AGS Heavy Ion Operation with the New Booster*

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Abstract

The AGS Complex has completed its second year of operation with heavy ion beams injected from the Booster for fixed-target research. The booster accepts Au^{33+} ions at about $1\,MeV/nucleon$ from the Tandem Van der Graaff and accelerates them to a final energy of about $192\,MeV/nucleon$. The extracted Au^{33+} beam is stripped to Au^{77+} before injection into the AGS. Substantial experience has been gained in the areas of injection, acceleration, vacuum, and stripping processes. Deliberately introduced coupling during injection resulted in 50% more beam and a much smaller emittance. A second rf system, for low frequency operation, reduced the vacuum losses and the number of harmonics switches required. Efficiency of stripping of Au^{33+} into Au^{77+} and various final charge states have been performed as a function of Au^{33+} final energy. At the end of the 1993 running period, the maximum intensity achieved in the AGS was about 3×10^8 nuclei-per-pulse (NPP) of Au^{77+} at a kinetic energy of $10.2\,GeV/nucleon$. In the fall of 1995, a new fast extraction system and beam transport line for RHIC injection will be commissioned. The plan for raising intensity and reducing emittance for RHIC injection will also be presented.

1 INTRODUCTION

1993 was the second year that Gold beams have been accelerated to $10.2\,GeV/nucleon$ kinetic energy at BNL. The results of the previous 1992 running period are described in ref. [1]. The Gold beam is being used for fixed target experiments to study relativistic heavy ion collisions. In the future Gold beams will be accelerated in the Relativistic Heavy Ion Collider (RHIC) to $100\,GeV/nucleon$ to study Gold on Gold collisions at a center-of-mass energy of $200\,GeV/nucleon$. For both programs it is important to achieve high Gold beam intensities. The collider program requires in addition small beam emittances. The acceleration of Gold beams has been made possible by the completion of the AGS Booster with its ultra-high vacuum that allows the acceleration of the only partially stripped Gold ions.

In section 2 the results of the 1993 Gold running period which included studies in preparation for delivering Gold beams to RHIC will be described . Section 3 describes plans for the future upgrades to increase intensity and reduce the beam emittance. The AGS Booster is also an essential tool for the high intensity proton operation for fixed target experiments such as rare Kaon decay studies. Section 4 summarized the results of the most recent very successful efforts to increase the proton beam intensity. Finally in section 5, the recent successful first test of a Partial Siberian Snake in the AGS to preserve the polarization of a proton beam is reported.

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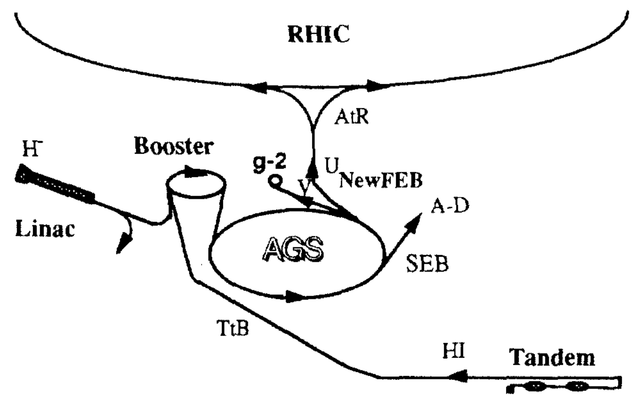

Figure 1: Schematic layout of the AGS/RHIC accelerator complex.

2 ACCELERATION OF GOLD BEAMS IN 1993

A schematic layout of the AGS/RHIC accelerator complex is shown in fig.1. The acceleration scheme used in 1993 consisted of stripping the Au^{14+} from the Tandem accelerator to Au^{33+} before injection into the AGS Booster at a kinetic energy of $1\,MeV/nucleon$. The beam was extracted from the Booster with a kinetic energy of $192\,MeV/nucleon$ and then stripped to Au^{77+} and injected into the AGS. In the AGS, the Gold beam was accelerated to a kinetic energy of $10.2\,GeV/nucleon$ and slow-extracted for the fixed target experiments.

