Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

THE OMNITRON: A VERSATILE MEDIUM-ENERGY SYNCHROTRON FOR THE ACCELERATION OF LIGHT AND HEAVY IONS*

Invited Paper

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April 26, 1966

Abstract

A novel guide-magnet configuration has been devised which makes possible the acceleration of all charge-to-mass ratios from 0.04 to 1. A concentric storage ring, with the associated beam-switching equipment, allows for the extension of beam duty factor to essentially 100%. The storage ring can also be used in a bootstrap acceleration of heavy ions in which the ions are injected at low e/m, accelerated to a moderate velocity, stored while the accelerating ring returns to minimum field, stripped to maximum e/m, and re-injected for further acceleration. With a pressurized 2.5 MV Cockcroft-Walton injector, the proposed system is capable of accelerating all ions from protons to uranium--to energies up to 1.5 BeV for protons and 0.3 to 0.5 BeV/nucleon for the heavier ions. Intensities of 10^{12} to 10^{13} nucleons/sec for the lighter ions ($M \leq 128$) are anticipated. The heavy-ion charge-exchange probabilities determine the vacuum requirements of this system. To minimize these requirements and to increase beam intensity, a 60/sec cycling rate has been chosen. The vacuum requirements and the special rf resonator and beam-switching problems attendant with the high cycling rate are discussed.

Introduction

The energy range of primary interest for heavy ions used in nuclear chemistry is determined by the excitation required for the formation of compound nuclei, 5 to 7 MeV/nucleon. The principal source of these ions during the past 9 years at Berkeley has been the Heavy Ion Linear Accelerator (Hilac). This accelerator produces a maximum energy of 10 MeV/nucleon and consists of a 500 kV dc injector and two Alvarez-type rf cavities, with provision for ion stripping at 1 MeV/nucleon between the two cavities. The injection energy, particle charge-to-mass ratios in both cavities, and the stripping velocity were designed for efficient acceleration of ions with mass up to 20 (neon).

Over the years, the nuclear chemistry requirements for increased currents of the heavier ions and for increased duty factor have been met with improvements to the Hilac that, in general, have kept pace with the requirements. With the completion of presently planned improvements, beams of argon ($M = 40$) adequate for all needs will be available. It is also expected that significant beams of krypton ($M = 84$) can be accelerated. The development of techniques to force the ions from synchronous phase and stop the acceleration process at any one of the drift tubes in the high-energy cavity has provided a method of satisfying the requirement for variable energy in the range 1 to 10 MeV/nucleon.

During the past few years, however, a substantially increased interest has developed in the ultra-heavy ions ($M \leq 240$) in this energy range. The principal problem of producing these heavier ions is indicated in Fig. 1, which shows the relative abundance of krypton and xenon ions of various charge-to-mass ratios (ϵ) available from the cold cathode PIG ion source used at the Hilac. Although extensive development of heavy-ion sources has been carried on over the past 10 years, at the Hilac and by a number of other investigators, significant improvement over this source has not been achieved, either in total current or in the enhancement of the higher charged states. The extremely small currents of ions with $\epsilon = 0.125$, the minimum ratio for Hilac injection, precludes the possibility of using this accelerator for the production of ultra-heavy ions.

In addition to the nuclear chemistry demand for the extremely heavy ions in the low-energy range, biophysics studies at the Hilac combined with the highly promising results achieved with medium-energy charged-particle medical therapy have created a high degree of interest in the use of heavy ions ($M = 40$) in this field. The general requirement for these ions is the ability to produce a precisely controlled dose in a precisely defined region of tissue at depth ranging up to 15 cm. These requirements, when transformed into beam specifications, demand a high-quality beam with a continuously variable and precisely controlled energy. The maximum energy is determined as that required to produce a 10 cm range for argon ions, approximately 400 MeV/nucleon.

This latter requirement is particularly difficult for the heavier particles in that their efficient acceleration and containment in a magnetic field of reasonable dimensions demands the use of fully stripped ions. Present techniques (passage of the ions through a thin foil) require argon ion velocities of about 0.15 c (10 MeV/nucleon) for reasonable stripping efficiency. The accelerator system designed to produce these high-energy heavy ions must provide for stripping at an intermediate energy.

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*Work done under the auspices of the U. S. Atomic Energy Commission.

