THE BEVALAC -- AN ECONOMICAL FACILITY FOR VERY ENERGETIC HEAVY PARTICLE RESEARCH *

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Summary

An economical means for the production of high energy, high intensity beams of a variety of heavy-ions is to utilize the existing LBL SuperHilac as an injector for the existing LBL Bevatron. Particle energies from 0.25 to 2.6 GeV/nucleon will be realized. The description of this facility, which will be in operation in late 1973, includes the general arrangements, the modest changes to each accelerator, beam transport line design, and a new bio-medical experimental area.

Introduction

The need for high energy heavy-ions in biomedical research was pointed out by Tobias et al. (1) long ago. Also cosmic ray physicists urged construction of a heavy ion facility. Two years ago, following the accelerator conference in Chicago, a proposal was made to inject heavy-ions from the SuperHilac into the Bevatron (5).

This year LBL will make available an intense source of high energy heavy-ions. Such particles will open up new research areas with a high promise of significant new contributions in nuclear physics and chemistry, in cosmic ray physics, particle physics, radiobiology and medical physics.

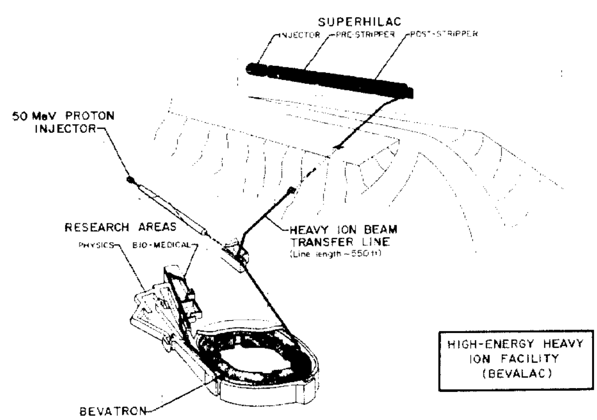

Fig. 1

A substantial research program with heavy-ions is presently underway at the Bevatron (2), but the intensity is restricted by limitations in the Injector Linac. Nearby is the LBL Hilac which in its improved version the Super-Hilac will make a very good heavy-ion injector. The combination of these two machines has been termed the Bevalac, Fig. 1. The expected particle variety, and their intensity is given in Fig. 2. The energy is variable from 0.25 to 2.6 GeV/u.

The great interest in high energy heavy-ions in the fields of radiobiology, radiation therapy and space medicine derives from the fact that ionization produced by highly charged particles is very dense and increases near the end of a well defined range. These properties make it possible to produce dense ionizations in well defined volumes of living tissue. The energy of the Bevalac will be sufficient to reach into any part of the human body. This will be a new and excellent tool for many important experiments and may lead to superior modes of radiation therapy.

This first phase of the Bevalac project, will be in operation by the end of 1973. It includes increasing the RF power of the Superhilac to yield 8.5 instead of 7.2 MeV/u, a 500 feet long beam transfer line, and modifications to the Bevatron including a Biomedical Experimental Facility. Thereafter time-share features will be incorporated into both machines to allow relatively rapid (1/2 hour) change-over in Energy or particle species. We expect that the heavy-ion program will absorb 1/4 to 1/2 of the total Bevatron operating time. The Superhilac is a very fast pulsing machine (40 pulses/second) compared to the Bevatron (10-17 pulses/minute). Only a very small part of its duty cycle (2-3%) is required for Bevalac injection. With time-share features the Superhilac Experimental program will be very little affected when serving as the Bevalac injector.

Super-Hilac Modifications

The performance of the Superhilac has been described in (3). Its energy is presently 7.2 MeV/u. This accelerator will deliver 5×10^{14} particles per second up to Neon (Mass 20) and 5×10^{12} particles per second of Krypton, (Mass 84) within an Emittance of π cm - m Rad. A energy spread of $\Delta E/E \leq 0.5\%$ FWHM is expected. Operation of the SuperHilac is in a pulsed mode with about 40 pulses per second and a 3-12 ms pulse duration. This represents a macrosopic duty cycle of up to 0.5.

The Superhilac post-stripper linac consists of six separate and individually excited RF cavities, which are used to produce the continously variable beam energy. Present RF equipment is adequate for only five of these cavities, producing a maximum energy of 7.2 MeV/u. To reach 8.5 MeV/u, which is necessary to efficiently fully strip the light ions up to mass 40, the final cavity will be powered. Equipment required for this project are: 1) an additional 0.8 MW amplifier, 2) its 0.1 MW driver, and 3) a series plate modulator, used to adjust the plate voltage of the amplifier from a 25 kV bus which is common to all of the RF amplifiers. Modest additional beam control and monitoring is also provided.

