FIRST OPERATION OF THE ATLAS POSITIVE-ION INJECTOR

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Abstract

The construction of the ATLAS Positive-Ion Injector (PII) is complete and beam acceleration tests are underway. The PII consists of an ECR ion source, on a high-voltage platform, providing beam to a low-velocity-acceptance, independently-phased, superconducting linac. This injector enables the ATLAS facility to accelerate any heavy ion, including uranium, to energies in excess of the Coulomb barrier. The design accelerating field performance has been exceeded, with an average accelerating field of approximately 3.2 MV/m achieved in early tests. Initial beam tests of the entire injector indicate that all important performance goals have been met. This paper describes the results of these early tests and discusses our initial operating experience with the whole ATLAS system.

Introduction

The ATLAS Positive-Ion Injector(PII) is a new injector [1,2] for the ATLAS superconducting linac developed with the goal of providing beams of extremely heavy ions up to and especially including uranium for the ATLAS user program. This capability was to be achieved while also maintaining the excellent beam properties which ATLAS users have come to expect from the tandem injector/ATLAS system. With the PII, ATLAS is now able to provide ions across the entire periodic table with properties including: energies greater than the Coulomb barrier, excellent longitudinal emittance giving good energy and time resolution, good transverse emittance, and beam currents generally higher than can be obtained from the ATLAS tandem injector.

The construction of the Positive-Ion injector has proceeded in three stages. In the first stage, completed in 1989, the ECR ion source, high-voltage platform, low-energy beamline, and the first linac cryostat with five resonators (giving an effective voltage of 4 MV) were completed and initial beam tests were conducted. In this stage the basic concepts were tested with lower-mass ion beams and shown to be sound. The second phase of construction, finished in 1990, resulted in the completion of a second cryostat and a total of ten resonators (7 MV). Heavier ion beams accelerated in tests during this second stage continued to show good results. The completed PII accelerated first beams in April, 1992.

This report describes the results of the initial months of using the complete PII for beam acceleration. Observed beam properties are summarized together with the results of earlier beam tests during the first two stages of construction.

