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RECENT ADVANCES IN DESIGN FOR LOW- AND MEDIUM-ENERGY HEAVY ION ACCELERATORS

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Introduction

In the late 1960s many fields of science experienced a weakening of support. Particle accelerators used in nuclear physics and chemistry research suffered especially. For a period of several years there were no new accelerators built and a number of facilities were either shut down or forced to develop new means for support. Today, the situation seems to be changing. We see a resurgence of activity throughout the world in the design and construction of low- and medium-energy accelerators, stimulated in large part by advances in heavy ion research. These new accelerators all involve either the development of new technology or a significant scaling and modernization of mature technologies. This paper reviews recent developments in the technology of electrostatic accelerators, linear accelerators, and cyclotrons for the acceleration of heavy ions.

Electrostatic Accelerators

Seven new tandem electrostatic accelerator installations are being built or are contracted.[1-7] In this type of machine, negative ions are accelerated to a positively charged terminal where they pass through a gas or thin foil "stripper" to become multiply charged positive ions and then are accelerated back to ground potential. The technology employed in all of these tandems has been developed to overcome the limitations of older machines and to satisfy the more stringent requirements for heavy ion acceleration. The characteristics of the seven tandems are summarized in Table 1. Two of the tandems on the list are significant modernizations of old accelerators. The tandem being installed at Padua is the STU that was tested to 21 MV without accelerating tubes by the builder, High Voltage Engineering Corporation, and for many years held the high voltage record. The tandem at Catania is a modification of the first MP (so-called Emperor) tandem ever built. It was designated MP-0 and was kept at HVEC as a development machine until the recent sale. All of the HVEC machines listed will use 150 kV ion source/injector systems from General Ionex Corporation.

The rubberized fabric charging belts of older electrostatic accelerators are being replaced by more reliable systems. Pelletron chains,[8] consisting of short metal cylinders coupled by insulating links are employed in the machines built by National Electrostatics Corporation (NEC). The Daresbury tandem and the HVEC modernizations utilize the Laddertron[9] system which resembles a chain ladder with closely spaced rungs insulated from each other. Compared to the conventional rubberized fabric belt, these systems have the advantages of high reliability and long life, uniform charge transport, predictable breakdown characteristics, and cleanliness.

The accelerating tubes of heavy ion accelerators must be designed to eliminate or compensate the secondary electron/ion production that results from the large charge-exchange cross section of heavy ions, especially the negative ions in the low energy tube. This is accomplished by the following means: designing the tube system to achieve very low pressure by providing

Table 1. Tandem Accelerators

Location	Description	Voltage (MV)	Completion Date	Features
Argentina, Buenos Aires[1] National Commission of Atomic Energy	NEC Pelletron - 20UD	20	1982	Linear tandem; conventional control
China, Peking[2] Atomic Energy Institute	Improved HVEC MP Model HI-13	13	1982	Pure SF_6, Terminal pumping; Laddertron charging
Great Britain, Daresbury[3] Daresbury Nuclear Laboratory, NRC	Daresbury developed and designed	30	1980	Laddertron charging; inorganic bonded tubes; pure SF_6, digital control
Italy, Catania[4] National Institute of Nuclear Physics	Improved HVEC-MP	13	1979/1980	Modified tank; pure SF_6; terminal cryopumping
Italy, Legnaro (Padua)[5] National Institute of Nuclear Physics	Improved HVEC-XTU	16	1979/1980	Pure SF_6; Laddertron charging system
Japan, Tokai[6] Japan Atomic Energy Research Institute	NEC Pelletron - 20UR	20	1979	Folded tandem; full digital control
U.S.A., Oak Ridge[7] Holifield Heavy Ion Research Facility Oak Ridge National Lab.	NEC Pelletron - 25URC	25	1979	Folded tandem; full digital control; 27.5 MV electrostatic design

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good pumping and using materials and fabrication methods to assure low outgassing rates; and by providing means for quickly removing the ions and electrons formed by the residual gas interactions thereby assuring that secondary ions and electrons are not accelerated sufficiently to produce large secondary ion and electron emission or x-ray loading.

NEC accelerators and the Daresbury accelerator use inorganic bonded Al_2O_3 tubes with Ti electrodes and additional pumping stations along the accelerating tube system to achieve operating pressures in the 10^{-8} to 10^{-7} torr range. Means are provided in both systems for secondary removal and for decoupling the tube system along its length by apertures and/or ion and electron traps.

