

## THE BEAM BUNCHING AND TRANSPORT SYSTEM OF THE ARGONNE POSITIVE ION INJECTOR

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### Abstract

A new positive ion injector (PII) is currently under construction at Argonne that will replace the existing 9-MV tandem electrostatic accelerator as an injector into ATLAS. It consists of an electron-cyclotron-resonance ion source (ECR) on a 350-kV platform injecting into a superconducting linac optimized for very slow ( $\beta \leq .007 c$ ) ions. This combination can potentially produce even higher quality heavy-ion beams than are currently available from the tandem since the emittance growth within the linac is largely determined by the quality of the bunching and beam transport.

The system we have implemented uses a two-stage bunching system, composed of a 4-harmonic gridded buncher located on the ECR high-voltage platform and a room temperature spiral-loaded buncher. A sinusoidal beam chopper is used for removal of tails. The beam transport is designed to provide mass resolution of  $m/\Delta m > 400$  and a doubly-isochronous beamline is used to minimize time spread due to path length differences.

### Introduction

The Argonne Tandem-Linac Accelerator System (ATLAS) has been in use since 1978 and has logged over 35,000 hours of beam time for research, providing ions of masses up to  $A = 127$ . The tandem accelerator is limited as an injector, however, by the poor performance of negative ion sources for some ion species, the deleterious effect on beam quality of stripping, the short lifetime of stripping foils, and the low transmission for heavy ions. The PII [1-3] will address these shortcomings.

A primary requirement of the PII is that it reproduce or improve upon the excellent beam quality available from a tandem electrostatic accelerator. Since the emittance growth within the linac is largely determined by the quality of the injected beam, it is important that the bunching and beam transport not degrade the transverse emittance and energy spread from the ECR ion source.

### Transverse Optics

Fig. 1 shows a layout of the PII ECR ion source, injection beamline, and cryostat. The PII will be used to accelerate beams for the ATLAS accelerator from throughout the periodic table. Consequently, the injection beamline was designed to be able to accelerate beams with rigidities up to 0.35 Tesla-m. The low velocity of heavy beams matched into the linac at  $\beta = 0.007$  requires relatively large apertures throughout the beam transport system. The focusing quadrupole doublets have 7.8-cm apertures and the 90-degree dipole bending magnets have a 7.62-cm vertical gap. The quadrupoles were measured to have less than 0.4% total harmonic content from  $n = 3$  through  $n = 12$  with no component  $> 0.1\%$  and the dipoles field uniformity was measured to be  $\Delta B/B < 3.0 \times 10^{-4}$  over a 10.0 cm-wide trajectory.

The ECR ion source will frequently be used to provide beams of rare isotopes from natural material, and consequently, the mass resolution of the injection

beamline must be sufficient to separate intense adjacent isotopes as well as the other extracted species with similar  $m/q$ . The resolution of the system results from two successive 90-degree magnets. The first magnet, on the ECR HV platform, has a mass resolution of  $m/\Delta m \approx 100$ . After acceleration from the platform, the first magnet of the isochronous bend provides an intrinsic mass resolution of approximately  $m/\Delta m \approx 900$ . This resolution is compromised, however, by the energy spread induced by the harmonic buncher located on the HV platform to an effective  $m/\Delta m \approx 400$ . Clearly, the magnets cannot resolve ion species with identical  $m/q$ , thus some contamination will still be unavoidable for certain isotope and charge-state combinations. In these cases, an adjacent charge state may need to be selected with some loss of intensity or energy, but for most species this will not cause a significant problem. In cases of extremely rare isotopes, enriched material may be used.

Beam transmission through the system in initial tests has been excellent, with nearly 100% achievable with reasonable care. A reduction in the transmission due to charge exchange can be induced by incorrect focusing or by steering an intense beam into the beamline wall, causing outgassing, but only when the pressure exceeds  $1 \times 10^{-6}$  torr. Normally, the beamline vacuums are  $2-3 \times 10^{-8}$  torr even with beam present. Under these conditions, charge exchange losses are less than 1% for medium and low mass ions.

