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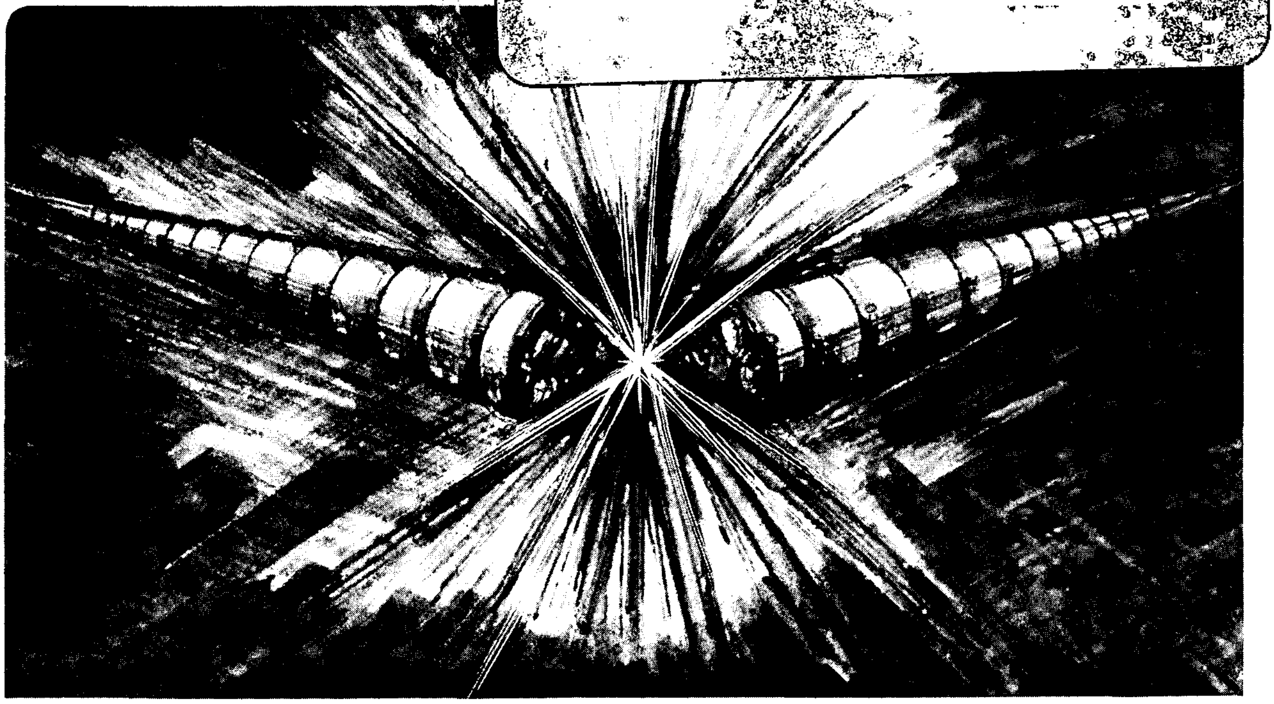

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ABSTRACT

Pioneering work at the Bevalac has given significant insight into the field of relativistic heavy ions, both in the development of techniques for acceleration and delivery of these beams as well as in many novel areas of applications. This paper will outline our experiences at the Bevalac; ion sources, low velocity acceleration, matching to the synchrotron booster, and beam delivery. Applications discussed will include the observation of new effects in central nuclear collisions, production of beams of exotic short-lived (down to 1 μsec) isotopes through peripheral nuclear collisions, atomic physics with hydrogen-like uranium ions, effects of heavy "cosmic rays" on satellite equipment, and an ongoing cancer radiotherapy program with heavy ions.

1. INTRODUCTION

As the field of heavy ion physics continues to develop, the trend has been to enhance capabilities of existing accelerator facilities by adding boosters or afterburners to increase available beam energy. The aim of this paper is to analyze the techniques best suited for producing and handling high energy beams of heavy ions, and to look at the fields of reseach which are opening up to use these beams. The experience provided by the Bevalac at the Lawrence Berkeley Laboratory is uniquely applicable to this study, as this facility pioneered many of the steps now being taken by many other laboratories into the field of high energy heavy ions. Analyzing the evolution of the Bevalac, both in capabilities and in its efforts to best meet the needs of the research fields that have developed, should provide valuable lessons for planning new facilities and upgrading of existing ones.

This paper will be divided into three sections; first a description of the Bevalac, outlining areas of the operation which have been found to be particularly relevant or unique to handling high energy heavy ion beams; then a description of the active research fields at the Bevalac, and any unique operational consequences of delivering beam for these applications; and finally a summary of salient features to be borne in mind in planning for new high energy heavy ion facilities, and a description of planned facilities to operate in this region.

2. THE BEVALAC: AN OVERVIEW

The Bevalac, shown in Figure 1, came into being in 1974 when the Transfer Line coupling the SuperHILAC and the Bevatron was completed [1]. These two accelerators had both had long and distinguished careers prior to this project; the Bevatron [2] for many years being the premier facility for high energy physics, discovery site for the anti-proton and a whole host of other elementary particles; while the HILAC (upgraded in 1971 to the SuperHILAC) and its sister machine at Yale were the first accelerators to provide heavy ion beams [3] for nuclear physics studies around the Coulomb barrier, including transuranic element and new isotope discoveries, Coulomb excitation studies, and other nuclear reaction and nuclear structure work. The linking of these accelerators provided a new future for both, and issued in the era of high energy heavy ion research.

2.1 INJECTORS

There are three ion sources presently in simultaneous use at the SuperHILAC, the layout of these injectors is shown schematically in Figure 2. The sources for all three injectors are of the PIG (Penning Ion Gauge) type [4], a well developed technology suitably matched to the high current, relatively high (positive) charge state heavy ion requirements for injection into the SuperHILAC Alvarez linacs. Each injector is tailored for a particular range of ion mass. The first, named EVE, at the lower right, is based on a 750 kV Cockcroft-Walton. Light gaseous ions up to mass 40 are transported through the low gradient high voltage column, and are bent around and down to the injection point of the first of the Alvarez linac tanks, called the Prestripper. To achieve the injection velocity of $\beta = .0155$ (E = 112 keV/amu) with the maximum available terminal voltage, the charge-to-mass ratio of the ions must be greater than 0.15, so ions of ${}_{40}\mathrm{Ar}^{6+}$ or ${}_{20}\mathrm{Ne}^{3+}$ are required, well suited to the charge state distributions available from PIG sources. For heavier ions up to about mass 170, the second injector called ADAM is used, it is a pressurized (N_2+ CO_2) Dynamitron with a maximum terminal voltage of 2.5 MV. It is located along but below the axis of the Alvarez tanks, so the beam is bent up to the injection point. The PIG source in this terminal is equipped with a sputter electrode, so metallic ions are available, a typical beam produced being $_{165}Ho^{8+}$.

