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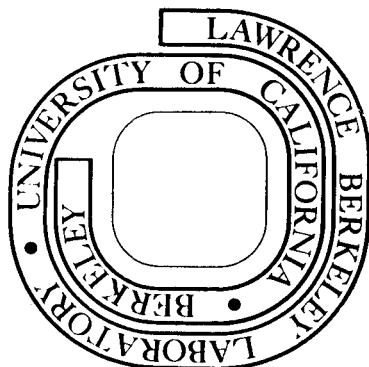
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1. INTRODUCTION

Over the last two decades, heavy ion beams have become increasingly important tools for scientific investigations ranging from the synthesis of heavy "man-made" elements to the fields of nuclear physics and biology and medicine.

In the context of this paper, a heavy ion is the nucleus of any element with an atomic mass larger than 4 amu (atomic mass units), deliberately excluding hydrogen and helium. Heavy ion accelerators are employed to accelerate and form the particles into pure and intense beams of the desired energy. Unstable isotopes are occasionally used if their halflife is long compared to the acceleration process.

The invention and development of the cyclotron in the 1930s by E. O. Lawrence, S. Livingston, and other collaborators, started particle physics, nuclear physics, and nuclear chemistry on the road of expansion to the major scientific enterprise we know today. The development of beams of protons, deuterons, alphas, and lithium ions from 60-in. cyclotrons throughout the world served a highly productive area of nuclear physics and chemistry. The Berkeley 60-in. cyclotron ran very intense beams until 1961, when the LBL 88-in. isochronous cyclotron and the ORIC (Oak Ridge Isochronous Cyclotron) took its place with strong emphasis on nuclear physics. Livingston and Blewett (1) give a detailed history of accelerator development prior to 1962.

Nuclear Chemistry research with heavy ion linacs dates from 1957, when the Lawrence Radiation Laboratory, together with Yale University, developed and built the first two productive heavy-ion linear accelerators delivering beams of 10 MeV/amu with masses up to 40 amu (2).

A similar development took place in Dubna, USSR in the Joint Institute for Nuclear Research (JINR).

Parallel developments with electrostatic accelerators, particularly the tandem Van de Graaffs (3), led to the attainment of higher and higher terminal voltages, up to the presently envisioned 20 and 30 MV. With the refinement of negative heavy ion sources (4), the tandem Van de Graaff accelerators entered the field of heavy ion nuclear physics, and now complement the linacs and cyclotrons. The excellent phase-space characteristics of these beams, including energy resolutions of up to 10^{-4}, make them ideal tools for precision nuclear physics experiments. The Yale group, with its MP-tandem, led the way in the use of Van de Graaffs for heavy ion research

Accelerator experiments with heavy relativistic ions were started in 1970, with the conversion of the proton synchrotrons at Princeton (5) (Princeton-Penn accelerator, which discontinued operations in 1975) and Berkeley (6) (Bevatron), to the acceleration of heavy ions. Initially, beams were limited in intensity and ion species by injectors, which had been designed for protons. At Berkeley, the limits were extended by injecting the beam of a high-intensity, low-energy heavy ion accelerator (SuperHILAC) into the Bevatron. This combination (the Bevalac) yields particle currents of about 10^9/sec for ions up to neon, sufficient for counter and coincidence experiments with high energy and particle mass resolution, and beams of reduced intensity up to iron. Available energies range from 100 MeV to 2.4 GeV per nucleon.

The applications of heavy ion beams in basic and applied research are numerous. At energies below the Coulomb barrier, very precise

nuclear quantities (e.g., energy levels, matrix elements) can be extracted. With beams of ^{136}Xe, rotational states with I = 24 have been excited in ^{238}U, and heavier projectiles should excite even higher states. Above the Coulomb barrier, aspects of nuclear interactions, e.g., the ion-ion potential or the effects of deformations on scattering and reaction processes, are studied. The investigation of transfer reactions and compound nucleus formation, as well as deep inelastic processes, advances our understanding of reaction mechanisms. The search for superheavy elements (Z = 114 to 126) constitutes another branch of ongoing research at modest energies. In atomic physics, improved yields for the production of molecular orbit x-rays or the observation of the predicted autoionization of positrons are expected from collisions between very heavy ions.

Above 20 MeV/amu, a qualitatively new feature appears in that now the estimated velocity of sound in nuclear matter is exceeded, opening up the possibility of studying nuclear matter at varying densities.

In the realm of nuclear physics at high energies, researchers are eagerly searching out novel features of interactions where a high number of baryons is simultaneously involved (7). Nucleons at high kinetic energies may be excited to the baryonic resonances, produce pions and kaons, or reabsorb them. In the process of a central collision, the initial ground state configuration of nuclei will be immediately transformed into a very hot piece of nuclear matter, where the binding energy per nucleon is readily overcome.

High-energy (above several hundred MeV per amu), heavy ion fragmentation cross sections are of particular interest to astrophysicists. They rely on these data to formulate models describing

the propagation of cosmic rays in space and to approach an understanding
of how the universe was created. Furthermore, very precise beams of
heavy ions are required to calibrate the sensitive instruments flown
in space studies.

One of the most exciting prospects is the generation of the
predicted abnormal states of nuclear matter that can be tested when
relativistic beams as heavy as Pb or U become available.

The application of heavy ions for radiation biology, radiation
therapy, and diagnostic radiology has fostered an entire new field
of heavy-ion work. The potential attractiveness of these beams for
radiotherapy lies both in their radiobiological effects and the fact
that a precise radiation dose can be delivered to a specific tumor
volume with minimal damage to normal tissue, compared with conventional
x-radiation therapy. At LBL's Bevalac facility, an active experimental
program is investigating these fields (8). Also, the first steps in
instituting an active patient treatment program are being taken.

Low charge-state heavy ions have been used in industry for some
time. The major application is ion implantation--the doping of
semiconductor materials by ion beams--to achieve far better uniformity
and dose control, and in some cases to produce devices that were
heretofore impossible to fabricate (9). Other uses of heavy ions
now under active investigation are changing the optical properties
of materials, changing magnetic properties of materials used for
bubble memory, enhancing surface hardness and corrosion resistance,
and altering properties of thin films (10). Ion implantation has
also been used in the production of superconductors and to modify the

coefficients of friction. At ORNL (Oak Ridge National Laboratory) heavy-ion beams are used to simulate radiation damage from reactor neutrons in the absence of large enough neutron fluxes (11).

Among the many types of potential and operational heavy-ion accelerators, the choice of the proper machine depends upon the intended use. The precise beams of tandem electrostatic accelerators and cyclotrons are most suitable for experiments with high resolution spectrometers. Linacs, with their relatively high intensity and velocities independent of mass, are excellent tools for chemistry-type experiments, overlapping with cyclotrons and electrostatic machines. Synchrotrons can produce high-energy beams of excellent quality at moderate cost. A survey of other component considerations and basic accelerator types is the subject of this paper.

2. SOME FUNDAMENTAL CONSIDERATIONS OF PARTICLE ACCELERATORS FOR HEAVY IONS

The major characteristics of a particle beam are: particle species, charge state (Sect. 2.1 and 4.1), kinetic energy, energy spread, and time structure. Also of great importance are beam intensity, emittance, and the related concept of brightness (Sect. 2.2). The time structure can be both macroscopic (duty factor), which is the proportion of time the beam is on and microscopic, which is the intensity modulation due to the accelerating rf.

A simple accelerator is an evacuated tube with a different electrical potential at each end. If V is the potential difference, an ion of charge qe will increase its energy by an amount $\Delta T = qeV$ in traversing the tube.

For many applications the energy per nucleon T_n rather than total energy T is the decisive quantity; this is given by $T_n = T/A$, where A is the mass number. Hence a particle falling through a potential V will gain $\Delta T_n = (q/A)eV$.

Consequently, the charge to mass ratio of an ion is a most important quantity. The lower the value of q/A, the greater the voltage V required to reach a given T_n. Another consideration is that the deflection of particles by magnetic fields--important for bending and focusing--is proportional to the rigidity Bρ, which is given by momentum divided by charge: $eB\rho = Mv/q = (A/q)\gamma m_p v$. Here the particle mass $M \equiv A\gamma m_p$, where m_p is the proton mass, and γ is the relativistic mass increase. Of two particles having the same energy per amu but different q/A, the particle with the lower q/A will have a higher rigidity, requiring stronger magnetic fields for beam handling.

In principle, the acceleration process for heavy ions differs from protons only in that q/A is different. However, major differences occur in the ion sources, in the need for low velocity (low β) accelerator structures, and in the fact that heavy ions gain and lose electrons in charge exchange processes.

The charge state is initially determined by the degree of ionization attained in the ion source, a device that typically contains a plasma from which charged particles are extracted. The extraction process forms the orginal beam and sets certain properties of it such as emittance, brightness and maximum macroscopic time structure. A fuller discussion of the parameters of ion sources is given in Sect. 4.1.

Beyond this starting phase of beam formation, the charge state at various stages of acceleration requires careful consideration. It can be increased by stripping (Sect. 2.1), usually reducing the intensity. Charge exchange processes with the residual gas can cause a sudden change in $B\rho$ and in most situations means loss of the particle.

When q/A from the ion source is very low, as it often must be for very heavy ions, acceleration is relatively slow, causing problems with transverse beam containment. The inherent repulsion of charged particles with equal polarity gives rise to space-charge forces which in turn require compensation by focusing forces to contain them. At nonrelativistic energies the space charge forces per unit length are inversely proportional to β^2 (where β = v/c, the velocity of the particle v relative to the velocity of light c). Special low β accelerating structures must be built in order to cope with this situation.

2.1. Charge Exchange

An ion passing through matter exchanges electrons with atoms in the medium. Two processes operate in competition--stripping of electrons from the moving ion and capture of electrons by it. The cross section for each of these processes varies with the nuclear charge z and the ion velocity β. At low velocities capture is dominant, while at high β stripping is more important. This is illustrated by figure 1, which shows stripping and capture cross sections for iodine ions in nitrogen gas. At sufficiently high velocities the ion will be fully stripped; at lesser velocities an equilibrium is quickly reached, depending upon z, β, and the nature of the medium traversed.

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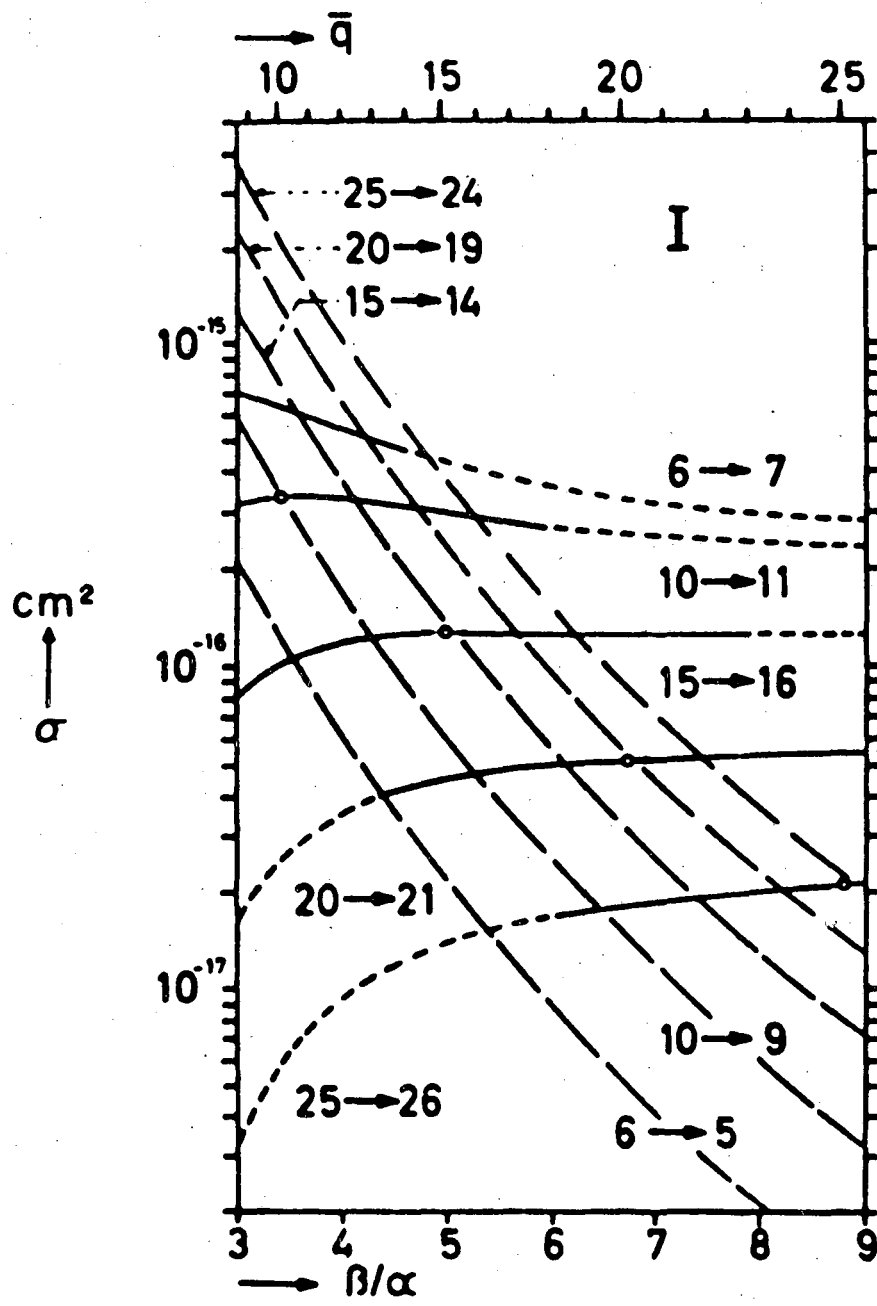
Figure 1 Calculated charge exchange cross sections of iodine in air, as a function of velocity. Velocity is plotted as β/α, where α is the fine structure constant, equal to 1/137. The upper scale on the graph is $\bar{q}$, the mean charge state of the stripped ions [from (12)].

Because of the statistical nature of the process, at equilibrium there will be a distribution of charge states about some mean charge $\bar{q}$. Due to the complexity of the interactions involved, there is no theory that explains in satisfactory detail the observed stripping behavior; instead a number of semi-empirical formulae have been relied upon in designing and operating heavy ion accelerators. With these formulas, reviewed in a paper by Betz (13), it is possible to predict mean charge states to ± 1, in the areas of β and z where measurements exist. Large extrapolations are risky. Some indication of the use of stripping for heavy ion accelerators can be obtained from an inspection of figure 2, in which the empirical formulas were used to plot equilibrium charge states as a function of T_n (energy per nucleon) for dense stripping media. The stripping region lies below a given z curve, the capture region above.

The acceleration of argon by the Bevalac serves as an illustration. Starting with q = 3 from the ion source, the first linac section accelerates to T_n = 1.2 for the first stripping, yielding $\bar{q}$ = 12.4. The next linac section accelerates to T_n = 8.5 where, after a second stripping, $\bar{q}$ = 17.3. Definite charge states must be used for each stage of acceleration. Here q = 12 is used after the first stripping, and q = 18 after the second stripping. After each stripping some beam intensity is sacrificed because several charge states are created and only one can be used. The loss is from 50-70% for argon at each stripping. For higher z ions the losses are greater due to the wider charge state distribution.
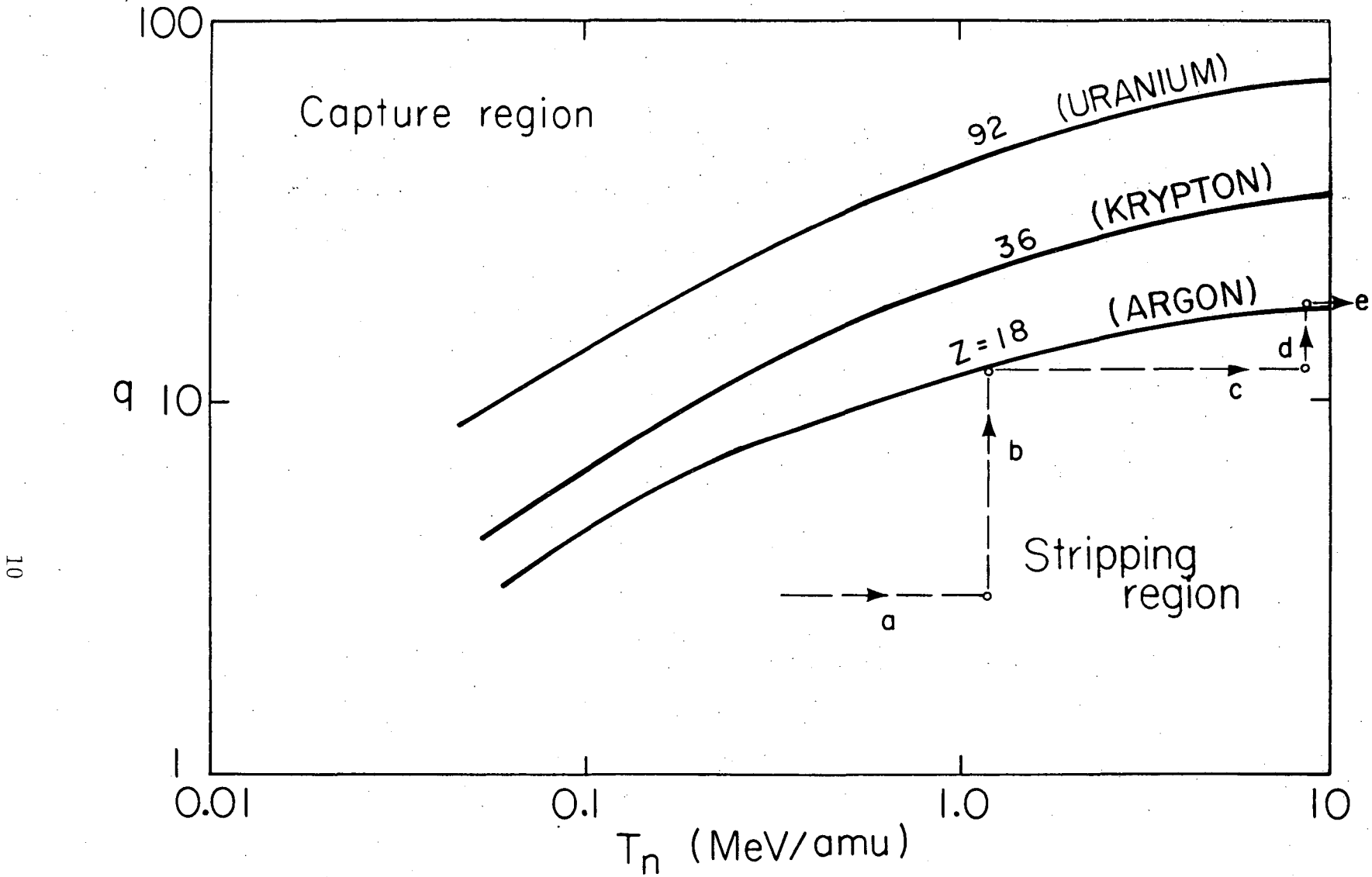
Figure 2 Calculated equilibrium charge states for dense strippers as a function of energy, for Z = 18, 36, and 92. The dotted lines indicate the processes of acceleration and stripping of argon ions in the Bevalac, which involves two stages of acceleration (a and c) and stripping twice (b and d). See Sect. 3.6.

