THE OAK RIDGE ISOCHRONOUS CYCLOTRON AS AN ENERGY BOOSTER FOR A 25 MV TANDEM

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Abstract

The maximum heavy-ion energy available at Oak Ridge will be substantially increased by using ORIC as an energy booster for the 25 MV "folded" tandem now being acquired. Beams of ions with mass up to A=160, with energy sufficient to overcome the Coulomb barrier on lead will be produced. The beams will enter the cyclotron through the dee stem, be directed by a magnet through the fringe and main fields to a stripping foil which lies on the appropriate orbit for acceleration. General orbit and beam transport codes have been used to aid in the design of the injection system.

1. Introduction

The Oak Ridge Isochronous Cyclotron (ORIC) will be used as an energy booster for the 25 MV "folded" tandem electrostatic accelerator that is now being acquired.[1,2] The order for the tandem has been placed; the required modifications to ORIC and the injection line components to couple the two machines together are being designed, and completion date for the system is the end of 1978. When the system is completed the two accelerators will be able to operate in conjunction or separately. Their performance capabilities are shown in Fig. 1. With the tandem injecting into ORIC, ions with mass up to approximately 160 amu will have sufficient energy to induce nuclear reactions. The expected beam intensity is approximately 0.1 particle microampere (pμA) for most beams.

The tandem is located about 37 m from the cyclotron (Fig. 2). The beam will travel between the two machines in a beam line equipped with focusing magnets, steering magnets and beam diagnostic instruments. At the cyclotron, injection is achieved by passing the beam through an inflection magnet so that it arrives at a stripping foil which is placed at the tangent point common to the injected beam and an orbit suitable for acceleration (Fig. 3).

Only relatively minor modifications to the cyclotron are required for beam injection. These include the addition of the beam transport line, inflection magnet, stripping foil holder, and redesign of the dee and RF trimming capacitors.

2. Beam Transport

For injection from the tandem into ORIC the beam will be bent into the horizontal injection beam line by 22.5° and 67.5° magnets separated by 5 m.[3] Regulating slits near the entrance of the 67.5° magnet will preserve isochronous transmission. Quadrupole lenses will be placed about 9 and 39 meters from the exit of the 67.5° magnet. The second quadrupole will be located either just outside the cyclotron or inside the dee stem, depending on the results of studies which are not yet complete.

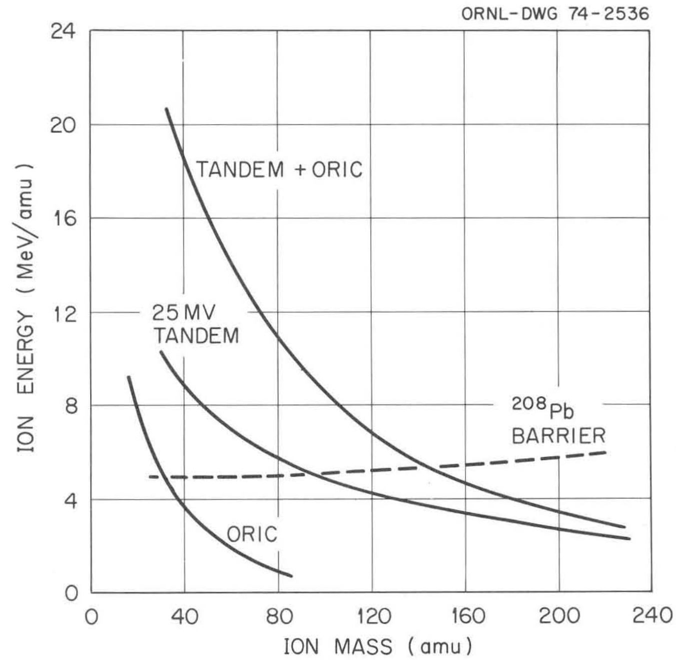


Fig. 1. Maximum energy at full intensity obtainable from ORIC with an internal ion source, the tandem, and from the combination of the two accelerators. In the two curves involving the tandem, gas stripping in the terminal is assumed, plus foil stripping in either the high-energy tube (tandem alone) or in ORIC (tandem + ORIC). Somewhat higher energy beams at lower intensity can be obtained by using higher charge states.