The heaviest ions require a more complex injection scheme, embodied in the third injector called ABEL, completed in a 1981 upgrade project [5]. Starting with a 750 kV Cockcroft-Walton terminal, lower charge state ions of high current (e.g. a few milliamps of $_{238}U^{5+}$) are transported at 15 keV/amu around an analysis magnet capable of isotopic separation of better than 1/200, to a Wideroe preaccelerator. This linac, operating at 23 MHz, exactly one third of the SuperHILAC Alvarez frequency, brings the ions to the required 112 keV/amu velocity. Arranged in a $\pi - 3\pi$ configuration, every other drift-tube is 1.5 periods long to accommodate focusing quadrupole magnets. In the transport line from the Wideroe to the Prestripper, located above the ADAM injector, the beam is stripped to the q/A required for the Prestripper ($q/A > .046$) by means of a fluorocarbon vapor stripper [6].

This stripper, based on a long-chain perfluoropolyether by the trade name of Fomblin [7] was developed as no suitable stripping technique existed at the time. Gas stripping does not produce a high enough charge state for the heaviest ions (U^{11+} is needed), and foil lifetimes for the available beam intensities are totally unsatisfactory. Earlier measurements of charge state distributions using Fomblin strippers at an energy above 1 MeV/amu [8] had indicated no advantage over a pure gas stripper, but it is apparent, as seen in Figure 3, that at the lower energies of interest here there is a significant gain to using large molecules (molecular weight > 3000) for stripping. A possible explanation for this may be that excitation cross sections are higher at these lower velocities, allowing for multiple interactions inside each molecule, thus presenting an effective density equivalent to that of a solid foil stripper. Fomblin also is well suited as a stripping medium, it is marketed as a diffusion pump fluid, and behaves well under ionizing bombardment, cracking into lighter volatile fragments instead of polymerizing into solid residues.

2.2 LINEAR ACCELERATORS

Beams from each of the three injectors are brought together at the entrance to the Prestripper at a pulsed (vertical) magnet capable of selecting any of the three beams, and switching between them at a rate of 36 Hz. This is an integral part of the Time Sharing mode of operation to be described below.

The first of the two 70 MHz Alvarez tanks is 20 meters long, and is divided into two independently-excitable cavities. The beam emerges at 1.2 MeV/amu, and passes through a carbon foil stripper of around 30 $\mu g/cm^2$ to bring it to a q/A of at least 0.160 (U^{38+}), the minimum required for Poststripper tank acceptance. The separation between tanks is 3.5 meters, insufficient for magnetic charge state analysis, so several charge states are injected and accepted by the Poststripper, adding to total beam intensity, but causing somewhat reduced beam quality. The Poststripper tank, 32 meters in length, is separated into six independent RF sections, allowing for continuous energy variability up to a maximum of 8.5 MeV/amu. Increments of about 1.2 MeV/amu are obtained by turning off individual tanks, energies in between can be tuned by adjusting gradient and phase controls of the last excited tank to achieve partial acceleration. Each of the drift tubes, 135 in the Prestripper and 77 in the Poststripper, has a quadrupole electromagnet thus providing a strong-focusing lattice for beam transport through the linac.

One noteworthy comment about the use of RF linacs for heavy ion acceleration is that ions of all masses emerge at the same velocity, there is no decrease in energy of beams of the heaviest elements, as is the case with cyclotrons or electrostatic accelerators. The price one pays for this feature is that all beams must have a minimum charge-to-mass ratio to be accelerated in the linac, leading to either larger, more expensive linacs if the q/A is not high, or to very sophisticated injectors to produce higher q/A's.

The high RF gradient levels needed for acceleration require a rather low duty cycle (less than 30%) due to RF power and tank cooling limits, but the need to run the accelerator in a pulsed mode in fact is utilized to good advantage in the Time Sharing mode of operation [9].

A very sophisticated control system allows for the arbitrary interleaving of pulses from the three injectors; the time between pulses is used to set RF gradients and phases, the pulsed injection and extraction magnets and a few pulsed drift-tube magnets, to select and transmit ions from one injector to one destination. Three separate consoles in the SuperHILAC control room, one for each injector, monitor the progress of each beam through the accelerator. An operator at one console appears to be controlling the entire accelerator, when in fact he is only affecting parameters for his Mode in the main Data Base. A master scheduler assigns each pulse to a given Mode, selects the proper parameters from the Data Base, and routes the appropriate diagnostic signals to the correct operator's console. As will be seen, this mode of operation is well suited for interfacing a rapid-pulsing accelerator such as the SuperHILAC with a slow-pulsing synchrotron.

2.3 TRANSFER LINE

After emerging from the Poststripper the 8.5 MeV/amu beam is directed either to one of 12 active SuperHILAC experimental areas, or into the Transfer Line to the Bevatron. The beam is usually stripped again at an early part of the Line (200 $\mu g/cm^2$ carbon foil) to present the highest possible charge state to the Bevatron (typically U^{68+}), allowing for the highest final energy. If lower final energy but higher intensity is desired, this stripper is not used, thus preventing the dilution into many charge states which occurs at this stripping stage. Placement of the stripper is important, as the required very thick foils can cause significant emittance growth of the beam through multiple scattering. This effect can be minimized by locating the foil at a tight waist of the beam.

Beam is transported through the array of 18 separately controlled stations of the Transfer Line, each with beam profile and intensity monitors [10]. Typical transmission efficiency is around 80%. Vacuum in the Line is between 1 and 5×10^{-6} torr, maintained by ion and turbo pumps.

2.4 LOCAL INJECTOR

At the base of the Transfer Line, beam from another linac can be merged into the injection line. This accelerator, located next to the Bevatron, served as its primary injector prior to construction of the Transfer Line. A recent upgrade project [11], which included the addition of an RFQ preaccelerator and a rebuilding of the 200 MHz Alvarez linac, has increased the ions it can deliver up to mass 40, at an energy of 5 MeV/amu. By providing an alternate source of ions for injection into the Bevatron, this injector has significantly increased the flexibility of the operations. This will be discussed further below.

