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Conf-750824--13

ACCELERATORS FOR HEAVY IONS

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Abstract

The use of heavy ion accelerators in nuclear physics, nuclear chemistry, atomic physics, and in material sciences studies is rapidly increasing. This paper reviews the present and developing scene in heavy ion accelerator concepts and technology. The area of applicability of various methods, likely avenues of future development and the trends of future requirements are discussed.

1. Introduction

Those who were associated with the first isochronous cyclotrons will remember that the proposals for new machines inevitably included a discussion of the virtues of the isochronous cyclotron for heavy ion acceleration. However, the use of isochronous cyclotrons for heavy ion acceleration was slow in developing. In 1963, R. S. Livingston reported the performance characteristics of the isochronous cyclotrons then operating;[1] of the 14 machines reviewed, none had yet accelerated heavy ions.

Since the mid 1960s, a renaissance of interest in heavy ions has developed. At the 1966 isochronous cyclotron conference there was a single paper on heavy ion acceleration. At this meeting we see great interest and numerous papers related to heavy ion acceleration on existing cyclotrons and many proposals for new and much more powerful facilities designed specifically for heavy ion acceleration. The principal accelerator types used for heavy ions include tandem electrostatic accelerators and linear accelerators, as well as cyclotrons. The energy versus ion mass characteristics for some representative heavy ion accelerators are shown in Fig. 1. The following sections review the status and development of the several accelerator types.

2. Tandem Electrostatic Accelerators

Tandem electrostatic accelerators have proved to be very popular for heavy ion acceleration. A wide variety of negative ions can be produced relatively easily; the energy of the ion beams is smoothly variable and the energy resolution can be quite good. The output energy of tandems is favorable for heavy ion acceleration. For protons, a tandem with a terminal voltage of 10 MV is equivalent to a 20 MeV compact cyclotron in terms of output energy; however, for lead ions the 10 MV tandem will easily produce a 100 MeV beam (with a foil stripper). To produce the same energy with a cyclotron would require a very large machine. For example, for Pb^{10+} ions, a K = 200 cyclotron† is

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required, which is roughly the same size as would be required for 200 MeV protons. An additional important reason for the popularity of electrostatic accelerators is that they have been available commercially. It has generally not been necessary for an institution to form an accelerator design group to acquire a state-of-the-art electrostatic accelerator.

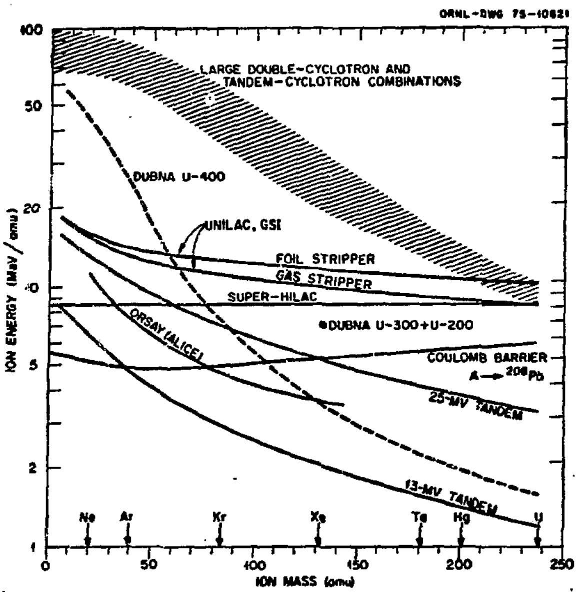

Fig. 1. Ion energy vs mass characteristics for several accelerators.

A very complete review of large electrostatic accelerators is provided by the special issue of Nuclear Instruments and Methods edited by D. Allan Bromley.[2] In addition to a review of the history of electrostatic accelerators[3] authored by the Editor, there are excellent papers on the technology of electrostatic accelerators and on most of the large machines.

2.1 Tandem Electrostatic Accelerators in Operation[3)]

Most of the tandem electrostatic accelerators now in use were manufactured by High Voltage Engineering Corporation in Burlington, Massachusetts. Twenty-six EN Model machines (5 MV terminal) were installed throughout the world during the period 1958-1969. Of the next largest model, the FN (7.5 MV terminal), 17 were installed in the period 1963-1969. The 10 MV MP tandems came into operation during the period 1965-1973; ten of these machines have been installed. Beginning in 1968 the National Electrostatics Corporation began manufacturing both single ended and tandem electrostatic accelerators. The NEC charging system uses "chain-belts" of small metal cylinders insulated from each other rather than a rubber-fabric or similar composition

*Operated by Union Carbide Corp. for the U.S. Energy Research and Development Administration.

†The energy from a cyclotron can be expressed as $E = Kq^2/A$ MeV. For a particular cyclotron, "K" is a constant related to the magnetic field-radius product, $K = 48.23\ B^2\rho^2$ MeV, MKS units. For low (non-relativistic) energies, K is approximately equal to the proton energy.

belt. The NEC accelerating tube design does not employ the inclined field principal developed by HVEC, but uses other methods for electron suppression. The NEC accelerating tubes are metal-ceramic bonded and routinely operate with much better vacuum than the HVEC accelerator. Large NEC accelerators now in operation include a Model 8UD (8 MV) at the University of Sao Paulo in Brazil and a 14UD (14 MV) at the Australian National University in Canberra.

