# THE ATLAS POSITIVE ION INJECTOR

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## Abstract

This paper reviews the design, construction status, and beam tests to date of the positive ion injector (PII) which is replacing the tandem injector for the ATLAS heavy-ion facility. PII consists of an ECR ion source on a 350 KV platform injecting a very low velocity superconducting linac. The linac is composed of an independently-phased array of superconducting four-gap interdigital resonators which accelerate over a velocity range of .007 to .06c. In finished form, PII will be able to inject ions as heavy as uranium into the existing ATLAS linac. Although at the present time little more than 50% of the linac is operational, the independently-phased array is sufficiently flexible that ions in the lower half of the periodic table can be accelerated and injected into ATLAS. Results of recent operational experience will be discussed.


## Introduction

Since the first operation of a superconducting heavy-ion linac in 1978 [1], the number and size of this class of accelerator has steadily increased [2]. Until the present project, all these machines have served as post-accelerators, increasing the energy of beams from tandem electrostatic accelerators. The largest of the post-accelerators is the ATLAS linac, completed in 1985 [3]. Performance of the ATLAS facility has been limited by characteristics of the 9 MV tandem injector to mass A < 127 and to beam currents of typically a few particle nanoamperes for the heavier ions.

Several years ago, we undertook to replace the tandem portion of ATLAS with a new injector which would provide greatly increased beam current, and extend the mass range of ATLAS to uranium[4,5]. The positive ion injector (PII) project was motivated by the availability of electron-cyclotron resonant (ECR) ion sources which can provide highly- positively-charged ion beams with good transverse and longitudinal emittance. The technical goal has been to incorporate an ECR source into a superconducting linac injector which maintains and exceeds tandem-like beam quality while matching the beam into ATLAS.

Construction has proceeded in several phases. First, the technology for a very-low-velocity superconducting linac was developed [6,7,8]. At the same time an ECR source was designed and built on a high voltage platform [9,10]. The source, beam transport and bunching system, and a small (3.5 MV) portion of the linac were com-

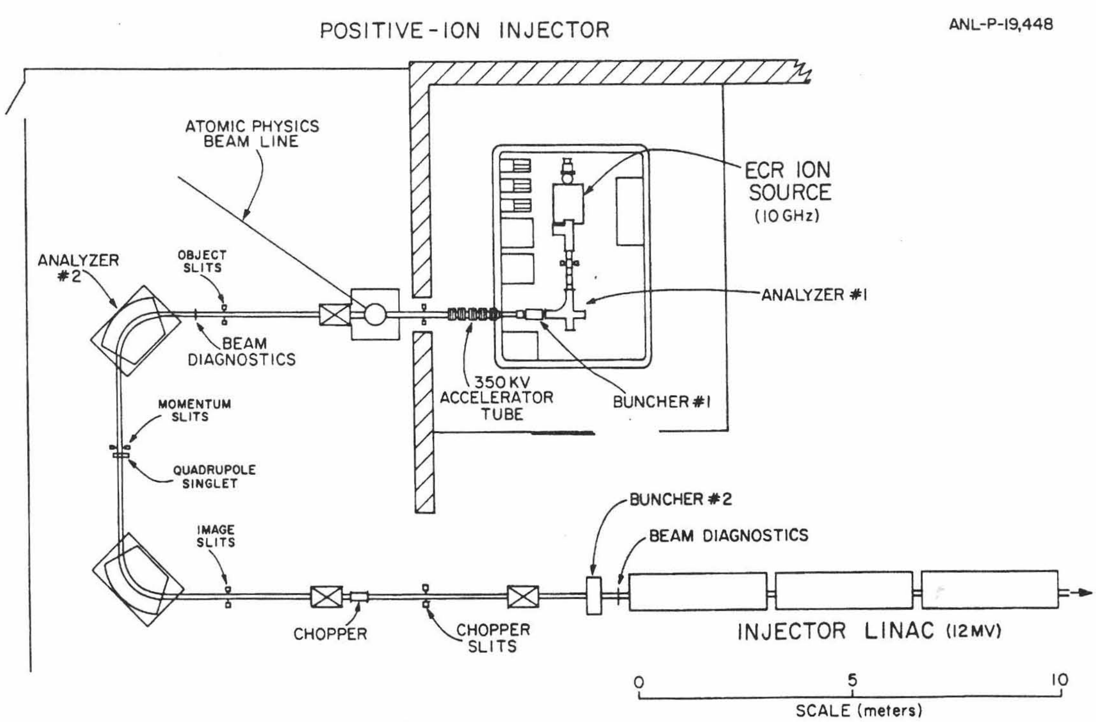


Fig. 1. Layout and major elements of the positive ion injector (PII).

