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Author
Alonso, J.R.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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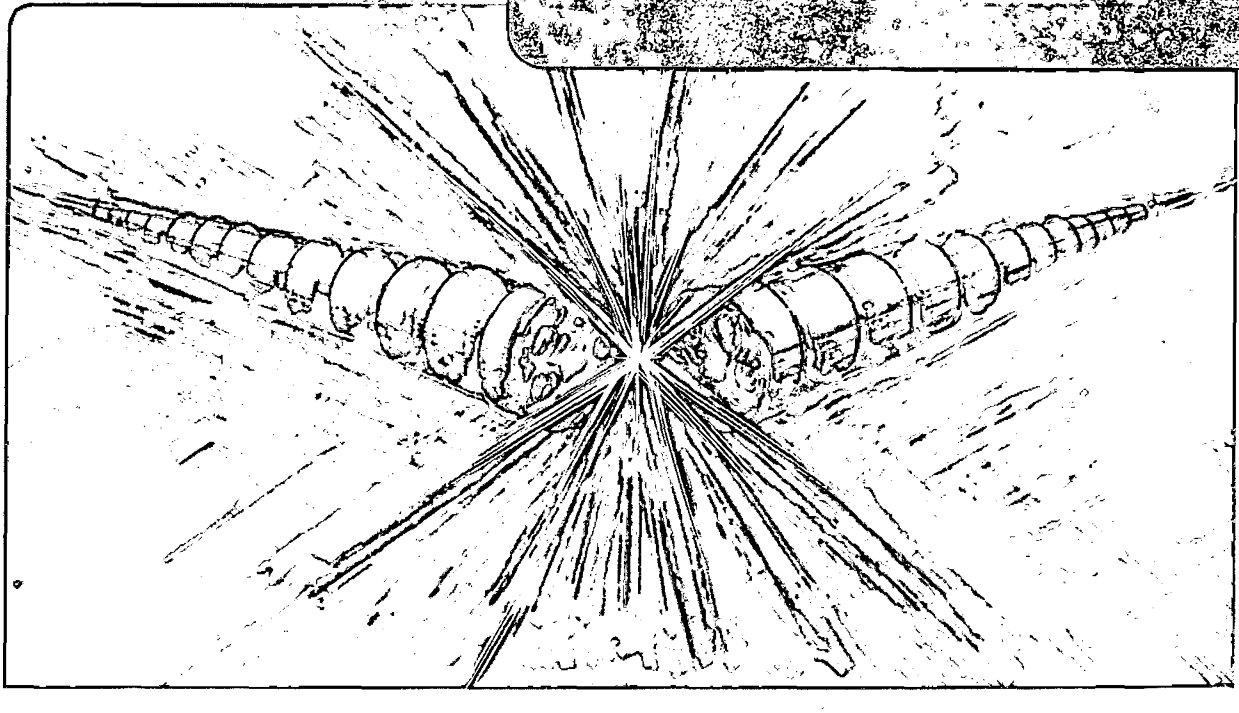

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J. R. Alonso
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Introduction

This year the Bevatron is celebrating its 30th birthday. The long history of this machine and its outstanding record of achievements both past and present are tributes to the solidity of the design of the accelerator, and also to the dedication and creativity of the people working with the machine. During these thirty years, in which the rapid progress of technology in the accelerator field has rendered many machines obsolete just a few years after their completion, the continuing productivity and scientific excellence of the Bevatron have produced a case study in the adaptability of a facility to changing priorities.

By continual redefinition of its mission and by well-suited technical upgradings, the Bevatron has remained at the cutting edge of scientific research. In this paper I shall trace these steps and the technical responses to the challenges presented along the way. Emphasis will be placed on problems of modernization of older equipment, and later on the unique requirements for accelerating heavy ions to high energies.

The operational experience of the Bevatron can be divided into four major periods: first, the commissioning and early experimental period, when the Bevatron was among the highest-energy machines available (1954-1962): second, a period of increasing beam intensity and higher sophistication in the experimental program (1963-1973): third, the light-ion (A less than or equal to 56) period (1974-1981); and finally, the ongoing heavy-ion period. Reference material for this paper was taken mainly from internal LBL reports and log books. If more information is required, please direct specific inquiries to the author.

