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COUPLED OPERATION EXPERIENCE AT THE HOLIFIELD HEAVY-ION RESEARCH FACILITY

R.S. Lord, J.B. Ball, E.D. Hudson, P.K. Kloeppel,[1] C.A. Ludemann,
J.A. Martin, S.W. Mosko, and N.F. Ziegler
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37830

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Introduction

The 25URC Pelletron tandem electrostatic accelerator and the Oak Ridge Isochronous Cyclotron (ORIC) comprise the accelerators of the Holifield Heavy-Ion Research Facility (HHIRF).[1-6] The two machines may be operated individually or coupled, with ORIC serving as an energy booster for the tandem. In the coupled mode (Fig. 1), the ion beam enters the cyclotron through the dee stem and is directed by the inflection magnet so that it is tangent to an orbit suitable for acceleration at a higher charge state. A thin carbon foil, placed at the point of tangency, strips the ions so that a substantial fraction are in the desired higher charge state. This fraction of the beam is then accelerated and extracted in the normal fashion. Full energy performance (25 MeV/A oxygen) was demonstrated during first coupled operation in January 1981. Routine coupled operation for experiments commenced in July 1982.

Computed Cyclotron Parameters

Beams up to mass 116 have been accelerated for physics experiments (Table I). As with the initial oxygen beam, setup and extraction of these beams using computed cyclotron parameters was straightforward and expeditious. The input parameters for the computation are: final energy, ion mass and charge to be extracted and injected ion energy and charge. The principal output parameters are: rf frequency, main coil current, trim and harmonic coil currents, foil azimuth and radius, inflection magnet position and field, and extraction system voltage, currents, and positions. Phase history, focusing frequencies, and residual first harmonic are provided to aid in evaluating the solution. The extraction system settings are obtained by operator interaction with a graphic CRT display. Using plots depicting the beam passing through the extraction elements, one can manipulate coil currents and mechanical settings to find approximate solutions. Auxiliary programs are used prior to parameter calculation to determine the best injection energy and initial and final charges.

Extracted beam is usually available without deviation from the computed settings. Only relatively minor tuning adjustments are required to optimize the extracted beam intensity. Changes from the calculated values for foil position are rarely required. Some trim coil currents may occasionally be changed by two or three percent. Harmonic coil currents are usually changed by small amounts to optimize extracted beam. In contrast to some other cyclotrons where the extraction path is largely independent of magnet excitation, the extraction path in ORIC varies in both position and shape. The electrostatic deflector entrance can be moved over a radius range of 7.5 cm and the positions of the two magnetic channels may vary in radius by about 5 cm. The calculated extraction system positions and currents are often modified slightly to achieve maximum extracted beam. It is presumed that this last effect may be due to lack of precision in the parameterization of the extraction system elements for the computation, or a relatively small coherent oscillation of the beam, resulting in a different direction or energy at the septum from that calculated by the program.

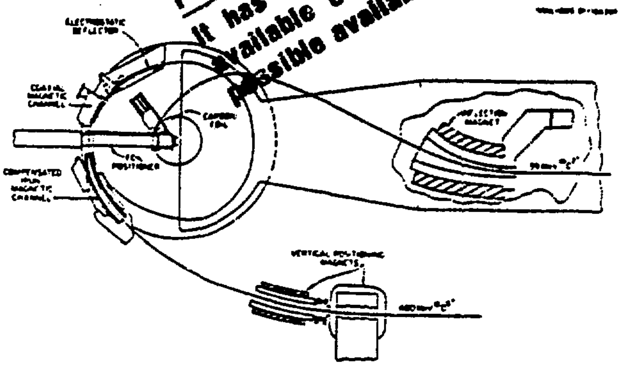

Fig. 1. Cyclotron injection and extraction system. In the example, 39 MeV $^{16}O^{2+}$ is injected. About 25% of the beam is stripped to 8+.

Because of saturation effects in the magnet poles, the radius of curvature of the beam in the electrostatic deflector varies from 1.6 m at low excitation to 1.15 m at full magnet excitation, resulting in a displacement of the midpoint of the deflector by 1.6 cm. The required radius of curvature is precomputed and the deflector/septum set to this value. Significant tuning of the curvature is not usually required.

A recently developed control software technique known as "micro-harmonics" permits fine tuning of azimuth and amplitude of any of the four first-harmonic controls while retaining as a base the values of harmonic coil currents computed to compensate for field errors. Micro-harmonic tuning is more precise and without the danger of loss of the optimum settings. Typical improvements in beam intensity after micro-harmonic tuning have been 10-50%.

Once the beam is optimized, all current settings are logged in the control computer, and are available for automatic setup the next time they are required. Usually, only main magnet coil adjustment is required if the beam is set up from previously logged parameters rather than from computed parameters.

Currents for the beam transport magnets are calculated from the NMR reading of the energy analysis magnet and the known excitation curves of the transport magnets.

