MASTER

ATLAS

*A PROPOSAL FOR
A PRECISION
HEAVY ION ACCELERATOR
AT
ARGONNE NATIONAL LABORATORY*

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FOREWORD

This document was prepared during February 1978. Its preparation was coordinated by L. M. Bollinger with contributions from many individuals at Argonne and some from outside Argonne.

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I. OUTLINE OF THE PROPOSAL

The objective of the proposed Argonne Tandem-Linac Accelerator System (ATLAS) is to provide precision beams of heavy ions for nuclear physics research in the region of projectile energies comparable to nuclear binding energies (5–25 MeV/A). By using the demonstrated potential of superconducting rf technology, beams of exceptional quality and flexibility can be obtained. The system is designed to provide beams with tandem-like energy resolution and ease of energy variation, the energy range is comparable to that of a ~ 50 MV tandem and, in addition, the beam will be bunched into very short (~ 50 psec) pulses, permitting fast-timing measurements that can open up major new experimental approaches.

The main accelerator component is to be a superconducting linac consisting of an array of independently-phased resonators of the split-ring type grouped in 7 accelerator sections. The rf technology for this system has been developed at Argonne where, since 1975, we have been building a prototype linac to boost the energy of heavy ions from the FN tandem. As is discussed in this proposal, all aspects of the technology (resonators, cryostats, beam bunching, rf control, etc.) have been thoroughly tested, and the construction of the prototype is well under way at this time. A beam will be accelerated through a section of 6 resonators during the Spring of 1978, an additional section will be put on line later in 1978, and a system containing 16 resonators will be in operation by mid 1979. The full booster is intended to have 4 sections, but funds for the last section are not yet available.

The proposed expansion of the tandem-superconducting-booster facility at Argonne will approximately double the maximum energy and mass range of projectiles and will add a second, larger, experimental area. With this capability, and the ability to accommodate two simultaneous users, ATLAS will become a powerful and unique user-oriented national facility for the exploration of nuclear structure with heavy-ion projectiles.

During the Fall of 1977, the Argonne FN tandem was substantially upgraded by installing a high-vacuum ($\sim 10^{-8}$ Torr) accelerator tube and a 150-kV injection system. During acceptance tests, a 350-pnA beam of $^{35}\text{Cl}^{8+}$ was analyzed for 4 hrs, the beam transmission was 70%, and loading effects

were small. Similarly, an analyzed beam of 130 pA of $^{58}\text{Ni}^{10+}$ has been accelerated without significant loading. In view of this encouraging performance, it is proposed that this upgraded FN tandem, with a few additional modifications, be the injector of the ATLAS facility.

The overall layout of the proposed accelerator system, shown in Fig. 1, indicates how ATLAS is formed by a cost-effective extension of an existing accelerator system. The whole injection system of the linac now exists, including the tandem and a beam-bunching system that enables ~75% of the dc beam from the source to be accepted by the linac. Also, the booster linac now under construction will exist, and considerable experience in its use will have been acquired. And, finally, most of the building structures and auxiliary facilities needed for the effective operation of ATLAS, including Target Area II, exist and will be supporting an intensive heavy-ion research program when ATLAS is funded.

The 40° bend in the beam direction near the mid point of the linac permits the beam to be split and to be directed simultaneously (in every micro-pulse) into Target Areas II and III. This is possible and exceptionally cost effective because, at the location of the bend, the beam will normally contain ions with several charge states, whereas in most experiments only one of these would be used. Thus, the two beams can be formed without loss of useful intensity. The operations of bending and splitting the beam can be carried out elegantly and inexpensively, without the need for rebunching, by using double-focusing superconducting magnets for bending and by controlling the longitudinal phase space by appropriate adjustment within the linac itself. The 40° bend also has the advantages of placing the new Target Area III in an open area where construction problems are reduced and where disruption of the ongoing research in Target Area II (with the beam from the booster) will be kept to a minimum.

The second, new half of the linac will be formed by a simple extension of the designs used in the booster. In particular, (1) the resonators will be fabricated in the same way, (2) the phase-control system will be identical, (3) the computer-based system for controlling the whole linac will exist, (4) flowing liquid helium for cooling will be distributed in the same way, and (5) the modular cryostats will be identical in size so that accelerator sections will be easily interchangeable. Thus, the developmental effort

required will be minimal and, indeed, important parts of the detailed engineering design have already been completed.

The new portion of the linac will be housed in a shielded tunnel that is large enough to permit complete accelerator sections to be transported into the main linac-assembly area adjacent to the present booster. All assembly will be done off line, and completely tested acceleration sections will be moved on line while still cold. This approach, which is also being used with the booster, is expected to maximize operational efficiency. Note that, because of the flexibility resulting from the use of independently-phased resonators, the linac can continue to operate effectively even when a whole accelerator section is missing.

In general terms, the performance of ATLAS can be described as being similar to that of an extremely large tandem (~ 50 MV) with two strippers: ATLAS has a similar dependence of maximum energy on mass, it has easy energy variability, and it has even better beam quality. The maximum available output energy is summarized in Fig. 2. Normally, the accelerator system would be operated with only two strippers in order to maintain an adequate beam intensity, but the use of a third stripper at the location shown in Fig. 1 would provide additional energy for experiments in which some intensity can be sacrificed.

The performance curves in Fig. 2 show that the available energy is far above the Coulomb barrier for projectiles in the lower half of the periodic table and falls below the barrier for the heaviest ions. The emphasis on projectiles from the lower half of the periodic table is a deliberate limitation on the scope (and the cost) of the proposed project. This choice in no way limits the possibilities for future expansion of the linac, which (as will be discussed later) can be achieved without moving the then established accelerator or the experimental areas.

As seen from Fig. 2, the maximum energies of the beam going into Target Area II is in a range < 15 MeV/A, depending on the projectile. Under many circumstances, the beam energy (but not the projectile) can be chosen independently of the requirements of the user of the beam from the full linac. Thus, the user in Target Area II has a degree of flexibility that considerably exceeds that of parasitic users of secondary beams at other heavy-ion facilities.

A characteristic and important feature of ATLAS is its exceptionally good beam quality. Because the phase space of the beam is controlled to an unusual degree during the stripping and linac-injection processes, non-linear effects can be largely avoided in both transverse and longitudinal phase space, and hence the excellent quality of the beam from the tandem can be preserved. Starting with a linac-output beam that typically has a relative energy spread of 10^{-3} and a time spread of <50 psec, a debuncher/rebuncher resonator located after the linac will manipulate the phase space of the beam into the configuration desired by the experimenter. Without loss of intensity, a relative energy spread $<10^{-4}$ or a time spread <25 psec can be readily provided. Ultra-short pulses such as this are expected to open up a wide range of new experimental possibilities.

The output beam intensity depends almost entirely on the performance of the tandem and on the stripping process, since the linac itself transmits almost all ions injected into it. Normally, strippers #1 and #2 (Fig. 1) will be used, and the beam from ATLAS in a single charge state is typically about 4% of the beam injected into the tandem, i.e., an output beam in the range from 30 to 100 pA. This is enough for most nuclear-structure experiments but, if more current is needed, it can often be obtained by sacrificing either maximum energy or beam quality.

Most other current proposals for national heavy-ion facilities in the United States are aiming at maximum projectile energies of 100-200 MeV/A for the lighter heavy ions. These facilities tend to be directed toward the exploration of possible qualitatively-new phenomena such as shock waves, density isomers, etc., which may appear when the projectile velocity approaches that required for pion production in the N-N system. Clearly, when two nuclear systems collide with energies much larger than their internal binding energies, the resultant phenomena, interesting though they may be, are not likely to be sensitive to nuclear structure. The present proposal is aimed squarely at the exploration of heavy-ion interactions in the range of energies in which the connection with nuclear structure is the most direct.

With projectile energies between 5 and 25 MeV/A, the wealth of structure that is embedded in the quantum-mechanical many-body system of the nucleus is most likely to be accessible. This is the energy region in

which high angular-momentum states, shape isomers, molecular resonances, the production of new far-from-stability nuclides, and many other aspects of nuclear structure are most likely to reveal themselves. And to explore this field will require a class of precision experiments that are likely to require considerable experimental time on accelerators and a substantial effort in terms of scientific manpower. In the context of the national and international effort in heavy-ion physics, the ATLAS facility would fill an important gap between the existing lower-energy heavy-ion tandems and cyclotrons, and the proposed new generation of large circular machines aimed at an order of magnitude higher energies.

We assume that ATLAS will be operated as a national facility for the general benefit of the nuclear-physics community and for some other areas of research.

The cost for ATLAS is estimated to be \$5.6M. If funded in FY 1980, it would be operational in 1982.

Fig. 1. Overall layout of ATLAS. construction and linac compone are indicated by cross hatchi

Fig. 1. Overall layout of ATLAS. New construction and linac components are indicated by cross hatching.

Fig. 2. Beams available from ATLAS in three experimental areas.

II. THE ACCELERATOR SYSTEM

In this section we summarize all aspects of the technology of ATLAS. The accelerator system incorporates all of the booster now under construction and also the existing FN tandem and beam-bunching systems, as shown in Fig. 1. The principal modifications and additions required for the formation of ATLAS are the following: (1) the ion-source system and the terminal of the tandem are improved, (2) the linac is extended by the addition of three new sections that are housed in a new tunnel, and (3) a new target area is added.

A. OUTLINE OF THE ACCELERATION PROCESS

Many of the main ideas involved in the design of ATLAS can be summarized by tracing each step of the acceleration process through the planned system. Starting at the ion source, negatively-charged ions are injected into the tandem at an energy in the range 150 to 175 keV. Before entering the tandem, the energy of the dc beam from the source is modulated by a harmonic buncher, which forms ion pulses about 1 ns wide at the terminal; the bunching frequency is either $\frac{1}{2}$ or $\frac{1}{4}$ of 97 MHz, the linac frequency.

The tandem operates in the usual way as a two-stage accelerator. In the terminal, a foil stripper $< 5 \mu\text{g}/\text{cm}^2$ thick is used for relatively light ions ($A \leq 50$), and a gas stripper $< 1 \mu\text{g}/\text{cm}^2$ thick is used for heavier ions. The basic beam quality of the whole accelerator is established by this stripping process, since beam-quality degradation further down stream can be largely avoided. A lower limit on the beam emittance is the product of the beam radius and angular straggling as the beam leaves the stripper; and a limit on the so-called longitudinal emittance (which determines the achievable energy and time resolutions of the output beam) is the product of the time spread and energy spread immediately after the stripper.

The injection optics of the tandem are designed to minimize the beam size at the terminal; a diameter of 4 mm is the design value. Similarly, the thickness of stripping foils is minimized.

The terminal voltage is held at 9 MV when the maximum output energy is required, but otherwise is dropped down to 8 MV in order to enable it to

carry a larger beam current. During any given run, the terminal voltage is usually held fixed, and the energy of the output beam is varied by changing conditions in the linac.

A single charge state in the beam from the tandem is selected for injection into the linac by means of a 90° superconducting analyzing magnet.

Before injection into the linac, the dc beam from the source is bunched into narrow pulses at half the 97 MHz frequency of the linac. The two-stage bunching system used for this purpose consists of (1) the pre-tandem room-temperature buncher mentioned above, (2) a superconducting post-tandem buncher, (3) a bunch-phase detector that dynamically links the phases of the two bunchers, and (4) a post-tandem beam chopper that eliminates unbunched ions between pulses. The function of the phase detector is to correct for changes in the time required for ions to travel between the pre-tandem and post-tandem buncher, as caused by variations in the numerous voltages that interact with the beam in the tandem and its injector.

The ion pulses injected into the linac are typically 50 psec wide (FWHM), which minimizes beam-quality deterioration within the linac, and the average beam intensity is $\geq 75\%$ of what it would be without bunching.

Just before entering the linac, the bunched beam comes to a time focus at the position of stripper #2, a carbon foil. For most beams, the increased ion charge given by this second stripping is needed to produce the desired energy gain in the linac. The stripper is located at the time focus, where the energy spread is large, in order to minimize beam-quality deterioration from energy straggling.

Essentially all ions injected into the linac are transmitted through it (independent of energy, phase, or charge) because of the number and strength of the focussing solenoids. Thus, all charge states from the second stripper are transmitted, and all above some critical charge receive roughly the same energy gain. Consequently, in most experiments it is necessary to use charge-state selection after the linac, but the full intensity of the multiply-charged beam may occasionally be useful.

When the charge-state of the tandem beam is large enough (as it may be for ions with $A \leq 60$), then the second stripper is not used and the beam intensity in a single charge state is higher, typically by a factor of 4.

The ion pulses injected into the linac are so small in transverse phase space (position and angle) and so confined in longitudinal phase space (time and energy) that the ions can be accelerated with very little loss in beam quality. The loss is minimized by tuning the focussing solenoids so that the beam remains physically small and by tuning the resonators so as to manipulate the phase space of the incoming beam into a shape that is matched to the acceptance of the linac. This strategy implies that most of the resonators are operated in a phase-focussing mode, but one or two resonators near the input end may need to be operated in a phase-defocussing mode.

The multiply-charged beam out of the first stage of linac acceleration is bent in such a way as to provide charge-state selection and beam splitting. The beam corresponding to some charge q_0 is directed into Target Room #2 and charge q_0+1 goes into the second stage of linac acceleration. The main path of the beam bender, formed of two superconducting magnets, is both isochronous and achromatic to first order, and does not significantly degrade the beam quality. By properly tuning a few linac resonators both before and after the bend, the longitudinal phase space can be adjusted so that rebunching is not required between the two parts of the linac.

A third stripper (a foil) may be used between the two parts of the linac to increase the ion charge and hence the beam energy, if beam intensity or beam quality can be sacrificed somewhat.

Acceleration within the second part of the linac takes place in the same way as in the first. As at the linac input, several resonators near the output can be tuned to shape the longitudinal phase space, in this case to satisfy the requirements of the experimenter.

Finally, as the beam enters the target room, it passes through a resonator that either rebunches it (in order to form a narrow pulse at the experiment) or debunches it (in order to obtain better energy resolution), depending on the experimental need.

The beam energy is determined by a time-of-flight measurement that involves passage of the beam through two of the resonant phase detectors developed for the bunching system. Since these nondestructive devices can easily measure the mean arrival time of a bunch with an accuracy of 10 psec, for the typical ion the energy can be measured with an accuracy of 2×10^{-4} if the flight path is 10 meters.

B. THE SUPERCONDUCTING LINAC

The main technological thrust of this proposal 's to make use of RF superconductivity for heavy-ion acceleration. Although this technology is quite new and appears to be regarded as untested and somehow mysterious by a wide segment of the scientific community, in fact it is by now highly developed and, overall, a superconducting linac is probably the most conservative technology that would be seriously considered for a major heavy-ion facility at this time.

Our confidence in the reliability of superconducting rf technology stems, of course, from the advanced state of development and construction of the superconducting heavy-ion-energy booster^{1,2} at the Argonne FN tandem. This project was started in 1975 with the primary objective of developing the accelerator technology by designing, building, testing, and using a prototype superconducting linac for heavy-ion acceleration. The design and component-development phase of the project has been completed, fabrication of components is in full swing, and assembly and testing of complete accelerator sections has started. A section that will provide at least 7 MV of voltage gain is scheduled to be put into beam-line operation in late Spring, 1978, and before the end of 1978 the accelerating power will be increased to at least 15 MV. Even the initial 7-MV voltage will double the beam energy for ions in the mass range $15 < A < 45$.

All of our experience to date indicates that RF superconductivity is a stable, reproducible technology that has good performance characteristics now and has great promise for future improvements. Well before the inception of the booster project, we had accumulated a wealth of encouraging experience with the helix structure, including the first acceleration of an ion beam with a superconducting rf device^{3,4}. Moreover, the specific task of building the booster has forced us to solve all of the messy engineering and fabrication problems that turn out to be the primary barrier to the construction of a reliable, useful device. This experience is giving reliable information about costs and schedule. And finally, the rapidly approaching linac-operation phase of the project provides the opportunity to uncover and correct any remaining problems that might be present. In short, superconducting-linac technology is highly developed now and will be tested in all respects by mid 1979.

¹L. M. Bollinger, et al, Proc. 1976 Proton Lin. Accel. Conf. (AECL-5677 Chalk River, 1976) p. 95

²L. M. Bollinger, IEEE Trans. Nucl. Sci. NS 24, 1076 (1977).

The linac proposed for ATLAS is approximately twice the size of the booster linac that is expected to be in operation by mid 1980, and the larger machine will be formed by merely expanding the booster. The only significant developmental effort required is the design and testing of a new variant of the split-ring resonator: a 46-cm long unit for the acceleration of the faster ions. All other features of the design will be the same as in the booster. Thus, most aspects of the linac can be described in great detail by describing the booster.

1. BRIEF DESCRIPTION OF THE BOOSTER

A schematic representation of the booster as it is expected to be in 1980 is shown in Fig. 3. The heart of the system is the split-ring resonator, a three-gap structure made of superconducting niobium. Superconducting solenoids at frequent intervals confine the radial excursions of the beam. The basic accelerating section of the linac consists of a linear array of these resonators and solenoids within a cryostat that can be isolated from the others both with respect to vacuum and cryogenics.

The four sections of the booster make use of resonators that have two lengths. One type is 35.6-cm long and is optimized for a projectile velocity $\beta \equiv v/c = 0.105$; it is now completely developed (sections C and D). A second, less-demanding, type is 20.3-cm long and is optimized for $\beta = 0.060$; it will be developed in late 1978 (sections A and B). Section C, with six resonators, will be completed and put on line in late Spring, 1978. Cryostat A is being used initially as a prototype in which two 35-cm units are mounted, but these will be replaced with the final 20-cm units by mid 1979. Section B, loaded mainly with the shorter units, will be built as soon as funding is available, probably in 1980.

The rather complicated schedule of events outlined above is summarized by Fig. 4, which shows the various configurations that will be used during the next two years to accelerate heavy-ion beams for the research program. The advantage of having modular cryostats is obvious from the figure; and the fact that linacs with such large changes in configuration can be useful emphasizes the versatility of a machine made with independently-phased resonators.

³J. Aron, et al, IEEE Trans. Nucl. Sci. NS-20, 76 (1973).

⁴J. Aron, et al, Proc. 9th Internat. Conf. High Energy Accel. (1974), p. 159.

Fig. 3. Schematic of heavy-ion booster.

SCHEDULE FOR HEAVY-ION BOOSTER

Fig. 4. Schedule for completion and use of the booster.

An indication of the appearance of the accelerator sections may be judged from Fig. 5, which shows a general view of the booster area during an early stage of assembly. Here section C is on the beam line and section A (in a temporary location) is open for assembly, with a resonator being lowered into position. Apparently because of the use of a wide-angle lens for the photograph, the 12-ft long cryostat C and indeed all lengths into the paper appear abnormally short. Target Area II is seen in the far background.

Each resonator consists of an inner drift-tube assembly made of pure niobium and a housing made of sheet niobium that is explosively bonded to copper, as shown in Fig. 6. The RF power dissipation into liquid helium is typically 4 watts per resonator. The inner assembly is cooled by 4.8K liquid helium within the hollow loading tube and drift tubes, and heat generated in the housing is conducted to a helium-cooled heat sink through the copper backing of the bonded niobium.

RF power is fed to the resonating drift-tube assembly from a 150-watt solid-state rf amplifier by means of capacitive coupling from a 3/8-inch diameter superconducting probe. Fast tuning is achieved by means of a high-power voltage-controlled reactance (VCX) developed for the purpose. This device, which is used to lock the rf phase of a resonator to the phase of a master oscillator, has been tested on a resonator in a beam-line cryostat and been shown to be more than adequate.

The design aim for the 35-cm resonators is an average accelerating field of 4.25 MV/m, which implies a voltage gain of 1.5 MV (i.e., 1.5 MeV per charge) from each unit. The resonators will initially be operated at a somewhat lower field, in the range 3.3 to 3.6 MV/m. Then, when more urgent tasks have been completed, the effort required to push the field up to the design goal will be undertaken. The accelerating field of the 20-cm units is expected to be at least 10% higher (for the same power dissipation) than the field in the larger units.

The resonators are cooled to a temperature of about 4.8K by means of flowing two-phase helium in a closed circulating system. The driving pressure for the flow is the refrigerator itself, which (with three compressors) supplies nominally 95 watts of cooling and a flow rate of 8 gm/sec at 4.6K. The cooling power can be increased to a 40% higher value by vaporizing the liquid-helium inventory in a 1000-liter storage dewar.

Fig. 5.

Fig. 6. Superconducting split-ring resonator for $\beta = 0.105$.

Superconducting solenoids are used to limit the transverse excursions of the beam. These hybrid magnets consist of a superconducting coil and a soft-iron return yoke and shield. The measured peak field is 7.6 Tesla; and the length of the coil is chosen to give a focussing power $P_s \equiv \int B^2 dz$ that is strong enough not only to counterbalance the defocusing action of the resonators but also is strong enough to allow the average beam size to be minimized through most of the booster for most ions. The solenoids are cooled by flowing liquid helium in the same way as are the resonators.

All of the cryostats for the booster and also ATLAS are end-loading units and, except for section A, all are of the same size. In each unit, the array of resonators is surrounded by a nitrogen-cooled heat shield and, outside of it, a vacuum wall (see Fig. 7). Even though the interior of the resonators is open to the outer vacuum region, including the warm outer vacuum wall, the pressure inside the resonators is very low ($< 10^{-8}$ Torr) during operation because of cryopumping on the outer surface of the resonators.

Each cryostat can be isolated from the others and removed from the beam line without disturbing the cooling or vacuum of the tanks remaining on the line. Once off line, the whole inner assembly of an accelerator section can be rolled out the end of the cryostat, and all disassembly can then be done in the open. When a section is ready to be put into service, it is cooled down off line, completely tested, and finally moved on line while still cold. While the maintenance of a section is carried out off line, the section remaining on line can be used for acceleration.

Both the booster and the bunching system are controlled with the assistance of an 11/34-model PDP computer, which interacts with CAMAC crates by means of serial instructions. In general terms, hard-wired feedback circuitry is used to control resonator phase and amplitude on a fast time scale, whereas the computer sets the reference values and monitors and controls phase and amplitude on a slow time scale. Similarly, the computer sets and monitors the solenoid fields. For other parameters, such as temperatures and vacuum pressure, the computer provides only monitoring. And finally, the computer is used to record and analyze beam diagnostic information, and this makes it possible to tune the linac rapidly. The present system has the basic capacity required to control ATLAS.

END VIEW OF LINAC CRYOSTAT

Fig. 7. End view of beam-line cryostat.

2. BOOSTER COMPONENTS AND PROCEDURES

a. Resonator Design and Fabrication

The heart of the linac is the accelerating structure, a superconducting resonator of the split-ring type. This class of resonator, first developed at Cal Tech⁵, with plated lead as the superconductor, was chosen for use in our booster⁶ primarily because it can be made mechanically rigid and therefore its resonant frequency is relatively insensitive to both mechanical vibration and field level, with the result that phase control can be achieved in a straightforward way.

A primary decision in the booster project was the choice of niobium as the superconductor. This choice was made because the high critical magnetic field and low surface resistivity of niobium maximize the possible resonator performance and hence, it was believed, was the cost-effective approach for a useful linac. Now that the developmental problems have been solved, the choice of niobium as the optimum material still appears correct.

A second primary decision was the choice of a relatively low resonant frequency (97 MHz) for the resonators. This low value has the advantage that bunching is easier, and an individual resonator gives a large energy gain, which minimizes the total number of linac components. But the low frequency was risky because fabrication of a larger resonator is more difficult and especially because the large stored rf energy makes phase control more difficult. As it has turned out, these problems have been overcome, and hence the low rf frequency is quite advantageous.

In order to limit the radial dimensions of the resonator, the original Cal Tech design was modified by bending the split ring inward so that the drift tubes are coaxial with the housing. This made it possible to achieve the desired frequency of ~ 100 MHz for a housing that is 16 inches in diameter.

Another large deviation from the Cal Tech design was the use of large drift tubes. This was done for three reasons:

- (1) to make the energy gain insensitive to the radial position of an ion,
- (2) to shield the beam axis from the influence of axially-asymmetric fields, and
- (3) to reduce the resonancy frequency.

As will be discussed later, the second reason has turned out to be very important.

⁵K. W. Shepard, J. E. Mercereau and G. J. Dick, IEEE Trans. Nucl. Sci. NS-22, 1179, (1975).

⁶K. W. Shepard, et al, IEEE Trans. Nucl. Sci. NS-24, 1147 (1977).

Two quite different designs of the split-ring resonator were tested in prototype form. The one chosen for use in the booster is shown in Figs. 6, 8, and 9. In Fig. 8, the end plates are removed, in the condition used for treatment of the superconducting surface. In Fig. 9, the end plates are in place, and the assembled resonator is ready to be lowered into the off-line cryostat that is used to test all resonators prior to installation in the beam-line cryostats.

The inner all-niobium drift-tube assembly of the resonator is made by forming and bending sheet metal and tubing and then beam welding the several pieces together. Great care is being taken to make all units with the same dimensions so as to have the same resonant frequency.

It would have been advantageous to have the drift-tube assembly demountable from the resonator housing. However, we were not able to find an rf seal that gave acceptably low rf losses and hence, in the final design, the drift-tube assembly is welded to the housing.

The cylindrical housing of the resonator is made of a new rf superconducting material consisting of niobium sheet that is explosively bonded to a copper backing. The niobium sheet provides the superconducting surface and the thermally conductive copper backing, in contact with a helium-cooled heat sink, keeps the niobium cold. Additional information about the new material and its properties is given in Appendix 1.

After a great deal of developmental effort (see Appendix 2), the preparation and use of the niobium-copper composite has been mastered and is giving excellent results: (a) the copper-niobium bond is rugged, (b) structures made of the composite are stiff enough to be relatively free of vibration, (c) the niobium surface is cooled better than it is by a helium bath in most structures, and (d) the surface resistivity is small. Additional detail about the design and fabrication of the housing is given in Appendix 1.

Both end plates of the resonator are demountable in order to make the interior accessible for surface treatment. Niobium is bonded to both sides of the copper in the end plates so as to eliminate bowing caused by the difference in the thermal-expansion coefficients of copper and niobium.

One of the more difficult technical problems in the resonator was the development of a good rf joint with which to attach the end plates to the cylindrical housing. This is a difficult and previously unsolved problem because the unavoidable oxide layer on niobium causes most forms of contact

Fig. 8.

Fig. 9.

to have unacceptably high rf losses. The problem was finally solved by making the rf contact through a collapsible H-shaped niobium gasket that abrades the mating surfaces as it is deformed. The rf resistance of the joint is a monotonic decreasing function of the force applied to the joint; in order to reduce the losses to a negligible level, it is necessary to use massive forces - about 3 tons per inch of gasket or 160 tons per end plate! This force is applied by means of the joining bolts shown in Fig. 6. Additional detail is given in Appendix 3.

The drift tube assembly is cooled by means of flowing, slightly sub-cooled, liquid helium that enters the loading tube from the bottom and completely fills the assembly. The main heat-transfer mechanism is nucleate boiling. Gas bubbles rise to the top of the drift tube where, with excess liquid, they are exhausted through a plastic tube into the main helium-outlet pipe. The parallel flows through the several resonators and solenoids in each accelerator section are approximately equalized by means of flow constrictors at the base of each element. With a total flow of 8 gm/sec of helium into a section, any individual resonator has ~ 16 watts of cooling available, but the refrigerator can provide only 4 watts per resonator on the average.

The heat sink for the outer housing is the 6-inch diameter helium-filled volume above the bottom flange of the resonator. Heat from the end plates is conducted to the cylindrical housing through the niobium rf gasket.

The three rf ports required for power input, phase control, and signal pickup are seen in Fig. 6.

Now that the techniques have been developed, the Argonne machine shops can fabricate resonators at the rate of 4 units in 3 months.

b. Resonator Performance

As of this writing, four niobium split-ring resonators of the 35-cm variety have been tested: (1) a prototype (P-1) made entirely of niobium, (2) the final prototype (P-2) in which the housing is made from the explosively bonded material, and (3) the first two of twelve production units based on the prototype P-2 described above. All units work well. Some of the developmental effort required to achieve the desired performance is given in Appendix 2. Here we restrict the discussion to the performance of the production-model units H-1 and H-2.

Maximum Accelerating Field

The level of accelerating field ξ_a now being achieved with the $\beta = 0.105$ resonator H-1 is described by Fig. 10, which plots resonator Q vs ξ_a . Here the accelerating field is defined by the relation

$$\Delta E_m = qL \xi_a, \quad (1)$$

where ΔE_m is the maximum energy gain obtainable for any ion of charge q in a resonator of length L between inside surfaces of end plates. The curves in the figure also show several levels of constant power dissipation. The data points give the measured performance at several stages of the surface preparation process.

When first tested after electropolishing the surface, the resonator Q is very high at low fields* but falls off rapidly at ~ 2 MV/m, presumably because of electron loading caused by field emission. Then, in order to improve the performance, helium gas is introduced into the resonator at a pressure in the range 10^{-4} to 10^{-5} Torr, and the resonator is operated at a field high enough to ionize the gas, and some ions are driven into nearby surfaces. By means of this "helium conditioning" process⁷, field emission is reduced, x-ray emission is reduced, and ξ_a can be increased. Earlier experience⁷ with helix resonators indicates that it is sometimes worth while to carry out the conditioning process for a period of days, but this level of effort has not yet been invested in helium conditioning the split rings. All our experience to date indicates that, after helium conditioning, the performance is stable in time. Indeed, if anything, the performance tends to improve with use.

From Fig. 10 one sees that, after the final stage of helium conditioning, the resonator operates at a field of 3.3 MV/m when the power loss is 4 watts, the design value for the helium refrigerator. However, the resonator operates well at much higher fields if the required cooling is available. This is of interest in two ways. First, an individual resonator can be operated in such a way as to use more than the average cooling without much effect on the others. And second, the overall cooling power of the system can be pulsed to $\sim 40\%$ higher than the steady-state value for periods of 50 hours by vaporizing the liquid helium in a 1000-liter storage dewar that is an integral part of the helium-distribution system (see Sec. II. B2h.)

*Unit H-2, which is in the first stage of testing, has an even higher low-field $Q_0 \approx 3.3 \times 10^9$ at 4.2K.

⁷R. Benaroya, et al, IEEE Trans. Mag. MAG-11, 413 (1975).

Fig. 10. Performance characteristics of split-ring resonator H-1.

The value $\xi_a = 3.3$ MV/m corresponds to a maximum field of 15.5 MV/m at the surface of the drift tubes, whereas our design aim is to achieve 20 MV/m (and 4 watts of heating), which would give $\xi_a = 4.25$ MV/m for the $\beta = 0.105$ resonators. This discrepancy is not very bothersome because (1) almost no effort has been made yet to push the split-ring resonator to its performance limit, and (2) all of seven helix resonators tested earlier^{3,4,7} operated with surface fields in excess of 20 MV/m, and one helix⁷ achieved 36 MV/m. During 1979 we plan to undertake a systematic investigation of the factors that limit maximum surface fields. Since 20 MV/m is far below any known physical limit on the surface field, there is the possibility that substantially higher fields will be obtained.

As is implied by the above, at this time the usable accelerating field of the $\beta = 0.105$ resonator is limited by electron emission that produces a somewhat soft barrier. Other phenomena, such as the magnetic critical field or a thermal instability caused by a surface defect, can produce hard barriers, but these are well above 4 MV/m and do not limit useful performance at this time.

Almost all of our effort to date has been devoted to the design and development of the $\beta = 0.105$ resonator. However, development of the smaller $\beta = 0.060$ structure is expected to be much easier because the fundamental problems have been solved and because the geometry of the smaller unit is more favorable, with the result that power losses on the various surfaces and in the rf joint will be smaller. Also, because of the change in geometry, the maximum usable accelerating field is expected to be somewhat greater (probably 10 to 20%) for a given power dissipation. Concentrated work on the $\beta = 0.060$ units required for section A will start in the second half of 1978.

Stability of Maximum Fields

There seems to be a widespread impression that superconducting rf surfaces are extremely unstable and easily deteriorate for no apparent cause. However, this has not been our experience during some seven years of investigating helix and split-ring resonators, many of which have been stored for extended periods of time, recycled repeatedly to room temperature, and abused in various ways. Three examples typify the qualitative nature of our experience.

(1) An exceptionally good helix resonator⁷ was subjected to deliberate contamination by air at atmospheric pressure. On the first exposure, the maximum electric field dropped from 36 MV/m to 26 MV/m, but additional exposure did not cause the performance to deteriorate further.

(2) A helix resonator⁸ was mounted on a beam line at the tandem for 18 months. During this period it was used on several occasions to accelerate a beam, it was repeatedly cycled in temperature between 1.8 and 80 K, and it had two vacuum accidents. In one accident, a power failure caused the vacuum pumps to be off and the temperature to rise over a 6-hour period, with a resultant release of quantities of condensed gas. In the second incident, the resonator was inadvertently cut off from its pumps for 6 weeks, during which time the pressure rose to $> 10^{-4}$ Torr. Then, to make matters worse, the unit was accidentally conditioned with oxygen gas rather than helium! In spite of this abuse, the unit was restored to approximately its original surface-field level (23 MV/m) merely by helium conditioning.

(3) The first production split-ring resonator was (a) tested in the off-line cryostat, where it gave the performance shown in Fig. 10, (b) warmed to room temperature and exposed to air for about a week, (c) moved to the beam line cryostat and tested, (d) warmed, exposed to air for several days, and (e) moved to a test cryostat and tested a third time, all with no observable change in performance.

Frequency Stability

Both the static rf field-induced frequency shift and the vibration induced variation are small in the split-ring resonator, and this is one of the main virtues of the structure. For the $\beta = 0.105$ resonator, the static shift is given by Δf (kHz) $\approx 0.13 \xi_a^2$, where ξ_a is in MV/m. Thus even at 4 MV/m, the shift is only about 2 kHz, which is small enough that our slow tuner (see Sec. II. B2d) can easily balance out the shift.

The vibration-induced frequency variation depends, of course, on the environment and on the design of the cryostat. In some cryostats, boiling cryogenic fluids seem to be the main source of noise. However, our beam-line cryostat is very quiet and the vibration-induced frequency variation is only about 50 Hz peak to peak; the fast-tuning system (described in Sec. II. B2e) can control variations that are three times as great as this.

⁸L. M. Bollinger, IEEE Trans. Nucl. Sci., NS-22 (1975) 1148.

Transit Time Effects

Under the assumption that the relative velocity of an ion does not change much during acceleration through a resonator, the energy gain may be written as

$$\Delta E = q \xi_a L F_v \cos \phi, \quad (2)$$

where L is the resonator length, ξ_a is the average accelerating field over the length L , the phase angle ϕ is measured relative to the peak of the acceleration curve, and F_v is the transit-time factor, which is a function of ion velocity v but not of time. We use the convention that $F_v = 1$ at its maximum value.

The transit-time factor for the $\beta = 0.105$ structure was determined from an integration in which the input for ξ_z was obtained experimentally, as a function of axial distance z , by means of a bead measurement. The experimental result for ξ_z is given in Fig. 11, and the corresponding F_v obtained from Eq. (2) is plotted in Fig. 12 as a function of the beam energy E . For each kind of structure, it is convenient to define a reference energy E_r by the convention that $E = E_r$ when F_v is at its maximum value. For the 0.105- β split-ring resonator, $E_r/A = 5.14$ MeV/A.

An examination of Fig. 12 shows two characteristic features. First, for $E < E_r$, the value of F falls off rapidly and goes through zero at $E \approx 0.30 E_r$; the oscillating behavior of F for $E < 0.30 E_r$ is not shown because the absolute value of F is too small there to be useful. Second, for $E > E_r$, the value of F falls off very slowly, and hence one obtains effective acceleration up to energies several times the reference energy of the structure. This wide velocity acceptance is one of the primary justifications for the use of short, independently-phased resonators. The velocity acceptance would be even greater for one- or two-gap structures, of course, but in our judgement the three-gap split ring is more cost effective for the linac as a whole.

The shape of the transit-time curve for the 0.060- β structure is expected to be closely similar to that given by Fig. 12, but the absolute value of E_r/A is ~ 1.7 MeV/A.

Fig. 11. Axial field distribution in the 0.105-6 resonator.

Fig. 12. Curve a: transit-time factor for 0.105- β structure. Curves b and c: transit-time curves for 0.135- β and 0.148- β structures (respectively) with peak values reduced in proportion to their accelerating fields.

Axial Asymmetry in the Accelerating Field

Because the split-ring structure itself is axially asymmetrical, there is necessarily an axially-asymmetric component in the accelerating field. The dominant effect of this kind is in the central gap, where the influence of the two arms of the split ring are felt. The parts of the ring that are directly adjacent to the drift tubes have a minimum effect because the two arms approach the drift tube on the same side. However, in the horizontal plane the two arms of the ring are on opposite sides of the gap and have opposite polarities.

The magnitude of the transverse field in the horizontal plane of the $\beta = 0.105$ resonator was determined by means of a bead measurement, which had to be performed with exceptional care because of the small magnitude of the effect. The result of the measurement is that the transverse field E_x is $6 \pm 1\%$ of the axial field E_z . The asymmetry in the vertical plane is too small to be detected.

The asymmetry in the 0.060- β structure is expected to be smaller because the drift tube provides better shielding to the gap. The magnitude of the asymmetry has not been measured, but it can be estimated. On the basis of a two-dimensional model, the asymmetry in the gap of the 0.105- β structure was calculated to be $E_x/E_z = 0.062$ at the center of the gap. Since this result agrees with the experimental value, it appears meaningful to use the rather crude model to calculate the transverse field in the 0.060- β structure. The result is $E_x/E_z = 0.016$.

The implications of the transverse field on the performance of the linac are treated in Sec. II.E. One may summarize the result by the statement that the effect is unimportant for the booster because of the large bore of the drift tube and especially because the large number of strong focussing solenoids continually drive the beam back to the axis.

c. Diagnosis of Resonator Problems

We have found that an essential key to success in producing high-performance resonators is the ability to locate where rf losses are occurring, from which information one can usually deduce the nature of a problem and fix it. (See Appendix 2). Two highly successful systems have been developed for this purpose. One system makes use of an array of typically 15 germanium resistance thermometers strategically located on the outer surface of the niobium-copper housing. Because only one region of the housing is cooled, heat conduction through the housing generates a temperature distribution that depends on the location of the heat source. Typically, temperature rises are ~ 100 mK, and temperatures are measured with a relative accuracy of ± 1 mK. Thus, the data are accurate enough to locate heat sources with considerable precision.

The conceptually simple but mathematically complex problem of interpreting the thermal data obtained from the temperature measurements was solved by making voltage measurements on a two-dimensional electrical model of the thermal system, as described in Appendix 4. This simple procedure allows one to test various hypotheses about the distribution of heat input on the surface of the housing. At various stages of development, it has been used to identify and quantify (a) losses in the rf gasket, (b) losses throughout the surface of the bonded niobium, and (c) localized losses resulting from an error in the design of an rf port.

A second diagnostic technique makes use of second sound in liquid helium (~ 18 m/sec) to locate the point at which a thermal breakdown originates on the surface of the split ring. Several fast thermometers within the helium record the time of arrival of the heat pulse resulting from a thermal instability, and these data typically locate the heat source with an accuracy of $\sim \pm 1$ cm. Because of the accuracy with which the surface defect can be located, it is feasible to remove it by treating a limited area of the surface rather than the whole resonator. Techniques for doing this by means of local electropolishing have been developed and successfully applied to resonator H-1, which initially was thermally unstable at 3.0 MV/m because of a shallow fissure in the surface of the loading tube. This and other similar experiences suggest that it will usually be feasible to use the existing diagnostic techniques to identify and correct defects in a new resonator with a moderate degree of effort.

Additional information about the diagnostic systems are given in Appendix 4.

d. Coarse and Slow Tuning

Frequency tuning is carried out at five levels of refinement:

(1) as part of the fabrication process, (2) by the choice of the thicknesses of the rf gaskets to the end plates, (3) by a manual elastic deformation of one end plate, when warm, (4) by a remotely-controlled deformation of the other end plate, when cold, and (5) by fast tuning with voltage-controlled reactance. All but the last of these are outlined here.

Step (1) involves a measurement of the rf frequency during the resonator-fabrication process and a determination of the axial length to which the resonator should be cut in order to obtain the desired resonant frequency. This procedure permits an adjustment of about ± 1000 kHz.

Step (2) involves the choice, during assembly, of the gasket thickness required to correct for any fabrication error. This step permits an adjustment of about ± 200 kHz.

Step (3) involves the deformation of one end plate, while warm, by the manual adjustment of the position of a machine screw. This provides a frequency change of at least $+ 70$ kHz.

Step (4) involves the deformation of the other end plate, when cold, by a remotely-controlled pneumatic device. This relatively simple device allows the frequency to be swept over the range $0 - 70$ kHz in about 30 seconds. It has two functions: one is to correct for the static frequency shift associated with changes in the operating field; the second is to center the resonance frequency within the control window (~ 150 Hz) of the fast tuner.

The fast tuning involved in step (5) is achieved by rapidly modulating the resonance frequency in such a way that the average frequency is identical to that of the master oscillator and the phase error is always small. The tuning range is typically ± 100 Hz. Since the fast tuner is the heart of the control system, it is discussed in some detail in the next section.

e. RF Control System

A long-standing question about superconducting linacs has been whether it is feasible to control the resonator phase, since the bandwidth of an unloaded resonator is ~ 0.1 Hz whereas mechanical vibrations induce rf frequency variations that are typically 10^3 to 10^5 times greater. Clearly, it is advantageous to minimize the vibration-induced frequency variations and this was one of the main considerations in the choice of the split-ring structure. This choice has been justified since, in spite of its large size, it exhibits a frequency variation of only about 50 Hz, peak to peak. Equally important, the static frequency shift induced by the rf field is only about 2 kHz under high-field operation, and hence there is no observable instability from electromechanical coupling. As a result, a relatively simple control system is able to lock the phase of each resonator to that of a master oscillator.

An overall layout of the rf control system is given in Fig. 13. Each resonator in the linac contains its own local rf control unit. These units, which are installed beside the tanks containing the resonators, contain the circuitry needed to adjust and maintain the amplitude and phase of the accelerating voltage to pre-set values, as commanded by the remotely-located computer system. The remote control operates at the much longer time scale of seconds to minutes. By keeping the fast operations near the resonator, the computer installation is greatly simplified, since no fast cabling is required. Control cabling can be simple twisted pairs, and mechanically operated switching can be used for multiplex functions. The computer itself is greatly simplified, since it maintains only supervisory control over the system, while the fast local control operates the resonator.

Local Control

The local rf control module uses four main feedback loops to power up and control the accelerating voltage in the resonator, as shown in Fig. 14.

Loop #1 contains a manually adjustable phase shifter, a voltage-controlled attenuator, and a 150-watt high-gain (56 db) amplifier. The loop is adjusted for positive feedback at 97 MHz, so that, when the unit is turned on, it functions as a self-excited oscillator, which powers the cavity to the level called for by loop #2.

Fig. 13. Schematic of the rf control system.

Fig. 14. Schematic of the local resonator-control system.

Loop #2 contains an envelope detector, a summing junction, and the dc amplifier to drive the voltage-controlled attenuator. This is a negative-feedback loop used to maintain the rf level in the cavity at a pre-set value determined by either a local control or a command generated by the computer. Tests show that the rf level in the cavity is stable to better than 1 part in 2000.

Loop #3 is the phase-control loop. In order for the linac to operate properly, the phase of the accelerating voltage in each resonator must be set and maintained at some constant value. In this system, a master oscillator at 97 MHz provides the reference phase for the system. Each resonator has its own adjustable phase shifter controlled by the computer. The phase of the accelerating field in the cavity is compared with the output of the adjustable phase shifter, and an error signal is generated that is used to fast tune the cavity to the correct phase. The fast tuning is obtained by means of an external voltage-controlled reactance (VCX) that is strongly coupled to the resonator and can be switched in or out in response to the error signal. The resulting resonant-frequency variations induced by the loop, which are within a range of about $\Delta f = 150$ Hz, are sufficient to compensate for fast frequency variations that arise from mechanical perturbations.

Loop #4, the slow tuner, operates in two modes. In the first mode, when the cavity is functioning at an average frequency other than the frequency of the master oscillator, the phase/frequency control circuits generate an error signal that causes a pneumatic device to deform the cavity end plate enough to match the resonant frequency to that of the master oscillator. The system has a tuning range of about 70 KHz and a tuning rate of about 2 KHz/sec. This tuning function is necessary because the slow changes in the resonant frequency of the cavity due to radiation pressure, temperature, aging of the cavity, etc., are far beyond the range of the fast tuner. The shift in frequency due to radiation pressure at 3 MV/m, for example, amounts to 1.2 KHz, about six times the range of the fast tuner.

The second slow-tuner mode occurs when the frequency of the cavity is within the range of the fast tuner and when phase lock is achieved in loop #3. The slow tuner is now controlled by the phase-error signal. The system acts to reduce the dc component of the phase-error signal to zero and thus maximizes the useful range of the fast tuner.