I High Energy Protons (1954-1962)

Designed as a weak-focusing synchrotron, the Bevatron consists of four 90° magnets with a field index n of 0.6, a 30-cm gap, pole-face width of 125 cm, and a total weight of about 10,000 tons. The magnets are powered by two large motor generator sets, and energy storage is provided by 70-ton flywheels rotating at around 900 rpm (total stored energy in these flywheels is around 1.25 gigajoules). Energy is transferred between flywheels and magnet via a bank of mercury ignitron rectifiers.

After initial authorization in 1949 and a 5-year construction phase, beam was first circulated around the Bevatron on February 15, 1954. The early months of operation were marked by the usual commissioning problems in a new accelerator -- floods, short circuits, fires, etc., many of these catastrophes arising because of the newness of switching and handling such high power levels. As experience was gained, operations stabilized into a state of high productivity, breaking new ground in particle physics. Beam intensity of 10^{10} protons per pulse at repetition rates of 6 to 10 pulses per minute was reached by February 1955, using injected peak currents of 400 A from the 10-MeV Alvarez linac injector.

Experiments were performed using internal targets, spiraling beams into fixed targets, and later by flipping targets into the beam. Most notable during this period was the discovery of the antiproton, first seen in September 1955. The configuration of the Bevatron during this early period is shown in Figure 1; it is apparent that little thought had been given to extensive experimental facilities, and the staff had believed it far too optimistic to think that beam intensities would be high enough to worry about much radiation shielding.

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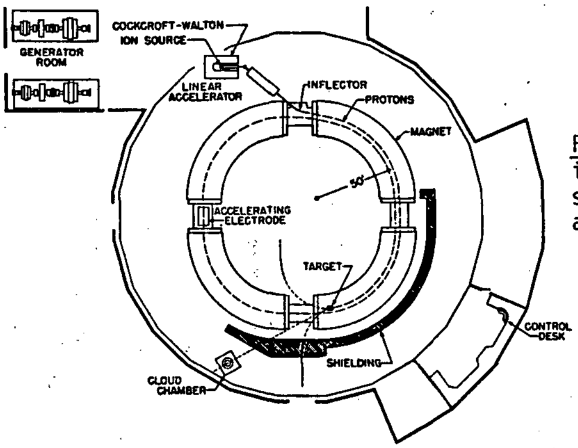

Figure 1 - Layout of the Bevatron early in 1954. Note almost total absence of shielding and primitive experimental area.

By 1959 beam intensity had increased to over 10^{11}, and Piccioni extraction -- controlled passage of the circulating beam through an energy-loss target to shift particle orbits into an extraction channel -- had been developed to the point where useful external beams were available. During this period several bubble chambers were brought on line, the largest -- the 72-inch (1.8 meter) liquid hydrogen chamber -- first receiving beam in June 1959.

By 1961 technical developments had reached a stage that demanded a major improvement program. The space-charge limit for a 10-MeV injector had long ago been reached, and even at these beam intensities (5 x 10^{11}), radiation levels were too high around the accelerator. Plans were drawn up, and a $10 million upgrade project was approved in 1962.

II High-Intensity Protons (1963-1973)

The aforementioned project consisted of several components: the construction of a new 20-Mev Alvarez linac injector, thereby increasing available beam intensity by about a factor of 10: providing shielding for the entire accelerator: and expansion of a well-shielded and instrumented external proton beam facility.

After a seven-month shutdown for the completion of these projects, the Bevatron resumed operation in January 1963, with continuing development of its experimental capabilities. During the following years more target stations were added, both internal and external to the machine, with the major efforts going to increase multiplicity of operation. During one operating period, as many as twelve experiments were taking beam simultaneously on the floor. At least three internal targets were active at once; some, called "traveling targets", could move inside the magnet gap along the beam direction to select the rigidity of the secondary particles emerging through the ports to active experiments. In addition, the extracted beam was split by means of septum and kicker magnets and delivered to at least two target stations, each servicing several experiments. Flexibility was added by a complex magnet ramping cycle, allowing flattops at three different fields and thus providing different energies within the same pulse. A glimpse of the Bevatron complex during this time period is shown in Figure 2. The vitality of the program during these years was demonstrated by the constant changing of the experimental area configuration. Major facilities were installed or removed every few months, keeping a full crew of riggers perpetually busy. Major improvements during this period included the development of resonant extraction, the construction of a large extension to the experimental area, and the addition of computer control to all areas of the accelerator and beam line operation.