There have been some notable tandem electrostatic accelerators built in other countries--two 5 MV vertical tandems were built by Metropolitan-Vickers in England; 5 MV machines were built by Toshiba and Mitsubishi in Japan; and in the U.S.S.R. a 5 MV vertical machine has been built and operated at the Institute of Electrophysical Equipment in Leningrad. The 4 MV folded tandem at the University of Auckland in New Zealand is especially noteworthy because of the use of the folded configuration in very high voltage tandems, as discussed in the following section. The largest tandem built to date is the HVEC Model XTU, rated at 16-18 MV. The machine, located at Burlington, Mass., has been operated only for testing. The high voltage generator structure has been to over 20 MV. With a set of MP tubes, over 15 MV has been achieved with beam.

Many tandems have been significantly upgraded to improve heavy ion acceleration capability and to achieve higher voltages. These improvements include the use of inclined field tubes (a HVEC development) to minimize electron loading effects and the use of polished stainless steel electrodes in the accelerating tube and SF_6 as insulating gas to improve the maximum voltage characteristics. Other modifications include conversion from fabric belt-type charging systems to the Pelletron or similar insulated chain link systems and modifications to the accelerating tube structure.

2.2 New Tandem Electrostatic Accelerators

At the Daresbury Nuclear Structure Laboratory in England a vertical tandem electrostatic accelerator with an ultimate voltage rating of 30 MV is being designed and built.[4)] A notable technical feature of the machine will be the use of a "laddertron" charging system in which metal "rungs" are connected at the ends by insulating links to form a ladder. Figure 2 shows a laddertron assembly installed in the pilot machine. A program of development and prototype testing is under way for the control components, the charging system, the resistor chain components, the accelerating tube, and the magnet systems. Essentially all of the components of the accelerator will be designed and built by the Daresbury group.

A second large electrostatic accelerator project is under way at Oak Ridge National Laboratory. This is the 25 MV tandem accelerator and associated facilities of the Oak Ridge Heavy Ion Laboratory.[5] The accelerator is being built by National Electrostatics Corporation. The most notable feature of the Oak Ridge tandem is the folded design. Fig. 3 shows a simplified layout of the tandem. Negative ions injected at the bottom are accelerated upward to the terminal where they are stripped to multi-charged positive ions. The stripped beams are bent

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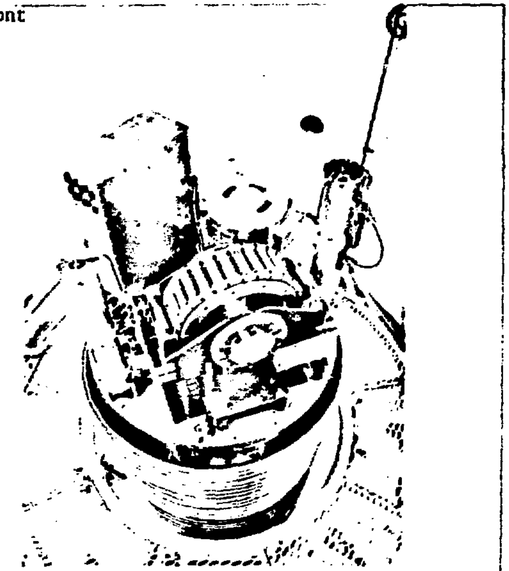

Fig. 2. Prototype Laddertron charging unit in the Daresbury pilot accelerator.

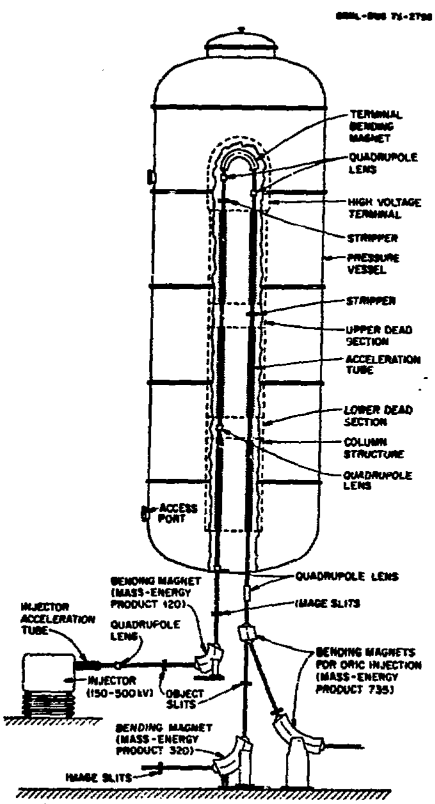

Fig. 3. Simplified layout of Oak Ridge folded tandem.

by a 180° magnet and the selected charge state is directed downward in a separate accelerating tube. The design offers significant economies in pressure vessel and building size, gas inventory, and, in addition, offers advantages of excellent charge selection in the terminal and location of the source at ground level. Table 1 lists some principal characteristics of the Oak Ridge tandem.

Table I. Preliminary Physical Parameters for ORNL 25 MV Tandem

Pressure Vessel Diameter (m)	10.5
Pressure Vessel Height (m)	29.9
Column Diameter (m)	3.35
Column Height (m)	18.89
Terminal Diameter (m)	3.96
Terminal Height (m)	4.87
Insulating Gas	SF_6
Maximum SF_6 Pressure (kg/cm^2)	8.78
Probable SF_6 Pressure (kg/cm^2)	6.3 - 7.3
Charging System	Dual "chain-belt"
Power Transmission	Rotating shafts total capacity ~50 hp

Other large tandems are planned or are being built. The Institute of Electrophysical Equipment in Leningrad is building a 10 MV Model EGP-20 based on the concepts of the 5 MV, Model EGP-10. A Model 14UD (14 MV) NEC tandem has been completed and is being installed at the Weizmann Institute in Israel. A Model 12UD is also being installed at the University of Tsukuba in Japan. The Japanese Atomic Energy Research Institute has chosen the NEC Model 20UR (20 MV - folded design) for their Nuclear Physics Laboratory at Tokai. Also in Japan, at Kyushu University, a 10 MV horizontal tandem is being designed and built. At the University of Milan in Italy, a tandem with 16-18 MV voltage rating is planned.[6] The accelerator is to be purchased in the U.S.