2.2 Emittance and Brightness

The concepts of emittance and brightness are crucial because they determine beam size and particle-flux that can be transmitted through a given ion optical system. Knowledge of linear dimensions of a beam and of physical boundaries like the vacuum chamber alone are inadequate, since any beam has a certain divergence, and strength and spacing of focusing elements must be taken into consideration. The concept of emittance is also helpful in understanding the minimum possible beam size at any point (for example at a target), and the relative importance of disturbances, such as electric and magnetic inhomogenities, on beam quality.

Particles can be described by giving position relative to three orthogonal axes x,y,z and momenta p_x, p_y, p_z along these axes. Beam particles form an ensemble in the six-dimensional phase space of coordinates and momenta. A fundamental theorem of statistical mechanics, known as Liouville's theorem, states that if the ensemble is Hamiltonian (i.e., if the equations of motion can be written in Hamiltonian form), then in the neighborhood of a given particle the density of particles in phase space remains constant in time (14). Charged particles acted upon by external electric and magnetic fields are Hamiltonian. Processes such as stripping are non-Hamiltonian, since knowledge of the particles' initial coordinates and momenta and the external forces acting upon them is not sufficient to describe beam behavior.

In some instances the equations of motion are separable with respect to one or more coordinate axes. For example, motion in the

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x plane might be independent of the other coordinates; in this case Liouville's theorem applies to the two-dimensional phase space x, p_x. This situation is often true in beam transport systems. Considering such a case of one-dimensional motion, we can examine the beam at time t_0 and see that a curve E in phase space will enclose all of the particles (see figure 3). At a later time t the particle distribution will be bounded by another curve E. It can be shown that, as a consequence of Liouville's theorem, the area enclosed by E_0 and E is the same and a particle within E_0 at time t_0 must be within E at time t. Taking z as the beam axis, the area in the x, p_x plane enclosed by E is called the normalized emittance. If the average beam momentum is p_0, and we transform to variables x, x', where x' $\equiv p_x/p_0$, the area occupied by the beam is called the emittance.

Beam intensity is also an important parameter. However, if a beam can be made more intense only at the expense of emittance, the amount of useful intensity might be no greater. To facilitate such comparison, beam brightness is defined as

$$B = I/E_x E_y , \qquad\qquad 1.$$

where I is the beam current and E_x, E_y are emittances of the transverse phase spaces occupied by the beam.

One might expect that beam brightness would be conserved, provided the acceptance of an accelerator is adequate to transmit emittance. This is rarely so because loss of intensity can occur from charge exchange with residual gas, from stripping to increase charge state, in rf trapping, etc. Furthermore, emittance can be diluted in
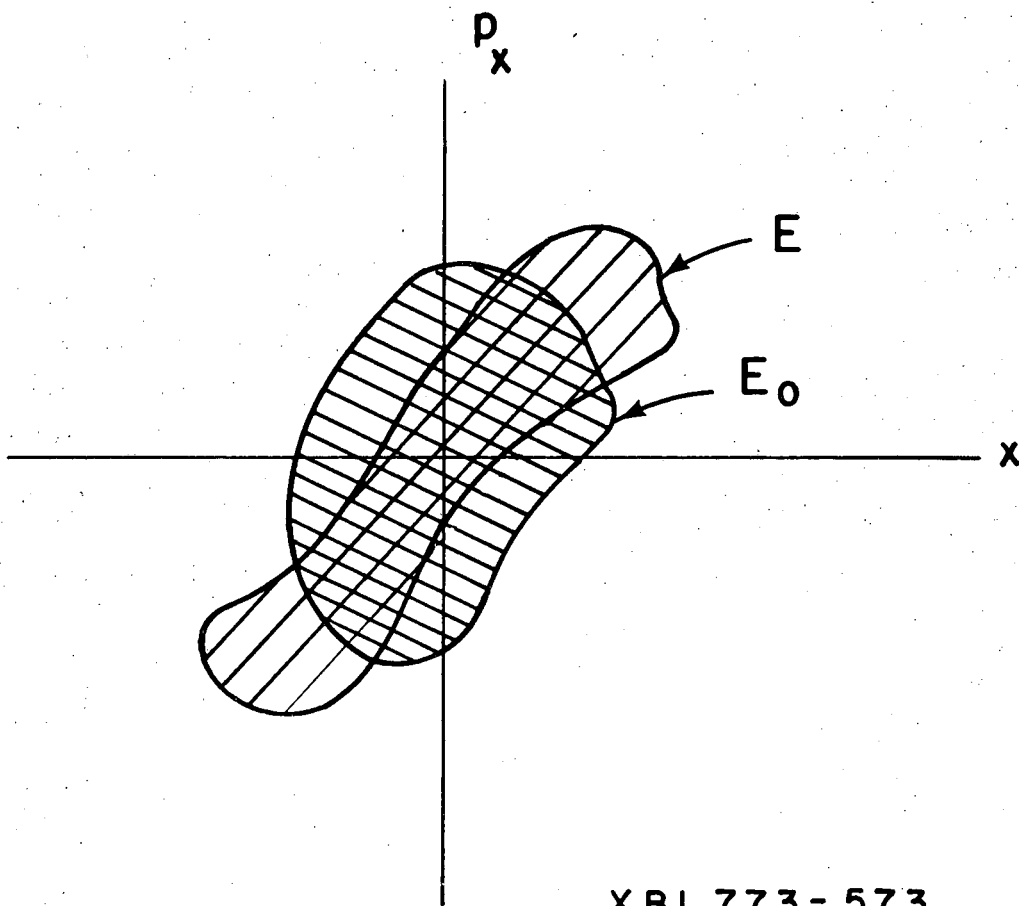
Figure 3 Representations of beam emittance in transverse phase space.
x = transverse position, p_x = transverse momentum.

an accelerator or transport system even though in a strict sense, Liouville's theorem is not being violated. This is illustrated with a common case in figure 4. Beam emittance E_0 which is here taken to be elliptical in area, is shown in (a). After passing through a linear transport system, emittance is as in (b), an ellipse E_1 of different shape but the same area. However, if the transport system contains nonlinear fields, the result can be as shown in (c), where the emittance E_0 has been transformed into E_2, a distorted shape with the same area. Unless stringent measures are taken such as compensating nonlinearities, subsequent beam transport must accept the larger emittance figure enclosed by the dotted curve E_3. For further discussion of these questions see Banford (15).

3. TYPES OF HEAVY ION ACCELERATORS

Electrostatic machines are in principle the simplest heavy ion accelerators; operating dc, they also inherently possess the highest duty factor. They have beams of low emittance and excellent energy resolution. They are restricted in maximum energy of ions, and with the large tandem systems are somewhat restricted in ion species because of the necessity for a negative ion source.

Linear accelerators can be built to any final energy. They can also have high duty factor. However, the accelerator structure is used only once by the ions, so cost sets a limit on length of structure and hence energy. High duty factor is also limited because of the cost of rf power of which only a small fraction will be transmitted to the beam, in typical applications.
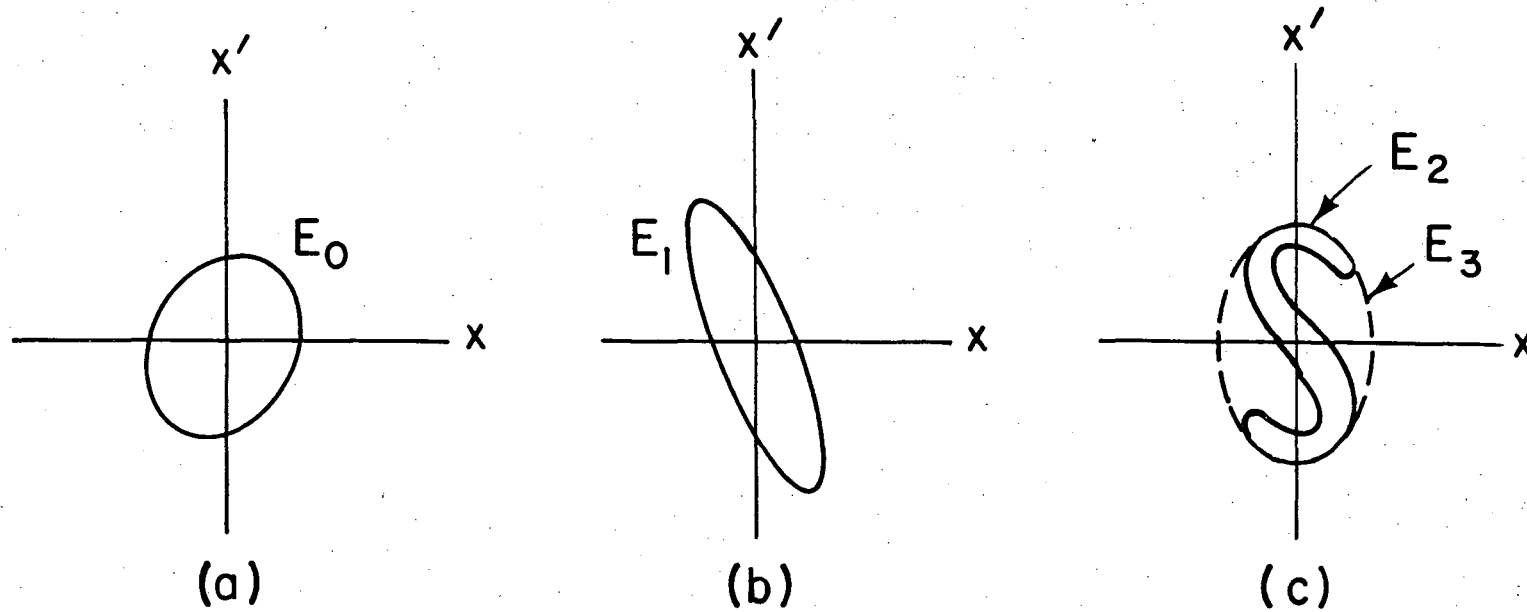
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Figure 4   A beam of elliptical phase space area E_0 in (a), when subjected to linear forces transforms to an ellipse of equal area E_1, in (b). However, when E_0 is subjected to nonlinear forces it translates to a non-elliptical shape E_2 in (c), which can only be enclosed by a larger ellipse E_3 for further linear transformations [after Banford (15)].
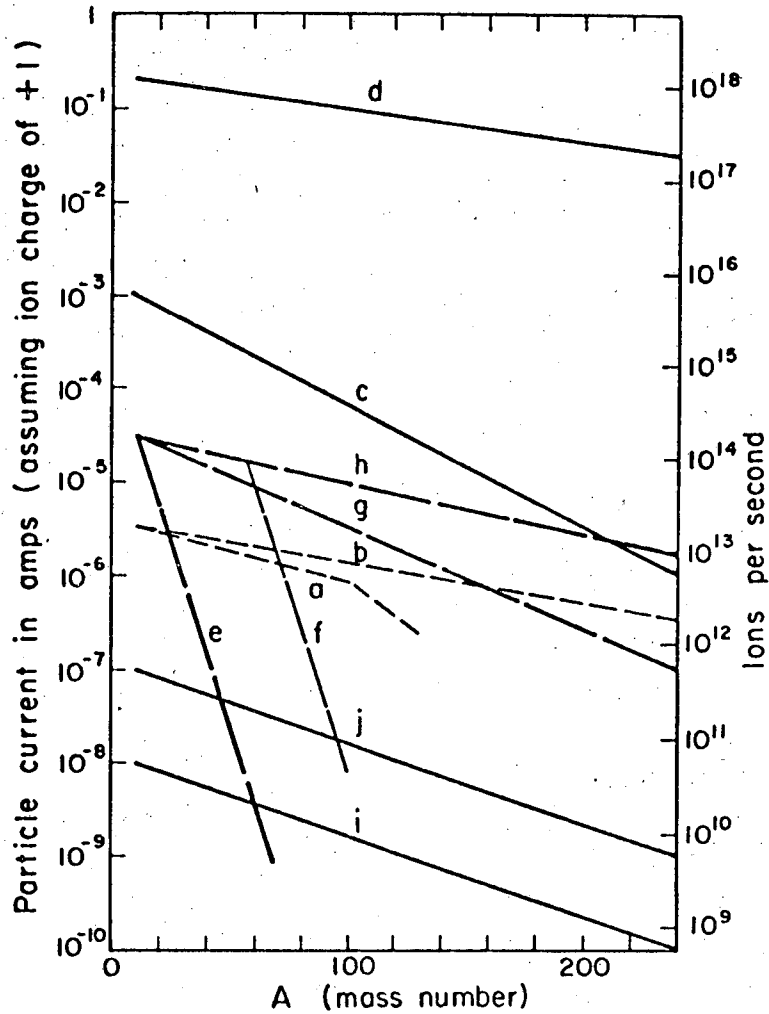
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Collective acceleration is still experimental, but is of interest because potentially it could be the most economical. The duty factor, however, is inherently low.

Cyclotrons economize on rf power by accelerating the particles again and again through the same structure. Maximum energy is set by the magnet dimensions and therefore cost. The duty factor is inherently high. When high energies as well as variable ion species and energies are needed, changes in magnetic field shape due to relativistic mass increases lead to sophisticated field shaping techniques.

Synchrontrons economize on both rf power and magnet. With present technology, the synchrotron is the most economical machine to reach high energies. The duty factor is inherently low, but can be stretched to ~25-50% at the cost of average intensity. Vacuum requirements are severe because of the ion's long path length.

In principle, any acceleration scheme conceived and developed for protons can be adapted to the acceleration of heavy ions, and most of the necessary modification to variable energy cyclotrons, synchrotrons and electrostatic accelerators can be readily accomplished even after the machine is built. Changes in linear accelerators must be considered at the design stage.

However, the existence of the fundamental technology has made possible rapid development of heavy ion accelerators with rather well defined specifications, including accelerator designs uniquely suited for the relatively low q/A heavy ions. Some of the performance characteristics of the major heavy ion accelerator types are shown in figure 5, as intensity vs mass number, and figure 6, which shows

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Figure 5 Approximate particle current vs mass number for heavy ion accelerator types. (a) 25 MV tandem electrostatic accelerator, (b) tandem + cyclotron or linac booster, (c) existing linacs, (d) proposed high intensity linac for heavy ion fusion, (e) existing K = 140 cyclotron, (f) proposed K = 500 superconducting cyclotron, (g) proposed tandem cyclotrons, each of K = 400, (h) proposed tandem superconducting cyclotrons, K = 500 and K = 800, (i) linac and synchrotron (Bevalac, after completion of current improvement program), (j) state-of-the-art linac + synchrotron (20 Hz rep rate synchrotron).
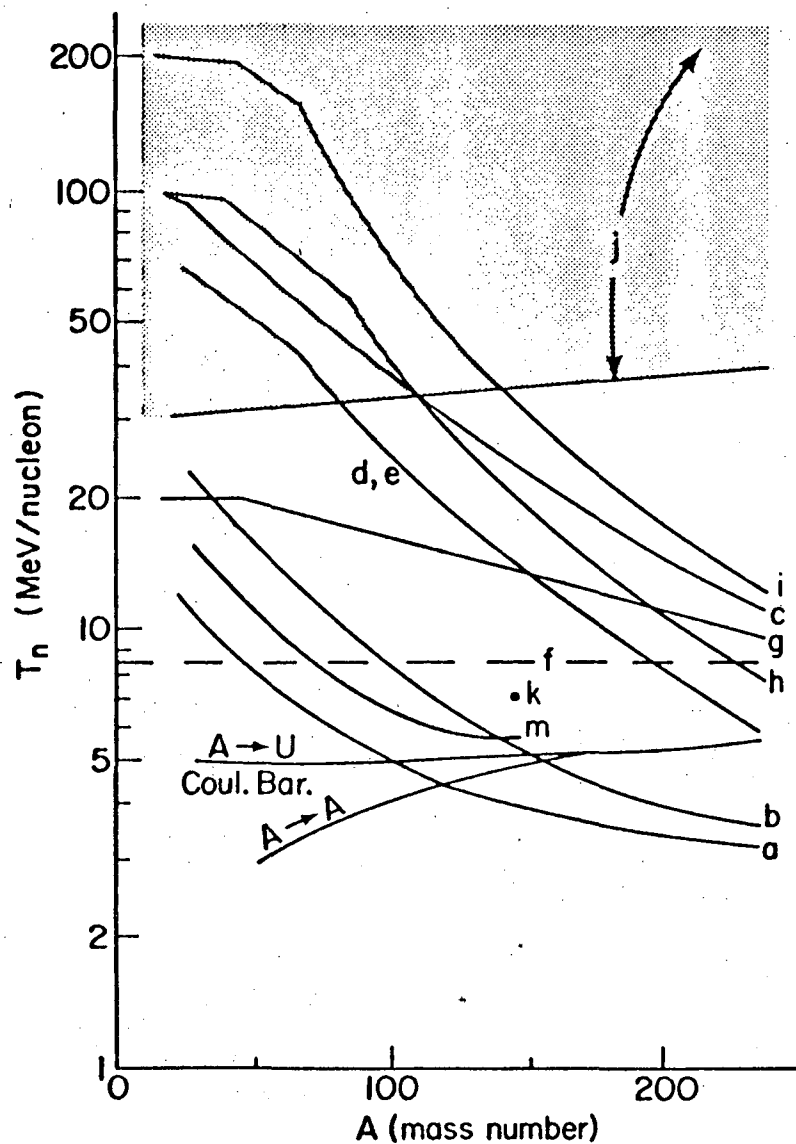
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Figure 6 Energy per nucleon vs mass number for several accelerators. The descriptive symbols are explained in Sect. 5. (a) HHIRF tandem (T25), (b) HHIRF phase I (T25 + K90), (c) HHIRF phase II (T25 + K90 + K400), (d) Chalk River (T13 + K500), (e) Rochester (T13 + K500), (f) SuperHILAC (D8.5), (g) UNILAC (D4.5 + L23.8), (h) GANIL (K25 + K400 + K400), (i) MSU (K52 + K500 + K800), (j) Bevalac (D8.5 + S2.6). Only lower limit is shown -- upper is T_n = 2.6 GeV/amu for A=20, and maximum T_n = 1.3 GeV/amu for A=238, (k) Dubne JINR U200 + U300, (m) JINR U400 (k725).