The tandems built by HVEC use accelerating tubes with glass insulating sections and highly polished stainless steel electrodes bonded with polyvinyl acetate. The electrodes are shaped to produce an electric field component perpendicular to the axis to cause secondary electrons and ions to be swept out of the tube quickly. The HVEC inclined field tube has a higher pressure tolerance, giving good performance in the 10^{-6} torr range. Additional electron trapping is also used with HVEC tubes with good results.

Recent experience with the MP tandem at Brookhaven National Laboratory[10] gives a good example of the improvements gained with upgrading. Through a series of improvements which included replacing the belt charging system with Pelletron chains, improving high voltage protection of resistors, installing the latest HVEC inclined field accelerating tubes and adding magnetic electron traps to the accelerating tubes, the usable voltage has been increased from 12 MV to 14 MV.

All of the NEC accelerators now under construction will use additional pumping along the accelerating tubes. For example, the Oak Ridge 25 MV tandem will use ion pumps in major and minor dead sections. Figure 1 illustrates some of the complexities of modern heavy ion tandems.

Terminal-charge selection is being planned for most of the machines under construction. When the negative ion beam passes through the gas or foil terminal stripper, the most abundant charge state will account for only a fraction, typically < 30%, of the ion beam; there will be a significant fraction of the beam in charge states both above and below the most probable state. The use of a terminal charge selector eliminates these undesired charge states that would otherwise be accelerated to a different energy and be eliminated by the energy analyzer. Eliminating the unwanted ions in the terminal will reduce the loading on the high energy tube and allow the accelerator optics to be set optimally for the single charge state.

Optics design for the new accelerators is being done very carefully. Studies for the Oak Ridge tandem show that the beam from conventional ion sources can be accelerated without loss except for the unavoidable effect of residual gas charge exchange and loss in the terminal stripper.[11,12]

Control systems for the new accelerator are a major departure from the designs of a few years ago. Daresbury, Oak Ridge, and Tokai machines will be exclusively digitally controlled systems. This has meant a significant effort toward hardening sensitive electronics against the effects of electrical transients.

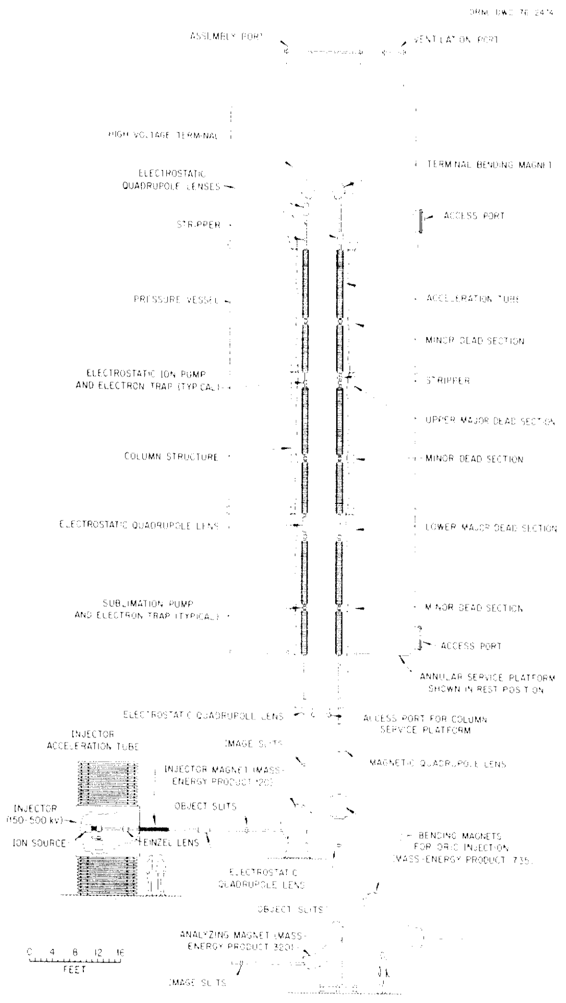

Fig. 1. Schematic drawing of the ORNL 25 MV tandem

The new NEC tandems and the Daresbury tandem are vertical machines. This has quite naturally led to architectural innovation. Figures 2, 3, and 4 show the buildings for the Oak Ridge, Daresbury and Tokai tandems. It should be noted that the more conventional structure at Tokai is the only one of the three completed on schedule and without difficulties.

