ALTERNATES TO THE CYCLOTRON FOR HEAVY-ION ACCELERATION*

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ABSTRACT

The status and future possibilities for several alternates to the cyclotron for heavy-ion acceleration are discussed. Linear accelerators, both conventional and superconducting, tandem electrostatic accelerators, and the electron ring accelerator are among the accelerator types and concepts reviewed and compared.

INTRODUCTION

The earliest practical acceleration of heavy ions to energies of interest for nuclear physics was in 1950 at the 60-Inch Crocker Cyclotron at the University of California, Berkeley.[1] Those early experiments accelerating carbon ions were quickly followed by others throughout the world. The first accelerator built solely for the acceleration of heavy ions was the 63-Inch Cyclotron (28 MeV - N^{3+}) at Oak Ridge[2] which was completed in 1953. The following years witnessed the construction of several cyclotrons and heavy-ion linear accelerators.[3] The situation remained relatively static until the interest in physics with heavy ions perked up in about 1968. Since that time there has been a real renaissance in heavy-ion acceleration. Many of the isochronous cyclotrons built since 1960 and first used chiefly for light particle acceleration are now being tooled up for heavy-ion programs. In the past few years there have been a spate of new proposals for heavy-ion accelerators to extend the range of useful projectile masses to the heaviest elements. Many of these are for cyclotrons with various kinds of injectors; many are for new linear accelerator variants. There is strong continued interest in very high voltage tandem electrostatic accelerators. Also, new and potentially very powerful new methods, the electron ring accelerator and other collective and coherent effects accelerators are being explored. This paper discusses the present and developing scene in the field of non-circular heavy-ion accelerators.

LINEAR ACCELERATORS

There were four heavy-ion linear accelerators built in the late fifties and early sixties. These were located at the University of California, Berkeley, Yale University, at the University of Manchester in England, and at the Physical-Technical Institute of the Ukraine at Kharkov in the USSR.[4] All of these had about the

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same energy limit of ∿ 10 MeV/u and were limited to ions of mass 40 or below. The accelerators were typically based on obtaining a minimum q/A of about 0.15 from the ion source and stripping to higher charge-state at about 1 MeV/U to give a q/A of about 0.3 in the post-stripper linac section. The best performance among the four machines was achieved by the Berkeley HILAC which profited by much development throughout its life. Its output ranged from a few particle micro-amperes of carbon down to about 0.06 particle microamperes of argon ions. The output of the other linacs was typically an order of magnitude lower, largely as a result of lower duty factor, 3% max vs 30% max for the HILAC. An additional limitation of the older linacs is the lack of energy variability. They are generally fixed energy devices although at Berkeley it was found possible to tune the voltage distribution in the post-stripper tank to give low currents of ions in the 2.5 - 7.5 MeV/u energy range.

It required the development of a second generation of heavy-ion linacs to circumvent the limitations of the earlier machines. The first example is the new Super-HILAC that replaces the older accelerator at Berkeley.[5] Fig. 1 is a schematic of the layout of the linac. Ions are injected from either a 3 MV parallel-fed pressurized cascade generator or from a 750 kV injector. The lower voltage unit is used for the mass range through argon. The ions are stripped to increase the ion charge at 1.2 MeV/u. An unique feature of the new design is the subdivision of the post-stripper tank by diaphragms into six electrically independent sections to give full-intensity energy variability over the energy range from 2.6 to 8.6 MeV/u.

Another second-generation accelerator is being built near Darmstadt in Germany.[6] A new institute, the Gesellschaft für Schwerionenforschung (GSI) has been formed to design and construct the facility and to plan and conduct the research program. It is an extensive installation, see Fig. 2. The many unique features include the use of a 350 kV dc injector feeding a Wideröe-type first section. The intermediate sections are of the Alvarez-type. The final section consists of 20 independently-driven cavities; these can be used to add or subtract energy at the output of the Alvarez-type intermediate section to give energy variability over a very wide range. This velocity flexibility in the final stage also allows light ions to be accelerated to the 20 - 30 MeV/u range. The schematic of the linear accelerator is seen in Fig. 3. The output current is expected to range from tens of microamperes for the lightest ions to ∿ 0.1 particle microamperes for uranium ions at 8.6 MeV/u. The UNILAC project is fully authorized and under construction with first beam anticipated in 1974.

The TALIX project[7] would add a helix-type linear accelerator to the Heidelberg tandem. In the helix-loaded cavity the phase velocity of the traveling wave is slowed by inductive loading; the phase velocity of the wave propagating down the helix is the velocity of light multiplied by the ratio of pitch to circumference as in Fig. 4. An early model of a one-meter section is seen in Fig. 5; later designs would use metallic support stubs at the voltage nodes. The energies expected from the TALIX are shown in Fig. 6. The present design is for 14 one-meter sections. It is planned to operate the accelerator at 25% duty factor at high repetition rate to achieve an accelerating gradient twice as large (∿ 2.2 MV/m vs ∿ 1 MV/m) but at the same average power level. The energies in the 25% duty-factor mode would range from 8.5 MeV/u for Br ions to 11.25 MeV/u for oxygen.

Yet another linac with helix-loaded cavities is being planned at Los Alamos Scientific Laboratory.[8] The main features and the energies of some output beam energies of the proposed linac are given in Table I. 148 individually-driven helix sections are planned. Injection will be from a 4 MV electrostatic unit.

