THE ORIC AS A HEAVY-ION INJECTOR FOR A SEPARATED SECTOR CYCLOTRON*

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ABSTRACT

The characteristics of the Oak Ridge Isochronous Cyclotron (ORIC) for the injection of heavy-ions into a separated sector cyclotron have been studied and found to be excellent. With a carbon foil between the accelerators the output energy of the ORIC is sufficient to give a stripped ion beam at least twice the charge state of the ORIC's extracted beam up to mass 200. This allows an ideal magnetic field match to a separated sector cyclotron with a magnet fraction of 0.58. The 37-MeV $^{40}Ar^{4+}$ beam from the ORIC was used to test the lifetime of 20-μg/cm^2 carbon foils. It was found that the stripping characteristics were unchanged after a total transmission of 5 x 10^{17} particles per cm^2. Results of the measurement of the ORIC beam loss as a function of pressure in the cyclotron tank and beam line are also presented.

INTRODUCTION

The successful acceleration of heavy-ions[1,2] by the ORIC suggests the possibility of using it as an alternate injector into the main cyclotron of the National Heavy-Ion Laboratory.[3] With an operational heavy-ion cyclotron, the problems of matching two cyclotrons can be investigated experimentally and projections based on actual measurements can be used in predicting the properties of such an accelerator system. In addition, the studies can indicate areas of improvement and development needed to enhance the effectiveness of the accelerator combination. The use of the ORIC as an alternate injector into the main cyclotron appears very attractive and would result in a very versatile and unique combination of accelerators for research with heavy-ions.

CYCLOTRON MATCHING AND ENERGY GAIN

The magnet characteristics of the NHL cyclotron were determined by (1) the requirement of an energy of 10 MeV/u for uranium ions with ion injection from a 20 MV tandem using gas stripping in the terminal and solid foil stripping between the tandem and the cyclotron, (2) the requirement for maximum energies of 100 MeV/u with complete avoidance of dynamical beam resonances to and beyond that energy, and (3) the desire to achieve (1) and (2) at minimum cost. The magnet is a

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four sector type with a magnet fraction (ratio of hill-angle to sector-angle) of 0.58 and a $B\rho$ of 3010 kG-cm.

It is possible to inject from one cyclotron into another over a broad range of conditions compatible with the injection system of the second cyclotron but only synchronous solutions are attractive from good beam quality and intensity considerations. Possible synchronous solutions are listed in Table I and the design selected is labeled ORIC's operating point. This point has the features of an energy gain of 19 in the main cyclotron, a common harmonic ratio for the two cyclotrons, and an injection radius equal to the ORIC's extraction radius.

Table I Synchronous conditions for ORIC and main cyclotron

$\frac{\text{Radius(ORIC)max}}{\text{Radius(NHL)min}}$	$\frac{\text{Energy(NHL)}}{\text{Energy(ORIC)}}$	$\frac{\text{Charge(NHL)}}{\text{Charge(ORIC)}}$	$\frac{\text{Harmonic(ORIC)}}{\text{Harmonic(NHL)}}$
*1.00	19.0	2.0	1/1,3/3,5/5,7/7
1.14	14.6	1.7	7/8
1.20	13.2	1.6	5/6
1.28	11.6	1.5	7/9
1.33	10.0	1.5	3/4
1.40	9.7	1.4	5/7
1.42	9.4	1.4	7/10

*ORIC's operating point.

Because the maximum average magnetic field of the ORIC is approximately twice that of the main cyclotron, the charge must be at least doubled by stripping between the two cyclotrons. For ions from the cyclotron with a total ionization potential less than 600 volts (these give intense beams) the condition is met by foil stripping[4] up to mass 200 (Fig. 1). For a charge-ratio greater than two, the magnetic field of the main cyclotron will be reduced to achieve synchronism. Thus it is seen that the characteristics of stripping with solid foils and the 2:1 ratio of average magnetic fields of the two cyclotrons combine to make them almost perfectly compatible for synchronous operation.