2.5 BEVATRON

As one of the two remaining weak-focusing synchrotrons still in operation [12], the Bevatron stands out as a landmark of Machine-building in the 1950's. Its massive size, 10,000 tons of steel, and complexity provided a great challenge to the engineers and physicists of the time; its endurance and continued reliable operation after thirty years is a tribute to these people, and how successfully they met this challenge.

With a pole gap of 30 cm, a pole-tip width of 1.5 meters, and a magnetic radius of 15.3 meters, the four 90° magnets can reach a maximum field of 12.6 kG, for a maximum rigidity of 19.2 T-m. This translates into an energy of 5 GeV for protons, 2.1 GeV/amu for light ions (of $q/A = 0.5$), and almost 1 GeV/amu for the heaviest ions (U^{68+}).

Beam is injected at a field of around 400 gauss, the large aperture allowing over 600 turns to be stacked, significantly increasing available intensity. RF is turned on slowly at around 200 kHz, providing adiabatic capture of about 60% of the beam, acceleration is generally in the first harmonic, and tops out at about 2.3 MHz, over a 10 to 1 frequency swing. The field ramping is at about 8 gauss/millisecond, flat-top times can range up to 1.5 seconds. Thus overall cycle rates are 1 pulse per 6 seconds for full-field operation, or 1 pulse per 4 seconds for fields below about 7 kilogauss.

Control of the frequency during acceleration is done without reference to the beam, a feature which has proven invaluable in efficient heavy-ion operation. Values are calculated for the proper frequency at each field value, in 1 gauss increments, for the ion q/A to be accelerated. After careful calibration of the digital-to-analog and voltage-to-frequency converters, beam is injected and accelerated. A B-dot loop generates interrupts at 1 gauss intervals causing a look-up of the frequency to be applied to the accelerating electrodes. Thus, the frequency is updated at about 100 μsec intervals. Minor corrections to the frequency can be applied by performing a "learned curve" procedure; the beam radius is sampled at frequent intervals during a pulse and corrections are calculated to bring this radius to the desired value. On subsequent cycles, these corrections are summed in to the analog voltages sent to the V-to-F converter, the beam itself is not used for active feedback. This procedure allows for the changing of the intensity of the beam in the accelerator by many orders of magnitude, to suit experimenter needs which might range from single-particle extraction for eye-flash observations on human subjects, to the highest intensities for nuclear chemistry bombardments, without affecting the quality or characteristics of the delivered beam. Having a large magnetic field aperture has been a contributing factor to the success of this procedure.

Another area where the large aperture has been useful has been in achieving the ultra-high vacuum needed for acceleration of the heaviest ions.

A liner [13], consisting of three nested boxes of copper-clad printed-circuit boards, surrounded by layers of aluminized mylar "superinsulation" was inserted into the magnet gap, (see Figure 4) causing a small reduction in effective magnetic volume but no apparent loss of beam. The boxes, maintained at 12 K, 77 K and room temperature respectively, provide a completely cryopumped enclosure for the beam, and maintain the pressure at a level below 1×10^{-10} torr, as measured by sensitive beam-survival tests.

The good vacuum is required to prevent beam loss due to electron pickup and loss processes during acceleration [14]. For ions that are fully stripped only electron pickup is important, and this process has a cross section which is very steeply velocity-dependent (β^{-6} or β^{-7}). Thus such fully stripped ions can survive acceleration in a relatively poor vacuum provided the injection velocity is high, or the rate of acceleration to a high velocity is large, so that dwell-time at low velocities is not long. Prior to the liner installation, the Bevatron vacuum of 1×10^{-7} torr was adequate for beams of fully stripped neon, argon, and other light ions. Heavier ions were not accelerated because the output energy of the SuperHILAC, 8.5 MeV/amu, was inadequate to fully strip anything much above argon. At these high velocities, electron-loss cross sections are much more slowly velocity dependent (β^{-2}) [14], making this process important throughout the acceleration process. For ions that are not fully stripped, then, one must significantly reduce the density of residual gas to ensure survival [15]. In the Bevatron, the beam storage time could be as high as 2 seconds or more, corresponding to a flight path of the order of 10^8 meters, requiring a pressure in the mid 10^{-10} torr range. As seen above, the installed cryoliner very adequately meets these requirements.

Once achieving the desired energy, a resonant extraction system brings about 60% of the beam to the experimental area, where it can be delivered to any of 12 different active experiments. Extracted beam emittance is around 30 π mm-mrad in both transverse planes, energy spread is better than 0.1%.

3. PERFORMANCE AND OPERATIONS PHILOSOPHY

Table I summarizes beams delivered. Ion species (and some of the lower intensities shown) are driven by experimental demand, not by capabilities of the accelerator. It is ironic that protons are now among the most difficult beams to obtain, the excellent vacuum making molecular hydrogen the preferred source of these ions when maximum energy is not required. The good vacuum also allows acceleration of other exotic species, such as Au^{11+}, an ion of interest for inertial-confinement fusion driven by heavy ions. Although beam intensities from the Bevalac are a few orders of magnitude too low, the charge state and energy approach the values needed for a heavy-ion fusion driver, and some relevant beam-target interaction studies can be performed.

Optimum operation of any major accelerator requires the maximizing of on-target hours. In most high energy facilities this is normally accomplished by beam splitting, and use of production targets so that many experiments can be receiving beam, either primary or secondary particles, at the same time. Operations at the Bevalac have evolved along different lines. Splitting beams of heavy ions requires that all experimenters receiving beam be willing to accept the same ion species at the same energy. As it is unusual to find such compatible users, Bevalac beams have generally been delivered to one single user at a time. Another reason for not splitting heavy ion beams is that such an action generally implies intercepting a small portion of the beam on a material septum. Reaction products from heavy ions striking this matter have momenta and magnetic rigidities which often overlap those of the primary beam, so will be difficult to separate from the primary beam. These contaminants form a halo around the primary beam which significantly adds to experimental background. As a result, most experiments are now run with no material in the beam upstream of the target. The cleanest beams obtained have been for the heaviest ions in the lowest charge states (e.g. U^{38+}). These beams have a low momentum but high magnetic rigidity, any collision will produce a new charge state or reaction products neither of which is likely to have rigidity anywhere close to that of the primary beam.

