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THE HOLIFIELD HEAVY ION RESEARCH FACILITY*

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The Holifield Heavy Ion Research Facility has been in routine operation since July 1982. Beams have been provided using both the tandem accelerator alone and a coupled mode in which the Oak Ridge Isochronous Cyclotron is used as an energy booster for tandem beams. The coupled mode has proved to be especially effective and has allowed us to provide a wide range of energetic beams for scheduled experiments. In this report we discuss our operational experience and recent development activities.

1. Introduction

The Holifield Heavy Ion Research Facility (HHIRF)[1-3] is located at the Oak Ridge National Laboratory and operated as a national user facility for research in heavy ion science. The facility operates two accelerators: a Pelletron tandem electrostatic accelerator designed to operate at terminal potentials up to 25 MV and the Oak Ridge Isochronous Cyclotron (ORIC) which, in addition to its stand-alone capabilities, has been modified to serve as an energy booster for ion beams from the tandem accelerator.

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General features of the performance of the facility accelerators are shown in Fig. 1, where ion energy per nucleon is plotted as a function of ion mass. The function shown for the tandem accelerator was calculated with the assumption of a gas stripper in the terminal, a foil stripper 1/3 of the way down the high-energy acceleration tube, and a final beam intensity of approximately 1/10 the intensity which would be available if the most probable charge state were selected at each stripper. The function for ORIC alone was calculated with the assumption of a final intensity of about 10^{11} particles/s while the function for coupled operation was again calculated for a final beam intensity of approximately 1/10 the intensity which would be available if the most probable charge state were selected at each stripper.

The present facility is the result of a project begun in 1974 to expand and modify the existing ORIC facility. Major construction activities of the project included the 25 MV tandem accelerator, a building addition to house the accelerator, additional experimental space, a building to house the gas-handling and storage system for the insulating gas, and modification of the ORIC to enable it to serve as a booster accelerator. The project was completed in June 1982, after which routine operation of the facility began.

The remainder of this paper will be devoted to two general subjects: operation of the tandem accelerator and operation of the ORIC as an energy booster. Emphasis will be placed on the period since our last report[3] at the Sixth European Tandem Conference.

2. Tandem accelerator

2.1. Introduction

The tandem accelerator is a model 25 URC accelerator provided by the National Electrostatics Corporation (NEC). Since the accelerator has been described previously,[1,4-7] only highlights will be noted here. The accelerator, which is insulated with pure SF_6 at pressures up to 0.7 MPa (gauge), has been designed to operate at terminal potentials up to 25 MV with analyzed beam intensities up to 1 pμA (6.2×10^{12} particles/s). The accelerator pressure vessel, which is approximately 30 m high and 10 m in diameter, houses a column structure 18.9 m high (excluding the high voltage terminal) of which 16.5 m is insulated. The accelerator has a vertical, folded configuration. The column structure is equipped with five dead sections with vacuum pumps in each dead section. In addition to the terminal magnet, which provides excellent charge-state separation, the column structure is equipped with three quadrupole lenses, three sets of steerers, and a "second" stripper located in the upper major dead section. The accelerator uses a CAMAC-based digital control system in which virtually all control and monitoring information is transmitted on six bit-serial highways.

2.2 Voltage performance

As discussed in detail in Ref. 3, initial voltage performance of the accelerator was disappointing. Although conditioned on occasion to 22 MV and operated with beam at 20.0 MV, the maximum terminal potential used for scheduled experiments was 19.0 MV with a more typical limit for scheduled experiments of 18.0 MV. Postulated contributors to this relatively poor performance included possible beam steering by the residual field of magnetic electron traps, SF_6 leaks, and irreversible tube damage which may have resulted from improper spark gap spacing and/or initial operation at excessive insulating gas pressure.

In the interval August-October 1983, a major tube replacement program was implemented in a cooperative effort by ORNL and NEC. Forty of the fifty-four 61 cm acceleration tube units were removed, reconditioned, and replaced. In addition, all electron traps were removed. The result of this work has been a significant improvement in voltage performance. Specifically, since this effort, the accelerator has been operated with beam at 22.5 MV, for scheduled experiments at 21.5 MV, and routinely for scheduled experiments at potentials up to 20.0 MV. This improvement in performance can be seen in Figs. 2 and 3 which show distributions of terminal potential for the year preceding the tube replacement effort and for the period following the tube replacement effort. It is also notable that only 60 full column sparks occurred in the period October 1983, through March 1985.