Table I Los Alamos Heavy-Ion Linac Characteristics

4 MV Injection		E_o = 1.25 MV/m
One Foil Stripping		P = 2.0 MW
100% Duty Factor		L = 112 ft
		N = 148
Ion	E_f (MeV)	Lab Barrier and Target (MeV)
^{18}O	163	95, ^{252}Cf
^{48}Ca	358	242, ^{252}Cf
^{76}Ge	475	382, ^{232}Th
^{100}Mo	549	501, ^{208}Pb
^{124}Sn	636	623, ^{208}Pb
^{136}Xe	661	691, ^{208}Pb
^{238}U	695	1446, ^{238}U

Table II summarizes some characteristics of both new and old linear accelerators.

Table II Selected characteristics of linear accelerators.

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Completed	Accelerator/Location	Maximum Energy[1] (MeV/u)	Mass Range[2] (A)	Energy Variability (MeV/u)	Duty Factor (%)	Beam Current (Particle μA)	Comments or Special Features
1957	HILAC, Berkeley	10.3	4 - 40	2.5 - 7.5	80 He; 15 Ar	C-5; Ne-0.14; Ar-0.06	Modified substantially from original design
1958	HILAC, Yale	10.1	4 - 40	fixed	3	C-0.12; Ne-0.009; Ar-0.00015	
1958	Kharkov Linac	10.0	4 - 20	fixed	0.14	C-0.0003	Pulse transformer injector grids 2nd tank
1963	Manchester Linac	9.9	4 - 40	5 - 9.9	3	C-0.3; Ne-0.02; Ar-0.0024	
1972	Super HILAC, Berkeley[3]	8.6	4 - 238	2.6 - 8.6	30 to 80	≥ 10 light ions to ∼ 0.1 for U ions	Uses diaphragms in last tank to aid variable energy
1974	UNILAC, Darmstadt	10.2/8.5 for U to 20 for ^{4}He	4 - 238	Large	25%	Ne-35; Kr-1; U-0.11	Uses 20 independent resonators to permit easily variable energy
Proposal	Los Alamos Helix Linac[3]	9 for ^{18}O 5.5 ^{100}Mo	4 - 238	Large	continuous	1 - 10	Uses 4 MV electrostatic injector for multi-sections helix loaded cavities
Proposal	TALIX, Heidelberg	11.25 for ^{16}O 8.7 for ^{81}Br	4 - 120	Large	25%	∼ 0.5 for Br	Uses Super-MP Tandem as injector with foil stripper for 14 1m helix sections

[1]For heaviest ion or as listed. For UNILAC two values are for solid/gas strippers.

[2]For rated energy or for energy for ∼ 6 MeV/u.

[3]Estimates of currents made by author.

SUPERCONDUCTING LINEAR ACCELERATORS

For several years, the possibilities of rf superconductivity for the acceleration of electron, protons, and heavy-ions have intrigued many accelerator designers. The early work, principally at Stanford University, was concerned mainly with electron linear accelerators but lately the emphasis has shifted toward accelerators for heavier particles.

At the Karlsruhe Nuclear Research Center in Germany a project is underway to develop a superconducting accelerator as a meson factory.[9,10,11] A short section of a linear accelerator with helix-loaded cavities is being evaluated as a first step. Much of the early work on superconducting rf accelerators has been with high frequency cavities suitable only for electrons. Protons and heavier ions require lower frequencies and the compactness of the helix structure is attractive. The present work at Karlsruhe is with a five-section helix, Fig. 7, constructed of niobium. Special polishing, heat treating, and anodizing procedures are used to give a smooth Nb-surface with a dense Nb_2O_5 coating (250 A° thick) of reliable and predictable properties. The test unit outside the cryostat is seen in Fig. 8; the 800 kV proton injector unit is located behind the large chamber. Some characteristics of the helix and results of the early tests are given in Table III.

Table III Characteristics of Karlsruhe Helix-Loaded Cavity

Tank Radius, (cm)	20
Tank Length, (cm)	54
Tubing, o.d./i.d. (mm)	6.3/4.8
Winding Radius (cm)	∿ 3
No. of Helix Sections	5
Frequency (MHz)	90
Energy Gain (MeV)	0.355
Stable Phase (deg)	30
Effective Accelerating Field (MV/m)	1.15
Mode	Π
E_{max}/E_{tw}	13.3
H_{max}/E_{tw} (G/MV/m)	312
Low Power "Q"	1.2×10^8
High Power "Q" (at Δf = 650 kHz)	0.3×10^8

The accelerating field that is achieved in these early tests is very respectable but not higher than can be achieved conventionally. Up to about 40 μA of beam have been accelerated but details of beam quality (emittance, energy spread, etc.) have not been completely measured. The "Q" is lower than expected but the most significant result is that the frequency modulation due to vibration of the springy helix was very large, 20 - 100 kHz. The low-field "Q" is about 1×10^8 and at peak field is about 3×10^7 which gives a power requirement of 3.5 watts. In a later run the f-m amplitudes were lower but it is clear that dynamic frequency stabilization must be employed. Present tests are with the rf power source phase-locked to the cavity fields; in October, 1972, they plan to test the dynamic frequency stabilization system.

At the California Institute of Technology another superconducting helix-loaded cavity program is underway.[12] Their early studies have all been with lead-plated helices. The recent work has been directed toward the stabilization problem. Dick and Shepard of that group report the successful use of sapphire rods to mechanically stabilize a helix and the successful development of a dynamic tuning system.[13] With the sapphire rods they were able to markedly reduce the frequency modulation and move the natural frequencies of the helix to a higher and more manageable domain, see Fig. 9. Without the sapphire rods or dynamic frequency control, the phase noise was $\sim 10^2$ radians. The dynamic reactance control, capable of about 200 watts reactive power, reduced the modulation to 10^{-2} radians. About 1200 watts would have been required for optimum results. Use of the dynamic reactance control with the helix with sapphire supports reduced the modulation to 10^{-3} radians. Their present lead-plated helices give Q's of $\sim 10^8$ and can be operated at accelerating electric field gradients up to 0.85 MV/m which corresponds to surface electric fields of 12 MV/m. These results are of course encouraging but it will still be necessary to build and test a prototype accelerator.