With the idea of further increasing the beam intensity, a surplus 50 MeV-linac was shipped from Brookhaven to Berkeley in 1972 and was installed in a building

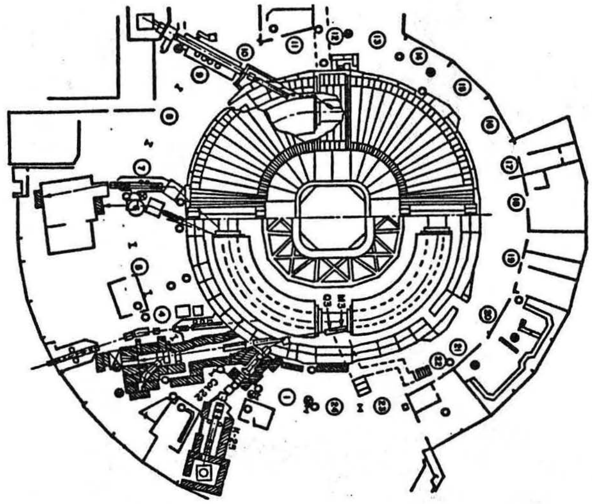

Figure 2 - Bevatron floor in 1964 after first significant upgrade project. Accelerator is totally shielded, has a new 20 MeV injector, a larger experimental hall and many active experiments.

adjacent to the Bevatron. However, just as this accelerator started delivering beams to the Bevatron, High Energy funding for the Bevatron was terminated.

In the years preceding this, development activities directed at accelerating ions other than protons had demonstrated that this was indeed possible. Ion beams of carbon, nitrogen, and even neon had been produced, although at very low intensities. Driven primarily by tremendous enthusiasm from the biomedical community to fully exploit these capabilities, a program was put together to convert the Bevatron to a heavy-ion machine. With joint funding by the Nuclear Science and Biomedical divisions of the U.S. Atomic Energy Commission (now the Department of Energy), this plan filled in perfectly the gap left by the withdrawal of the High Energy Physics Program from the Bevatron.

III The Bevalac - Light Ions (1974-1981)

The prime ingredient in the plan for conversion of the Bevatron into a heavy-ion machine was the total reworking of its injection scheme. To bring heavy ions to the necessary conditions for injection into a synchrotron takes substantially more effort than is needed for protons. Lower charge-to-mass ratios mean less energy-gain for a given accelerating gradient, requiring longer structures, and the large number of possible charge states an ion can be in generally rob from available intensity. In the present case, however, the fortuitous location of the SuperHILAC, an almost ideal injector, presented the perfect solution for delivering heavy ions to the Bevatron. This accelerator, itself originally built in 1958 and upgraded in 1970 for higher mass capabilities, consisted of two high-voltage terminals, followed by two Alvarez linacs separated by a stripper at 1.2 MeV/amu. With a final energy of 8.5 MeV/amu, the injection rigidity of $q/A = 0.5$ (after a second stripping at 8.5 MeV/amu) was well within the range of proton rigidities normally accepted by the Bevatron. The mass range available at the SuperHILAC -- good intensities up to xenon (A=136) -- were substantially higher than the Bevatron could handle, as was the repetition rate of 36 Hz, but as we shall see, these capabilities were used to expand the system flexibility at a later date.

To bring these ions to the Bevatron, it was only necessary to build a 150-meter transfer line joining the SuperHILAC exit and the 100 meter injection line just installed between the new 50-MeV linac and the Bevatron (see Figure 3). The coupling of these machines became known as the Bevalac. First beam went through the new line early in 1974 and was easily injected and accelerated in the Bevatron.

For the next years, the new fields of research with relativistic heavy ions unfolded: the biomedical program used one third of the available research time in studies leading to clinical use of such beams for cancer radiotherapy and high quality imaging, and the nuclear science efforts concentrated on fragmentation reactions and on searching for hydrodynamic and other bulk-matter effects in central collisions.

