INITIAL OPERATION OF ORIC WITH TANDEM INJECTION

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Abstract.- Coupled operation of the 25 MV tandem and ORIC was achieved on January 27, 1981. The initial beam was 324 MeV $^{16}O^{8+}$ followed shortly by oxygen at 400 MeV--the maximum design energy. Following additional installation and testing of the tandem, coupled operation for a nuclear physics experiment began in August. Performance of the system was in close agreement with that predicted from calculations.

1. Introduction.- ORIC[1] is a K=100 ($K=ME/q^2$) cyclotron built in the early 1960's as a light-ion machine with heavy-ion capabilities, and recently operated almost exclusively as a heavy ion accelerator. With an internal ion source, it is useful for nuclear experiments up to about ion mass 40. In 1975, construction commenced on a 25 MV tandem accelerator to be installed near the cyclotron.[2,3] The scope of this project included provision for injecting the tandem beam into the cyclotron for energy boosting.[4,5] In coupled operation, particles of up to mass 160 may be accelerated to energies above the nuclear interaction barrier (Table 1). Further extension of the capability of this facility by increasing ORIC to K=300 is the subject of another paper at this conference.[6]

2. Injection System.- The tandem is located about 36 meters from the cyclotron. It utilizes a "folded" configuration having a vertical column with a 180-deg magnet following the stripping channel in the terminal. The injection system includes the pair of magnets that turn the beam path from vertical to horizontal, two quadrupoles, an inflection magnet to aim the beam at the right spot in the cyclotron, a movable stripping foil inside the cyclotron and the control and diagnostic systems.

A beam bunching system (Fig. 1) is provided for the purpose of matching the time characteristics of the injected beam to the phase acceptance of the cyclotron.[7] The buncher consists of two klystron-type units with one meter separation, operating on the fundamental frequency of the cyclotron and the second harmonic, respectively. The beam is bunched before entering the low-energy acceleration tube of the tandem while it still has very low energy (~300 keV), keeping the voltage requirements of the buncher cavities low (~1000 V). Design of the beam transport system following the buncher was carefully controlled to provide minimum time dispersion at the stripping foil in the cyclotron (100-150 psec).

At about the midpoint between the tandem and the cyclotron, the beam passes through a capacitive pick-up. The phase of the signal from this detector is compared with the phase of the cyclotron rf resonator, and a phase-lock circuit is used to maintain a

TABLE 1. ANTICIPATED OPERATING PARAMETERS FOR MAXIMUM ENERGY PER NUCLEON

ION	E/A (MeV)	Q_{FINAL}	Q_{INJ}	ENERGY GAIN	R AT FOIL (mm)	FOIL LIFE (hr)
^{16}O	25.0	8^+	2^+	5.3	2.5	385
^{28}Si	25.0	14^+	6^+	4.0	2.3	167
^{35}Cl	23.3	17^+	8^+	3.6	2.2	117
^{40}Ca	25.0	20^+	9^+	4.0	2.2	82
^{58}Ni	19.9	26^+	9^+	4.6	2.7	29
^{79}Br	13.4	29^+	10^+	3.9	3.0	14
^{107}Ag	10.1	34^+	9^+	4.3	3.5	6
^{127}I	8.0	36^+	10^+	3.7	3.6	4
^{158}Gd	6.1	39^+	9^+	3.8	4.2	2
^{238}U	3.1	42^+	9^+	3.0	5.1	0.7

NOTES:

1. For gas stripping in the terminal and an intensity of $\geq 10^{11}$ part/sec.
2. For 25-MV tandem voltage. Most beams could be run at lower injection energy with some reduction in beam intensity and foil lifetime. Lower energy beams can be obtained with the same or higher intensities.
3. The life of the foils, formed by ethylene gas glow discharge, has been estimated (ref. 8) for thickness t = 10 μg/cm², spot size 1 x 5 mm, and 1 pμA injected:

$$T(\text{p}\mu\text{A min/mm}^2) = [0.0073t\ (\mu\text{g/cm}^2) - 0.0101]\ \frac{E(\text{eV})}{MZ^2}$$

4. Operation at energies above the Coulomb barrier could be extended to about mass 200 by the use of foil stripping in the terminal, but the estimated life of the terminal foil is only a few minutes.

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constant phase relationship between the beam phase at this point and the cyclotron rf phase. The capacitive probe has a length of 34 cm and requires ~100 nA to produce sufficient signal strength to drive the phase-lock circuit.

