Reports

Acceleration of Uranium at the Bevalac

Abstract. *Recent upgrading projects have extended the mass range of particles that can be accelerated at the Bevalac to include any element of the periodic table to energies above 1 billion electron volts per atomic mass unit. This capability was verified on 11 May 1982 with the production of a uranium beam at 147.7 million electron volts per atomic mass unit.*

The Bevatron at Lawrence Berkeley Laboratory was shown to be capable of accelerating heavy ions in 1971 (*1*), when nitrogen ions produced by the local Alvarez linac injector were successfully accelerated, extracted, and identified. The original beam intensities were very low, of the order of 10^6 ions per Bevatron pulse, limited by the use of the proton injector for producing heavy-ion beams. The Bevalac (Fig. 1) came into being in 1973 (*2*), when a transfer line was built connecting the Bevatron and the SuperHILAC, a linear heavy-ion accelerator that could produce beams of ions up to mass 200 at energies to a maximum of 8.5 MeV/amu. In this configuration, heavy ions from the SuperHILAC could be transported and injected into the Bevatron and subsequently accelerated to relativistic energies (up to 2.1 GeV/amu).

With the new injection capability a national relativistic heavy-ion program was launched. Nuclear science, astrophysics, biomedical, and even atomic physics experiments have been conducted with beams ranging from protons to iron. The biomedical program (*3*), for instance, has proceeded from early radiobiology with cells and animals to an ongoing clinical large-field radiotherapy program treating up to 20 cancer patients per day.

As progress was made in heavy-ion physics, it became apparent that acceleration of ions with the heaviest masses would be desirable and might open up new fields hinted at by the results for lighter ions. As a result, a proposal to upgrade the Bevalac for uranium beam capability was submitted and received funding in 1980.

The extension of the ion mass range to elements heavier than iron was limited by two factors: the availability of adequate intensities of the heavier beams and the vacuum in the Bevatron accelerating ring. Although SuperHILAC beams of ions up to xenon (maximum mass, 136) were of adequate intensity for the Bevalac, beams of heavier ions were much weakened and suffered from short ion-source lifetimes and poor reliability. The construction of a new preaccelerator system tailored to the heaviest ions was required.

The new injector system (named Abel, to go along with Adam and Eve, the two existing injectors) incorporates innovations in many areas of accelerator technology. The high-intensity Penning ion gauge (PIG) ion source produces ions of all elements; a sputter electrode is used for nongaseous materials. Beam intensities as high as several particle-milliamperes of ions with charge-to-mass ratios (Q/A) greater than 0.021 (U^{5+}) are produced. The ions are accelerated from the high-voltage terminal of a 750-kV Cockroft-Walton power supply to an energy of 15 keV/amu, the velocity required for injection into a new Wideroe preinjector linac. A 90° bend following the high-voltage terminal provides adequate resolving power to isolate any isotopic species, eliminating the need for separated isotope material in the ion source.

The Wideroe linac, modeled after a similar structure at GSI in Darmstadt (*4*), accelerates the beam to 112 keV/amu, the injection energy required for the first tank at the SuperHILAC. After the Wideroe, the beam passes through a fluorocarbon vapor stripper (*5*), which raises its charge state to meet the minimum requirements for the SuperHILAC ($Q/A > 0.046$, U^{11+}).

The need for an improved vacuum in the Bevatron can be understood in terms of atomic collisions. The capture and acceleration time of the beam in the Bevatron is of the order of 1 second, and the total flight path thus approaches 10^8 m. In this distance the probability of an interaction with a gas atom is very high—more than 1000 interactions were occurring for each ion in the Bevatron 10^{-7} torr vacuum.

