THE POSITIVE-ION INJECTOR OF ATLAS: DESIGN AND OPERATING EXPERIENCE*

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Abstract

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The recently completed Positive-Ion Injector for the heavy-ion accelerator ATLAS is a replacement for the tandem injector of the present tandem-linac system. Unlike the tandem, the new injector provides ions from the full range of the periodic table. The concept for the new injector, which consists of an ECR ion source on a voltage platform coupled to a very-low-velocity superconducting linac, introduces technical problems and uncertainties that are well beyond those encountered previously for superconducting linacs. The solution to these problems and their relationship to performance are outlined, and experience in the operation of ATLAS with its new injector is discussed.

1. Introduction

The main subject of this paper is the new Positive-Ion Injector (PII) of the heavy-ion accelerator ATLAS. To understand this injector one needs to know something about ATLAS as a whole: user requirements, design issues, technical challenges, and shortcomings. The layout of the ATLAS facility is shown in Fig. 1. Until recently ATLAS has been a tandem-linac system in which a 9-MV tandem is the source of ions for injection into a superconducting (SC) linac. The ATLAS linac consists of two parts: the original prototype "booster linac" built in the mid 1970's (the first useful superconducting accelerator for ions) and the 1985 ATLAS addition. The most recent upgrade is PII, on the left in Fig. 1.

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Even though the SC linac is now the main part of ATLAS, beam requirements and the operating mode are still those of a large tandem. That is, a wide range of ions are accelerated, the output-beam energy is easily varied, the transverse emittance ϵ_r of the beam is good, and the ion species and/or beam energy are changed frequently. The one major difference is the inherent pulsed character of the linac beam, which is an immense asset for some research because it permits time-of-flight and other fast-timing measurements to be carried out with a level of refinement that was not feasible previously for heavy ions. The pulse-resolution width achieved is 100 to 200 ps.

The tandem-linac version of ATLAS functions as follows: the DC beam from the negative-ion source is bunched before injection into the tandem, stripped by a thin ($\sim 2 \mu\text{g}/\text{cm}^2$) carbon foil in the terminal, accelerated to ground potential, chopped to remove unbunched ions, stripped a second time if a higher charge state is needed, analyzed, and rebunched to form narrow (~ 100 ps) beam pulses that are matched in longitudinal phase space to the linac. The phase of the pre-tandem buncher is controlled by the beam-pulse-arrival time at a "phase detector" near the rebuncher.

The SC linac of ATLAS consists of an array of short independently-phased RF accelerating structures and SC focussing solenoids, both at $\sim 4.6^\circ\text{K}$. Resonators with RF frequencies of 97 and 145.5 MHz are used, both harmonics of the beam-pulse frequency, 12.125 MHz. Each resonator has 3 accelerating gaps, a small enough number to enable it to accelerate well over a range of velocity.

2. Description of the Positive-Ion Injector

The tandem-linac version of ATLAS is a valuable research tool that has provided $>45,000$ hr of beam on target for research. However, the tandem injector has two serious drawbacks: (1) an inability to provide beams in the

upper half of the periodic table and (2) less beam current than some users want. The new injector PII shown in Fig. 2 removes both of these deficiencies. The PII consists of an ECR source on a 350-kV platform coupled to a CW 12-MV drift-tube SC linac. A refined beam-preparation system matches the beam to the linac in 6-dimensional phase space. First discussed publicly in 1984 [1], PII was completed in March 1992 and is now being used for research. Features of the injector have been reported [2-10] throughout its development and construction.

The ECR ion source [6] was designed in 1986 and its characteristics are typical of other ECR sources of that time. RF power is provided by a 10-GHz klystron. The ion-extraction voltage for the source is in the range 12 to 18 kV. The source and other equipment on the platform are powered (140 kW) by isolation transformers.

The beam-bunching system [5] consists of a gridded 4-harmonic buncher on the voltage platform and a high-Q 24.25-MHz room-temperature spiral resonator at the linac entrance. The harmonic buncher, which has a fundamental frequency of 12.125 MHz, is an improved version of one developed for the tandem [11].