When both buncher cavities are in operation, about half of the beam can be bunched into ±3 degrees of the rf frequency. This is required to achieve an energy spread of 1 part in 1000. Preliminary measurements made by varying the buncher phase indicate that the phase acceptance for transmitting through the cyclotron may vary from ±3 deg to ±30 deg depending on the tuning of the cyclotron. The increase in beam intensity resulting from turning on the buncher is a factor of 5 to 10, depending on how the cyclotron is tuned.

The effect of the buncher on the time structure of the beam on a target 20 meters from the cyclotron can be seen in Fig. 2.

The injected beam must be sufficiently rigid as it enters the cyclotron so that it can cross the cyclotron field and arrive at the stripping foil (Fig. 3). This, when the radial limits on the travel of the foil are considered, implies also that a stripping ratio of ~2:1 or greater is required to capture the beam in an orbit suitable for acceleration. For lighter ions, it is necessary to limit the charge change that occurs in the tandem terminal to assure that a 2:1 charge change at the stripping foil in the cyclotron is achievable. For carbon, nitrogen, and oxygen, which would normally be almost fully stripped in the terminal with ordinary pressures in the stripping channel, this is accomplished with no significant loss of intensity by operating the stripping channel at lower than normal pressure, thus intensifying the desired charge state.[9] For the heavier particles, higher charge states in the terminal are usable and desirable to achieve maximum final energy.

3. Beam Monitoring Diagnostic System.- Six quartz-plate viewers with closed-circuit television cameras have been provided for setting up a beam through the injection system. With these viewers the position of the beam can be adjusted to coincide with the axis of the injection line, the shape can be monitored approximately, and it can be determined whether the beam is passing through the quadrupoles on-axis. One of the quartz viewers is located inside the cyclotron and can be substituted in place of the foil for aiming and focusing the beam. The beam also caused the foil or its support wire to glow visibly during operation. A 3-meter fiber-optic viewing system was required so that this TV camera could be mounted where the cyclotron stray field was sufficiently low. This system worked well during the first run, but for unexplained reasons we were unable to view the beam in the cyclotron in later runs. In addition to the TV monitoring systems two Faraday cups are used, one at each of the beam waists. The first is located after the regulating slits between the 25-deg and 65-deg magnets that turn the beam path from vertical to horizontal. Tuning for maximum beam passing through the slits at this point produces a waist that is required for minimum time dispersion. The second cup, about halfway along the line, is capable of measuring the time structure of the beam for initial adjustment of the buncher. Final adjustment of the buncher is, of course, done by observing the intensity of the beam extracted from the cyclotron while varying buncher phase and amplitude. A foil can be inserted into the beam ahead of the 65-deg magnet so that the charge state distribution of

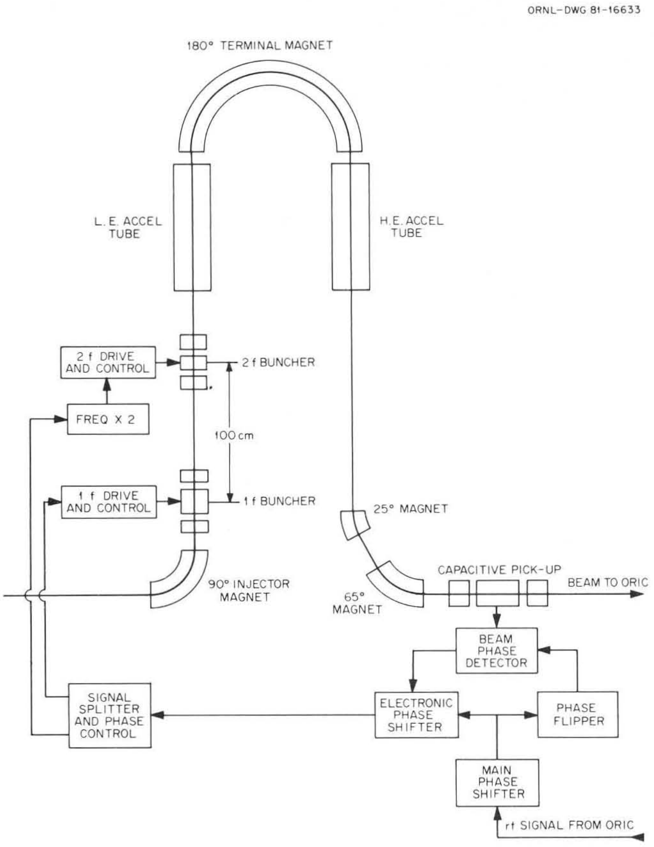
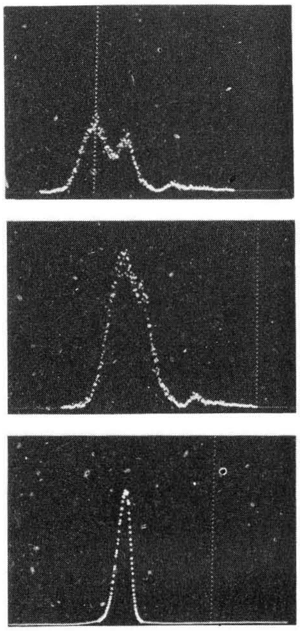