As a consequence of not splitting beams, the goal of optimizing on-target hours must be met by striving for the greatest possible flexibility of operation, being able to quickly change configurations of the accelerator to deliver different beams to different experiments. This is done by reducing tuning time between experiments to a bare minimum, through reproducible monitoring and control of critical parameters, and by finding programs whose most efficient utilization of beams allows for time sharing of the accelerator resources. In the case of the SuperHILAC, the rapid switching between injectors allows for Time Sharing, running of both the Bevalac and a full-scale low energy nuclear research program, the sparse Bevalac needs hardly impacting the ongoing local program. At the high energy end of the

Bevalac, the radiotherapy and nuclear science programs fall somewhat into the same category. Careful setup of a patient requires almost half an hour of work, with an actual treatment time of about one to two minutes. By switching to a different beam line, ion and energy between patients, a second user can have almost full-time use of the beam. Switching at the Bevalac is somewhat slower than at the SuperHILAC, but still, reproducible switches are routinely performed about 40 times a day, and take usually one minute or less [16].

A consequence of this operational flexibility, and the availability of several injectors is that often times four or five different ions will be run at several different energies in just a few days. In addition to the switching between patients, such a capability is most useful for survey experiments, and for short exposures or calibrations. Figure 5 shows another view of the Bevalac, as seen through the eyes of the Bevalac Scheduler; the multiple combinations of injectors, experiments and running modes represent a complexity which is about equivalent to the task of juggling the extensive user communities with their disparate and often incompatible requirements from the accelerators.

4. APPLICATIONS: HIGH ENERGY HEAVY ION RESEARCH PROGRAMS

Research activities at the Bevalac are divided between two major programs, the Biomedical effort receiving one third of the time, while physics research (divided between nuclear science, atomic physics, and industrial applications) is assigned the other two thirds of the available research hours. Each of these programs are exploring new and exciting areas of research, highlights of which are discussed below.

4.1 NUCLEAR SCIENCE

Central collisions of the heaviest ions at the highest energy available offer the greatest promise for new discoveries, with firm beliefs that a Quark-Gluon Plasma will be created in such a reaction. Although it is felt that energies at the Bevalac are too low to create such a state of matter, experiments with high-multiplicity detectors (the Plastic Ball [17] and the Streamer Chamber [18]) have studied such collisions for unusual signatures. Interesting behavior has been observed; hydrodynamic flow of nuclear matter [19], and evidence for significant compression of nuclear matter [18,20] to densities above four-times normal nuclear density. Such studies are leading to an understanding of the nuclear equation of state, of great interest to astrophysicists studying supernova explosions and neutron stars, as well as to nuclear theorists. There is little doubt that this work at the Bevalac has been a great stimulus for interest and new projects in high energy heavy ions around the world.

Peripheral fragmentation reactions are a means of producing extremely interesting species for study [21]. At energies above 100 to 200 MeV/amu grazing collisions between a projectile and target nucleus lead to nuclear excitation and loss of a few nucleons, but with little change to the momentum of the projectile. Such "kinematic focusing" of reaction products allows for efficient transport, analysis and purification of secondary beams. In one experiment [22], fragmentation of a ^{48}Ca beam produced about 15 never-before seen neutron-rich isotopes of lighter ions in a 24 hour run. In another, beams of helium isotopes from mass 3 to 8 were produced and used for total reaction cross section measurements, yielding nuclear radii of these isotopes [23]. ^{19}Ne and ^{11}C beams of very useful intensity can be produced (about 1 μCi per pulse for ^{19}Ne), and are being used extensively for medical tracers that can be implanted in any desired site of the body [24]. Applications for these Radioactive Beams produced at high energies are growing continually; an improvement program at the Bevalac is currently underway to enhance capture, purification and delivery efficiency of these beams [25].

High energy heavy ions are even of interest in nuclear studies close to the Coulomb Barrier, reverse-kinematics using very heavy beams on very light targets allow for study of fission and compound nucleus processes that would normally be masked by target thickness effects. This energy range also provides interesting opportunities to study nuclear processes in the transition region where the mean-field approximation, valid at lower energies, begins to break down [26].

4.2 ATOMIC PHYSICS

Studies of electron pickup and loss processes at high energies has proven most interesting [27,28], the highlight has been the observation of fully-stripped uranium ions at energies above 500 MeV/amu, for high Z strippers (low Z materials are very poor strippers at these energies). Such work is of interest for design of new accelerators [29], booster energies and accelerator vacuum systems all depending critically on these measurements.

Production of uranium ions with one and two electrons allows for Lamb shift measurements in this heavy system. Such experiments are currently being performed [30], and are expected to provide landmark data for QED theorists.

4.3 SPACE SCIENCES

Heavy ions from the Bevalac can reproduce a very large part of the cosmic ray mass and energy spectra, and so provide an excellent calibration tool for instruments flown in satellites. An active program of pre- and post-flight calibrations has been in progress for several years [31], coordinated by NASA and the Space Sciences Laboratory of the University of California.

A recent program has brought industrial users to study the effects of high energy heavy ions on satellite computer components and systems, to design satellites better able to function and survive in hostile space environments [32].

4.4 MEDICINE WITH HIGH ENERGY HEAVY IONS

Charged particles offer interesting possibilities for medical treatments; dE/dx varying inversely with energy indicates that the greatest portion of a particle's energy is lost in the last stages of deceleration. This phenomenon leads to the characteristic "Bragg Peak" behavior of stopping ions illustrated in Figure 6, and allows for doing the greatest biological damage at the site where the beam stops, with significant sparing of tissue located along the entrance path of the beam. In addition, since ionizing power varies as Z^2, using heavier ions increases the effective killing power of each ion because of higher concentration of energy deposition along the ion path. Coupling these properties with the fine control one has over the stopping point of the beam (about 1 mm) and good edge definition of the radiation field, all lead to a potentially far superior tool for radiation therapy than X-rays [33]. Energy required for the beams must be sufficient for penetration to the deepest part of the body, or about 30 cm. This is met with the 225 MeV/amu alpha particles used at the LBL 184 Inch Synchrocyclotron, and the 600 MeV/amu neon ions used for treatments at the Bevalac.

Treatments with charged particles fall into two general groups: tumors which have been very resistant to conventional radiotherapy techniques, for which the higher specific ionization of heavy ions is expected to increase effectiveness of the treatments; and tumors located so close to critical structures that conventional treatment fields cannot avoid damaging these organs. Examples of the latter are highly effective treatments of small eye tumors and intraspinal tumors wrapped around the the central nerve cord, in both cases the superb dose-localization property of charged particles allows sharp enough definition of the irradiation field to almost totally avoid dosing tissues as close as 1 to 2 mm away.

