A PROPOSED NATIONAL HEAVY-ION ACCELERATOR AT OAK RIDGE*

J. A. Martin, E. D. Hudson, R. S. Lord, M. L. Mallory,
W. T. Milner, S. W. Mosko, and P. H. Stelson
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

ABSTRACT

The proposed National Heavy-ion Laboratory will be provided with a multi-stage accelerator system integrated with the existing Oak Ridge Isochronous Cyclotron (ORIC) facilities. The main accelerator stage is to be a four-sector isochronous cyclotron that will provide beam energies up to 100 MeV/u. Ions may be injected into the large cyclotron from either a 20 MV tandem electrostatic accelerator or from the ORIC. The ion energies range from 100 MeV/u for oxygen to 10 MeV/u for uranium. Maximum beam intensities range from $\sim 10^{13}$ particles/second for oxygen to 2×10^{12} particles/second for uranium. The sector magnet angle for the cyclotron is 52° which yields radial and axial focusing frequencies of $\nu_r = 1.1 - 1.2$ and $\nu_z = 0.6 - 0.8$. The field-radius product of the magnet is 3018 kG-cm at a maximum magnetic field of 16 kG. The rf system is tunable over the range 6 - 14 MHz to accommodate acceleration on harmonics 2 - 11. Second harmonic resonators are provided to increase the phase acceptance and/or the energy resolution.

INTRODUCTION

In 1969 a facility was proposed for accelerating particles to energies ranging from 7.5 MeV/u for the heaviest elements, to 300 MeV/u for protons and alpha particles.[1] Since that proposal, substantial changes in concept have resulted from re-evaluations of the interests and requirements of prospective experimenters and from continued design studies. The characteristics of the system have been modified to reflect 1) the increasing importance of research with heavy ions, and 2) the fact that other facilities will exist for light-ion experiments in the 100 - 300 MeV range. In recognition of the "national" aspects of the project, substantial experiment area has been provided (~ 1850 m^2). The proposed configuration of the three accelerators and the experiment area is shown in Fig. 1. The

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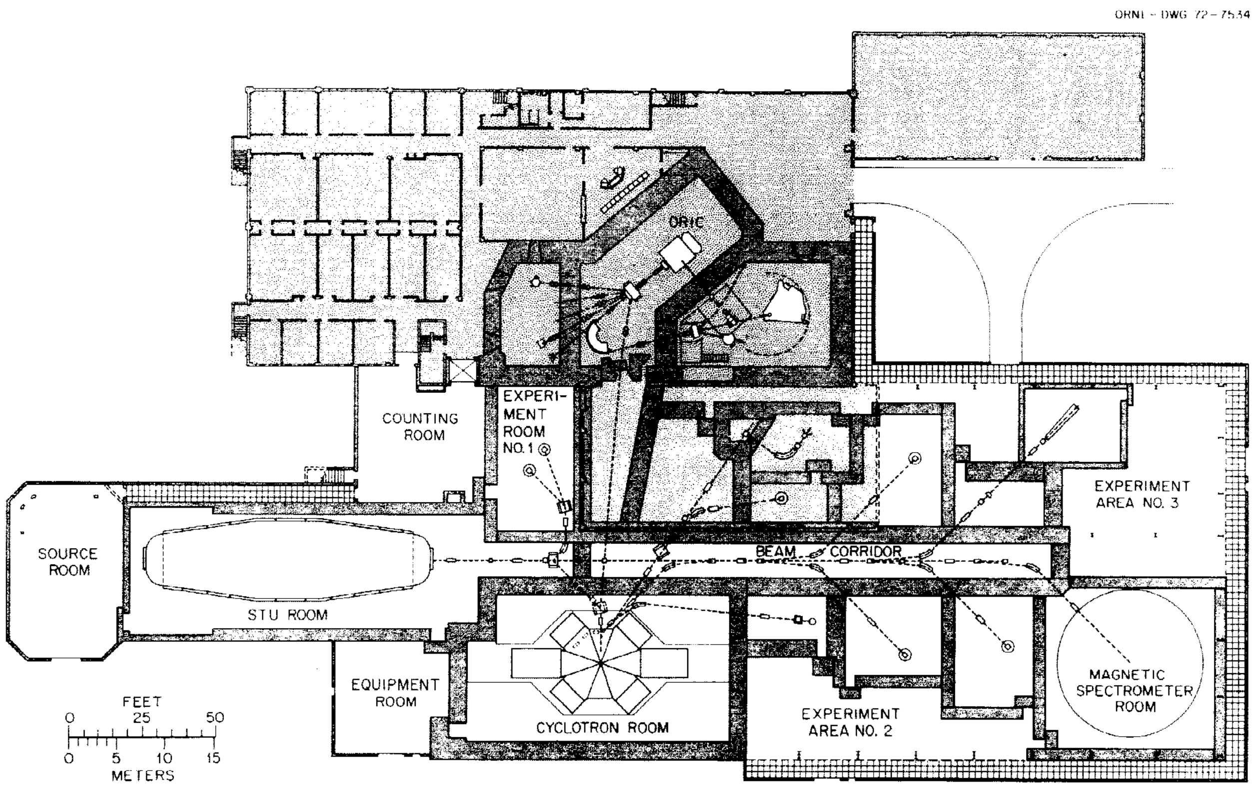