Fig. 1. Beam bunching system block diagram.


a. Buncher off.
Dee voltage detuned by 300 volts.
3.5 nsec (FWHM)

b. Buncher off.
3 nsec (FWHM)

c. Buncher on.
1 nsec (FWHM)

Fig. 2. Time spread of extracted beam 20 meters from the cyclotron.

the stripped beam in the cyclotron can be determined prior to injection.

4. Beam Dynamics Computations.- In 1977, the magnetic field of the cyclotron was remeasured10) to obtain data for the fringe field and for the high main magnet fields that are now used. The field data was parameterized11) and programs have been developed for computing trim and harmonic coil settings, injection trajectories, foil azimuth and radius, inflection magnet strength and position, and extraction system mechanical and magnetic settings. The extraction system program is operator interactive so that the system parameters may be iteratively adjusted while observing a graphic display of the calculated extracted beam trajectory.

The programs for acceleration and extraction of the beam have been in routine use with the internal source since June, 1980, and have proven very successful in producing extracted beam with only minor tuning by the operator. The injection program has proved invaluable in predicting the foil position and inflection magnet setting for the first injected beams. The operating position of the foil, determined by optimizing the extracted beam, was only a few millimeters from the predicted position.

5. Operating Experience.- In January, 1981, the tandem, although still undergoing acceptance tests, was made available for two brief tests of coupled operation. During the first 24-hour test the transport and diagnostic systems were checked out with beam, which was then stripped and accelerated to full radius. Because of a water leak in one of the extraction channels when it was energized, we were unable to extract the beam. Two weeks later a period of three days was allotted to testing coupled operation. The first extracted beam (324 MeV $^{16}O^{8+}$) was obtained on January 27 within a few hours of starting the test. The parameters are given in Table 2. This beam was used briefly to obtain a scattering spectrum, then the energy was increased in steps to the full design value (25 MeV/amu) by raising the cyclotron frequency and magnetic field. At this point further measurements were made using a ^{208}Pb foil target and a broad range spectrograph (Fig. 4). The energy resolution during this experiment was ∿ 115 keV (FWHM), or about 1 in 3500. This was as good as, or better than, the predicted energy spread of the beam, and substantially better than the energy spread measured in the previous experiment at 324 MeV.

Following the January operation, installation and testing of the tandem continued. The next opportunity for coupled operation came on July 31, 1981. A brief attempt was made to extract an oxygen beam at 10 MeV/A. This effort was abandoned in favor of a higher energy when high conductivity of the cooling water for the cyclotron internal probe made it useless for measuring small beam currents. Radiation from the probe, which is normally used as a tuning aid, did not exist at this energy. The conductivity problem was subsequently corrected and the probe radiation could have been enhanced by the use of beryllium, but the requirements of the physics experimental program strongly influenced the decision to return to the 400 MeV oxygen beam that had been developed in January. Following a number of relatively minor but time consuming difficulties, a beam with sufficient intensity and stability to meet the needs of the experimenters was obtained on August 20. Typical parameters are shown in Table 2. No measurement of energy resolution was made during this experiment, but it is interesting to note that under the best conditions the beam passed through the energy analyzing magnet without any loss, and 70 to 80 percent of the beam passed through a 1-mm-dia hole at the target, 3 meters from the last quadrupole. 100% transmission through the analyzing magnet is consistent with an energy spread of 1:1000 or better. When the internal cyclotron source is used, the transmission is typically 10 to 30 percent through the analyzing magnet and the minimum spot diameter at the target is about 6 mm. During this experiment it was necessary to limit the beam intensity to about 10 nA at the target to avoid saturation of the electronics in the detector systems. Because of the need to limit our electric power costs during the remainder of the fiscal year (through September) this experiment was terminated on August 22.