At Stanford University[14,15,16,17] another approach has been taken. Believing (based on their own measurements) that the helix structure was too flimsy and beset by mechanical instability problems to make a practical linac, the group at Stanford, has concentrated on the development of compact re-entrant cavities of heat-treated niobium, Fig. 10. Surface electric fields up to 25 MV/m have been obtained but a more consistently reached value is 12 MV/m. A novel feature of the Stanford cavity was the use of a piezoelectric motor to change the cavity gap to tune its frequency to match a stable source. At low fields, Q values of about 10^9 at 4° K and 7×10^9 at 2° K are achieved. These values decreased at full power to 2×10^8 and 3×10^8, respectively.

Hilton Glavish[14] states that with cavities of this type he can achieve accelerating gradients (taking into account waste space, transit time factors, etc.) of 0.18 MV/ft at $\beta = 0.04$, 0.5 MV/ft at $\beta = 0.08$ and 0.7 MV/ft for $\beta = 0.16$ which suggests that rather high injection velocities are needed. These values are for 400 MHz cavities with 10 MV/m surface fields. One of the main problems to be solved in a continuing program is to find out why surface fields of 25 MV/m can not be reached consistently. Also they plan to build 5 or 6 cavities to use with their FN tandem to get some practical experience accelerating ions.

At Argonne National Laboratory[18] successful tests with an Nb_2O_5 anodized niobium helix-loaded cavity have led to a proposal to build a full scale accelerator. Accelerating gradients up to 2 MV/m have been achieved reliably with a helix that has been treated fairly roughly and was in room-temperature air for 90 days. The dependence of Q on electric field is plotted in Fig. 11. Unlike the Karlsruhe experience the Q improved with age. With confidence that dynamic tuning problem will be solved and that no new unsurmountable ones will arise, the Argonne group proposes the system shown schematically in Fig. 12. The design parameters of the accelerator are given in Table IV. The construction of a two-cell linac with injection from a 1 MeV Van de Graaff is underway to study the control problem and other critical aspects of an operating linear accelerator.

Table IV Characteristics of Proposed Argonne Linac

Length Overall	45 m
Material	Niobium
Helices	28 Groups of 5 $\lambda/2$ sections
Temperature	1.8 K
Frequency	65 MHz - CW
PQ	385×10^8
Typical Q	10^8
Axial Electric Field	2 MV/m
Surface Electric Field	< 20 MV/m
Magnetic Field	< 1000 G
Energy	10 MeV/A U^{37+}
Resolution	$< 10^{-3}$
Intensity	$\sim$ 1/3 of dc beam from Tandem

DC ACCELERATORS

A quite different accelerator for research with both light and heavy ions is the super-voltage tandem. This type of accelerator with terminal voltages in the 20 - 30 MV range has been studied by the High Voltage Engineering Corporation and the National Electrostatics Corporation in the US and in England by a group centered at the Daresbury Nuclear Physics Laboratory. The Daresbury proposal[19] will be discussed as representative of the concept. A drawing of the vertical tandem is seen in Fig. 13; the principal characteristics are given in Table V.

Table V Daresbury Tandem Characteristics

Tank Length (m)	45
Tank Diameter (m)	7.6
Column Length (m)	42
Column Diameter (m)	2.15
Terminal Surface Gradient (MV/m at 30 MV)	16
Column Gradient (MV/m at 30 MV)	2.2
Estimated Cost (pounds)	4.25×10^6

The energies of some representative beams (calculations by the author) are given in Table VI. The present design study program includes studies of the accelerating tube construction, accelerator structure, stripping foil reliability, and the charging system. A novel charging belt called the laddertron is being developed and tested. It consists of two chains with individually insulated metal links arranged parallel to each other with metal cross-bars. This is said to have superior charge capacity and wear characteristics. The schedule for the project envisions completion of the design study by the end of 1972.

Table VI Beam Energy of 30 MV Tandem

Ion	Ion Energy[1] Gas Stripping[2] (MeV/u)	Foil Stripping[2] (MeV/u)
^{19}F	14.8	15.3
^{35}Cl	11.4	12.6
^{79}Br	6.1	8.9
^{127}I	3.8	6.7
^{208}Pb	2.2	4.3
^{238}U	1.8	3.9

[1] The ion energy for maximum intensities - higher energies are available at some cost of intensity.

[2] Foil or gas stripping in the terminal - foil stripping at 1/3 point of down-tube for both cases.

ELECTRON RING ACCELERATORS

Of the many collective and coherent acceleration methods that have been discussed in recent years the electron ring accelerator (ERA) has attracted the most interest. Programs directed toward the development of practical ion accelerators based on the ERA concept are being pursued at Dubna,[20] at Karlsruhe,[21] at Garching[22] in Germany, at the Universities of Bari and Lecce in Italy[23] and at the University of California, Berkeley[24] and at the University of Maryland[25] in the USA. In the ERA a stable high density electron ring is produced by injecting beam from an electron accelerator into a weak magnetic field. To increase the electron density and hence the maximum electric field or "holding power" of the ring it is compressed by increasing the magnetic field. The high density electron ring is then loaded with ions and accelerated to high velocity. The positive ions are accelerated by the self-field of the electron ring. The electrons are easily accelerated to high velocities in short distances hence the possibility of compact, high-energy accelerators. If sufficiently dense, stable electron rings can be produced, the effective accelerating fields can be much higher than can be achieved by other means. The cross section of the ERA experiment at Lawrence Berkeley Laboratory is shown in Fig. 14.