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energy per nucleon vs mass number. The reasons for the wide disparity in performance of the various types will become clear as each type is discussed in detail.

3.1. Electrostatic Accelerators

Electrostatic accelerators utilize an insulated belt or chain to carry charge up to a terminal that is maintained at a high potential. Ions are accelerated through the potential difference between terminal and ground. Research and development on this type of accelerator was led by Van de Graaff for many years and the machine is frequently referred to using his name.

The Van de Graaff accelerator is the only type that has achieved voltages above 10 MV. Another high voltage generator is the Cockcroft-Walton (16), and shunt-fed form of it, the Dynamatron (17). Voltages up to 4 MV with relatively high currents of many milliamperes make the Cockcroft-Walton generator a desirable preinjector for linacs.

For electrostatic accelerators above about 1 MV, pressurized vessels are used to contain the high voltage components. This permits work with much higher electric fields and thus reduces the physical size of the apparatus, which is limited by breakdown and corona phenomena. Sulfur-hexafluoride alone or mixtures with nitrogen and carbon dioxide are used as insulating gas with pressures up to 250 psi.

The accelerating column, of course, must have a high vacuum to avoid unwanted charge exchange for heavy ions. With electric-field gradients in the accelerating tubes of 2-3 MV/m, a conditioning process is necessary for steady, reliable operation. Conditioning a large electrostatic accelerator, a sensitive task involving, it seems, both
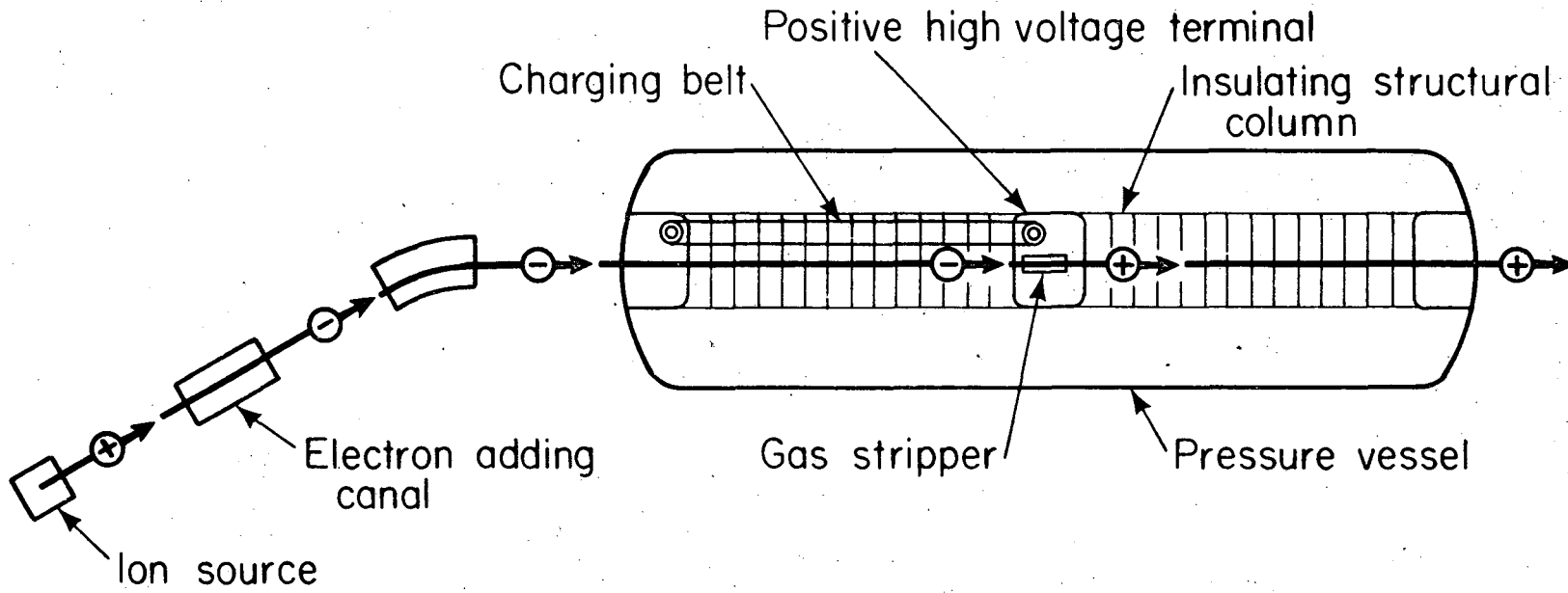
folklore and technical skill, requires many hours to accomplish. The fundamental objective in conditioning is to eliminate by controlled discharges small (often microscopic) irregularities on the high voltage surfaces.

A modern development has been the "tandem," in which negatively charged ions are accelerated up to the high voltage terminal, where they are stripped, then accelerated to ground (18) (see figure 7). New charging techniques have been devised, which replace the traditional charging belt with metal charge carriers called pellet chains. With these chains there is reduced chance of spark damage and frictional loss to the gas is low, giving modest power input and eliminating cooling requirements (19).

An example of the latest tandem technology is a 25 MV machine by NEC (National Electrostatics Corporation) now under construction at Oak Ridge National Laboratory (figure 8). The tank is oriented vertically with the terminal at the top. A 180° bending magnet is placed in the terminal, and the same column is used both for the negative and positive ion beams. This folded arrangement saves substantially in both tank and building height. The ion source is located at the base of the accelerator for convenience and building economy (20).

Another large tandem facility is under construction at Daresbury in England. Initial operation at 20 MV, with later upgrading to 30 MV is planned. This machine is also placed in a vertical tower, but with the ion source at the top (21).

Electrons or ions released from surfaces in the accelerating tube are suppressed by installing diaphragms with reduced apertures at

Positive high voltage terminal

Charging belt

Insulating structural column

Electron adding canal

Gas stripper

Pressure vessel

Ion source

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Figure 7 Schematic of a tandem electrostatic accelerator [after Van de Graaff (18)].
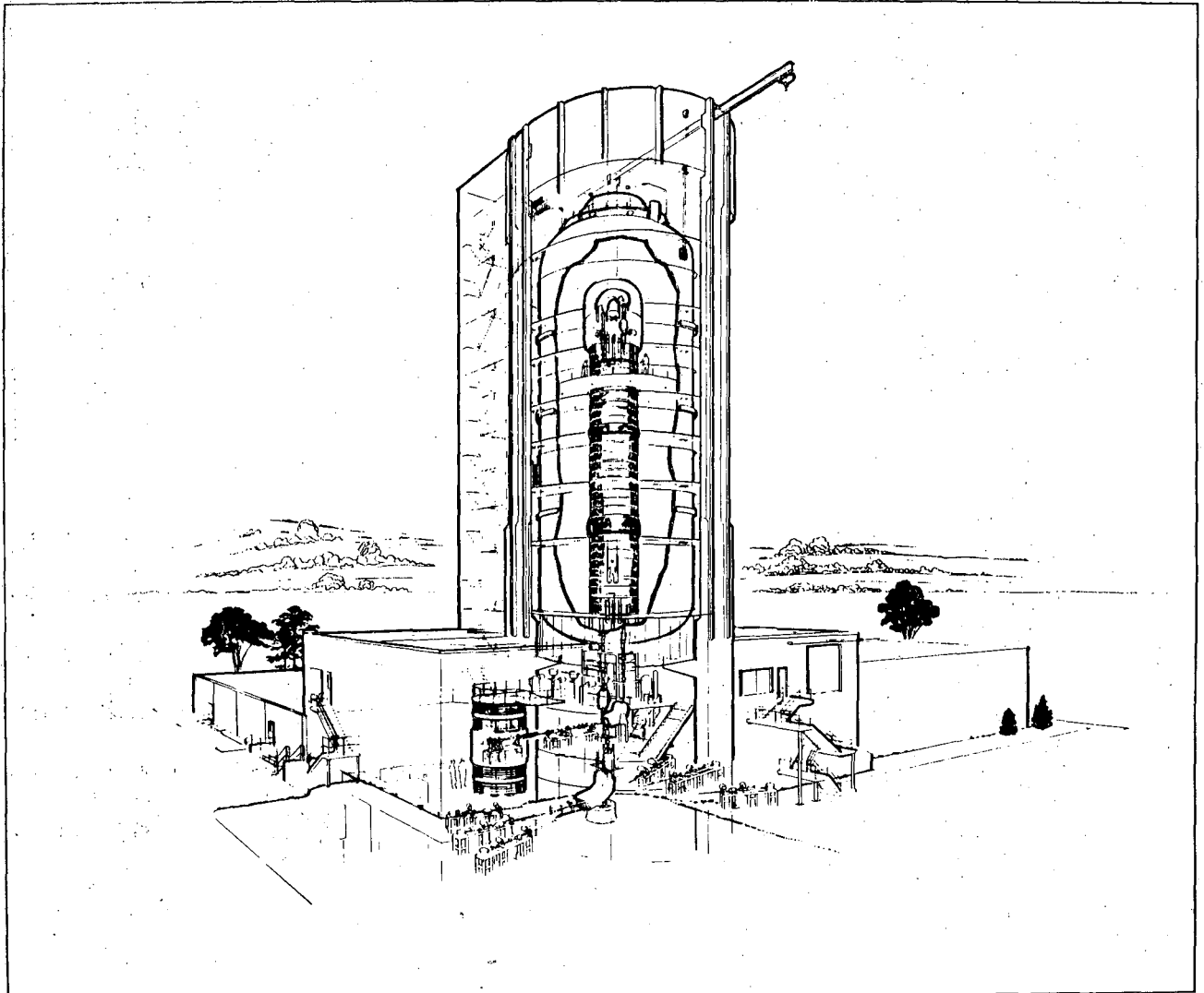
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Figure 8 View of HHIRF 25 MV tandem built by NEC. A negatively charged beam from the ion source is bent 90° and accelerated upward to the terminal, where after stripping, it is bent 180° and accelerated downward through the same potential. A 90° magnet is arranged to rotate about a vertical axis in order to deliver the beam to any one of several radial transport lines.

intervals along the tube.. Most ions or electrons originating between diaphragms are stopped at the next diaphragm. A few proceed to the second diaphragm where they are stopped. Thus, positive-negative ion exchange, which is responsible for "electron loading," is depressed in a simple and elegant fashion. Other means are the introduction of magnetic fields or inclined electric fields.

Quadrupole lenses are appropriately located for beam control; with beam profile monitors and steering elements, beam transmission from source to target is straightforward. A change in beam energy or in charge state is easily and quickly accomplished by a skilled operator.

Beams from an electrostatic accelerator can be injected into a cyclotron or a linear accelerator booster to extend energies to 8 MeV/amu or more. The 25 MV Oak Ridge tandem will inject into the cyclotron "ORIC" to provide ions to energies above 9 MeV per nucleon for mass 100. Planning is also well advanced on an open sector cyclotron booster to provide energies above 10 MeV per nucleon for all ions (22) (see figure 9). A similar arrangement of lower energy is being constructed at the Hahn Meitner Institute in Berlin.

At Argonne National Laboratory plans are under way to utilize an existing tandem for injection into a superconducting linac (23). Similar arrangements are being pursued at other laboratories.

Two attractive features of electrostatic machines are dc operation and modest power requirements. To reach higher energies, the problem of ion exchange on the surface of the accelerating tube must be overcome. Experiments show that clean surfaces of titanium or stainless steel have much higher thresholds for discharge than these metals when coated
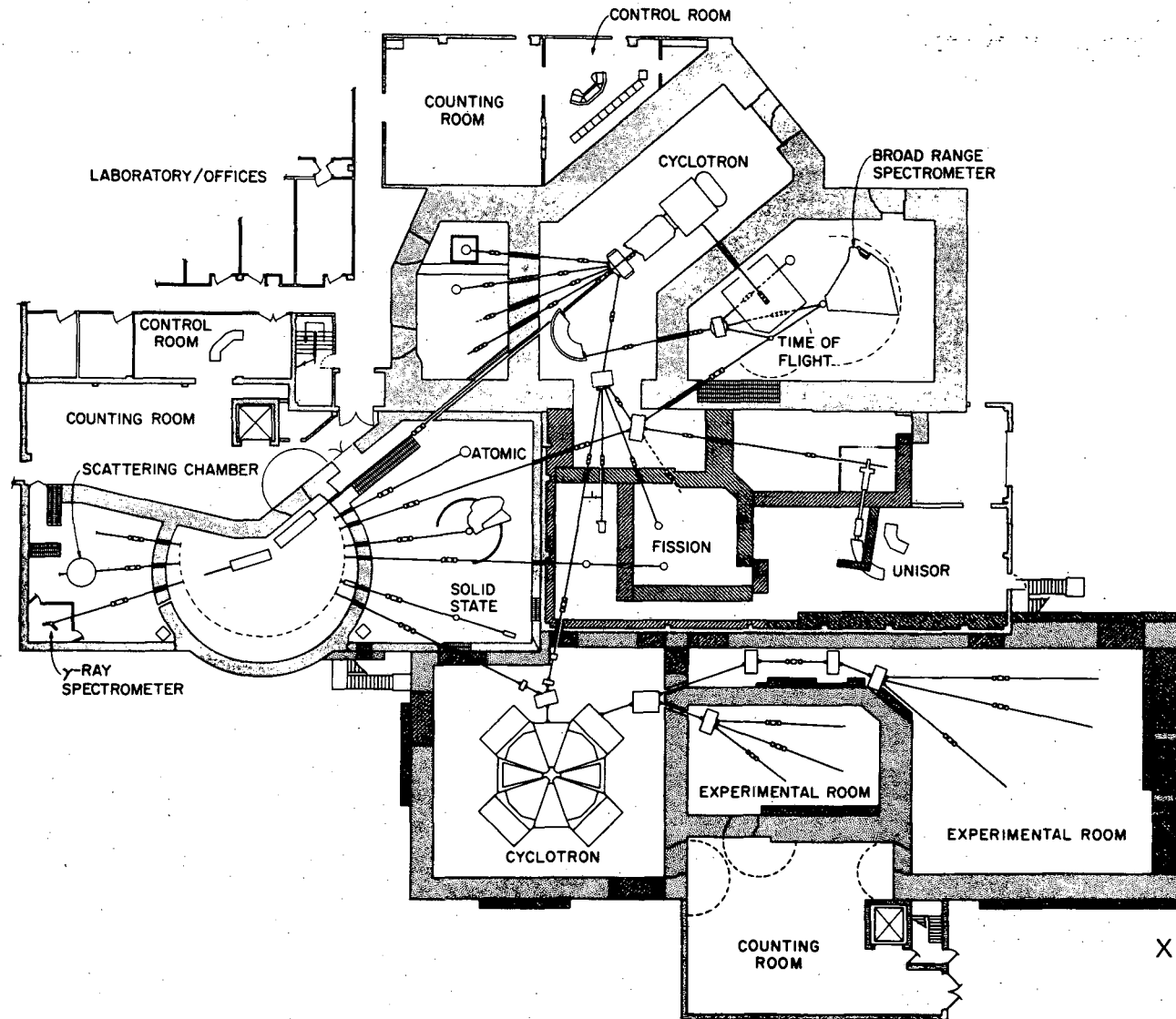
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Figure 9 Plan of HHIRF facility. The radial transport lines from the tandem are at the left. The K = 90

cyclotron (ORIC) is at the top. The future K = 400 cyclotron is at the bottom. This cyclotron can

receive a beam directly from the tandem, as well as from ORIC.

with condensed vapors. As tube length is increased, vapors migrate out more slowly and conditioning becomes more difficult. Another effect sets in. Condensed molecules dislodged by impinging ions temporarily form a gas, can be ionized and can increase discharge, which when fed by vapor from condensed layers can spread to disruptive proportions. An all metal and ceramic bakeable tube is very helpful for minimizing discharge problems, but recent difficulties have shown that vapors introduced inadvertently can persist over a long period.