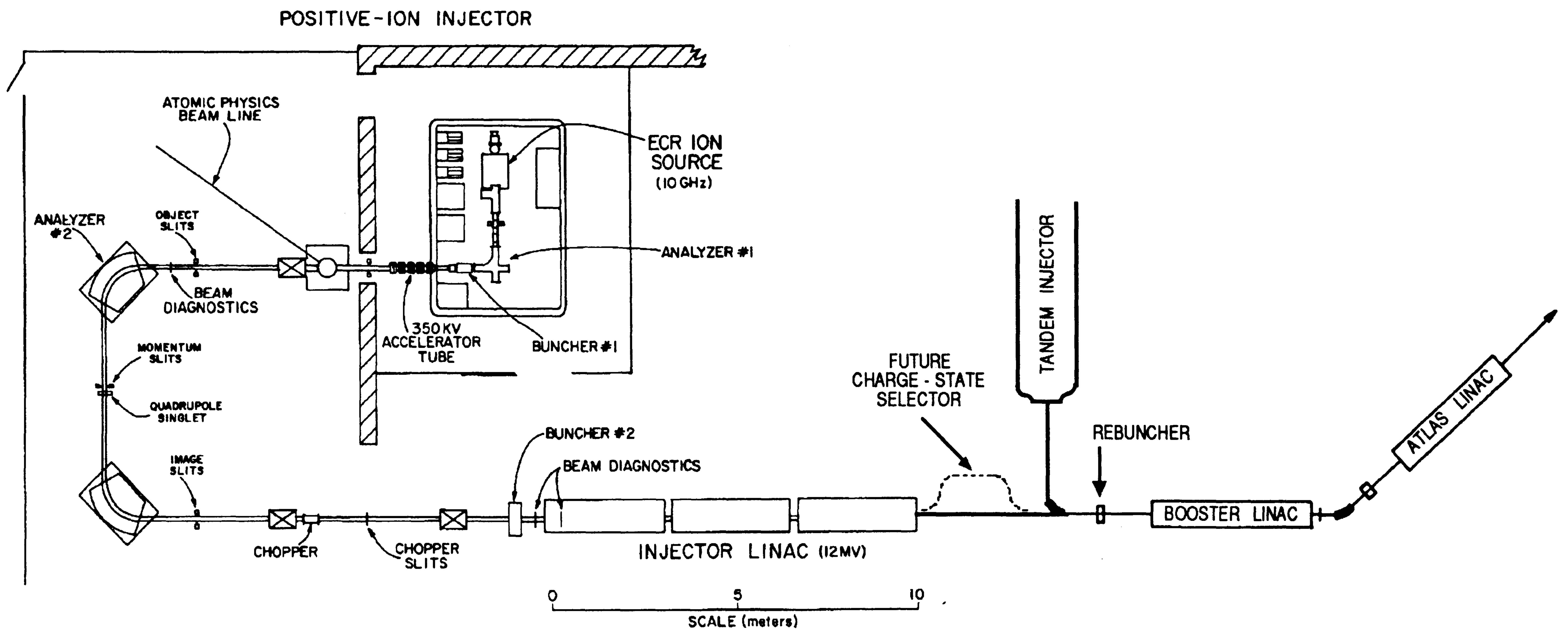

Fig. 1. Schematic floor plan of the ATLAS facility. The new PII is shown to scale with the remainder of the facility compressed and not to scale.

System description and performance status

The ATLAS Positive-Ion Injector design is based on a unique combination of technologies - an electron cyclotron resonance(ECR) ion source producing high charge-state ions and an independently-phased superconducting resonator linac. Such a design makes use of the high charge-state ions from the ECR ion source by accelerating them efficiently in a continuous-wave superconducting linac. The low emittance beams from the source are bunched by a sophisticated two-stage bunching system into narrow time packets for injection into the linac. The tightly bunched beam is then accelerated in the linac with a nearly linear dependence on phase error which minimizes distortion of the beam phase space. The result is an accelerator for nuclear physics near the coulomb-barrier with uniquely desirable beam properties including continuous-wave operation, easy energy variability, good beam-emittance properties in longitudinal and transverse phase space, and adjustable on-target energy and time spread.

The floor plan for the ATLAS PII in figure 1 shows the major components of the injector. The ECR ion source is mounted on a 350 kV high-voltage platform in order to provide ions to the linac with the required velocity of $\beta \approx 0.009$. New high-voltage isolation transformers have solved the early problems of high voltage breakdown and exhibit lower voltage ripple characteristics. The ECR ion source performance generally meets or exceeds the project design goals in routine operation. For the heaviest beams, 1 eμA of $^{208}Pb^{24+}$ and $^{238}U^{28+}$ was achieved, but the beam current for $^{238}U^{28+}$ was more typically 300-600 enA when UF_6 was used as a source material.

A three-component bunching system prepares the continuous beam from the ECR ion source for acceleration in the linac. First a four-harmonic gridded single-gap buncher, located on the ion source high-voltage platform, [3] compresses 60-70% of the beam into 1-3 ns FWHM bunches. The unbunched tails are removed by a sine-wave chopper assisted by the momentum resolution slits of the first 90^o analyzing magnet after the high-voltage platform. Finally, a sine wave buncher near the entrance to the linac rebunches the beam into bunch widths of 0.2-0.5 ns at the first accelerating resonator.

The linac consists of eighteen(18) independently-phased 4-gap resonators [4] in three cryostats providing approximately 12MV of acceleration voltage. Interspersed among the resonators are eleven superconducting solenoids which provide the necessary transverse focusing in the linac. The eighteen resonators in the PII linac have performed well. An improved design [5] of the fast tuner system (VCX) for resonator phase control has allowed the PII resonators to operate at higher field levels with phase lock maintained essentially 100% of the time. The average accelerating field for PII resonators has averaged between 3.0 and 3.5 MV/m during these tests.

Initial operating experience

Acceleration studies have now been conducted with a variety of beams. The beams used and the PII accelerated energies are listed in Table 1. Also listed are beam used in tests during the first two stages of construction. If the beam was used for test experiments, that is also noted in the table by an asterisk.

The results of beam tests at the first and second stage of construction, indicated that the beam quality from the PII was largely as calculated. The most serious problem identified in these tests was that transmission through the linac portion of PII was only 30-70%. The temporary beamline set up for these tests did not properly match the linac acceptance and it was felt that the transmission problems were due to this compromise.

The first beam transmission tests through the completed PII have confirmed this analysis. Unaccelerated beam transmission is 100%. The bunching system compresses approximately 60% of the DC beam into acceptable bunches. The total transmission through the PII linac of the bunched and accelerated beam is generally between 90-100%, giving a total efficiency of DC beam usage of 50-60%.