pleted and first tested with beam in early 1989 [11]. Early this year, the system was operated with 7 MV of linac installed. PII will be fully completed in early 1991 when the linac is enlarged to 12 MV. This final injector will accelerate uranium ions up to more than 1 MeV/A, enough for ATLAS to accept the beam and further accelerate to ≈ 8 Mev/A.

In what follows, the design and status of the several elements of PII are reviewed, then results of operational tests are discussed.

## Elements of the PII System

The elements and layout of PII are shown in Fig. 1. The primary features, reviewed in detail below, are:

1. An ECR source on an open-air, 350 KV high-voltage platform, designed to produce beams up to uranium at velocities of .008c.
2. A two-stage harmonic bunching system which produces bunches of less than 300 psec time width at the linac entrance.
3. A very-low-velocity superconducting linac, which accelerates over the range $.007 < \beta < .06$, and which produces very little emittance growth.

## ECR Source and Voltage Platform

The ECR source is in most respects a typical 10 GHz source. Unique features are operation on a 350 KV platform and provision for radial access to the plasma region. This latter feature is to facilitate introducing solid source materials (in the form of wire, for example) into the plasma. To provide good beam bunching and longitudinal beam quality, the platform voltage must be stable to better than 1 part in $10^4$.

Construction of the ECR source and high-voltage platform was completed in 1987. The source has been used since then both for beam tests and for several atomic physics experiments: much of this work has been reported elsewhere [9,10]. Some important results are that: 1) a variety of beams have been produced from solid samples with very high efficiency, 2) more than 1 e$\mu$A of $^{238}U^{24+}$ has been produced, and 3) the voltage on the high voltage platform is sufficiently stable for excellent beam quality.

