CONF-790743--9

HEAVY-ION-LINAC POST-ACCELERATORS

by

Lowell M. Bollinger

MASTER

Prepared for

Symposium on

Heavy Ion Physics from 10 to 200 MeV/A

Brookhaven, New York

July 16-20, 1979

UofC-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the
U. S. DEPARTMENT OF ENERGY

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) among the U. S. Department of Energy, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona
Carnegie-Mellon University
Case Western Reserve University
The University of Chicago
University of Cincinnati
Illinois Institute of Technology
University of Illinois
Indiana University
Iowa State University
The University of Iowa
Kansas State University
The University of Kansas
Loyola University
Marquette University
Michigan State University
The University of Michigan
University of Minnesota
University of Missouri
Northwestern University
University of Notre Dame
The Ohio State University
Ohio University
The Pennsylvania State University
Purdue University
Saint Louis University
Southern Illinois University
The University of Texas at Austin
Washington University
Wayne State University
The University of Wisconsin

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the U. S. Department of Energy.

Heavy-Ion-Linac Post-Accelerators*

Lowell M. Bollinger
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

The main features of the tandem-linac system for heavy-ion acceleration are reviewed and illustrated in terms of the technology and performance of the superconducting heavy-ion energy booster at Argonne. This technology is compared briefly with the corresponding technologies of the superconducting linac at Stony Brook and the room-temperature linac at Heidelberg. The performance possibilities for the near-term future are illustrated in terms of the proposed extension of the Argonne booster to form ATLAS.

I. INTRODUCTION

I have been asked to give a brief review of the characteristics of linacs used as energy boosters for heavy-

---

*Work performed under the auspices of the Office of Basic Energy Sciences of the U. S. Department of Energy.

ion beams from tandem electrostatic accelerators. Three linacs of this kind need to be considered: (1) the superconducting linac at Argonne, now a useful (but incomplete) machine, (2) the room-temperature linac at Heidelberg, also in use and incomplete, and (3) the recently funded superconducting linac at Stony Brook, being built in collaboration with a group from Cal Tech. Although these three projects make use of rather different technologies, they all have the same basic objectives — to extend the energy range of the tandem without much loss of beam intensity or beam quality. That is, the characteristics of these tandem-linac systems are all aimed at the needs of precision high-resolution nuclear-structure physics of the kind that could be carried out with a very large tandem, if one could afford to buy such a tandem.

II. BASIC FEATURES OF A TANEM-LINAC ACCELERATOR SYSTEM

Before starting to discuss the characteristics of any particular tandem-linac system, let us make sure that the basic acceleration process is understood. Figure 1 is a schematic of the main elements in a tandem-linac system. The tandem is operated in the usual way, with a negative-ion source near ground potential and a stripper in the high-voltage terminal.

Before injection into the linac, the ion beam from the tandem is usually stripped a second time in order to increase the charge state. However, if the linac has enough accelerating power to provide the desired output-beam energy at the original charge state, then the second stripper is not used, thus increasing the beam intensity. Several schemes for three-stage stripping are feasible, but there is rather little interest in them because of the loss in beam intensity.

In order to preserve the beam quality of the tandem, the linac requires an injected beam that is bunched into very narrow pulses ($\lesssim$ 100 ps) synchronized to the rf frequency of the linac. Also, because of the low intensity of a doubly-stripped tandem beam, the bunching process must be carried out without much loss of intensity. These demanding objectives (narrow pulse and high efficiency) are achieved by two-stage bunching[1]: (1) a harmonic buncher before the tandem puts most of the dc beam from the source into pulses that are about 1 ns wide at the tandem output, and then (2) a more powerful post-tandem resonator compresses the tandem pulse to the desired 100-ps width. A beam chopper removes unbunched particles.

A new and essential feature of the bunching system is the need to correct continuously for the effect of uncontrolled variations in the transit time of the beam through the tandem. This is achieved by sensing continuously the rf phase with which the beam bunch arrives at the post-tandem buncher and by using this information to control the phase of the pre-tandem buncher. Since beam bunches may not be intense enough to be detected individually and nondestructively, the phase detector needs to be able to sense the integrated effect of many pulses.

A distinctive feature of the linacs of interest for this paper is that they all consist of an array of many short, independently-phased fix-frequency rf resonators; the rf frequencies involved in the several linacs range from 97 to 152 MHz. Because each resonator has only a few (two or three) accelerating gaps, it can accelerate effectively over a fairly wide range of ion velocity, as seen in Fig. 2. The velocity profile of the system of resonators is established by adjusting the phase of each resonator to match the phase of the beam incident on it. The output beam energy can be varied easily and rapidly by varying the phase and/or accelerating field of the last resonator.