The sequence of acceleration and stripping was chosen to minimize beam losses from charge exchange processes with residual gas. For Gold ions with a significant number of electrons left, the losses are dominated by electron stripping at the lowest energies and by electron pick-up

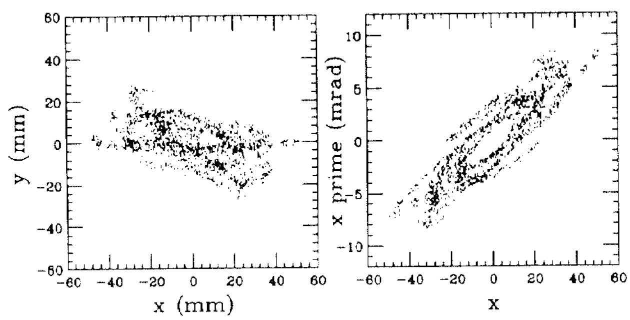

Figure 2: Simulation of the beam spot of the circulating Gold beam for unperturbed tunes $\nu_x^o = 4.833$, $\nu_y^o = 4.780$, and skew quadrupole induced tune splitting $\Delta\nu_{SQ} = 0.054$ after injection is complete.

otherwise. The requirements, imposed by these charge exchange processes, have to be balanced with the stripping efficiencies that can be achieved in stripping foils located between the acceleration stages.

The Tandem accelerator delivers a Gold beam with very small transverse emittance which allows a very efficient multi-turn phase space painting scheme for injection into the Booster. The injection scheme was extended into the vertical plane by purposely running the Booster with significant X-Y coupling during injection. This allowed phase space painting in both horizontal and vertical planes. The optimum parameters during the 1993 run were found for unperturbed tunes (without coupling) of $\nu_x^o = 4.833$ and $\nu_y^o = 4.780$ and a skew quadrupole induced tune splitting of $\Delta\nu_{SQ} = 0.054$. The splitting of the unperturbed tunes

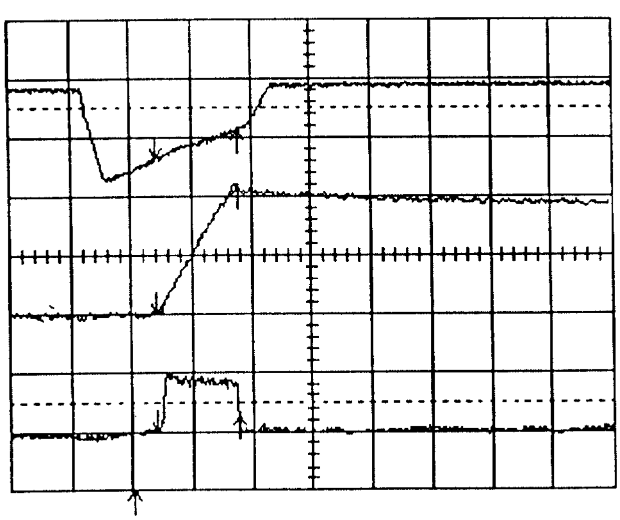

Figure 3: Scope traces of the injection kicker (top), the circulating beam current (middle), and the beam pulse from the Tandem (bottom) during injection. One horizontal box corresponds to $500\,\mu s$.

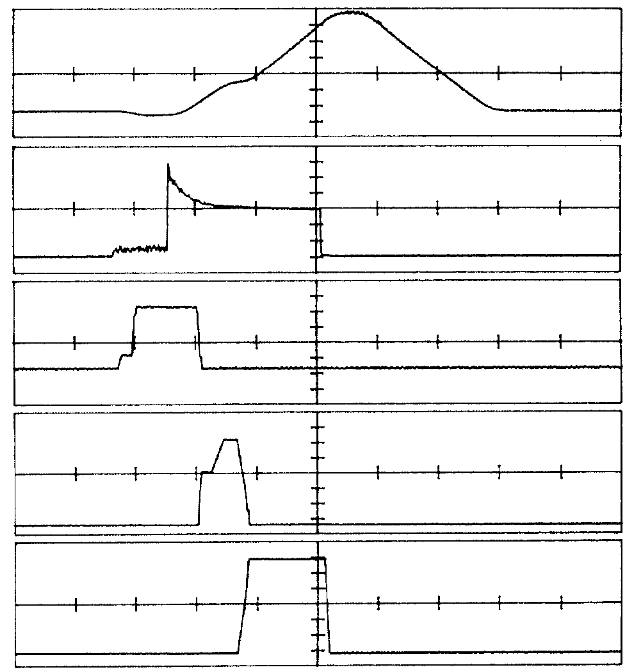

Figure 4: Rf program for acceleration in Booster. From top to bottom the Booster main magnet cycle, the circulating beam current, and the excitation of the 'low frequency' (harmonic number $h = 12$), the first ($h = 12$) and second ($h = 6$) 'high frequency' cavity are shown. The time divisions are $0.5\,s$.