The tandems at Tokai, Oak Ridge, and Daresbury are in the installation phase. High voltage tests without accelerating tubes were recently completed for the NEC 20UR tandem at Tokai. A terminal potential of 23 MV was reached, with 18 sparks in six hours. At 22 MV there were no sparks in one and one-half hours.

Linear Accelerators

Following the building of the HILAC at Berkeley and Yale and the linacs at the University of Manchester, England, and at the Physical-Technical Institute of the Ukraine at Kharkov, Ukraine, there were no new heavy ion linac accelerators built until the UNILAC at GSI, Darmstadt came into operation in 1975. Recently, there has been a resurgence of interest and several new projects are now underway. Table 2 lists seven heavy ion linear accelerator construction or development projects.[13-19] Essential elements stimulating the increasing activity are the development of new accelerating structures uniquely suited to the acceleration of very low velocity heavy ions, and maturing of the

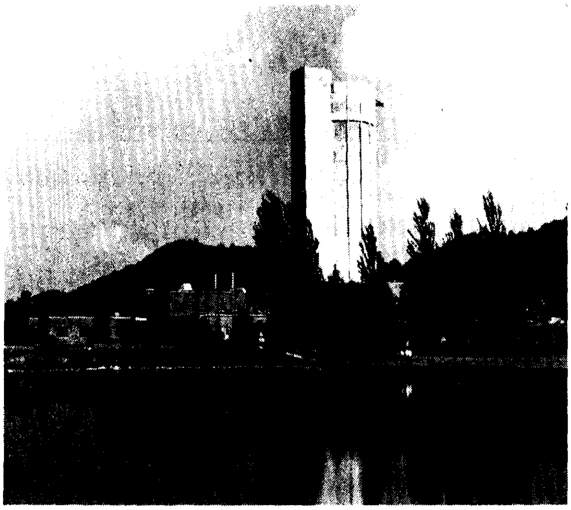

Fig. 2. The building for the Oak Ridge folded tandem is 165 ft (50 m) in height.

Fig. 3. The Daresbury tower rises to a height of 225 ft (69 m).

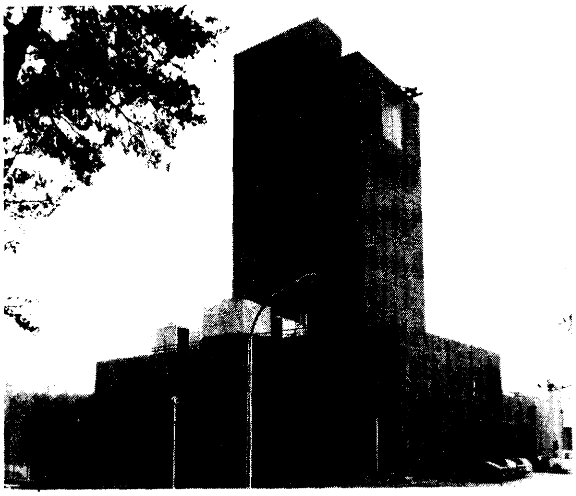

Fig. 4. The new tandem building at JAERI. It is about the same height as the Oak Ridge tower.

technology of rf superconductivity. At least four new accelerator structures, the helix resonator, the spiral resonator, the split-ring resonator, and the Interdigital H-structure have been developed for low-velocity applications. Figures 5, 6, and 7 show, respectively, examples of helix, spiral, and split-ring resonators. The helix and spiral resonator have been used in both room-temperature and superconducting resonators. The split-ring resonator with very favorable ratio of peak surface electric field to peak surface magnetic field seems presently favored for superconducting systems. All of the new structures except the Interdigital H consist of a large number of independently phased resonators which may be adjusted to accelerate ions over a very wide velocity range without changing the frequency. The new projects, with the exception of the SuperHILAC injector, are tandem post-accelerators. This application comes naturally; the heavy ion linear accelerator needs an injector--the tandem serves this purpose well. The linear accelerator is an extendable device--the development can be done on a reasonably small scale and useful prototypes can be constructed without a significant commitment to a large accelerator.

A small linac booster can give a significant energy increase to the beam from a tandem. For example, the normal bromine beam (gas stripping in terminal) from a 10 MV tandem would be 70 MeV Br^{+6}. This beam would strip to 18+ in a foil stripper; the energy gain in only a 5 MV linear accelerator would be 90 MeV, to give a final energy of 160 MeV. A 20 MV booster added to a 10 MV tandem would give a final energy of 430 MeV or $\sim$ 5 MeV/A, which is adequate for many nuclear physics experiments.

