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## Summary

High Energy Heavy-Ion Beams have become a standard operational feature of the Bevatron. A diversified experimental program using these beams complement the traditional proton-physics program, and at present accounts for about one-quarter of the Bevatron operation time. Beams of ion species up to mass number 20 (neon), and with intensities up to $10^8$ particles per pulse for carbon, are available on target in the extracted beam channel. Initial heavy-ion operation began a year-and-one-half ago and for the most part utilized existing Bevatron features and capabilities. Acceleration of ion species heavier than helium-ions, however, required the adaptation of a side-extracted PIG ion-source to the Bevatron pre-injector. The immediate success of this development effort and the concomitant demand for experimental beam time motivated an improvement program to provide higher beam intensities, improved beam control and monitoring, and closed-loop beam control for intensities as low as $10^6$ particles per pulse. Single particle beam dynamics has been invest igated. Predicted operation settings based on these studies are found to be close to actual running parameters. Losses due to recombination are well explained with existing theories for single electron capture.

## Introduction

In August 1971, the first high-energy heavy-ion beams were accelerated in the Bevatron.[1,2] Deuteron, alpha particle, and nitrogen beams were extracted at energies between 250 MeV/nucleon and 2.1 GeV/nucleon. Nitrogen ions were also accelerated to a total energy of 36 GeV, or about 2.57 GeV/nucleon. At 2.1 GeV/nucleon the intensity of the extracted deuteron beam was $10^{11}$ particles per pulse.

The remarkable success of this initial effort continued through a month of intensive experimentation and study. During this period Bevatron performance proved to be very stable. Reprogramming the elements of the injection, acceleration and extraction systems was easily and flexibly accomplished using existing conventional and digital control facilities.

Concurrent with the successful acceleration and extraction of heavy-ion beams, a program of measurements was begun to determine beam quality and characteristics, and to undertake preliminary experiments to establish a basis for a multi-diciplinary high-energy heavy-ion research program. Particle identification was accomplished by using a 9-element counter telescope consisting of lithium-drifted silicon detectors.[3] Pulse-height information from each detector was recorded on magnetic tape and processed initially by an on-line PDP-8 computer. The data was subsequently analyzed on the CDC-6600 computer, yielding charge, mass and energy information. Extracted beams were found to be ~95% pure. Background ions were determined to have the same rigidity, i.e., momentum per unit charge, as the primary beam and were the result of fragmentation of primary particles.

An immediate demand for experimental beam time confirmed predictions that heavy-ion beams would provide a new and heretofore unavailable tool for fundamental research. In the past $1\frac{1}{2}$ years a broad program of research emcompassing the fields of high-energy physics, astro-physics, nuclear chemistry, and biology and medicine has been carried out. The heavy-ion program has been integrated into the continuing proton physics program and now accounts for one-quarter of the operating time.

The following research programs are illustrative of the work that has been carried out or is in progress:

### High Energy Physics and Astro-Physics

- Heavy-Ion Total Cross-Section Measurements
- Heavy-Ion Fragmentation Studies
- Range and Ionization Studies
- Study of Coherent Production of π, K-mesons and Hyperons in Nucleus-Nucleus Collisions
- dp Backward Elastic Scattering
- Nuclear Fragmentation Induced by High-Energy Heavy-Ions
- Production and Study of a Mono-energetic Neutron Beam Tagged with Protons by Stripping High-energy Deuterons
- Emulsion Exposure - Study of Multiplicity of Pions, Gray and Black Track Producing Particles, Nucleon-Nucleon Cascades, Spallation of Target Nuclei, etc.
- Calibration of Particle Detection and Identification Systems which are to be used in Satellite and Balloon Flights.

