OPERATIONAL EXPERIENCE FOR COUPLED OPERATION OF THE HOLIFIELD TANDEM ELECTROSTATIC ACCELERATOR AND ISOCHRONOUS CYCLOTRON*

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Summary

Coupled operation of the 25 MV tandem accelerator and the Oak Ridge Isochronous Cyclotron of the Holifield Heavy Ion Research Facility began in January 1981. Since that time the use of the cyclotron in this mode has become routine. Thirty-six different ion species in the range from ^{9}Be to ^{150}Nd have been accelerated; 106 separate beam setups have been provided.

Since the beginning of coupled operation, significant improvement of cyclotron systems, and setup and operating techniques, have been made. The graphite electrostatic deflector septum formerly used for high-current light ion beams has been replaced by a thin molybdenum septum. Extraction system positioning mechanisms have been refined and recalibrated and more precise and reliable position readouts have been provided. The computer-based control system has been improved. The frequency range of the rf system has been increased to eliminate an energy dead-band. Cyclotron setup calculations have been improved and standardized methods have been developed to consistently achieve well-centered orbits, correct beam extraction system positions, and electrostatic and magnetic strengths. A totally new beam bunching system has been installed. The improvements in the phase-lock system of the beam buncher have been especially effective. A large number of obsolete and unreliable power supplies have been replaced.

Overall performance improvements include:

- Beam extraction efficiency has been increased from ~ 50% to ~ 70%.
- Accuracy of obtaining the desired energy without fine tuning is now ~ 1% compared to 2-3% in early coupled operation.
- Beam setup time (tuning) has been reduced by ~ 20%.
- Unscheduled maintenance has been reduced by a factor of two.

Introduction

The Oak Ridge Isochronous Cyclotron (ORIC)[1] is a K = 100 (K = ME/q^2) cyclotron completed in the early 1960's as a versatile accelerator with variable energy for both light and heavy ions. In the early years of operation, it was used principally for light ion acceleration. Beginning in 1969, the research program began to shift toward experiments using heavy ions as projectiles; by 1976, 80% of cyclotron operation was devoted to heavy ion acceleration.

During the period 1976-1980, modifications were made to the cyclotron to enable it to be used as an energy booster for beams from the 25 MV tandem accelerator. The tandem accelerator[2,3] is a Model 25 URC Pelletron built and installed by the National Electrostatic Corporation. Installation of the tandem accelerator was completed in February 1980; first beam through the accelerator was obtained in May 1980. In August 1980 acceptance tests at 17.5 MV were completed. The installation phase of the NEC contract was completed in June 1982. First coupled operation of the tandem and the cyclotron was on January 27, 1981, when a $^{16}O^{+8}$ beam at 324 MeV was extracted from the cyclotron.[4]

Beam Injection System

Beam Transport

The beam transport system between the tandem accelerator and the cyclotron is shown in Fig. 1. The cyclotron and the tandem accelerator are separated by a distance of about 36 m. The system includes the 25°-65° magnet pair that bends the beam path from vertical to horizontal, two quadrupole doublets to provide focusing, and an inflection magnet to direct the beam into the cyclotron to pass through the stripping foil at the proper radius and angle. The energy control slits for the tandem are located between the 25° and 65° magnets. A capacitive pickup unit (CPU) for monitoring the performance of the buncher and to provide a control signal for the buncher phase lock is located about midway between the tandem accelerator and the cyclotron. The systems directly associated with the cyclotron are illustrated in Fig. 2.

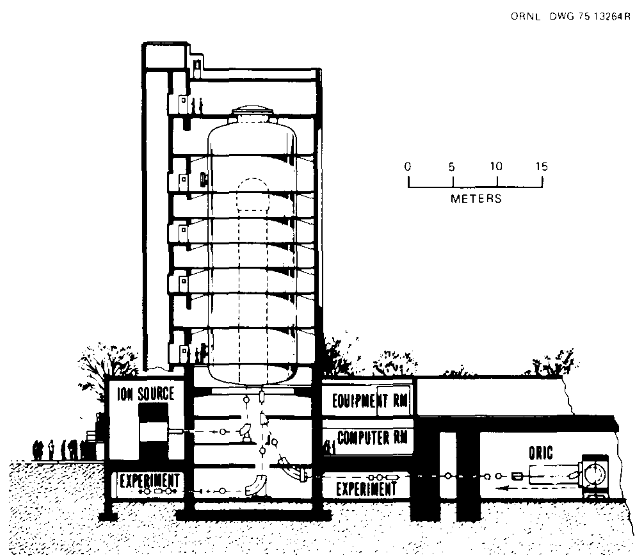

Fig. 1. Beam transport between the tandem accelerator and the cyclotron.

Foil Positioner and Injection Limits

The ORIC stripping foil positioner[5] (Fig. 3) is inserted radially and is interchangeable with the internal ion source. The positioner is driven by stepping motors located outside the vacuum system. Position readout is via synchro's and synchro-to-digital converters. The motor controllers and s-d converters are standard CAMAC modules interfaced to the control computer via a CAMAC serial highway. Protection against interference of the beam monitoring probe and the foil positioner is provided by a

*Research sponsored by the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

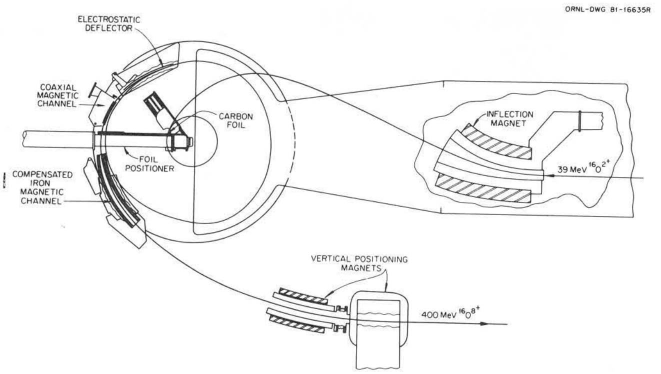

Fig. 2. Beam enters the cyclotron through the rf resonator, and is directed by the inflection magnet to the stripping foil which is placed at the radius and angle appropriate for acceleration of centered orbits. The inflection magnet can provide bend-angles of 17 to 37 degrees to accommodate a wide range of beam rigidities and stripping foil positions.