Normally, the linac is operated in a phase-focussing mode in which a beam-energy excursion tends to be corrected by means of its interaction with the phase. The degree to which the incident-beam quality is preserved depends in a complicated way on this phase-focussing effect and on the extent to which the accelerating field varies linearly with time over the width of the beam pulse. This linearity requirement, which is rather extreme, is another distinctive feature of the new heavy-ion boosters and is the reason that the incident beam pulse should be exceptionally narrow.

Radial excursions of the beam are controlled by focussing elements located frequently along the linac. These transverse lenses are needed to counterbalance the defocussing effect of the resonators but especially to control the unavoidable tendency of a beam with non-zero emittance to diverge. In order to minimize non-linear effects in both transverse and longitudinal (energy-time) phase space, the beam diameter should be much smaller than the diameter of the drift-tube aperture.

Because of the rather small size of the beam within the linac, easily achieved because of the good emittance of a tandem beam, the beam transmission of the linac is essentially 100 percent. Thus, the intensity of the beam out of the linac depends primarily on the performance of the ion source and tandem and on the stripping process. For double stripping, the output-beam intensity (particles per sec) can be in the range 2 to 4% of the intensity injected into the tandem, for very heavy and lighter ions, respectively.

Although the essential quality of the incident beam can be preserved in the linac, the acceleration process is such that the output beam may have a rather large energy spread. Also, even if the beam pulse is very narrow at the linac output, it may be greatly broadened by the time it reaches a down-stream experiment. Thus, in order to benefit from the inherent beam quality (small product $\Delta E \Delta t$), one must debunch the beam (increase Δt and decrease ΔE) if a small energy spread is desired and rebunch the beam if a narrow pulse is desired by the experiment. A single resonator well downstream from the linac can perform either of these functions, and such a debuncher/rebuncher should be considered to be an integral part of a tandem-linac accelerator system.

III. BRIEF DESCRIPTION OF ANL SUPERCONDUCTING LINAC

The linac of a tandem-linac system was described above in terms of rather general ideas related to performance. In order to give a taste of the hardware required to achieve this performance in practive, let me describe briefly the Argonne superconducting booster[1-4]. The layout of the accelerator system is shown in Fig. 3. The tandem is an upgraded FN tandem, the booster is located in a former target room, and the beam from the booster goes into a small new experimental area*. The bunching system between the tandem

---

*Figure 3 does not show the proposed ATLAS system, which involves an extension of the linac and the construction of a large new target area (see Fig. 12).

and the linac has the general characteristics described in section II and is described in detail in Ref. 5 and 6.

A schematic representation of the booster as it is expected to be in late 1980 is shown in Fig. 4. The heart of the system is the split-ring resonator[7], 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 different lengths. One type is 35.6 cm long and is optimized for a projectile velocity $\beta \equiv v/c = 0.105$ (sections C and D). A second type is 20.3 cm long and is optimized for $\beta = 0.060$.

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. 5. The rf power dissipation into liquid helium is typically 4 watts per resonator. The inner assembly is cooled by 4.8 K liquid helium within the hollow loading tubes 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-in diameter superconducting probe. Fast tuning is achieved by means of a high-power voltage-controlled reactance (VCX), which is used to lock the rf phase of each resonator to the phase of a master oscillator.

The performance characteristics of the high-β resonators are given by Fig. 6. The design aim is an average accelerating field of 4.25 MV/m for a power loss of 4 watts, which implies a voltage gain of 1.5 MV (i.e., 1.5 MeV per charge) from each unit. Note that the performance of individual resonators is at this goal. The resonators in the booster are initially being operated at a somewhat lower field, in the range 3.0 to 3.5 MV/m, and will gradually be pushed up to the design goal when several limitations have been removed. The accelerating field of the 20-cm units is about the same (for the same power dissipation) as the field in the larger units but, of course, the integrated voltage gain of the shorter unit is smaller.

The resonators are cooled to a temperature of about 4.8 K by means of flowing two-phase helium in a closed circulating system[8]. 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 7 gm/s at 4.6 K.

The superconducting solenoids[9] used to limit the transverse excursions of the beam are hybrid magnets consisting 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 beam to be focussed to a waist between each pair of solenoids. Flowing liquid helium cools the solenoids in the same way as the resonators.

All of the cryostats for the booster are end-loading units, and except for section A, all are of the same size. An assembly drawing of a cryostat with resonators in place is shown in Fig. 7, and an impression of an accelerator section during assembly is given by Fig. 8.

