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A MULTI-ACCELERATOR SYSTEM FOR HEAVY IONS*

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Summary

The accelerators for the new National Heavy-Ion Laboratory (NHL) being planned at Oak Ridge will provide beams of all ions from helium to uranium with energies ranging from 100 MeV/u for light ions to 10 MeV/u for the heaviest ions accelerated.[1] The heart of the proposed accelerator system is a large 4 sector isochronous cyclotron of the separated sector type with an energy rating of 440 q^2/A MeV. Ions are to be injected into the large cyclotron from either a large tandem electrostatic acclerator or from the Oak Ridge Isochronous Cyclotron (ORIC). The ORIC will generally suffice as the injector up to the mass 160-180 range, beyond which use of the tandem is necessary. Beam intensities will range from 10^{13} ions/sec for 100 MeV/u oxygen to ~2 x 10^{12}/sec for 10 MeV/u uranium ions. The beam emittance is expected to be less than 10 mm-mrad and the energy spread less than 0.1%. The large cyclotron uses auxiliary RF accelerating cavities operating at twice the main RF frequency to flattop the effective accelerating voltage waveform to thus increase the phase acceptance and reduce the energy spread of the beams.

Introduction

The National Heavy Ion Laboratory accelerator concept has risen out of what we have viewed as a compelling national need for additional facilities for research with heavy ion beams. The accelerator will provide beam of ions with low emittance and low energy spread over the full mass range and with energies high enough to exceed the Coulomb barrier of the heaviest target nuclei. Such a facility will open up many new and as yet completely unexplored areas of nuclear, atomic, and solid state research. In discussing the need and desired characteristics of possible new heavy ion accelerators the Ad Hoc Panel on Heavy-Ion Nuclear Science and Facilities (Committee on Nuclear Sciences, National Research Council) made the following statement.[2]

> *Taking into account the scientific needs and our knowledge of accelerator technology the Panel concludes that a new national heavy-ion facility should be built using present state-of-art and that it should have the following parameters.*
>
> *(a) Ion-range: Beams of all elements up to uranium.*
>
> *(b) Energy: At least 8 MeV/nucleon and preferably 10 MeV/nucleon with smooth variation down to 2 MeV/nucleon.*
>
> *(c) Beam current: 10^{13} particles/sec is desirable above and 10^{11} particles/sec is the objective for all elements.*
>
> *(d) Energy homogeneity: Less than 1/2000, achieved, if necessary by beam analysis, and this narrow energy band should deliver 10^{10} particles/sec.*
>
> *(e) Beam emittance: Less than 10 mm-mrad.*

The proposed accelerator system meets these requirements easily, as will be seen later. In addition, because either the 20 MV tandem or the ORIC may be used independently, there will always be two beams available for use by experimenters. Also, the unique capability to provide light heavy-ion beams with energies up to 100 MeV/u will open up new areas of research in nuclear physics and chemistry, and in materials science.

The new facility, Fig. 1, is to be built adjacent to the existing structures of the Oak Ridge Isochronous Cyclotron (ORIC). Additional separate shielded research areas are to be provided so that several experiments may be in process or setup at the same time. Ten new experiment stations are provided; most of the new areas may be served by either the tandem or the cyclotron.

In the principal mode of operation a 20 MV tandem is used as the injector for the large separated-sector isochronous cyclotron. For the acceleration of lead ions for example, Pb^- ions generated in the ion source of the tandem injector are accelerated to the positive 20 MV terminal of the tandem where they pass through a gas stripping cell. Emerging from the gas cell, the most probable charge of the ions would be 7+. After passing through a charge selector the Pb^{7+} ions would be accelerated back to ground potential and would have reached an energy of 160 MeV. The beam then passes through a second stripping cell to further increase the charge. For a foil stripper the most probable charge is 34+ and the final energy from the tandem cyclotron combination would be 11.7 MeV/u or 2445 MeV.

