FIRST OPERATIONAL TESTS OF THE POSITIVE-ION INJECTOR FOR ATLAS

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Abstract

This paper summarizes the status and first operational experience with the positive-ion injector for ATLAS. The new injector consists of an ECR ion source on a 350-kV platform followed by a superconducting injector linac of a new kind. In Phase I of this project, the ECR source, voltage platform, bunching system, beam-transport system, and a 3-MV injector linac were completed and tested in early 1989 by the successful acceleration of an $^{40}Ar^{12+}$ beam. Most of the new system operated as planned, and the longitudinal emittance of the 36-MeV beam out of the injector was measured to be only 5 π keV-ns, much smaller than the emittance for the present tandem injector. When completed in 1990, the final injector linac will be enlarged to 12 MV, enough to allow the original ATLAS linac to accelerate uranium ions up to 8 MeV/u.

Introduction

ATLAS is a heavy-ion accelerator [1] designed for nuclear-physics research in the neighborhood of the Coulomb barrier. Until now it has consisted of a composite machine in which a 9-MV tandem electrostatic accelerator and its negative-ion source inject heavy ions into a superconducting linac. Parts of this system first went into operation in 1978, and by now the superconducting linac has operated with beam on target for more than 35,000 hours, substantially more than any other superconducting accelerator of ions.

ATLAS is a good research tool in its present form, but it has two drawbacks: (a) the mass range of its projectiles is limited to the lower half of the periodic table and (b) its beam intensity is smaller than some users need. Both limitations are caused by the tandem injector and particularly by foil stripping at low energy in the tandem terminal. Consequently, some 4 years ago we undertook a major upgrade of ATLAS with the following goals:

(1) to extend the ion mass range up to uranium,
(2) to increase the beam current by two orders of magnitude for all ions and, at the same time,
(3) to preserve the good qualities of the tandem injector, including CW operation and excellent beam quality.

After considering several possibilities, we decided that the optimum approach for us was to replace the tandem injector with the positive-ion injector [2,3] represented schematically in Fig. 1. Here the heavy-ion source consists of an electron cyclotron resonance (ECR) source on a high-voltage platform [4]. Highly charged ions from this source are analyzed and bunched on the voltage platform, accelerated to ground potential, analyzed and bunched a second time [5], and then injected into a superconducting injector linac of a new kind [6]. The linac consists of an array of short, independently phased, superconducting resonators operating at exceptionally low RF frequencies for superconducting structures. Superconducting solenoids at frequent intervals are used for beam focussing.

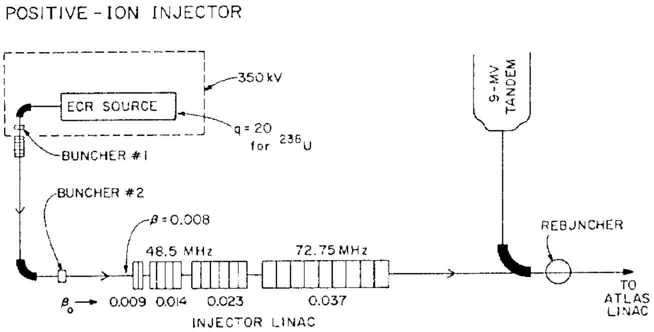

Fig. 1 Schematic of the positive-ion injector. Focussing solenoids in the injector linac not shown.

The new injector system incorporates several features that might have caused severe technical problems: (a) An ECR source has not previously been operated on a voltage platform. The voltage instability of this platform should be less than 10^{-4} of the voltage for good beam bunching. (b) The low velocity ($\beta \approx 0.008$) of some ions incident on the linac and the need for excellent beam quality require accelerating structures with lower RF frequencies and much lower β than any previous superconducting structures. These requirements maximize the problem of RF phase control in the presence of mechanical vibration and necessitated the development of a new class of superconducting accelerating structures. (c) Excellent longitudinal beam quality requires bunching that is challenging because of the low beam velocity. (d) The low velocity of ions incident on the linac and the high accelerating fields of the accelerating structures lead to a relative rate of velocity increase at the front end of the linac that may exceed any experienced in previous linacs. This rapid acceleration generates problems in both transverse and longitudinal phase space [2,7].

The project is being carried out in three phases. The ECR source and voltage platform, the beam transport and preparation system, and a 3-MV injector linac have been built in Phase I; the superconducting injector linac will be enlarged to 8 MV in Phase II; and in Phase III, to be completed in late 1990, the injector will be enlarged to 12 MV. This final injector is designed to accelerate uranium ions up to ~ 1.0 MeV/u, enough to enable ATLAS to accept the beam and accelerate it to ~ 8 MeV/u. The whole accelerator, composed entirely of superconducting linac, is shown in Fig. 2.

Operational Tests of the New Injector

On February 28, 1989, the Phase I Positive-Ion Injector for ATLAS was used, for the first time, to accelerate ions up to the velocity required for injection into ATLAS. A 1-μA, 1.95-MeV beam of $^{40}Ar^{12+}$ ions from the ECR source was accelerated to 33 MeV by the five superconducting resonators of the Phase I injector linac. This beam was then further accelerated to 173 MeV by the ATLAS linac and delivered through a refined collimator to a gamma-ray facility for a 6-hour test experiment.