Voltage performance continues to be limited by a tendency to spark with occasional spark-induced deconditioning. This limit is typically observed for the full column at gradients in the order of 0.8 MV/unit and for groups of 4 and 5 units (between dead sections) at gradients in the order of 0.9 MV/unit.

Our efforts to improve voltage performance are focussed at this time on two major areas. The first is the use of the hydrogen arc discharge cleaning technique. Following the work of Isoya et al.[8] and Korschinek et al.[9] we have developed a technique for hydrogen arc discharge cleaning of acceleration tubes and applied this technique to both small systems (in collaboration with NEC) and to five units of the 25 MV tandem accelerator. More detailed accounts of this work are given in other contributions to this conference.[10,11] Our second effort to improve voltage performance is development (in collaboration with NEC) of a compressed geometry tube based on the initial work of Assmann et al.[12] Our initial work on the compressed geometry concept, using the 3 MV NEC test machine, is described in another contribution to this conference.[13] Our present plan is to refine the design described in Ref. 13 and begin installation of compressed geometry tubes in 1986. As part of this effort, we also plan to more carefully explore the voltage limitations of the column structure (with tubes removed).

2.3 Operational experience

Although the initial voltage performance of the tandem accelerator has not met our original expectations, we have been pleased with other aspects of our operational experience. Specifically, reliability of the accelerator system has continued to improve so that we now suffer only minimal delays in the scheduled experimental program. During periods of scheduled operation in the last two years, we have averaged more than 450 hours/month of beam available for research and less than 66 hours/month of unscheduled maintenance (including unscheduled tank openings). The Pelletron chains have now operated more than 22,000 hours without problems while the insulated drive shafts have operated more than 27,000 hours without serious problems. Primary causes of unscheduled tank openings have been vacuum leaks, control system failures, and power supply failures.

The flexibility of the accelerator system is well illustrated by the variety of beams provided for scheduled experiments. As shown in Table 1, we have provided beams ranging from ^{1}H to ^{197}Au at energies up to 1000 MeV (for ^{79}Br with coupled operation).

2.4 Development

Significant simplifications effected in the past two years include removal of magnetic electron traps, disablement of virtually all 500 W casting georators (so that the 2.5 cm apertures are no longer heated) and removal of three of six Pelletron chains.

In addition, we have, in cooperation with NEC, improved the motion feedthroughs for column Faraday cups, variable apertures, and the terminal gas stripper tube so as to minimize the frequency of vacuum leaks. We have also installed pumping ports and filament assemblies for hydrogen arc discharge cleaning, improved shorting rod contacts and the shorting rod feedthrough seal, improved ventilation and cooling for column electronics, improved instrumentation and readouts for several column components and installed cryopumps near the entrance of the low-energy acceleration tube and the exit of the high-energy acceleration tube (for maintenance operations).

In addition to several control system hardware improvements, we have continued to develop computer programs which improve the effectiveness with which we can utilize the accelerator. These include both automatic and on-request data logging functions, an improved beam set-up program and programs which facilitate energy calculation as well as mass and charge-state identification.

2.5 Negative ion sources

All operation of the tandem accelerator since October 1983, has been with the radial and axial geometry sources described by Alton et al. in this conference.[14,15] We have found the radial geometry source to be well suited to the production of hydride beams while the axial geometry is well suited for the production of metallic ions. Both sources have exhibited excellent reliability, long lifetimes, and low sample consumption rates.

2.6 Macropulsing

Motivated by our interest in using the tandem accelerator as a synchrotron injector,[16] we have begun development of components which will allow us to use the tandem accelerator in this mode. As described in Ref. 17, the ORNL axial geometry ion source was modified to provide low repetition-rate pulsed beams with pulses typically 100 μs in length and amplitudes in the range 100 eμA - 350 eμA (depending on ion species). To demonstrate pulsed operation of the tandem accelerator, a macropulsed beam of $^{16}O^{-}$ with repetition rate 8 pps, pulse length 100 μs, and average pulse intensity 100 eμA was injected into the accelerator and an accelerated beam of $^{16}O^{6+}$ with average pulse intensity 140 eμA was observed. A 6 $\mu g/cm^2$ carbon terminal foil stripper and a terminal potential of 14.1 MV were chosen for the demonstration. When corrected for the expected charge state fraction of approximately 50%, the observed fractional transmission was 47% — a value typical of d.c. beams with similar accelerator parameters. No deleterious effects of any kind were observed on accelerator operation due to the macropulsed beam.