All of the listed projects are progressing well. The tests of the helix structure at Heidelberg and Saclay met the design goals. The room-temperature booster at Heidelberg operates quite well and is in routine use for physics research and has proved to be quite reliable. The somewhat negative aspect of the large power consumption ($\sim$ 20 kW/cavity) is offset by simplicity and reliability. Prototype studies at Argonne, including the routine operation of the booster in physics experiments, are solving the major problems. Similarly, the results at Stony Brook are quite promising. Of the superconducting accelerator projects, the Argonne accelerator is nearest completion. Recent tests of eight cavities together gave an average acceleration gradient of 2.8 MV/meter, with the best cavity capable of 3.7 MV/meter. The present project includes 17 sections to provide approximately 15 MV.

The H-structure accelerator at Munich is interesting because the total electrical power is low; however, the concept seems difficult to extend to higher voltages over a large velocity range.

Cyclotrons

There are seven active heavy ion cyclotron projects and another seven major proposals in various stages of development. The characteristics of the 14 projects are given in Table 3.[20-33]

With the single exception of the Dubna U-400, all of the new large cyclotrons are used in multistage systems; the final-stage cyclotron is injected by another cyclotron or by an electrostatic accelerator or linear accelerator. The beam from the injector is passed through a stripper foil or gas cell to increase the charge state. For example, in acceleration of uranium ions to 8.5 MeV/A in the GANIL system, U^{+9} ions are accelerated to 33.1 keV/A in the small injector cyclotron and to 0.53 MeV/A in the first large cyclotron. After passing through a stripper foil the beam is accelerated in the final stage as U^{+35}.

Table 2. Linear Accelerator Projects

Location	Description	Injector	Completion Date	Additional Comments
France, Saclay, CEA[13]	Nb Helix 108 MHz based on Karlsruhe design; 20 MV total gain	FN	1983 based on 1979-80 start	Proposal under discussion
Germany, Heidelberg,[14] U. of Heidelberg	Cu spiral resonators 108 MHz; 8 unit β=0.1 prototype gives 5-6 MV; 20 additional units in 5 sections being added.	MP	Prototype - 1977 Complete - 1979	In routine use for nuclear physics. Additional sections for 20 MV pulsed/10 MV cw being built.
Germany, Karlsruhe,[15] KFK	Nb Helix 108 MHz; 3-section prototype; achieved $\sim$0.6 MV per section; tested at Heidelberg MP	MP/FN	1976/1977	Transferred to Saclay to be used for evaluations and as buncher
Germany, Munich,[16] University and Technical Univ.	Cu Interdigital H-type structure; variable frequency 55-80 MHz; 1-5 m section; design gain = 4.7 to 5.5 MV	MP	1977/1978	Being used for physics at $\sim$ 5 MV voltage gain; rf power $\sim$50 kW
United States, Argonne National Laboratory[17]	Nb split-ring resonators, 11 sections β = 0.06 13 sections β = 0.105 15 sections β = 0.135	FN	1979 - 15 MV 1980 - 25 MV 1983 - 50 MV	Provides C, N, O 25 MeV/A A=100, $\sim$ 5 MeV/A; design gradient 4.25 MV/meter
U.S., Berkeley[18] Lawrence Berkeley Laboratory	Wideröe linac injector for SuperHILAC for high intensity, high charge-state heavy ions	-	1981	Provides high intensity beams of very heavy ions at 0.11 MeV/A. Will give SuperHILAC intensities of 10^{13} particles/sec for U 10^{14} particles/sec for Xe.
U.S., Stony Brook,[19] State U. of New York	Pb plated split-ring resonators; 151.7 MHz; 16 β = 0.055; 21 β = 0.1; total gain 18 MV at 2.5 MV/m	FN	1981	Design based on 2.5 MV/m; prototype low β resonators have routinely achieved 3 MV/m.

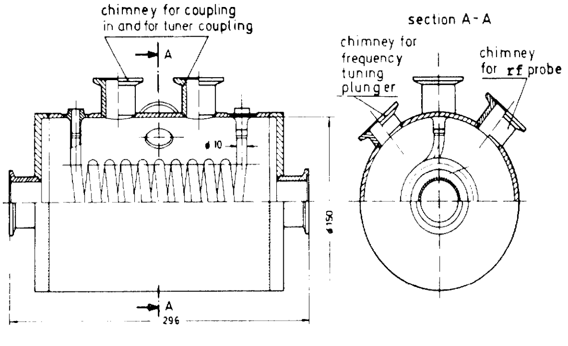

Fig. 5. A half-wave helix resonator as used in the Karlsruhe/Heidelberg tests.

