A survey of methods of accelerating heavy ions*

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ABSTRACT

The many and varied methods for accelerating heavy ions to energies useful for nuclear physics and nuclear chemistry are reviewed. The traditional methods using cyclotrons and linear accelerators are being upgraded in a variety of ways. Schemes incorporating new accelerator physics, the collective effects systems, and charge changing systems are under development and may emerge soon as important new methods. Superconducting linacs are rapidly coming into their own and may be serious contenders as heavy ion accelerators in the near future.

1. INTRODUCTION

The purpose of this paper is to review the principal methods of acceleration of heavy ions as concisely as possible. Because of the fact that a number of papers are being presented on the details of particular projects, especially those which have isochronous cyclotrons as one portion of the accelerator, I will not attempt to review or to duplicate reporting on this area. Because some interesting alternatives to cyclotrons will not be reported elsewhere at this time, I will try to say enough to define clearly the general systems being planned for various machines which are either underway or which are being studied in a serious way. I will, at the outset, make a few remarks about the relationship of the size of cyclotrons to the injection energy and the charge state planned. For any details, however, on such machines, I refer the reader to the various specific papers being presented and the impressive number of large proposal documents which are now circulating, particularly in the United States.

In order to provide a broad introduction to the general topic of heavy ion acceleration, I have prepared a series of three tables. In the first table, Table 1, is shown the historical acceleration of heavy ions in a number of different

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Table 1. EARLIEST HEAVY ION ACCELERATORS

Date	*Machine*	*Location*	*Typical particle*	*Energy*	*Extracted beam*
1940	37-in. Cyclotron	Berkeley	$^{12}C^{2+,6+}$	50 MeV	8/s*
1950	60-in. Cyclotron	Berkeley	$^{12}C^{2+,6+}$	100 MeV	10^5/s
1953	225-cm Cyclotron	Stockholm	$^{12}C^{2+,4+}$	130 MeV	10^{11}/s*
1953	63-in. Cyclotron	Oak Ridge	$^{14}N^{3+}$	28 MeV	2μA
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

cyclotrons, the earliest being in 1940 in the 37-in cyclotron at Berkeley, in which an internal beam of a few particles per second was obtained. The first heavy ion nuclear reactions were observed in 1950 on the 60-in cyclotron, also in Berkeley. Here an extracted beam of 10^5 particles/second was used. In all of this early cyclotron work, it is presumed that C^{2+} ions emerged from the ion source, were stripped somewhere near the centre of the cyclotron to 6+, and were then accelerated approximately on the same e/m as a deuteron. The first cyclotrons designed to accelerate heavy ions coming directly from the ion source were the 63-in cyclotron in Oak Ridge and the 120-cm cyclotron at Leningrad. Here external beams in the microampere range and at 1 to 2 MeV per nucleon were obtained. The next two tables, Table 2(a) and Table 2(b), summarise the accelerators which constitute the bulk of today's heavy ion acceleration. The

Table 2(a). HEAVY ION MACHINES OPERATING DURING AND AFTER 1958

	Heaviest ion reaching 6·0 MeV/amu	*Typical external beam* Particle	*Energy* MeV	*Average current* eμA	pμA
Heavy ion linear accelerators					
Berkeley	$^{40}_{18}Ar$	$^{12}C^{5+}$	120	15	3
Kharkov	$^{40}_{18}Ar$	$^{12}C^{4+}$	120		
Manchester	$^{40}_{18}Ar$	$^{14}N^{5+}$	140	0·3	0·06
Yale	$^{40}_{18}Ar$	$^{12}C^{5+}$	120	1	0.2
D.C. machines					
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 U.S.A.
1 in Canada
2 in Germany

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 usually confusing as the charge state is often not given, but the beam current is of course larger in proportion to the extra charge state being used. I have 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 honour of the late cyclotron's inventor. Note that 3 pμA can be obtained from a linear accelerator, although currents are usually lower than this. All of the particles in the case of linear accelerators are accelerated to about 10 MeV/amu.

Next on the chart are listed the d.c. 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, e.g. Coulomb excitation and other experimental programs where the full barrier energy is not required. A typical current for ^{12}C as shown is ¼ pμA.

Table 2(b). HEAVY ION MACHINES OPERATING DURING AND AFTER 1958

	Heavy ion reaching 6·0 MeV/amu	*Typical external beam* *Particle*	*Energy* MeV	*Average current* eμA	pμA
Classical fixed frequency cyclotrons					
Dubna, 310-cm	$^{64}_{30}Zn$	$^{12}C^{4+}$	84*	80	20
Kurchatov, 150-cm	$^{20}_{10}Ne$	$^{12}C^{4+}$	94	20	5
Tokyo, 160-cm	$^{16}_{8}O$	$^{12}C^{4+}$	101	1·4	0·3
Isochronous cyclotrons					
Dubna, 200-cm	$^{40}_{18}Ar$	$^{12}C^{4+}$	210	24	6
Harwell, VEC	$^{20}_{10}Ne$	$^{14}N^{4+}$	98	30	7·5
		$^{12}C^{4+}$	118	5	1·25
Oak Ridge, ORIC	$^{20}_{10}Ne$	$^{12}C^{4+}$	118	5	1·25
Orsay, 200-cm	$^{40}_{18}Ar$	$^{14}N^{5+}$	125	1	0·2

*Not at full energy

Table 2(b) summarises 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 probably holds the record for current as may be noted, 20 pμA for ^{12}C. And finally, I list 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 an evaluation in a 'contest sense' as to which machine produces the greatest current. It is clear that 1 to 10 μA of extracted beam is fairly common. In the case of Orsay, more recent information is that the particle current is above 1 μA.

With this brief introduction, I would now like to turn to the various broad classifications of heavy ion accelerators and to make a few appropriate remarks about each.

