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First operational experience with the positive-ion injector of ATLAS

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Abstract

The recently completed positive-ion injector for the heavy-ion accelerator ATLAS was designed as a replacement for the tandem injector of the present tandem-linac system and, unlike the tandem, the positive-ion injector is required to provide 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 initial experience in the acceleration of heavy-ion beams through the entire ATLAS system is discussed. The unusually good longitudinal beam quality of ATLAS with its new injector is emphasized.

1. Introduction

Until now, the heavy-ion accelerator ATLAS [1] has consisted of a 9-MV tandem injector coupled to a superconducting linac. This system has been in operation, in various stages of development, since 1978 and has provided experimenters with a total of >45,000 hours of beam on target.

In its tandem-linac form ATLAS has proved to be valuable for a wide variety of research but also has several weaknesses, the most important of which are (1) a projectile-mass range limited to the lower 40% of the periodic table and (2) smaller beam currents than some users want. Both of these weaknesses originate in the tandem and its foil stripper in the terminal. Consequently, in 1983 we began to search for some kind of improved injector that could ultimately replace the tandem. After considering various possibilities (including a large tandem, a tandem with an ECR ion source in the terminal, and a continuous-wave RFQ linac) we concluded that for our needs the optimum solution was a positive-ion injector of the kind that is the subject of this paper. The basic concept for this injector is an ECR ion source on an open-air voltage platform followed by a superconducting drift-tube linac, as shown in basic outline in Fig. 1. This concept was first discussed [2] publicly in 1984.

The main requirements for the new injector were (and are): (1) an ability to accelerate all stable nuclei from velocities as low as $\beta \approx 0.008$ up to $\beta \geq 0.04$, (2) beam currents much greater than are obtainable from the tandem injector, (3) beam quality as good as that of the tandem beam in both transverse and longitudinal phase space, and (4) reasonable cost. Initially, the primary technical difficulties were perceived to be: (1) poor beam transmission caused by defocussing in the low-velocity accelerating structures, (2) serious distortions of longitudinal phase space at the low-velocity end of the linac, and (3) an inability to bunch adequately beams of heavy low-velocity ions. The solutions adopted to minimize these difficulties were: (1) to use short independently phased accelerating structures, (2) to use RF frequencies that are as low as feasible for superconducting structures, and (3) to provide transverse focussing with a superconducting solenoid after each resonator in the low-energy end of the injector linac.

2. Description of the positive-ion injector

The Positive-Ion Injector (PII), first conceived in 1983-84, was completed in March 1992. The layout of the system [3-5] and its main components are shown in Fig. 2. The ECR ion source is mounted on a 350-kV platform. Beam from the source is magnetically analyzed and then bunched on the voltage platform. The beam is then accelerated to ground potential, analyzed with better resolution in Analyzer #2, and transported toward the injector linac along an isochronous beam path. A chopper on the linac-injection line removes unbunched ions, and a second buncher at the input to the injector linac rebunches the beam so as to form a narrow beam pulse at the first accelerating structure in the linac. The injector linac consists of 18 superconducting resonators housed in 3 large cryostats. About 225 W of LHe cooling at 4.6 k is available for the linac.

In a little more detail, 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 12-18 kV. The source and other equipment on the platform are powered (140 kW) by isolation transformers, and apparatus on the platform is cooled by deionized water circulating from ground potential. The original set of isolation transformers proved to be unsatisfactory and had to be replaced by units manufactured by a different company.

The performance goals for the source are shown in Fig. 3, which gives the ion charge state as a function of atomic number for several beam currents. For our application, the most important of these curves is the one for 10 eμA since, for the heaviest ions, it is necessary to strip the beam at the output to PII in order to obtain the high charge state required for the beam to be accelerated effectively by the main ATLAS linac. In general terms, the demonstrated performance of the source is consistent with the 10-eμA curve for single-isotope material in the lower 60% of the periodic table but the 10-eμA goal has not yet been achieved for most of the heaviest nuclides. However, since little effort has been devoted to the development of such beams, it is expected that the design goal will be met during the next year.

The beam-bunching system 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 the one developed originally for the tandem [7]. Although the actual distance from the first to the second buncher is quite long (~30 m), the effective distance relative to the beam energy on the platform is only ~1.5 m.

The main technical challenge 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 0.04 without serious degradation of beam quality. The four different kinds of resonators [8-10] shown in Fig. 4 are used for this purpose. All of these units have four accelerating gaps formed by two 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 that is explosively bonded to copper. These resonators are cooled by gravity-fed liquid helium from a dewar along the top of the cryostat, and the dewar is feed continuously by flowing LHe.

Some key parameters for the resonators are given at the bottom of the figure. Two features of these parameters are worth noting. First, the accelerating fields F_O are design goals that must be achieved in order for PII to be able to accelerate uranium ions effectively. Second, 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, as will be discussed later.

The configuration of the injector linac as a whole is shown by Fig. 5. Note that there is a focussing solenoid before and after each of the resonators at the front end of the linac, and each of these solenoids can form a waist in the following accelerating structure. This frequency of beam focussing may be more than is needed, but we didn't want to take any chances.

In order to minimize the deterioration of longitudinal beam quality it is important for the incident beam bunch to be narrow (~0.3 to 0.5 ns) at the first resonator. In order to be able to form this bunch reliably, a "fast Faraday cup" [11] with a time resolution width of ~0.2 ns can be inserted into the beam in the small gap after the first resonator. As far as we know, this is the first time that a diagnostic detector of such sophistication has been used in the cold region of a superconducting accelerator. The detector works reliably in this unusual location.

3. Performance of PII

Tests of PII have been carried out at three different phases of the construction process, as summarized by Table 1. From the table one sees that ion species from throughout the periodic table have been accelerated. Of course, for the first two series of tests the beam was accelerated through only a part of the injector linac. However, a Type I_1 resonator and at least one Type I_2 resonator were present in all tests, and it is believed that these low β units are the main source of beam-quality degradation in the injector linac. Consequently, it became clear at an early stage [12] that the potential problems associated with the low-velocity end of the machine had been largely avoided.

The projected beam energy at the output of PII for a complete complement of resonators is given by Fig. 6, where it is assumed the accelerating field F_a for each resonator is equal to some constant ρ times the design field F_o listed in Fig. 4. From Fig. 6 one sees that it is essential for the resonators of PII to be able to perform as well as planned since for the heaviest ions ($A/q \approx 10$) the output energy depends sensitively on F_a. On the other hand, for lighter ions the output energy is insensitive to F_a. This behavior is qualitatively obvious from the relatively small velocity range over which a 4-gap structure can accelerate effectively. Transit-time curves for the PII resonators are given in Ref. 9.

In off-line tests of the PII resonators the maximum accelerating fields were much greater (in many cases twice as great) as the design fields. However, in the initial beam acceleration tests it was only with difficulty that the design fields could be sustained. Finally, during the 1990-test period, it was established that the fast tuner used to control the RF was limiting the field. This tuner [13] is a voltage-controlled reactance (VCX) in which a set of PIN diodes is switched in response to a phase-error signal. The location and size of this device, which is operated at liquid-nitrogen temperature, is shown in Fig. 4.

Once the problem was understood, a thoroughgoing study of the VCX was undertaken in order to determine in detail the optimum parameters for the device. This study resulted in major improvements [14] and permits the VCX to operate reliably with a tuning capacity of 30 kVA of RF reactive power (which is equivalent to a 7.5-kW amplifier), remarkable performance for such a small device that dissipates only ~100 W of RF power. Now, with the improved VCX's installed, the resonators operate with ease at their design fields. However, it is not feasible for us to operate the whole linac at field levels greater than ~20% above the design levels because of limited LHe cooling capacity.

In addition to beam energy, 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? Although there has not yet been time to study this matter thoroughly, the results to date are very encouraging. For transverse phase space, the emittance ϵ_r is about the same as for equivalent beams from our tandem with a foil stripper. That it, the normalized emittance $\gamma\beta\epsilon_r \sim 0.2\ \pi$ mm-mrad. For all ions studied (including ^{208}Pb), the emittance is small enough to permit the beam to fit comfortably into the transverse acceptance of the injector linac and, for the completed linac, the beam transmission is ~100%. In the 1989-90 beam tests the transmission had not been good, perhaps because of several known defects in the system during those preliminary tests.

Good longitudinal beam quality receives special emphasis at ATLAS because many of our users require very narrow and stable beam pulses. In order to be able to provide such beam pulses to the user, the primary requirements at the input to the injector linac are: (1) an energy stability better than 1 part in 10^4, (2) a longitudinal emittance that is small enough to allow the 1^{st}-stage buncher to form beam pulses < 3ns (FWHM) wide at the

2^{nd} stage buncher, and (3) a layout that permits the 2^{nd}-stage buncher to form pulses in the range 0.3-0.5 ns wide in the first accelerating structure. All of this has been achieved.

During the construction of the injector linac, as our understanding of the beam optics progressed, a source of considerable concern was the unusual (indeed, pathological) behavior of the first few resonators. An example of such behavior is shown in Fig. 7, where the dependence of energy gain on entrance phase angle is plotted for the first resonator. This behavior bares no resemblance to the familiar cosine curve that is assumed for most accelerating structures. The explanation for the difference is, of course, transit-time effects caused by the extremely rapid increase in ion velocity within the first resonator, where beam energy is more than doubled. Another example [9] of the impact of transit-time effects is the shape of the dependence of energy gain on velocity, which has a maximum at a much lower velocity than is expected from the geometry of the structure. These calculated effects were disturbing initially but do not seem to have any negative impact on performance. Indeed, as may be seen from Fig. 7, in the region of phase where one operates the dependence of energy gain on phase is more linear than for a cosine dependence, and this linearity presumably tends to reduce longitudinal phase-space distortion. In any case, the injector linac is easy to tune and, once tuned, operates stably for long periods of time.

In order for the injector to be able to preserve the inherently good longitudinal beam quality of the ECR ion source it is necessary to bunch, chop, and analyze the beam with some care before it enters the linac. In general terms, some fraction of the beam (~70% at PII) is bunched into narrow pulses and a chopper (sweeper) removes the background caused by unbunched ions.