Fig. 1. National Heavy-ion Laboratory accelerators and experiment area. The existing ORIC facility is lightly shaded. An HVEC STU tandem injector is shown; an alternate would be an NEC 20-UD tandem.

tandem, main cyclotron, and experiment areas are to be built adjacent to the existing ORIC facility to take advantage of the substantial heavy-ion capabilities of this accelerator.[2] Either the tandem or the ORIC may be used independently for heavy or light-ion experiments when not being used as an injector for the main cyclotron. Injection from the ORIC will be through a 45 meter path length.[3] The energy multiplication of the main cyclotron when used with the ORIC will be a factor of 19, and will range down to 9 when used with the tandem as the injector. Ten experiment stations will be provided initially with the possibility of expanding to about 25.

SEPARATED-SECTOR CYCLOTRON

The main isochronous cyclotron is of the separated-sector type with four magnet sectors of 52° angular extent (Fig. 2 and Table I). This design gives strong axial and radial focusing with complete freedom from resonances in the ion motion that might deteriorate the beam quality (Fig. 3). The focusing frequencies were determined from magnetic field measurements of a single sector magnetic model (scale 1:11) with field terminating plates on either side to simulate the effect of adjacent sectors.

Ion acceleration is provided by 30° wedge-shaped dees located in two opposite spaces between magnet sectors. Two auxiliary 15° dees, operating at the second harmonic, are located within the main accelerating system (Fig. 4). The frequency range of the system is 6 - 14 MHz, and acceleration harmonics from 2 - 11 are used. Frequency variation is accomplished by shorting planes, with capacitive tuning for fine adjustment. Other rf system characteristics are listed in Table II.

Based on the report of Schmelzer,[4] and on the Omnitron proposal,[5] a vacuum design goal of 10^{-7} torr in the main cyclotron has been chosen. The vacuum pumping system will be a combination of cryopumps and diffusion pumps with a Roots blower backed by a mechanical pump. Two cryopumps and two diffusion pumps will be located in each resonator. These will pump the magnet gaps as well as the resonators. The pump-down time to reach 10^{-3} torr will be $\sim$ 1.2 hr, and to reach 10^{-7} torr should be less than 15 hr. Additional vacuum system parameters are given in Table III.

INJECTION AND EXTRACTION

Four of the six elements of the injection system (Fig. 5) must be moveable to accommodate a wide range of injection radii corresponding to different energy gain ratios. The elements in the magnet gap will be of the self-shaping magnetic septum type.[6] The magnets which bring the beam into position for injection are of the picture frame type with Hyperco yokes. Preliminary calculations with the computer program TRIM[7] indicate that it is possible to achieve the 23 kG required for the "worst" case with reasonable power and

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Table I NHL 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° hills)
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

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Table II Accelerating System Characteristics