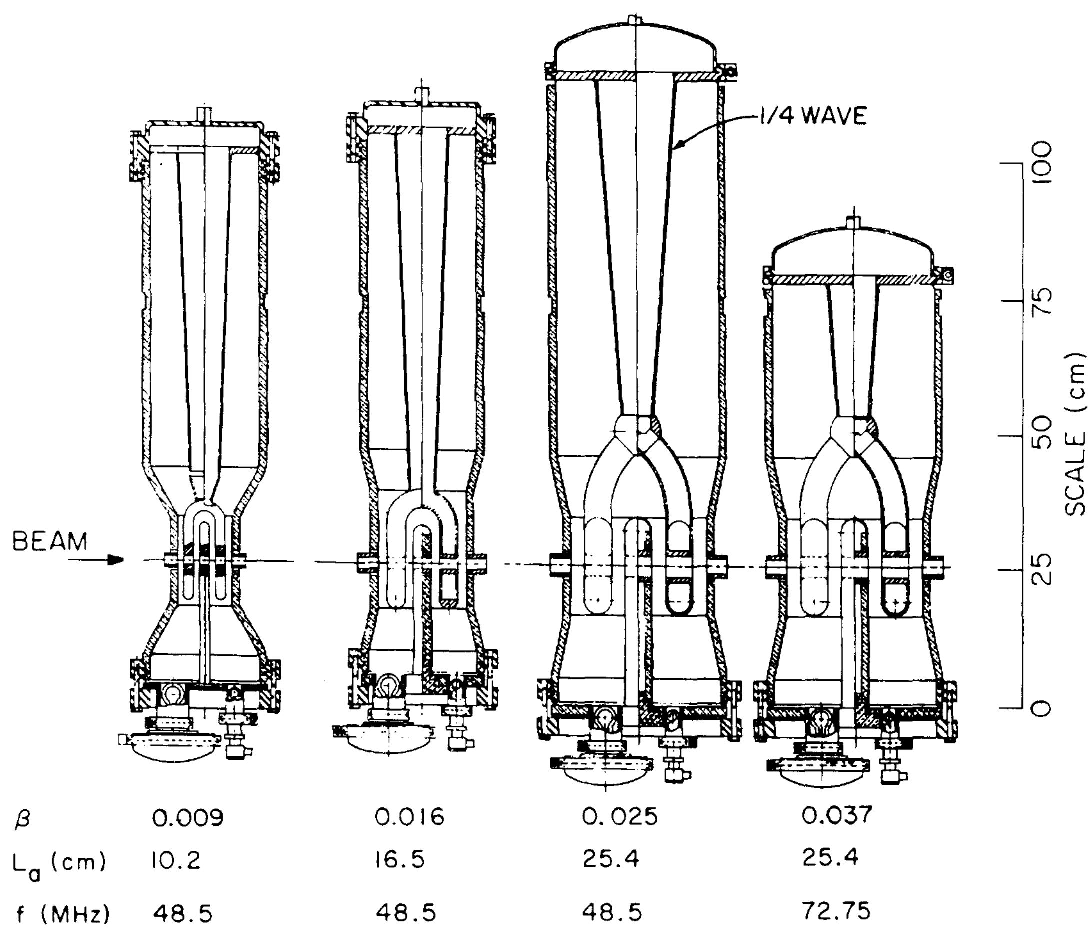


Fig. 2. Four resonant geometries used for the injector linac.

**Beam Bunching and Mass Analysis**

Mass analysis is performed in two stages: first with a 90° magnet on the high voltage platform with a resolution of ≈ 1%, and second with a larger 90° magnet at ground potential with a resolution of ≈ .2%

The two-stage bunching system is similar to that used for ATLAS. The first stage is a gridded-gap using a four-harmonic approximation to a saw-tooth voltage with a fundamental frequency of 12.125 MHz. The amplitude of the first stage is adjusted to form a time waist about 35 m downstream, at the second stage buncher. The second stage is a two-gap, normally-conducting spiral-loaded resonator, operating at 24.25 MHz, which forms a time waist ≈ 1 m downstream, at the entrance to the linac.

Beam pulse widths are measured with a fast detector in which incident ions strike a 10 $\mu$ tungsten wire and the resulting electrons are accelerated to a channel-plate detector. For example, with a $^{40}Ar^{12+}$ beam, the pulse formed by the first stage buncher was 1.2 nsec, and the second stage buncher could form a 130 psec bunch at a detector 55 cm downstream. This time spread is remarkably small for such a low energy beam (0.061 MeV/A).

**The Injector Linac**

The injector linac is formed from four types of independently-phased, four-gap accelerating structures (shown in Fig. 2.) The linac is based on the fact that short, high-gradient superconducting accelerating structures can be closely interspersed with short, powerfully focusing superconducting solenoids. The rapid alternation of radial and longitudinal focusing elements maintains the beam in much the same way as does a Wideroe-type rf structure with magnetic lenses in the drift-tubes, but with the simplicity and versatility of independently controlled, modular elements.

The construction sequence for PII has been based on this versatility. Fig. 3 shows the velocity acceptance characteristics of the four resonator types of PII. The discrete points represent the single-resonator velocity increments for a $^{238}U^{24+}$ beam, and the whole string of points show the passage of such a beam through the 18 resonant cavities that will form the final configuration of the PII linac.

Beams of lower mass, however, enter the linac typically with much higher charge to mass ratios: the velocity increments are correspondingly larger and the linac requires fewer resonant cavities of each type to bring such beams up to ß=.05 for injection into ATLAS. In fact, the linac can be configured to provide a useful capability with as few as five resonant cavities, as was shown in the first series of beam tests [11]. To realize such inherent flexibility, the linac cryostats were designed to permit the spacing and sequence of focusing and accelerating structures to be easily changed.