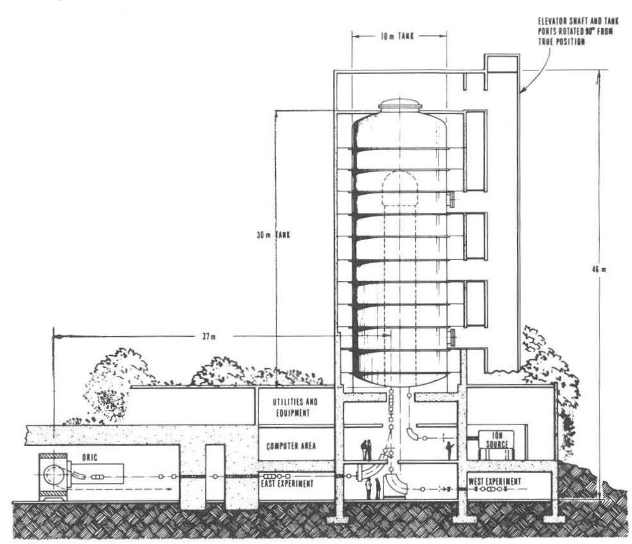


Fig. 2. Cross section of 25 MV tandem-cyclotron system showing injection beam transport line to ORIC.

*Operated by Union Carbide Corporation for the U.S. Energy Research and Development Administration.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 622-625

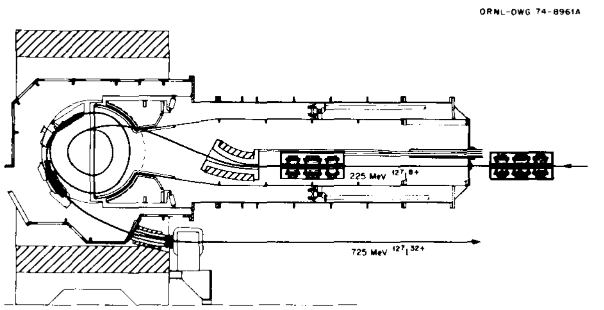


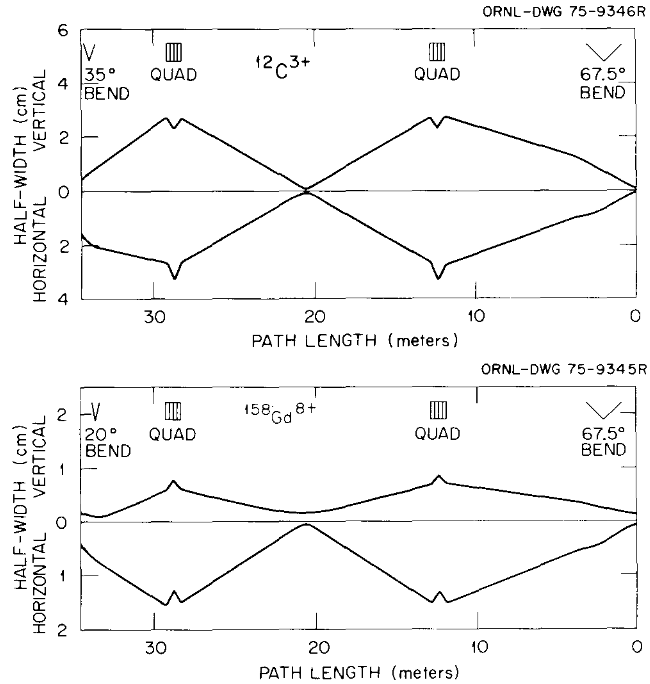
Fig. 3. Cross section of ORIC with a 225 MeV $^{127}I^{8+}$ beam from the tandem stripping to 32^{+} and accelerating to 725 MeV. The inflection magnet is movable to accommodate the full range of beams. The quadrupole is shown in the two alternate locations now being studied.

The optical system, which includes the bending magnets, the quadrupoles, the inflection magnet, and the fringe field of the cyclotron, must transform the nearly circularly symmetric beam emerging from the tandem to an image on the stripping foil approximately 1 mm radially by 5 mm axially. The small radial width is dictated by the small edge-to-edge spacing between the beam at the foil and the first accelerated orbit; the larger axial dimension was chosen in consideration of foil lifetime and is also consistent with the weaker axial focusing in the cyclotron. The properties of the system were studied with the computer programs OPTIC II[4)] and TRANSPORT[5)] in the external beam lines and with a general orbit code (GOC) for the portion inside the cyclotron magnetic field.