A subject that is rarely discussed is the process of beam chopping, which enlarges the transverse emittance because of the sweeping motion of the beam and introduces an energy spread because of the fringing fields at the ends of the sweeping plates. In most applications, the energy spread produced by chopping is masked by other effects, but at PII the effect can be very destructive because of the inherently small energy spread of its beam. This problem can be effectively eliminated in two ways at PII. One is to form an upright phase ellipse at the chopper and then limit the RF voltage on the chopper plates so that the chopper removes the background between pulses but does not shape the pulse itself.

In the mode described above, the chopper eliminates the background effectively without a noticeable deterioration in longitudinal phase space, but it does not eliminate tails on the beam pulses. Such tails can be removed by using the 2^{nd} analyzing magnet in the way illustrated by Fig. 8. Here one sees the saw-tooth-like wave form generated by the 1^{st}-stage bunch. About 70% of the ions are within the linear region that results in a narrow beam pulse, and most of the remainder is a background pulse. However, ions near the maximum and minimum of the bunching voltage cause undesirable tails on the bunched beam pulse. These tails can be eliminated by using the analyzing magnet to remove the ions in the transition region where the energy excursion caused by the buncher is greatest. This procedure causes some loss of beam current, of course, but it improves both transverse and longitudinal beam quality, and the ECR source often provides much more beam current than is needed.

In addition to removing beam-pulse tails, the longitudinal emittance of the main part of the beam pulse can be reduced by using the analyzing magnet to limit the energy spread of the beam, as shown in Fig. 8(c). This idea has not yet been tested quantitatively in practice, but it is believed that the longitudinal emittance can be reduced by about a factor of 3 in this way if adequate beam intensity is available. In principle, this concept of improving longitudinal emittance is valid at any part of the acceleration process but, in fact, unusual circumstances are required for the method to be feasible and worth while.

4. Beam tests of the complete ATLAS system

The layout of the entire ATLAS facility is shown in Fig. 9. The focus of this paper is on PII, at the left-hand end of the facility. Of equal interest, however, is the apparatus in the new experimental area labelled Target Area IV, apparatus that is aimed explicity at exploiting the new research capabilities made possible by PII. One such experimental system that has recently gone into operation is the Fragment Mass Analyzer (FMA), which is closely similar to the recoil mass spectrometer at the Laboratori Nazionali di Legnaro. Even more important is the APEX (ATLAS Positron Experiment) apparatus, which is designed to investigate in more detail the unexpected behavior of positron-electron pairs created when two very heavy nuclei (e.g., ^{238}U on ^{238}U) interact at energies near the Coulomb barrier. This phenomenon, which has been studied intensively for several years at GSI, is still not understood. It is expected that the CW character of the ATLAS beam and improvements incorporated into the experimental apparatus APEX will allow considerably more refined data to be acquired and will lead to a better understanding of this potentially important phenomenon.

Returning to accelerator technology, when a beam is accelerated from the ECR ion source all the way through ATLAS to the experimental area, seven different types of independently phased accelerating structures are involved, as summarized in Table 2. This is probably some kind of record for diversity. Having many types of resonators does not cause any special operational problem, but it did require a substantial prototype-development effort and it limits the beam-pulse rate to a maximum value of 24.25 MHz. As desired by beam users, the actual beam-pulse frequency is only 12.125 MHz, and therefore most of the RF "buckets" are empty for all seven resonator types.

The energy performance goals for ATLAS are summarized by Fig. 10, where the primary goals are those for the heaviest ions (^{238}U). These goals for ^{238}U cannot be met at this time because of deficiencies in the main ATLAS linac, but work is now in progress to remove these deficiencies by changing the velocity profile of the main linac to be optimum for ^{238}U and by replacing the original fast tuners with the improved units discussed earlier in connection with the performance of the resonators in PII. This upgrading process for the main linac is expected to lead to the following schedule for 6-MeV/A uranium beams: 0.1 pnA of beam current in July 1992, 1.0 pnA in December 1992, 5 pnA in June 1993, and a gradual increase to 10 pnA thereafter.

To date, there has been time to accelerate only two beams from the completed PII on through the main ATLAS linac. The first of these was $^{30}Si^{9+}$, which was deliberately chosen as an easy test case. This beam was used in a γ-ray experiment which had the following beam requirements: isotopic purity, E/A $\approx$ 5 MeV/A, good transverse emittance ($\epsilon_r \lesssim 1\ \pi$ mm - mrad), and long-term stability in both beam-spot position and in beam-pulse arrival time. All of these requirements were easily satisfied.

The second beam accelerated through ATLAS was ^{208}Pb, which was extracted from the source as $^{208}Pb^{24+}$, accelerated by PII to 240 MeV, stripped in front of the booster linac, and then accelerated through to the output of ATLAS as $^{208}Pb^{39+}$. The output energy was 1020 MeV. For this projectile the question of how to tune a stripped beam with multiple charge states had to be addressed. The planned long-term solution to this problem is to install a charge-state selector after the stripper, as shown in Fig. 11. This selector is now being designed but will not be operational for another year or so. In the mean time, some way must be found to tune a beam that is a mixture of ion species.

Our short-term solution to the multiple charge-state problem is to tune the booster linac with a "guide" beam, as illustrated in Fig. 12. Here, the guide beam is $^{16}O^{3+}$, which has the same charge-to-mass ratio as $^{208}Pb^{39+}$. For convenience, this guide beam is obtained from the tandem but it could in principle come from PII.

The subject of guide-beam technique is emphasized here not only because we need it now in order to be able to tune multiply charged beams but also because it is of long-term interest for AMS (accelerator mass spectroscopy), as indicated by M. Paul in an earlier paper at this conference. In very general terms, the requirements for the relationship between the guide beam and the beam of interest are that they should be matched in charge-to-mass ratio, velocity, and phase at the input to the linac involved (booster linac for $^{208}Pb^{39+}$). With such matching, not only the ion species of interest but also other charge states will be accelerated through the booster linac, and magnetic analysis at the linac output is needed to eliminate the unwanted ions. Ideally, one should also match transverse phase space if the q/A values of the guide beam and the projectile of interest are not the same but, since beam transmission is very insensitive to focussing parameters, this refinement is unnecessary for our needs.

A more quantitative indication of the degree of refinement needed for the matching process can be inferred from an analysis such as is illustrated in Fig. 13. Here the longitudinal phase space has been calculated on the the assumption that acceleration in the linac is continuous, with a constant accelerating field and phase angle. Of course, these conditions are not accurately satisfied for the ATLAS linacs, but comparisons with calculations based on more realistic models show that the continuous-acceleration model gives qualitatively valid results if one uses an accelerating field that is an average over all space in the linac.

The separatrix (acceptance) in Fig. 12 is drawn for a 240-MeV beam of $^{239}Pb^{39+}$ under the assumption that the booster linac is tuned with a beam of $^{16}O^{3+}$ for a phase offset of - 15°. The small circle around -15° shows the size of a perfectly matched $^{208}Pb^{39+}$ beam that has a longitudinal emittance $\epsilon_z \approx 30\pi$ eV-ns. In practice, the ^{208}Pb and $^{16}O^{3+}$ beams cannot be matched perfectly but, in order to ensure that all phase space of the ^{208}Pb beam falls inside the separatrix, it is desirable for its central ray to fall within the dashed circle. That is, relative to the guide beam $^{16}O^{3+}$, one should try to have E/A for $^{238}Pb^{39+}$ matched to ~ ± 0.5% and phase angle matched to ± 0.15 ns = ± 5°.

The above discussion assumes that the $^{208}Pb^{39+}$ beam and its guide beam $^{16}O^{3+}$ have the same value of q/A, as in fact they do. If this were not true, then one should match the central rays of the two beams by requiring that $(q/A)_1 F_1 \cos \phi_1 = (q/A)_2 \cos F_2 \phi_2$ for each resonator. From this relationship one sees that the two values of q/A can differ considerably without making it difficult to satisfy the matching condition. Consequently, it is always possible to find a guide beam that has a satisfactory value of q/A. This discussion ignores transverse phase space and thus does not include some refinements that may be needed for AMS measurements, for which the beam of interest is so weak that one cannot check quickly whether it has been accelerated and transmitted properly.

5. Measurements of longitudinal emittance

Few measurements of the longitudinal emittance ϵ_z for low-energy heavy-ion beams have been reported, and yet the magnitude of ϵ_z has an important impact on the character of the research program. This relationship was recognized at ATLAS from the inception of our tandem-linac system in the early 1970's, and consequently those of us who designed and built ATLAS have insisted that the experimenters must have good longitudinal beam quality, whether or not they know that they need it. This emphasis on the importance of having small values of ϵ_z is continued in this section.

In our work, we define longitudinal emittance ϵ_z as the area in energy-time phase space under the assumption that the phase space is describable by an ellipse. That is $\epsilon_z \equiv \pi \, \Delta E_0 \Delta t_0$, where ΔE_0 and Δt_0 are half widths at half maximum. This quantity is exactly analogous to the commonly used convention for transverse emittance ϵ_r except that, unlike ϵ_r, for ideal linear acceleration ϵ_z is independent of beam energy.

In an experimental determination of ϵ_z, usually ΔE_0 is too small to be measured directly with existing detectors whereas Δt_0 can be measured. Thus, approximate values of $\Delta E_0 \Delta t_0$ can be obtained easily by measuring pulse widths under two conditions, as is illustrated in Fig. 13. Method A is applicable only if a beam with a small energy spread is bunched and then drifts, without further manipulation, to a time waist. From a knowledge of the characteristics of the bunching system one knows the initial width δt of the linear region that is bunched and the effective path length for bunching, and consequently one can easily calculate the energy spread ΔE_0 involved. The time spread Δt_0 at the waist can be measured directly.

Method B is applicable when the beam is known to have an approximately upright phase ellipse as, for example, at the output of a linac. Then, as shown in Fig. 13, ΔE_0 can be determined by measuring the pulse width at a distant detector, and Δt_0 can be determined by rebunching the beam and measuring the pulse width at the resulting time waist. The error caused by the uncertainty of whether or not the initial phase ellipse is, in fact, upright is unimportant if the drift paths are long enough.

