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RELATIVISTIC URANIUM BEAMS--THE BEVALAC EXPERIENCE*

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Overview

This paper will address areas where relativistic heavy ion accelerators differ from proton facilities. Salient areas are: 1) the specialized injectors for heavy ions; ion sources, structures for very low charge-to-mass ratio (q/A) ions, and stripper optimization; 2) special requirements for the synchrotron ring; ultrahigh vacuum, flexible controls and instrumentation. These areas are discussed in the context of the Bevalac, as well as our idea for a next-generation relativistic heavy ion accelerator.

Introduction

The emergence of relativistic heavy ion physics as an exciting and promising new area of research has led to a good deal of study into the factors that go into designing accelerators for such ions. Questions being asked include: 1) in what areas do heavy ion accelerators differ from the more conventional proton machines; and 2) can retrofitting programs easily convert existing proton machines into universal ion accelerators? From our experience with the Bevalac we can isolate two general areas of importance for relativistic heavy ion accelerators.

First, injector requirements are much more severe. Ion sources are very complex; they must handle source material in different physical forms and must be optimized for high intensity high charge state beams. Charge-to-mass ratios for the heaviest ions are low, requiring higher gradients or longer accelerating structures; intensity requirements are greater because of losses in the various stripping stages; and the energy of injection into the synchrotron is driven not only by ring constraints, but by the desire to strip to the highest possible charge state for maximum final energy.

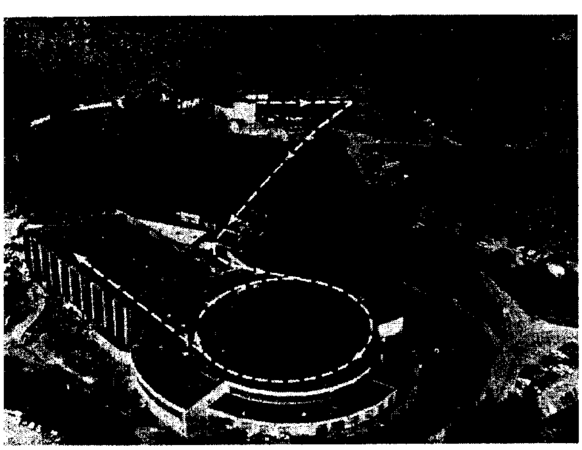

Fig. 1. Aerial view of the Bevalac. A transfer line runs down the hill, connecting the SuperHILAC and the Bevatron.

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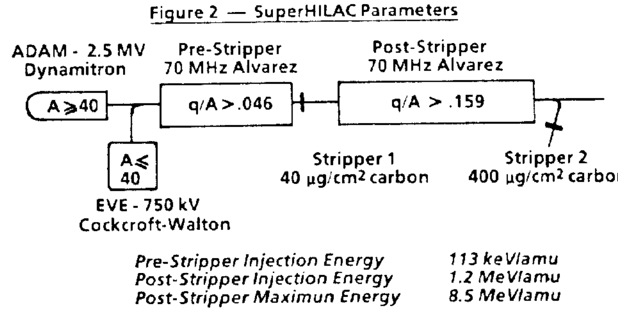
Second, the synchrotron must be versatile enough to adapt to the widely varying conditions of the full spectrum of ions, energies and intensities requested. Some specific considerations along these lines are: an ultrahigh vacuum to accelerate ions that cannot be fully stripped at the injection energy; a flexible inflection system to handle widely differing q/A values; beam diagnostic instrumentation with sensitivities covering many (at least six) orders of magnitude; external beam lines with continuous vacuum paths from ring to target; and a sophisticated control system to handle the wide range of operating conditions routinely encountered.

In what follows, we will explore these ideas, in the context of our operating experience with the Bevalac and its recent uranium-beam upgrade program.

The Bevalac - pre 1982

Figure 1 shows the Bevalac, consisting of the SuperHILAC serving as the injector, connected by a transfer line to the Bevatron. The SuperHILAC has undergone many modifications in its twenty-five-year history of valuable service to the nuclear science community. Its configuration prior to the last upgrade is summarized in Figure 2. With its two injectors ADAM and EVE producing beams of high intensity through mass 150, and with a final energy of 8.5 MeV/amu, the SuperHILAC is well-suited for its use as the Bevalac injector.