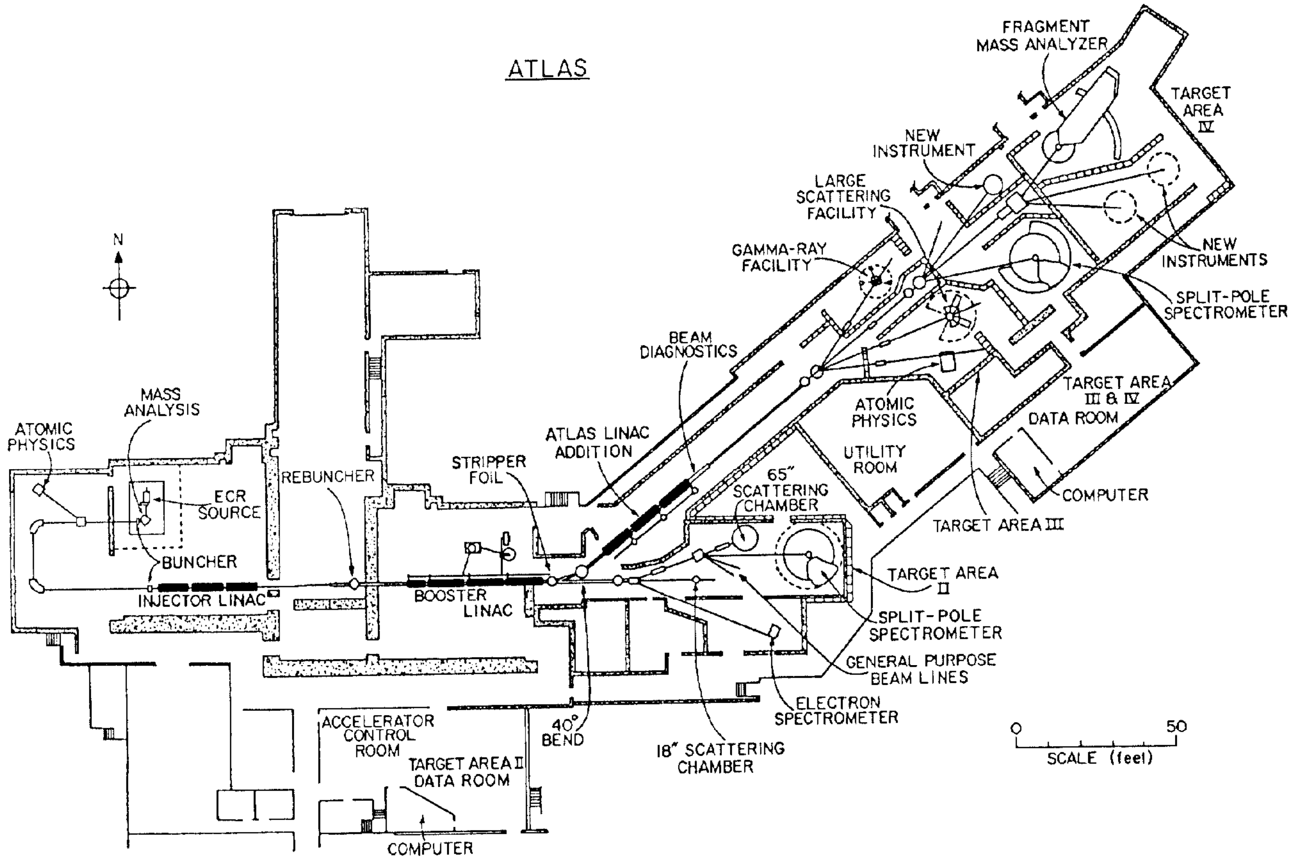

Fig. 2 Layout of ATLAS. The positive-ion injector, shown in its final form, is on the left. Only one of the three cryostats of the injector linac is in use for the Phase I system.

The remainder of this paper summarizes the performance of the positive-ion injector (PII) during the initial test and a following test in which a 2.44-MeV $^{40}A^{12+}$ beam from the source was accelerated to 36 MeV by the injector linac.

ECR Source. The ion source, which has been in use since late 1987, operated stably during the period of several days required for the test, as expected. The beam extracted from the source was originally 1μA and was then reduced to about 200 nA in order to match the requirements of the planned measurement with the beam after acceleration through ATLAS.

Voltage Platform. The platform voltage was 150 kV and 190 kV in the two tests. Its ripple (peak to peak) was measured to be ~ 15 volts. A ripple of this magnitude has little effect on beam bunching.

q/A Analysis. The charge-to-mass ratio of the beam is analyzed in two stages: first on the voltage platform with a 90° magnet having a q/A resolution width of about 1.0% (FWHM), and then at ground potential with a large 90° magnet having a nominal resolution of 0.2%. Both magnets functioned well.

Beam Bunching. The 2-stage beam-bunching system for PII is similar to the one used successfully for many years at the present tandem injector: a harmonic buncher which operates on the beam at low energy followed at higher energy by a buncher with a sinusoidal wave form. The important new feature for PII is that there is no stripping foil between the two bunchers, and consequently the phase ellipse can be manipulated with greater freedom.