3. Coupled Operation

3.1 Introduction

The ORIC is a k=100 ($k=mE/q^2$) variable frequency, isochronous cyclotron built in the early 1960s as a light-ion accelerator with heavy-ion capabilities.[18] Its performance with an internal ion source is shown in Fig. 1. The method in which it is used as an energy booster for tandem beams is shown schematically in Fig. 4.[19] The tandem beam is brought into the evacuated resonator and deflected upward by an inflection magnet so as to strike a stripper foil which has been placed at an appropriate location. Both the longitudinal position of the inflection magnet and the azimuthal and radial position of the stripper foil are remotely adjustable. Upon passing through the stripper foil, a fraction of the beam is stripped to a charge state appropriate for further acceleration. Ions with this charge state are then accelerated and extracted in the usual way. A double-drift klystron buncher,[20,21] located just before the low-energy acceleration tube of the tandem accelerator, bunches the tandem beam into 1-2 ns bunches which coincide with the rf acceptance window of the cyclotron for an accelerated beam energy dispersion, $\Delta E/E$, of 10^{-3} (FWHM). Components provided as part of the HHIRF project included a 36 m transport line, the buncher noted above, bunch phase detectors in the transport line, the inflection magnet and foil positioner noted above, and appropriate diagnostic components. In addition, extensive revisions were made to the cyclotron dee structure to allow traversal of the injected beam.

3.2 Operational experience

We have found that operation of the ORIC as an energy booster is both straightforward and effective. The complete list of beams, with maximum energies, produced since the start of routine operation (June 1982) is given in Table 2. Of special interest are beams provided with separated isotope probes (^{17}O, ^{18}O, ^{116}Cd, ^{116}Sn, and ^{150}Nd) and the maximum energy beam (1000 MeV ^{79}Br). As a result of improved beam setup techniques, the cyclotron transmission efficiency, corrected for bunching efficiency and charge state fraction, is typically 70% resulting in extracted beam intensities in the range 1 to 100 pnA. While the analyzed beam energy dispersion, $\Delta E/E$, is typically 1×10^{-3} (FWHM), coupled operation of the ORIC in a dispersion-matched mode[22] with a modified Elbek broad range spectrograph[23] has resulted in an effective beam energy dispersion as low as 2×10^{-4} (FWHM).[24]

3.3 Development

A significant improvement in beam setup capability has resulted from the discovery that the compensated-iron magnetic extraction channel (see Fig. 4) can be operated in an unbalanced mode so as to introduce a first harmonic component in the magnetic field at the extraction radius which excites the $\nu_r = 1$ resonance at extraction giving an enhanced turn separation at the electrostatic deflector entrance. Using this technique, we have been able to: (1) extract beams at larger radii, reducing magnet power usage for a given energy; (2) improve average extraction efficiency from about 30% to about 70%; (3) improve the accuracy of the prediction of extracted beam energy; and (4) by careful adherence to the computer predicted settings, substantially reduce the time required to achieve extracted beam.

Another important development is a recently completed phase-lock circuit. This circuit, which stabilizes the phase of beam bunches injected into the ORIC, utilizes a tuned resonant circuit which is excited by a cylindrical capacitive pickup element located in the transfer line between the tandem accelerator and ORIC. A phase error signal, which is generated by comparing the phase in the tuned resonant circuit with the ORIC rf phase, is used to control the pre-accelerator buncher phase so as to reduce time jitter in the injected beam. The effectiveness of this system is shown in Fig. 5 where we show beam pulse widths with and without the phase-lock circuit. Two of the most important features of this circuit are that it functions with beam currents as low as 10 enA — a factor of five lower than the original phase-lock circuit, and that it operates over a frequency range 4 to 16 MHz.

4. Summary

With almost three years of operational experience, the HHIRF tandem accelerator has proven to be a reliable and flexible accelerator — both in stand-alone mode and as an injector. Steady progress has been made in improving its terminal voltage capability and it is expected that development efforts now underway will result in achievement of its design voltage in the next few years.