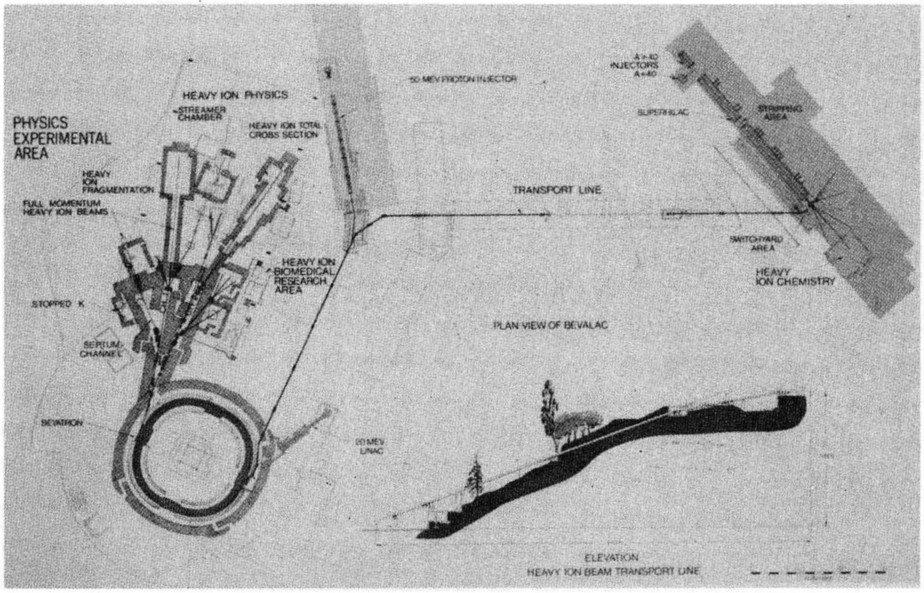

Figure 3 - The Bevalac, 1974, formed by construction of the Transfer Line between the SuperHILAC and the Bevatron. Note the expanded experimental area and the newly completed Experimental Hall. (CBB 740-7911)

Beams available at the time were ions up to mass 40 at reasonable intensities, around 10^9 ions per pulse for the lighter ions. Ion mass was limited to those ions which could be fully stripped at the SuperHILAC exit energy. This limit existed because of the poor vacuum in the Bevatron, and the problem of electron pickup and loss of the circulating beam interacting with residual gas atoms. (If an ion changes its charge state, it no longer satisfies the proper relationship between velocity, rigidity, and radius, and is rapidly lost from the beam.) Electron pickup cross sections fall very rapidly with increasing velocity (data indicate β^{-6}) while electron loss has a much slower velocity dependence (β^{-2}). Thus, an ion not fully stripped will suffer charge-changing reactions much further into the acceleration cycle than will an ion with no electrons.

At 8.5 MeV/amu, argon is about 50% fully stripped by a 200-μg/cm^2 carbon foil. Iron, mass 56, has at this energy a fully stripped fraction of less than 3% and represented the heaviest beam that was attempted at the time. Cosmic-ray physicists were keenly interested in such a beam to calibrate satellite instruments, and with great effort several runs were made, at very low intensity. A technique was employed for these runs which was also used during later uranium runs, that of using a tracer ion of a lighter, more abundant species, but with the same q/A as the desired ion, to tune up the accelerator. $^{15}N^{7+}$ matches $^{56}Fe^{26+}$ to better than 1%, and its use as a tracer allowed useful experiments to be conducted at intensity levels below the sensitivity threshold of any of the existing beam diagnostic instrumentation. The viability of the tracer technique points out one of the problems inherent in heavy-ion acceleration, namely, unambiguous knowledge of exactly what is being accelerated. We have had cases where incorrect beams have been delivered; confusing lithium and carbon, nitrogen for silicon, even nitrogen for neon. Experimenters have learned to always design apparatus that can measure what they are getting.

Very early in the Bevalac program, it was pointed out by the disgruntled SuperHILAC experimenters that 99% of the capabilitity of their accelerator was being wasted while this machine was serving as an injector for the Bevatron. This led to the development of what is called the Time-Sharing mode of operation, a concept which has proven to be crucial in achieving maximum productivity in a heavy-ion accelerator complex such as ours.