In treatments such as these the stopping point of the beam must be ascertained with extreme accuracy. This is difficult since the beam usually traverses heterogeneous tissue structures to reach the tumor under treatment, and calculation of effective stopping power (and hence beam range) often cannot be done with the desired degree of confidence. In several cases now, the afore-mentioned ^{19}Ne radioactive tracer has been employed to verify range calculations in patients under treatment.

The encouraging experience from many years and several hundred patients under treatment has been enough to justify studies for continuing charged particle treatments in a clinical setting. A proposal is presently being prepared for submission to build a hospital-based heavy ion accelerator dedicated to medical treatments [34].

5. SOME CONCLUSIONS ABOUT HEAVY ION BOOSTERS

Experience from the Bevalac indicates that there is a growing list of very interesting applications for beams of higher energy heavy ions, and that such beams are not difficult to obtain given the proper accelerator components and techniques.

The key ingredient is the presence of a good injector for heavy ions, and quite fortuitously, many of today's existing low energy accelerators can serve quite adequately in this capacity.

Other important considerations relevant to the design of a high energy booster which have been learned from the Bevalac are summarized below.

Operational Flexibility is needed to ensure optimum use of the facility. Rapid ion, energy and configuration changes are highly desirable to most efficiently meet the needs of the experimental community.

Good vacuum (at least 10^{-10} torr) ensures survival of low energy partially stripped ions, and provides for flexibility of charge states accepted and accelerated.

Easily adjusted beam intensity. Difficulty in varying delivered beam intensity without compromising beam purity because of fragmentation reactions indicates that intensity is best controlled at lower energies, prior to the final energy boost. Being able to accelerate pulses of widely-varying intensity in the synchrotron without retuning is a highly desirable feature.

6. FUTURE DIRECTIONS

In the past year there has been a sudden surge of interest in higher energy facilities. The project to couple the Brookhaven Tandems to the AGS has been reported earlier in this Conference [35], providing initially ions up to sulphur at 15 GeV/amu. It is expected that a booster will be added in the foreseeable future to extend the mass range in the AGS to gold, and that ultimately the AGS itself will serve as the injector for a large set of collider rings to be built in the existing ISABELLE tunnel. On a slightly less ambitious scale, an injector is being prepared by a GSI-LBL-CERN collaboration to inject oxygen ions into the CERN SPS for experiments in the 70 to 250 GeV/amu range [36]. This injector, consisting of an ECR source and an RFQ will be on line early in 1986 for a first round of experiments later in the year.

At somewhat lower energies, GSI has started construction of the SIS-18 project [37], a 2 GeV/amu ring injected by the Unilac, and a smaller storage ring for cooling, accumulation and other beam studies. This project is expected to be completed in the early 1990's.

Still in the proposal stage are projects at ORNL to use Holifield as an injector for a 10 GeV/amu collider [38]; the Minicollider project [39] at LBL, a set of 4 GeV/amu rings injected by the Bevalac or a suitably enhanced synchrotron; and the afore-mentioned dedicated medical accelerator [34].

With the growing prominence of the research opportunities at higher energies, and with the desirability of making maximum use of existing facilities, it is not surprising to see this level of activity; nor will it be surprising to see other laboratories with well established low energy programs push for enhancements to reach much higher energies. Such moves should be strongly encouraged!

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FIGURE CAPTIONS

Fig. 1 Layout of the Bevalac at the Lawrence Berkeley Laboratory. The SuperHILAC on the right produces beams of any ion which are transported through the Transfer Line to the Bevatron. Energies of 2.1 GeV/amu for light ions and 1 GeV/amu for uranium are achieved. (CBB-7411-7912)

Fig. 2 Injectors at the SuperHILAC. EVE, the 750 kV Cockcroft-Walton at lower right in the Plan View, is used for ions up to mass 40. ADAM, the 2.5 MV Dynamitron located under the Medium Energy Beam Transport line, produces beams up to mass 170. The ABEL injector consists of a 750 kV Cockcroft-Walton and a Wideröe linac pre-accelerator, and is used for the heaviest ions. Three different ion species can be injected into the SuperHILAC, switching between the three separate users occurring at a 36 Hz rate. (XBL-7910-12105A)

Fig. 3 Charge state distributions for Pb ions at 112 keV/amu, the injection energy of the SuperHILAC Prestripper, for air, Fomblin and carbon foil strippers. The high-charge-state tail of the Fomblin distribution produces good fractions of 11+ and 12+ ions for acceleration. (XBL-785-862)

Fig. 4 Ultra-high vacuum system of the Bevatron. Three nested copper-clad fiberglass boxes placed between the pole tips of the Bevatron magnet are held at temperatures of 300 K, 77 K and 12 K and provide a completely cryopumped beam enclosure. The average pressure, measured in sensitive beam-survival tests, is below 1 x 10-10 torr. (CBB-817-6461)

Fig. 5 Schematic view of the Bevalac as seen by the Scheduler, illustrating the diversity of operational possibilities. SuperHILAC injectors and extraction point switching occurs at a rate of 36 times per second, typically 34 pulses going to dedicated SuperHILAC experiments and 2 pulses to the Bevatron. The Bevatron can be injected by either the SuperHILAC or from one of two sources at the Local Injector, extracted beam can be switched to any of the 9 experimental stations. Bevatron ion, energy and beam-line switching occurs in one minute or less, allowing for efficient use of the beam between radiotherapy patient treatments. This Rapid Switching mode of operation ensures maximum efficient utilization of the beam resources available. (XBL-852-9751)

Fig. 6 Bragg Curve for a 475 MeV/amu 12C beam, measuring relative ionization as the beam slows down and stops in water. The greatest rate of energy deposition occurs at 26 cm, the stopping point of the beam. Concentrating stopping ions into a tumor can cause great damage, with significant sparing of normal tissue traversed on the way to the tumor. The small tail beyond 26 cm arises from nuclear fragmentation products, lighter ions produced with the beam-ion velocity having longer range than the primary ion. (XBL-807-3526)