At present 10 of 18 resonant cavities have been completed and are operational. Accelerating field levels obtained in off-line tests average above 4 MV/m. The average on-line level is 3 MV/m, the original design goal, but is presently limited by characteristics of the fast-tuning system and is not believed to be a fundamental limit. The lowest velocity resonator (ß = .008), has over the past 18 months repeatedly operated, with beam, at gradients above 6 MV/m.

**Beam Tests and Operation**

The highly adaptable nature of the linac has permitted a series of beam tests as construction of the low-velocity linac has proceeded. This has included several periods of actual operation of ATLAS injected with the PII system.

First beam through PII was obtained in February 1989, with a 3.5 MV configuration of the linac. A 1$\mu$A beam of $^{40}Ar^{12+}$ was accelerated to as much as 36 MeV. In the course of these tests the beam was injected into ATLAS, accelerated to 173 MeV, and used for a brief (6 hr) experiment. In spring of 1990, with a 10-resonator , 7 MV configuration of the linac, another series of tests was performed.

A variety of beams have been accelerated, including $^{3}He^{1+}$, $^{13}C^{4+}$, $^{16}O^{6+}$, $^{40}Ar^{12+,13+}$, $^{86}Kr^{15+}$, and $^{92}Mo^{16+}$. In addition to tests for shakedown and development of PII, the system has been used to inject ATLAS

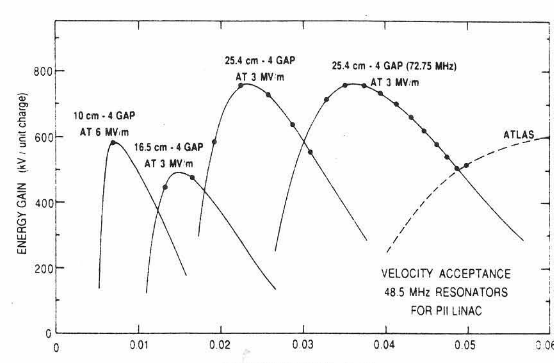


Fig. 3. Velocity acceptance profile for the resonators forming the low velocity linac. The discrete points show the single-resonator velocity increments for a $^{238}U^{24+}$ beam.

and deliver beam for several experiments for a time period totaling more than four weeks.

Operation of the PII system has been characterized by excellent reliability and stability. Even in these early tests, all elements of the system typically run for extended periods, several days, with little or no operator intervention.

A primary goal for the new injector has been to achieve beam quality competitive with that of the tandem, especially in longitudinal phase space. We have measured longitudinal emittance at the output of PII in a direct and unambiguous way by measuring the width of two time distributions: 1) the time spread at the rebuncher between PII and the ATLAS linac, and 2) the width of a time waist formed by the rebuncher.

Measured longitudinal emittance of several beams is shown in Table I. It should be noted that the observed beam quality by no means represents a limit for PII, as the machine is in several respects not in optimum configuration. It is already clear, however, that the beams have substantially smaller longitudinal emittance than similar tandem beams, and that PII sets a new standard of quality for heavy-ion beams.

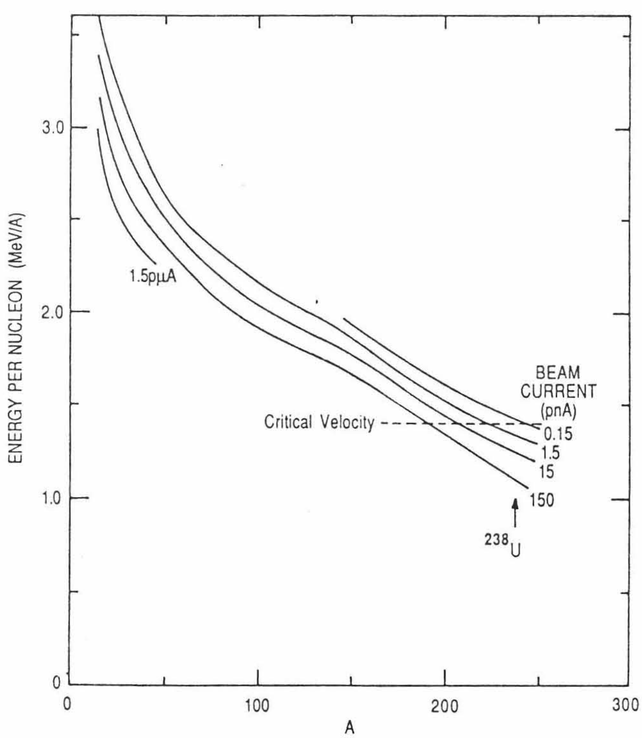


Fig. 4. PII output energy as a function of mass and beam current. The critical velocity shown is the minimum velocity for acceptance and further acceleration by the ATLAS linac.