J. M. Peterson of LBL, Berkeley has described the characteristics and possible operation of an ERA for heavy ions.[26] He finds that for reasonable injected electron currents and compressor parameters that it may be possible to achieve 10 MeV/u uranium ions using magnetic expansion acceleration (causing the ring to move axially in a solenoid magnetic field of decreasing strength) of only 1.7 meters in length; a 120 meter solenoid might yield 300 MeV/u. The estimates of output of such an accelerator are 10^{11} ions per second for uranium and 6×10^{11} ions per second for argon. In the Berkeley ERA (and in most other ERA concepts as well) the initial electron ring is compressed by increasing the magnetic field but there are other possibilities as will be discussed later.

Experimentally much progress has been made on the ERA but not yet enough to demonstrate a practical accelerator design. Early experiments at the Lawrence Livermore Laboratory produced accelerating fields of 13 MV/m for protons but attempts to duplicate this success with a new apparatus have eluded the group. The chief problems seem to be instability of the ring during compression. Many of the resonances are of the single-particle type but others are much more complicated like the negative-mass instability. At Berkeley the main effort these days is to understand the resonances. They are studying the resistive wall effect and the possibilities of introducing energy spread into the injected beam which would reduce the resonance strength.

The group at Dubna has had better success. They have demonstrated a holding power of 60 MV/m and have accelerated alpha particles to an energy of 29 MeV in a distance of 40 cm. They are now building a more powerful apparatus and new results will be forthcoming.

A quite different approach to the ERA is being pursued at the University of Maryland by Martin Reiser and associates.[25] The Maryland design, Fig. 15 is based on the use of a static compressor. An intense hollow electron beam produced from a ring cathode is passed through a cusp magnetic field; the axial momentum is converted mainly to angular momentum. The residual axial velocity can be made arbitrarily small by adjusting the magnetic field strengths. The beam slows down in the increasing magnetic field but because there is no axial stability the ring would quickly expand because of the electron velocity-spread. A special means of trapping the ring must be provided. One of the better methods is said to be the use of a resistive wire at the point of magnetic field minimum (as in Fig. 14). This couples and dissipates the oscillation energy. It is estimated for a 6 MeV/u beam with acceleration by solenoidal magnetic field expansion, that 2×10^{11} ions can be accelerated with a ring of 5×10^{13} electrons at the rate of 10 rings (pulses) per second to give a beam of 2×10^{12} ions/sec. Such repetition rates are beyond the present Maryland design but serve to indicate the range of possible development. The static compressor system will face many of the same possibilities of resonance problems as the other ERA methods but the different geometry and time-scale may make the effects quantitatively different. First operation of the Maryland injector is to be in the latter part of 1972 with completion of other components to follow soon after.[27]

CONCLUSIONS

From the foregoing it should be clear that there is wide interest in heavy-ion acceleration with non-circular accelerators. The levels of activity in circular and non-circular heavy-ion acceleration methods seem to be about equal with an advantage somewhat on the side of the linear accelerator because of the work on the Super-HILAC and because of the advanced state of construction of the UNILAC project.

With respect to performance, most cyclotron proposals with high-mass performance equivalent to the largest heavy-ion linacs, say 10 MeV/u at mass 238, would give much higher energies for light ions - 100 MeV/u from the cyclotrons vs 20 - 30 MeV/u from the linacs. Thus the cyclotrons have an advantage in diversity for a broader research program.

With respect to output currents, linacs and cyclotrons are roughly equal with equivalent ion sources with some advantage going to the cyclotrons because of easier cw operation. The two-stage cyclotron projects which use tandem injectors would tend to have lower light-ion currents than that might be achieved with linacs because of the out-put limitations of the tandem but if a cyclotron injector is used (as in the Oak Ridge Proposal using the ORIC as the alternate injector) the outputs can be roughly the same or higher for the cyclotron. Either type of accelerator is capable of more light-ion current than can be usefully used in most applications.

Concerning a comparison of costs, there was not enough data available on a common basis to make a quantitative analysis. The author's opinion is that for the most flexible schemes, the costs are roughly the same; the UNILAC cost is probably about the same as the cost of large tandem-cyclotron combinations. The development program costs would be about the same or a little larger for the linac; it is believed that the cyclotrons are somewhat less complex devices than the new multi-stage linacs with wide-range variable energy capability such as the UNILAC.

Superconducting linear accelerators remain difficult to assess. On one hand they have important potential advantages of cw operation with small rf power requirements, the possibility for easy energy variation and good stability. On the other hand the development programs are not far enough along to clearly answer all of the crucial questions concerning control problems, long term superconducting surface stability, etc. For the helix-loaded cavities, the frequency control problem has been solved only in a limited way and not in an operating accelerator. The re-entrant cavities seem to be largely free from the frequency stability concerns but cavities with low enough frequencies to give good low-velocity longitudinal and radial transit time factors have not been built. It is believed with either cavity type, a prototype linac needs to be operated for a year or more and subjected to evolutionary development before a sound proposal with a definite construction schedule and cost estimate can be made. This would be especially true for an accelerator that would be the main tool of a major research laboratory.