3.2. Heavy Ion Linear Accelerators

Although static potentials of electrostatic accelerators now under construction at Oak Ridge and Daresbury are expected to operate in the 25-30 MV range, a limit is set by voltage breakdown between the two terminals.

A much higher effective potential can be obtained by arranging the accelerating tube so that a more modest accelerating potential is repeatedly applied to the ions in transit. Such an accelerator, or linac, will consist of many short accelerating stations arranged in sequence; in principle, there is no upper limit to the ion energy that can be achieved. Although a variety of linac structures have been employed to accelerate charged particles, the ones that so far have proved most practical as heavy ion accelerators fall into the category of drift-tube linacs.

A drift tube is a cylindrical metal (usually copper) shell, closed at each end except for an axial hole for passage of the ions. A number of drift tubes are arranged in sequence, with gaps between (figure 10), and an electric field is established in the gaps. The field originates
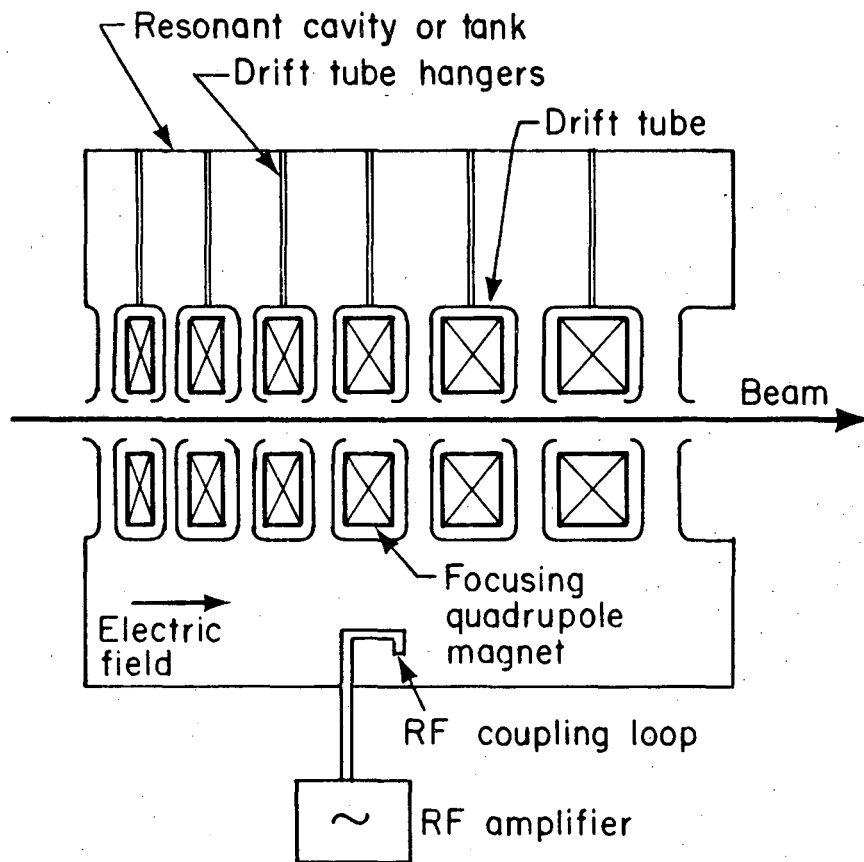
Figure 10 Schematic of a drift tube rf linac.

with a rf oscillator, so that it periodically changes direction. Ions
are accelerated in the gaps during the period when the field has the
proper polarity; during the part of the cycle when the field is reversed,
the ions are shielded from fields by the drift tube.

The behavior of a beam of ions traversing a linac can best be seen
by first visualizing what happens to a reference particle, usually
called a synchronous particle, as it is accelerated. It will gain
exactly the right amount of energy at each gap by remaining (usually)
at a constant phase angle relative to peak rf voltage. As the ion
gains energy its velocity will increase, so if rf phase is to remain
constant the separation of gaps must increase. This leads to drift
tube spacings that are determined by synchronous velocity. Once the
linac is built, the spacings are fixed and the synchronous velocity
at a given point cannot be changed. The situation is different if the
gaps are electrically independent of one another, allowing rf phase
at each gap to be varied at will. In such a single-gap linac the
synchronous velocity profile can be varied in an arbitrary manner,
so long as it remains a continuous function, by proper programming
of the rf gap phase.

A beam will be successfully accelerated if the particles remain
near to the synchronous particle in both longitudinal and transverse
phase space. The conditions for longitudinal phase stability in a
linac require the electric field to be rising at the time the
synchronous particle crosses the gap, because particles arriving at
a gap earlier than the synchronous particle will then receive less
energy, and consequently arrive later at the next gap. Particles

arriving later than the synchronous particle gain more energy, hence arrive at the next gap earlier. Electric gap fields also impart transverse radial forces on the particles; if the rf phase is correct for longitudinal stability, these radial forces will be directed away from the axis, that is, defocusing. Therefore, additional positive restoring forces must act on the particle to keep the bunch together during linac transit. The usual means for accomplishing this is to add focusing elements such as magnetic quadrupoles, either inside the drift tubes, or in gaps between drift tube structures. Radial defocusing forces are inversely proportional to β^2, and because of the difficulties in offsetting them, these forces limit the use of linac structures to accelerate very low velocity ions. The lower β limit varies with the type of structure. With presently operating machines it is about $\beta = 0.005$ for the Wideröe structure and $\beta = 0.015$ for the Alvarez structure.

The structure diagrammed in figure 10 is an Alvarez linac. In this machine, a cylindrical tank is made to resonate to the desired frequency in the T_{010} mode, giving an axial electric field with a maximum along the center. The drift tubes are supported by hangers attached to the tank wall. The cell length, or gap-to-gap distance advanced by the ions each n rf cycles is just $\beta\lambda$, where λ is the rf wavelength. The rf phase advance in one cell is $2n\pi$. In principle, n can be any integer, but in practice the accelerating field becomes inefficient when n is greater than 1. A typical Alvarez heavy ion linac is the SuperHILAC (24), with rf of 70 MHz, $\lambda = 43$ m. The tank diameter, set by the requirement for resonance, is 3.0 m, about $3\lambda/4$.

For $\beta \ll 0.015$ the cell length $\beta\lambda$ becomes too short for adequate quadrupole focusing unless λ is made larger, which requires a resonant tank of larger diameter and hence greater cost. The difficulty can be avoided by using a Wideröe structure (sometimes called a Sloan-Lawrence structure), which does not rely upon a resonant cavity, but instead delivers rf power to the drift tubes by means of two conductors connected alternately to the drift tubes. Thus adjacent drift tubes have opposite polarity, and particles advance odd multiples of π in rf phase between one gap and the next, with the distance traveled being $n\beta\lambda/2$, where n is an integer. Figure 11 is a drawing of a Wideröe linac similar to the UNILAC design. The drift tubes are arranged in a $\pi-3\pi$ sequence to allow room for quadrupoles in every other drift tube. The short drift tubes are connected to and supported by a metal pipe, which in turn is connected to three rf tuning stubs. The long drift tubes are suspended from the tank wall, which serves as the other conductor.

Recalling that the energy gained by an ion in a linear accelerator depends upon the charge number q in addition to the effective accelerating potential difference, we see that to reach high energies it is important to have q as high as possible. Ion sources show a strong intensity decrease with increasing q, so that in a practical linear accelerator one faces a compromise between energy and intensity. This compromise is partially offset by the fact that once a moderate velocity has been reached, stripping can produce a higher q than could be achieved ordinarily in an ion source. Consequently, a typical heavy ion linear

A ←

OUTER
DRIFT TUBE

INNER
DRIFT TUBE

BEAM
DIRECTION ⟹

STEMS

STUB LINE
INNER CONDUCTOR

SHORTING PLATE

SECTION A-A

A ←┘

DRIFT TUBE LINE

STUB ASSEMBLY

RF DRIVE LOOP

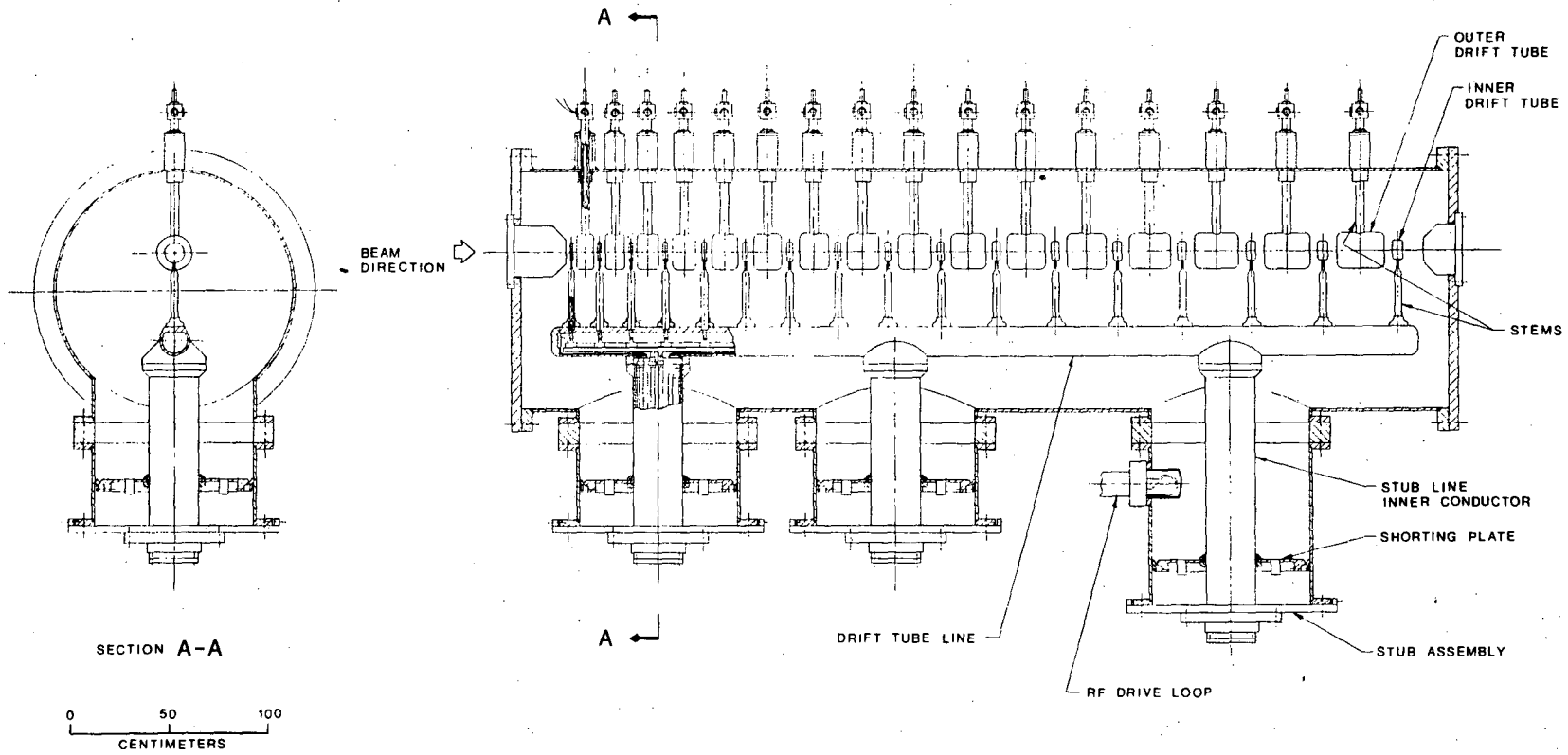0   50   100

CENTIMETERS

Figure 11   Drawing of a Wideröe drift tube linac.

XBL 765-1864

accelerator design will usually have an ion source providing ions of
moderate q injected in a dc accelerator that reaches β = 0.005 to
β = 0.015, then a linac that accelerates to a modest energy, after
which the ions are stripped to a q that is two to four times the
injected q. This is followed by another linac stage to reach the
final energy. Stripping does exact a penalty in loss of two-thirds
or more of original beam intensity, due to creation of many charge
states, only one of which can be usefully accelerated in most cases.

The state of the art in heavy ion linacs is typified by the
UNILAC, built and operated by GSI at Darmstadt, Germany (25) (figure 12).
Two dc injectors of 320 kV, each containing two ion sources, are used
to assure continuous operation. A Wideröe linac operating at 27 MHz
provides the first stage of acceleration, from β = 0.005 to β = 0.055
(T_n = 0.012 to 1.4 MeV/amu). A view of the drift tube structure of the
Wideröe is shown in figure 13.

After being accelerated to 1.4 MeV/amu in the Wideröe linac, the
beam is stripped before being injected into the next section, an
Alvarez linac. Note that the 1.4 MeV/amu beam is taken through a siding
before being further accelerated (figure 12). The purpose of this
siding is to analyze charge states resulting from the stripping process,
permitting only one charge state to enter the poststripper. A small
experimental area has been installed to utilize rejected
charge states. After being accelerated to 4.5 MeV/amu in the Alvarez
section, the ions enter a chain of 20 resonant single gap cavities, each
one cell long. This permits each cavity to be driven independently
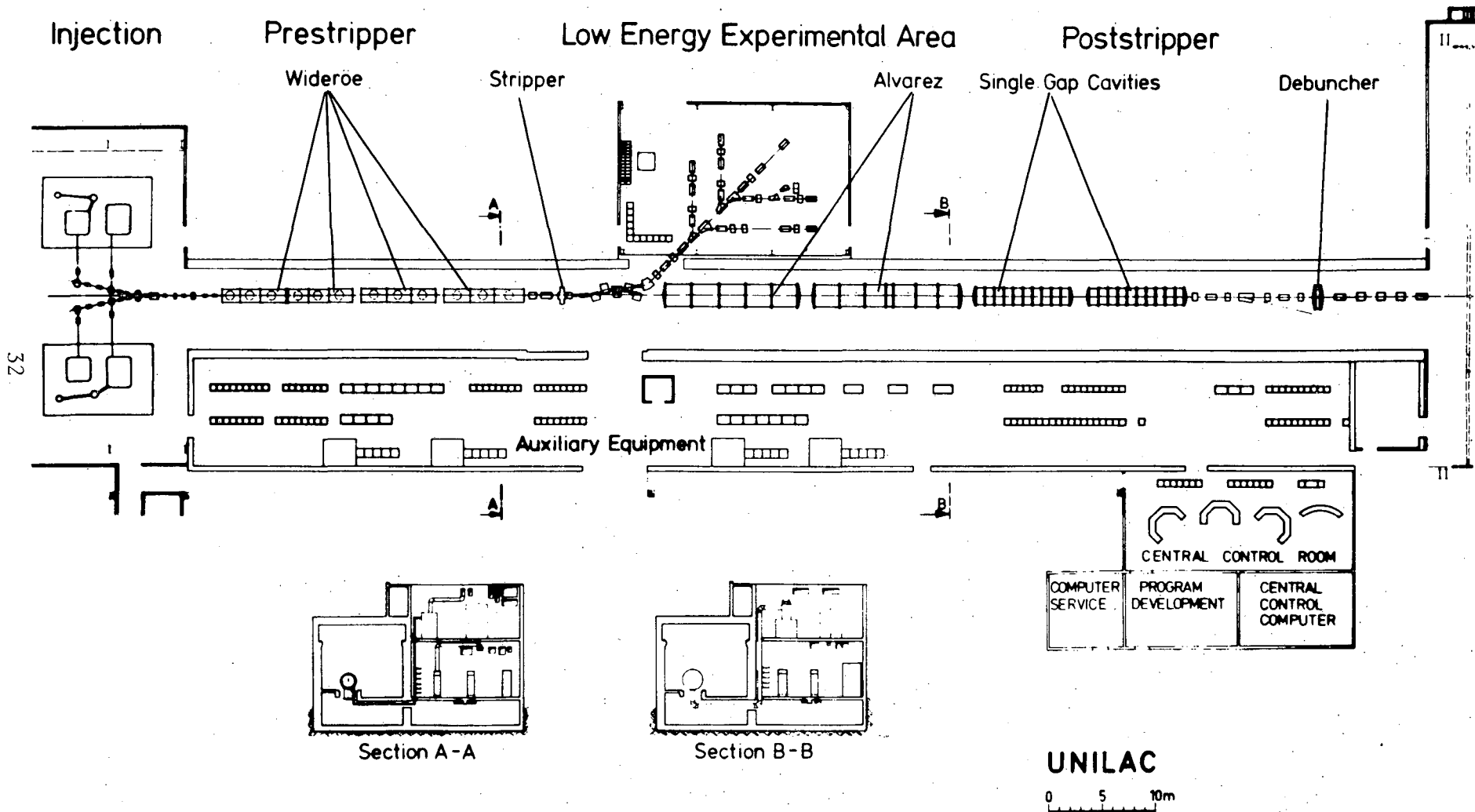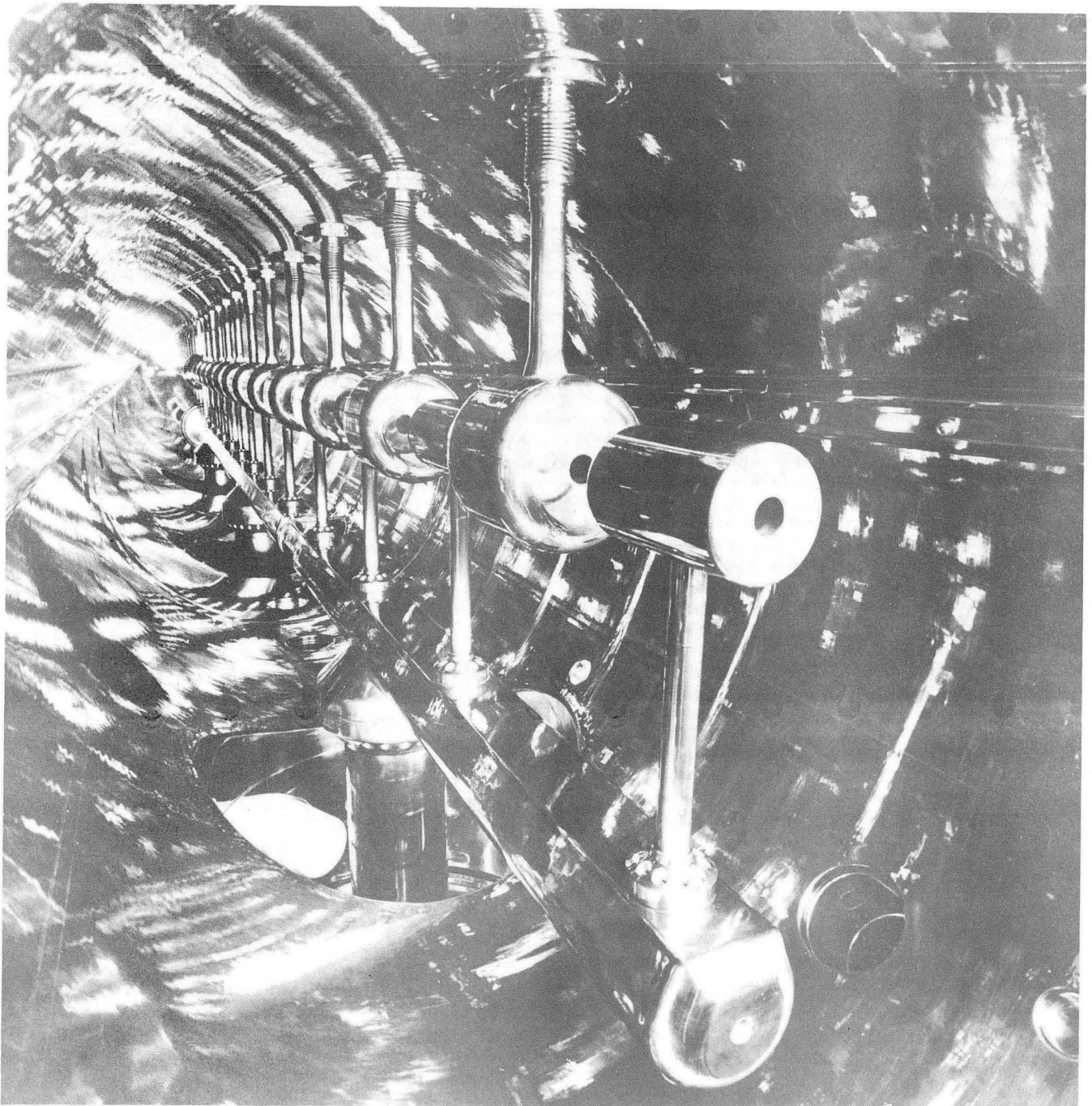of its neighbor, allowing arbitrary phase differences. The synchronous