The magnetic field capable of containing a fully stripped 400 MeV/nucleon argon ion will also contain a 500 MeV alpha or a 1500 MeV proton. Since these energies fall well within the range acceptable for medium-energy physics and light-ion medical physics, we have added as a basic accelerator design requirement, modest intensities of these ions.

In addition to the variety of particles and the energies noted, all of the research programs demand a high beam duty factor ($\approx 50\%$), completely variable energy and, in some cases, a high energy resolution. A summary of the requirements of the various research programs is shown in Table I.

Table I. Omnitron beam requirements.

Low-energy nuclear chemistry	
Mass number	40 - 250
Energy range	3 - 10 MeV/nucleon, variable
Energy resolution	$\leqslant 0.5\%$
Intensity	$\geqslant 10^{11}$ particles/sec
Duty factor	$\geqslant 0.5$
Biophysics/ Medical	
Mass number	1 - 40
Energy range	50 - 400 MeV/nucleon, variable
Energy resolution	$\approx 0.5\%$
Intensity	10^{12} particles/sec, M = 1 10^{11} particles/sec, M = 2 10^{10} particles/sec, M = 12 - 40
Duty factor	$\geqslant 0.5$
Medium-Energy Physics	
Mass number	1 - 4
Energy range	$\geqslant 1000$ MeV, variable
Intensity	$\geqslant 10^{12}$ particles/sec
Duty factor	$\geqslant 0.5$

In designing an accelerator to satisfy these requirements the following general restrictions should be noted:

(1) Conventional PIG ion sources are capable of removing electrons with ionization potentials up to about 120 V. The injection charge-to-mass ratio in the low-energy section of the accelerator should not be such that any of the ions to be accelerated require charge states where this figure is exceeded.

(2) The stripping of high-Z ions is extremely inefficient except for complete stripping at high velocities. If possible, the complete acceleration cycle of the ultra-heavy ions should be accomplished without stripping.

Since the nuclear chemistry groups require the acceleration of elements with mass up to 240, the accelerator injection charge-to-mass ratio is restricted to $0.04 \leqslant \epsilon \leqslant 0.06$.

Figure 2 shows the magnetic guide field necessary to contain particles of various energies and various ϵ, over the entire range of interest. With a maximum guide field of 3×10^6 G-in., an ion with $\epsilon = 0.05$ can be accelerated to approximately 7 MeV/nucleon. With this field the high-energy biophysics ions (alpha, carbon, nitrogen, oxygen, and neon) can be accelerated to 500 MeV/nucleon with $\epsilon = 0.5$, and argon will reach 400 MeV/nucleon with $\epsilon = 0.46$. Protons can be accelerated to a maximum of 1500 MeV.

The figure also indicates the minimum guide field, 9×10^4 G-in., considered feasible for an alternating-gradient synchrotron (300 G in the magnets). Protons require an energy of 2.5 MeV to be injected into this ring and, since all other ϵ's can be injected with this voltage, this specifies the maximum injector potential.

The synchrotron ring with these parameters is thus capable of satisfying the energy requirements of all of the research groups. However, unless flat-topping of the guide magnets is used, the duty-factor requirement cannot be met and, in addition, an auxiliary medium-energy injection system is necessary to provide the high charge states required to achieve high-energy heavy ions for biomedical uses.

Both the intensity requirements and the problems of charge exchange for the multiply charged beams indicate the necessity of cycling the system at the maximum possible rate. For the Omnitron the cycling rate has been chosen at 60/sec, limited primarily by the rf voltages required to achieve the high acceleration rate. The analysis of the cost of providing a flat-topping power supply for a magnet system cycling at this rate, as compared with that of an auxiliary dc storage ring, is only slightly in favor of the flat-top supply. The storage ring has the significant advantage that it will not only provide for the high duty factor, but also makes possible the utilization of the synchrotron as its own injector for ions that must be stripped at high velocities to achieve the maximum required energy. In this mode of operation the heavy ions are injected in a low charge state, accelerated to an intermediate energy, stored while the synchrotron magnetic field returns to minimum, completely stripped, reinjected into the synchrotron, and accelerated to high energy (see Fig. 3). Although the overall cycling rate of the system is decreased by a factor of 2 in this process, it is preferred to all other methods of injection, since the longitudinal distribution of the beam is maintained constant during the low-energy acceleration cycle and the entire beam can be transferred back into the synchrotron.