The most damaging interactions

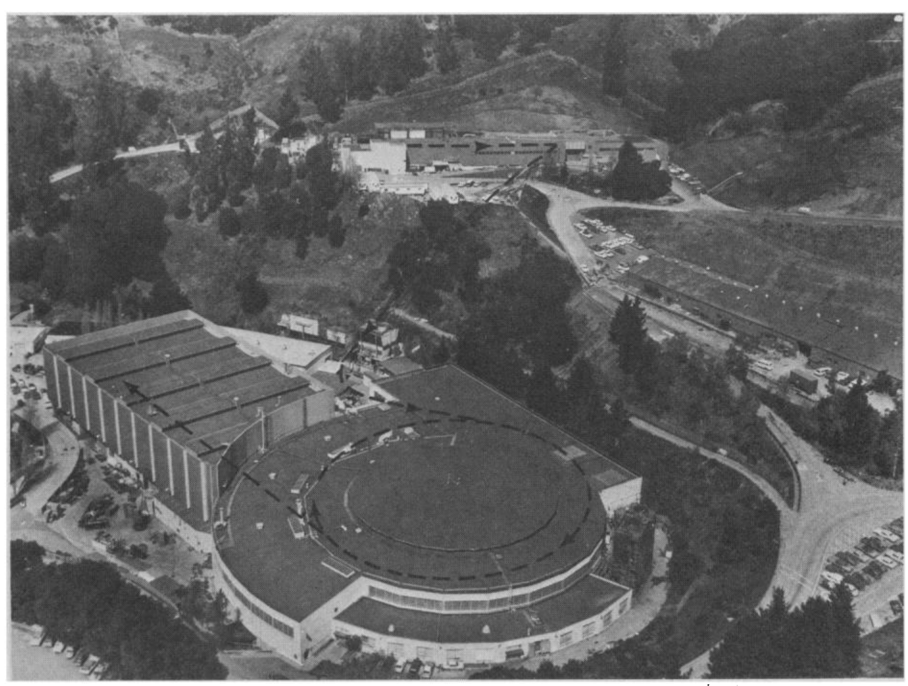

Fig. 1. The Bevalac complex. The dashed line indicates the path of a heavy ion from the SuperHILAC (top of photograph) to the Bevatron, where final acceleration occurs.

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change the charge state of an ion; the ion either picks up or loses an electron, its charge-to-mass ratio changes, and it rapidly falls out of synchronization with the accelerating fields and is lost. The normal focusing forces in the accelerator are more than adequate to compensate for the small-angle scattering from other (non–charge-changing) collisions with residual gas atoms.

Although quite complex in nature, electron pickup and loss interactions are fairly well understood (*6*). Of greatest importance to us is the velocity (β) dependence of these processes. Electron loss collisions are generally explainable by Born approximation arguments and follow a β^{-2} dependence, while electron capture processes are much more dependent on ion-orbital velocity matching, and fall off very rapidly at high energies (β^{-6} or greater).

In experience at the Bevalac with fully stripped ions, substantial beam losses were observed in the first few milliseconds of acceleration, but thereafter no losses were apparent. Early attempts to accelerate partially stripped (Ar^{17+}) ions (*7*) indicated less than 1 percent survival of the beam after 250 msec, with an internal pressure of 1×10^{-7} torr.

The inability to fully strip ions heavier than iron at the SuperHILAC energy meant that the pressure in the Bevatron would have to be reduced to $\sim 10^{-10}$ torr. To achieve this, a cryogenically pumped liner (see Fig. 2) was installed inside the quadrants of the original vacuum tank. This liner (designed by J. Meneghetti) consists of nested boxes of printed-circuit boards. The innermost box of copper-clad Nema-G 10 is cooled by helium gas at 12 K flowing through stainless tubes attached at the corners. The copper is etched in a striped pattern with

Table 1. Intensities and maximum energies of high-mass beams accelerated to date in the upgraded Bevalac.

Ion	Observed intensity (particles per pulse)	Maximum energy (MeV/amu)
$^{56}Fe^{24+}$	1×10^8	1700
$^{93}Nb^{37+}$	1×10^7	1550
$^{129}Xe^{45+}$	2×10^6	1300
$^{238}U^{68+}$	1×10^3	1000

the fingers pointing toward the center of the Bevatron; this provides good heat conduction throughout the bore without the eddy-current problem one would have with a continuous metallic sheet. Many layers of superinsulation (striped aluminized Mylar blankets) separate the inner box from a second, similarly patterned box cooled by liquid nitrogen. More superinsulation isolates this box from a fiberglass case that supports and protects the liner. The original chamber is maintained under vacuum, eliminating atmospheric stresses on the new liner. The extensive use of organic materials may seem surprising; however, at 12 K the outgassing rate of these materials is not measurable. On the contrary, the total air-pumping speed of the helium-cooled surfaces is many millions of liters per second. Pumping for hydrogen and helium is provided by activated-charcoal panels on the vertical edges of the helium box and by small auxiliary diffusion pumps in the straight sections of the Bevatron.

The four straight sections were handled differently, since injection, extraction, beam diagnostic, and acceleration hardware is located in these areas. Only liquid nitrogen cooling is provided in these areas, but insulation and encapsulation of components at room temperature (water-cooled magnets) has kept heat loads within reason. The high-quality vacuum is ensured by preventing any surface at room temperature from having line-of-sight access to the inner Bevatron bore.

