

## CHARGE EXCHANGE INJECTION AT THE AGS\*

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### Summary

The AGS has been brought into operation in October 1982 with multi-turn  $H^-$  charge exchange injection. The injection area of the AGS has been modified to bring the  $H^-$  beam from the 200 MeV linac through the main magnet fringe field to a stripping foil located within the magnet aperture. The injection system is described in detail and initial performance of the accelerator is reported.

### Introduction

Charge exchange injection, as an alternative to the traditional multiturn process, has been discussed for more than two decades. In this scheme, a beam of  $H^-$  ions is brought onto the closed orbit of the accelerator, where a proton beam is created by stripping of the electrons. One of the earliest suggestions for this mode of injection was attributed to M.G. White with regard to transferring beam from a synchrotron to a storage ring.<sup>1</sup> A more detailed discussion was presented by Budker and Dimov in 1963.<sup>2</sup> This method has been used successfully at the Argonne ZGS<sup>3</sup> and in the Fermilab booster.<sup>4</sup>  $H^-$  injection was first proposed for the Brookhaven AGS in 1972 by A. Maschke et al.<sup>5</sup>  $H^-$  ion source studies for this project began in 1980 and conversion took place during the summer shutdown last year.<sup>6</sup>

For conventional multiturn  $H^+$  injection at the AGS, the linac was required to deliver typically 70 mA of beam for a duration of 100  $\mu$ s. This provided nominally for 20 turns in the machine, but inflector septum losses limited the injection efficiency to 25%. With charge exchange injection, this efficiency should be as high as 95%. One of the immediate benefits of this process is the substantial reduction of residual radiation levels in the injection area, minimizing personnel exposure and lowering the frequency of equipment failure. A factor of three reduction in beam current required from the linac, and thus reduced beam loading of the linac rf system, should give even more reliable linac operation and monetary savings from reduced tube repair and replacement.

For the AGS physics program, the introduction of  $H^-$  injection has several important benefits. New intensity records were achieved soon after the commissioning studies. Additionally, the flexibility of the system should permit further increases in intensity by using betatron stacking to fill the horizontal aperture up to the operational limits of the machine. Increased brightness of the circulating beam at specific intensities is desirable for future injection into the Brookhaven CBA.

### $H^-$ Injection Into the AGS

The opposite charges of the injected and circulating beams make it possible, with charge exchange

injection, for the two beams to coincide at the location of a stripping foil. The full horizontal aperture of the AGS was filled during the highly inefficient 20-turn proton injection process, so that the initial circulating beam had an emittance more than 5 times larger than the injected beam. In contrast,  $H^-$  injection can permit the overlap of multiple turns of injected beam on the same central orbit, leading to a circulating proton beam of higher brightness than the incoming beam. The injected pulse length is limited only by gradual emittance growth due to scattering of the circulating beam on its multiple passes through the stripping foil and by space charge limits. The calculated rate of emittance growth is approximately  $.03\pi$  mm-mr/turn horizontally and  $.015\pi$  mm-mr/turn vertically. Additional flexibility is obtained using a programmable orbit bump to control the extent and density of circulating beam in horizontal phase space.

In the AGS, the longest straight section is 3 meters, which severely limits the possibilities for a local orbit bump configuration as in the Fermilab Booster.<sup>4</sup> The A20 straight section of the AGS was the location of the pulsed inflector magnet for the proton injection system. A pulsed  $1/2\lambda$ , radial orbit bump was used to match the partial acceptance to the inflector. For  $H^-$  charge exchange injection, instead of bringing the beam into the straight section through a translating bend at an inflector, the beam is deflected  $3.5^\circ$  toward the AGS 13 meters upstream of the A20 straight section. This guides the beam through the fringe field of the two AGS magnets just before the A20 straight section. The injection trajectory crosses the A20 straight section and enters the downstream ring magnet (B1) well inside the good field region. The fringe field traversed by the injected beam is approximately linear in that region. Ray-trace calculations using mid-plane field map values predict phase space dilution of less than 30%, smoothly distributed over the phase ellipse. Normalized emittances of the 70 mA proton beam were approximately  $5\pi$  mm-mr in each plane. The  $H^-$  beam line was designed for similar values of emittance, as indicated by the Fermilab results.