Figure 2 — SuperHILAC Parameters



The transfer line between the SuperHILAC and the Bevatron was built in 1973. It covers a distance of 250 meters, including a 15 meter vertical drop, the elevation difference between these two hillside machines.

The Bevatron is a weak focusing synchrotron, built in 1954 as a showpiece for high energy physics, and boasting what was then a world-record 6.2 GeV as its maximum energy. Through constant upgrading and innovations it has remained as a forefront research tool; its conversion to the Bevalac is in keeping with this tradition. Basic parameters for the Bevatron are given in Table I.

Capabilities of the combined facility as it existed prior to 1982 are given in Figure 3a. In the years since its commissioning as the Bevalac, it has become a unique facility with multi-national programs in nuclear physics, astrophysics, atomic physics and biomedicine, the latter including a significant program of cancer radiotherapy with heavy ions.

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Table I — Bevatron Parameters

Ring diameter [m]	15
"Lattice"	Weak focusing, n = 0.6
Maximum field [T]	1.26
Injection field [T]	0.02 to 0.15
Frequency swing	>10/1 (2.5 MHz max.) (1st harmonic acceleration)
Maximum rigidity [Tm]	19.2
Power source	2 100-MW motor generators
Total stored energy [MJ]	>650 (flywheels)

The Uranium Beams Upgrade Project

A study of how to extend the capabilities of the Bevalac to the range shown in Figure 3b was undertaken in 1975. Under the direction of Hermann Grunder, this study isolated two primary needs: an ion source and injector for high intensity very heavy ions at the SuperHILAC and an improved vacuum at the Bevatron.

Funding was provided in 1979, and parallel construction efforts began. The new injector, named ABEL, was completed in the spring of 1981, with the first beam delivered to an experiment in June 1981. The Bevatron vacuum liner project required two 6-month shutdown periods, the first in July 1980 for preparation of the Bevatron to accept the liner, the second a year later, for the actual installation. First pumpdown took place in December 1981; first beam was accelerated in February 1982. Uranium was successfully accelerated in May,[1] with the full energy and intensity goals being met by February 1983.

In the following sections an abbreviated description of the two projects will be given; the reader is referred to our Final Report[2] for additional technical details.

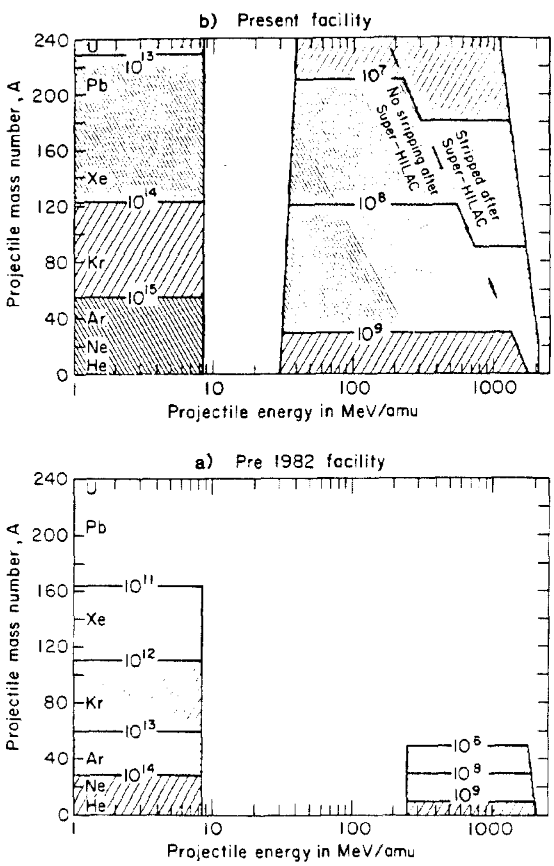

Fig. 3. Ion and beam intensity capabilities of the Bevalac; a) prior to the U-Beams Project and b) after the upgrade. SuperHILAC intensities (on the left side of the figure) are in particles-per-second, Bevalac numbers are in particles-per-pulse.