The above and other methods have been used to measure ϵ_z at five locations along the acceleration path of ATLAS, as shown in Fig. 14. Although it is easy to make these measurements, the data acquired to date is fragmentary. Also, measured values probably have some scatter because the quality of the linac tune has an impact on the value of E_z at locations C, D, and E. Nevertheless, one can draw several interesting conclusions. First, the value of ϵ_z is degraded somewhat by traversal of the beam path from A to B, as seen from the results for $^{40}A^{11+}$ (12-MV injector linac). This conclusion is supported by other measurements for which the measured widths were not recorded. Probably the observed degradation is caused by imperfections in the nominally isochronous beam transport system.

Second, if the injector linac is properly tuned, ϵ_z is not degraded much by acceleration through PII, as shown by the $^{40}Ar^{12+}$ data (3-MV injector) and by the qualitative behavior of other beams.

Third, the value of ϵ_z tends to increase with increasing ion mass. This effect is not surprising since the initial energy spread is expected to increase with increasing charge state, and since any imperfections in beam-path lengths or non-linear acceleration would depend on A/q. The data are too fragmentary to draw any firm conclusions about the origins of the observed trend in the data.

Finally, and most important, the values of ϵ_z for beams from PII are substantially smaller than those from our 9-MV tandem with a foil stripper. These small values of ϵ_z for PII set a new standard of excellence for longitudinal beam quality for heavy-ion accelerators.

6. Conclusions

The results presented in this paper demonstrate that all of the design goals for our new positive-ion injector have been achieved. The fundamental beam-optics problems for low-velocity ions were avoided or were less severe than was initially feared. Instead, the main difficulties (isolation transformers, fast tuners, vacuum leaks) turned out to be engineering in nature. In spite of several demanding beam-optics requirements, the new injector linac can be tuned with surprising ease and, once tuned, the system operates stably for days.

The entire ATLAS accelerator is now ready for use with the new injector, and routine operation for research will be initiated as soon as an improved radiation system has been completed and official approval is given, both expected in July 1992. The enhanced capabilities of ATLAS provided by PII are expected to change and strengthen the research program immensely. In particular, beams near the heavy end of the periodic table will now play a major role, and lighter beams that are not available from the tandem injector will also be important.

The improved longitudinal beam quality provided by PII is expected to result in data of superior quality, especially for experiments that involved detection of charged particles and use flight time for particle identification. The small longitudinal emittance now available will enable the experimenter, for the first time, to have both good energy and time resolution.

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Table 1. Beams Accelerated by PII

Injector Linac Size	Beam Acceleration Period	Ion Species
3 Mv	Feb.-Dec., 1989	$^{3}He^{2+}$, $^{13}C^{3+}$, $^{40}Ar^{12+}$, $^{86}Kr^{19+}$
7 Mv	Apr.-Aug., 1990	$^{83}Kr^{15+}$, $^{86}Kr^{15+}$, $^{86}K^{21+}$, $^{92}Mo^{16+}$
12 Mv	Apr.-Present, 1992	$^{30}Si^{7+}$, $^{40}Ar^{11+}$, $^{132}Xe^{13+}$, $^{208}Pb^{24+}$

Table 2. Accelerating Structures of ATLAS

TYPE	No. of Gaps	RF Frequency (MHz)	β	Active Length (cm)	Nominal Voltage (MV)	Number of Units
I_4	4	48.5	0.008	10	0.45	1
I_2	4	48.5	0.015	16	0.48	2
I_3	4	48.5	0.024	25	0.76	5
I_4	4	72.75	0.036	25	0.76	10
L	3	97	0.065	20	0.61	12
H	3	97	0.105	36	1.07	20
V	3	145.5	0.16	36	1.07	10
Buncher		12.125				

Figure Captions

1. Basic concept for the positive-ion injector of ATLAS.

2. Layout of the positive-ion injector (PII) of ATLAS.

3. Performance goals for the ECR ion source of PII.

4. The four classes of accelerating structures in the injector linac of PII. The quantity L_a is the active length, D is the aperture (diameter) of the drift tubes, and F_o is the design goal for accelerating field.

5. Configuration of the PII injector linac.

6. Energy performance of the injector linac. The quantity ρ is the ratio of the actual accelerating fields to the design fields of resonators and ϕ_o is the operating phase angle, usually ~15°.

7. Energy gain of the I_1 accelerating structure of PII vs incident phase angle ϕ_{in} for $^{40}A^{12+}$ ions with an incident energy of 60 keV/A. The zero for ϕ_{in} is chosen to be the phase for which energy gain is a maximum when the accelerating field is vanishingly small. The operating phase angle is ϕ_o.

8. Beam-pulse shaping by means of magnetic analysis.

9. Layout of the ATLAS facility.

10. Projected performance of the whole ATLAS system.

11. Planned charge-state selector for stripped beams from PII.

12. Use of guide beams to tune multiple-charge-state beams.

13. Energy-time phase space of a 240-MeV beam of $^{208}Pb^{39+}$ at the entrance to the booster linac.

14. Methods used to measure longitudinal emittance ϵ_z.

15. Measured values of ϵ_z at various locations along the acceleration path of ATLAS.

Figure Captions

1. Basic concept for the positive-ion injector of ATLAS.

2. Layout of the positive-ion injector (PII) of ATLAS.

3. Performance goals for the ECR ion source of PII.

4. The four classes of accelerating structures in the injector linac of PII. The quantity L_a is the active length, D is the aperture (diameter) of the drift tubes, and F_o is the design goal for accelerating field.

5. Configuration of the PII injector linac.

6. Energy performance of the injector linac. The quantity ρ is the ratio of the actual accelerating fields to the design fields of resonators and ϕ_o is the operating phase angle, usually ~15°.

7. Energy gain of the I_1 accelerating structure of PII vs incident phase angle ϕ_{in} for $^{40}A^{12+}$ ions with an incident energy of 60 keV/A. The zero for ϕ_{in} is chosen to be the phase for which energy gain is a maximum when the accelerating field is vanishingly small. The operating phase angle is ϕ_o.