Experience with operation of the ORIC as an energy booster has been particularly successful, providing a new range of ion-energy combinations for use in experiments and demonstrating the power and flexibility of a tandem accelerator as an injector for a cyclotron booster.

5. Acknowledgements

The work reported here and the success of initial operation of the Holifield Facility has been the result of the hard work of many people. It is a pleasure to acknowledge the contributions of present and former ORNL staff members J. A. Benjamin, S. L. Birch, M. R. Dinehart, D. M. Galbraith, H. D. Hackler, C. L. Haley, C. A. Irizarry, J. W. Johnson, N. L. Jones, C. T. LeCroy, R. S. Lord, J. E. Mann, C. A. Maples, R. L. McPherson, G. D. Mills, W. T. Milner, S. N. Murray, and P. T. Singley.

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Table 1

HHIRF Beams Provided for Scheduled Experiments

Beam	Maximum Energy (MeV)	Mode*
^{1}H	25	T
^{9}Be	158	C
^{10}B	168	C
^{11}B	169	T,C
^{12}C	300	T,C
^{16}O	405	T,C
^{17}O	381	C
^{18}O	352	T,C
^{19}F	190	T
^{24}Mg	178	T,C
^{25}Mg	132	T
^{26}Mg	132	T
^{28}Si	240	T
^{32}S	717	T,C
^{34}S	155	T
^{35}Cl	692	T,C
^{37}Cl	160	T
^{40}Ca	210	T
^{45}Sc	200	T
^{46}Ti	184	T
^{48}Ti	581	T,C
^{50}Ti	229	T
^{52}Cr	230	T
^{56}Fe	842	T,C
^{58}Ni	934	T,C
^{60}Ni	228	T
^{63}Cu	189	T
^{64}Ni	290	T
^{79}Br	1000	C
^{90}Zr	395	T
^{107}Ag	374	T
^{109}Ag	733	C
^{116}Cd	495	C
^{116}Sn	684	T,C
^{120}Sn	240	T
^{150}Nd	760	C
^{197}Au	591	T

*T = Tandem alone; C = Coupled mode.

Table 2

HHIRF Beams Provided with Coupled Operation

Ion	Maximum Energy (MeV)	Injected Ion	Injection Energy (MeV)	Tandem Voltage (MV)
$^{9}Be^{4+}$	158	$^{9}Be^{1+}$	20	9.8
$^{10}B^{5+}$	168	$^{10}B^{2+}$	40	16.0
$^{11}B^{5+}$	169	$^{11}B^{2+}$	38	15.9
$^{12}C^{6+}$	300	$^{12}C^{2+}$	54	17.8
$^{16}O^{8+}$	405	$^{16}O^{2+}$	39	12.8
$^{17}O^{8+}$	381	$^{17}O^{2+}$	44	14.6
$^{18}O^{8+}$	352	$^{18}O^{3+}$	68	16.9
$^{24}Mg^{8+}$	178	$^{24}Mg^{2+}$	20	6.6
$^{32}S^{15+}$	717	$^{32}S^{6+}$	123	17.5
$^{35}Cl^{16+}$	692	$^{35}Cl^{6+}$	124	17.7
$^{48}Ti^{17+}$	581	$^{48}Ti^{6+}$	93	13.3
$^{56}Fe^{22+}$	842	$^{56}Fe^{8+}$	170	18.9
$^{58}Ni^{23+}$	934	$^{58}Ni^{9+}$	170	17.0
$^{79}Br^{28+}$	1000	$^{79}Br^{9+}$	164	16.4
$^{109}Ag^{29+}$	733	$^{109}Ag^{8+}$	128	14.2
$^{116}Cd^{25+}$	495	$^{116}Cd^{7+}$	115	14.6
$^{116}Sn^{29+}$	684	$^{116}Sn^{7+}$	145	18.8
$^{150}Nd^{33+}$	760	$^{150}Nd^{13+}$	211	15.1