The storage ring must be capable of storing beam of the maximum $B\rho$, so that its parameters are essentially the same as those of the synchrotron. The diameters of the two rings have been chosen as nearly equal as possible, to avoid the problems of multi-turn injection in either ring.

The proposed accelerator therefore consists of a 2.5 MV dc injector; an alternating-gradient synchrotron covering the range 9×10^4 to 3×10^6 G-in.; a dc alternating-gradient storage ring concentric with the synchrotron, but with slightly larger diameter; and the necessary ring-to-ring beam-transfer equipment (see Fig. 4). The various components of this system and the estimates of beam currents are discussed below.

Synchrotron and Storage Rings

Both the synchrotron and the storage ring consist of 64 guide magnets and 16 Collins quadrupoles arranged in eight superperiods, each consisting of two normal FOFO'DODO' cells and one 10 ft drift space.

The synchrotron radial focusing magnets are 27.5-in. effective length and the defocusing, 28.5 inches. Both magnets have a field gradient $k = 4.52$ and are operated in the range $0.300 = B = 10.5$ kG. Arranged in the chosen configuration, these provide 5.25 radial and 5.30 vertical betatron oscillations in the 359 ft circumference. Four of the 10 ft drift spaces are used for the rf resonators and associated beam-monitoring equipment, and one for injection. The three remaining drift spaces are available for inter-ring transfer and ejection.

The structure of the concentric storage ring is identical to that of the synchrotron, except for slight differences in the magnet lengths, magnet spacing, field gradients, and Collins drift space required to maintain similar betatron oscillation frequencies in the slightly larger circumference (394 ft). The elements in the storage ring are offset by 22.5 deg from the corresponding elements in the synchrotron, to simplify the ring-to-ring transfer.

The apertures of the two rings are identical, ellipses with major axes 3.2 and 1.6 inches. Larger apertures are required for the Collins straight sections.

It is to be noted that the particle motions produced by magnetic forces only are independent of ϵ, and are therefore identical for all particles. However, the synchrotron motions, which are produced by combined magnetic and electric forces, are not only dependent on ϵ but also on the rf harmonic number; and the synchrotron frequencies and amplitudes, the injection bucket size, etc. are variable. Studies of particle motions with the aid of SYNCH and APERT, IBM 7094 computer codes, indicate that for the configuration chosen, all of these parameters fall well within practical operating limits over the range $0.04 \leqslant \epsilon \leqslant 1$. In addition, the 2.5 MV injection allows wide latitude in the choice of harmonic number (see section on acceleration) for the lower ϵ, so that the synchrotron motions can be easily adjusted for optimum operation.

Accelerating System

The acceleration rate required for the synchrotron is

$$\text{Energy gain/turn} = V_g \epsilon e \sin\phi_s = 2\pi R \frac{d(mv)}{dt}$$

$$= 2\pi R \dot{B}\rho \; \epsilon e,$$

where

V_g = total gap voltage,

$2\pi R$ = mean orbit circumference,

ϕ_s = synchronous phase angle,

$$\dot{B}\rho = \frac{(B\rho)_f - (B\rho)_i}{2} \Omega \sin\Omega t.$$

The total gap voltage required for the particles to follow the change in magnetic field is thus independent of ϵ.

The accelerating frequency is

$$f_{rf} = hf_0 = \frac{h \epsilon e \overline{B}}{2\pi m},$$

where

$\overline{B}$ = mean orbit magnetic field,

h = harmonic number,

e, m = proton charge and mass.

The accelerating frequency is therefore proportional to ϵ; however, by adjustment of the harmonic number the frequency program can be made identical for all ions, except for relativistic effects. With the 2.5 MV injection (Fig. 2) the maximum frequency swing of about 16:1 is required for alphas ($\epsilon = 0.5$), with a 6.5:1 swing required for ions with $\epsilon = 0.04$. A wide latitude in choice of the harmonic number is thus possible for the heavy ions.

The rf system chosen for the Omnitron is similar to that of the Princeton-Penn accelerator[1] and consists of two biased ferrite resonators, one tuned to cover the range 1.6 to 7.5 Mc and the other 7.0 to 33 Mc, with a midrange cross-over.