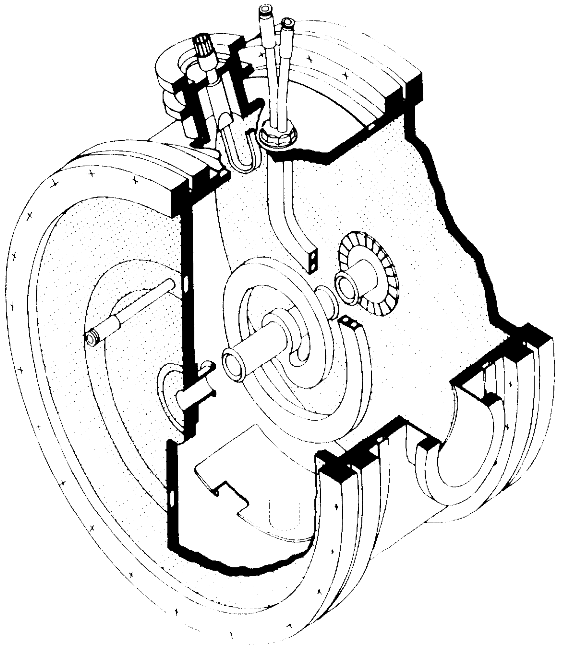

Fig. 6. The copper spiral resonator used in the room-temperature Heidelberg postaccelerator.

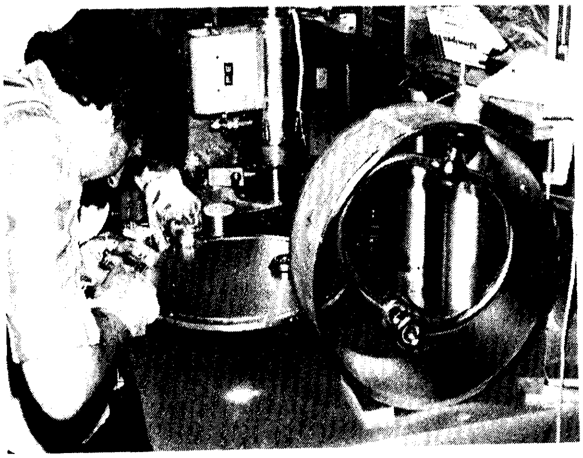

Fig. 7. A lead-plated split-ring resonator as used in the Stony Brook linear accelerator

Table 3. Heavy Ion Cyclotron Projects

Location	Description	Completion Date	Comments
Canada, Chalk River[20] Chalk River Nuclear Laboratories	K=520 superconducting magnet 4-sector; MP tandem injector	1981	50 MeV/A light heavy ions; 10 MeV/A U ions; magnet and rf tests underway.
China, Lanchow[21] Lanchow Institute of Modern Physics	K=450 separated-sector 4x52°; K=70, 1.5 m cyclotron injector	1983	50 MeV/A light heavy ions; 6 MeV/A Xe; model work underway
France, Caen[22] Grand Accélérateur National d'Ions Lourds (GANIL)	Three-stage system; small cyclotron followed by two K=400 separated-sector cyclotrons 4x51°; will be major new laboratory	1982	100 MeV/A light heavy ions; 8 MeV/A uranium ions
France, Grenoble[23] Institute de Sciences Nucléaires Rhone-Alpes Accelerator System (SARA)	K=120 separated-sector cyclotron 4x48°; uses existing K=90 conventional cyclotron as injector	1980	20 MeV/A carbon; 15 MeV/A argon; construction well underway
Germany, Munich[24] Technical University	K=1200 separated-sector cyclotron with superconducting coils; MP tandem injector	1985 Proposal	300 MeV/A light heavy ions; 24 MeV/A U; present program: design and 1:1 models
Italy, Legnaro (Padua)[25] National Institute of Nuclear Physics	K=550 superconducting magnet 3-sector , 16 MV XTU tandem injector. Designed at U of Milan	1983 Proposal	55 MeV/A light heavy ions; 14 MeV/A U ions; 1:6 magnet model tested
Japan, Saitama[26] Institute of Physical and Chemical Research	K=620 separated-sector 4x50°; variable frequency linac injector	1984 Proposal	120 MeV/A light heavy ions; 15 MeV/A uranium; linac under construction
Japan, Osaka[27] Osaka University - Research Center for Nuclear Physics	Three-stage system; K=90 injector followed by two separated-sector cyclotrons. K=230 4x33° and K=460 8x19° weak spiral; linac injector for heaviest ions	Proposal	550 MeV protons; 118 MeV/A light heavy ions; 12.5 MeV/A uranium
U.S.A., Brookhaven[28] Brookhaven National Lab.	K=800 isochronous conversion of SREL synchrocyclotron. May include superconducting coils.	1986 Proposal	200 MeV/A light heavy ions; ∿ 20 MeV/A uranium
U.S.A., College Station[29] Texas A&M University	K=400 superconducting cyclotron injector for existing K=150 conventional cyclotron	1984 Proposal	∿ 35 MeV/A light heavy ions; 5 MeV/A uranium
U.S.A., East Lansing[30,31] Michigan State Univ.	K=1200 superconducting cyclotron; K=500 superconducting cyclotron injector	1984 (Injector 1979)	200 MeV/A light heavy ions; 20 MeV/A uranium K=500 magnet operating
U.S.A., Oak Ridge[32] Oak Ridge National Lab.	25 MV folded tandem coupled to existing K=100 cyclotron (ORIC)	1979	25 MeV/A light heavy ions; 6 MeV/A A=160
U.S.A., Oak Ridge[33] Oak Ridge National Lab.	K=1200 superconducting cyclotron replaces ORIC; 25 MV tandem injector	1986 Proposal	200 MeV/A light heavy ions; ∿ 45 MeV/A uranium; new cyclotron replaces ORIC.
U.S.S.R., Dubna[34] Institute for Nuclear Reactions, U-400	K=625 conventional cyclotron Conversion of U=300 Penning ion source	1979	50 MeV/A light heavy ions; 5 MeV/A up to A = ∿ 100