Figure 12   Plan of the UNILAC accelerator at Darmstadt.

XBL 774-8441

32

XBB 774-3259

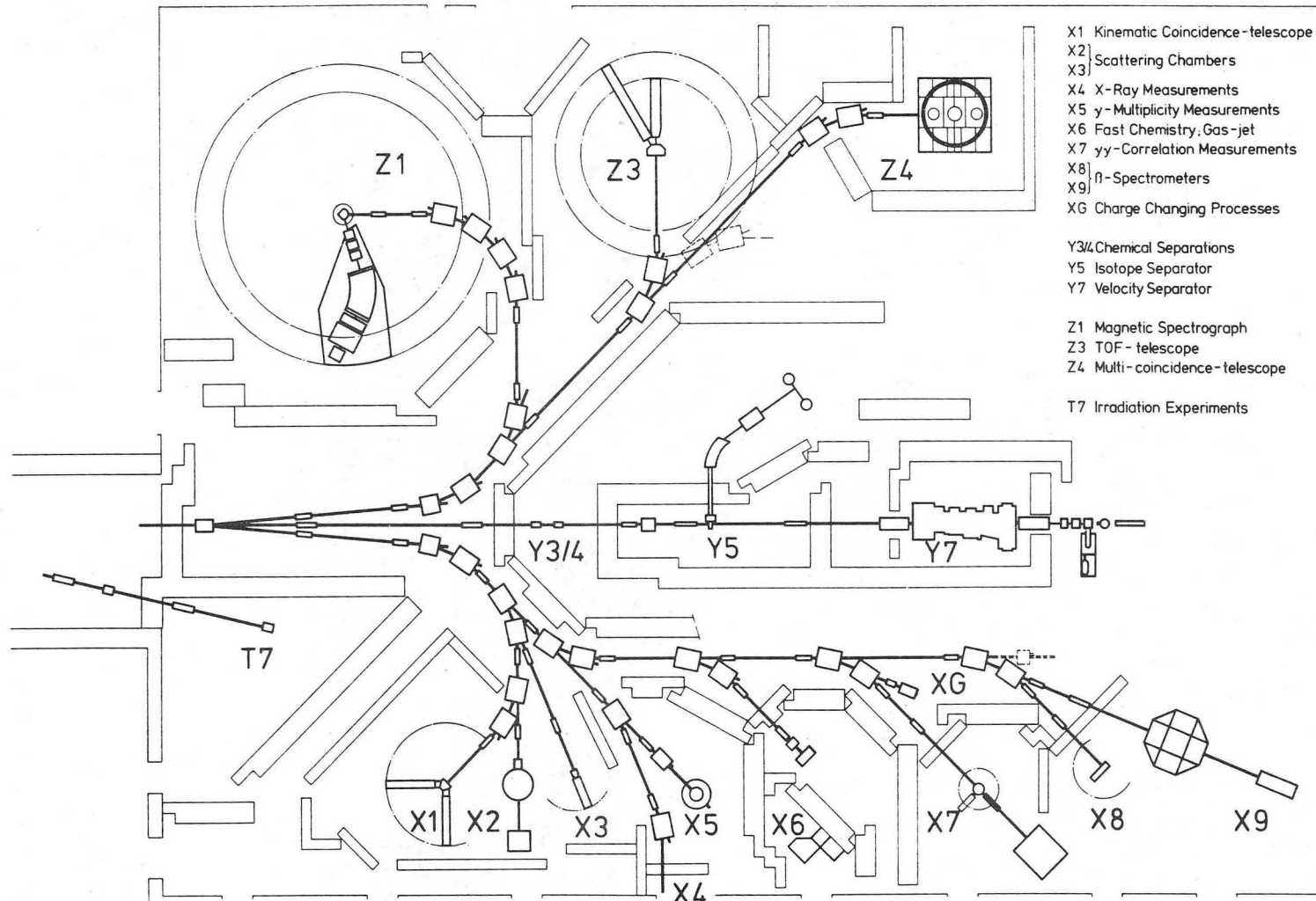Figure 13 Photograph looking inside a Wideröe tank at the UNILAC.

particle profile may then be chosen at will. Variable energy operation
is easily accomplished, including the possibility of deceleration. At
the end of the machine, neon energies from 2 to 15.4 MeV/amu and uranium
energies from 2 to 8.5 MeV/amu can be achieved. A plan of the experi-
mental area is shown in figure 14. Figure 15 is a view from above of a
portion of this area.

Improved linac structures for heavy ions are being developed in a
number of laboratories. Figure 16 shows the Argonne split ring super-
conducting cavity, a unit of the tandem postaccelerator (23). At
Heidelberg helix resonators (26), and at Munich, an interdigital drift
tube structure (27), have been built as tandem postaccelerators. At
Stanford University, substantial experience with superconducting niobium
cavities has been gained in the design of an electron accelerator.
Efforts are underway to make this technology available to heavy ion
acceleration (28).

3.3. Collective Acceleration

In an early paper Veksler (29) suggested forming a bunch of
electrons with some ions imbedded in it, then finding some way to
accelerate the entire system. Electrons, being much lighter than ions,
and hence having a very large q/A, can be accelerated more readily. The
ions will be trapped by coulomb forces and will be carried along with
the electron bunch. This idea is known today as collective acceleration.
Successful acceleration of protons and other ions has been achieved
experimentally by a number of collective methods.

The electron bunch can be produced in the form of a ring (electron
ring accelerator--ERA) (30) or an intense burst (intense relativistic

X1 Kinematic Coincidence-telescope
X2 } Scattering Chambers
X3
X4 X-Ray Measurements
X5 γ-Multiplicity Measurements
X6 Fast Chemistry; Gas-jet
X7 γγ-Correlation Measurements
X8 } ß-Spectrometers
X9
XG Charge Changing Processes

Y3/4 Chemical Separations
Y5 Isotope Separator
Y7 Velocity Separator

Z1 Magnetic Spectrograph
Z3 TOF-telescope
Z4 Multi-coincidence-telescope

T7 Irradiation Experiments

XBL 774-8440

Figure 14 Plan of experimental area of UNILAC. Accelerator is at left; beam from the accelerator is switched into one of the three beam lines, and each of these serves several experiments.

35
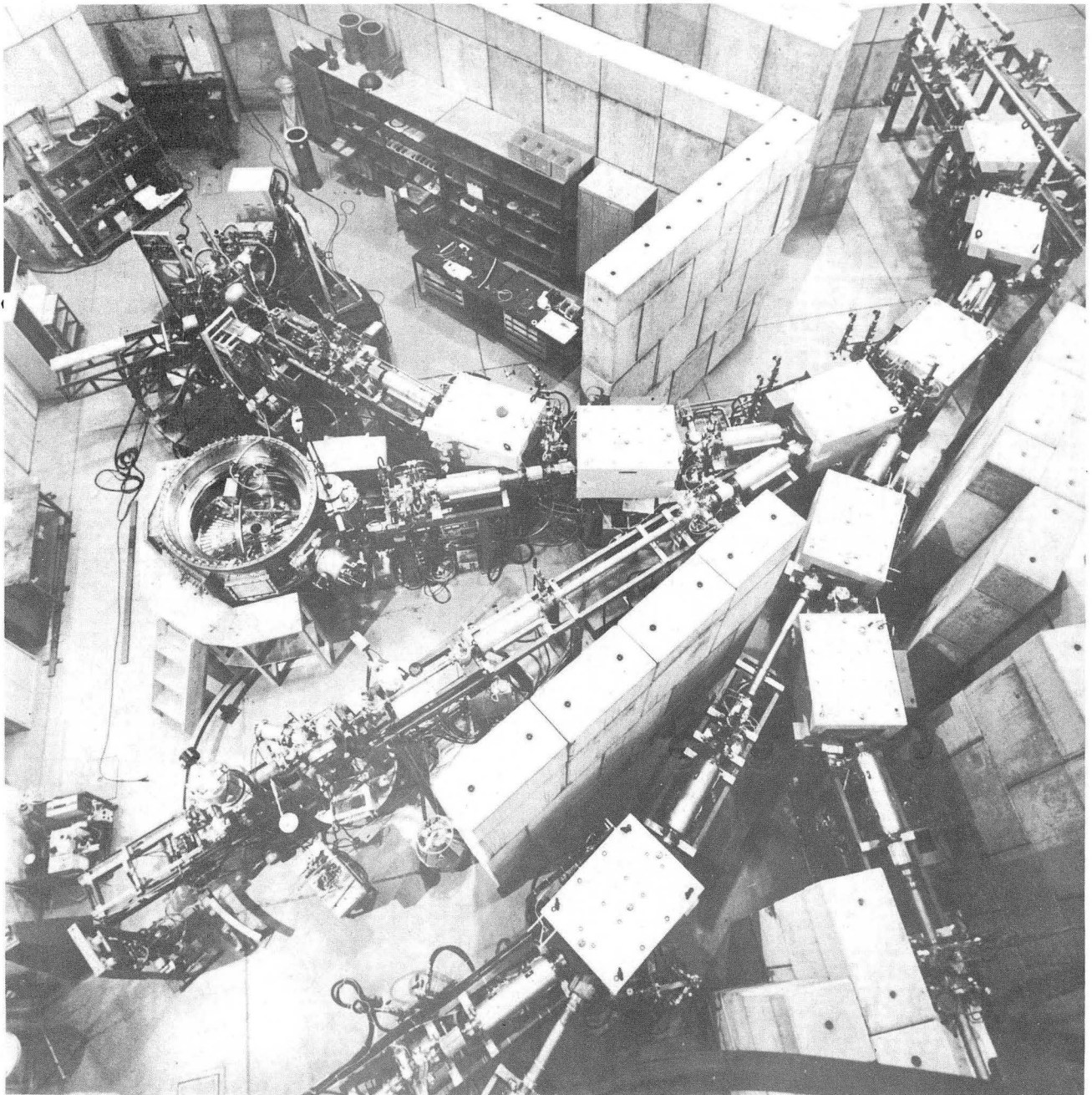
XBB 774-3258

Figure 15 View from above of a portion of the UNILAC experimental area. Just visible in the upper right hand corner are the three beam lines of figure 14; the circular structure at left center is the scattering chamber labeled X2 in figure 14.

RF COUPLING PORT
He OUTLET
RF COUPLING PORT
He OUTLET
BEAM AXIS
He INLET
14"
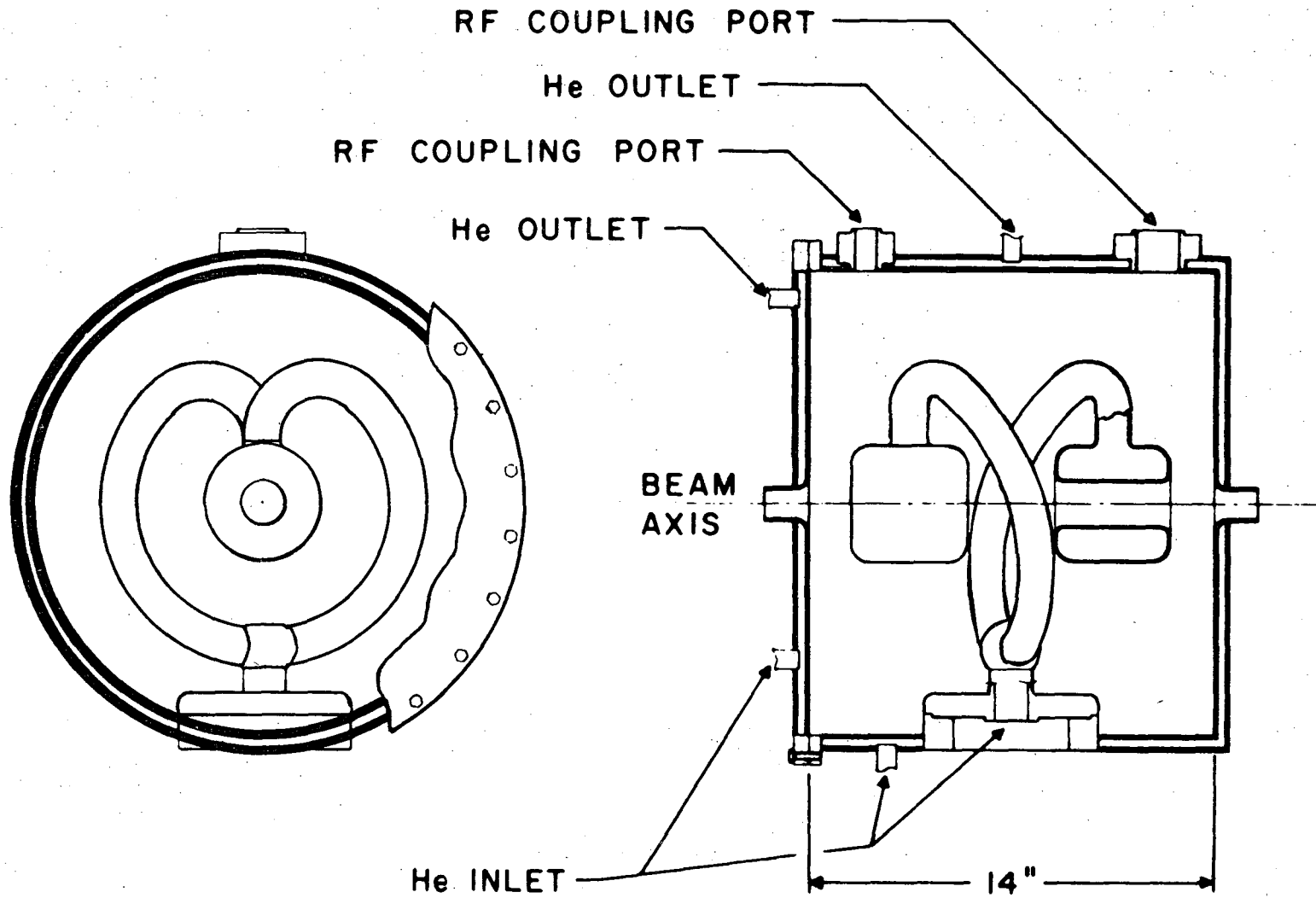
XBL 773-8230

Figure 16   Superconducting split ring accelerator cavity. This is one

unit of the Argonne postaccelerator.

electron beam--IREB) (31). Both methods are capable of short bursts of
ion beams after the carrier electrons are separated from the embedded
ions. The IREB may well emerge as a useful heavy ion source. Typical
IREBs have an energy from 100 keV to 10 MeV and currents of 10 kA to 1 MA
with pulse length from 10 nsec to 100 nsec. The electron density
achieved in IREBs is 10^{11}–10^{13} cm^{-3}. IREB development is being conducted
at a number of laboratories. However, in most cases heavy ion production
is not the main goal of such work, but an incidental byproduct. Groups
are actively pursuing various ERA collective techniques at the
University of Maryland (U.S.), the Max Planck Institut in Garching
(West Germany), the Joint Institute for Nuclear Research at Dubna, and
the Institute for Theoretical and Experimental Physics at Moscow (U.S.S.R.).