The stripping foil is located inside the gap of the B1 magnet where the reverse bending of the  $H^-$  beam has brought it tangent to the bumped equilibrium orbit, as shown in Fig. 1. Since this is the location of a maximum of the horizontal beta function of the AGS, placement of the stripping foil there uses the most horizontal aperture. Its location at this vertical beta minimum is important for polarized proton injection, in order to minimize depolarizing growth vertically due to foil scattering.

### HEBT Transport and Injection Area

The high energy beam transport (HEBT) line consists of four individual sections; transport from the linac to the AGS, the bending section, AGS matching section and the transport line to the Brookhaven linac isotope-production (BLIP) facility.<sup>7</sup> The linac tank quadrupoles and majority of the HEBT quads were

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unchanged in position and gradients in this conversion. This was accomplished by demanding linac input emittance conditions of a waist in both planes as it was in the  $H^+$  case. The upper HEBT section remains as originally designed, a nearly periodic focusing structure with a betatron phase advance of  $\pi/2$  per cell. The bending section was designed to be achromatic and dispersion-free requiring the reversal of the magnet polarities. Three of the matching section quadrupoles and several steering elements were re-located because of space limitations near the ring.

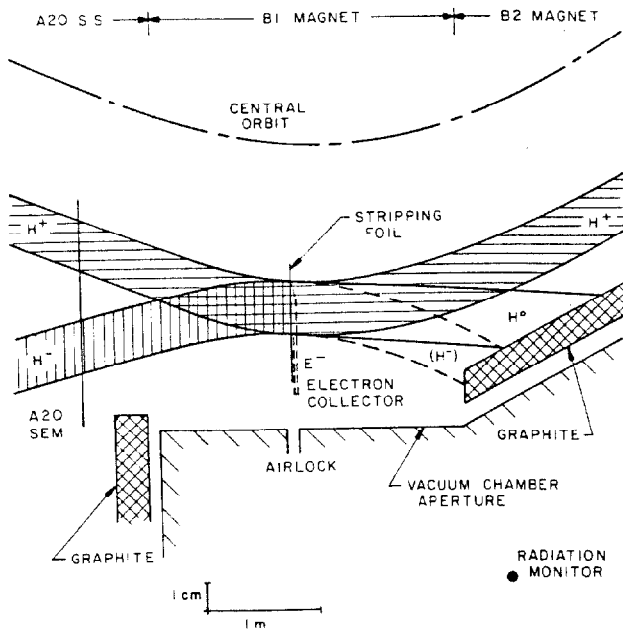


Fig. 1 - AGS injection area layout.

A destructive emittance measuring device is located downstream of the achromatic bend at the image point of the dispersion-free section. Transport parameters can then be calculated to match the HEBT emittance to the acceptance of the AGS. Three standard linac SEMS (single wire Secondary Emission Monitors) are located before and one after the  $3.5^\circ$  bend. These devices in addition to the SEM unit located in the A20 straight section yield sufficient information to establish correct beam steering at the stripping foil.

Two vacuum chambers, having in common an additional 2.5 cm of aperture to the outside of the machine, were installed in the two ring magnets downstream of the A20 straight section. The B1 chamber was provided with a port for the stripping foil holder and airlock. A block of graphite, 1.2 cm thick, was fastened along the outer edge of the B2 chamber aperture to reduce activation by the neutral hydrogen beam which emerges from the stripping foil at the 1% level.<sup>8</sup> A graphite block protects the B1 flange from accidental beam mis-steering.

The stripping medium is a carbon foil of surface density  $200 \mu\text{g}/\text{cm}^2$  as used at Fermilab and is supported by a C-shaped aluminum frame to which it is cemented using techniques described in Ref. 9. The frame is mounted on a stainless steel harp which closely matches the vertical aperture of the vacuum chamber. The assembly is inserted from the inside of the AGS ring and the harp holds the foil at the outside of the aperture during operation. The foil can be retracted into an airlock for replacement or inspection through a viewing window.