Operation with the ORIC as the injector proceeds with multiply-charged positive ions being accelerated directly from an ion source at the center of the cyclotron. After acceleration and extraction the ORIC beam passed through a foil stripper to double the charge after which it is accelerated in the large cyclotron. Ta^{13+} ions would be accelerated in the ORIC to about 50 MeV stripped to Ta^{20+} and then accelerated in the large cyclotron to an energy of 5.4 MeV/u (970 MeV).

The Main Cyclotron

The main accelerator in the system is a 4-sector isochronous cyclotron with straight sectors. Two of the open spaces between the sectors are used for the RF cavity accelerator systems; the two other open spaces provide room for the beam injection and extraction systems and various diagnostic and beam control devices. The plan and elevation sections of the cyclotron are shown in Figs. 2 and 3. Table I gives the principal characteristics of the cyclotron.

Magnet System. The included angle of the sector magnets, 52°, was chosen to provide strong axial and radial focusing of the ions without any possibility of resonances in the ion motion that might be caused by the magnet periodicity or by magnetic field imperfections. The design was based on the calculations of Gordon[3] for "hard-edged" magnetic fields and on model measurements. In Fig. 4 are plotted ν_z and ν_r, respectively, the number of axial and radial oscillations per sector as determined by numerical orbit dynamics calculations for a 52° magnetic field. These calculations used magnetic field measurements --

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Table I. NHL Separated-Sector Cyclotron Characteristics (Design Goals)

Uranium energy (MeV/u)	10
Relativistic energy limit (MeV/u)	100
Minimum q/A ratio for 10 MeV/u	0.15
$B\rho_{max}$ (kG-cm)	3018
Energy Constant, K ($E = K\ q^2/A$)	440
Maximum magnetic field (kG)	16.0
Magnet fraction, f	0.58 (52°)
Number of sectors	4
Injection energy, U ions (MeV/u)	0.6
Energy ratio (E_f/E_i)	9 - 19
Radius ratio (R_f/R_i)	3 - 4.3
Injection mean radius at $R_f/R_i = 3$,(m)	1.05
Extraction mean radius (m)	3.15
RF system frequency, 10 MeV/u (MHz)	13.22
RF system frequency range (MHz)	6 - 14
Harmonic number (for 10 MeV/u uranium)	6
Magnet weight (tons)	2300

(1° azimuthal, 0.25 in. radial increments) from 0.088-scale model measurements. The locus in ν_r-ν_z space for acceleration to 10 MeV and 100 MeV and the several resonances lines to be avoided are shown. Table II gives the principal magnet characteristics.

Table II. Magnet Characteristics

Number of sectors	4
Sector angle, deg	52
Height, ft	18
Diameter, overall, ft	37.5
Main coil power, kW	540
Number of trimming coils	40
Trimming coil power, kW	100
Magnet gap, steel, in.	4
Magnet gap, available for beam, in.	2.75
Magnet weight, tons	2300
Main coil copper weight, tons	18

RF System. The voltage for accelerating the ions is provided by 30° wedge-shaped "dees" located in the open spaces between magnet sectors. Two such accelerating structures are provided in opposing valleys. Auxiliary 15° electrodes operating at the second harmonic of the main RF are located within the 30° resonators, see Figs. 2 and 3. These serve to provide an effective flattop to the accelerating voltage waveform to increase the phase acceptance of the accelerator without sacrificing energy resolution, as illustrated in Fig. 4. The principal characteristics of the RF system are given in Table III.