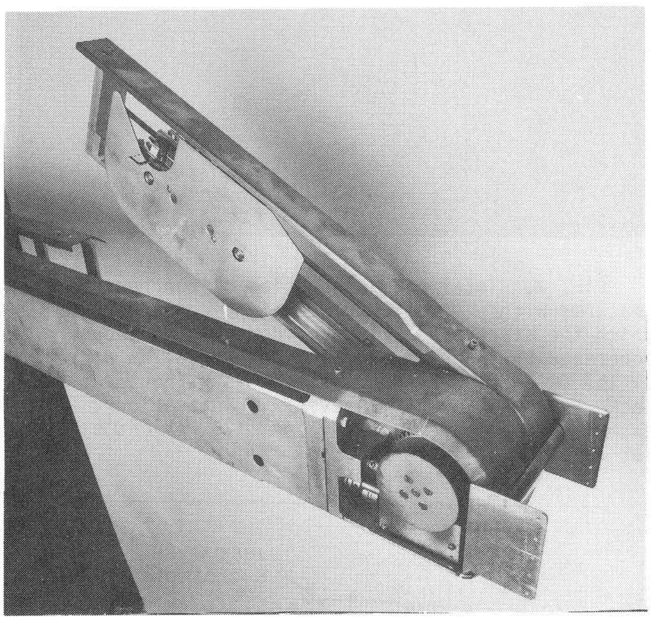

Fig. 3. The stripping foil positioner mechanism is shown in a typical operating position with the foil carrier in place.

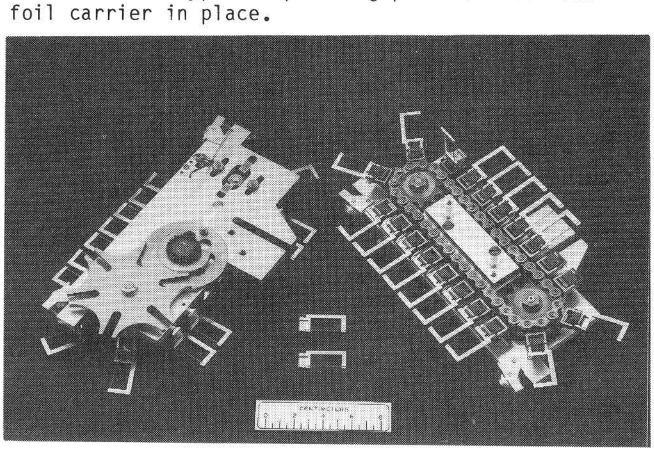

Fig. 4. Front and back view of the foil carrier. In the front view (right) the beam shield has been removed.

microprocessor which continually monitors the positioner and beam probe locations and vetoes any dangerous request from the control computer. The foils are contained in a foil carrier (Fig. 4) which can contain up to 20 foils.

The foil positioner can place the stripping foil within a range of azimuths of approximately 85° and a range of radii between 25 cm and 50 cm, the latter corresponding to energy gain ratios, E_{ext}/E_{inj}, of 10.6 and 2.2. This wide variation of foil location gives exceptional flexibility for choice of injection energies and charge states. Except at the highest energies, which require the maximum charge-state obtainable within the energy limitations of the tandem accelerator, it is almost always possible to choose tandem and cyclotron charge-states that give maximum charge-state fractions. The beam injection limits for the cyclotron are shown in Fig. 5.

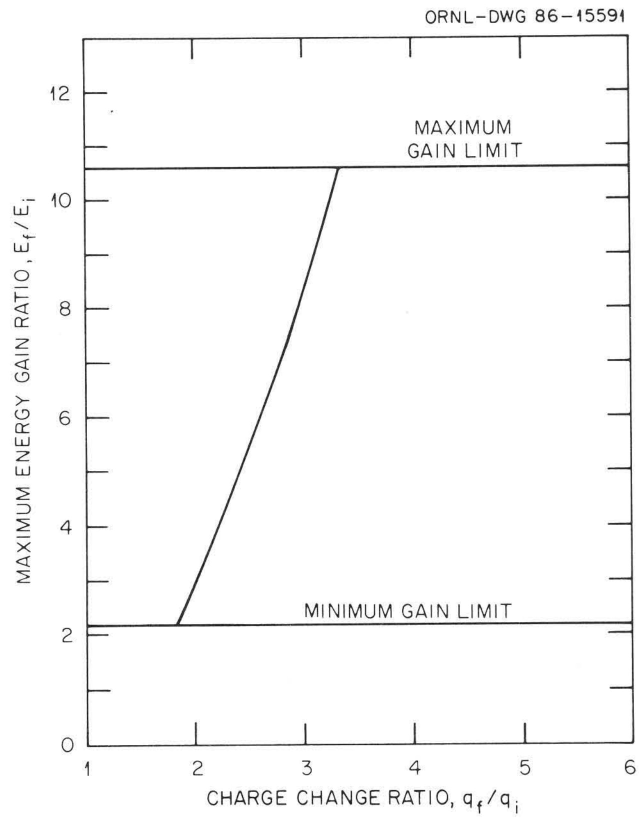

Fig. 5. Beams may be injected into the cyclotron if the point defined by the charge-change ratio, qf/qi, and the energy gain ratio, lies to the right of the curved line and is within the minimum and maximum energy gain limits.

The injection system parameters are determined by a computer program which calculates the location of the inflection magnet, the inflection magnet current, and the radius and azimuth of the stripping foil. Recent improvements to this program include incorporation of the stripping foil energy loss in the calculation and provision for avoidance of beam obstructions in the dee structure.