With two high-voltage platforms, each tuned for a different ion, and with suitable fast-switching magnets, it was possible to assign each of the 36 pulses in one second to either ion at any given energy and to deliver it to any given beam line. In the 10 milliseconds or so between pulses, the computer looks up the stored parameters for the next pulse, sets up the switching magnets and rf parameters, and sends the proper ion to its intended destination. After full implementation of this mode of operation in 1976, Bevatron injection was almost transparent to an ongoing SuperHILAC research program.

In 1978 patient radiotherapy began at the Bevalac. This program, requiring about six hours each day for four days a week and with between 10 and 20 patients under treatment at any one time presented many operational problems for the accelerators. Requiring two major configuration changes each day, we found ourselves spending a huge amount of time tuning, with little left over for research. This, coupled with the very inefficient beam usage of the therapy program -- 2 minutes of beam followed by half an hour to set up the next patient -- led us to look very carefully at the most desirable way of operating a heavy-ion facility such as ours to ensure maximum productivity.

With protons our experience had been that maximum productivity was obtained by increasing multiplicity, adding more users to run simultaneously, each taking another slice of reaction products from a common target. This philosophy does not work with heavy ions, as most experimenters need primary beams, and few of these are satisfied with the same ion at the same energy when they have the whole periodic table to choose from.

Beam splitting with protons is accomplished with septum magnets, but even this is unacceptable for heavy ions, as ions striking the septum break up to form a beam halo that almost invariably ends up in the experimental station causing unwanted background.

The only good solution then is to develop extremely rapid configuration switching (in less than one minute) to allow each user his own ion and energy and to interleave these users in the most productive fashion. On a different time scale, this operating mode, called Fast Switching, is the exact analog of the time-sharing mode at the SuperHILAC. We are at present in the final stages of fully implementing this capability; early indications are that we should achieve very high productivity with this flexible mode of operation, which will allow patient treatments to proceed relatively unnoticed in the background of an ongoing nuclear science experiment.

IV Uranium Beams (1982 - present)

The last remaining frontier for the Bevalac was to produce beams of the heaviest elements. To do this required two things: obtaining high intensities of these beams from the SuperHILAC and ensuring that they would survive in the Bevatron. The first goal was achieved by adding a third injector to the SuperHILAC -- a high-current low-charge-state PIG source (4 ema U^{5+}), followed by a Wideroe linac and a stripper to bring the beam to the required input parameters for the first Alvarez tank (112 keV/amu, U^{11+}).

Since it is impossible to fully strip the heaviest ions at 8.5 MeV/amu, the vacuum in the Bevatron had to be improved to the point that the mean free path of an ion for a charge-changing collision was much greater than the distance traveled during acceleration. This indicated a pressure in the mid 10^{-10} torr range.

The large bore of the weak-focusing Bevatron worked in our favor in that we were able to insert a cryopumped liner that has easily met and surpassed the vacuum requirements. Fabricated from inexpensive, easily assembled parts (copper-clad fiberglass), the three nested boxes (inner at 12°K, middle at 77°K, outer at room temperature) block only about 2.5 cm from around the beam bore. Many layers of super-insulation (aluminized Mylar) keep the heat load down; total heat load at 12°K is less than 150 watts. Circulating beam tests have shown that the average pressure around the ring is less than 10^{-10} torr.

Since the completion of this project, we have been delivering an ever-increasing range of beams for wide-ranging experimental programs, from atomic physics with zero-, one-, and two-electron uranium ions to central-collision studies where multiplicities of over two hundred have been observed in gold + gold reactions. Table I gives a list of beams we routinely deliver, with typical intensities. Higher intensities for lower-charge-state beams arise by elimination of the stripper at the exit of the SuperHILAC, but a price must be paid in terms of final beam energy.

Figure 4 shows the present experimental floor arrangement, a significant evolution from earlier days. Emphasis now is on high-multiplicity detectors designed for experiments where all particles from a reaction can be detected, allowing observation of mass-flow, entropy, temperature, and other thermodynamic properties of the reactions. Such experimental facilities now in operation are the Plastic Ball, a 1000-detector array of plastic scintillators occupying almost 4π around the target; HISS, a large-volume (3 m^3) high-field (3 T) superconducting spectrometer; and the streamer chamber, a high-volume visual detector. The three biomedical caves are seen at the top of the figure; all patient treatments are performed in the one nearest the Bevatron.