Figure Captions

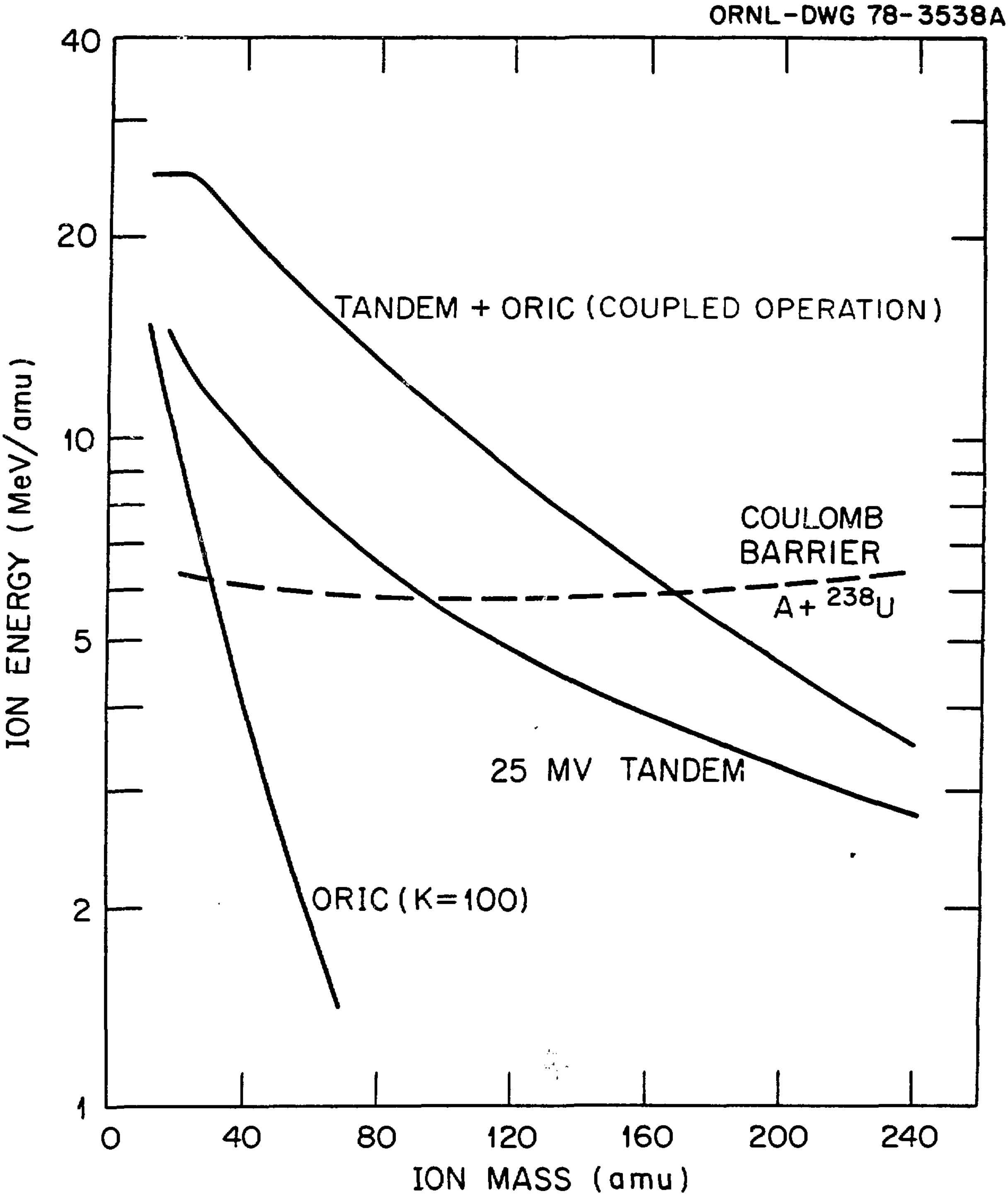
Fig. 1. Ion energy performance functions for the Oak Ridge Isochronous Cyclotron (ORIC), the Oak Ridge 25 MV tandem accelerator, and coupled operation of the 25 MV tandem accelerator and ORIC. Assumptions used in calculating these functions are discussed in the text. (ORNL-DWG 78-3538A)

Fig. 2. Terminal potential distribution for the period June 1982, through July 1983. The number of runs (tunings with beam) summed over 1 MV intervals is plotted as a function of terminal potential. (ORNL-DWG 85C-9688)

Fig. 3. Terminal potential distribution for the period October 1983, through March 1985. The number of runs (tunings with beam) summed over 1 MV intervals is plotted as a function of terminal potential. Cross-hatched areas indicate runs devoted to machine research rather than scheduled experiments. (ORNL-DWG 85X-9687)

Fig. 4. ORIC injection and extraction system used in coupled operation. In the example shown, 39 MeV $^{16}O^{2+}$ is injected and stripped to $^{16}O^{8+}$. (ORNL-DWG 81-16635R)

Fig. 5. 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 measured for a 30 enA, 125 MeV $^{32}S^{6+}$ beam for a period of four minutes each.