With the magnets operating with a 60 cycle/sec biased sine wave over the range 0.3 to 10.5 kG, a maximum energy gain per turn of $150\,\epsilon$ keV is required. With the synchronous phase angle at

40 deg, the total gap voltage must be 240 kV. This will be provided by four resonator systems (each with a gap voltage of 60 kV) situated symmetrically around the ring. Since these systems will be operated in phase, the allowable harmonic numbers will be restricted to those divisible by four.

The close spacing of the slow ions at high harmonic numbers requires that each resonator voltage be applied across a single gap, rather than the double-gap systems normally used with proton accelerators. With this exception, and that of the wide frequency range, the resonator and rf control system will closely follow present synchrotron practice.

Ion Source and Injection

The synchrotron space charge limit is given by the expression $Q = 6 \times 10^{-15}$ V coulombs, where V is the injector voltage. If the system is operated for all ions at 2.5 MV, the injection time is given by $\tau = 5\sqrt{\epsilon}$ μsec. It is apparent from these expressions that the peak current required from the ion source is $3\sqrt{\epsilon}$ mA, varying from 0.6 to 3.0 mA over the entire range of ions to be accelerated. These modest ion-source requirements are exceeded by the Hilac ion source for all gaseous elements up to xenon. The average beam drain on the injection is about 1 μA.

The high-voltage generator will be a 100 kc shunt-fed Cockcroft-Walton supply utilizing fast solid-state diodes. The stack construction and characteristics are similar to the Hilac injector[2], except that the entire high-voltage generator and terminal will be housed in the pressure vessel and operated in an atmosphere of sulfur hexafloride.

The calculated capacity of the terminal and the Cockcroft-Walton stack characteristics are such that ripple and terminal sag during the beam pulse will be negligible. Regulation will be to about 1.5 kV (1:1500). The system emittance and energy spread is expected to be considerably better than required by the synchrotron.

Conventional transport and electrostatic inflection will be used.

Ejection

In the case of multiple acceleration, the transfer of beam between the synchrotron and the storage ring must be accomplished in a single turn. This requires a deflection system with a rise time fast compared with the orbit period of the most energetic ion (i.e., protons, with $t = 0.407$ μsec) and with a duration longer than the period of the slowest ion ($\epsilon = 0.40$, $t = 5.6$ μsec). The fast pulse rate together with the rise-time requirement is somewhat more stringent than presently operating equipment. However, a test ferrite magnet system has been built and is now under study.[3] It consists of a 6 μsec pulse line switched with a hydrogen thyratron. Experimental measurements show that it is capable of filling an 8-in. long ferrite window magnet with an aperture 3.2 × 1.6 in. to 2 kG in approximately 80 nsec.

These magnets will be used for both ejection and injection in the transfer process. In the former case the rise-time requirements mentioned above are applicable; in the latter, the fall time rather than rise is of importance. In the storage-synchrotron transfer, advantage can be taken of the increased charge state to reduce the magnetic field requirements.

The space available in the Collins straight sections requires that the fast-extraction magnets provide approximately 2.5 mr deflection for convenient septum spacing.

Slow extraction from the storage ring will be accomplished by a resonant system in which the beam will be expanded toward a septum located in one of the straight sections. Maximum expected beam loss in this process is about 10%.

Vacuum System

The investigation of beam losses due to interaction with residual gas in the vacuum chamber indicates that for all ions and charge states the most severe problem occurs in the low-energy heavy-ion acceleration cycle, and that scattering will be at least an order of magnitude less important than charge exchange. The losses to be anticipated from charge exchange have been estimated from data available in the literature[4, 5] and from recent measurements at 1 and 10 MeV/nucleon at the Hilac. The beam attenuation due to charge exchange is

$$n/n_0 = \exp - [10^{27} P \int_0^t \sigma(\beta)\, \beta\, dt],$$

where

P = pressure in torr,

$\sigma(\beta)$ = total charge-exchange cross-section in cm^2,

t = acceleration period,

$\beta = v/c$.

The available data indicate that for +4 krypton ions in argon gas, as a typical case, the product $\sigma(\beta)\beta$ remains fairly constant at approximately 10^{-17} cm^2 over the range $0.01 \leq \beta \leq 0.07$, the low-energy cycle of the Omnitron. The attenuation for this case is thus

$$n/n_0 = \exp - (10^{10} Pt).$$

In order to achieve reasonable transmission the product Pt must be maintained at less than 10^{-10}. The presence of the accelerating period in this expression emphasizes the importance of the fast cycling of the accelerator. For the 60/sec rate chosen the vacuum must be maintained with an average pressure at less than 10^{-8} torr, argon equivalent.