3. Linear Accelerators for Heavy Ions

The older machines now operating include the HILAC at Yale University and heavy ion linear accelerators at the University of Manchester, England, and at the Physical Technical Institute in Kharkov, Ukrainian S.S.R. They can provide beams in the mass range up to argon at the energy of about 10 MeV/amu but have output currents substantially less than a particle microampere.

The newest heavy ion linear accelerators, the Super-HILAC at Berkeley in operation since about 1972, and the UNILAC at Darmstadt to be operational at the end of the year, represent a second generation of heavy ion linear accelerators. A third generation is developing which will use both new accelerating structure concepts and the application of superconductivity in a variety of ways.

3.1 Super HILAC

The Super-HILAC[7] at Lawrence Berkeley Laboratory has evolved from the older Berkeley HILAC. Improvement in intensity has been achieved through improved injection, improved focusing, and increased duty factor. The Super HILAC can now routinely deliver 20 pµA of neon ions, 2 pµA of argon ions and 10 pnA of krypton ions at 8.5 MeV/amu.[8] The energy of the Super HILAC is independent of ion mass. Routine operation with ions heavier than krypton awaits improvement of the ion injection system. Changes to improve the Super HILAC are planned as part of the Bevalac Improvement Program to be discussed later.

3.2 UNILAC

The UNILAC[9] at the GSI (Gesellschaft für Schwerionenforschung) at Darmstadt, Germany will be the newest linear accelerator for heavy ions. Beam has been accelerated in the low energy stages of the machine since early this year; full energy operation is expected by the end of 1975. Beams already have been accelerated from the ion source, through the injection system, the pre-stripper stage and into the low energy experimental area at an energy of 1.4 MeV/amu. The UNILAC combines a number of different accelerating structures to obtain flexibility of operation. A 320 kV dc injector delivers beams to the linear accelerator at 0.12 MeV/amu. The pre-stripper, a Wideröe ($1/2\ \beta\lambda$) structure accelerates the beam to 1.4 MeV/amu. After stripping to a higher charge-state, a pair of Alvarez cavities accelerate the beam to 5.9 MeV/amu. Following the Alvarez sections a series of 20 single-gap cavities provide additional energy gain. These cavities are arranged to be independently energized and phased so that they can be used to either add or subtract energy from one or both of the Alvarez sections. In this way the output energy may be varied; when using a gas stripper for ^{238}U, the energy range will be from 1.4 to 8 MeV/amu. Higher energy, especially for very heavy ions, will be obtained with foil stripping. The maximum output energy depends on ion mass as shown in Fig. 1. The GSI laboratory at Darmstadt will provide essentially complete research and support facilities for heavy ion research and will be one of the largest single-purpose research facilities.

3.3 New Linear Accelerator Structure Developments

In 1972, at the time of the last cyclotron conference, the helix resonator and re-entrant cavity resonator were the principal new accelerating structures being considered for new heavy ion accelerators. Interest in both of those structures has continued and two new structures, the spiral resonator and the split-ring resonator have been developed.

The spiral structure was initially proposed and developed for superconducting application by G. J. Dick and K. W. Shepard,[10] California Institute of Technology, and developed for warm copper applications by a group at Los Alamos Scientific Laboratory.[11] The spiral cavity has advantages with respect to the helix structure of better mechanical stability and less frequency shift with RF field level. In the Los Alamos studies, very large shunt impedances were demonstrated and accelerating fields as high as 2.6 MV/m were demonstrated. A single cavity designed for β=0.025 gave a shunt impedance of 43 MΩ/m. This value is said to be substantially better than can be achieved with helix resonators. The effort at Los Alamos has since been discontinued. The University of Washington in Seattle is proposing a linac based on the Los Alamos and Cal Tech concepts,[12] see Table 2.

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Table 2. Active and Proposed Linear Accelerator Projects

Location/Project	Description	Status and Cost	Estimated Completion Date
Argonne National Laboratory[18] Argonne, Illinois	Helix and split ring resonators are evaluated for post-accelerator for 9 MV tandem. Will provide voltage gain of ~13.5 MV.†	Active project; ~ $2 M total $ 1.3 M accelerator	1978-1979
University of Frankfurt Frankfurt, Germany	Warm-copper spiral resonators as post-accelerator for 7 MV tandem. To provide 7.5 MV voltage gain.	Proposal	-
Max-Planck Institute for Nuclear Physics, Heidelberg, Germany	Prototypes for warm-copper spiral and superconducting helix resonator are to be evaluated for post-accelerator for 13 MV tandem. Voltage gain will be 10-13 MV depending on design. 13 MV would give 6 MeV/amu Br ions. Decision on resonator type and proposal will come early 1976.	Proposal early 1976; 10 MV spiral resonator cost ~ $1.2 M	-
Stanford University[19] Stanford, California	Post-accelerator for 9 MV tandem would employ 90 superconducting niobium re-entrant cavities to provide voltage gain from ~10 MV for Br to ~17 MV for protons. First phase is to be 36 cavities at cost of $1.3 M.	Proposal $3.2 M, accel. $0.6 M, bldg.	4 years from approval
University of Washington Seattle, Washington	Warm-copper spiral resonators as post-accelerator for 9 MV tandem. 41 resonators (4 gaps ea.) would provide 20 MV at 100% duty factor, 45 MV at 20% duty factor.	Proposal ~ $3 M	4-5 years from approval
State University of New York Stony Brook, New York	Superconducting split-ring resonators; post-accelerator for 9 MV tandem. Cooperative development with California Institute of Technology. Will provide ~20 MV voltage gain.	Study ~ $2 M	-

†The design voltage gain gives a means for calculating energy gain. For example, the ^{127}I beam from a 10 MV tandem would have an energy of about 100 MeV and would be stripped to I^{27+}. The energy gain in a 10 MV linac section would be 270 MeV. The final energy would be 370 MeV, or 2.9 MeV/amu.