During the last few days of operation, a problem developed that has the potential for serious impact on the operations schedule and a not insignificant effect

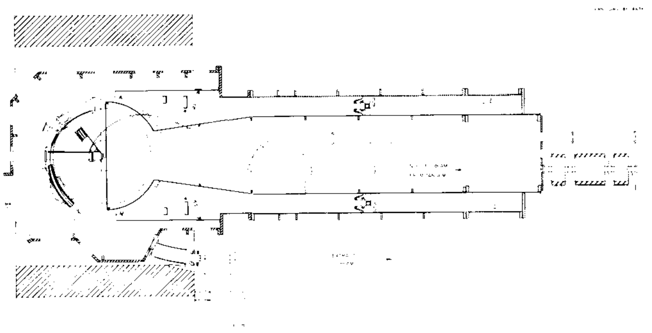


Fig. 3. Beam enters the cyclotron through the rf resonator, is directed by the inflection magnet to the stripping foil which is placed on an orbit suitable for acceleration. The incoming beam must have a sufficiently large rigidity (Bρ) to cross the field to the foil. The inflection magnet has an angular range of 17 to 37 deg to accommodate beams of different rigidity requiring different deflection angles.

TABLE 2. PARAMETERS FOR FIRST COUPLED OPERATION

	January	August
Tandem:		
Terminal Voltage	12.2 MV	12.2 MV
Injector Voltage	300 kV	300 kV
Low Energy Ion	OH^-	OH^-
Accelerated Ion	$^{16}O^{2+}$	$^{16}O^{2+}$
Analyzed Current	400 nA	670 nA
Output Energy	39 MeV	39 MeV
Cyclotron:		
Accelerated Ion	$^{16}O^{8+}$	$^{16}O^{8+}$
Circulating Beam	180 nA	275 nA
Extracted Beam	125 nA	190 nA
Energy	324 MeV	400 MeV
Analyzed Beam on Target	60 nA	55 nA
Energy Gain	8.3	10.3

on the budget. An internal short circuit, at first intermittent, then continuous, developed in a portion of the winding of the inflection magnet located inside the dee stem. It was possible to work around the problem by increasing the current in the magnet to make up for the shorted turns. This type of magnet failure is unprecedented in the history of ORIC. It is being studied to determine the cause (cooling water failure, fabrication error, design error, etc.) and whether removal and repair will be required.

During these experiments we did not experience a foil failure. This was consistent with the predicted life of 150 pμAh of 38 MeV ^{16}O beam for the 5-10 μg/cm^2 carbon foils made by deposition of carbon from an ethylene gas discharge.

Acknowledgments

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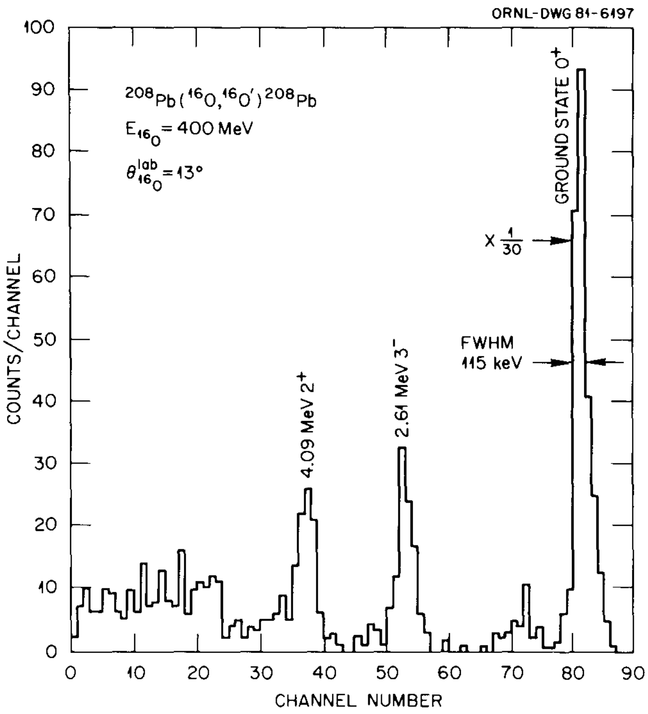

Fig. 4. Spectrum of ^{16}O ions scattered from a ^{208}Pb target. Scattered particles were detected using a silicon position-sensitive detector placed in the focal plane of a magnetic spectrograph. Clearly visible are peaks from elastic scattering (ground state) and excitation of 2.61- and 4.09-MeV levels of the ^{208}Pb nucleus. The measured energy resolution was 115 keV (FWHM), which includes contributions from such sources as the beam energy spread, beam angular divergence, inherent detector resolution, electronic noise spread and energy straggling in the target.

" DISCUSSION "

H. BLOSSER : Would you fill us in on the status of the 25 MV tandem in its stand alone configuration ? What voltages ? What beams ?

C.A. LUDEMANN : The tandem has completed its 17.5 MV acceptance tests and is being used in experiments with terminal voltages up to 22 MV. Late this year, National Electrostatics Corporation, the manufacturer of the machine, will return to Oak Ridge to complete the machine and acceptance tests at 25 MV. Ion species used in nuclear physics experiments to date include O, Ni and Ti.