8. Beam-pulse shaping by means of magnetic analysis.

9. Layout of the ATLAS facility.

10. Projected performance of the whole ATLAS system.

11. Planned charge-state selector for stripped beams from PII.

12. Use of guide beams to tune multiple-charge-state beams.

13. Energy-time phase space of a 240-MeV beam of $^{208}Pb^{39+}$ at the entrance to the booster linac.

14. Methods used to measure longitudinal emittance ϵ_z.

15. Measured values of ϵ_z at various locations along the acceleration path of ATLAS.

ANL-P-20,666

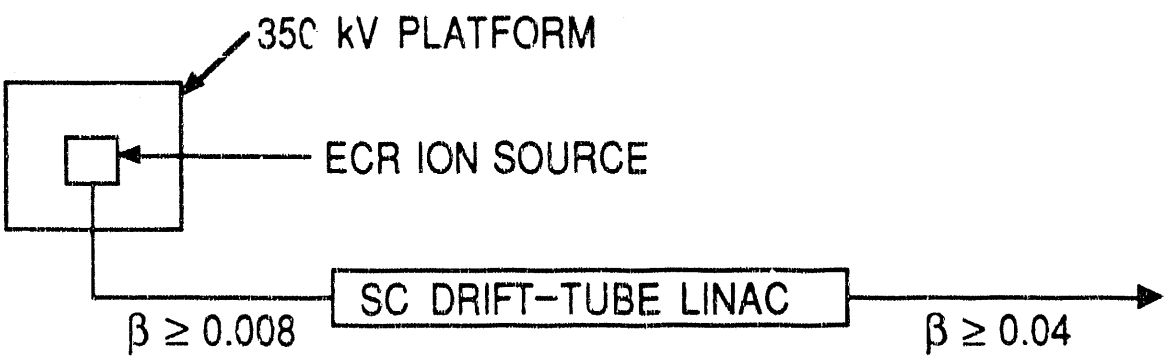


Fig. 1

ANL-P-19,448

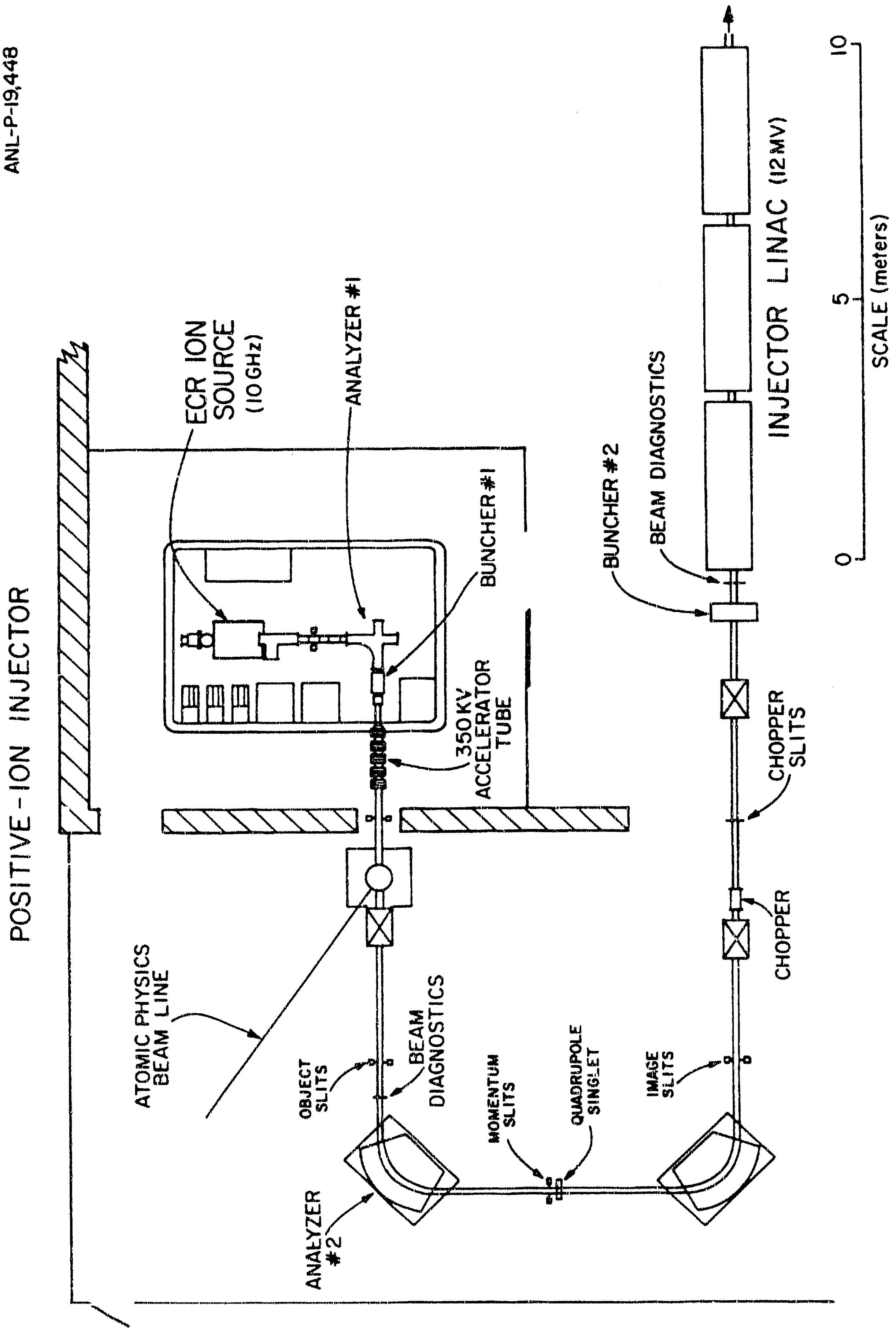


Fig. 2

ANL-P-20,711

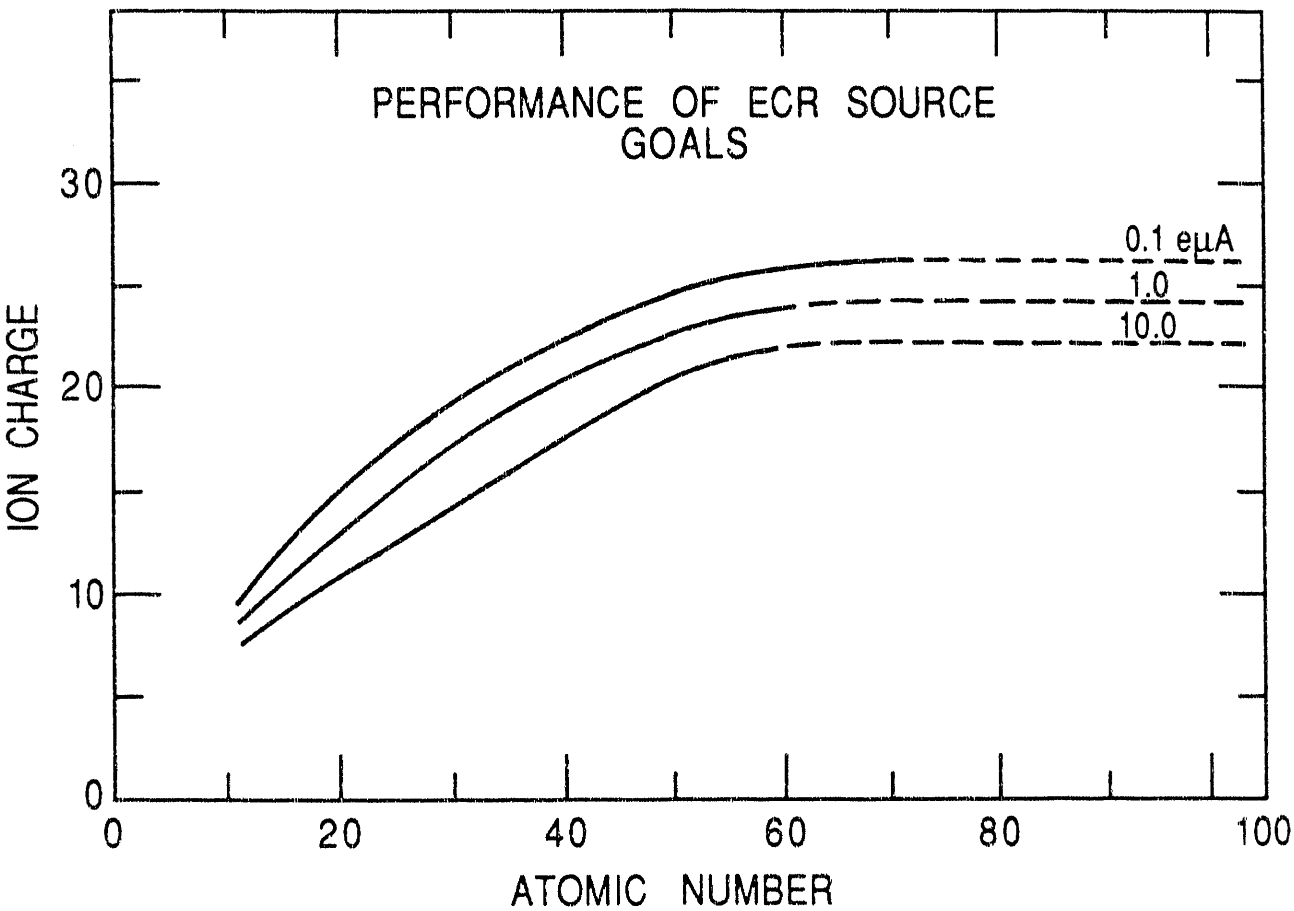
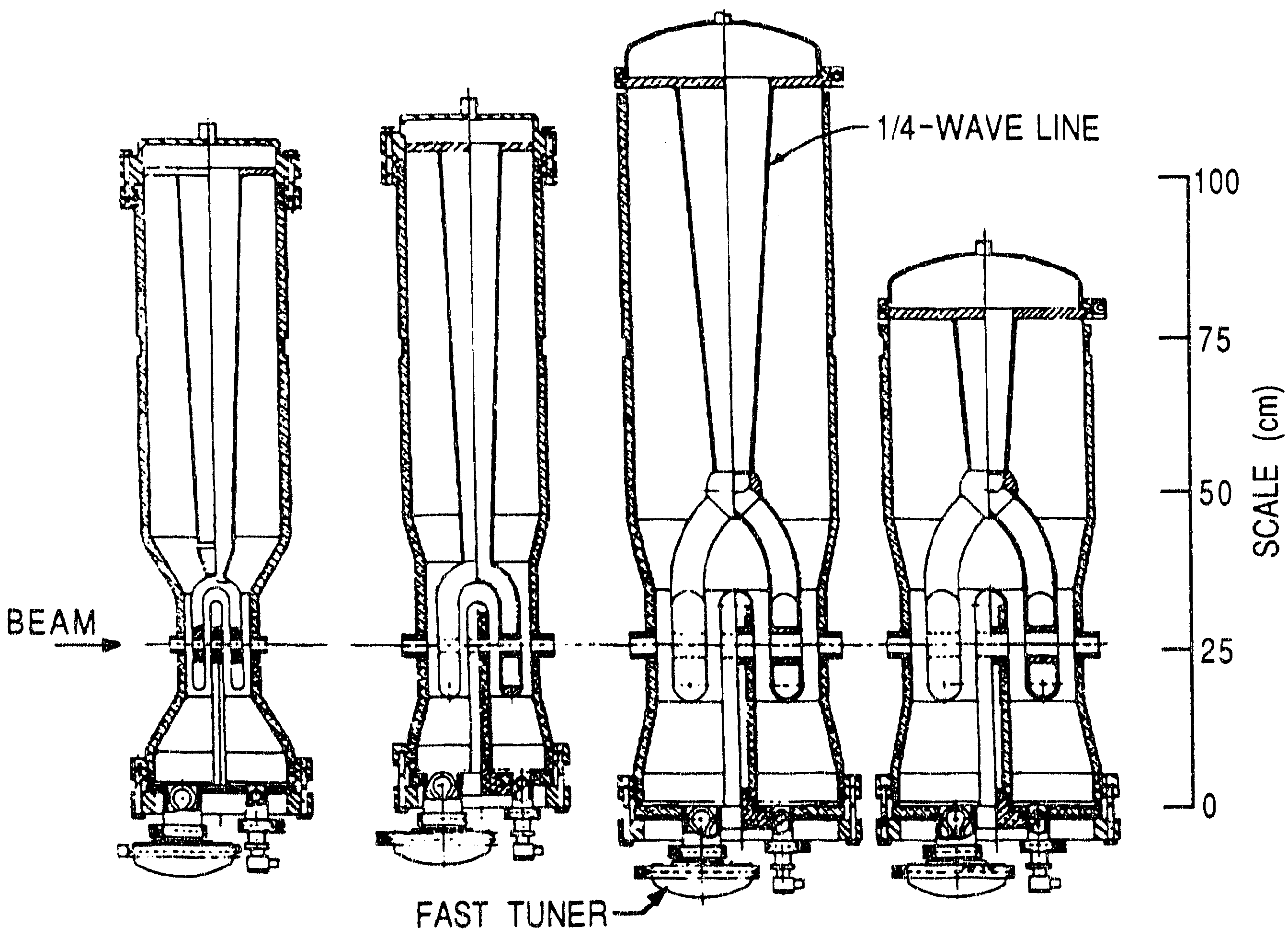


Fig. 3

RESONATORS FOR POSITIVE - ION INJECTOR



TYPE	I_1	I_2	I_3	I_4
β	0.009	0.016	0.025	0.037
L_a (cm)	10.2	16.5	25.4	25.4
D (cm)	1.5	1.9	3.8	3.8
f (MHz)	48.5	48.5	48.5	72.75
F_0 (MV / m)	4.5	3.0	3.0	3.0

