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PERFORMANCE OF THE BEVALAC*

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ABSTRACT

The performance of the Bevalac is reported. The Bevalac uses the LBL SuperHILAC as the heavy ion injector to the Bevatron. Ion species up to ^{40}A have been accelerated to energies of 1.9 GeV/A at modest intensity. Neon has been accelerated to 2.1 GeV/A at an intensity of $4 \cdot 10^{10}$ particles per pulse. The modifications to the SuperHILAC and Bevatron are briefly reviewed and the computer control system is described. Results of the first phase of operation and plans for further improvements are reported.

Introduction

Interest in high-energy heavy ions extends to a number of fields of science--nuclear physics and chemistry, cosmic ray physics, particle physics, radio-biology, and medical physics. In chemistry and physics, heavy particles offer the possibility of experimentally studying the interactive and possible non-linear effects of aggregates of nuclear particles that cannot be studied with simpler systems. Interest in the fields of radiobiology, radiation therapy and space medicine derives from the fact that the ionization produced by these particles is very dense and increases near the end of a well defined range. This property makes it possible to produce well-defined volumes of dense ionization deep in living systems with relatively little ionization in the surrounding tissues. This will be a new and excellent tool for many important experiments and may lead to a superior mode of radiation therapy. The importance of this facility to space medicine derives from the fact that it will produce beams which overlap a substantial portion of the heavy particle cosmic ray spectrum to which astronauts are exposed.

This project[1] is designed to take advantage of the unique circumstance that the SuperHILAC, an accelerator specifically designed to produce intense beams of a wide range of heavy ions at an energy of 8.5 MeV/A, is located sufficiently close to the Bevatron that the SuperHILAC may serve as its injector. This combination makes it possible to produce intense beams of many different ions at energies from .25 to 2.5 GeV/A.

Performance

The initial phase of Bevalac operation extended from the beginning of August 1974 through the first week of December 1974. During this time, no computer control of the accelerator components over and above the normal Bevatron functions was in operation.[2] The SuperHILAC was fully dedicated as an injector to the Bevatron, and its experimental program was held in abeyance during Bevalac operation. The program called for 56 hours of operation in a 2-1/2 day period every two weeks. Of the 56 hours, the first 12 to 16 hours were devoted to tune-up and optimization of all the beam control elements, and the final 40 to 44 hours to research or machine studies.

In this initial phase of operations, eleven periods of operation were scheduled for Bevalac operation, ten of which were successful. Beams of Carbon, Neon and Argon were accelerated. In addition, Alpha beams of high intensity, approaching 10^{10} particles per pulse can be produced using the modified 20 MeV injector linac in a $2\beta\lambda$ mode. Table I lists the important milestones of this first phase of Bevalac operation. These intensities do not represent the maximum that can be achieved with present source output.

TABLE I

Date	Particle	IPB**	EPB†	E(GeV/A)
8/1	$^{12}C^{+6}$	$1.3 \cdot 10^{9}$	10^{8}	2.1
8/10	$^{12}C^{+6}$		$5 \cdot 10^{8}$	2.1
3/12	$^{20}Ne^{+10}$		$1.5 \cdot 10^{8}$	2.1
9/2	Septum Magnet leak		Preinjector down	
9/19	$^{20}Ne^{+10}$	$2.5 \cdot 10^{9}$	3.10^{8}	.4
9/30	$^{40}A^{+18}$	$5 \cdot 10^{6}$	10^{6}	1.8
10/14	$^{20}Ne^{+10}$	$4.5 \cdot 10^{9}$	$2 \cdot 10^{8}$	.4
10/28	$^{40}A^{+18}$	$5.6 \cdot 10^{6}$	$1.1 \cdot 10^{6}$	1.8
11/11	$^{20}Ne^{+10}$	$3.0 \cdot 10^{9}$	$3.3 \cdot 10^{8}$	.4
11/19	$^{12}C^{+6}$	$6.7 \cdot 10^{9}$	$2.2 \cdot 10^{9}$	2.1
11/26	$^{20}Ne^{+10}$	$4.0 \cdot 10^{10}$	$8.0 \cdot 10^{8}$	.4

**IPB: Internal Particle Beam
† EPB: External Particle Beam

The second phase of Bevalac operation will begin in March 1975, with the computer-controlled time-sharing system in operation. In this mode of operation, the SuperHILAC will have two injectors, one serving the Bevalac with ions up to ^{40}A, and the other serving the SuperHILAC experimental program. In addition, all magnets in the Bevalac transfer line will be controlled and monitored from an operator console, rather than by set-point operation from the power supply knobs.