In addition to the four control loops described above, the local control module generates an out-of-lock signal for use as a gating signal by experimenters. Also a sample of the cavity rf signal is heterodyned down to 50 KHz to provide an independent measure of cavity rf phase and amplitude at a point remote from the local control units. These low-frequency signals will be multiplexed and sampled intermittently by analog-to-digital converters and used as input to the computer for logging, calculating, and correcting the local control modules.

Fast Tuner

The rf control system is straightforward except for the fast-tuning VCX used in loop #3. At the highest accelerating fields, even the modest tuning range used here requires large amounts of rf energy to be handled (up to 5 KVAR), and it cannot be allowed to contribute significantly to the thermal load on the liquid helium. The frequency tuning must respond to mechanical vibration modes of the cavity up to several hundred hertz.

Fig.15 is the equivalent circuit of the fast-tuning system, where L and C represent the 97 MHz resonator, C_c is the small capacity linking the tuner probe to the drift-tube assembly, and C_1 is the capacity which provides the required voltage-controlled reactance. In our device, the switch consists of 4 PIN diodes driven by circuitry outside of the cryostat. The VCX itself is attached to the resonator, inside the cryostat (see Fig. 6). When the switch opens and closes the frequency increases and decreases, respectively. The PIN-diode drive circuitry turns the diode switch on and off at a rate of about 25 KHz. Within the 40- μ sec period, the switch can be turned on for a controlled time extending from $\sim 2 \mu$ sec to 38 μ sec. This modulation of the duty cycle (the fractional time on per period) can continuously vary the frequency of the cavity, as averaged over many 40- μ sec time intervals.

The duty cycle of the switch is controlled by the phase-error signal. When the frequency of the cavity varies because of mechanical vibrations, the phase-error signal varies the duty cycle of the switch in such a way as to hold the phase between the master oscillator and the cavity approximately constant. While the instantaneous frequency of the cavity varies from one switch position to the other at the 25 kHz rate, the phase of the accelerating voltage undergoes a small variation whose maximum peak to peak value is about $\Delta\phi = 1^\circ$.

Since the diode losses are relatively low in both states and since the transition time between states is kept short (~ 200 nsec), the efficiency of the tuner is good. For example, the system dissipates about 80 watts of rf power for a tuning power of about 4 KVAR. However, only a fraction of a watt is dissipated in the liquid-helium system; the remainder is taken up by the liquid nitrogen that cools the VCX assembly.

The low power input to the liquid helium results from the design of the fast tuner, which is shown in Fig.16. The vacuum dielectric capacitor is formed by the two copper surfaces contained within the housing at the top. The PIN diodes and the copper-ceramic probe assembly are maintained at LN_2 temperature and are electrically connected to the helium-cooled resonator by means of a 0.002-inch-wall stainless steel cylinder, which is designed to be the optimum compromise between rf-power dissipation and thermal isolation.

The small size, low losses, and wide tuning range of the VCX make it an especially effective fast tuner.

Fig. 15. Equivalent circuit of resonator linked to VCX consisting of capacitance C_1 and diode switch.

Fig. 16. Cross section of the VCX. The connection between the PIN-diode driver and the PIN diodes is not shown. The copper probe is cooled to liquid-nitrogen temperature by thermal conduction through the alumina ceramic, an electrical insulator.

f. Solenoid Lens

The superconducting solenoid is an inexpensive and compact lens with which to confine the radial extension of the beam. Although the lens action in a solenoid results from a second-order effect, the short superconducting solenoid has much greater focussing power than a normal quadrupole of the same size because of the high fields obtainable.

Our solenoid is a hybrid magnet consisting of a commercially-wound superconducting coil surrounded by iron that functions as a return yoke and also as a magnetic shield. This assembly, shown in Fig. 17, is contained within a vessel through which flows liquid helium. The maximum central field of the present magnets is 7.6 T, but the solenoid container is large enough to allow the field to be increased to >8.5 T by rebuilding the magnet, if necessary in the future.

Two models of the solenoid are used in the booster: one with an overall length of 25 cm and the other 32 cm. A prototype of the 25-cm unit was built and tested,^{9,10} and the field level and the distribution were found to be in good agreement with the results of a computer calculation made with the TRIM program. Also, the residual field on the axis about 3 cm outside the solenoid housing was measured to be less than 50 mG, and hence cannot cause a significant level of trapped flux in the resonator.

Additional detail on the selection of the parameters of the solenoids is given in Appendix 5, a reproduction of a design note.

g. Cryostats

Except for section A, the cryostats are modular units, all of the same size, that can fit at any of the locations determined by the helium-distribution system. The smaller section A is special because it is being used initially as a developmental prototype.

An end view of the cryostats is given in Figs. 7 and 18, and a side view of a standard unit in Fig. 19. The basic, interchangeable, cryostat is a 3-ft diameter vacuum tank and a nitrogen-cooled copper heat shield that is attached to the tank. Superinsulation is not used because it would degrade the vacuum. Everything inside the heat shield is attached to the removable

⁹ A. H. Jaffey and T. Khoe, Nucl. Instr. Meth. 121, 413 (1974).

¹⁰ A. H. Jaffey, R. Benaroya, and T. K. Khoe, Proc. 1976 Proton Lin. Accel. Conf. (AECL-5677, Chalk River, 1976), p. 102.

Fig. 18. End view of the cryostat assembly. A 1500-l/sec turbo pump hangs from the large T on the right.

Fig. 19. Side view of a standard cryostat with 6 resonators and 3 solenoids (section C or D). Item (a) is the manifold through which all instrumentation lines are fed. Item (b) is a solenoid extending into the decoupling snout. The end plate (c) has a vacuum valve built into it.

end cap of the vacuum tank, through which all electrical and cryogenic services are provided to the resonators and solenoids. The cryostat rests on the four posts that are adjustable in all dimensions, as shown at the bottom of Fig. 19.

In order to minimize the space required to link the cryostats together, the vacuum valves at each end of each tank are built into the end flanges. Also, to provide the clearance needs to remove a tank from the beam line, the final solenoid is mounted within a "snout" that is coupled to the main tank by means of a 12-inch diameter welded bellows (see Fig. 19).

The main support and alignment structure for the resonators consists of a pair of 6-inch-diameter stainless steel pipes that are linked together for helium distribution. The dimensions of this "ladder" assembly were chosen so as to limit the maximum static deflection to about 0.015 inches. The pipes rest on rollers that are supported from the bottom of the cryostat. The estimated heat leak of a full-scale cryostat loaded with all components is 29 watts.

The supporting ladder can be rolled out the end of the cryostat onto the matching rollers of an assembly system. All assembly of components is done with the cryostat in this open position. Also, helium-leak tests of most of the vacuum systems and many electrical tests can be done in the open position. The inner assembly is then rolled into the tank and pumped down, in preparation for cooling.

Except for the solenoid currents, all controls and signals in and out of the cryostat come by way of a nitrogen-filled instrumentation line. The input/output cables associated with each resonator enter the instrumentation line by way of a flange on which are mounted the needed individual feedthroughs. This approach assures that all cables going to the resonators are firmly clamped to nitrogen temperature at a well-specified place, and vacuum degradation by cables is minimized.

The whole ladder assembly, including the resonators, is precooled by flowing two-phase nitrogen in a special distribution system. Cooling channels that form part of this system are welded along opposite sides of

each support pipe, and nitrogen flows in parallel through each of the four channels in order not to damage the ladder by differential contraction. The resonators and solenoids are precooled by means of a heat exchanger coupled to a copper flange at the base of each unit. About 8 hours is required to lower the temperature of the whole ladder assembly to about 90°K.

Cooling from nitrogen to helium temperatures is accomplished by flowing liquid helium into the pre-cool system. If the cool-down is slow enough to make effective use of the heat capacity of the helium gas, then only about 100 l of liquid helium are required for the cool-down.

When the precooling and some preliminary tests have been completed, the cryostat is attached to the main helium-distribution system and the final tests of the accelerator section and the conditioning of resonators are carried out before it is moved onto the beam line.

The essential elements of the vacuum system are: (a) a 1500-l/sec turbomolecular pump permanently attached to the cryostats, (b) a conductance of about 1500 l/sec through baffles in the heat shield that separates the turbo pump from the open inner volume of the cryostat, and (c) various cold surfaces that function as massive pumps. The only vacuum gauge is mounted on the 10-inch T that couples the turbo pump to the tank.

A typical pump-down schedule is described by Fig. 20. Here two points need further elaboration. (1) When the instrument line is cooled to nitrogen temperature, it functions as a very large pump ($\sim 10^5$ l/sec) for water vapor and other condensibles, and yet it does not significantly cool the resonators, thus allowing the resonator interiors to continue to outgas. (2) Since all pressures are read at the pump, we do not have quantitative information about the pressure within the resonators, the point of primary interest. In particular, after the cooling cycle begins, the pressure within the whole volume enclosed by the heat shield is very much less than is measured at the gauge. Also, no molecules from the warm vacuum wall can enter a resonator interior without first hitting a helium-cooled surface; only molecules traveling within a narrow ray along the beam axis can enter.

A worry in the design of the cryostat was the possibility that an explosion could occur if a sudden and massive vacuum failure caused large

Fig. 20. Cryostat pump-down schedule.

quantities of air to be condensed on the helium-filled 6-inch support pipes. An experiment was conducted to check on the possibility. The results obtained, as given in Appendix 6, show that there is no danger.

h. Helium Refrigeration and Distribution

The refrigerator for the booster is a CTI 1400 with three compressors, which nominally yields 95 watts of cooling at 4.6°K or, alternatively, liquifies 34 l/hr of helium. Normally, the system will be used in the closed-cycle refrigeration mode. The layout of the helium distribution system is shown in Fig. 21.

A schematic representation of the helium distribution system is given by Fig. 22. The basic idea is that the refrigerator compressors provide the pressure to drive continuously-flowing helium through the distribution system and the resonators. The available flow rate is not large enough to permit parallel flow through all resonators of the linac, and therefore the several sections are connected in series, with a heat exchanger after each section to recondense any gas that is generated. The secondary of each heat exchanger is cooled by the slightly-colder two-phase helium returning to the refrigerator.

In more detail, two-phase helium from the refrigerator flows, at a rate of 8 gm/sec, through a heat-exchanger coil in the bottom of a 1000-liter storage dewar. There the gas is condensed, and the temperature is reduced to near that of helium in the dewar, ~4.6 K. At this temperature, the flowing helium is slightly subcooled.

The subcooled helium flows into cryostat D by way of a liquid-nitrogen-shielded transfer tube. Within the cryostat, the helium flows through all resonators and solenoids in parallel, where it boils; typically 20% of the helium is vaporized. The outflowing two-phase helium leaves the cryostat by way of a second transfer tube and enters a heat exchanger, where the gas is recondensed and the liquid subcooled slightly. The flowing subcooled helium is then ready to be directed into the next cryostat.

After passing through all of the cryostats, the helium at a pressure of 1.65 Atm expands through a Joule-Thompson valve to a pressure of 1.40 Atm, and the temperature drops from 4.8 to 4.6 K. Gas is generated by the expansion, of course, but some liquid remains. The two-phase mixture

Fig. 21. Plan view of booster tanks, helium-distribution system, and beam-bunching hardware.

returns to the storage dewar by flowing in series through the secondaries of the several heat exchangers.

The quantitative details of the operation of the distribution system depends, of course, on the heat loads; an example is given in Appendix 7. In more general terms, if the heat load is exactly equal to the refrigeration capacity (95 watts), then the helium level in the storage dewar remains constant: from the total flow of 8 gm/sec, about 5.4 gm/sec is vaporized in the distribution lines and linac, and the other 2.6 gm/sec returns to the storage dewar as liquid, where it is vaporized while cooling the initial stream of the two-phase helium coming from the refrigerator. If the linac vaporizes less than 5.4 gm/sec, then more liquid returns to the storage dewar and the liquid level rises. On the other hand, the linac can be cooled at a rate greater than 95 watts by vaporizing more than 5.4 gm/sec and thus depleting the inventory of liquid. The maximum cooling rate is obtained by vaporizing all 8 gm/sec of the flow, which corresponds to about 135 watts of cooling. With the present storage capacities, this level of additional cooling can be sustained for about 50 hours, which is long enough to be useful for many experiments. A helium-mass balance is achieved in the above operations by means of a 12,000-gal pressurized-gas-storage tank outside of the building, which automatically provides gas when the refrigerator has excess capacity and stores gas when the inventory of liquid is being used up.

i. Computer-Based Linac-Control System

The booster linac is controlled and monitored by a system based on a PDP 11/34 computer. In the initial state of use, this system has the following functions: (1) to set and monitor all parameters of resonators and solenoids, and to control long-term drifts, if any; (2) to monitor many sensors such as thermometers; (3) to automate most part of the tuning operation. Other tasks will probably be added as experience is acquired. However, all fast controls of resonator phases and amplitudes will continue to be performed by the hard-wired control system discussed in II.B2 e.

A schematic representation of the control system is given in Fig. 23, where the PDP 11/34 computer is shown to be interfaced via CAMAC to a variety of devices. A series of options of increasing sophistication are available

Fig. 23. Computer-based linac-control system.

to the operator and are selected from a menu displayed on the "Touch Panel" of Fig. 24. The most primitive of these options connects a pair of knobs via CAMAC to the computer, which then can output an appropriate signal to the device under control and also show on the LED display the name and value of the parameter being adjusted. The operator, by adjusting the knob, controls the device. We do not expect this to be a normal mode of operation except during the initial operation of the accelerator, during trouble shooting, and during fine tuning. More sophisticated options include:

- 1) Setting the field amplitudes of buncher, chopper, resonators, and solenoid lens from interpolation in a table built from records of earlier operation of the accelerator,

- 2) Calculation and setting of a parameter from known values of other parameters. For example, we expect to be able to calculate the settings of the solenoid lenses from the known fields and phases of the resonators.

Other important functions of the computer will be to maintain records of the accelerator operation, to monitor certain parameters for exceptional conditions (for the superconducting accelerator, principally the critical temperatures), and to monitor all other aspects of performance of the accelerator.

We expect that the operator will interact with the system primarily through the touch panel, raster display, control knobs and LED displays. The raster display will normally contain one of several status tables describing current operating parameters for either the buncher and resonators, the solenoids, or the temperature sensors. The raster display will also serve as a bulletin board for the operators by displaying alarm and information messages; these will have priority over the display of status tables.

The Tektronix terminal and Versatec printer/plotter will serve, for the most part, the system programmer and accelerator supervisors who will need access to stored data on accelerator performance and accelerator parameters.

The programs to perform these operations are being written for the most part in Fortran under the operating system RSX-11 M supplied by

Fig. 24. Control board of computer-based linac-control system.

Digital Equipment Corporation. This laboratory has a record in computer-based control and nuclear-data acquisition extending back 15 years. Many of the programs and techniques needed for linac control are available and require only small modifications.

This computer system is relatively small, but it will easily handle the control functions outlined here, and it can be easily expanded both in software and in hardware. The CAMAC data highway, with additional crates, would allow control to be extended to lenses and bending magnets of the tandem, and to additional accelerating and focussing elements added to the accelerator, and to beam-transport elements between the accelerator and target.

j. Alignment

Alignment of the linac is carried out in three steps: (1) the beam axis is established optically; (2) the resonators and solenoids in an individual accelerator section are optically aligned (while warm) on their support ladder, thus establishing an optical axis for the section; (3) the orientation of the assembled and cold section is adjusted until its axis coincides with the beam axis, as determined from the influence of the solenoids on a highly-collimated calibration beam. It appears that all of this can be done with much greater precision than is necessary, because of the small emittance of the incident beam, the large bore of the resonators, and the strength of the solenoids.

Step (1) of the procedure uses conventional optical techniques.

In connection with step (2), the resonator-support system has been designed to make it possible to locate individual resonators on an axis with an accuracy of about 0.1 mm, although such accuracy is not needed. The support structure contracts during cool down, of course, but it does not bend, and thus the initial alignment is preserved. Having the resonator located with an accuracy of ~ 1 mm is adequate to preserve the beam quality.

In step (3), the accelerator section is placed in approximately the right position on the beam line, and a highly-collimated beam of any easily-obtained ion is directed through the section onto a detection system

(such as balanced collector slits) that defines the beam position near the linac output. First, the beam position at the detector is established without using any focussing elements beyond the analyzer magnet. Then an individual solenoid in the section of interest is turned on, and the change in position of the output beam is measured. Using the adjustment screws on the cryostat-support posts, the axis of the whole accelerator section is varied until the solenoid at each end of the section gives no steering action. The section axis is then coincident with the beam axis.

k. Linac Tuning

The linac is tuned by making use of a combination of experimental and theoretical information. An interactive computer program is used to determine the set of accelerating fields $\mathcal{E}_r$ and phases ϕ_r that give the desired output-beam energy and longitudinal phase space for the r^{th} resonator. The corresponding fields for the solenoids are determined in the same way. The fields of both the resonators and the solenoids can be set to these values from stored knowledge of calibration constants. However, the phase settings must be determined experimentally for each new incident beam, since the phase ϕ_r relative to the beam is related to the phase reading θ_r of the control system by the relation $\phi_r = \theta_r + \theta_r^0$, and the constant θ_r^0 is a very sensitive function of the history of the beam prior to entering the r^{th} resonator.

The phase tuning required to determine the set of θ_r^0 starts with the first (upstream) resonator, with all others off, and successively works toward the last resonator, with all upstream resonators set to operate in their final modes. For each resonator, the calibration constant θ_r^0 is determined by measuring the energy change induced by the resonator. In principle, two such measurements are enough to determine θ_r^0 .

The energy spectrometer used for resonator tuning consists of a gold foil that scatters a small fraction of the beam onto a surface-barrier detector. The pulse-height (i.e., energy) spectrum is recorded in a conventional way, in the control computer, which deduces the centroids of spectra corresponding to several trial values of θ_r . From these centroid values, the calibration constant θ_r^0 is calculated by the computer in an obvious way.

In principle, the calibration could be carried out in a few seconds per resonator.

For the above operation to be meaningful, the energy-gain detector must respond only to the charge-state of interest, of course. A crude magnetic analyzer is used to select this charge state.

During the phase-calibration procedure, the computer automatically adjusts the fields in the solenoids (based on stored information about the latest energy profile) to values required to conduct the beam to the detector.

The procedure outlined above is expected to give approximately the desired energy in a straightforward way, and the final energy can be adjusted accurately to the desired value by varying the phase and/or perhaps the field of the last resonator.

It is probable that phase tuning can be made even more automatic and rapid than is implied above by using one of the phase detectors (developed for bunching) as the energy-change detector. Since the phase detector is excited by the full beam, its response is very fast, and in principle the speed of tuning would be limited only by the speed with which the resonators and solenoids can be brought to the appropriate power levels.

3. THE ATLAS LINAC

Because of the flexibility resulting from the use of independently-phased resonators, one has a number of options in the choice of characteristic for the ATLAS linac. Some of these options are considered in Fig. 25, which describes the maximum beam energies obtainable from several linacs injected by a 9-MV tandem. All of the linacs considered are formed by the addition to the booster of three more accelerator sections which use various combinations of resonators of the following sizes: $\beta = 0.035$, $\beta = 0.060$, $\beta = 0.105$, and $\beta = 0.135$. In the calculation of the output energies for this figure, the terminal stripper is assumed to be gas, the second stripper is a foil, and the charge-state selected for acceleration after each stripping is at the peak of the charge-state distribution.

Fig. 25. Comparison of options in the design of the ATLAS linac. The table gives the total number of resonators, including those in the booster. The energies are for peak intensities with a gas stripper in a 9-MV tandem terminal.

In addition to performance, Fig. 25 gives an estimate of the cost differences (including escalation and contingency) between the several tandem-linac systems. The costs of the linac part of the four systems are within \$0.5M of being equal. However, if the FN tandem were required to accelerate the heaviest ions, it would need to have a much higher injection voltage in order to make it feasible to bunch effectively, and this need increases the overall costs of options III and IV significantly.

In view of its low cost and excellent performance for ions with $A < 100$ ($A < 150$ with foil stripping), we have chosen linac II as being optimum at this time. However, the modular nature of the linac design and the proposed configuration shown in Fig. 1 makes it easy and relatively inexpensive to extend the performance later to the heaviest ions.

A key feature of the planned new configuration is the 40° bend shown in Fig. 1. The initial motivation for the bend was the desire to preserve Target Area II as an experimental area. It is immediately clear, however, that an even more important function of the bend is to allow the beam to be split and simultaneously directed to two independent experiments. This is achieved easily and naturally at the bend, without loss of intensity to either experiment, because the beam already contains several charge states from the second stripper (see Fig. 1), and only one of these would normally be used. As discussed later, a unique feature of this beam splitting is that (within certain limitations) the energies of the two beams may be independently chosen.

a. Summary of Design Plans

The ATLAS linac consists of the booster in its entirety and three additional accelerator sections of the same general kind as described earlier. As far as we now know, there are no significant changes in approach that should be used, merely an extension of the established technology.

The plans for the main sub-systems of the ATLAS linac are as follows.

Resonators. The split-ring resonator will be used as the accelerating structure, and a new model of the structure optimized for higher ion velocities will be developed.

RF Control. The method of frequency and phase control will be the same as in the booster.

System Control. The present control computer has the basic capacity to handle the large linac, and control will be extended to beam lines and to some tandem functions.

Beam Focussing. Superconducting solenoids will continue to be used as the focussing elements.

Cryostat. The design of the cryostats will be the same as in the booster, and the same length of module will be maintained, thus making it easy to change the velocity profile of the linac by moving accelerator sections.

Helium Refrigeration and Distribution. An additional ~ 200 watts of helium refrigeration will be installed, and the method of helium distribution will be the same as in the booster.

Since so much of the technology for the ATLAS linac is the same as for the booster, the remainder of this section is limited to those features that are different.

b. Accelerating Structure

The main function of the three new sections required for the ATLAS linac is to increase the maximum energy of ions with $A \leq 100$. This purpose can be achieved merely by adding more $\beta = 0.105$ structures but, because of transit-time effects, the structure gradually loses its accelerating power as the energy increases above ~ 10 MeV/A. Thus, it is advantageous to use some structures designed for ions with high velocities, as shown by the behavior of the transit time curves of Fig. 12. Here the amplitudes of the curves for the 0.135- β and 0.148- β structures are reduced relative to 0.105- β curve to take into account the fact that the average accelerating field falls off with increasing resonator length.

If the transit-time factor were the only consideration, it would be desirable for the final resonators of ATLAS to be optimized for $\beta = 0.18$, which would approximately triple the E/A range over which effective acceleration is possible. However, at this time we do not feel that it would be wise to plan to extrapolate the established technology by such a large factor. Rather, we propose to use a structure optimized for $\beta = 0.135$ ($L = 46$ cm), which extends the possible range of E/A by 65% relative to the $\beta = 0.105$ structure.

The basic design of the 0.135- β resonator will be the same as that of the 0.105- β model shown in Fig. 3. A total of 15 of the new units will be used, with 5 in each cryostat. Two superconducting solenoids will be used for beam focussing in each section, one after the first pair of resonators and the second at the end. For each solenoid, $\int B^2 dz = 99 \text{ T}^2\text{m}$.

The main questions about the performance of the 0.135- β structure are concerned with (1) increase in stored energy, which makes phase-control harder, and (2) the increased magnitude of the transverse field in the central gap. There appear to be adequate answers to both these questions if the length is not pushed beyond the planned 46 cm.

First consider phase control. It is likely that the present VCX of the fast tuner has enough power (~ 5 kVA reactive) to handle a larger structure. In any case, if it should turn out to be inadequate, it would be a straightforward matter to use two VCX tuners of the same kind in parallel.

The question about the asymmetry of the field is more complex. To a good approximation, the angular deflection $\Delta\theta$ caused by a single resonator is

$$\Delta\theta \approx \frac{1}{2\pi} \left(\frac{\mathcal{E}_x}{\mathcal{E}_z} \right) \left(\frac{\Delta V}{E/q} \right) \cos \phi, \quad (3)$$

where $(\mathcal{E}_x/\mathcal{E}_z)$ is the ratio of transverse and axial fields in the gap, $q\Delta V$ is the energy gain of the structure when the transit-time factor is unity, and E is the projectile energy. For most particles entering the new part of the linac, $E/q \approx 30$ MV and hence the $\Delta\theta$ caused by a single 0.105- β structure is ~ 0.75 mrad. As is shown in Sec. III, a value of this magnitude caused the beam in the linac to wander by about ± 1.5 mm, which causes a negligible degradation in beam quality. The corresponding displacement for the $\beta = 0.135$ structure is ± 3 mm, which is small enough to be unimportant.

Even though the displacements caused by the field asymmetry do not cause a serious problem, it would be desirable to eliminate the effect. It appears possible to do so by modifying the shape of the facing edges of the drift tubes so as to generate a transverse field that cancels the influence of the ring. The shaping should not present any severe fabrication problem.

c. Beam Bending and Splitting

A schematic representation of the proposed bending and splitting system is shown in Fig. 26.

Beam Bending

In bending the beam, the primary design problem is to make the distance between linac stages short enough to avoid, if possible, the need for rebunching. This requirement (and also to some extent building-space limitations) forces one to use superconducting magnets, which permit the

Fig. 26. Schematic of system for bending and splitting ATLAS beam. Focussing elements for Area II beam are not shown.

most rigid beam ($AE/q^2 \approx 550$ MeV) to be bent with a radius of curvature of about 0.70 m. However, in order to provide the space required for charge-state separation, it is probably desirable to have ρ be somewhat larger, say 0.8 m. The design of superconducting magnets is discussed below in Sec. II.B3f.

In order to make the path approximately isochronous, a small waist will be formed between the two 20° magnets.* Transverse focussing is provided by superconducting solenoids. Thus, the waist between the last pair of resonators of the first-stage (booster) linac is transformed to the first waist in the second-stage linac. A first-order beam-optics calculation shows that the time spread induced by the bend is $< \pm 20$ psec if $E/A < 2$ MeV/A. Since the beam pulse is deliberately debunched to a width of $\sim \pm 70$ psec before leaving the first-stage linac, the 20 psec time spread is negligible.

Perhaps the trickiest question about the bend is whether or not rebunching is required. Fortunately, it can be avoided by using resonators within the linac itself to manipulate the longitudinal phase space. Fig. 27 gives an example of how this can be done by using two resonators in the phase-defocussing mode. Calculations carried out with the ray-tracing program described later show that non-linear effects that degrade beam quality are largely avoided if the phase spread is always less than $\pm 4^\circ$ (that is, less than ± 120 psec). As seen in the figure, it is feasible to meet this requirement and still restore the phase ellipse to its original matched condition.

*An alternative arrangement that makes use of only one 30° bend also looks attractive.

Fig. 27. Phase-ellipse manipulations in neighborhood of 40° bend in linac.

Beam Splitting

As discussed in Sec. II.E, the booster linac transmits all charge states formed in the second stripper, and all of those above some critical value are accelerated to about the same energy. The desired separation of the charge states is accomplished at the intermediate waist, where the spacing is typically 3 cm per charge. Since the waist size is typically < 2 mm, the charge states are well separated.

A septum magnet near the waist is used to increase the angle between the beams for the charge states of interest. On the basis of experience at the ZGS, a field of 0.3 T is readily achievable. At this field, the septum magnet would need to be about 0.7 m long to deflect beams with $A \approx 100$ by 6° , which is needed to allow the beam to clear the second 20° magnet.

The beam line leading into Target Area II has not been fully designed. However, qualitative considerations show that it will be feasible to find a practical configuration that is approximately isochronous.

A discussion of the relationship between the energies of beams going into Target Areas II and III are given in Sec. III.

Third Stripping

There are some experiments for which it would be desirable to increase the energy somewhat by stripping the beam a third time before injection into the second-stage linac, even though this would entail a further loss of intensity. The third stripper can be at any one of three places made accessible by the bend: (a) before magnet M1, (b) between M1 and M2, and (c) after M2 in Fig. 26. Since the concept of a third stripping is not essential to this proposal, we will merely mention some of the considerations involved in stripping at the three possible locations. Bearing in mind, in this discussion, that the beam out of the first-stage linac normally contains components from the several charge states formed in the second stripper, and most of these components have approximately the same energy, as discussed in Sec. II.E.

The easiest situation to understand is one in which the third stripper is at position (b). In this case, the two 20° magnets are used to select individual charge states both from strippers #2 and #3. Because of the increase in charge at stripper #3, the energy of the beam out of the second-stage linac is increased.

If the third stripper is placed at position (a), then the distributions formed by the several incident charge states are superimposed, and the intensity for the charge state at the peak of the new distribution is almost the same as the peak of the original distribution. Most of the beam associated with any selected charge state of the new distribution can be transmitted through the achromatic bending-magnet system to the second-stage linac and then accelerated by it. Here the intensity is not much reduced by the third stripping, but the beam emittance may be degraded and a large energy spread ($\sim 3\%$) may be introduced.

If the third stripper is at position (c), the second-stage linac receives a multiplicity of charge states. As in the first-stage linac, all of these are transmitted to the output, where they may be useful to the limited class of experiments that can tolerate the relatively large energy spread ($\sim 2\%$).

d. Refrigeration

It is proposed to install ~ 200 watts of additional cooling power for the operation of the enlarged linac, to provide additional cooling for the booster, and to operate cryogenic magnets and vacuum pumps. For purposes of estimating costs, we have assumed that the added refrigeration would cost twice that of the present system. However, after we have more experience with the present system, we intend to determine whether the added refrigeration could be acquired in a more cost-effective way.

e. Future Expandability

The use of independently-phased resonators and the modular nature of the cryostats makes it easy to expand ATLAS, insofar as the linac is concerned. However, this expandability may be illusory if it requires moving the experimental area. The configuration of ATLAS makes it easy to avoid this problem in two steps.

First, the planned linac tunnel is long enough to accommodate two accelerator sections in addition to the three proposed for ATLAS. These would allow the system to be expanded painlessly to provide beams above the Coulomb barrier for all ions.

Second, if a more extensive expansion is required, it can be achieved in a cost-effective way by adding accelerator sections in front of the present booster. An illustration of this concept is given in Fig. 28, which shows that the linac can be extended almost without limit in this way.

Fig. 28. Concept for future expansion (blackened tanks) at front end of ATLAS linac.

f. Superconducting Analyzing Magnet

The 90° magnet now used to analyze the beam from the tandem has a mass-energy product $AE/q^2 = 52 \text{ MeV-AMU}$ and a radius of curvature of 0.87 m. This magnet is entirely inadequate because, even with a foil stripper in the terminal, it can only bend ions up to $A = 47$ when the terminal voltage is 9 MV. To be able to bend uranium ions from gas stripping (the long term goal) one requires a magnet with a mass-energy product of $AE/q^2 \approx 500$.

Because of severe limitations on space, it would be very difficult to accommodate a much larger iron magnet in the tandem vault. Also, a much larger radius of curvature would cause an unacceptable time spread in the pulsed beam. Thus, we are forced to use a superconducting magnet to replace the present 90° analyzer.

Discussions with designers at the ZGS make it clear that the cost-effective approach to the analyzer-magnet problem is to use the technology developed for the superconducting dipoles required for high-energy-accelerator applications. In these applications, it is only feasible to bend the beam through a relatively small angle, and hence it is natural to form the dipole field by appropriate superconducting windings around a straight cylindrical support tube. In our problem, this form of magnet has the drawback of imposing a severe limitation on the angle of bend, but it seems unwise to consider any other possibility at this time because of the developmental effort that would be required.

As a rule of thumb, it is advisable for the length-to-bore ratio of a superconducting dipole to be ≥ 5 in order to limit the influence of fringing fields. Under this condition, it seems feasible to bend a beam through at least 30° but not much more. Thus, insofar as bending is concerned, a 90° magnet can be formed by using three dipoles in series, all within a common magnetic shield and cryostat. Even with the unavoidable dead spaces in such a system, the overall radius of curvature can be quite small, because the magnetic field in the magnet can range from 4 to 6 T, depending on the level of effort devoted to fabrication.

In most superconducting magnets at high-energy accelerators, the field is constant in magnitude over the useful volume and the ends are perpendicular to the axis. Such a field would not function as an analyzer without external focussing elements, the addition of which is unattractive from several view points. Alternatively, focussing can be achieved by designing a field that varies laterally in the appropriate way. Although no

detailed studies of this approach have been carried out yet, designers at the ZGS believe it to be feasible, and we intend to try it.

The beam optics associated with several possible magnet systems are discussed in Appendix 10. As seen there, by using the appropriate transverse variation in field one can form a system that has any of the usual focussing properties. In particular, one can make the system of magnets be singly focussing and have approximately the same effective radius of curvature as the present 90° analyzer.

We plan to start detailed design studies of superconducting magnets for use in heavy-ion physics in late 1978 and continue in 1979.

A useful analyzer system to replace the present iron magnet will be built and installed in 1980. All of this work will be carried out as a joint effort by members of the Physics and Accelerator Research Facilities Divisions.

The same approach as is outlined above will be used to fabricate the 20° magnets required to bend the beam into the second-stage linac. The design problem is generally less demanding in this application because the bending angle is smaller and the planned double focussing requires a smaller field gradient.

C. THE FN TANDEM

1. INTRODUCTION

The Argonne FN tandem has undergone a number of substantial changes, so that practically all that remains of the original HVEC machine are the structural parts, hoops and terminal spinning. The charging system, accelerator tube and voltage distribution system have all been replaced by components manufactured by the National Electrostatic Corporation. The accelerator performs very well for heavy ions; the results of the acceptance tests at the completion of the recent upgrading in December 1977 are given later in this section. As it stands, the accelerator is now capable of providing several hundred pA of beam current analyzed in one charge state, the limitations are entirely those of the ion source and the stripper foils in the terminal. There is every indication that well beyond Ni beams present tandem will be a very adequate injector of heavy ions to the superconducting linac.

In order to improve the performance of the tandem, and especially to increase performance for beams heavier than Ni, a series of relatively minor improvements are planned as a part of the ATLAS proposal. At the low-energy end, a 90° injection magnet is needed, primarily for adequate mass resolution. For the terminal, two interchangeable stripper systems will be built: a gas stripper with pumping adequate to maintain the high vacuum in the accelerator; and an improved foil stripper, with provision for mechanical motion of the foil and a quadrupole triplet to improve the acceptance of the high-energy accelerator tube.

The dates of the various major past upgradings of the Argonne tandem facility, and the operating times for each configuration are summarized in the table below.

2. DESCRIPTION OF PAST UPGRADES AND PERFORMANCE

The Argonne FN tandem was installed in 1967 as a conversion from the smaller EN machine. It was installed with a 100% SF₆ system, the first large tandem to do this. The accelerator was converted from a belt to a

pelletron charging system in 1973, and at the same time the voltage dividing resistors were replaced by a separately pressurized corona tube. This change has proven to be extremely stable and reliable in operation, the terminal voltage stability has been excellent and the problems associated with belts and resistors have disappeared, reducing minor troubles at the tandem enormously.

In late 1977, in preparation for the superconducting booster, the Argonne tandem underwent a major upgrading. The purpose of this upgrading project was to improve the heavy-ion acceleration capabilities of the tandem. To this end we installed a high-vacuum accelerator tube, replaced all vacuum components, constructed a new high-voltage (150 kV) terminal for the ion source, and completely revised the optics of the low-energy system.

The most risky element of this upgrading was the new accelerator tube. We replaced the inclined-field HVEC tube with one manufactured by NEC. The NEC tube is a straight one with cylindrically-symmetric optics. Ours incorporated a new feature, permanent magnets placed in the dead sections to suppress high-energy electrons. While the optics of this tube are excellent and should allow for very good transmission, there seemed to be some electron loading problems with heavy ions experienced at Canberra, and also some breakdown problems at Munich and at Tsukuba. The new accelerator tube, having a different gap distance from HVEC, required its own voltage-distribution corona system.

The vacuum upgrading was completely successful, the measured pressure is now $\sim 2 \times 10^{-8}$ Torr, at least two orders of magnitude better than before. The voltage-carrying capability of the accelerator tube seems much as before, it conditioned during the acceptance tests to above 9 MV, there seems to be no obvious barrier and in time we expect to go somewhat higher.

The main purpose of the upgrading was improved heavy-ion acceleration. The results of the acceptance tests are summarized in the enclosed Table. The observed currents are somewhat higher than the acceptance tests called for, while injected beams required to achieve these are at least a factor of two lower. Thus the transmission of the system is uniformly a factor of two higher than required in the acceptance test.

No loading current was observed for oxygen beams, and the loading quoted for chlorine beams cannot be definitely attributed to electron loading;

it does not constitute a serious limit. The main problem in going to higher beam currents is the lifetime of the stripper foils. Various schemes to improve on this lifetime will be attempted in the near future.

To summarize, the 1977 FN upgrading, completed on schedule in 4 months, has been very successful. The ANL tandem is the first major electrostatic accelerator in the U.S. to operate with the Herb (NEC) accelerator tubes, the first horizontal tandem anywhere to use several new NEC features such as magnetic electron traps and a second corona system for the accelerator tube.

3. DESCRIPTION OF THE PRESENT TANDEM

a. Accelerator Structure

i). The column is the HVEC FN column structure with a 0.998 in. modulus. The insulating gas is SF_6 and the operating pressure normally 100 psi.

ii). The charging system consists of two Pelletron chains. The maximum upcharge is 80 μa per chain. (The upcharge may be increased by increasing the SF_6 tank pressure to 120 psi.) The charging system has had one minor failure in 20,000 hours of operation. The terminal voltage fluctuation is $\pm 150\text{V}$ with a dominant 0.6 Hz frequency.

iii). The voltage distribution along the column is achieved by an independently pressurized corona system that uses pure SF_6 . The maximum allowable overpressure is 30 psi over tank pressure. Each plane has three corona needles and an internal spark gap. The first 8 planes of corona tube at the low-energy end of the accelerator use a point-to-plane distance about half that used in the remainder of the accelerator, reducing the voltage gradient at the entrance to the machine and thus reducing the beam size of the image at the stripper. The normal operating current for the column corona is in the range of 8–15 μa . The corona acts as a variable resistance and allows one to retain adequate stiffness of the voltage distribution over the entire operating range (2.8–9.5 MV) of the tandem.

Summary of Acceptance Tests on Argonne Tandem with NEC Tube
(12/77)

Ion Species	Injected Energy (keV)	Terminal Voltage (MV)	Injected Current (pA)	Analyzed Current (pA)	Calculated Transmission %	Charge State out	Loading Current (μ A)	Time (hrs)
^{16}O	132	5.5	2000	400	65	5^{+}		2
^{16}O	132	8.0	1800	580	70	6^{+}		4
^{35}Cl	122	5.5	2800	300	50	7^{+}	≈ 30	4
^{35}Cl	135	8.0	2000	360	65	8^{+}	≈ 20	4
^1H	110	3.0	750	500	70	1^{+}		4
$^{58}\text{Ni}^{\text{a}}$	132	7.5	1500	130	50	10^{+}	≈ 30	≈ 1

^aThe Ni beam results were not a part of the acceptance tests but represent a short test run on 2/18/78 and 2/25/78. The foil lifetime was ≈ 30 min. with this beam.

iv). The accelerator tubes are the standard NEC accelerator tubes. The low-energy and high-energy sides of the accelerator have 24 accelerator tube sections each. The guaranteed voltage holding capability is 333 kV per accelerator tube unit. Since the modulus of the NEC accelerator tube is 0.50 in. and the one of the column 0.998 in., the accelerator tubes are provided with their own independently pressurized corona tubes for voltage distribution. These corona tubes have the same characteristics as the ones used for the column, they normally draw ~ 20 μ A. The first accelerator tube at the low-energy end also has its corona system arranged to insure operation at half the voltage gradient of the remainder of the system. The accelerator tube sections are separated by apertures mounted in heater plates and the column structure is tied to the accelerator tube assembly at each of these apertures.

v). The dead sections in the low-energy and high-energy sections of the accelerator contain an electron trap and the capability to use a Ti sublimation pump. The pump is not connected at this time and would only be essential if gas stripping were used in the terminal—an option not available at this time. In addition, the dead sections contain electron traps consisting of permanent magnets and apertures. The electron traps are designed to suppress electrons generated on or near the axis, since these electrons would not be suppressed by the electrode structure of the accelerator tube and could generate substantial loading of the accelerator through ionization of the insulating gas. By limiting the electron energy to 4.5 MeV (half the terminal voltage) and stopping them in a low-Z material surrounded by high-Z material, the x-ray loading of the machine is essentially eliminated. The high-energy dead section has an aperture with a diameter of 12 mm. to prevent the heavy-ion beam from hitting the electrode structure in the last 8 ft. of the accelerator.

vi). The terminal box contains, at the present time, an NEC 115-foil foil changer which will be replaced in May by a 230-foil model. It also has two Ti sublimation pumps which use a 375 watt Mini Ti-ball sublimator. The sublimators pump adequately at 230 watts and therefore, both sublimators are operated from a 500 watt generator driven by the high-energy chain. The motor for the foil changer uses a 200-watt generator from the other chain.

At the present time, the foil changer is actuated by a string from the low-energy side. A terminal-communication system that uses a micro-processor has been developed and has operated in the terminal, but it has not yet achieved the level of reliability necessary for routine use. As a backup, alternate methods of control are also being developed, although we expect the problems with the microprocessor to be eliminated by the end of this year.

The entrance aperture to the terminal is 6 mm in diameter; it is designed as an electron stop similar to the one in the dead sections. The exit aperture has a diameter of 9 mm, and also functions as a stop for electrons generated in the high-energy side of the machine, as well as preventing heavy-ion beams of low-charge states, which might not be adequately focussed by the high-energy accelerator tube lens action, from hitting the accelerator tube. NEC requires such apertures to be at least 10 cm from the first active accelerating electrode. From an optical point of view, the stripper should be as far as practical from the high-energy tube entrance; the distance is 60 cm in our machine.

vii). Vacuum conditions and accelerator-tube conditioning. After baking, the pressures measured at the base of the machine and at the terminal are normally in the low 10^{-8} range. Since it is necessary to avoid hydrocarbon contamination of the accelerator, the tubes are pumped by Ti sublimation pumps. The accelerator conditions rapidly to voltages in excess of 8.5 MV, but conditioning above 9.2 MV requires a day or more and an excellent vacuum.

b. Injection

i). Ion sources. The tandem has three ion-source stations. Two of these stations inject into the machine through an injection magnet with a 40° bend. The third station injects through a 20° bending magnet, with the magnetic field of the first magnet set at zero field.

The West 40° ion-source station uses a direct-extraction duoplasmatron or a Penning source with an extraction energy of about 35 kV. The center station has the Li exchange source for production of He beams

at 40 keV. The East 40° station allows preacceleration of the ion beams to 150 kV and uses the inverted Cs sputtering source developed by Chapman at FSU. This is the heavy-ion source for the Tandem Linac Accelerator System, while the other sources are used to support some of the research programs not using the Linac. The ion source is housed in a tubular structure with rounded corners which does not produce an observable corona discharge or corona current for the range of voltages up to 140 kV. Since the Linac requires pretandem bunching, a very small energy spread is required, typically ~ 50 eV in the 150 keV heavy-ion beam. Adequate mass separation prior to injection into the accelerator is essential. In order to allow adjustment of the beam intensity without source change or defocussing, a 4-position attenuator is inserted in the beam line. The magnet is provided with coils which allow injection at 40° with a mass energy product of about 15. The Chalk River power supply system is used on the extraction and einzel lens power supplies which allow remote control of the essential functions of the ion-source system. A very low ripple 150 kV power supply for the cage is on order.

ii). The low-energy beam line from the magnet to the accelerator tube is shown in Fig. 29, it consists of the single-gap buncher, a set of electrostatic deflection plates (X_1, Y_1), the low-energy cup, a 1-in all-metal valve, an electrostatic quadrupole triplet (without deflection capability), a 2-1/2" einzel lens, a set of electrostatic deflection plates (X_2, Y_2) and a 4-jaw slit (not yet installed). The einzel lens is necessary for the injection of low-energy ion beams from the West and center stations but not used for the high-energy injections. The beam-line components and accelerator tubes were aligned with a laser system which allows a precision an order of magnitude greater than transit alignment procedures; consequently, the short (8 in.) deflection plates usually require voltages less than 100 V. The quadrupole triplet is almost balanced and normally operates in the 4 to 5 kV range. In typical operation, about 70% of the particles on the low-energy cup reach the high-energy cup for ions up to Ca.

LOW ENERGY BEAM LINE

Figure 29. Low-energy beam line, Argonne tandem.

iii). Beam optics. The 150-kV injection of the Argonne tandem is designed to operate as a constant Q (= terminal voltage/injection energy) system with a 150-keV beam for 9-MV terminal voltage. For $Q = 60$, the waist W_2 (which forms the object for the accelerator) is located about 43 cm from the first active electrode. Figure 30 depicts the beam optics schematically at the low-energy end.

The preaccelerated beam is injected through a 40° bending magnet. In order to compensate the astigmatic focussing introduced by this double focussing magnet, an electrostatic triplet QT is used to produce the waist at W_2 . The use of electrostatic quadrupole triplet allows the production of the vertical and horizontal waists at the same distance from the accelerator tube both with approximately a 1 mm radius. The location of the vertical and horizontal waists at the same positions could not be achieved with einzel lenses and is quite important to keep the increase in beam diameter at the terminal that is introduced by buncher B within reasonable limits.