The main goal for the injector linac is to accelerate the heaviest ions from their very low incident velocity of $\beta \approx 0.008$ up to at least 0.045 without much degradation of beam quality. Four different kinds of resonators [4,7] are used for this purpose. All of these units have 4 accelerating gaps formed by 2 drift tubes driven by a quarter-wave line and a third drift tube tied to the housing. The quarter-wave line and the drift tubes are pure niobium whereas the housing is made from niobium explosively bonded to copper. Some key parameters for the resonators are given in Table 1. Note that the active length of the first unit is only 10 cm, and in this short space the beam energy is more than doubled. This extremely rapid increase in beam velocity generates some unusual beam-optics effects. A critical issue in the design of a low-

velocity linac is how to control beam defocussing caused by the RF acceleration process, a problem that increases rapidly with decreasing beam velocity. In PII this problem is controlled with SC solenoids located before and after each resonator near the front end of the linac. See Fig. 5 in [9].

3. Performance of PII

Tests of PII have been carried out at three different phases [8-10] of the construction process and, as summarized by Table 2, ion species from throughout the periodic table have been accelerated. For the first two series of tests [7] only a part of the injector linac was installed. However, a Type I₁ resonator and at least one Type I₂ resonator were present in all tests. Since it is believed that these low- β_0 units are the main source of beam-quality degradation, it became clear at an early stage that the potential problems associated with the low-velocity end of the machine had been largely avoided.

At the design field levels of the resonators, the beam energy out of PII ranges from ~ 1.1 MeV/A for ^{238}U to ~ 2.0 MeV/A for ions with $q/A = 0.5$ (Fig. 6 of [9]). In off-line tests of resonators the maximum accelerating fields are much greater than the design values (Table 1), and in on-line operation they perform well at the design levels.

A topic of major interest for PII is beam quality; specifically, are the transverse and longitudinal emittances seriously degraded during acceleration through the injector linac? The results [8-10] to date are very encouraging. For transverse phase space, the normalized emittance $\gamma\beta\epsilon_r \approx 0.2 \pi$ mm-mrad, about the same as for equivalent beams from our tandem with a foil stripper. Beam transmission approaches 100% for all ions. Good longitudinal beam quality receives special emphasis at ATLAS because many of our users require very narrow and stable beam pulses. To achieve such pulses, at the input to the injector linac we require: (1) an energy stability better than 1 part in 10^4 ,

(2) longitudinal emittance small enough for the 1st-stage buncher to form beam pulses < 3ns (FWHM) wide at the 2nd stage buncher, and (3) a layout that permits the 2nd-stage buncher to form pulses in the range 0.3-0.5 ns wide in the first accelerating structure. These have all been achieved.

Initially, a source of concern was the unusual (indeed, pathological) behavior of some characteristics (Fig. 7 of [9]) of the first few resonators because of the rapid increase in beam velocity. However, both calculation [12] and performance show that this behavior does not cause much degradation in beam quality. The injector linac is easy to tune and operates stably for long periods of time.

4. Beam acceleration with the complete PII-ATLAS system

Most of the beams from PII listed in Table 2 have been accelerated through the main ATLAS linac and some have been used for research. All of this experience indicates that the complete PII-ATLAS system operates as planned [8-10].

The energy-performance goals for ATLAS are summarized by Fig. 3. The superiority of PII as an injector is obvious. The main challenge is to achieve the indicated performance for the heaviest ions such as ^{238}U . This goal is not yet fully achievable because of imperfections in the main ATLAS linac. In particular, the velocity profile of the linac was originally optimized for a charge-to-mass ratio of ~ 0.34 , whereas for ^{238}U a profile suitable for ~ 0.17 is needed. This change and other improvements are now underway and will be completed by mid 1993. In the meantime, the present system can accelerate all ions to $\sim 80\%$ of the levels indicated in Fig. 3, and these beams from PII are in great demand by ATLAS users.

The acceleration of uranium ions was first successfully accomplished [10] in late July and repeated in September. In the first run, 300

electrical $nA(enA)$ of $^{238}U^{28+}$ from the ECR ion source was accelerated by PII to 293 MeV. These ions were then stripped to a $42+$ charge state and accelerated to 1363 MeV (5.7 MeV per nucleon) in the main ATLAS linac. The beam current at the accelerator output was about 6 enA. Taking into account the low stripping fraction of the $42+$ charge state, the overall transmission of the system (source to ATLAS output) was excellent, about 40%. Improvements completed and/or in progress are expected to increase soon the ^{238}U beam current by an order of magnitude.

