another practically tractable approach, that completely eliminates the path shift problem, can be affected by re-centering the inflector electrodes according to the actual central beam trajectory [2]. By use of powerful numerical tools, a high

transmission efficiency, small electrode gap spiral inflector with zero path shift has been designed that can operate at an electrode voltage of approximately 12 kV for injection of 50-keV proton beams into the ORIC (~40% lower than that of conventional large gap spiral inflectors.) Fig. 3 shows the zero path shift device with a vertical bending radius of A = 4.06 cm.
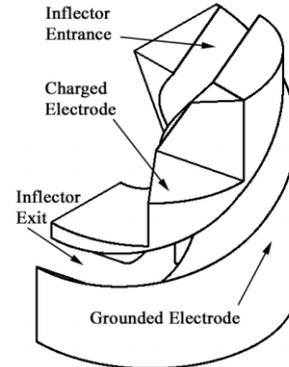
Fig. 3. The spiral inflector for the ORIC [7].

3 THE BEAM BUNCHING SYSTEM

An ideal beam-bunching system should use a saw-tooth waveform. However, a high-power, high-frequency saw-tooth wave generator is expensive and quite difficult to realize in practice. Typically, beam bunchers utilize sinusoidal waveform generators with a few higher order harmonics. The ORIC injection system uses a double-drift tube design. Among the advantages of this type of beam bunching system, include simplicity in structure, ease of control and operation, and low cost. One of the drawbacks of the design is that the tube length depends on beam velocity. With this buncher, ~65% of the injection beam will be captured (e.g., approximately 130 μA of beam will be captured from an ion source capable of generating 200 μA DC beams of H^-, D^- and He^{++}) and therefore, the intensities of the bunched beams will be high enough for injection into the ORIC. However, higher injection efficiency (>70%) can be achieved with a multiple-harmonic bunching system that is insensitive to variations in beam velocity [8].
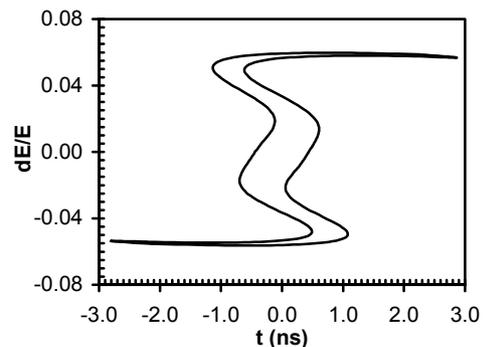
Fig. 4. Simulated longitudinal beam envelope for 50-keV bunched proton beam at entrance to the spiral inflector.

The buncher must be mounted as close as possible to the entrance to the magnet yoke to reduce beam pulse widths as required for efficient injection of beams into the RF field of ORIC. Only a vacuum valve and a Faraday cup follow the buncher before entrance to the magnetic yoke. Fig. 4 displays simulations of the longitudinal phase of the beam bunching system for a 50-keV proton beam. The optimized drift lengths of the first and second buncher are, respectively, 8.03 cm and 3.96 cm with no grid installed (a little less than $\beta \cdot \lambda/2$ because of the transit time factor). A beam chopper is needed to remove the long tails produced by the beam-bunching system. Their removal will reduce beam scattering and consequently, activation of components in the cyclotron. In order to be compatible with the operating frequency range of the ORIC, the bunching system must be tunable between 14 and 19 MHz.