ORNL-DWG 78-3538A
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20
10
5
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1
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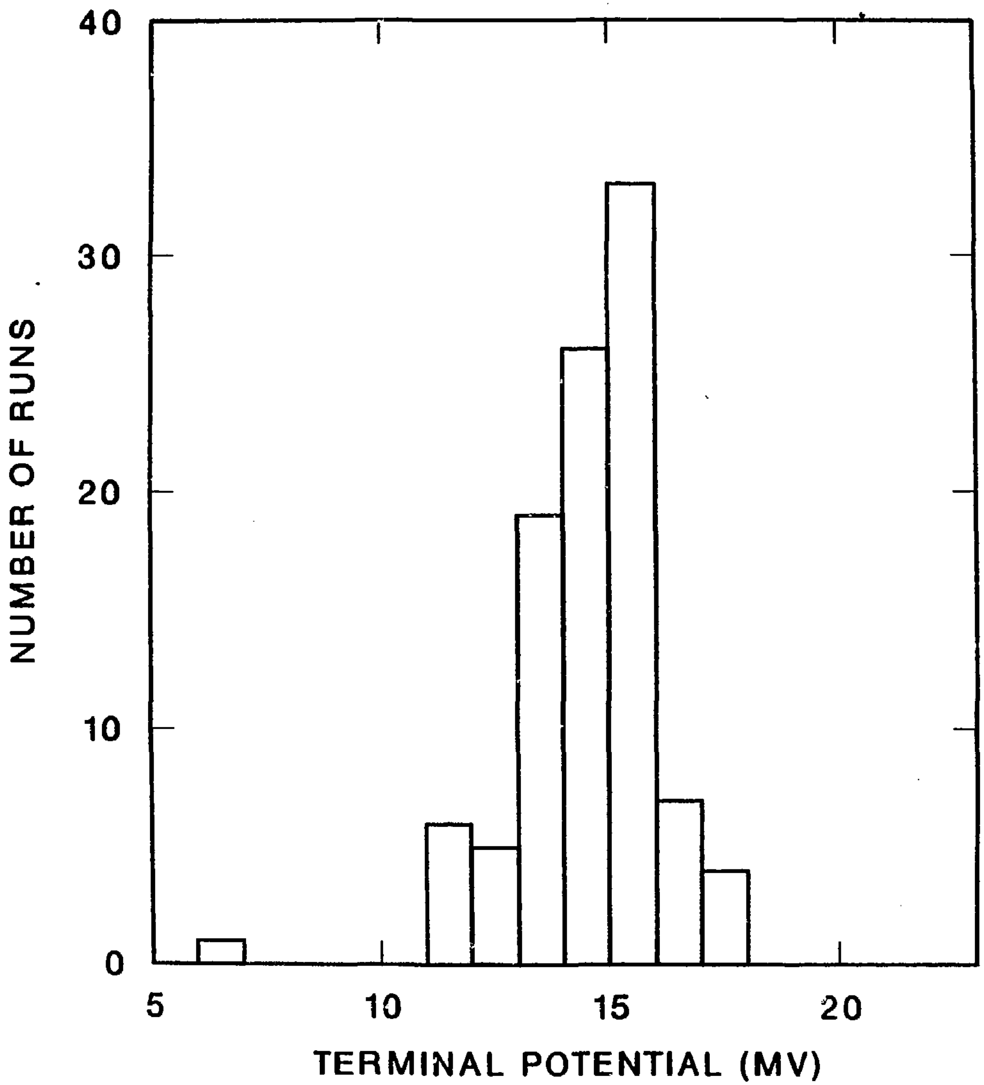
ION MASS (amu)
TANDEM + ORIC (COUPLED OPERATION)
COULOMB
BARRIER
A + 238U
25 MV TANDEM
ORIC (K=100)

