# BUNCH-TO-BUCKET INJECTION OF LINAC BEAM INTO THE BROOKHAVEN AGS*

J.M. Brennan, L.Ahrens, J. Kats
AGS Department, Brookhaven National Laboratory
Associated Universities, Inc., Upton, NY 11973 USA

## Summary

A new fast beam chopper has been used to study injection and capture in the AGS. The chopper[1,2] is a fast beam switch with 10 ns rise and fall times that can be programmed on a bunch-by-bunch basis and is synchronized to the net accelerating voltage of the synchrotron, thus allowing bunch-to-bucket injection of the 200 MeV $H^-$ linac beam. The studies so far have concentrated on simple injection scenarios, at reduced intensity, where longitudinal effects are well separated from transverse. The evolution of the pre-bunched beam during the transition from injection to acceleration has been examined. Results have shown the importance of the detailed linac beam energy distribution. The ability to control the longitudinal emittance of the beam with the fast chopper has been used in other machine studies. This report includes a description of a measurement of the longitudinal coupling impedance of the AGS by the beam transfer function technique which utilized the control of longitudinal emittance provided by bunch-to-bucket injection. Plans for improvements to the chopper equipment are also described.

## Introduction

Efficiency of acceleration in the AGS typically exceeds 90%, even at the highest intensities of 1.9 x $10^{13}$ particles per pulse. The efficiency of utilization of the linac beam, by contrast, is much lower, on the order of 60%. This is due in part to the fact that the continuous beam from the linac must be bunched into the phase-stable region of the rf wave before it can be successfully accelerated. But it is also due to other strong effects that are active at injection, such as, betatron stacking of the charge-changing $H^-$ beam and space charge-dependent tune shifts. These effects interact strongly. For example, the amplitude of the radial excursions due to synchrotron motion adds with the amplitude of the betatron motion and uses up the available horizontal aperture. Also, the bunch length, which is determined by the details of the rf capture process, affects the charge density in the beam which in turn determines the space charge tune shift. In the AGS, the situation is complicated still further by the rising magnetic field during injection.[3] The field increases by 0.5 T/s, shrinking the average radius of the equilibrium orbit of the 200 MeV linac beam by 3.5 cm/ms. Because the betatron and synchrotron motions give the beam a large horizontal size, an unaccelerated beam spirals into the inside aperture in about 1 ms. The total amount of beam that can be injected and accelerated through the first few milliseconds of the cycle is determined by the competition of these diverse effects.

One way to clarify our understanding of the injection and capture process is to take direct control of the bunch structure of the beam before it is injected. The fast chopper was built for this purpose and its capabilities include extensive control of the detailed time structure of the beam. In fact, each leading and trailing edge of the bunches to be injected can be independently programmed with respect to the phase of the net rf voltage in the synchrotron. Because the rise and fall times of the bunch edges are 10 ns or less, good definition of the initial population of longitudinal phase space is possible.

Beyond just eliminating rf capture losses, injection of pre-bunched beam has other benefits. The presence of time structure on the beam enables the beam position pick-ups to function on the first turn. A precise determination of the revolution frequency (linac beam energy) can be made with the rf voltage turned off. The total effective rf voltage can be determined from the frequency of the synchrotron motion of a single injected bunch. The longitudinal emittance can be controlled independently of intensity. And, ultimately, the shape of the longitudinal phase space distribution function can be manipulated by painting the beam into phase space.

Several machine studies experiments in the AGS have been performed utilizing the benefits of the chopped beam. So far the goal of painting experiments has been to try to achieve no-painting by eliminating incidential painting from mis-matched phase, frequency, or bucket shape. The benefits of painting would be hard to quantify before the less subtle determinates of injection and capture efficiency are understood. Some experiments have used a low longitudinal emittance beam to study the longitudinal coupling impedance of the machine at the energy at which the Booster beam will be injected.[4] The machine studies experiments, performance of the chopper, and plans for future improvements are described in this report.