### Bio-Medical Programs

- Ionization Studies in Tissue and Tissue Equivalents
- Bragg Curve Measurements in Biologically Equivalent Systems
- Linear Energy Transfer (LET) Measurements
- Oxygen Enhancement Ratio (OER) Measurements at the Peak of the Bragg Curve and on the Plateau
- Measurement of the Relative Biological Effectiveness (RBE) of Heavy Ion Beams
- Eye-Flash Studies with Human Subjects
- Study of Heavy-Ion Induced Retinal Damage in Animals Caused by Heavy-Ion Beams
- Study of the Response of Normal and Tumor Cells to Heavy-Ions
- Study of Abnormalities in Growth and Development of Biological Systems that have been exposed to Heavy-Ion Beams
- Study of the use of high-energy, separated, beam

of radioactive isotopes produced by fragmentation. Such beams may allow precise implantation of radioactive isotopes in a subject, without surgery

In high energy physics the experimental results to-date have demonstrated the importance of heavy-ion research programs in the understanding of nuclear interactions, with direct application in the fields of cosmic-ray research and high energy astrophysics.

In the field of biology and medicine, heavy-ion beams are providing valuable data which may lead to important applications in the fields of diagnosis and therapy.

During the past year a development and improvement program was completed to increase heavy-ion beam intensities and to provide more sophisticated beam control and monitoring. This program resulted in an increase by more than a factor of ten in the flux of carbon, nitrogen and oxygen ions. Beams of neon with modest intensity have also been accelerated (See Table I).

TABLE I

PRESENT INTENSITY WITH 20 MEV PROTON LINAC

| ION | Charge State in Linac | (Particles per Pulse on Target) |
|---|---|---|
| $^{1}H$ | +1 | $>10^{12}$ |
| $^{2}H$ | +1 | $2 \times 10^{11}$ |
| $^{3}He$ | +1 | $10^{11}$ |
| $^{4}He$ | +2 | $2 \times 10^{10}$ |
| $^{12}C$ | +4 | $1 \times 10^{8}$ |
| $^{14}N$ | +5 | $1 \times 10^{7}$ |
| $^{16}O$ | +5 | $1.5 \times 10^{7}$ |
| $^{20}Ne$ | +6 | $10^{5}$ |

## Ion Sources

The duoplasmatron used for proton operation was adaptable for the production of deuteron and alpha particle beams. However, it was unsuitable for the production of high charge states of heavier elements. Because of a practical limitation on the electric field gradient in the present 20 MeV Linac, it was necessary to provide an ion-source that would produce abundant quanties of ions with a charge to mass ratio $\epsilon/m \geq 1/3$. Hence, a side extracted PIG source of the cold cathode type, developed at the Berkeley Heavy Ion Linear Accelerator (HILAC), was adapted for use in the Bevatron Cockcroft-Walton preaccelerator (Fig. 1 and Fig. 2). The pulsed source magnet is powered by an 800 volt, 400 ampere power supply that utilizes an SCR switching bridge to discharge alternately two capacitor banks through the magnet. The duty cycle is 1 half-sine-wave-per-second with a rise time of 15 msec. Operating field is 400 gauss.

Arc power is provided by a dual supply with an adjustable triggering spike of 0-8 KV and a pulse line capability of 0-8 KV at 10 amperes. Operation at 10KW, at a duty cycle of $1 \times 10^{-3}$, gives 100 μamp of $O^{5+}$. The lifetime of the cathodes exceeds 500 hours after which cathode erosion causes sufficient arc instability to warrant cathode replacement.

To insure arc stability the extraction electrode is turned on 100 μsec after the arc is started. The extractor supply is rated at 40 KV at 10 mA and pulse rise time is 30 μsec.

The source beam travels through an arc of 105 degrees in order to maintain adequate horizontal focussing and beam separation. Vertical focussing is acheived by orienting the exit magnet pole tip 6 degrees from normal.

## Linac

Acceleration of heavy ions through the 20 MeV linac requires the linac to be operated in the 2βλ mode producing an ion velocity $\frac{1}{2}$ that of a 20 MeV proton. The kinetic energy of the accelerated ion is then 5 MeV/nucleon. Deuteron and alpha acceleration ($e/m = \frac{1}{2}$) is accomplished with approximately the same electric field gradient in the tank as for protons and with identical quadrupole magnet settings. For quintuply charged nitrogen ($e/m = 5/14$), the electric field gradient and the quadrupole currents must be increased by 40%. These values could be readily achieved. A practical limit for the linac field gradient, however, places a limit on the e/m of a particle to be accelerated at $\geq 0.3$. Thus to accelerate $Ne^{5+}$ a special "bake-in" is used. It was found that a sufficient gradient could be achieved by alternately pulsing the linac tank to high and low field levels. Under these conditions occasional spark-downs occur. In this event the spark is detected by a photo cell and the pulse line is crow-barred. The following pulse is sent to a dummy load to allow the linac vacuum to recover.