The main operational challenge for beams stripped at the output of PII is how to tune the booster linac with a beam containing many charge states. This problem will be eliminated in 1993 by the installation of a charge-state selector between the stripping foil and the booster linac. Until then, the booster will be tuned with a "guide" beam that has the same q/A ratio and the same velocity as the ion species of interest. The guide beam used to tune for $^{238}U^{42+}$ was $^{34}S^{6+}$ from the tandem. This tune allows $^{238}U^{42+}$ to be transmitted with high efficiency, but other charge states of ^{238}U are also accelerated. These unwanted beams are eliminated by magnetic analysis in the 40° bend after the booster linac. The guide-beam technique seemed difficult to implement initially but, after tuning several stripped beams, the procedure has become routine.

One of the most gratifying characteristics of PII-ATLAS performance is the excellent longitudinal beam quality. Figure 4 shows longitudinal emittance ϵ_z as a function of A/q , where ϵ_z is defined to be $\pi \Delta E_0 \Delta t_0$ and both ΔE_0 and Δt_0 are half widths at half maximum. The data for PII are not a systematic set since they were acquired as a by-product of accelerator tests over a period of time and under different conditions [8-10]. Nevertheless, the figure shows clearly that: (1) ϵ_z tends to increase with increasing A/q

and (2) the values of ϵ_2 for beams from PII are substantially smaller than for beams from our tandem injector.

In summary, experience to date in the operation and use of PII as the ATLAS injector has demonstrated that all design goals for PII have been met. Beam energies for PII exceed design values, beam transmission of the injector linac approaches 100%, the longitudinal emittance sets a new standard of excellence, and the system runs stably for long periods of time. The new injector has expanded immensely the research capabilities of ATLAS.

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Table 1

Parameters of PII accelerating structures: β_0 is optimum ion velocity, L_a is active length, D is aperture diameter, F_a is design accelerating field

	<u>I_1</u>	<u>Resonator Type</u>		<u>I_4</u>
		<u>I_2</u>	<u>I_3</u>	
β_0	0.008	0.015	0.023	0.036
L_a (cm)	10.2	16.5	25.4	25.4
D (cm)	1.5	1.9	2.5	2.5
f (MHz)	48.5	48.5	48.5	72.75
F_a (MV/m)	4.5	3.0	3.0	3.0

Table 2

Beams accelerated by PII. In most cases, ATLAS energies are not maximum capabilities.

PII Linac Size	Date	Ion Species	Beam Energy		ϵ_z (π keV-nm)
			PII (MeV)	ATLAS (MeV)	
3MV	1989	$^3\text{He}^{2+}$	2.8	28	<1
3MV	1989	$^{13}\text{C}^{3+}$	8.7	42	
3MV	1989	$^{40}\text{Ar}^{12+}$	37	173	5
3MV	1989	$^{40}\text{Ar}^{11+}$	34	239	
3MV	1989	$^{86}\text{Kr}^{19+}$	56	229	
7MV	1990	$^{83}\text{Kr}^{17+}$	89	641	
7MV	1990	$^{86}\text{Kr}^{15+}$	88	415	19
7MV	1990	$^{92}\text{Mo}^{16+}$	92	440	
12MV	1992	$^{28}\text{Si}^{5+}$	43	114	
12MV	1992	$^{30}\text{Si}^{7+}$	54	161	9
12MV	1992	$^{40}\text{Ar}^{11+}$	77	--	
12MV	1992	$^{83}\text{Kr}^{15+}$	127	765	
12MV	1992	$^{132}\text{Xe}^{13+}$	53	--	
12MV	1992	$^{208}\text{Pb}^{24+}$	248	1018	16
12MV	1992	$^{238}\text{U}^{28+}$	293	1363	

Figure captions

1. Layout of ATLAS.
2. Layout of the Positive-Ion Injector.
3. Projected performance of ATLAS.
4. Summary of data for longitudinal emittance ϵ_z .

ATLAS (1992)

Fig. 1

POSITIVE-ION INJECTOR

Fig. 2

Fig. 3

Fig. 4

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