It has not been necessary to do significant fine-tuning of the injection system. One of the foil positions is provided with a phospher which may be viewed via telescope and TV camera. The beam is focused to a line ~ 1 mm radially x 5 mm axially by adjustment of the quadrupole currents. The inflection magnet current required to optimize the beam location on the foil is typically within 1% of the predicted value.

Beam Bunching System

A beam bunching system (Fig. 6) matches the time characteristics of the injected beam to the phase acceptance of the cyclotron.[6] The buncher consists of two klystron-type units with one meter separation, operating at the fundamental and second-harmonic of the cyclotron frequency. The beam is bunched before entering the low-energy acceleration tube of the tandem accelerator while it still has very low energy (~ 300 keV), thus keeping the voltage requirements of the buncher cavities low (a few kV). The beam transport system following the buncher was carefully designed to provide minimum optics-related time dispersion at the stripping foil in the cyclotron (100-150 psec).

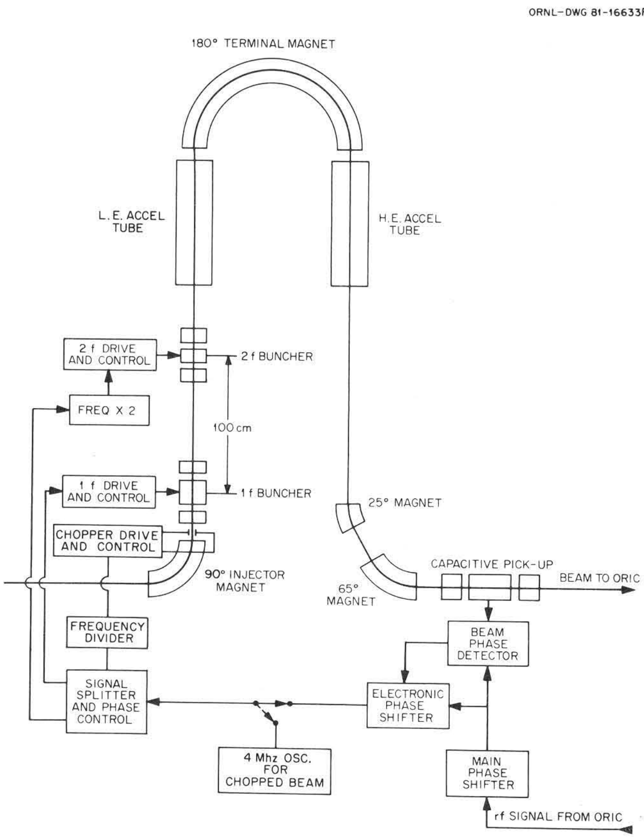

Fig. 6. Block diagram of the beam chopping and bunching system.

At about the midpoint between the tandem accelerator and the cyclotron, the beam passes through a capacitive pickup. The phase of the signal from this pickup is compared with the phase of the cyclotron rf resonator, and a phase-lock circuit is used to maintain a constant phase relationship between the beam phase at this point and the cyclotron rf phase. A new phase-lock circuit has been developed which provides a more stable phase for beam currents as low as 10 enA which is a factor of five better than the original circuit. The circuit operates over a frequency range of 4-16 MHz. The effectiveness of this system is shown in Fig. 7 which shows beam pulse widths with and without phase-lock. Transmission through the cyclotron is critically dependent on beam phase-width and phase stability. Fig. 8 shows the variation of beam current with relative phase for 701 MeV $^{32}S^{+15}$ ions at several post-cyclotron locations. The figure illustrates the broad phase acceptance of the cyclotron for unanalyzed beam and the quite narrow acceptance (6-9°) for energy-analyzed beams.

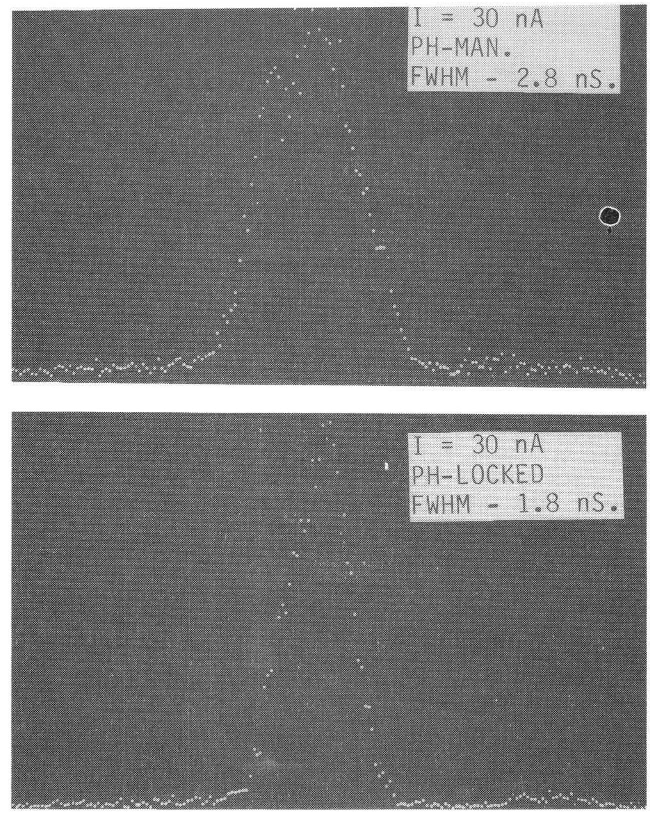

Fig. 7. Total time-dispersion of bunched beams measured with a time-to-pulse-height converter for which the start signal is provided by gamma rays generated by the beam and the stop signal is provided by the ORIC rf. The upper figure is without phase lock while the lower figure is with phase lock. The examples shown were for a 30 enA, 125 MeV $^{32}S^{+6}$ beam for a period of 4 min each.