Table III. Accelerating System Characteristics

Peak voltage, fundamental, kV	250
Second harmonic voltage, % of fundamental	26
Power, fundamental, kW	400
Power, second harmonic, kW	100
Resonator length, m	8.6
Resonator diameter (maximum), m	3.3
Amplitude stability	1 in 10^4
Phase stability, deg	±0.1

Vacuum System. Vacuum requirements in accelerating heavy ions are more severe than for light ions because of larger charge-exchange loss cross sections. The design of the NHL vacuum system was based on the report by Schmelzer[4] and the Omnitron proposal.[5] The available data predict an ion transmission of 98.5% when accelerating U^{36+} ions from 1 to 10 MeV/u at a pressure of 10^{-6} torr. The NHL vacuum system has been designed to achieve an operating pressure of 10^{-7} torr to provide a reasonable safety factor with respect to the lack of knowledge of the charge-exchange cross sections and to allow operation with modest beam losses in the face of less than ideal vacuum system performance. To achieve the desired vacuum with minimum possibility of contamination of the vacuum chamber by the pumping equipment cryogenic panels augmented by small diffusion pumps for noncondensible gases have been chosen as the most satisfactory system. The cryopumping system will reduce the pressure to $\sim 10^{-7}$ torr in 15 hours in spite of the large volume and surface areas. The principal characteristics of the vacuum system are given in Table IV.

Table IV. Vacuum System Characteristics

Volume (ℓ)	95,000
Surface (cm^2)	7×10^6
Pumping speeds (ℓ/sec)	
Air	140,000
Water vapor	10^6
H_2, He, Ne	28,000

Injection and Extraction. To match the various modes of injection, i.e. injection from the ORIC or from the tandem, with various combinations of gas or solid stripping, it is necessary that the radius of injection into the cyclotron be adjustable. Injection from the ORIC requires an energy gain of 19 (radius-ratio of 4.35) to satisfy frequency matching conditions; the energy gain-ratio required with injection from the tandem may vary from 5 to 25 depending on the ion mass, energy, and the stripper combination used. The present design provides for variation of energy gain ratio over the range from 9 to approximately 20. The elements in the magnet gap will be of the septum magnet type.[6] The magnets which bend the beam into position for injection are "picture frame" magnets with Hyperco yokes. Calculations with the computer program TRIM[7] show that it is possible to reach the 23 kG needed for the "worst case" with reasonable power input and gap efficiency. The highest

fields are only required for the highest energies with injection from the ORIC or when using the tandem as the injector with a gas stripper before the cyclotron. When foil stripping is used between tandem and cyclotron for uranium acceleration (injection at 160 MeV, q = 36+) to reach 10 MeV/u, the magnetic field in the main injection magnets is only 18 kG.

The beam extraction system consists of a 1.5 meter-long electrostatic deflector followed by -0.4 kG and -4.0 kG septum magnets on successive hills. The natural turn spacing for the heaviest ions (1.6 cm) is large enough that the beam can be extracted directly without providing special means to enhance the turn spacing. On the other hand, for light ions at 100 MeV/u, q/A = 0.5, the turn spacing is only 0.26 cm, which will necessitate the use of precessional motion to give some enhancement of the turn spacing. Table V summarizes the natural turn spacings for typical ions at injection and extraction.

Table V. Turn Spacings for Injection and Extraction

Particle	Energy (MeV)	Turn Spacing (cm)[a] At Minimum Injection Radius	At Maximum Injection Radius	At Extraction
Proton	100	2.6	1.8	0.54
^{4}He	400	1.3	0.87	0.26
^{12}C	1200	1.3	0.87	0.26
^{238}U	2380	4.7[b]	3.9	1.6

[a]For average radius, transit-time factors and RF voltage distribution taken into account.

[b]For 140-MeV injection.

Beams

The accelerators of the NHL are designed to provide beams of all elements with energies high enough to overcome the Coulomb barrier of the heaviest elements. The beams will be of high quality with emittance typically less than 10 mm-mrad (full phase-space area) and energy spread $\Delta E/E$ less than 10^{-3}. With special care it is believed that the energy spread can be reduced to 10^{-4} or better.