The radio frequency-magnetic field characteristics for the ORIC and the main cyclotron is shown in Fig. 2. The dead-band between the

ORIC and the main stage - both the first and third harmonics of the orbit frequency are outside the NHL frequency range and the ORIC cannot use the second harmonic - is indicated by the shaded areas.

For ions from a Penning source with total ionization potentials of 600 and 1200 V,[5] corresponding to microampere and nanoampere beam levels respectively, the energy of the main cyclotron as a function of mass is given in Fig. 3. It is seen that the ORIC and the main cyclotron are capable of accelerating ions up to mass 200 with reasonable total ionization potentials to sufficient energy to exceed the Coulomb barrier of uranium.

PHASE ACCEPTANCE

Matching of the ORIC's beam phase width to the beam phase acceptance of the main cyclotron is necessary for maximum intensity and minimum energy spread. The beam phase width acceptance of the main cyclotron is quite large (30°) because of the flat topping of the rf voltage. The external pulse width for ORIC's first harmonic beam has been measured to be 6° and for higher harmonics the phase width is expected to be smaller.

In transporting the ORIC beam a distance of 45 m to the main accelerator, the beam phase width from the ORIC will increase as a result of the energy spread. Fig. 4 shows the phase acceptance of the main cyclotron as a function of beam energy spread for various harmonic modes. The energy spread (fwhm) for a third harmonic heavy-ion beam has been measured to be 0.6%;[6] that value is indicated in the figure. The acceptance for the above conditions is 80% for the third harmonic, 50% for the fifth harmonic, and 35% for the seventh harmonic. The acceptance can be increased by either a phase rebunching or by the more desirable method of improving the energy spread from the ORIC.

The energy straggling[7] induced by passage of the beam through a 20-$\mu g/cm^2$ carbon foil is given in Fig. 5 as a function of mass for particle energies of 0.25 and 0.5 MeV/u and for the ORIC at its maximum energy, $E = 100\ q^2/A$ for ions with total ionization potentials of 600 V. For energies available from the ORIC, the energy straggling is less than 0.1%. Placement of the stripping foil just before the main cyclotron will reduce the beam losses due to straggling to a small value.

AXIAL AND RADIAL EMITTANCE MATCHING

Matching of the axial and radial emittance of the ORIC beam to the acceptance of the main cyclotron requires careful consideration because of the change of acceleration planes between the two machines. The radial emittance of the ORIC beam must fit the axial acceptance of the main cyclotron and vise versa. Calculations of the axial admittance of the main cyclotron give an acceptance of 140 mm-mrad for a 1.27 cm beam at 0.4 MeV/u.

Fig. 6 gives the full angular spread[8] due to multiple scattering that occurs in passing through a 20-μg/cm^2 carbon foil as a function of mass. For a 1-cm diameter beam the angular divergence will increase by 5 mrad or less for the energy range applicable to the ORIC. The 70 mm-mrad emittance area beam of the ORIC will increase to approximately 120 mm-mrad at mass 200. This beam should fit into the main cyclotron; however, the injection system will have to be carefully designed to give good matching. The smaller value of the ORIC axial emittance (30 mm-mrad which will increase to 80 mm-mrad for mass 200 after stripping) should be easily accommodated within the radial aperture of the injection system.

BEAM INTENSITIES

It is possible to predict the extracted heavy-ion beam intensity from the ORIC. The first parameter needed for the predictions of intensities of different charge states for a given ion is the relative dc intensities of multiply-charged ions[9] extracted from a "mode 2" Penning discharge source. The second parameter required is the relative efficiency of beam capture as a function of rf harmonic and this has been measured by Jones _et al._[10] The beam intensity loss for the higher harmonics is attributed to the reduced phase acceptance of the cyclotron at the first rf gap crossing. A way to increase the phase acceptance of the first rf gap is to decrease the rf transit time of the gap crossing by dc injection on the first orbit. This method is now being investigated on the ORIC.

