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THE ACCELERATION OF HEAVY IONS†

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The history and present status of the acceleration of heavy ions is reviewed. Some of the factors influencing the choice of accelerating systems for heavy ions are analyzed. A comparison of relative ion source performance is given, as is a discussion of the stripping estimates of the most recent Nikolaev average ion charge interpolation formula. Some considerations of the many new ideas for heavy ion acceleration are included. The author hopes that soon heavy ion science can obtain better accelerators to overcome a grave lack of needed capability which exists at present.

1. INTRODUCTION

The use of particle accelerators as instruments for the study of nuclear science may be dated from the year 1932 when first the Cockcroft–Walton and soon thereafter the cyclotron were used to produce beams of protons energetic enough to produce transmutations. During the first few years after this opening of the era of experimental nuclear science, the only accelerator projectiles used were protons, deuterons, and α-particles. But before the end of this first decade of infant nuclear science, the 1930s, the idea of using heavy ions as projectiles was conceived. It was, however, some years hence before successful acceleration of heavy ions produced a useful tool for the nuclear physicist. During our two most recent decades, the 1950s and 1960s, a great variety of interesting and important nuclear physics and nuclear chemistry has been successfully undertaken using the techniques associated with heavy ions. At the present time nuclear scientists are genuinely aglow with many new and exciting ideas for experiments which may have results of great scientific, and possibly practical, importance. Since the earliest days of accelerators, the experiments which could be undertaken were determined largely by the mass and energy of particles which could be processed to useful energies in the available accelerators. Even today this is yet again the situation with the ideas and the needs of nuclear scientists far outstripping the capabilities of existing nuclear machinery. Because of the great swelling of interest in recent years in the possibilities for experimentation with ions much heavier than those now commonly accelerated, including most or all of the top end of the periodic table and certainly including uranium, many of the world's governments are being besieged by scientists on behalf of a bright array of different proposals for accomplishing this. Because, at the present time, in the United States and in most of the other countries of the world, funds available for basic research are being curtailed or withdrawn, rather little practical response has been made to this worldwide outcry for better and more powerful heavy ion accelerators. Because of this present rather unproductive situation, a great deal of thought and study now is going into seeking a method for accomplishing the acceleration of the heaviest projectile masses to suitable energies at low capital cost. As of the present there are many intriguing and perhaps promising ideas but little has yet been demonstrated with sufficient clarity to appear credible to the nuclear science community for the immediate future.

2. HISTORY

The importance of ions heavier than helium for the study of nuclear phenomena was recognized during the first decade of particle accelerators. Alvarez(1) and Tobias undertook studies in the 37-in cyclotron at Berkeley and in 1940 demonstrated that 50 MeV C^{6+} ions could be detected. It turned out, however, that the low intensities and the contamination of light ion beams in these early trials made nuclear experiments quite impractical. It was in the second decade of particle accelerators in 1950 that the first heavy ion nuclear reactions(2) were observed, with beams of about 10^5 particles per second of 120 MeV C^{6+} ions in the 60-in cyclotron at Berkeley. Although these beams were used successfully, they were not very well suited for experimental work because of a very large energy

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spread in the beam and because of the very low intensities available. There is general concurrence that the mechanism for acceleration in the early cyclotron work was first C^{2+} ions emerging from the source (accelerated on the third harmonic of the deuteron ion rotation frequency), and subsequently through gas stripping near the center of the cyclotron formation of C^{6+} ions accelerated approximately on the deuteron fundamental frequency. The wide physical extent of the area occupied by the various sources of origin of the ions then could account for the large energy spread observed. Other cyclotrons which developed beams of this e/m of 1/6 to e/m 1/2 system were the 180-cm cyclotron at Saclay,[3] the 156-cm cyclotron at Birmingham,[4] and the 225-cm cyclotron at Stockholm, Sweden,[5] the latter with unique variable magnetic fields. The first accelerators in which ions from a source were accelerated directly without any intermediate stripping were the 63-in cyclotron of Oak Ridge[6] giving 2.0 MeV/u $^{14}N^{3+}$ and the 120-cm cyclotron at Leningrad[7] at first producing 1.1 MeV/u later somewhat higher energy, also using $^{14}N^{3+}$. The participants in this earliest work are cataloged in Table I. The dates given are of the earliest publication, for each respective laboratory.

TABLE I

Earliest heavy ion accelerators

Date	Machine	Location	Typical particle	Energy	Extracted beam
1940	37-in Cyclotron	Berkeley	$^{12}C^{2+,\,6+}$	50 MeV	8/sec†
1950	60-in Cyclotron	Berkeley	$^{12}C^{2+,\,6+}$	100 MeV	10^5/sec
1953	225-cm Cyclotron	Stockholm	$^{12}C^{2+,\,6+}$	150 MeV	10^{11}/sec†
1953	63-in Cyclotron	Oak Ridge	$^{14}N^{3+}$	28 MeV	2 μA
1953	156-cm Cyclotron	Birmingham	$^{12}C^{2+,\,6+}$	120 MeV	
1955	180-cm Cyclotron	Saclay	$^{12}C^{2+,\,6+}$		
1956	120-cm Cyclotron	Leningrad	$^{14}N^{3+}$	16 MeV	0.5 μA

† Internal beam.

Subsequent to these early experiments two lines of development were followed to obtain larger beams of suitable energy and coherence. One of these was to design, or adapt, a larger cyclotron to run on a single charge state, as for example C^{4+}, in which this charge state is produced in the ion source. An example of this was the 1.5-m cyclotron at the Kurchatov Institute[8] where C, O, and N particles were accelerated using ions directly from a source, to about 8 MeV/u. The other was the adaptation of the Alvarez-type linac to accelerate heavy ions. The so-called Hilacs using this principle were built at Berkeley[9] and at Yale.[9] Linear accelerators of somewhat different designs were built at Manchester[10] and Kharkov.[11] Machines based on variations of these two approaches are responsible for most of the present-day nuclear research with heavy ions.

Dc machines can also be used to accelerate heavy ions. Early work was done at Saclay and at the Universities of Minnesota and Chicago, especially with lithium ions to study very light elements.[12] With the advent of tandem Van de Graaffs in 1958 it became possible to get ions, heavier than lithium, to energies of interest. The first heavy ion work using a tandem was done at the Chalk River Laboratory[13] in Canada. There are now eight Emperor tandems[14] in various parts of the world, which can give particles for example (with a terminal gas stripper) of about 3.5 MeV/u for $^{32}_{16}S$. This is substantially below the barrier for uranium but is still an interesting and useful energy for targets of light elements. During the last 10 years, a large new group of isochronous variable-energy cyclotrons[15] have been constructed. In principle any of these cyclotrons can be adjusted to the correct resonance conditions for partially stripped heavy ions. As will become evident later, the charge-to-mass ratio of the available ions determines the maximum mass of particle which can be accelerated to an energy above the Coulomb barrier in a cyclotron of given size.

3. PRESENT PERFORMANCE OF HEAVY ION ACCELERATORS

In the last fifteen years the powerful and dynamic region known as heavy ion nuclear physics has emerged; and yet more than perhaps any other field of physics, it is one which has been limited during its whole history by the performance of accelerators which support it. Tables II and III summarize the accelerators which constitute the bulk of today's heavy ion acceleration. The tables are arranged to show in the left-hand column the heaviest ion which each accelerator can produce with an energy sufficient to interact with the heaviest elements.

Note that all linear accelerators can accelerate approximately up to ^{40}Ar. Some typical performance on carbon and nitrogen ions is also indicated for each case. It should be noted that the average current is quoted in both eμA, for electrical microamperes, and pμA, for particle microamperes. It is evident that the quotation of currents in a heavy ion machine is unusually confusing as the charge state is often not given, but the beam current is of course larger in proportion to the extra charge states being present. The author has tried to advance the argument in other places that a new unit of current standing for pμA, or particle microamperes, should be given a name, perhaps the Lawrence, in honor of the late cyclotron's inventor. Note that 3 pμA can be obtained from

TABLE II
Heavy ion machines operating during and after 1958

	Heaviest ion reaching 6.0 MeV/u	Typical external beam			
		Particle	Energy MeV	Average current	
				eμA	pμA
Heavy ion linear accelerators					
Berkeley[9]	$^{40}_{18}$Ar	$^{12}C^{5+}$	120	15	3
Kharkov[11]	$^{40}_{18}$Ar	$^{12}C^{4+}$	120		
Manchester[10]	$^{40}_{18}$Ar	$^{14}N^{5+}$	140	0.3	0.06
Yale[9]	$^{40}_{18}$Ar	$^{12}C^{5+}$	120	1	0.2
Dc machines[14]					
25 EN tandems, 6 MV	$^{3}_{2}$He	$^{12}C^{4+}$	30	1	0.25
13 FN tandems, 7.5 MV	$^{3}_{2}$He	$^{12}C^{4+}$	37	1	0.25
8† MP tandems, 10 MV	$^{10}_{5}$B	$^{12}C^{4+}$	50	1	0.25

† 5 in USA, 1 in Canada, 2 in Germany.

TABLE III
Heavy ion machines operating during and after 1958

	Heaviest ion reaching 6.0 MeV/u	Typical external beam			
		Particle	Energy MeV	Average current	
				eμA	pμA
Classical fixed frequency cyclotrons					
Dubna, 310-cm[19]	$^{64}_{30}$Zn	$^{12}C^{4+}$	84†	80	20
Kurchatov, 150-cm[8]	$^{20}_{10}$Ne	$^{12}C^{4+}$	94	20	5
Tokyo, 160-cm[20]	$^{16}_{8}$O	$^{12}C^{4+}$	101	1.4	0.3
Isochronous cyclotrons					
Dubna, 200-cm[16]	$^{40}_{18}$Ar	$^{12}C^{4+}$	210	24	6
Harwell, VEC[17]	$^{20}_{10}$Ne	$^{14}N^{4+}$	98	30	7.5
		$^{12}C^{4+}$	118	5	1.25
Oak Ridge, ORIC[18]	$^{20}_{10}$Ne	$^{12}C^{4+}$	118	5	1.25
Orsay, 200-cm[21]	$^{84}_{36}$Kr‡	$^{14}N^{5+}$	125	1	0.2

† Not at full energy. ‡ Anticipated.

a linear accelerator, although currents are usually lower than this. Each of the particles in the case of linear accelerators are accelerated to about 10 MeV/u.

Next on the chart are listed the dc machines. This tabulation is not intended to be complete, but rather to show typical performance. It should be pointed out that the EN and FN tandems are limited to ^{3}He for nuclear reactions on uranium and the MP tandems to ^{10}B. Of course, much of the work done on the tandems consists of using heavy ions below the barrier for Coulomb excitation and other experimental programs where the full barrier energy is not required. A typical current for ^{12}C as is shown is 1/4 pμA.

Table III summarizes the situation with respect to cyclotrons. First are shown three classical fixed-frequency cyclotrons which do not have sector-type focusing. The Dubna 310-cm machine goes to ^{64}Zn and the others are as shown. The Dubna machine probably holds the record for current as may be noted, 20 pμA for ^{12}C. And finally are listed four isochronous cyclotrons which are presently involved at least part of the time in running heavy ions. The relative currents shown are intended to be typical and not a hard evaluation as to which machine produces the greatest current. It is clear that 1 to 10 pμA of extracted beam is fairly common. In the case of Orsay, more recent information is that the ion current is above 1 eμA.

4. ION SOURCES

The design of heavy ion accelerators depends crucially on the performance of an ion source. A review of the performance and design of available sources and the prospects for new sources is therefore pertinent. Sources fall naturally into two classes:

(1) Arc discharge sources of either the Penning[22] or Von Ardenne[23] design. Generally these are the types now used in operating machines.

(2) Sources using basically new or different systems with the goal of achieving substantially higher states of stripped ion species than can existing sources. The performance of these new sources is highly speculative at present.

Some of the principal investigators who have developed ion sources which have run or are running in various accelerators are listed in Table IV.

TABLE IV

Ion sources used in heavy ion accelerators

Laboratory	Date of earliest publication	Investigators
Oak Ridge	1954	Zucker and Jones[24]
Berkeley	1956	Ehlers, Anderson[25]
Kurchatov	1957	Morozov, Makov, Ioffe[26]
Dubna	1960	Pasyuk, *et al.*[27]
Saclay	1960	Papineau, *et al.*[28]
Orsay	1962	Basile, *et al.*[29]
Tokyo	1968	Kohno, *et al.*[20]
Harwell	1968	Bennett, *et al.*[17]

A set of data which intercompares the performance of various sources has been compiled by Bennett[30] and is presented here in slightly modified form on a set of two tables. The data are from published papers on bench tests of the various respective sources.

