THE BEAM OPTICS OF THE ARGONNE POSITIVE-ION INJECTOR

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Abstract

The beam optics for Phase I of the Argonne Positive-Ion Injector linac system have been studied for a representative set of beams. The results of this study indicate that high charge state beams from an ECR source can be accelerated without significantly increasing the transverse or longitudinal emittance of the initial beam. It is expected that the beam quality from the PII-ATLAS system will be at least as good as presently achieved with the tandem-ATLAS system.

Introduction

The goals of the Argonne Positive-Ion Injector(PII) project are to increase the beam currents by a factor of order 100 compared to those presently available and to provide heavy ions of energies of at least 8 MeV/A through uranium. These goals should be met while at the same time maintaining the present beam quality and flexibility of the system.

To achieve these goals an accelerator system is being developed that consists of two major components: a) an electron-cyclotron resonance (ECR) ion source[1] on a 350-kV platform and b) a low-velocity matched superconducting linac[2] with an eventual total effective voltage of about 12 MV. The linac is made of short, independently phased superconducting resonators[3] interspersed with superconducting solenoids to provide transverse focusing for the beam. The project will procede in three phases.

The first phase of this project is underway and will consist of the ECR ion source and a single cryostat with five resonators.[4] This small system is expected to provide a total voltage of approximately 3 MV for a velocity matched particle.

We have investigated the beam optics in this Phase I configuration for light and medium mass beams. This paper presents the results of this investigation and describes the calculational tools used.

Method of Calculation

A ray tracing program with cylindrical symmetry was used to investigate the beam optics of the PII linac. A total of 150 particles were initialized with a uniform random distribution within the assumed injected phase ellipse. The particles were then projected through the linac using two different algorithms.

Single particles were traced through the resonant cavities by numerically integrating the equations of motion with a step size of approximately 1 mm. The electromagnetic fields in these very-slow-wave structures can be accurately represented near the drift tubes with a near-field, electrostatic approximation. The quasi-static fields were calculated numerically using a matrix approximation to Poisson's equation for the actual drift-tube geometries. The fields were calculated over a mesh of points on and near the beam axis and a look-up table was formed for each type of resonant cavity. The particle tracing routine used the look-up table to obtain electromagnetic field values at each particle position. The calculated field values agree, within an experimental error of several percent, with dielectric perturbation measurements of the field on the beam axis. The calculated values are estimated to be accurate to a few parts in 10^5, and are in fact the most accurate values available for the actual electromagnetic fields.

The treatment of the solenoids and drift regions was by a first order matrix formalism. Each particle's initial position and divergence was transformed to an exit position and divergence. Because cylindrical symmetry was assumed in these calculations, the angular rotation of the ellipse in the solenoid was ignored.

Assumed Linac Geometry and Initial Beam Properties Assumed

The extremely good longitudinal beam quality of the present ATLAS system allows experiments to be carried out using a resonator either to form a time waist on target which is approximately 150 ps FWHM or to debunch and produce an energy resolution of the order of 10^{-3}. It is important that the PII-ATLAS system continue to provide beams of very high quality.

In order to maintain, or possibly improve, the present level of beam quality, the nonlinear acceleration and transport effects must be minimized throughout the system. The requirement that the beam be captured in an RF bucket is not a sufficiently stringent condition. Rather it is desired that acceleration occur without appreciable emittance growth. The ability of the linac to accelerate the injected beam in a linear fashion is strongly dependent on the actual initial area of the beam phase space and the shape of the injected ellipse.

The transverse phase space volume occupied by the beam from the ECR source system is determined by the inherent source properties and second order transport errors. The normalized emittance of beams from ECR ion sources is not well known but recent emittance measurements[5] are in the range for of 0.1 to 0.2π mm-mr. A value of 0.2π mm-mr has generally been used for these calculations.