The rf capture and transmission efficiency for a given charge-state on any harmonic is also needed to estimate intensities. This has been obtained by measuring the intensities of low charge-state heavy-ion beams with the ORIC. The results of the calculation of beam intensities are given as a function of mass in Fig. 7. All beam intensities are normalized to the first harmonic capture efficiency. The energies are the output energies of the NHL cyclotron. The efficiency of transmission has been assumed to be the same for all charge states. The measurements on charge-exchange attenuation presented later show that the assumption is incorrect. Therefore the intensity predictions for the heavy masses of Fig. 7, which are based on low charge-state measurements, are an underestimate of the available beam intensity.

CARBON FOIL LIFETIME

Large currents of 37-MeV Ar^{4+} were used to test the lifetime of 20-μg/cm^2 carbon foils that are to be used between the accelerators. The test foils were 1.9 cm in diameter and mounted on aluminum frames. A collimator directly in front of the foil confined the beam to the central 0.8-cm diameter region of the carbon foil. After stripping the beam was passed through an analyzing magnet to obtain the charge-state distribution of the stripped ions. The distribution was monitored as a function of time and the intensity of the primary 4+ peak was observed. Any increase in the 4+ peak would be an indication of development of "pinholes" in the foil. Fig. 8 is the charge state distribution at the beginning and end of bombardment. No change in charge distribution was detected after 5 x 10^{17} particles per cm^2 or 12 particle μA-hrs. Only a darkening of the foil over the region where the beam passed through was observed. In addition, experiments at a pressure of 10^{-3} torr likewise showed no deterioration of stripping characteristics. A 13-MeV Ar^{3+} beam used in an attempt to study the energy dependence showed no foil lifetime effect after 0.3 particle μA-hrs. The foil lifetime does not appear to be a problem for the ORIC beams tested.

CHARGE EXCHANGE LOSSES

The influence of the pressure in the cyclotron on beam intensity for various ions has been measured. A controlled air leak at the center of the cyclotron was used to vary the pressure as the external beam current was monitored. The results obtained for various beams, shown in Fig. 9, indicate that a factor of ten improvement in pressure can result in an output improvement of at least a factor of ten for most beams. The ORIC vacuum system is to be improved as a part of a cyclotron improvement program presently in progress.

The beam-line attenuation was measured also. A 2-m beam-line section that had restricted gas flow and a controlled air leak was used. The transmitted beam was magnetically analyzed for the different charge states as a function of pressure. Fig. 10 is the transmitted beam intensity of 37-MeV Ar^{4+} as a function of pressure and indicates for these ions, the necessity of having a beam line pressure of 2 x 10^{-6} torr for less than 10% loss over a distance of 45 m (the distance between the ORIC and the main cyclotron).

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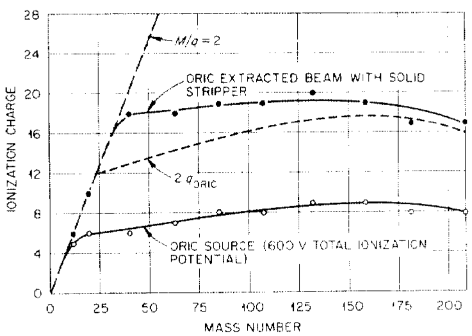

Fig. 1 The ORIC ion source charge state at a total ionization potential of 600 V as a function of mass is given. In all cases the beam from the ORIC strips to greater than twice the source charge, when a 20-μg/cm^2 carbon stripper is used.

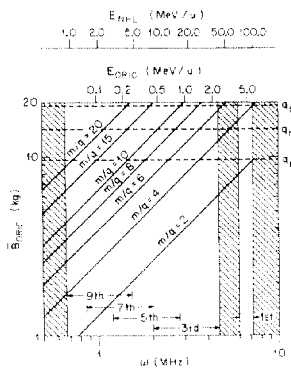

Fig. 2 The rotational resonance curve for the ORIC and the main cyclotron. The mass to charge ratio pertains to the ORIC ion source.