2. CYCLOTRONS

First, let us look at cyclotrons which, in principle, can be either classical or isochronous; I believe almost all new machines being planned will be sector-focusing and isochronous because of the superior performance which this system provides. Consider the relationship $T = kQ^2/A$. This is a convenient way of characterising 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. In Fig. 1, is shown a plot of k of this relation plotted against $B\rho$ in kilogauss centimetres. 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 9,290 kg cm, protons of 2·0 GeV energy.
Thus you can see one is talking about very large magnets if one considers a k of 4000. Fig. 2 is intended to demonstrate the requirements for accelerating ions

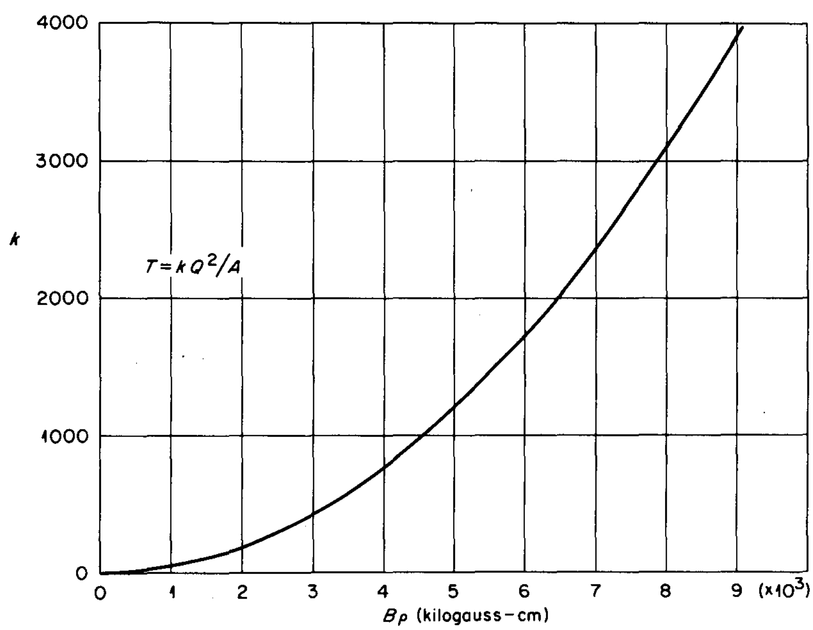


Fig. 1. The size of a cyclotron may be expressed conveniently by a number k *from the formula* $T = kQ^2/A$, *where* T *is the kinetic energy of the particle,* Q *is the charge state, and* A *is the atomic mass number. The relation between this constant,* k, *and the magnetic-field-radius product is plotted*

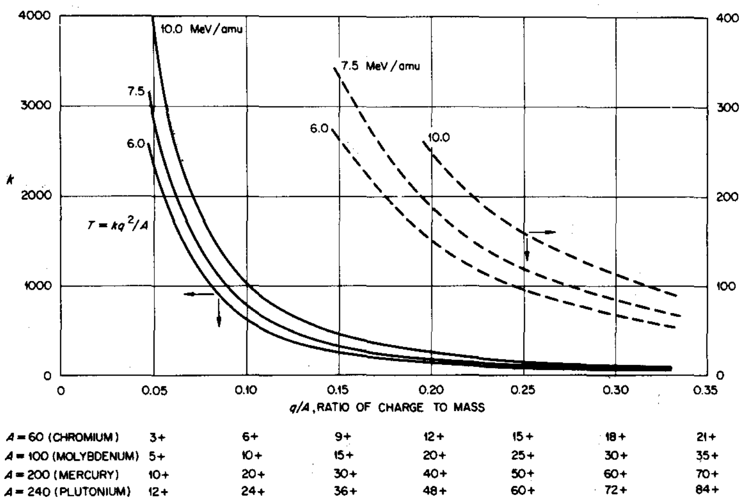


Fig. 2. The size of cyclotron necessary to produce heavy ions of various desired energies. The scale at the bottom gives examples of ions of various masses with different hypothetical charge states to illustrate the different regions of possible design and operation. The dotted lines are for an expanded scale for smaller cyclotrons using very high (Q/A)'s

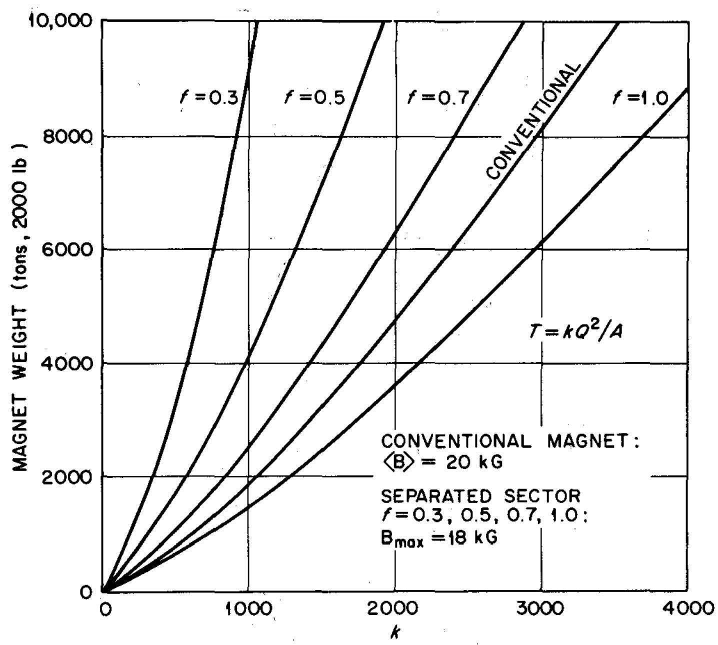


Fig. 3. Magnet weights have been calculated for various size cyclotrons. The f *values refer to the fraction of the magnet circumference which is occupied by pole pieces and magnetic field. The lower* f *values are required to produce necessary focusing for protons and other relativistic particles. The* f = 1·0 *is for reference only as a lower limit. Lack of access would prevent such a magnet from being practical*

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/amu. As Q/A 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 you all know, with light ions, Q/A in the range 0·25 to 0·35 can be readily obtained. This accounts for why all of the existing cyclotrons which generally have k's below 100 are very useful in this region. The new cyclotrons, being reported at this conference generally are providing k's of 300 or above, and as you can see, this calls for a charge-to-mass ratio of 0·15. At present such states have to be obtained by stripping in a solid foil from a tandem Van de Graaff or some other suitable