Development of spiral resonator structures is also being conducted at both the University of Frankfurt[13] and the University of Heidelberg.[14] One of the University of Heidelberg resonators is shown in Fig. 4. The resonator has been run at full power level of 20 kW. The shunt impedance of 58 MΩ/m results in an effective accelerating voltage of 0.3 MV/resonator at 20 kW or 0.6 MV (at 80 kW 20% duty factor).

K. W. Shepard and co-workers[15] have recently proposed and demonstrated the superconducting split-ring cavity, Fig. 5. This development has come as a result of their optimization studies for superconducting resonators. They have achieved accelerating fields as high as 4 MV/m and have operated a cavity at over 3 MV/m for a long period of time. The split-ring resonator has much higher mechanical stability than the helix resonator, approaching the stability of the re-entrant cavity; for the same physical diameter the frequency can be three times lower, making beam bunching easier. Further development of the split ring structure is continuing at the California Institute of Technology, at Argonne National Laboratory and at the State University of New York at Stony Brook. A proposal for a post-accelerator linac for the Stony Brook FN tandem is being developed jointly with California Institute of Technology.[16]

Studies of superconducting helix resonators are continuing in Germany at the University of Frankfurt,[13] at the Institute for Experimental Nuclear Physics in Karlsruhe,[17] and the Max-Planck Institute, Heidelberg.[14] The latter two institutions are cooperating in the building and testing of a prototype superconducting helix accelerator for a post-accelerator for the Heidelberg MP tandem.

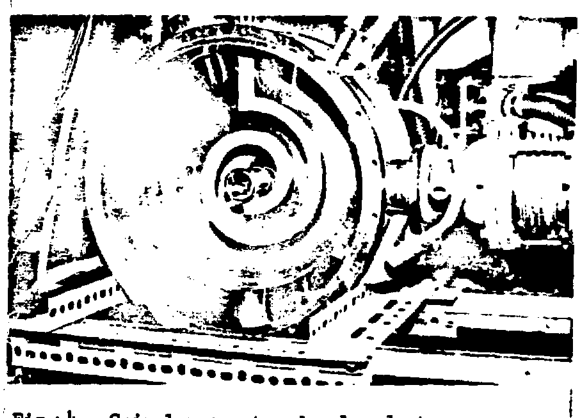

Fig. 4. Spiral resonator developed at Max-Planck Institute, Heidelberg.

3.4 New Linear Accelerator Projects or Studies

There are six new projects being built or being proposed. Table 2 summarizes some of the characteristics of these accelerators.

Fig. 5. Split-ring resonator

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4. Cyclotrons

4.1 Cyclotrons now Operating

More than 70 cyclotrons are listed in F. T. Howard's latest compilation "Cyclotrons–1975."[20] Of that number, 26 are large enough to be generally useful for heavy ion acceleration ($K \geq 40$) and 16 of these 26 are currently accelerating heavy ions. Intermediate size cyclotrons ($K = 75$-100) with significant heavy ion programs include the Berkeley 88-Inch Cyclotron, the Texas A&M University Variable Energy Cyclotron, the Oak Ridge Isochronous Cyclotron, the Harwell Variable Energy Cyclotron, the Grenoble Isochronous Cyclotron, CYCLONE at the University of Louvain, and the Cyclotron of the Institute of Physical and Chemical Research in Japan.[21] As an example of energy capability, $^{40}Ar^{8+}$ would be accelerated to an energy of 160 MeV in a K=100 cyclotron.

Two larger machines are used for heavy ion acceleration at the Laboratory for Nuclear Reactions of JINR, Dubna.[18] The U-200, ($K = 156$) delivers very high currents of light heavy ions, for example, 60 microamperes of 5 MeV/amu carbon ions, C^{3+}, and useful beam of heavier ions in the mass region beyond Ar. U-300, a classical (not isochronous) cyclotron, K=250, is the largest cyclotron now accelerating heavy ions. 50 microamperes of 182 MeV $^{22}Ne^{3+}$ 3 μA of $^{40}Ar^{7+}$ and 3×10^{12} particles/sec of $^{136}Xe^{9+}$ are examples of the performance of the U-300. The U-200 and U-300 have been used in a coupled mode, with the larger machine injecting into the smaller. By this means a beam of 925 MeV $^{132}Xe^{28+}$ at an intensity of 2×10^{10} particles per second have been achieved; Xe^{8+} ions were accelerated to 0.92 MeV/amu in U-300 and injected into the U-200 cyclotron by stripping.[19]

At the Institute de Physique Nucléaire, Orsay, the ALICE/CEVIL accelerator routinely provides beams of ions as heavy as ^{84}Kr for nuclear physics research.[22] A linear accelerator injector, energy of 1.15 MeV/amu, injects into a K=75 isochronous cyclotron. Some typical beams presently available are 100 nA $^{16}O^{6+}$ at 160 MeV; 300 nA $^{20}Ne^{8+}$ at 220 MeV; 300 nA $^{40}Ar^{13+}$ at 300 MeV; 30 nA ^{63}Cu at 367 MeV; and 10 nA ^{84}Kr at 400 MeV.[23] The performance for the heaviest ions is limited by the requirement of high charge state from the ion source, for example, 8^+ for Kr. Efforts are being made to reduce this requirement by increasing the linac voltage; an intensity gain of a factor of two or three is hoped for.