The linac is pumped by 5-vac-ion pumps with a pumping speed of 6000 liters/sec. The operating pressure is $3 \times 10^{-7}$ torr.

Operation of the linac in the 2βλ mode yields an overall transmission of 5%. This is a factor of ten less than the transmission in the 1βλ mode used for protons.

## Stripping and Monitoring of the Beam before Injection

Acceleration of particles in the Bevatron is restricted to fully stripped ions. The stripping cross-section for partially stripped ions is unacceptably high at the Bevatron vacuum of $3 \times 10^{-7}$ torr., and with the rate of rise of the Bevatron guidefield of 7.8 kG/sec. Thus a stripping foil at the exit of the linac is used to fully strip the ions before injection into the Bevatron. A foil wheel allows the selection of one of nine foils. A 50 $\mu g/cm^2$ aluminmum foil strips an $O^{5+}$ beam to $O^{8+}$ with an efficiency of about 35%.

Measurement of beam intensity and contamination is accomplished with foil absorbers, magnetic deflection, and a solid state silicon detector 1.5 mm thick and 1.0 cm in diameter. The detector can be swung through angles up to 40° to the line of the incident beam. Beam purity is optimized by observing the ion output of the linac using the beam monitoring system and a pulse-height-analyzer display while tuning the linac electric field gradient, the linac quadrupole currents and the source magnetic field. The contamination of a $Ne^{6+}$ beam with $O^{5+}$ and $N^{4+}$, for example, can be kept to less than 5%.

Figure 3 shows schematically the acceleration scheme for nitrogen.

## Acceleration in the Bevatron proper

As heavy-ions are injected at half the velocity of protons the RF acceleration frequency has to be lowered by a factor of two at injection for first harmonic operation. This capability was already built into the RF system. Trapping efficiency for first harmonic operation is somewhat above 10%.

After injection, the acceleration system assumes immediate control of the acceleration process. Ions are automatically guided through the acceleration process to the energy desired for extraction.

Production of high intensity beams of all ions is a natural goal for the Bevatron. However, it is necessary to have the capability to accelerate small quantities of ions because of experimental considerations, or simply because the injection yield of higher atomic number ions is low. Recognizing this constraint as a need for "open-loop" acceleration, the accelerator has been brought to the level of stability and precision required for that job. The accelerating frequency open-loop program to guide the ions from injection to extraction is also provided. Both machine stability and frequency program depend heavily upon the "multi-processor" control facility. This includes five mini-computers, each dedicated to a major facet of the accelerator environment.

## Magnetic Guide Field - Acceleration cycle

The magnetic guide field precision is $\pm 7 \times 10^{-5}$ of maximum field. This is nominally $\pm 1$ gauss. The guide field stability required during beam extraction is twice this precision, nominally $\pm \frac{1}{2}$ gauss. The computer responsible for the guide field control also provides the various pole-face-winding control signals. The windings modify and condition the guide field to the extent necessary for satisfactory injection, capture, and early acceleration of heavy ions.

## RF Acceleration Cycle

Injection and RF turn-on timing is provided by digital comparators, and a 0.01 gauss resolution digital-integrator. The internal beam monitors utilized to exercise control of the ion beam consists of a pair of induction electrodes. One is split diagonally to provide radial information. The second monitors the total beam. A phase detector compares induction electrode beam phase with RF accelerating electrode phase to correct beam phase error. The signal to noise ratio of the overall beam induction electrode system limits its closed-loop phase feedback system usefulness to $5 \times 10^7$ circulating charges. Noise equivalent to $5 \times 10^6$ charges is present and is accounted for by the thermal noise in the 125 Ohm signal transmission system.