During injection, the equilibrium orbit is locally bumped into the stripping foil by two magnets located approximately one quarter betatron wavelength upstream and downstream of the foil. These magnets were used for proton injection, but required new programmable power supplies. These supplies are capable of providing a constant current to maximize horizontal brightness of the circulating beam or a falling current to uniformly fill the AGS acceptance and reduce space charge effects. After injection, the bumps are removed within 70  $\mu\text{s}$  to minimize scattering and heating of the foil by the circulating beam. The maximum required current for the bumps is 1500 A for a duration of 3 ms. Each power supply consists of a common-emitter series regulator powered by a 0.075 F capacitor bank. The series regulator consists of 180 parallel npn transistors driven by 24 pnp transistors.

The loss of a stripping foil or severe mis-steering of the incoming beam can allow all or part of the  $H^-$  beam to continue past the foil location. This negative beam is deflected into the upstream end of the B2 vacuum chamber and graphite stop. A radiation monitor, consisting of an argon filled length of "air-dielectric" coaxial cable, is located adjacent to this area and is connected to the linac Fast Beam Inhibit (FBI) system.

The transverse character of both the injected  $H^-$  beam and the circulating  $H^+$  beam are measured using the SEM unit located in the A20 straight section (Fig. 1). The horizontal scanning wire first intersects the incoming  $H^-$  beam and then the spatially well-separated accumulating  $H^+$  beam. At each position (2 mm step size) the time development of the processed signal from the wire is digitized at 0.5  $\mu\text{s}$  intervals over the injection period. In this way a projection in space and time is developed over many (typically 50) injection cycles.

Stopped electrons from the  $H^-$  beam produce a signal approximately one order of magnitude larger and opposite in sign from that produced by the ejection of secondary electrons by either the  $H^+$  or  $H^-$  beam. The fact that the  $H^+$  beam usually accumulates over many turns compensates for the lower response, yielding the same amplifier dynamic range requirement for both signals. Figure 2 shows a scan taken with the unit during the commissioning of the system. The opposite polarity of the injected beam signal has been inverted by the program.

To monitor charge exchange in the stripping foil, an electrically isolated 4 cm x 4 cm aluminum electrode is positioned downstream and perpendicular to the foil to intercept the stripped electrons as they bend in the ring magnetic field. The resulting current pulse, amplified outside the ring and transmitted to the control room was especially useful in the early tuning to indicate the presence of  $H^-$  beam at the foil, for steering adjustments, and for diagnosis of foil integrity.

#### Operation

The transmission efficiency from Linac to the AGS matching section is greater than 90% and has been demonstrated to be insensitive to small rotations of the linac transverse phase space ellipses. At present, only an empirical solution for the matching section has been utilized. Studies aimed at emittance matching from HEBT to the AGS using the programmable injection bump are in progress. The injection efficiency is derived using a HEBT beam current transformer located just before the last quadrupole

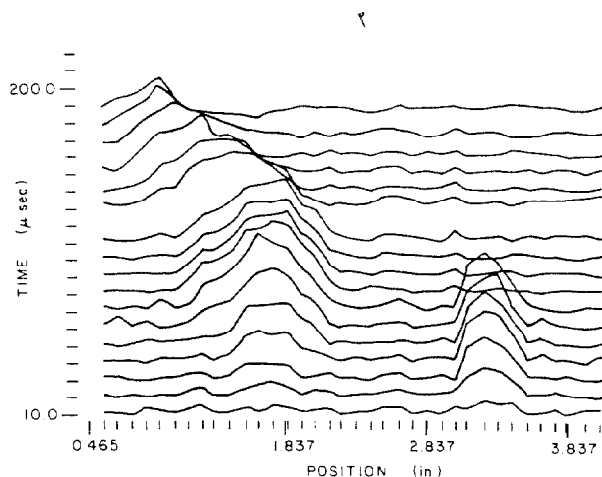


Fig. 2 - A20H SEM scan depicting the injected beam (right), and circulating beam (left) showing the collapse of the  $1/2 \lambda$  bump of the central orbit.