4.2 New Projects Being Completed

There are several new cyclotron projects under construction which are either dedicated to heavy ion acceleration or which have very significant heavy ion acceleration capability. Table 3 summarizes some of the physical and performance characteristics of those machines. Brief descriptions follow.

Table 3. Heavy Ion Cyclotron Projects in Progress

Location	Description	Estimated Completion Date
University of Louvain Louvain-La-Neuve Belgium	New injector, 70 q^2/A MeV, will inject ions into existing cyclotron CYCLONE (110 q^2/A MeV)	1979
Hahn-Meitner Institute Berlin, Germany	4 sector SSC, 100 q^2/A MeV with 6 MV electrostatic injector, > 7.5 MeV/A to Ar.	1976
Indiana University Bloomington, Indiana, USA	4 sector SSC, 220 q^2/A MeV with 16 q^2/A MeV injector. Initial heavy ion operation limited.	1975
Laboratory for Nuclear Reactions, JINR, Dubna, USSR	U-400 conventional isochronous cyclotron, 625 q^2/A MeV; 6.1 MeV/A Xe^{13+}, 7.2 MeV/A Kr^{9+}.	1976
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA	25 MV tandem electrostatic accelerator injects into 90 q^2/A MeV conventional isochronous cyclotron (ORIC). Will provide ≥ 6 MeV/A up to A=160.	1979

4.2.1 Indiana University Cyclotron[24,25] is a three-stage accelerator which will in initial configuration produce light ion beams up to 220 q^2/A MeV. The system consists of a 600 kV DC accelerator followed by a 16 q^2/A MeV injector cyclotron and the large separated sector cyclotron. In initial operation the accelerator will be limited to very light heavy ions, for example, the acceleration of ^6Li to 125 MeV (in this case the energy is limited by the acceleration of Li^{1+} ions in the final stage). Later, a more powerful injector platform will provide the capability of highly-charged ions. Further in the future there is the possibility of using a tandem electrostatic accelerator or other large injector accelerator to further improve the heavy ion capability.

4.2.2 VICKSI.[26] The VICKSI (Van de Graaff Isochron Cyclotron Kombination für Schwere Ionen being built for the Hahn-Meitner Institute in Berlin consists of a K=100 separated sector cyclotron with a modified High Voltage Engineering Corporation Model CN (6 MV) single-ended Van de Graaff accelerator as the injector. The design aim for the cyclotron is 0.1 pμA beam at energies up to 200 MeV at $\Delta E/E = 0.1\%$ for the mass range from carbon to argon. The cyclotron is being built by Scanditronix (Sweden).

4.2.3 CYCLONE Injector.[27] At the Université Catholique de Louvain, Belgium, an injector cyclotron is being built to provide high energy, multicharged beam for injecting by stripping into the existing CYCLONE machine (110 q^2/A MeV for heavy ions). The new injector will have an energy rating of 70 q^2/A MeV. Some expected beams are: up to neon at 27 MeV/amu at 2 kW of extracted beam; 10 MeV/amu Ar at 6×10^{12} particles/sec; 20 MeV/amu Ar at 2×10^{11} particles/sec; 6.6 MeV/amu Xe at 10^9 particles/sec. The cyclotron is a relatively conventional 4-sector machine and will be built in the University shops.

4.2.4 *U-400 at Dubna*[28] At the Laboratory for Nuclear Research at the Joint Institute for Nuclear Research in Dubna, a very large isochronous cyclotron is being built especially for the acceleration of heavy ions. The machine is being built using the classical cyclotron U-300 as the base. The new U-400 will be a 4-sector cyclotron similar in general design to U-200 but will have a different pole face structure to provide focusing up to 50 MeV/amu at slightly below maximum magnetic field. The cyclotron will provide heavy ion energies of 625 q^2/A MeV at 20 kG central field. A few of the beams and expected intensities include 14.1 MeV/amu $^{64}Zn^{7+}$ at 2.5×10^{13} particles/sec, 7.2 MeV/amu $^{84}Kr^{9+}$ at 1.3×10^{13} particles/sec and $^{132}Xe^{73+}$ at 10^{11} particles/sec.

4.2.5 Oak Ridge Heavy Ion Laboratory - Phase I.[29] The facilities being provided for injection of beams from the new 25 MV tandem into the ORIC for further acceleration are an important part of the new Heavy Ion Laboratory project at Oak Ridge National Laboratory. Figure 6 compares the beam energy that can be obtained with the tandem alone and with the use of the ORIC as an energy booster. Beam energy will range from a maximum at 20 MeV/amu for A=40 to about 3.5 MeV/amu at A=200 at the maximum intensity of ∿ 0.1 pμA. Nuclear reactions with a lead target (threshold ∿ 5 MeV/amu) will be achieved with ions of masses up to A = ∿ 150. Slightly higher energy may be achieved at a reduced intensity. As an example of operation of the system, $^{127}I^{8+}$ from the tandem is injected into the cyclotron at an energy of 225 MeV, changed to $^{127}I^{32+}$ at the stripping foil, accelerated to 725 MeV in the ORIC, then extracted and used in existing experimental facilities. This facility is expected to be operational in early 1979. The 25 MV tandem is described elsewhere in this report.