The sources listed in Tables V and VI represent a number of different designs, all but one, however, being versions of a Penning discharge. In each the discharge is initiated and maintained by a collimated beam of electrons oscillating between two opposing cathodes through a positively charged anode chamber in the presence of a magnetic field of several thousand gauss, oriented parallel to the axis of the device. The principal variations in the design are illustrated in the different versions. In some the cathodes are heated, either resistively or by electron bombardment. These sources will generally start at lower anode potential. In some the anti-cathode floats at a negative potential close to the applied potential. This feature gives some design freedom as the need for an electrical connection between ends of the source is eliminated. Sources labeled 'cold cathode' have, in general, different methods of cathode cooling so that cathode temperature during operation may in fact, due to ion bombardment, be rather high. In most sources the ions are extracted at right angles to the source and field axis. However, two cases are shown for axial extraction where the ions are brought out parallel to the magnetic field. In a number of the sources, operation is pulsed, with the anode potential being applied for usually a few milliseconds and repeated several times per second.

Table V shows the performance of twelve different sources operating to produce highly charged nitrogen beams. A perusal of this table reveals that some 5 to 10 per cent of the current can be brought to the four plus state or a Q/A for nitrogen of 0.285.

TABLE V

Nitrogen ions from Penning[22] Gaseous Discharge Sources

Source features	Authors	Arc conditions: Potential volts	Current amps	Pulse length msec	Percentage of nitrogen ion current in charge state: 1	2	3	4	5	6
Hot cathode, Floating anti-cathode	Jones and Zucker[24]	500	2.5	Continuous	42.6	41.3	12.9	3.4		
Hot cathode, Floating anti-cathode	Ehlers[31]	350	1.5	Continuous	36.0	45.0	17.0	2.0		
Cold cathode	Jones and Zucker[24]	600	5.1	Continuous	28.2	31.4	30.4	9.8		
Hot cathode	Makov[32]	580	4.6	Continuous	25.2	39.9	29.0	5.5	0.4	
Hot cathode	Papineau, Benezech and Maillard[28]	300	10.0	Continuous	40.0	46.6	12.3	1.0	0.05	
		350	40.0	15.0	22.2	41.8	31.4	4.6		
Hot cathode	Mavrogenes, Ramler and Turner[33]	300	10.0	Continuous	22.0	42.0	31.2	4.2	0.15	
Hot cathode	Basile and Lagrange[29]	520	5.0	Continuous	33.0	33.5	30.0	3.5	0.15	
Cold cathode	Bennett[34]	730	8.0	Continuous	15.8	37.0	37.0	9.6	0.6	0.006
Hot cathode	Pigarov and Morozov[35]	800	35.0	0.02	9.2	21.7	35.0	20.0	14.1	
Cold cathode	Anderson and Ehlers[36]	2000	1.3	2.0	47.8	42.4	8.5	1.2		
Cold cathode, End extraction	Bennett[37]	2000	2.0	2.0	63.0	32.0	5.0			
Cold cathode, End extraction	Mineev and Kovpik[38]	800	8.0	0.2	38.8	46.6	14.6			

TABLE VI

Performance of heavy ion sources on krypton and xenon

Source	Authors	Ion	Arc conditions: Potential (volts)	Current (amps)	Pulse length (msec)	Repetition rate (cps)	1	2	3	4	5	6	7	8	9	10	11	12
Duoplasmatron (Heidelberg, Unilac)	Ilgen[39]	Kr	175	18	3	10	5.5	28.5	45.7	17.0	3.3							
		Xe	295	31	3	10	6.6	20.2	29.0	19.4	14.2	7.5	3.4			0.66		
Penning (Berkeley, Hilac) Cold cathode	Ghiorso, Main, and Smith[40]	Kr	2000	1.5	2		8.3	14.9	16.5	19.2	16.2	13.9	5.8	2.5	2.0		0.17	
		Xe	2000	1.5	2		6.7	11.4	12.2	13.8	16.5	12.7	12.0	6.9	4.2	2.5	0.8	0.4
Penning Hot cathode	Pasyuk, Tretiakov, and Gorbatchev[11]	Kr	450	12.7	1	100	4.3	10.3	23.6	25.8	19.3	10.7	4.3	1.5	0.1	0.01		
		Xe	600	13	1	100	1.8	5.5	14.8	16.6	17.5	16.6	12.9	11.0	2.4	0.7	0.2	0.05
Penning Cold cathode		Kr	2000	1.5	1	100	25.6	23.0	16.9	14.1	9.5	6.4	2.6	1.2	0.7	0.2		
		Xe	2000	1.5	1	100	23.6	19.6	16.5	12.5	9.9	6.4	5.7	3.1	1.7	0.9	0.2	0.1
Penning (Harwell V.E.C.) Cold cathode	Bennett[34]	Kr	600	2.0	Continuous		9.0	26.1	32.7	17.0	9.1	5.0	0.78	0.26	0.03			
		Xe	660	2.5	Continuous		0.8	7.1	20.9	21.0	19.4	14.6	11.2	4.9				

In one source with very short pulse lengths, more than 10 per cent of the current was in the five plus state. Other workers have in general not achieved this level of performance.

Table VI shows the performance of five sources producing highly stripped ions of krypton and xenon. One may note that 2 to 5 per cent xenon 9 plus, $Q/A = 0.068$ and 1 to 2 per cent krypton 9 plus, $Q/A = 0.107$ can be achieved. Smaller amounts of xenon 12 plus, $Q/A = 0.090$, have also been observed in two of the sources. It is interesting in the light of these performance data to review the ionization potentials listed in Table VII.(42) We have seen cases above for appreciable percentages of the ion output being in states requiring between 200 and 300 V for removal of the last electron. If this line of reasoning is valid, one might have reasonable expectation of achieving at least uranium 13^+, $Q/A = 0.054$, in the range to one percent of total ion source current.

In summary arc discharge sources appear very satisfactory for light ions up to neon or perhaps argon. For heavier ions the achievable Q/A seems to decline with mass and will be no better than about $Q/A \sim 0.05$ in the region of uranium. Significant improvement in arc sources still can and no doubt will be made, but, in an effort to achieve important advances in high performance, a number of laboratories are investigating sources invoking radically different principles.

A comprehensive review of these investigations is beyond the scope of this paper, but four general areas of development may be listed.

1. Richard Levy and collaborators are developing a device(43) in which they inject electrons into a toroidal vacuum chamber with an azimuthally symmetric magnetic field in a manner such that a cloud of electrons is formed creating a potential well of $\sim$400 kV. Heavy ions will be trapped in this potential and are expected to reach rather high ionization states. Intensity estimates suggest that heavy ion currents could be of the order of 10^{13} ions/sec of Kr^{20+} or 10^{11} ions/sec of U^{60+}. There are problems in extraction of these ions and in achieving sufficiently high potentials and containment times but these matters must be pursued experimentally.

2. Sources using intense laser pulses are being studied at the laboratories in Dubna by members of Flerov's staff and in France by Tonor(44) and Rabeau. Ions of up to 6 or 7 plus have been obtained and it is hoped that this number can be raised considerably. However, because the repetition rate for such a source is difficult to make very large, it is unlikely that high intensity sources will result from these investigations.

3. At Oak Ridge the thermonuclear research group has studied a device known as ELMO.(45) This is an rf cavity located between two magnetic mirrors into which high power millimeter wavelength rf power is coupled and in which a high temperature plasma is produced by electron cyclotron heating. The electron density in the 5–10 keV energy range is of the order of $10^{12}/cm^3$. Useful currents of highly charged ions by single impact ionization are predicted. Measurements on the distribution of charge states of heavy ions from this device are planned in the near future.

TABLE VII
Ionization potentials (eV)

State	Element						
	C	Ne	Ar	Cu	Kr	Xe	U
I	11.3	21.5	15.8	7.7	14.0	12.1	4.8
II	24.4	41.1	27.6	20.3	24.6	21.1	12.8
III	47.9	63.4	40.9	36.8	36.9	32.1	19.6
IV	64.5	97.1	59.7	57.1	48.9	41.9	31.3
V	392.0	127.6	75.2	79.9	61.2	51.7	48.1
VI	490.0	158.0	91.2	103.0	74.2	61.6	64.9
VII		207.0	124.0	139.0	106.0	87.4	91.5
VIII		239.0	143.0	166.0	129.0	101.0	106.0
IX		1196.0	422.0	199.0	241.0	184.0	121.0
X		1362.0	479.0	232.0	280.0	210.0	136.0
XI			539.0	266.0	322.0	237.0	160.0
XII			618.0	368.0	365.0	265.0	177.0
XIII			686.0	401.0	414.0	295.0	212.0

4. Donets and collaborators at Dubna are studying a source identified as EBIS.[46,47] Donets has reported the observance of N^{6+}, O^{7+}, and Au^{19+}. He believes ultimately the source can reach 5 μA of U^{38+}. In this source a high intensity electron beam serves to provide for multistep ionization of heavy ions. The heavy ions are trapped by a radial potential depression induced by the electron beam space charge and in the axial direction by means of external potentials. The time of ion containment is limited to about 20 msec by neutralization of the electron beam space charge by residual gas ions. The electron energy in the initial tests was 7 keV, the electron beam density 8 amp/cm^2, and the pressure 10^{-9} torr. A new test model of this source providing increased primary electron current density and improved vacuum is now being assembled for test.

5. STRIPPING

An alternative method for obtaining ions in high charge states consists of passing the ions through solid or gaseous strippers. If suitable ion velocities are available, very high charge states can be produced, in general higher than with contemporary gas discharge ion sources. Two basic limitation of this technique are that only a fraction ($\sim$20 per cent for heavy elements) of the emergent ions will be in the desired charge state thus reducing achievable intensity, and in the case of solid strippers, intense beams tend to damage the foils leading again to intensity limitations. Gaseous strippers are, of course, not subject to damage but in general produce charge states for heavy elements which are considerably lower than those produced in solids at equivalent energies.

Many experimental and theoretical investigations of charge changing cross sections and equilibrium charge distributions have been made, although rather limited experimental work has been done at the heaviest end of the periodic table. To determine the most probable equilibrium charge states in regions of ion atomic number and energy not yet explored experimentally, it is necessary to rely on empirical formulas such as developed by

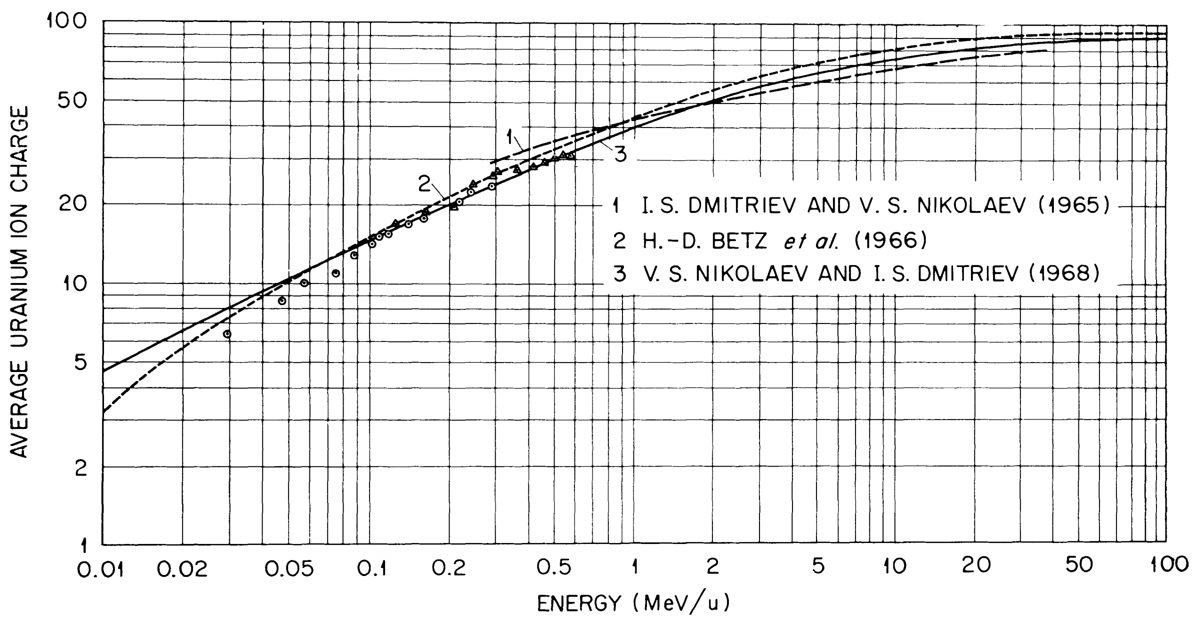


FIG. 1. Calculations by three formulas compared with measurements of the average charge of uranium ions passed through a solid stripper. *Curve 1*: I. S. Dmitriev and V. S. Nikolaev,[49] 1965. $\bar{q}/Z = [\log(v/Z^{\alpha_1}m)]/[\log(nZ^{\alpha_2})]$ for range $0.3 \leqslant \bar{q}/Z \leqslant 0.9$. v is in units of 10^8 cm/sec; $\alpha_1 = 0.1$; $\alpha_2 = 0.6$; $m = 1.2$; $n = 5.0$; Z = atomic number. α_1, α_2, m and n depend on stripper characteristics. *Curve 2*: H.-D. Betz *et al.*,[48] 1966. $\bar{q}/Z = 1 - C(0.71Z^{a})^{\beta/\alpha}$. $\beta = v/c$. α = fine structure constant. Z = atomic number. $a = 0.053$ for solid stripper; $C = 1.030$ for U in solid stripper (C depends slightly on Z and stripper). *Curve 3*: V. S. Nikolaev and I. S. Dmitriev,[50] 1968. $\bar{q}/Z = [1 + (v/Z^{\alpha}v')^{-1/k}]^{-k}$ for solid strippers and $Z \geqslant 20$. Z = atomic number, v = velocity, cm/sec. $v' = 3.6 \times 10^8$ cm/sec, $\alpha = 0.45$, $k = 0.6$. Constants do not depend on Z. *Experimental Points*: Open circles, ○, H.-D. Betz *et al.*[48] Triangles, △, Grodzins *et al.*[51]