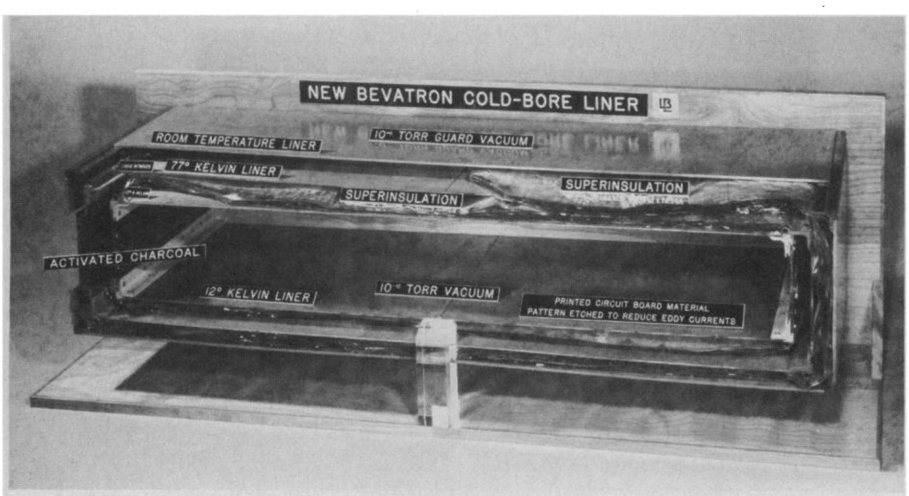

Fig. 2. Cross section model of the new Bevatron cold-bore liner showing the various components.

Installation and cool-down of the vacuum liner were completed in December 1981. The system has been under vacuum now for 6 months and has performed flawlessly. The average pressure in the machine is about 1×10^{-10} torr, and the total 12 K heat load is of the order of 150 W, well within the limits of the installed refrigeration capacity.

The average pressure was determined by means of a beam-survival experiment. As part of an extensive program of measurements of cross section for charge pickup and loss at the SuperHILAC (*8*), accurate values for these cross sections were determined for C^{4+} ions at 7.2 MeV/amu. To measure the vacuum, C^{4+} ions were injected into the Bevatron and coasted at this energy for extended periods, while beam loss was being measured. From the previously measured cross sections, the average gas density seen by the ions was deduced.

During the first months of 1982 the renovated Bevalac has been brought back into full service. New heavier beams have been accelerated at increasing intensities, while nuclear science and radiotherapy programs have picked up where they left off after the July 1981 shutdown to install the liner. Table 1 summarizes our experience with heavy-ion beams at the Bevalac and shows the highest energy achievable for these beams in this accelerator. Intensities for all but the heaviest ions are within a factor of 10 of the design goals, and have been adequate for the experiments performed to date.

During the program of developing heavier beams, new tuning procedures have had to be worked out. The use of stripping foils at various stages of acceleration has created a difficult tuning environment for the heaviest beams because of the broad, essentially Gaussian distribution of charge states emerging from each foil. For example, uranium stripped at 8.5 MeV/amu will have a charge-state distribution with a full width at half-maximum (FWHM) of about ten charge states, no one charge state constituting more than 12 percent of the total beam. Since each stage of acceleration is best matched by a single charge state (a well-defined Q/A), the presence of many charge states, often not separable by our beam diagnostic instrumentation, leads to great difficulty in achieving optimum tuning. The problem is greatest at the highest masses since more charge states are present and they are more closely spaced in Q/A. To alleviate the problem, a tracer tuning technique was developed.

A light, partially stripped ion is chosen which is very closely matched in Q/A to the heavy ion desired (generally to better than 0.2 percent). Since charge states for light ions are widely separated in Q/A, it is straightforward to isolate the desired charge state and tune it through the transfer line and Bevatron acceleration process. Because of Q/A matching, this tuning will also serve for the heavier ion; all that is required is that the heavy-ion beam position and velocity at the top of the transfer line be matched to those of the tracer.

In operation, the technique has worked exceptionally well. For xenon beams (Ne^{7+} tracer), close to theoretical transmission through to the experimental target is achieved with no adjustments of any transfer line or Bevatron parameters, and the final success with uranium was achieved by tuning with a tracer, after two unsuccessful attempts without it.

For the 11 May attempt to accelerate uranium, a tracer of Fe^{16+} was selected for the U^{68+} ions expected from the stripper; N^{4+} ions could have been used, but an iron source was operating at the time and was most convenient. While the Bevatron operators were tuning the Fe^{16+} ions from one injector down the transfer line and through the Bevatron, the SuperHILAC operators worked at peaking the Abel uranium beam. On completion of the tracer tuning, the beam was switched from iron to uranium while we watched a scintillator signal from the external beam line at the Bevatron. As the energy matching was done, by slowly varying the last SuperHILAC tank parameters, the scaler counts slowly grew from 10 per spill on up through 100 to finally more than 1000.