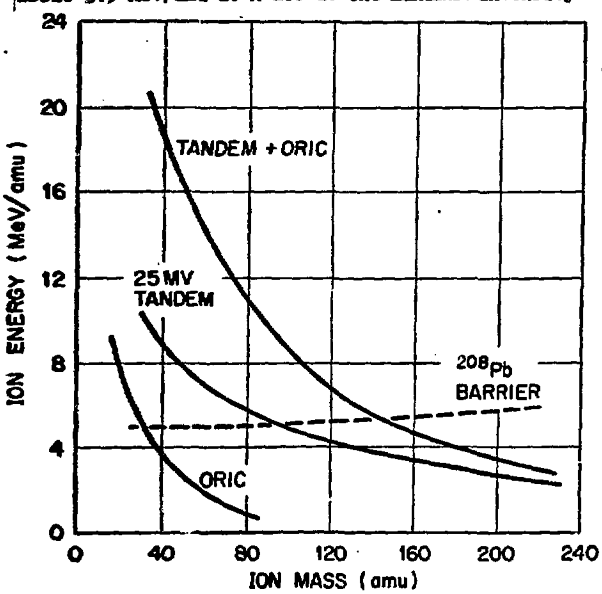

Fig. 6. Ion energy vs ion mass for 25 MV tandem-ORIC combination.

4.3 Proposed Cyclotron Projects

Several new heavy ion cyclotron projects are being planned, see Table 4. Four of these projects, the GANIL project in France, the Phase II project for the Oak Ridge Heavy Ion Laboratory, the South African National Accelerator Facility, and the Quebec Heavy Ion Project are large-scale efforts toward major national facilities. The Chalk River, Michigan State University, and the University of Milan superconducting projects are somewhat smaller in scale and scope, and are viewed as development projects.

4.3.1. GANIL.[33] The GANIL project (Grand Accelerateur National á Ions Lourdes) is a multi-accelerator project for heavy ions being planned as a national facility for France under the joint auspices of the French Atomic Energy Commission (CEN) and the National Institute of Nuclear and Particle Physics. The system consists of three stages. The main stages are two identical K=400 separated-sector cyclotrons. Ions from the first of these cyclotrons are stripped and the selected high charge injected into the second. The injector for the first stage may be either a compact cyclotron or a small (1 MV) electrostatic accelerator. The two large cyclotrons may be used separately when only medium energy light ions are needed. The cyclotrons have 52° sectors, which provide good ion focusing to beyond the design limit of 100 MeV/amu. The RF systems of both cyclotrons will include 3rd harmonic dees for flat-topping of the accelerating voltage to increase the intensity and energy resolution. For high resolution beams, $\Delta E/E = 4 \times 10^{-4}$, the maximum intensity is expected to be about 10^{11} particles per second for very heavy ions and 10^{12} particles per second for light ions. For an energy resolution of 10^{-3}, the light ion intensity is expected to be an order of magnitude larger.

The project is expected to cost approximately $40,000,000 (1974). The beginning of the project is anticipated for 1976; time for completion will be about five years. Sites near Caen, near Bordeaux, and between Lyon and Grenoble are being evaluated.

4.3.2. Oak Ridge Heavy Ion Laboratory - Phase II[31] Phase II of the Oak Ridge project will consist of the addition of a K=300 4-sector isochronous cyclotron and additional experimental areas adjacent to the existing ORIC and Phase I projects. The cyclotron is similar in concept to the K=440 cyclotron that was included in the National Heavy Ion Laboratory proposal.[32] The new K=300 cyclotron will be able to accelerate beams from either the 25 MV tandem electrostatic accelerator or from the ORIC. With injection from the tandem, the beam energies near maximum intensity will range from ∿ 75 MeV/amu for light heavy ions to 10 MeV/amu for heavy ions like uranium. With the tandem as injector, the beam intensity will be typically about 1 pμA. With the ORIC as injector, intensities for light heavy ions can be in the 10-100 pμA range in favorable cases because of the low charge state required. For a final energy of 75 MeV/amu, the ions accelerated in ORIC would be C^{3+}, O^{4+}, etc., ($q/A \simeq 1/4$).

4.3.3 South African National Accelerator Facility.[33] A study has been made at the University of Stellenbosch under the sponsorship of the Government of the Republic of South Africa for a multi-cyclotron accelerator facility to satisfy developing national research needs. Much of the emphasis in the design is on light-ion capabilities to satisfy the requirements of medical uses. The 4-sector separated-sector cyclotron will provide protons to 200 MeV and heavy ions with energies to 200 q^2/A MeV. A variety of injectors are being discussed. With the present injector choice, a K=8 solid pole cyclotron, the accelerator would give modest heavy ion energies, Ar^{7+} at 245 MeV, for example. With a K=50 cyclotron as injector, with doubling of the charge-state by stripping between the injector cyclotron and the main stage, expected ion energies are: C^{6+}, 50 MeV/amu; Ne^{10+}, 50 MeV/amu; Ar^{12+}, 18 MeV/amu and Kr^{12+}, 4 MeV/amu. Intensities are expected to exceed 1 pμA. The site for the accelerator has not been selected; however, a location near Capetown is favored by the planners of the facility.

4.3.4 Quebec Heavy Ion Facility.[34] In Canada, a joint project of Laval, McGill, and Montreal Universities is in the preliminary planning stage. As envisioned the accelerator would be a double-cyclotron system with a K=28 compact cyclotron injecting into a large separated sector cyclotron (K=500). It is anticipated that this combination will provide above 10 MeV/amu for all ions up to A=180.

