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OPERATIONAL EXPERIENCE WITH HEAVY IONS AT BNL: AN UPDATE*

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Summary

Since May, 1986, the heavy ion transfer line (HITL) which joins the Tandem Van de Graaff facility and the AGS at Brookhaven National Laboratory has permitted the acceleration of heavy ions (up to sulfur) to 14.5 GeV/nucleon.[1-3] The Tandem, operating with a pulsed ion source, supplies a fully stripped ion beam at about 7 MeV/nucleon which is transported via the HITL to the AGS. A low frequency rf system accelerates the beam in the AGS to about 200 MeV/nucleon and the high frequency rf system, normally used for proton acceleration, completes the acceleration to 14.5 GeV/nucleon. The high energy ion beams are delivered to four experimental beam lines using standard resonant extraction. Following is an update of the performance and operational characteristics associated with the production, transport, and acceleration of these ion beams.

History

A brief history of the heavy ion effort at BNL is given in Table I. The runs through November, 1986, have been discussed in References 1-3. Here we shall focus on the runs after November, 1986.

Table I

Run	Comments
5/86	First O^{8+} beam from HITL injected and spiralled in AGS.
7/86	Low frequency rf system accelerates O^{8+} in AGS to 200 MeV/nucleon.
10/86 11/86	O^{8+} accelerated to full energy of 14.5 GeV/nucleon, extracted, and delivered to experimenters. Si^{14+} at 6.7 MeV/nucleon successfully transferred from Tandem to AGS.
3/87 4/87	Si^{14+} beam commissioned and delivered to experimenters at 14.5 GeV/nucleon.
11/87 12/87	Si^{14+} delivered to experimenters at 14.5 GeV/nucleon.
6/88	O^{8+} delivered to experimenters at 14.5 GeV/nucleon.
12/88	Si^{14+} delivered to experimenters at 14.5 GeV/nucleon.

Sources, Tandem, and Transfer Line

The oxygen beam (O^-) from a high intensity pulsed negative ion source[4] is injected into an upgraded Model MP Van de Graaff accelerator,[5] MP7, and with the configuration of foils shown in Figure 1, fully stripped oxygen (O^{8+}) at 7 MeV/nucleon is produced for further acceleration in the AGS. The O^- source has produced up to 4 x 10^{11} negative ions per pulse (125 particle μA for 500 μsec) and has produced over 10^6 pulses over a six-week period without any maintenance. Fully stripped oxygen ion currents of up to 125 μA have been delivered to the AGS. During the oxygen run of June, 1988, O^{8+} currents of 100 μA or more were delivered to the AGS for better than 90% of the time.

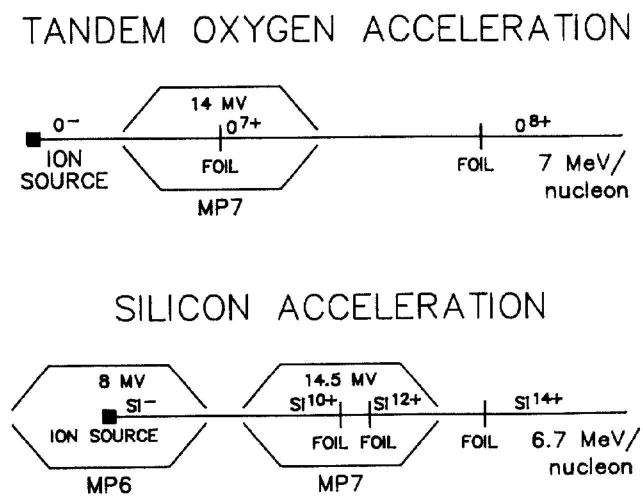

Figure 1. Tandem operating modes during heavy ion operation.

To obtain fully stripped ions heavier than oxygen, two MP accelerators must be used. For the case of silicon acceleration, a high intensity pulsed sputter ion source is installed in the terminal of a second MP tandem, MP6, and with the configuration of tandems and foils shown in Figure 1, fully stripped silicon (Si^{14+}) at 6.7 MeV/nucleon is produced. The Si^- source has produced up to 70 μA of Si^- with pulse width of 200-400 μsec. Fully stripped silicon ion currents of up to 25 μA have been delivered to the AGS. During the silicon run of December, 1988, Si^{14+} currents of 20 μA or more were delivered to the AGS for better than 90% of the time.