### Longitudinal Optics

Beam bunching for the injector is done in two stages, with the first buncher located on the ECR high-voltage platform (B1), and the second buncher (B2) placed immediately in front of the first resonator cryostat. A parallel plate chopper is located on the beamline upstream from the second-stage buncher to remove tails.

The longitudinal emittance of the beam injected into the linac is the result of summing the energy spread of the ion source with all the emittance enlarging processes of the transport system. The energy spread from the source can be approximated as  $5q$  eV [4-5] where  $q$  is the charge state of the ion. The primary energy spread additions are from the waveform non-linearity of B1, voltage variations of power supplies, path length differences through focusing and bending elements, and longitudinal fringe fields in acceleration sections. Because of the low velocity of the ions, considerable care is taken to minimize all of these effects.

Ions are bunched on the ECR HV platform after extraction from the source, typically at 12 kV. B1 is a gridded, harmonic, 12-MHz buncher, identical in most respects to the pre-tandem buncher that has been in use at ATLAS for a number of years [6]. It differs only in the use of four harmonics rather than three in order to optimize the sawtooth waveform linearity.

The transit time of ions through the beamline after acceleration is  $\approx 10-15 \mu s$ , thus the ECR platform voltage must be stabilized to at least  $\Delta V/V < 1 \times 10^{-4}$  to avoid adding significant time spread to the beam.