4 IN-YOKE SOLENOID

The distance from the entrance to the magnetic yoke to the median plane of the ORIC is ~1.5 m. Over this distance, the axial magnetic field inside the yoke increases from nearly zero to more than one Tesla, the action of which is equivalent to a magnetic mirror that reflects injected beams. When designing an axial injection system, careful attention must be given to solving this problem. In beam optics studies, the axial magnetic field was treated as a series of equivalent solenoids, as illustrated in Fig. 5. A focusing element inside the yoke is necessary to compensate for the strong magnetic mirror effect that otherwise would lead to loss of >75% of injected beams. The installation of a solenoid inside the ORIC magnet yoke is quite challenging because of the small-bore diameter in the yoke (~12 cm). A special solenoid with an outer diameter of 12 cm and inner diameter of 6 cm was designed to mount inside the yoke for matching the injected beam as indicated in Fig. 1.
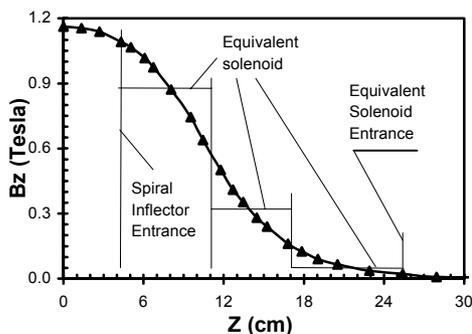
Fig. 5 Axial magnetic field in the yoke treated optically as a series of equivalent solenoids.

From beam optical studies with the in-yoke solenoid, no significant beam emittance deterioration occurs in the axial injection system at beam intensity levels up to 200 µA. When the axial injection system is well matched, the beam transport efficiency is expected to be nearly 100% for bunched beams, injected into the cyclotron *dee*s. Fig. 6 shows simulated beam envelopes at the entrance and

exit to the spiral inflector. As noted, they are well confined in the spiral inflector and coupled to the ORIC *dee*s.

a) Entrance to the spiral inflector

b) Exit from the spiral inflector
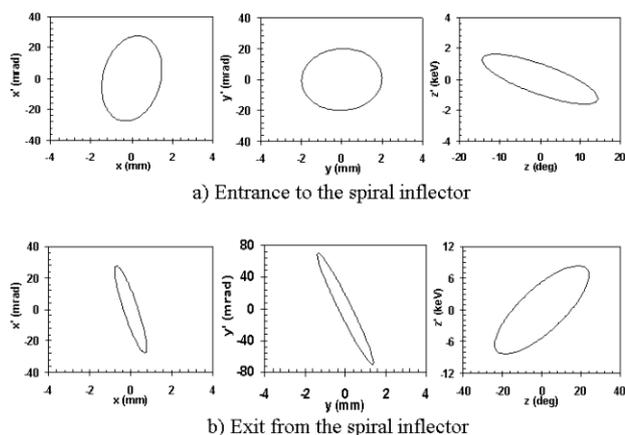
Fig. 6. Simulated beam envelopes for a 50-keV proton beam at entrance to and exit from the spiral inflector

5 CONCLUSIONS

According to computational studies, ~65% of the DC beams extracted from the external ion sources will be injected into and accelerated by the cyclotron with the proposed axial injection system. It is expected that more than 100 µA of high quality, primary light-ion beams will be extracted from the ORIC using either the existing septum extraction system for He^{++} beams and a foil stripping extraction system for extracting either H^+ or D^+ beams. In combination with an appropriately designed raster scan system for use in dispersing the beam-on-target power density, the new injection system will make possible the production and post acceleration of RIBs with intensities of 10 to 20 times those presently available at the HRIBF.

REFERENCES

1. http://www.phy.ornl.gov/hribf/
2. Y. Zhang, G. D. Alton, "*Electric field distribution in a spiral inflector for cyclotron injection applications,*" to be published in this proceedings.
3. A. J. Cox, et al., Nucl. Instrum. Methods 18 (1962) 25.
4. *ANSYS,* ANSYS Inc., Canonsburg, PA.
5. P. Belicev and D. V. Altiparmakov, Nucl. Instrum. Methods Phys. Res. A456 (2001) 177.
6. D. Toprek, D. Reistad, B. Lundstrom and D. Wessan, Nucl. Instrum. Methods In Phys. Res. A486 (2002) 539.
7. Y. Zhang, G. D. Alton and B. A. Tatum, "*The design of a spiral inflector*", to be published.
8. R. Zierl, W. Czech, P. Kienle*, et. al.*, Nucl. Instrum. Methods 164 (1979) 219.