The beam intensity will increase as the limitations imposed by ion source are reduced. LBL has recently funded an in-house ion source development program aimed at increasing the intensity of all three heavy-ion accelerators in the Laboratory: the Bevalac, the 20 MeV Bevatron injector and the 88-in. Cyclotron.

Another intensity limitation occurs from the scattering of the circulating ions in the Bevatron by the residual gas molecules. The Bevatron cryopump[3] reduces the average pressure in the ring to $3 \cdot 10^{-7}$ Torr. For $^{40}A^{+18}$, the intensity is reduced by approximately a factor of two by charge exchange at the beginning of the acceleration in the ring. The effect of small angle Coulomb scattering on a background gas as heavy as nitrogen indicates that induced betatron amplitudes are small compared to the chamber dimensions and produce only a minor dilution of transverse phase space. There is a considerable uncertainty in the values of the

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charge-changing cross-sections at the energies of interest, and the observed losses, due to all possible mechanisms, are at least a factor of two larger than the calculated losses. The acceleration of $^{84}Kr^{+36}$ will be attempted shortly.

To accelerate ions much heavier than $^{40}A^{+18}$, the background pressure must be reduced. Currently under study is an inner vacuum chamber with cryogenic and Titanium sputter pumping that will reduce the base pressure to the 10^{-9} Torr region. Acceleration of very heavy ions such as ^{238}U; the acceleration of partially-stripped ions, thus lowering the minimum extraction energy; and studies of charge exchange cross-sections at high energies, then become possible.

Beam Monitoring

The most critical part of the beam transport system is the line leading from the poststripper exit to the entrance to the transfer line, a series of five dipole magnets with a total angle of 131°. Vertical slits and TV monitored viewing screens are placed at three locations along this line during tune-up. A simple Faraday cup, remotely operated from the control room, can be inserted after each magnet.

Beam is stripped at the SuperHILAC exit and only the fully stripped charge states are transmitted down the transfer line. For this reason we are greatly concerned with the efficiency of stripping foils at 8.5 MeV/A. The equilibrium charge state at this energy is close to Z up to Neon, but for Argon, only about half the ions are fully stripped. The stripper material is important, for we have observed higher 18+/17+ ratios with pure carbon (1.4) than with aluminum (0.5).

The stripping-foil current, a non-destructive type of monitor, allows the SuperHILAC and Bevatron operator to monitor performance on a pulse-to-pulse basis and importantly, gives pulse shape information. Another nondestructive monitor is a beam toroid developed especially for the heavy ion beam by J. Cuperus while at LBL on leave from CERN. It has a nickel iron core, and a sensitivity 25 nA.

The wide range of intensities of beams accelerated in the Bevalac required extension of the range of the monitors in the Bevatron. The Bevatron beam induction electrode (BIE) sensitivity has been improved by a redesign of the preamplifier system and by a reduction in its bandwidth with a heterodyne tracking narrow band amplifier. The signal-to-noise improvement of about 100 has enabled a beam of 10^6 charges to be observed. Improvements in the phase feedback system are being studied.[5]

The spill control during extraction is provided by a thin scintillator that the external particle beam passes through. Two photomultipliers view the scintillator: one is integrated and the other is counted, the integrated output used at higher beam intensities.

Monitoring of the heavy ion beams at the Bevalac for biomedical and nuclear science experimentation was originally achieved with primitive low-intensity beam locating devices. Most of these devices consisted of the already existing intrumentation for high-intensity proton monitoring and had limited application for the heavy ion intensities then available (10^4 to 10^8 charges/sec). Heavy ions, unlike protons, fragment into nuclei of smaller atomic number when passed through matter with a relatively high probability (σ_{frag} ~1 barn). An ideal monitor would have low mass and wide dynamic range, and be capable of providing spatial resolution and intensity information sufficient for tuning a magnetic channel.

Plastic scintillators viewed by TV cameras and secondary emission monitors (SEM's) were not sufficiently sensitive for the initial intensities available.

An inexpensive and portable image-intensified scintillator with video output was developed.[6] The sensitivity of the plastic scintillator plus the high gain of the intensifier tube (~10^5) allowed monitoring down to the 10^4 charges/sec-cm² level.