The preacceleration is achieved with three NEC general-purpose accelerator tubes A_1 , A_2 , and A_3 . The beam from the source will normally produce a waist following preacceleration. The waist location W_1 is chosen to be about halfway between the end of A_3 and the entrance of the magnet. A 30-kV 2-1/2" einzel lens with a normal operating focal length of about 2 m is located close to the entrance of the magnet. This lens provides a virtual object for the lens formed by the 40° magnet and the quadrupole triplet QT. In order to enable one to produce the waist W_1 for different accelerating voltages at approximately the same location, the distance of the source to the preaccelerator tube was chosen to be about 70 cm, and the face of the ionizer of the inverted sputter source was chosen as the origin. The source is followed immediately by a 1.25" einzel lens and the voltage gradient across A_1 is chosen to be half that of A_2 and A_3 . Under these conditions, it is feasible to produce a 0.7 mm radius waist with a divergence of 14 mr at W_1 . The divergence at W_2 is 10 mrad. The beam injected into the tandem then has an emittance of 4 mm mr $\sqrt{\text{MeV}}$, which is at least a factor of two smaller than the acceptance of the accelerator.

A beam with the above values of W_2 is expected to produce a waist of 2 mm radius at the stripper, and the energy modulation by the pretandem buncher will increase this radius by approximately 5%. The divergence of the beam in the terminal prior to stripping is about 0.7 mr. If one uses

Figure 30

Fig. 30. Injection optics for the 150-kV ion beam into the Argonne tandem. S is the ion source, L_1 and L_2 are cinzel lenses, A_1 , A_2 and A_3 are the three sections of the preaccelerator tube, M is the 40° magnet, B the buncher, QT the electrostatic quadrupole triplet, and AE the entrance to the accelerator tube. W_1 and W_2 are the locations of the two beam waists.

foil stripping, the multiple scattering in the foil will significantly increase the rms divergence of the beam. For ions with $A > 60$ the transmission of the most probable charge state can be increased significantly by the introduction of quadrupole triplet lens in the terminal. Calculations indicate that with a $5 \mu\text{g}/\text{cm}^2$ C stripper foil the transmission for $^{127}\text{I}^{9+}$ increases from ~40% to over 60% when such a lens is used.

c. Improvements in Progress

A number of projects, designed to improve the operation of the tandem, are under way at present. These activities are expected to be completed in the next 18 months, before the start of the ATLAS project.

i). Terminal pumping control. On a temporary basis, one of the two Ti sublimator pumps in the terminal is operated by a 500 watt generator driven by one of the chains. Experimentally it has been established that for these pumps to operate adequately, 230 watts is sufficient. In the next phase of pump operation, both Ti sublimators will operate simultaneously, with each pump subliming titanium approximately 10% of the time and operating on standby (less than 200 watts) 90% of the time. This provides adequate pumping speed and optimizes pump lifetime.

ii). Power to terminal. A drive shaft to provide additional power to the terminal will be designed in the next few months. There is sufficient clearance in the column structure to locate a 1" lucite drive shaft which will be supported on ball bearings on the column structure every 6 in. or 8 in. and which can drive a 2 kW 3 phase 400 cycle generator in the terminal. This generator is sufficient to power four Ti sublimation pumps simultaneously. The driveshaft will also power a 500 watt generator in the dead section. The design will utilize the experience at the Argonne Dynamitron and in several instances the detailed design of the Munich MP driveshaft.

Several minor improvement projects are also in progress.

iii). Beam diagnostics. A four-jaw slit with remote control and readout is to be installed at the low-energy end of the tandem. The slit will also help define the mass resolution of the injected beam.

iv). Vacuum system. Several improvements are planned in the vacuum system, in particular the turbomolecular pumps near the tandem are to be replaced by cryopumps.

v). Ion source. The 150-kV power supply for the injector will be replaced by one with lower ripple and remote controls for the sputter source will be implemented.

Summary of Upgradings of the Argonne Tandem

Date		Total tandem hours	Total hours in this configuration
June 8, 1967	Shut down EN	29,155	29,155
August 25, 1967	FN conversion acceptance test		
December 3, 1973	Shutdown	64,294	35,044
December 19, 1973	Chain- corona-tube acceptance test		
August 4, 1977	Shutdown	83,666	19,356
December 8 & 9, 1977	Accelerator tube acceptance test		
February 22 , 1978	Current status	84,735	1,069

4. TANDEM MODIFICATIONS FOR ATLAS

The ATLAS proposal is concerned primarily with adding substantially to the linac part of the tandem-linac booster. A few modifications will be required for the tandem, all of them aimed at improving performance for heavier ($A > 60$) ion species. These include an improved source magnet, buncher, gas stripping capability in the terminal, modification to improve stripper foil lifetimes, terminal focussing for use with the foil stripper, and new magnetic elements at the high-energy end of the accelerator to handle particles with increased rigidity.

a. Ion Sources

The inverted Cs sputtering source is an excellent source for atoms with a reasonable sputtering coefficient and relatively high values of electron affinity (~ 1 eV or higher). It also uses comparatively large target areas for the Cs beam.

For the production of beams from separated isotopes, the Middleton sputtering source is preferable since it allows the use of small quantities of separated isotopes and, as shown by Kutschera in the case of ^{48}Ca , the opportunity to recover most of the material.

In our case, space and beam optics considerations will make it desirable to construct a rather compact version of the Middleton Source.

b. Injection Magnet

The present injection magnet has a mass-energy product estimated at about 15. In the injection geometry used in the accelerator, it is not practical to place an aperture at the waist in front of the accelerator tube and, consequently, one cannot fully utilize the mass separation provided by the magnet. For the injection of 150-kV U beams, a mass energy product of about 1 part in 300 is very desirable. It is proposed to use a 90° bending magnet with a mass-energy product of about 60 located beyond the present 40° injection magnet, as shown in Fig. 1. To achieve adequate coupling of the ion beam with the accelerator, an additional quadrupole triplet

between the preaccelerator and the 90° magnet is necessary and the gradient of the preaccelerator will have to be reduced by the addition of one section of general purpose accelerator tube to the preaccelerator system.

c. Gas Stripping in Terminal

Gas stripping in the terminal of the tandem is desirable for heavier ion species, where stripper foil lifetimes are likely to be the limiting factor in beam intensity. The use of gas stripping, however, introduces serious problems with the NEC accelerator tubes. In order to preserve the high vacuum in the accelerator tube it is necessary to remove all the gas in the terminal. The relatively limited space in the FN terminal puts a limit on the length of a stripper tube; the gas flow is $\sim 0.1-0.2$ g/day of N_2 .

There are two ways of removing the gas flow in the terminal. One is to use a cryopumping system. This is feasible, though somewhat awkward, because of space limitations. The advantage is that the gas can be pumped off whenever the accelerator is shut down. If care is taken to use sufficiently pure gas, there should be no danger of contaminating critical surfaces on the accelerator tube. The alternative is to trap the gas in Ti, using several Ti sublimators. This requires on the order of 1g/day of Ti evaporated, again entirely feasible. In fact, such a system has been designed, built, and tested by NEC for Battelle-Pacific Northwest Laboratory.

At this time a choice between the two alternatives for gas stripping has not been made, but the feasibility and approximate costs are well established.

d. Foil Motion and Focussing in Terminal

Foil stripping in the terminal is the mechanism whereby negative ions are stripped at present in the FN. This gives somewhat higher positive charge states than a gas stripper, and therefore higher external energies. Two modifications are intended for foil stripping in the ATLAS system. One is the construction of a new foil-changing system which will have an increased capacity of about 1000 foils and will also allow the foil to be moved continuously while it is bombarded by the beam. It has been shown that such motion increases the

foil lifetime by about a factor of four. The other is the addition of a quadrupole triplet in the terminal. Because of multiple scattering, a considerable fraction of the beam for $A \approx 60$ will be intercepted by the aperture in the high-energy dead section. Calculations show that a properly-tuned electrostatic quadrupole triplet in the terminal after the stripper foil can increase the transmission of a $^{127}\text{I}^{9+}$ beam through the accelerator by as much as 70%. This quadrupole triplet is not necessary for gas stripping.

In order to avoid venting of the accelerator tubes while changes are being made in the terminal (e.g. reloading of the foil changer or replacement of the triplet by the gas stripper assembly) gate valves will be located at the ends of the terminal box assembly. The terminal box system will be redesigned to allow the positioning and change of the gas stripper assembly and the electrostatic quadrupole assembly without the need for a realignment of the system.

e. High-Energy Quadrupoles

The magnetic alternating gradient lenses at the present time in the high-energy beam lines are used to refocus a mass-energy product 36 beam with an object and image distance 5 feet from the boundary of the lens pair. For the heavier beams stronger quadrupoles will be required.

D. BEAM BUNCHING

1. BUNCHING REQUIREMENTS

As was pointed out before, one of the characteristic features of the proposed Tandem-Linac system is its excellent beam quality. This is made possible by the fact that good energy resolution and emittance are provided by the tandem injector and a narrow time pulse is formed by a sophisticated bunching system; as a result, the linac can operate in a highly linear mode and in this way preserve the quality of the incident beam.

The necessary bunching performance is best discussed in terms of the longitudinal emittance $\Delta E \cdot \Delta t$, where ΔE is the energy spread and Δt the time spread of the beam when the phase ellipse is upright. When the energy and phase angle for injection into the linac are chosen correctly, the longitudinal emittance $\Delta E \Delta t$ is preserved during acceleration in the linac. In addition to a non-linear accelerating force, various other effects can degrade the beam quality, and these effects are minimized if the phase ellipse of the incident beam is matched to an acceptance ellipse of the linac. Thus, for optimum performance of the linac (in the sense of minimizing $\Delta E \Delta t$), the phase ellipse of the injected beam should have a specific ratio $\Delta E / \Delta t$, and hence for any given value of $\Delta E \Delta t$, it should have a specific pulse width Δt . (See Sec. II.E).

A typical example will indicate the magnitude of the beam-bunching problem. Consider a linac that accelerates ^{58}Ni ions at an incident energy of 1.7 MeV per nucleon. Let the rf frequency be 97 MHz, the accelerating field 4 MV/m, the phase angle 20° (relative to the peak field), and the ion charge 20. Then, if $\Delta E \Delta t = 14$ keV-nsec, a matched input beam should have pulses with a time spread of about 49 psec. (FWHM). The corresponding energy spread of the incident beam is 226 keV.

The need for an input-pulse width < 100 psec and a correspondingly small energy spread is not the only demanding requirement on the bunching system for a tandem-linac accelerator; the other is to be able to bunch a large fraction of the dc beam into the desired narrow pulses. Under many circumstances, there is little beam current to be wasted because of the limitations of negative-heavy-ion sources and because of the need for double stripping in a tandem-linac system. Also, since the planned bunching system has no beam chopper

Figure 31

Fig. 31. Schematic of the complete bunching system (except for beam chopper).

before the tandem, any unbunched beam reduces the useful beam current even when the source intensity is adequate. Consequently, it is desirable to be able to bunch >75% of the beam from the source.

Because of the important impact that bunching has on the quality of the beam out of the linac, a prototype bunching system which involves all components of the system planned for the booster (and for ATLAS) was set up and successfully tested. The planned bunching system, the tests with the experimental setup, their results and conclusions are discussed below.

2. MAIN ELEMENTS OF THE BUNCHING SYSTEM

Figure 31 outlines the bunching system planned for the booster, a system designed to bunch 75% of the dc beam into pulses <100 psec at 97 MHz. It consists of four major components: (1) a pre-tandem room-temperature buncher that forms a large fraction of the dc beam into pulses about 1 nsec wide at a frequency of 48.5 MHz, (2) a superconducting resonator that compresses these pulses down to the desired 50 psec width, (3) a phase detector that dynamically couples the phases of the two bunching systems, and (4) a post-tandem beam chopper that removes the small background of unbunched ions. In addition to these four components, the first few resonators of the linac function in effect as part of the bunching system; if their phases are properly chosen, they match the pulse ellipse of the beam to the requirements of the remainder of the linac.

The sequence of bunching events in the post-tandem region are illustrated in Fig. 32. The ion bunch leaves the tandem terminal with a fairly wide spread in time (± 0.5 nsec) and a narrow spread in energy. The time spread is determined by the characteristics of the pre-tandem buncher and the energy spread by energy straggling in the stripper. The phase ellipse shears forward somewhat before reaching the superconducting post-tandem buncher, which, in a highly-linear operation, tilts the phase ellipse as shown. As the bunch travels toward the linac, the phase ellipse shears forward and is upright (a time focus) when it arrives at the second stripper. Because of the large energy spread induced by the post-tandem buncher, energy straggling in the stripper foil introduces relatively little additional energy spread.

POST-TANDEM BUNCHING OF ^{58}Ni

Fig. 32. Illustration of post-tandem bunching.

Because of the need for a time focus at (or near) the second stripper and because the bunching path length is fixed, a single bunching structure cannot, in general, match the beam to the linac. However, the first few resonators of the linac can perform this task of debunching and matching the beam to the main part, as discussed in Sec. F.

The geometrical layout of the main components of the bunching system to be used with the booster is shown in Fig. 21. This same system will be used with ATLAS.

The relationship between the bunching system planned for ATLAS and the prototype system that has been tested is shown in Fig. 33. The prototype, now in operation, will be maintained as a research tool for use with beams from the tandem alone. Note that the main components of the two systems are arranged along the beam line in differing orders. This difference creates some interesting differences in the control logic for the chopper (as discussed in II.D5) but not in performance.

A minor and perhaps confusing difference between the prototype and linac bunching systems is the fact that the pulsing frequencies are not the same; the pulse rate desired for the linac is 48.5 MHz (half the linac frequency), whereas the prototype was tuned and tested at 46 MHz in order to match the resonance frequency (92 MHz) of an existing superconducting helix resonator used for post-tandem bunching.

As is discussed in some detail in the following sub-sections, the prototype bunching system has been thoroughly tested and has been found to be operational in all respects. The essence of the performance is contained in Fig. 34, which gives the measured time distribution obtained with the complete system; about 75% of the dc beam is in the peak. In these measurements, 50-MeV ^{16}O ions were scattered from a $100\text{-}\mu\text{g}/\text{cm}^2$ Au foil and detected in a 50-mm^2 , $100\text{-}\mu$ totally-depleted silicon surface-barrier detector placed 20 cm from the target and at approximately a 15° scattering angle. The solid points were measured without the post-tandem chopper in operation, the open circles when the chopper was active. Pulse widths as small as 45 psec were obtained in short runs. In extended runs, the width broadened to about 70 psec. Bearing in mind the fact that the resolution width of the detector used on the measurement is ~ 50 psec, the result is entirely adequate for our needs.

TANDEM-LINAC BUNCHING SYSTEM

Fig. 33. Schematic layout of the prototype and linac bunching systems.

Fig. 34. Measured time distribution obtained with complete bunching system.

In view of the importance of bunching, we now consider in some detail the design, testing, and analysis of the prototype bunching system.

3. PRE-TANDEM BUNCHING

a. Wave Form

The pre-tandem buncher consists of a single gridded accelerating gap on which is impressed a sawtooth-like wave form obtained by combining the first four harmonics of the beam-pulsing frequency, 46 MHz. The ideal bunching wave form is one that gives the ion an energy gain δE specified by

$$\delta E(t) = -E_0 \left(\left(1 - \frac{t}{\tau} \right)^{-2} - 1 \right) \quad (4)$$

where E_0 is the energy of the ion entering the buncher, τ is the transit time required for an ion of this energy to travel from the buncher to the position of the time focus, and t is the time at which an ion arrives at the buncher. We use a convention on time in which the ion that arrives early has a positive time. Equation (4) is valid for $-\frac{T}{2} < t < \frac{T}{2}$ (where $T \equiv f^{-1}$ is the period of the pulsing frequency f) and under the assumption that the energy gain in the buncher is acquired instantaneously. When $T \ll \tau$, as is usually the case,

$$\delta E(t) \approx -2 \frac{t}{\tau} E_0. \quad (5)$$

Because of the practical difficulty in applying the ideal energy modulation, bunchers generally use sine-wave excitation. However, the advantages of approximating the ideal wave form by using up to four sine-wave harmonics has long been recognized. An example of such a wave form is one that causes the energy change δE to be

$$\delta E = \delta E_0 (-\sin \omega t + 0.40 \sin 2 \omega t - 0.18 \sin 3 \omega t + 0.06 \sin 4 \omega t), \quad (6)$$

where δE_0 is the maximum energy gain of the fundamental component, and

$-180^\circ \leq \omega t \leq 180^\circ$. Here the relative amplitudes were chosen to give a visual approximation to a sawtooth wave form. Figure 35 shows the corresponding calculated time spectrum at a detector located L meters downstream from the buncher when $\delta E_0 = 3.70 E_0 \omega^{-1} \tau_0^{-1}$. The microstructure in each pulse is associated with the harmonic content of the wave form. Under most circumstances, this microstructure would not be observable, of course, because of various time-spreading effects discussed below. The intensity distribution has an rms width of 0.097 nsec, and 74% of the dc beam is contained within ± 0.204 nsec, i.e., within a total of 6.8° of phase. This distribution is roughly equivalent to a Gaussian distribution for which the full width at half maximum (FWHM) is 0.23 nsec. In comparison, a single sine wave bunches only 31% of the dc beam when the parameters are adjusted to give a distribution with the same 0.097 nsec rms width. The advantage of the harmonic buncher is apparent.

b. Transit-Time Effects in the Pre-Tandem Buncher

When the distance an ion moves during an rf period is comparable to the spacing of the field-forming electrodes of the buncher, transit-time effects are very important. Figure 36 shows the ratio $\delta E / \delta E_m$ of the actual energy gain δE to the ideal energy gain δE_m when transit-time effects are ignored. The figure demonstrates that, in order for the gap to accelerate effectively, the gap width L should be less than say $2\lambda/3$, where $\lambda \equiv v/f$ is the distance the ion moves in one period of a sine-wave exciting the buncher. On the other hand, in order that the particle not lose the energy gained after it passes the driven gap, it must enter a region where the electric field extends over a distance much greater than λ ; i.e., the spacing to the next electrode should be large compared to λ .

c. Acceleration-Field Inhomogeneities in the Pre-Tandem Buncher

Although the ideal single-gap buncher should accelerate ions uniformly, independent of their transverse position, any realizable electrode configuration will produce electric fields that vary with transverse position. This nonuniformity was investigated for various electrode configurations by means of a computer program which calculates the potential distribution in the region of the electrode and the axial and transverse energy gain of a

Fig. 35. Calculated idealized pulse shape for pre-tandem buncher. In practice, microstructure is washed out by time-broadening effects.

Fig. 36. Calculated transit-time factor $\delta E / \delta E_m$ for accelerating gap of width L .

paraxial ion when one electrode is excited sinusoidally. The results showed that best performance should be expected for aligned grids.

d. Construction of Pre-Tandem Buncher

The buncher grid was made from 0.005-inch thick molybdenum by photo etching. Figure 37 shows a cross section of the electrode assembly. The insulator is made from machinable glass-ceramic. The grids are clamped 1.5 mm apart and self aligned on pins in the copper electrodes. Sputtering estimates were made assuming that three atoms are sputtered per impacting ion. For a beam spread uniformly over the grid, the half-life of the grids was estimated to be 900 μA -days. The present grids have been exposed to the beam for about 110 μA -days without a clearly observable change in appearance.

e. Choice of Bunching Frequency

The fundamental frequency of the pre-tandem buncher must be the same as the frequency of the post-tandem buncher (92 MHz) or a subharmonic of it. The choice of the frequency is a compromise between several conflicting requirements and especially between the desire to have the pulse width be as short as possible, which implies a high pulsing frequency, and the need to have the time between pulses be long enough to avoid overlapping of the time spectra of successive beam pulses in a time-of-flight experiment.

We have chosen to operate the pre-tandem buncher at 46 MHz, the first subharmonic of the rf frequency. In order to illustrate some of the reasons for this choice, consider the ion-mass resolution obtainable in a time-of-flight experiment in which the velocity and energy of an ion are measured independently and used to calculate the ion mass A . The heaviest ion that can be identified without an overlapping of the time spectra for successive pulses is one for which $\Delta A = 1$ and $\tau = T$, where $T \equiv f^{-1}$ is the period between beam pulses. One calculates that the upper limit on identifiable ions is $A_L = 52, 95$ and 148 for $f = 92, 46$ and 23 MHz, respectively.

In practice, there is some unavoidable flight-path uncertainty ΔL . For $\Delta L = 0.5$ mm and $L = 20$ cm, the limiting masses are $A_L = 51, 86$ and 119 for $f = 92, 46$ and 23 MHz, respectively. Moreover, in order not to have pulse-overlap effects, all ions must satisfy the conditions $E/A \geq 1.77, 0.44$ and 0.11 MeV/nucleon for $f = 92, 46$ and 23 MHz, respectively.

Fig. 37. Pre-tandem-buncher accelerating structure.

The above example shows that the beam-pulsing frequency has an important bearing on both the mass range and the energy range of ions that can be studied by the time-of-flight method. We have chosen $f = 46$ MHz as optimum for intermediate-mass projectiles, and we assume that it may sometimes be necessary to use the redundancy of information obtainable from the detector system in order to unscramble overlapping spectra.

In the long run, it will be desirable to have a bunching system whose pulsing frequency can be varied to meet the differing requirements of various kinds of measurements. For ATLAS, the system will be modified so that the bunching frequency can be reduced to $97/4$ MHz, if needed.

f. Electronic System

In order to excite the bunching grids efficiently with modest power, high-Q resonant circuits are employed, as shown in Fig. 38. One grid is connected to a coaxial line which resonates at the fundamental and third-harmonic frequencies. The other grid is connected to a coaxial line which resonates at the second and fourth harmonics. To provide the optimum sawtooth shape for bunching, the amplitudes and phases of the four harmonics must be accurately set and maintained.

It is clear that there is need for a practicable way of adjusting the seven parameters that determine the wave form. The harmonic content of the pulsed beam current depends on its time structure. A system has been designed to amplify the second, fourth and sixth harmonics from resonant cavities and measure the ratios of their amplitudes. From these data, the pulse width and the fraction of beam in the pulse can be determined rapidly and hence buncher tuning can be carried out with relative ease.

Since the transit time of ions through the tandem can vary (if any accelerating voltage varies) it was necessary to develop a system to stabilize the time of arrival of the bunch at the post-tandem buncher. This is done, in essence, by allowing the train of beam pulses from the tandem to excite a resonant detector and by using this signal to generate an error signal that controls the phase of the pre-tandem buncher. The way in which the phases of the two bunchers are linked by the phase detector is shown in Fig. 39.

Fig. 38. Resonant lines for pre-tandem buncher.

Figure 39

Fig. 39. Control system for pre-tandem buncher.

Further information on the phase detector is given in Sec. II.D6 below.

g. Experimental Results

The performance of the buncher was measured by recording the distribution in arrival times at a surface barrier detector of particles scattered from a gold foil $\sim 100 \mu\text{g}/\text{cm}^2$ thick. The reference time was derived from the master oscillator which excited the buncher circuits. The time spread introduced by the detector and electronics is known to be less than 0.1 nsec FWHM, so that its effect on the measurements can be neglected.

Buncher characteristics were studied in a series of measurements carried out in twelve separate runs on the tandem. The ions bunched were ^1H , ^{15}N and ^{16}O from a direct-extraction duoplasmatron at 26 keV and ^{12}C and ^{16}O from a Chapman-type inverted sputter source at 90 keV. These projectiles span the velocity range for which the buncher is intended. Both foil and gas stripping were used in the terminal. Other operating conditions for particular measurements are given in Table II-1.

Because of its relatively high velocity, the ^1H beam is the easiest to bunch; typically, the measured widths are 0.6 nsec (FWHM), and 76% of the dc beam is in the peak. The effectiveness of the phase-lock system can be seen from the spectra in Fig. 40, taken with 90-keV ^{12}C ions that were accelerated to 45 MeV. The spectrum shown by curve b was accumulated over a 1.5-hour period with the phase-lock system operating. The pulse width is 0.9 nsec and the peak contains 76% of the dc beam. When the phase-lock system was not used, the peak broadened to 1.2 nsec FWHM during a 15-min period of data accumulation, as shown by spectrum a. This increase in pulse width is due to time-varying transit times caused primarily by ripple and other variations in the injection and lens voltages.

h. Factors Limiting Pre-Buncher Performance

Various factors limiting the performance of the bunching system were calculated and the results are summarized in Table II-1. In order to provide calculations with which to compare the experimental bunching results and also to indicate the direction of planned future improvements, information

Table II-1. Analysis of results of measurements
with the pre-tandem buncher.

Beam Assumptions	^1H	^{15}N ^{16}O	^{12}C	^{12}C	^{58}Ni
$E_{\text{injection}}$ (keV)	26	26	90	150	150
Source ΔE (eV)	10^a	10^a	13^b	13^b	10^b
Bunching Frequency (MHz)	46	46	46	40	49
E_{tandem} (MeV)	17	56	45	45	90
ϵ_x (mm-mrad)	0.8	2.3	2.0	1.0	1.5
Stripper ($\mu\text{g}/\text{cm}^2$)	0.5	10	10	5	5
<u>Bunch-Broadening Effect</u>					
(a) <u>Time Spread Before Stripper</u>					
Buncher wave form	0.24	0.24	0.24	0.24	0.24
Buncher mesh size	0.08	0.93	0.18	0.13	0.43
Source ΔE	0.23	0.93	0.16	0.08	0.13
Beam convergence	<0.03	<0.10	<0.05	<0.04	<0.07
Einzel lens	<0.04	<0.13	<0.08	<0.06	<0.13
Space charge	<0.01	<0.01	<0.01	<0.01	<0.01
(b) <u>At Stripper</u>					
Total $\Delta\tau$	0.34	1.34	0.31	0.28	0.51
ΔE (keV)	0.9	23	17	12	28
$\Delta E\Delta\tau$ (keV-nsec)	0.31	31	5.3	3.4	14
(c) <u>Time Spread After Stripper</u>					
Drift in accelerator tube	<0.01	0.15	0.12	0.09	0.22
Path to detector	0.01	0.20	0.18	0.12	0.23
$90^\circ + 15^\circ$ magnets	0.08	0.48	0.40	0.20	0.47
(d) <u>Time Spread at Detector</u>					
Calculated	0.35	1.47	0.59	0.40	0.83
Measured	0.6	1.4	0.9		

^aDirect extraction source.

^bSputter source.

Fig. 40. Measured time distributions of ion pulses from pre-tandem buncher.

is given for the following five sets of experimental systems: ^1H , ^{12}C , and ^{16}O ions in the accelerator system actually used in our measurements and ^{12}C and ^{58}Ni ions in the recently upgraded tandem.

Time-Varying Voltages. Calculations were made of the potential distribution and the transit times for paraxial paths in a 3-inch einzel lens as a function of distance from its axis. One calculates that when -36 kV is put on the center electrode, the transit time of a 90-keV ^{12}C ion is increased by over 20 nsec; and hence a 1% rms ripple on the lens voltage would produce about 0.6 nsec spread in transit time for ^{12}C ions and about 1.3 nsec for ^{58}Ni ions.

The transit time through the tandem can also change with time, even when the terminal voltage is constant, if the distribution of the accelerating voltages changes. In one experiment, with 56-MeV oxygen ions, a shift of 4 nsec was observed when the voltage-distribution corona current was increased from 10 to 30 μA .

The phase-lock system should effectively remove these time-correlated phase shifts within a few milliseconds, and hence they should not cause much broadening in the measured time spectra.

Random Effects. In addition to the time-correlated effects outlined above, numerous random effects need to be considered and are outlined below. In an einzel lens, there is an uncorrelated effect in which the transit time through the lens increases with the radial distance of the path from the axis. The calculation shows, for example, that the transit time for a 90-keV ^{58}Ni ion that is 2 cm from the axis is approximately 1 nsec longer than that for an axial ion, which indicates that the effect can be important.

The energy spread ΔE_s of the ion source produces a transit-time spread

$$\Delta \tau_s = \frac{1}{2} \frac{\Delta E_s}{E_0} \frac{L}{v} = \frac{L}{2} \frac{\Delta E_s}{E} \sqrt{\frac{5181}{E/A}} \quad (7)$$

where $\Delta \tau_s$ is in nsec, ΔE_s and the injection energy E_0 are in MeV, the effective distance L from the buncher to the time focus is in meters, and v is the ion velocity. The values of ΔE_s given in Table II-1 are expected averages

extracted from various published experimental results. Since they can depend sensitively on the operating conditions of the source, they represent only approximate values.

Because of the good emittance of the tandem-linac system, beam convergence and divergence effects are almost negligible.

The bunch width calculated from the wave form alone, as seen in Fig. 35, is expected to be ~ 0.24 nsec FWHM when 75% of the beam is bunched. This assumes that all ions passing at the same time through the gridded gap receive the same acceleration whereas, in fact, the energy gain imparted to an ion in the middle of a grid mesh is somewhat less than at the boundaries. An analytic expression for the spread in transit time induced by this effect was obtained. The result for the time spreads given in the table indicate that the transverse variation in energy gain severely limits buncher performance when $A \gtrsim 80$ if the injection energy is 150 keV. The problem could be ameliorated by reducing the bunching frequency, by increasing the injection energy, or by reducing the mesh of the accelerating grid.

In order to treat the influence of space charge in a meaningful way, one must take into account the fact that both the transverse and longitudinal dimensions of a beam bunch vary greatly during the bunching process. Such calculations have been carried out, and we find that, for our geometry and for beam currents less than 10 μ A, space-charge effects are negligible. Even when the beam current is large enough to cause significant interactions between ions, the effect on the bunch may be unimportant. There is a strong tendency for the effect to be linear in the sense that the velocity of the space-charge-induced motion varies linearly with distance along the bunch. Hence, the space-charge repulsion merely tends to shear the bunch phase ellipse in energy-time space, and this effect can be counterbalanced by adjusting the energy gain imparted by the buncher.

The most basic measure of the quality of a bunched beam is the value of the product $\Delta E \Delta t$ for the beam bunch as it leaves the terminal stripper, because in principle it is possible to avoid enlargement of this product downstream from the terminal. As the ion bunch leaves the stripper it has an upright pattern in ΔE vs Δt phase space. The area of this pattern is conserved during the linear operation of acceleration down to ground potential but, as shown in Fig. 41, the pattern shears forward and hence the overall time

Fig. 41. Illustration of E-t phase space of a heavy-ion beam in a tandem: (a) before stripper, (b) after stripper, (c) before magnet, (d) after magnet, (e) at detector.

distribution formed by a projection onto the time axis is broadened. From the examples given in Table II-1, we see that the transit-time spread induced by energy straggling is negligible for very light ions but is increasingly important for heavier ions. As mentioned earlier, this kind of correlated effect is not necessarily harmful, since the phase-space area remains unchanged and the effect can be reversed by the use of additional bunching elements.

A final source of path-length variation is the 90° analyzing magnet at the output of the tandem. For the accelerator system used for these investigations, we calculate for a ^{12}C beam at 45 MeV that the transit-time variation in the magnet is $\Delta\tau \approx 0.74$ nsec. For this same system, the emittance would be much larger for heavier ions, and consequently the time spread introduced by the magnet could be unacceptable. However, in future measurements, we expect to use thinner stripping foils in the tandem terminal, and the newly-upgraded tandem is expected to have improved optics. Thus, in Table II-1 we use for ^{58}Ni the value $\epsilon = 1.5$ mm-rad, for which $\Delta\tau = 0.87$ nsec. Obviously, the time spread caused by the analyzer magnet is a major problem. However, since the time spread is proportional to ϵ , it will be substantially smaller when a gas stripper is used in the terminal.

In the measurements reported here, the total transit-time spread caused by bending magnets after the tandem is not quite as large because the 90° analyzing magnet is followed by a switch magnet that bends the beam through an additional 15° in the same direction. The total time spread introduced by this pair of magnets is about 60% of the value for the 90° magnet alone.

Comparing measured and calculated time resolutions for the pre-buncher we find reasonable agreement, in view of the uncertainties involved in some of the calculations. In any case, for the ions investigated the tests fully verify that it is feasible to obtain the desired beam pulse approximately 1 nsec wide and containing more than 75% of the intensity of the dc beam.

i. Implications for ATLAS

The results outlined above show that the pre-tandem buncher is excellent for relatively light ions but that two factors tend to limit performance as the ion mass increases. One is the variation in the accelerating field as a function of transverse position. It is believed that this problem

can be solved in either of two ways: (1) by making a smaller grid mesh, which is quite feasible, and/or (2) by operating the buncher at a lower frequency, which also is easy. Thus, with a few modifications, the present pre-tandem bunching system is expected to be suitable for use with ATLAS, which emphasizes ions in the lower half of the periodic table. However, if it were necessary to accelerate the heaviest ions, it would probably be necessary to increase the injection voltage to ≈ 300 keV.

The second factor that limits performance to an important degree is the 90° analyzing magnet, which introduces a spread in path lengths. Since the magnet must function as an analyzer, the path-length spread may be an unavoidable problem. However, as is discussed in Sec. II.B2, we intend to replace the present 90° iron magnet with a superconducting magnet, and it may be feasible to design a beam-optical system (such as two 45° bends) that meets all the requirements: good mass analyzer, isochronous, and reasonable size and cost.

4. POST-TANDEM BUNCHING

The basic ideas involved in post-tandem bunching are outlined in Fig. 32. Since the ion pulses involved here are so extremely narrow, it might appear that time-spreading effects are much more serious than for pre-tandem bunching. In fact, the situation is considerably less complicated. This comes about mainly from the fact that the post-tandem buncher performs an almost linear operation, and then the bunch merely drifts along an almost straight path. The total time spread of the beam, including beam divergence, space-charge effects, and others, is estimated to be less than 20 psec. The major contribution to the observed pulse (Fig. 34) comes from the time-resolution width of the detector system itself. Since measurements between two surface-barrier detectors in a $\Delta E/E$ telescope have yielded time resolutions of at best 65 psec, it is believed that the time distribution measured for the pulsed beam is still dominated by the detector resolution. In any case, the measured resolution of the pulsed beam satisfies the bunching requirements set by the linac.

The post-tandem buncher used in the prototype system is one of the superconducting-helix $\lambda/2$ resonators (type G) discussed in Ref. 6. The small size of the helix makes it attractive for this application but, in order to avoid the need to develop a slow tuner for the helix, we are using a 0.060- β split ring as the buncher for the booster and for ATLAS. The structure is greatly underworked in this application.

5. BEAM CHOPPER

A beam chopper is required in order to eliminate unbunched ions and to reduce the tails of the main ion pulse. For light ions, the operation has always been performed before the beam is injected into the tandem. However, for heavy ions, which move at very low velocities before entering the tandem, a pre-tandem chopper would have to be a distributed deflection system. Such a system would be complex, at best, and therefore we have chosen to do all chopping after acceleration through the tandem.

a. Chopper for the Booster

The chopper for the booster consists of a pair of beam-deflection plates 36 cm long, 3 cm wide, and separated by 1.0 cm. These plates are part of a resonant circuit operating at $97/4$ MHz, i.e., at half the frequency of the buncher. The chopper system is designed to provide a deflection voltage of as much as 20 kV.

The location of the chopper is shown in Fig. 21, where it is seen to be upstream of the analyzer magnet. This position was chosen so as to avoid having defining slits directly in front of the linac, where slit scattering might be a problem. Rather, the slits are now well upstream, as seen in Fig. 21. The chopping plates sweep the beam in a vertical plane so as not to upset the operation of the analyzer magnet.

An unusual aspect of our design is that the beam is relatively large at both the chopping plates and at the defining slits, with a waist in between. Intuitively this may seem like a poor arrangement. However, a quantitative analysis shows that it is, in fact, the way to minimize the sweeping voltage required if one can satisfy the condition $z_1 z_2 = Y^2$, where Y is the characteristic length of the waist and z_1 and z_2 are the distances to the waist from the chopper and from the slits. Fortunately, this condition can be satisfied rather well, because a waist in the vertical plane within the analyzer has an appropriate characteristic length (see Appendix 10).

The location of the chopper upstream of the phase detector introduces some complications in the logic of the phase-stabilization systems. Suppose, for example, that the beam pulse arrives at the chopper with the wrong phase, with the result that the wanted ions are swept to one side and only background

is transmitted to the phase detector. Because this background has no time structure, the phase detector would not detect the phase error, and the system would remain locked on the wrong ions. We have concluded that the easiest way to solve this problem is as follows: (1) the chopper is turned off when the intensity sensed by the phase detector drops below some pre-set value, since a large reduction in intensity is an indication that the pre-tandem buncher may be out of lock; (2) this allows all of the beam to be transmitted to the phase detector, and the phasing error is corrected; (3) when the beam intensity returns to normal, the chopper is turned back on. This corrective sequence of events is not expected to happen often and it does no harm, since the whole sequence can be completed in a few milliseconds.

A sinusoidal chopper such as we are using has two undesirable properties: (1) it necessarily introduces some degradation in the transverse emittance associated with the chopping plane (the y plane), and (2) it necessarily generates some energy spread. Both problems have been examined with care.

Emittance. A meaningful examination of the problem of degraded emittance requires that one simultaneously take into account the influence of chopper sweeping and beam pulsing. This is best done by numerical integration for assumed operating conditions. Using this approach, we have demonstrated that emittance degradation is not severe if (1) the chopper slits are not too wide, and (2) the sweep rate is not too great. The optimum situation for our bunching system is one in which the chopping slits width is roughly twice the beam width, and the sweep rate is adjusted so that only the edges of the pulse are eliminated. Then very little intensity is lost and the emittance is enlarged by a factor $\sqrt{2}$. Since the enlargement is in the y plane (not the experimenter's scattering plane) the effect is not judged to be important.

Energy Spread. An energy change is imparted by the chopper to all ions off its mid plane because these ions feel the influence of fringing fields in the same direction when entering and leaving the plates, an effect caused by the change in rf phase.

In order to be quantitative, consider the usual geometry in which the chopper slits are at a waist of size y_0 and divergence y'_0 ; also, let the distance L to the sweeping plates be much greater than a characteristic length. Then, one can easily show that the induced energy spread is

$$\Delta E = 2 y'_0 \frac{E}{v} \frac{dy}{dt} = 2 \frac{\epsilon}{y_0} \frac{E}{v} \frac{dy}{dt} = z \epsilon \frac{E}{v} \frac{d(y/y_0)}{dt} \quad (8)$$

where y'_0 is the angle at the waist of the unswept beam and $\frac{dy}{dt}$ is the sweep rate of the beam at the waist. This is sometimes written as

$$\Delta E = 2 \epsilon \frac{E}{v} \frac{1}{\Delta t}, \quad (9)$$

on the assumption that the beam sweeps through a distance y_0 during the pulse length Δt .

The substitution of representative parameters into Eq. (8) shows that the energy spread is uncomfortably large, typically 5–10 keV. The last form of Eq. (8) emphasizes that there are only two ways to diminish ΔE for a given energy: (1) by reducing the beam emittance, and (2) by reducing the relative sweep rate. In order to reduce the emittance, a gas stripper should be used. The sweep rate can be reduced without difficulty, of course, but this has the drawback that the tails on the time distribution are lengthened and this may result in a tail on the energy distribution. For many experiments this would be unimportant because the tail is so weak. In any case, if the sweep rate is reduced to a value $d(y/y_0)/dt \approx 0.3/\Delta t$, then the tailing may be acceptable and the energy spread of the beam is not enlarged greatly.

6. PHASE DETECTION AND STABILIZATION

A variation in any voltage involved in accelerating an ion from the source to the tandem output can cause the time of transit between the pre-buncher and post-buncher to vary, and such variations, if not corrected, would cause the ion bunch to arrive at the post-tandem buncher with the wrong time. It is almost out of the question to expect the tandem to be stable enough to avoid the phenomenon, as may be appreciated from the fact that the transit time through the tandem is typically 5 μ sec, whereas we would like the arrival time of the bunch to be matched to the post-tandem buncher with an accuracy of ~ 0.1 nsec. Clearly, some form of phase stabilization is required.

The unusual element in the phase-stabilization system is the phase detector, a resonant system excited by the beam. The detector itself is a room-temperature helical half-wavelength resonator with an unloaded $Q \approx 2000$.

The helix is a slow-wave structure in which current, stimulated by the axial electric field of a moving bunch of ions, flows along the spiral at approximately the velocity of light, but the forward progress along the beam line is reduced in proportion to the pitch of the helix and approximately matches the velocity of the ion beam. Thus, for a time period of about 5 nsec, each ion bunch is coupled to the helix for energy transfer.

The resonator is simultaneously excited both by the periodic ion bursts passing through it and by an rf reference signal which is reversed in phase at an audio rate of 1 kHz. The vector-voltage relationships between the reference and the beam-induced signals are shown in Fig. 42, where vector 101 is the reference voltage for one-half period of the sample cycle, and vector 100 is the beam-induced signal. The desired condition is shown by Fig. 42(a).

In 42(b), the desired beam phase is shown with vectors 103 and 104 equal in amplitude. This results in a constant-amplitude signal out of the detector. In 42(c), the condition of early arrival of the beam is shown; here vector 103 is larger than vector 104, and the detector output signal is the amplitude-modulated wave shown. In Fig. 42(d), the condition of late

1(a)

1 (b) BEAM PHASE OK

1 (c) BEAM PHASE EARLY

1 (d) BEAM PHASE LATE

Fig. 42. Wave forms in phase detector.

Fig. 43. Schematic of complete phase-detection system.

BEAM - ENERGY MEASUREMENT

EXAMPLE OF PERFORMANCE

^{58}Ni IONS AT 400 MeV

PHASE UNCERTAINTY $\approx 0.3^\circ = 8 \text{ psec}$

$$\frac{\Delta E}{E} = \frac{6 \times 10^{-4}}{L}$$

APPLICATIONS

MEASUREMENT OF ABSOLUTE ENERGY

CONTROL OF TANDEM TERMINAL

CONTROL OF BEAM ENERGY

Fig. 44. Concept for time-of-flight system to measure beam energy.

beam arrival is shown; vector 104 is now larger than vector 103, and the phase of the amplitude modulation is 180° different than that for Fig. 42(c).

The combined signal is sensed by a capacitive probe, amplified by a low-noise preamplifier, and applied to the input of a radio receiver. After amplification and detection by the radio receiver, the resultant signal is applied to a synchronous detector operated at the same 1 kHz frequency. As shown in Fig. 43, the output of the synchronous detector controls the phase of the buncher via an electronic delay in the rf input to the buncher.

The performance of the phase stabilization fulfilled all expectations. The system was found to be surprisingly sensitive, operating well with beam charge currents as low as 10 picoamperes. The system was designed to measure phase errors of $\leq 4^\circ$ in a time of 10^{-3} sec for a current of 1 nA, and bench tests indicate that it meets this specification.

Although the phase detector was initially developed as part of the beam-bunching system, it was soon obvious that it offers an elegant way to measure the beam velocity. The idea, as illustrated by Fig. 44, is to measure the difference in phase between two of the detectors and from this, knowing the separation L , to determine an absolute velocity. The data given on the figure show that it is feasible (typically) to measure the beam energy to an accuracy of 10^{-4} in a flight path of 10 m.

The time-of-flight method outlines above will be used to measure the absolute energy of beams both from the booster and from ATLAS.

E. DEBUNCHING

Debunching involves operations that are similar to those of bunching, but it appears to be a less well-known technique. The basic idea is simply that, for a fixed value of the product $\Delta E \cdot \Delta t$, one can decrease ΔE by increasing Δt . The steps involved are illustrated in Fig. 45. In both case I and case II, the initial phase ellipse shears in time as the bunch drifts toward the debuncher. The debuncher operates linearly on the elongated phase ellipse and makes it upright, thus reducing the energy spread.

In case I, we consider an example in which the ratio $\Delta E/\Delta t$ is small, resulting in a shearing that is so small (for a given path length L) that

Fig. 45. Reduction of Energy Spread by Debunching.

the initial and final energy spreads do not differ much. Case II shows that a beam with the same initial phase-space area can be debunched much more effectively if the initial value of the ratio $\Delta E/\Delta t$ is increased. As discussed in Sec. II.F, in an independently-phased linac it is easy to do this by operating the last few resonators in the phase-defocussing mode.

More quantitatively, it can easily be shown that the energy spread ΔE , after debunching is related to the parameters (subscript o) before debunching by

$$\frac{\Delta E_1}{\Delta E_o} = \left[1 + \left(\frac{L}{2E} \right)^2 \left(\frac{5181}{E/A} \right) \left(\frac{\Delta E_o}{\Delta t_o} \right)^2 \right]^{-1/2} \rightarrow \frac{2E}{L} \left(\frac{E/A}{5181} \right)^{1/2} \frac{\Delta t_o}{\Delta E_o}, \quad (10)$$

where L is in meters, energies are in MeV, and time are in nsec; any tilt of the initial phase ellipse is ignored. Again, one sees the dependence of ΔE_1 on the ratio $\Delta E_o/\Delta t_o$ and the advantage gained from the ability to use the resonators of the linac to enlarge this ratio.