The maximum energies for full intensity beams from the tandem-cyclotron combination range from 100 MeV/u for the lightest ions (including protons and deuterons) to 10 MeV/u for uranium ions. The maximum intensities are expected to range from 10^{13} ions/sec for light ions like oxygen to about 2×10^{12} ions/sec for heavy element beams. These intensities are based on the injection of 25 μA of negative ions and take into account the efficiency of stripping and bunching and appropriate transmission factors. The tandem-cyclotron combination can be operated with either a gas or solid stripper in the terminal of the tandem and between the tandem and the cyclotron. There are very great differences in energy obtained from the system depending on the stripper choice and the distance of the chosen charge states from the maxima of the charge-state distributions. The maximum energies vary with ion mass for various combinations of gas and solid strippers as in Fig. 6. The energy vs mass curves of Figs. 7 and 8 illustrate the possibilities for increased energy at reduced intensity for acceleration of charge states above the peaks of the charge distribution. These characteristics were calculated without regard to energy gain ratio considerations which may limit the intensity over narrow ranges of the parameters.

With the ORIC as the injector, output energies above the Coulomb barrier of all elements will be obtained for accelerated ions up to mass 180 (tantalum). The energy can be increased in a limited way (at the expense of intensity) by using higher charge states from the ORIC. Final beam energies from the large cyclotron when using the ORIC as the injector are shown in Fig. 9. Data are given for two levels of total ionization potential. At the 600 V level microampere beams are obtained; at the 1200 V level the currents are in the nanoampere range. The beam intensities that will be available with ORIC as the injector range from the particle-microampere level ($\sim 6 \times 10^{12}$ cm/sec) for the light elements (Ne) up to perhaps one-tenth particle-microampere at mass 200. An important advantage of the ORIC as an injector is to provide the means for acceleration of ions of the inert gases heavier than He; the negative ions as are required by the tandem are unknown. The required multicharged beams of Ar, Kr, and Xe have already been produced with the ORIC.

In the multi-accelerator arrangement of the NHL, either the ORIC or the tandem will always be available for independent research. Both accelerators have important independent capabilities. The ORIC currently provides a variety of light ion beams: 67 MeV protons, 40 MeV deuterons; 80 MeV alpha particles; and 120 MeV ^{3}He ions. Heavy ions are available routinely with energies up to 100 q^2/A MeV. Some important heavy ion beam currently in routine use for nuclear research physics include 80 MeV $^{10}B^{3+}$, 120 MeV $^{12}C^{4+}$, 160 MeV $^{14}N^{5+}$, 140 MeV $^{16}O^{5+}$, 110 MeV $^{20}Ne^{5+}$, and 155 MeV $^{40}Ar^{8+}$.

The 20 MV tandem will be a unique and very powerful research tool that will enable many investigations that are not now possible, especially those requiring high resolution beams at intermediate mass. The intensity-energy characteristics for typical heavy-ion beams from the tandem are shown in Fig. 10. The energy spread of tandem beams can be as low as a few thousand electron volts and the beam emittance of the order of 10 mm-mrad or less. The National Electrostatics Corporation Model 20 UD and the High Voltage Engineering Corporation Model STU accelerators are being considered for this application.

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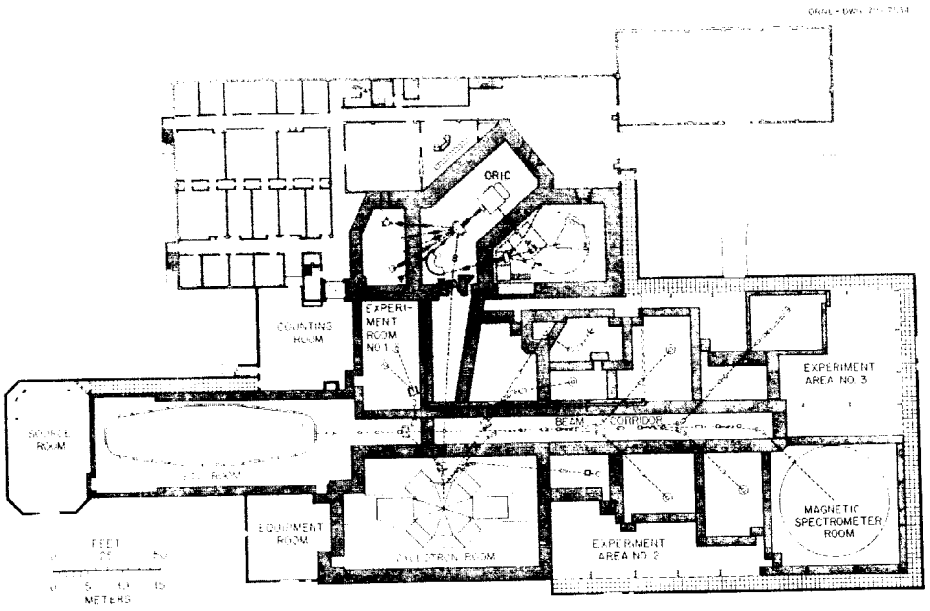