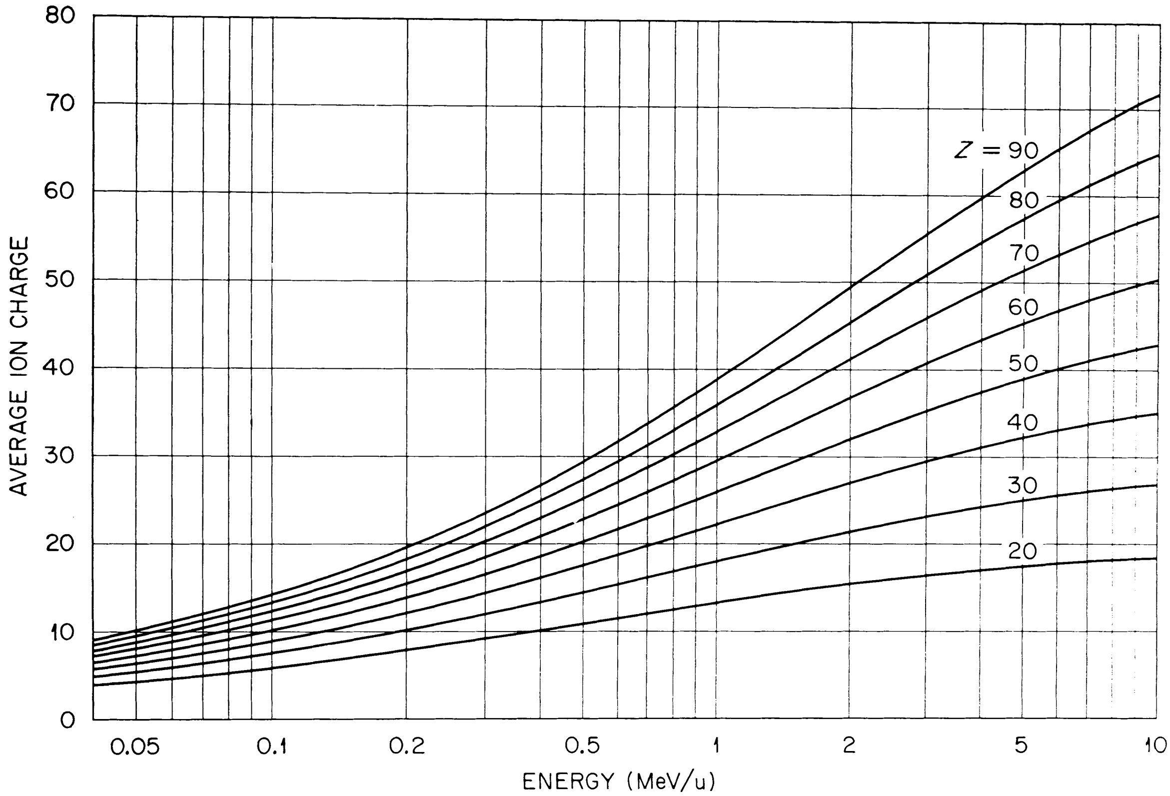


FIG. 2. The average charge of ions passed through a solid stripper according to the empirical formula of V. S. Nikolaev and I. S. Dmitriev,[50] 1968.

Betz *et al.*[48] or by Nikolaev and Dmitriev.[49,50] Because the designs of some accelerator systems depend rather crucially on the stripped states of uranium, we have found it interesting to plot the relations given in the three references, for atomic number 92 for a solid stripper. These are shown in Fig. 1 along with the experimental measurements of average charge states for uranium reported by Betz *et al.*[48] and by Grodzins *et al.*[51] To provide a convenient method for estimating stripped charge states, graphs of the most recent Nikolaev and Dmitriev relationship are displayed in Fig. 2 showing the average charge as a function of ion energy for a range of atomic numbers. A thorough treatment of this complex subject is beyond the scope of this review. For more complete information, the reader is referred to the recent literature on stripping.

6. CYCLOTRONS

The development of the isochronous cyclotron with controllable focusing and adjustable particle parameters has made it an attractive means of accelerating heavy ions. As the motivation increases to obtain energetic ions of heavier and heavier atoms, the principal requirement is for an increase in the size of the cyclotron. This, of course, becomes uneconomic beyond some definite but perhaps not well defined magnitude. Consider the relationship $T = kQ^2/A$, where T gives the particle energy, Q is the ion charge state, and A the atomic mass of the projectile. This relation is a convenient way of characterizing the size of a cyclotron and is a reasonable approximation for heavy ions below 10 MeV/nucleon, although it is not precise for protons or other light particles in the relativistic region. It has recently become the custom to characterize the size of cyclotrons using the number k as for example in Table VIII. As is evident present day cyclotrons vary between k of 70 and k of 250. In Fig. 3 is shown a plot of k of this relation plotted against $B\rho$ in kilogauss centimeters. In the range of interest for heavy ion cyclotrons, for reference, note that 5×10^3 kG cm will bend protons of 830 MeV energy and 9290

TABLE VIII

Some heavy-ion cyclotron energy ratings using k in the relation ($T = kQ^2/A$)

Cyclotron	k
Orsay, ALICE	70
Dubna, 200-cm	156
Dubna, 310-cm	250
Harwell	84
Indiana University	240
Oak Ridge	80

kG cm, protons of 2.0 GeV energy. Thus it is apparent that very large magnets are required to correspond to a k of 4000. Figure 4 is intended to demonstrate the requirements for accelerating ions in various charge states. At the bottom of the graph are indicated the charge states for typical ions from different regions of the periodic table. Note that 0.05 Q/A could be Cr^{3+}, Hg^{10+}, or Pu^{12+}. Any of these ions presumably can be made with present day technology in arc-type gaseous discharge ion sources. For a cyclotron without an injector or without stripping, for these heaviest ions and lowest charge states, one then needs a k in the vicinity of 2500 to 4000 depending on whether the goal is 6 MeV or 10 MeV/u. As Q/A of the ion approaches 0.1, the k required for the cyclotron comes down in the range 500 to 1000 and at 0.15 it becomes even more modest. The dotted lines on the graph refer to the scale on the right hand side with k's from 0 to 400. As is well known, with light ions, Q/A in the range 0.25 to 0.35 can be readily obtained. This accounts for why existing cyclotrons which generally have k's below 100 are very useful in this region. The new cyclotrons, being planned and proposed, generally are providing k's of 300 or above, and as is apparent, this calls for a charge-to-mass ratio of at least 0.15. At present such charge states have to be obtained by stripping in a solid foil from a tandem Van de Graaff or some other suitable accelerator. The studies of selection, matching, and optimizing injector systems and cyclotrons constitute a game which has been going on at a rather frenzied pace in the United States for more than a year.

The two graphs, Figs. 5 and 6, are intended to show roughly what the weights of magnets would be for different regions of the preceding figure. The f number shown on these graphs is simply the fraction of the magnet circle which is occupied by a magnetic field. It is shown for four cases: f equal to 0.3, 0.5, 0.7, and 1.0. The 1.0 case may be regarded as 'for reference only' because a magnet designed like this would have impractical access. A magnet which would be practical would be the line shown as 'conventional', which is for an H-shaped yoke. The magnet weights were calculated[52] by a simple computer program in which the gap was assumed to be 3 in, the field under the

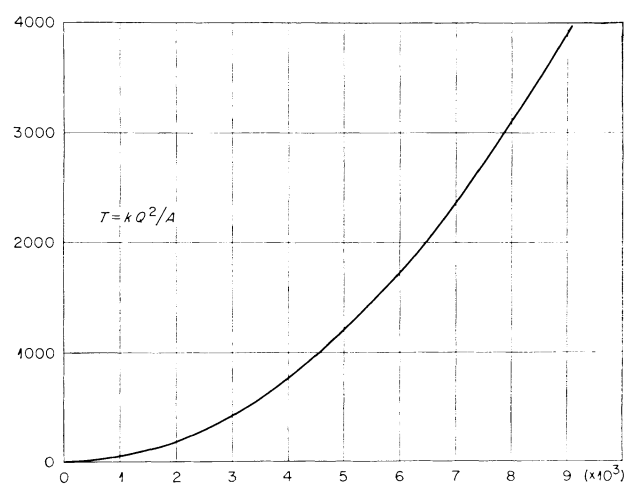


FIG. 3. The size of a cyclotron may be expressed conveniently by a number k from the formula $T = kQ^2/A$, where T is the kinetic energy of the particle, Q is the charge state, and A is the atomic mass number. The relation between this constant, k, and the magnetic-field-radius product is plotted.

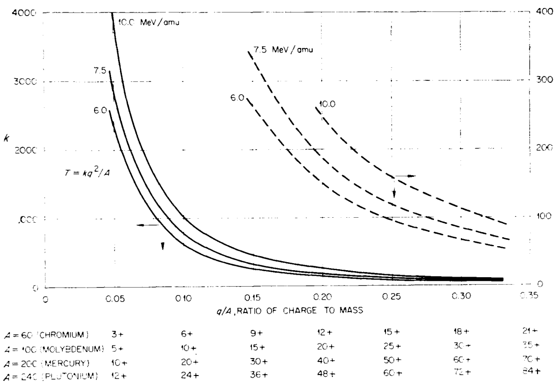


FIG. 4. The size of cyclotron necessary to produce heavy ions of various desired energies. The scale at the bottom gives examples of ions of various masses with different hypothetical charge states to illustrate the different regions of possible design and operation. The dotted lines are for an expanded scale for smaller cyclotrons using very high (Q/A)'s.

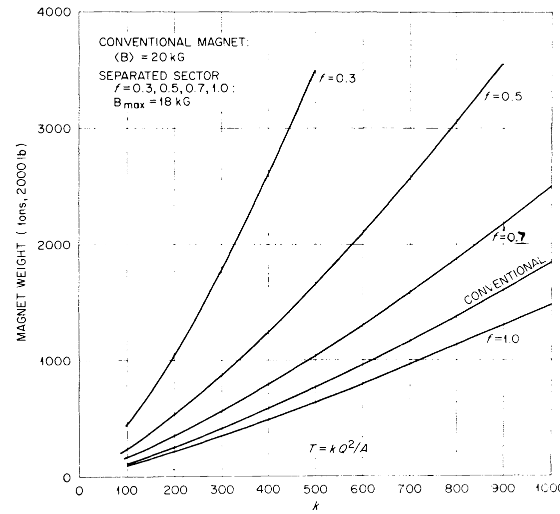


FIG. 6. This is an extension of Fig. 3, in which the lower portions of the scales have been expanded. These magnets would be applicable for cyclotrons using highly stripped ions.

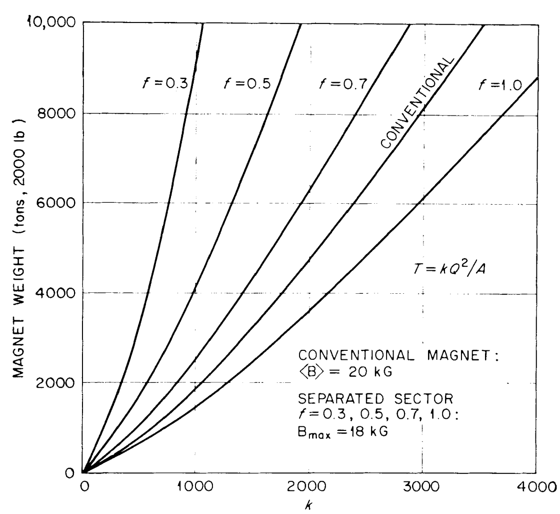


FIG. 5. Magnet weights have been calculated for various size cyclotrons. The f values refer to the fraction of the magnet circumference which is occupied by pole pieces and magnetic field. The lower f values are required to produce necessary focusing for protons and other relativistic particles. The $f = 1.0$ is for reference only as a lower limit. Lack of access would prevent such a magnet from being practical.

poles 18 kG, the return path area equal to the pole area, and suitable allowance of space for coils provided. It is apparent that about 8000 tons of steel would be required for a magnet reaching 7.5 MeV/nucleon with an ion source charge-to-mass ratio of 0.05.