In each cryostat, the array of resonators is surrounded by a nitrogen-cooled heat shield and, outside of it, a vacuum wall (see Figs. 4 and 7). Even though the interior of the resonator is open to the outer vacuum region, including the warm outer vacuum wall, the pressure inside the resonators is extremely low ($<< 10^{-8}$ Torr) during operation because of cryopumping on the outer surfaces 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 line. Once off line, the whole inner assembly of an accelerator section can be rolled out the end of the cryostat, and all disassembly is then done in the open. When a section is ready to be put into service, it can be 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 sections 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 temperature 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 beam from the linac passes into a small new target room that houses a large new scattering chamber, an existing spectrograph, and various specialized reaction chambers. A debunching/rebunching resonator on the main beam line manipulates the phase ellipse of the output beam to meet the needs of the experimenter.

IV. STATUS OF ANL BOOSTER PERFORMANCE

From the point of view of most members of this audience, the most important news about the superconducting linac is, I suppose, that it is now a working reality for heavy-ion acceleration. The four-section ANL booster described by Fig. 4 is some eighteen months from completion but, because of its modular characteristics, the two completed sections are already being used to provide useful beams for nuclear-physics research. The first beam-acceleration tests, with two resonators, were made in June 1978, and this small beginning has by now progressed to the almost routine operation[3] of the accelerator system shown in Fig. 9. In total, some 1800 hours of beam time have been logged.

In the most recent series of runs, carried out with eight resonators throughout the month of June 1979, four different nuclear-physics experiments were performed. Three ion species were accelerated, as summaried by Table I. The maximum energies achieved imply that, on average, the resonators provide 1.2 MV of accelerating potential, yielding a total of 9.3 MV. Equivalently, the average accelerating field within the resonators is 3.3 MV/m. The energy performance of the tandem-linac system as a whole may be summarized by the statement that it is equivalent to that of a 15-MV tandem with two stripper for ions with $A \geq 40$.

As many of you are aware, one of the most difficult problems connected with the use of superconducting resonators has been to control the influence of mechanical vibrations on the resonant rf frequency and hence on the rf phase. This problem has recently been solved[3] in the ANL resonators by simultaneously using two control techniques: (1) negative phase feedback with stored energy from a voltage-controlled reactance is used to lock the resonator phase to the master oscillator, and (2) amplitude modulation and electromechanical coupling is used to dampening mechanical motion. During the June 1979 runs, all eight resonators were in phase lock about 99% of the time, and almost all out-of-lock time was generated by occasional malfunctions by two of the eight resonators.

As a result of the recent breakthrough in phase control, the superconducting booster now runs with great reliability and has been operated for many long periods of time (∿ 24 hours) without human intervention. Throughout the set of runs in June 1979, the system was operated by the beam users much of the time, with linac-development personnel available on an on-call basis. Even the procedures involved in changing beam energy are simple enough that the user can carry them out after a few minutes of instruction.

A very attractive feature of the independently-phased linac is that, because of its modular design and because of the flexibility provided by independent phase, almost any resonator configuration can accelerate a beam, and hence the linac can provide useful beams long before the system is completed. The past and projected performance of the ANL booster at several stages of completion are summarized by Fig. 10. The present eight-resonator system is useful mainly for ions with $A \lesssim 40$, since the high-β resonators now in use cannot effectively accelerate the slow-moving ions of greater mass. The next step, scheduled for completion in October, will be to add four more resonators and thus increase the beam energy substancially. And finally, the mass range will be extended, first by putting four low-β resonators in section A (early 1980) and then by adding section B, which ultimately will have seven low-β resonators.

V. COMPARISON OF LINAC POST-ACCELERATORS

Time limitations do not permit me to give descriptions of the Stony Brook-Cal Tech and the Heidelberg linacs except in the bare outline given by Fig. 11 and Tables II and III. The planned sizes of the systems are summarized in Fig. 11, where the length drawn for each linac is proportional to its accelerating voltage and where the status of construction and funding is indicated. Note that, because of its more powerful injector, the Heidelberg linac provides a substancially higher beam-output energy, for a given linac voltage, than do the other two systems.

Tables II and III provide the basis for a comparison of the technologies and the costs of the three boosters. The main thrust of the ANL design has been to develop the ultimate in resonator and linac performance. The best available rf superconductor (niobium) was chosen so as to minimize rf losses on the helium-cooled surfaces, and the rf frequency was made as low as feasible so as to minimize the difficulty of beam bunching. Both decisions have resulted in severe developmental and fabrication problems. Now that the technology is well developed, however, one need consider only construction and operating costs, and operational effectiveness.