approximately adjusted the aspect ration of the circulating beam to the aspect ration of the Booster acceptance. Fig.2 shows the result of a simulation of the injection process for the same tune and coupling parameters used during the run. Fig.3 shows oscilloscope traces of the injection kicker, the circulating beam current and the beam pulse from the Tandem during injection. Typically about 40 turns were injected with an efficiency of 65%.

The revolution frequency in the Booster swings from $69\,kHz$ to $830\,kHz$. To cover this large frequency range two sets of cavities and two harmonic numbers were used. The time sequence for the rf program is shown in figure 4. The beam is adiabatically captured at the harmonic number 12 using counter phasing between the two 'low frequency' cavities. At one third of the way through the acceleration cycle, one of the 'high frequency' cavities takes over at the same harmonic number 12. After this cavity reaches its frequency limit the harmonic number is changed to 6 by coalescing two bunches into one using the second 'high frequency' cavity at half frequency. The beam is then accelerated to extraction at harmonic number 6.

The beam loss at the beginning of the Booster acceleration cycle is significant. Even at the ultra-high vacuum level of $3 \times 10^{-11}\,Torr$ in the Booster, at least some of the loss can be attributed to charge exchange reactions with the residual gas which, for Au^{33+}, is dominated by electron

Where	Ion	$p[\frac{GeV/c}{nuc.}]$	$\epsilon^{hor.}_{N,95\%}[\mu m]$	$\epsilon^{vert.}_{N,95\%}[\mu m]$	$\epsilon^{long.}[\frac{eVs}{nuc.\ bunch}]$	Particle Int.[NPP]
Tandem	Au^{33+}	0.04	0.05π	0.05π		11.5×10^8
Booster inj.	Au^{33+}	0.04	5.5π	3.3π	0.02	7.5×10^8
Booster extr.	Au^{33+}	0.63	4.0π	5.0π	0.025	6.3×10^8
AGS inj.	Au^{77+}	0.63	14π	14π	0.45	3.6×10^8
AGS extr.	Au^{77+}	11.1	17π	15π	1.00	3.0×10^8
RHIC design	Au^{79+}	11.5	10π	10π	0.30	30×10^8

Table 1: Summary of beam parameters of the 1993 Gold running period. The longitudinal emittance in the AGS was purposely increased to facilitate slow beam extraction for the fixed target program.

stripping even at low energy[2].

The Gold beam is extracted from the Booster at a kinetic energy of 192 $MeV/nucleon$ and then passes through a 56 $\frac{mg}{cm^2}$ thick Carbon stripping foil to be stripped to Au^{77+}. The thickness of the Carbon foil was chosen to give the maximum yield of Au^{77+} ions. Fig. 5 shows the horizontal beam profile after the foil and two beam transport dipole magnets. The beam profiles were measured with a multi-wire profile monitor. The various charge states are clearly visible giving a Au^{77+} yield of about 65%.

After transfer into the AGS the beam, which occupies a quarter of the AGS circumference, was debunched and then adiabatically recaptured with harmonic number 12. This was required by the available frequency range of the AGS rf system but also significantly reduced the high frequency structure of the slow-extracted beam.

Table 1 summarizes the main beam parameters for the 1993 running period. For the slow-extracted beam program, controlling the transverse emittance growth was not of primary concern. The observed increase of the transverse emittance between the Booster and the AGS was due to both beam blow-up in the stripping foil and also injection mismatch in the AGS. The longitudinal emittance was purposely increased to improve slow beam extraction.

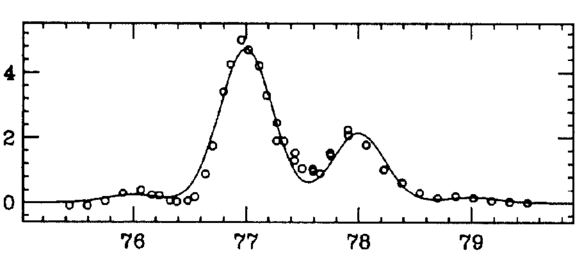

Figure 5: Horizontal beam profile downstream of the 56 $\frac{mg}{cm^2}$ thick Carbon stripping foil. The horizontal units were determined to reflect the charge states of the peaks[2]. The solid line is a fit to the data consisting of multiple equally spaced gaussians profiles.