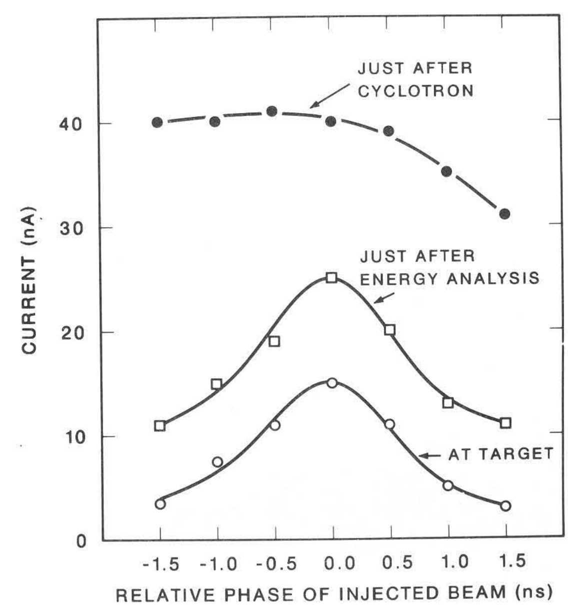

Fig. 8. Beam current at several post-cyclotron locations for 700 MeV $^{32}S^{+15}$. One nsec is equivalent to a phase shift of 4.6 degrees.

A new bunching system was installed this year which includes all of the refinements developed during the past five years and is controlled through the tandem control computer rather than through a separate system as formerly used. In addition, the new system includes a chopping system to provide chopped beam at 1.0 and 4.0 M pps. This system will provide ~ 1-nsec-wide pulses with essentially zero background between pulses.

Beam Extraction

The beam extraction system (Fig. 2) for the cyclotron consists of three principal elements: a 60-cm-long electrostatic deflector which provides gradients up to about 70 kV/cm; a 25-cm-long coaxial septum magnet which produces magnetic field reductions up to 3 kG; and a compensated-iron magnetic channel which provides field reductions up to approximately 6.5 kG. The electrostatic deflector provides a beam separation of ~ 2 cm at the entrance of the coaxial magnet. The electrostatic deflector and coaxial magnet together serve to provide a beam separation of about 6.5 cm at the entrance of the compensated-iron channel.

In 1982 several extraction system modifications were implemented to improve extraction efficiency and to increase the reliability of component position sensing. The 1.5-mm graphite slotted septum of the electrostatic deflector was replaced with a 0.25-mm metal septum, and the shape of the septum was made to conform more closely with the known orbit shape.

Linear position sensing potentiometers were installed on both magnetic extraction channels, and position readings are available in computer scanned data channels. Previously, the extraction channel position data was obtained from synchro readouts which were coupled to positioner drive systems. These synchros were subject to calibration loss each time the drive systems were uncoupled for maintenance.

The coaxial magnet stray field produces negligible effects on the circulating beam; however, the currents of the compensated-iron channel must be set correctly to prevent disturbance of the accelerated beam by the stray magnetic field.

The compensated-iron magnetic channel has inside and outside coils whose currents determine both the internal and external magnetic field. The internal field must be adjusted to give the correct extracted beam path; the external field must be adjusted to give the correct first-harmonic field component for enhanced turn separation at extraction radius. The internal and external fields of the channel are linearly dependent on the inside and outside coil currents. Thus there exist a unique pair of channel currents for any desired extraction path and first-harmonic balance condition.

In practice, the situation is confused because the effect of the channel external magnetic field on the circulating beam is strongly dependent on channel position, and the rigidity and q/M of the beam. Complicating matters further, the descriptions of the external fields of the channel that are incorporated in the setup computer programs seem to be inaccurate.

One solution to these difficulties would have been a time-consuming and difficult remeasurement of the external field of the channel but we chose to approach the problem experimentally. The first step was to fix the position of channel. By calculation, channel entrance and exit radii were determined which readily allow extraction of all beams with $60 \leq ME/q^2 \leq 100$ and $0.25 \leq q/M \leq 0.5$. The channel has been fixed at this position for all runs during the past two years. Beams are extracted with minor adjustment of the channel coil currents and the positions and strengths of the deflector and coaxial magnetic channel.

Fixing the compensated-iron magnetic channel position has allowed a systematic study of coil currents for correct first-harmonic balance. The solid line in Fig. 9 is the measured first-harmonic balance line; any pair of coil currents on that line give exactly the same path through the electrostatic deflector and the coaxial magnetic channel. Different points on the line correspond to different magnetic channel strengths. The data points are for 17 runs made during 1984-1985. The setup program gives an approximately parallel line with ~ 300A higher current in the outside coil. The increased understanding of the behavior of the extraction system has led to much more consistent setup of beams. Beam extraction efficiency now averages about 70% and the desired energy is typically obtained within 1%.

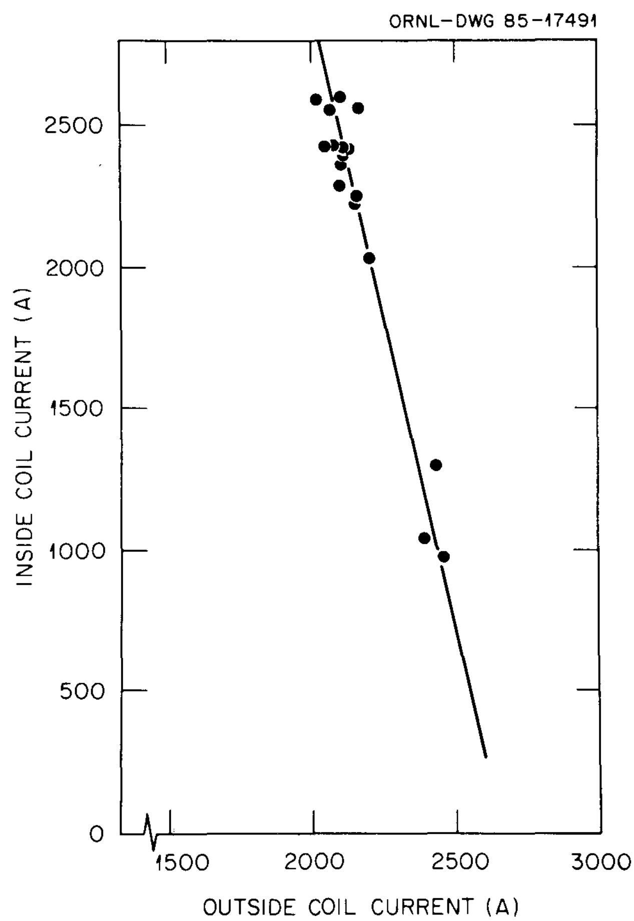

Fig. 9. The straight line is from measured pairs of inside and outside coil currents which give the required first-harmonic component to the ORIC magnetic field to deflect a q/A = 0.23 beam at K = 100. The lower channel entrance and exit radii were set at 85.8 and 92.4 cm. The data points show the coil currents for all cyclotron runs made in the period September 1984-October 1985.