Fig. 1. National Heavy-Ion Laboratory. The existing ORIC facility is lightly shaded. The outline of HVEC STU tandem accelerator is shown; an alternate plan would use a NEC 20-UD tandem.

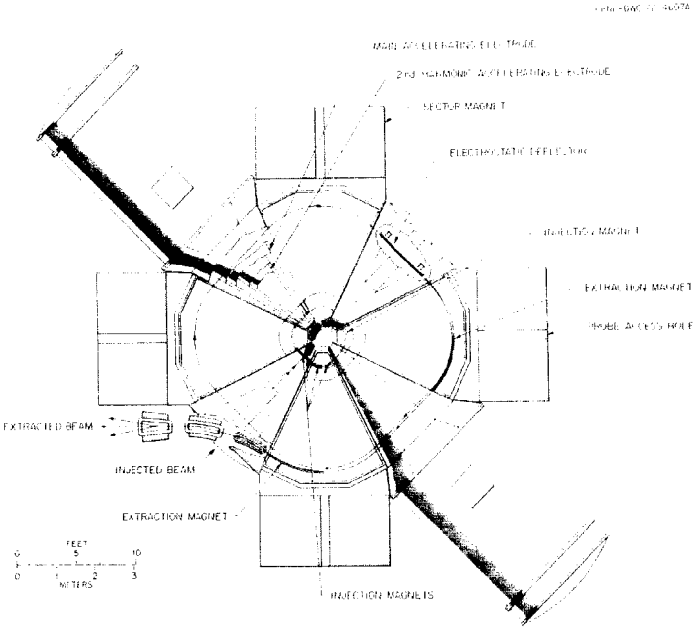


Fig. 2. Plan section of the cyclotron. The injection magnets are movable to allow adjustment of injection radius.