## Injection Experiments

The intent in these experiments was to exercise an injection strategy on a simple well-defined machine, avoiding, at this stage, the subtle and non-linear effects that arise at high intensity. Although the results of the experiments should be predictable, the exercise builds a foundation for a systematic attack on the problem of clean injection at high intensity. The main difference between a simple and a high intensity injection is the intentional painting of longitudinal and transverse phase space to make the beam physically big. We chose to turn off painting and forgo the advantage of low charge density in favor of working aperture. Even for high intensity there must be an optimum compromise between these effects, and one would like to turn painting on in a controlled fashion to obtain the optimum. In the horizontal coordinate, painting was turned off by holding the equilibrium orbit on the stripping foil with ramped local orbit bumps that compensate the rise in the main bending field. During 350 microsec of injection (73 turns) the equilibrium orbit moved in by 12 mm. It is important that the beam is not accelerated during injection, otherwise the linac beam at the end of

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injection would be below the equilibrium momentum and have a large betatron amplitude.

The rf frequency was set to create a stationary bucket[2] (df/dt = 0.7 kHz/ms) during injection and for 1 ms after. The rf voltage during injection was low so that the bucket height was comparable to the beam's energy spread. During the 1 ms after injection, the rf voltage was raised to the maximum available (280 kV). The ramp up comprised six synchrotron periods at the full voltage. The rate of change of frequency then changed to the value needed to make a moving bucket to hold the radius constant (33 kHz/ms). The quasi-adiabatic rise in voltage should shorten the bunches enough that when the bucket shrinks as the phase angle changes, all particles remain in the bucket. The radial motion during the 1 ms of voltage rise in the stationary bucket is excessive, however, so the dB/dt was reduced by a factor of two for these experiments.

The results are shown in Figure 1, which are mountain range displays of a longitudinal pick-up signal. Figure 1a shows the injected beam stacking and some bunch compression as the voltage rises. The injected bunch occupied 90° of phase and was carefully centered in the bucket by adjusting the rf frequency and the chopper phase. A large coherent motion of the bunch in the bucket can be seen. The origin of this coherent motion was pursued. One likely explanation is a phase perturbation in the rf cavities when voltage is increased due to a level dependance of the tuning of the cavities. However, this type of coherent oscillation should be strongly damped when the phase loop of the beam control system is engaged. Figure 1b shows the behavior after the phase loop has been switched on. A good deal of coherent motion remains even with the phase loop working. Striving to understand the cause of this residual coherence led to an examination of the linac beam.

(a) (b)

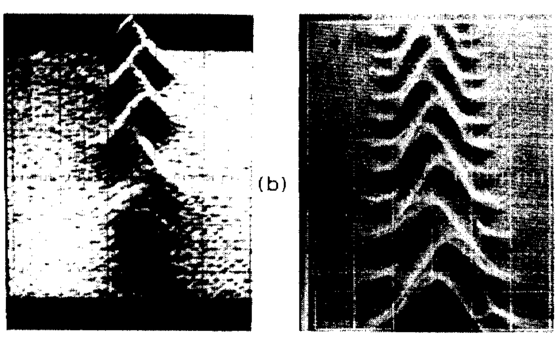

Fig. 1. Mountain range displays of longitudinal pick-up at injection. Left, first 1 ms, stacking and begining of voltage rise, 100 ns/div. Right, after phase loop on, 50 ns/div.

## Analysis of Linac Beam

The chopper controls the time structure of the linac beam but the distribution in the energy variable is also relevant to matching to the rf bucket. Measuring the energy distribution is more difficult than the time distribution. One can look at the spatial distribution after a dispersive bend but this is invariably obscured by the transverse emittance. Fortunately, chopped injection provides a means for examining the energy distribution. When a single bunch is injected into the bucket, its synchrotron motion will rotate the energy coordinate into the time coordinate in 1/4 of a synchrotron period. If the bunch is as short as $\pm 45°$ the motion will be essentially linear. The total effective rf voltage must be known but this is self-calibrating because the synchrotron period is easily determined from the bunch shape oscillations and this fixes the rf voltage.