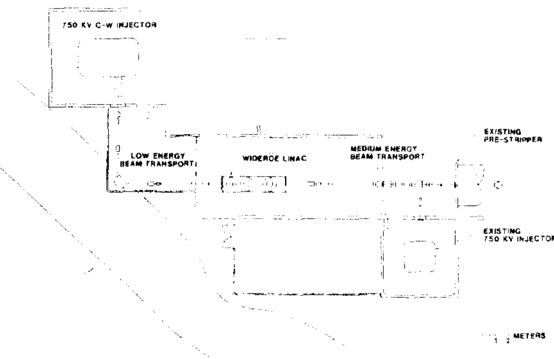

Fig. 4. Plan view of the new ABEL injector at the SuperHILAC.

Third Injector[3]

The Third Injector Project team, headed by T. Elioff, included J. Staples and F. Selph, physics; R. Yourd, mechanical engineering, and H. Lancaster electrical engineering. The injector layout selected is shown in Figure 4; it consists of a high voltage platform, a Wideröe linac and a vapor stripper, all combining to deliver a beam of the required energy (113 keV/amu) and q/A (>.046) at the pre-stripper entrance.

Ions are produced in a dual-headed PIG source developed by B. Gavin.[4] This source delivers particle-milliampere beams of U^{5+} ions; equally intense beams of other ions, metallic or gaseous, are also available. The dual-head feature allows one source-head change without breaking vacuum, an excellent aid for efficient running. The low-energy transport line takes the 15.8 keV/amu beam from the 750 kV Cockcroft-Walton[5] to the Wideröe[6]. The 90° magnet in this line has adequate analyzing power to separate isotopes, avoiding the need for expensive isotopically enriched source materials. The beam is next accelerated in the Wideröe linac to the SuperHILAC injection energy of 113 keV/amu. This linac is a π-3π structure (the longer drift tubes containing focusing quadrupoles), and operates at 23.4 MHz, one-third of the SuperHILAC frequency. The beam is then passed through a fluorocarbon vapor stripper[7] that brings the charge state to an acceptable q/A for pre-stripper acceptance.

A sophisticated distributed microprocessor-based control system was designed to handle all aspects of the injector operations,[8] from operator consoles to parameter control and beam diagnostic instrumentation. Using a large number (25) of 16-bit processor boards in a star network, this system provides excellent computing bandwidth, which translates to very good response time and very complete information to the operator.

Bevatron Vacuum Liner[9,10]

The primary limitation on the mass-range shown in Figure 3a was imposed by the relatively poor (10^{-7} Torr) vacuum achievable in the Bevatron. Vacuum-related beam loss arises from charge-changing collisions between ions and residual gas atoms. At high velocities, electron loss predominates over electron pickup, so beam survival is substantially enhanced by the acceleration of fully stripped ions. The energy needed to completely strip an ion is strongly dependent on its atomic number; at the SuperHILAC energy of 8.5 MeV/amu light ions are easily stripped, but ^{56}Fe is the practical upper limit: only 3% of an iron beam is fully stripped at this energy. To obtain higher mass beams in the Bevatron either the injection energy must be increased (to fully strip heavier ions) or the vacuum in the ring must be improved (to allow acceleration of partially stripped ions). The first alternative is not practical for the heaviest ions; recent experiments with our newly available uranium beams have shown that even at 1 GeV/amu only 80 to 90% of the uranium ions are fully stripped (in a tantalum foil). At 400 MeV/amu this figure drops to 40%.

Therefore, one must ascertain what vacuum is necessary for survival of partially stripped ions. An extensive set of cross section measurements[11] at the SuperHILAC has generated the data shown in Figure 5, from which we see that pressures in the 10^{-10} Torr range would guarantee survival of any mass beam in any reasonable charge state during the few seconds of the Bevatron acceleration cycle.