The 640 meter long HITL joining the Tandem and the AGS contains two long straight sections which use quadrupole doublets in a point-to-point focusing scheme, and three major bending sections which are achromatic in the horizontal plane. Special quadrupole configurations near the Tandem and the AGS provide optimal matching into the transport line and into the AGS. Beam profile monitors (harps) and Faraday cups[6] can be inserted pneumatically. The vacuum maintained by passive distributed getter pumps[7] in conjunction with a few small ion pumps, is better than 10^{-9} Torr throughout the line.

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AGS Injection

Standard positive ion multiturn injection with a dc electrostatic septum bends the injected beam through an angle of 9.2 degrees and onto a distorted equilibrium orbit. Two dipoles spaced one-half betatron wavelength apart generate the local orbit distortion (bump) and are programmed to decrease to zero field during the injection process. This permits the circulating beam to miss the septum on successive turns. The efficiency of this process is sensitive to the horizontal tune, and operational experience has determined that a tune of 8.8 with the bump falling to zero over 14 turns (300 μsec) yields the most acceptance. Nominally, 12 turns of the ~ 1π mm-mr O^{8+} or ~ 2π mm-mr Si^{14+} beams from the transfer line are stacked in the AGS with an estimated efficiency of approximately 50%.

The circulating beam intensity was below the threshold necessary to obtain orbit information via the normal pick-up electrode system. A few high gain pick-ups were deployed around the ring permitting first-turn survival observation and injection stacking and tune measurements. It was found that emperical tuning of the horizontal eighth and ninth orbit harmonics yielded significant improvements in the accelerated beam intensity. Additionally, any programmatic changes in the main magnet cycle, and therefore remnant field, forced retuning of the injection orbit.

Acceleration

Normal proton acceleration at the AGS is accomplished using a ten cavity rf system which sweeps from 2.5 MHz to 4.5 MHz. The time variation of the frequency is obtained from the accelerating bunches ("bootstrap"); phase and radial control also are derived from beam signals. To accommodate the wider frequency swing and lower intensities associated with heavy ion acceleration, new low level and high level rf systems were built.[8,9] The basic frequency program for this new system is derived solely from a measure of the ramping AGS magnetic field. A single rf cavity covers the early acceleration from 500 kHz to 2.5 MHz at which point the cavities of the normal proton system take over. The low level rf drive for the low frequency range can come only from the new frequency program. For the high frequency part of the acceleration cycle, the low level drive can be obtained either from the new program or from the old bootstrap system. Operationally, the bootstrap low level has controlled this frequency range.

Injection occurs with the two gaps of the low frequency cavity at their maximum voltage of 6.5 kV each. The rate of change of magnetic field is 0.92 Gauss/ms and remains at this value until after the hand off to the high frequency cavities. Capture efficiency was not sharply sensitive to these parameters. Fine tuning of the acceleration frequency relative to table values was allowed using an analog function added to the program output. This proved valuable for rapidly optimizing the frequency program. The same effect could then be duplicated by changes in the function describing the calibration of the magnetic field measuring device.

Successful acceleration required the closing of a phase loop comparing the output phase of the programmed frequency generator against the beam bunch phase and adjusting the output frequency appropriately. Without this, beam intensity would gradually disappear over the first 50 ms of acceleration. Capture efficiency was sensitive to details of the timing, gain, and frequency response of the phase loop. A radial loop was not used on the low frequency system.

In order to transfer acceleration from the single low frequency cavity to the ten high frequency cavities the latter had to be tuned to the "hand-off" frequency. This tuning is accomplished using a coarse main tuning current, programmed from the rf frequency, identical for all cavities. Ten vernier currents which servo on forward and reverse power from each cavity, require a voltage in the cavities such that the high frequency system would dominate the low frequency system. Therefore, for light ion acceleration, the vernier corrections cannot be applied until the cavities are in control of the beam. The peak voltage available to a circulating particle increased drastically at handoff, from two gaps of 7 kV each to 40 gaps of 3 kV each over about 1 ms. Handoff efficiency which was close to 100% was not extremely sensitive to this ratio. Presented with a prebunched beam, the bootstrap easily assumed control; a single phase shift adjustment in that circuitry allowed bucket phase matching. Once over to this system, lossless acceleration to full field occurred with the standard rf manipulations for transition passage and extraction debunching. Normal resonant extraction at a horizontal tune of eight and two-thirds completed the cycle. The performance characteristics of the AGS heavy ion program are summarized in Table II.