In the example above, two K = 400* cyclotrons of the GANIL system have a maximum $B\rho$ value of $\sim$3000 kG-cm (an average magnetic field of $\sim$ 10 kG and a beam radius of 300 cm). If a single cyclotron was used to accelerate U^{+9} to the same energy, the K value required would be approximately 6000 MeV (11125 kG-cm)! This example illustrates why the multistage systems with interstage stripping are widely used.

Most of the new projects stem from two major concept developments: the separated-sector cyclotron as pioneered at Indiana University, and the cyclotron with superconducting magnet as developed at Chalk River Nuclear Laboratories, Michigan State University, and the University of Milan.

Separated-sector cyclotrons have the advantages of easy beam extraction, good access, operational flexibility, and easy beam diagnostics (phase probes, etc.). The latter advantage accrues because the ion stripping can be done outside the cyclotron and the unwanted charge states can be removed before injection. The only significant disadvantage is the large size and cost of the magnet and limited energy gain per stage caused by central region space limitations. The large GANIL cyclotrons each have a weight of 1700 tons.

The GANIL project is the largest and most advanced of the separated-cyclotron projects. Tests of a prototype sector magnet will be completed in early 1979. Figure 8 shows the novel resonator system for the frequency range 6.5-14 MHz that was developed to achieve mechanical stability and compactness. A half-wave transmission line system would have been very large and difficult to stabilize.

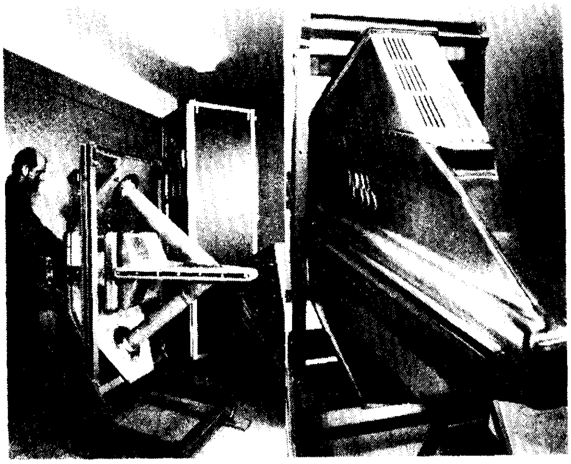

Fig. 8. The 1:3 model of the resonator system for the large GANIL cyclotrons. The accelerating electrode system (left) fits into the rf liner (right). Tuning is by panels that vary both the inductance and capacity.