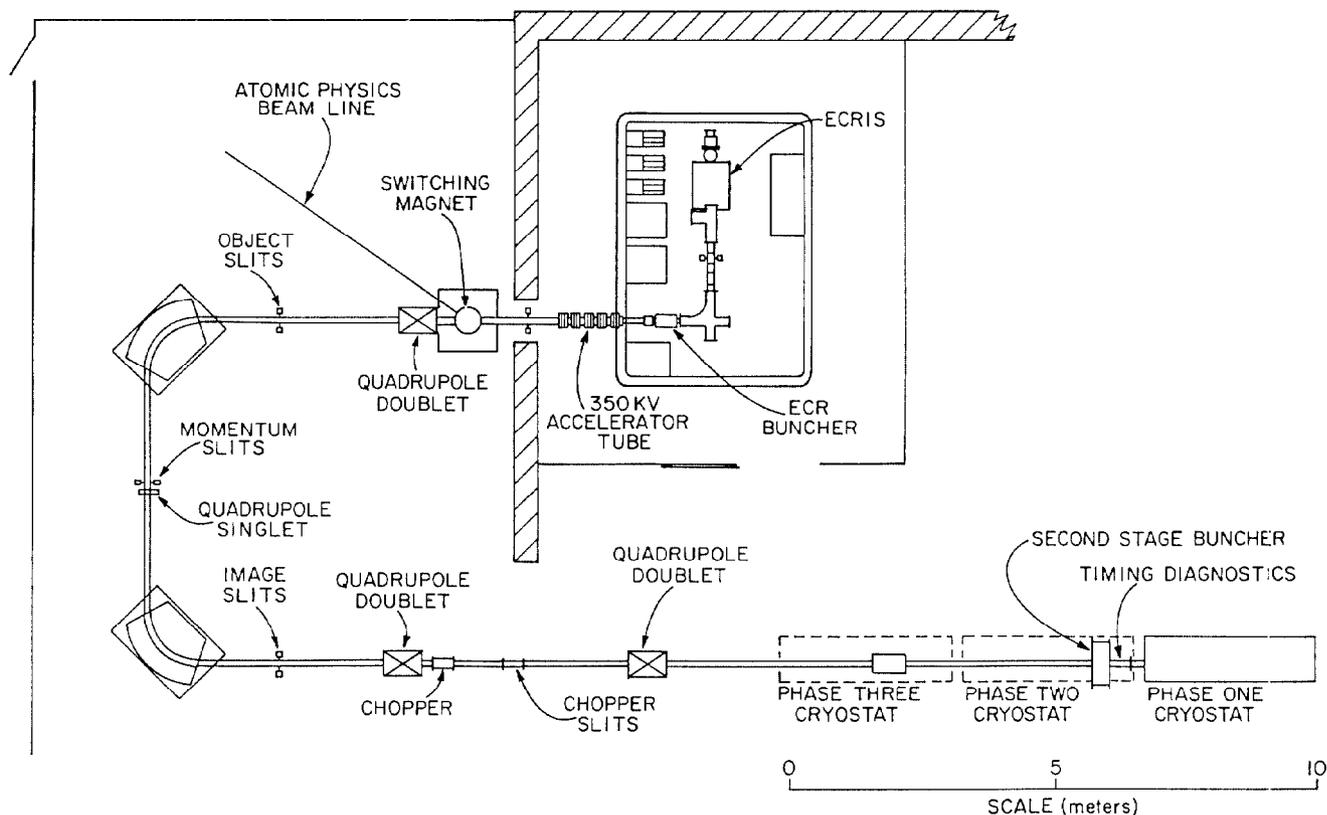


Figure 1. Layout of the injection beamline.

Variation in path length of ions as they traverse the dipole magnets could also degrade the beam pulse timing but the use of a doubly-isochronous beam transport system can prevent this from occurring. Two 90-degree dipoles are combined with an intermediate quadrupole singlet to produce path lengths with  $\Delta L/L < 3 \times 10^{-5}$ , most of which is the unavoidable result of the momentum dispersion introduced by the first-stage buncher. Uncorrected beam pulse widths are about 3 ns FWHM. Beam tests have shown that the effect of the quadrupole singlet is as expected, typically reducing the time spread of the beam pulse by about a factor of two.

The transit time of the beam pulse through the beamline is strongly dependent on the details of the tuning. Even small changes in focusing or steering parameters can cause a centroid shift of several nanoseconds if constraints in the form of slits and apertures are not imposed. Once established, however, the stability of the system is sufficient to maintain a constant transit time over a period of days.

B2 forms the final time focus at the first resonator of the PII. It is a 24-MHz, room temperature, spiral-loaded, 2-gap structure, producing the required effective accelerating potential of 49 kV with 400 w of input power. The buncher is placed as close to the resonator cryostat as possible, leaving only enough room for the diagnostics chamber.

Beam pulse timing diagnostics are required at the linac entrance, since the longitudinal and transverse emittance growth of the beam as it passes through the linac is sensitive to the shape of the longitudinal phase ellipse of the injected beam. Silicon surface barrier detectors have been used for beam pulse timing

diagnostics measurements at ATLAS, but for the PII, beam energies are too low to achieve the required resolution. In addition, a nondestructive detector that can be used continuously during accelerator operation is desirable. A microchannel-plate detector (MCP) system is used. The detector consists of a thin ( $10 \mu\text{m}$ ) wire axially mounted in a cylindrical electrostatic (2.5 kV) potential. The ion beam enters and exits through 8.5 mm apertures orthogonal to the wire. Electrons generated at the wire surface by ion collisions are swept along radial lines, and those which exit at nearly 90 degrees to the beam pass through a small aperture into the microchannel plate. Calculations have shown that the transit time differences of the electrons due to the initial energy spread should be small, thus the inherent resolution of the detector should be limited only by the MCP. We hope to eventually realize a detector resolution of  $\approx 60$  ps, and initial beam tests have been encouraging. A similar detector used at the SUNY superconducting linac exhibits enhanced background with age, presumably due to field emission from the surface roughening caused by beam sputtering [7]. We may have seen this effect, but the increased background could be readily eliminated by a reduction in wire-anode voltage without a sacrifice in detector resolution. The greatest limitation of this detector is the high efficiency. Since MCP counting rates of 10 kHz are obtained from only 1 pA of beam, the beam from the ECR source must be reduced by at least a factor of  $10^3$ . This is currently accomplished with a set of four jaw slits mounted at the exit of the ECR platform acceleration tube, but there is some concern that this may prejudice the bunching measurements by selecting only a small portion of the available phase space. Additional tests will be conducted to determine whether a gridded beam attenuator might allow easier

measurements with a more representative sample of the beam.