Achieving this pressure inside the Bevatron presented no small problems to the design team headed by T. Elioff, R. Avery and J. Meneghetti. The size and construction of the main Bevatron vacuum chamber precluded its conversion to an ultrahigh vacuum system. However, there was adequate space for the installation of a vacuum liner, a completely separate vacuum system inside the main vacuum enclosure. The final design is shown in Figure 6, and incorporates numerous innovative ideas. The liner consists of three nested fiberglass boxes, separated by layers of superinsulation and cryogenically cooled (inner box at 12°K, middle at 77°K, outer at room temperature). The two inner boxes use copper-clad Nema G-10 sheets with narrow stripes etched across the boards perpendicular to the beam direction. These stripes reduce eddy currents while still providing heat conduction from the cooling tubes attached at the corners. Activated charcoal panels on the inner radius edge provide additional pumping for hydrogen and helium. The original Bevatron vacuum system is maintained as a guard vacuum and to

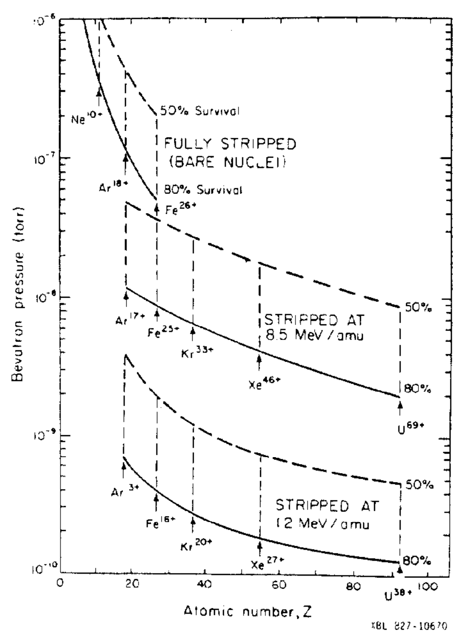

Fig. 5. Vacuum requirements for beam survival in the Bevatron. Most stringent requirements are for ions not stripped at the SuperHILAC exit.

eliminate atmospheric structural stresses on the fiberglass assemblies.

The nested-box assemblies were installed throughout the Bevatron, except for the straight sections where the RF system, inflection system and plunging extraction magnets were located. LN-cooled boxes were installed in these areas, and enclosed paraphernalia were either LN-cooled or specially canned to minimize gas loads.

Cooldown from room temperature takes about four days. Four CTI 1400 refrigerators are used for this cooldown but only one, running at half speed, is needed to keep the system cold (confirming the engineering heat-load calculations).

Commissioning Experience

Both components of the U-Beams project have come on line very rapidly, and have performed to specifications. Outstanding ion source and control system performance, and excellent reliability have highlighted ABEL performance. The new Bevatron vacuum liner has been cycled several times now, and has proven to be efficient, reliable, easily maintainable, and very forgiving of pressure bursts and power outages.

Determination of the average pressure around the machine circumference has been performed with a beam-survival measurement. A carbon-4+ beam was injected into the Bevatron at 5 MeV/amu, accelerated to 7.2 MeV/amu, and then coasted at this energy. The C^{4+} charge-changing cross sections were measured for this energy at the SuperHILAC, so the beam survival time gives an upper-limit measure (because other loss mechanisms can contribute) of the ambient pressure. Measured survival times of approximately 1 second translated to average pressures of about 5×10^{-10} Torr, including the effects of the much higher pressure ($P = 1\text{-}2 \times 10^{-9}$ Torr) in the straight sections.

An analysis of the uranium beam intensity through the various components of the Bevalac is given in Table II. The major losses occur as a result of stripping, because the single incident charge state is diluted into many final states.

Everyday Living with Heavy Ion Beams

The development of new heavy ion beam capabilities at the Bevalac has proceeded in an orderly fashion. We have accelerated the whole range of ions, from protons to uranium, achieving the design intensity goal for uranium just this past month. Exciting experiments have been performed with these new beams; the first nuclear collisions with 1 GeV/amu uranium ions, observed in nuclear emulsions, are being eagerly analyzed by groups around the world; and the most interesting uranium-stripping measurements mentioned earlier are providing valuable

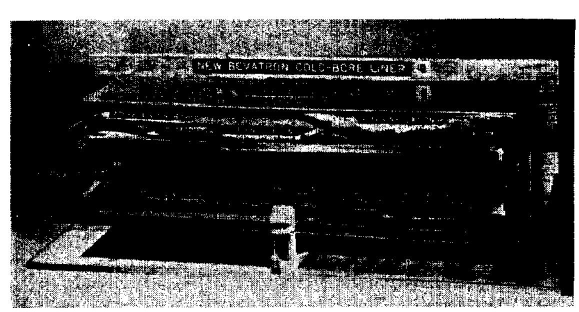

Fig. 6. Cross section of the new vacuum liner installed in the Bevatron. This cryogenically-cooled fiberglass assembly brings the average pressure in the beam path down to the low-10^{-10} Torr range.