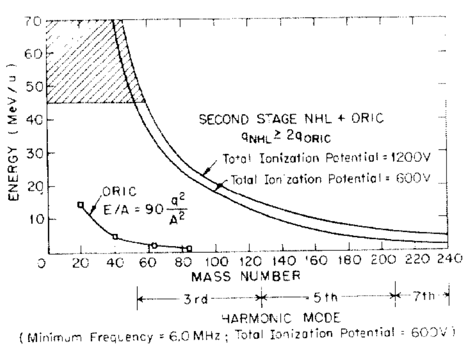

Fig. 3 The energy vs ion mass characteristics with the ORIC as an injector. The performance estimates are shown for ions with total ionization potential of 600 and 1200 volts.

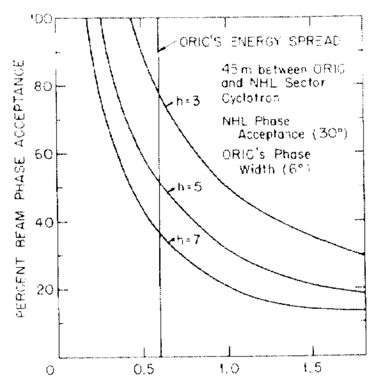

Fig. 4 The percent beam phase acceptance as a function of energy spread. The measured energy spread of the ORIC for a first harmonic beam is .6% and has a phase width of 6°.

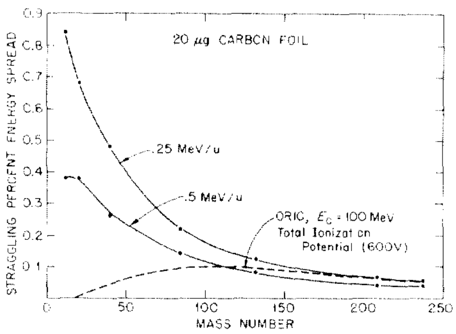

Fig. 5 The nuclear straggling of ions for passage through 20-μg/cm² carbon foil as a function of mass.

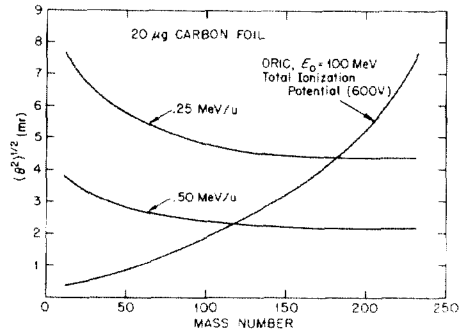

Fig. 6 The angular spread due to passage through a 20-μg/cm² carbon foil as a function of mass. For mass 200, the increased emittance is still safely within the accpt- ance of the main cyclotron.

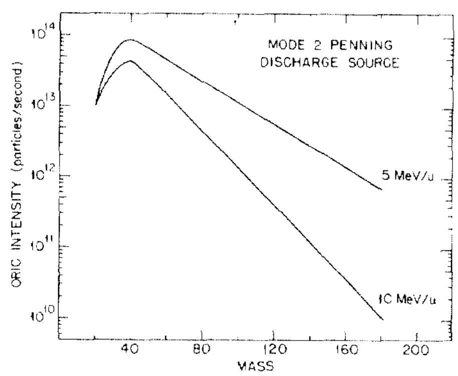

Fig 7 The beam intensity from the ORIC normalized to first harmonic capture efficiency as a function of mass for energies of 5 and 10 MeV/u from the main cyclotron.