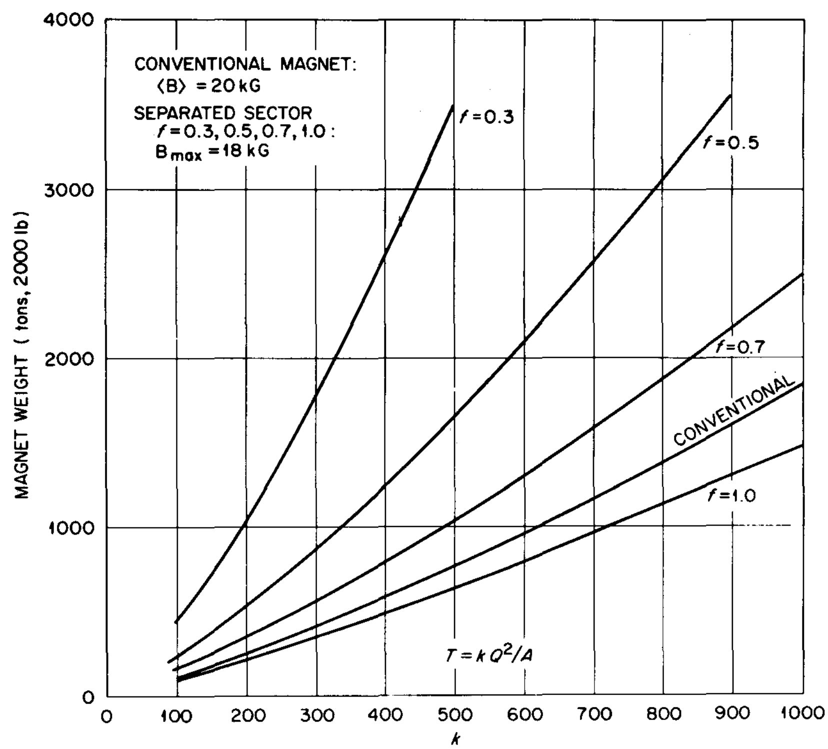


Fig. 4. This is an extension of Fig. 3 in which the lower portions of the scales have been expanded. These magnets would be applicable for cyclotrons using highly stripped ions

accelerator. The studies of selection, matching, and optimising injector systems and cyclotrons constitute a game which is going on at a rather frenzied pace in the United States at the present time.

The two graphs, Figs 3 and 4, 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: 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 impossible access. A magnet which would be more practical

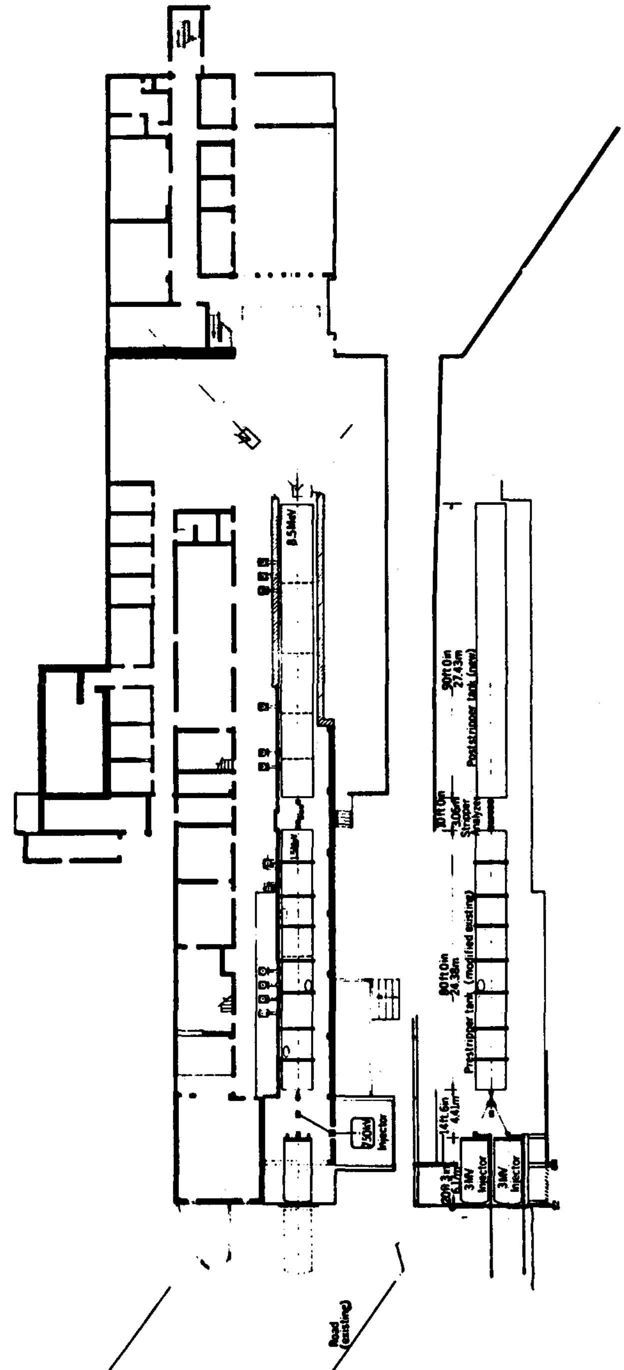


Fig. 5. A sketch of the superHILAC as it is planned to be fitted into the existing HILAC building at the LRL. New prestripper and poststripper tanks will be constructed extending into the present experimental area. New areas for research will be placed in the present shop area

would be the line shown as 'conventional', which is for an H-shaped yoke. The magnet weights were calculated by a simple computer program in which the gap was assumed to be 3 in, the field under the poles 18 kG, the return path area equal to the pole area, and suitable allowance of space for coils provided. You can see 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.

Fig. 4 is intended to survey the region of interest for cyclotrons with injectors. If one desires light particle capability as well as heavy ion capability in the cyclotron, the region $f = 0{\cdot}3$ to $f = 0{\cdot}5$ is of greatest interest. So one can see that magnets in the 1000 to 3000 or 4000 ton class are receiving a great deal of attention for today's cyclotrons.

3. LINEAR ACCELERATORS

We next turn to consideration of one of the proposed new linear accelerators which 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 to rebuild their linear accelerator as shown in Fig. 5. 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 3. Note that variable energy in roughly 1 MeV/nucleon steps can be obtained 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. 6. A pressure lock is being designed to facilitate rapid source changes.