Radial-position beam-control is achieved by a feed back servo-system. The radial induction electrode information is acquired by the computer responsible for acceleration. The software employs an algorithm to calculate the proper output signal to be sent to the master oscillator. Futher reference modifications, inserted by operators, are prescribed by particular operating modes. Radius is held within $\pm 0.05$ inches. The radial feedback system operates satisfactorily at beam levels as low as $5 \times 10^8$ charges.

## Learned Curve - Digital Control

All initial tuning of the accelerator for ions heavier than deuterium is done with helium ions. Intensities of $5 \times 10^{10}$ charges have been accelerated. All machine parameters are optimized for tracking and extraction. The entire set of parameters is then "memorized". For some data this means digital control word values are recorded on a rotating magnetic disc. For others, hard copy data logging is employed; but for the radial position control feedback system, the entire error signal curve is recorded in a peripheral core memory. The correction update frequency is 1 KHz. The total RF program is approximately 3.8 seconds duration, from injection to end of extraction. Thus, a 4 thousand word memory is required.

Once memorized, the entire acceleration process now moves to an open-loop condition. The recorded frequency-modulation program is "played-back" during an acceleration cycle. Performance is checked, to insure that closed vs. open loop operation is indistinguishable. At this point, conversion of the injector source to a heavier ion such as oxygen may be carried out.

The Bevatron will satisfactorily accelerate any of several ions with an e/m ratio of $\frac{1}{2}$, over an enormous dynamic range of intensities. This range will cover at least $10^1$ to $10^{12}$ particle per pulse. With the "learned-curve" facility, ion varieties and intensities may be changed frequently. It is only necessary to have, in memory, a learned-curve for each operating energy desired.

## Extraction

Heavy ions are extracted from the Bevatron using the normal resonant extraction system designed for protons. Preliminary tune-up of the system is done using alpha particles. The extraction system has been described in detail in previous reports [4, 5] and will only be briefly mentioned here.

The normal radial tune of the Bevatron has a $\nu r$ of 2/3 - 0.02. A perturbation magnet provides a $\nu$ shift of 0.02 to bring the beam into the 2/3 resonance for extraction.

Three modes of operation are used for spilling beam into the extraction system. In the first mode the spiller magnet current is programmed with a preset waveform to give the desired spill. This mode is used for beam-spills of about $3 \times 10^5$ particles or less. For higher intensity beam-spills the spiller current is controlled by a feedback circuit using a scintillator, photomultiplier, and integrator circuit. This closed-loop-feedback provides a more uniform beam spill as it substantially reduces the structure caused by power supply ripple on the main Bevatron magnet and the perturbation magnet.

As the energy of the extracted beam is lowered, both the vertical and horizontal beam sizes are larger because of less damping of the betatron oscillations. At about 250 MeV/nucleon, an energy typically used for bio-medical experimentation, the large radial beam size makes the normal mode of beam spill, using the spiller, very difficult. For this mode, better control of the resonant extraction has been achieved by moving the beam radially inward into the perturbation magnet with the spiller current off. This can be achieved either by rf or field tracking of the beam radius.

## Heavy-Ion Tuning and Monitoring

Heavy-ion beam intensities presently achievable at the Bevatron preclude conventional visual monitoring with a scintillator-vidicon device. However, visual monitoring of intensities as low as $10^4$ particle per second has been achieved with image-intensification. A 3/8" scintillator and cascaded 3-stage image intensifier (RCA 8606), viewed by a vidicon and capable of luminance gains of $10^5$, has been successfully used to monitor and tune a completely ionized oxygen beam. In addition, multi-wire proportional chambers operated in the charge-integrating mode have been successfully employed to produce two dimensional beam profiles for tuning purposes. In areas inaccessible to either the image intensifier or the multi-wire proportional chambers, direct exposure of Polaroid film has been employed.

Future plans include monitoring stations consisting of two digitized multi-wire proportional chambers with adequate resolution to measure angular divergences of the order of one milliradian. Beam tuning of low intensity heavy-ion beams will be accomplished by measuring and displaying the appropriate beam profiles and emittance ellipses using the position-angle co-ordinates of individual beam particles. At higher intensities the chamber will be operated in the charge-integrating mode.