Figure 6 is intended to survey the region of interest for cyclotrons with injectors. An injector might be another cyclotron or a dc accelerator or a tandem. It is clear that the size of a magnet for a cyclotron to cover acceleration of particles of interest to energies well above the barrier will be much smaller if with a special injector and a stripping foil between the injector it is possible to work at higher Q/A. If one desires light particle capability as well as heavy ion capability in the cyclotron, the region $f = 0.3$ to $f = 0.5$ is of greatest interest.

The maximum proton energy of any isochronous cyclotron is limited by the resonance $\nu_r = 2$. Thus the maximum energy of about 850 MeV represents a real limit for protons in an isochronous cyclotron. This corresponds to $B\rho$ of 5.1×10^3 kG-cm, or $k = 1240$. Thus it is evident that magnets in the 1000 to 3000 or 4000 ton class are receiving a great deal of attention for today's cyclotron proposals.

7. LINEAR ACCELERATORS

The heavy ion linac or Hilac has for many years been an enormously productive machine at several laboratories. It has served as the vehicle for many important discoveries in the heavy ion field. However, as interest grows in accelerating ions in the high mass portion of the periodic table, present day Hilacs are no longer adequate. Three proposals for new or improved linear accelerators are now in various stages of consideration or development. Each of these is designed to reach the uranium region; that is bombarding uranium with uranium with sufficient energy to cause nuclear reactions. Scientists at Lawrence Radiation Laboratory are proposing[53] to rebuild their linear accelerator as shown in Fig. 7. This sketch shows how the superHILAC will be fitted into the present HILAC building. There will be an enlarged pre-stripper section designed to operate for a range of e/m's (0.042 to 0.15), the latter for use without a stripper in the case of light ions. The present experimental area will be moved to make room for a 100-ft post-stripper. New experimental areas will be provided in place of existing shop areas. The design parameters for the superHILAC are shown in Table IX.[54] Note that variable energy in roughly 1 MeV/nucleon steps can be obtained

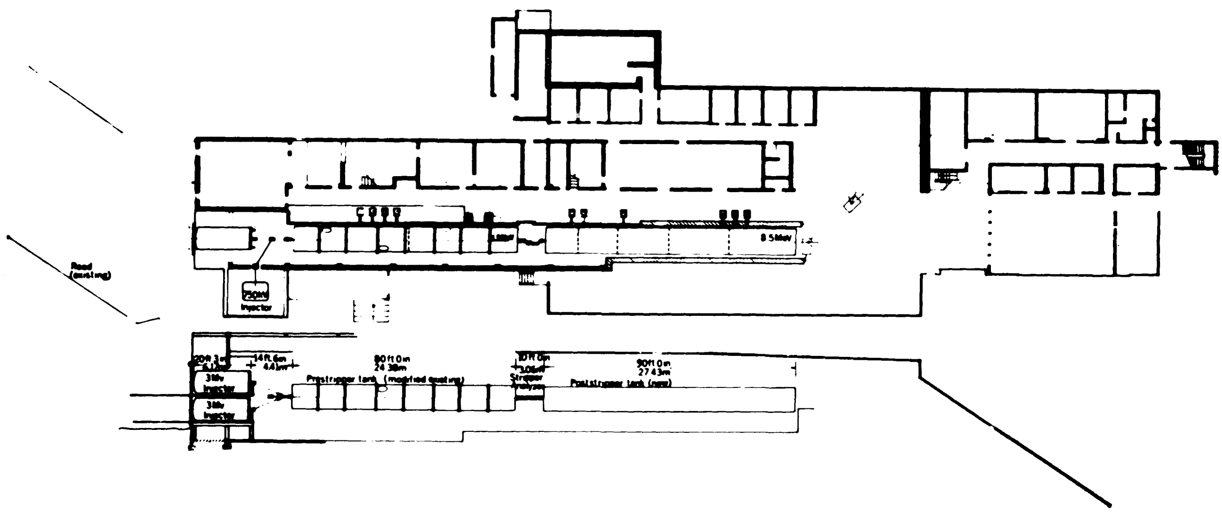


FIG. 7. A sketch of the superHILAC as it is planned to be fitted into the existing HILAC building at the LRL. New pre-stripper and post-stripper tanks will be constructed extending into the present experimental area. New areas for research will be placed in the present shop area.

TABLE IX

SuperHILAC Alvarez cavities. Preliminary design parameters

	Pre-stripper			Post-stripper (not to scale)						
T energy (MeV/u)	0.1125	0.58	1.2	1.2	2.61	3.47	4.66	6.36	7.56	8.60
β velocity	0.0155	0.0353	0.0505	0.0505	0.0744	0.0858	0.0993	0.1159	0.1262	0.1345
n cell number	0	84	141	0	26	37	50	66	76	84
L_n $\beta\lambda$ cell length (m)	0.062	0.141	0.202	0.202	0.295	0.341	0.395	0.461	0.502	0.535
E max. av. grad. (MV/m)	1.5(tilt)	2.0(flat)	2.0	1.6(tilt)	2.0(flat)	2.0	2.0	2.0	2.0	2.0
ϕ syn. phase (deg.)	−20·0	−20·0		−10·0	−10·0	−10·0	−10·0	−10·0	−10·0	
Tank length (m)	8.30	9.78	18.08	6.44	3.52	4.81	6.88	4.84	4.17	30.66
Tank length (ft)	27.23	32.09	59.32	21.13	11.55	15.78	22.57	15.88	13.68	100.59
ϵ (e/m)	0.042 (Heavy nuclei) Stripping 0.15–0.17 (Heavy nuclei)									
	0.15 (Light nuclei) No Stripping 0.15 (Light nuclei)									
Frequency 73 MHz										

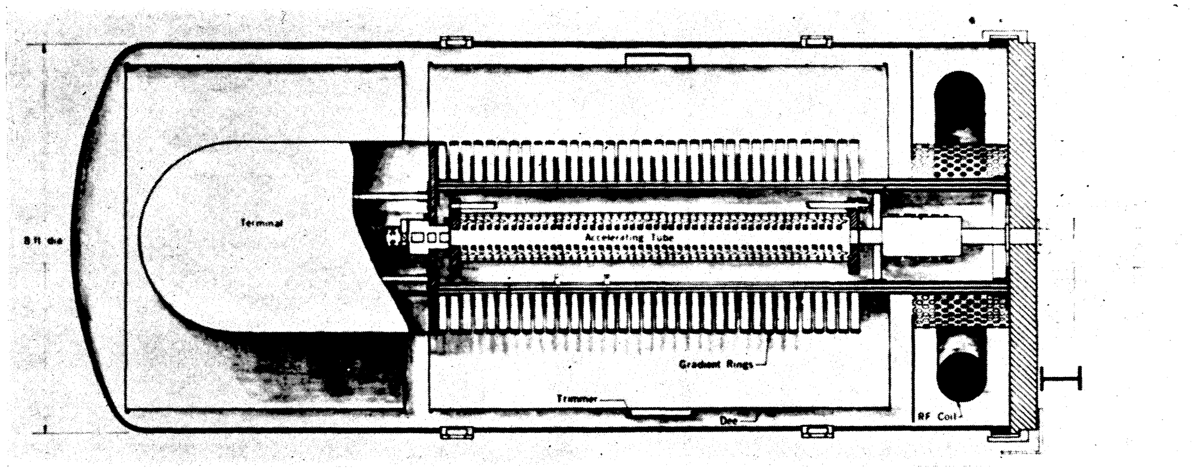
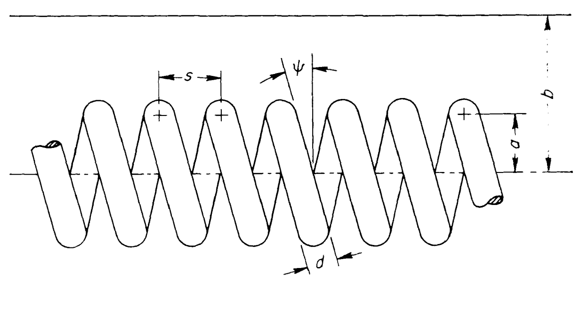


FIG. 8. A section of the dc injector for the superHILAC. Not shown on this sketch is a planned 'pressure lock' to enable fast source changes in the terminal without disturbing the pressurized system.

by shutting off various post-stripper sections. Additional variation can be obtained by varying the gradient tilt. The 2.8 MV injector is shown in Fig. 8. A pressure lock is being designed to facilitate rapid source changes.

A second linac which is being studied intensively and which has been proposed for various applications in the heavy ion field is the HELAC[55, 56] being studied at the University of Frankfurt. The scheme for this accelerator is illustrated in Fig. 9. This may be described as a spiral-loaded-waveguide in which standing waves are set up and in which a sinusoidal electric field on the axis moves with a phase velocity determined primarily by the relationship $v = c(s/2\pi a)$ where c is the velocity of light,



$$v = c\,\frac{s}{2\pi a}$$

FIG. 9. A sketch of the spiral conductor which is the key to the HELAC concept.

TABLE X
HELAC parameters

	Injector		Helix		Stripper	Helix			
	Wideröe or dc		27.12 MHz		Gas	108.48 MHz		108.48 MHz	
Energy (MeV/u)		0.13		1.4			4.5		7.0
Q/A (min)			11/238, 0.046			25/238, 0.105		25/238	
Stage voltage (MV)	2.8		27.5			29.5		23.8	
Length (m)			45			35		21.3	
Number of sections			30			28		17	
Power (MW) pulse			1.3			1.3		1.7	
Voltage gradient (MV/m)			1.06			1.22		1.63	

a is the radius, and s the pitch of the helix; by suitable design it is clear that an appropriate velocity for heavy ions can in principle be obtained. A number of electron and proton models have been built at Frankfurt and their performance measured experimentally. On the basis of this initial success a heavy ion accelerator has been proposed with the characteristics shown on Table X. The first injector needs to be either a short Wideröe linac or possibly a 3 MV dc machine. A HELAC structure 45 m long operating with a Q/A as low as 0.046 would precede a gas stripper followed by two sections of 108 MHz HELACS. The total number of HELAC sections each a meter long would be 75. The total pulsed power is about 4.3 MW. The duty factor would be about 25%. The two figures, Fig. 10 and Fig. 11, are photographs of a typical structure. In these photographs may be seen the aluminum oxide support insulators which are located at the nodes of the standing waves. The view of the structure mounted inside its outer container is shown on Fig. 11.

A third linear accelerator aimed at heavy ion acceleration is the UNILAC.[57, 58] This is being studied in Heidelberg by Professor Schmelzer and his group, and is in a rather advanced state of development. It may be noted in the tables on this accelerator that there are a number of similarities to the HELAC just discussed. This is more than a coincidence as the developers of the HELAC have endeavored to make their designs compatible with the UNILAC parameters so that any piece of the HELAC might be substituted for the appropriate portion of the UNILAC. However, at the present time, it appears that each project will proceed somewhat independently. Note, as shown on Table XI, that the UNILAC consists of a Wideröe accelerator up to 1.4 MeV/u, a series of Alvarez tanks up to 4.3 MeV/u, and then a series of single cavities which can be independently phased to