**TABLE I**
**Measured Longitudinal Emittance**

| Projectile | Post-injector Stripping | $\epsilon_z$ (KeV - nsec) Tandem | PII |
|---|---|---|---|
| $^{3}He^{2+}$ | no | | $<1.0\pi$ |
| $^{16}O^{6+}$ | no | $15\pi$ | |
| $^{16}O^{8+}$ | yes | $20\pi$ | |
| $^{40}Ar^{12+}$ | no | | $5\pi$ |
| $^{58}Ni^{10+}$ | no | $30\pi$ | |
| $^{58}Ni^{19+}$ | yes | $40\pi$ | |
| $^{86}Kr^{15+}$ | no | | $19\pi$ |

## Conclusions

The results of beam tests to date indicate that all design goals for the PII system will be met. Fig. 4. shows, as a function of ion mass, the beam currents and output energies that will be available from PII in its final, 18 resonator configuration, expected to be complete in early 1991.

Tests of the partially completed system already demonstrate that the combination of an ECR ion source with a low-velocity superconducting linac provides an alternative to tandem electrostatic accelerators that is not only cost-effective, but can also provide increased beam quality and increased beam current.

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## References

1. J. Aron, R. Benaroya, L. M. Bollinger, B. E. Clifft, W. Henning, K. W. Johnson, J. M. Nixon, P. Markovich, K. W. Shepard, Proceedings of the 1979 Linear Accelerator Conference, Mantauk, New York, 10-14 September 1979, Brookhaven National Laboratory Report BNL-51134, p. 104 (1979).

2. K. W. Shepard, Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, Illinois, March 20-23, 1989 , p. 1764 (1989).

3. J. Aron, R. Benaroya, J. Bogaty, L. M. Bollinger, B. E. Clifft, P. DenHartog, K. W. Johnson, W. Kutschera, P. Markovich, J. M. Nixon, R. Pardo, K. W. Shepard, G. P. Zinkann, Proceedings of the 1984 Linear Accelerator Conference, Seeheim, W. Germany, 7-11 May 1984, GSI Report GSI-84-11, p. 132 (1984).

4. L. M. Bollinger and K. W. Shepard, Proceedings of the 1984 Linear Accelerator Conference, Seeheim, W. Germany, 7-11 May 1984, GSI Report GSI-84-11, p. 217 (1984).

5. R. C. Pardo, L. M. Bollinger, and K. W. Shepard, Nucl. Instrum. and Methods B24/25, p. 746 (1987).

6. K. W. Shepard, Proceedings of the 1986 Linear Accelerator Conference, Stanford, California, June 2-6, 1986, SLAC Report 303, p. 269 (1986).

7. K. W. Shepard, Proceedings of the 1987 IEEE Particle Accelerator Conference, Washington, D.C., March 16-19, 1987, p. 1812 (1987).

8. K. W. Shepard, P. K. Markovich, G. P. Zinkann, B. Clifft, R. Benaroya, Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, Illinois, March 20-23, 1989, p. 974 (1989).

9. R. C. Pardo, P. J. Billquist, and J. E. Day, Journal de Physique C1 supp. #1, p. 695 (1989).

10. R. C. Pardo and P. J. Billquist, Rev. Sci. Instr. 61(1), p. 239 (1990).

11. L. M. Bollinger, P. K. Den Hartog, R. C. Pardo, K. W. Shepard, R. Benaroya, P.J. Billquist, B. E. Clifft, P. Markovich, F. H. Munson Jr., J. M. Nixon, G. P. Zinkann, Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, Illinois, March 20-23, 1989, p. 1120 (1989).