Table II — Uranium Beam Intensity Analysis

	Transmission Factor	Peak Current
Source	--	1 pmA
Column, low-energy transport	.75	750 pμA
Wideröe	.5	375 pμA
Medium energy transport	.8	300 pμA
Stripping 5+ to 12+	.05	15 pμA
Pre-stripper	.5	7.5 pμA
Stripping 12+ to 38+	.15	1.1 pμA
Post-stripper	.5	570 pnA
Stripping 38+ to 68+	.14	80 pnA
Transfer line	.5	40 pnA
Bevatron capture/acceleration	1×10^8/pμA	4×10^6 ppp
Extraction	.5	2×10^6 ppp

data for designs of new relativistic heavy ion accelerators.

As rapidly as the new beams have been developed, the demand for them has increased, so that now over 70% of our nuclear science program is run with beams of iron or heavier. We have met a sufficient number of the ion and intensity design specifications to confidently say that Figure 3b is an accurate representation of the beams available from the Bevalac. In this figure we observe that the highest energies are achieved by stripping at the SuperHILAC exit. However, much higher Bevalac intensities are available (typically 7-10 times higher) if the beam is not stripped, albeit at a lower maximum energy. Thus, an energy-intensity tradeoff is possible, depending on experimental needs.

Although our operational experience has been very popsitive, we have encountered several problem areas that are unique to heavy ions. Discussion of these areas may be of value in illustrating how running a heavy-ion facility differs from running a proton or electron accelerator.

Tuning difficulty. Stripping heavy ions distributes the beam into many charge states, with magnetic rigidity differences scaling as $\Delta(q/A)$. This problem is most severe for the heaviest ions. As an example, in the transfer line four uranium charge states crowd into almost the same spatial separation as that between two iron charge states. In addition, if there is energy spread in the beam greater than 0.5%, different uranium charge states will overlap in a magnetic analysis system. Even identifying which charge state is being tuned--necessary for using the correct RF curve in the Bevatron--is difficult if the absolute energy value is uncertain.

Two solutions are available: direct energy and charge-state measurements using specialized instrumentation, or clever tuning techniques. While we are working on the former (by installing high-resolution profile monitors for charge state analysis and a long-baseline time-of-flight system for energy measurements) we have meanwhile successfully used a tracer technique for tuning our heaviest beams. This method consists of using a lighter ion in a charge state selected to match the q/A of the heavier beam. For example, $^{56}Fe^{16+}$ matches $^{238}U^{68+}$ to better than 0.25%. The transfer line, inflection, Bevatron ring, extraction and external beam line are all tuned with the tracer ion, which is pure and of good intensity. Then, the primary beam is presented at the top of the transfer line: it will be transmitted if a good match to the rigidity of the tracer is made. So the entire tuning problem is reduced to a single variable, and slight adjustments in the final post-stripper tank gradient and phase are all that are needed to bring the beam to the Bevalac experimenter's target. This technique has been used successfully now for tuning xenon ($^{20}Ne^{7+}$), gold ($^{55}Mn^{17+}$) and uranium beams.

Poor multiplicity and scheduling incompatibilities. From the standpoint of efficient machine utilization, the very flexibility of a heavy ion facility is also its curse. Ordinary beam-sharing techniques to increase user multiplicity, such as septum splitting and sequential target placement, will be useful only if users can be found who can use the same ion at the same energy. Our experience is that this rarely happens. Septum splitting is unpopular with experimenters anyway, since heavy ions produce substantial contamination in the form of nuclear reaction fragments from the septum. These contaminants are extremely difficult to remove, thus resulting in a substantial degradation in beam quality.

The Bevalac program has another difficulty as well, namely the necessity to integrate the nuclear science program with a very active radiotherapy program. The need for daytime fractions for as many as 20 patients per day and for four treatment days per week relegates nuclear science experiments to late-nights and weekend running periods.