The 1st-stage buncher is a grided gap with a saw-tooth-like wave form generated by a 12.125-MHz fundamental frequency and its first three harmonics. This buncher on the voltage platform modulates the energy of ions accelerated by the extraction voltage of the source, 13 kV in these measurements. The amplitude of the 1st-stage buncher is adjusted to form a waist in time about 35 m downstream at ground potential, near the second-stage buncher.

The measured pulse width formed by the first-stage buncher was $\Delta t = 1.2$ ns (FWHM). All time distributions reported here were measured with a fast detector in which incident ions strike a 10-μ tungsten wire and the resulting electrons are accelerated to a channel-plate detector.

The 2nd-stage buncher is a 2-gap room-temperature spiral resonator operating at 24.25 MHz - twice the beam-pulse rate. The time waist formed by this buncher at a detector 55 cm downstream was $\Delta t = 130$ ps (FWMH). This time spread is remarkably small, since the beam energy was only 0.061 MeV/u; previously, for heavy ions only beams from tandems (with energies > 1.0 MeV/u) had been bunched to less than ~ 1 ns.

Various pulse widths measured with 1-stage and 2-stage bunching can be used to deduce the longitudinal emittance ϵ_z of the beam entering the injector linac. The value derived is $\epsilon_z \approx 4\pi$ keV-ns when the full beam is used (ϵ_z is the area in energy-time phase space). Although this value is already very small, it can be reduced to $\epsilon_z \approx 1\pi$ keV-ns by using the 2nd-stage analyzing magnet to limit the energy spread of the beam accepted for use. This procedure reduces beam intensity, but it is sometimes useful because the ECR source provides more beam than is needed in many experiments.

The one problem experienced with the bunching system is that the 2nd-stage buncher is too far (~ 1.9 m) from the first resonator and consequently beam matching to the linac is poor in longitudinal phase space, i.e., the beam pulse is too wide at the first resonator. This is a temporary problem, since the injection geometry will be better for the final Phase III linac and since a better match can be obtained by using a higher injection voltage.

One has considerable flexibility in matching the beam to the linac by adjusting the pulse width incident on the 2nd buncher. The only limitation is that the incident pulse must be narrow enough to fall within the linear range of the 2nd buncher, say, within ± 2 ns.

Transverse Emittance. The measured transmission of the 2.44-MeV $^{40}Ar^{12+}$ beam through two widely spaced apertures indicates that $\epsilon_x \approx \epsilon_y \approx 12\pi$ mm-mrad. This is about what was expected.

Injector Linac. The 3-MV Phase-I injector linac consists of four types of independently-phased 4-gap accelerating structures [6] optimized for $\beta = 0.009$, $\beta = 0.015$, $\beta = 0.025$, and $\beta = 0.038$. The Phase-I system has one unit of each type except that there are two $\beta = 0.025$ units. A superconducting focussing solenoid follows each of the first three resonators.

The linac was operated stably, with all resonators under phase control, for about ten days. In spite of the low RF frequency, phase control was maintained easily. In the second run, the total accelerating voltage of the linac was ~ 3.5 MV (after correcting for transit-time effects), somewhat greater than the design value of ~ 3.1 MV. See [8] for more detail.

The one disappointment was that the transmission through the linac was poor - about 30%. We are confident that this problem can be eliminated by reducing the following potential difficulties: (1) Earth's magnetic field. For the ion involved, this field was troublesome because our long injection beam line was unshielded. (2) Alignment of linac. The center line of the linac was probably misaligned relative to the incident beam. (3) Alignment of resonators. Several mechanical problems within the cryostat caused at least one individual unit to be misaligned. (4) Focussing elements. The transverse optics at the front end of the injector linac are complex, and it is hard to optimize parameters. (5) First resonator. The accelerating field of the first resonator was larger than required, thus causing unnecessary defocussing.

Quality of Accelerated Beam. A primary goal for the new injector is to achieve beam quality that is competitive with that of the tandem, especially in longitudinal phase space. Many doubted whether this could be done.

The longitudinal emittance of the beam out of PII can be determined reliably by measuring the widths of two time distributions: (1) the time spread at the rebuncher between PII and the booster linac and (2) the width of a time waist formed by the rebuncher. We obtain

$$\epsilon_z = 5\pi \text{ keV-ns.}$$

This result is about 5 times smaller than the emittance of a tandem beam for ions in the same mass range, thus establishing a new standard of performance. Also, it is better than we had hoped for. Our measurements were not complete enough to determine to what extent the emittance is degraded by acceleration through PII, and we don't yet have any experimental data on how ϵ_z depends on ion mass.

Conclusions and Near-Term Plans. The results of the beam tests of the Phase I positive-ion injector indicate that all of our design goals for PII will be met. The good beam quality is especially gratifying since there are so many ways in which the beam from the source can be degraded.

The various problems that have been revealed by the beam tests will be corrected during April and then, beginning in late May 1989, the new Phase-I injector will be used (when needed) as the ATLAS injector during normal operation for research.

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