Fig. 4

ANL-P-20,659

CONFIGURATION OF PII LINAC

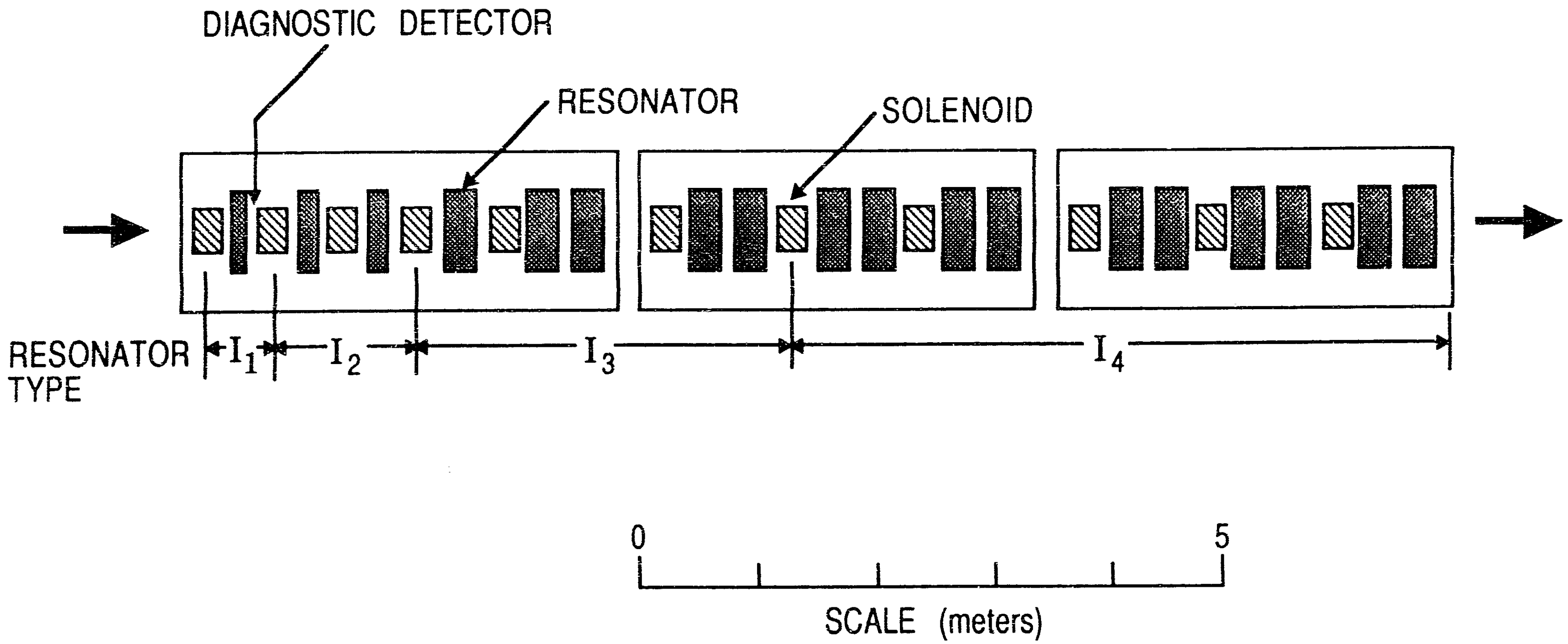


Fig. 5

ANL-P-20,521

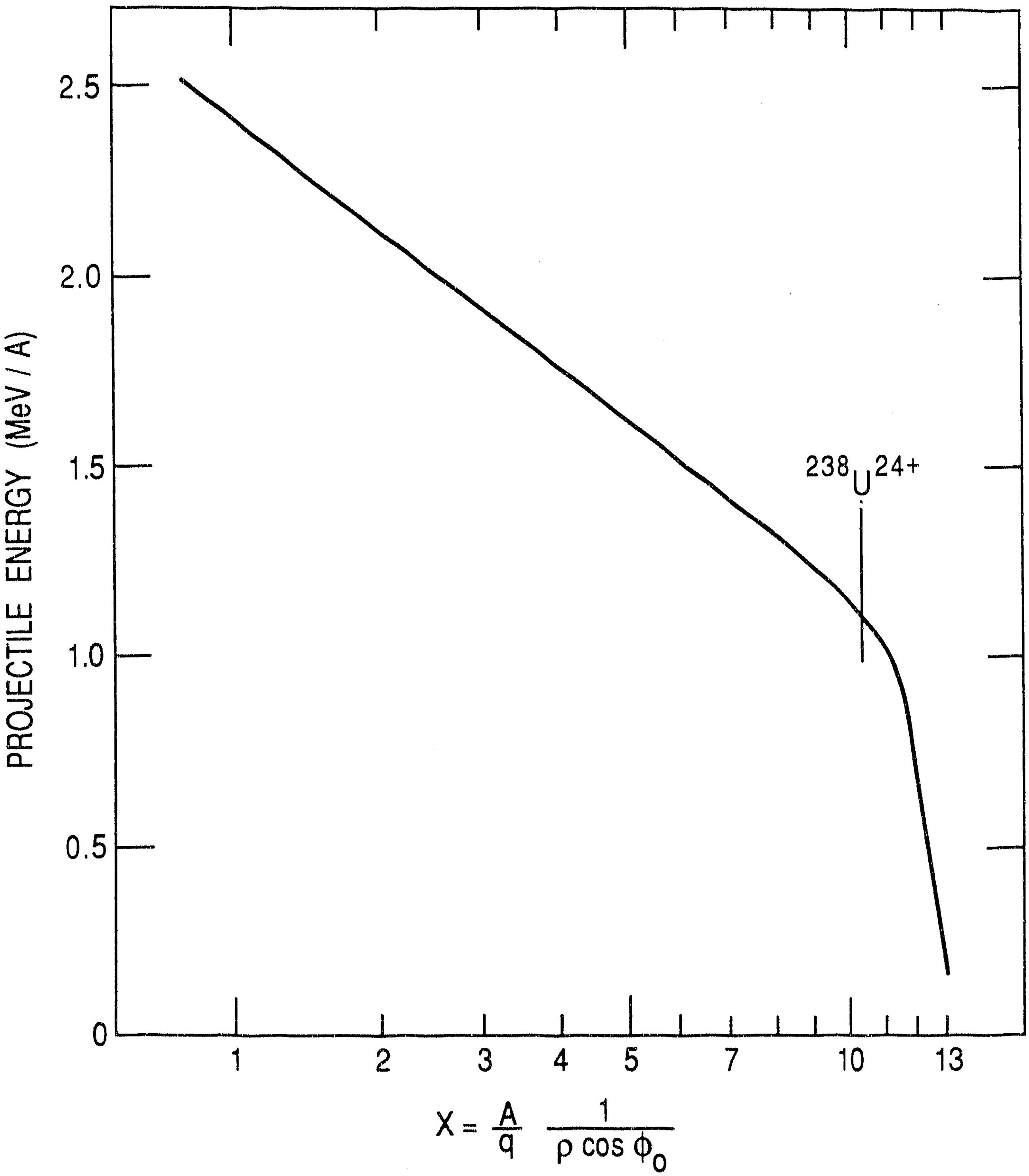


Fig. 6

ACCELERATING WAVE FORM FOR I_1 RESONATOR

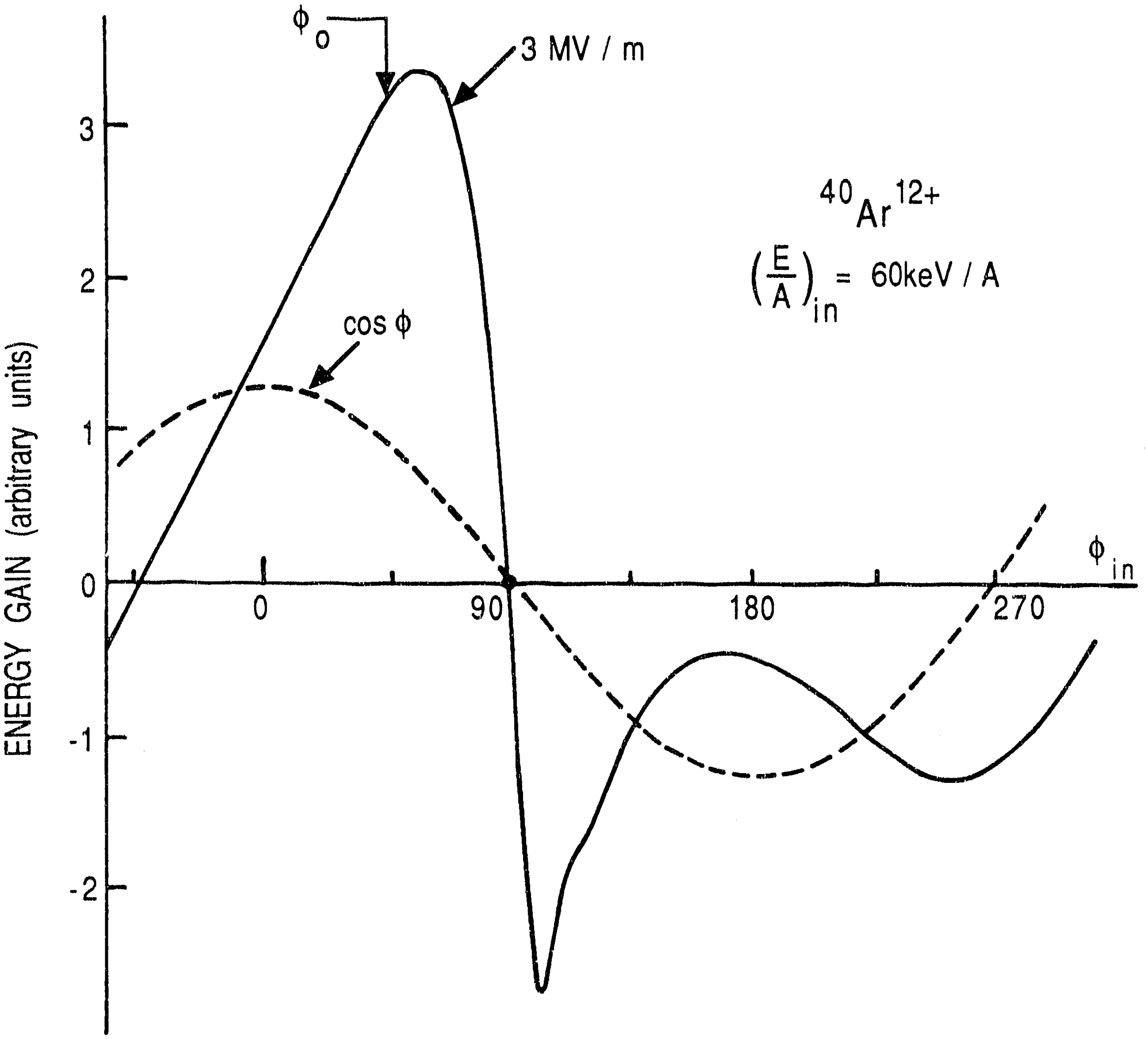


Fig. 7

BUNCHING AT PII

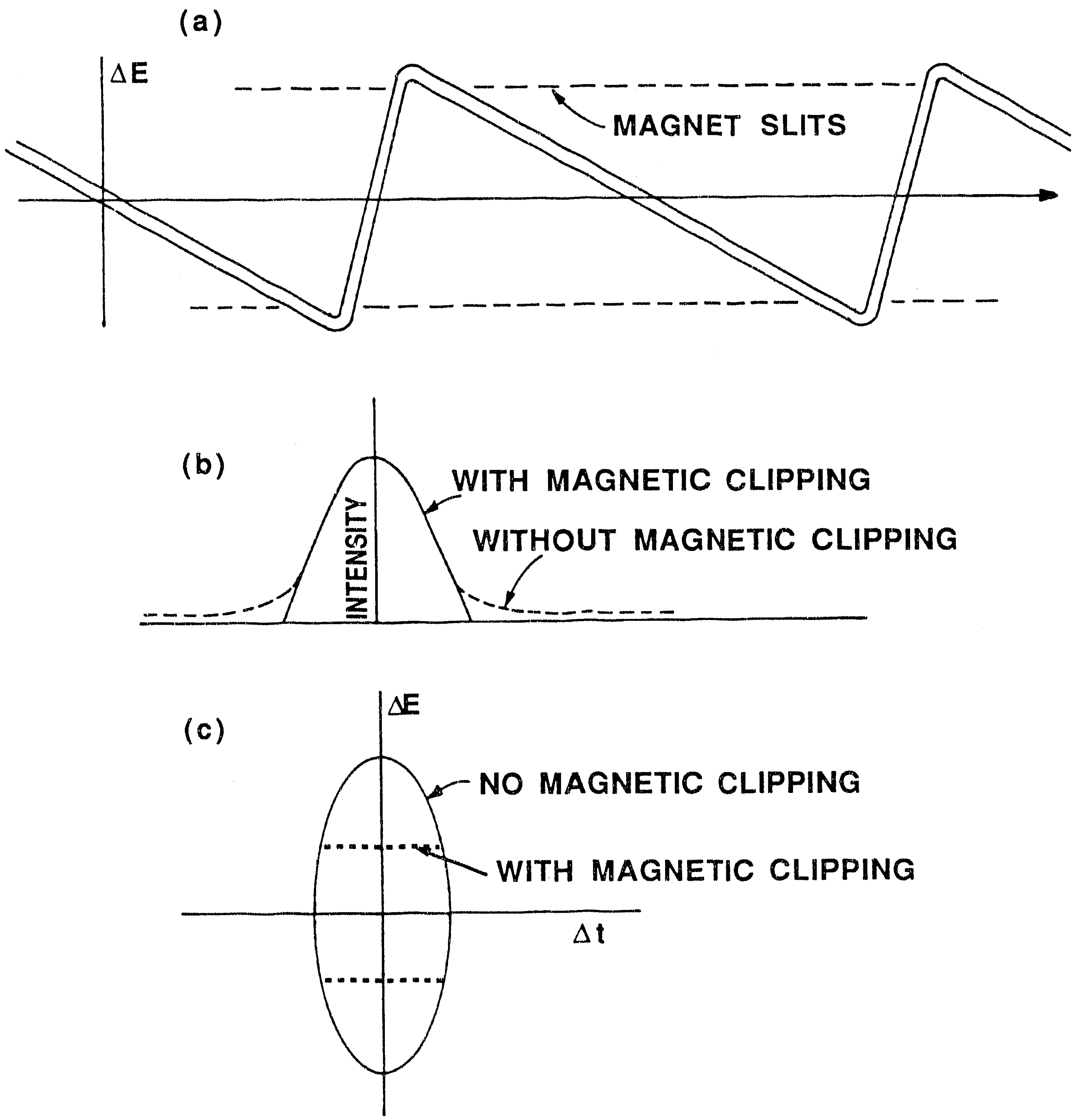


Fig. 8

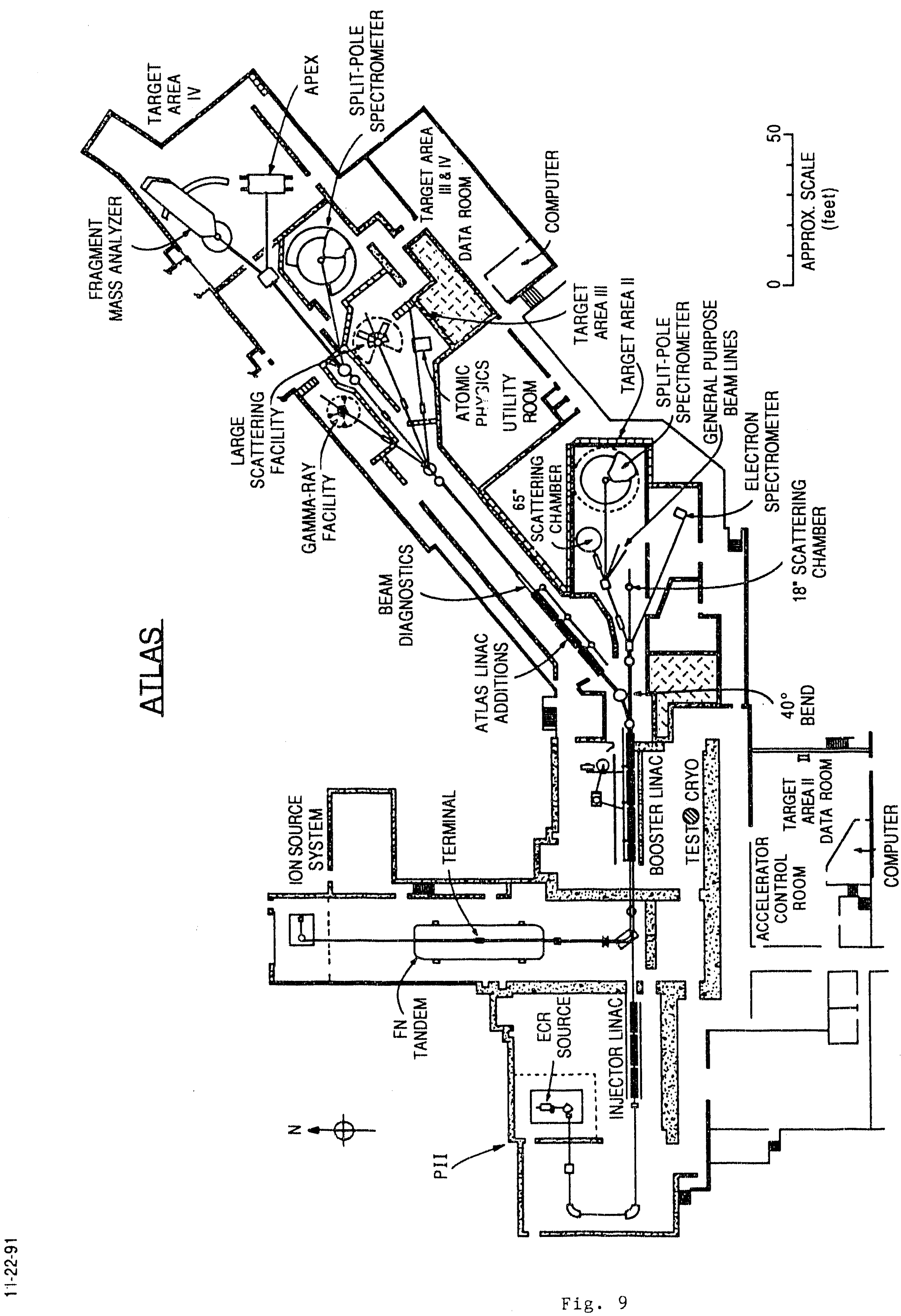

ATLAS
TARGET AREA IV
APEX
SPLIT-POLE SPECTROMETER
TARGET AREA III & IV DATA ROOM
COMPUTER
FRAGMENT MASS ANALYZER
TARGET AREA III
TARGET AREA II
SPLIT-POLE SPECTROMETER
GENERAL PURPOSE BEAM LINES
ELECTRON SPECTROMETER
18" SCATTERING CHAMBER
ATOMIC PHYSICS
UTILITY ROOM
LARGE SCATTERING FACILITY
GAMMA-RAY FACILITY
65" SCATTERING CHAMBER
BEAM DIAGNOSTICS
ATLAS LINAC ADDITIONS
40° BEND
BOOSTER LINAC
TEST CRYO
TARGET AREA II DATA ROOM
COMPUTER
ACCELERATOR CONTROL ROOM
ION SOURCE SYSTEM
TERMINAL
FN TANDEM
ECR SOURCE
INJECTOR LINAC
PII
N
0
50
APPROX. SCALE (feet)
11-22-91