The limit on how far debunching can be carried is set by the requirement that the debunching resonator should be highly linear. For beams of the quality expected from ATLAS, this means typically that the bunch width should remain within about $\pm 30^\circ$ (i.e., within ± 0.85 nsec). If we call the limiting time spread $\Delta t_{\max} \equiv C$, we can write $\Delta E_1/\Delta E_o = \Delta t_o/C$, which emphasizes the fact that debunching is much more effective when the initial time spread is very small.

These simple relationships tend to explain why debunching has been so little used at existing rf heavy-ion accelerators (which tend to have poor beam quality) and lend support to our plan to use it extensively with beams from ATLAS.

F. BEAM DYNAMICS

We have attacked the problem of beam dynamics in an independently-phased linac in three different ways: (1) by means of analytic theory, both linear and non linear, (2) by means of a computer program that traces the trajectories of individual projectiles through the linac, and (3) by means of a matrix formulation of the acceleration process. Each approach has its function: the analytic theory provides a qualitative understanding of the phenomena involved; ray tracing gives detailed information that cannot be obtained analytically; and the matrix formulation (still being programmed) assists the linac operator by rapidly solving the problem of setting all resonator and solenoid parameters for optimally transporting the beam through the linac and delivering a beam of the required properties.

1. BASIC CONCEPTS FOR LONGITUDINAL PHASE SPACE

In this section we state, without proof, several useful results that can be derived for the special case of continuous acceleration.

A central idea of the theory is the concept of matching. In the case of a long linac with a well-defined velocity profile, the longitudinal phase space can be represented in the well known way shown in Fig. 46. A particle near the synchronous phase ϕ_s undergoes an elliptical orbit in this space, oscillating in phase and energy. A beam is said to be "matched" to the linac if its boundaries in phase space coincide with one of the "acceptance ellipses" of the linac. Thus, although the matched beam rotates in phase space, it is not distorted, i.e., the beam quality is not degraded.

The condition for matching is as follows: in all parts of the linac, the energy spread must be related to the time spread by

$$\frac{\Delta E}{\Delta t} = 1.32 \times 10^4 \left[\frac{q}{A} \bar{\mathcal{E}}_a f \sin \phi_s \right]^{1/2} A^{1/4} E^{3/4}, \quad (11)$$

where f is the rf frequency in Hz, $\bar{\mathcal{E}}_a$ is the average accelerating field in MV/m, the time spread Δt is in seconds, and energies are in MeV. Here we use a phase convention in which the accelerating field is $\mathcal{E}(z,t) = \bar{\mathcal{E}}_a \cos \phi$, where ϕ is positive for phase focussing.

Another useful form of Eq. 11 is

$$\Delta E = 115 \left[\frac{q}{A} \bar{\mathcal{E}}_a f \sin \phi_s \right]^{1/4} A^{1/8} E^{3/8} (\Delta E \Delta t)^{1/2}, \quad (12)$$

which emphasizes the importance of a small longitudinal emittance for good

Fig. 46. Trajectories in phase space for continuous acceleration in a linac with a conventional velocity profile.

energy resolution. As a numerical example, let $A = 58$, $q = 20$, $\mathcal{E}_a = 2$ MV/m, $f = 97$ MHz, $E = 1000$ MeV, $\phi_s = 20^\circ$ and $\Delta E \Delta t = 30$ keV-nsec $= 30 \times 10^{-12}$ MeV-sec. Then $\Delta E = 0.81$ MeV and $\Delta t = 37$ psec. In this example, we use the low value $\mathcal{E}_a = 2$ MV/m because it is intended to be an average gradient that includes the effect of drift spaces.

The angular rate of rotation $d\psi/dz$ of a matched phase ellipse can be deduced under the same set of assumptions. We obtain

$$\frac{d\psi}{dz} = 4.74 \times 10^{-6} \left[\frac{q}{A} \frac{f}{\beta^3} \mathcal{E}_a \sin \phi_s \right]^{1/2} \quad (13)$$

where $d\psi/dz$ is in radians per meter and β is the relative velocity of the projectile. Here numerical calculations show that the angle ψ rotates typically through 4π in a linac such as ATLAS. Clearly, one is far from having a statistical situation in which the phase ellipse rotates many times and thus loses its memory of the incident conditions; rather, there is a very direct relationship between the incident and the outgoing phase ellipses.

All of the above is derived on the assumption that the linac has a velocity profile corresponding to the projectile velocity (i.e., the projectile is always synchronous). In fact, our linac consists of many adjacent structures with the same dimensions, and the projectile velocity may not correspond to the synchronous velocity of any of them. This situation may be understood within the framework leading to Eqs. 11, 12, and 13 by recognizing that, for resonators which are not synchronous with the projectile, the representative phase point will rotate around a point which lies at $\phi_s = 90^\circ$ and at a reference energy E_r corresponding to the resonator synchronous velocity. This is true because a particle, once synchronous, can remain synchronous (hence with stable representative phase point) only if it does not gain energy. Thus, within each resonator, the center of the phase ellipse executes a trajectory lying on a curve which is symmetrical with respect to $\phi_s = 90^\circ$.

Fig. 47 gives an example of phase trajectories for a ^{40}Ca ion accelerated by a linac consisting of 12 independently-phased resonators, all of the same length. The phase of each resonator is adjusted so that the particle arrives at the center when $\phi = 20^\circ$. The initial velocity of the projectile is very much lower than the synchronous velocity of the structure, thus, the phase slips through almost 180° in the first structure, and the energy gain is small. Gradually, as the particle gains

Fig. 47. Trajectories in phase space for a linac of independently-phased resonators.

energy, the phase slippage diminishes and the energy gain per resonator increases. At about the ninth resonator, the projectile velocity is well matched to the structure, and from then on the direction of phase slippage is reversed.

Although the acceleration described by Fig. 47 may appear to be very different from that in a conventional linac with a monotonically-increasing velocity profile, the behavior of the phase ellipse relative to its own center is essentially unchanged under most circumstances. Thus, Eq. 11, 12, and 13 may still be used as a guide to the qualitative behavior of the phase ellipse.

In ATLAS, the second stripper is located immediately in front of the linac, and consequently all charge states are injected. All of these enter with the same energy and phase, but each will have a different synchronous phase since, in order to remain synchronous, each must acquire the same average energy gain $\Delta E \propto q \cos \phi_s$. The question of what happens to the various charge states is explored in Fig. 48, which illustrates the acceleration of ^{40}Ca in a system tuned to accelerate Ca^{15+} with $\phi_s = 30^\circ$. In the figure, the center of the phase ellipse for the Ca^{15+} ions is represented as being fixed, whereas the centers of all others move. This motion is stable if $q_i \cos \phi_i > 15 \cos 30^\circ$ for the i^{th} ion, and otherwise is unstable. Thus, the acceleration is unstable when $q \leq 13$.

The energies of the various charge states that do have stable motion can lie anywhere on the indicated circles, depending on the amount by which they have rotated in phase space. In this illustration, the ions with $q > 15$ have rotated through roughly $\frac{5}{2} \pi$ radians. Notice that the energies of all these ions must lie within a band about ± 2 MeV wide. This is a relative spread of only 1%.

2. TRANSVERSE OPTICS

Because of the low emittance of the injected beam, quite modest focussing requirements would satisfy the matching of linac acceptance with the beam emittance. However, the need for good energy resolution requires that the average size of the beam within the accelerating structures be minimized. Because the latter goal sets more severe requirements on focussing capabilities, it dominates the design of the transverse optics. To achieve the desired result, the solenoids have been made strong enough

Fig. 48. Multiple-charge acceleration, linac output phase space.

to be able to form a minimal waist between each pair of resonators for a wide range of ions. The details of how to adjust the focussing power to achieve the desired minimum beam size is discussed in Appendix 12.

3. RAY-TRACING PROGRAM

The ray-tracing program, used for the detailed investigation of beam dynamics, is designed to calculate the trajectory of a particle through an arbitrary, predetermined sequence of resonators, solenoids or drift spaces, which may be placed in any prescribed order. The characteristics of each unit is prescribed, including field distribution, field intensities, length and phase offset. The trajectory is calculated by numerical solution of coupled differential equations of motion, using a program that does the same kind of calculation as a sophisticated Runge-Kutta routine. A trajectory is calculated for a reference particle, which travels along the axis, given its charge, mass and injection energy. The trajectories of other particles are calculated, given charge, mass, injection energy and phase relative to the reference particle, and injection radius and slope. The energy, transit time, radius and slope may be read out at the linac end as well as at many points along the trajectory.

The computer routine is quite efficient. Depending upon the amount of output desired, five to ten trajectories can be calculated in each minute of computer time (IBM-370).

One of the first exercises with the program was to establish that it gave results for longitudinal phase space that are consistent with the analytic theory. An example of the good degree of agreement is given by Fig. 49, which shows the energy-phase ellipse for a ^{40}Ca beam in a twelve resonator linac. The numbers attached to the various ellipses give the resonator whose output is displayed. There are two important points about the data. First, the ray-tracing gives an output that is almost what was predicted. Second, there is no indication of distortion of the phase ellipses, again expected for this case.

Having established that the rotation of the phase ellipses can take place without distortion, we then investigated under what conditions distortion is important. Fig. 50 gives the result of such an investigation. Here the objective was to have the output ellipse be extended in time in order to reduce the energy spread. This was done by accelerating an

Fig. 49. Longitudinal phase space during acceleration in an independently-phased linac. Numbers attached to curves designate resonator numbers.

Fig. 50. Longitudinal phase space during acceleration in an independently-phased linac. Numbers attached to curves designate resonator numbers.

approximately matched beam through to resonator #9, using #9 and #10 to debunch the beam, and then using #11 and #12 to rotate the ellipse into a horizontal position. The debunching part of the operation was quite successful but the rotation by the last two resonators introduces significant distortions. The magnitude of the distortion can be accounted for quantitatively in terms of the curvature of the $\cos \phi$ accelerating field term at the phase angle involved. The distortion would not have been visible if the phase spread had been smaller (say $< 4^\circ$) or if the synchronous phase angle had been close to 90° .

One of the most interesting problems for the ray-tracing program was to study multiple-charge acceleration. Figure 51 gives results on this question for ^{40}Ca ions accelerated in a 12-resonator linac. The linac was tuned to accelerate Ca^{15+} with a 20° phase offset. As was expected, all ions with $q \geq 15$ were accelerated to almost the same energy. Moreover, all ions are transmitted down the linac, including those that receive no net acceleration. Since phase slippage is very large for ions that are not accelerated, the result implies that all ions injected into the linac are transmitted, independent of their charge, velocity, or phase. This behavior can be explained by the fact that the solenoids are spaced rather closely, and each one strongly focusses the beam.

The fact that all ions are transmitted through the linac with rather small deviations from the axis has the important implication that the fraction of ions that can strike the superconducting surfaces is very small. This can't help but be beneficial.

4. SPECIAL PROBLEMS OF BEAM DYNAMICS

Several special aspects of the beam dynamics need to be mentioned. They are problems only in the sense that they must be understood; and all of them illustrate once more the immense versatility of a design based on independently-phased resonators.

a. Matching at the Linac Input

The beam pulse incident on the linac has a sharp time focus at or near the second stripper, about $\frac{1}{2}$ meter in front of the first resonator. Thus, the longitudinal phase ellipse has sheared forward by the time it

Fig. 51. Transverse phase space at output of linac for multiple-charge acceleration.

reaches the resonator and, in addition the energy spread induced by the buncher is usually too great for good matching to the linac. Figure 52 is an illustration of how matching can be achieved by use of the first few resonators of the linac itself.

The mode of operation of the resonators is shown by the diagram at the bottom of Fig. 52. The symbol (+) means a resonator operated in the phase-focussing mode and (-) means phase defocussing. In this example, where the ion is Ni^{20+} at an energy of about 1.7 MeV/A, the resonator phase offset is assumed to be about $\pm 25^\circ$.

The basic strategy is to rotate the phase ellipse to the position shown by curve 4 and then reduce the energy spread by means of resonators operating in the phase-defocussing mode. In order to achieve this kind of sophistication in practice will undoubtedly require a considerable amount of experience and the use of calculational techniques such as are discussed in Sec. 5 below.

b. 40° Bend in the Linac

The beam-optical properties of the 40° bend in the linac were outlined in Sec. II, B3. In so far as longitudinal phase space is concerned, the considerations there are similar to those at the linac input, and the desired wide pulse at the bend can be achieved in the way shown in Fig. 27.

c. Influence of Asymmetry in Field

The magnitude of an asymmetry in the accelerating field was discussed in Sec. II, B2b and II, B3b. As mentioned there, the effect of this asymmetry is not great under most circumstances. An example of this is given by Fig. 53, which shows the behavior of a $^{58}\text{Ni}^{20+}$ beam in the first twelve 0.105- β resonators. Here the curve gives the trajectory in the x plane of the centroid of motion. The influence asymmetries in the preceeding 0.060- β resonators has been ignored because it is so small.

Fig. 52. Illustration of use of first few linac resonators to match longitudinal phase space.

Fig. 53. Beam excursions resulting from field asymmetry in 0.105- β resonators. Diagram at bottom represents elements of accelerator sections C and D of booster.

5. MATRIX-TRANSFORMATION PROGRAM

Although the linac is to be tuned experimentally, resonator by resonator, the linac operator needs a way to determine rapidly what strategy should be followed in order to produce the desired output phase ellipse. A matrix of the acceleration problem is being developed with this specific objective in mind.

The effects of longitudinal or transverse forces acting on particles travelling from one point to another in the linac can be summarized by linear transformations in the coordinate pairs $(\Delta T, \Delta \phi)$ or (r, r') . The matrix components of these transformations are evaluated either numerically from the trajectory calculations or by analytical methods. Appendix 11 describes an analytical method for evaluating matrices for the transverse motion. Appendix 12 presents an analytical method for calculating the matrices for motion in longitudinal phase space. The ray-tracing program has been adapted for calculating these matrices as well, and can be used to check on the analytical results. The shape of the ellipse describing the beam in longitudinal (or transverse) phase space can be calculated from one point of the linac to another by a sequence of matrix multiplications.

The computer program being developed to carry out these operations is an interactive one in which the operator is able to make many trials rapidly. Something of this kind is essential if the various special modes of operation mentioned in this proposal are to be practical. Generally, it will be known from experience what general approach should be followed to obtain a desired output. However, the operator must know in detail how to set resonator amplitudes and phases and solenoid strengths, and this will be determined by an intelligent search through multiple parameter space. As a part of this procedure, the program will allow accurate matching of the input beam with the transverse and longitudinal properties of the linac. Presumably, in time a library of effective solutions will be accumulated.

G. NEW CONSTRUCTION

The building to house the extension to the linac and the new Target Area III will be added to the present FN-tandem facility. It will include a linac tunnel, an equipment access tunnel, a large target area, and a small equipment shed. Figure 1 shows schematically a plan view of the proposed addition. In the figure, the walls of new construction are shown cross hatched; the utility shed is not shown.

The addition is conceptually designed to be as inexpensive as possible, consistent with the proposed experimental program. The design will also minimize construction time and will minimally interfere with the ongoing experimental program.

The linac tunnel, about 85 feet long, will be constructed of reinforced concrete. Its interior width will be 15 feet; its height, 13 feet. The floor elevation here and throughout the new construction will be the same as that in the existing facility. The walls and roof will be two feet thick and will be covered with earth for additional shielding. A 2' x 2' service trench will run the entire length of the tunnel. An eight inch floor slab will be poured on compacted fill topped by crushed limestone. Footing drains will be provided throughout the new structure.

A short access tunnel to facilitate the moving of linac sections and experimental equipment to and from the new area will be located as shown in Fig. 1. It will be constructed of reinforced concrete and will have a six feet wide by ten feet high cross section.

The experimental area will be formed by an all-steel, prefabricated self-supporting arch erected on appropriate concrete footings. The structure will be water proofed and covered with a six inch layer of concrete. It will then be back filled with three feet of earth to provide adequate radiation shielding. The floor will consist of an eight-inch reinforced-concrete slab poured on compacted earth fill, topped by crushed limestone. The surface area will be 75 feet long and 42.5 feet wide. Special pads and footings will be provided for certain massive experimental devices. A system of service trenches, 2' x 2', will be located in the target area.

A large service door and personnel access doors will be provided. Four jib cranes will be strategically located in the area.

Major pieces of mechanical and electrical equipment will be located in the utility shed. It will be a 25-foot square masonry building located southeast of the target area (No. III) and connected with it by service pipes.

Substation C in the Physics Building will be expanded to provide an additional 400 kVA of electrical power for the expanded facility. Of this, 200 kVA will be used for normal building services and 200 kVA will be allocated to experimental facilities. Two separate feeders will serve the area, one for the building equipment and the other for scientific equipment. Half the power for scientific purposes will be supplied as 440V, three phase, and the other half as 208, three phase, and 110 volt, single phase. Service outlets will be located around the walls and in the trenches.

All lighting will be fluorescent to reduce the use of electrical energy. The present system of cable trays and patch panels for experimental cables will be extended into the new area. In addition, the building telephone, paging, fire detection, and alarm systems will be extended into the area as well as the local intercom system.

Provisions are being made for 36 tons of cooling capacity and for 100,000 BTU's of heating. Up to four tons of cooling are provided for scientific equipment. The relative humidity in the area will be maintained at $50\% \pm 2.5\%$. The entire area will be protected by a sprinkler system. The heat exchangers, pumps, air handling units, and other such equipment will be located in the utility shed. In addition, a cooling tower will be located near the shed.

H. EXPERIMENTAL AND SUPPORT FACILITIES

1. EXPERIMENTAL FACILITIES

The experimental areas associated with ATLAS are indicated in Fig. 1. As can be seen, the layout is designed to take full advantage of beams from all three major components of the accelerator system. Namely, existing Target Areas I and II make use of beams available from the FN tandem alone and from the booster linac, respectively; while the proposed new Target Area III uses the full-energy beams from ATLAS. This layout provides the opportunity to perform a large variety of experimental studies spanning a wide energy range while making the most efficient use of experimental space.

a. New Experimental Area

A tentative layout of the proposed new experimental area (Target Area III) is shown in Fig. 54. As can be observed, the area is designed to accommodate a number of experimental stations, including a magnetic spectrograph. The stations indicated on the zero-degree beam line are expected to be used for irradiations, with no rebunching. The other beam lines will be designed for optimum energy or time resolution by making use of debunching or rebunching, respectively. The experimental stations located on these lines will include systems for measuring charged-particle reactions, γ multiplicities, and neutron time of flight. A large magnetic spectrograph is shown at the rear of the experimental hall.

The layout of the beam lines is to a large extent determined by the small bending angles, which are used to preserve the excellent time resolutions of the beams produced by the linac. In view of the stiffness of the beam involved, superconducting dipoles of the kind discussed in Sec. II.3e will probably be used for this application. To permit access to various experimental stations while beam is being run elsewhere in the area, movable shielding walls are planned.

b. Existing Experimental Areas

Target Area I accepts beams from the tandem and Area II from the linac booster. In the following we list the experimental facilities

Figure 54. A possible schematic layout of beam lines for the new Target Area III.
 The interior partitions are to be built of portable shielding blocks.

that exist or will exist in the areas before the implementation of ATLAS. The detailed disposition of this equipment, and other new facilities, among the target areas, after ATLAS becomes operational, will have to be decided at a later date.

i). Target Area II. This experimental area was constructed in 1977, and installation of the experimental equipment shown in the layout in Fig. 1 will be completed in 1979-80. In the initial operations in 1978, experiments will be performed on the zero-degree beam line, which will accommodate four experimental stations. Later, with the installation of the rebuncher and the charge-selector magnet, the locations of the various experimental stations will be changed to that indicated in the figure.

The layout of the beam lines was made after careful study of the beam optics to insure maximum quality of the beams with regard to spatial, energy, and timing resolutions. With the bunching system and optics of the booster, the beam quality will be determined almost entirely by processes that occur before the beam enters the linac; i.e., the beams on target are expected to have tandem-like quality. The expected properties of ^{16}O , ^{40}Ca and ^{58}Ni beams in this target area are shown in the table in Section III.

For many kinds of heavy-ion research, a poor vacuum in the beam lines and experimental chambers can place serious limits on the kinds as well as the quality of experiments that can be carried out. Accordingly, the vacuum system was designed to be clean, with a minimum of organic contamination. Five experimental stations are now planned for Target Area II, with some space available for other stations, if the need arises.

A new general-purpose 65-inch Scattering Chamber has been designed and is being fabricated for installation in 1978. The large diameter allows for high angular accuracy and sufficient space for time-of-flight measurements in a large class of studies. Its height of 36 inches provides the capability for out-of-plane motion of detectors. Four independent arms allow for both angular and radial motion. The chamber vacuum will be hydrocarbon-free to prevent carbon buildup on targets and to comply with vacuum requirements of the linac system. The design of the chamber provides the flexibility for a large variety of measurements which can utilize the excellent energy and time resolutions of the beams in both singles and coincidence studies.

A Neutron/Charged Particle Time-Of-Flight (TOF) Chamber of thin-wall design is being constructed for the study of heavy-ion-induced reactions. The rotating-seal arrangement, combined with a small-angle exit port, establish a one-meter flight path in vacuum for TOF measurements of charged particles in the angular range 0° to 160° . This experimental station, with its provisions for neutron/charged-particle TOF-coincidence measurements, will complement the investigations possible with the 65-inch scattering chamber.

A general purpose Gamma-Ray Facility which allows for angular-distribution and coincidence measurements will be installed. The design allows for several coincidence experiments: Ge(Li) - Ge(Li), Ge(Li) - sum/multiplicity spectrometer, Ge(Li) - particle detector, and particle-detector - sum/multiplicity spectrometer. The sum/multiplicity spectrometer consists of two $6'' \times 9''$ annular NaI detectors, each segmented into optically-isolated quadrants which allow for simultaneous measurement of total γ -ray energy in a reaction as well as for γ multiplicity. The two detectors will be placed very close to each other, with the target in between. Thus, one has eight separate sectors, and the total solid angle approaches 4π . Signals from each sector will be summed to give the total γ energy. The number of sectors firing will give a measure of the multiplicity. A bore will be made for inserting a Ge(Li) or another NaI detector such that the latter can be as close as 2" from the target. The two halves of the spectrometer can also be separated to accommodate a pill-box scattering chamber housing Si or gas detectors. Since the spectrometer has such a large solid angle, coincidence measurements with it will have rates close to the singles rates. It can be used to enhance the sensitivity to very high-spin transitions in (H.I.,xn) and Coulomb-excitation reactions, as well as to obtain information on γ -decay energies and multiplicities in such processes as fission and deep inelastic collisions. For γ -ray measurements, the target chamber will accommodate a 3-position, rotatable target ladder. The beam can either be stopped at the target (allowing 0° measurements) or at a Faraday cup ~ 2 m downstream.

There will be an electron spectrometer consisting of a solenoid-Si(Li) detector combination. It will be possible to shield the target so that only the electrons from residues which have recoiled out of the target will be detected. In this manner, electrons delayed by a few ps after the

reaction can be observed. For longer delay times, the pulsed-beam structure of the linac can be employed, with the spectrometer operating in the conventional mode without target shielding. In the design of this target facility, a modular approach is taken in order that many target chambers can be interchanged with minimum beam-line disruption. Thus, a large variety of experiments can be performed. It should, for instance, be possible to incorporate the g-factor chamber and magnet presently used with the FN tandem.

A Target Station for Delayed Activities which will be used for the study of nuclei far from stability will be installed. Several target chambers already in existence will be moved from Target Area I and made operational. These are: (1) a multi-target rabbit system for β - γ spectroscopy studies of delayed activities with half-lives longer than one second, (2) a helium-jet recoil transfer system and a noble gas transfer system for β , γ and β -delayed particle studies on nuclides with half-lives longer than one second, and (3) an in-beam chamber for β , γ and β -delayed particle measurements on nuclides with half-lives shorter than one second.

The multiple rabbit uses a carousel arrangement to hold an array of up to 8 targets which may be sequentially bombarded and sent pneumatically to a shielded area for counting. The multiple feature enables targets to lie unused for a period so as to help slow down the buildup of contaminant long-lived isotopes, which are almost always produced along with the desired species. The helium-jet recoil transfer transports radioactive recoils in a gas stream and deposits them onto a paper tape, which is subsequently moved in front of the shielded detectors. The advantage of this scheme is that a fresh source is always counted, and no buildup of unwanted isotopes occurs. At present, the tape-transport speed limits the half-lives that can be studied to 1.5 sec or longer. The noble-gas-transfer system utilizes the fact that radioactive noble gases can be rapidly separated from all contaminants. It operates in a manner similar to the helium-jet, except that the gas stream passes through traps which remove all activities except noble gases. Separation times of 2 seconds are easily achieved. The in-beam chamber has thin mylar windows which allow energetic β rays to be observed in detectors outside the vacuum system. The narrow width (2.5 cm) allows two Ge(Li) detectors to be placed on either side for use in coincidence β - γ studies. The collimation and beam dump are designed to minimize backgrounds.

A Magnetic Spectrograph System will be installed to make use of high-resolution beams for spectroscopic studies of reactions induced by heavy ions. The existing Enge split-pole spectrograph from the cyclotron laboratory will be installed by mid-1978 and put into operation when the rebuncher-charge selector beam line becomes available. A high-quality vacuum system will be built to minimize carbon buildup on targets and charge exchange in the spectrograph. The focal-plane detector systems for the spectrograph are expected to be patterned after the gas ionization-proportional counters developed at Argonne by Erskine for use in heavy-ion studies with FN Tandem beams. These counters, which measure the experimental parameters dE/dx , E_{total} , and position ($B\rho$), are capable of unambiguous particle identifications and energy resolutions of $E/\Delta E \gtrsim 1000$. The detectors will be appropriately modified for the higher energies and heavier ions available from the linac. When combined with the excellent beam properties, they should make the spectrograph a powerful spectroscopic instrument.

ii) Target Area I: The layout of Target Area I is indicated schematically in Fig. 1. The area houses six experimental stations, some of which have been used routinely for years in studies performed with beams from the FN Tandem. It is anticipated that some of these experimental stations will be moved to Target Area III when ATLAS is nearing completion.

The Enge Split-Pole Spectrograph, with the capability of analyzing particles with ME/q^2 up to ≈ 95 amu-MeV and obtaining resolutions of $E/\Delta E \geq 2000$, has been used extensively in both light and heavy-ion-induced reaction studies utilizing both emulsions and focal-plane-detector systems. As noted above, the gas ionization-proportional counter focal plane detector system developed at Argonne provides the particle identification and energy resolutions ($E/\Delta E \geq 1000$) necessary for spectroscopic study of reactions induced by heavy ions. Techniques have been developed for making measurements of inelastic and transfer reactions possible at very forward angles (including 0°).

The 70-inch Scattering Chamber, with its four independent arm motions, has been used extensively in charged-particle measurements of reactions induced by heavy ions. Because of its large size, the chamber has been ideal

for time-of-flight measurements and in fusion studies, which necessitate measurements at small angles (e.g. $\theta_L \approx 2^\circ$). The recent installation of a superconducting buncher on the beam line for the scattering chamber produces pulse widths $\Delta t \approx 50$ psec making new classes of reaction studies possible.

The Gamma-Ray Goniometer located on the center beam line permits the study of angular distributions or correlations of energetic γ rays where the emphasis is on high energy resolution and low backgrounds. The first objective is achieved by large NaI crystals embedded in LiH, an annular plastic detector (used in anti-coincidence) and a Pb shield. The second objective is accomplished by focussing the beam after it transverses the target chamber into a well shielded beam stop located some distance from the chamber. Construction of two large (25 cm $\times$ 30 cm) NaI crystal spectrometers is currently being completed. Initial tests showed that a resolution of 2.3% for 17-MeV gamma rays (which is better than any other system reported in the literature), while the resolution at 20 MeV at a counting rate of 250 KHz is better than 5%. The spectrometers have been used at LAMPF and at Argonne in radiative-capture experiments (labeled D in Fig. 1) and in studies related to fundamental research on weak interactions.

A general-purpose Prompt Gamma-Ray Facility is located in the area. This station permits study of either (1) γ -angular distributions, (2) γ - γ coincidences and correlations, or (3) γ -n and γ -charged-particle coincidences and correlations. Different chambers are available for the various measurements. A 7 $\times$ 7 ft.² table provides the support for the neutron or gamma detectors.

A g-Factor and Lifetime Measurement Facility has been in use for several years using pulsed beams with pulse widths as narrow as 1 ns and with a period of up to 1 μ s to measure nuclear lifetimes. A second pulsing system with pulse widths variable from 0.1 μ s to several seconds and with periods from 6.4 μ s to minutes has been used for both lifetime and g-factor measurements. The g-factor measurements were made with liquid targets in a magnet capable of generating magnetic fields of 25000 Gauss and in Helmholtz coils capable of generating fields of 400 Gauss.

The Delayed-Activities Target Station, presently located in this target area, which consists of several systems (i.e. a Multiple Rabbit, a Helium-Jet Recoil Transfer System, and a Gas Transfer System), has been discussed previously and will be installed in Target Area II in mid-1978.

c. Data Room and Computer System

A data-recording room located adjacent to the tandem-linac control room (Fig. 1) houses experimental-area monitoring and control systems, electronics, and an on-line computer. Permanent cabling to all three target areas runs to centrally-located patch panels which allow signals to be patched to various locations in the room. A large pool of electronics (NIM and CAMAC) exists for general usage, including modules developed at Argonne for use in fast timing measurements in the pico-second range.

A complete system based on the DEC PDP 11/45 mini-computer is dedicated to on-line data acquisition and analysis and is composed of 120K words of core memory, a floating-point processor, a 1.2M word removable cartridge disk, a fast (125 IPS) magnetic tape unit, an electrostatic line printer/plotter, a standard hardcopy terminal, a storage tube graphics terminal, a CRT terminal, and a complement of CAMAC hardware. A sophisticated software system supports data acquisition via any standard CAMAC module (scalars, ADC's, DAC's or gate modules), a commercially available ADC interface, and a special ADC interface, designed and built in house, which operates in either list mode or direct-memory access mode and allows data accumulation at very high rates. Another PDP 11/45 with similar peripherals, but excluding the ADC interfaces, is available elsewhere in the building for off-line data analysis and software development.

The software system is implemented under DEC's DOS/BATCH-11 operating system with significant extensions for interrupt-driven, foreground data acquisition. It includes a set of dynamic memory-management routines for manipulating core and disk-resident data sets, and a sophisticated command-language processor capable of executing core-resident functions, linked overlay functions residing on disk, or lengthy command-sequence files (a mechanism by which a frequently executed sequence of commands may be listed in a disk file and invoked by specifying the file name as one would any single function name). The modular programming concept was applied extensively to optimize flexibility, minimize core requirements and software overhead, and

provide for future growth; no single "data-acquisition program" exists, per se. As the physicist user defines his source of data and analysis requirements by calling standard system functions, foreground routines are dynamically loaded into core and linked to the appropriate hardware interrupts and nuclear spectrum data sets are created in memory. The foreground routines are written in reentrant code and can be shared among many independent processes, where appropriate. This approach allows each user to dynamically tailor the core-resident software to match his own needs with minimal overhead and maximum flexibility.

2. SUPPORT FACILITIES

As a national laboratory, Argonne has on site an arsenal of technical facilities and services. Moreover, scientific personnel in the Physics and Chemistry Divisions are currently engaged in a number of research programs which relate directly to the utilization of ATLAS. These include heavy-ion studies at the present ANL Tandem as well as at the LBL super-HILAC, cyclotron, and BEVALAC. Other related research programs are pursued in charged-particle, atomic, neutron, fission, and medium-energy physics. These utilize Argonne facilities such as the FN Tandem, Dynamitron, electron linac, and cyclotron and also use facilities such as LAMPF at other laboratories. The close interaction of scientists in these and other sub-disciplines is strongly encouraged. Argonne has a strong group of nuclear theorists who have a long tradition of constructive interaction with the experimental programs.

The main library and computer center are conveniently connected to the Physics building.

The resources available to Argonne in terms of technical facilities and services have already been indicated in the discussion of the superconducting linac project. In the following, the most obvious services of importance to research at ATLAS will be briefly summarized.

a. Technical Support Facilities

An Electronics Division which works in instrument development, circuit and system application, feasibility studies, and commercial-equipment application is available on site. The division has special groups for

fabrication and maintenance, nano-second circuitry, and data handling. Machine, optical, plastic, and other shops are also available. Since commercial suppliers are used whenever possible, the laboratory shops are used primarily in "state of the art" projects requiring extraordinary tolerances, rapid response, or new techniques.

A broad-range effort in the Chemistry Division includes programs in heavy-element and nuclear chemistry. Techniques and facilities for the safe handling of highly radioactive actinide elements are available. In addition, an isotope separator for the preparation of a wide variety of targets is operated routinely.

b. Computation Center

The Applied Mathematics Division operates a major computational center that provides services to the whole Laboratory. Currently the center contains an IBM 370/195 computer complex with an extensive array of peripheral devices, supplemental memories, and coordinating computers. This system can be conveniently addressed via remote job entry stations for batch operations or remote terminals for TSO operations. In the near future, a link will exist allowing access from the PDP 11/45 systems. Remote job entry is also supported via ARPANET to various computers around the country.

III. PERFORMANCE OF ATLAS

The characteristic feature of ATLAS is the high degree of flexibility in all aspects of its operation. This flexibility is possible because of the use of short independently-phased resonators, and the possibilities can be realized because they were recognized at an early stage and built into the design.

Beam-performance characteristics of special importance for the experimental program are:

- (1) the acceleration of projectiles over a wide range of energy and mass,
- (2) easy energy variability,
- (3) excellent emittance and energy resolution,
- (4) ultra-short pulses, and
- (5) a high pulse rate with no macrostructure.

As mentioned before, the best one-sentence summary of this performance is that it is similar to that of a 50-MV tandem with two strippers.

Examples of estimated beam parameters for several representative ions in Areas III and II are given in Tables 1 and 2, respectively. Here the maximum energy is that obtained when the product of stripping fractions is 0.02. The beam intensity corresponds to the somewhat lower energy obtained when the charge state having the maximum intensity is selected after each of two strippings. The indicated energy spread and time spread cannot be obtained simultaneously.

Almost as important as the good beam characteristics is the fact that various design features tend to make the operation of ATLAS exceptionally cost effective and research efficient. These features include:

- (1) the availability of two beams with independently-selected energies,
- (2) the availability of three separate target areas, two fed by beams from the linac,
- (3) the capability of using the linac effectively when individual resonators or even complete sections are not functioning,
- (4) the off-line servicing of linac sections,

Table III-1. Characteristics of beams in Area III. All widths are FWHM.

	$^{16}_O$	$^{40}_{Ca}$	$^{58}_{Ni}$	$^{80}_{Se}$	$^{103}_{Rh}$
Max. Beam Energy (MeV)	415	940	1230	1450	1520
Beam Current (pnA)	400	55	40	35	30
$\epsilon_x = x' \cdot x$ (mm mrad)	1.0	1.0	1.0	1.0	1.0
$\epsilon_y = y' \cdot y$ (mm mrad)	1.4	1.4	1.4	1.4	1.4
$\Delta E \cdot \Delta t$ (keV-nsec)	15	20	25	30	35
$(\Delta E/E)_{\min}$	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
$\Delta t_{\min}$ (psec)	40	40	40	40	40

Table III-2. Characteristics of beams in Area II. All widths are FWHM.

	$^{16}_O$	$^{40}_{Ca}$	$^{58}_{Ni}$	$^{80}_{Se}$	$^{103}_{Rh}$
Max. Beam Energy (MeV)	260	550	675	770	760
Beam Current (pnA)	400	55	40	35	30
$\epsilon_x = x' \cdot x$ (mm mrad)	1.0	1.0	1.0	1.0	1.0
$\epsilon_y = y' \cdot y$ (mm mrad)	1.4	1.4	1.4	1.4	1.4
$\Delta E \cdot \Delta t$ (keV-nsec)	~ 20	~ 30	~ 50	~ 70	~ 90
$(\Delta E/E)_{\min}$	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$
$\Delta t_{\min}$ (psec)	~ 100	~ 100	~ 100	~ 100	~ 100

- (5) the feasibility of tuning the linac rapidly, and
- (6) the low electric-power requirements.

Additional detail on operating and beam characteristics are given below.

A. ENERGY AND MASS RANGE

The maximum beam energies provided by ATLAS to the three experimental areas are given by Fig. 2 as a function of projectile mass.

The considerations leading to the choice of the design parameters that determine the energy and mass ranges were discussed in Sec. II. B3. The dependence of the achievable range on various operating parameters is described here.

In order to calculate the beam energy of the accelerator system, one needs input concerning the mean charge and the charge-state distribution resulting from stripping; the assumption used for the calculational results presented here are summarized in Appendix 10. The other input required is information about the average accelerating field $\mathcal{E}_a$ in the resonators. Here our basic assumption is that $\mathcal{E}_a$ will be limited by the condition that the maximum value of the surface electric field should not exceed 20 MV/m, a subject discussed in Sec. II.B2a.

The dependence of performance on the terminal stripper and on the terminal voltage V_t is shown in Fig. 55. Here one sees that the maximum achievable energy does not depend much on the stripper when the beam energy $E_0 = (q+1)V_t$ incident on the linac is far above the cut-off value caused by transit-time effects in the first resonator. However, when this critical value is approached, the nature of the stripper is all important.

Similarly, the output energy is insensitive to the terminal voltage when the tandem energy is well above the cut-off energy of the linac. This has the important implication that the tandem can often be operated at the voltage for which the highest beam current can be transmitted.

Returning to the subject of stripping, the advantages of using a foil in the terminal to strip the heavier ions is apparent from Fig. 55. However, there is considerable uncertainty whether the lifetime of a foil bombarded by such ions will be long enough to be generally useful. Therefore, in the performance projections given here, we assume that a gas stripper is used in the terminal for $A > 50$ unless it is stated otherwise.

Fig. 55. Maximum beam energy vs projectile mass for various terminal conditions. All curves are for the condition $f_1 f_2 = 0.02$.

Special cases for which foil strippers are expected to be useful for all ions are when the beam from the source is very weak or when target currents ≤ 10 pA are required by the experimenter. When the source is weak, it may be advantageous to omit the second stripping in order to preserve the beam intensity. The maximum energies obtainable with a single stripping are given in Fig. 56.

The maximum beam energy available in Target Area II is shown in Fig. 2. As mentioned earlier, the energies of the primary and secondary beams may be selected independently to a considerable extent. If the user in Area III does not require the maximum energy, then the energy of the second beam may be reduced, if desired. The relationship between the two beams is complicated because there are so many options in how the resonators and strippers would be used to maximize the requirements of both beams; however, if the primary beam is reduced in energy by some factor, it is usually allowable to reduce the energy of the second beam by a larger factor. For example, if the energy of a primary ^{58}Ni beam is reduced by 20%, then the energy of the second beam may be selected to be anywhere in the range 0.6 to 1.0 times its maximum value.

An attractive feature of the independently-phased linac is that an increase in the accelerating field $\mathcal{E}_a$ results in an increase in beam energy. This is especially important for a superconducting linac since such increases are to be expected in a new technology, and developmental work with that aim is planned.

Fig. 56. Maximum beam energy vs projectile mass when only terminal stripping is used.

B. ENERGY VARIABILITY

Variation of the energy of the ATLAS system is accomplished by varying the operation of the linac, with the tandem and bunching systems left undisturbed. Energy variation is particularly easy when the range to be covered is small, say, < 4% of the maximum energy. In this case, the energy can be changed simply by varying the phase of the last resonator, which sweeps the energy over a total range of typically 50 MeV. This simple operation can be completely controlled by the computer, and the time-of-flight energy-measurement system will provide continuous information about the absolute value of the energy.

When the desired energy range is greater than can be covered by the last resonator, it is necessary to adjust one or more other resonators. Often this will involve merely turning off the last resonator and varying the phase of the second last resonator. However, to change the energy by a large factor would usually require a retuning of a larger number of resonators. Also, the linac must be retuned when any parameter of the incident beam is changed but, since this operation will be computer controlled, it can be completed in a matter of minutes.

C. BEAM INTENSITY

The intensity of the output beam is determined almost entirely by the characteristics of the tandem and by the stripping processes, since the linac itself accelerates almost all ions injected into it. The high transmission of the linac results from the fact that the incident beam has excellent quality in both transverse and longitudinal phase space.

The output beam intensity I (in particles per sec or in μA) may be written as

$$I = I_1 B T_t T_L f_1 f_2 f_3, \quad (14)$$

where I_1 is the beam injected into the tandem, B is the fraction of ions bunched tightly enough to be transmitted by the chopper, T_t is the transmission of the tandem, T_L is the transmission of the linac, and f_1 , f_2 , and f_3 are the stripping fractions of the three strippers. If only two strippers are used, as is normally the case, $f_3 = 1$. Also, $T_L \approx 1$.

As discussed in Sec. II.D, the bunching efficiency B is about 0.75 for normal operation. It could be made somewhat greater by tuning the buncher with this aim, but the pulse width would necessarily increase and hence the beam quality would be poorer.

The transmission T_t of the newly-upgraded tandem is a parameter that is not well understood yet. As one sees from Table II-2, measured transmissions are in the range 0.5-0.8, but these measurements were made without terminal pumping and without optimum conditions in the injection system. Thus, it is reasonable to expect that the transmission will ultimately be higher. For purposes of estimating intensities, we assume $T_t \approx 0.7$.

Inserting the above values into Eq.(14), one obtains $I/I_1 \approx 0.5 f_1 f_2$ for normal operation, which shows that the product $f_1 f_2$ is the main determinant of the output beam intensity. At the peak of the charge-state distribution, the product ranges from $f_1 f_2 \approx 0.4$ for ^{16}O to $f_1 f_2 \approx 0.07$ for $A = 130$, ignoring the small influences of the atomic structure of the ion and the composition of the stripper.

From the above discussion one sees that the main question about the output beam intensity is how much current the tandem can accelerate. Two limitations need to be considered: (1) the beam-carrying capacity of the tandem itself, and (2) the lifetime of the stripping foil, if a foil stripper is used. Neither question can be answered with precision at this time, since there is rather little operating experience with new accelerator tubes in the tandem. However, Table II-1, in Sec. II.D, shows that, during the acceptance test, the beam injected into the tandem were about 2.0 and 1.8 pA for ^{16}O and ^{37}Cl , respectively. Also, it has been shown that the tandem can accept at least 1 pA of injected Ni beam. Since the operation of the injection system was far from optimum during all of these tests, and since there was no significant indication of beam loading, we expect that the tandem will be able to tolerate at least 1 pA of incident beam of any of the ions to be accelerated by ATLAS. If so, output beam intensities can range from ~ 400 pA for ^{16}O to ~ 35 pA for $A \approx 130$, if charge states are selected from the peaks of two stripping distribution. This is more than enough beam for most nuclear-structure investigations, especially in view of the good beam quality. Experiments with oxygen beams from tandems are typically done with 5 - 50 pA.

The foil lifetimes that have been measured for ions such as bromine at energies near 10 MeV are in the range 50 to 100 min per μA of current per cm^2 of foil area in the beam. For our beam spot 4 mm in diameter, this implies a lifetime in the neighborhood of 10 minutes per μA of incident beam. This is almost too short to be practical, since even a 1000-foil changer would be exhausted in about 7 days. However, if the incident beam current were reduced to (say) 0.2 μA , the lifetime would be entirely adequate.

D. TRANSVERSE EMITTANCE OF THE BEAM

When a foil stripper is used, the beam emittance is determined largely by the spot size and by the angle of multiple scattering in the terminal stripper. The angular divergence of the beam incident on the foil is almost small enough to be neglected. Similarly, the influence of multiple scattering in the second stripper is small if the beam spot is small at the stripper. Because of the small beam size and the large bore of the drift tubes in the linac resonators and solenoids, non-linear effects in their focussing action is small and can be neglected.

Detailed examples of calculations of beam parameters at several points in the acceleration process are described in Appendix 10. The data in the table in the appendix confirms the general conclusions stated above and show that the beam injected into the linac has an emittance $\epsilon_x \equiv x \cdot x'$ of about 1.0 mm mrad for ^{16}O and 1.5 mm mrad for ^{58}Ni ions when the terminal stripper is a foil 5 $\mu\text{g}/\text{cm}^2$ thick. As discussed in Sec. II.D, the beam chopper causes the vertical emittance ϵ_y to be about 40% greater.

When a gas stripper is used, it can be thinner, and hence the multiple scattering is less. Consider, for example, the action of a 1 $\mu\text{g}/\text{cm}^2$ gas stripper on the same ions (^{16}O and ^{58}Ni) treated in Appendix 10. Now the angular straggling induced by the stripper is 5 times smaller, and as a result emittance of the ion source is the dominant factor. Thus, the final emittance of both beams, before injection into the linac, is about 1 mm mrad.

Since typically the beam energy is increased by an order of magnitude by acceleration in the linac, in principle the emittance of many beams going into Target Area III could be as small as 0.3 mm mrad. However, it seems wise at this time to assume that the emittance of the beam delivered to the

experimenter will be ~ 1 mm mrad because of non-linear effects in the beam-transport system. However, the potential for an exceedingly small emittance clearly exists and could be tapped if it were important to do so.