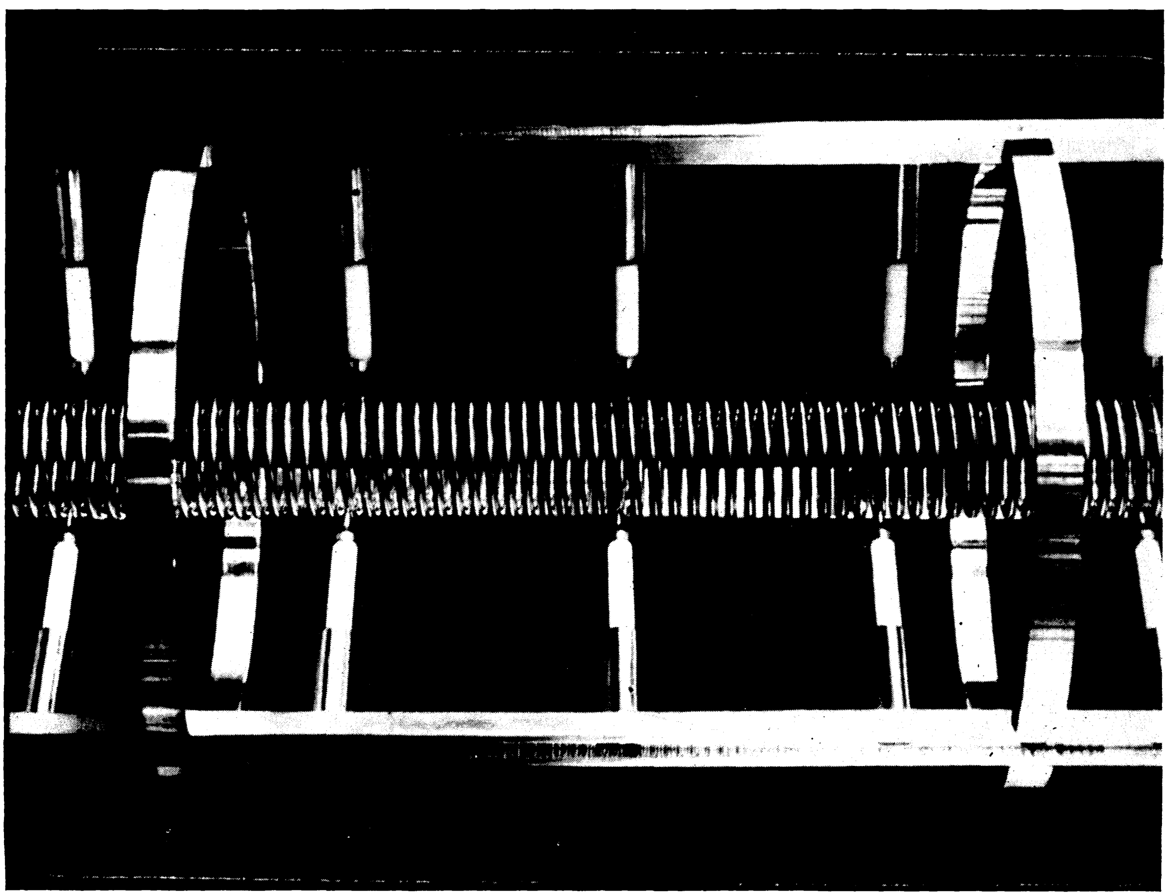


FIG. 10. A photograph of the assembled HELAC structure.

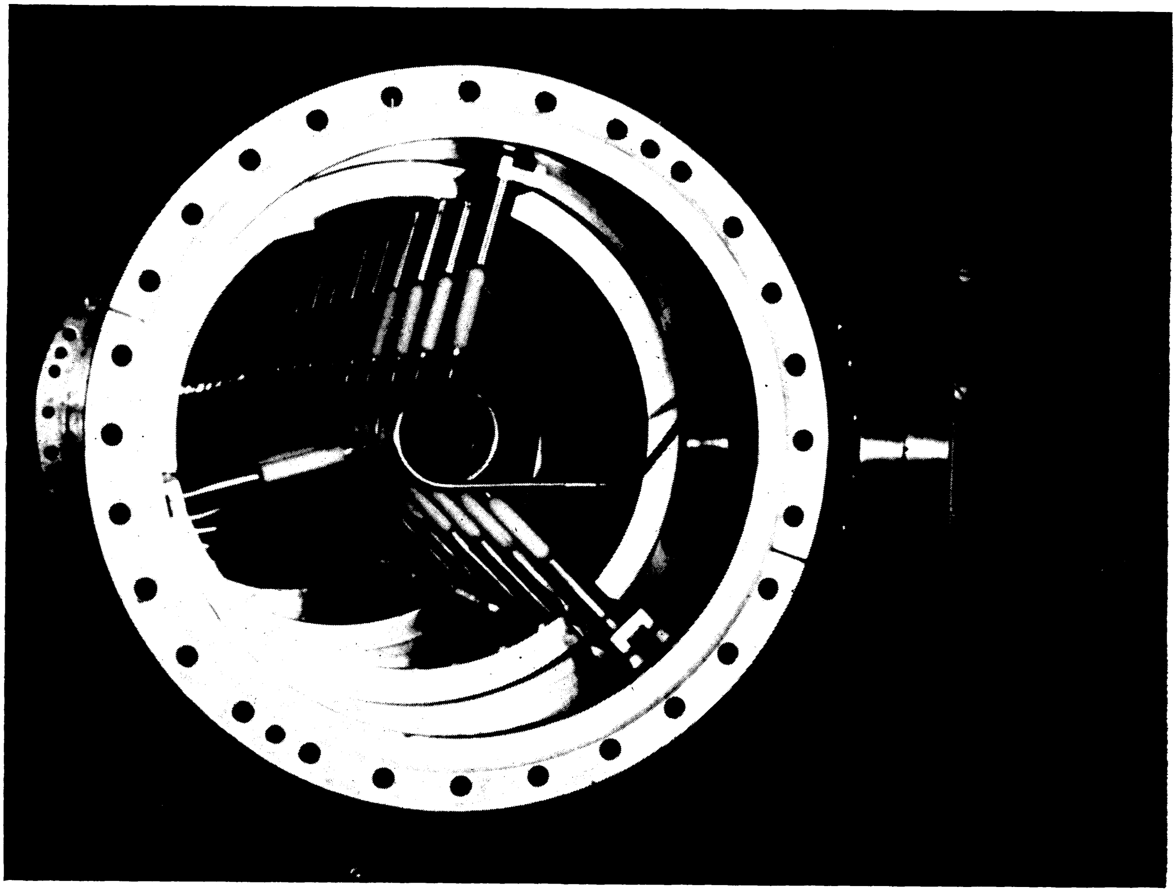


FIG. 11. A photograph showing the HELAC structure placed in its outer cylindrical casing.

TABLE XI
UNILAC parameters

	Source	Buncher	Wideröe	Stripper	Alvarez		Single cavities		Debuncher
Length (m)		1	27	8	20		20		10
Energy (MeV/u)		0.012		1.4		4.5		7.0	
β, v/c		0.005		0.0546		0.098		0.123	
Q/A (min)			11/238		25/238				
Stage voltage (MV)	0.253		30.05		29.57		23.75		
f (MHz)			27.12		108.48		108.48		
Power (MW) pulse			1		2		3.3		
Mean accel. field (MV/m)			1.23		1.75		1.32		

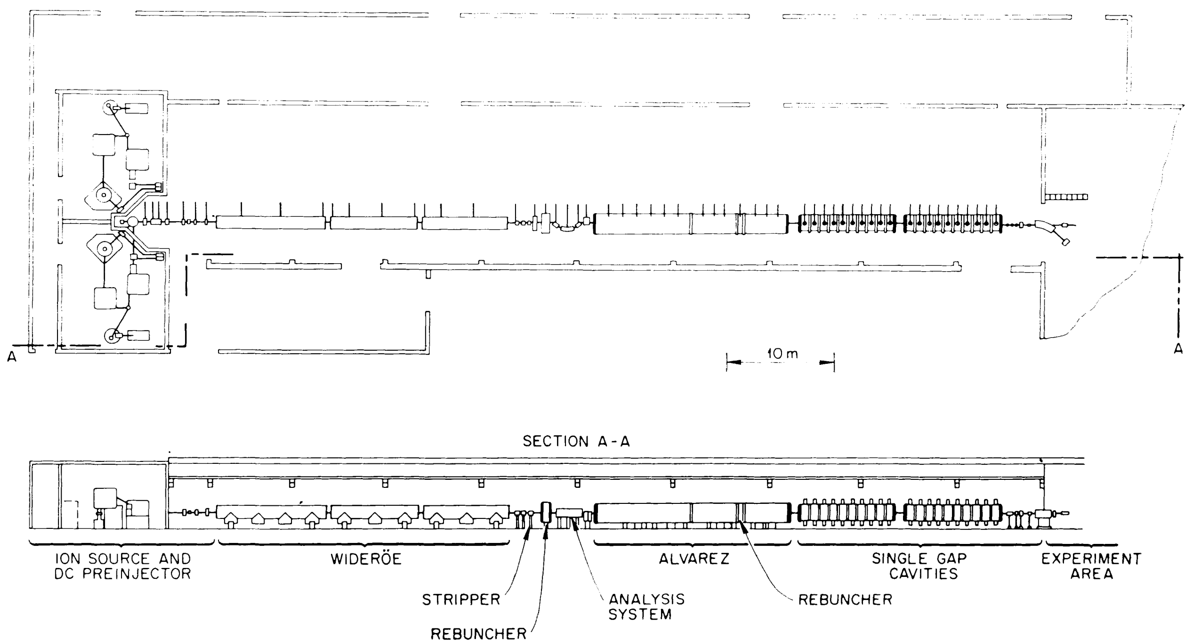


FIG. 12. A sketch of the system proposed for the UNILAC. It consists of four basic elements: injector, Wideröe linac, Alvarez linac, and a series of single gap separately phased cavities.

provide energy variation up to 7 MeV/u. The frequency of this linac, it may be noted, is, not by coincidence, identical with the HELAC; it is rather the source of the HELAC frequency selection. The peak power here is about 6.3 MW. A sketch of this machine is shown in Fig. 12 where one can readily identify the various components. This figure is approximately to scale. The plan as of late 1969 is that this machine will be built and installed at a new German federal laboratory to be established at Darmstadt, midway between Heidelberg and Frankfurt.

8. DC ACCELERATORS

Dc accelerators have historically played an important role in the acceleration of a wide variety of particles. Because of the characteristics of stripping cross sections, it turns out that dc accelerators become especially attractive to serve as heavy ion injectors if the terminal voltage can be in the region of 15 to 20 MV. The development in the United States of the new 16 to 20 MV TU tandems and the 30 MV unit under study in England make this a promising possibility. An interesting version of this approach is embodied in the HILAB proposal,[59] a plan to combine a new TU tandem with an existing Emperor tandem. A sketch of the proposed arrangement is shown in Fig. 13. The scheme here is to use negative ions stripped at the center of the TU with a gas stripper and then stripped again at a single foil stripper at ground potential. The beam subsequently can be sent to the terminal of the MP with an additional 10 MV multiplied by the charge state. It is alternately possible to do experiments using a 90° analyzing magnet and the switching magnet shown with the tandem. The TU's nominal rated terminal voltage is 16 MV but preliminary tests by the High Voltage Engineering Corporation recently show[60] that it may be able to go to 20 MV or even higher. A feature of such machines as this is the gigantic container pressure vessel which is pictured under construction recently in Burlington, Massachusetts, Fig. 14. Figure 15 gives the approximate performance which might be expected under various assumptions from this accelerator. The barrier for uranium for various Z's is identified in the appropriate line and the tandem accelerating various Z projectiles with 16 MV on the terminal and 20 MV on the terminal are shown. Uranium can be bombarded only up to approximately Z of 40 or so in this scheme. However, it is possible by adding extra foils which were indicated on Fig. 13 that one

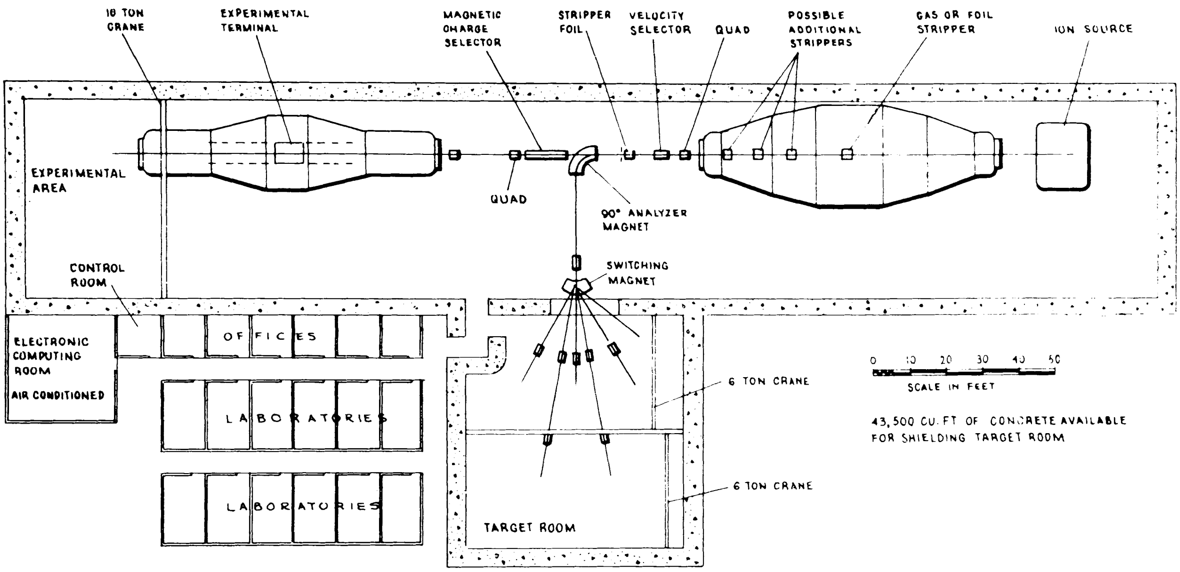


FIG. 13. The proposed arrangement for the HILAB showing the TU tandem feeding heavy ions to the experimental terminal in the MP tandem. Alternative stripper locations are indicated.