Table II

AGS Heavy Ion Program System Performance

	O^{8+}	Si^{14+}
Tandem Output Energy	6.7 MeV/ nucleon	6.7 MeV/ nucleon
Typical Pulse Width	250 μsec	250 μsec
Current after final stripping and chopping	145 μA	30 μA
HITL Efficiency	86%	75%
AGS Injection/Capture Efficiency	30%	30%
AGS Acceleration Efficiency	60%	60%
AGS Intensity	$4x10^9$ ions/ pulse	$4x10^8$ ions/ pulse
AGS Energy	14.5 GeV/ nucleon	14.5 GeV/ nucleon

Having achieved this operational mode of acceleration, the next objective was to accelerate through the entire frequency range under the control of the field-generated frequency program of the new low level rf. The motivation here is to reduce or eliminate dependence on beam-generated signals and hence on some minimum beam intensity. By rather crude adjustments of the frequency program, large radial excursions which otherwise destroyed the beam could be contained. Ultimately, transition was survived and full acceleration achieved, but only after tedious tuning which is expected to be sensitive to the magnetic field program. Acceleration on the new system was accomplished both with and without a radial loop, but the phase loop remained essential. In the future, it is planned to add a reference signal proportional to the stable phase angle, derived from the measured rate of change of the magnetic field and the gap voltage. This should reduce the need for the phase loop and reduce the radial excursions.

Beam to Experiments

The experimental program comprised experiments with intensity requirements ranging from 10^9 ions/spill to 10^4 ions/spill with the majority of experiments at the lower intensity range. This required providing ~ 0.01% of the beam to a typical experiment while maintaining reasonable beam purity.

The oxygen and silicon beams were delivered to the experiments using the proton transport system. The AGS switchyard incorporates a series of electrostatic splitters and thin-septum magnets enabling the delivery of beam to four primary beam lines simultaneously. This system was used to adjust the accepted beam intensity in a particular beam line to 2-100% of that extracted, depending on the experimental requirement. The transport optics were then adjusted to provide a large, defocused beam spot (~ 2.5 cm x 2.5 cm) on a small aperture collimator. Chosen collimator apertures ranged from 0.22 to 0.025 cm. The acceptance into the external beam lines was only crudely measured, yielding an upper limit of 0.15 mm-mr vertically and horizontally. The beam was then focused on a momentum-defining slit, using point-to-point imaging to provide elimination of projectile fragments from the first stage collimator. The remaining transport optics were tuned to match experimental requirements.

Beam intensities of 10^4-10^5 ions/spill were below the sensitivity limit of the instrumentation used for tuning proton beams. Proportional wire chambers with new, higher sensitivity electronics were used to provide profiles of the transported beam. Further work on this instrumentation will include vacuum compatible, plunging actuators to minimize beam contamination.

A beam spot of dimension 2 mm vertical and 3 mm horizontal was provided to Experiment 802,[10] which measured a beam purity of approximately 99%. Figure 2 shows a typical pulse height plot obtained at an intensity of ~ 2 x 10^4 silicon ions/spill.

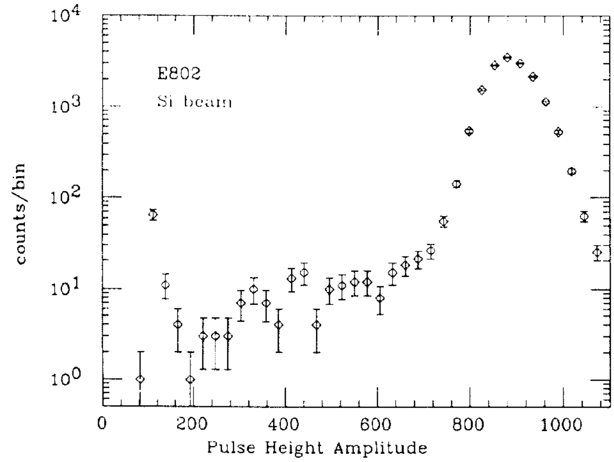

Figure 2. Pulse height plot for E-802 Si beam.

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10. AGS Experiment 802 is a collaboration of Argonne, Brookhaven, Columbia, Hiroshima, LBL, MIT, Tokyo, and UC Riverside.