I should next like to turn to another linac which is being studied intensively and which has been proposed for various applications in the heavy ion field. This is the HELAC being studied at the University of Frankfurt. The scheme for this accelerator is illustrated in Fig. 7. This may be described as a spiral-loaded-wave-guide in which standing waves are set up and in which a sinusoidal electric

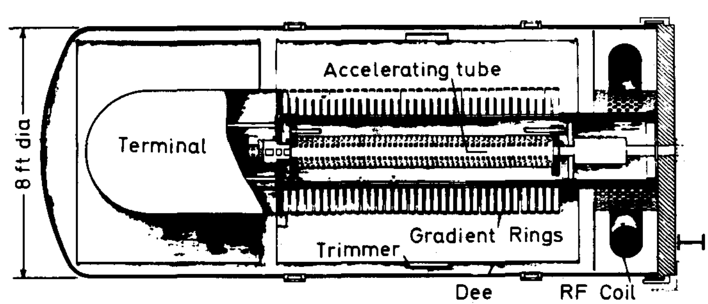


Fig. 6. A section of the d.c. injector for the superHILAC. Not shown in this sketch is a planned 'pressure lock' to enable fast source changes in the terminal without disturbing the pressurised system

Table 3. SUPERHILAC ALVAREZ CAVITIES: PRELIMINARY DESIGN PARAMETERS

	Prestripper			*Poststripper (not to scale)*						
T energy (MeV/n)	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
(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)					

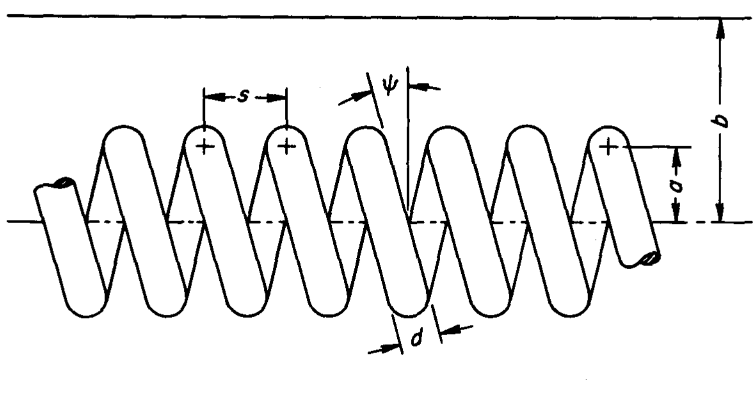
Frequency 73 MHz

field on the axis moves with a phase velocity determined primarily by the relationship given in the figure, the ratio of $s/2\pi a$ times the velocity of light. 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 in Table 4. The first injector needs to be either a short

Table 4. HELAC PARAMETERS

	Injector	*Helix*	*Stripper*	*Helix*	*Helix*
	Wideroe or d.c.	27·12 MHz	Gas	108·48 MHz	108·48 MHz
Energy (MeV/amu)	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

Wideroe linac or possibly a 3 million V d.c. 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 metre long would be 75. The total pulsed power is about 4·3 MW. The duty factor would be about 25%. The next two figures, Figs 8 and 9, are photographs of the structure. In these photographs may be seen the aluminium



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

Fig. 7. A sketch of the spiral conductor which is the key to the HELAC concept

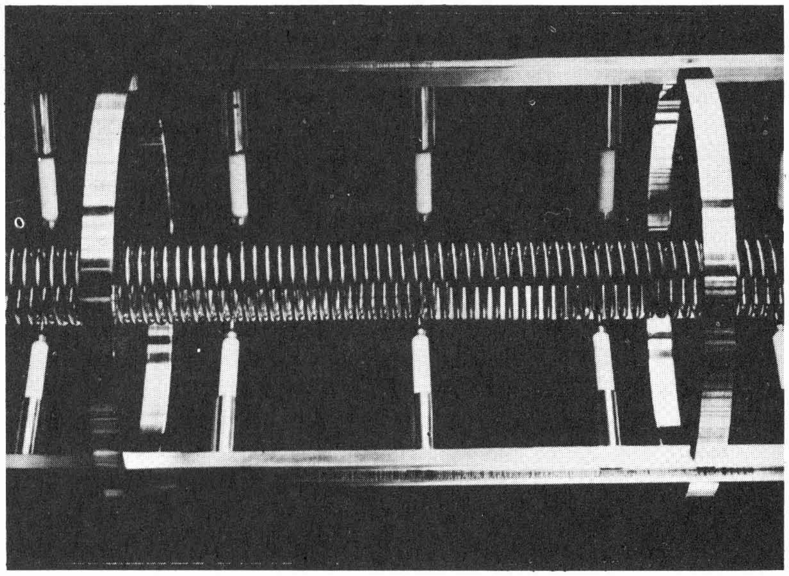


Fig. 8. A photograph of the assembled HELAC structure

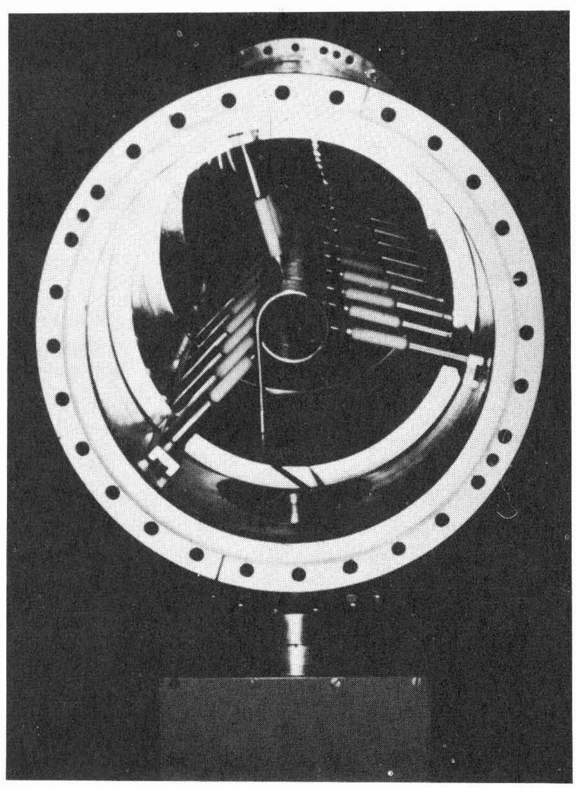


Fig. 9. A photograph showing the HELAC structure placed in its outer cylindrical casing

oxide support insulators which are located at the nodes of the standing waves.