Control Computer

In June 1985, the original 13-year-old ORIC control computer was replaced by a MODCOMP Classic II/55. Approximately ten percent of the existing control software had to be rewritten to conform to this new generation machine's architecture and operating system. The new hardware will insure the long-range availability of spare components as well as reliability of the system. The increased size of memory and disk storage will enhance the capability for software development.

Two current areas of program development are designed to improve on-line monitoring of operation as well as evaluation of machine performance. A voice-synthesized annunciator will augment CRT readout of errors detected in operating parameters. CRT graphics will aid analysis of beam-energy resolution as well as the internal distribution of ion current in the machine.

Two operator-assistance features that are expected to reduce occasional setup errors are also being developed. Operating parameters will be set directly from values computed from our setup code with minimal manual intervention. Furthermore, the independent controls for the currents in the inside and outside coils of our compensated-iron extraction channel will be replaced by the more appropriate physical parameters "strength" and "balance." This transformation will mathematically constrain the two currents and provide better control of the first-harmonic field component produced by the channel.

Other Cyclotron Systems

The cyclotron rf system has continued to operate quite reliably. The noise and stability of the rf voltage are approximately 1:2000. One recent improvement is an increase in the upper frequency limit from 18.0 to 20.1 MHz to give a full 3:1 span. This was accomplished by reducing the dee aperture by 2.5 mm thereby reducing dee capacitance. This improvement has eliminated an energy dead-band between 4.7 and 5.8 MeV/nucleon.

A program for replacement of obsolete power supplies has continued. All of the original trimming coil and harmonic power supplies have been rebuilt or replaced. All of the newer power supplies are SCR regulated units with transductor current measurement.

Coupled Operation Experience

Beam energies provided by the facility are consistent with Fig. 10 which shows estimated energy performance for tandem terminal voltages of 18 and 25 MV. Beams provided during the last three years are listed in Tables 1, 2, and 3. These demonstrate the wide variety of beams provided, and some of the improvements in quality and consistency of operation that have been realized. Beam extraction efficiency has improved from the 50-60% range to ~70%. The desired energy is now typically achieved within 1% and in most instances corresponds to extraction of the beam within one or two turns of the predicted turn-number. For the runs tabulated, the number of turns varies from ~360 (400 MeV $^{16}O^{+8}$) to ~160 (750 MeV $^{150}Nd^{+33}$).

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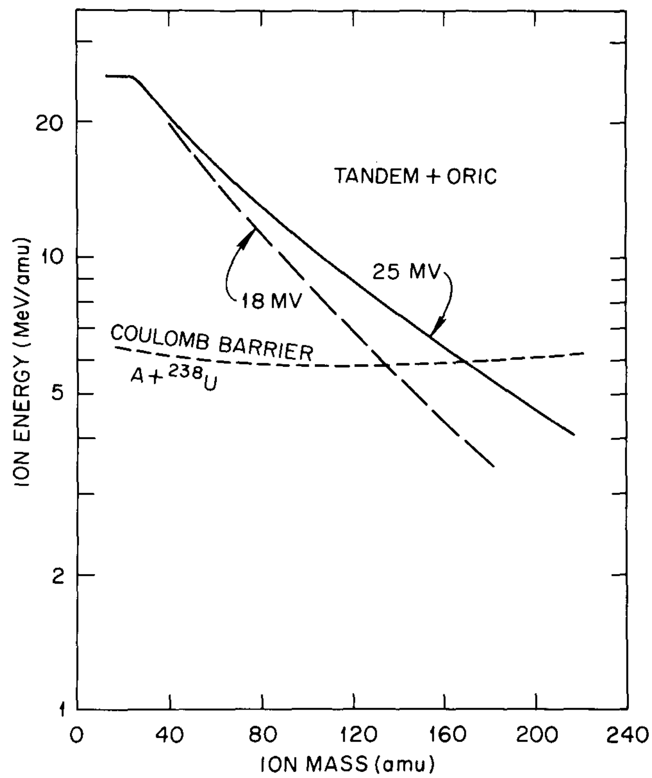

Fig. 10. Maximum ion energy vs. ion mass for coupled operation of the tandem accelerator and cyclotron.

Table 1. Coupled operation for research for the period October 1, 1983 through September 30, 1984