ORNL-DWG 85C-9688



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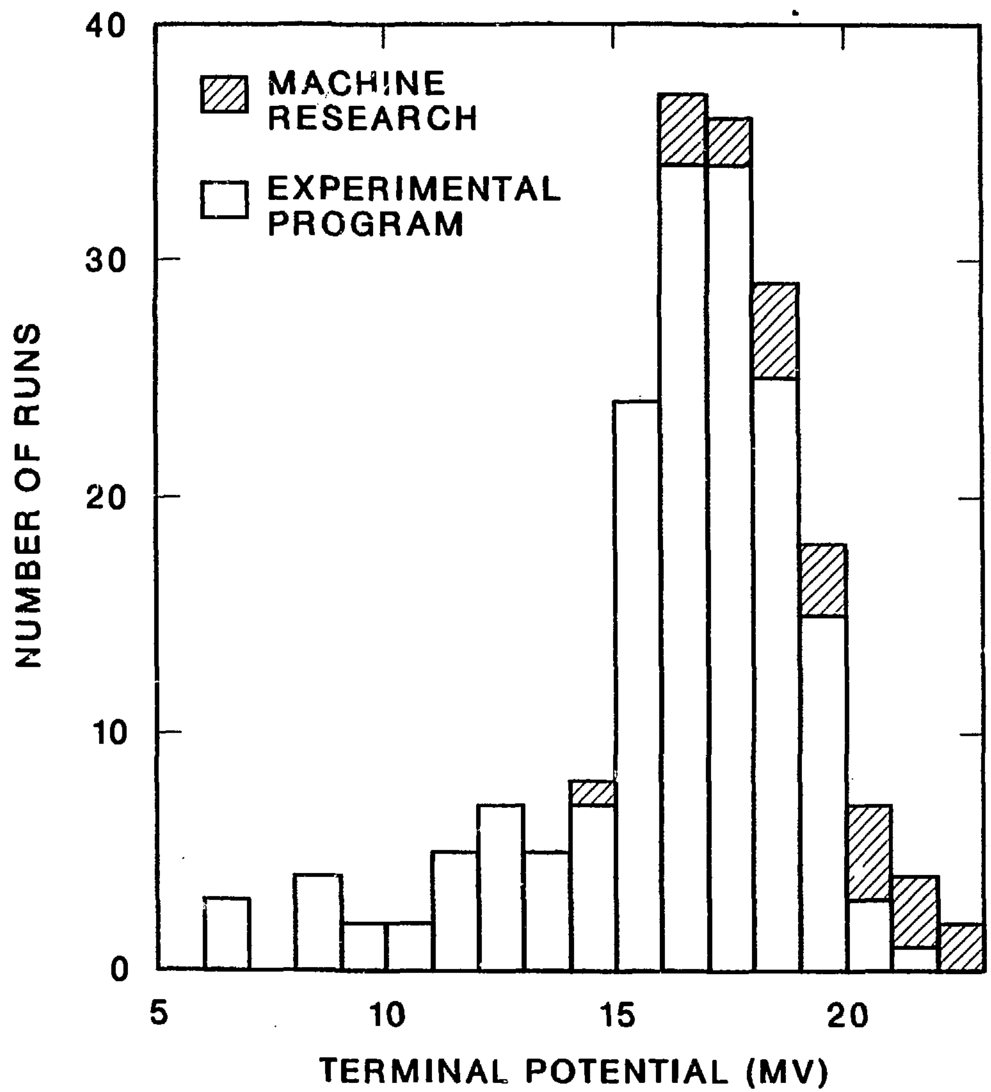