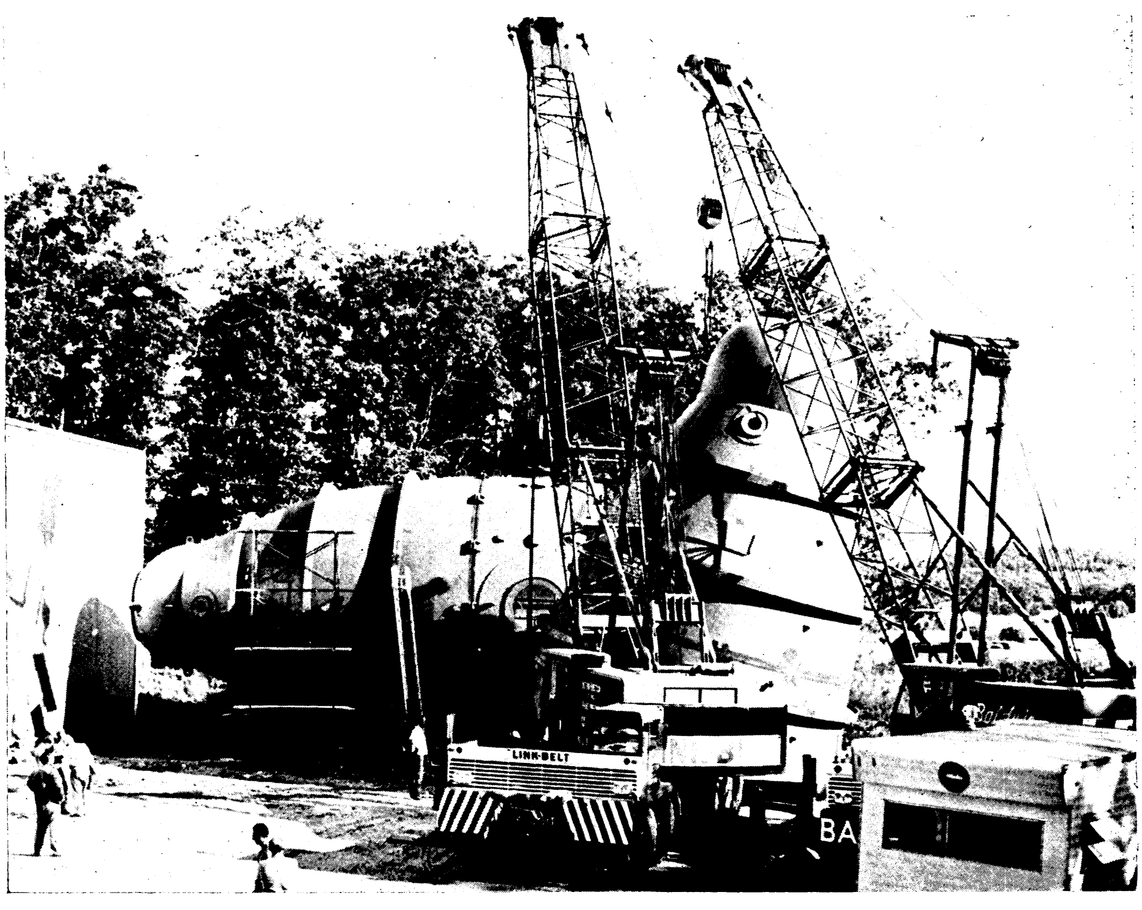


FIG. 14. A photograph of the installation of the giant pressure vessel for the TU tandem during installation at Burlington, Massachusetts.

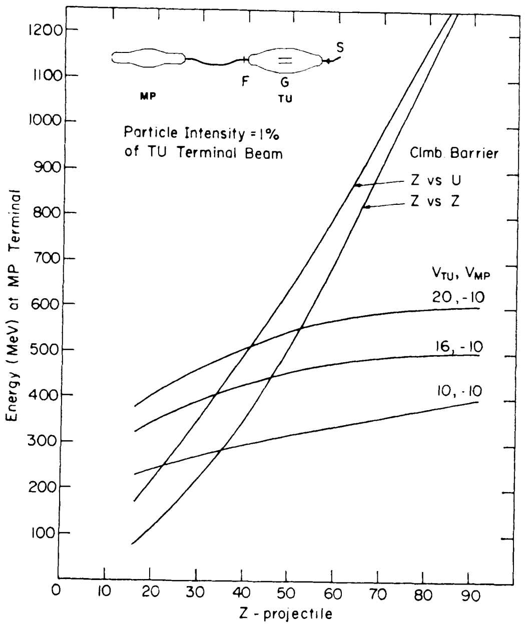


FIG. 15. The energies of heavy ions in the HILAB arrangement are shown for different possible operating potentials. For a 20 MV terminal potential, $Z=40$ heavy-ions can penetrate the Coulomb barrier for uranium.

could go somewhat higher. While this is thought to be a very useful interim facility or even permanent facility in the intermediate energy range, it is not thought to be an answer for a universal accelerator where any projectile can be accelerated against the heaviest elements.

9. HYBRID TANDEM-CYCLOTRON ACCELERATORS

Many laboratories and universities have reviewed the possible schemes for achieving a complete spectrum of high energy heavy ions. A substantial number of groups have concluded that a combination dc tandem coupled to an isochronous cyclotron will give the highest and most versatile performance. Table XII gives the characteristics of some of the principal proposals in the United States. The differences in these proposals reflect varying research interests, specialized accelerator experience, and results of optimization studies. In Fig. 16 is shown the relationship between cyclotron size and terminal voltage of injector. The cyclotron size corresponds to an energy for heavy ions of 7.5 MeV/u.

The comparative total costs using high and low injection energies have been studied by various groups. Studies at ANL[16] have shown that the total costs are nearly constant over the injection energy range of 10–15 MV. The choice of injector voltage thus depends substantially on other factors.

The general arrangement of a hybrid tandem cyclotron is illustrated in Fig. 17. This shows the Argonne National Laboratory proposed beam experiment arrangement. A schematic of a cyclotron is shown in Fig. 18. This is the four-sector cyclotron plan[62] as proposed by the Oak Ridge National Laboratory.

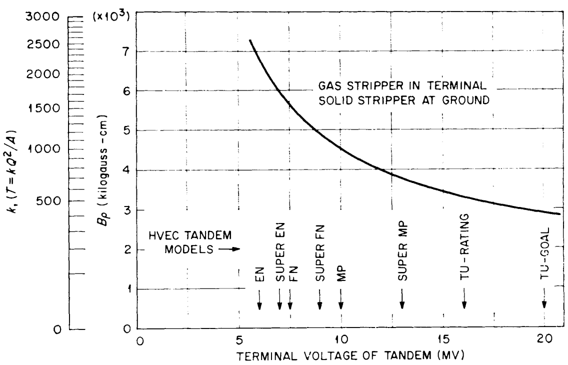
TABLE XII

Characteristics of some proposed hybrid heavy ion accelerators

	Argonne National Laboratory	Rochester, Brookhaven, Los Alamos and Indiana University	Maryland University	Michigan State University	Oak Ridge National Laboratory
Cyclotron					
Number of sectors	6	4	4†	6	4
Sector angle, degrees	20°	36°		~24°	45°
Spiral	none	none		weak	none
k, $T=kQ^2/A$	420	240	185	720	330
Injector	16 MV tandem	various tandems	cyclotron + 9 MV tandem	9 MV tandem or cyclotron	16 MV tandem
Heavy ion source	negative	negative	negative	negative, tandem positive, cyclotron	negative and positive
Uranium ion energy (MeV)	10	~6	~10	~9	7.5
Proton energy (MeV)	350	200	140	600	300

† Not separated sector

FIG. 16. The $B\rho$ and energy constant of a cyclotron to accelerate uranium ions to 7.5 MeV/u, as required for varying terminal potentials of a tandem Van de Graaff injector.



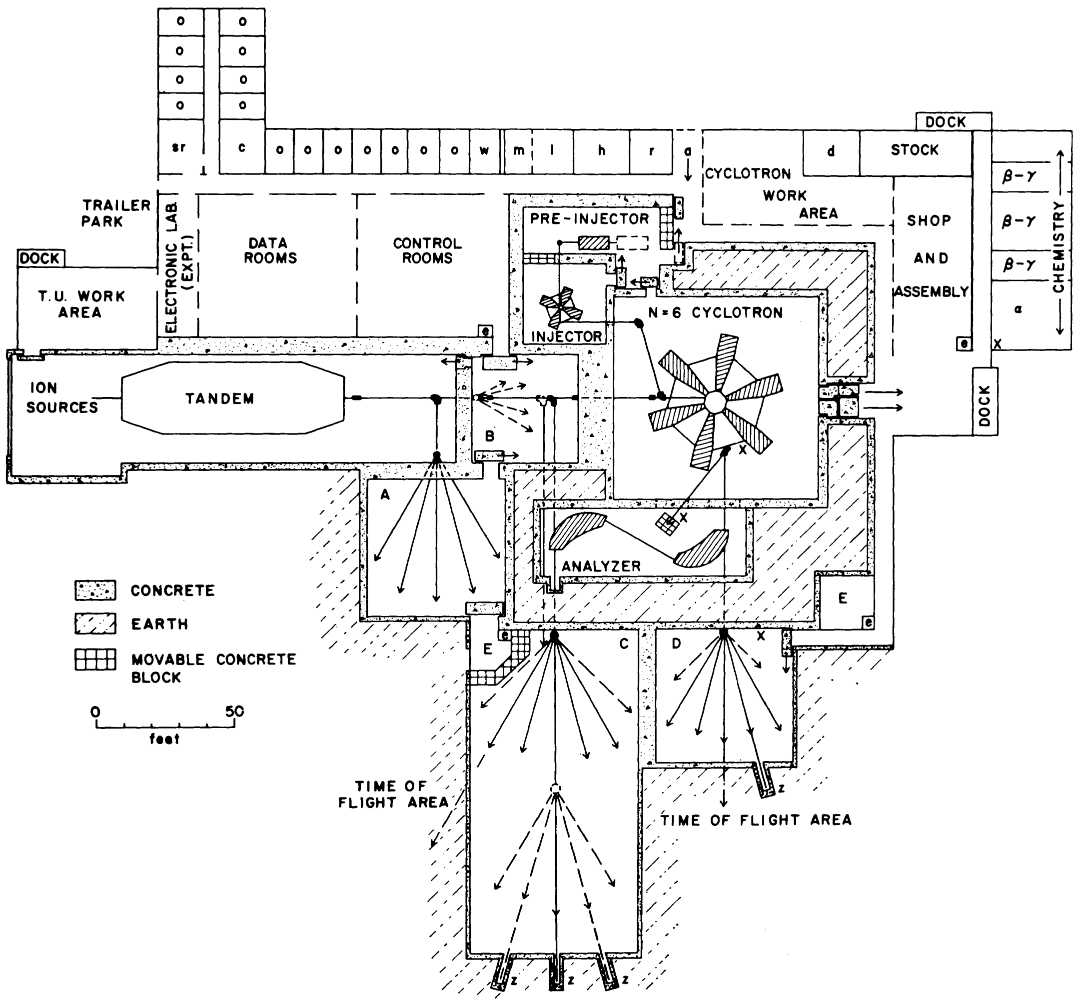


FIG. 17. Plan view of building and general arrangement of TU tandem injecting into a six-sector cyclotron. Auxiliary injector for light particles permits independent operation of the tandem when desired. Possible beam analyzing system and shielded experiment rooms are indicated. From ANL Midwest Tandem Cyclotron Proposal.