The Bevatron acceptancetime is 500 μ sec every 4 to 6 seconds. The SuperHilac is therefore very inefficiently utilized when operated exclusively as an

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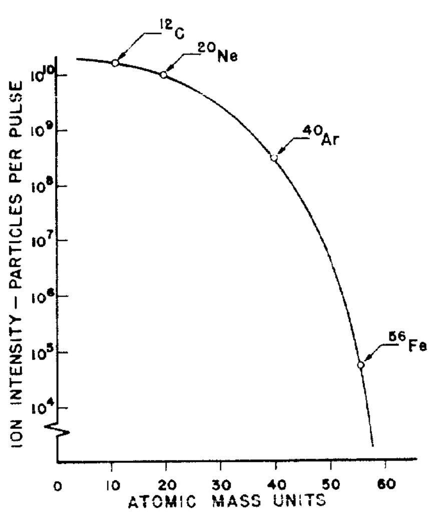
injector for the Bevatron. A portion of the Bevalac project therefore, is the modification of the Super-Hilac to provide for its operation in a time-shared mode. In this mode the accelerator will supply each second of lighter ions for injection into the Bevatron, and the remaining pulses of the heavier ions for Super-Hilac Experimental low energy research.

In the linac although the betatron oscillation frequencies and amplitudes differ substantially for different ions, stable transverse motions can be achieved for a wide range of charge-to-mass ratios (ε), with a single drift-tube focusing strength ($0.045 \lesssim \varepsilon \lesssim 0.20$ in the prestripper linac, and $0.16 \lesssim \varepsilon \lesssim 0.35$ in the postripper).

The operation of the linac on a pulse-to-pulse time-share basis requires the rapid adjustment of the electric gradients by as much as five to one and tuning of the phases. Pulsed magnets at the entrance to the prestripper linac inject particles alternately from one injector or from the other. Pulsed magnets at the exit of the post stripper-tank direct the particles to the appropriate transprot channel. In addition, since the betatron oscillations are different for different particles, pulsed dipoles and quadrupoles within the linac system will be required to match the accelerator emittances to each other, and to the different transport lines. The stored energy of these magnets, both dipoles and quadrupoles and the required rise time are both modest (8 - 40 joules and t = 8-10 ms).

In this mode of operation the linac is controlled essentially as two separate accelerators, and two control stations will be provided. Each of the two stations will be capable of monitoring certain common parameters, with special monitoring and controls sequenced to the appropriate control position at the appropriate times.



EXPECTED BEVALAC ION INTENSITIES
(FULLY STRIPPED IONS)

Fig. 2

Beam Transfer Line

The heavy-ion beam transfer line is an unconventional application of a conventional experimental area function -- unconventional in that, during the first 500 feet, the particles lose 141 feet of elevation while traversing a wooded hillside. Thereafter, they proceed another 300 feet horizontally in the 50 MeV proton injection transport line before entering the Bevatron. To remain non-interfering with a proposed future road, approximately 140 feet of the hillside line will be underground. The underground section is accommodated in a 3 feet diameter steel culvert pushed into place -- an economical procedure which also yields the least ecological disruption of the hillside. In terms of rigidity, fully stripped ions from the Superhilac are equivalent to a proton of 42 MeV kinetic energy. The transport line will match the emittance and momentum spread of the Superhilac, and will have achromatic bends of 20° at the top of the hill and 66° at the bottom. Average vacuum will be 10^{-6} torr to minimize electron recapture by the fully stripped ions. Beam position and intensity monitoring will normally operate in the 10^8 to 10^{12} ppp range, but will be effective down to 10^6 ppp.

The beam transport is based upon quadrupole doublets at 20 meter intervals. Where the line is underground, a double length free of magnets has been achieved by using a larger-aperture doublet; here the beam diameter reaches a maximum of 12 cm. The bend into the 50-MeV proton injection line contains two 33° bending magnets with a dispersion-recombining quadrupole triplet between them. The bend lies in an inclined plane but the matched beam is circularly symmetric at entrance and exit to permit a rotation of the principal axes. A final doublet matches to the 1 cm waist acceptance in the 50 MeV proton transport line.

Most focussing elements are existing 4" diameter quadrupoles. Bending magnets are of the tape-wound design recently developed at the Hilac (4). All magnets are supplied with close-fitting "all weather" enclosures.