Keefe has reviewed progress in the field of collective acceleration
in a recent review article (32).

3.4. Isochronous Cyclotrons

In a cyclotron, ions are made to describe quasicircular orbits in a
magnetic field. This magnetic field is usually established between the
poles of a large circular electromagnet, with the particle orbits con-
strained to the midplane. An ion of charge q and mass M will have an
orbital frequency given by

$$f_p = \frac{q\bar{B}e}{2\pi M} \qquad 2.$$

where $\bar{B}$ is the average value of the magnetic field. Acceleration is
accomplished by inserting D-shaped electrode plates, called dees, above
and below the orbital plane, and attaching them to a rf resonator so that
voltage of the appropriate frequency is seen by the particles. In a heavy
ion machine the range of q/M values that must be accommodated can be large,

requiring a variable frequency rf system. In addition, it is often
necessary to further extend the range by employing harmonic acceleration,
in which the rf frequency f_{HF} is given by $f_{HF} = hf_p$, where h is a
positive integer. The values of h that can be used in a given cyclotron
will depend upon dee geometry (single dee or multiple symmetric dees)
and the manner in which they are phased relative to one another. The
necessary condition to satisfy, regardless of the number of dees or the
harmonic number, is that the rf voltage be attractive as the ion enters
the dee, and repulsive as it leaves the dee, so that the ion is accel-
erated both upon entering and leaving. Figure 17 shows a section through
the midplane of the LBL 88-inch machine. The dee is 180° in extent,
filling the upper half plane in the drawing.

A useful cyclotron must provide some means for axial focusing of the
ions. Early cyclotrons relied upon the weak focusing principle in which
the magnetic field decreased with radius. In such a cyclotron, however,
the energy ions can attain is limited by their relativistic mass increase.
The ion mass can be written as $M = m_0 \gamma A$, where m_0 = nucleon mass,
A = mass number, γ = total energy divided by rest energy. Since m_0 and
A are constants, we see that in equation 2 all values are constants ex-
cept $\bar{B}$ and γ. If $\bar{B}$ decreases, as it must in a weak-focusing machine, the
revolution frequency will decrease and the ion will slip in phase relative
to the rf. As the ion gains energy γ will increase, causing further slipping.

In an isochronous machine $\bar{B}$ is made to increase with radius such
that $\bar{B}/\gamma$ remains constant, hence the revolution frequency remains
constant. Axial focusing with these machines is obtained by azimuthal
variation of the magnetic field (the term AVF cyclotron for Azimuthally
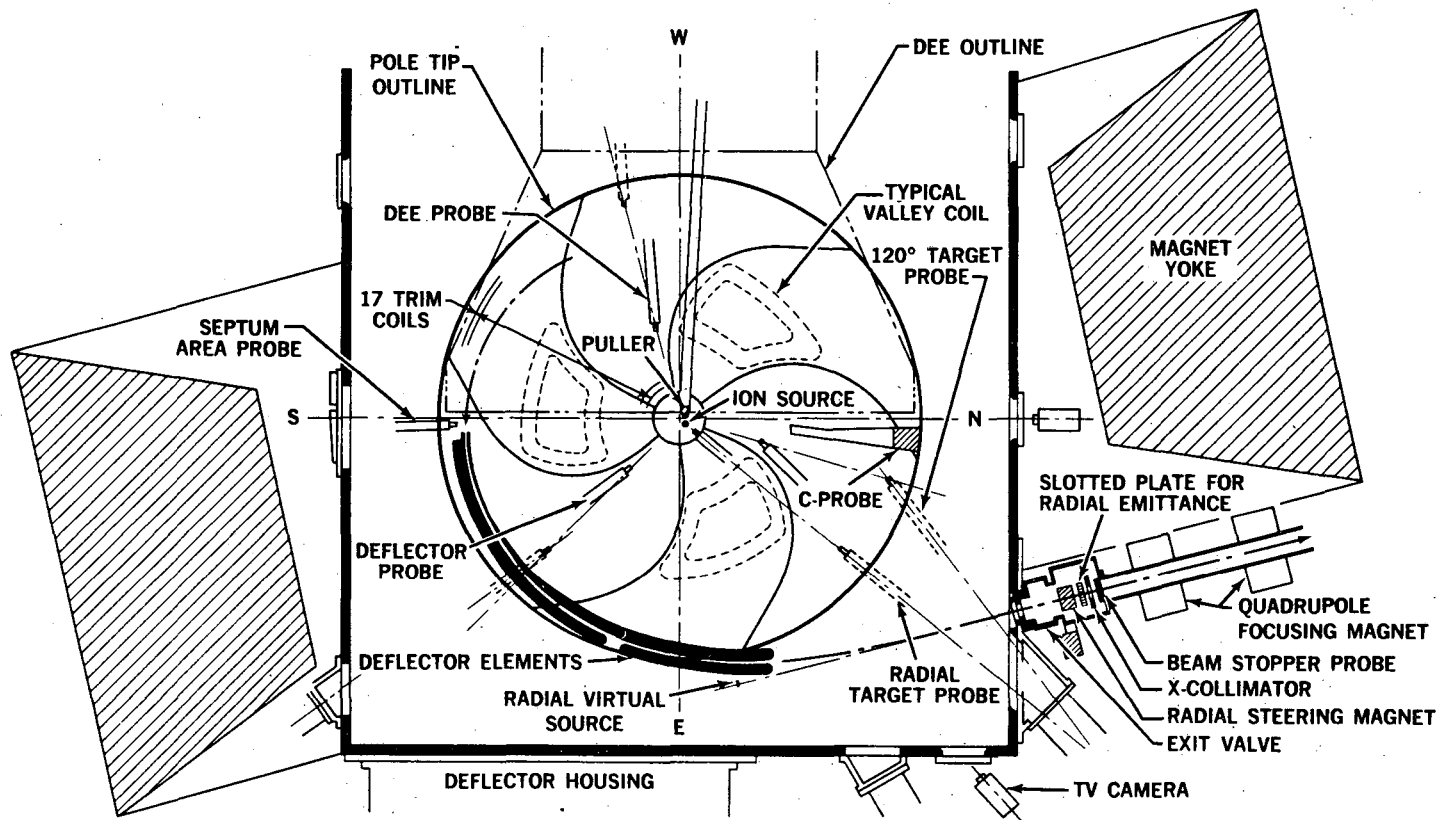
XBL 678-4699

Figure 17   Plan of an isochronous cyclotron (the 88 inch, at LBL).

Varying Field cyclotron is often used). The magnetic field is divided into several (usually three or four) sectors, each consisting of a narrow iron gap followed by a wider gap, so that the ion sees a field that fluctuates in amplitude. This produces a scalloped orbit, with nonnormal crossing of field boundaries, resulting in an axial focusing component at each crossing. Additional axial focusing is obtained if the field boundaries, instead of being radially straight, are made to curve at a constantly increasing angle away from the radial. The machine shown in figure 17 has three sectors, with moderate spiral boundaries. For orbital stability at least three sectors are required, because isochronism requires that the radial betatron frequency ν_r (i.e., the number of radial oscillations about the equilibrium orbit per revolution) be approximately equal to γ, so that $\nu_r \simeq 1$ at the center of the machine, and greater than 1 as the ions gain energy. If the number of sectors $N = 2$, there will be a betatron-oscillation phase advance of π per sector, a condition for which the focusing forces are unstable (known as the π stopband). With $N = 3,4 \ldots$ this is avoided. As ions gain energy, another stopband will be reached when $\gamma \simeq N/2$; this energy for $N = 3$ is 469 MeV/amu. For further details on isochronous cyclotron design, see Ref. (33).

In an isochronous cyclotron, since particles of different energy have the same revolution frequency, there is no longitudinal phase stability such as exists for a linac or synchrotron. If the field shape is exactly isochronous, particles that are injected into the center at a particular rf phase remain at this phase until maximum energy is reached. Any departure from the isochronous field, however,

will cause particles to slip in rf phase, and with slippage beyond ±π, the particles will be lost to further acceleration. This condition limits the allowable magnetic field departure from isochronism. Typically, field tolerances must be held to one part in 10^{-5} or better.

It can be shown that there is no field contour that will satisfy equation 2 for all radii as q/A is allowed to vary. This means that for a variable-ion machine, some means must be incorporated for appropriately shaping the field for the ion being accelerated. Usually, trim coils are employed, although movable shims also have been used. An accurate field mapping is necessary for various field levels and effects of trim coils or shims, so that field level and profile can be set to the required accuracy for a particular ion.

A number of methods are used for injecting ions into the innermost orbit. The simplest is to insert an ion source into the cyclotron. The diameter of the source is kept small, and the dee voltage is made large enough so that the first orbit clears the back of the ion source. Another method is to locate the ion source outside the magnet, with an axial transport system, terminating in a 90° inflector to inject into the first orbit. This can be combined with stripping (see figure 19). Still another means is employed with large separated sector cyclotrons. By preaccelerating the ions in another cyclotron or tandem-Van de Graaff, they have substantial energy at injection, yielding a larger first orbit.

Extraction is usually accomplished by exciting a betatron-oscillation resonance and thus increasing the radial position of the particle orbit in one revolution at a specified azimuth sufficient to insert a septum of an electrostatic or magnetic channel. This channel in turn will

counteract the guide field and let the particle escape in controlled fashion.

The maximum energy that can be attained in a cyclotron depends upon q/A and is given by $T_n \cong Kq^2/A^2$, where K is a constant for a particular accelerator. This expression is exact in the non-relativistic limit. Since present heavy ion cyclotrons seldom exceed $\gamma = 1.02$, the factor K is useful for comparing the capabilities of cyclotrons. Figure 18 shows a plan of the GANIL project, now under construction in France, which will incorporate four cyclotrons, two (labeled CO_1 and CO_2) of K = 25 and two (labeled CSS_1 and CSS_2) of K = 400 (34).

3.5. Superconducting Cyclotrons

A new type of cyclotron, the so-called superconducting cyclotron, is a focus of major development effort. It combines high field superconducting magnet techniques with the basic isochronous cyclotron technology. Using superconducting main coils, the cyclotron's magnetic field can be raised by a factor of approximately three, to the 50 kG level. This high magnetic field leads to a major reduction in size and cost, even when the added expenses of cryogenic equipment and special conductor are included. (A superconducting cyclotron as estimated by H. Blosser is roughly one half the cost of a conventional isochronous cyclotron of the same energy and one third the cost of a separated sector isochronous cyclotron.)

The anticipated properties of such a cyclotron make it a very attractive component for a number of heavy ion accelerator systems. Figure 6(d), (e), and (i) compares estimated performance curves of superconducting
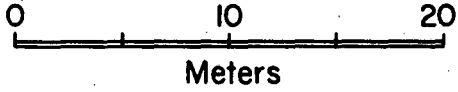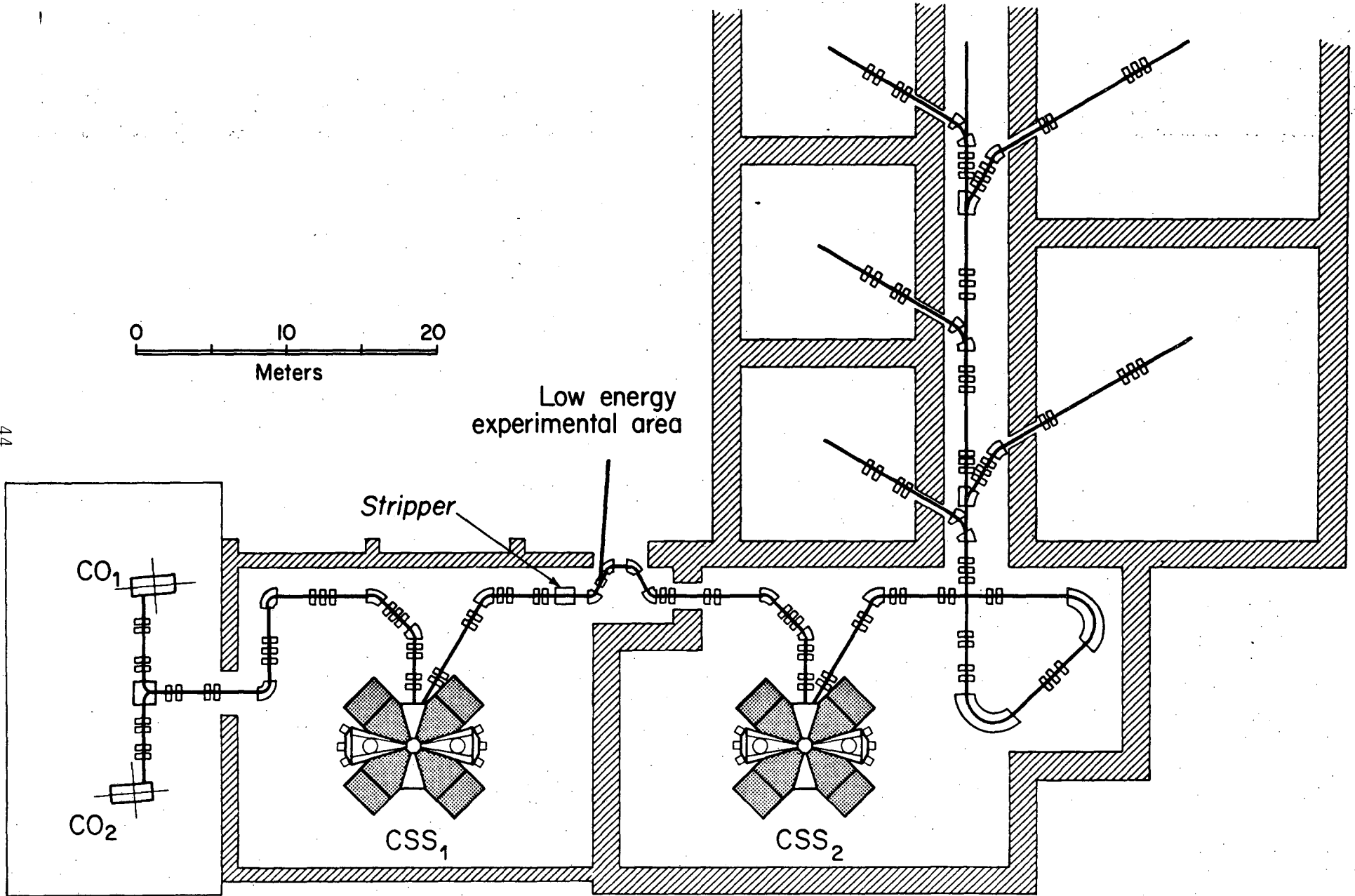
XBL 774-799

<u>Figure 18</u> Plan of the GANIL facility. The two large cyclotrons are connected in tandem, with a stripper between them.

cyclotrons with other heavy ion accelerators. The expected high
operating energies (above the constraints of the Coulomb repulsion,
surface interactions and normal density); will permit qualitatively new
aspects of nuclei (such as high density, supersonic and coherent mesic
phenomena) to become the subject of sensitive investigation.

The superconducting cyclotron was first explored by a group at
Michigan State University (35) in the early 1960s, but the idea was
laid aside because of then underdeveloped conductor technology. A
group at Chalk River (under J. Fraser) reconsidered the idea (36) in
1973, concluding that superconducting coil technology had reached a
level of development that not only established feasibility, but also
offered a major economic breakthrough, lowering costs for both
construction and operation. Today three laboratories are actively
exploring superconducting cyclotron technology: the Atomic Energy of
Canada Laboratory at Chalk River, Ontario, the University of Milan
Cyclotron Laboratory at Milan, Italy, and the Michigan State University
Cyclotron Laboratory at East Lansing, Michigan. The long-range goals
of all three involve the pairing of two accelerators. At Chalk River
and Milan, the first stage accelerator is envisaged as a large tandem
electrostatic accelerator with the second stage a superconducting
cyclotron of $K = 500$. In contrast, the MSU plan involves two
superconducting cyclotrons--a $K = 500$ machine that injects into a
$K = 800$ machine.

All three groups are presently involved in constructing prototype
superconducting magnets; the prototypes at Chalk River (37) and MSU (38)
are full scale, and the one at Milan (39) is 1/6th scale. Also, all

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expect to have their prototype magnets in operation in 1977. Successful operation of these magnets will substantially advance the overall feasibility of superconducting cyclotrons, since all other major components operate at room temperature and involve established technologies. Major design constraints are set by the large attractive force (approximately 1000 tons) between the upper and lower halves of the coil, the need for good thermal insulation of the main coil, and the need for a sharp magnetic field edge to facilitate extraction. All three projects plan a solenoidal-like main superconducting coil with a small median plane gap for injected and extracted beams and control hardware. The winding is further divided into two major sections so that shifting of ampere turns from one coil section to the other will approximately match the variation in field shape required by particles of different mass. Major features of the structure planned at Chalk River are shown as an example in figure 19.

The main coil superconductor is a NbTi and Cu composite. In the MSU design, this coil is tightly packed onto a large stainless steel spool, with a picket fence lattice between radial layers to allow helium cooling. All three projects use a massive magnet yoke, more or less completely encasing the coil. The major access to internal components will be from top and bottom by raising or lowering the appropriate elements of the yoke with a system of precision jacks.