Solid pole (not separated-sector) cyclotrons with superconducting magnets have the advantage of great compactness, even in the K = 1200 size. The proposed ORNL K = 1200 cyclotron is shown in Fig. 9. The magnet is 4.4 meters in diameter, 3 meters high, and weighs only 260 tons. Disadvantages of this type superconducting cyclotron include complicated access for maintenance and a complex beam extraction system. In these low-flutter, high-spiral cyclotrons, beam capture at injection is via stripping to increase the charge. There may be difficulties in beam diagnostics that arise because the undesired charge states will be partially accelerated.

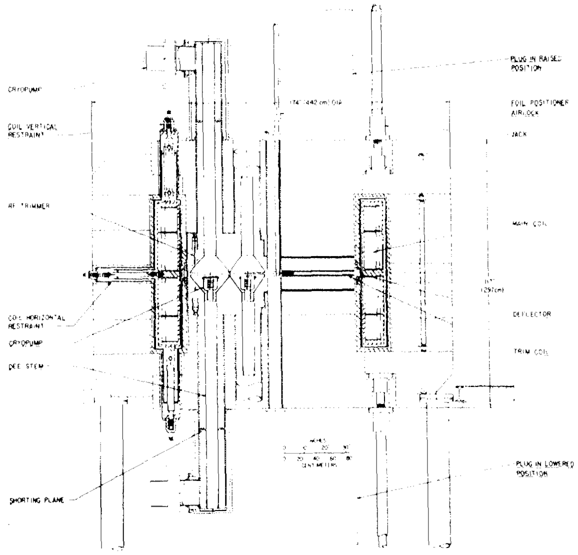

Fig. 9. The Oak Ridge K = 1200 superconducting cyclotron. The magnet configuration will be essentially identical with the MSU K = 800 design.

Presently the Chalk River and MSU K = 500 cyclotrons are nearing completion. Measurements of the MSU magnet made in 1978 showed essentially perfect agreement with calculations. One of the interesting advantages of superconducting magnets with fully saturated iron is that the magnetic field may be calculated with great accuracy. There is no need to do magnet modeling, as is required for conventional magnets.

An interesting development at the Technical University, Munich, combines superconducting coils and the separated-sector style of construction. The peak magnetic field will be approximately 4.5 T and the average magnetic field will be about 2.3 T. Figure 10 shows the plan of the cyclotron. A drawing of one sector magnet is shown in Fig. 11. A 1:10-scale model is shown in Fig. 12. The Munich cyclotron will not require stripping to inject but may use either gas or foil stripping with charge-state analysis before injection. Design and systems modeling are presently underway.

This year should see the first operation of the MSU K = 500 superconducting cyclotron and the operation of the ORIC with the 25 MV tandem as injector. During the next few years many new cyclotron projects will be completed; it is an exciting time for cyclotron designers!

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*It has become customary to discuss cyclotron size in terms of the magnetic field bending capability "K" as ME/q^2 (MeV); the maximum energy of an ion from a cyclotron is given by $E = K\,q^2/A$. This is a useful equation for low energies, but loses accuracy at high energy because of relativistic effects. The nonrelativistic K value is obtained from the magnetic field radius product by $K = [B\rho/144]^2$, where $B\rho$ is in units of kG-cm.

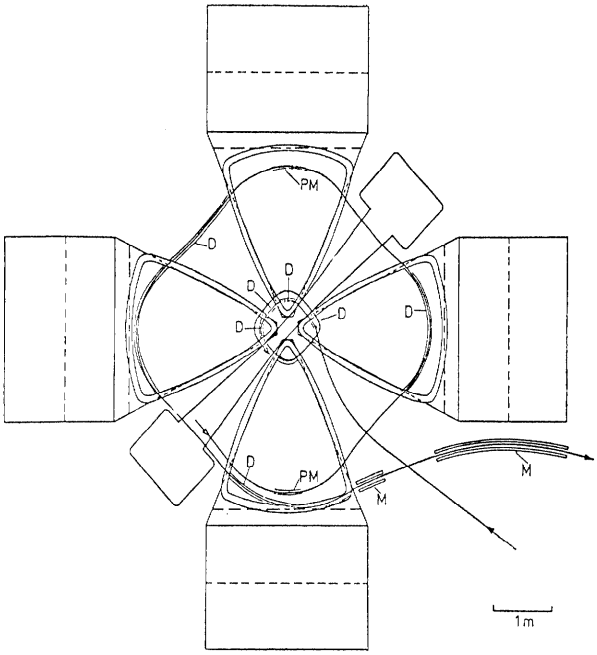

Fig. 10. The median-plane plan of the Munich superconducting cyclotron showing injection and extraction paths. Elements are as follows: M-magnet; MS-magnetic steerer; D-electrostatic deflector.