Peak voltage, fundmental, 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

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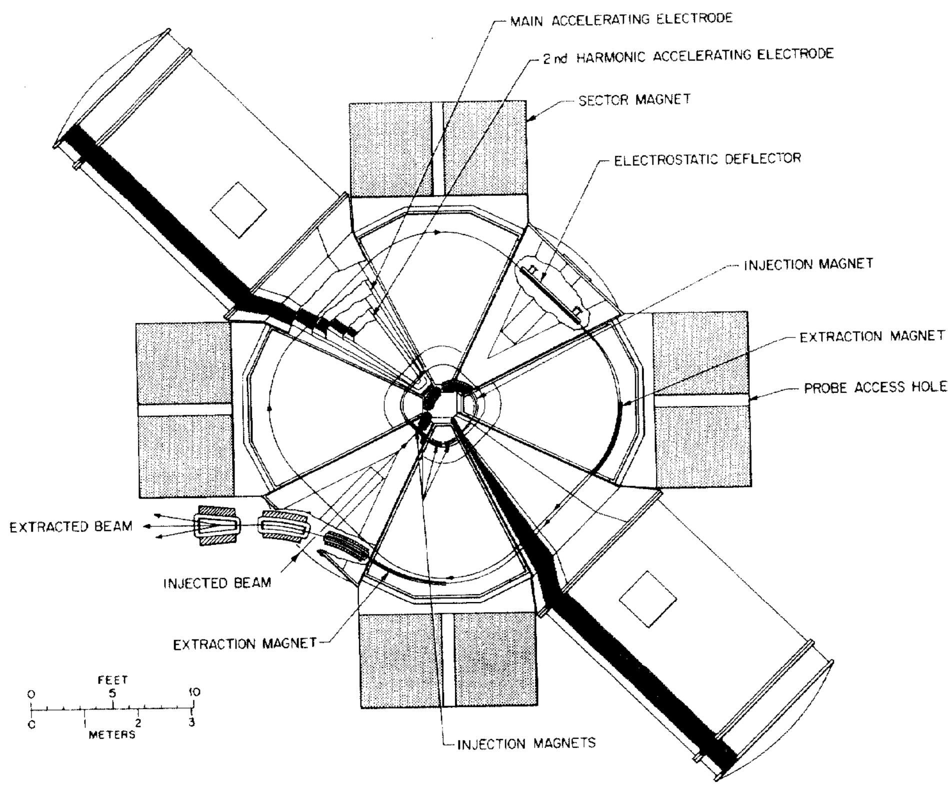

Fig. 2. The main cyclotron.

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Table III Vacuum System

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

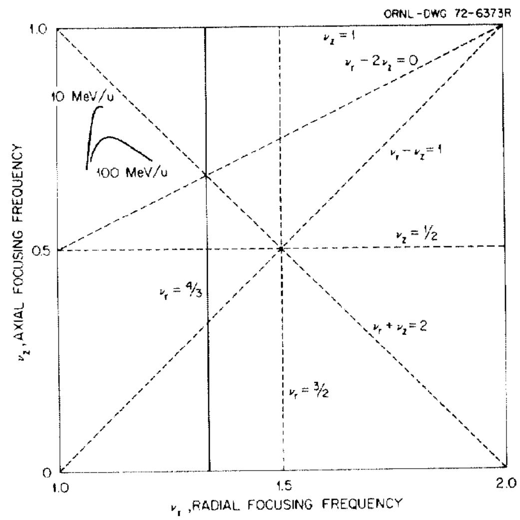

Fig. 3. Focusing frequencies for the main cyclotron.

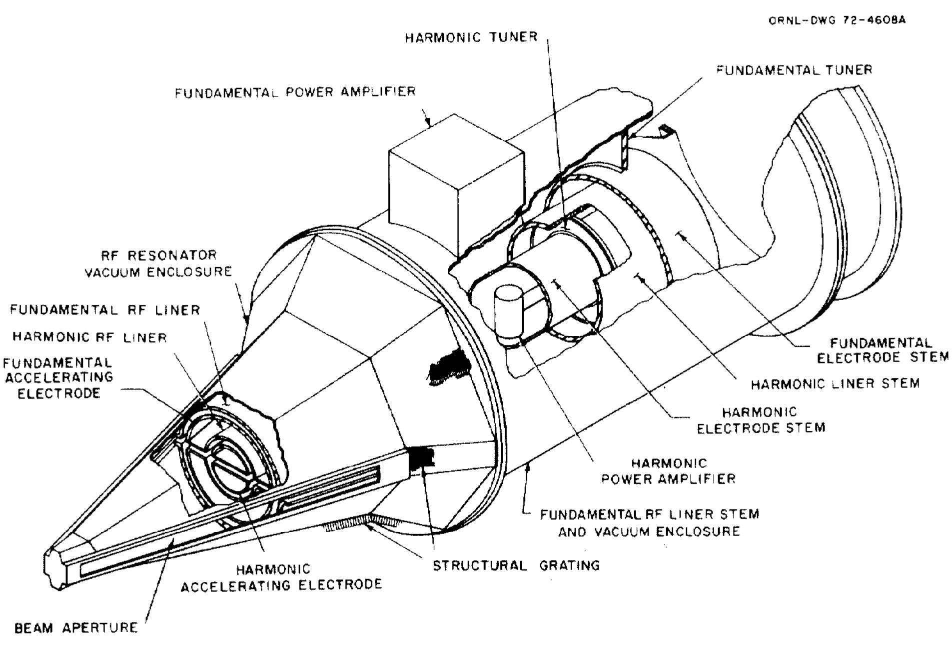

Fig. 4. Accelerating system for the main cyclotron.

efficiency. The highest fields are required only when operating at maximum energy and highest mass for maximum output with gas strippers between the tandem and the cyclotron, and for the highest energies from the ORIC. With a stripping foil between the tandem and the cyclotron, the injection energy is ∿ 160 MeV and the required magnetic field strength of the injection magnets is only 18 kG. The optics of the proposed system have not been studied in detail but a careful calculation of a similar system showed excellent matching of the beam to the axial and radial acceptance of the cyclotron.