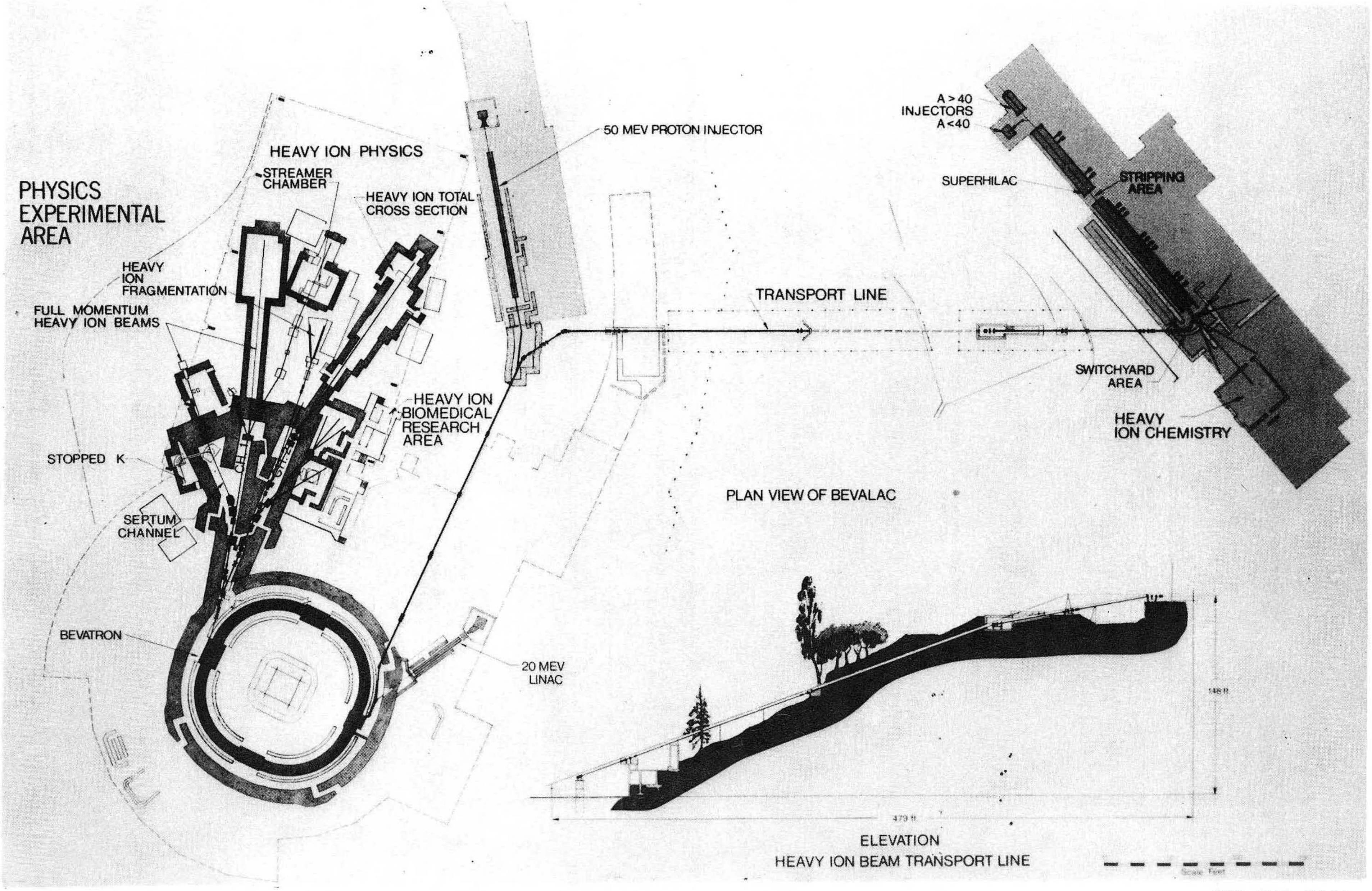
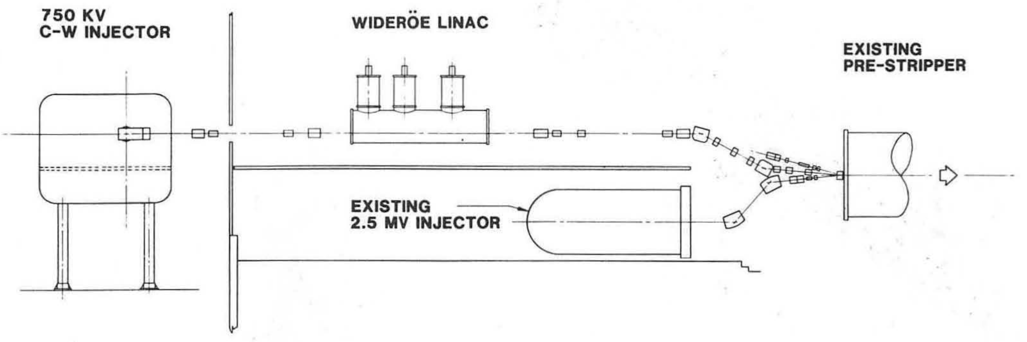
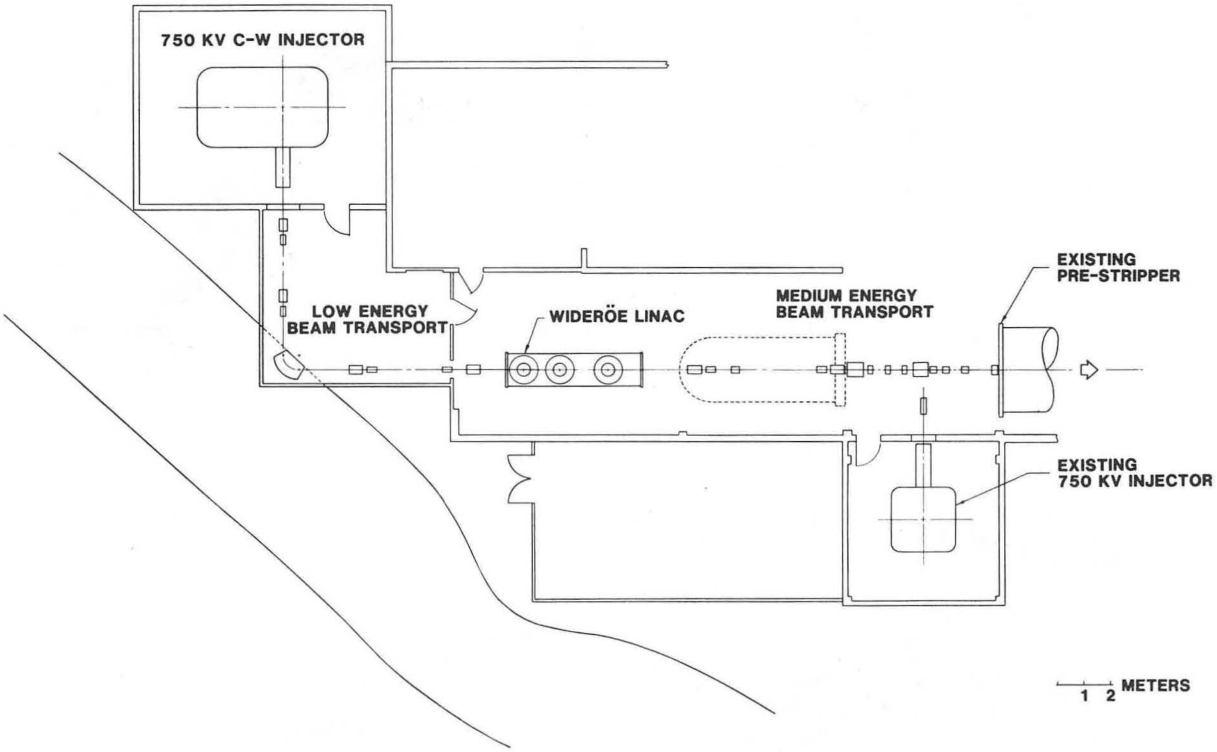