E. LONGITUDINAL EMITTANCE OF THE BEAM

The product $\Delta E \cdot \Delta t$ plays a role in energy-time phase space that is equivalent to $x^1 \cdot x$ in angle-position space, and hence it is often called the longitudinal emittance. As with the transverse emittance, the beam-optical system can be designed so that the value of $\Delta E \cdot \Delta t$ is almost unchanged after the beam leaves the terminal stripper. In this case, ΔE is dominated by the energy spread caused by energy straggling in the stripper, and Δt is determined by the pulse width formed by the pre-tandem buncher.

The properties of the pre-tandem beam buncher are discussed in some detail in Sec. II.D, where it is shown that the existing buncher can form ion pulses at the terminal that are ~ 1 nsec wide (FWHM), depending somewhat on the ion mass. It appears that it would be difficult to improve greatly on this performance.

Because of the influence of charge-changing effects, energy straggling has recently been found to be considerably larger than was predicted formerly. In particular, new data and analyses^{1,2,3,4} are consistent with a straggling energy spread given by

$$\Delta E_s \approx 1.05 Z \sqrt{w} \quad , \quad (15)$$

when the projectile energy is well above the Bragg maximum, here ΔE_s is a FWHM in keV, Z is the nuclear charge of the projectile and the foil thickness w is in $\mu\text{g}/\text{cm}^2$. When the projectile energy is below the Bragg maximum, ΔE_s falls off with decreasing energy in a way that appears to be poorly understood but can be estimated roughly from the data in Ref. 1-4. When the terminal voltage is 9 MV and the stripper is a foil $5 \mu\text{g}/\text{cm}^2$, examples of estimated values of ΔE_s are as follows: 14 keV, 28 keV, and 35 keV, for ^{16}O , ^{58}Ni , and $A = 100$ ions, respectively. Thus, as these same ions leave a terminal foil stripper, the product $\Delta E \cdot \Delta t$ is typically 7, 14, and 18 keV-psec. If the stripper is a gas, the product will be smaller by a factor of 2 or 3.

In this discussion we have assumed so far that the terminal voltage is completely stable. In practice, since installing the Pelletron charging chain, the voltage variations are usually small enough to be negligible.

Another possibility is that changes in the voltage distribution along the accelerator tube may cause a change in the transit time of an ion through the tandem. This phenomenon is observed but, as discussed in Sec. II.D, the phase detector that is a part of the bunching system eliminates the influence of this effect and indeed of all other variations in voltage.

There are three places between the tandem and the linac at which the phase-space area can be enlarged. The first is the 90° bending magnet, where differences in path length are serious for very heavy ions but not, for example, for an ion such as ^{58}Ni . A second is the chopper, discussed in II.D5.

The third danger point is the second stripper. Since this stripper must be fairly thick ($\sim 25 \mu\text{g}/\text{cm}^2$) to obtain an equilibrium distribution of charge states, energy straggling is quite large, typically 100 to 200 keV. The influence of this straggling is minimized by placing the stripper near the linac entrance, where the post-tandem superconducting buncher forms an extremely narrow time focus. Since the small time spread is accompanied by a large energy spread in the beam (see Sec. II.D), the effect of the additional straggling is minimal.

Within the linac itself, the product $\Delta E \cdot t$ is largely preserved if the beam is matched to the linac acceptance in the way discussed in Sec. II.E.

Finally, it would be easy to enlarge the product $\Delta E \cdot \Delta t$ at the bend in the linac or in the experimental areas. However, this can be avoided by the careful design of beam-transport systems.

E. ENERGY RESOLUTION

As mentioned above, in order to minimize the loss of longitudinal beam quality within the linac, it is desirable to match the phase space of the beam to the longitudinal acceptance of the system. This subject is discussed in Sec. II.F, and in Appendix 11. For present purposes, an approximate example will suffice. Consider a ^{58}Ni beam accelerated under typical operating conditions to an energy of 1000 MeV. Let the product $\Delta E \cdot \Delta t = 25 \text{ keV-nsec}$. Then, the matched condition would require $\Delta E \approx 625 \text{ keV}$ and $\Delta t \approx 40 \text{ psec}$, and the output beam would have these characteristics if the linac were operated in the matched mode of operation.

If the energy spread of the matched beam is too large for the experimental application, the spread can be reduced by the technique of debunching, as discussed in Sec. II.D. The essential idea of debunching is to form an upright phase ellipse in which the time spread is enlarged so that (since $\Delta E \cdot \Delta t$ is constant) ΔE is reduced. As illustrated in Fig. 25, this is achieved by letting the beam drift along a distance L , thus introducing the desired time spread δt , at which point a resonator pulls the elongated phase ellipse into the desired orientation. It is simple to show that the debunched energy spread δE is related to the original spread ΔE and the other parameters by

$$\delta E \approx \frac{2 K E^{3/2}}{(5181A)^{1/2} L \Delta E} = \frac{2 \Delta t E^{3/2}}{(5181A)^{1/2}}, \quad (16)$$

where K is the constant $\Delta E \cdot \Delta t$ in MeV-nsec, and E and ΔE are in MeV; the equation is approximately valid if $\delta E \leq 3 \Delta E$. This relationship emphasizes how debunching depends on the various beam parameters involved. In particular, debunching is more effective (small $\delta E/\Delta E$) if L and ΔE are large and if E is small (still assuming $\Delta E \Delta t$ is fixed).

By way of illustration, consider again the 1000 MeV ^{58}Ni beam with $K = 25 \times 10^{-3}$ MeV-nsec and $\Delta E = 0.5$ MeV, and let $L = 10$ m. Then, Eq. (16) gives $\delta E/\Delta E = 0.46$ which does not satisfy the condition $\delta E/\Delta E \ll 1$. The problem is that the phase ellipse did not spread out enough in time with the assumed values of L and ΔE . Thus, for debunching to be effective, the energy must be deliberately spread out before the beam leaves the linac. This can be done by operating the last two or three resonators in the phase-defocussing mode, which can easily make $\Delta E = 4$ MeV, for example, as illustrated in Sec. II.D. Now Eq. (16) gives $\delta E = 72$ keV, a considerable improvement over the matched beam. A reduction in energy spread of this magnitude or more (if L is increased) is expected to be a routine feature of beams from ATLAS.

The relative energy spread of 10^{-4} given in Table III-1 for Target Area III is a representative value that could be reduced if there were a reason to do so. The value given for beams going into Target Area II is much greater (5×10^{-4}) because we tentatively assume that it will not be worth while to have a separate debuncher; rather, the linac itself will be used to debunch the beam somewhat.

G. TIME RESOLUTION

The ion-bunches coming out of the linac are as narrow (< 50 psec) as are usable in most experiments at this time. The main challenge is how to deliver the narrow pulse to the experimenter. One problem is that the pulse shears in phase space as it drifts to the target. This problem can be solved by rebunching the beam, and a resonator for this purpose is associated with Target Area III, as shown in Fig. 1. Here again, as with debunching, the achievable pulse width can be reduced by deliberately increasing the energy spread of the beam before it leaves the linac.

The second problem is to avoid having the ion pulse broadened by the beam transport system, where the only significant broadening is caused by bending magnets. In principle it is feasible to build accurately isochronous bending systems, of course, but this would be too expensive for most beam lines. Rather, we plan to use the well-known idea of limiting time spread by placing a small waist at the center of the bend. In such a system

$$\Delta t = \pm 2 x_m \sqrt{\frac{5181}{E/A}} \sin \frac{\theta}{2}, \quad (17)$$

where x_m is the beam half width at the mid plane of the magnet. The expression gives, for example, a spread of ± 6 psec for a 1000-MeV ^{58}Ni beam if $x_m = 1$ mm in a 20° bend. Thus, it is evident that the time spreads introduced by the bending magnets are negligible for most beams unless the bending angle is very large.

The time spread of 40 psec given in Table III-1 for Target Area III is a representative value that could be reduced, if important. The value given for beams going into Target Area II will probably be greater because a larger number of bends is involved.

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IV. SCIENTIFIC JUSTIFICATION

A. INTRODUCTION

In the field of nuclear physics there has probably been more anticipatory prose written in connection with heavy-ion accelerator proposals than for almost any other type of facility. This reflects the severe shortage of funding for new facilities over the past decade. It is not our purpose here to attempt yet another review of heavy-ion physics, mentioning all the appropriate topics. Instead we wish to focus on some of the scientific frontiers which could be explored (with unique precision) by the ATLAS facility.

The nucleus is a bound collection of nucleons, a quantum-mechanical many-body system, that has provided unparalleled opportunities for studying the physics of such systems in the laboratory. Our present understanding of the nucleus is in terms of relatively simple excitations that involve either single-nucleon or few-nucleon probes, or of rotations, vibrations, and giant resonances that are excited by electromagnetic fields or comparable gentle nuclear collisions.

It is qualitatively clear that in order to excite modes of excitation very different from the ground state, nuclei have to be subjected to more drastic disruptions that will influence the motion of many nucleons, and explore the response of the nucleus under very different conditions. The interaction of two pieces of nuclear matter, with kinetic energies comparable to their binding energies, is just such a stirring device, which may excite nuclei into possible new many-particle modes or cause them to rotate with very high angular velocity.

Some qualitative features of the dynamical aspects of heavy-ion collisions are beginning to emerge from explorations with present facilities. Our present view of these results is in terms of qualitative, semiclassical parameterizations, optical models, hydrodynamic collisions with friction, etc. This may perhaps be compared to the study of nuclear reactions prior to the early 1950's when qualitative aspects of nuclear reactions were becoming apparent. Resonances at low energies, and some evidence of forward peaking and evaporation at higher energies were seen, but the detailed study, the harvesting of nuclear-

structure information that became possible as direct reactions were better understood and as the parameters of the shell model and the collective models fell into place has taken at least two decades, and is still incomplete.

The ATLAS facility is aimed squarely at the study of the interface between heavy-ion reactions and nuclear structure. It is an extremely flexible accelerator of inherently high energy and time resolution, with easy energy variability over a large range of bombarding energies. The energy region between 5 and 25 MeV per nucleon is the one in which the effects of detailed nuclear structure are most likely to be apparent.

So far, most of the experience in high-resolution, heavy-ion experiments has come from studies with existing cyclotrons and tandems. The heavy-ion linacs at Berkeley and Darmstadt are making major contributions to our overall view of heavy-ion reactions especially the strongly-damped collisions, to atomic physics, and to the study of nuclear structure by gamma-ray spectroscopy. The experiments at the various other accelerator facilities tend to focus on those classes of experiments which best fit their specific characteristics. The tandem facilities are characterized by relatively light-mass beams at relatively low bombarding energies, with high beam quality and easy energy variability. Cyclotron facilities have tended to focus on lighter mass beams at higher energies. The beams have good energy and spatial resolution; however ion species available are limited and energy variation is generally not easy. The linac facilities have focussed on heavier projectiles ($A \geq 40$) with beams of relatively low resolution and relatively poor emittance. The Bevalac can attain GeV per nucleon energies and is aimed at the exploration of relativistic heavy-ion phenomena. The ATLAS facility extends the excellent beam qualities and precise energy variability typical of tandems to higher bombarding energies and heavier ion species. It covers approximately the same range as would a hypothetical 50-MV tandem. In addition, its beams will have excellent timing properties, bunched to approximately 50 psec with high repetition rate, which will be of unique value for particle identification and coincidence measurements.

B. HEAVY-ION REACTIONS

Perhaps the most striking phenomenon which has emerged from the study of heavy-ion-induced reactions is the observation that the distribution of reaction strength is very different from that expected from reaction models which had been developed for lighter projectiles [Proceedings, 1974-77]. For example, let us consider the $^{16}\text{O} + ^{40}\text{Ca}$ system which has been studied over a large energy range in an ANL-LBL collaboration [Vigdor, 1976] and compare fusion and total reaction cross section as a function of energy. While the fusion cross section at lower energies, as expected, nearly exhausts the total reaction strength, at higher bombarding energies the fusion cross section becomes a steadily decreasing fraction of the total. This saturation of the fusion cross section seems to be connected with the appearance of a new reaction process in which target and projectile tend to retain their identity but the relative kinetic energy of the fragments is damped into internal excitation. These "strongly-damped" or "deep-inelastic" processes account for a large fraction of the total reaction strength at higher bombarding energies and for heavy target-projectile systems at even relatively low energies; they have been the subject of intensive study in the last few years [Schröder, 1977].

The connection between elastic, quasielastic, strongly-damped and fusion reactions is still unclear. Some effort has been made to study the systematics of the cross sections as a function of bombarding energy and target projectile mass, but the information available is still very limited. Existing results have forced modifications of conventional reaction theory in an attempt to account for the observed behavior. Models have been presented that describe selected features of the fusion and the strongly-damped cross sections rather well, but there as yet is no unified model that accounts for all of the competing processes and includes what is relevant of the detailed structure of the interacting nuclei. This structure has been found experimentally to cause large differences in the distribution of reaction products. In the following sections we will focus on some of the studies possible at the ATLAS facility which can utilize its beam properties to investigate microscopic aspects of the reaction data.

1. QUASIELASTIC REACTIONS

a. Elastic Scattering

This is the simplest of the direct reactions since in first order no rearrangement is involved and the interaction is described roughly by an average optical potential. The comparison of the empirically-determined optical potentials with ones calculated from matter distributions is still at a very early stage, and is limited by the range of available data. It is interesting to note that up to now no unambiguous elastic scattering data exist for systems where both nuclei are heavier than ^{40}Ca [Dobre, 1977]. In reactions between heavier nuclei a roughly-defined total quasielastic cross section has been measured, but the individual contributions from elastic and inelastic scattering and from transfer processes have not been resolved.

To study elastic scattering in heavy systems, it is obviously necessary to have sufficient energy resolution to resolve it from other processes, in particular from inelastic scattering. None of the present heavy-ion accelerators with sufficient energy to surmount the Coulomb barrier in heavier systems has been able to achieve the required energy resolution, nor does one expect to easily obtain such resolution from future high-energy heavy-ion cyclotrons. In addition to energy resolution it is necessary to have complete, clean particle identification to distinguish elastic scattering from transfer channels. The excellent timing properties of the pulsed beam from ATLAS will allow mass measurements without the use of the usual time-start detectors, that tend again to degrade energy resolution. An additional aspect of heavy-ion elastic scattering and of quasielastic processes, is the study of their behavior as a function of bombarding energy. The ease with which energy changes are possible and excitation functions measured speaks for the usefulness and efficiency of the accelerator.

The need for measurements of excitation functions has become obvious through recent measurements [Barrette, 1977] of ^{16}O and ^{12}C elastic scattering to backward angles from targets of ^{28}Si and ^{40}Ca . Pronounced resonance-like structure is seen in detailed excitation functions taken in small energy steps over a wide range of bombarding energies. This behavior

was unexpected for such a heavy system; it had been thought to be restricted to systems involving light nuclei with masses $A \leq 16$. It will be of great interest to study this behavior in heavier systems, at higher energies and in other reactions channels.

The elastic channel, of course, is coupled to the other quasielastic channels. The direct-reaction cross section concentrated at the nuclear surface exhausts a large fraction of the total cross-section in surface partial waves. The details of this coupling between various peripheral channels promises to yield information about the details of nuclear structure.

b. Inelastic Scattering

The direct reaction channels most likely to be coupled strongly to the elastic are those for inelastic scattering to excited states in projectile and target nuclei. Both Coulomb and nuclear excitations are important; while it has been shown recently that the Coulomb excitation to low-lying collective states is in itself strong enough to require explicit coupling to the elastic channel, the more interesting aspect is the information contained in the nuclear contribution to the excitation process. Again the reaction mechanism is far from adequately understood. Recently we have shown at Argonne in inelastic scattering of ^{16}O from ^{40}Ca that the effect of a strongly-coupled state on the elastic wave function may be rather important in the description of the inelastic excitation to another state, even when the two excited states under consideration are not directly coupled to each other [Rehm, 1978]. At first sight the implications of this result seem to complicate the analysis of inelastic scattering, and most probably also of transfer reactions; yet it also raises the hope that some of the long-standing discrepancies in a theoretical description of heavy-ion transfers and inelastic scattering may eventually be resolved. Preliminary measurements show that the strength of the direct inelastic processes increases with increasing energy. It may well be that even when the coupling to these states becomes more important the analysis will remain relatively simple. It is clear that more detailed investigations are required at higher energies, and such investigations require high-quality beams.

Inelastic scattering to giant resonances is another topic that requires high-energy beams with resolution good enough to reveal structure

potentially present in the overall resonance shapes. It may be observed that recent studies of the E2 giant resonance by inelastic alpha scattering seem to have been most productive in the regime of energies we are discussing, 10-25 MeV/A.

c. Transfer Reactions

Heavy-ion induced direct transfer reactions have been studied extensively at lower energies, but data at higher energies have been obtained only for a very few cases and such data are generally not as complete and detailed as for lower energies. However, the fraction of the total reaction processes which goes into transfer channels, both direct and strongly-damped (and also probably with reaction mechanisms in between these two) increases strongly with increasing bombarding energy. It is not known what fraction direct reactions contribute to the total transfer cross sections. To obtain such information will require measurement not only of gross properties but also of individual transitions or groups of transitions.

At higher energies direct transfer processes may populate high-spin states with a drastic rearrangement of shell structure. For instance, will the spin-orbit force disappear when one has a highly aligned state with a large fraction of the nucleons rotating together with a similar angular velocity? Such effects have not yet been identified, it is clear that one prerequisite is a high-quality beam at high energy. The identification of relevant states would provide an exacting test of many aspects of nuclear-structure calculations.

An important aspect of direct-reaction cross sections is their dependence on bombarding energy. Very few studies have been carried out on the energy dependence of direct reactions to specific states; few such studies extend to high energies and none involve heavy projectiles ($A > 16$). For instance, dramatic effects were found in the excitation function for a direct reaction in recent measurements at Argonne. In an attempt to extend the results on resonance structure observed in the elastic scattering of systems such as ^{16}O on ^{28}Si to other channels, the excitation function for the direct α -transfer reaction ($^{16}\text{O}, ^{12}\text{C}$) on ^{24}Mg was measured at 0° in the laboratory. The results show strong resonant structures not expected from simple direct reactions. It will be interesting to extend such

measurements to heavier systems and to higher energies. It will also be of interest to study transfer excitation functions at backward angles, again requiring higher-energy heavy projectiles. While the present resonances are most likely connected with fragmented shape resonances of the composite system and may fade away at sufficiently high bombarding energy, it may still be interesting to investigate the systematics of back-angle cross sections. Recent Hartree-Fock calculations [Koonin, 1978] suggest that at sufficiently high bombarding energy central collisions (those involving the lowest partial waves) may not lead to fusion but rather to backscattered fragments. The appearance of such backscattering at higher energies, and the study of the specific channels involved in such events, may lead to new sorts of detailed information on nuclear structure. Again, for detailed studies a high-quality beam is essential. It should be noted that for these experiments the extremely good time structure of the ATLAS ion beams may be as useful as their good energy resolution. In principle in any true two-body reaction the measurement of the two scattering angles and the two flight times unambiguously determines the reaction kinematics. The high-quality pulsed-beam characteristics of the linac will therefore be extremely useful in the study of many of the questions just discussed.

This is also true for cases where light fragments are emitted from one or both of the reaction partners. In this case the measurement of energy and flight time of the two heavy fragments will yield the summed mass of the light fragments emitted. Detailed studies under suitably-chosen conditions, for example when the projectile mass is preserved in one of the heavy outgoing fragments, covering a range of energies and a variety of light evaporated particles will provide information on the reaction mechanisms as well as on the structure of the nuclear states involved.

The enhancement of large angular-momentum transfer in heavy-ion-induced transfer reactions can be used to locate states involving excitation of d, f and g configurations in lp-shell nuclei. At incident energies of about 200 MeV we expect to see $1f_{7/2}$ and possibly $1g_{9/2}$ transfer. For example, the $^{13}\text{C}(^{11}\text{B}, ^{10}\text{B})^{14}\text{C}$ reaction should excite a $J^\pi = 3^+, 4^+$ doublet around 14 MeV and a $4^-, 5^-$ doublet around 16 MeV, and in like fashion the $^{12}\text{C}(^{11}\text{B}, ^{10}\text{B})^{13}\text{C}$ should populate $7/2^-$ and $9/2^+$ states. Such data, in conjunction with extended shell-model calculations, should yield valuable information about high-spin states in light nuclei [Dehnhard, 1978].

d. Exchange Effects on Quasielastic Reactions

Exchange effects in heavy-ion elastic scattering are predicted to decrease with increasing energy; we can hope to learn about their importance by studying the energy dependence of elastic scattering cross sections. A specific exchange process of particular interest is the elastic transfer of the N nucleons by which projectile and target differ. This process is known to influence large angle cross sections significantly. It would be of interest to measure back-angle excitation functions in a variety of systems involving sd-shell nuclei, with ^{28}S or ^{32}S beams, studying both the elastic and the appropriate transfer cross section [Dehnhard, 1978].

2. STRONGLY-DAMPED COLLISIONS

One of the surprises in studies of the interactions between very heavy ions was the discovery that a dominant fraction of the total reaction cross section leads to strongly-damped collisions, also called deep-inelastic processes [Schröder, 1977]. A large fraction of the available kinetic energy is converted into internal excitation and the outgoing reaction products possess energies comparable to the Coulomb interaction energy of two more or less spherical, touching fragments. In the heavier systems these processes seem to be clearly separated from the quasielastic events in the energy spectrum. With respect to other parameters, for example mass transfer, gamma and particle multiplicity and final-state polarization, differences between the two reaction types remain but are less pronounced and less clear in their interpretation. One does not of course, expect a completely clear-cut separation between the quasielastic and strongly-damped processes. Any microscopic view of the reaction mechanisms leads to a gradual transition from single to multi-step processes with increased inelasticity. Until now only macroscopic models have been applied, whose underlying physical assumptions, for example fluid dynamics or diffusion processes, exclude the consideration of detailed nuclear structure. Structure enters later in a somewhat tangential way when one attempts microscopic calculations of the parameters of the empirical models. The macroscopic approach seems justified on account of the large number of degrees of freedom involved on the one hand and the lack of detailed structure found experimentally on the other. Experimental efforts have been

almost exclusively directed to the study of the macroscopic aspects of the reactions, at least in part because of experimental limitations imposed by beam and detection characteristics. These limitations will be hard to overcome in very heavy systems; however in the intermediate-mass range improvement seems feasible both in beam quality as demonstrated by the characteristics of the proposed linac, and by the experimental techniques developed recently in time-of-flight and magnetic spectrograph measurements. *The intermediate-mass range seems to be of particular physical interest.* In light systems the deep inelastic component is not clearly established and in any case strongly overlaps with quasielastic processes. In the very heavy systems both regions are kinematically well separated. A microscopic description covering the full range from quasielastic to strongly damped collisions will involve extrapolation over a region where little experimental data exists. In the intermediate-mass region it has been found in the systems $^{40}\text{Ca} + ^{40}\text{Ca}$ and $\text{Cu} + \text{Cu}$ that additional processes occur in the energy region between the quasielastic and deep-inelastic regimes. These and other similar systems seem particularly suited for detailed investigation. The study of the dependence of these reaction processes on bombarding energy and on the detailed structure of the entrance channel, their variations as a function of the angular momentum brought into the system and of the neutron excess of the composite system, their particle and gamma multiplicities as a function of the properties of both entrance channel and composite— all such studies, with emphasis on the extraction of nuclear-structure information, need to be carried out with the best resolution and beam quality that can be achieved. It appears that none of the heavy-ion accelerators at present in operation or planned in the near future will possess characteristics suited for these important studies to the extent permitted by the proposed superconducting linac.

3. HEAVY-ION-INDUCED FUSION

Heavy-ion-induced reactions leading to complete fusion and compound formation have attracted much attention in recent years. In this section we want to discuss the reaction aspects of complete fusion; the spectroscopic studies that are performed in the decay of the compound nucleus are mentioned elsewhere.

Interest in the fusion reaction arises from the fact that its behavior can vary drastically with the bombarding energy, entrance channel and compound system formed. Fusion dominates the total reaction cross section in the lighter systems, at energies from the Coulomb barrier to a few times the barrier energy. At this energy, however, the fusion cross section levels off, while the total reaction cross section continues to rise. This is the region where strongly-damped collisions come into play, eventually accounting for an appreciable fraction of the total cross section. The balance between fusion and the rest of the reaction cross section depends on the form of the yrast line and consequently the moment of inertia of the compound nucleus, a critical internuclear distance (most probably determined by the density overlap) which needs to be reached, and at the highest energy, the liquid-drop limit on the maximum angular momentum the system can carry becomes relevant. These factors depend in some measure on the specific structure of the interacting nuclei and the nature of the compound nucleus. At Argonne, for example, it was recently demonstrated that the fusion cross section depends sensitively on the entrance channel and possibly reflects nuclear shell closures [Sperr, 1976]. It was also found that for very light systems involving ^{12}C and ^{16}O nuclei the fusion cross section fluctuates as a function of incident energy and shows resonant behavior. All these measurements involve detailed excitation functions and it is no coincidence that the most complete experimental information has been obtained at tandem energies, though it appears even more interesting to extend these measurements to higher energies. Because of the difficulty in changing energies in small steps, very little detailed information has been obtained at higher energies and for heavier systems with the present high-energy heavy-ion accelerators.

For the heavier systems competition from strongly-damped collisions becomes very strong even close to the Coulomb barrier until for the heaviest systems there is no evidence for complete fusion. It is of great interest to acquire detailed experimental information for the intermediate systems. First, the region where the fusion cross section vanishes should be sensitive to nuclear-structure effects. Second, it is very important to establish limits on fusion cross sections in order to predict the cross sections for formation of nuclei far from the valley of stability, superheavy nuclei

for example. The linac will be very well suited for such detailed studies through its great versatility in the ion beams, time structure, and energy variability.

4. FISSION

Heavy-ion-induced fission can result from any of the reaction processes discussed in the preceding chapter, provided the fissioning nucleus is excited to energies above its fission barrier, the latter depending on the total angular momentum brought into the system. Fission may thus follow heavy-ion-induced direct reaction processes—inelastic scattering and transfer reactions; it may proceed after total fusion from the compound nucleus or it can be induced by the strongly-damped processes in one or both of the residual nuclei.

Heavy-ion direct-reaction-induced fission has been little studied, only with rather light projectiles ($A \approx 16$) and close to the Coulomb barrier. Potentially it may prove a fruitful process to investigate since specific configurations are preferentially populated in a direct reaction process and thus the detailed dependence of the subsequent fission on the reaction parameters can be studied. In particular one might hope to populate states in the secondary minimum in the potential of the fissioning system and carry out detailed investigations of delayed-fission events. Direct-reaction-induced fission below the Coulomb barrier can be studied to learn about the Coulomb deformations induced in colliding nuclei before nuclear forces become effective. Experimentally the direct-reaction-induced fission is a multiparameter event, since in addition to the fission fragment the direct reaction product must be observed. However, with the excellent timing properties of the linac, flight-time measurements can be performed with ease, without the complication of a multiple-start detector configuration.

Fission following complete fusion can yield valuable information about the properties of nuclei at very high angular momentum. This is discussed in more detail in the section of high-angular momentum states. Another significant property of the compound nuclei formed in heavy-ion reactions is their high recoil velocity. This can be used to search for delayed fission events or particle evaporation. If fission or particle

evaporation occurs promptly, the reaction products will show the typical kinematic features of decay in flight. If on the other hand the recoiling nucleus is stopped and subsequently a delayed decay occurs, the kinematic characteristics will be quite different; for example, for binary fission the stopped compound nucleus will decay into two fragments that emerge back to back in the laboratory system whereas the decay in flight may yield an appreciably smaller angle between the two fission fragments. Similarly, lines in the energy spectrum of emitted particles will be Doppler shifted for decay in flight.

Recent studies of fission following strongly-damped collisions [Dyer, 1977] show that detailed information about the angular momentum transfer and the degree of spin polarization in the primary reaction can be obtained by this method [Back, 1978]. The situation is experimentally complicated since the strongly-damped processes themselves show characteristics of the two-body decay of a partially equilibrated system. Here again it seems desirable to have the excellent timing characteristics of the linac to do effective multiparameter experiments. This also holds true for ternary fission, a process very little investigated.

Fission channels exhibit strong threshold phenomena; as in light-ion-induced studies, a detailed study of this threshold behavior in small energy steps may provide valuable information on the detailed structure of the fissioning system. In addition, since fissioning compound systems are of greatest interest in the mass region $A = 150$ to $A = 250$, it appears that intermediate-mass projectiles, for example Ni isotopes, will be most useful. The proposed linac is ideal for such studies.

5. NUCLEAR TEMPERATURE AND HEAVY-ION REACTIONS

An interesting perspective on heavy-ion-induced nuclear reactions can be gleaned from recent studies of reactions with light ($A \approx 16$) heavy ions incident on heavy targets, spanning an energy range from a few MeV to several GeV per nucleon. When the reaction cross sections are analyzed in the various energy regions with the appropriate reaction models and with the common aim to deduce information on the characteristic nuclear temperature one finds a rather striking energy dependence. At a few MeV/A the nuclear

temperature is low, typically 1 to 2 MeV, slowly rising with energy. Between 5 and 20 MeV/A incident energy there is a rapid transition during which the nuclear temperature appears to rise to 8 MeV, the average binding energy of a nucleon in the nucleus, and then levels off with essentially no further variation up to the highest bombarding energies of a few GeV/nucleon.

This interpretation of the cross sections in terms of the concept of temperature should of course be viewed with caution. The temperature extracted from the data is model-dependent. Data over a sufficiently-wide energy range is available only for ^{16}O ions. The indications are, however, that some sharp change in the character of the dominant reaction processes occurs between 5 and 20 MeV per nucleon. Extension of these studies of the energy dependence of the reaction cross sections to other projectiles is clearly of interest.

C. NUCLEAR STRUCTURE

1. NUCLEAR STRUCTURE AT HIGH ANGULAR MOMENTUM

Our present knowledge of discrete nuclear states is, with isolated exceptions, limited to $I < 22 \hbar$. For larger spin values $I > 25 \hbar$ one expects new avenues in nuclear structure physics to open since the rotational energies involved are comparable to shell effects and Coulomb energies.

Perhaps the most dramatic of the phenomena predicted at high angular momenta is the possibility of changes in shape with increasing I . The increasing centrifugal force is expected to drive the nucleus towards oblate equilibrium shape. A possible scenario is that a nucleus which was prolate in its ground state would first become triaxial, as its angular momentum increases, then oblate, and finally would quickly become prolate again on its way to fission. In the oblate regime angular momentum is expected to be most efficiently generated by aligning a number of nucleon spins along the symmetry axis rather than by collective rotation. In fact, it will be very interesting to study the competition between collective rotation and particle alignment as a function of angular momentum. A system of non-interacting fermions is expected to have, on the average, a rotational relation between energy and angular momentum— $E \sim \hbar^2/2\mathcal{I}_{\text{rigid}} I(I+1)$.

The study of the yrast line over a wide region of spin will explore the limits of validity for this simple relationship. Shell effects should introduce significant perturbations and constitute a separate subject for study.

The possibility of new simple configurations of nuclei becoming accessible through heavy-ion reactions is one of the major incentives for such studies. An example is the class of states called second-minimum shape isomers, or fission isomers, that were indeed found with the aid of heavy-ion beams almost a decade ago. Several dimensions are opened for such nuclear-structure studies by the properties of ATLAS. In the dimension of angular momentum we clearly have a large unexplored region. Collective models have been discussed most fully, but drastic rearrangements of shell structure also may take place. More generally, heavy ions may open up new configurations quite independent of spin. The shape isomers are only one example of a possible large class of such phenomena. Here we discuss recent results suggesting resonances in systems as heavy as $A = 40$ and 44 which suggests special simplicities for certain states. Finally, in isospin space there is a large domain of nuclear properties to be explored far from the usual line of stability. These far-from-stability nuclei are of interest not only to nuclear physics but also in astrophysics because of their role in element formation.

a. Study of Discrete γ rays and α particles

The fluctuations in the otherwise monotonic increase of energy with spin of the yrast line can lead to so-called yrast traps [Bohr and Mottelson, 1974]. The occurrence of such high-spin isomers opens the possibility of studying discrete states with ultra-high spins ($I = 20 - 60 \hbar$) in the "quiet" out-of-beam environment provided by the decay of the isomers. A recent survey [Pedersen et al., 1977] has identified a group of high-spin isomers which are promising candidates for γ -decaying yrast traps. Much work remains to be done on detailed γ -ray spectroscopic studies of high-spin isomers in order to elucidate their detailed properties. Only then can definitive statements be made about the isomeric nuclear shapes.

While the "quiet" out-of-beam environment in which the decay of high-spin isomers can be observed undoubtedly provides a distinct advantage, there is now hope that we can observe in-beam γ transitions from much

higher spin states than has hitherto been possible. We propose to enhance the contribution from the largest angular momenta by using a sum energy/multiplicity spectrometer to simultaneously select high γ -decay energy and high-multiplicity events. The use of heavy projectiles ($A \approx 50$) will make it possible to form compound systems with minimum excitation energy for given angular momentum. This will be kept not much larger than the maximum spins to be studied (30–50 $\hbar$). With this approach, background contributions will be minimized. Finally Doppler broadening will be kept small by allowing the evaporation residues to recoil into vacuum and observing the γ rays along the direction of recoil. As spin increases, α decay from states near the yrast line begins to compete effectively with γ emission since the α particle can remove a large amount of angular momentum. Grover and Gilat [1967] have pointed out that it should be feasible to observe sub-Coulomb α 's, i.e., those with energies below the maximum in the α -evaporation spectrum. Such α 's from near the yrast line should exhibit fine structure in their energy spectrum, reflecting irregularities in the yrast line. In fact, the observation of this structure would be a signature of energetically-favored aligned states. In other words, we have here another tool with which to study yrast states at very high angular momenta. Furthermore, since the sub-Coulomb α 's are predicted from a statistical model of nuclear de-excitation, they provide a test of the model. Such α 's can be enhanced by selecting the channels following the evaporation of 3 or 4 neutrons from the compound system. This can be accomplished by coincidence with discrete γ rays or with the appropriate γ -decay energy as measured in the sum/multiplicity spectrometer. (The total γ -decay energy decreases with increasing number of emitted neutrons.)

b. Direct Lifetime Measurements of Continuum γ Rays

Gamma decays of the heavy-ion-induced compound nucleus proceed along the yrast line (the sequence of states of lowest energy for a given total angular momentum) and usually end in the ground-state rotational band, with well-separated individual lines in the gamma-ray spectrum. The energies of these discrete lines increase with increasing spin within the rotational band. Transitions above the ground-state rotational band between

yrast states with spins higher than 20-30 $\hbar$ are not well separated but lead to a more or less structured continuum in the gamma-ray spectrum, when measured with an energy resolution of a few keV. The energies of these transitions are higher than any within the ground-state band and generally range from 1 to 3 MeV. The continuum gamma spectra are generally interpreted as originating from the decay of several parallel bands along the yrast line, below the neutron binding energy. The fact that these transitions proceed between states of very high angular momentum in the compound nucleus makes their study particularly interesting. Indications of gross structure which have been seen experimentally, may point to higher backbending regions or to changes in the decay properties due to the single-particle structure of highly aligned states with rotational bands built on them. In any case, changes in the decay probabilities mean changes in lifetimes of the nuclear states involved. The measurement of lifetimes in the continuum region is therefore of considerable interest, because it is expected that an understanding of these transitions will yield valuable information on the structure of nuclear states at the highest angular momenta.

To cite a specific example, shape evolution as a function of spin should be reflected in the decay time of the excited states. If a nucleus, prolate in its ground state, becomes oblate at high spin, then the γ decay following population by neutron emission should proceed immediately to the yrast region with little competition from the enhanced E2 transitions characteristic of collective rotation. Transitions along or near the yrast line should involve change of particle configurations and will be considerably retarded compared to the fast E2 transitions between collective states. Even if no long-lived yrast traps materialize, the resultant continuum transitions should have lifetimes longer than a few picoseconds.

Direct measurements of these lifetimes through Doppler-shift recoil distance and attenuation methods are not feasible because of the lack of discrete lines in this energy region. The proposed superconducting linac with its time structure will allow direct lifetime measurement. Because of its excellent time resolution (considerably less than 100 psec) direct timing against a fast detector and measurement of centroid shifts of the time coincidence spectrum of the order of a few picoseconds will be possible. Since we are interested in the continuum gamma spectrum with rather limited structure, the energy resolution provided by a NaI detector will be sufficient.

The time resolution may be provided by a plastic detector in front of the NaI which detects a fraction of the energy of the Compton-scattered gamma ray; the NaI detector then detects the escape energy. By appropriate selection of Compton-scattered events, the energy deposited in the plastic scintillator may be kept essentially constant, independent of the total gamma energy deposited in both detectors. Such techniques have been used to measure lifetimes (down to a few picoseconds) for radioactive sources. With the time resolution of the pulsed linac beam being better than that of a plastic scintillator, such time resolutions will be possible in the in-beam experiments. In particular, since only one gamma detector is involved in the latter case, it has the additional advantage over measurements with radioactive sources in that the in-beam measurements are essentially singles measurements; the rf-signal of the beam pulses yields one timing signal with 100% efficiency. Compared to pulsed in-beam experiments at slowly-pulsed machines, the time structure of the proposed linac has the additional advantage for lifetime measurements between beam pulses, that one is operating in effect in a dc-beam situation as far as accidental coincidences are concerned. This is due to the high rf-frequency at which the linac operates so that up to a data rate of 1 MHz the event probability per beam pulse is considerably smaller than one.

There is another feature of continuum transitions that may be used to distinguish whether transitions in the yrast region are between collective or particle states: in the former case the continuum angular distribution should be predominantly E2 in character.

In the measurements of the continuum gamma-ray lifetimes and angular distributions one would plan to investigate nuclei in the well-deformed region, where one expects fast rotational transitions up to very high spins and compare these to regions where phase transitions, shape isomers and spin isomers (yrast traps) due to such things as the single-particle structure of highly-aligned states are expected.

c. Lifetime Measurements with Conversion Electrons

Lifetimes in the ps range have traditionally been measured by Doppler-shift and attenuation measurements. In a different approach employing conversion electrons [Kankeleit et al., 1976], a solenoid focuses onto a Si(Li) detector only electrons which have recoiled out of a shielded target.

The recoil distance into the active region of the solenoid is proportional to the time after the reaction. This method has an advantage over the γ -ray Doppler-shift measurement since prompt transitions are much more easily shielded out. We propose to use such a device to measure discrete high-spin transitions which are delayed by a few ps, thereby extending the time range over which yrast traps can be searched. Delayed continuum electron transitions can, of course, also be investigated and their conversion coefficients measured when combined with γ -ray measurements described in the previous section. The use of projectiles heavier than the targets will increase the recoil velocities and facilitate measurements. Finally, the electron spectrometer can be used in the traditional way to obtain conversion coefficients, which uniquely identify transition multipolarities. For isomeric transitions which have isotropic angular distributions because of the loss of alignment, this would be indispensable information in a spectroscopic study.

d. Limits of Angular Momenta that can be Accommodated by Nuclei

At very high spin, nuclei are expected to fission. Knowledge of the maximum angular momenta that nuclei can accommodate will provide important information on nuclear dynamics (shell and liquid drop effects) and the fission process itself. To date, data on angular momentum limits have come from fusion cross sections and γ -ray multiplicity measurements [Britt et al., 1977, Newton et al., 1977]. Whereas such measurements provide indirect information, it should be possible to observe directly the limits of nuclear stability by studying the onset of fission as the bombarding energy is increased. By requiring a coincidence between the two fragments and noting the time of flight with respect to the beam pulse, one should obtain a very clear signature of fission.

For nuclei with $A \lesssim 150$ the maximum possible angular momentum may be determined not by fission but by α decay. (In fact, it is of great interest to study the competition between these two modes of decay as a function of A .) Information on α decay at high spin may be obtained by examining the α -evaporation spectrum as a function of the incoming angular momentum. Since the available α -decay energy is greater at larger spins,

the higher energy portion of the α spectrum may provide the most useful information. It may prove interesting to study the correlation between α energy and the subsequent γ -decay energy and multiplicity, as measured in the sum/multiplicity spectrometer. This correlation should reveal the energy and angular momentum of the system before and following α decay, and also the spread in these quantities.

It is also of some interest to determine whether α emission occurs before or after fusion, and what the energy and angular momentum distributions are in each case. If emission before fusion determines the maximum partial wave for fusion, then the measurements of fusion cross sections and γ -ray multiplicities reflect this limitation and not the stability limits of nuclei.

Shell effects may induce unusual stability in states that would otherwise fission or α decay promptly. In this case, lifetimes of the order of a few ps or longer may result. Such short half-lives may be measured by utilizing the high recoil velocities available in heavy-ion-induced reactions. An arrangement in which prompt decays are shielded should allow α particles or fission fragments from states with lifetimes longer than ~ 1 ps to be observed quite clearly. The existence of such isomers may enable us to investigate states with angular momenta very close to the maximum possible in a nucleus.

e. Fission of the Compound Nucleus at High Angular Momentum

One promising method to study the behavior of nuclei at very high angular momentum is to investigate their decay by fission. Under certain conditions the compound nucleus will fission from the high angular momentum states only; in addition this will be first-chance fission, so no preceding particle decay will mask the energy and angular momentum of the decaying compound nucleus. By choice of projectile and target (most favorable is a symmetric entrance channel) the compound nucleus can be produced at relatively low excitation energy and with rather high angular momentum. The competition between fission and neutron emission in the compound nucleus is changed in favor of fission with increasing angular momentum. This is a simple consequence of the fact that the moment of inertia at the saddle-point deformation is larger than the ground-state deformation. At threshold energies, fission is therefore most likely to occur for the high angular

momentum states. The behavior of these nuclei at high angular momentum can be studied by measuring the fission cross section as a function of energy near threshold. First one may try to understand the threshold behavior through a comparison with theoretical calculations and extract information on the fission barrier height and the moments of inertia of very high angular momentum states. Out of such studies should come answers to many interesting questions concerning the fission process itself. For example, how excited are the fragments? What spins do they carry? What is the relative orbital angular momentum? Answers may be provided by experiments in which the γ -decay energy and multiplicity are measured. One can also study the threshold behavior as a function of neutron excess in the entrance channels in reactions of, say, $^{60,64}\text{Ni}$ on targets of $^{112,126}\text{Sn}$. The occurrence of isomeric states at the yrast line, shape transitions etc. may reflect themselves in the details of the fission threshold behavior. It is obvious, that such structures may require high-precision measurements of excitation functions in small energy steps and excellent intrinsic beam resolution, both requirements satisfied at the moment at upgraded tandems. These, however, do not deliver the heavy-ion beams with the energy necessary to perform such studies. Again the linac, with its excellent beam quality, will permit studies of this area of nuclei at very high angular momenta.

Some of the experiments on fission will be carried out with the sum/multiplicity filter to determine the γ -decay energy and multiplicity coincident with the fragments. (The partitioning of sum energy and multiplicity is straightforward in symmetric fission.) This method should be particularly effective for a rapid survey of a large number of different systems.

f. Coulomb Excitation

The availability of ions of very large Z such as ^{208}Pb offers the prospect of Coulomb excitation of very high-spin states. Since only states connected to the ground state by strong $E2$ matrix elements are excited, a different set of levels may be populated than in $(\text{H.I.}, \text{xn})$ reactions. In particular, it should be possible to excite states that are not yrast, e.g., in those cases where the ground-state band has crossed another and is no longer yrast. The use of the sum/multiplicity spectrometer promises

to make it possible to observe higher spins than has hitherto been possible. (The higher spin states, of course, have a larger γ -decay energy.)

High-energy, high-Z heavy ions can transfer a large amount of energy into internal excitation via the electromagnetic field. Multiple Coulomb excitation theory, combined with nuclear structure models for collective modes can make clear quantitative predictions regarding this mode of energy dissipation. Detailed tests become possible that are not feasible at higher energies where transfer reactions and nuclear excitations play an important role.

Measurement of magnetic moments of high-spin states will become practical through Coulomb excitation. The problem with such measurements in heavy-ion reactions is that precession in an external field can take place at any time during the cascade preceding a particular transition. Only in Coulomb excitation is the whole process understood in sufficient detail to permit quantitative extraction of magnetic-moment information. Again the time structure of the ATLAS facility will be well suited to such precision measurements. Furthermore, the high recoil velocities obtained with projectiles from ATLAS will enhance the transient magnetic field, as found in a recent Chalk River study, and thus further facilitate such measurements.