The charge-exchange cross-sections are

dependent on the charge state of the projectile and its velocity, and on the composition of the residual gas. The composition of the residual gas is in turn dependent on the outgassing characteristics of the chamber material, the system conductance for the various gas species, and on the pumping characteristics and history of the applied pumps. These factors complicate considerably the detailed analysis of the vacuum system requirements; however, investigation has shown that no single pumping system can provide optimum vacuum conditions. Several combinations have been considered, all of which appear capable of providing beam transmission in excess of 0.9 for the low-energy cycle with ions up to mass 126 (xenon). Preliminary estimates for these systems indicate no particularly advantageous combination with regard to cost.

Favored at present, but subject to later revision primarily on the basis of reliability, is a system consisting of 4 to 5°K cryopumps located between each guide magnet, cooled by a tube carrying high-pressure 4°K helium completely around the guide rings, and backed by a turbomolecular pump to handle the light gases and to rough the chamber.

In the vicinity of the rapidly varying magnetic fields the chamber must be of an insulating material; an investigation of the vacuum properties and strengths of available materials has indicated the superiority of α-alumina for this purpose. These will be elliptical cylinders, lightly metallized on the inner surface to prevent the build-up of charge, and metal-bonded to stainless steel flanges. These sections will be heliarc-welded in place to the stainless steel tube comprising the remainder of the vacuum chamber.

With a vacuum system of this complexity, <u>in situ</u> baking is impossible. Preprocessing, including high-temperature vacuum degassing, of all chamber components, and extreme care in the assembly of the system will be necessary. Rapid-closing valves, supplemented by acoustic delay tubes, will be used between the accelerator and the cave areas, to prevent disaster in the event of experimenter error.

Radiation Problems and Cave Facilities

The pressures required for the acceleration of particles of low charge-to-mass ratio assure that essentially no scattering losses will occur for the high-energy, fully stripped ions. In addition, for those ions with $\beta \geq 0.2$, the charge exchange becomes negligible. The loss of high-energy beam in the fast transfer from the synchrotron to storage ring can be eliminated by emptying a series of buckets to accommodate the ejection magnet rise time. Thus extreme radiation problems in the rings can be eliminated, except in the region of the slow-extraction system on the storage ring.

For the aperture chosen the space charge limit is given approximately by the expression $N = 2.5 \times 10^6$ V/n particles per second, where V is the injector voltage and n is the charge number. With the 2.5 MV injector, maximum beams of a few tenths microampere are possible, with a few-nanoampere loss expected on the slow-extraction septum. However, the modest cost of increasing the proton injection energy by a factor of 20 or more with a linear accelerator, and the probable increased demand for mesons for both medical therapy and medium-energy physics makes it mandatory that the shielding and cave system be designed in such a manner so as not to preclude eventual increase in proton currents to 10 to 15 μA.

The ring shielding has thus been designed as a double concrete wall, originally to be filled with compacted dirt which can later be removed and replaced with high-density material to provide for the high beam currents.

The high-energy cave system consists of a long alley, parallel to an existing hill that can later serve as a beam dump, and the beam is deflected 45 deg into any one of a series of caves along its length. Alteration of this system to accommodate the increased beam currents will consist primarily of addition of shielding to the caves.

The low-energy cave system is located approximately 180 deg around the ring, opposite the high-energy extraction septum. This system consists of a central alley from which the beam can be deflected in both directions into the caves, which require only 1 to 2 ft of concrete shielding.

The magnetic transport equipment is identical for both cave systems since they are both required to handle the full-momentum beam (3×10^6 G-in.).

Beam Estimates

In estimating the beam intensities that can be produced by the Omnitron the following assumptions have been made:

(1) Ion-Source Output and Synchrotron Space Charge Limits

The calculations of the space charge limits as compared with the Hilac ion-source output indicate that, over the range $1 \leq M \leq 126$ and for injection at 2.5 MV, space charge will limit the accepted beam at $5 \times 10^{12}/n$ particles per second (n = charge number).