(a) (b)

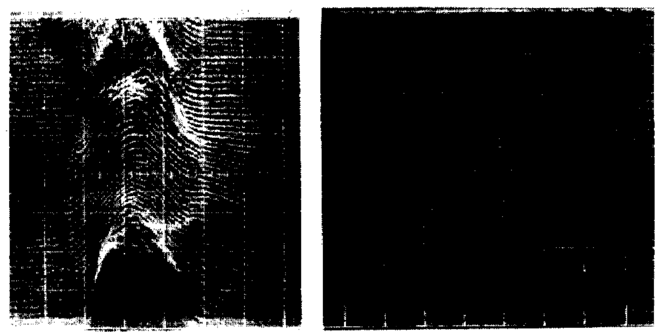

Fig. 2. Evolution of one bunch injected into:
(a) a matched bucket, 50 ns/div
(b) a high voltage bucket, 20 ns/div.

Figure 2 shows two mountain range photos of a single bunch injected into matched bucket, 2a, and into a high voltage bucket, 2b. One can see a structure on the bunch in 2a which shows that the energy distribution is not symmetric. By injecting into a high voltage bucket, the bunch stays in the linear part of the bucket and gives a clear picture of the energy distribution. Figure 3 is a single trace measurement of a bunch at just 1/4 synchrotron period from injection. The measurement was made with the LeCroy 7200 digital oscilloscope. This plot gives a detailed picture of the energy distribution in the linac beam. The horizontal axis is equivalent to 0.4 MeV/Division, with low energy on the right.

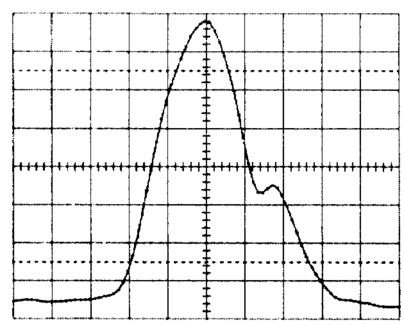

Fig. 3. Linac beam energy distribution, revealed in time distribution at 1/4 synchrotron period. Horizontal scale is 0.4 MeV/div.

Two conclusions were drawn from this and similar measurements. The energy spread in the linac beam is $\pm 1.1$ MeV, 2.7 times larger than previously assumed, and the detailed structure of the distribution can be changed completely by changing the phase at which the RFQ output beam is injected into the linac. Figure 2b is a case where the shoulder has been moved from the low to the high energy side of the distribution by changing this phase.

## Application of Low Emittance Beam to Z/n Measurement

The chopper was used to produce a low emittance beam for a measurement of the longitudinal coupling impedance of the AGS at 2.25 GeV/c on a 1 second flattop. The technique was to observe the shift in the phase oscillation frequency of the coherent quadrupole mode as a function of beam intensity.[5] The frequency shift was determined from the bunched beam transfer function of the quadrupole mode. Figure 4 shows the phase of two transfer functions at different intensities (bottom = 4.2 x $10^{10}$, top = 16 x $10^{10}$ particles/bunch), measured with a HP3562A Dynamic Signal Analyzer. The quadrupole mode was stimulated by modulating the rf voltage with wideband noise centered around twice the synchrotron frequency. The beam response was obtained from a detection of the peak signal of the longitudinal pick-up. The transfer function was the ratio of the detected beam signal to the detected rf voltage.

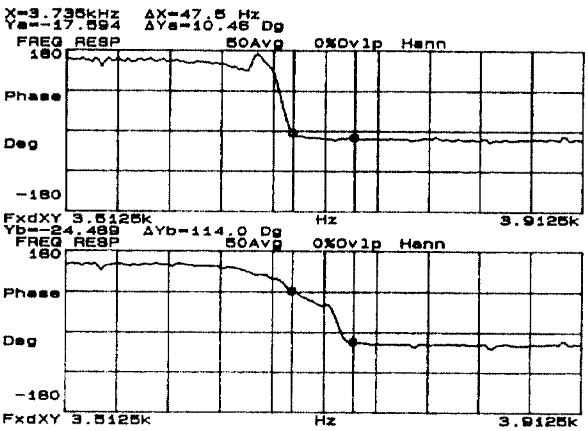


Fig. 4. The phase of the bunched beam transfer function for the coherent quadrupole mode. Top, high intensity. Bottom, low intensity.