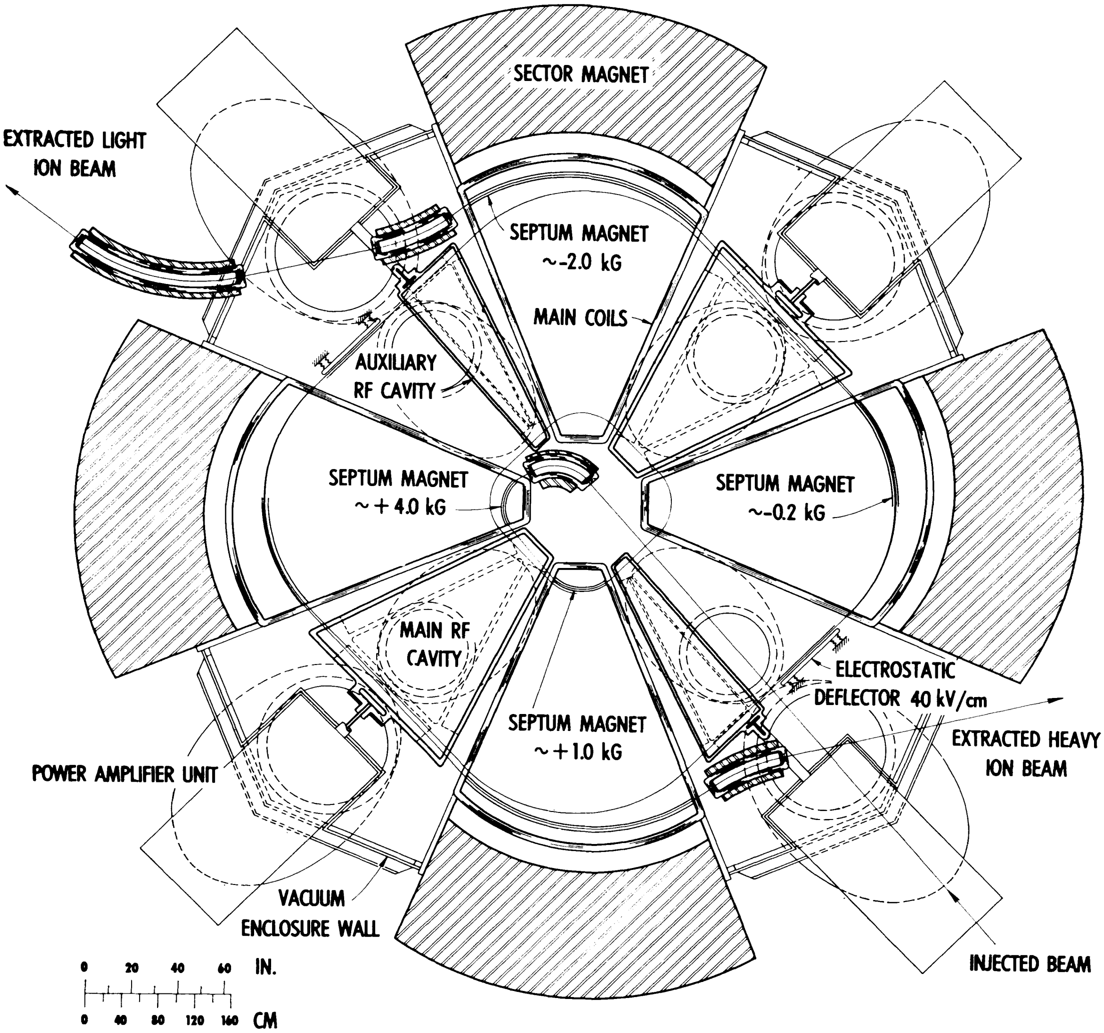


FIG. 18. Plan view of the separated sector heavy ion cyclotron. An external injection system and two separate beam extraction systems are indicated. From ORNL APACHE Proposal.

10. ELECTRON RING ACCELERATOR

The electron ring accelerator belongs to a relatively new class of accelerators which has come under investigation during the last few years. In the Soviet Union it has been designated 'the Collective Method of Ion Acceleration' and is being studied by Sarantsev[63] and collaborators at Dubna. In the USA it is usually called the 'Electron Ring Accelerator' and is under study at the Lawrence Radiation Laboratory.[64] A sketch is shown of the principal features of the electron ring device, Fig. 19. In this machine an intense beam of electrons is injected into the ring in a weak magnetic field. Following this the magnetic field intensity is increased, the ring compresses, and its kinetic energy increases. Finally, the magnetic field is caused to be asymmetric allowing the electron ring to drift out into a weaker field region. This causes the electron ring to expand and to accelerate converting some azimuthal energy into longitudinal energy. Alternatively, or subsequently, the electron ring can be accelerated longitudinally with a series of electric fields suitably phased. Some preliminary operating data on the electron rings which have been run during 1969 are shown on the next two figures. In Fig. 20 are shown some of the operational sequences of the electron ring accelerator. As the field rises to 17 kG, the energy of the ring increases to 18 MeV and the major radius of the ring decreases to 3.5 cm. The time scale is 500 μsec. In Fig. 21 are shown photographs of some diagnostic observations. The dimensions of the compressed ring can be seen from the synchrotron light, 1.6 mm axially and 2.3 mm radially. The lifetime of the ring was about 7 milliseconds in these observations, as seen from the radiation. This limit is believed due to crossing the $n \simeq 1$ region as the magnetic field starts to decay.

At Yerevan in early September 1969, Sarantsev[65] reported that his group at Dubna has succeeded in accelerating Nitrogen^{3+} to 4 MeV/u. He stated that an intensity of 10^8 atoms per pulse has been obtained. The proof of this result was through the nuclear reaction

$$\mathrm{N} + \mathrm{Ce} \rightarrow \mathrm{Tb} \searrow \alpha$$

Important questions which remain for the electron ring accelerators are the intensity which can be

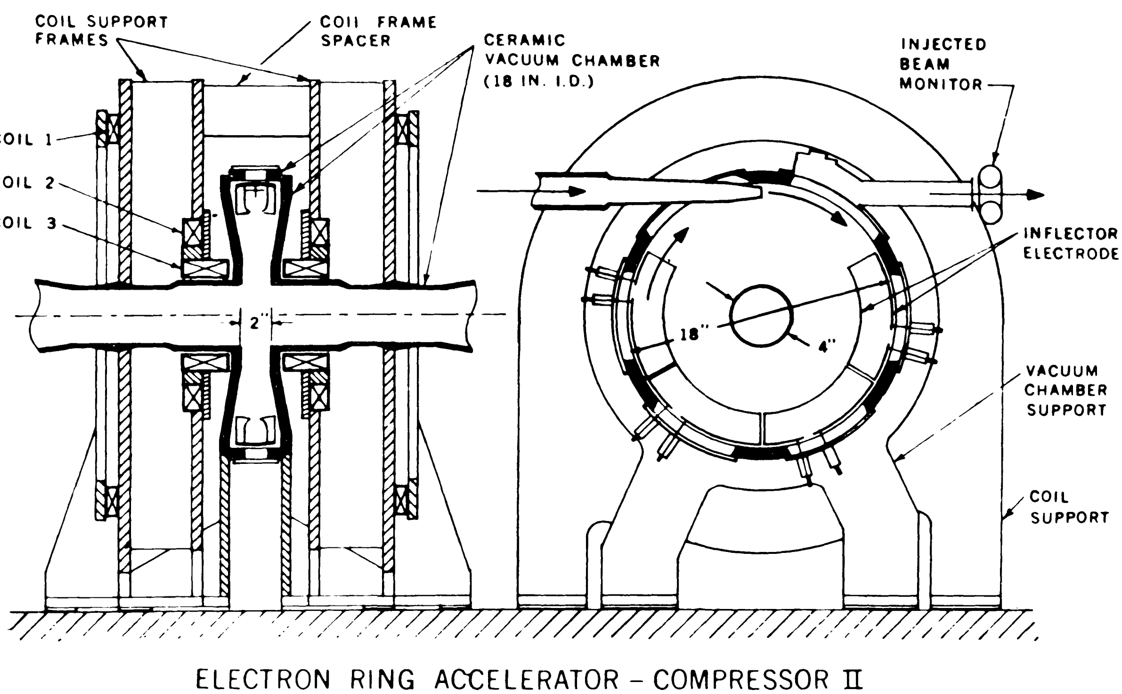


FIG. 19. A sketch of an electron ring apparatus studied at Lawrence Radiation Laboratory. After injection of an intense beam of electrons in a weak magnetic field, additional coils are activated and the energy of the trapped electron ring increases.

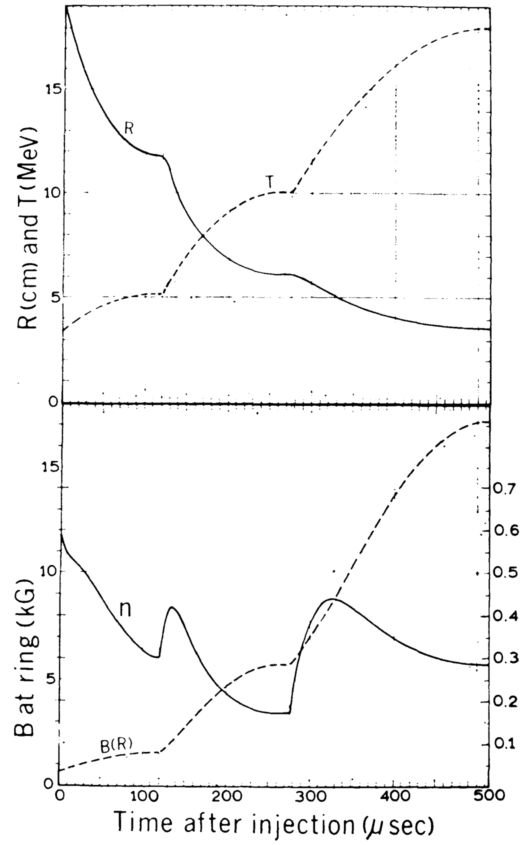


FIG. 20. The sequence of operations in the electron ring accelerator are analyzed. Over a 500 μsec period, the field is raised to about 17 kG, the radius of the ring decreases to 3.5 cm and the electron kinetic energy increases to 18 MeV.

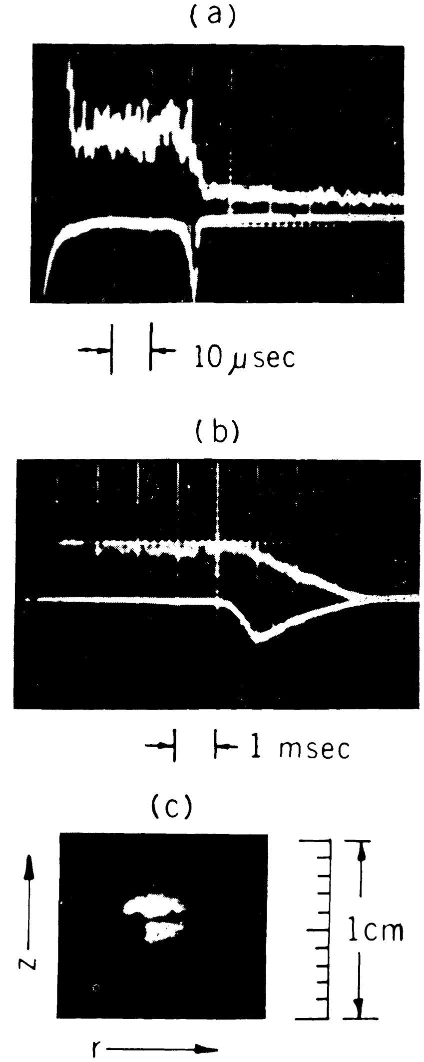


FIG. 21. Diagnostic information on the ERA is obtained. The upper traces in (a) and (b) are the 22 GHz microwave signals; the lower traces are X-ray signals. In (c) the synchrotron light shows the dimension of the ring cross section to be a few millimeters. The ring studied here is stable for more than 5 m/sec.

achieved and the emittance of the beam which can be extracted from the device. The hope is that an inexpensive high performance accelerator can be developed through use of these principles of collective effects.

11. ELECTRON BEAM ACCELERATORS

Intense relativistic beams of electrons have recently become available in the technology. These beams are pulsed and in the range of 20,000 to 200,000 amp at 0.3 to 10 MeV in energy. The pulse duration may vary in the vicinity of 5 to 50 nanoseconds. It is possible that such intense electron beams may produce highly stripped ions and indeed may cause acceleration of such ions. Several groups in the United States are studying this technology and the associated phenomena. Already observations of the stripping of a few electrons from nitrogen ions has been observed and energies in excess of 1 MeV/u have been observed.[66] It is possible that continued development may lead to higher charge states and higher accelerated energies.

12. CHARGE CHANGE ACCELERATOR

A novel scheme for the acceleration of heavy ions which is known as the charge change accelerator[22] is being developed by Professor Hortig at the Max-Planck Institute in Heidelberg. This rather intriguing device is shown in a sketch in Fig. 22. A tandem accelerator with a negative terminal potential of about 4 or 5 million volts has a gas stripper at high potential and 2 solid strippers, one at each end at ground potential. An achromatic magnetic mirror system is provided to reverse

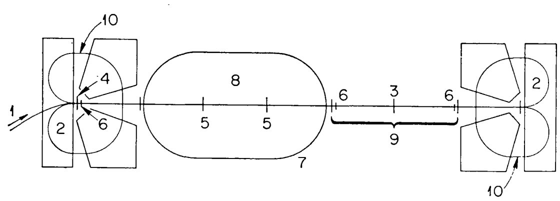


FIG. 22. A sketch of the basic features of the charge-change method of accelerating heavy ions.