At this point beam characterization studies were performed, with the emulsion and CR-39 exposures discussed in the following reports (*9*, *10*) forming the final verification of the ionic species as uranium.

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Characteristics of the Ionization Tracks and Interactions of Uranium-238 Nuclei in Emulsion

Abstract. *The acceleration and extraction of uranium-238 nuclei by the Bevalac have been confirmed by their visual detection in nuclear research emulsion. A preliminary result for the collision mean free path for stopping uranium-238 (energy ≤ 115 million electron volts per nucleon) is 3.1 ± 0.6 centimeters. Qualitative characteristics of the observed uranium-nucleus collisions are also described.*

An integral part of the first successful acceleration and extraction of ^{238}U nuclei at the Bevalac was the exposure of nuclear research emulsion detectors to obtain visual confirmation of the acceleration of uranium nuclei. Two exposures of emulsion-detector packets containing 1 by 3 inch, glass-backed 50- and 200-μm-thick Ilford G-5 emulsions were made immediately after beam monitors indicated the presence of extracted ^{238}U nuclei. The energy of the ^{238}U ions was, from the machine parameters, estimated to be 147.7 MeV per nucleon.

Both exposures were successful. The uranium ions entered the edges of the emulsions, parallel to the emulsion surfaces. With maximum track densities of

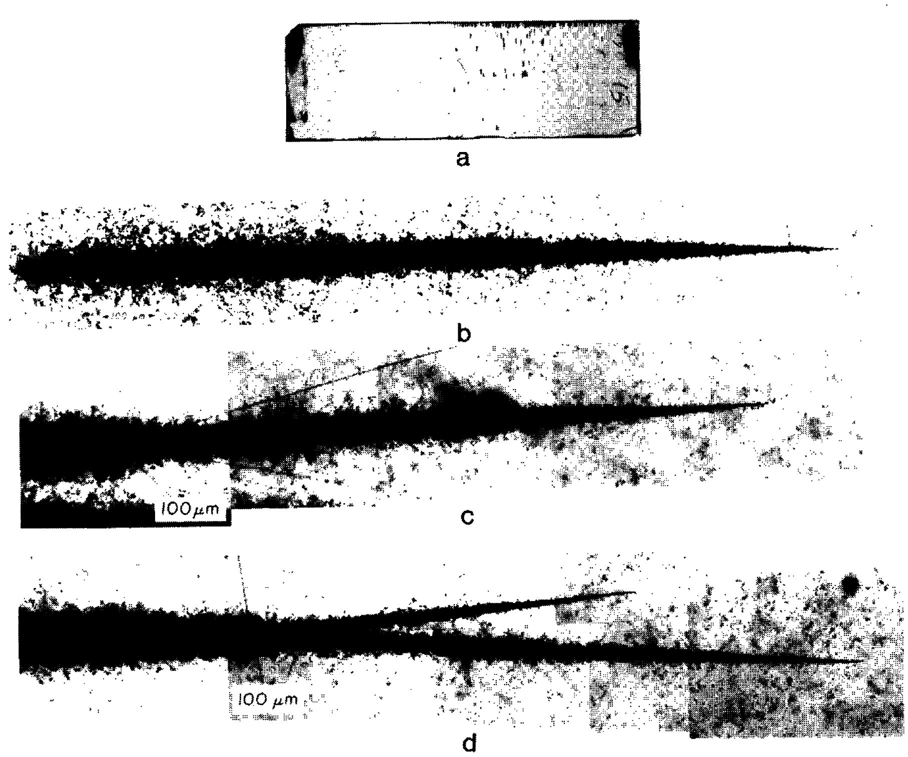

Fig. 1. (a) Contact print of a 1 by 3 inch, 200-μm emulsion plate exposed to ^{238}U ions at 115 MeV per nucleon. The tracks of the ions, 1.5 mm in length, are visible to the naked eye and are seen to enter the upper leading edge of the emulsion and at grazing incidence to the surface of the emulsion. (b) Photomicrograph of the track of a stopping ^{238}U ion in emulsion. The ion enters from the left and has a range of 1.5 mm. A 100-μm scale is indicated. (c) Interaction leading to the fragmentation of the uranium nucleus, where both heavy (one) and light projectile fragments are produced. (d) Example of a collision leading to binary fission of the uranium projectile.