4.3.5 The Chalk River Superconducting Heavy Ion Cyclotron.[35] At the Chalk River Nuclear Laboratories

Table 4. Cyclotron Proposals and Development Projects

Location/Name	Description	Estimated Completion
Quebec Heavy Ion Facility, near Montreal, Canada	K=500 4-sector SSC with K=28 compact cyclotron as injector. Provide ≥ 10 MeV/amu to A=180.	1980 (Study)
GANIL To be national facility of France. Site not chosen.	Multi-cyclotron accelerator system. Small injector cyclotron is followed by two K=400 cyclotrons. Energy > 10 MeV/A for all ion masses and up to 100 MeV/A for light ions.	1980 (Study)
Republic of South Africa Site not chosen	K=200 4-sector SSC with small cyclotron injector. Will accelerate protons to 200 MeV. Designed for wide variety of medical and applied research uses as well as basic physical research.	1980
Oak Ridge National Laboratory Heavy Ion Facility Oak Ridge, Tennessee USA	K=300 4-sector SSC is used as post-accelerator for 25 MV tandem or for ORIC energies ≥ 10 MeV/A for all ion masses and up to 75 MeV/A for light ions.	1982-1983 (Study)
Chalk River Nuclear Laboratory Chalk River, Canada	K=500 superconducting cyclotron post-accelerator for 13 MV tandem. Will provide ≥ 10 MeV/A for all ion masses and up to 50 MeV/A for light ions.	Full-scale prototype program complete 1977
University of Milan Milan, Italy	K=500 superconducting cyclotron as post-accelerator for 16-18 MV tandem.	Study
Michigan State University East Lansing, Michigan USA	K=400 superconducting cyclotron post-accelerator for 13-25 MV tandem injector. With 13 MV injector would provide ≥ 10 MeV/A for all ion masses and light ions up to 75 MeV/A.	Full-scale prototype program complete 1977

in Canada a cyclotron with superconducting magnet coils is being designed as a booster for the CRNL Model-MP tandem Van de Graaff. This emerging new class of cyclotrons is based on the concept of using superconducting coils in a configuration similar to that used for bubble chamber magnets with separated iron pole tips arranged to provide as much focusing as possible. At the design field of 5T the pole-tips are fully saturated and the magnetic field can be considered as the sum of the field distribution produced by the fully saturated pole tips, and the azimuthally constant "air core" field of the super-conducting coil system. H. G. Blosser and D. A. Johnson[36] have shown that the maximum energy of heavy ions in a saturated magnet as limited by focusing may be expressed as $E = K_f\ q/A$, where K_f is the proton energy limit of the cyclotron as determined by flutter. Thus the energy limit for a superconducting cyclotron is given by the smaller of the energies given by $E = K_f\ q/A$ (focusing limit) or $E = Kq^2/A$ (bending limit). An additional energy limitation may occur for light ions as a result of the inability to satisfy the necessary charge changing requirements to capture the beam in the proper orbit for acceleration.

Figure 7 illustrates the ion mass-energy constraints for the Chalk River cyclotron. The CRNL design has a K factor ($E=Kq^2/A$) of 500, obtained with a magnetic field of ∿ 5T at a maximum beam radius of 0.65 m. The compactness of the cyclotron is illustrated by Fig. 8. The diameter and height are both about 3 m. The project at Chalk River is proceeding with a full-scale magnet and RF prototype program.

4.3.6 Michigan State University.[37] The concept of the MSU cyclotron is similar in many respects to the Chalk River design but differs in details. The present plan at MSU is for a K=440 MeV cyclotron with K_f=150. A two-year study will include a full-scale magnet and RF system prototype. The injector for the machine has not been determined. The injection system is being evaluated for the requirements of matching tandems ranging in voltage rating from 13 to 25 MV. The technology to be employed in the beam extraction system, whether it is to be a superconducting element or more conventional magnets, has not been determined. Extraction studies are to be part of the development program.

4.3.7 Other Superconducting Cyclotron Studies. Studies at Berkeley[38] and Oak Ridge[39] have followed the same general rationale as the MSU and Chalk River concepts. A new study program is just beginning at the University of Milan[6] to investigate the feasibility of a cyclotron with superconducting coils as an energy booster for a 16-18 MV tandem.

4.3.8 Recycle Acceleration. Recycle acceleration of heavy ions in cyclotrons has been brought closer to realization. The recycle method offers a possibility of increasing the energy from small cyclotrons by use of stripping to increase the charge state. Recent experiments by M. L. Mallory and E. D. Hudson have demonstrated the principal features of the method.[40] In recycle acceleration, ions are passed twice through the same cyclotron; ions accelerated on the first cycle are reinjected into the cyclotron, stripped to higher charge state and accelerated again on a different (lower) harmonic of the RF. The relation $q_1h_1 = q_2h_2$ between the initial and final charge and harmonic numbers must be satisfied. The Mallory and Hudson experiments demonstrated simultaneous acceleration and extraction of beams with different charge states.

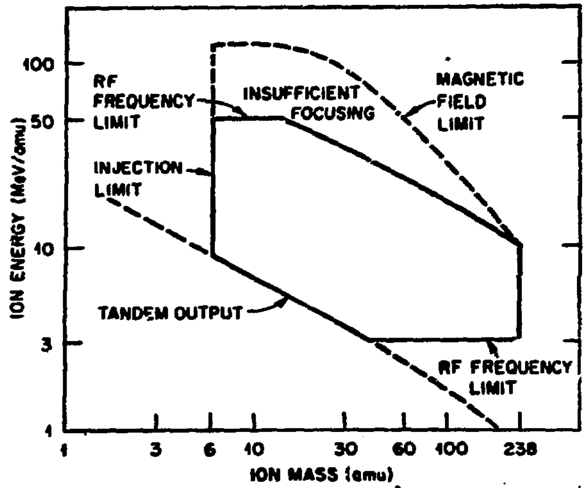

Fig. 7. Ion energy vs ion mass for CRNL superconducting cyclotron.