(2) Charge Exchange

Charge-exchange losses will occur for the heavy ions in both the low-energy synchrotron cycle and in the storage ring. A transmission of 75% is assumed in both cases. A negligible loss of the fully stripped ions in the high-energy cycle is assumed.

(3) Fast-Transfer Efficiency

The ring-to-ring transfer losses are dependent on the rise time of the fast kicker magnet as compared with the orbit frequency of the ions, with the expected transfer efficiency of $(1 - tf_0)$, where t = rise time, here assumed at

Table II. Omnitron parameters.

	Synchrotron	Storage
Maximum kinetic energy		
$\epsilon = 0.5$	500 MeV/N	500 MeV/N
Protons	1500 MeV	1500 MeV
Injection potential	2.5 MV	
Orbit frequency		
Maximum	2.47 Mc	
Minimum	0.0356 Mc	
Energy gain/turn		
Maximum	150 keV	
Synchronous phase angle	40°	
Total gap voltage		
Maximum	240 kV	
Number of resonator systems	4	
Maximum gap voltage	60 kV	
Maximum frequency swing (ϵ = 0.5)	16:1	
Number of guide magnets	64	64
Configuration	FOFODODO	FOFODODO
Profile parameter	4.516/m	3.836/m
Betatron frequency		
Vertical	5.30	5.30
Radial	5.25	5.25
Ring radius, effective	17.44 m	19.13 m
Magnet guide field		
Maximum	10.5 kG	10.5 kG
Minimum	0.300 kG	1.0 kG
Injection phase area	3×10^{-3} rad-cm	3×10^{-3} rad-cm
Number of Collins straight sections	8	8
Length	4.8 m	5.33 m
Length of drift space	3.0 m	3.2 m

80 nsec, and f_0 = ion orbit frequency.

(4) Stripping Efficiency

This refers to the fraction of ions that appears in the acceptable charge state on passage of the beam through a thin foil and applies only to the multiple-acceleration operation. Fifty per-cent of an argon beam can be fully stripped at 10 MeV/nucleon and this figure[6] is used in estimating intensities of all beams requiring multiple acceleration. Also to be noted for this case is the fact that the system operates at a repetition rate of only 30/sec.

(5) Slow-Extraction Efficiency

Systems similar to that proposed for the Omnitron achieve efficiencies of 90% and this figure is used in the beam estimates. Under these conditions the beam estimates are shown below in Table III.

Table III. Omnitron beam intensity.[a]

Energy (MeV/nucleon) →	5-10	50-100	100-500	500-1500
Protons	5	4.0	3.5	3
Alpha	2.5	2.0	1.5	--
Carbon	2.2	0.7	0.5	--
Neon	2.2	0.7	0.5	--
Argon	1.1	0.35	0.25	--
Krypton	0.45	--	--	--
Xenon	0.36	--	--	--

[a] All values times 10^{12}/sec.

Estimates of intensities of ions heavier than xenon are problematical in that ion-source output of the charge states necessary are unknown and no information exists of charge exchange cross sections for these ions. It is to be noted, however, that for ions for which the space charge limit exceeds the ion-source output, multiple-turn injection can be utilized up to an estimated four turns. For the very heavy ions, stripping at 2.5 MV before injection can be utilized to achieve the necessary charge state.

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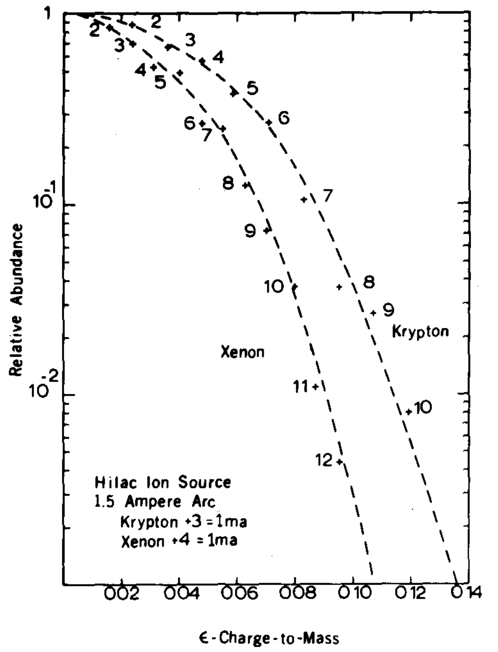

Fig. 1. Hilac ion-source output.

