# ISOCHRONOUS CYCLOTRON HARMONIC BEAM EXPERIMENTS*

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## Summary

We have previously described a system for boosting the energy of heavy ions in isochronous cyclotrons by recycling.[1] This system requires simultaneous acceleration of two beams on different harmonics, all-magnetic extraction, external separation, and reinjection of the lower energy beam. The first three requirements have now been demonstrated on a limited scale using simultaneous beams from an internal ion source, and without building a reinjection system. A $^{6}Li^{1+}$ beam on the third harmonic at an energy of 4 MeV and a $^{6}Li^{3+}$ beam on the fundamental at an energy of 36 MeV were simultaneously accelerated on the Oak Ridge Isochronous Cyclotron (ORIC), extracted and separated, demonstrating the major principles of recycle without closing the loop.

## Introduction

We have investigated the feasibility of simultaneous harmonic acceleration of two beams (recycle) in the ORIC and found this acceleration mode theoretically possible.[1] The harmonic acceleration concept and the engineering changes needed on ORIC to implement recycle acceleration are illustrated in Fig. 1. The high harmonic (or first pass) beam originates at the ion source located in the center of ORIC. This beam is accelerated to the extraction radius of the cyclotron and is extracted by an all-magnetic extraction system followed by a velocity selector. In the electrostatic velocity selector the first pass beam is deflected down and away from the present beam extraction path. An external septum magnet further separates the first pass beam and steers it to a beam transport system that is located approximately 25 cm above the floor of the ORIC vault. At this level the beam is transmitted to a three-component 180° bending magnet that controls the beam phase by varying its path length. At the exit of the 180° magnet the beam enters the injection system path,[2] and passes through an inflection magnet and then stripped to a higher charge state by a carbon stripping foil, located between the turns of the first pass beam. The higher charge state that satisfies the harmonic requirements is reaccelerated, enters the extraction system, and is directed into the existing beam transport system of ORIC. The complete engineering changes needed to demonstrate recycle on ORIC require major modifications. The septum magnet replaces the present electrostatic deflector. A velocity selector and a beam transport system to reinject the first pass beam must be built. Experiments that verify the recycling accelerating concepts have been made without modifying ORIC.

## Harmonic Beam Accelerating Experiment

Beams of the same mass and of a different charge state, for example, $^{16}O^{6+}$, on the first harmonic and $^{16}O^{2+}$ on the third harmonic, were accelerated simultaneously on ORIC. To accomplish the simultaneous acceleration of two beams from the ion source to full radius requires a special beam phase history[1] because of the relativistic mass difference between the two beams.

Calculated transit times of harmonic beams crossing the ion source to dee gap[3] are plotted in Fig. 2. These times indicate an initial phase shift that allows simulation of the proposed recycle phase history with ions starting from the ion source. For example, a beam of $^{16}O^{2+}$ on the third harmonic requires a transit angle of 65° during the first gap crossing, and its phase at the second gap crossing is 30°. A beam of $^{16}O^{6+}$ on the first harmonic requires a transit angle of 30° during the first gap crossing, and its phase at the second gap crossing is -30°. Calculations using this initial phase shift indicated that $^{16}O^{6+}$ and $^{16}O^{2+}$ would be accelerated simultaneously to full radius on ORIC when starting from the ion source.

In order to verify that two beams were being accelerated to the maximum radius of ORIC, the beams were extracted and scattered from a gold foil into a solid state detector where the energy deposited in the detector was used to identify the beams. The results of the first "two-beam" experiment on ORIC, where only the voltage of the electrostatic deflector was varied by the theoretical amount, is shown in Fig. 3. A $^{16}O^{2+}$ beam at the correct energy was extracted with a deflector voltage of 15 kV and a $^{16}O^{6+}$ beam at the correct energy was extracted with a deflector voltage of 45 kV. This experiment verified that the first and third harmonic beams are simultaneously accelerated from the ion source to the extractor of ORIC.