2. NUCLEI FAR FROM STABILITY

One of the interesting aims of nuclear research is the manipulation of nuclear matter to form unusual nuclides far from the usual line of stability. The energy and beams provided by ATLAS open a vast and previous inaccessible region of the periodic table to studies of nuclei far from stability. A great deal of attention has focussed in the past on possible superheavy elements with $Z \gtrsim 114$ and relatively long lifetime. Searches so far have not been successful. If these nuclei indeed have ground states that are long lived it will take a great deal of ingenuity and skill to find the reactions that will allow pieces of conventional nuclear matter to come together, coalesce, and cool down, leaving a superheavy nucleus in its ground state. There are a number of other regions of the periodic table where further study of unstable nuclei would be extremely valuable.

a. $N = Z$ Nuclei

From the viewpoint of nuclear structure, an interesting group of nuclei to study are those near the $N = Z$ line. In particular the β^+ decays of the odd-odd $N = Z$ nuclides provide a chance to observe the variation of pairing effects with increasing nuclear mass. All the light odd-odd $N = Z$ nuclei including the deuteron have $T = 0$ ground states, with a low-lying $T = 1, J = 0^+$ state. However, beginning with $^{34}_{17}\text{Cl}$ the $T = 1$ state becomes the ground state for all heavier nuclei (up to $^{62}_{31}\text{Ga}$) with the exception of $^{38}_{19}\text{K}$ and $^{58}_{29}\text{Cu}$. Particle stability is predicted for the $N = Z$ odd-odd nuclides up to about $N = Z = 60$, so it is probably possible to extend further our knowledge of the isospin structure of such nuclei. If it turns out that, as expected, the $T = 1$ state remains the ground state, it will be interesting to see whether the $T = 0$ excitation moves to higher energies with increasing mass. It might also be possible to investigate whether or not the $T = 2$ state becomes the ground state in odd-odd $T_z = \pm 1$ nuclei around $A = 80$.

If such an inversion occurs one will be in a position to undertake a very sensitive test of isospin selection rules in β decay. The ground state of the $T_z \equiv \frac{N-Z}{2} = -1$ nucleus will have $T = 2$; in its β^+ decay to the $T_z = 0$ daughter $T = 2, 1$, and 0 states will be available with the largest phase space available for the $T = 0$ states. Hence the $\Delta T = 1, 0$ selection rule for β decay can be directly tested. The electromagnetic decay of the $T = 2, T_z = 0$ daughters are also of interest because they violate the $\Delta T = 0, \pm 1$ selection rules for electromagnetic decay.

Precise measurements of the half lives and decay energies of the superallowed β^+ transitions involved are also of great interest to theories of the weak interaction. The conserved vector current hypothesis predicts that all of the transition rates of this type will be identical, after small charge-dependent corrections are made. These charge-dependent corrections are too small to be readily investigated in lighter systems but for $Z > 30$ they amount to more than 1%. With the new heavy-ion beams and higher energies from ATLAS, it should be feasible to produce many of the odd-odd $N = Z$ nuclei and to study their decays.

b. Nuclear Masses

The ground state mass of nuclei far from stability is of great interest. It is not clear how the nuclear density behaves for extreme values of $(N \sim Z)$. Any changes in density would have a large effect on the binding energy.

Masses far from stability can be measured experimentally in a systematic fashion using present-day techniques and compared to various predicted values. Most theories work fairly well near the line of stability, but large differences between various theories arise as the nuclei become less tightly bound. Applications to astrophysics are particularly important in this regard, since calculations of nucleosynthesis by rapid neutron capture (r-process) currently rely exclusively on mass predictions for neutron-rich heavy nuclei. Even if accurate mass measurements are not possible, a determination of the boundaries of nucleon stability would be valuable. This will be most easily done on the proton-rich side of the valley of β stability, and heavy-ion reactions are virtually the only way to reach the region of the nuclear map.

c. Beta-Delayed Particle Emission

Nuclei which β decay to unbound states in the daughter nucleus will produce β -delayed particles. This mode of decay is expected to be a predominant one for many nuclei as yet unobserved. Spectroscopic information derived from the study of β -delayed particle emission include masses, level densities and widths, half lives, and β strength to regions of high excitation. Both delayed protons and alphas have been observed following β decay of proton-rich nuclei. In some cases it may be possible to observe a new mode: β -delayed ^3He emission, which has been predicted but never seen.

At present at the Argonne tandem a number of facilities are available for such studies: a multiple rabbit, a helium-jet recoil transfer system, and a gas-transfer system. These are described in more detail in connection with experimental facilities.

To study very short-lived nuclides down to below 1 ms in lifetime, a modification of the split-pole spectrograph is under consideration. It is a relatively simple matter to add a Wien filter to the spectrograph in order to select recoil nuclei at 0° by mass and charge. It should then be possible to study decay properties of compound nuclei that are produced with cross sections as low as nanobarns, as long as their lifetime is comparable to transit times in the instrument. This technique may be especially useful in studying the transuranic region, where cross sections are low because of prompt fission competition.

3. RESONANCES

One of the most intriguing aspects of heavy-ion interactions has been the appearance of resonant structures. Some evidence for such structures, referred to as molecular resonances, were observed around 1960. Measurements since that time have located resonances in a variety of elastic-scattering and reaction channels, almost always involving ^{12}C and ^{16}O as both target and projectile. Perhaps the most recent evidence has come from the study of fusion cross sections, where regularly-spaced resonances are seen in $^{12}\text{C} + ^{12}\text{C}$, $^{16}\text{O} + ^{16}\text{O}$, and $^{16}\text{O} + ^{12}\text{C}$, and nowhere else. These resonances are rather broad and are reproduced, at least qualitatively, by the optical potentials used in fitting elastic-scattering data— in other words they seem to be shape resonances. The sharp resonances in specific reaction channels of earlier experiments stem from the underlying intermediate structure that fragments the shape resonances.

For $^{16}\text{O} + ^{16}\text{O}$ and $^{12}\text{C} + ^{12}\text{C}$ the target and projectile are identical and only even partial waves contribute. For $^{16}\text{O} + ^{12}\text{C}$ this restriction does not apply, and one may expect to see a halved spacing between resonance structures. No such doubling of the number of resonances is seen. Is there a nuclear-structure reason for this? Does the $^{16}\text{O} + ^{12}\text{C}$ system form a symmetrical object that produces a quasirotational band for the trajectory of resonances? We do not know the answer. Another intriguing point is the fact that the resonances appear only in those evaporation residues from the fusion reaction that are α particle nuclei. Is this only because the resonances are of high angular momentum and α -particle evaporation can dissipate angular momentum effectively or is there a nuclear-structure reason for this phenomenon? Also, it is difficult to explain why such systems as $^{12}\text{C} + ^{13}\text{C}$, $^{12}\text{C} + ^{14}\text{N}$, $^{13}\text{C} + ^{15}\text{N}$, $^{12}\text{C} + ^{18}\text{O}$ show no sign of resonances.

These resonant phenomena in heavy-ion interactions were restricted to the above very few systems until very recently. In 1977 the Stony Brook group discovered sharp resonances in the back-angle elastic and inelastic scattering of ^{16}O from ^{28}Si . Similar results have since been found in $^{12}\text{C} + ^{28}\text{Si}$ by a Stony Brook—Brookhaven collaboration, and at Rochester, and in $^{12}\text{C} + ^{40}\text{Ca}$ by an Argonne—Chalk River collaboration. In recent work at Argonne very pronounced resonances were seen in the $^{24}\text{Mg}(^{16}\text{O}, ^{12}\text{C})^{28}\text{Si}$ reactions.

In all these cases resonances are rather broad with a spacing of 2 to 3 MeV. Thus known resonant effects are no longer confined to the realm of very simple nuclei and are emerging in a rather spectacular way in the interaction of heavier systems.

We can see qualitatively that the existence of such resonances implies that there are simple modes, strongly coupled to the elastic and quasielastic channels, that do not mix strongly into more complicated configurations. Whether they can be reproduced by optical-model shape resonances or whether more complicated interactions (possibly α -particle exchange) will be required is not at all clear. But what is clear is that we are just beginning to open a new window on nuclear structure of a very special sort. Many painstaking experiments will be needed to explore these resonances, and indeed whole trajectories of resonances, before an understanding can be achieved. It may well be that the excitation functions for elastic scattering, transfer reactions, and fusion cross sections have to be supplemented by direct reactions at much higher energies. Thus the resonances seen in ^{40}Ca by $^{12}\text{C} + ^{28}\text{Si}$ scattering may show up very dramatically if one were to do an $^{28}\text{Si}(^{24}\text{Mg}, ^{12}\text{C})^{40}\text{Ca}$ "stripping" reaction in which a ^{12}C nucleus were stripped into ^{28}Si to form the same family of resonances. One may well need 300–400 MeV ^{24}Mg ions for such an experiment. The versatility of the ATLAS facility is ideally suited for the exploration of this fascinating frontier of nuclear structure.

D. ATOMIC PHYSICS

In the last few years there has been a large increase in the amount of atomic research based on accelerators traditionally used for nuclear physics. These studies have included beam-foil spectroscopy, channeling, electron and x-ray spectroscopy, and work on charge-state distributions, stopping power and multiple scattering. In many areas, a knowledge of the associated atomic physics may be vital to experiments in nuclear physics (e.g. the transient-field effect in nuclear g -factor measurements, the stopping power in Doppler-shift measurements on nuclear lifetimes, the influence of ionic charge states upon resolution and yield determinations in

heavy-ion-induced reactions, etc.). The beams available from ATLAS will permit studies of this type to be extended into regions of higher projectile energy and into a wide range of projectile species. The high quality of the beams at ATLAS will be a significant factor. The availability of very short (~ 10 psec) beam pulses will lead to a new level of precision in measurements of the lifetimes of many atomic states. Argonne has an active group working in accelerator-associated atomic physics, in particular beam-foil spectroscopy, dissociation of fast molecules, and channeling.

Examples of some areas of research in atomic physics with ATLAS are as follows.

1. BEAM-FOIL SPECTROSCOPY

Experiments in this area could include measurements on Lamb shifts and on the atomic structures of 2-electron and 3-electron heavy ions. The high energies and intensities available from ATLAS will produce strong photon signals in these experiments, thereby enabling precise tests of present many-body, fully-relativistic structure calculations.

Both the atomic spectra and transition probabilities of highly stripped heavy ions that appear as impurities in the high-temperature fusion reactors are largely unknown. The resonance lines of various ions of the LiI, NaI and CuI isoelectronic sequences are already useful for diagnostic work in these plasmas. ATLAS beam energies are necessary for beam-foil studies of most of these highly stripped ions. The above sequences are presently used because they form simple one-electron spectra. However, studies of the associated 2-electron spectra, which could be made with ATLAS, would be useful both for the theory of atomic structure and for high-temperature plasma diagnostics.

2. NUCLEAR-ATOMIC REACTION COINCIDENCES

In studying nuclear reactions that have large cross sections, one can exploit techniques involving coincidences between a nuclear reaction and an associated atomic reaction. Examples of nuclear reactions in which these techniques may be useful are elastic scattering, fusion reactions, and deep-inelastic collisions.

Coincidences between elastically-scattered particles and x-rays have previously been measured to study dependence of the x-ray production on impact parameter. The particles have been observed in the forward hemisphere. Central collisions, where the particle is scattered backwards have not been pursued. While the cross sections for these events are small, the payoff may be substantial in the form of structure, possibly discrete lines, in the x-ray spectra of the combined-atom transitions. Such structure has been predicted and if found at back angles, would substantially expand the information from the otherwise exponentially-falling, structureless combined-atom x-ray spectra. In particular it would stimulate the investigation of x-ray spectra where the combined charge of the two colliding atoms exceeds considerably that of any known element.

A study of the x-rays from a fused system by detecting coincidences between x-rays and the recoiling compound nucleus has not yet been performed. Such a study appears interesting from several points of view. First it would allow an element analysis of the evaporation residues. From an atomic point of view the atomic-shell hole production in this catastrophic collision would be of interest. By double element determination, once for the x-ray and also directly for the evaporation residue, delayed particle decays might be determined, although this process may be too weak for detection. For a delayed nuclear process with lifetime around 10^{-17} sec, the x-ray emission lifetime may be of similar magnitude so that either of them could be used as a clock on the other.

Similar considerations also hold for the deep inelastic collisions, although they are expected to take place on a much shorter time scale.

3. COULOMB SCATTERING AND SCREENING IN HEAVY-ION COLLISIONS

As known from light-particle scattering the Coulomb cross section (Rutherford scattering) begins to deviate from its $\sin^{-4}(\theta/2)$ behavior at very forward angles and finally, at zero degrees has zero derivative. The detailed shape of this scattering behavior depends on the electron screening between the two colliding ions. It appears that studies which map out the scattering cross section around zero degrees will give information on screening effects,

especially in heavy systems, where the inner electrons are more tightly bound.

4. PLASMA EFFECTS IN SOLIDS

Heavy ions incident on semiconductors induce regions of heavy ionization along their flight path. Timing measurements which determine collection rise times and plasma-induced delays for various ions and ionization densities may allow a quantitative study which should benefit the design and application of systems involving semiconductor detectors in heavy-ion reactions. Of course, the pulsed-beam timing structure will be of great use in such measurements.

5. X-RAY AND ELECTRON SPECTROSCOPY

This already well-developed area of study will benefit from the increased energies available for heavy-ion beams from ATLAS. It will be possible to create more highly excited states and also to make few-electron systems in sufficient quantities to permit detailed and precise measurements of decay energies and transition probabilities for a wide range of projectiles.

6. MOLECULAR-ION BEAMS

The acceleration of singly-charged molecular-ion beams to energies of several tens of MeV may be feasible. Experiments with molecular-ion beams have shown great promise in many areas of atomic physics. These include the interactions between fast charged projectiles and volume plasmons excited in target foils, structure determinations for molecular ions, and studies of charge-state distributions both inside and downstream from gas and solid targets.

7. BEAMS OF SLOW, HIGHLY-CHARGED ATOMS

An intriguing possibility for atomic physics is to take a highly-stripped ion and use the linac cavities to decelerate it to velocities of a

few keV/A. Such deceleration is possible in principle, even though transit-time effects will be unfavorable in the cavities, since the total accelerator gradient of the linac is much larger than that of the tandem. Such beams would be unique and would permit study of a hitherto unexplored realm of atomic physics.

8. LASER SPECTROSCOPY ON RADIONUCLIDES

Recent work by Greenlees at the University of Minnesota has shown the feasibility of precision atomic-physics measurements with very low intensity beams of atoms, down to single atoms, atomic beam fluxes of 10 atom/sec crossing the laser beam [Greenlees, 1977]. From the optical hyperfine structure, magnetic moments and charge radii may be deduced. All one needs is to compare data from a stable isotope with known radius and g-factor to data on radioactive isotopes of the same element. With ATLAS, it should be possible to carry out measurement for a large range of isotopes; small production cross sections and lifetimes as short as a few seconds should be no problem [Greenlees, 1978].

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V. MANPOWER AND OUTSIDER USER POLICY

The purpose of this section is to review the manpower available for the ATLAS project, both in its construction and operation, and in its utilization for research. In the latter context, the intended policy towards outside users will be reviewed.

A. TECHNICAL MANPOWER

A group at Argonne has been active in the development of superconducting resonators since 1971. The present booster project was started in 1975, and by now those involved constitute a highly qualified group with ample experience in the technology required for the linac part of ATLAS. They are listed, with principal areas of responsibility, in the attached table. The listing by activity does not imply that the group is compartmented. In fact, the opposite is the case; each member of the group also plays a significant role in other activities.

Many essential tasks connected with the development and construction of the booster are carried out by Argonne personnel who are not a part of the core group.

a) The fabrication of the resonators and cryostats, including beam welding, is carried out in Central Shops. The work is coordinated by a planning engineer who is a member of that division.

b) Computer control of the linac is implemented by R. Daly of the Electronics Division and R. E. Holland, J. E. Kulaga and R. Straz of the Physics Division.

c) Beam bunching and phase detection has been and continues to be developed by W. Henning (Physics) and R. N. Lewis and F. J. Lynch (Electronics).

d) Technical Support in assembly and installation is being supplied by the Support Group of the Physics Division (J. Worthington et al.).

e) The tandem operation group is headed by J. L. Yntema; it includes two chief technicians, seven technicians and a technical staff member in the Physics Division. They have primary responsibility for all matters related to the tandem and will be getting increasingly involved with the operation of the whole facility.

f) The technical expertise that resides in various research divisions of the Laboratory has provided important guidance in several special areas, including the materials properties of niobium, fabrication of niobium, chemical and surface analyses, superconducting magnets, and numerous aspects of accelerator technology.

g) Finally, the staff of the Physics and Chemistry Divisions active in Heavy Ion research have been involved in numerous ways to help with the technical problems associated with beam handling, optics, diagnostics, and the development of the new accelerator area for the linac.

SUPERCONDUCTING LINAC PROJECT

Experienced Manpower

Project Management

Lowell M. Bollinger, Senior Physicist (PHY)
Cornell University, PH.D., 1951

Resonator and Cryostat Development

Kenneth W. Shepard, Physicist (PHY)
Stanford University, PH.D., 1970

Ralph Benaroya, Electrical Engineer (CHM)
Case Institute of Technology, M.S. in E.E., 1951

Clement H. Scheibelhut, Chemical Engineer (ENG)
University of Wisconsin, B.S., 1947

Theodore E. Sterling, Mechanical Designer (ENG)
Joliet Junior College, 1955

Vincent Patrizi, Electro-Mechanical Tech III (PHY)
DeVry Technical Institute, 1962

Surface and Materials Problems

Arthur H. Jaffey, Senior Chemist (CHM)
University of Chicago, Ph.D., 1942

Paul Markovich, Engineering Specialist (CHM)
Purdue University, B.S. - EET, 1972

RF Control

Kenneth W. Johnson, Engineering Specialist (CHM)
Thornton Jr. College

Benny E. Clift, Engineering Specialist (CHM)
DeVry Technical Institute

Liquid-Helium Distribution

Jack M. Nixon, Mechanical Engineer (CHM)
Rice University, B.S.M.E., 1948

Beam Diagnostics

Thomas P. Wangler, Physicist (PHY)
University of Wisconsin, Ph.D., 1964

Accelerator Theory

Tat K. Khoe, Senior Physicist (ARF)
Delft Institute of Technology, Netherlands, Ph.D., 1960

Budget and Procurement

Jack Aron, Accelerator Engineer (CHM)
Cleveland State University, B.S., 1955

B. SCIENTIFIC MANPOWER AT ARGONNE

Argonne has had a major research effort in heavy-ion physics over the past ten years. In the Physics Division, this work has centered on the FN tandem, with some use made also of facilities at Brookhaven, Berkeley, Chalk River and the GSI in Darmstadt. In the Chemistry Division, a small group has been active at the SuperHILAC, Bevalac and LBL cyclotron.

The scientific staff at the Argonne tandem has also been active in many aspects of instrumentation development in heavy-ion physics. In particular, pioneering work was done on fast timing, in the 50-100 psec region, and in developing a heavy-ion focal plane detector for a magnetic spectrograph. This group is, at present, deeply involved in instrumenting the linac booster, in developing new instruments and adapting existing ones to the new needs, as is discussed in section II.F. The skills and experience of this group will be directed towards developing the new experimental area associated with ATLAS.

It is not the purpose of this document to review the scientific and instrumentation activity of this group; the list below is only to remind the reader of the available scientific manpower to work with at the ATLAS facility.

Permant Research Staff Associated with Heavy-Ion Physics. (Total effort: ~5 man years experimental and 2-1/2 man years theoretical.) Members of the Physics and Chemistry Divisions are designated by the letters (P) and (C), respectively.

A. Primarily in heavy-ion research

J. R. Erskine	(P)
W. Henning	(P)
T. L. Khoo	(P)
D. G. Kovar	(P)
J. P. Schiffer	(P)
K. Wolf	(C)

B. Partly involved in heavy-ion research

I. Ahmad	(C)
B. B. Back	(C)
C. N. Davids	(P)
A. M. Friedman	(C)
R. E. Holland	(P)
L. Meyer-Schützmeister	(P)
R. K. Smither	(P)
B. Zeidman	(P)

C. Theorists involved in many aspects of heavy-ion research (P)

A. R. Bodmer
D. Kurath
R. D. Lawson
M. H. Macfarlane
S. Pieper

In addition to the permanent staff, there are approximately three full-time equivalent postdoctorals and three graduate students associated with heavy-ion research. Argonne staff members involved in atomic physics research relevant to ATLAS are D. S. Gemmell (P) and H. G. Berry (P).

This group of scientists constitute a strong in-house group capable of carrying out an effective research program as well as developing new instruments essential for probing the frontiers of heavy-ion physics. We do not plan to increase the size of this group, in order to allow outside users ample access to the facility.

C. OUTSIDE USERS

The ATLAS facility will be operated as a National Facility with all beam time for research allocated on the basis of scientific merit. A Program Advisory Committee similar to those at other major facilities, with a majority of members from outside Argonne, will be asked to review all proposed experiments. Scheduling will have to be the responsibility of the facility management, especially because of the need to schedule compatible experiments at the two independent beams.

An outside user program is by no means a new venture for Argonne. The Tables below summarize the percentage of time allocated to universities and lists the names of the institutions that have been involved. Since the capabilities of the ATLAS facility would be entirely unique, it is probable that some choices and selection will have to be made among the various requests for beam time. This is best carried out by an open procedure utilizing a Program Advisory Committee.

Argonne is located approximately 30 minutes by car from Chicago's O'Hare airport. Housing and cafeteria services are available on the Argonne site, and there are numerous motels in the near vicinity. Office and laboratory space will be made available for outside users, and some scientific and technical manpower will be provided to assist users in the operation of equipment associated with the facility.

University Use of the Argonne Tandem

(Percent of Scheduled Time)

Period	Outside User Groups	Thesis Students	Total
1965-70	18	4	22
1971-75	16	8	24
1976-77	16	17	33

List of Home Institutions of Outside Users of the Argonne Tandem (1968-78)

Alberta, University of	Michigan State University
Beloit College	Minnesota, University of
Case Institute	Munich, University of
Chicago, University of	Northern Illinois University
Cleveland State University	Northwestern University
Columbia University	Notre Dame University
DePaul University	Ohio University
Duke University	Pennsylvania, University of
East Texas State University	Purdue University
Florida State University	Princeton University
Illinois Institute of Technology	Rochester, University of
Illinois, University of (Chicago)	Stanford University
Illinois, University of (Urbana)	Washington University (St. Louis)
Indiana University	Washington, University of
Iowa, University of	Wayne State University
Kansas, University of	Western Michigan University
Kansas State University	West Georgia College
Massachusetts Institute of Technology	Wisconsin, University of (Eau Claire)
Merrimack College	Yale University

VI. COST ESTIMATES AND SCHEDULE

A. CONSTRUCTION COSTS

Estimates of the funding required to carry out the ATLAS project are summarized in Table VI-1. Except for the grand total, estimates are in terms of current dollars. Since the main cost in the project is for the linac and since the proposed linac is an extension of an existing technology and prototype machine, the costs can be estimated with unusual accuracy.

B. SCHEDULE

An outline of the major components in the schedule for the construction of ATLAS is given in the attached figure. As with the cost estimates, experience with the construction of the prototype booster are providing accurate information on the time required to carry out various design and fabrication tasks. Note from the schedule that the ATLAS project will begin to enhance the performance of the tandem-booster accelerator system about a year after ATLAS is funded. The upgrading of the tandem injector will improve the performance for very heavy ions, and the installation of more helium refrigeration will increase the accelerating power of the then existing linac by about 10%.

In the proposed schedule, the new Target Area III is available for occupancy by late 1981, and one or two new sections of linac are installed immediately. These sections are first used to accelerate ion beams into Target room III in early 1982, and the full linac is available for use by late 1982.

C. OPERATING COSTS

Estimates of the additional fiscal support required annually for the operation of ATLAS are given in Table VI-2. It is assumed that the accelerator will be operated around the clock, seven days a week. The estimates are in terms of FY1978 dollars.

Table VI-1. Cost estimates for ATLAS.

Costs in \$1000

	<u>Item</u>	<u>Total</u>
1. Building Construction		695
a. Engineering	116	
b. Structures	275	
c. Heating, ventilating, air conditioning	124	
d. Power and Lights	168	
2. Linac		2660
a. Engineering and installation	250	
b. Accelerating structures	918	
c. RF power and controls	216	
d. Cryogenic services	402	
e. Focussing element	90	
f. Cryostats and vacuum	380	
g. Beam bender and splitter	179	
h. Computer control	50	
i. Prototype resonator	75	
j. Miscellaneous	100	
3. Tandem		350
a. Ion-source and injection system	200	
b. Terminal	80	
c. Output beam line	70	
4. Experimental Area		280
a. Beam line with debuncher	200	
b. Shielding	80	
Total (FY 78 costs)		3985
Contingency		682
Project total in 1978 \$		4667
Project total for FY1980		5600

Table VI-2. Estimates of Annual Incremental Support Required
for the Operation of ATLAS

	<u>Costs</u> <u>(\$1000)</u>
Accelerator Operating Personnel	140
Materials, Services, Power and Building Maintenance	<u>200</u>
TOTAL	340

SCHEDULE FOR CONSTRUCTION OF ATLAS

APPENDIX 1.

NIOBIUM-COPPER COMPOSITE RF SUPERCONDUCTING MATERIAL

Early in the developmental phase of the Heavy-Ion Booster project it became apparent that a fresh approach was needed to solve the problem of cooling the outer housing of the superconducting rf resonators. Reduction of resonator fabrication costs and improved resonator rigidity were goals.

The use of a material new to rf superconducting resonator technology was considered, namely, a composite of pure niobium sheet explosively bonded to copper plate. This composite material is used to fabricate the resonator housing and end plates. By having a small area of the copper of the housing in contact with liquid helium, conduction through the copper cools the entire resonator housing. In the Argonne split-ring resonator, this material has provided excellent mechanical rigidity, has reduced liquid-helium plumbing complexity and costs within the cryostats by a significant amount, and has reduced resonator fabrication and material costs somewhat.

The composite material is produced commercially* by holding a flat sheet of 1/16" thick niobium about 1/16" away from a flat sheet of 3/8" thick copper. An explosive, ammonium nitrate powder containing 4 wt % aluminum powder, is placed against the niobium sheet and the explosive is detonated at one corner. As the shock wave in the explosive moves across the sheet of niobium, the niobium is deformed and forced into contact with the copper at an estimated pressure of 1.2×10^6 psi. This produces a plasma at the point of contact, scrubbing clean the surfaces and briefly melting both metals. A true metallurgical bond is formed between the two metals, with a copper-niobium alloy at the interface.

* Northwest Technical Industries of Port Angeles, Washington.

Considerable testing of the composite was done before committing to its use. Extensive thermal cycling between room temperature and liquid nitrogen temperature showed no degradation of the bond even though the copper must yield at the interface because of differential thermal expansion of the two metals. The bond integrity was examined with an ultrasonic inspection technique. Non-bond areas as small as 1/16" in diameter could be detected. Few such areas are observed, typically five or six of say 1/4" diam per square meter. One sample that was thermally cycled had a small unbonded region. This region did not grow during the course of the testing and no new defects appeared.

Measurements at 4.2 K established a lower bound of $85 \text{ mW/cm}^2\text{-}^\circ\text{K}$ for the thermal conductivity across the Nb-Cu interface. The actual interface conductance is probably much larger than the above number, but the anticipated heat loads are $\approx 5 \text{ mW/cm}^2$, so that the measurements were not pursued.

The rf surface resistivity R_s of small samples of the composite was measured with the test resonator system. At 193 MHz and 4.2 K, an upper bound $R_s < 1.5 \times 10^{-7} \Omega/\text{square}$ was obtained for surface magnetic fields $B_s \leq 200$ Gauss. These measurements indicated that the composite material would be satisfactory for the outer housing of the split-ring resonator for accelerating field gradients of at least 4 MV/m.

Fabrication with the composite material required a learning period. Forming procedures, such as rolling, extrusion of ports, etc., are fairly straightforward and make use of the ductility of niobium. Reductions in area of approximately 50% can be accomplished without intermediate anneal. Machining the composite is no more difficult than for pure niobium.

In joining, electron-beam welding is used. Tests showed that the copper must be removed from the niobium at least 3/32" back from the weld joint. Great care must be taken to assure removal of all copper from the bared niobium to prevent cracks and fissures in the weld. A chemical etch of the bared niobium followed by a visual inspection at 20 $\times$ magnification prior to welding was found necessary.

Preparation techniques for the superconducting niobium surface such as electropolishing and oxypolishing are the same as for pure niobium. The composite can be stress-relief annealed at temperatures up to $\sim 700^{\circ}\text{C}$. However, heating sufficient to change the grain structure of the niobium after fabrication is not possible.

The first split-ring resonator (P-2) made with the composite material initially displayed dissapointingly high rf losses in the Nb-Cu composite. Heavy electropolishing improved performance, and after removal of some $400\ \mu$ of the original Nb surface of the resonator was marginally adequate as an accelerating structure (Appendix 2).

The fact that removal of the original surface, which had been directly exposed to explosive during the bonding process, tended to improve performance suggested trying to protect the niobium from the explosive. Thus the bonding procedure was changed so that a thin sheet of rubber is glued to the niobium sheet on the side facing the explosive. Composite material prepared in this way exhibits a surface resistivity as low as observed in the earlier small-sample tests and has proven entirely satisfactory.

APPENDIX 2.

SUPERCONDUCTING RESONATOR DEVELOPMENT

A. Introduction

This appendix outlines the development of the niobium split-ring resonator that is the basis of the Argonne Heavy-Ion Energy Booster. The work was based on the niobium technology that had been developed in previous work with helically-loaded superconducting resonators. The tasks were to extend this technology to the considerably larger and more complex split-ring resonant geometry, and to develop procedures to increase the reproducibility and reliability of resonator performance.

A statistical analysis was made of the superconducting surface resistance and electron loading properties observed in the extensive previous tests of helically loaded resonators, and the results were used to project the performance of the very different split-ring geometry. This projection indicated that accelerating field gradients in the range 3 - 5 MV/m would be obtained with electron loading being the limiting factor. A design goal of an accelerating gradient of 4.2 MV/m with an rf input power of 4 watts per resonator was established, although it was clear that somewhat lower gradients would be acceptable.

Construction of the prototype (P-1) split-ring resonator, shown in Fig. 1, was begun in early 1975. At this time, it was realized that an essential design element, an rf current-carrying demountable joint, had yet to be demonstrated, and might prove to be a major problem. Concern over this and other potential problems motivated the simultaneous construction of a system, namely the Test Resonator described in Appendix 3, which would permit various aspects of the technology to be isolated and tested in an expeditious manner.

Construction of the double-walled niobium housing required for circulation of liquid helium coolant proved more difficult and expensive than anticipated, due to the large number and complexity of welds required. An alternative mode of construction was sought, eventually resulting in the composite material described in Appendix 1.

B. Tests of Resonator P-1

The initial test of P-1 showed very large rf losses (Fig. 2, curve A) and it was conjectured that these occurred in the rf current carrying demountable joint between the split-ring element and the cylindrical housing.

This joint consisted of a Nb knife-edge machined onto the split ring base, heavily clamped to the housing. Replacing this joint with an indium gasket seal resulted in even greater rf losses.

At this time (Feb. 1976), the test resonator system was completed, making possible systematic development of a demountable joint (Appendix 3). This work indicated that indium seals were entirely unsuitable for an rf joint to niobium and that Nb gaskets could be used at the end plate seal, but not to demount the base of the split ring element, where rf currents are relatively large.

On the basis of the test resonator results, the demountable joint at the base was eliminated by electron-beam welding the split ring element to the cylindrical housing. Also the indium gasket seal at the end plate was replaced with a Nb wire gasket. These modifications produced the performance shown in Figure 2, curves B and C.

Although the performance at this point had become marginally acceptable for a linac, work with P-1 was discontinued for several reasons. Excessive rf loss still occurred in the joint between end plate and housing because of insufficient clamping pressure on the Nb gasket. Modification of the flanging to increase gasket loading would be expensive and time consuming. Also, several weld failures during cooldown had occurred in the double-walled housing. Since small sample tests of the Nb-Cu composite material looked promising, effort was focussed on a second-generation resonator in which the double wall was eliminated.

C. Tests of the P-2 Resonator.

The P-2 resonator, shown in Fig. 6 in the main text, differed from P-1 in the use of the Nb-Cu composite material for the outer housing, and in that both ends were demountable and employed the Nb "H" gasket developed with

the test resonator. By demounting both ends, better access to the interior for chemical processing was obtained.

Early tests of P-2 yielded the performance shown in Fig. 3 curve A. The diagnostic system described in Appendix 4 indicated that rf losses were occurring predominantly in the Nb-Cu composite housing. The resonator was electropolished to the extent of removing 100 μ from the Nb surface and the performance shown in Fig. 3 curve B resulted. At this point, rf losses in the composite material were at an acceptable level, although higher than desirable. However, the evidence was strong that surface damage during the explosive bonding process was responsible for the degraded performance. Thus, it was decided to change the bonding process to better protect the Nb surface during bonding, and on this basis to proceed with construction of the first six resonators for the linac.

The P-2 resonator, however, suffered from more than one problem. The maximum field level was limited by a thermal instability or breakdown at a well-defined field level that changed only upon electropolishing the resonator. During the above tests, this limit was in the range 1.5 - 2.2 MV/m. Second sound measurements showed that the initiating defect was always on one of the loading tubes but would shift location by several cm on electropolishing. Microscopic examination of the Nb surface failed to reveal any flaw.

The split ring element was cut out of the housing, given a 4-hour heat-treatment at 1250°C and re-welded into place. This procedure, generally considered to be a panacea for malfunctioning resonators, gave no significant increase in the breakdown level.

A discussion with metallurgists at the firm supplying the Nb (Teledyne Wah-Chang) yielded the fact that heavy anodic oxidation of Nb will often reveal trace impurities and work damage as a discoloration of the anodic film. P-2 was anodized to form a 2200 Å thick oxide and a number of discolored spots, ~ 1 mm in diameter, were seen scattered over the regions in which thermal breakdown had occurred. A process of filing away Nb material at the discolorations and then electropolishing and anodizing the resonator was iterated until no regions of discoloration remained. Local removal of as much as 0.5 mm of Nb was required to obtain this result.

Upon then testing the resonator, the limit of thermal stability was found to have increased to 2.7 MV/m. An additional 50 μ of material was removed by electropolishing, and the performance shown in Fig. 3 curve C was obtained. No thermal instability was observed.

D. Linac Resonators (H-series)

It was hoped that the extensive diagnostic procedures developed in the course of ten months of struggling with the P-2 resonator would expedite production of the linac resonators. These differ from P-2 only in the addition of two rf ports on the cylindrical portion of the housing to permit coupling to the rf drive and phase control system.

The initial test of the first of these resonators, H-1, yielded the performance shown in Fig. 4 curve A. The maximum field level was limited by a thermal instability at 3 MV/m. The thermometry indicated that large rf losses were occurring at the larger of the two coupling ports and that the thermal instability was a separate effect occurring at a weld of the loading tube to the base mounting stub.

A die penetrant test of the weld showed a small fissure that had been exposed in electropolishing the resonator. The fissure proved to be shallow, since it was removed by electropolishing $\sim 75 \mu$ from the weld area.

Consideration of the rf losses at the coupling port exposed a design error that allowed too much rf current in an indium seal at the port. This seal was replaced with a Nb gasket.

After the above modifications, H-1 performed as shown in Fig. 4 curve B. Only three tests were required to obtain this performance. The H-1 resonator has been recycled to room temperature and atmosphere several times in tests of various systems with no significant change in the performance shown in Fig. 4 curve B.

At this writing, only the initial test of the second linac resonator (H-2) has been performed. The Nb-Cu composite in the resonator performs as well as does H-1. A thermal instability occurs at $E_a = 1.2$ MV/m. The initiating defect is on the loading tube and work is in progress to remove it.

E. Conclusions

Superconducting niobium technology has been successfully extended to the split-ring resonant geometry. At present, these devices present the most effective available means for the linear acceleration of heavy ions.

The superconducting components of the H-series resonators permit performance exceeding the design goal of 4.2 MV/m at 4 watts per resonator. Performance is presently limited to the range of 3 - 4 MV/m by field-emitted electron loading. Future development will focus on surface treatment and processing to reduce this loading.

Figure 1. The P-1 all-niobium split ring resonator. The outer housing is double-walled to permit cooling by circulation of liquid helium. The left end plate is demountable to provide access for chemical processing.

Figure 2. Performance of the P-1 resonator. Curve A is for the split ring element demountably joined to the cylindrical housing. Curves B and C with the split ring welded in place. Curve B is prior to helium conditioning of the resonator, Curve C after.

Figure 3

Figure 3. Performance of the P-2 resonator. Curve A is an early result. Curve B shows performance after removal of a 100 μ layer from the original Nb surface. Curve C shows performance after removal of several defects from one of the loading arms.

Figure 4

Figure 4. Performance of the H-1 resonator. Curve A is the initial test result. Curve B shows performance after removal of a small fissure in an electron beam weld on a loading arm, and modification of an rf coupling port.

APPENDIX 3.

TEST RESONATOR SYSTEM: DEMOUNTABLE JOINT DEVELOPMENT

A. Introduction

Efficient development of many aspects of superconducting resonator technology requires a simple and rapid means of measuring rf loss properties. The split-ring resonator, and accelerating structures generally, are not suitable for this task since they are complex, expensive to modify, expensive to test, and have a long cycle time between tests.

To provide a testing capability for the Heavy Ion Booster Project, a test resonator system, shown in Figure 1, was constructed. The resonator is of the form of a quarter-wave resonant coaxial line, with a demountable joint at the shorted end.

By demounting the center conductor and replacing it with one of different geometry, wide variations in the electromagnetic properties of the resonator can be obtained without changing the outer resonator housing, rf couplings, cryogenic plumbing, or vacuum system. For example, in order to measure rf losses in demountable joints, a center conductor of large diameter was used, which maximizes the effect of losses in the joint on resonator Q, the measurable quantity. To measure rf losses in a Nb-Cu composite material, a center conductor of small diameter, formed of the composite, was used to maximize the effect of the surface resistance of the center conductor.

The resonator is sufficiently small that a test cycle can be completed in one or two days and requires relatively little liquid helium.

B. Demountable Joint Development

Tests were made of several demountable seal designs, using the test resonator configuration shown in Fig. 1. This configuration is 450 times more sensitive to rf losses in the joint than the split-ring accelerating structure. I.e., rf losses in the demountable joints would

limit the split-ring resonator Q to a value 450 times that measured for the test resonator with a given type of demountable seal.

The design goal for a demountable joint was a test resonator $Q > 8 \times 10^6$ for a peak rf magnetic field B_j at the joint of 14 Gauss. RF losses in such a joint would be less than 10% of the allowable total for a split ring accelerating structure operating at an accelerating field gradient of 4 MV/m.

1. Indium Gasket Seals

Since successful rf joints to superconducting lead have been made with indium seals, the first joints tried on the (niobium) test resonator were of this type.

Figure 2, curve A, shows typical performance for such a seal. The losses are a factor of 30 greater than desired.

A small rf voltage could be observed outside the resonator, across the indium joint. This, and other experimental evidence, indicated that indium gaskets do not make metal-metal contact with niobium but simply cover, without penetrating, the oxide layer naturally present on a niobium surface. The magnitude of the observed external rf voltage agreed well with the value calculated for a capacitive reactance given by the dimensions and dielectric properties of the niobium oxide layer.

Thus, it was found that indium gaskets do not provide metallic contact with a niobium surface and that rf currents through such a joint flow in a form of a displacement current through the oxide on the niobium. By anodizing the niobium, several oxide thicknesses were tried, but none produced sufficiently small rf loss.

2. Demountable Joints with Niobium Gaskets

The next series of tests were performed using gaskets of 1/32" niobium wire clamped between two flat niobium surfaces. In Fig. 2, curves B, C, and D show results for a typical wire gasket. As can be seen, the effect of clamping pressure on rf loss is quite marked, and high loading is required.

In initial tests, this type of gasket seemed quite promising, and in fact such a gasket was successfully used to mount the end plate on the P-1 split-ring resonator. Extensive testing, however, showed a lack of reproducibility: some gaskets exhibited rf losses a factor of ten higher than the design goal.

Since increasing loading pressure seemed to reduce rf losses, a knife-edge gasket was designed to greatly increase the unit pressure at the Nb-Nb interface. The H-shaped geometry shown in Fig. 3 resulted. The double knife edge prevents twisting of the gasket under load. The gasket is typically loaded to 5000 lbs/linear inch.

This type of gasket performs typically as well as the wire gasket performance shown in Fig. 2D. More than 30 H-type gaskets have been used on split-ring resonators and have in all cases performed satisfactorily.

C. Conclusions

The test resonator system has been of immense value in expediting development of a demountable joint. Additionally, this system permitted measurement of the surface resistance of the Nb-Cu composite material prior to its use in a split-ring resonator.

In the future, it is probable that the test resonator system will be of value in studies aimed at reducing electron loading in the split-ring accelerating structures.

Figure 1. The test resonator mounted to the dewar insert. The configuration shown is with a large diameter center conductor used for testing demountable joints.

Figure 2. Test resonator Q as a function of the peak rf magnetic field B_J at the demountable joint. Curve A is for an indium gasket joint. Curves B, C, and D for a gasket of 1/32" D N6 wire with a loading force of 630, 1260, and 2700 lbs. per inch length of gasket, respectively.

Figure 3. Cross section of the H section niobium knife edge gasket presently in use on the split ring resonators.

APPENDIX 4.

DIAGNOSTIC TECHNIQUES

The Argonne split-ring resonators are of unprecedented complexity for superconducting rf structures. Each resonator consists of 25 separate niobium parts joined by 32 electron beam welds.

The least defect in the niobium surface, such as microscopic fissures, impurity inclusions, etc., can degrade resonator performance to an unacceptable extent. All of the resonators so far constructed have exhibited a variety of defects during initial tests. Adequate performance can be obtained only by a process of identifying and removing the defects.

Therefore it has been essential, not only for resonator development, but also for resonator production, to have a means of rapidly and accurately locating sources of rf loss within a resonator. This has been accomplished with the two complementary thermometric systems described below.

A. Second Sound Measurements

One frequently-observed class of defect consists of a localized source of rf loss in a region of high surface magnetic field ($B \approx 100$ Gauss). As the rf field level is increased, the increased rf power loss causes the defect and adjacent superconducting surface to warm up. When the defect is warmed to the transition temperature of the surrounding niobium, the resonator becomes thermally unstable and a normal region grows rapidly until virtually all of the rf energy initially present in the resonator is converted to heat; i.e., the instability is manifested by a sudden collapse of the rf field in the resonator at a well-defined critical field level. The time required for the collapse process is typically two or three milliseconds.

The rf power required to initiate an instability is generally quite small. For example, in our present $\beta = 0.105$ resonators a localized defect dissipating only 10^{-3} watts could cause a thermal instability at an

accelerating field of ~ 3 MV/m. A normal region 10^{-3} inch in diameter would constitute such a defect. It is not practical to observe such defects directly: they can, however, be located with fair precision by exploiting the superfluid properties of liquid helium.

Thermal instabilities occur in regions of high surface magnetic field which, in the Argonne split-ring resonator, is the loading tube, a .090" wall niobium tube cooled by liquid helium which fills the interior. When the resonator goes unstable, several joules of heat energy are injected into the liquid helium in a few milliseconds. If the helium is superfluid, $T < 2.17^\circ\text{K}$, an entropy fluctuation, or second-sound wave, propagates outward from the point of heat injection at a velocity of ~ 20 m/sec.

By locating several germanium resistance thermometers inside the loading tube, the second sound pulse can be observed as a temperature fluctuation. The arrival of the pulse at a given thermometer is determined by the time of flight from the region of heat injection into the liquid helium, which is centered on the defect causing the thermal breakdown.

By measuring the time of flight to several differently-placed thermometers, the location of the defect can be unambiguously determined.

Figure 1 shows an oscilloscope photograph of the phenomenon observed. The upper trace shows the rf field level in a split-ring resonator, which is being pulsed to an effective accelerating field $E_a = 3.0$ MV/m. At this field level the resonator is thermally unstable and the rf field collapses.

The lower trace displays the temperature of a germanium resistance thermometer located inside the loading tube. The structure of this thermometer is such that it responds to a second-sound pulse by "ringing" in temperature at a frequency of ~ 1 kHz: in Fig. 1, this begins 13 msec after the collapse of the rf field. Thus, it can be inferred that the defect in the superconducting resonator is ~ 26 cm from this particular thermometer.

In practice, this method typically locates a defect within 1 or 2 cm which then permits microscopic examination of the region in question and some form of local repair.

B. Measurement of Thermal Gradients in the Resonator Housing

The housing, end plates, and demountable joints of the resonators are cooled by conduction through the copper of the niobium-copper composite material. Thus, measurement of the thermal conductivity and temperature distribution in the copper provides a means of determining the detailed distribution and magnitude of rf losses in these portions of the resonator.

To obtain this information we strategically locate an array of typically 15 germanium resistance thermometers on the outer surface of the niobium-copper housing. Additionally, several electrical heaters are placed on the housing, to permit introduction of known quantities of heat at known locations. This provides a check on the functioning of the thermometer array and allows determination of the magnitude and uniformity of the thermal conductivity of the copper. The temperature changes observed are typically ~ 100 mK and can be measured with an effective accuracy of ~ 1 mK. Thus the data are accurate enough to locate and quantify heat sources with considerable precision.