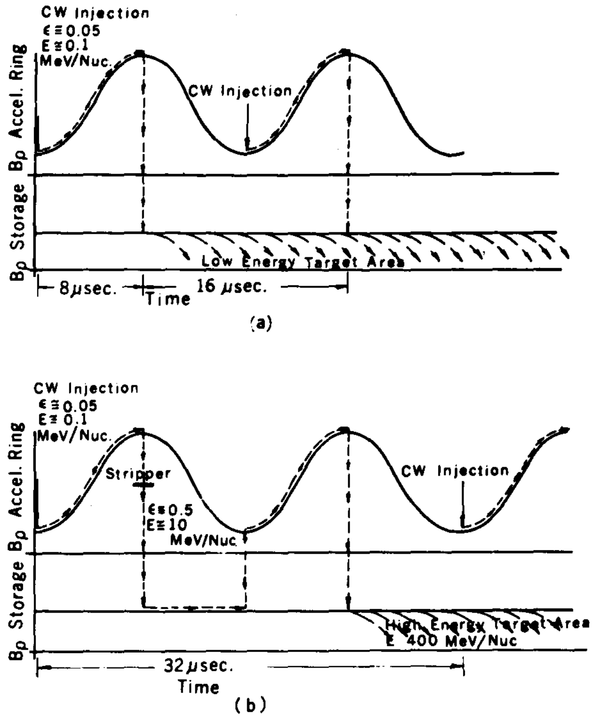

Fig. 3. Omnitron acceleration cycle.

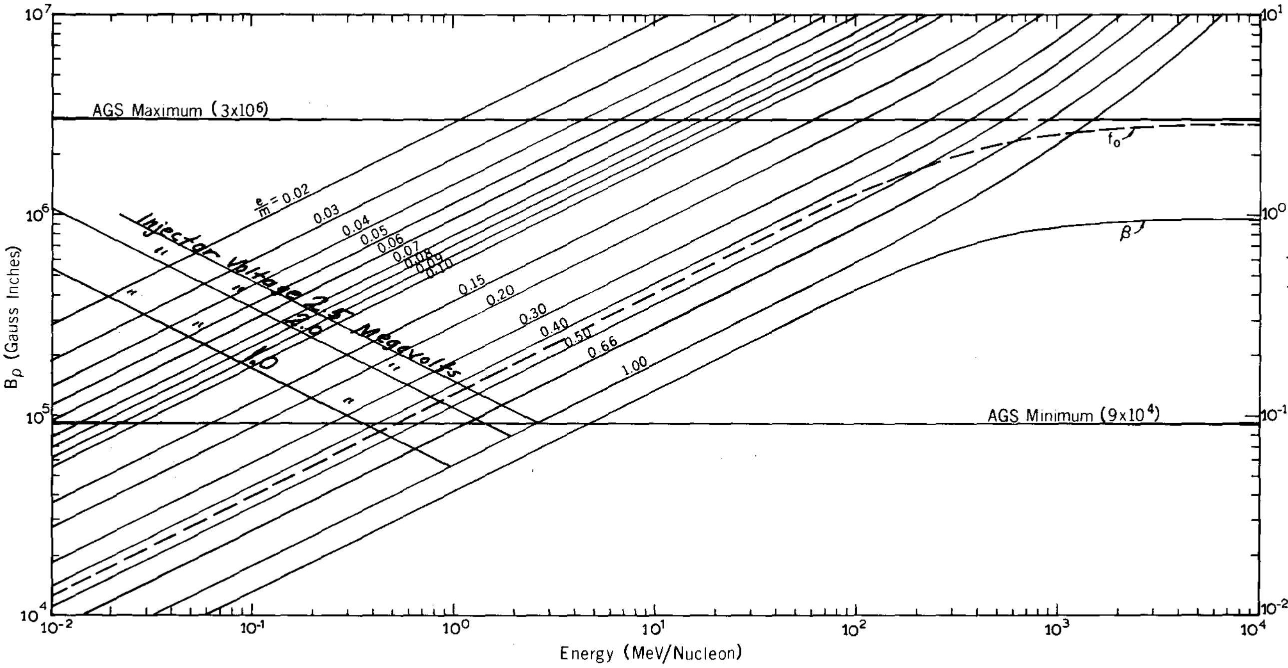

Fig. 2. Bρ vs energy per nucleon.