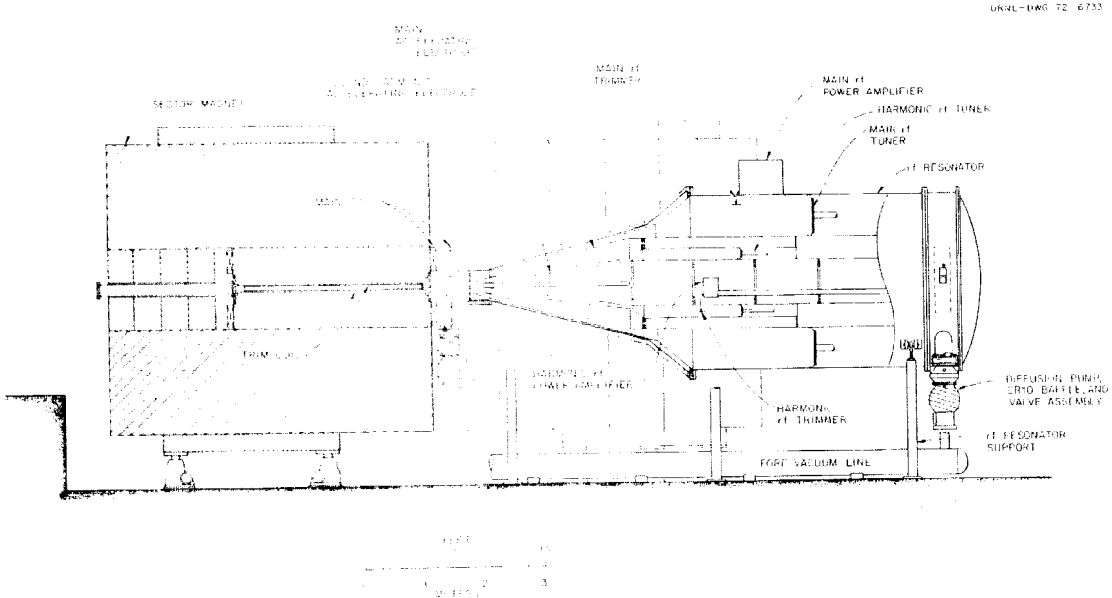


Fig. 3. Elevation section of the cyclotron. The RF resonators are circular in cross section.

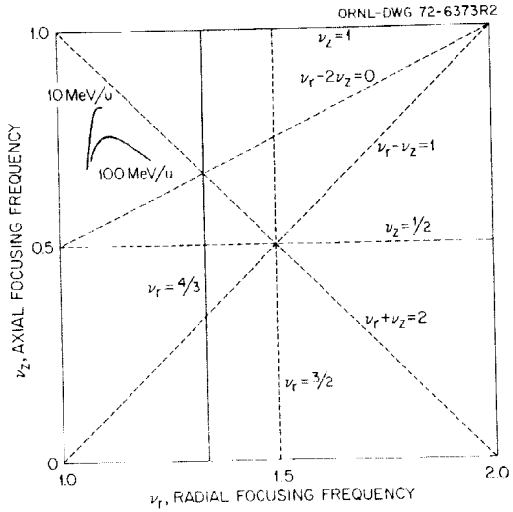


Fig. 4. Focusing characteristics from model data.

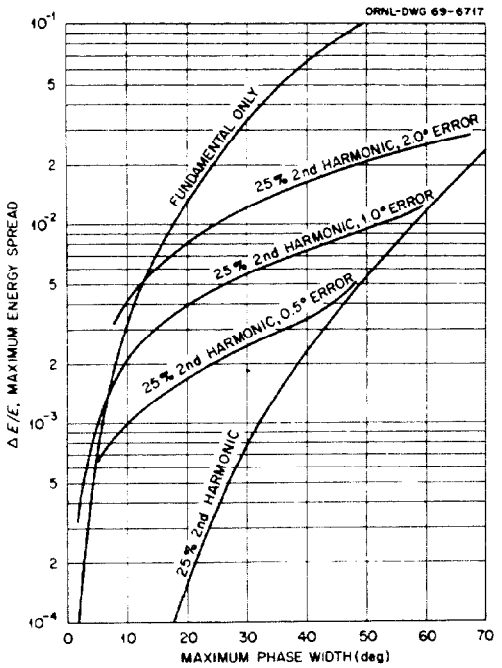


Fig. 5. The energy deviation $(E_{max} - E_{min})/E_{av}$ vs phase width for 25% second-harmonic amplitude and various phase errors.

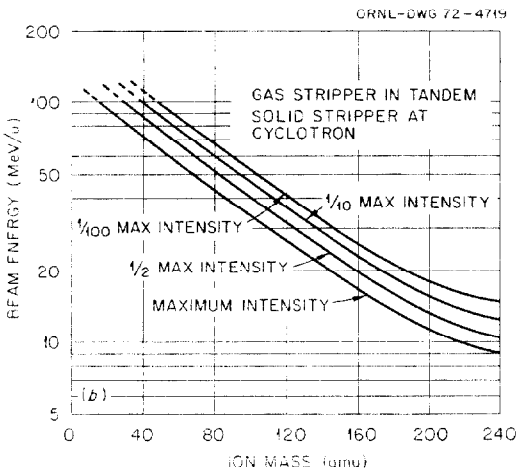


Fig. 7. Ion energy-ion mass relations for several relative intensities. 100% intensity varies smoothly from 10^{13}/sec to 2 x 10^{12}/sec from oxygen to uranium.