Turn spacing for the injected beams is large (3.9 to 4.7 cm for uranium) so that no difficulty is expected in designing septum magnets to give adequate clearance. The turn spacing in the extraction region is adequately large for the heaviest ions at 10 MeV/u (1.6 cm), but for the lighter ions at 100 MeV/u with $q/A = 1/2$, ΔR is only 0.26 cm. Some artificial means for increasing the turn spacing will be helpful, and perhaps necessary, to obtain perfect beam extraction for the light ions. This can be achieved by taking advantage of the properties of the precessional motion of ions oscillating coherently about the equilibrium path. This can give large enhancement in the turn spacing and is particularly suited to this type of cyclotron because of the linearity of focusing characteristics. The beam is extracted well before the magnet edge and the accompanying region of non-linear dynamics is reached.

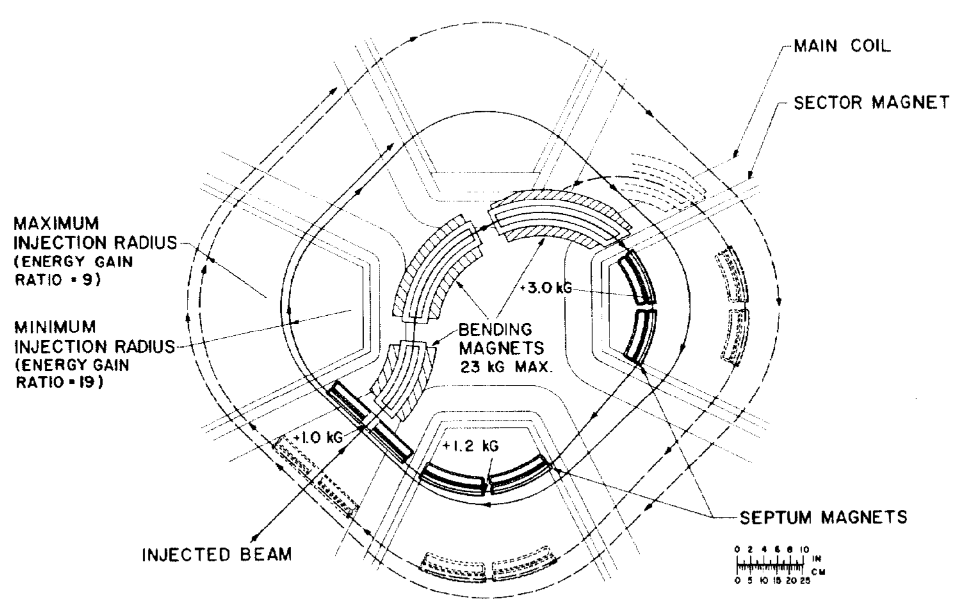

Fig. 5. Injection system for the main cyclotron.

BEAMS

The NHL accelerators will provide beams of all elements with more than enough energy to overcome the Coulomb barrier to produce nuclear reactions with targets of even the heaviest elements. The energy definition, $\Delta E/E$, of the beams is expected to be routinely better than 10^{-3}, and with special care 10^{-4} can be realized.

The beams from the tandem-cyclotron combination encompass the whole mass-range from the lightest to the heaviest elements. The maximum energies range from 100 MeV/u at the light end to 10 MeV/u for the heaviest ions. The maximum intensities vary from over 10^{13} ions/sec for chlorine to $\sim 3 \times 10^{12}$ ions/sec for heavy elements. The tandem-cyclotron combination can be operated with either a gas stripper or a solid stripper between the accelerators. The maximum beam energy available depends on which stripper is used, and on how far from the equilibrium charge state the beam chosen for injection lies. Maximum intensity can be achieved when operating with a beam corresponding to the equilibrium charge state after stripping. At the sacrifice of intensity, the energy can be increased by using a higher charge state from the stripper (Fig. 6a, b). The use of light gases gives full intensity beams at energies to 6 MeV/u, up to mass 150. The use of heavy gases (fluorcarbons) can extend the mass range for 6 MeV/u to tantalum (Fig. 6c). With a solid stripper between machines, 10 MeV/u can be achieved at nearly full intensity for uranium. It will not be necessary to use a solid stripper in the terminal of the tandem.