The bunching efficiency of the harmonic buncher will not exceed 70%. The remaining unbunched beam must be removed in order to avoid unwanted beam pulses between the primary bunches and to maintain the best possible beam quality. A sinewave chopper operating at one half the bunch frequency has been installed in the PII injection beamline to remove the unwanted beam components. The chopper plates have been curved to provide adequate field uniformity across the beam transverse plane while minimizing the overall size of the plates. The maximum operating field of the chopper is 6 kilovolts, but in general will operate at significantly lower fields. The use of a chopper of this type has two deleterious effects on the transmitted beam. The first effect is to provide a net acceleration to particles which are vertically displaced from the chopper's axis. The energy gain is approximately linear in off-axis position. Such differential energy gain causes a significant emittance growth to the beam. It is possible to experience an emittance growth in excess of a factor of 4 over what is expected from the ECR source and bunching system prior to the chopper if the chopper is operated in a high-field mode. The second effect is that the chopper will cause a net vertical deflection to the beam even for the synchronous particle. This deflection can cause serious degradation of the beam optics if not minimized. Both effects can be reduced by lowering the maximum field required in the chopper. The momentum analyzing slits of the first magnet in the isochronous bend region can be used to remove the beam near the extremes of the harmonic buncher waveform. This beam has been given the largest energy gain by the buncher but also generally experiences a poor waveform from the buncher. It is this beam which forms the near tails of the bunched beam and sets the voltage requirements for the chopper if not removed in some other way. By removing this portion of the beam with the magnet momentum slits, the chopper voltage can be reduced by a factor of 3 to 4. The result is acceptable chopper operation.

#### Bunching Results

Fig. 2 shows the bunching performance achieved with the first and second stage bunchers. Both spectra were obtained using the wire detector immediately in front of the first cryostat. With B1 alone, widths as narrow as 1.1 ns FWHM can be achieved with care, and < 1.7 ns FWHM is observed routinely. When the amplitude of B1 is reduced to underbunch and B2 is used to form a time waist at the detector, pulse widths as narrow as 135 ps FWHM have been measured. To project this waist to the first accelerating resonator, the amplitude is reduced and calculations indicate that pulse widths of  $\approx 250$  ps FWHM should be obtained. Although no means of direct measurement at this location exists, initial acceleration tests with a  $^{40}\text{Ar}^{+12}$  beam have shown that the bunching system performance is sufficient. The longitudinal beam emittance after PII acceleration was measured to be less than 20 KeV-ns.

Work supported by the U. S. Department of Energy, Nuclear Physics Division, under Contract W-31-109-ENG-38.

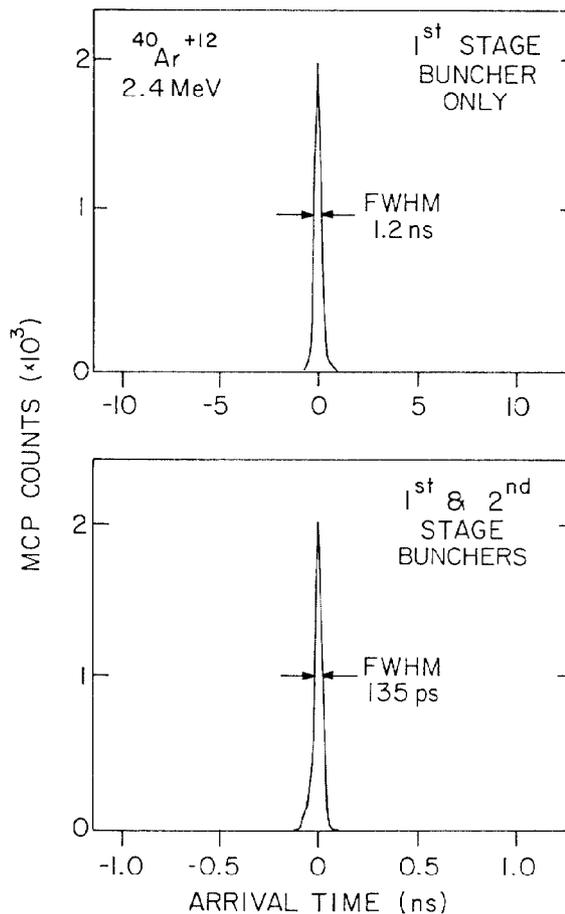


Figure 2. Bunching performance of first and second-stage bunchers.

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