## Magnetic Extraction Experiment

The extraction system of ORIC is composed of an electrostatic deflector and a two-component magnetic extractor. The first magnetic extraction component has a 3 mm septum. The electrostatic deflector was moved to a larger radius so that the entrance of the first magnetic extractor was exposed to the circulating beam of the cyclotron. Experiments with an all-magnetic extraction system were tested and beams that were magnetically extracted are listed in Table 1.

## Simultaneous Harmonic Acceleration and Magnetic Extraction

Calculations indicated that $^{6}Li^{1+}$ on the third harmonic and $^{6}Li^{3+}$ on the first harmonic at the cyclotron energy constant of $E_O$ = 24 MeV would both have the turn separation to clear the magnetic extractor septum width. The phase requirement for simultaneous acceleration from the ion source to the extraction radius is easily met for these two beams. A high-intensity beam of $^{6}Li^{1+}$ was magnetically extracted and identified by energy and stripping measurements. Identification of the $^{6}Li^{3+}$ companion beam was difficult because of the high intensity of $^{6}Li^{1+}$. The normal method of reducing beam intensity is to add gas to the ion source, but adding gas to the ion source preferentially decreases the high charge state ions. The presence of $^{6}Li^{3+}$ was established by inserting an aluminum absorber to stop all of the $^{6}Li^{1+}$ before it reached the energy detector. The simultaneous detection was achieved by defocusing the extracted beam with a quadrupole until an acceptable count rate was obtained. This gives a small count rate for $^{6}Li^{3+}$; a spectrum obtained is shown in Fig. 4. A 60 micron thick silicon detector was used in this experiment and partially stopped the energetic $^{6}Li^{3+}$ beam. This experiment verified the simultaneous acceleration and magnetic extraction of harmonic beams starting from the ion source.

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## Beam Separation Experiment

The difference in velocity (a factor of 3) between the $^{6}Li^{1+}$ and $^{6}Li^{3+}$ allows the two beams to be separated easily by a velocity selector. An electrostatic parallel plate deflector was installed in the external beam line. After the beams pass through the deflector they enter a steering magnet that redirects the beams onto two particle detectors separated by 6.3 cm (Fig. 5). A collimator was placed in front of detector No. 1 to reduce the large beam intensity of $^{6}Li^{1+}$. Figure 6 shows the energy spectra obtained simultaneously in the two detectors; $^{6}Li^{1+}$ in detector No. 1 and $^{6}Li^{3+}$ in detector No. 2. This experiment verified simultaneous harmonic acceleration, magnetic extraction, and electrostatic beam separation where the two beams originated in the ion source.

## References


1. E. D. Hudson, et al., IEEE Trans. Nucl. Sci., NS-20, No. 3, 173 (1973).

2. R. S. Lord, et al., proceedings of this conference.

3. M. L. Mallory, et al., IEEE Trans. Nucl. Sci., NS-20, No. 3, 147 (1973).


## Acknowledgements


We would like to thank the ORIC operations staff whose fine cooperation in running the cyclotron made this data possible, and F. Irwin who helped develop the lithium ion source.


Table 1. Magnetically extracted beams

| Particle | Energy (MeV) |
|---|---|
| $^{4}He^{2+}$ | 24 |
| $^{6}Li^{1+}$ | 4 |
| $^{6}Li^{3+}$ | 36 |
| $^{12}C^{2+}$ | 8 |
| $^{16}O^{2+}$ | 10 |
| $^{16}O^{3+}$ | 23 |

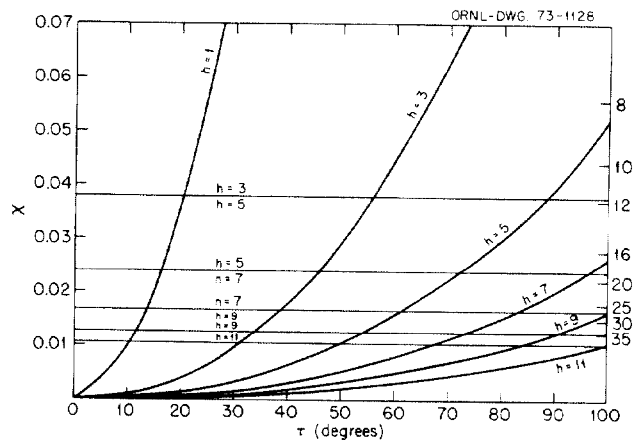


Fig. 2. The transit angle in rf degrees as a function of χ (a geometry parameter) for an initial starting phase of -60°. For a given geometry, χ is related to a particular value of m/q. The transit angle for a given m/q value is larger for the higher harmonics. The harmonic curves (h) are given and the horizontal lines indicate the rf harmonic bands at $E_0$ = 90 for ORIC.