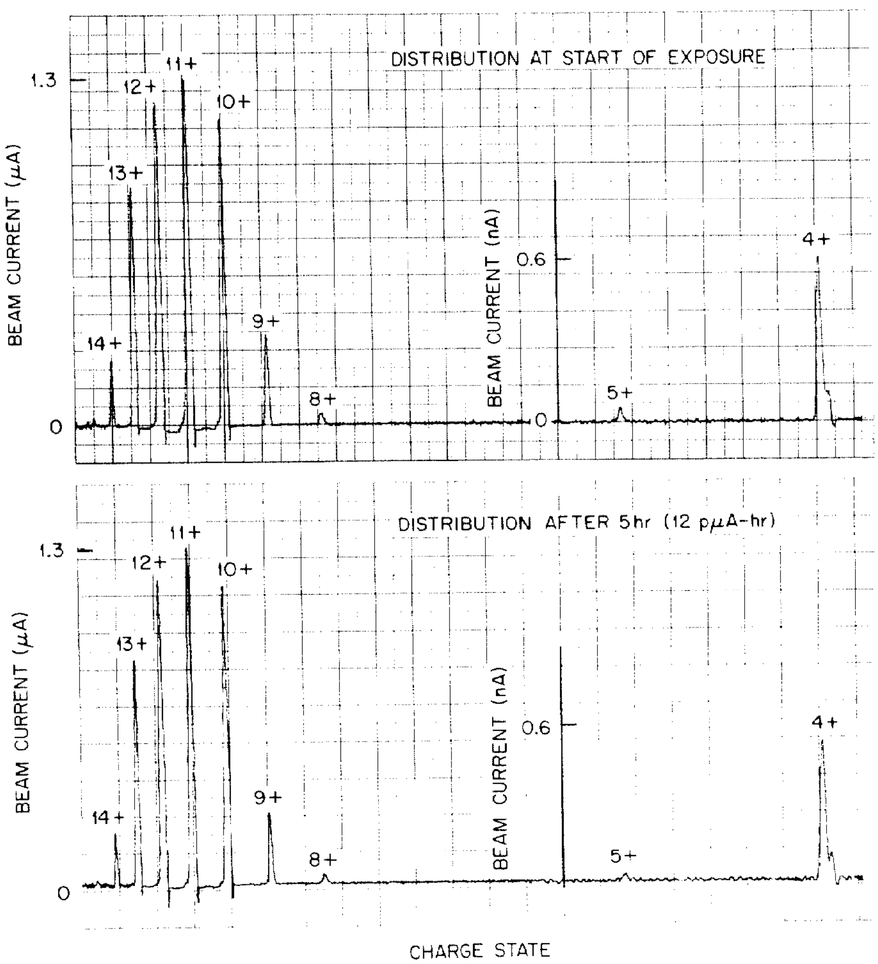

Fig. 8 Charge-state spectra observed at beginning and end (after 12 particle microampere-hours) of 37-MeV argon beam stripped by a 20-μg/cm² carbon foil.

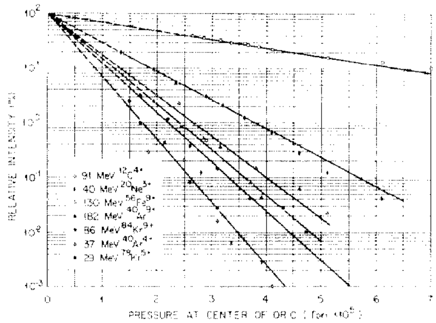

Fig. 9 The beam attenuation from the ORIC as a function of pressure. All beams are normalized to 100% for zero pressure.

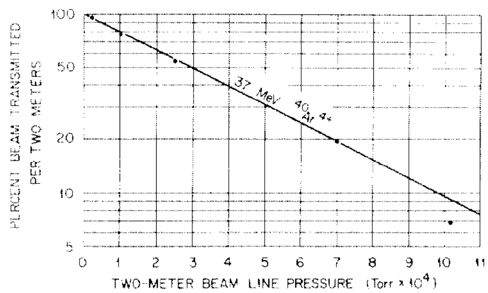

Fig. 10 The transmission of 37-MeV Ar^{4+} as a function of pressure in 2 m of the ORIC beam line.

DISCUSSION

RICKEY: I wonder if you expect any particular problems from the fact that what is vertical in ORIC will be horizontal on the other machine and vice versa?

MALLORY: It is advantageous that we have a rotation of acceleration planes between the two machines. The tough emittance match is in the radial direction. The smaller emittance area of ORIC is in the axial direction, so it is advantageous that we have rotation of acceleration planes.