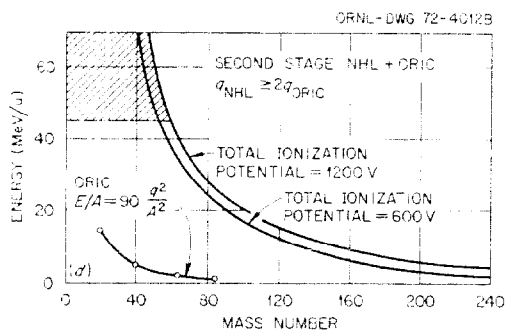


Fig. 9. The energy vs ion mass characteristics with the ORIC as the injector for the large cyclotron.

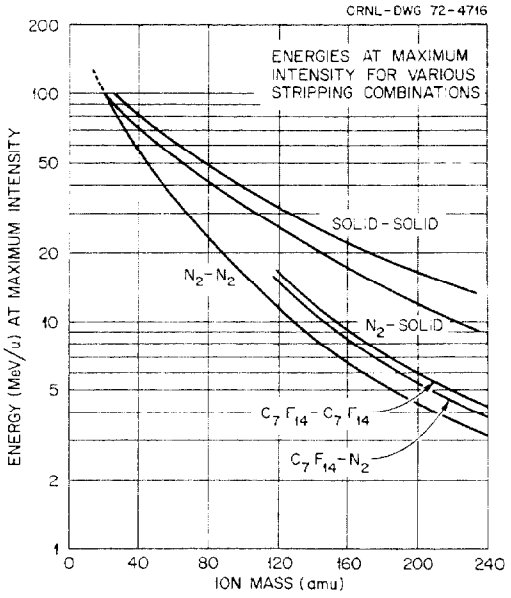


Fig. 6. The dependence of maximum ion energy on ion mass for various combinations of strippers.

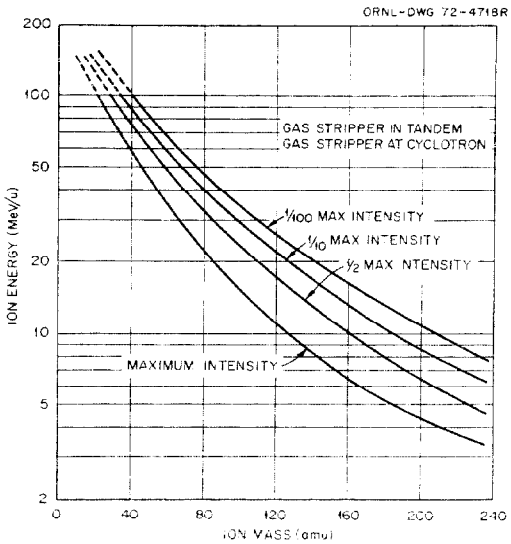


Fig. 8. Ion energy-ion mass relations for several relative intensities with gas strippers.

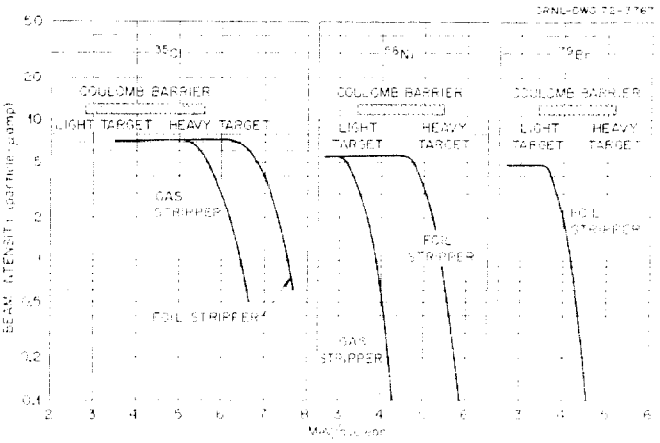


Fig. 10. Intensities of heavy-ion beams accelerated by a 20 MV tandem.