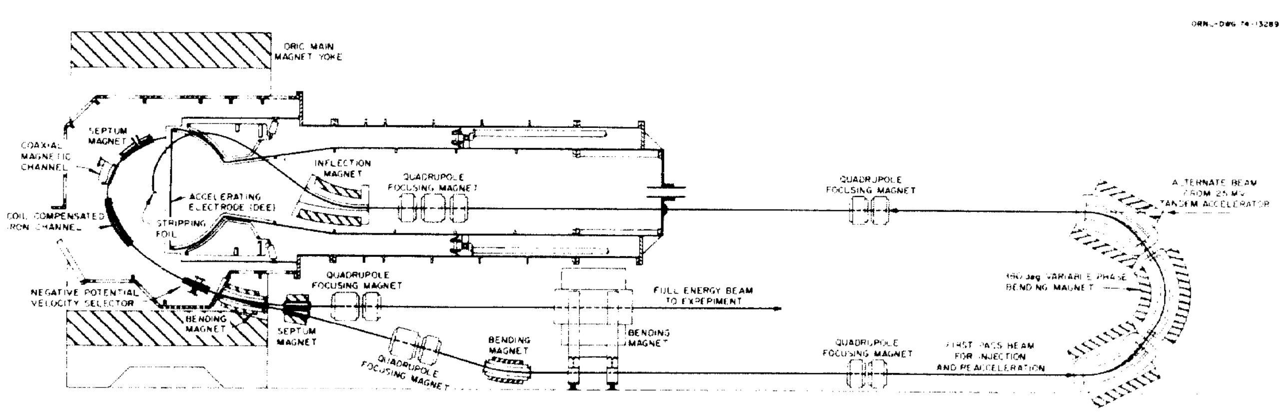


Fig. 1. The engineering layout for implementing the harmonic beam acceleration concept on the ORIC is shown. The injection line from the 25 MV tandem accelerator is under construction. To complete the concept on ORIC would require the substitution of the septum magnet for the electrostatic deflector and the first pass beam transport system through the 180° variable phase bending magnet.

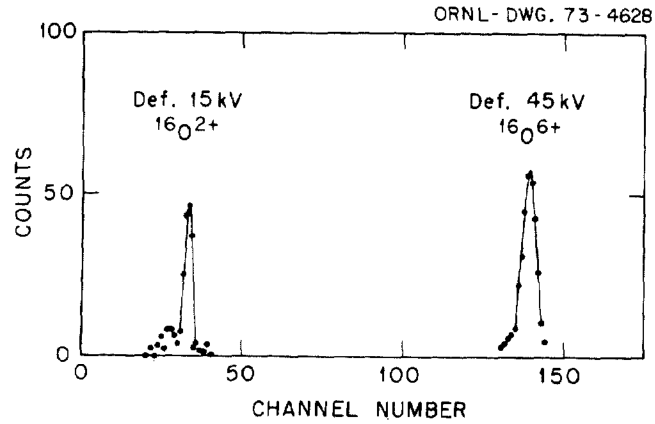


Fig. 3. The energy spectrum obtained from two beams extracted at a voltage of 15 kV and 45 kV of the electrostatic deflector. The peaks are at the right channel location to be identified as $^{16}O^{2+}$ and $^{16}O^{6+}$.