Date	Ion	Desired Energy (MeV)	Measured Energy (MeV)	Error(1) (%)	Extraction Efficiency (%)	Injected Ion	Injection Energy (MeV)	Tandem Voltage (MV)
2/5/84	$^{32}S^{+15}$	700	717.0	+ 2.4	48	$^{32}S^{+6}$	122.8	17.5
2/19/84	$^{18}O^{+8}$	350	351.7	+ 0.5	65	$^{18}O^{+3}$	67.9	16.9
4/7/84	$^{16}O^{+8}$	400	400.7	+ 0.2	68	$^{16}O^{+3}$	67.5	16.8
4/9/84	$^{16}O^{+8}$	400	401.1	+ 0.3	60	$^{16}O^{+3}$	67.5	16.8
5/8/84	$^{56}Fe^{+22}$	820	841.7	+ 2.6	76	$^{56}Fe^{+8}$	170.0	18.9(2)
6/15/84	$^{32}S^{+12}$	320	317.8	- 0.6	55	$^{32}S^{+3}$	66.9	16.6
6/19/84	$^{11}B^{+5}$	170	168.9	- 0.6	68	$^{11}B^{+2}$	38.4	15.3(3)
6/22/84	$^{10}B^{+5}$	170	168.3	- 1.0	78	$^{10}B^{+2}$	39.6	15.8(3)
6/27/74	$^{16}O^{+8}$	400	399.7	- 0.1	~100	$^{16}O^{+3}$	68.0	16.9
7/6/84	$^{35}Cl^{+16}$	700	692.1	- 1.1	75	$^{35}Cl^{+6}$	124.5	17.7
8/8/84	$^{16}O^{+7}$	208	206.6	- 0.7	61	$^{16}O^{+2}$	32.6	10.8
8/14/84	$^{24}Mg^{+8}$	180	177.6	- 1.3	64	$^{24}Mg^{+2}$	20.1	6.8(4)
8/17/84	$^{150}Nd^{+33}$	750	760.7	+ 1.4	67	$^{150}Nd^{+13}$	211.0	15.1(5)
9/11/84	$^{58}Ni^{+23}$	900	916.0	+ 1.8	68	$^{58}Ni^{+9}$	170.4	17.0
9/13/84	$^{48}Ti^{+17}$	576	581.4	+ 0.9	56	$^{48}Ti^{+6}$	92.9	13.3(6)
9/25/84	$^{116}Sn^{+29}$	700	684.1	- 2.3	78	$^{116}Sn^{+7}$	144.9	18.8

NOTES: Error (%) = $[(E_{meas.}/E_{des.}) - 1.00] \times 100$; (2) FeH^-; (3) B_2^-; (4) MgH_3^-; (5) NdH^{3-}; (6) TiH^-.

Table 2. Coupled operation for research for the period October 1, 1984 through September 30, 1985

Date	Ion	Desired Energy (MeV)	Measured Energy (MeV)	Error[1] (%)	Extraction Efficiency (%)	Injected Ion	Injection Energy (MeV)	Tandem Voltage (MV)
10/6/84	$^{32}S^{+15}$	720	715.1	- 0.7	80	$^{32}S^{+6}$	131.7	18.8
10/11/84	$^{58}Ni^{+23}$	930	910.0	- 2.1	75	$^{58}Ni^{+9}$	167.4	16.7
11/2/84	$^{58}Ni^{+23}$	930	907.8	- 2.4	90	$^{58}Ni^{+9}$	167.2	16.6
2/21/85	$^{58}Ni^{+23}$	930	933.9	+ 0.4	70	$^{58}Ni^{+9}$	179.8	18.0
2/26/85	$^{17}O^{+8}$	375	376.7	+ 0.4	85	$^{17}O^{+3}$	71.9	17.9
2/28/85	$^{17}O^{+8}$	325	326.0	+ 0.3	70	$^{17}O^{+3}$	71.9	17.9
3/1/85	$^{32}S^{+15}$	700	700.8	+ 0.1	75	$^{32}S^{+6}$	125.3	17.9
3/3/85	$^{116}Sn^{+27}$	630	634.4	+ 0.7	55	$^{116}Sn^{+7}$	138.5	17.3
3/27/85	$^{16}O^{+7}$	215	212.3	- 1.3	85	$^{16}O^{+2}$	53.4	17.8
3/29/85	$^{12}C^{+6}$	300	299.6	- 0.1	75	$^{12}C^{+2}$	53.9	17.8
4/10/85	$^{17}O^{+8}$	375	375.1	+ 0.0	60	$^{17}O^{+3}$	71.9	17.9
4/30/85	$^{32}S^{+15}$	700	703.5	+ 0.5	75	$^{32}S^{+6}$	133.7	17.9
6/25/85	$^{58}Ni^{+24}$	1005	1009.8	+ 0.5	90	$^{58}Ni^{+9}$	177.8	17.7
8/8/85	$^{32}S^{+15}$	700	713.7	+ 2.0	75	$^{32}S^{+6}$	126.2	18.0
8/26/85	$^{16}O^{+8}$	400	403.3	+ 0.8	75	$^{16}O^{+3}$	71.3	17.7
8/30/85	$^{58}Ni^{+23}$	930	917.7	- 1.3	55	$^{58}Ni^{+9}$	179.9	18.0
9/2/85	$^{32}S^{+15}$	720	725.2	+ 0.7	70	$^{32}S^{+6}$	127.0	18.1
9/4/85	$^{58}Ni^{+24}$	1005	1008.5	+ 0.3	75	$^{58}Ni^{+9}$	178.2	17.8
9/9/85	$^{58}Ni^{+24}$	1005	1010.6	+ 0.6	70	$^{58}Ni^{+9}$	178.8	17.9
9/11/85	$^{58}Ni^{+22}$	600	597.6	- 0.4	70	$^{58}Ni^{+9}$	179.9	18.0

NOTES: (1) Error (%) = $[(E_{meas.}/E_{des.}) - 1.00] \times 100$.

Table 3. Coupled operation for research for the period October 1, 1985 through September 30, 1986