The solution to both of these problems lies in improved flexibility of accelerator control and beam switching capabilities. Increased on-target hours can best be achieved by reductions in tuning time, and by the ability to rapidly switch the machine configuration for different experimental requirements. For example, the treatment of a radiotherapy patient requires only about one to two minutes of beam time, but the setup of the next patient can take a half hour or more. During this time, of course, the beam can be used elsewhere. We have been using "fast-switching" techniques for several years now, switching beam lines and beam energies between two users in less than one minute. During a normal therapy day as many as 30 to 40 switches are performed, making about 70 to 80% of the time available to the non-therapy user.

To make this technique most useful, we must also switch ions quickly. This will provide complete independence of the two users, and in fact will permit the nuclear science program to go back to the more desirable operating schedule of long blocks of running time. Such ion switching is most efficiently performed with two injectors, each tuned with a different ion, ready to be switched at the Bevatron inflection point. To this end, we are presently upgrading our Bevatron local injector from its present mass limit of carbon to the heaviest ion requested by the radiotherapy program, namely argon. To accomplish this we are building a heavy ion RFQ[12-15], and will be adding a new source platform and rebuilding the front end of the 200 MHz Alvarez linac tank. When completed in early 1984, this injector will provide all of the required radiotherapy beams, allowing the transfer line to be dedicated to the heavier beams of interest to the nuclear science program.

This rapid switching effort represents the closest we can come to a full interleaving of two research programs without unacceptably constraining the operating conditions for either. For further increases in flexibility of operation, as well as for satisfying desires for higher energies and higher intensities, thoughts have turned towards designing a new machine. This accelerator, called the Tevalac, is based upon our solid base of experience with the Bevalac, and although built mostly from new hardware and modern technology, represents only a modest extrapolation from our current operating philosophy. A description of our present concept is given below.

The Next Step - the Tevalac

As presently envisioned, the Tevalac will consist of two rings, of 6 Tesla superconducting magnets located one above the other in a tunnel that surrounds the present Bevatron site.[16] It will be injected by an upgraded SuperHILAC, and will use much of the present Bevalac experimental areas and physical plant facilities.

Higher intensity beams will be achieved by various incremental changes in the SuperHILAC performance, such as the installation of a high-current source. A very promising metal-vapor arc source is presently being investigated; possible gains of a factor of 10 in beam current are hoped for. Other planned changes include the elimination of two of the stripping stages by rebuilding the pre-stripper to accelerate U^{5+} beams to 1.2 MeV/amu, and injecting the main rings with beams that are not stripped again at the SuperHILAC exit. Each of these will greatly boost beam currents. There is a good match between upgraded injector performance and the ring space-charge limit, resulting in a net intensity increase of about 10^2 to 10^3 over the present Bevalac.

The dual-ring concept plays a crucial role in achieving the design goals of energy and flexibility. The demonstrated need to reach energies of at least 1 GeV/amu to guarantee the complete stripping of uranium ions argues strongly for using the main ring for accelerating the beam both before and after stripping. (A small booster ring to bring the low-charge-state beam to the 1 GeV/amu stripping energy ends up being as large as the main ring.) The procedure would be as follows; unstripped (U^{38+}) ions are injected to R1, accelerated to 1 GeV/amu and transferred with stripping into the stretcher/holder ring R2. After R1 has been reset to the proper field, the U^{92+} beam is reinjected into R1 and further accelerated to the maximum 10 GeV/amu final energy.

The stretcher ring also plays an important role in guaranteeing higher user multiplicity . A single pulse of one ion injected into R2 can be slowly extracted for an experiment while R1 is accelerating a different ion for another experiment. These are but two of the operating modes possible with this highly flexible concept; others are detailed in our preliminary Tevalac proposal.

The basic machine parameters are summarized in Table III; as can be seen, all components of this accelerator are within the state of the art. Magnets similar to those needed have been constructed at LBL, have achieved the desired ramp-rate, and have reached almost 9 Tesla (at 1.8°K). Furthermore, much of the research experience and experimental technology developed at the Bevalac are directly transferable to the new accelerator, so that new physics regimes can be explored productively as soon as the machine comes on line.