Continuing with the review of linear accelerators aimed at heavy ion acceleration, let us turn now to the UNILAC. This is being studied in Heidelberg by Professor Schmelzer and his group, and is in a rather advanced state of development. You will note in the tables on this accelerator a number of similarities to the HELAC just discussed. This is more than a coincidence as the developers of the HELAC have endeavoured 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 in Table 5, that the UNILAC consists of a Wideroe accelerator up to 1·4 MeV/amu, a series of Alvarez tanks up to 4·5 MeV/amu and then a series of single cavities which can be independently phased to provide energy variation up to 7 MeV/amu. You will note the frequency of this is, not by coincidence, identical with the HELAC; it is perhaps the source of the HELAC frequency selection. The peak power here is about 6·3 MW. A schematic sketch of this machine is shown in Fig. 10, where one can readily identify the various

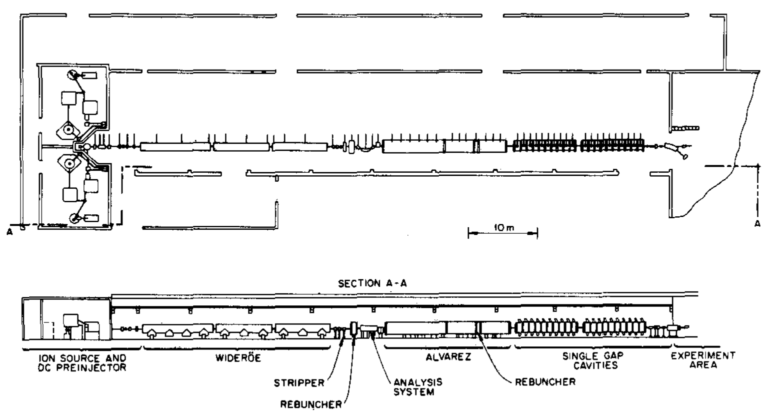


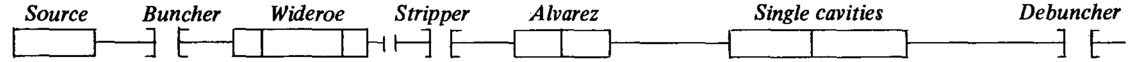
Fig. 10. A sketch of the system proposed for the UNILAC. It consists of four basic elements: injector, Wideroe linac, Alvarez linac, and a series of single gap separately phased cavities

components. This figure is approximately to scale. The latest plan as I was advised in mid-july by Dr. Schmelzer 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.

4. D.C. ACCELERATORS

Next I would like to turn to a consideration of d.c. accelerators. One of the most prominent of these is embodied in the HILAB proposal, a plan to combine a new TU tandem with an existing Emperor tandem. A sketch of the schematic arrangement of this is shown in Fig. 11. The scheme here is to use negative ions

Table 5. UNILAC PARAMETERS



	Source	*Buncher*	*Wideroe*	*Stripper*	*Alvarez*		*Single cavities*		*Debuncher*
Length (m)		1	27	8	20		20		10
Energy (MeV/amu)		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		

stripped at the centre 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 million V multiplied by the charge state. It is alternately possible to do experiments using a 90° analysing magnet and the switching magnet shown with the tandem. The TU's nominal rated terminal voltage is 16 MV but it is thought by the High Voltage Engineering Corporation that it may be able to go to 20 MV. A feature of such machines as this is the gigantic container pressure vessel and this is shown under construction recently in Burlington, Massachusetts, Fig. 12. Fig. 13 gives the approximate performance which might be expected under various assumptions from this

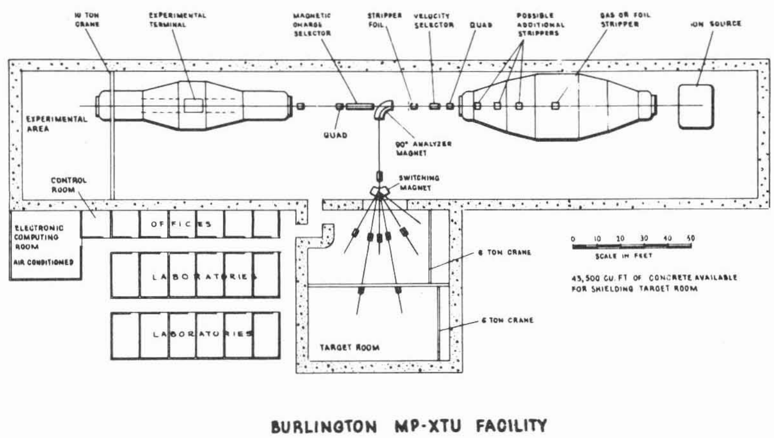


Fig. 11. The proposed arrangement for the HILAB showing the TU tandem feeding heavy ions to the experimental terminal in the MP tandem. Alternative stripper locations are indicated.

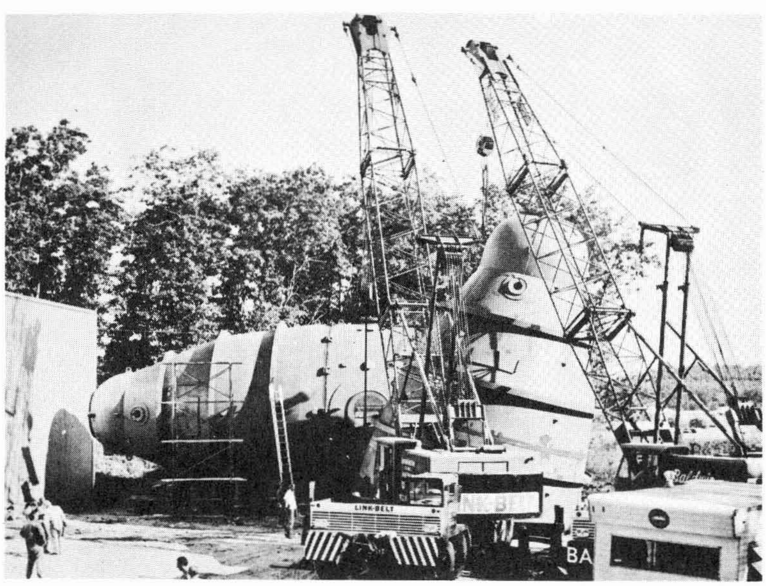


Fig. 12. A photograph of the installation of the giant pressure vessel for the TU tandem during installation at Burlington, Massachusetts