The DC beam from the ECR source will be bunched in two stages in order to prepare it for injection into the PII. The first stage of bunching will occur on the high voltage platform. Bunching on the platform is important, not only to reduce the voltage requirements for the first capture buncher, but also to reduce the effect of instabilities in the high voltage (350kV) ion source system. The beam transport to the linac must also be made isochronous so that path length differences in the magnets do not add unduly to the time spread in the beam. When these various effects are considered, it appears that the longitudinal emittance of the beam injected into the PII linac will be between 10 and 20 keV-ns for most beams through mass (A) ~ 58. In these calculations, longitudinal emittance values between 20 and 96 keV-ns have been studied.

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The linac geometry assumed in these calculations is shown in Fig. 1. Resonators and solenoids are alternated through the first three short resonators in order to maintain a small beam diameter in the accelerating regions. After the third resonator, the beam energy has increased enough to allow pairs of resonators to be alternated with a single solenoid. Even so our calculations show that some longitudinal emittance growth can occur at this point for slower beams.

The solenoids modeled in this calculation are shorter version of superconducting solenoids used in the present ATLAS linac. The solenoid effective length is assumed to be 7.5 cm and the actual physical length is assumed to be 18 cm. These assumptions imply that field strengths of about 10 T. will be required for some solenoids for the heaviest beams.

Results of Calculations

The beams $^{16}O^{7+}$ and $^{58}Ni^{15+}$ have been studied extensively for the 3-MV machine. The heaviest beams such as uranium cannot be effectively accelerated until the remainder of the project is completed. Therefore only a cursory investigation of these heavier beams has been undertaken. The design study for the complete PII will be undertaken later. A summary of the important parameters for the most informative cases is given in Table I. The beam ellipses in radial and longitudinal space shown in Figs. 2-3 correspond to the first ^{58}Ni case in Table I.

For a wide variety of assumed entrance conditions and beam parameters, we find that the linac provides acceleration without significant ($\leq 10\%$) growth in transverse emittance and with growth in longitudinal emittance of approximately 20-30%. The longitudinal emittance is significantly more sensitive to the precise details of the acceleration process than is the transverse emittance.

One reason for the excellent linearity of the acceleration process in these early stages of the linac is the modular nature of the design. The use of small resonant cavities which are flanked by focusing solenoids means that the beam radius is extremely small inside a resonator where the radially varying accelerating field is located. Therefore, the beam not only experiences relatively small radial forces but also the longitudinal emittance is not badly distorted by the variation in longitudinal accelerating fields with radius.

Another important point is that these resonators do not behave, in general, as simple lenses. The extremely rapid variation of velocity for particles in a resonator and the four-gap structure of the resonator produce a form of alternate phase focusing within each resonator.[6] The result is that, for the cases reported here, the first resonator is strongly focusing in both transverse and longitudinal phase space. The transverse and longitudinal focal length for the first resonator is approximately 15cm. in the case of the ^{58}Ni studies when operated at a phase angle (ϕ) of 22 degrees with respect to maximum energy gain.

The details of the effect are very strongly dependent on initial velocity and the charge to mass ratio (q/A) of the particle. Therefore, we do not plan to exploit this feature in the PII. Instead the choice of forming a radial waist in each resonator minimizes the radial focusing effects as well as the defocusing that occurs in other situations. In fact, the variation in resonator radial lens strength results in less than a 10% effect on the required solenoid field strengths.