Operations

The complete list of runs since the start of routine operation for experimental physics 29 July 1982 - 15 March 1983) is shown in Table I. The most frequently used beam is 400 MeV $^{16}O^{8+}$ (maximum energy per nucleon). The beam with the most total energy is the 1 GeV $^{79}Br^{28+}$. The tandem voltage for most runs is between 12 and 16 MV. In many cases this voltage is sufficient for optimum performance. For some beams, such as 835 MeV $^{58}Ni^{23+}$ or 1000 MeV

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[1] Permanent address: Monmouth College, Illinois.

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$^{79}Br^{28+}$, increased intensity would result from higher tandem voltage because more beam would be in the desired charge state after stripping inside the cyclotron. As heavier ions are accelerated, higher terminal voltages will be required. At the present time, the tandem voltage is limited by some defective tube sections in the column. These will be replaced soon.

It is not always necessary to change the beam energy from the tandem when the final energy is changed. For example (Table I), runs 6 and 7, 403 MeV $^{16}O^{8+}$ and 200 MeV $^{16}O^{7+}$, were produced with the same tandem beam. Other examples are runs 4 and 5 (^{58}Ni) and runs 10 and 11 ($^{16}O^{8+}$). In the first case, both the final charge state and the injection radius were changed; in the second, only the injection radius was changed.

The tandem has operated with extremely good voltage stability. The buncher system[7] has exhibited easy tuning and excellent stability. It has proved possible in most runs to operate the buncher without the use of the phase-lock system.

TABLE I

	Extracted Beam		Injected Beam		
Run	MeV	Ion	MeV	Q_{inj}	V_T (MV)
1	400	$^{16}O^{8+}$	39	2^+	12.8
2	347	$^{16}O^{8+}$	39	2^+	12.8
3	855	$^{58}Ni^{23+}$	142	8^+	15.5
4	889	$^{58}Ni^{23+}$	142	8^+	15.5
5	457	$^{58}Ni^{19+}$	142	8^+	15.5
6	403	$^{16}O^{8+}$	39	2^+	12.8
7	200	$^{16}O^{7+}$	39	2^+	12.8
8	158	$^{9}Be^{4+}$	17	1^+	9.4
9	402	$^{16}O^{8+}$	39	2^+	12.8
10	402	$^{16}O^{8+}$	39	2^+	12.8
11	349	$^{16}O^{8+}$	39	2^+	12.8
12	494	$^{116}Cd^{25+}$	112	7^+	14.7
13	616	$^{116}Sn^{28+}$	112	7^+	13.8
14	401	$^{16}O^{8+}$	39	2^+	12.8
15	613	$^{116}Sn^{28+}$	112	7^+	13.8
16	631	$^{116}Sn^{28+}$	112	7^+	13.8
17	403	$^{16}O^{8+}$	39	2^+	12.8
18	884	$^{58}Ni^{23+}$	141	8^+	15.6
19	884	$^{58}Ni^{23+}$	141	8^+	15.6
20	818	$^{56}Fe^{22+}$	138	8^+	15.3
21	821	$^{56}Fe^{22+}$	138	8^+	15.3
22	404	$^{16}O^{8+}$	31.5	2^+	10.4
23	1000	$^{79}Br^{28+}$	158	9^+	15.8
24	381	$^{17}O^{8+}$	36	2^+	12.0
25	445	$^{35}Cl^{13+}$	45	3^+	11.1
26	445	$^{35}Cl^{13+}$	45	3^+	11.1
27	315	$^{35}Cl^{12+}$	45	3^+	11.1
28	373	$^{35}Cl^{12+}$	45	3^+	11.1
29	241	$^{35}Cl^{11+}$	45	3^+	11.1
30	679	$^{32}S^{15+}$	87	5+	14.5

Beam Intensity

Beam losses occur at several points in the coupled configuration. If we consider only the losses occurring after the beam exits the tandem, the principal reasons for loss are: 1) only about half the bunched beam is within the ± 3-degree window needed for acceleration with energy spread of 1:1000; 2) the fraction of beam in the desired charge state after stripping in the cyclotron is typically less than 30%--or less than 5% in extreme cases; 3) the efficiency of extracting beam from the cyclotron can be anywhere from 30 to 80% depending on turn spacing, beam phase width, beam centering, etc. Beam loss due to interaction with residual gas has not been measured but seems to be negligible. Pressure in the injection line is about 5×10^{-8} torr. Pressure in the cyclotron is about 10^{-6} torr.

Table II gives the measured beam intensity at various points for several typical runs. Predicted intensities with 50% bunching efficiency and calculated stripping efficiency assumed are also tabulated. The differences between actual and predicted beam intensities may be attributed to inexact knowledge of the charge fraction, bunching efficiency, and charge exchange. A detailed study has not been undertaken since all available accelerator time has been allocated to experimental physics and to developing new beams.