Date	Ion	Desired Energy (MeV)	Measured Energy (MeV)	Error[1] (%)	Extraction Efficiency (%)	Injected Ion	Injection Energy (MeV)	Tandem Voltage (MV)
12/9/85	$^{10}B^{+5}$	170	170.1	< 0.1	65	$^{10}B^{+2}$	45.0	18.7[2]
12/11/85	$^{18}O^{+8}$	350	350.2	0.1	75	$^{18}O^{+3}$	70.2	17.48
12/14/85	$^{58}Ni^{+23}$	930	936.4	0.7	85	$^{58}Ni^{+4}$	179.6	17.9
1/12/86	$^{81}Br^{+24}$	610	604.1	- 1.0	65	$^{81}Br^{+9}$	142.1	17.7
4/3/86	$^{58}Ni^{+22}$	750	738.7	- 1.5	65	$^{58}Ni^{+9}$	178.0	17.9
4/22/86	$^{32}S^{+13}$	450	442.6	- 1.6	65	$^{32}S^{+6}$	126.6	18.0
5/1/86	$^{17}O^{+8}$	375	375.1	< 0.1	70	$^{17}O^{+3}$	71.8	17.9
5/17/86	$^{12}C^{+6}$	300	297.6	- 0.8	70	$^{12}C^{+2}$	53.9	17.9
5/14/86	$^{58}Ni^{+23}$	912	910.3	- 0.2	70	$^{58}Ni^{+9}$	179.9	18.0
6/4/86	$^{32}S^{+15}$	700	702.7	+ 0.4	55	$^{32}S^{+5}$	108.5	18.0
8/10/86	$^{58}Ni^{+23}$	912	911.2	- 0.1	60	$^{58}Ni^{+9}$	170.0	17.0
8/12/86	$^{28}Si^{+11}$	336	333.3	- 0.8	75	$^{28}Si^{+3}$	67.4	16.8
9/3/86	$^{56}Fe^{+20}$	672	673.8	+ 0.3	70	$^{56}Fe^{+7}$	143.2	17.9[3]
9/13/86	$^{35}Cl^{+16}$	700	703.4	+ 0.5	75	$^{35}Cl^{+6}$	125.2	17.8

NOTES: (1) Error (%) = $[(E_{meas.}/E_{des.}) - 1.00] \times 100$; (2) $^{10}B^{16}O^-$ injected; (3) $^{56}FeH^-$ injected.

Table 4 is a summary of all coupled runs to date illustrating the great versatility of the tandem-cyclotron system. The table includes thirty-six different ion species from ^9Be to ^{150}Nd and 106 different beam setups. Operation of the cyclotron has continually improved since the beginning of coupled operation. Table 5 summarizes the time distribution for the last four years. There has been no operation with the internal ion source during the past three years. The amount of time devoted to machine studies has steadily declined. No time was spent on that activity last year. Unscheduled maintenance has been significantly reduced.

The Holifield Facility

A plan view of the facility is shown in Fig. 11. The experimental facilities include two areas that can be served only by tandem beams, four areas that are served only by cyclotron beams and four areas including five experiment stations that can receive beams from either the tandem or the cyclotron. The principal experimental devices of the facility include a broad range spectrograph ($ME/q^2 = 225$) equipped with a vertical drift chamber detector system, a 4π spin spectrometer with 72 NaI detector (Ge detectors and BGO Compton-suppression units are

Table 4. Ions Accelerated in Coupled Operation January 27, 1981 — September 30, 1986

Element	Ion	Energy [MeV] No. of Runs)
Beryllium	$^{9}Be^{+4}$	160 (1)
Boron	$^{10}B^{+5}$	170 (2)
	$^{11}B^{+5}$	170
Carbon	$^{12}C^{+6}$	300 (2)
Oxygen	$^{16}O^{+7}$	200 (4)
	$^{16}O^{+8}$	300 (2), 350 (2), 400 (19)
	$^{17}O^{+8}$	325 (1), 375 (5)
	$^{18}O^{+8}$	350 (6)
Magnesium	$^{24}Mg^{+8}$	180 (1)
Silicon	$^{28}Si^{+11}$	340 (1)
Sulfur	$^{32}S^{+12}$	320 (1), 350 (1)
	$^{32}S^{+13}$	450 (1), 500 (2)
	$^{32}S^{+15}$	680-720 (9)
Chlorine	$^{35}Cl^{+11}$	240 (1)
	$^{35}Cl^{+12}$	315 (1), 370 (1)
	$^{35}Cl^{+13}$	445 (2)
	$^{35}Cl^{+14}$	530 (1)
	$^{35}Cl^{+16}$	700 (2)
	$^{35}Cl^{+17}$	680 (1)
Titanium	$^{48}Ti^{+17}$	580 (1)
Iron	$^{56}Fe^{+20}$	670 (1)
	$^{56}Fe^{+22}$	820 (3)
Nickel	$^{58}Ni^{+16}$	350 (1)
	$^{58}Ni^{+17}$	350 (2)
	$^{58}Ni^{+19}$	460 (2)
	$^{58}Ni^{+22}$	600 (1), 750 (1)
	$^{58}Ni^{+23}$	~ 900 (13)
	$^{58}Ni^{+24}$	1010 (3)
Bromine	$^{81}Br^{+24}$	600 (1)
	$^{81}Br^{+28}$	1000 (1)
Silver	$^{107}Ag^{29+}$	730 (1)
Cadmium	$^{116}Cd^{+25}$	495 (1)
Tin	$^{116}Sn^{+27}$	630 (1)
	$^{116}Sn^{+28}$	620 (3)
	$^{116}Sn^{+29}$	700 (1)
Neodymium	$^{150}Nd^{+33}$	750 (1)

being added), a time-of-flight spectrometer, and a 1.6 m scattering chamber. The 0.8 m scattering chamber has been replaced by a heavy-ion/light-ion detector (HILI) which will be able to measure a large fraction of the light and heavy particles emitted in heavy-ion reactions from heavy projectiles with energies greater than ~ 10 MeV/nucleon.[7] The detector system will include four large-area gas-filled ionization chambers to characterize heavy fragments and to provide event triggers; 192 scintillation telescopes in two 6 x 16 arrays will provide position and identity of light fragments.

Cyclotron beams are routinely used in high resolution experiments with the broad-range magnetic spectrograph. Results are shown in Figs. 12 and 13 for two experiments. For these experiments, the spectrograph and the 153°, n = 1/2, beam analyzing magnet are operated in a dispersion-matched mode. The slits of the 153° magnet are typically set to provide a resolution of 0.8 - 1.0 x 10^{-3}.

The facility is operated as a national user facility and is available to users throughout the US as well as those from other countries. During the period October 1, 1984 - September 30, 1985, the number of users from various institutions was as follows: U.S. Universities - 86; non-U.S. institutions - 12; Oak Ridge National Laboratory - 53; other national laboratories - 7.