Chief among the phenomena to be searched for will be quark deconfinement, as the nuclear temperatures and densities achievable in the collision of two very heavy ions at Tevalac energies are predicted to be at or above the threshold for the formation of a quark-gluon plasma. In fact, the environment present in these collisions may be close to the conditions present at the beginning of the Universe, thus potentially creating a new research field for our new heavy ion accelerator... experimental cosmology!

Table III — Tevalac Parameters

	R1 Accelerator	R2 Stretcher/ Holder
Peak Field, B_{max} [T]	6	6
Ramp Rate, $\dot{B}$ [T/s]	1	<< 1
Rigidity $B\rho$ [Tm]	94	47
Circumference [m]	460	460
Energy, E_{max} (U^{92+}) [GeV/amu]	10	4.6
Beam emittance at injection ε_V, ε_H [μm]	60, 30	
Space Charge Limit (U^{38+})	3.3×10^{10}	
Ring Pressure [Torr]	1×10^{-11}	

References

1. J.R. Alonso, R.T. Avery, T. Elioff, R.J. Force, H.A. Grunder H.D. Lancaster, J.R. Meneghetti, F.B. Selph, R.R. Stevenson, R.B. Yourd, "Acceleration of Uranium at the Bevalac," Science 217, 1135, 1982.
2. The Bevalac Staff, "High Intensity Uranium Beams from the SuperHILAC and the Bevatron: Final Report," LBL-14881, March 1982.
3. J.W. Staples, H.D. Lancaster, R.B. Yourd, "The LBL Wideröe-Based Heavy Ion Injector Project," IEEE NS-28, 3479, 1981.
4. B. Gavin, S. Abbott, R. MacGill, R. Sorensen, J. Staples, R. Thatcher, "A High Current Pulsed Ion Source for Metallic Ions," IEEE NS-28, 2684, 1981.
5. J. Hinkson, G. Behrsing, E. Hazelton, W. Hearn, H. Lancaster, "A New, Rugged High Power Cockcroft-Walton Power Supply," IEEE NS-28, 2961, 1981.
6. J. Fugitt, D. Howard, F. Crosby, R. Johnson, M. Nolan, G. Yuen, "A Simplified RF Power System for Wideröe-Type Linacs," IEEE NS-28, 2955, 1981.
7. J.R. Alonso, B.T. Leemann, "Fluorocarbon Vapor Stripping of Low Beta Heavy Ions," IEEE NS-26, 3718, 1979.
8. S. Magyary, H. Lancaster, F. Selph, M. Fahmie, C. Timossi, J. Glatz, A. Ritchie, J. Hinkson, R. Benjegerdes, D. Brodzik, "Operating Experience with a New Accelerator Control System Based upon microprocessors," IEEE NS-28, 2201, 1981.
9. The Bevalac Vacuum Improvement Team, "Improving the Bevatron Vacuum to 10^{-10} Torr", IEEE NS-28, 3260, 1981.
10. R.T. Avery, T.F. Henderson, K. Kennedy, J.R. Meneghetti, J. Alonso, "Performance of the New Cryogenic Vacuum System at the Bevatron", this conference, LBL-15260.
11. J. Alonso, H. Gould, "Charge Changing cross sections for Pb and Xe ions at Velocities up to 4×10^9 cm/sec," Phys. Rev. A26, 1134, 1982.
12. S. Abbott, R. MacGill, R.D. Yourd, "Mechanical Design of a Heavy Ion RFQ," this conference, LBL-15142.
13. J. Staples, "Beam Dynamics and Vane Geometry in the LBL Heavy Ion RFQ," this conference, LBL-15141.
14. H. Lancaster, H.R. Schneider, "Improved Field Stability in RFQ Structures with Vane Coupling Rings," this conference, LBL-15140.
15. S. Abbott, D. Brodzik, R.A. Gough, D. Howard, H. Lancaster, R. MacGill, S. Rovanpera, H. Schneider, J. Staples, R. Yourd, "RFQ Development at LBL," 7th Conference on Applic. of Accel. in Research and Industry, Denton, Texas, Nov. 1982.
16. LBL Accelerator & Fusion Research Division and Nuclear Science Division, "The Tevalac, a National Facility for Relativistic Heavy Ion Research to 10 GeV per Nucleon Uranium," LBL Pub. 5081, December 1982.