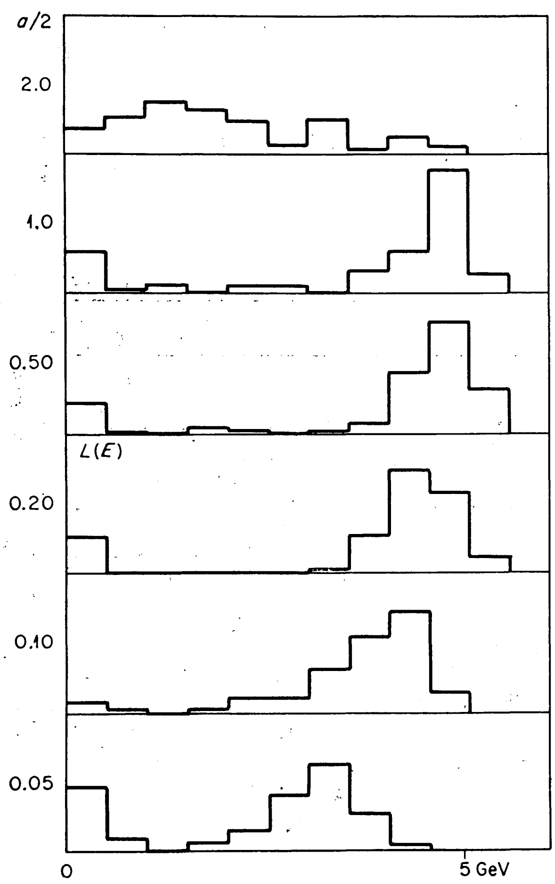


FIG. 23. Monte Carlo calculations of energy achieved by charge changing with various sizes of solid strippers.

the direction of the ions and send them back through the high voltage region with multiple traversals. The average energy gain is given by the difference in the equilibrium charge states in the gas and solid strippers multiplied by the potential. Monte Carlo calculations have been performed to develop further information on the performance of the machine. One plot of Monte Carlo calculations, giving the energy achieved as a function of the size of the solid stripper, is shown, Fig. 23. If the solid stripper is too large, as at the top, then particles can acquire strong transverse oscillations and are lost in the accelerator. If the strippers are too small, however, some of the particles will miss the stripper and then the energy will not be as high as optimum. Note that the computed energy achieved varies up to 5 GeV. The principal problems in the accelerator are the design of suitably achromatic mirrors and development of solid strippers which will have adequate lifetimes. These problems are both under investigation now at the Max-Planck Institute.

13. SYNCHROTRONS

Perhaps the most obvious method of reaching large energies $\gg 6$ MeV/u is through the synchrotron. Modern alternating gradient designs give by far the lowest cost per unit of final field-radius product. The chief technical problem to be solved in such a design is the very high vacuum which must be maintained for the long orbit paths. The principal uses for such an energy range are expected to be in the biological or medical fields. When sufficient motivation develops, it seems like a promising avenue to pursue. The synchrotron being a pulsed device means that the final mean current achievable is inherently somewhat lower than in cyclotrons, linacs, or tandems. However, for biological research the achievable intensity probably matches the research requirements very satisfactorily. Because of its very large magnetic field-radius product, a synchrotron can also be used for acceleration of low charge state ions (e.g. uranium 12 plus) to energies in the region of 10 MeV/u. The stringent vacuum requirements are still applicable and intensities would generally be lower than with cyclotrons and linear accelerators. A thorough study of a heavy ion synchrotron system was conducted at Lawrence Radiation Laboratory recently under the name Omnitron.[68] Even more recently proposals to convert[69] the Princeton Pennsylvania Accelerator, a 3 GeV rapid cycling synchrotron, to heavy ion acceleration have been made. The PPA proposal is described in a paper elsewhere in this issue.

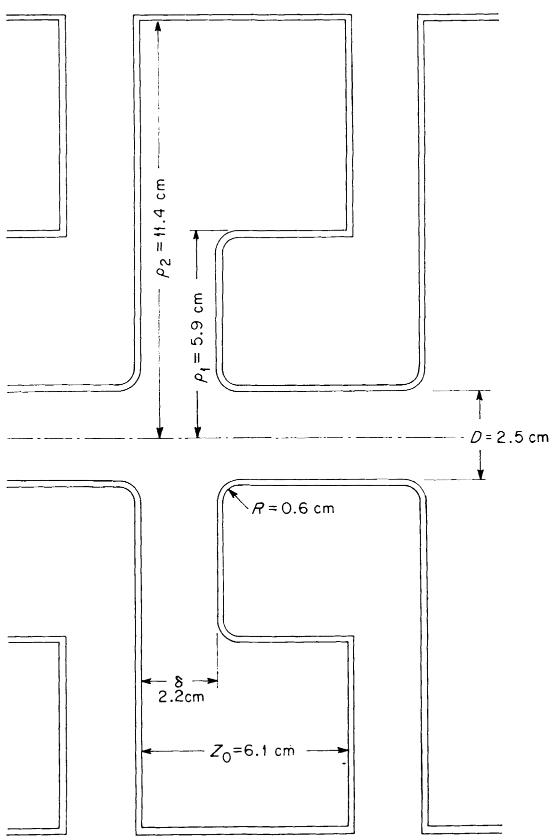
14. SUPERCONDUCTING LINACS

A subject of much current interest and optimism is that of superconducting accelerators for heavy ions. The group under Fairbank and Schwettman at Stanford University has been studying superconducting linacs[70] intensively for several years. At the present time, the design of a 2 GeV superconducting electron linac is well along. It will be housed in a 500 ft tunnel, 30 ft underground. This tunnel has been completed. The experimental station at the end of the tunnel is now being erected —a massive structure with a concrete roof 7 ft thick. The production cavities are now being fabricated, as is the cryogenic equipment. It is expected that this accelerator will be operating in one to two years and that its energy can be extended to perhaps 8 GeV by incorporating multiple traversals of the accelerator.

A limited amount of thought has been given by the Stanford group to the design of proton and heavy ion superconducting linacs. These would, of course, differ somewhat from the electron linacs but would follow in most ways the same general approach. The section of a possible cavity for a heavy ion linac operating at 650 MHz is shown in Fig. 24. One plan would be to have somewhere between 75 and 300 such cavities independently phased so that the linac can be adjusted for different velocity profiles.

An alternative idea is the use of a superconducting version of the Helac, the ambient temperature version of which was described in an earlier section of this report. Some development work is now being started at Stanford University on measuring the characteristics of helical structures of lead plated copper and eventually of niobium structures. It is much too early to evaluate the relative merits of these alternatives for superconducting heavy ion accelerator design.

One problem which is frequently raised with respect to superconducting linacs is the feasibility of control under high beam loading. Figure 25 shows the field probe signal and the input power



Re-Entrant Cavity For Heavy-Ion Linac 650 MHz.

FIG. 24. A section of possible superconducting niobium cavity for a heavy ion linac.

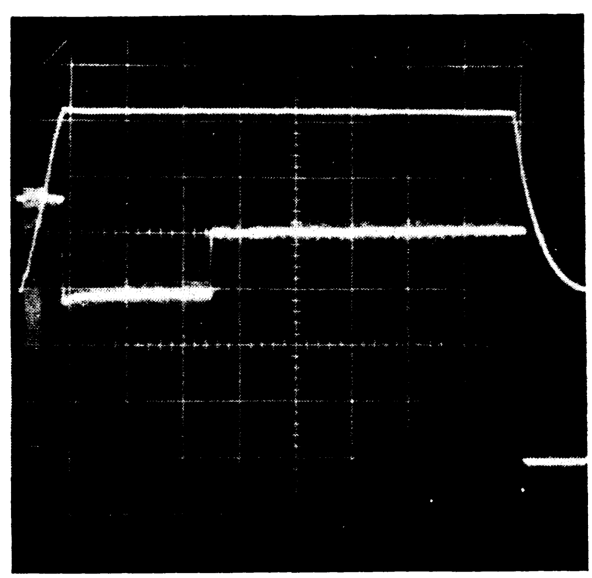


FIG. 25. Oscilloscope traces showing effect of regulating circuits as a 50 μA beam comes on. The field probe signal trace is at the top, the klystron input power at the bottom.

as the beam comes on in an electron linac test cavity with a beam of approximately 50 μA. From the flatness of the upper trace, it appears here that regulation to a few parts in 10^4 can be readily accomplished. The Stanford people have expressed the belief that a 60 MV proton linac could be built for perhaps about 1 million dollars. The cost of a heavy ion linac would depend on more detailed design development and on whether it is desired to go to full energy without stripping. This would require some 300 cavities and it would, of course, cost considerably more. The long-range outlook for superconducting heavy ion linacs is thus not easy to assess. In the opinion of the Stanford group, with the completion of the first phase of their 2 GeV linac, the full technology will be thoroughly demonstrated. They would then take the position that it will be rather straightforward to move into such fields as the heavy ion linac.

15. PROPOSALS FOR NEW ACCELERATORS

During 1968 and 1969 the explosively growing interest in the acceleration of heavy ions manifested itself in a flood of new projects and proposals. This was due in considerable measure to the growing awareness of the possibility of the existence of the stable superheavy elements at atomic numbers of 114, 124, and 126. It was reinforced by a general acceptance which spread through the nuclear science community that heavy ions are effective and underexploited tools of nuclear investigations. During the summer of 1969 some 54 different possible proposals or studies were screened in an attempt to survey and review all of the pertinent activity. The following tabulation, Tables XIII and XIV, show the summation of this survey. Of necessity this is a continually changing and progressing scene. It is obvious that many modifications of plans and intentions will be made in the future; some of these presumably may already be in effect.

16. THE FUTURE OF HEAVY ION ACCELERATION

It is clear that there are many alternative methods of heavy ion acceleration which are both feasible and practical. At the present time, with the world's existing accelerators, it is not possible to accelerate above the Coulomb barrier with projectiles heavier than about mass forty; thus an enormous unexplored region of nuclear pheno-

TABLE XIII

Heavy ion projects

System	Place	Features	Status
Cyclotron, isochronous without injector	Cal. Tech.	4-sec (Maryland)	Proposal
	Dubna	Conversion to 400-cm	Design
	Dubna	8-meter	Study
Electrostatic, tandem	Burlington, HVEC	MP + TU tandems	Construction
	Cambridge, MIT	TU tandem	Proposal
	Rutherford	30-MV terminal	Study
Linear accelerators	LRL–Berkeley	Conversion to superHILAC	Construction
	Frankfurt U.	Helical linac	Study
	Darmstadt–Heidelberg U.	Wideröe–Alvarez linac	Design
	Strasbourg U.		Study
	Lyon, France		Study
Synchrotrons	LRL–Berkeley	Omnitron	Study
	Prin–Penn	Inject. and modifications	Proposed
New type accelerators	Heidelberg	Charge-change accel.	Study
	Stanford	Superconducting linac	Study
	Cal. Tech.	Superconducting linac	Study
Inadequate information	Marburg U., Germany		
	Yale U., U.S.A.		

TABLE XIV

Heavy ion projects. Isochronous cyclotrons with injectors

Place	Status	Energy and particle (MeV/u)	Cyclotron	Injector
Argonne	Proposal	350 p; 10 U	6-sector	TU tandem
Bohr Institute	Study			
Brookhaven	Proposal	50 p; 5 U	4-sec (Ind)	2 MP tandems
Carnegie–Mellon	Study	20 U	conversion, fm	linac
Florida State	Study	7.5 U	6-sec (MSU)	FN, MP tandem
Indiana University	Study		4-sector	tandem
Karlsruhe	Study			
Los Alamos	Proposal	100 p; 6 U	4-sec (Ind)	FN tandem
Michigan State	Proposal	600 p; 9.0 U	6-sector	cyclotron or tandem
Oak Ridge	Proposal	300 p; 7.5 U	4-sector	TU tandem
UCLA-Group	Study		4-sector	two-gap cyclotron
U Maryland	Study	10 U	4-sector	tandem + 4-sec
U Rochester	Proposal	6 U	4-sec (Ind)	MP tandem

mena awaits, impregnable but inviting to many hundreds of the world's nuclear physicists and nuclear chemists. All of the necessary techniques are now available to build new powerful and versatile machines. Both the new linacs and the hybrid tandem-cyclotrons, described in the foregoing, can reach through and to the top of the periodic table. The linacs, in general, will lack certain versatility for extended energy range studies, kilovolt width precision beams, high energy helium 3, deuterons and protons, and the multiple combination uses (two different beams at once, one from the tandem and one from the cyclotron). However, the upgraded linac is the least expensive and the fastest route to the acceleration of uranium.

The more radical methods, charge-change, electron ring, or superconducting linac may, in five years, emerge as superior or less expensive heavy ion routes. New super-ion sources may convert existing cyclotrons to more powerful producers of heavy ions.

However, only one obstacle at present is holding back an immediate new great forward stride in science. Hopefully soon some government will be able to provide the financial resources to pluck the succulent plum which is dangling before the eyes of the world's expectant scientists.

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