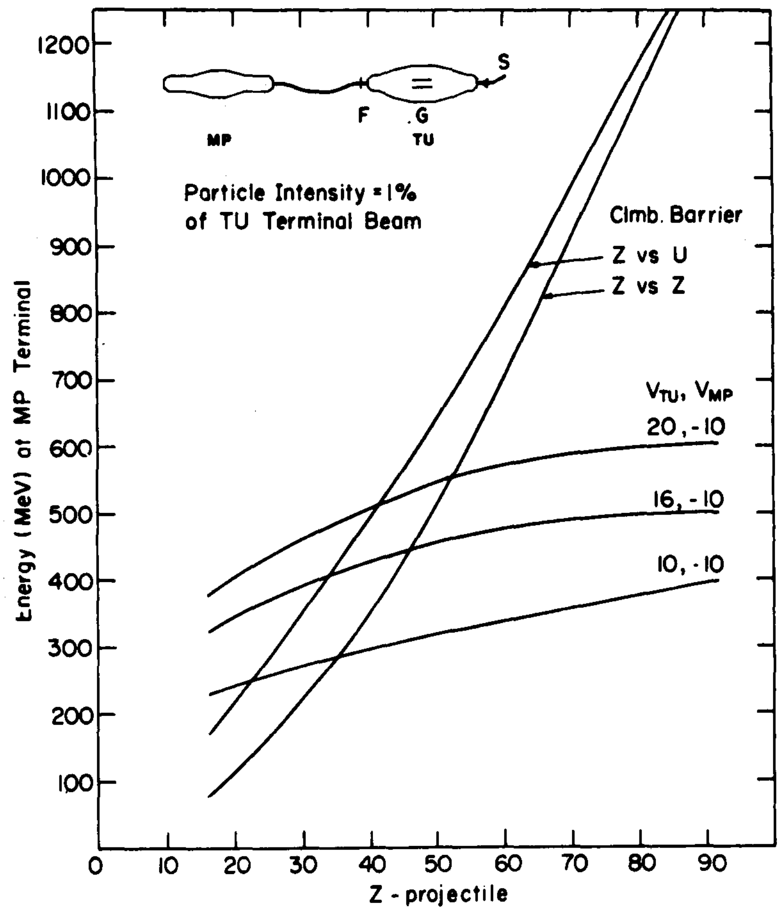


Fig. 13. The energies of heavy ions in the HILAB arrangement are shown for different possible operating potentials. For a 20 MV terminal potential, $Z = 40$ *heavy-ions can penetrate the Coulomb barrier for uranium.*

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 $Z = 40$ or so in this scheme. However, it is possible by adding extra foils which were indicated in Fig. 11 that one 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 anything can be accelerated against the heaviest elements.

5. ELECTRON RING ACCELERATOR

We next turn to the subject of the electron ring accelerator. This relatively new class of accelerators has been under investigation during the last few years. In the Soviet Union it has been called 'the Collective Method of Ion Acceleration'

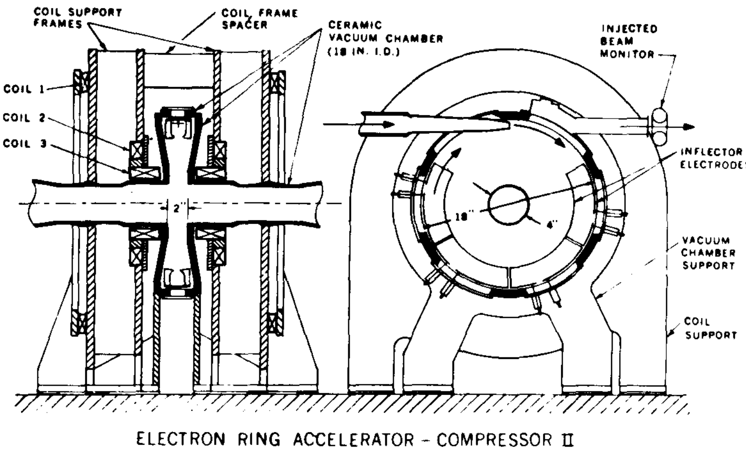


Fig. 14. A sketch of an electron ring apparatus studied at Lawrence Radiation Laboratory. After injection of an intense beam of electrons in a weak magnetic field, additional coils are activated and the energy of the trapped electron ring increases

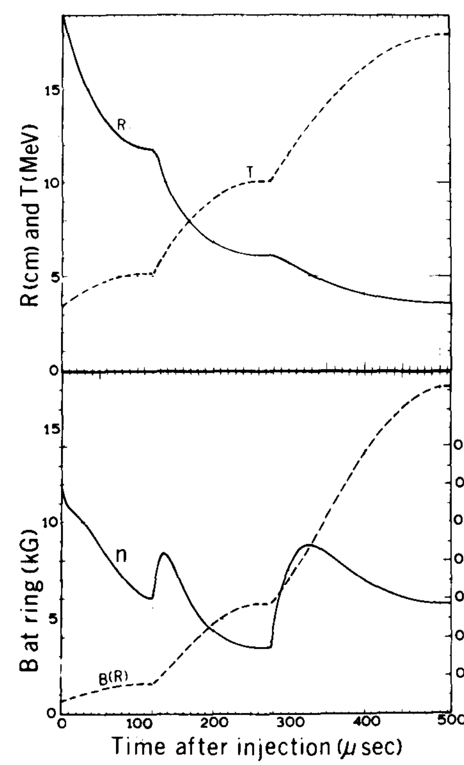


Fig. 15. The sequence of operations in the electron ring accelerator are analysed. Over a 500 μs period, the field is raised to about 17 kG, the radius of the ring decreases to 3·5 cm and the electron kinetic energy increases to 18 MeV

and is studied by Sarantsev and collaborators at Dubna. In the U.S.A. it is called the 'Electron Ring Accelerator' and is under study at the Lawrence Radiation Laboratory. A sketch is shown of the principal features of the electron ring device, Fig. 14. 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 a few months ago are shown on the next two figures. In Fig. 15 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 μs. In Fig. 16 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