The ERA is similarly difficult to assess. The results so far are exciting but much more experience will be needed before scientists can plan research facilities based on ERA schemes.

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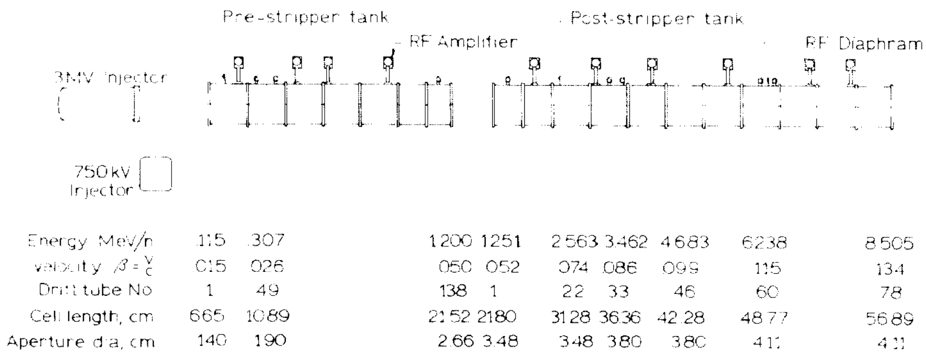


Fig. 1 Some characteristics of the Super-HILAC.

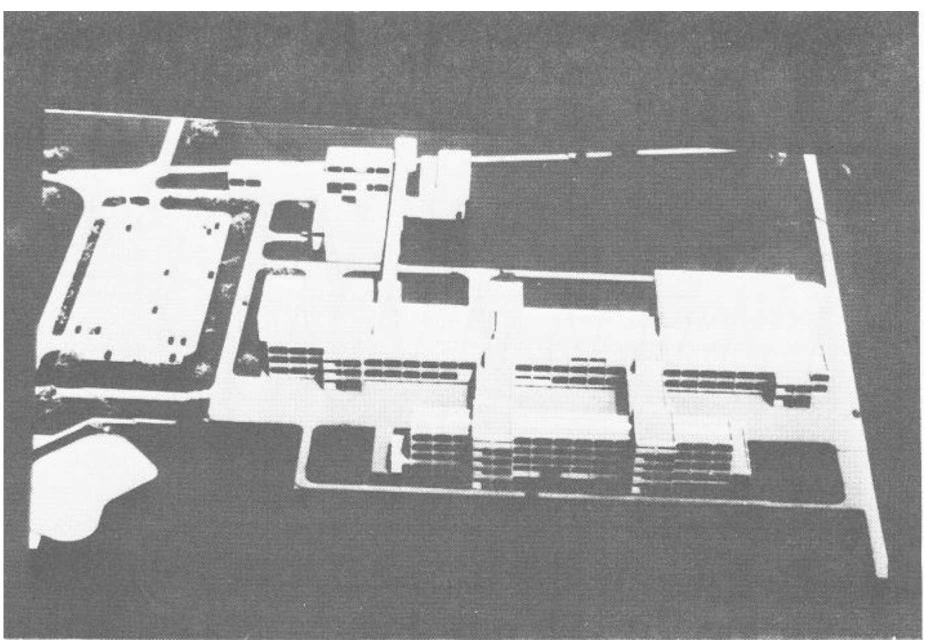


Fig. 2 Photograph of model of the UNILAC facility of the GSI at Darmstadt. The length of the main building is 252 meters.

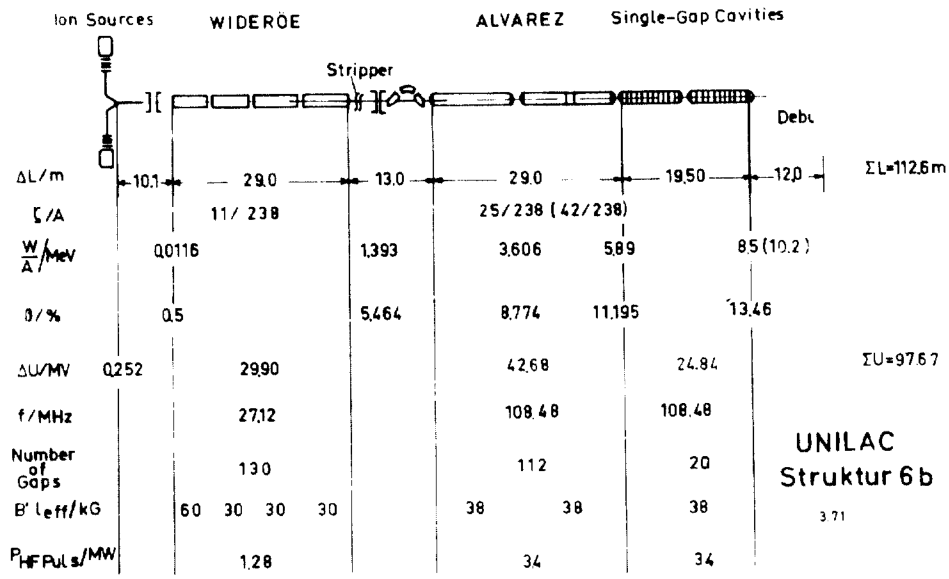
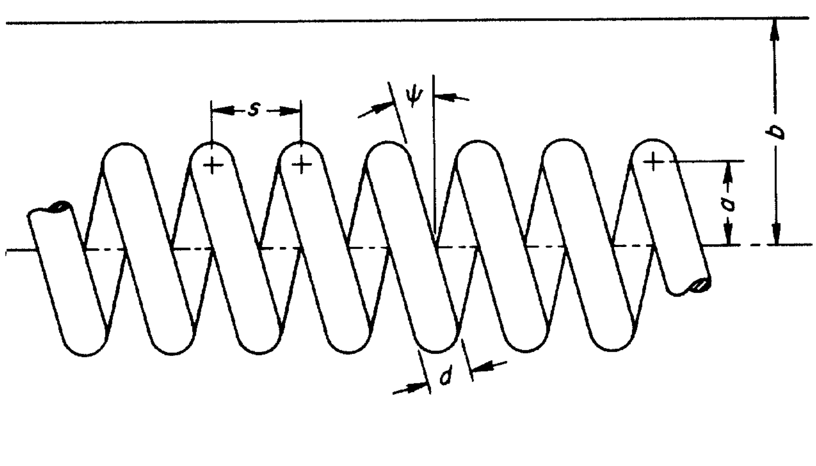


