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The ATLAS Positive-Ion Injector Project*

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Abstract

The goal of the Argonne Positive Ion Injector project is to replace the ATLAS tandem injector with a facility which will increase the beam currents presently available by a factor of 100 and to make available at ATLAS essentially all beams including uranium. The beam quality expected from the facility will be at least as good as that of the tandem based ATLAS. The project combines two relatively new technologies - the electron cyclotron resonance ion source, which provides high charge state ions at microampere currents, and RF superconductivity which has been shown to be capable of generating accelerating fields as high as 10 MV/m, resulting in an essentially new method of acceleration for low-energy heavy ions.

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Introduction

Superconducting heavy-ion linacs are one of the most successful applications of RF superconductivity today. Their development as energy boosters for existing tandem electrostatic accelerators has served to constrain many of the design parameters of the linacs such as frequency, synchronous velocity range, and phase stability requirements. The relatively low emittance and low energy spread of beams from a tandem provided an opportunity to develop an accelerator system with increased particle energy as well as beam properties which had not previously been available in the few MEV/A regime, for example, narrow beam pulses and ($\text{FWHM} \approx 0.1 \text{ ns}$) excellent energy resolution ($\Delta E/E \approx 10^{-3}$).

The existing ATLAS facility provides beams of heavy-ions through approximately mass 130 primarily for nuclear physics research. Available energies range from over 20 MeV/A for lighter ions down to approximately 5 MeV/A for mass 130. In discussions with our user group concerning future program needs, two major areas of focus emerged. The first was a desire to increase the beam intensities for all ion species available by a factor of ten to one hundred over what is possible from our present negative-ion source and tandem injector. The second was to obtain beam energies of 7 to 10 MeV/A for all possible masses through uranium. These features were desired without compromising the present qualities of the ATLAS facility: good beam quality, ease of operation, and continuous wave (cw) operation.

The Positive Ion Injector (PII) project [1] will address these goals by replacing the negative-ion injector and FN tandem with an electron cyclotron resonance (ECR) positive-ion source and a superconducting linac of a new design which makes use of the high field gradients possible from superconducting structures. The total effective accelerating voltage for the

completed Positive Ion Injector will be approximately 12MV. The beams from this new injector accelerator will then be further accelerated in the existing ATLAS superconducting linac. A schematic representation of the completed facility is shown in Figure 1. Figure 2 is an enlargement showing the Positive Ion Injector in more detail.

The positive ion injector project will progress in three phases. In the first phase, which is underway, the ECR source system and a 3MV prototype linac is being constructed. Even this small injector will provide sufficient energies and beam currents to exceed the tandem performance in some ways. Phase II will increase the total voltage of the PII to 8MV. Finally, the complete uranium capability of the machine will be realized in Phase III with the enlargement of the PII to a total voltage of 12MV.

The ECR positive ion source

The electron cyclotron resonance (ECR) positive-ion source has been demonstrated to be an exciting new technological development in the production of extremely high currents of high charge-state heavy ions. Much of the early development has come from the efforts of Geller [2]. The beam properties of the ECR source which make it an attractive option for this application are:

- 1) high charge state heavy ions,
- 2) small energy spread (apparently less than $5 \cdot Q$ ev),
- 3) good transverse emittance ($\gamma\beta\epsilon \approx 0.2 \pi \text{ mm-mr}$),
- 4) high operational reliability, and
- 5) large beam currents in comparison to a negative-ion source.

For the PII project, the ECR positive-ion source will be mounted on a high-voltage platform providing up to 350-kv potential for preacceleration of

the ions. This will produce, for example, 7 MeV $^{238}\text{U}^{20+}$ with a velocity of .008c. The ions will be bunched in a two stage bunching system providing a pulsed beam with a time width of the order of 0.3ns for injection into the linac. In Figure 3 the charge state of ions expected from an ECR source across the periodic table are plotted on three curves representing three different levels of electrical beam current. The curves shown represent a smoothed, by eye, fit of published information for all heavy ion ECR sources as of early 1986.

A most important question for our application of ECR sources is the possibility of obtaining ions from solid materials. ECR sources have historically operated only with gases. In the last two years, a number of laboratories have begun to use solid material feed. The experience from these laboratories is quite encouraging and, for many solid materials which have been attempted, one sees that the results fit quite nicely on the curve of figure 3. Use of solid material as the primary feed material for the ECR source is an extremely high priority for this project. Therefore, a significant effort has been expended in order to make the source design as flexible as possible for accepting solids.