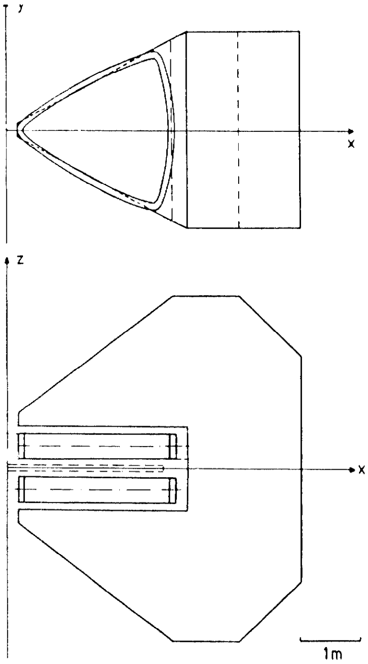

Fig. 11. The Munich sector magnet. There is no iron within the SC coils.

ECR Ion Source

At the Centre d'Etudes Nucléaires, Grenoble, R. Geller has developed a multistage electron cyclotron resonance (ECR) ion source.[35] A cold ion plasma created in the first stage diffuses through a second stage containing a hot plasma with $n = > 3 \times 10^{11}\ \mathrm{cm}^{-3}$. Continuous beams of several microamperes of C^{+6}, N^{+7}, Ne^{+9}, A^{+11}, and Xe^{+18} have been extracted with good emittance. The latest version of the source, designated SUPERMAFIOS "B", operates with second-stage electron cyclotron resonance of 8 GHz at a magnetic field of about 3000 gauss. Power consumption of the present model is about 3 MW. Superconducting coils and/or permanent magnet elements have been proposed to decrease power requirements and to increase magnetic field and electron resonance frequency. If the hot electron density in the second stage depends on the square of the heating frequency, as has been postulated, increasing the frequency to 36 GHz would provide fully stripped ions up to at least xenon.

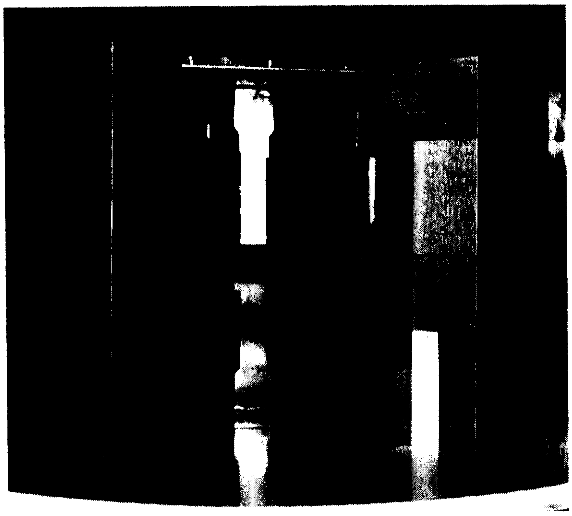

Fig. 12. The 1:10 scale model of the Munich superconducting cyclotron.

ECR sources are now being built for the cyclotrons at Kernforschungszentrum Karlsruhe, Germany, and at the University of Louvain, Belgium. An ECR source has been proposed for the Berkeley 88-Inch Cyclotron. The projected increases in heavy ion energy using ECR sources are very significant. Some design goals for the LBL source are: fully stripped ions (∿ 40 MeV/A) to A=20, 26 MeV/A Ar^{+16}, up from present 6.5 MeV/A Ar^{+8}; 5 MeV/A Xe^{+23}, up from present ∿ 0.8 MeV/A Xe^{+9}.

EBIS Ion Source

A new electron beam ion source (CRYEBIS) based on the principal of ion containment with successive ionization in an intense electron beam has recently been operated at Orsay.[36] The Orsay EBIS employs a superconducting solenoid to provide a magnetic field of 3 Tesla. Preliminary data show A^{+18} intensities up to 10^{10} ions/sec. With additional development, intensities up to 2×10^{13} are expected for fully stripped N and Ne, 3×10^{11} for Ar^{+18} and 5×10^{11} for Kr^{+34}. If these goals are met, the source will be very attractive for cyclotrons. The EBIS source appears to be simpler and probably less expensive than the ECR source, but the output will ultimately be limited by achievable electron beam density and power dissipation levels.

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