Ion source design also differs among the three projects. The Chalk River design omits entirely the use of a central ion source since the cyclotron is always intended to be a second-stage accelerator. For testing purposes Milan provides a central ion source in its second-
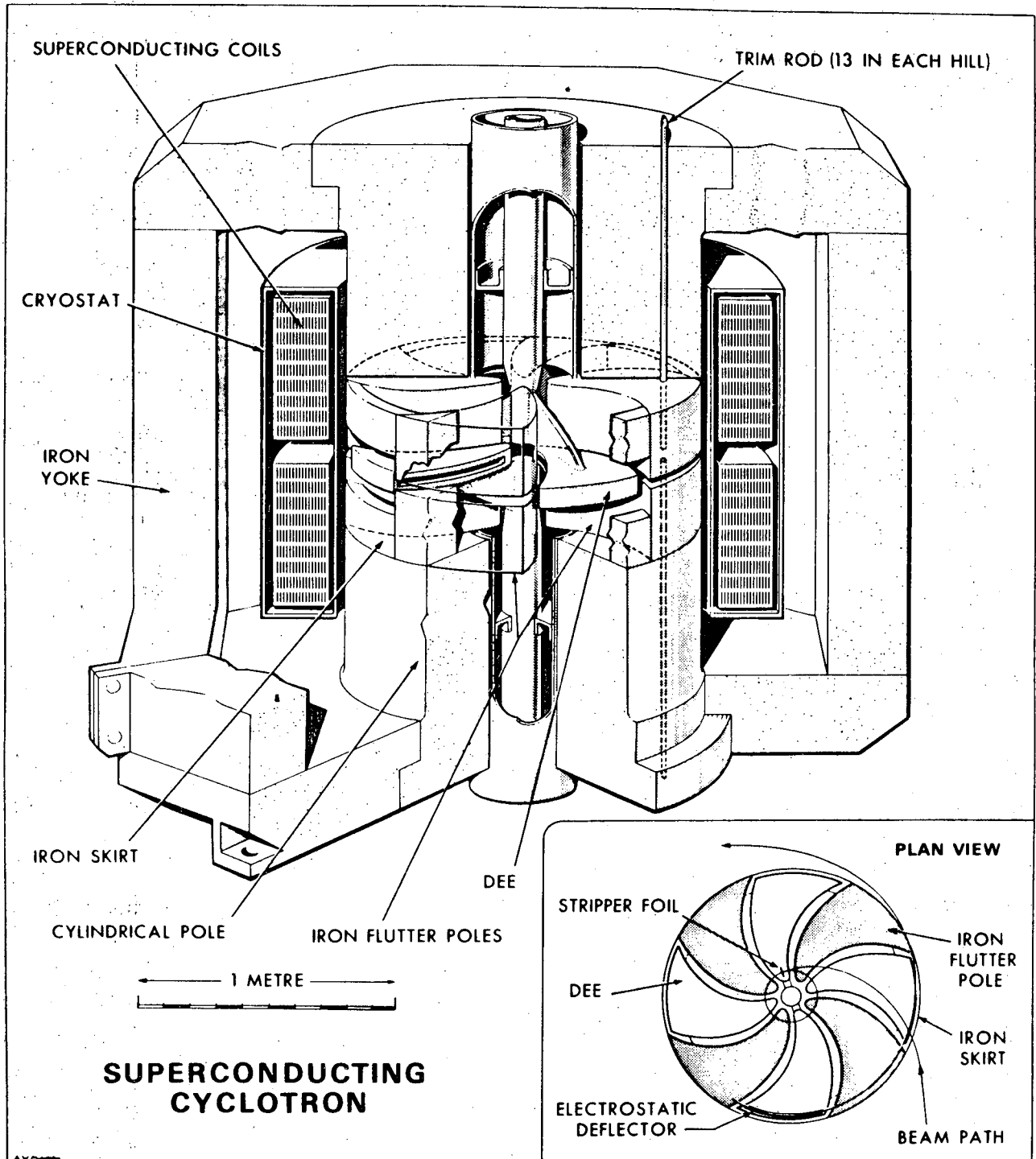
Figure 19 The superconducting cyclotron under construction at Chalk
River, Canada. The insert drawing shows the method of external
injection. A stripping foil placed near the center lowers the rigidity
of the beam so that it is trapped in the first orbit.

XBL 774-8439

stage superconducting cyclotron and will then shift to use of the electro-static first-stage accelerator. The MSU prototype magnet includes an interchangeable central geometry to allow the 500 MeV magnet to be set up as a conventional cyclotron with a central ion source, or alternatively used to study central region design of a second-stage booster accelerator.

Beam quality for the superconducting cyclotrons is expected to be generally similar to that of present heavy ion isochronous cyclotrons, with some improvement in intensity as a result of the much better vacuum systems provided in the design. The new machines are expected to produce beams of moderate emittance and energy spread in the microampere range and low emittance and energy spread at reduced intensity, characteristics that are well matched to contemplated experimental programs in heavy ion physics.

3.6. Heavy Ion Synchrotrons

To attain energies above 100 MeV/amu the synchrotron becomes economically attractive as a heavy ion accelerator. The synchrotron consists of a ring of guide field magnets whose apertures need only accommodate a single orbiting beam. The particles complete $10^4 - 10^6$ revolutions with a modest energy gain each revolution. This is in contrast to a linac, in which particles traverse the accelerating rf system only once, and to the cyclotron with its guide field magnet large enough to enclose a platter comprising orbits all the way from injection to extraction energies. In addition to guide field magnets, the synchrotron has straight sections for injection, extraction, rf cavities, vacuum pumping stations, and auxiliary magnets of various kinds.

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The magnetic field is programmed to rise in a predetermined manner, usually either linearly or sinusoidally. As the field rises, the rf must change to be in step with the particles, and the energy gained by the particles must be just sufficient to keep them within the magnetic guide field. Particles will oscillate about a synchronous phase angle, as in the linac, causing the beam to be bunched. If the rf is the same as the orbital frequency, there is only one bunch, but if, for practical reasons, the rf is choosen as a multiple of the orbital frequency, then the number of bunches depends upon the harmonic number. Beam control is usually accomplished by feedback systems in which the beam bunches themselves are used to generate radius and phase information and to control the position of the beam.

Such positive feedback systems depend on sufficient beam intensity for favorable signal-to-noise ratio. Heavy ion beams don't always possess sufficient intensity, or very low intensity may be desired, so in these cases the rf must be preprogrammed. But establishing the correct rf settings may require an accuracy on the order of one part in 10^6, a severe test of component reproducibility. One way to solve this problem is to run a light tracer ion with adequate intensity and a q/A as close as possible to the desired heavy ion beam to find the correct rf settings, which are then recorded in a computer. For a discussion of the theory of synchrotrons, see Refs. (40,41).
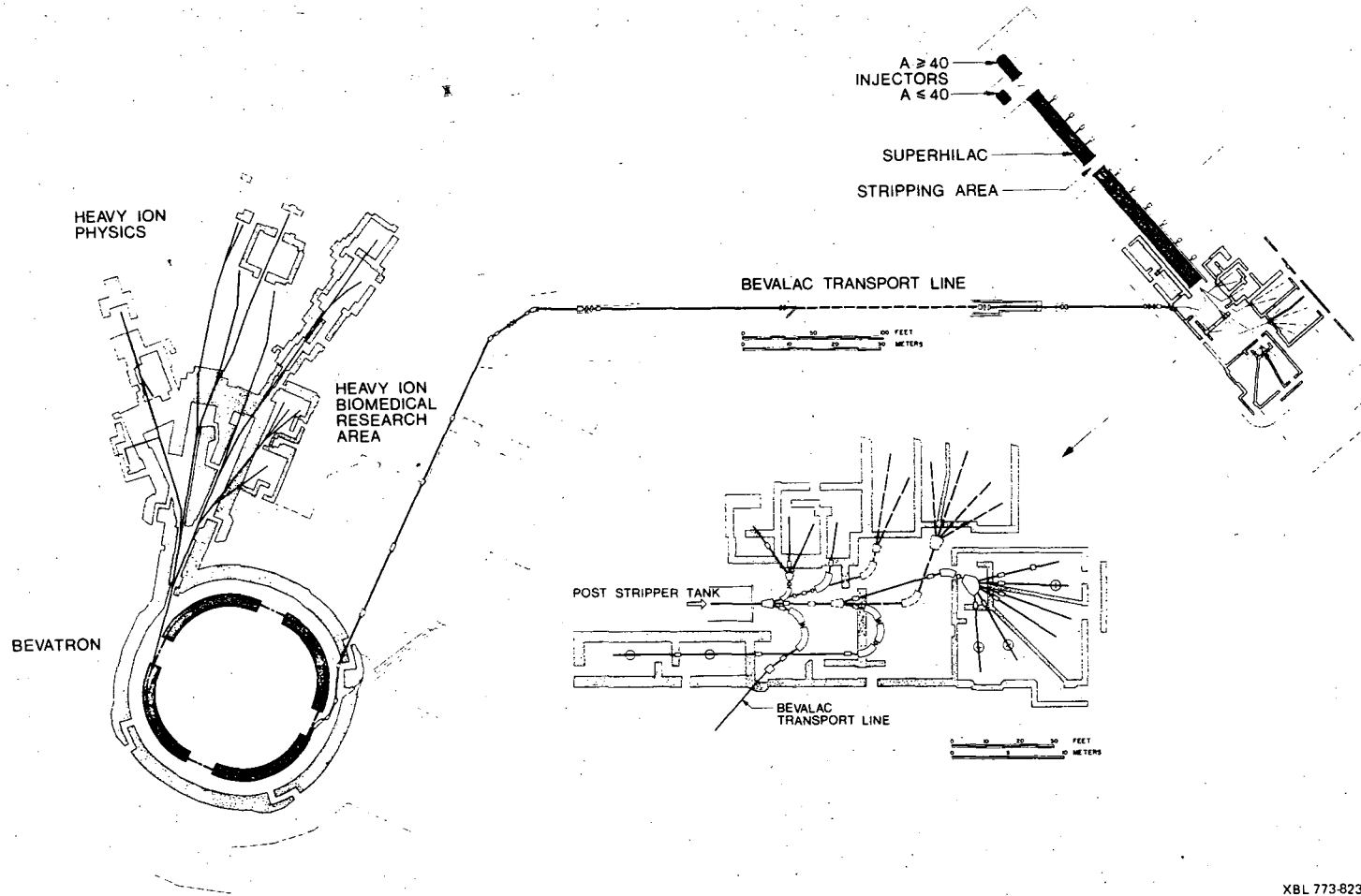
Because of the relatively large cross section for charge exchange processes with the residual gas, and a long path during acceleration, a good vacuum is needed in heavy ion synchrotrons. Any change of

charge state will cause immediate loss, because the magnetic rigidity is inversely proportional to ionic charge.

Depending on length of acceleration, ion species, charge state and tolerable losses, a vacuum of 10^{-9} to 10^{-10} Torr may be required. The vacuum requirement is less severe for fully stripped ions because their energy at injection is high enough to render the capture cross sections much smaller than the stripping cross sections (see Sect. 2.1). Inversely, if fully stripped ions are desired, then the minimum injection energy is determined. Contrary to the proton synchrotrons, space charge effects for heavy ions to date are small. Hence, the magnetic field at injection must only be high enough to avoid problems with remnant fields. This establishes a minimum of $B\rho$ at injection and, therefore, the injection energy for a given q/A. The maximum energy attainable will then depend upon the ratio of maximum to minimum magnetic field. This ratio will usually fall in the interval 20 to 40.

To obtain intense beams of proper emittance, energy spread and charge state, an air insulated Cockcroft-Walton dc accelerator and an rf linac with short pulses are the favored components of an injection system.

Following the shutdown of the Princeton– Pennsylvania Accelerator, there remains only one operating heavy ion synchrotron, the Bevalac facility located at Lawrence Berkeley Laboratory, figure 20 (42). Since the Bevatron itself was originally built to accelerate protons, its parameters had to be adapted for heavy ion acceleration; it can now achieve maximum particle rigidities of 229 kG-m (2.6 GeV/amu for fully stripped particle with q/A = 1/2). Its injector system consists

A ≥ 40
INJECTORS
A ≤ 40

SUPERHILAC

STRIPPING AREA

HEAVY ION
PHYSICS

BEVALAC TRANSPORT LINE

HEAVY ION
BIOMEDICAL
RESEARCH
AREA

POST STRIPPER TANK

BEVATRON

BEVALAC
TRANSPORT LINE

XBL 773-8231

Figure 20   Plan of the Bevalac facility at LBL. The synchrotron is
in the lower left hand corner. The SuperHILAC injector is at the upper
right.

of a 2.5 MV pressurized and a 750 kV air insulated Cockroft-Walton dc accelerator, either of which can inject into the SuperHILAC, an Alvarez-type linac of 8.5 MeV/amu (43). The high-intensity beam from this machine is then transported via a 250 m-long transfer line for injection into the Bevatron synchrotron. With an operating vacuum of 2.10^{-7} Torr in the Bevatron, only fully stripped beams can be accelerated. The heaviest particle accelerated to date is ^{56}Fe, which at 8.5 MeV/amu from the linac yields about 5% of 26+ (fully stripped) with a 400 $\mu g/cm^2$ carbon stripping foil.

In accelerating the iron beam, the intensity was too low for operation of the feedback loops, so $^{15}N^{+7}$ (q/A = 0.4667) was used as a tracer particle for $^{56}Fe^{+26}$ (q/A = 0.4643). An improvement program is planned that will permit acceleration of very heavy (A~200) and partially stripped ions.

4. IMPORTANT ACCELERATOR COMPONENTS

In this section we attempt to round out the sketch that has been given of each accelerator type with a discussion of some vital components common to all, with emphasis on those features that are of most importance for the heavy ion machines.

4.1. Ion Sources for Heavy Ion Accelerators

The ideal ion source for a modern heavy ion accelerator should provide beams of all atomic species at high intensity, good emittance and long lifetime. The source should be easily accessible for maintenance. For accelerators that require positive ions from the source, high charge states are desirable. Cyclotron energy is

proportional to charge squared, and linac length can be reduced by using ions with highest charge states. For tandem electrostatic accelerators the charge state is -1 (only a few low intensity ion species have been produced with -2 charge).

High charge state ion beams for positive ion accelerators can be produced by electron bombardment of atoms and ions in a plasma or by stripping of fast ions. For electron bombardment sources, the product of flux density and ion confinement time must be sufficient to produce the desired charge state. Electron energies should be 10s of eV up to hundreds or several thousand eV, depending upon the degree of ionization to be achieved.

For a more complete discussion of heavy ion sources, see Ref. (44).

The traditional heavy ion source for cyclotrons and linacs is the PIG (45,46) (see figure 21). Gas is introduced into the vertical tube where the arc is struck between the two cathodes. The arc follows the direction of the magnetic field. Electrons for the arc are supplied by the cathodes. Ions are extracted through an aperture in the side or one end of the discharge tube (side-extracted or axially extracted PIG). Solid materials can be fed into the source by placing them in a cathode or tangent to the bore in the anode, or by use of an oven.

Another type of source that has been used for heavy ion production is the duoplasmatron, which also establishes a plasma in a magnetic field, with the ions extracted axially (47). It has undergone many years of development for high-intensity (hundreds of mA), high-quality pulsed beams of protons at high-energy synchrotron laboratories, and

Edge, magnet poles

Ion
trajectory

Anode

Extractor
(stainless steel)

Plan view

0   1   2

Scale (in.)

Cathode
(tantalum)

Insulator

(Cu)

Top pole piece

Extractor (stainless steel)

Gas line

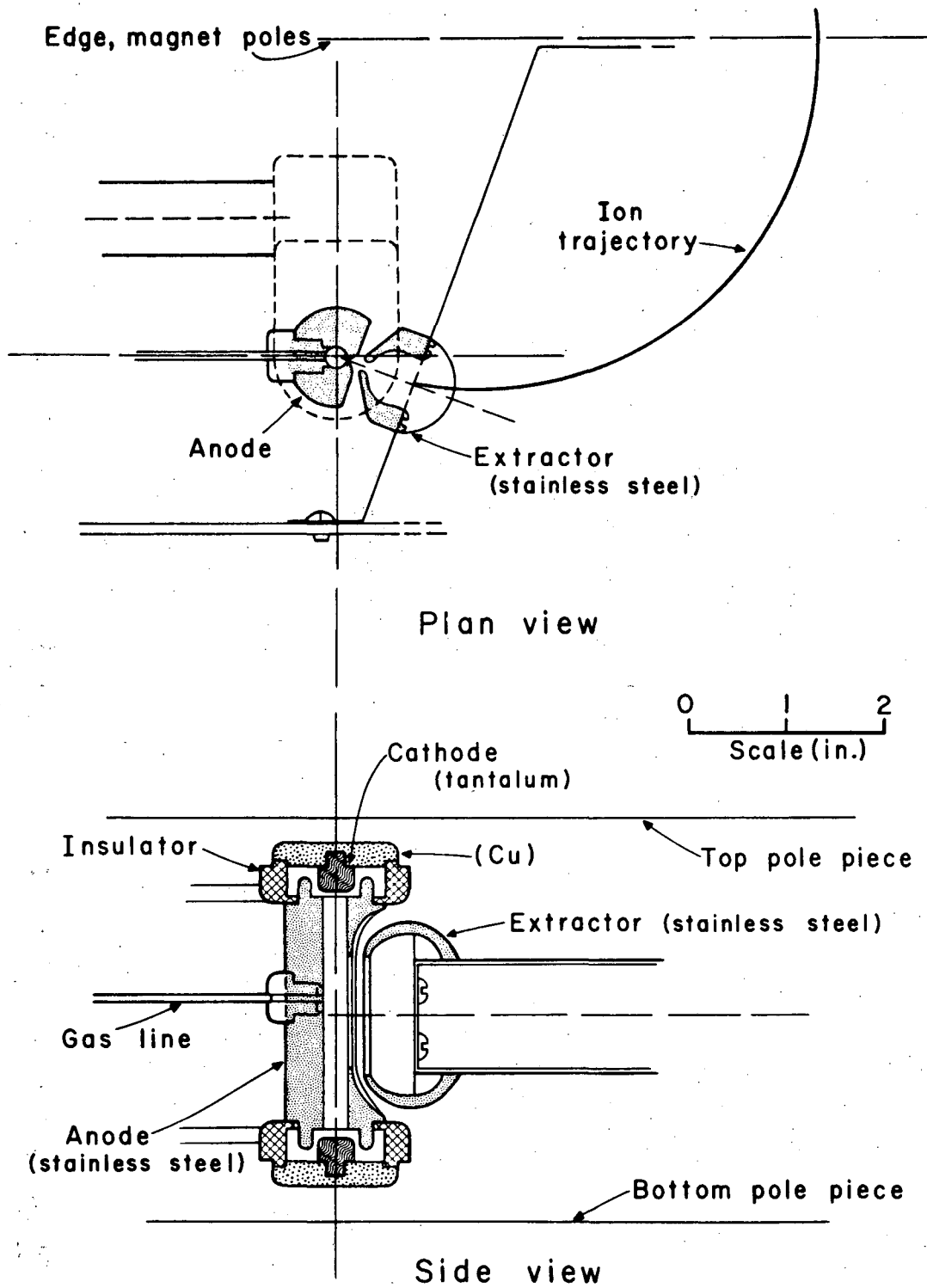Anode
(stainless steel)

Bottom pole piece

Side view

MU-27840

Figure 21 The PIG ion source as installed in a cyclotron.

has recently been used for heavy ions at the UNILAC heavy ion linac.