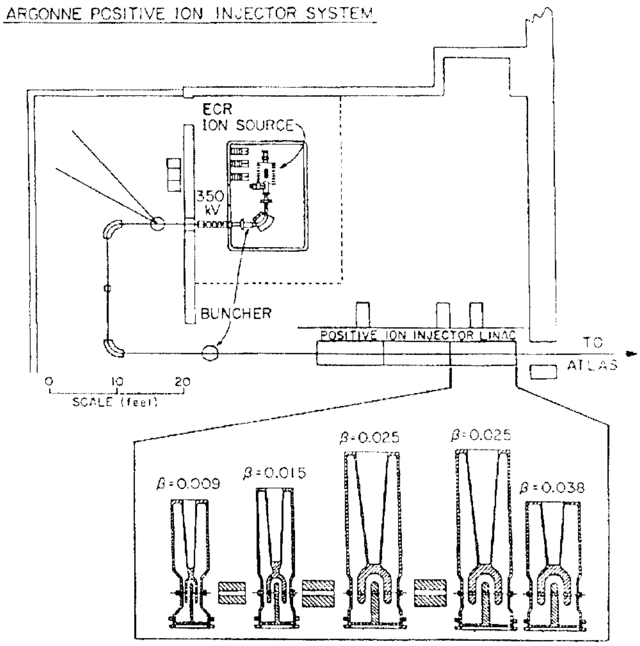

Fig. 1
The geometry in PII linac used in these studies.

A most important question to address in this study concerns what approximations may be made in obtaining a qualitative understanding of the acceleration process in this accelerator. For many accelerators, it is possible to derive useful matching criteria using a uniform acceleration model. This model and other requirements lead to conditions on the shape of the beam ellipse presented to the linac which result in minimum emittance growth. For such a condition, the energy spread at the entrance to the linac for a beam of emittance (dUdt) should be:

$$\delta U = 115[(q/A)*F*\sin\phi]^{1/4} A^{3/8}(dUdt)^{1/4} \quad {}^{7} \qquad (1)$$

where F is the RF frequency.

The last two entries in Table I compare a beam prepared according to equation (1) as opposed to injection of a beam whose time width is the same as for a beam of lesser emittance. The longitudinal emittance growth is dramatic in the 'poorly matched' case. The use of the analytical model clearly gives a useful guide to the proper shape of the longitudinal emittance ellipse for minimum distortion to occur during acceleration.

These studies predict that the problems of beam blowup in the low velocity region of the PII will not be significant. Emittance growth in the accelerator for beams with the properties assumed here should be small. This is due to the separated function design of the linac and to alternating phase focusing effects in each resonator. Other sources of emittance growth such as RF phase and amplitude instabilities and second order path length effects in the beam transport system are not expected to be serious problems in maintaining good beam properties.

Table I

Beam Optics Parameters for The Argonne Phase I PII

Ion	Init. Energy (MeV)	Final Energy (MeV)	Init. Transverse γβε(mm-mr)	Final Transverse γβε(mm-mr)	Init. Rad mm.	Init. Div. mr.	Init. Longitudinal ET(keV-ns)	Final Longitudinal ET(keV-ns)	Init. DE keV	Init. DT ns.
$^{16}O^{7}$	2.59	16.20	0.32	0.34	1.5	12.	20.	20.	96.	0.2
$^{58}Ni^{15}$	5.50	42.35	0.22	0.24	1.5	12.	33.	40.	92.	0.2
$^{58}Ni^{15}$	5.50	42.35	0.22	0.24	1.5	12.	100.	25.	208.	0.5
$^{58}Ni^{15}$	5.50	42.35	0.22	0.28	1.5	12.	100.	300.	480.	0.2