Fig. 1

CBB 740-7911



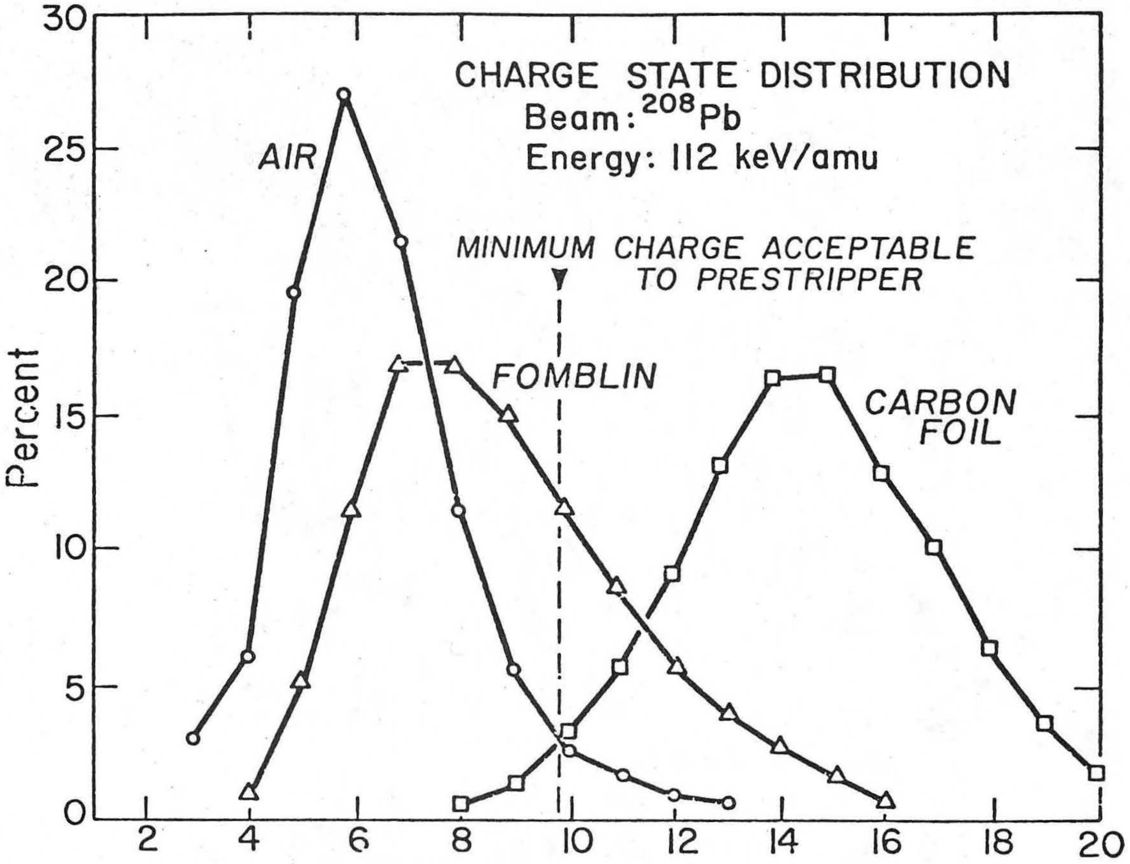
PROPOSED SUPERHILAC INJECTOR AREA
ELEVATION VIEW



PROPOSED SUPERHILAC INJECTOR AREA
PLAN VIEW

XBL 7910-12105 A

Fig. 2



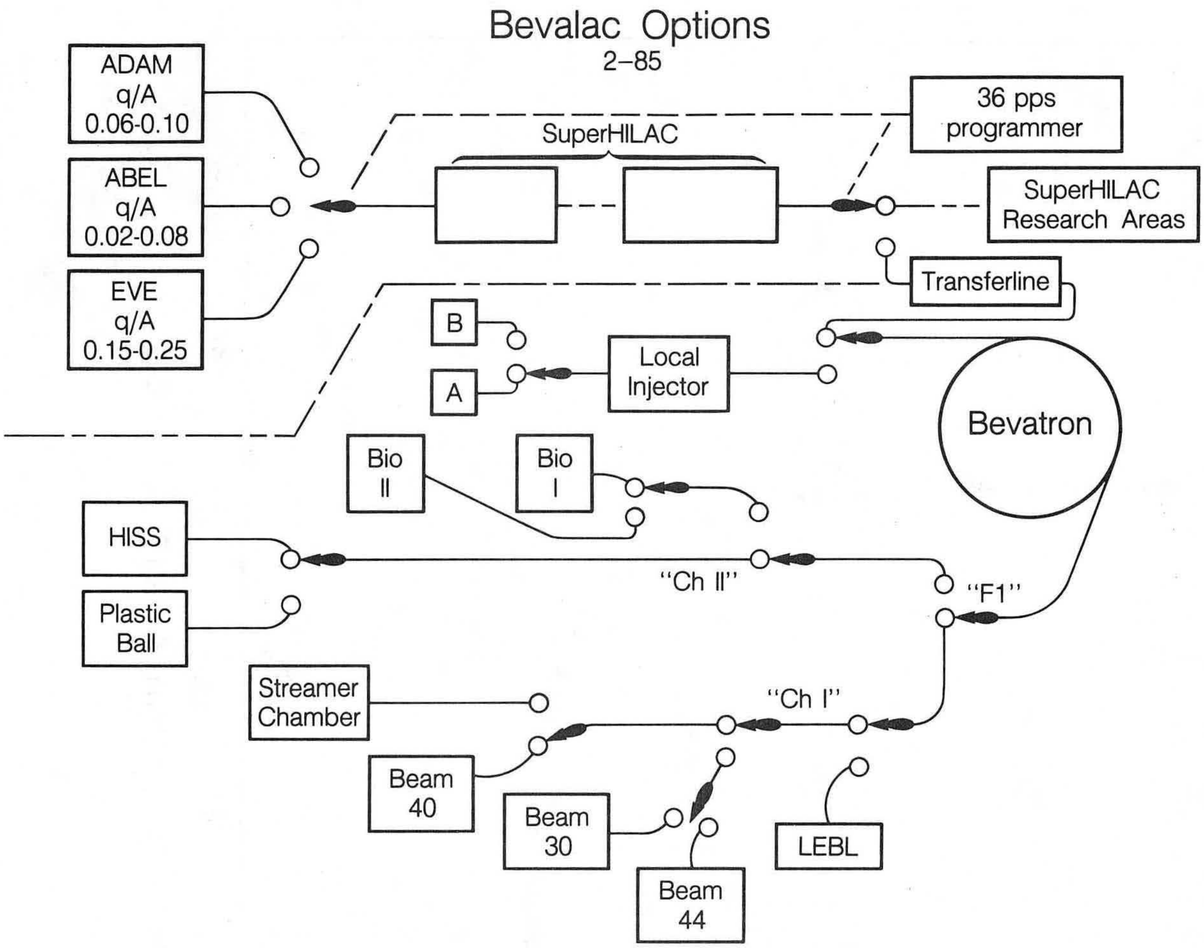
CHARGE STATE

XBL 785-862

Fig. 3

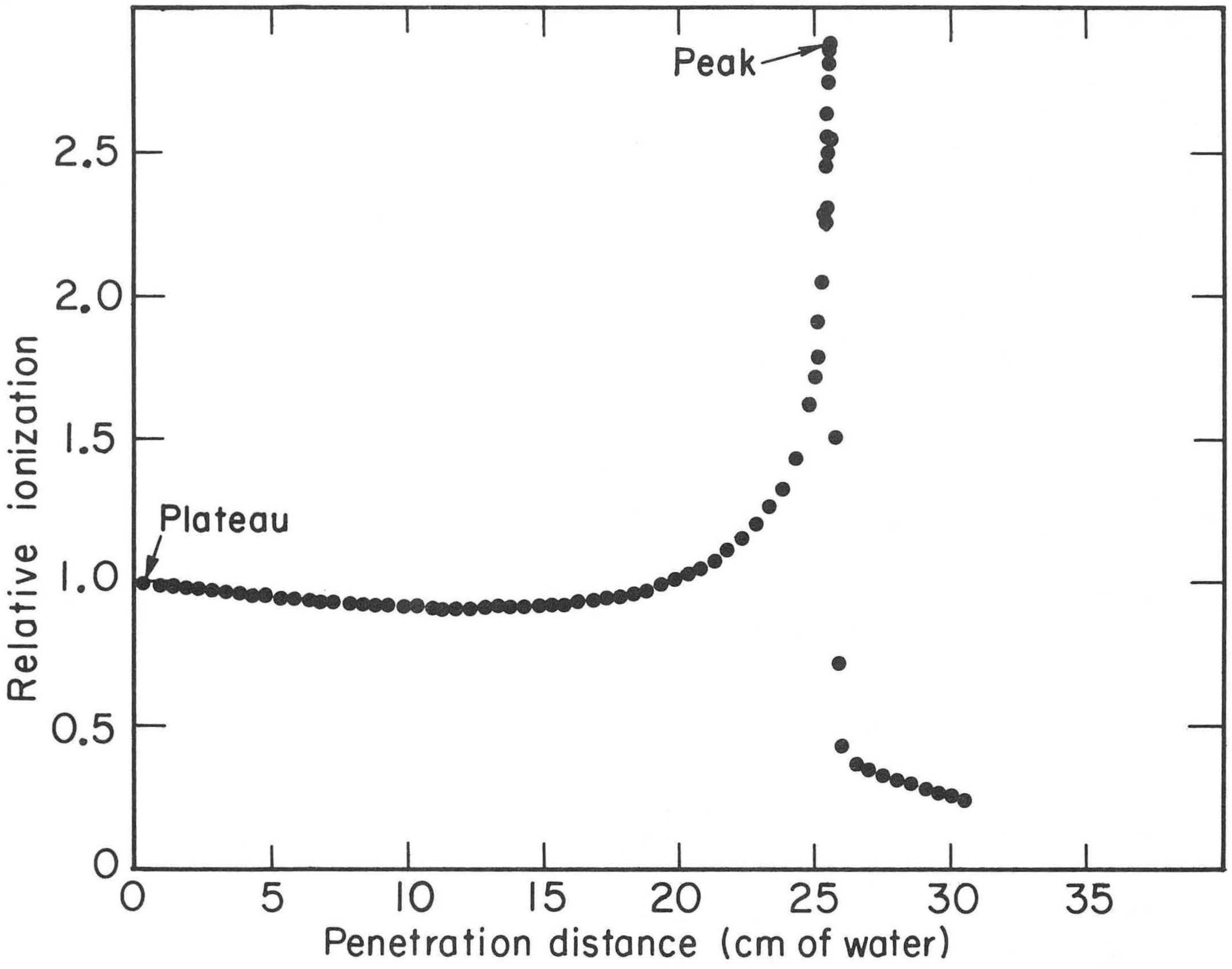
CBB 817-6460

Fig. 4



XBL 852-9751

Fig. 5



XBL807-3526

Fig. 6

Table I

Partial list of ions accelerated at the Bevalac, and observed intensities. Some of the intensities are set by experimental requirements, and so may be lower than what is technically possible to achieve. An energy-intensity trade-off can be made by accelerating different charge states of the same ion; lower charge state ions arise from eliminating one stripping stage at the SuperHILAC hence reducing charge state dilution, but the higher rigidity of the ions means that final energy must be lower.

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