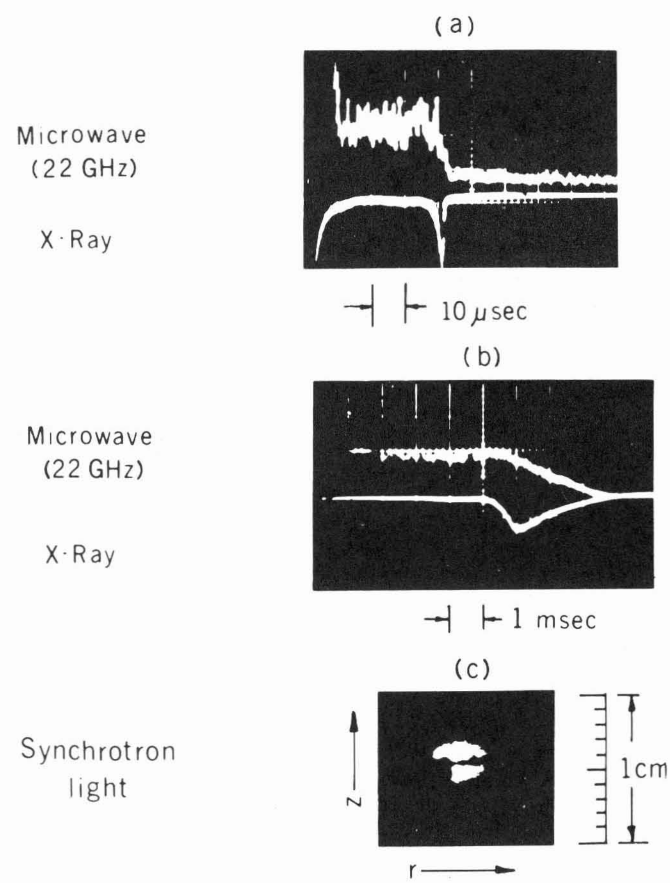


Fig. 16. Diagnostic information on the ERA is obtained. Synchrotron light shows the radii of the ring cross-section to be a few mm. The ring studied here is stable for more than 5 ms

ring was about 7 ms 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 reported that his group at Dubna has succeeded in accelerating Nitrogen^{3+} to 4 MeV/amu. He stated that an intensity of 10^8 atoms per pulse has been obtained. The proof of this result was through the nuclear reaction.

$$N + Ce \rightarrow Tb \rightarrow_{\alpha}$$

Important questions which remain for the collective effects accelerators are the intensity which can be achieved and the emittance of the beam which can be extracted from the device. Whether the intensity will be large enough and the emittance small enough to do high class experiments is, of course, a point of major interest for this device.

6. CHARGE CHANGE ACCELERATOR

Next we turn to the device known as the charge change accelerator being developed by Professor Hortig at Max-Planck Institute in Heidelberg. This rather intriguing device is shown in a sketch schematically in Fig. 17. A tandem accelerator with a negative terminal potential of about 4 or 5 million volts has

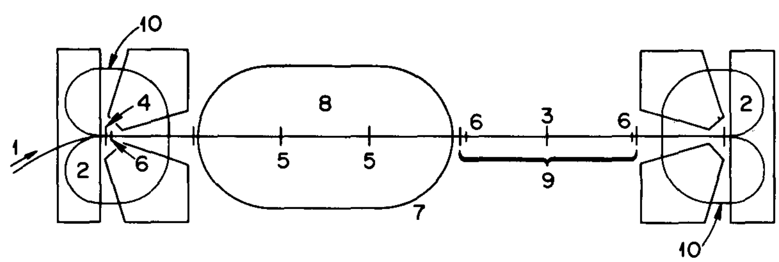


Fig. 17. A sketch of the basic features of the charge-change method of accelerating heavy ions

a gas stripper at high potential and two solid strippers, one at each end at ground potential. An achromatic magnetic mirror system is provided to reverse 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. 18. 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

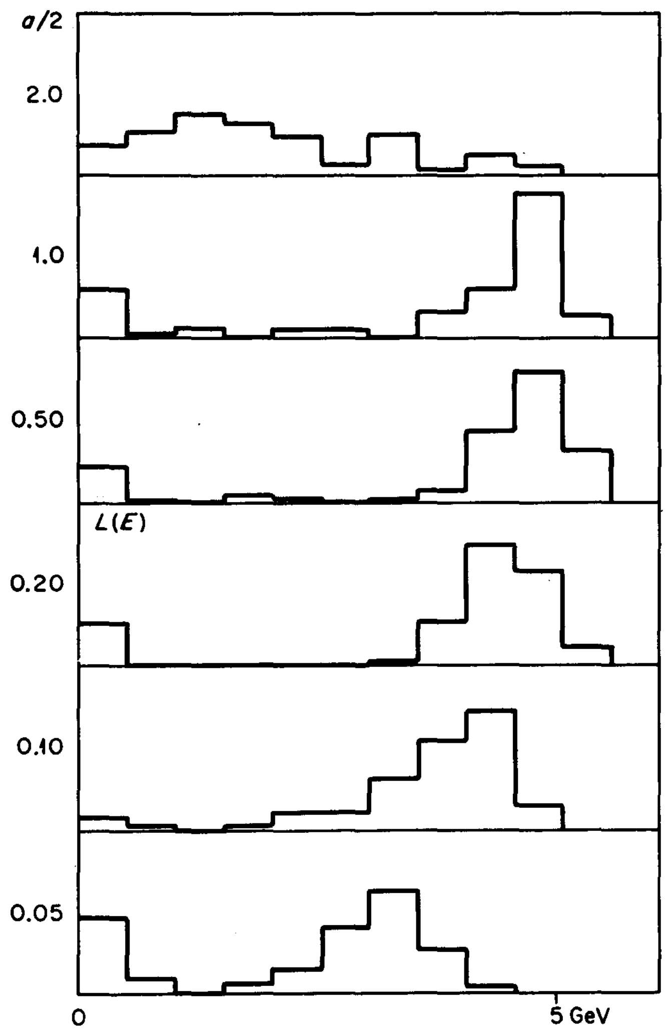


Fig. 18. Monte Carlo calculations of energy achieved by charge changing with various sizes of solid strippers

energy will not be as high as optimum. Note that the 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 being worked on now at the Max-Planck Institute.