The ORIC may be used very effectively as the injector for the large cyclotron over a wide range of ion mass thus freeing the tandem for research demanding its unique capabilities.[3] In this mode of operation output energies will be above the Coulomb barrier up to the region of mass 180 (tantalum). As in the tandem-cyclotron combination, energy can be increased over a limited range at the expense of intensity by using higher charge states from the ORIC. Final beam energies for ions from the ORIC ion source for two levels of total ionizaion potential are shown in Fig. 6d. At present microampere beams are available at the 600 V level; nanoampere beams are obtained at the 1200 V level. Only the ORIC can provide beams of the noble gases neon, argon, krypton, and xenon. Negative ion beams such as are required for acceleration of noble gases by the tandem are unknown except for low intensity He^- beams. Beams of the required multi-charged positive ions have already been produced in the ORIC. The intensities that will be available from the large cyclotron with injection from the ORIC range from the particle-microampere level ($> 6 \times 10^{12}$ ions/sec) for light elements such as neon and argon, to perhaps one-tenth that at mass 200.

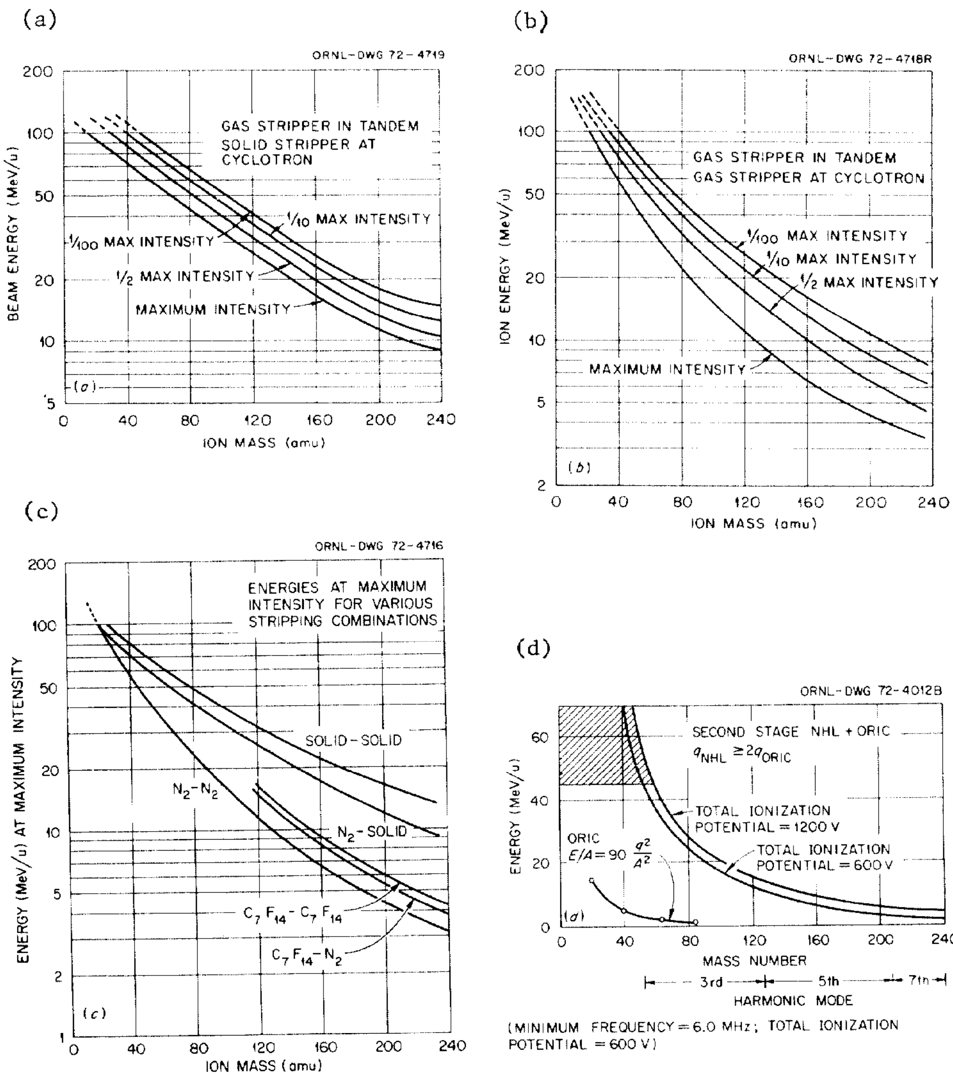

Fig. 6. Beam energies and intensities for various tandem stripping combinations and for ORIC as an injector.

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