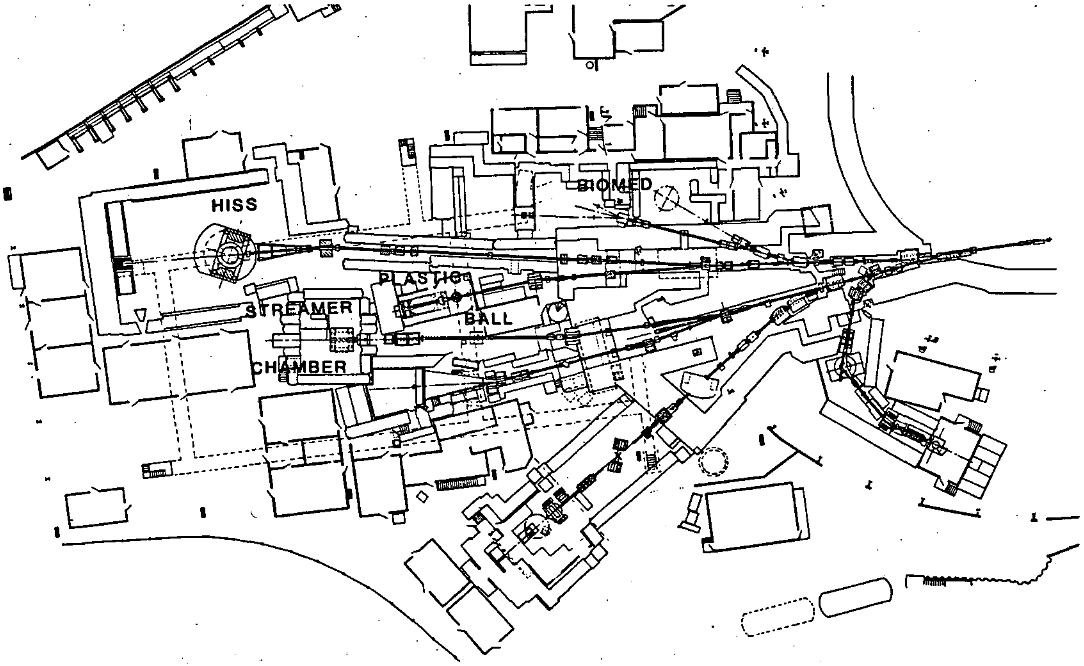

Figure 4 - Present Bevalac experimental floor.

Bevalac ion species and intensities

Table I

Ion	Intensity*	Ion		Intensity*
Hydrogen-1	2×10^{9}	Manganese-55		1×10^{6}
H_2^+	1×10^{9}	Iron-56	24 +	2×10^{8}
Helium-4	3×10^{9}	Krypton-84		1×10^{7}
Carbon-12	5×10^{9}	Niobium-93		2×10^{6}
Oxygen-16	6×10^{9}	Xenon-129		3×10^{6}
Neon-20	1×10^{10}	Lanthanum-139	57 +	7×10^{5}
Aluminum-27	5×10^{8}	Lanthanum-139	32 +	8×10^{7}
Silicon-28	6×10^{9}	Gold-197	62 +	1×10^{5}
Argon-40	1×10^{9}	Gold-197	37 +	1×10^{7}
Calcium-40	4×10^{7}	Uranium-238	68 +	1×10^{6}
Calcium-48	1×10^{7}	Uranium-238	40 +	1×10^{7}

* Particles per pulse in the external beam channel.

Future

Theorists now predict that collisions of very heavy ions should lead to temperatures and densities where nucleons break down into a quark-gluon soup not unlike conditions existing during the Big Bang. As is usually the case, though, such conditions are predicted to occur at energies just beyond those available with existing facilities.