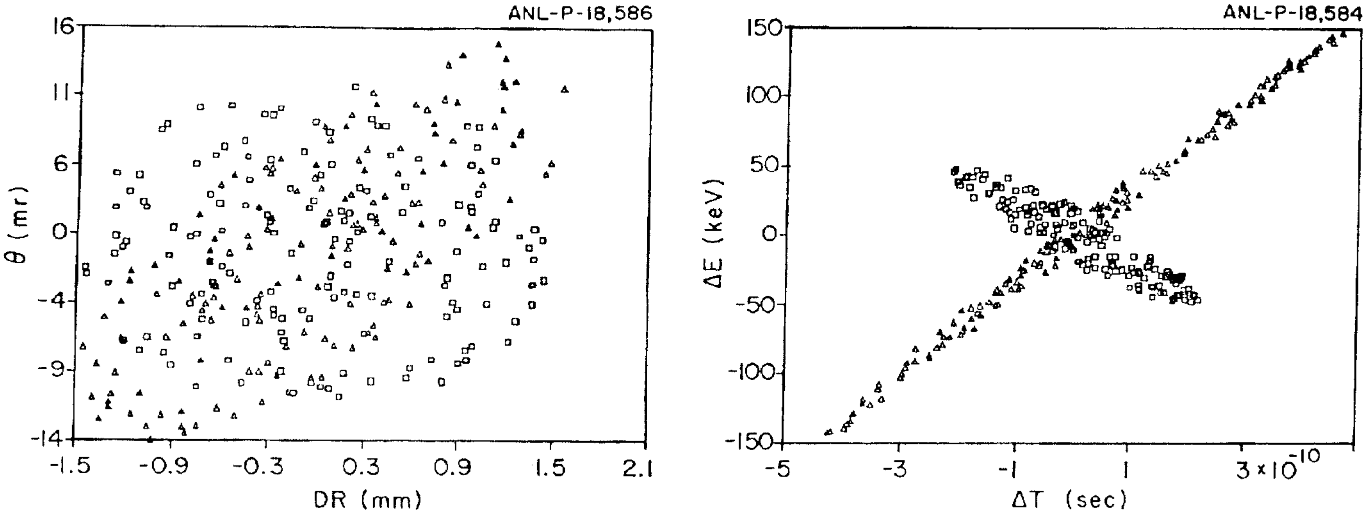

Fig. 2a

Fig. 2b

The radial (a) and longitudinal (b) phase ellipse into (□) and out of (Δ) the first resonator in the Phase I PII. This case is for $^{58}Ni^{15+}$ corresponding to the second entry in Table I.

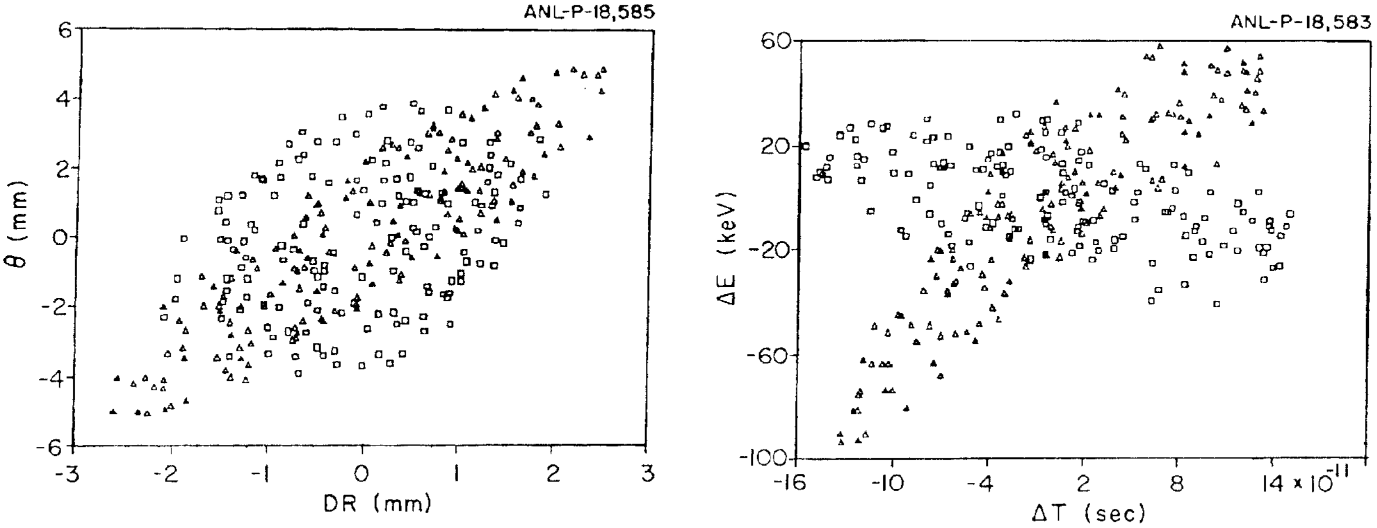

Fig. 3a

Fig. 3b

The radial (a) and longitudinal (b) phase ellipse into (□) and out of (Δ) the fifth resonator. The case is the same as described in Fig. 2.

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