Conclusion

Operation of the tandem accelerator and cyclotron in the coupled mode has proven to be highly versatile and straightforward. The efficiency and quality of operation have steadily improved since first operation in 1981.

New accelerators are being planned. Our proposal for a 2-Tm heavy ion storage ring for atomic physics (HISTRAP) is described in another paper at this conference.[10] A longer-range plan is for construction of an intermediate energy facility to provide beams with energies up to ~ 1.5 GeV/nucleon. As presently conceived, the facility would include three synchrotron rings: a 4-Tm fast-cycling booster ring, a 15-Tm main accelerator ring and a 10-Tm storage/cooling ring. Injection would be directly from the tandem accelerator which is expected to provide pulsed currents in the 100 μA range for favorable ion species.

Acknowledgments

The success of coupled operation of the Holifield tandem accelerator and cyclotron has been the result of the dedication and hard work of many people. The authors wish to acknowledge the contributions of S. L. Birch, M. R. Dinehart, H. D. Hackler, C. L. Haley, C. A. Irizarri, N. L. Jones, C. T. LeCroy, R. L. McPherson, C. A. Maples, G. D. Mills, and S. N. Murray.

Table 5. Cyclotron Operations Summary

Activity	Oct. 1, 1982 Sept. 30, 1983	Oct. 1, 1983 Sept. 30, 1984	Oct. 1, 1984 Sept. 30, 1985	Oct. 1, 1985 Sept. 30, 1986
Research - coupled mode	1,445	1,331	1,369	1,100
Research - stand alone	280	0	0	0
Tuning	761	494	444	385
Machine Studies	161	130	73	0
Unscheduled Maintenance	694	205	139	144
Scheduled Shutdown	5,409	6,624	6,735	7,131
Total Hours	8,760	8,784	8,760	8,760

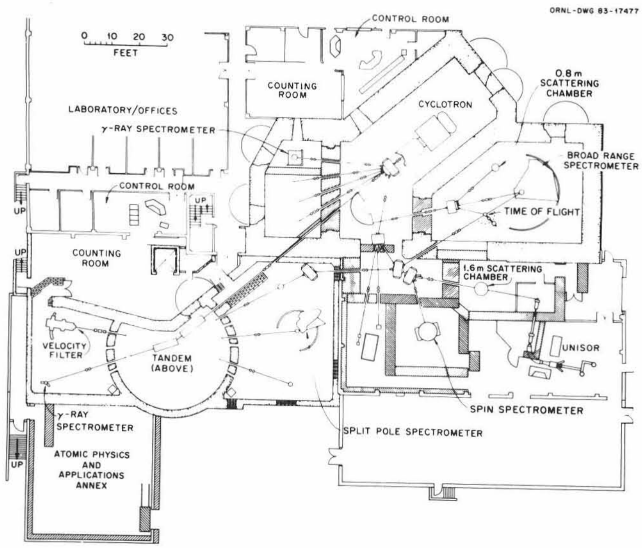

Fig. 11. Layout of accelerators, beam lines, and experiment stations of the Holifield facility.

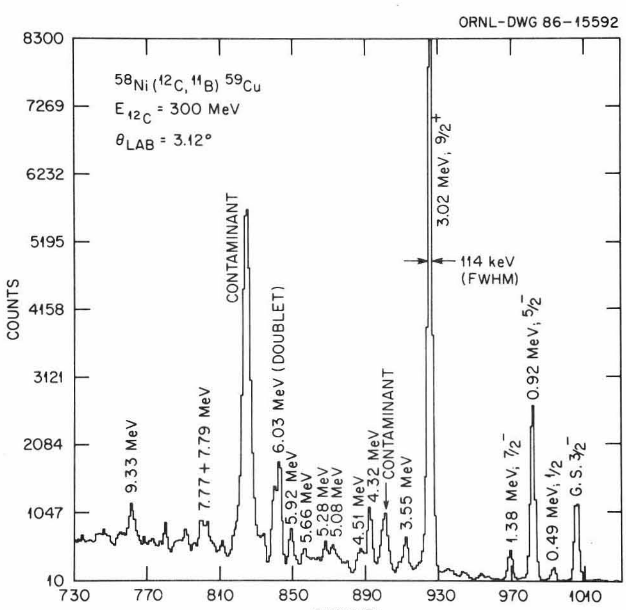

Fig. 12. In this experiment, using the broad-range spectrograph with vertical drift chamber detector, the overall energy resolution was 1/2600 FWHM.[8]

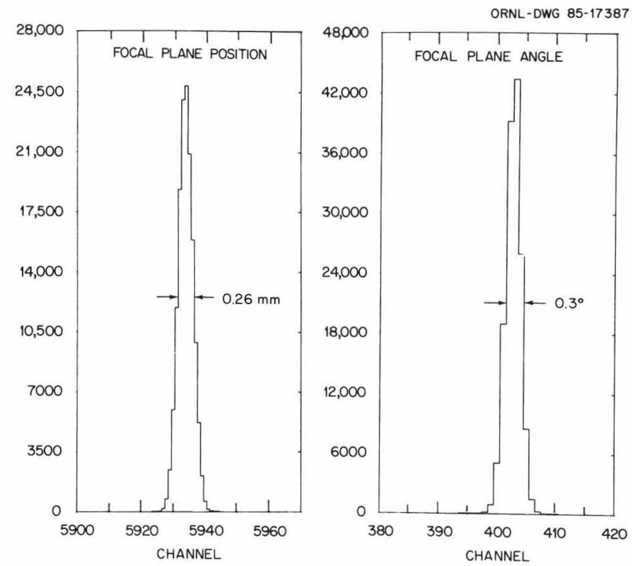

Fig. 13. Position and angle resolution obtained with the broad-range spectrograph and the vertical drift chamber detector using a 1 GeV ^{58}Ni beam at 0^{o}. The dispersion was 600 keV/mm. The energy resolution is 1/6400 FWHM.[9]

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