Boosting the energy of the Bevatron is not a realistic option, but what is possible is to use the Bevatron as an injector to a small storage-ring system. Called the Minicollider, these two superconducting rings can fit quite readily into the existing site with a minimum of impact on present facilities. Studies presently in progress indicate that, although the emittance of the Bevatron beam is much larger than desired, collimating, stacking, and cooling of many Bevatron pulses can achieve the intrabeam scattering limit of intensity in the collider. Injected at 400 MeV/amu, (stripped from U^{38+} to U^{92+}) and slowly accelerated to 4 GeV/amu (fixed-target equivalent of 50 GeV/amu), the expected luminosity of 10^{-24} cm^{-2} sec^{-1} will yield about one central collision every second, a totally acceptable data rate.

Feasibility studies are continuing, as are siting, costing, and superconducting R&D efforts. Such a project will be a worthy continuation of the thirty-year tradition of the Bevatron.

Recapitulation - Facility Improvements

In looking back over the very successful upgrade programs at the Bevatron, one finds that several key factors were present in each.

Timeliness and Mission. Each program was clearly oriented towards better fulfillment of the mission of the accelerator, and each represented the next logical step in the facility's development.
Enhancement of Capabilities. Each program added significant new capabilities to the accelerator, sometimes to the degree of allowing a redefinition of its mission.
Realistic Goals. Although some programs involved substantial efforts, all projects could be viewed essentially as "evolutionary" -- that is, as logical extensions of existing capabilities. Areas difficult to upgrade, such as the main magnet and its power supply, were never seriously considered for major upgrades.

Application of New Technology. Areas where significant operational advances could be made by applying new technology were obvious candidates. These included computer controls, cryogenics for vacuum pumping, resonant extraction techniques, RFQ linacs, and new instrumentation.

Adequate Staff. To plan improvements, sell them to funding agencies, and actually carry them out requires a substantial commitment in money and manpower. Of the present Bevalac staff of about 200 people, over 50% are involved with R&D and project implementation. This percentage has been as high or higher in the past.

Unique Criteria for Heavy-Ion Acceleration

Our experience has shown that certain factors are of particular importance for successfully delivering heavy-ion beams.

Source of Ions. The choice one must make is between high-charge-state, low-current sources, most notably the EBIS, or low-charge-state, high-current sources such as the PIG. Although injection accelerators are much smaller for the high-charge-state sources, and although one does not have the losses associated with multiple stripping sections, there always exists the risk of having insufficient intensity for a viable program. The conservative approach of a larger, multi-stage injector is certainly more costly, but is more able to deliver adequate beams. With such an injector, intensity upgrades can be designed as relatively modest improvements, easily meeting the criteria given above. In fact, we are at present completing such an upgrade on our 20-MeV injector, and we are planning an upgrade for the SuperHILAC. In all fairness, one should say that having the SuperHILAC so close to the Bevatron was not a small factor in determining which option we chose.

Vacuum. The main ring vacuum is critical unless ions are fully stripped or are injected at very high energies (above several hundred MeV/amu). Charge-changing processes are worst at injection energies. A pressure of 10^{-10} torr should be aimed for.

Instrumentation. Beam intensity is a problem, especially during initial tuning of a beam. One must have very sensitive instrumentation. We are able to detect down to about 10^6 charges in the Bevatron, but we have techniques mentioned above using tracer ions for delivering to experiments beams of much lower intensities.

Beam Verification. We often encounter problems in selecting and identifying which charge state we are injecting. Isotope separation is a factor for many atomic species; but perhaps the largest problem is confusing very different ions with like charge-to-mass ratios. As mentioned earlier, lithium-6 and carbon-12 can go through two strippers and three accelerating sections and remain indistinguishable, as can nitrogen and silicon (of concern for radiotherapists treating with silicon). Active verification techniques we employ now are energy measurements of injected beam (using a silicon crystal) and on-line beam range measurements in the experimental areas. One must be on guard for these problems; they always happen when you least expect them.

Operational Flexibility. The best use of a heavy-ion facility demands that ions, energies, and beam lines be set up and changed very quickly. Having many ions to choose from greatly reduces the value of splitting and sharing the same beam, as you will rarely find two experimenters wanting the same beam and energy. Flexible operating modes require a very good control system and a highly competent operations crew; otherwise, it is likely that one will spend all the time doing nothing more than tuning the machine.

In summary, the first thirty years of the Bevatron have been extremely productive and exciting, and we are closely watching how the next thirty years develop.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720