More recently beam current integrating multi-wire chambers have been installed in the external beams of the Bevalac.[7] The 0.05 mm Be-Cu signal wires of the chamber, arranged in two 32-wire orthogonal grids, provide horizontal and vertical beam profiles. The signal grids are sandwiched between three HV planes of 0.05 mm Be-Cu wire at a 1 mm spacing. Thin Kapton windows (0.08 mm) seal the chambers which are positioned in air gaps in the transfer lines. Chambers with 0.25 mm Aluminum windows are operated within the external beam vacuum pipe and are remotely positioned. The gas selected for operation in the ionization mode is Argon + CO_2, but for high gain (~10^5) proportional mode operation, a Charpak mixture is chosen. The nominal mass thickness of the chambers which remain in the beam line during experimental operation is less than 50 mg/cm².

A readout and display system capable of simultaneously handling output from 16 different chambers has been developed for Bevalac external beam monitoring. The converted analog x- and y- profiles are displayed on an x-y oscilloscope. Information from one chamber may be stored for sixteen consecutive beam pulses in an alternate mode of operation.

Operating at -3.5 kV and integrating for the duration of the external beam spill, the chambers and readout system are sensitive to 10^4 charges/sec. During full intensity proton operation, the chambers are operated at -300 V in the ionization mode. Relativistic beams of Carbon, Oxygen, Neon, Argon and a secondary $K^{\pm}$ beam have been successfully tuned and monitored with the system described here.

The biomedical experimental area deserves special mention. Heavy ion beams up to 1 GeV/A can be delivered to two experimental areas. An additional low intensity beam line, bent vertically through the shielding, will provide beams of up to 300 MeV/A for microscopic studies of radiation effects at the cellular level.

One external beam is focussed at a collimator in the biomedical beam line and delivered to the experimental area in Cave I, designated eventually for human radiotherapy. Another beam goes to Cave II for fundamental radiobiological and pre-therapeutic experiments. A switching magnet at the entrance to Cave II divides the beam into one of three channels. Two of the channels are equipped with precision optical benches for positioning samples for irradiation. Dosimetric devices and a digitally controlled variable water column are also situated on the optical benches. Large and small animal and tissue culture irradiations and experimental radiography are conducted in this cave.

Use of Facility

Heavy ions have been accelerated at the Bevatron since 1971 for the use of nuclear scientists and groups investigating biomedical effects of relativistic "multi-baryons". Prior to the inauguration of the

Bevalac in August, 1974, the quantity of ions available was small: representative numbers are 10^7 Carbon, 10^6 Oxygen, and 10^4 Neon ions per pulse. Such intensities were useful for some survey experiments and a very preliminary set of investigations into the life sciences.

The successful tests and performance of the Bevalac have led to a broadening of the scope of experimental proposals presented to our Program Advisory Committee. These proposals include experiments in nuclear physics which continue work begun here on fragmentation studies of heavy ions, experiments in nuclear chemistry involving isotope production by relativistic heavy ions, and life science studies including pre-clinical studies of the therapeutic effects of heavy-ion radiation in the treatment of certain types of cancers. These studies have now become possible because the Bevalac can provide Neon intensities, for example, which require only minutes of irradiation time for biological samples. Consequently, the disturbance to a biological system is minimal and restricted to the effects of the ionizing irradiation. Similarly in the nuclear sciences, the intensities now allow investigators to look for rare isotopes and decay products with expected half-lives on the order of 30 minutes in an environment where the signal-to-noise ratio is at least 1 or more. Experimental detectors have run the full range available to the experimenters: foils irradiated then subjected to counting techniques, emulsions, scintillator-photo-multipliers in spectrometers, and the Berkeley Streamer Chamber.

For these experiments some 306 operating hours were used in the last four months of the year. These hours are about 23% of the total operating schedule for the final six months of 1974 and represent an auspicious start to a program based on an accelerator system which came into existance in August, 1974.

The growth of the number of experiments is shown in Table II.

TABLE II - Monthly Distribution of Bevalac Experiments

Month	Group	No. of Experiments
August	Nuclear Science	1
	Biomedical	1
September	Nuclear Science	1
	Biomecial	4
October	Nuclear Science	4
	Biomedical	10
November	Nuclear Science	5
	Biomedical	17

An expansion of experimental facilities, particularly in the biomedical and radiological areas, is under way to accommodate this growing experimental program.

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