TABLE 1
Beam Parameters Used in ATLAS Positive-Ion Injector Commissioning Tests

Injector Linac Size	Date	Ion Species	PII Exit Energy (MeV)	ATLAS Energy Used (MeV)	Long. Emit. (π keV• ns)
3 MV	1989*	$^{3}He^{2+}$	2.8	28	<1
3 MV	1989	$^{13}C^{3+}$	8.7	42	
3 MV	1989*	$^{40}Ar^{12+}$	37	173	5
3 MV	1989	$^{40}Ar^{11+}$	34	239	
3 MV	1989*	$^{86}Kr^{19+}$	56	229	
7 MV	1990	$^{83}Kr^{17+}$	89	641	
7 MV	1990*	$^{86}Kr^{15+}$	88	415	19
7 MV	1990	$^{92}Mo^{16+}$	92	440	
12MV	1992	$^{30}Si^{7+}$	54	161	9
12MV	1992	$^{40}Ar^{11+}$	77	---	
12MV	1992	$^{132}Xe^{13+}$	53	---	
12MV	1992	$^{208}Pb^{24+}$	248	1018	16
12MV	1992	$^{238}U^{28+}$	293	1363	
12MV	1992	$^{28}Si^{5+}$	43	114	

The transverse and longitudinal emittances of beams provided by the tandem-injected ATLAS facility are very small. This feature has been exploited in the design of experiments where the excellent time structure and energy spread of the beam can be used to clearly identify reaction products, and in the accelerator design where relatively small apertures ($\approx$ 1.6 cm$\varnothing$) have been used while achieving excellent transmission. Maintaining the good beam quality obtained with the tandem-injected lighter ions was an important design criterion for the PII development. Calculations indicated that the PII injector could be expected to provide lighter ion (A<80) beams with even lower emittance than beams from ATLAS with the tandem injector. This was due in part to improved emittance from less stripping (in many cases none will be required) as well as better beam transport optics.

The longitudinal emittance of a number of beams has been measured during all three stages of the PII development. The results of these measurements are given in Table 1. The longitudinal emittance measured for these beams is approximately one half the measured longitudinal emittance of beams of similar mass from the tandem.

The transverse emittance of the system in not so well studied at this point. These expectations were that the transverse emittance of PII beams would be similar to that of beams from the tandem injector. The qualitative information and quantitative inferences support this view. The only quantitative results at this point is a measure of the emittance of the $^{208}Pb^{24+,39+}$ at 4.9 MeV/u. The normalized transverse emittance for this beam was measured to be $\gamma\beta\varepsilon = 0.2\pi$ mm• mr.

First acceleration of uranium

The first acceleration of uranium ions with the new Positive-Ion Injector of ATLAS was successfully accomplished during the week of July 27. A beam of up to 300-600 electrical enA $^{238}U^{28+}$ was provided by the ECR ion source and accelerated by the PII linac to 293 MeV. This beam was stripped to a 42+ charge state and further accelerated to 1363 MeV (5.7 MeV per nucleon) in the 'Booster' and 'ATLAS' linac. Beam current after stripping and acceleration was 6 enA at the exit of the accelerator (for 300 enA injected).

A number of important techniques were demonstrated and developed. The most important of these was the highly successful demonstration of tuning the 'booster' portion of the ATLAS linac with a 'guide' or 'analog' beam from the tandem injector. In this case $^{34}S^{6+}$, which has the same charge-to-mass ratio (q/m) as $^{238}U^{42+}$, was used. In addition to the same q/m ratio, the analog beam must also be injected with the same velocity and phase as the uranium beam. Corrections for energy loss in the stripping foil must be properly included in determining the matching conditions. This analog beam technique is necessary because a number of charge states are now injected into the 'booster' portion of the linac and so, before completion of the charge-state selector (planned for installation in FY93; see Fig. 1), 'tuning' of a single selected charge state is not possible for this section of the linac.

Beam transmission through the PII linac was excellent during this test. Total transmission through PII was 85-95%. Including bunching efficiency, over 50% of the DC source beam was delivered through the PII linac to the entrance of the booster linac. Transmission through the remainder of the ATLAS linac was approximately 80% after accounting for the stripping fraction to the 42+ charge state. This successful test built on a previous test of accelerating $^{208}Pb^{24+,\,39+}$ to 4.9 MeV per nucleon in May.

Conclusion and short-term plans

The initial test acceleration of beams using the new Positive-Ion Injector for ATLAS is nearly complete. During these tests, the beams have been used to actually carry out four experiments, further demonstrating reliability and beam quality. The use of the PII for routine operation is now ready to begin but a number of areas for improvement still need to be addressed.

Reliable operation for ^{238}U at 6 MeV/u is the goal which we now will work toward. We will strive to make improvements in cryogenic system capacity, resonator field level, and ion source operation in order to achieve this goal. The results of our initial operating tests are very encouraging and make us confident that this next goal will soon be achieved.

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