The beam path for the portion between the inflection magnet exit and the stripping foil was determined by computing with the GOC in the reverse direction from the required image at the foil to the inflection magnet. The computations were then continued from that point toward the tandem using the beam parameters determined by the GOC as input for OPTIC II and TRANSPORT. Calculations were also performed in the normal beam direction for the external transport.

Vertical and horizontal profiles of the beam from the regulating slits to the exit of the inflection magnet are shown in Figs. 4 and 5. For quadrupole lengths of 1.2 m the maximum gradients are approximately 1 kG/cm. For beams with the anticipated emittance of 19 π mm mrad $MeV^{1/2}$ the maximum calculated excursion from the optic axis is 1.6 cm for $^{158}Gd^{8+}$ and 3.4 cm for $^{12}C^{3+}$.

The "acceptance window" for good energy resolution and single turn extraction in ORIC is ±3° of the RF period. Since the operating frequency of ORIC varies from 22.5 to 7.5 MHz the times corresponding to ±3° of the RF period are 0.74 to 2.2 nsec. A double klystron buncher has been studied that will bunch 50% to 70% of the d.c. beam from the tandem into the 6° window at ORIC.[3)] The buncher will be placed between the ion source and the low-energy acceleration tube of the tandem. Isochronous transmission of the bunched beam through the tandem and



Figs. 4,5. Vertical and horizontal beam profiles in the injection line for $^{12}C^{3+}$ and $^{158}Gd^{8+}$ beams from the tandem having emittances of 19 π mm mrad $MeV^{1/2}$. An asymmetric beam is required following the inflection magnet to achieve a 1 x 5 mm image on the stripping foil.

the injection line is achieved by having a crossover in the center of the 180° magnet in the terminal of the tandem, and by careful choice of the magnets that achieve the 90° bend at the exit of the tandem.

3. Beam Injection

Injection paths in the cyclotron magnetic field (including the fringe field) have been studied for a variety of ions.[2,6)] In two cases the calculations were checked by comparison with orbits obtained by using a current carrying wire in the actual magnetic field to simulate the beam. Reasonably good agreement between the computations and the wire-orbit measurements was obtained. However, since the magnetic field data now available for injection calculations do not cover the full range of magnet currents now used--nor is the accuracy in the fringe field as high as desired--we plan to re-map the field to correct these deficiencies.

Injection paths for different ions vary considerably. Figure 6 shows an example of two such paths. For lighter ions the beam must pass through the region now occupied by the upper RF trimming capacitor and through the periphery of the dee. This requirement has caused a redesign of the trimmers and their drive mechanisms, and also of the dee. In the new design the periphery of the dee and of the trimmers has been removed to accommodate the injected beam. In the design of the new dee special attention has been given to enlarging the radius of curvature of corners where voltage breakdown can occur.

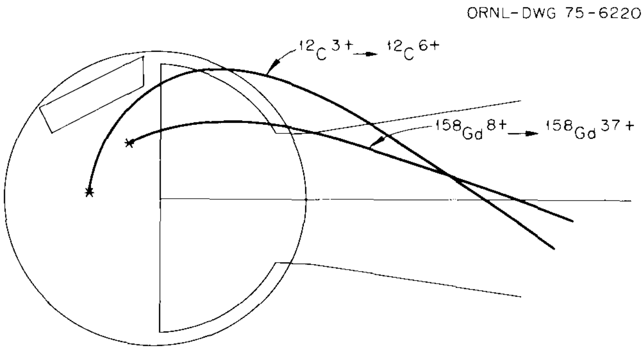


Fig. 6. Central ray injection orbits in the cyclotron field for $^{12}C^{3+}$ and $^{158}Gd^{8+}$. The coordinates of the stripping foil are r = 42 cm, θ = 177° and r = 40 cm, θ = 113° for C and Gd, respectively.