7. SUPERCONDUCTING LINACS

Finally we turn to the subject of superconducting accelerators for heavy ions. The group under Fairbank and Schwettman at Stanford University have been studying superconducting linacs intensively for several years. At the present time, the design of a 2 GeV super conducting electron linac is well along. It will be housed in a 500 ft tunnel, 30 ft under ground. This tunnel has been completed. The experimental station at the end of the tunnel is now being erected. It is 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 8 GeV by incorporating multiple traversals of the accelerator.

A small amount of thought has been given by the Stanford group to proton and heavy ion linacs which would, of course, differ somewhat from the electron linacs but which would follow in most ways the same general procedures. The section of a possible cavity for a heavy ion linac operating at 650 MHz is shown in Fig. 19. The 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. One problem which is frequently brought up as a question on

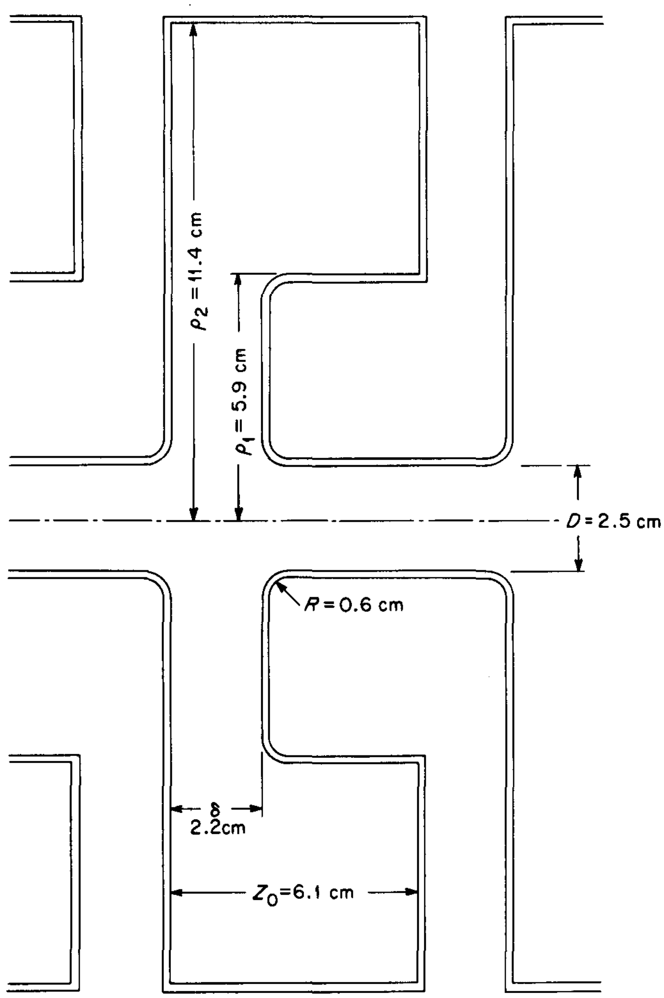


Fig. 19. A section of a possible superconducting niobium cavity for a heavy ion linac

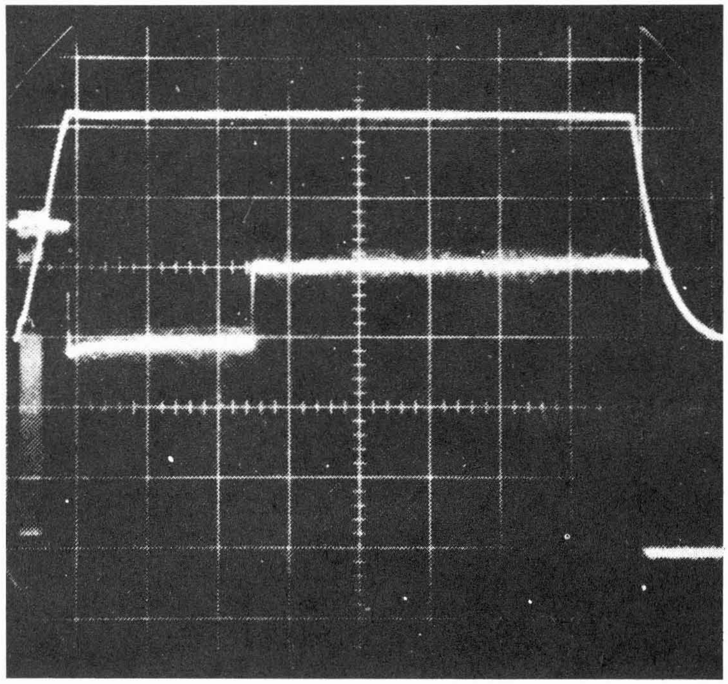


Fig. 20. Oscilloscope traces showing effect of regulating circuits as a 50 μA beam comes on. The field probe signal trace is at the top, the kystron input power at the bottom

superconducting linacs is the feasibility of control under high beam loading. Fig. 20 shows the field probe signal and the input power as the beam comes on in an electron linac test cavity with a beam of approximately 50 μA. It appears that regulation to a few parts in 10^4 can be readily accomplished. The Stanford people believe that a 60 000 000 V proton linac could be built for about 1 000 000 dollars. The cost of a heavy ion linac would depend on more detailed design development and on whether it is desired to go the full acceleration without stripping. This would require some 300 cavities and it would, of course, cost somewhat more. The long-range outlook for superconducting heavy ion linacs is difficult to assess. In the opinion of the Stanford group with the completion of the first phase of their 2 GeV linac, they feel the full technology will be thoroughly demonstrated and they would take the position that it is rather straightforward to move into such fields as the heavy ion linac. I am inclined to believe that anyone seriously interested in heavy ion projects should take an extremely careful look at this technology. In the end each group must evaluate it for themselves.

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DISCUSSION

Speaker addressed: R. S. Livingston (ORNL)

Question by C. Bieth (Orsay): What type of focusing system is used in a superconducting HILAC for heavy ions?
Answer: I think they are magnetic quadrupoles.

Question by H. Blosser (MSU): From the Stanford linac slide it would appear that the linac requires a minimum velocity of something like 0·1 c. Do you know the Stanford plan for achieving this initial velocity?
Answer: Although the studies at Stanford are not yet very advanced, they recognise a problem at low velocity. They have given some consideration to use of a superconducting HILAC and also would need a d.c. injector of perhaps 2 MV.

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