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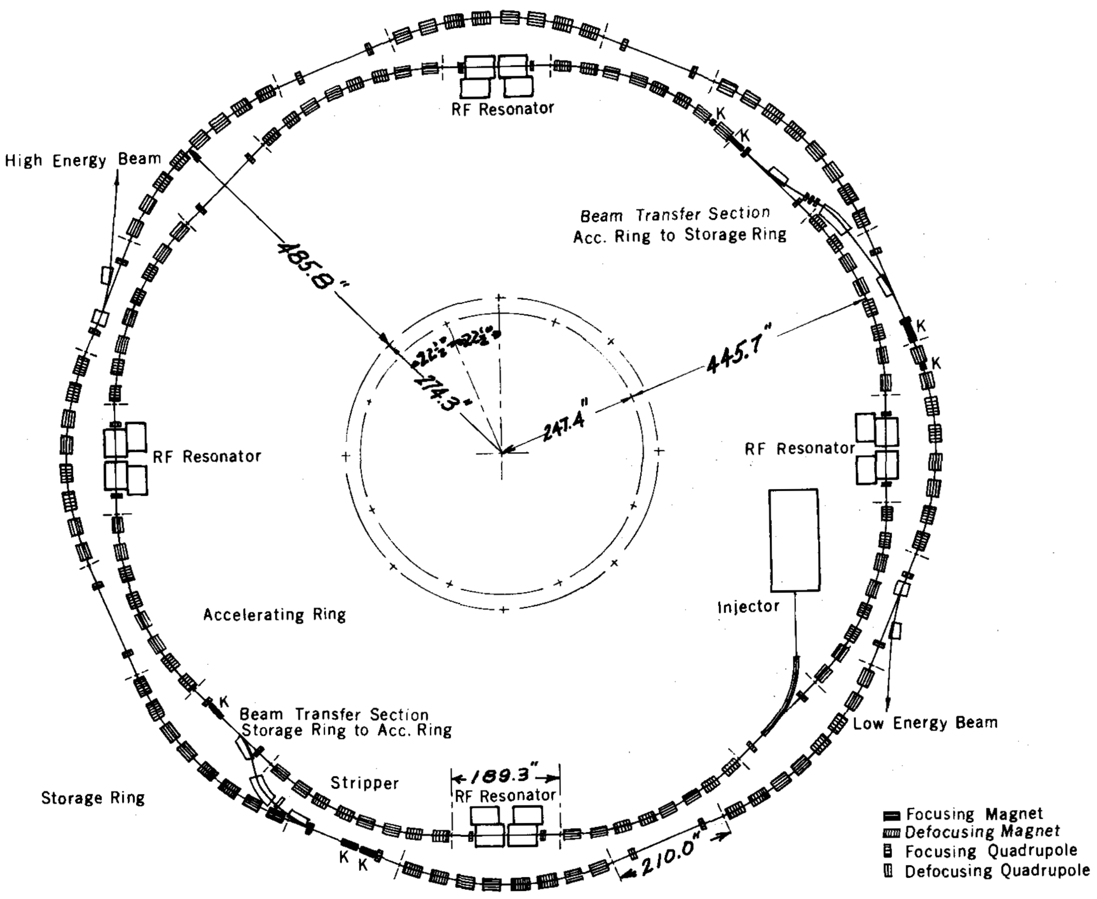

Magnet Ring General Arrangement

Fig. 4. Omnitron layout.

DISCUSSION

LIVINGSTON: Isn't 0.05 μA for your heaviest ions a bit marginal for looking for the new elements?

MAIN: Our new-element man says he can do it with this beam. Naturally he would like to have considerably more, but he says he can do much work at this beam intensity.

VOGT: How does your beam of very heavy particles compare with that of the next generation of the DC machines, which might have 25, 30, or 40 MeV on the terminal?

MAIN: I am not sure about that. It depends on what can be done with stripping. We understand that, for this range of above 7 MeV per nucleon, the DC machines will be a factor of perhaps 100 down in beam current.

DMITRIEVSKY: Where do you get the name, "Omnitron"?

MAIN: That name, "Omnitron" refers to all the problems that you get into if you try to deal with biomedics, nuclear chemists, and medium-energy physics, all at the same time on one machine.