The conceptually-simple but mathematically-complex problem of interpreting the temperature data is solved by making voltage measurements on an electrical analog of the thermal system. Heat flow in the housing is essentially two dimensional. Thus the housing can be electrically simulated by a geometrically similar piece of resistance paper. Injection of heat is simulated by injection of current and the analog of temperature is voltage. In practice, such a model proved easy to construct and use.

Figure 2 shows the thermometer placement used. Figure 2 is a map of the housing surface generated by making an axial cut of the cylindrical housing opposite the liquid-helium port and unfolding it.

Table 1 compares a measured temperature profile with those predicted by the analog model for two different rf loss mechanisms: column A for all rf loss due to a uniform surface resistance in the housing wall, and column B for all rf loss in the demountable end-plate seals. The data clearly indicate the rf loss to occur predominantly in the housing wall.

Distributed loss mechanisms, such as discussed above, are the most difficult cases to distinguish with this method. Localized losses, such as occurred in an rf port on the H-1 resonator, are readily observable from the data, and further analysis is scarcely necessary.

Table 1

Comparison of observed and predicted temperature rise, due to heat flow, of various points on the resonator housing. Measured values are for 1.0 watt rf input to resonator. Column A contains the predicted values for 1 watt of rf loss into a uniform surface resistance on the housing wall. Column B, the predicted values for 1 watt of rf loss into the demountable seals to the end plates.

Thermometer	Measured	A	B
#1	37 m°K	37	31
#2	18	17	25
#3	33	37	31
#4	16	17	25
#5	78	78	98
#6	84	87	84
#7	*	78	98
#8	83	78	98
#9	89	87	84
#10	79	78	98
#11	97	94	122
#12	99	99	112
#13	96	94	122
#14	74	70	135
#15	72	70	135

* Thermometer failed.

Time $\rightarrow$ (5 msec/div)

Figure 1. Oscilloscope display of the second-sound pulse associated with thermal breakdown of a resonator. The upper trace displays the rf field in the resonator, which is driven to $E_a = 3$ mV/m at which point the resonator becomes thermally unstable and the field collapses. The lower trace displays the temperature of a sensor which shows a second-sound pulse arriving 13 msec after breakdown.

Figure 2. Diagram of the thermometer placement on cylindrical housing.

APPENDIX 5.

SOLENOID STRENGTH REQUIREMENTS FOR
FULL-LENGTH HEAVY-ION LINAC BOOSTERDATE
October 21, 1976I. INTRODUCTION

The following discussion gives the method used for choosing the solenoid strengths to be used in the heavy-ion linac booster. The calculations cover the solenoids to be used in the second stage as well as in the first stage (at present under detailed design). As noted below, the calculations can only be approximate, depending as they do on a calculation model known to be an approximate one. However, the error tends to be conservative, and, in any case* linac resolution is not sensitive to deficiencies in solenoid focusing strength over a broad region.

The solenoid strengths needed can only be defined for a given accelerator layout, in particular, amongst the primary input data are the spacings between the solenoids. In this respect, another approximation will be made for simplicity, in that the space occupied by inter-cryostat mechanisms (valves, etc.) will be neglected. This is on the conservative side, since including this space would actually increase the inter-solenoid distance at the "joint", hence allowing a weaker solenoid to serve with adequate focusing.

Fig. 1 gives the layout.

The distances are considered below. These are based upon the following dimensions assumed:

1. For the low- β resonator, the internal axial distance between walls is 20.0 cm.
2. For the high- β resonator, the distance is 35.5 cm.
3. The distance between the inner wall of a resonator and the containing can of the succeeding solenoid is 6.4 cm (2 1/2").
4. The distance between the neighboring inner walls of two consecutive resonators is 8.9 cm (3 1/2").

*This subject will be covered in a later note.

CRYOSTAT D

CRYOSTAT C, Low- β sections

CRYOSTAT D, High- β sections

Fig. 1.

5. The focusing solenoid total length L_T is comprised of the coil length L_C and of L_S which corresponds to the length occupied by coil form, shields, spacings and end plates of containing can. We take

$$L_S = 2 \left(\underset{a}{0.95} + \underset{b}{0.50} + \underset{c}{4.0} + \underset{d}{0.95} \right) = 12.8 \text{ cm}$$

where a = thickness of coil form end

b = spacings and mu-metal shield

c = iron shield thickness for a solenoid

with nominal central field $B_0 = 6.8 \text{ T}$.

d = thickness of vacuum end plate and spacing

$$\text{and } L_F = L_C + L_S \quad [1]$$

If the central field is increased from the nominal 6.8 T to 8.0 T in order to increase the solenoid focusing power, then the magnetic flux configuration will be kept approximately the same if the return path cross-section area is increased so as to preserve the same flux densities in the iron. Then c above is increased by the ratio $8.0/6.8 = 1.18$ or c becomes 4.7 cm. Hence, L_S is increased by 1.4 cm to 14.2 cm.

The goal of the focusing is to make the minimum beam diameter occur at or close to the space between the pair of resonators, and this should occur for each pair. This will insure that the beam diameter remains as small within the resonators as the beam emittance will allow it to be. This in turn minimizes the energy resolution degradation due to the Bessel function effect (radial variation of axial accelerating field) and to the radial acceleration in the center gap arising from the voltage variation along the split ring loop.

II. Basis of the Calculation

To calculate the solenoid focusing required, we use the periodic structure theory.[†] It doesn't really fit our system, which is not actually periodic, but the approximation will be good enough. The solenoid strengths are chosen so that the radial motion of any given particle has a particular periodicity.

[†]E. D. Courant and H. S. Snyder, "Theory of the Alternating-Gradient Synchrotron," Annals of Physics 3, 1-48 (1952)
This will be briefly discussed in the later note.

In the geometrically periodic system, L is the distance between the solenoid center (considered as a thin lens) and the center of the two-resonator system, as in Fig. 2.

Fig. 2.

For the periodic particle motion desired, L is the solenoid focal length when the resonator defocusing effect is neglected. Appendix 2 illustrates the nature of the periodic motion by considering certain particle motions within the beam.

When the defocusing effect of the resonators is included, the required solenoid focal length is given by

$$\frac{F_S}{L} = 1 - \frac{1}{2} \frac{1}{1 + \frac{F_R}{L}} \quad [2]$$

Where F_S = focal length of solenoid (magnitude)

F_R = focal length of resonator pair

L = distance between solenoid center and
the position between the resonators of the pair.

and

$$\frac{1}{F_R} = \pi \frac{q}{A} \frac{e}{M_0 c^2 \lambda_0} \frac{\sin \phi}{\beta^3} \bar{E}_{ax} L_{cav} \quad [3]$$

$$\frac{1}{F_S} = \left(\frac{1}{2} \frac{q}{A} \frac{ec}{M_0 c^2} \right)^2 \frac{1}{\beta^2} P_S \quad [4]$$

$$P_S = \int_{-\infty}^{\infty} B_z^2 dz \quad [5]$$

where

$$c = 3 \times 10^8 \text{ m/s}$$

$$\lambda_0 = c/f = \text{free space wavelength} = 3 \times 10^8 / 96.6 \times 10^6 \\ = 3.10 \text{ m}$$

$$\frac{q}{A} = \text{charge number to mass number ratio}$$

$$\frac{e}{M_0 c^2} = \frac{\text{electronic charge}}{\text{energy equivalent of elementary mass}} \\ = \frac{e}{931.504 \text{ MeV}} = \frac{1}{9.315 \times 10^8 \text{ volts}}$$

$$P_S = \text{solenoid strength (T}^2\text{m} = \text{volt}^2 \text{ sec}^2 \text{ m}^{-1}\text{)}$$

$$\phi = \text{phase angle (from peak)}$$

$$\bar{E}_{ax} = \text{average axial accelerating field, including} \\ \text{the defocusing transit time factor}$$

$$L_{cav} = \text{length of cavity, between the walls (meter)}$$

In the derivation of Eq. [2], the solenoids and resonators have been treated as simple lenses whose effects have been combined. Further, the two resonators are treated as one unit with center between the two resonators. The distance L is taken as the distance between solenoid center and resonator center. This is an approximation required to satisfy the periodic structures formulation. There will, in fact, be a slight displacement of the minimum beam diameter from this resonator center because energy gain through the two resonators makes them not equivalent as defocusing lenses. The effect, however, is small on the accuracy scale required here.

Calculations will be made for $^{58}\text{Ni}^{20+}$. The focal lengths resulting will work quite well for ions with lower q/A values because there is considerable conservatism in the results. Thus, even if the solenoid focal lengths achieved are longer than required

for ideal periodic focusing for a particular q/A , if the input radial ellipse is appropriately shaped, the beam can be handled so that it is never more than a modest amount larger than the minimum that occurs with the periodic focusing case. (As mentioned above, this will be discussed in a forthcoming note.)

Other parameter choices are

$$\begin{aligned}\phi &= 20^\circ \\ E_{ax} &= 4 \text{ MV/m}\end{aligned}$$

Then*

$$\frac{1}{F_R} = \pi \frac{20}{58} \frac{\sin 20^\circ (4.0) L_{cav}}{931.504 (3.10) \beta^3} = 5.132 (10^{-4}) \frac{L_{cav}}{\beta^3} \quad [6A]$$

$$\frac{1}{F_S} = \left(\frac{1}{2} \frac{20}{58} \right)^2 \left(\frac{3 \times 10^8}{9.3150 \times 10^8} \right)^2 \frac{P_S}{\beta^2} = 3.083 (10^{-3}) \frac{P_S}{\beta^2} \quad [6B]$$

The cavities occur in pairs, so that for

$$\text{Low resonator } \beta \quad L_{cav} = 2 (.20) = 0.40 \text{ m}$$

$$\text{High resonator } \beta \quad L_{cav} = 2 (.355) = 0.71 \text{ m}$$

So, for

$$\text{Low resonator } \beta, \quad F_R = 4871 \beta^3 \quad [7A]$$

$$\text{High resonator } \beta, \quad F_R = 2744 \beta^3 \quad [7B]$$

and

$$F_S = 324.2 \frac{\beta^2}{P_S} \quad [8]$$

*The assumption that E_{ax} in Eq. [6A] is 4.0 MV/m for any β is not correct for particle β -values which differ markedly from the resonator- β . This is due to the fact that E_{ax} contains the defocusing transit time factor, which is not close to unity when the two β -values differ considerably. For simplicity of calculation, however, we neglect this effect. This approximation does not cause a serious practical error, because:

(1) Although the calculation (and tables) below includes all cases, including ones where resonator- β and particle- β are very different, these cases would not be used in an actual linac, because the energy gain transit time factor F_t would also drop too low, and

(2) The magnitude of the F_R -effect is modest, so an error in its value has only a moderate effect on the solenoid strength calculations.

III. Solenoid Strengths Along the Linac

Since the focal length depends upon the velocities, we first trace the energy gain through the linac structure, with results in Table 1. Needed are the velocity at the center of the solenoid (equal to the velocity after the second resonator of the previous pair) and the velocity at the center of the following resonator pair (equal to the velocity after the first resonator of this pair).

Since the axial field is assumed to be the same through the linac, as is the phase ϕ , the energy gain depends only upon the resonator length and the transit time factor F_t . The latter measures the mismatch between the average particle velocity (or β) and the β of the resonator. Fig. 3 (made by L. Bollinger) shows the variation of F_t relative to the particle energy given as U/U_s . U_s corresponds to $\beta = 0.060$ for the low- β unit and to $\beta = 0.105$ for the high- β unit.

$$U_s (\text{low } \beta) = 1.681 \text{ MeV/A}$$

$$U_s (\text{high-}\beta) = 5.178 \text{ MeV/A}$$

Then, the energy gain in MeV/nucleon is, per resonator,

$$\Delta T = E_{ax} (\cos \phi) \left(\frac{q}{A}\right) F_t L_{cav} \quad [9]$$

or

$$\Delta T (\text{low } \beta) = 4.0 (0.940) \frac{20}{58} (0.20) F_t = 0.259 F_t \frac{\text{MeV}}{A}$$

$$\Delta T (\text{high } \beta) = 4.0 (0.940) \frac{20}{58} (0.355) = 0.460 F_t \frac{\text{MeV}}{A}$$

Assuming that Ni is accelerated as $^{58}\text{Ni}^{1-}$ to a 9.8 MV terminal, and is there stripped to $^{58}\text{Ni}^{9+}$, the energy entering the linac is

$$\frac{(1 + 9) 9.8}{58} = 1.690 \text{ MeV/A}$$

Table 1 shows the ion energies and normalized velocities ($\beta = v_z/c$) after every resonator.

Table 2 shows the focal lengths of the resonator pairs, calculated from Eqs. [7A] and [7B], and using the β at the center of the pair. As noted above, the perturbation from this approximation is not important.

Table 1. Energies and Normalized Velocities After Each Resonator

Resonator	Solenoid	Type of Resonator	F_t (from Fig. 3)	Output Energy (MeV/A)	Corresponding $\beta = v/c$
	1			1.690	0.0602
1		Low β	0.998	1.948	0.0646
2		Low β	0.967	2.198	0.0686
	2			2.198	0.0686
3		Low β	0.946	2.443	0.0723
4		Low β	0.917	2.681	0.0757
	3			2.681	0.0757
5		Low β	0.881	2.909	0.0788
6		Low β	0.852	3.130	0.0818
	4			3.130	0.0818
7		Low β	0.821	3.343	0.0845
8		Low β	0.782	3.546	0.0870
	5			3.546	0.0870
9		High β	0.916	3.967	0.0920
10		High β	0.960	4.409	0.0970
	6			4.409	0.0970
11		High β	0.987	4.863	0.1018
12		High β	0.998	5.322	0.1064
	7			5.322	0.1064
13		High β	0.996	5.780	0.1109
14		High β	0.985	6.233	0.1151
	8			6.233	0.1151
15		High β	0.972	6.680	0.1191
16		High β	0.957	7.120	0.1229
	9			7.120	0.1229
17		High β	0.940	7.552	0.1266
18		High β	0.920	7.975	0.1300
	10			7.975	0.1300
19		High β	0.902	8.390	0.1333
20		High β	0.883	8.796	0.1365
	11			8.796	0.1365

Table 2. Focal Length of Resonator Pairs

<u>Resonator Pair</u>	<u>F_R (meter)</u>
1 and 2	1.31
3 and 4	1.84
5 and 6	2.38
7 and 8	2.94
9 and 10	2.14
11 and 12	2.90
13 and 14	3.74
15 and 16	4.64
17 and 18	5.57
19 and 20	6.50

The focal lengths of the solenoids are now calculated from Eq. [2]. The drift space is given by (in cm)

$$L = \frac{1}{2} L_C + \frac{1}{2} L_S + L_{Res} + 6.4 + \frac{1}{2} (8.9) \quad [10]$$

where, as given above, L_C = coil length, L_S = axial length of shields, spaces and containing can, L_{Res} = length between inner walls of the resonator, 6.4 = effective distance between resonator inner wall and solenoid container, and 8.9 = distance between neighboring inner walls of resonators.

L_{Res} = 0.20 m for a low- β resonator and L_{Res} = 0.355 m for a high- β one. L_S = .128 m for a 6.8 T solenoid and L_S = 0.142 m for a 8.0 T one. The value of L_C used depends upon the solenoid strength P_S required. Hence, the evaluation of P_S requires iterative calculation, since the required coil length L_C cannot be defined until the focusing power of the solenoid is defined.

Table III gives some values of P_S as a function of L_C for two central fields, $B_0 = 6.8$ T and $B_0 = 8.0$ T. These values have been interpolated and extrapolated from some TRIM calculations and are close to the correct values [the coil configurations in the calculation differed a little from the ones considered here]. Fig. 4 shows the same data.

An example illustrates the iteration for calculating L_C .

TABLE III. Solenoid P_s -values versus Solenoid Coil Lengths (L_c)

L_c (cm)	P_s ($B_o = 6.8$) tesla ² meter	P_s ($B_o = 8.0$) tesla ² meter
6	1.918	2.655
7	2.356	3.261
8	2.802	3.878
9	3.255	4.504
10	3.719	5.148
11	4.177	5.781
12	4.635	6.415
13	5.090	7.045
14	5.552	7.684
15	6.015	8.325
16	6.478	8.966
17	6.941	9.607
18	7.404	10.248
19	7.867	10.888
20	8.329	11.528
22	9.254	12.808
24	10.179	14.088
26	11.103	15.368
28	12.028	16.648
30	12.953	17.928

Consider the first part of the linac with S1 and R1. The focusing power needed will be low enough so that the unit will be a 6.8 T one. Then $L_s = 0.128$ m. Assume $L_c = 10.0$ cm. Then, from Eq. [10], $L = 0.05 + 0.064 + 0.20 + 0.0445 = 0.423$ m. From Table 2, $F_R = 1.313$ m, so in Eq. [2],

$$F_s = 0.423 \left[1 - \frac{1}{2} \frac{1}{1 + \frac{1.313}{0.423}} \right] = 0.423 [0.878] = 0.371 \text{ m}$$

From Table 1, in solenoid S1, $\beta = 0.0602$, so from Eq. [8], the required $P_s = 324.2 \beta^2 / 0.371 = 3.167$. Interpolating in Table III or using Fig. 4, the required coil length would be $L_c = 8.80$ cm. Starting over, $L = 0.417$, $F_s = 0.367$ and $P_s = 3.204$, so $L_c = 8.89$ cm.

In Table IV, the values of L_c are calculated for the various solenoids. Iteration has been used where necessary, but has been stopped when successive L_c -values differ by < 0.5 cm.

Calculation has been made for both the 6.8 T and 8.0 T type coils even though it is not likely that the latter will be useful for the lower energy end. Solenoid 11 has not been calculated, because the focusing requirements at the linac end need defining before the P_s -value needed is determined. In any case, it is not likely to exceed the values given in Table IV, because the focal point needed will probably be farther away than the length of a resonator.

It is evident that the length gain in going from $B_o = 6.8$ T to $B_o = 8.0$ T is not large. The total ΔL_T in Table IV (last column) indicates that if the higher field units were used throughout, and if optimum solenoids were used, the overall linac length would be decreased by only 20 cm. In fact, one would wish to modularize, using no more than two or three different values of L_c (hence, L_T), and this would cut the length savings. It might, however, be useful to use $B_o = 8.0$ for the last two cryostats (solenoids 6 to 10) where the length savings are largest.

IV. Solenoid Strengths Needed as Function of Particle- β

For more general considerations, it seems worthwhile to calculate some curves which give P_s -values for a less specific case. The previous calculation has required definition of the ion species (q and A), the energy gain in each resonator ($\bar{E}_{ax}$, ϕ , F_t) and the specific defocusing effect of each resonator. In a less accurate calculation, one can omit the iteration step by assuming an average cell length for each of the low- β and high- β cells, thus neglecting the effect of changing the solenoid length on the cell length. This will introduce an error in predicting too small a P_s -value when the actual cell length is smaller than the average, and inversely when the cell length exceeds the average. But, as mentioned before, there is really a great deal of slop in the choice of P_s , because the resolution can be made to deteriorate slowly as P_s gets below the optimum value calculated as above.

Table IV. Solenoid Strengths (P_s) and Solenoid Lengths Required for Minimum Size Focusing*

Solenoid No.	$B_o = 6.8 \text{ T}$						$B_o = 8.0 \text{ T}$						ΔL_T (cm)
	$\frac{F_s}{L}$	L (meter)	F_s (meter)	P_s (T^2m)	L_c (cm)	L_T (cm)	$\frac{F_s}{L}$	L (meter)	F_s (meter)	P_s (T^2m)	L_c (cm)	L_T (cm)	
1	0.879	0.417	0.367	3.20	8.89	21.7	0.880	0.414	0.364	3.23	6.94	21.1	0.6
2	0.906	0.426	0.386	3.95	10.51	23.3	0.907	0.423	0.384	3.98	8.16	22.4	0.9
3	0.923	0.433	0.400	4.65	12.03	24.8	0.924	0.426	0.394	4.72	9.33	23.5	1.3
4	0.935	0.441	0.412	5.26	13.37	26.2	0.936	0.432	0.404	5.37	10.34	24.5	1.7
5	0.892	0.587	0.524	4.69	12.11	24.9	0.893	0.581	0.519	4.73	9.35	23.6	1.3
6	0.914	0.598	0.547	5.58	14.06	26.9	0.916	0.589	0.538	5.67	10.82	25.0	1.9
7	0.930	0.608	0.566	6.49	16.03	28.8	0.931	0.597	0.556	6.60	12.30	26.5	2.3
8	0.941	0.618	0.582	7.38	17.96	30.8	0.942	0.604	0.569	7.55	13.78	28.0	2.8
9	0.949	0.627	0.595	8.23	19.78	32.6	0.951	0.612	0.582	8.42	15.15	29.3	3.3
10	0.955	0.636	0.608	9.02	21.49	34.3	0.957	0.617	0.590	9.28	16.49	30.6	3.7

19.8=SUM

- *L = Distance between solenoid center and space between resonator pair
 F_s = Focal length of solenoid
 P_s = Focusing power required, $\int B_z^2 dz$
 L_c = Coil length (cm)
 L_T = Overall solenoid length, including shield and can
 ΔL_T = $L_T (B_o = 6.8) - L_T (B_o = 8.0)$

As long as approximations are in order, another one will simplify the presentation. In Eq. (3), F_R is a function of $\frac{q}{A}$, $\sin \phi$ and $\bar{E}_{ax}$. It is troublesome to include the effect of these parameters in the simplified calculation, so we fix on some values of the three parameters and just include the effect of varying β , which has a greater influence. This approximation is not serious, since Table IV shows that the total range of the F_R -effect lay between 4 to 12% for the case considered, i.e., for practical combinations of resonator- β and particle- β . We shall then take, as before, $q/A = 20/58$, $\phi = 20^\circ$ and $\bar{E}_{ax} = 4.0$ MV/m. Then F_R is given by Eq. [6A]. Now Eq. [5] can be written as

$$\frac{1}{F_S} = \left(\frac{q}{A}\right)^2 \frac{1}{\beta^2} \left[\frac{1}{2} \frac{3 \times 10^8}{9.3150 \times 10^8} \right]^2 P_S = \left(\frac{q}{A}\right)^2 \frac{1}{\beta^2} \frac{P_S}{38.56} \quad [11]$$

So, from Eq. [2], the optimum P_S is approximately

$$P_S = \frac{38.56 \beta^2}{\left(\frac{q}{A}\right)^2 L \left[1 - \frac{1}{2} \frac{1}{1 + \frac{F_R(\beta)}{L}} \right]} \quad [12A]$$

where

$$F_R(\beta) = \frac{\beta^3}{L_{cav}} 1949 \quad [12B]$$

and $L_{cav} = 0.40$ m for a low- β pair and 0.71 m for a high- β pair. In Eq. [12A], we take $L = 0.42$ m when a low- β pair follows the solenoid and $L = 0.59$ m when a high- β pair follows. Reference to Table IV shows that we have conservatively chosen the shortest L -values for each case. In calculating $F_R(\beta)$ from Eq. [12B], we neglect the fact that the average β in the two resonators following a solenoid is actually larger than β is in the solenoid. This will tend to slightly overemphasize the magnitude of the defocusing effect.

The most convenient way of presenting Eq. [12A] is to give P_S as a function of β (or the equivalent E/A MeV per nucleon) for the $^{58}\text{Ni}^{20+}$ case with $(q/A)^2 = (20/58)^2 = 0.1189$. Then for any other

q/A -value, P_s is given by

$$\frac{P_s(X)}{P_s(^{58}\text{Ni}^{20+})} = \frac{0.1189}{\left(\frac{q}{A}\right)_X^2} \quad [13]$$

To the accuracy considered here, it is sufficient to take P_s vs. L_c in Fig. 4 as linear so that the solenoid focusing power P_s is related to the coil length L_c by:

$$\text{For } B_0 = 6.8 \text{ T, } P_s = 0.460 L_c - 0.88 \quad [14A]$$

$$\text{For } B_0 = 8.0 \text{ T, } P_s = 0.638 L_c - 1.23 \quad [14B]$$

The results for $q/A = 20/58$ are presented in Table V and the same data are shown in Figs. 5 and 6. The tables contain values for the entire E/A -range for both the high and low- β resonator case and for both the $B_0 = 6.8 \text{ T}$ and $B_0 = 8.0 \text{ T}$ case. Many of the values are not pertinent, e.g., low E/A and high β -resonator will usually not combine, nor high E/A and low β , nor low E/A and $B_0 = 8.0 \text{ T}$. They are put in for completeness, and may have some use. The "non-physical" combinations, however, have a further error. For example, low E/A and a high- β resonator will have a low transit time factor, so that using $E_{ax} = 4 \text{ MV/m}$ in Eq. [3] will not be correct. Hence, as noted above, the F_R -value used in constructing the table is also incorrect, but the error is not large, because the F_R -value enters only as the correction in Eq. [2].

Sample Calculation. For $E/A = 2.4 \text{ MeV/nucleon}$ in the solenoid. The solenoid has two low- β resonators following it. $E/A = 2.4$ corresponds to $\beta = 0.0717$. It is assumed that the same β applies to the two resonators, and with $L_{cav} = 0.40 \text{ m}$, Eq. [12B] gives $F_R = 1.79 \text{ m}$ for $q/A = 20/58$, and with $L = 0.42 \text{ m}$, Eq. [12A] gives $P_s = 4.38$. The coil length L_c is calculated from Eqs. [14A] and [14B] and the total length L_T of the solenoid assembly is given by $L_T = L_c + L_s$ where $L_s = 12.8 \text{ cm}$ for $B_0 = 6.8 \text{ T}$ and $L_s = 14.2 \text{ cm}$ for $B_0 = 8.0 \text{ T}$. Then for $B_0 = 6.8 \text{ T}$ ($L_c = 11.43$, $L_T = 24.23 \text{ cm}$) and for $B_0 = 8.0 \text{ T}$ ($L_c = 9.43$, $L_T = 23.63 \text{ cm}$).

Table V. P_s and Solenoid Lengths as a Function of E/A for $q/A = 20/58$.

MeV/A	P_s (for $\frac{q}{A} = \frac{20}{58}$)		For $B_0 = 6.8$ T				For $B_0 = 8.0$ T			
	(T^2m)		Low β		High β		Low β		High β	
	Low $\beta^a)$	High $\beta^b)$	$L_T^{c)}$		$L_T^{c)}$		$L_T^{d)}$		$L_T^{d)}$	
			L_C (cm)	L_T (cm)	L_C (cm)	L_T (cm)	L_C (cm)	L_T (cm)	L_C (cm)	L_T (cm)
1.7	3.27	2.66	9.03	21.83	7.69	20.49	7.06	21.26	6.09	20.29
1.8	3.43	2.78	9.37	22.17	7.95	20.75	7.31	21.51	6.28	20.48
2.0	3.75	3.00	10.06	22.86	8.44	21.24	7.80	22.00	6.64	20.84
2.2	4.06	3.23	10.74	23.54	8.94	21.74	8.29	22.49	7.00	21.20
2.4	4.38	3.46	11.43	24.23	9.43	22.23	8.79	22.99	7.35	21.55
2.6	4.70	3.69	12.12	24.92	9.93	22.73	9.29	23.49	7.71	21.91
2.8	5.01	3.91	12.81	25.61	10.42	23.22	9.78	23.98	8.06	22.26
3.0	5.33	4.14	13.51	26.31	10.90	23.70	10.29	24.49	8.41	22.61
3.2	5.65	4.36	14.20	27.00	11.39	24.19	10.79	24.99	8.76	22.96
3.4	5.97	4.58	14.89	27.69	11.87	24.67	11.29	25.49	9.11	23.31
3.6	6.29	4.81	15.59	28.39	12.36	25.16	11.79	25.99	9.46	23.66
4.0	6.93	5.25	16.98	29.78	13.33	26.13	12.79	26.99	10.16	24.36
4.4	7.57	5.70	18.37	31.17	14.31	27.11	13.79	27.99	10.87	25.07
4.8	8.21	6.15	19.76	32.56	15.28	28.08	14.79	28.99	11.57	25.76
5.2	8.85	6.60	21.15	33.95	16.26	29.06	15.80	30.00	12.27	26.47
5.6	9.50	7.05	22.55	35.35	17.24	30.04	16.81	31.01	12.98	27.18
6.0	10.14	7.50	23.95	36.75	18.22	31.02	17.82	32.02	13.68	27.88
6.5	10.94	8.06	25.69	38.49	19.43	32.23	19.07	33.27	14.56	28.76
7.0	11.75	8.63	27.45	40.25	20.67	33.47	20.34	34.54	15.45	29.65
7.5	12.55	9.19	29.19	41.99	21.88	34.68	21.60	35.80	16.33	30.53
8.0	13.35	9.75	30.93	43.73	23.11	35.91	22.85	37.05	17.21	31.41
8.5	14.14	10.32	32.66	45.46	24.35	37.15	24.09	38.29	18.10	32.30
9.0	14.95	10.88	34.40	47.20	25.57	38.37	25.35	39.55	18.98	33.18
9.5	15.75	11.44	36.15	48.95	26.79	39.59	26.61	40.81	19.86	34.06
10.0	16.55	12.01	37.88	50.68	28.02	40.82	27.86	42.06	20.75	34.95
10.5	17.34	12.57	39.61	52.41	29.25	42.05	29.11	43.31	21.64	35.84
11.0	18.13	13.14	41.33	54.13	30.47	43.27	30.35	44.55	22.52	36.72

- a) P_s for case where two low- β resonators follow the solenoid
b) P_s for case where two high- β resonators follow the solenoid
c) Total solenoid assembly length $L_T = L_C + 12.8$ cm, where L_C = coil length
d) $L_T = L_C + 14.2$ cm

For $q/A \neq 20/58$, the same results can be used with a little manipulation, but the analogs of Figs. 5 and 6 are not presented for the general case. This for another q/A -value, P_s is calculated from Eq. [13], L_c is calculated from Eqs. [14A] or [14B] and L_T from $L_T = L_c + L_s$.

Example. Consider $^{81}\text{Br}^{23}$, with $q/A = 23/81 = 0.2840$ with two low- β resonators. Then at $E/A = 2.4$ MeV/nucleon, from Eq. [13], $P_s(\text{Br}) = (0.1189/0.08066)(4.38) = 6.46 \text{ T}^2\text{m}$. Then at $B_0 = 6.8 \text{ T}$, $L_c = (6.46 + 0.88)/4.60 = 15.96 \text{ cm}$ and $L_T = 15.96 + 12.8 = 28.76 \text{ cm}$.

Appendix 1. Coil and Shield Dimensions for 8.0 Tesla Solenoid

To operate at a central field of 8.0 T, it is necessary to increase the number of ampere-turns per unit length by increasing the coil diameter, and to decrease the current density, so that the inner wires do not exceed the allowable current for the increased field. A question was put to Ken Efferson of American Magnetics, Oak Ridge, by Ralph Benaroya (phone conversation, September 27, 1976) asking what coil diameter would be required to give 8.0 T for an air coil, given the same I.D. as the constructed coil and a coil length of 15.0 cm. His reply was:

Increase the coil outer radius by 1/4 inch (0.64 cm)
and the outer diameter of the coil form flange by the
same amount.

This provides some conservatism in allowable current, since the iron shield increases the magnetic efficiency, hence allows a given B_0 at a lower current than for a pure air coil.

The inner coil radius (1.443 cm) remains the same as the first coil and the outer radius increases from 3.60 cm to 4.24 cm. The cross-sectional area changes from $(3.60 - 1.443) 15.0 = 32.36 \text{ cm}^2$ to $(4.24 - 1.443) 15.0 = 41.96 \text{ cm}^2$. For the original coil, the current density for a central field 6.8 T is (211 Design Note RB-107, 3/9/76) $J = 25510 \text{ A/cm}^2$. Taking the central field as proportional to $\mathcal{N}I$, where $\mathcal{N}$ = total number of turns and I = current, $B_0 = K\mathcal{N}I = KN^2I (\text{Area}) = KJ (\text{Area})$, where K is a constant and N = number of turns/cm both axially and radially. Then for $B_0 = 8.0 \text{ T}$, $J = (8.0/6.8) \times (32.26/41.96) (25510) = 23145 \text{ A/cm}^2$ or 91% of the original current density.

What is the impact on the shield of the use of 8.0 T for B_0 . The primary consideration is whether the inner diameter needs enlarging to accommodate the increased diameter of the coil, and especially the coil form flange, which is even larger. The shape of the flux lines in the TRIM calculations indicate that the shielding pattern is adequate even with a gap separation of 10 to 12 mm. A closer spacing would only improve the shielding. A subsidiary consideration is that there should be a reasonably-sized channel for the liquid and vapor helium. The constructed

shield had an outer radius of 8.00 cm and an inner radius of 5.25 cm. The proposed larger coil has an outer radius of 4.24 cm, so the coil-shield spacing would be 10 mm, which is certainly adequate. The coil form in the constructed coil has an outer radius of about 4.2 cm, the larger one would be about 4.7 cm, which would also be compatible with an inner radius of 5.25 cm for the iron shield. Hence, the inner diameter of the shield may remain unchanged.

However, as in considering the end-plates above, the cross-sectional area of the cylindrical part of the shield must be increased to allow the larger flux to pass without increasing the field in the iron. Hence, the iron thickness needs increasing from $(8.00 - 5.25) = 2.75$ cm to $2.75 (8.0/6.8) = 3.24$ cm or an increase of 5 mm. Hence, the outer shield radius is increased to 8.5 cm. The mu-metal cylindrical shield radius is then increased from 8.73 cm to 9.3 cm.

Allowing 3/8" for an annular space surrounding the mu-metal shield and a 1/4" cylindrical wall, the structure would have a radius of $9.3 + 1.6 = 10.9$ cm.

As noted above, the end plate thickness of the iron shield is increased by 7 mm, so the overall shield length is increased by 1.4 mm.

The cost estimate for the larger diameter coil is \$2400 for one and \$1970 per unit in a 10-unit order. The built one cost \$1250. Shield costs should not be changed significantly.

Appendix 2. Radial Motion in the Focusing Process

It is instructive to consider the motion of particular particles and their positions on the radial phase ellipse. If the structure is geometrically repeated periodically and we set the condition that the phase ellipses shall have the same periodicity, then, as noted above, the solenoid focal length is the distance L between the solenoid center and the center of the resonator pair (Fig. A.2), when the defocusing effect of the resonator is neglected. This concept is based upon treating the solenoid as a simple lens, with all of its effect occurring at a single z -value. For a simple lens, a ray coming in parallel to the axis is bent at the lens and crosses the axis at a distance from the lens equal to the lens focal length. When the ray comes from an object point on the axis, the ray is bent at the lens and crosses the axis at the image point. If the distances of both points from the lens are the same, then this distance is twice the focal length.

These points are illustrated in Fig. A.2, in the central part. The solenoid is replaced by two half-lenses, both occurring at the same z -value. This allows us to portray the phase ellipses at the three "locations": (1) when the beam is just entering the lens, (2) at the lens center, and (3) when the beam leaves the lens.

The particle trajectories P and T, parallel to the axis before entering the solenoid, are both bent to cross the axis at C, a distance L from the solenoid center. The trajectory Q, starting from the axis a distance $2L$ to the left of the solenoid center, crosses the axis again at a distance $2L$ to the right (i.e., at the next solenoid center). The ray T (and the ray P) is parallel to the axis before entering the first half-lens, is bent towards the axis at the center, and is further bent by the second half-lens. The ray Q is moving away from the axis at an angle θ before entering the first half-lens, is parallel to the axis at the center, and is headed toward the axis after leaving the second half-lens, with the same value of $|\theta|$. A distortion has been made in the figure, since it is intended that the ray Q have reached the largest radial extent, but this is not shown, for clarity's sake, to avoid overlap with the P and T rays.

At the bottom of Fig. A.2 is shown a representation of the radial phase ellipses characterizing the entire beam, as well as the positions of the particular trajectories on the ellipses. There is a distortion here as well, since all three ellipses on the left side are intended to represent the radial characteristics at the same $z = z_{sol}$, the left-most one before the beam enters the simple lens, the center one corresponding to the mid-lens, and the right one just after the beam leaves the simple lens.

In the first ellipse, the beam entering the solenoid is a diverging one. P and T are trajectories parallel to the axis, (hence, $R' = 0$) but do not correspond to the outside of the beam (i.e., are not at R_{max}). The first half-lens bends them toward the axis, hence $R' > 0$ (up) for P and $R' < 0$ (down) for T, but both remain at the same R-value (since z has not changed). Q represents the ray corresponding to R_{max} . The first half-lens does not change the R-value of Q, but bends the ray so that it is parallel to the axis ($R' = 0$). The second half-lens bends the rays further, and P and T have the maximum $|R'|$ -values possible in the beam, but keep the same $|R|$ -values. Q has an increased $|R'|$ -value and remains at R_{max} .

In drifting through the distance L, R' -values do not change, so P and T keep the maximum $|R'|$ -values, but P and T cross the axis ($R = 0$) and Q is at $R = 1/2 R_{max}$. Through the next drift, R' -values do not change, but the ellipse shears, so P changes from negative R-values to positive ones (and inversely for T). R-values for Q remain positive, and Q crosses the axis ($R = 0$) at the second solenoid. P and Q become parallel again ($R' = 0$) after leaving the second solenoid.

*Radial Ellipses in
a Focusing Cycle*

FIG. A.2

APPENDIX 6.

LIQUID-HELIUM SAFETY

If a massive vacuum failure occurred when one of the HIB cryostats was in operation, the liquid helium inventory would vaporize and require venting to the room to avoid over-pressurizing the internal structure.

The worst-case failure of this type is postulated as a very rapid opening of one of the beam holes. The beam hole is 1 3/4 inches in diameter and an experiment shows that a 12-foot cryostat would go from full vacuum to ambient pressure in 10 seconds with a leak of that size.

Theoretical calculations to predict the time-pressure relationship of such a mishap are hampered by lack of good heat transfer data involving condensation and freezing of air and the thermal conductivity of frozen air.

Therefore, a decision was made to devise and run an experiment to get the required information.

The goal of the experiment was to determine the Pressure-Time relationship for the postulated mishap.

To reach this goal,

$$1.) \Delta P_c (T) = \Delta P_e (T)$$

for all times T_i

where subscript c refers to the cryostat and subscript e refers to the experiment.

To satisfy the above,

$$2.) \quad P_c(T) = P_e(T)$$

for all times T , P being the density of the exhaust gas.

Also,

$$3.) \quad \frac{V_c}{M_c(T)} = \frac{V_e}{M_e(T)}$$

for all times T ,
where V is the volume of the Helium
and M is the rate of mass removal.
 $M(T)$ assumes a heat input proportional to V . i.e., $\frac{V_c}{A_c} = \frac{V_e}{A_e}$ where

A is the heat transfer area.

The above conditions may be used in the relationship

$$4.) \quad \Delta P = \frac{\phi G^2 \ell}{2 P d}$$

$$\text{where } G = \frac{M}{A}$$

M = mass flow rate

A = area of vent tube

ℓ = length of vent tube

d = diameter of vent tube

and $\phi \sim \left(\frac{1}{Gd}\right)^{1/4}$ for turbulent flow

equating $\Delta P_c = \Delta P_e$ to find ℓ_e and d_e

$$5.) \quad \frac{G_c^{7/4} \ell_c}{P_c d_c^{5/4}} = \frac{G_e^{7/4} \ell_e}{P_e d_e^{5/4}}$$

and

$$6.) \quad \frac{M_c^{7/4} \ell_c}{d_c^{19/4}} = \frac{M_e^{7/4} \ell_e}{d_e^{19/4}}$$

and

$$7.) \quad \frac{\ell_c}{d_c^{19/4}} = \frac{\ell_e}{d_e^{19/4}} \left(\frac{M_e}{M_c} \right)^{7/4} = \frac{\ell_e}{d_e^{19/4}} \left(\frac{V_e}{V_c} \right)^{7/4}$$

for the experiment

$$\frac{V_e}{V_c} = \frac{1}{25} \text{ with } l_c = 36" \text{ and } d_c = 1 \frac{3}{4}" \text{ by design}$$

Also, to be consistent, the vacuum volume of the cryostat V_c^1 and the vacuum volume of the test cryostat V_e^1 should be in the same ratio, i.e., $\frac{V_e^1}{V_c^1} = \frac{1}{25}$. The actual ratio was $\frac{1}{25.1}$.

$$V_c = 65.4 \text{ liters} \quad V_e \text{ req'd} = \frac{65.4}{25} = 2.62 \text{ liters}$$

the actual V_e was 2.56 liters

$$\frac{V_c}{A_c} = \frac{65.4 \text{ liters}}{20,250 \text{ cm}^2} = \frac{2.62}{A_e} \quad A_e = 811.2 \text{ cm}^2 \text{ req'd.}$$

the actual A_e was 820 cm^2

Assume $d_e = .430$ (1/2" OD x .035 wall)

find l_e

use Eq. 7.)

$$\frac{l_c}{d_c^{19/4}} = \frac{l_e}{d_e^{19/4}} \left(\frac{1}{25}\right)^{7/4}$$

$$\frac{36}{1.75^{19/4}} = \frac{l_e}{.430^{19/4}} \left(\frac{1}{25}\right)^{7/4} \quad l_e = 12.8"$$

the actual l_e used was 12.75"

The area of the "leak hole" used in the experiment should be 1/25 the area of the leak hole in the cryostat (1.75" dia).

$$A_c^L = 2.405 \text{ in}^2 \quad A_e^L \text{ required} = 0.096 \text{ in}^2$$

$$D_e^L = 0.350" \text{ dia}$$

$$\text{the actual } D_e^L = 0.375"$$

$$A_e^L \text{ actual} = 0.110 \text{ in}^2$$

The Experimental Equipment

A test cryostat was available that had a 12 7/8" ID x 39" deep. A 3/8" thick cover with "O" ring groove was fitted to the top. The cover contained ports for evacuating the cryostat, a feed thru for the pressure sensing line to the test vessel, and the ball valve that contained the "leak hole". Also, a centrally located hole in which the vent line from the test vessel was welded.

The test vessel was a 7" long piece of 6" OD x 0.120 wall stainless with 3/8" thick stainless end plates. The vent tube was welded into the center of the top end plate and a two-foot long piece of 1/8" OD stainless tube was also welded into the top plate. This served as the vessel pressure sensor line.

The pressure sensor was a Stathan strain gage with a 0-100 psig range. It was precalibrated with gas using a precision pressure gage.

Pressure was recorded on a Honeywell strip chart recorder - 0-100 psi full scale and 0.85 mm/sec chart speed. (2"/min).

The Experiment

The ball valve containing the leak hole was closed and the cryostat evacuated with a roughing pump. The pump was valved off and liquid helium transferred into the vessel to overflowing. The transfer tube was removed and the strip chart started. The ball valve containing the leak hole was opened rapidly, the helium vaporized and escaped through the vent tube, and the pressure-time relationship recorded on the strip chart.

The Results

There was an induction period of about 1 sec during which the pressure did not rise. At that time, it rose smoothly to a maximum

of 3.75 psig (934 mm mm Hg abs) in 1 1/4 seconds. The pressure then fell to ambient in 11.8 secs.

There was no indication of pressure build-up in the cryostat due to vaporization of condensed air on the outside of the LHe vessel.

Discussion

The results of the experiment were surprising but not unwelcome.

As can be seen from the above graph, most of the helium was expelled in about 8 seconds. Assuming that the helium was exhausted as a gas at 4.4°K, an average velocity of 103 ft/sec (31 meters/sec) can be calculated as well as a ΔP of 0.36 psi. Inspection of the chart shows that the peak ΔP was about 10 times the average. This indicates that the peak velocity was about the $\sqrt{10}$ times the average or about 100 meters/sec. At this velocity, we have a mass flow rate of 200 gms/sec. Vaporization of this much helium requires an overall heat transfer rate of 4.9 watts/cm². Comparison of this heat transfer rate with nucleate boiling coefficients and condensing vapor coefficients indicate that it is about what is expected.

The rapid drop in pressure from the peak, which must have happened while the majority of the helium was still in the vessel, indicates the formation of an insulating layer of frozen air/water on the outer surface of the helium vessel.

Assuming most of the liquid helium was gone at the 9 sec mark, an overall heat transfer rate of 1.5 watts/cm² can be calculated for that time.

The above calculations assume very good heat transfer coefficients on the helium side, i.e., about .8 watts/cm²-°K typical of nucleate boiling. In other systems with less vent area, the pressure and temperature could rise above the critical point. This could result in much reduced heat transfer on the helium side and therefore lower overall heat transfer rates.

Extrapolating the test results and above calculations to the large HIB cryostats, a maximum pressure of 6.4 psig is calculated.

In the above calculations, the Reynolds number (Re) for the gas flowing through the vent tube ranges from 20×10^6 to 200×10^6 . This is well beyond the range of good engineering data for determining friction factors. What evidence there is suggests that the friction factor reaches a minimum value and then is relatively constant with respect to Re.

While equation 4 indicates a continuing dependence with Re, ($\phi = (\frac{1}{Gd})^{1/4}$) its use in the scaling equation (#7) is not thought to lead to significant error.

Conclusion

The present helium vent design for the HIB cryostats is safe.

APPENDIX 7.