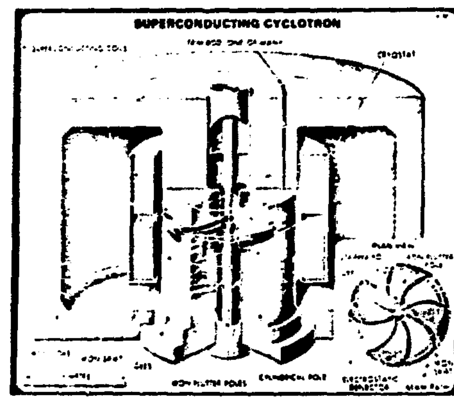

Fig. 8. Early version of the CRNL cyclotron.

5. Synchrotrons for Heavy Ion Acceleration

The use of synchrotrons for heavy ion acceleration is becoming important with increasing interest in research with heavy ions in the energy regions of several hundred MeV/amu. The coupling of the Super HILAC to the Bevatron has provided useful beams of very high energy ions. The Bevalac[41] now provides ions from helium to krypton in the energy range of 200 MeV/amu to about 2000 MeV/amu at intensities of about 3×10^{10} particles/pulse (a pulse every 6 sec) through Ne, 5×10^8 for Ar, and about 10^4 (expected) for Kr.

To extend the energy range downward and to provide higher intensities, a program of modification to both the Super HILAC and the Bevatron is being planned.[42] The improvements will include: (1) an increase in Super HILAC output for high-mass ions by providing a new injector, and (2) extension of the capability of the Bevatron for accelerating partially ionized ions by improving the vacuum. The latter improvement will allow the mass range to be extended downward to the 30 to 100 MeV/amu range. The new injector for the Super HILAC will be a Wideröe linac patterned closely after the UNILAC design. Intensities from the Super HILAC for ions above argon will be increased about two orders of magnitude. A peak output of the Super HILAC for U ions is expected to be about 3 particle microamperes. The output of the Bevalac would be about 10^{10} particles/pulse to A=30, 10^9 to mass A=120, and 10^8 to A=210.

At Dubna in the U.S.S.R., there are plans for a 15-20 GeV/amu superconducting synchrotron with room temperature booster; a feasibility study is being made in Japan for a facility (the Numatron) to operate in about the same energy range as the Bevatron.

The increasing interest in higher energy heavy ions suggests that such considerations may play an important role in planning future heavy ion accelerators. It is not unlikely that the concept of a fast cycling synchrotron will again become important.

6. Other Heavy Ion Acceleration Methods

The Electron-Ring Accelerator (ERA) and various linear collective acceleration methods are still being developed in active programs. Eighteen papers on collective acceleration and intense beams were presented at the 1975 Particle Accelerator Conference.[41] Although some experimental successes were reported and better theoretical understanding is developing, practical collective effects accelerators appear to be far in the future.

7. Conclusions

From the foregoing it should be clear that there is a tremendous amount of activity in the heavy ion field, and that the types and characteristics of heavy ion accelerators being employed and developed are widely diverse. One conclusion that may be drawn is that there is no clear superiority of any particular accelerator type for all applications.

The mass-energy ranges of representative types of accelerators are shown in Fig. 9. The limitations of ordinary cyclotrons (single-stage) and tandems are clearly apparent. It would require gargantuan and impractical machines of either type to achieve 10 MeV/amu for high-mass ions. Linacs have a characteristic that leads to a relatively slight rise of specific energy for low mass ions; thus they seem less well-suited to developing current interest in research with highly energetic heavy ions. Linac costs scale roughly linearly with energy, so it would seem impractical to attempt to achieve 100 MeV/amu with present concepts. The two-stage accelerators with a large cyclotron second stage have the useful characteristic of very high energies for light ions—a bonus advantage for a machine designed primarily to achieve a minimum of 10 MeV/amu for the full mass range. When high energies—200 MV/amu and above—become important for the heaviest ions, we will need to look to synchrotrons or perhaps superconducting cyclotrons.

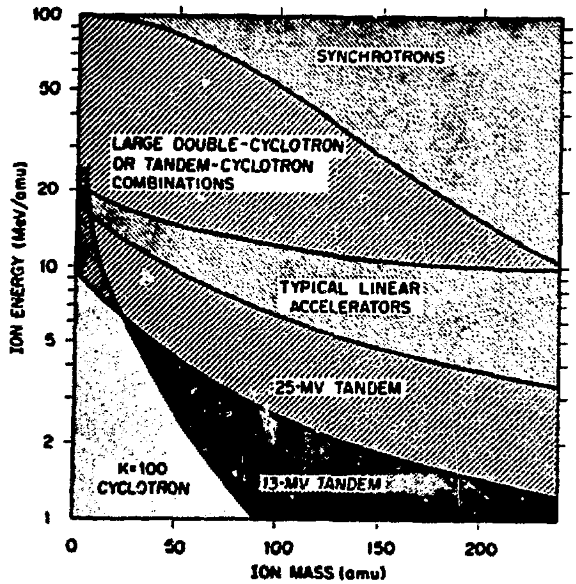

Fig. 9. Approximate regions of application of various accelerator types.

The other dimensions of accelerator performance—beam emittance, energy spread, and flexibility—are not addressed in this paper except to remark that electrostatic accelerators remain the standard. With electrostatic accelerators it is easy to achieve low emittance beams with low energy spread, good stability and easy energy variability. Some of these characteristics have been achieved in specific accelerators of other types, but not in general. It remains, then, a challenge for the future to achieve those characteristics routinely in other accelerators.

8. Acknowledgements

The author wishes to thank all those who provided information on their accelerators. Unfortunately it was not possible to include or acknowledge all interesting and useful contributions.

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