Fig. 3 The characteristics of the UNILAC.



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

Fig. 4 The spiral conductor of the helix-loaded cavity.

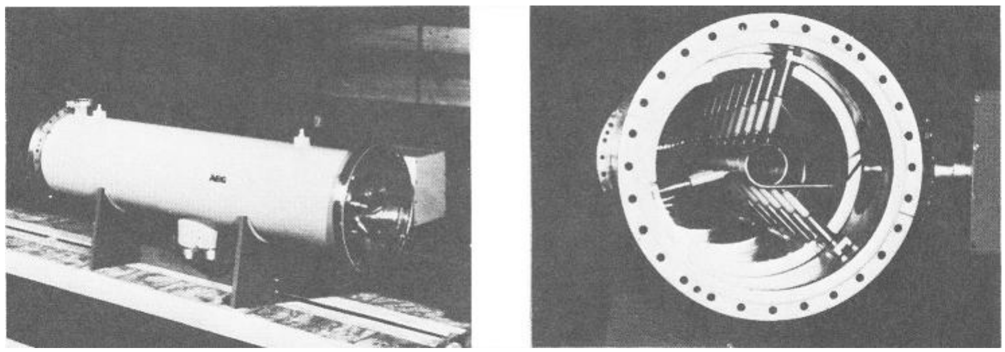


Fig. 5 Two views of an early one-meter helix-loaded cavity. The resonant frequency is 108 MHz.

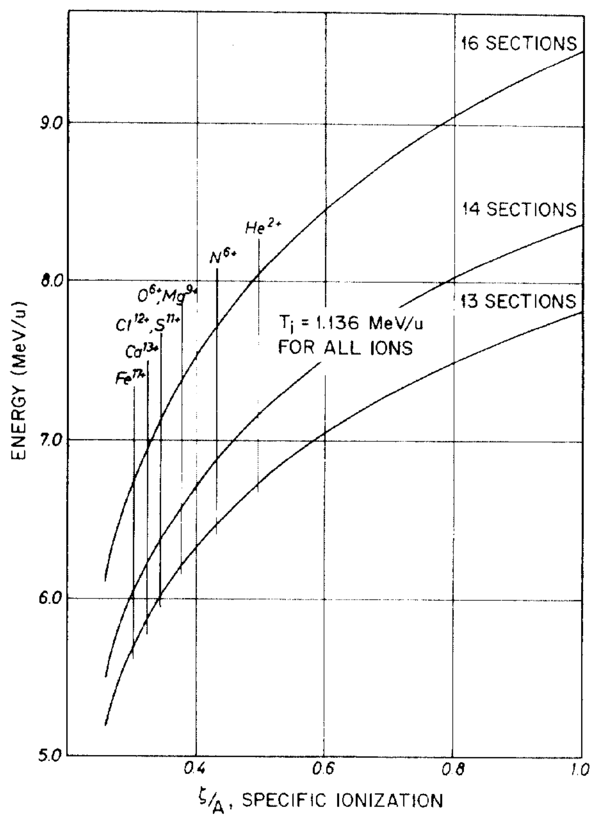


Fig. 6 Output energies for various ions for several versions of TALIX.

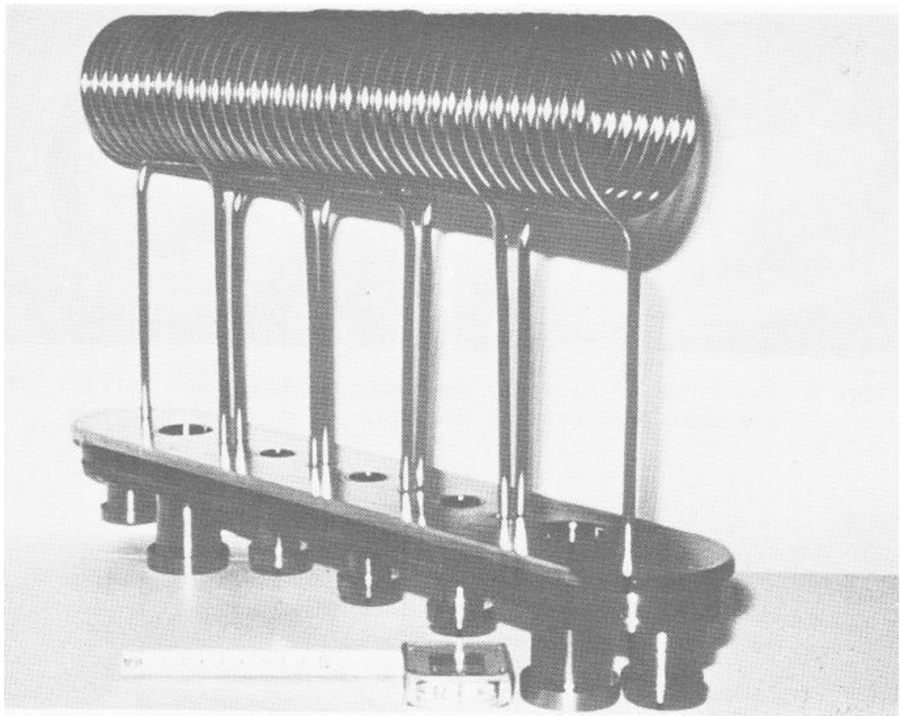


Fig. 7 The 5-section Nb helix of the Karlsruhe experiment.