Initial alignment requirements are not severe. Bending-magnets are positioned within 1 mm of the system centerline, quadrupoles within 2 mm and, in addition, the quadrupoles have a pointing accuracy of approximately 1 part in 2500. During operation beam position monitors and printed-circuit steering magnets greatly relieve demands on mechanical alignment precision. Initial alignment is accomplished using optical tooling on a line of sight external to the vacuum. External alignment promises the most reliable non-interfering means to check alignment during the project's operating life.

The vacuum line is principally thin-walled 8 inch diameter stainless steel pipe 35 feet between supports. This diameter is large with respect to particle beam size but accomodates the sag from long spans, decreases the positional sensitivity of those structures supporting only the vacuum pipe and improves vacuum pumping conductance. Four pumping station utilizing LN-trapped oil diffusion pumps provide the high vacuum.

Beam position detectors are provided at all focussing stations and consist of remotely-actuated, multiply-segmented Faraday cups. Conversion to digital form is done a the target and signals transmitted to control room computers for analysis and display.

Concrete shielding houses are used at each end of the line. Local shielding is used at other positions. An interlocked-access exclusion area is provided by a chain fence spaced 15 feet to either side of the transfer line. In addition BF_3 radiation detectors coupled to alarm circuits are provided at intervals along the beam line.

throughout the facility, e.g. the detectors of beam intensity and beam position will range from image-intensifiers ($\geqslant 10^4$ particles per spill), through ordinary scintillation counters over proportional chambers, to secondary emission monitors. A complete control of the ion-optical characteristics of the beam is important because most beam contamination has