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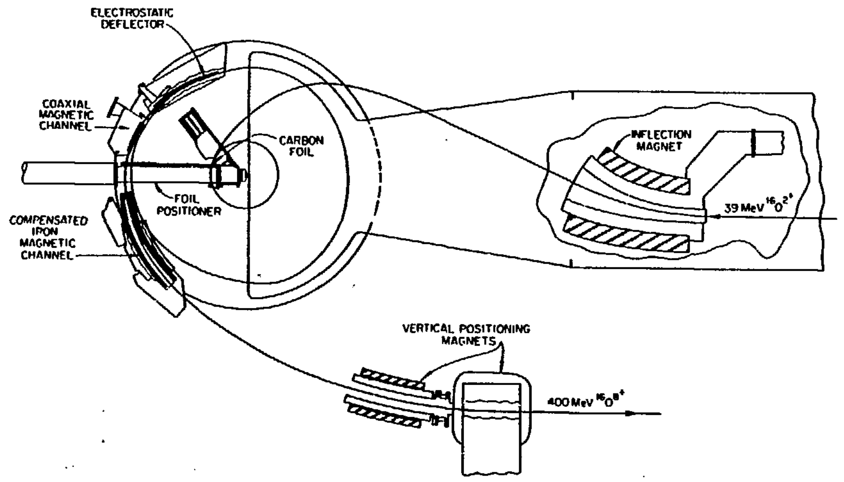
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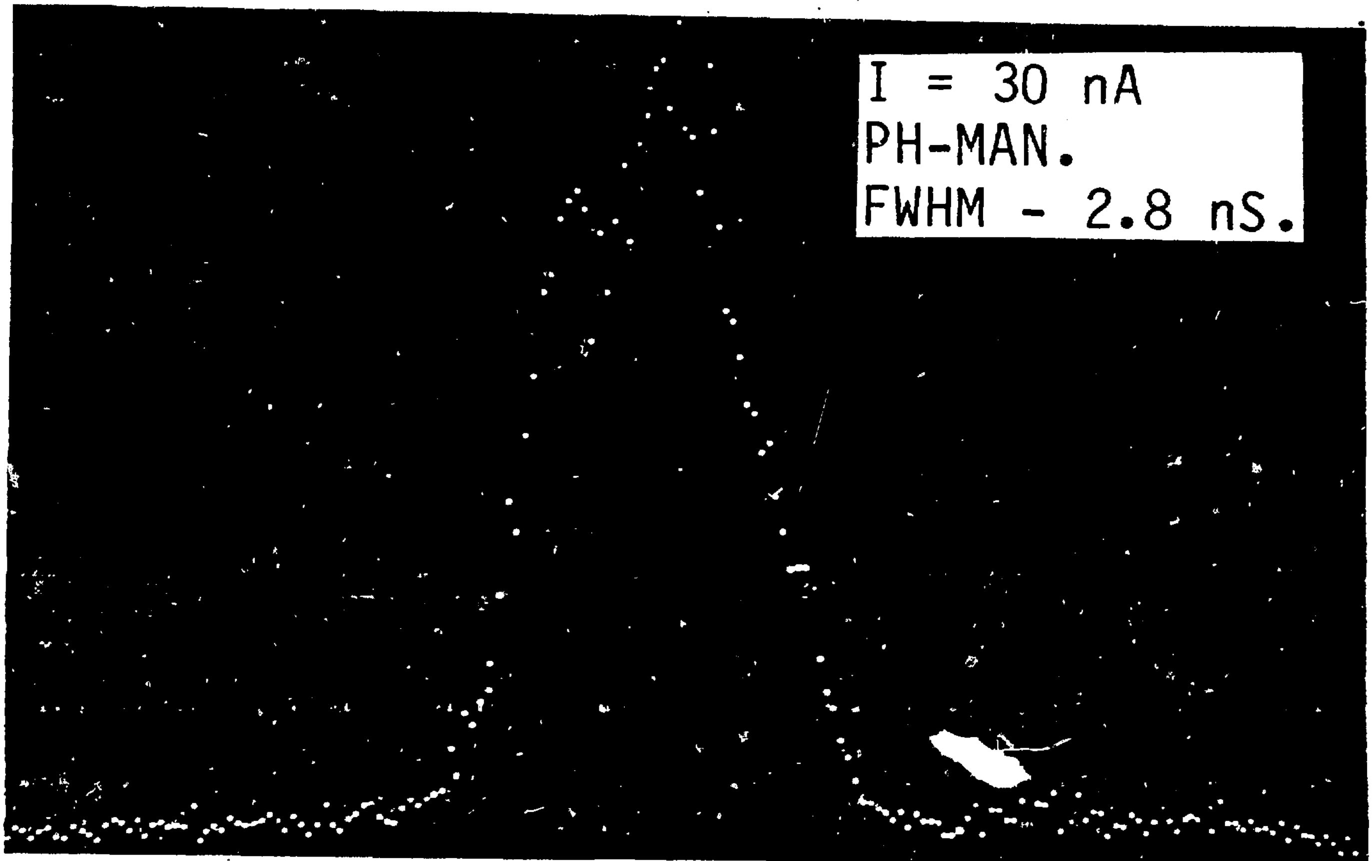
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