The frequency at which the phase of the transfer function has changed by 180° is the frequency of the incoherent quadrupole mode. This frequency is related to the coupling impedance, Z/n, by the relation,[6]

$$f_q = 2f_o \left[1 - \frac{3I}{\pi^2 V_o h} \left(\frac{2\pi R}{\ell}\right)^3 Z/n\right]^{1/2}$$

where: $f_q$ is the incoherent quadrupole mode frequency, $f_o$ is the synchrotron frequency at zero intensity, I is the beam current per bunch, h is the harmonic number, $V_o$ is rf amplitude, R is the average radius of the orbit, and $\ell$ is the bunch length. The $\ell^{-3}$ dependence of the effect is the reason the low emittance beam was necessary for the measurement. By injecting 90° bunches it was possible to achieve a longitudinal emittance of 0.3 eV·s, compared to 1.0 eV·s that is obtained with injection of continuous beam. The bunch length difference between these two cases, 13 m and 25 m, implies a factor of 7 enhancement in the effect and makes the sensitivity of the measurement practical, Figure 4. By measuring transfer functions at 5 intensities between 0.38 and 2.3 x $10^{12}$ particles in 12 bunches, a Z/n of 157 Ohms was obtained.

## Chopper Performance and Future Improvements

The chopper produces the desired time structure on the beam with good definition of the edges and stable phase relation to the rf bucket voltage. The phase reference is taken from a vector sum of gap voltages of all 10 accelerating stations. The sum voltage is amplified to a fixed level in a chain of Plessy SL532C low phase shift limiting amplifiers. The rejection of unwanted beam between pulses is greater than 99%.

The commercial Digital Delay Generator that stores the detailed pulse program has never worked reliably. All the experiments carried out so far have been done with fixed edges of the bunches throughout the injection. A new DDG was designed and built in-house that has given reliable performance in tests. The in-house DDG uses a commercial iLBX 150 ns memory board that feeds data to two pair of Analog Devices AD9501 digital delay chips. The memory board resides in a Multibus backplane and interfaces directly to a standard device controller of the computer control system. The pairs of delay chips interlace control of alternating pulses. One member of each pair controls a leading edge and the other controls a trailing edge. When one pair is timing a given pulse the other is being loaded with new data. In this way there is zero deadtime between pulses. A persistent "on" state can be made by extending a trailing edge beyond the leading edge of the subsequent pulse. A pulse is inhibited by making the trailing edge precede the leading edge.

The chief shortcoming of the chopper is its interaction with the transverse optics of the 35 keV $H^-$ beam, on which it operates. Even though the voltage of the chopper is zero when the beam is switched on, it still affects the tune of the transport optics because the beam is space charge neutralized by ionization of the residual gas. When the chopper is in operation, the neutralizing ions are affected and the line must be retuned. The consequence of this is a reduction in the peak beam intensity available that is proportional to the time the beam is off between bunches. The reduction is approximately 20% at a 75% duty factor and 60% at a 25% duty factor. Operationally it is a disadvantage to require a special tune of the line for chopper operation.

Because the chopper will be part of standard operations with the new Booster, these deficiencies are deemed unsatisfactory. A new chopper is under construction that will operate between the 750 keV RFQ and the linac. The beam there is essentially unneutralized, because it is bunched at 200 MHz, so there should be no interaction between the chopper and the transport optics. The same drive electronics will be used for the new chopper. The new chopper will be roughly twice as long with half the separation between deflecting plates. The main difference from the 35 keV chopper is that the rejection slits where the deflected beam is stopped will be located right at the optical waist. This has an advantage of approximately a factor of five over the 35 keV case where this is not possible because there the waist is inside the RFQ.

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## References

1. J.M. Brennan, et al., Proceedings EPAC, Rome 1003 (1988).
2. J.M. Brennan, et al., Proc. 1989 IEEE Part. Accel. Conf. (Catalog No. 89CH2669-0), 1154
3. E. Raka, et al., IEEE Trans. Nucl. Sci. NS-32, 3110 (1985).
4. E. B. Forsyth and Y.Y. Lee, Proc. 1987 IEEE Part. Accel. Conf. (Catalog No. 87CH2387-9), 867
5. D. Boussard, et al., CERN Int. Rep. PS/OP/LR/Note 80-16, 1980.
6. S. Hansen, et al., IEEE Trans. Nucl. Sci. NS-22, 1381 (1975).