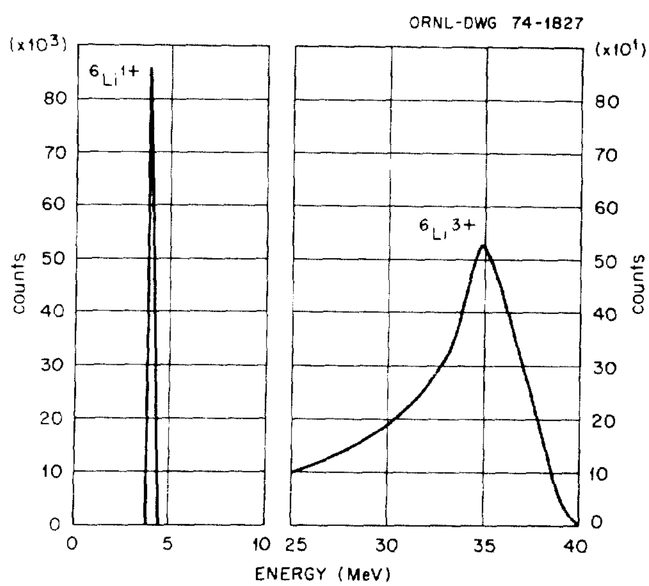


Fig. 4. The energy spectrum of two beams from the scattering of a gold foil into a detector is shown. The beams were simultaneously accelerated and magnetically extracted, and are identified as $^{6}Li^{1+}$ on the 3rd harmonic and $^{6}Li^{3+}$ on the 1st harmonic.

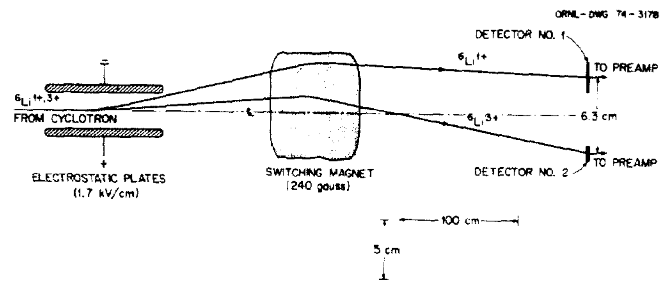


Fig. 5. The experimental configuration for confirming the separation of the simultaneous magnetically extracted harmonic beams of $^{6}Li^{1+,3+}$ is shown. After passing through the electrostatic plates, the beams are redirected by the switching magnet to two detectors separated by 6.3 cm.

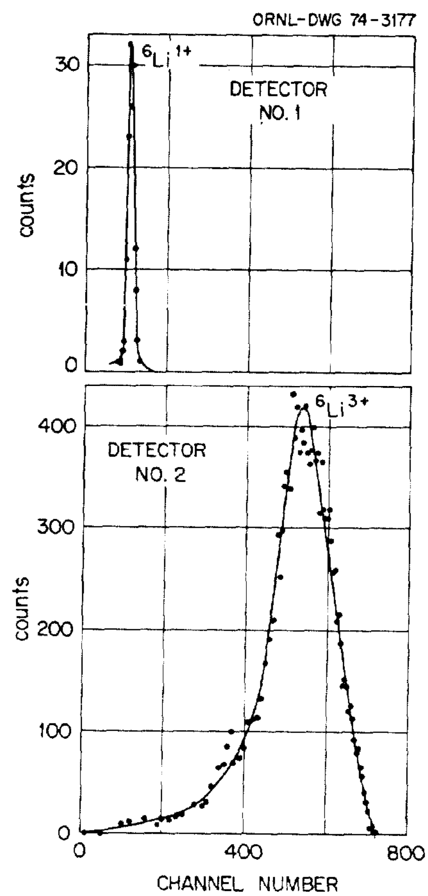


Fig. 6. The energy spectra obtained simultaneously in detector No. 1 and No. 2 for the accelerated and electrostatically separated harmonic beams of lithium is shown. The $^{6}Li^{1+}$ is at an energy of 4 MeV and the $^{6}Li^{3+}$ is at an energy of 36 MeV. A collimator was placed in front of the No. 1. detector to reduce the intensity of the $^{6}Li^{1+}$ beam.