(due to space limitations), and a beam current transformer in the ring located almost a full turn from the injection area. The injection efficiency as presently measured is 75%. Results of recent studies, however, suggest possible aperturing in HEBT after the current transformer and first turn losses in the AGS ring. The typical linac beam pulse has a current of 20 mA and a duration of 190  $\mu$ s. It appears that essentially all of the injected beam is hitting the stripping foil. The radiation monitor located at the downstream end of the B1 ring magnet shows no beam loss during normal operation, while intentional mis-steering gives a clear response.

Residual radiation levels in the injection area are  $10^{-2}$  times lower than those produced by the multi-turn proton injection system. Maximum levels observed have been several hundred mRem/hour, while previous peak levels were 10-20 Rem/hour.

If the incoming  $H^-$  beam is chopped to be shorter than one revolution period of the AGS ring (4.8  $\mu$ s at 200 MeV), the position-measuring, electrostatic pick-up electrodes around the ring respond to the beam. With sufficient amplification, each pair allows the coherent betatron oscillation of the pulse around the equilibrium orbit at that pick-up location to be traced out on an oscilloscope by taking differences and sums from the pair in the usual manner. The position and angle of the injected beam in both the horizontal and vertical planes, and of the equilibrium orbit itself, can be adjusted to null the oscillations and hence bring the beam to the foil tangential to and on the equilibrium orbit (Fig. 3). The equilibrium orbit is adjusted radially all around the machine by changing the ring magnet field at injection time. A local radial variation is possible using a low field  $3/2 \lambda$  bump at the injection region. Additional tuning radially, and all orbit variation vertically is accomplished using the AGS low-field dipole correction array.

In conclusion, the operational experience with the AGS  $H^-$  injection system has been excellent. A new intensity record of  $1.25 \times 10^{13}$  protons/pulse was set within the first month of operations. It is possible to inject more than  $2.5 \times 10^{13}$  protons with little immediately obvious space charge loss. At

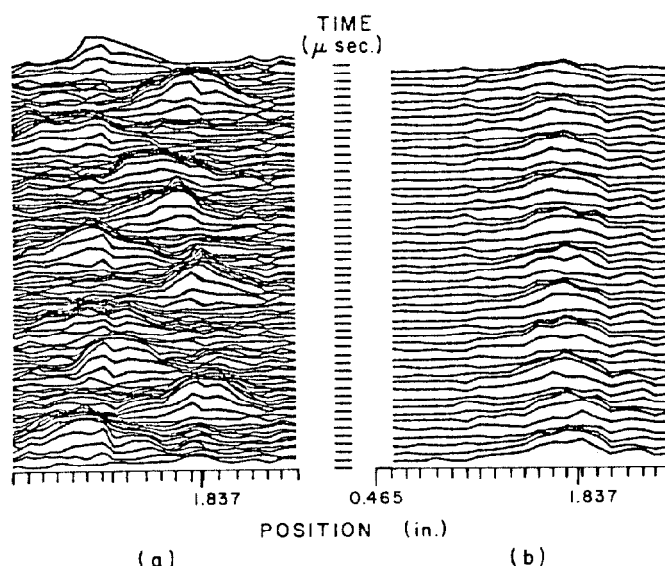


Fig. 3 - A20H SEM scan of the circulating beam (a) mis-steered at the foil, and (b) bump-matched to the  $H^-$  trajectory at the foil.

present, this is almost twice the beam that has been captured by the rf system. The injection process appears to be more forgiving of small misalignments and thus is more stable than the  $H^+$  inflector system. This is expected as the beam is not being steered against a solid septum but into the acceptance of the AGS. Studies are continuing to examine the detailed properties of the  $H^-$  system and to optimize its efficiency toward further intensity gains.

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