A more complete description of the ECR source design can be found in [3]. The source is expected to be operating by June, 1987. During the remaining construction and testing time of the PII, the source will be available for development and may be used by other experimental programs such as the atomic physics program at Argonne later.

The Linear Accelerator

The linac design adopted is a superconducting linac of independently-phased resonators. The first stages of acceleration will consist of short

resonator structures followed by superconducting solenoids to refocus the beam. The initial cell length is short because of the use of superconductivity for both the RF resonators and transverse focusing solenoids.

Essentially two issues dominate the design of a low-velocity heavy ion linac. One issue is the problem of transverse defocusing, and the emittance growth that can occur if the beam size is allowed to become too large in the accelerating field regions. The second is the design of suitable accelerating structures for ions with velocities as low as, in this case, $0.008c$. When a linear accelerator operates in the 'phase focusing' mode the beam is continually rebunched in longitudinal phase space in order to preserve the beam quality. Because of the phase requirements for longitudinal focusing, the accelerating fields are radially defocusing to the beam. This compounds the problem of the large unnormalized emittance due to low ion velocity. If these problems are allowed to result in large beam sizes in the accelerating regions, then emittance growth can occur in both transverse and longitudinal phase space due to variations in the accelerating field with radius. These radial defocusing forces must be counteracted by some other focusing forces in order to maintain acceptable beam size and with a periodicity which is determined partially by the beam emittance and partially by the accelerating fields and structures. This problem is quite severe at low velocities because the beam emittance is relatively large and also the beam rigidity is small.

Our approach to this problem separates the accelerating regions and transverse focusing regions into physically discrete, alternating regions. These regions can be kept short due to the choice of single cavity, high gradient superconducting resonators and short, iron shrouded superconducting solenoids for focusing. The choice of radially focusing solenoids and the

separation of these focusing elements from the accelerating region is quite important in minimizing beam size in the resonators. The small beam size in the resonators minimizes the coupling between the radial and longitudinal phase space. A picture of the low velocity region of the positive-ion injector for the Phase I PII is shown in figure 2. The first resonator, approximately 10 cm long, provides about 500 kv of accelerating potential and approximately doubles the beam energy. The radial defocusing effects produced by the first resonator are compensated by the superconducting solenoid which immediately follows. The large energy gain provided by these resonators also assists in the transverse dimension by reducing the unnormalized transverse phase space rapidly. As the beam energy increases the beam divergence decreases and the ratio of accelerating region to transverse focusing region can be allowed to increase. At the end of the low-velocity accelerating region, the beam velocity will be approximately $.03c$ and the remainder of the accelerating process can be handled in a manner essentially the same as is presently employed in the existing ATLAS linac.

The sequence of resonant cavities shown in Figure 2 for Phase I will be modified as the PII is expanded in Phase II and III. Additional resonators of the $\beta = .015$ and $\beta = .028$ class will be required for acceleration of the heaviest of ions such as uranium. Also, the design of the resonators identified as $\beta = .045$ is still being developed. Therefore these are shown only as "white boxes".

Low-Velocity Accelerating Structures

The PII linac requires superconducting accelerating structures that match particle velocities a factor of six lower than has previously been done. This is being accomplished by going to a low frequency and also by using a short

accelerating gap [4].

The low frequency is achieved by using a coaxial quarter-wave resonant line, which has such good mechanical stability that operation at 48.5 MHz, one-half the ATLAS frequency, is possible. A short accelerating gap is obtained by terminating the line with a four-gap interdigital structure, rather than a simple drift-tube. Several different versions of this type of resonator are required to span the velocity range in the injector linac.

The first of these structures has been constructed and tested and found to provide accelerating fields up to 10 MV/in at 4.2 K [5].

The matched velocity for the first cavity is .009c and because of the high gradients achieved, it is the only resonator of this type which will be needed, even for uranium acceleration. The mechanical stability of this resonator is good enough that phase control with our present techniques will work well.

A prototype of the second resonator type required is near completion and probably will be tested in November of this year.