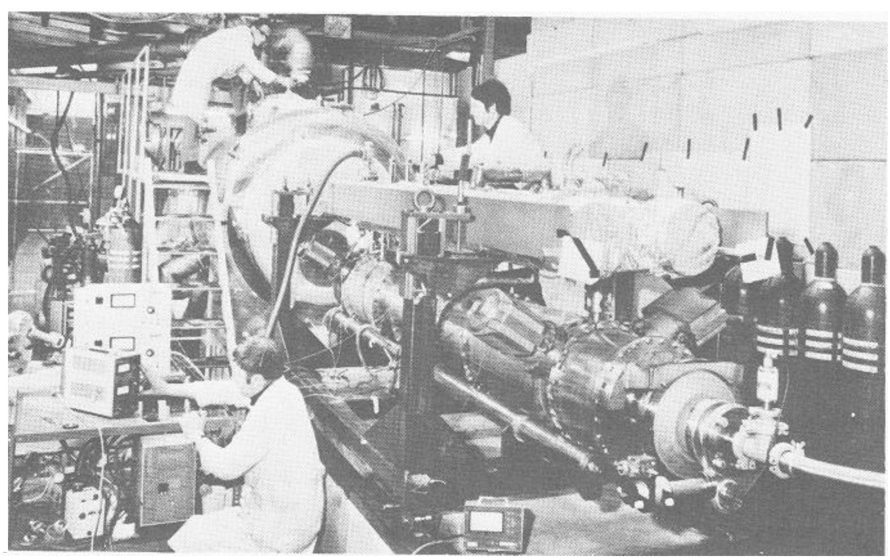


Fig. 8 The helix-section installed in the rf cavity. The whole assembly fits the cryostat tank seen in the background.

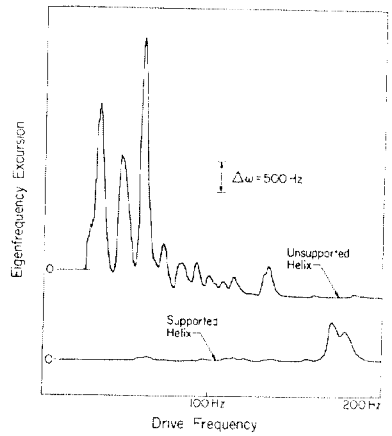


Fig. 9 Resonance frequency shift spectra for helical resonantor driven by audio frequency accelerator varying as Ω^{-1}.

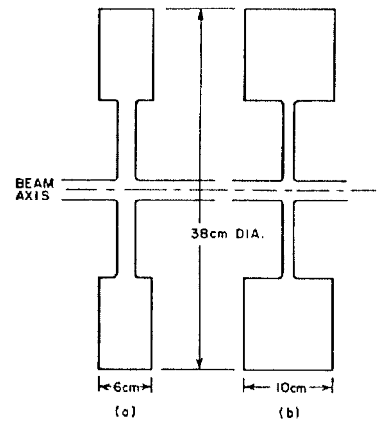


Fig. 10 Re-entrant cavities.
(a) for high β - 430 MHz
(b) for intermediate β - 217 MHz.

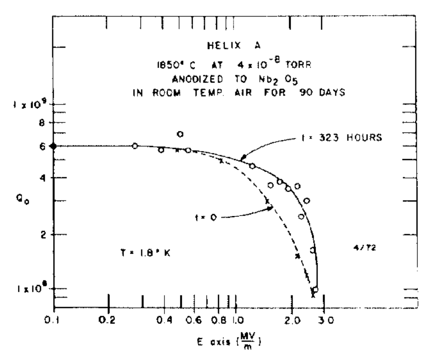


Fig. 11 Q vs axial electric field for superconducting helix at Argonne National Laboratory.

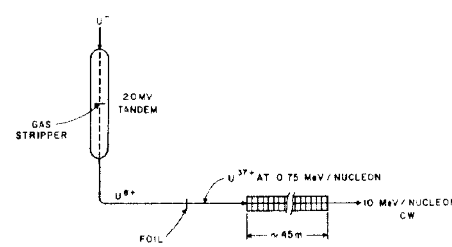


Fig. 12 Schematic of the operation of the Argonne accelerator.