3 FUTURE UPGRADES

For the operation of the AGS as RHIC injector the emittance growth needs to be limited to the values listed at the bottom of table 1. The transverse emittance growth between the Booster and the AGS will be reduced by carefully focusing the beam at the stripping foil and controlling the injection errors into the AGS for which a digital wideband transverse damper is available[3].

In a separate study it was shown that a small longitudinal emittance can be maintained throughout the acceleration cycle for low intensity Au^{77+} beam. However, at higher intensity significant emittance growth at transition, probably due to space charge, was observed. With the recently commissioned transition "jump" system[4] it should be possible to avoid emittance growth from transition crossing.

The beam intensity can be increased six fold at Booster injection by eliminating the low energy stripping foil between the Tandem and the Booster, injecting Au^{14+} di-

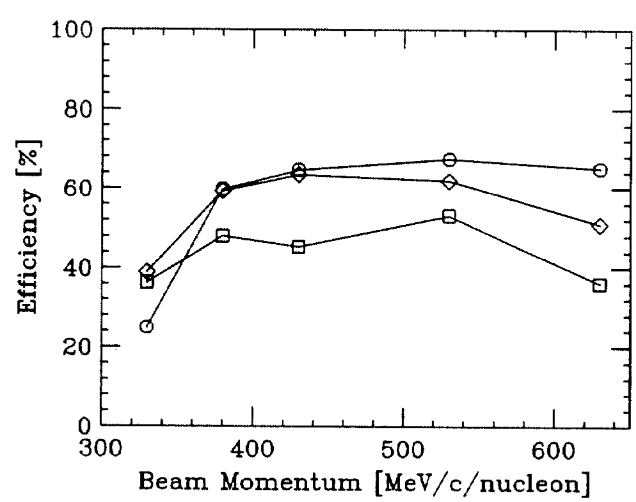

Figure 6: Stripping efficiencies in percent as a function of beam momentum for Carbon foils with a thickness of 56 $\frac{mg}{cm^2}$ (circle), 27 $\frac{mg}{cm^2}$ (diamond), and 18 $\frac{mg}{cm^2}$ (square), respectively.

rectly into the Booster. In addition, the elimination of the stripping foil between the Tandem and the Booster will reduce the transverse emittance at the Booster injection, which can improve the efficiency of the coupled multi-turn injection process. However, the lower charge state at Booster injection increases the cross section for electron stripping. Studies using the Au^{33+} beam indicate that the Booster vacuum may need to be improved to take full advantage of Au^{14+} injection into the Booster. Also, the higher rigidity of the Au^{14+} beam reduces the Booster extraction momentum to $330\,MeV/c/nucleon$. The lower beam momentum has two consequences: First, the pulse length of the extraction kicker system of the Booster needs to be doubled. Secondly, at this lower momentum the stripping efficiencies to Au^{77+} become marginal and the stripping foil material and thickness has to be chosen carefully. A detailed set of measurements have been performed with the Au^{33+} beam at lower extraction momentum and various materials and thicknesses of stripping foils. As fig. 6 shows a careful choice of the stripping foil can still give adequate yield of Au^{77+}. Overall, a net intensity increase of about a factor of four can be expected from the Au^{14+} injection into the Booster. A first test of this scheme will take place this fall.

Up to twice the total charge per beam pulse could be delivered by the Tandem during the 1993 run. However, the lifetime of the foil in the Tandem terminal was drastically reduced. New foil holders with a higher capacity will alleviate this problem in the future.

The combined intensity gains of the upgrades should allow us to reach the required intensity for RHIC operation. In the fall of 1995, a new fast extraction system in the AGS and a beam transport line will be commissioned for RHIC injection.

4 HIGH INTENSITY PROTON RUNNING

For high intensity proton running, four beam pulses are accelerated in the Booster to $1.5\,GeV$ kinetic energy and injected into the AGS with a repetition rate of $7.5\,Hz$. Average Booster extraction intensities in excess of the design value of 1.5×10^{13} protons per cycle have been achieved with a peak value of 1.75×10^{13}. To reach these high intensities many second and third order stop bands had to be carefully corrected[5].