Performance

The expected energy performance of the Positive Ion Injector during the three phases of the project is shown in Figure 4 for high current charge states from the ECR source. Figure 5 shows the resulting energy performance of ATLAS during project while Figure 6 emphasizes the beam current capabilities resulting from the project at a representative energy. This performance is compared to the present ATLAS capabilities using the tandem as the injector. These results depend strongly on the actual performance of the ECR source. The performance discussions here assume charge states and currents taken from Figure 3. For heavier beams, one to two

additional stripping foils are also assumed to be used in these calculations. The use of foil stripping and higher charge states from the ECR source are the cause for the loss in beam intensity of heavier ions that is indicated in Figures 5 and 6 for the earlier phases of the project. It is apparent from Figures 5 and 6 that even the small 3MV injector prototype of Phase I allows a new regime of current and energy to be accessed that is unavailable with our tandem.

One of the most exciting possibilities of the PII comes from the potentially excellent longitudinal beam quality from the accelerator. The inherent ECR source energy spread is not well known, but all information [6,7] indicates that it is less than $5 \cdot Q$ ev where Q is the ion charge state. This low energy spread has encouraged us to consider various ways in which this property can be exploited in order to yield improved beam timing and energy spread. Many issues come into consideration in an effort to keep the longitudinal emittance as low as possible. The features of the design that bear strongly on this issue are:

- I. highly stable source power supplies ($dE/E=10^{-4}$),
- II. first stage bunching on the high voltage platform,
- III. use of a driven bunching wave form to obtain as good a wave form as possible,
- IV. use of a doubly isochronous transport system from the source to the PII, and
- V. careful design of the PII optics in order to minimize emittance growth in the acceleration process.

These issues are being studied rather thoroughly using a combination of calculational aids. For the PII, a ray-tracing program in transverse and longitudinal phase space has been used. This approach was required because of

our concern about coupling between the radial dimension and longitudinal dimension and due to the short focal length of the first resonators, which make the normal matrix optics assumptions suspect in the early stages of acceleration. The case studies completed so far indicate that the longitudinal emittance growth during the early, most difficult region of the accelerator never exceeds a 50% increase from the input value from the source system.

The transverse phase space for sources in which ions are produced in magnetic fields is expected to be constrained by the requirements of angular momentum conservation as the particles emerge into a field free region. This emittance limit scales as q/A which implies that the emittance for the heavier ions with $q/A = 0.1$ may be less than that for lighter ions where $q/A = 0.5$. Again, actual emittance data is scarce for these sources. Measurements on a Geller source [8] and the Berkeley source [9] indicate the transverse emittance to be less than what would be expected from the theoretical model. In fact it appears that the beam emittance decreases with increasing charge state. Using the empirical transverse emittance data on ECR sources, beam optics calculations show that the coupling between radial and longitudinal phase space can essentially be ignored in our design geometry and there is no transverse emittance growth in the early stages of acceleration. These pleasant results can largely be attributed to the high ion charge state from the ECR ion source, the large accelerating RF field of the superconducting resonators, and the strong radially symmetric focusing of the superconducting solenoids. We believe that the longitudinal emittance of the beam from the PII may be a factor of 2 better than is presently obtained with our tandem system. For heavier beams, the improvement may be even more significant. Therefore, we expect our PII-ATLAS facility to set new standards in beam

current and beam quality for heavy-ions.

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Figure Captions

- Figure 1. Plan view of the ATLAS facility and the Positive Ion Injector project.
- Figure 2. Schematic view of the Positive Ion Injector. The magnified regions show the family of low velocity resonators which are planned for the PII project and these possible arrangement during Phase I and some details of the ECR ion source.
- Figure 3. Charge state distribution from ECR sources. Data for this figure were taken from a wide variety of published and unpublished literature. The smooth curves for three different current intensities are used in calculation of the expected performance of the PII and ATLAS.
- Figure 4. Expected beam energy from the Positive Ion Injector as a function of mass for the three project phases. Termination of the tandem curve at mass 120 reflects the inability of the tandem to transmit adequately heavier beams and the limitation of performance due to foil lifetime.
- Figure 5. The beam energies expected from ATLAS with different injector assumptions but within assumed beam intensity of 3 pA.
- Figure 6. Beam current from ATLAS versus mass number for the various possible injector types at a fixed energy of 5 MeV/A. The beam

currents shown reflect the choice of charge states required from the source for a given total accelerating voltage and the need to perform additional stripping to higher charge states for the various configurations.

ATLAS

Fig. 1

ARGONNE POSITIVE ION INJECTOR SYSTEM

Fig. 2

Fig. 3

Fig. 4

Fig. 6