# OPERATIONAL EXPERIENCE WITH LIGHT IONS AT BNL*

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## Summary

A new transfer line has joined the Tandem Van de Graaff facility and the AGS at Brookhaven National Laboratory, permitting the acceleration of light ions (up to sulfur) to 14.5 Gev/nucleon [1]. The Tandem, operating with a pulsed ion source, supplies a fully stripped ion beam at about 7 Mev/nucleon to the AGS. A new low frequency rf system accelerates the beam in the AGS to about 200 Mev/nucleon. The previously existing rf system completes the cycle. High energy ion beams are delivered using standard resonant extraction to four experimental beam lines. Details of techniques and preliminary performance and operational characteristics are discussed.

## Tandem and Transfer Line

Beams from a high intensity pulsed negative ion source system [2] accelerated in one of the upgraded Model MP Van de Graaff accelerators [3], MP-7, were used to deliver fully stripped 7 Mev/nucleon oxygen ions for further acceleration in the AGS. The long term performance and reliability of this system were demonstrated by producing up to $4\times10^{11}$ negative oxygen ions per pulse (125 particle µamps for 500 µsec), and maintaining operation for over $10^6$ pulses over a six week period without any ion source maintenance. Fully stripped oxygen ion currents of up to 90 µamps were delivered to the AGS for better than 90% of the time.

The beam transport system joining the Tandem and the AGS was installed in a new 640 meter long tunnel. Each of three major bending sections is achromatic in the horizontal plane and the long straight sections comprise a simple doublet line with point-to-point focusing. Beam profile monitors (harps) and Faraday cups [4] can be inserted pneumatically. Special lens configurations near the Tandem and the AGS provide optimal matching into the transport line and into the AGS. The vacuum, maintained by passive distributed getter pumps [5] in conjunction with a few small ion pumps, is better than $10^{-9}$ Torr throughout the line.

To obtain fully stripped ions heavier than oxygen, both MP accelerators must be used. For this purpose, a high intensity pulsed sputter ion source was installed in the terminal of a second MP Tandem, MP-6, (see Fig. 1). This source has delivered intensities of up to $4\times10^{11}$ negative silicon ions per pulse (100 particle µamps for 600 µsec) for more than $10^5$ pulses at 8 MeV/nucleon. An eight hour effort in Nov. 1986 resulted in a beam intensity of $6\times10^9$ fully stripped 6.7 Mev/nucleon silicon ions per pulse at the AGS.

## 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 1/2 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 2π mm-mr O(8+) beam from the transfer line is stacked in the AGS with an overall efficiency of approximately 50%.

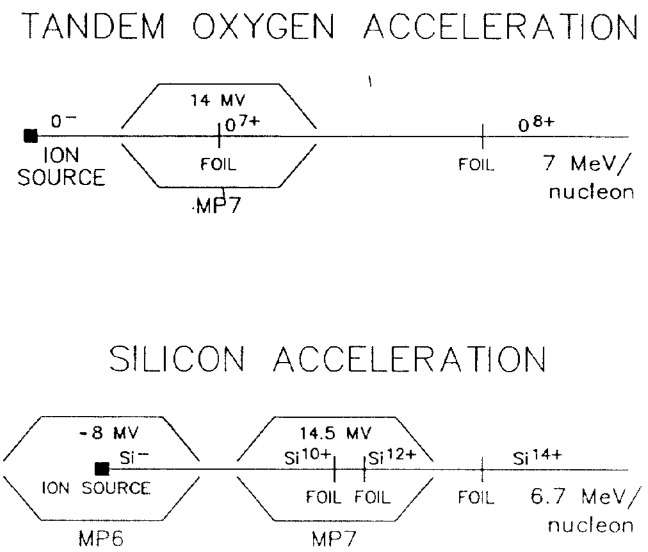

Fig. 1. Tandem operating modes during light ion operation

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 10 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 accomodate the wider frequency swing and lower intensities associated with light ion acceleration new low level and high level rf systems were built [6,7]. 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 .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

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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 10 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 light ion program are summarized in Table 1.

Table 1
AGS Light Ion Program
System Performance*

| | O(8+) | Si(14+) |
|---|---|---|
| Source Current | 100 uA | 100 uA |
| Pulse Width | 250 μsec | 250 μsec |
| Tandem Mode | 2-stage | 3-stage |
| Tandem Eff. (incl. stripping) | 12.5 % | 3.2 % |
| Tandem Output Energy | 7.0 MeV/ nucleon | 6.7 MeV/ nucleon |
| AGS Injection Eff. | ~50 % | ~30 % (est.) |
| AGS Capture Eff. | ~10 % | ~10 % (est.) |
| Beam-Gas Survival | ~100 % (est.) | ~60 % (est.) |
| AGS Intensity | $5\times10^8$ ions/ pulse | $2\times10^8$ ions/ pulse (est.) |
| AGS Energy | 14.5 GeV/ nucleon | 14.5 GeV/ nucleon |

*estimates for Silicon operation not yet confirmed

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. The average extracted intensity of $5\times10^8$ ions/spill therefore required providing 0.01% of the beam to a typical experiment while maintaining reasonable beam purity.

The oxygen beam was delivered to the experiments using the proton transport system. The AGS switch-yard 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 [8], which measured a beam purity of approximately 99%. These measurements were made at an intensity of ~$10^4$ ions/spill.

## References

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