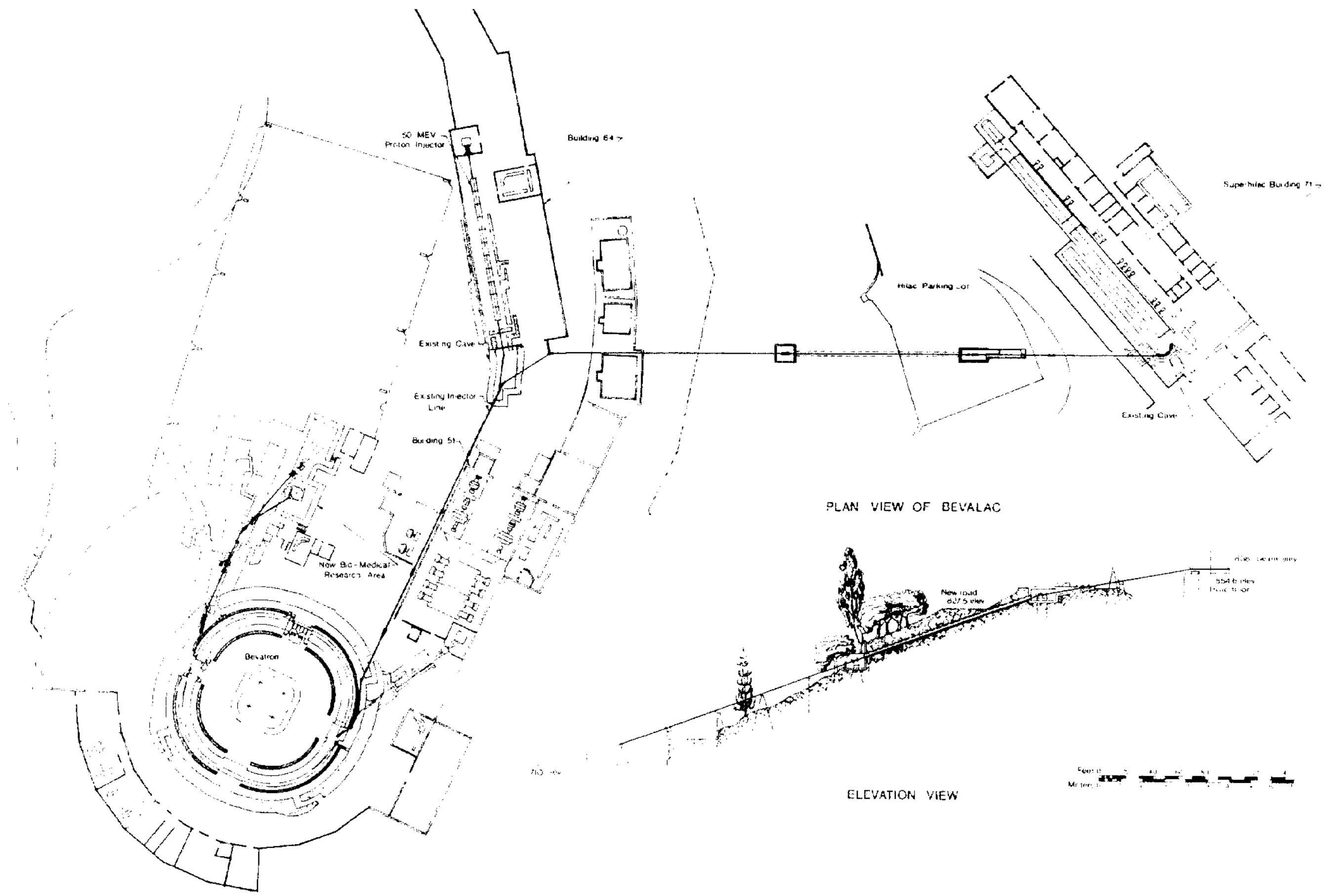


Fig. 3

Layout of Super-Hilac, Bevatron, and Beam Transfer Line

Bevatron Accelerator and Experimental Facilities

The acceleration cycle of the Bevatron for heavy ions is described elsewhere (2). With the intensities outlined in Fig. 2 no space charge problems are anticipated. Hence, improvements to the Bevatron proper are all in the direction of making this variable particle, variable-energy facility as flexible and reliable as possible for the experimenter.

The very diversified experimental program anticipated, not only demands for drastically different beam intensities (10 to 10^{10} particles per pulse), but also for widely differing spill characteristics. As a consequence various methods of beam spill, with an without feedback have been and will continue to be developed. The large dynamic range of machine parameters applies not only to extraction and spill characteristics; it is a major challenge

its orgin in fragmentation of the primary beam. A substantial computer control capability is the crucial factor for successful operation of such a diversified facility.

The Be alac is planned to operate in what is termed a "limited time sharing mode". This implies that changing from protons to heavy ions, or changing the heavy ion particle or energy, or target station shall be accomplished in a short time, e.g. 1/2 hr. This will be particularly important for the bio-medical experiments since these experiments demand long setup times but relatively short exposure times.

Experimental Facilities

Setups for physics and chemistry experiments using high energy heavy-ions differ insignificantly from those which have been used with the Bevatron in the past. However, the nature of most bio-medical experiments is sufficiently different from physics experiments to require the building of special experimental caves (Fig. 4). Shielding requirements are modest compared to those for high intensity proton beams. For the foreseeable future high intensity exposures are expected to be short. Specifications for the ion-optical properties of the ion beam lines require achromatic transport for sharp images. A good energy selection is required when fragmented beams are desired. The difficulty from an ion-optical viewpoint lies in the wide range of beam spot characteristics required. Irradiation fields of one square foot are not uncommon, whereas minimal spot size with sharp edges may have been required in the preceding experiment. The ideal bio-medical cave will evolve only as one gains experience in this exciting field.

As pre-clinical experiments are approached, and finally true therapy, a large number of auxiliary facilities will have to function together with the primary beam delivery. Fortunately LBL bio-medical personnel have a wealth of experience from the 184" treatment facility with which to expedite efficient use of this Bevalac facility.

Acknowledgements

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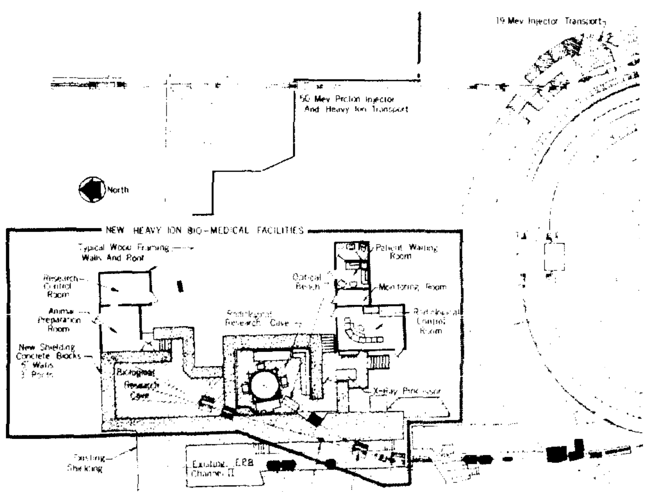

Plan of bio-medical research area

Fig. 4