This year, an upgrade of the AGS rf system[6] and a transition "jump" system were completed and successfully commissioned. With these new systems on line, the intensity of the proton beam accelerated in the AGS to $24\,GeV$ and slow-extracted to fixed target experiments was increased significantly to more than 3.7×10^{13} protons per pulse as of this writing. The details of this effort is described elsewhere[4]. The beam intensity increase achieved this year and the further increase to 6×10^{13} protons per pulse planned for next year are well matched to the recent upgrades in the capacity of the extraction beam lines and the 6 target stations and are driven by the increasing demands of the fixed target experiments.

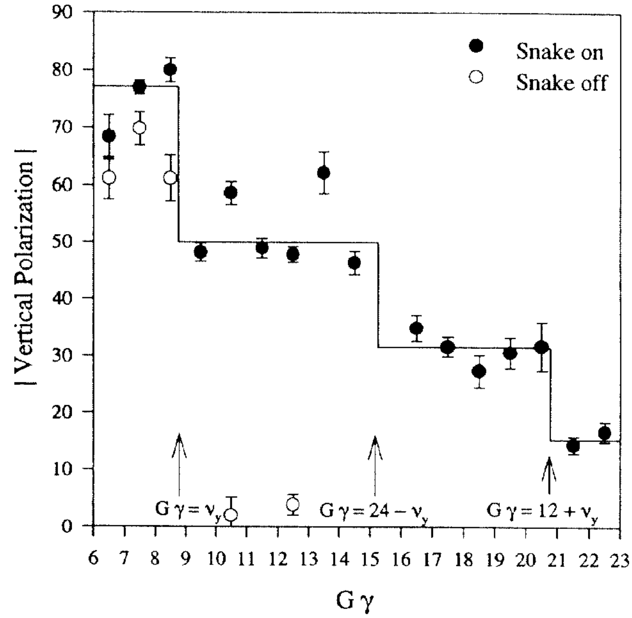

Figure 7: Absolute value of the vertical polarization as a function of $G\gamma$. Note that partial depolarization is due to intrinsic spin resonances at $G\gamma = \nu_y, 24 - \nu_y$, and $12 + \nu_y$.

5 POLARIZED PROTON ACCELERATION

During acceleration of polarized protons in circular accelerators, the polarization may be lost when the spin precession frequency passes through a depolarizing resonance. These resonances occur when the number of spin precession rotations per revolution $G\gamma$ ($G = 1.793$ is the anomalous magnetic moment of the proton, $\gamma = \frac{E}{m}$) is equal to an integer (imperfection resonances) or equal to $kP \pm \nu_y$ (intrinsic resonances). Here $P = 12$ is the superperiodicity of the AGS, $\nu_y = 8.8$ is the vertical betatron tune and k is an integer. The depolarization is caused by the small horizontal magnetic fields present in all ring accelerators which, at the resonance condition, act coherently to move the spin away from the stable vertical direction. Traditionally, the depolarizing resonances in the AGS were corrected by the tedious harmonic correction method for the imperfection resonances and the tune jump method for the intrinsic resonances[7].

The experiment E-880 at the AGS has recently demonstrated the feasibility of polarized proton acceleration using a local 9° solenoidal spin rotator, also called a 5% partial Siberian Snake[8, 9] in reference to a full Siberian Snake, which rotates the spin by 180°. A 5% Snake is sufficient to avoid depolarization due to the imperfection resonances without using the harmonic correction method. Figure 7 shows that depolarization is limited to the intrinsic resonances which can be overcome in the future with the proven tune jump method. At 25 GeV, the polarized protons will be transferred to RHIC, opening up the possibility for a 250 GeV on 250 GeV polarized proton collider.

6 CONCLUSIONS AND ACKNOWLEDGMENT

The delivery of 10.2 $GeV/nucleon$ Gold beam has now become a reliable component of the AGS program serving several fixed target relativistic heavy ion experiments. The AGS with the Booster is also breaking new ground accelerating very high intensity and polarized proton beams. This successful program was only possible due to the dedicated effort of the entire staff of the AGS Department.

7 REFERENCES

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