The duoplasmatron has higher intensity than the PIG, better emittance and lifetime, but lower average charge states. For heavy ion linac requirements (e.g., UNILAC) of $q/A \geq 0.38$ the duoplasmatron is preferred over the PIG for ions lighter than xenon.

Several other types of sources are under development for high charge states. One is the electron cyclotron resonance, or ECR source. Here the high energy electrons used to strip ions are produced from the magnetically confined plasma by feeding in microwave energy at the cyclotron resonance frequency of the electrons in the applied magnetic field (48).

Another is the electron beam ion source (49). In EBIS, a usually superconducting solenoid of 1 m length confines an electron beam from a gun placed at one end. The magnetic field keeps the beam limited to a radius of a few millimeters as it drifts down the solenoid axis to the collector at the other end. A pulse of gas injected at the gun end is ionized and confined radially by the potential well of the electron beam. A raised field at either end confines the ions longitudinally for typically 10 – 100 msec, until the desired charge state is reached. Then the barrier is lowered at the solenoid exit, providing beam extraction. The output current averaged over long times is orders of magnitude less than for the other sources, but the unique high charge states would make possible significantly higher energies from cyclotrons than with the other sources. Also, the pulsed nature of the source, and the delivery of fully stripped ions (presently up to neon), make it a good match to synchrotron requirements.

Other sources that have great potential for high currents of low charge state ions are the multi-aperture sources developed for ion propulsion (50) and for injection of multi-ampere beams of hydrogen into thermonuclear fusion reactors (51).

Tandem electrostatic accelerators must rely upon negative ion sources. The recently developed cesium sputter ion source (52) is able to deliver much improved yields compared with earlier sources, and can be used with a much greater range of ion masses.

In summary, a large amount of work is being done at many different laboratories on new types of ion sources to achieve greater intensity and higher charge states. The reason for this intense effort is that the design of accelerator systems depends critically on ion sources. A doubling of the charge state, for example, will cut in half the electric field required for acceleration, and also reduce the magnetic rigidity by one-half. At the present time, however, the PIG and duoplasmatron sources are almost exclusively relied upon for heavy ion accelerators.

4.2. Control Systems

An adequate control system will have some means for adjusting accelerator parameters to achieve optimum output. All heavy ion accelerators described in this paper are sufficiently complicated to require many adjustable parameters in order to change ions, energy, etc. Some means should also exist for recording parameters for future use. Analog control systems have been used in the past, but great progress has been made recently in implementing computer control systems for accelerators (53). They will perform the duties mentioned

above admirably, and have other useful features.

One of the great advantages of a computer control system is its
potential for retaining a great amount of data, which can be presented
to the operator on a selective basis. This permits the use of
sophisticated instrumentation where necessary, while at the same time
reducing the number of meters, displays, recorders, etc., competing
for the operator's attention. In figure 22 is shown schematically
the computer control system installed at the SuperHILAC. A central
processor is used to transmit and receive information from operator
consoles, and is also linked to standard peripheral devices. Two
auxiliary computers are used for real-time control of accelerator
hardware, while a third is used for graphic displays of beam data.
This system employs four minicomputers for accelerator control because
the complexity of operation at the SuperHILAC requires it; at other
accelerator installations a single minicomputer could perform all
functions adequately.

The diagram in figure 22 shows two operator control consoles
employed to run the accelerator in the "timeshare" mode in which two
different ions--argon and xenon, for example--are transmitted through
the machine on successive pulses, and delivered to separate experimental
areas (43). Each console is devoted to one of the ions and an operator
at that console tunes his ion beam independently of the other beam.
This type of operation illustrates how accelerator capabilities may be
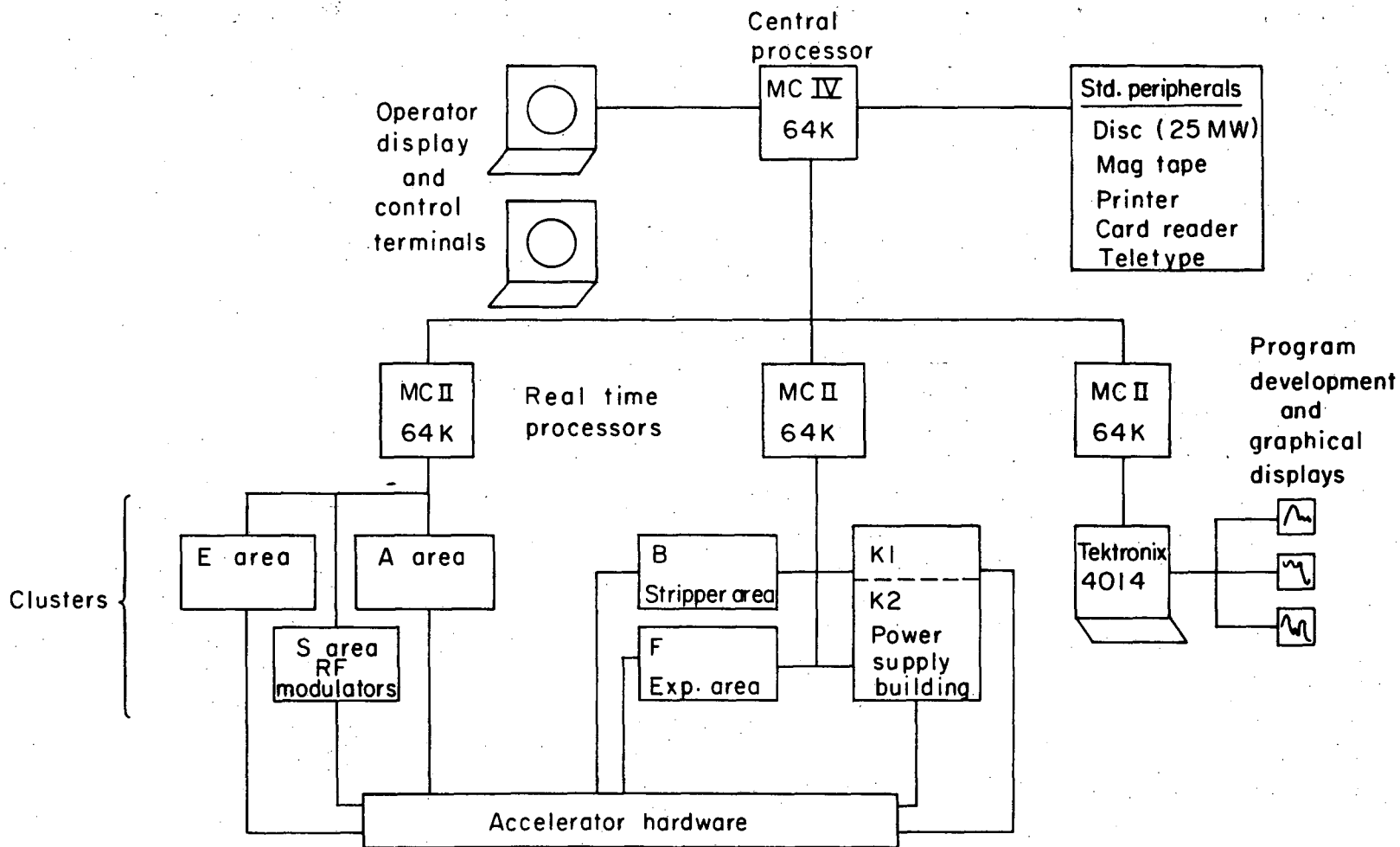extended with the imaginative use of control computers.

Figure 22 Schematic of SuperHILAC computer control system.

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4.3. Beam Instrumentation

For a heavy ion accelerator to operate properly, it is necessary to measure beam intensity, energy, charge state, mass number, emittance, etc. In spite of the great importance of such instrumentation, space does not permit a discussion in this paper. The interested reader is referred to instrumentation journals, accelerator conference reports, and internal laboratory memoranda.

4.4. Beam Transport Systems

Few accelerators could be utilized effectively without a beam transport system of some kind, either to carry a beam from the source to the accelerator, or from the accelerator to a target area. Design of beam transport systems has been described by several authors (15,54). Here only some basic considerations will be touched upon.

1) With heavy ion beams, good vacuum is necessary, particularly at low β, to prevent beam loss due to charge exchange.

2) In transporting heavy ion beams, charge state analysis, and sometimes isotopic analysis, can be very helpful. For example, for elements with several naturally occurring isotopes, only one of which is desired for acceleration, the mass separation can best be done in the injection line.

3) Clearly, a transport system should be able to transmit source or accelerator emittance without loss. However, as a safety factor the transport system should be designed to transmit a somewhat larger emittance, say by a factor of 2, to minimize time and beam loss in correcting small errors in parameters that inevitably occur.

5. TABLE OF HEAVY ION ACCELERATOR FACILITIES

Table 1 lists existing and proposed heavy ion facilities. The second column indicates the accelerator type by a prefix followed by a number from which the maximum energy can be determined. A plus sign indicates accelerators linked in series. Facilities in boldface type are operating or are under construction; others are proposed. Meaning of symbols:

Dn = Drift tube linac, max. energy n MeV/amu

En = Simple electrostatic accelerator, max. operating voltage n MV.

Kn = Isochronous cyclotron, max. energy $n \, q^2/A^2$ MeV/amu

Ln = Linear accelerator with independently phased resonators with max. total accelerating voltage n MV, max. energy n q/A MeV/amu.

Sn = Synchrotron with maximum energy n GeV/amu for ion of q/A = 0.5.

Tn = Tandem electrostatic accelerator, max. operating voltage n MV.

6. FUTURE PROSPECTS FOR HEAVY ION ACCELERATORS

The many plans for expansion of existing heavy ion accelerator facilities and for construction of new facilities (see Sect. 5) are an indication of the keen interest in these machines as tools for nuclear physics. Many of these projects are for isochronous cyclotrons; the next largest number involve electrostatic accelerators. There is a trend to higher energies, as evidenced by the number of projects using two accelerators, some with a tandem injecting into a cyclotron, some with two cyclotrons in series. One (the GANIL project) plans to use three cyclotrons in series.

Linear accelerators have not been used as often as tandems

Table 1. Existing and proposed heavy ion facilities.[a]

Location	Type and energy	Remarks	Reference
Argentina			
Buenos Aires	T20		
Australia			
Canberra (Aust. Nat'l U)	T14	NEC 14UD	(55), p.227
Belgium			
U. of Louvain	K70+K110	CYCLONE	(56), p.80,618
Brazil			
U. of Sao Paulo	E4+T8	NEC 4U,8UD	(55), p.213
Canada			
Chalk River	T13+K520	Superconducting Cyclotron	(37,57)
Quebec	K28+K500	Superconducting Cyclotron	(56), p.580
Denmark			
U. of Aarhus	T7	EN Tandem	(58)
Copenhagen	T9	FN Tandem	(58)
France			
Caen	K25+K400+K400	GANIL	(34)
Grenoble	K90		(56), p.614
Orleans	K50	Constr. by CGR-MeV	(56), p.275
Orsay	D1.2+K75	ALICE	(59)
Orsay	T12	MP tandem	
Strasbourg	T12	MP tandem	
Saclay	D5+S1.2	EBIS Source development	
Germany			
Berlin	E6+K120	VICKSI	(60)
Darmstadt	D4.5+L23.8+S1.0	UNILAC	(25)
Heidelberg	T13+L3+L9	Helix resonator postaccel.	(26)
Munich	T13+L5	Interdigital H-type postaccel.	(27)
India			
Calcutta	K140		(56), p.84
Israel			
Weizmann Inst.	T14	NEC 14UD	
Italy			
Catania, Sicily	T13		(58)
Padua	T16+K540	XTU, SSC Dev. at U. of Milan	(61)

Table 1. Cont'd.

Location	Type and energy	Remarks	Reference
Japan			
Osaka U. (RCNP)	K120		(56), p.95
Kyushu U.	E5+T10		(62)
Saitama (IPCR)	L16	RILAC	(63)
Saitama (IPCR)	K77	WFC	(82)
Tohoku U.	K50	CGR-MeV, Sumitomo Collab.	(56), p.79
Tokai (JAERI)	T20	NEC 20 UR	(58)
Tokyo U. (INS)	K68		(56), p.103
Tokyo U.	D10+S1.4	Numatron (INS Study)	(81)
Tsukuba U.	T12	NEC 12UD	
Netherlands			
U. of Groningen	K160		(83)
Poland			
Warsaw U.	K178	Modified U-200	(56), p.107
South Africa			
Cape Town	K200		(56), p.117
Sweden			
U. of Uppsala	K200	Exist. synchrocyclotron conv.	(56), p.127
Switzerland			
Villagen	K135	SIN Injector	(64), p.257
United Kingdom			
Daresbury	T20 (T30)		(21)
Harwell	K86	VEC	
Oxford	E8+T7		
USA			
Argonne	T10+L15	SSRR postaccel.	(23)
Berkeley	K140	88 Inch	(76), p.265
Berkeley	D8.5+S2.6	SuperHILAC, Bevalac	(24,42,43)
Brookhaven	T8+T12	MP Tandems	(66)
U.C. Davis	K90	NHIP	
Indiana U.	K16+K220	NHIP	(67)
U. of Maryland	K180	MUSIC	(68)
U. of Minnesota	T12		(69)
Michigan State U.	K50+K500+K800	K500&K800 are superconducting	(38)
Los Alamos	E8+T9	FN Tandem	(70)
Oak Ridge	T7	EN Tandem	
Oak Ridge	T25+K90+K400	HHIRF, K90 is called ORIC	(20,22)
U. of Rochester	T11+K500		(71)
Stonybrook	T9+L12	SSRR postaccel.	(72)
Texas A&M U.	K147		(73)
U. of Washington	T7+T9+L	FN Tandems	(74)
Yale U.	T13	MP Tandem	(75)

Table 1. Cont'd.

Location	Type and energy	Remarks	Reference
USSR			
Dubna (JINR)	K156+K250	U-200, U-300 (WFC)	(76)
Dubna (JINR)	D4+S4.6		
Dubna (JINR)	K725	U-400	(77)
Kazakhstan	K50		(56), p.630
Kiev	K140	U-240	(56), p.326
Leningrad	K140	U-240	(78), p.692
Moscow, Kurchatov I.	K60		(56), p.205
Moscow, Radiotech. I.	L102		(79)
Kiev	T20	EGP-20	(80)

[a]ABBREVIATIONS

EBIS - Electron Beam Ion Source

HHIRF - Holifield Heavy Ion Research Facility

INS - Institute for Nuclear Study

IPCR - Institute of Physical and Chemical Research (RIKEN)

JAERI - Joint Atomic Energy Research Institute

JINR - Joint Institute for Nuclear Research

NEC - National Electrostatics Corporation

NHIP - No Heavy Ions Planned

ORIC - Oak Ridge Isochronous Cyclotron

RCNP - Research Center for Nuclear Physics

SIN - Swiss Institute for Nuclear Research

SSC - Superconducting Cyclotron

SSRR - Superconducting Split Ring Resonators

WFC - Weak Focusing Cyclotron

or cyclotrons for nuclear science because of their greater cost.
Interest in linacs remains high, however, because they potentially have
fewer limitations in intensity, particle species and in maximum energy.
They are also superior as a synchrotron injector. Work in several
laboratories is devoted to the development of more efficient linacs.
The prospect for heavy ion synchrotrons for nuclear science in the near
future is promising. Present activity indicates that at least two,
and perhaps as many as four will be started in the next five years.

There is growing interest from radiotherapists in using dedicated
heavy ion machines for the treatment of cancer. The ion mass used
would be in the range A=12 to 40, with energy around 500 MeV/amu.
Duty factor could be low, intensity modest ($\sim 10^9$ pps). A synchrotron
is the likely choice to fit the requirements.

The use of heavy ions as projectiles to trigger a thermonuclear
reaction for fusion power generation has recently emerged as an
attractive possibility. The requirement is for beams with A$\sim$200,
$T_n \sim 200$ MeV/amu, with $\sim 10^{15}$ W of peak power in a 10^{-8} sec burst. There
is no existing accelerator with these capabilities, but they seem to be
within a reasonable extrapolation of existing accelerator technology.
Studies are under way at several national laboratories to establish
feasibility.

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