HEAT BALANCE IN HELIUM-DISTRIBUTION SYSTEM

The closed-cycle helium-distribution system for the heavy-ion booster can be operated in a wide variety of conditions, as is suggested by the descriptive outline given in Sec. II.B2h. This appendix gives some additional detail for the particular set of assumptions about heat loads specified by Fig. 1. Here the indicated heat loads are of two kinds:

(1) the active rf-power dissipation in resonators, and (2) the static heat leaks of cryostats and distribution lines. The rf losses depend, of course, on the field levels at which the resonators are being operated, and in the example treated here maximum losses are assumed.

Some understanding of the processes involved in the operation of the refrigeration system can be obtained from Fig. 2, which shows a simplified thermodynamic cycle on a pressure-enthalpy diagram.

The conditions of the helium before final expansion in the Model 1400 refrigerator are assumed to be $P_A \approx 9.0$ atm, $T_A \approx 5.5$ K (at point A). After expansion (at point B) $P_B = 1.78$ atm, $T_B = 4.9$ K, and the mass fraction of vapor $x_B = 0.25$. This mixture passes through heat exchanger HX1 in the 1,000-liter dewar, where it is condensed and sub-cooled to $T_C = 4.7$ K (at point C) adding 40 W to the dewar liquid.

Sub-cooled liquid enters cryostat D, absorbs about 36 watts, and leaves with a quality $x_D = 0.21$ at point D. The mixture then passes through a sub-cooling heat exchanger HX2 located in a distribution-line cold box adjacent to the cryostat. The 36 W added in the cryostat and line are removed, and the liquid is again sub-cooled to 4.7 K at point E. In a similar way, the heat added in cryostats C and B is removed in coils HX3 and HX4, so that in every case the fluid entering a cryostat is slightly sub-cooled. Helium leaving cryostat A at point J has a quality of about 0.09 and is sent in series to the low heat-load buncher cryostat.

At point K, where $P_K = 1.78$ atm, $T_K = 4.9$ K and $x_K = 0.13$, the fluid is expanded through a J-T valve to $P_L = 1.4$ atm, $T_L = 4.6$ K, and $x_L = 0.24$. The low-pressure return stream passes through the shell sides of HX4, HX3, and HX2, absorbing the heat of condensation and sub-cooling the high pressure stream; the quality increases at each stage.

In this example, all of the liquid is vaporized at point 0, leaving no liquid to replenish the bath in the dewar. In this case, the dewar liquid will be vaporized by the load from HX1. When the liquid is used up in this way, 1 l/hr of liquid consumption gives about 2.5 W of refrigeration. If the dewar contains about 800 liters above the heat exchanger coil and, if the load for condensing and sub-cooling is 40 W, the liquid inventory should last for about $(800 \text{ l} \times 2.5 \text{ hrW/l})/40 \text{ W} = 50$ hours. During this pulsed type of operation, the maximum system load is 135 W. For steady-state continuous operation in which the liquid level in the dewar remains constant, the maximum load is 95 W, the rated capacity at 4.6 K of the model 1400 with liquid nitrogen precooling and three compressors.

Figure 1

Figure 1. Helium-distribution system. The assumed heat loads are shown. The letters shown at various points in the loop can be used with Fig. 2 to identify the thermodynamic state at that location.

Figure 2

Figure 2. Pressure-enthalpy diagram for the helium-distribution system. The letters shown label various states in the cycle and correspond to the letters in Fig. 1. The assumed heat loads are described in the text.

APPENDIX 8.

COMPUTER-AIDED ACCELERATOR CONTROL

A. Introduction

In this appendix we describe schematically the main features of a computer program which is planned to help the operator in controlling the accelerator. A diagram of the connection of the PDP 11/34 computer to peripheral devices, including a CAMAC serial data highway is shown in Figure 23 of the main text. The accelerator operator will interact with the system by means of the control panel shown in Figure 1; the panel will be interfaced to the computer through the local CAMAC crate. Devices to be read and controlled will be interfaced to the computer through a CAMAC serial data highway. A Tektronix terminal and Versatec printer-plotter will also be available.

The control programs are being written for the most part in Fortran under the RSX-11M operating system provided by Digital Equipment Corporation. RSX-11M provides services in the form of multi-tasking and event flags which make the design of the program simpler.

Program flow will be controlled through a "Touch Panel". The "Touch Panel" provides 16 transparent switches over a raster display which will be used to label the switches. A second raster-scan TV monitor will display status information and messages to the operator. When the program is loaded, the "Touch Panel" switches will be labeled as shown in Figure 2, and the computer will wait for a selection from this menu. The three primary parts of the program will provide for solenoid control, buncher, chopper and resonator control and temperature monitoring. Each of these sub-programs has associated with it a "Touch Panel" menu and a Status Table (to be displayed on the TV monitor). Selecting one of the switches of Figure 2 will usually result in a new sub-menu displayed on the "Touch Panel" and one of the three status tables displayed on the TV monitor. The following pages describe the responses to the sub-menus and the structure of the status tables.

Figure 1. Control panel

SET SOLENOID			
SET RESONATOR			
SCAN TEMPERATURE SENSORS			
ENTER TANDEM PARAMETERS			

Figure 2. Main menu displayed on "Touch Panel" when the program is first loaded. Unlabelled switches provide room for expansion.

B. Solenoid Options

The menu of Figure 3 will appear when the "SET SOLENOID" switch of the menu is touched. At the same time, the Solenoid Status Table will be displayed on the TV monitor as shown in Figure 4; most of the entries in this menu are self explanatory. Selections of a numeric entry in the first two rows will identify the selection on the "Touch Panel" display, set the power supply to current given in the status table, open the persistent switch and finally, connect the control panel knobs to the power supply and display the current on the LED numeric display. (These last connections are, of course, software connections made through CAMAC.) The operator may now manually adjust the solenoid. After making the setting, the operator may select another option on the menu (which may be an exit to display of the main menu). At this point, the control knob will be disconnected, the persistent switch closed, and the newly-selected routine entered. We regard this manual

routine described above as a necessary, though perhaps seldom-used option. Nothing would be more frustrating than having the solenoids set automatically by a series of elaborate programs which failed to take care of an occasional rare exceptional case where a manual adjustment was necessary.

We believe the options of the third row in Figure 3 will be the ones normally used. "Reset Solenoids" will automatically, without operator intervention, reset all solenoids to the currents given in the status table. This refresh function will also be scheduled through RSX-11M to be performed at regular intervals.

"Set All Solenoids" will probably be the most useful option. Since the focal length required for each lens is known and since this focal length is a function of the energy, mass and charge of the ion at each lens, the solenoid currents can be calculated from information in the "Resonator Status Table" (to be described below). "Set All Solenoids" will make this calculation and set currents in all of the solenoids simultaneously. When the operation is completed, the operator will be notified on the TV monitor; he may then choose another option or exit to displaying the main menu.

1	2	3	4
5			
RESET SOLENOIDS	SET ALL SOLENOIDS	PRINT SOLENOID STATUS	
			EXIT

Figure 3. Set solenoid sub-menu.

SOLENOID NUMBER	PERSISTENT SWITCH POSITION	CURRENT	TIME OF LAST REFRESH
1	Closed	15.6	15:31
2	Closed	20.3	15:35
3	Closed	21.4	15:37
4	Closed	25.6	15:40
5	Closed	28.9	15:43

Figure 4. Solenoid Status Table with typical entries.

C. Resonator Options

If the operator had chosen the "Set Resonator" option of the main menu in Figure 2, the menu of Figure 5 would be displayed on the "Touch Panel" and the "Resonator Status Table" of Figure 6 would be displayed on the TV monitor. As in the case of the solenoids, the options of the first three lines of the menu are the most primitive and result in the connection of the control knobs of Figure 1 to the phase and amplitude controls of a particular resonator and the LED numeric displays connected to display these phases and amplitudes. Downstream of the resonators will be a chamber in which a scattering foil may be placed in order to measure accelerated ion energy. The result of this measurement will be updated periodically and displayed on the TV monitor. Selection of another switch on the "Touch Panel" will immediately disconnect the knobs and LED display and enter the appropriate routine.

Briefly, the other options of Figure 5 are "Phase Calibrate" which will search for a phase of the resonator relative to the master oscillator so that the ion beam energy will not be changed in passing through the resonator. This defines a zero phase relative to the ion beam

CHOPPER	BUNCHER	1	2
3	4	5	6
7	8	9	
PHASE CALIBRATE	SET ALL RESONATORS		EXIT

Figure 5. Set resonator sub-menu.

RESONATOR NUMBER	AMPLITUDE	PHASE	TIME
1	4.56	20.3	16:41
2	4.63	24.5	16:45
3			
4			
5			
6			
7			
8			
9			

Figure 6. Resonator Status Table with a few typical values.

which is necessary for properly setting the resonator. "Set All Resonators" will calculate zero phase for each resonator from the energy of the ions as a function of the distance from the phase detector.

D. Scan Temperature Sensor Options

If the "Scan Temperature Sensors" switch of Figure 2 is chosen, then the sub-menu of Figure 7 will label the "Touch Switch" panel and the Temperature Status Table of Figure 8 will be displayed. Sensors of two types will be used, thermocouples for higher temperatures and Ge resistors for liquid helium temperatures. The option labels are self explanatory and provide for obtaining a permanent record, for obtaining an immediate measurement, for setting the temperature limit at which an alarm is to be given to the operator, for measuring repeatedly one specified sensor, and for turning off the alarm message. Under normal circumstances the temperature sensors would be scanned at regular intervals for exceptional conditions.

MEASURE ALL	MEASURE ONE	SET TEMPERATURE LIMITS	SET TIME
IGNORE MESSAGE	SCROLL STATUS TABLE		
			EXIT

Figure 7. Sub-menu displayed after selecting "Scan Temperature Sensors" option of Figure 2.

SENSOR	TYPE	TEMPERATURE	LIMIT	TIME
1	TC	82	85	3:21
2	GE	4.1	5	3:15
3				
4				
5				
6				
7				
8				
9				

Figure 8. Temperature Status Table with a few typical values.

APPENDIX 9.

THE SUPERCONDUCTING 90° ANALYZER MAGNET

An essential part of any electrostatic accelerator system is the beam analyzer magnet, since this magnet determines the energy stability of the accelerator as well as guarantees that only the particular beam of interest is transmitted to the target, rather than possible satellite beams of other charge states and species. When heavy-ion projectiles are accelerated in a tandem Van de Graaff, the bending power required of this analyzing magnet grows nearly in proportion to the mass of the ion accelerated. An increase of either the strength of the magnetic field or the radius of curvature will increase the binding power of the magnet. However, in upgrading an existing facility, it is likely to be quite undesirable to change the basic geometry of the accelerator vault and target room beam lines. Therefore, increasing the strength of the magnetic field would be the most convenient choice if this can be accomplished.

Fortunately, magnetic fields about three times greater than the maximum fields in conventional iron magnets, can be readily produced in a superconducting dipole magnet. Many magnets of this type have already been designed and constructed at high-energy physics accelerators. We propose to use this style of dipole magnet and adapt it to the special circumstances needed to make a 90° analyzing magnet for our FN-model Van De Graaff accelerator.

The basic idea (shown in Figure 1) is to use three identical dipole magnets with $\cos \theta$ windings. Three dipoles are needed since bending angles greater than 30° are not convenient for this style of magnet. These dipoles will be rigidly mounted on a common support frame to form a mechanically-stable unit much like a conventional analyzer magnet.

The overall optics is similar to what is needed for conventional 90° analyzer magnets. Either a single or double focussing analyzer is possible. However, in our application single focussing is preferred to fit with the original beam transport scheme which uses quadrupole doublets and a special geometry. To produce a single focussing analyzer, separate

quadrupole windings as well as hexapole windings need to be added to the main $\cos \theta$ dipole windings.

A schematic cross section of the magnet is shown in Fig. 2. The outer layer is a cylindrical iron pipe which serves to support the large, outward magnetic forces acting on the coil. The superconducting windings are wrapped tightly around an inner pipe which is part of the cryostat. Dipole windings of the $\cos \theta$ type can readily produce a magnetic field with a 0.1% uniformity over a wide area. A cold bore design has been chosen to minimize the cost.

For proper focussing, the quadrupole winding needs to produce a magnetic field with a field index of about -0.9. A hexapole winding will produce a small hexapole field component to compensate for aberrations caused by the fact that the central ray does not follow the physical center line of the dipole winding.

The size of the superconducting analyzer is controlled by the overall dimensions of the original 90° analyzer. To fit a single-focussing 90° analyzer into this same space, a system with an 85 cm radius of curvature is required. With a magnetic field strength of $45 \text{ Kg} = 4.5 \text{ T}$, an analyzer magnetic with a mass-energy product of 500 MeV-amu results.

The design and engineering of the superconducting magnet will be carried out by the superconducting magnet group at Argonne, which has had a wide range of experience ranging from superconducting magnets for bubble chambers to the record-setting superconducting magnet sent to Russia for a MHD electric power generator.

SUPERCONDUCTING ANALYZING MAGNET

Figure 1. Schematic view of superconducting analyzing magnet system.
Three magnets each bend the beam 30° and provide the necessary
horizontal focussing.

Figure 2

Figure 2. Schematic view of superconducting analyzing magnet construction. Details of the cryostat are not shown.

APPENDIX 10.

BEAM TRANSPORT FROM THE TANDEM TO THE LINAC

A system to transport the beam from the tandem accelerator to the superconducting linac is described and analyzed in this report. The profile of the beam envelope is given in Figure 1. The restrictions due to various apertures, slits, and beam pipes are also shown. Table I contains specific details of the beam characteristics and the magnetic fields required by the magnetic elements for three beams of interest.

A. High-Voltage Terminal

The characteristics of the waist at the foil stripper in the high-voltage terminal of the tandem were obtained by assuming that the beam-spot radius was 2.5 mm. The beam divergence of the waist is determined by multiple scattering in the stripper foil as well as by the angular spread of the beam arriving at the stripper. To compute the latter it was assumed that the acceptance of the low-energy acceleration tube and injection system could transmit all of the beam from a source which has a normalized emittance of $7 \pi \text{ mm-mrad-MeV}^{1/2}$. This emittance represents typical values of the 50% contours from a conventional Middleton sputter source. The angular spread introduced by multiple scattering in the carbon foil was calculated with the theory of Sigmund and Winterbon [N.I.M. 119, 541 (1974)]. This is an expanded version of the theory of multiple scattering due to Meyer. The angles given in the table are half-width-at-half-maximum values.

B. Analyzer Object Waist

The dimensions of this waist were chosen to meet several conditions. In the x-direction (horizontal) the beam radius must be less than about 0.3 mm to insure adequate momentum analysis by the 90° analyzing magnet and thereby sufficient energy stability for the tandem accelerator. The y dimension (vertical) of the waist needs to be about 7 times larger than the x dimension

so that the waist at the linac entrance will be the same size in x and y. For beams of the emittance that we have, an analyzer object waist of 0.24 mm by 1.65 mm is suitable. If the beam dimension in y is much larger than this, waist-to-waist transfer will not occur since the y divergence becomes too small.

C. Second Stripper

The second stripper, if used, will be located near the object waist of the 90° analyzer. The foil thickness used is selected to insure charge equilibrium. Because the beam is less divergent in the y direction, the effects of multiple scattering are more serious in this direction, but not of major consequences since the increase in y emittance is only about 24% for a ⁵⁸Ni beam. This effect of multiple scattering could be somewhat less since calculations show that it is possible to reduce the size of the beam about 10% by moving the y waist downstream from the object point of the 90° analyzer by about 70 cm.

D. Quadrupole No. 3

A single quadrupole doublet is used to convey the beam from the 90° analyzer to the entrance waist of the linac. The major problem here is to couple the beam coming from the 90° analyzer which has a short characteristic length (~7 cm) in the x direction, with linac which requires a beam with a long characteristic length (~1.5 m). This cannot be done with a single lens. A design was developed which used two quadrupole doublets between the analyzer and the linac. The main difficulty with this design was that it complicated considerably the construction and operation of the beam chopper, since a quadrupole needed to be located between the deflection plates and the chopping slits and the size of the beam in the deflection plates was quite large.

An alternative way to do the coupling is to use the first solenoid of the linac as a matching lens instead of introducing an extra quadrupole. This method was finally adopted. However, since the linac requires a beam

nearly symmetric in x and y, the ratio of the x and y dimensions of the waist at the object point of the 90° analyzer are now closely fixed. A waist size of 0.24 by 1.65 mm in radius should give good performance of the 90° analyzer. The characteristic length at the linac entrance is about 0.4 meters. The first linac solenoid has the capability of matching this waist to the rest of the linac.

E. Magnetic Field Strengths

The field strengths required by the quadrupoles to focus the beam are all within the capabilities of the standard quadrupoles used at the tandem. These quads can produce field strengths of up to about 2.3 Kg. The second pole set in quadrupole No. 2 requires the largest field, 2.04 Kg field for a $^{58}\text{Ni } 9^+$ beam. This could be reduced if necessary by moving the quadrupole upstream without affecting overall performance of the beam-transport system.

TABLE I.

BEAM CHARACTERISTICS

Tandem terminal to linac entrance waist

Beam Particle	^{16}O	^{40}Ca	^{58}Ni
<u>Injected Beam Emittance</u>			
$\epsilon\sqrt{E}$ (mm-mrad-MeV $^{1/2}$)	7	7	7
<u>HV Terminal</u>			
Voltage (MV)	9	9	9
ϵ_{in} (mm-mrad)	2.33	2.33	2.33
r_{in} (mm)	2.5	2.5	2.5
stripper thickness ($\mu\text{g}/\text{cm}^2$)	5	5	5
$\theta_{\text{scatt.}}$ (mrad)	0.58	1.28	1.69
ϵ_{out} (mm-mrad)	2.75	3.97	4.83
q	6+	9+	9+
<u>Quadrupole No. 1</u>			
$B_{\text{O}} \# 1$ (Kg)	-0.551	-0.715	-0.866
$B_{\text{O}} \# 2$ (Kg)	0.566	0.725	0.873
x max (mm)	6.0	7.2	8.7
y max (mm)	4.4	5.2	6.3
<u>Quadrupole No. 2</u>			
$B_{\text{O}} \# 1$ (Kg)	-0.923	-1.15	-1.37
$B_{\text{O}} \# 2$ (Kg)	1.35	1.70	2.04
x max (mm)	4.0	4.8	5.8
y max (mm)	3.3	3.5	3.7

TABLE I. contd.

Beam Particle	^{16}O	^{40}Ca	^{58}Ni
<u>90° Analyzer Object Waist</u>			
Energy (MeV)	63	90	90
ϵ (mm-mrad)	1.038	1.254	1.526
x_0 (mm)	0.24	0.24	0.24
y_0 (mm)	1.65	1.65	1.65
<u>Second Stripper</u>			
stripper thickness ($\mu\text{g}/\text{cm}^2$)	20	25	30
$\theta_{\text{scatt.}}$ (mrad)	0.23	0.44	0.68
ϵ_x (mm-mrad)	1.039	1.258	1.534
ϵ_y (mm-mrad)	1.105	1.449	1.894
<u>90° Analyzer*</u>			
B (Kg)	8.821	11.11	13.38
<u>Quadrupole No. 3*</u>			
$B_0 \# 1$ (Kg)	1.12	1.42	1.71
$B_0 \# 2$ (Kg)	-1.02	-1.28	-1.55
x max (mm)	9.7	11.6	14.2
y max (mm)	6.3	7.4	8.8
<u>Linac Entrance Waist*</u>			
x_0 (mm)	0.64	0.64	0.64
y_0 (mm)	0.59	0.61	0.62

*without second stripper

Conventions: x horizontal

y vertical

 x_0 is the beam radius in x-direction

$$\epsilon = x_0 x_0'$$

Figure 1

Figure 1. Beam envelope distribution.

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APPENDIX 11.

ANALYTIC CALCULATION OF LONGITUDINAL TRANSFER MATRICES

Although the matrices for transforming the phase ellipse down the linac can be evaluated numerically from the computer program for calculating trajectories in the linac, it is often convenient to use an analytical approach. The theory of such an analytical calculation follows.

A. Longitudinal Transfer Matrix in the Resonator.

Note: From the $(\Delta\phi, \Delta T)$ definitions used, the trajectory of a particle in the $(\Delta\phi, \Delta T)$ plane rotates clockwise as the beam advances through the linac.

The field of the resonator is written as

$$\mathcal{E}_{ax}(z, t) = \mathcal{E}_{ax}^0 \sum_n a_n \cos \frac{2\pi n z}{L_{cav}} \cos(\omega t - \phi) \quad [1]$$

Then the energy gain per nucleon in the resonator is

$$\frac{q}{A} \int \mathcal{E}_{ax}(z, t) dz = \frac{q}{A} \mathcal{E}_{ax}^0 L_{cav} \cos \phi \tau_L(av), \quad [2]$$

with the longitudinal transit time factor

$$\tau_L(av) = \frac{1}{2} \sum_n a_n \left[\frac{\sin \left\{ \pi \left(n - \frac{fL_{cav}}{v} \right) \right\}}{\pi \left(n - \frac{fL_{cav}}{v} \right)} + \frac{\sin \left\{ \pi \left(n + \frac{fL_{cav}}{v} \right) \right\}}{\pi \left(n + \frac{fL_{cav}}{v} \right)} \right]$$

and v is the average particle velocity in the resonator. For the center of the bunch (reference particle)

v_0 = average velocity

T_0 = energy per nucleon

ϕ_0 = phase offset

The convention used is that for any other particle, $\Delta T = T - T_0$, $\Delta\phi = \phi - \phi_0$,

$\Delta t = t - t_0$, $\Delta v = v - v_0$ relative to the bunch center.

Then setting $\overline{\mathcal{E}}_{ax} = \mathcal{E}_{ax}^0 \tau_L(av)$, and treating the energy gain per unit length in the cavity as a constant, from [2]

$$\begin{aligned} \frac{d\Delta T}{dz} &= \frac{q}{A} \overline{\mathcal{E}}_{ax} \{\cos \phi - \cos \phi_0\} \\ &= - \frac{q}{A} \overline{\mathcal{E}}_{ax} \sin \phi_0 \Delta \phi + \text{higher order terms in } \Delta \phi, \end{aligned} \quad [3]$$

where it has been assumed that the Δv is small enough that the change in τ_L may be neglected.

Differentiation of

$$\Delta \phi = \omega \int \left(\frac{1}{v_0} - \frac{1}{v} \right) dz$$

gives

$$\frac{d\Delta \phi}{dz} = \omega \left(\frac{1}{v_0} - \frac{1}{v} \right) = \omega \frac{\Delta v}{v_0^2} + \text{higher order terms in } \Delta v. \quad [4]$$

For small $(\Delta \phi, \Delta T)$ values, the higher order terms in [3] and [4] may be neglected. To the first order,

$$\frac{\Delta v}{v_0^2} = \frac{\Delta T}{mv_0^3}$$

where m is the rest mass of the particle. Hence, the basic differential equations are:

$$\frac{d\Delta \phi}{dz} = P(z) \Delta T \quad [5]$$

$$\frac{d\Delta T}{dz} = -Q(z) \Delta \phi \quad [6]$$

where

$$\begin{aligned} P(z) &= \frac{\omega}{mv_0^3} \\ Q(z) &= \frac{q}{A} \overline{\mathcal{E}}_{ax} \sin \phi_0 \end{aligned} \quad [7]$$

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The first order Eqs. [5] and [6] can be combined to eliminate ΔT and to yield a single second order differential equation in $\Delta\phi$

$$\Delta\phi'' - \frac{P'}{P} \Delta\phi' + PQ\Delta\phi = 0 \quad [8]$$

where prime denotes differentiation with respect to z . Substituting the new variable

$$X = P^{-1/2} \Delta\phi \quad [9]$$

in [8] we obtain

$$X'' + [PQ - \frac{3}{4} \left(\frac{P'}{P}\right)^2 + \frac{1}{2} \frac{P''}{P}] X = 0 \quad [10]$$

From [7], we find

$$\frac{P'}{P} = -\frac{3}{2} \frac{T'}{T} \quad \text{and}$$

$$\frac{P''}{P} = -\frac{3}{2} \frac{T''}{T} + \frac{15}{4} \left(\frac{T'}{T}\right)^2$$

$$\text{Hence } X'' + K^2 X = 0 \quad [11]$$

$$\text{where } K^2 = PQ + \frac{3}{16} \left(\frac{T'}{T}\right)^2 - \frac{3}{4} \frac{T''}{T} \quad [11A]$$

Eq. [11] is in the form of a harmonic equation, except that $K^2(z)$ is a slowly varying function of z . Introducing in [11] the new variables

$$\psi = \int_0^z K ds \quad \text{and } Y = \sqrt{K} X \quad [12]$$

Then $\frac{d\psi}{dz} = K$, and we obtain

$$\frac{d^2 Y}{d\psi^2} + \left[1 + \frac{3}{4} \left(\frac{K'}{K}\right)^2 - \frac{1}{2} \frac{K''}{K}\right] Y = 0 \quad [13]$$

It can be shown that $\frac{3}{4} \left(\frac{K'}{K}\right)^2 - \frac{1}{2} \frac{K''}{K} \ll 1$ and [13] reduces to

$$\frac{d^2 Y}{d\psi^2} + Y = 0$$

The general solution of this harmonic equation can be written in the form

$$Y = C_1 \cos \psi + C_2 \sin \psi$$

Back substituting with [9] and [12] to return to the $\Delta\phi$ and z variables, we find

$$\Delta\phi = \sqrt{\frac{P}{K}} \left(C_1 \cos \int_0^z K dz + C_2 \sin \int_0^z K dz \right)$$

Substitution of this in (5) gives

$$\Delta T = \sqrt{\frac{K}{P}} \left(-C_1 \sin \int_0^z K dz + C_2 \cos \int_0^z K dz \right)$$

With the initial conditions $\Delta\phi = \Delta\phi_i$ and $\Delta T = \Delta T_i$ when $z = 0$ (at the beginning of the resonator), we obtain

$$C_1 = \sqrt{\frac{K_i}{P_i}} \Delta\phi_i \text{ and } C_2 = \sqrt{\frac{P_i}{K_i}} \Delta T_i, \text{ so}$$

$$\Delta\phi = \sqrt{\frac{P}{P_i} \frac{K_i}{K}} \Delta\phi_i \cos \int_0^z K dz + \sqrt{\frac{P_i P}{K_i K}} \Delta T_i \sin \int_0^z K dz \quad [14]$$

$$\Delta T = -\sqrt{\frac{KK_i}{PP_i}} \Delta\phi_i \sin \int_0^z K dz + \sqrt{\frac{P_i K}{K_i P}} \Delta T_i \cos \int_0^z K dz \quad [15]$$

In most cases, the last two terms in [11A] can be neglected relative to PQ and we have

$$\begin{pmatrix} \Delta\phi \\ \Delta T \end{pmatrix} = (M) \begin{pmatrix} \Delta\phi_i \\ \Delta T_i \end{pmatrix}$$

where

$$(M) = \begin{pmatrix} \sqrt{\frac{4P}{P_i}} \cos \psi + \sqrt{\frac{4P_i P}{Q^2}} \sin \psi \\ -\sqrt{\frac{4Q^2}{PP_i}} \sin \psi + \sqrt{\frac{4P_i}{P}} \cos \psi \end{pmatrix} \quad [16]$$

and

$$\psi = \int_0^z K \, dz \approx \int_0^z \sqrt{PQ} \, dz \quad [17]$$

B. Longitudinal Transfer Matrix in a Drift Space.

In [16], set $P = P_1$ (since $\Delta T = \Delta T_1$) and $Q = 0$ (since $\overline{\mathcal{E}}_{ax} = 0$); we obtain the transfer matrix of a drift space

$$M = \begin{pmatrix} 1 & P L \\ 0 & 1 \end{pmatrix} \quad [18]$$

where L is the length of the drift space and P is given by [7].

APPENDIX 12. TRANSVERSE MOTION AND FOCUSING

Calculating the effect of transverse forces in the linac provides:

- (1) the focusing strength-values for correct transverse beam behavior, and
- (2) details of transverse beam behavior at any point along the linac.

Solenoid Focusing and Resonator Defocusing

The paraxial transverse equations of motion in solenoid and resonator may be written (respectively) as

$$\frac{d^2 r}{dz^2} = \frac{dr'}{dz} = -K_S(z)^2 r \quad \text{and} \quad \frac{d^2 r}{dz^2} = K_R(z)^2 r, \quad [1]$$

(The solenoid focuses, the resonator defocuses). Neither $K_S(z)$ nor $K_R(z)$

are constant with z , but a suitable average may be treated as constant within the solenoid or resonator, to an adequate approximation. For further simplification of calculation,

another approximation may be used, in which the integrated transverse force in solenoid or resonator is applied as a delta function. In this approximation, each system is treated as a thin lens. For the solenoid,

$$K_S(z)^2 = \Gamma B_z(z)^2; \quad \Gamma = \left(\frac{1}{2} \frac{q}{A} \frac{ec}{m_0 c^2} \right)^2 \frac{1}{\beta^2} \quad [2]$$

Averaging,

$$K_S^2 L_S = \int_{-\infty}^{\infty} K_S(z)^2 dz = \Gamma \int_{-\infty}^{\infty} B_z(z)^2 dz = \Gamma B_0^2 L_S, \quad [3]$$

where L_S is defined as the "effective solenoid length" and B_0 is the central axial field. It is readily shown that if the focal length $F_S \gg L_S$,

$$\text{then} \quad \frac{1}{F_S} = K_S^2 L_S \quad [4]$$

For the resonator, the axial field is written in Fourier components as

$$E(z, t) = E_{ax}^0 \sum a_n \cos \frac{2\pi n z}{L_R} \cos(\omega t - \phi) \quad [5]$$

where L_R = electrical length of resonator and ϕ is the phase offset. Then,

a similar average gives, for $F_R \gg L_R$,

$$\frac{1}{F_R} = \int_{-\infty}^{\infty} K_R(z)^2 dz = \pi \frac{q}{A} \frac{e}{m_0 c^2} \frac{E_{ax}^0 \sin \phi}{\beta^2} \tau_{av}^R \quad [6]$$

where τ_{av}^R is a suitably normalized radial transit time factor, averaged over all harmonic components.

For calculating particle motion, the solenoid is treated as a thin lens

acting at the center, with a drift space before and after the lens. Thus, the motion from beginning to end of the effective solenoid length is described by the matrix equation

$$\begin{pmatrix} n \\ n' \end{pmatrix}_{out} = \begin{pmatrix} 1 & \frac{1}{2}L_S \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{F_S} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{1}{2}L_S \\ 0 & 1 \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}_{in} \quad [7]$$

where ("in", "out") refer to the ends of the effective solenoid length.

The resonator is treated similarly, with the equivalent thin lens at the center and a drift space fore and aft. Then

$$\begin{pmatrix} n \\ n' \end{pmatrix}_{out} = \begin{pmatrix} 1 & \frac{1}{2}L_R \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{F_R} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{1}{2}L_R \\ 0 & 1 \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}_{in} \quad [8]$$

For focal length values F_S and F_R actually occurring in the linac, the condition $F_R/L_R \gg 1$ holds, but $F_S/L_S \gg 1$ does not. Hence, the resonator is a thin lens to a good approximation, but the solenoid is not. In fact, using this approximation leads to underestimating the solenoid current required for the desired focusing. Nevertheless, the simple equations from this approach provide useful preliminary values for the solenoid strength needed. Eq. [1] can be solved without this approximation and an explicit matrix determined. It is most useful with a constant K_S , an average of $K_S(z)$. The matrix is given by:

$$\begin{pmatrix} n \\ n' \end{pmatrix}_{out} = \begin{pmatrix} \cos K_S L_S & \frac{1}{K_S} \sin K_S L_S \\ -K_S \sin K_S L_S & \cos K_S L_S \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}_{in} \quad [9]$$

with

$$K_S L_S = \sqrt{\Gamma} \int_{-\infty}^{\infty} B_z(z) dz = \sqrt{\Gamma} B_0 L_S \quad [10A]$$

and

$$\sqrt{\Gamma} = \frac{1}{2} \frac{q}{A} \frac{ec}{m_0 c^2} \frac{1}{\beta} \quad [10B]$$

This L_S is not the same as in [3], because of the different modes of averaging.

Although the solenoid strength value from [9] is more accurate, solving the resulting transcendental equation is harder, and a more easily calculated explicit solution may be formed from another approximation. With K_S^2 and L_S^2

defined in [3], the solenoid is replaced by two thin lenses, each with half the full solenoid strength (hence, focal length $2F_S$), placed a distance aL_S from each solenoid end. The full solenoid is then three drift spaces and two thin lenses. Over the entire L_S -length (Fig. 1).

$$\begin{pmatrix} r \\ r' \end{pmatrix}_{out} = \begin{pmatrix} 1 & aL_S \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2F_S} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_S(1-2a) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2F_S} & 1 \end{pmatrix} \begin{pmatrix} 1 & aL_S \\ 0 & 1 \end{pmatrix} \begin{pmatrix} r \\ r' \end{pmatrix}_{in} \quad [11]$$

For the dimensions used in the linac, [11] is a good approximation for $a \approx 1/8$.

Application of Periodic Structures Theory

(Based upon results from: Courant and Snyder, Ann.Phys. 3, 1 (1958)).

The theory applies when the equation of transverse motion is

$$\frac{d^2 r}{dz^2} + h(z)r = 0 \quad [12A]$$

and the coefficient $h(z)$ is periodic along z with a period $2L$, so that

$$h(z + 2L) = h(z) \quad [12B]$$

This means that both structures and radial forces are repeated at regular intervals. Eq. [12A] applies quite accurately in the linac, but [12B] less so, primarily because the spacings have some changes from periodicity, particularly between cryostats, but also because focusing (and defocusing) strengths change as the particle energy increases. Nevertheless, this theory is useful as a local approximation to each portion of the linac.

Following are some results of the theory:

- (1). Over one period distance ($\Delta z = 2L$), the transformation matrix may be

$$\text{written as } \begin{pmatrix} r \\ r' \end{pmatrix}_{out} = \begin{pmatrix} \cos \mu + \alpha \sin \mu & \beta \sin \mu \\ -\gamma \sin \mu & \cos \mu - \alpha \sin \mu \end{pmatrix} \begin{pmatrix} r \\ r' \end{pmatrix}_{in} \quad [13]$$

μ is the "radial oscillation phase change per period".

- (2). Each particle undergoes a "pseudo-harmonic" motion along z , and at any

$$z, \quad \gamma r^2 + 2\alpha r r' + \beta r'^2 = A_0 = \text{constant}, \quad [14]$$

the equation of an ellipse. (γ, α, β) are functions of z . The

largest Λ_0 -value applying to the particles in the beam may be identified with the beam emittance ϵ , and the ellipse [14] is then an envelope enclosing all (r, r') coordinates of particles in the beam.

- (3). At any z , the maximum r -value in the beam is

$$r_{MAX} = \sqrt{\epsilon \beta(z)} \quad [15]$$

- (4). Since $d\beta/dz = -2\alpha$, r_{MAX} in the beam is smallest (or largest) at a z -value where $\alpha = 0$, i.e., where the ellipse axes lie along the (r, r') axes. If such a z -value is chosen for the end of a period, then [13]

$$\text{becomes} \quad \begin{pmatrix} r \\ r' \end{pmatrix}_{out} = \begin{pmatrix} \cos \mu & \beta \sin \mu \\ -\gamma \sin \mu & \cos \mu \end{pmatrix} \begin{pmatrix} r \\ r' \end{pmatrix}_{in} \quad [16]$$

- (5). Since $\beta\gamma = 1$, the matrix has two independent components, $\cos \mu$ and $\beta \sin \mu$. To minimize β at the end of the period, $\sin \mu$ is maximized at $\mu = \pi/2$, hence $\cos \mu = 0$. r_{MAX} is then the smallest attainable whether it is a maximum or minimum (over z).

The purpose of correctly determining focusing strengths is to insure that: (1) none of the beam injected from the tandem strikes the beam tube or resonator, and (2) within the resonators, the beam remains as close to the axis as possible. The latter is desired because the accelerating field increases away from the axis, hence too large an r -range in the beam leads to deterioration of energy resolution. The emittance of the tandem beam is small enough and the dimensions of beam tube and resonators are large enough that, given even moderate focusing strength, collision with the walls is no problem. The chief goal of optimally controlling the focusing is to minimize r -values in the resonators, and this is achieved by getting the minimum β -value at point B in Fig. 2.

Although the linac is not in fact an actual periodic structure, it is quasi-periodic. The solenoid focusing strength may then be calculated by treating each cell (containing two resonators and one solenoid), as a local "period", and applying the formalism of the periodic structures theory. The transfer matrix for one cell is calculated, introducing the actual $h(z)$ function or its equivalent. The resulting matrix elements are equated to those in [16] and choosing the μ -value then defines the focusing strength needed. The

approximation treating the solenoid as a thin lens provides the simplest equations, but the process can also be carried out with the more accurate treatments of the solenoid.

In Fig. 2A, $\Delta z = AC$ is one cell, as is $\Delta z = BD$. Even with the uniform dimensions shown, the focal lengths of the three resonators differ, because the velocities (v_2, v_3, v_5) are not the same. For the periodic structures application, the focal length F_R may be taken as the average for the two resonators used in one cell. Then

$$\begin{pmatrix} n \\ n' \end{pmatrix}_C = M_{AC} \begin{pmatrix} n \\ n' \end{pmatrix}_A \quad \text{and} \quad \begin{pmatrix} n \\ n' \end{pmatrix}_D = M_{BD} \begin{pmatrix} n \\ n' \end{pmatrix}_B \quad [17A]$$

with

$$M_{BD} = \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{F_R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{F_S} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{F_R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \quad [17B]$$

where (using $L_{12} = L_1 + L_2$)

$$\left. \begin{aligned} m_{22} = m_{11} &= 1 + \frac{2L_{12}}{F_R} + \frac{2L_1L_2}{F_R^2} - \frac{L_1L_2}{F_RF_S} - \frac{L_{12}}{F_S} - \frac{L_1L_{12}}{F_RF_S} - \frac{L_1^2L_2}{F_R^2F_S} \\ m_{12} &= 2L_{12} + \frac{2L_1L_2}{F_R} + \frac{2L_2L_{12}}{F_R} + \frac{2L_1L_2^2}{F_R^2} - \frac{L_{12}^2}{F_S} - \frac{2L_{12}L_1L_2}{F_RF_S} - \frac{L_1^2L_2^2}{F_R^2F_S} \\ m_{21} &= \frac{2}{F_R} - \frac{1}{F_S} + \frac{2L_1}{F_R^2} - \frac{2L_1}{F_RF_S} - \frac{L_1^2}{F_R^2F_S} \end{aligned} \right\} \quad [17C]$$

If the value μ_0 is chosen for the phase advance per cell, then $m_{11} = m_{22} = \cos \mu_0$ and (with $\delta_1 = L_1/F_R$ and $\delta_2 = L_2/F_R$)

$$\frac{F_S}{L_{12}} = \frac{1 + \delta_1 \left(1 + \frac{L_2}{L_{12}} + \frac{L_2}{L_{12}} \delta_1 \right)}{1 + 2(\delta_1 + \delta_2) + 2\delta_1\delta_2 - \cos \mu_0} \quad [18]$$

Since $m_{12} = \beta_0 \sin \mu_0$, where β_0 is the β -value at D (or B) in Fig. 2A,

$$\frac{\beta_0 \sin \mu_0}{2L_{12}} = 1 + \delta_2 \left(1 + \frac{L_1}{L_{12}} + \frac{L_1}{L_{12}} \delta_2 \right) - \frac{L_{12}}{2F_S} \left(1 + 2\frac{L_1}{L_{12}} \delta_2 + \frac{L_1^2}{L_{12}^2} \delta_2^2 \right) \quad [19]$$

Similarly, β_1 , the β -value at the solenoid center A or C, is evaluated from M_{AC} , where F_S and F_R are averages for the two solenoids and two resonators, respectively. Then

$$M_{AC} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2F_S} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{F_R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{F_R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2F_S} & 1 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \quad [20]$$

As expected, $m_{11} = m_{22}$ are the same as in [17C], and from $m_{12} = \beta_1 \sin \mu_0$,

$$\frac{\beta_1 \sin \mu_0}{2L_{12}} = 1 + \delta_1 + \frac{L_2}{L_{12}} (\delta_1 + \delta_1^2) \quad [21]$$

Example. $^{58}\text{Ni}^{20+}$ ion at $\beta = 0.09$, $\mathcal{E}_{ax}^0 = 3.5$ MV/m, $q/A = 20/58$, $\phi = 20^\circ$.

From [6], $F_R = 4.31$ m. In the linac, $L_1 = 0.394$ m, $L_2 = 0.230$ m, $L_{12} =$

0.624 m. Then $\delta_1 = 0.0914$, $\delta_2 = 0.1067$. From [18], $1/F_S = 1.993 -$

$1.407 \cos \mu_0$. For two μ_0 -values (45° , 90°), F_S , β_0 and β_1 are given by

μ_0	F_S	$\frac{\beta_0 \sin \mu_0}{2 L_{12}}$	$\frac{\beta_0}{2 L_{12}}$	$\frac{\beta_1 \sin \mu_0}{2 L_{12}}$	$\frac{\beta_1}{2 L_{12}}$
90°	0.501 m	0.472	0.472	1.128	1.128
45°	1.003	0.827	1.169	1.128	1.595

Operationally, the solenoid F_S has been calibrated against current, and this value is applied for focusing.

From [15], r_{MAX} for the beam is smaller at point B (Fig. 2A) when $\mu_0 = \pi/2$, and is also smaller at the greatest beam excursion (solenoid center). This result is illustrated in the example. The shorter focal lengths needed for $\mu_0 = \pi/2$ of course require higher solenoid currents. The high fields available in the superconducting solenoids used in the linac will allow the choice of $\mu_0 = \pi/2$ for all ions except the very heaviest where q/A is low. For these, μ_0 will be allowed to decrease somewhat, so $\cos \mu_0 > 0$.

For more accurate results, the matrix in [9] may be substituted for that in [7], using Fig. 2B to construct the sequence of matrices. Matrix multiplication gives equations analogous to [17C] which contain terms in $\cos(K_S L_S)$ and $\sin(K_S L_S)$; $K_S L_S$ is calculated by solving the transcendental equation. Comparably accurate results derive from the two-thin lens approximation for a solenoid, as in Eq. [11], using Fig. 2C to construct the matrix sequence. An explicit solution like, though more complicated than, [18] can be written.

Calculating F_S is repeated for each "period" down the linac, because of changes in L_1 and L_2 and in the particle velocity. The equations are modified where the structure in a cell is not symmetric, as at the shift from low- to high- β resonators and between cryostats.

The (m_{12}, m_{13}) values set the (β, γ) values, which determine the shape of the (r, r') ellipse in [14]. The ellipse shape transforms down the linac with the same matrices as are used in [17B] or [20], or the equivalent matrices when a different solenoid model is used.

A beam is matched if it is injected into the linac with an ellipse shape which will transform into the correct (β, γ) values at the equivalent B position (Fig. 2). The solenoid strength calculations with the thin-lens approximation are adequate, especially with a beam of as low emittance as that of a tandem, to focus the beam so it gets through the linac. The more accurate solenoid calculation allows realistic estimation of the beam ellipses. However, because of the approximation involved in applying periodic structures theory, accurate minimization of the beam size and correct matching uses "fine-tuning". This involves use of an interactive computer program which allows the beam ellipses to be calculated down the linac using successive matrix multiplication.

Fig. 1

Fig. 2A

Fig. 2B

Fig. 2C

APPENDIX 13.

CHARGE-STATE DISTRIBUTIONS

The centroid and width of the charge-state distributions after passage through thin foils or gas volumes are very important for the prediction of the performance of heavy-ion accelerators. These distributions have been studied for a large number of ion species and energies. Much of this work has been summarized in the review article by Betz [Betz, 1972], while some data for higher-energy heavy ions were published more recently by Clark et al. [Clark, 1976].

It is found that the charge distribution is quite well described by a Gaussian curve of the form

$$F(q) = \frac{1}{\sqrt{2\pi}d} \exp \left\{ - (q-q_0)^2 / 2d^2 \right\}, \quad (1)$$

where q_0 is the mean value and d is the standard deviation of the distribution. Nilolaev and Dimitriev [Nilolaev, 1968] have found the following relationship between d and q_0 ,

$$d = 0.5 \sqrt{q_0 [1 - (q_1/z)^{5/3}]} \quad (2)$$

where q_0 for solid strippers is given by

$$q_0^{\text{foil}} = \frac{1}{[1 + (\frac{v_1 z^{0.45}}{v})^{5/3}]^{2/3}} \quad (3)$$

Here $v_1 = 3.6 \times 10^8$ cm/s and v is the ion velocity.

We have found that the average charge-state distribution for gas strippers (O_2 , Ne and Ar gasses) is well represented by the relation

$$q_o^{\text{gas}} = \frac{Z}{[1 + (\frac{1.75 v_o Z^{0.55}}{v})^{5/3}]^{2/3}}, \quad (4)$$

where $v_o = 2.2 \times 10^8$ cm/s is the Bohr velocity.

The above relations give a good representation of both the data analyzed in Betz' review article and of more recent data for higher energies [Clark, 1976], and are therefore used in the calculation of the beam energy and intensity performance of ATLAS.

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