Fig. 9

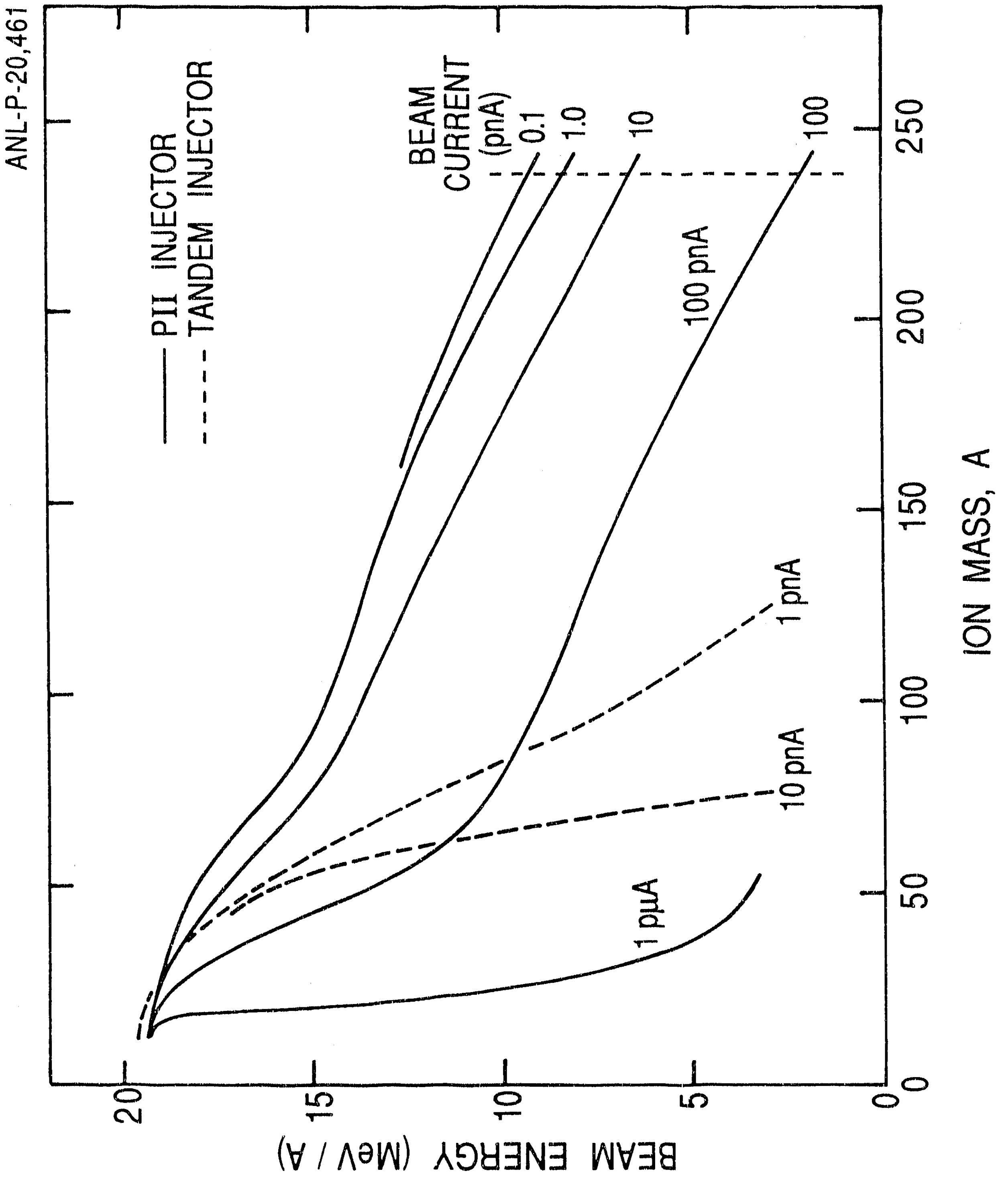

ANL-P-20,461
PII INJECTOR
TANDEM INJECTOR
BEAM CURRENT (pnA)
0.1
1.0
10
100
100 pnA
1 pnA
10 pnA
1 pμA
BEAM ENERGY (MeV / A)
ION MASS, A
0
5
10
15
20
50
100
150
200
250

Fig. 10

ANL-P-20,660

PLAN FOR CHARGE-STATE SELECTOR

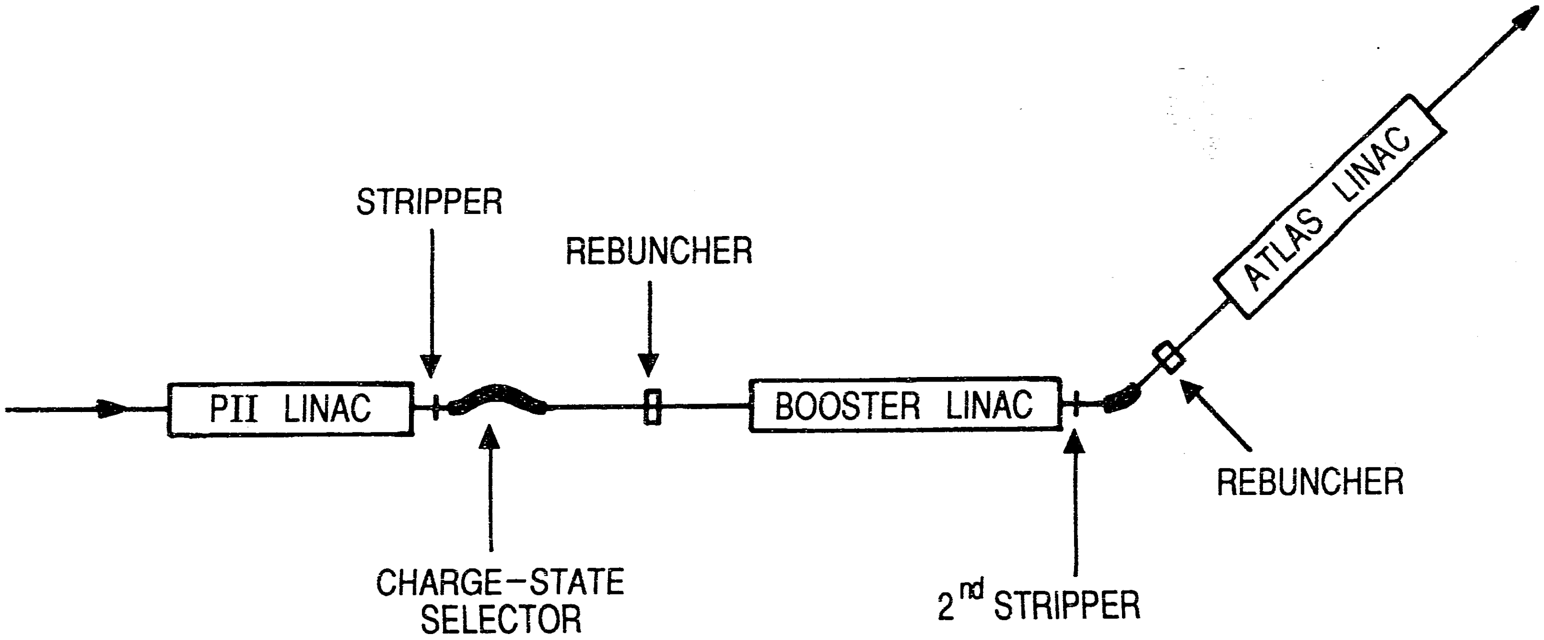


Fig. 11

ANL-P-20,663

TUNING WITH GUIDE BEAM

REQUIRED BEAM:

$^{208}Pb^{24+} \rightarrow {}^{208}Pb^{39+}$ (FROM PII)

GUIDE BEAM:

$^{16}O^{3+}$ FROM TANDEM

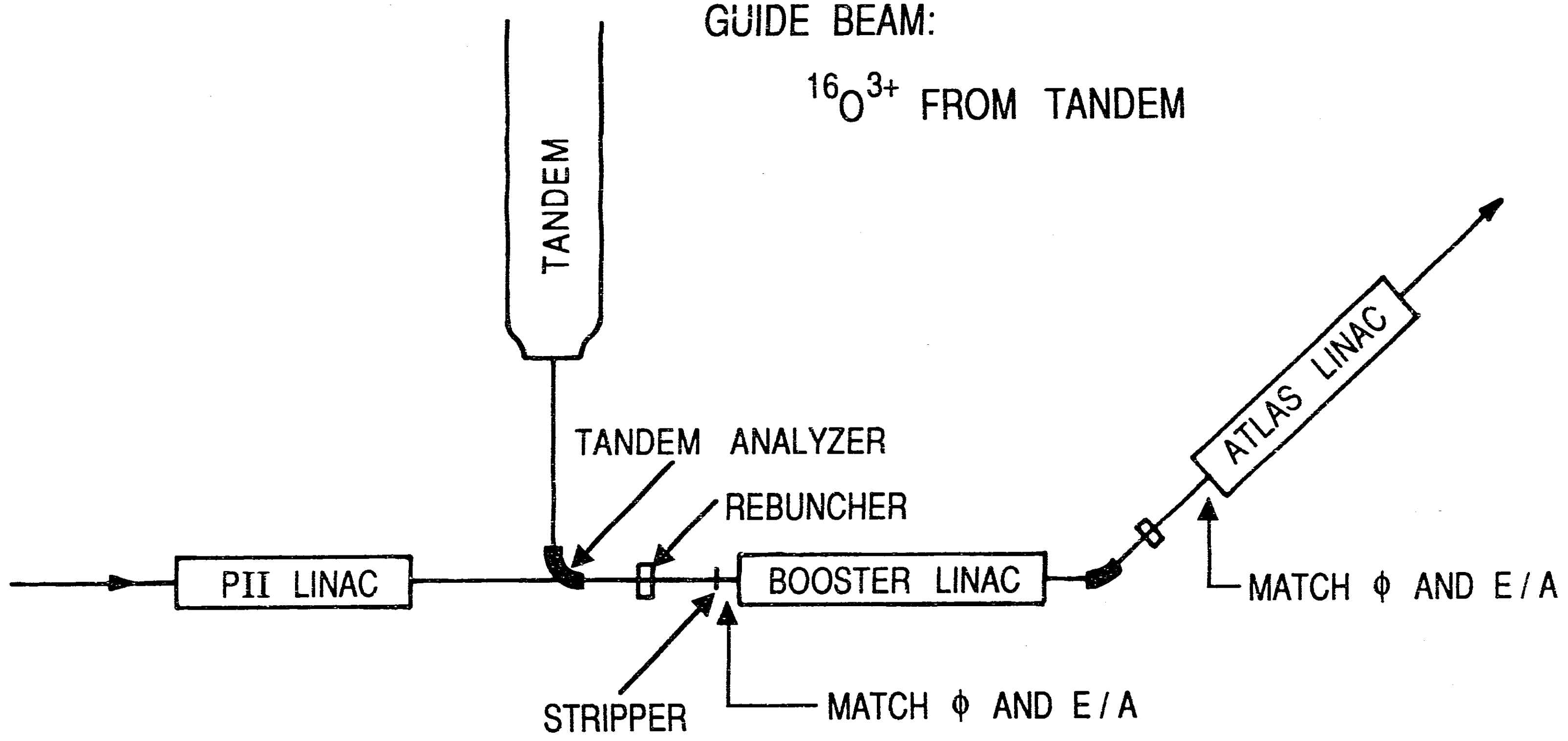


Fig. 12

MATCHING $^{208}Pb^{39+}$ BEAM TO BOOSTER INPUT

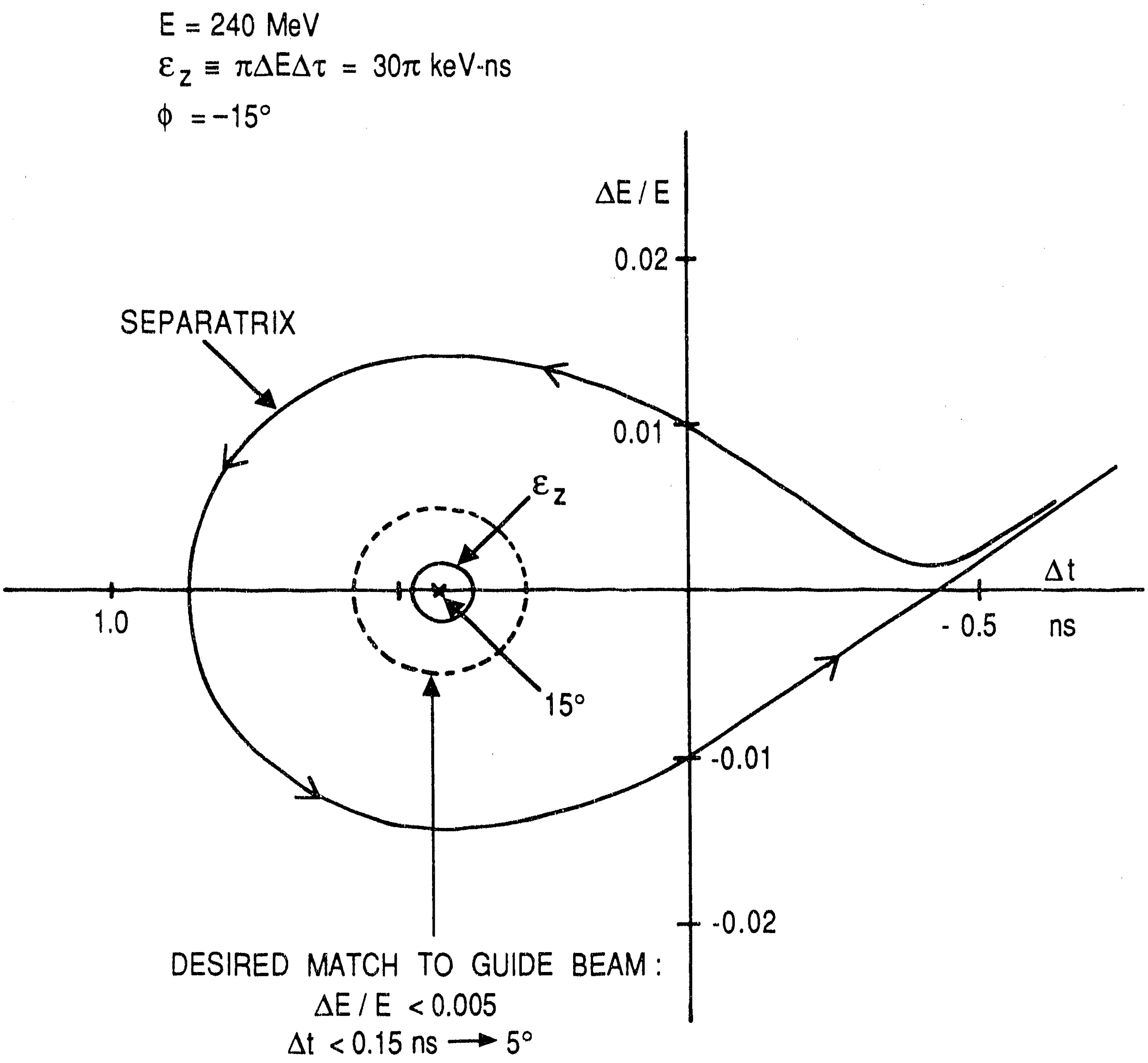


Fig. 13

MEASUREMENT OF LONGITUDINAL EMITTANCE ε_z

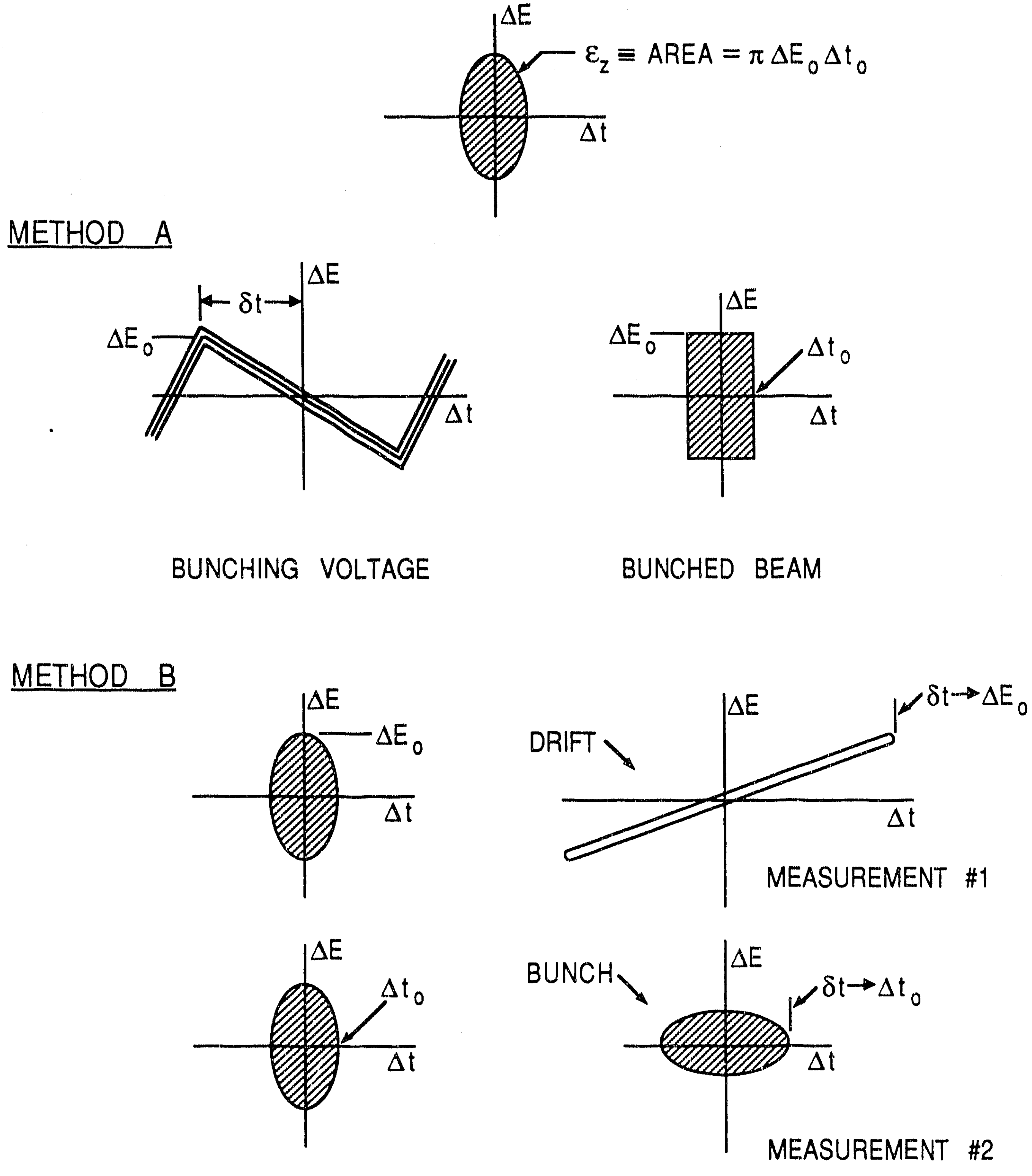
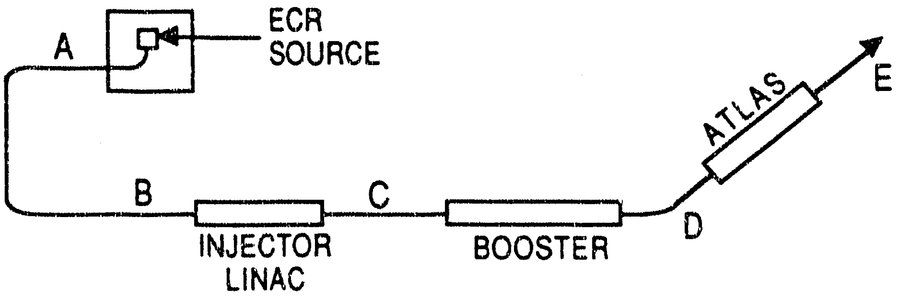


Fig. 14



LONGITUDINAL EMITTANCE IN π keV-ns

INJECTOR LINAC	ION	MEASUREMENT AT LOCATION A	B	C	D	E
3 MV	$^{3}He^{2+}$				<1	
3 MV	$^{40}Ar^{12+}$		4	5		
3 MV	$^{86}Kr^{19+}$		13			
7 MV	$^{86}Kr^{15+}$					19
12 MV	$^{30}Si^{7+}$			9		
12 MV	$^{40}Ar^{11+}$	3.0	4.6			
12 MV	$^{208}Pb^{24\rightarrow 39+}$			16		
TANDEM	$^{16}O^{6+}$			15	15	
TANDEM	$^{16}O^{6\rightarrow 8+}$			20	20	
TANDEM	$^{58}Ni^{10+}$				30	
TANDEM	$^{58}Ni^{10\rightarrow 19+}$				40	

Fig. 15

END

DATE FILMED

9/9/92