In the old design the smallest radius of curvature of a corner was 4.4 mm. In the new design the minimum radius is 9.5 mm; however, in most places having high voltage the radius of curvature is 12.7 mm. With the improved geometry and without the internal ion source when ORIC is operating as a booster, it is expected that stable operation at higher voltages will be achieved. The voltage level for stable operation is expected to be increased to about 100 kV from the present value of 70 kV.

The injected beam must cross the gap between the dee and the trimmer capacitor and back into the dee again, and is subject to a changing electric field during these gap crossings. Computations have shown that because of the narrow phase width of the beam the effect of these gap crossings on the phase space and energy spread is negligible.

3.1 Inflection Magnet

The inflection magnet is of the "picture frame" type with windings in the gap. The windings are folded back at each end to allow passage of the beam. The magnet will be mounted in the dee stem inside the cyclotron vacuum system. The windings and leads are contained in a vacuum tight enclosure to prevent deterioration of the cyclotron pressure by outgassing of the insulation.

The position of the magnet assembly can be remotely adjusted parallel to the axis of the dee stem over a range of 1.2 meters, and the poles are large enough in radial width to accept beams with radii of curvature from 120 to 280 cm. These features make it possible to accommodate the widely differing injection orbits (Fig. 6). The maximum field required in the inflection magnet is 15 kG.

3.2 Stripping Foils

The stripping foil holder will be adjustable over a wide range of radii from 23 to 50 cm and in azimuth from 100 to 180°. Position accuracy will be 0.25 mm radially and 0.1° azimuthally. The foils will be supported from a radially inserted arm which will occupy the space now used by the internal ion source. Provisions will be made for several foils (10-20) in a "magazine" so that foils can be changed quickly without breaking vacuum. A magazine of foils will also be changeable without breaking vacuum by withdrawing the foil holder into the existing source vacuum lock.

Foil lifetime at high energies is at present an unknown factor; however, measurements and experience with foils in beams of about 1 MeV/u give encouraging results. Stripping foils in ALICE (1.15 MeV/u) have a 24 hr life with 10 μA of Ar^{4+}, and with 1 μA of Kr^{8+} an indefinite lifetime.[7] In a lifetime test a foil in the external beam of ORIC survived 12 pμA-hr of 0.9 MeV/u Ar^{4+} without failure and without any measurable change in the stripping characteristics.[8] The range of energies of the beams incident on the stripping foil will be from approximately 1 to 7 MeV/u.

From the GOC the turn spacing between the injected beam at the foil and the first accelerated orbit has been obtained.[6] For the lighter ions the edge-to-edge spacing is approximately 0.7 mm and for the heavier ions it is about 3 mm.

4. ORIC Admittance

The maximum axial and radial admittance of the ORIC may be inferred from the measured emittance of the ORIC beam.[9] These values, 30 mm mrad axial and 70 mm mrad radial,[10] are nominally independent of energy and particle type and are therefore assumed to be characteristic of the geometry of the cyclotron, established principally by the admittance of the extraction system.

The 70 mm radial admittance transforms (according to momentum ratio) to a larger value at injection. For 225 MeV $^{158}Gd^{8+}$ accelerated to 4.9 MeV/u the injection is at 53% of extraction radius; the corresponding radial admittance is 132 mm mrad. This value is to be compared with the ^{158}Gd beam emittance from the 25 MV tandem of approximately 5 mm mrad (this includes the increase caused by scattering in passing through a 20 μg/cm^2 foil). The turn spacings for this case are 6.2 mm at injection (to be compared with the spot size on the foil of 1 mm) and 3.3 mm at extraction (to be compared with a septum thickness of approximately 1.5 mm). In practice, the turn spacing may be increased if needed by introducing coherent radial oscillations.

The axial admittance of the extraction system, transformed to the injection radius, for ^{158}Gd is 57 mm mrad. Assuming $\nu_z = 0.2$, that emittance corresponds to a beam width of about 12 mm. The design value of the dee aperture is 24 mm. The axial emittance of the ^{158}Gd beam from the 25 MV tandem after passing through the stripping foil is about 8.6 mm-mrad. The corresponding uniform beam width is about 4.7 mm. The predicted beam size appears to be comfortably within the axial acceptance of the cyclotron.

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