## Conclusion

The first step has been taken to provide the research community with a flexible high-energy heavy-ion accelerator. This goal has been achieved. The Bevatron, therefore, again occupies a unique position among high energy facilities. A vigorous, multidisciplinary research program has developed spontaneously around the heavy-ion capability and is competing for research time.

The spectrum of beams available for experimental use has been vastly expanded with the addition of heavy-ion primary beams. Secondary beams produced by fragmentation of primary ions provides beams of all isotopes of every element with a mass lower than the parent element. Thus, with magnetic separation, a very wide choice of stable and unstable beam particles is available.

Preliminary bio-medical investigations have demonstrated a very favorable Bragg Peak for heavy-ions at tissue depths suitable for radio-therapy. The biological effectiveness of these beams for treatment of tumor tissue surrounded by normal tissue is very promising.

At the present time we are very encouraged and are looking forward to the Bevalac[6] project, which will extend the capability of the facility to mass species as high as calcium, and will provide substantially higher beam intensities.

The Bevatron will continue to maintain a flexible operational and development posture and will encourage the development of the broadest possible experimental program.

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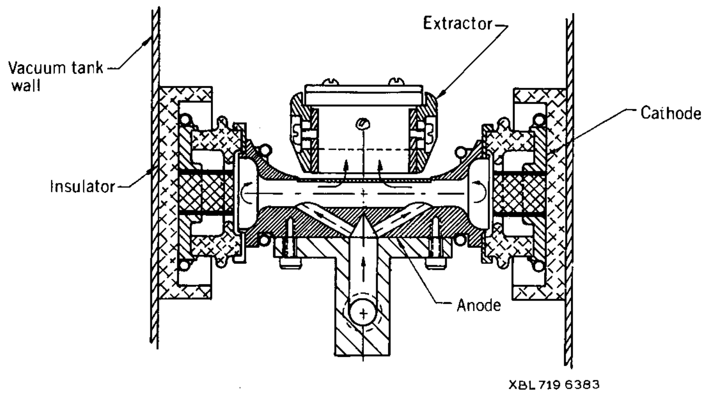

Fig. 1 Side Extracted, cold cathode PIG-Source

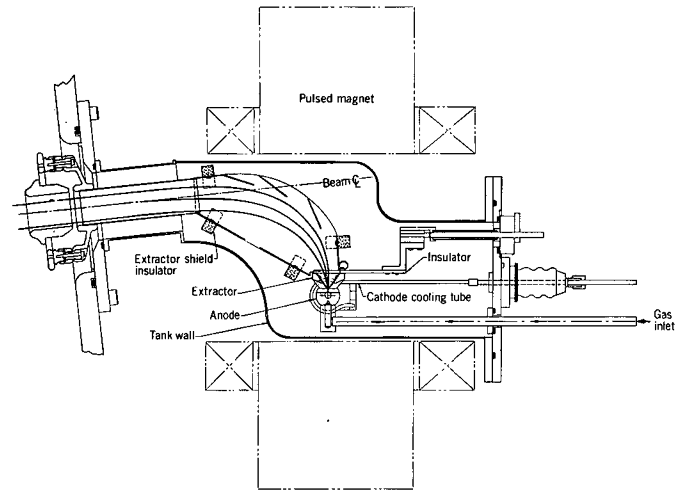

Fig. 2 PIG Source Assembly

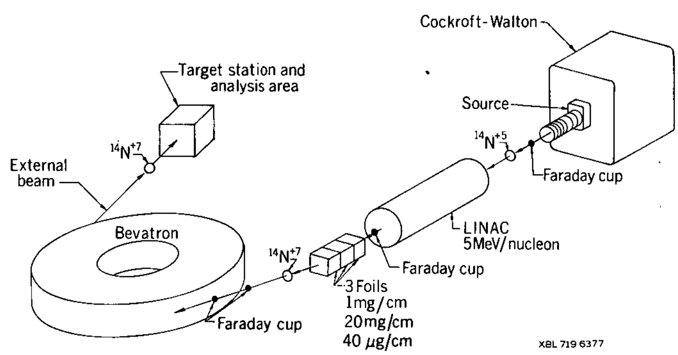

Fig. 3 Schematic layout of the acceleration scheme for nitrogen.

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