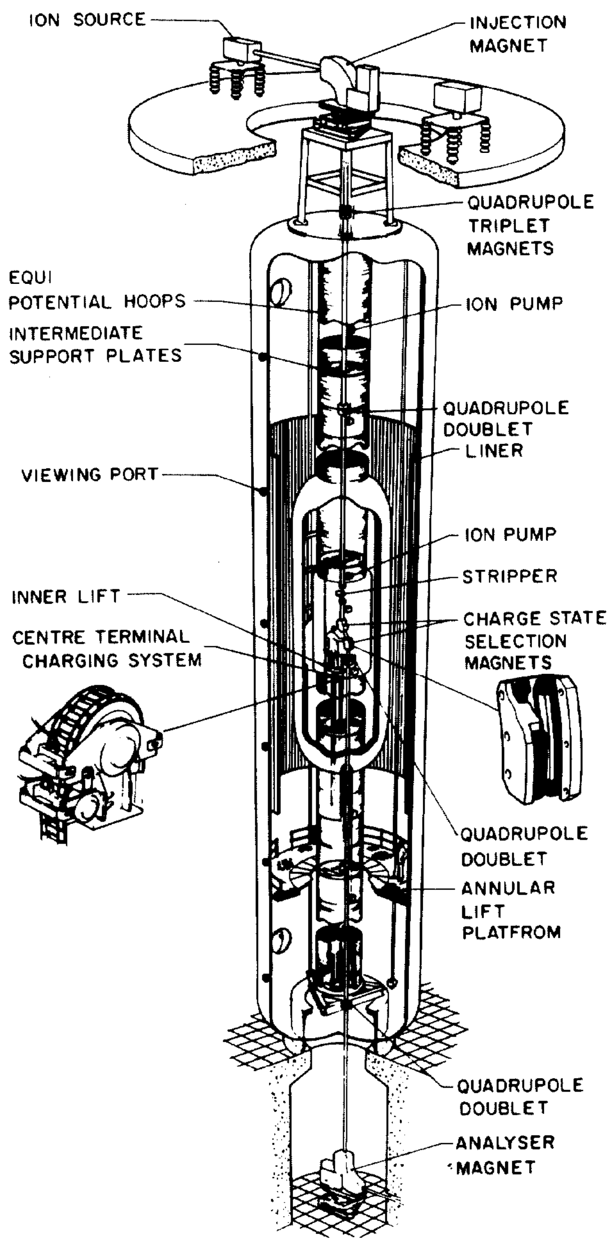


Fig. 13 Schematic drawing of the proposed Daresbury tandem showing some mechanical features.

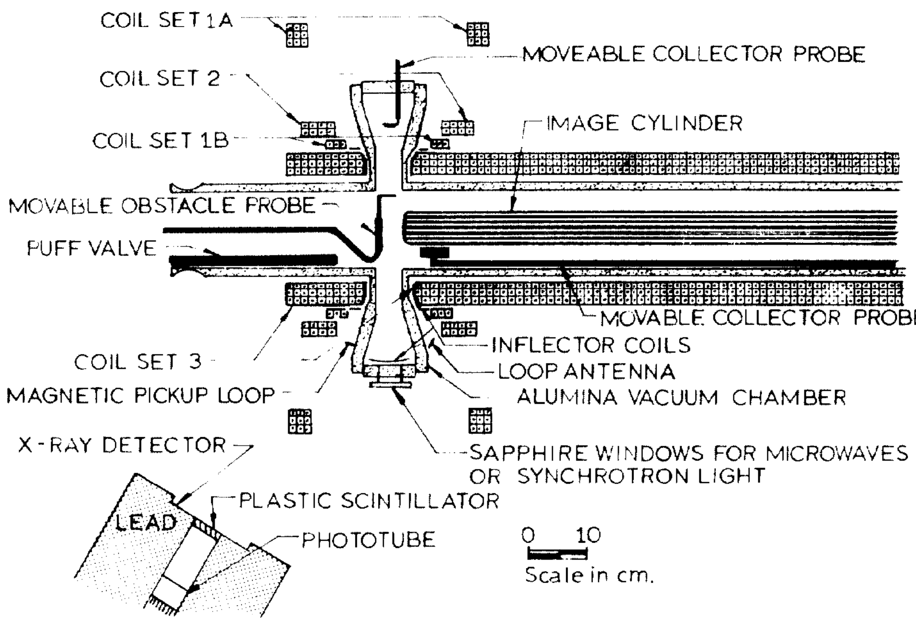


Fig. 14 Cross-section of the Berkeley ERA compressor.

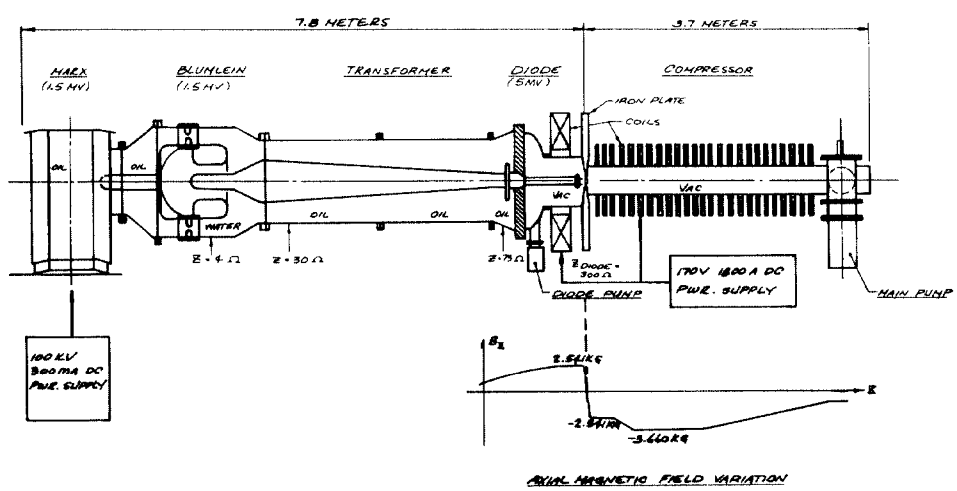


Fig. 15 The University of Maryland static magnetic field ERA.