TABLE II

Ion	Beam from Tandem (pnA)	Cyclotron Circ. Beam		Extracted Beam		
		Meas. (pnA)	Pred. (pnA)	Meas. (pnA)	Pred.* (pnA)	Max.** Observed (pnA)
^{9}Be	9	3	4.7	2.3	3.5	3.3
^{16}O	18	3.2	2.3	1.9	1.4	60
^{17}O	8	1.1	0.44	3.3	1.7	3.3
^{58}Ni	29	1.4	1.6	0.43	0.48	1.3
^{116}Cd	5	0.32	0.53	0.16	0.27	0.5

* The predicted currents include factors for bunching efficiency (assumed to be 0.5) and stripping efficiency (assuming a foil of equilibrium thickness). The observed extraction efficiency was used.

**Record maximum intensity observed for this ion. The other numbers are self consistent.

Stripping Foil Lifetimes

In the 30 runs that have been made in coupled mode, only two foils have failed completely during operation. However, it was found that the ^{58}Ni and ^{56}Fe beam intensities could be increased 20-40% if foils were changed about once in 24 hours. New foils are inserted into the beam in less than one minute by operating the foil carrier which holds up to 20 foils. Some minor beam steering and harmonic coil current adjustment are sometimes useful to re-optimize the beam after a foil change. In general, foil life has equalled or exceeded expectations. Glow-discharge foils are used in thicknesses up to 20 μg/cm² because of their long life. At the present time, vapor deposited foils are used for thicknesses greater than

20 μg/cm^2. The maximum thickness foil we expect to need for equilibrium thickness will be ~ 100 μg/cm^2.

Residual Radiation

During a routine radiation survey when the cyclotron extraction system was removed for repair, alpha activity was discovered on the extraction elements and other nearby components. The sources were identified as ^{208}Po, ^{209}Po, and ^{210}Po through measurement of the alpha particle energies.

For a variety of projectile target combinations, many different multinucleon transfer reactions and subsequent radioactive decay-chains can lead to these Po isotopes. An experimental measurement of the cumulative production cross sections for these Po isotopes in reactions of 320 MeV ^{56}Fe with Ta was subsequently performed using the stacked foil technique. Production cross sections of ~ 100 millibarns were obtained. These long-lived, alpha-active nuclides presumably may be formed when: 1) the sum of nucleons in the target and projectile exceeds 210-230; 2) the total number of protons is at least 84, and 3) the projectile energy is sufficient to produce the required multinucleon transfer (~ 10 MeV/A).[8]

To avoid the potential health hazard of alpha-contaminated accelerator components, we have substituted molybdenum for tantalum and tungsten wherever these metals were exposed to the high energy beam--principally the tungsten septum and tantalum extraction system shields. The effect of this substitution on polonium production is shown in Fig. 2. This information on alpha activity is preliminary and is supplied only to alert others to potential problems.

Conclusion

Coupled operation of the tandem and ORIC has, in most respects, equalled or exceeded expectations. From the very first operation it has been easy to obtain the desired beam using computed settings. Energy resolution has, in some cases, exceeded expectations substantially. In two measured cases, the beam energy resolution was 1:1500 and 1:3500, respectively. (In many cases, resolution is unimportant and is not measured.) Foil lifetime has not been a problem, and most mechanical and electrical systems have performed to their full potential.

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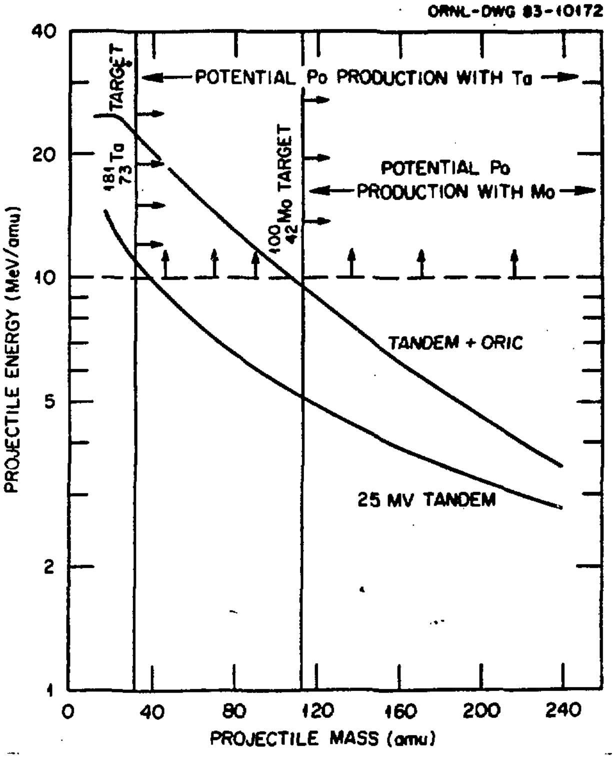

Fig. 2. The potential for producing polonium exists to the right of the target lines (^{181}Ta, ^{100}Mo) and above the energy threshold (~ 10 MeV/A). Substituting molybdenum for tantalum and tungsten shields and septum moves the polonium production potential effectively out of range of HHIRF capability if 10 MeV/A is the threshold energy.

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