The individual ANL resonators are very costly but, because of the large energy gain provided by each unit, the overall system cost is competitive with other designs. The small number of units required to form a complete booster is expected to be advantageous from the point of view of operational ease and reliability. The low rf frequency and large drift tubes help preserve the incident beam quality.

The recently funded Stony Brook linac[10,11] will also consist of superconducting split-ring resonators[12], but the superconductor is lead plated on a copper base, a technology developed at Cal Tech. As in the Argonne design, two sizes of resonators will be used: 16 units with $\beta = 0.055$ and 21 units with $\beta \approx 0.10$.

The lead-plated resonators cost much less than the ANL niobium structure, but the higher surface resistivity and the low critical magnetic field of lead are drawbacks that have important impacts on the resonator design. In particular, the properties of lead result in a design with (1) a relatively high rf frequency (152 MHz), (2) very small drift tubes, and (3) a simple circular form for the loading arms that support the drift tubes. These characteristics make resonator fabrication, helium distribution, and phase control considerably easier than for the ANL design. On the other hand, more helium refrigeration is required, and the smaller resonator size and lower accelerating fields measured to date combine to give an energy gain that is less than half that of the ANL resonators. Thus, although I do not have complete information about the projected costs of the Stony Brook linac, it appears that the overall construction costs per MV of acceleration are roughly the same for the two superconducting systems. The extent to which the higher rf frequency and the smaller drift tubes of the Stony Brook resonators are disadvantageous for beam quality remains to be seen from operational experience.

Although the technology involved in the Heidelberg room-temperature linac is entirely different from that of the superconducting linacs, the basic concepts are similar. The Heidelberg linac[13,14] consists of an array of independently-phased resonators of the spiral type, a two-gap structure with a single small-diameter drift tube. Because of the rather broad velocity acceptance of a two-gap accelerating structure (see Fig. 2), only one size of resonator is needed for a 10-MV booster of ions in the lower half of the periodic table.

The dominating cost of the room temperature linac is the cost for the rf-power transmitters. Consequently, the main emphasis of the Heidelberg design has been to minimize overall costs by using a 20-kw transmitter (a standard size in the communications industry) to drive each resonator and by optimizing resonator performance for this particular power level. The result is a system in which the accelerating field is relatively small and energy gain per resonator is small for continuous-wave operation, but the overall linac cost is lower than it would be if the accelerating field (and hence the power disappation) were substancially greater.

From our present prospective, the main drawbacks of the Heidelberg linac are its construction and operating costs, which are both substancially greater than for an equivalent superconducting linac. On the other hand, the fact that all components are obtainable commercially is an immense asset for most laboratories. The operational disadvantage of having very many independently controlled units (because of the low energy gain per resonator) tends to be counterbalanced by the easy accessibility of all components in a room-temperature system; also, many nuclear physicists seem to regard high-power rf technology as being easier to master than superconducting rf technology, but this may be a matter of taste.

A clear operational advantage of the room-temperature device is that the maximum beam energy can be extended substancially by operating the resonators in a pulsed mode. For example, the accelerating voltage of the Heidelberg resonators increase from 0.33 to 0.60 MV when they are pulsed with a 25% duty factor to a power level of 80 kW. Superconducting resonators can also be operated in a pulsed mode, but this capability is of little interest because, at the customary operating field, power loss increases so very rapidly with increasing field (see Fig. 6). On the other hand, the superconducting devices have a greater potential for future improvements in CW operation.

VI. THE ATLAS PROPOSAL

All of the tandem-linac systems described above are the first of their kind, prototypes of what is likely to be a steady stream of future accelerators. The most immediate of these future projects is the Argonne Tandem-Linac Accelerator System (ATLAS)[4], which has been favorably reviewed for funding in FY1981. Here I will mention only those features of ATLAS that illustrate some interesting aspects of the tandem-linac accelerator concept.

The overall layout of ATLAS is shown by Fig. 12. The present tandem and the 4-section booster described earlier will continue to be used in their original configuration. ATLAS involves the addition of three more linac sections and the construction of a large new target area.

The mass-energy performance of ATLAS is given by the upper curve of Fig. 13, where it is assumed that a gas stripper is used in the tandem terminal for A > 50. To some extent, the shape of the performance curve (which depends on resonator characteristics) is a matter of choice, especially with regard to the location of the mass cutoff. For ATLAS, it has been decided to emphasize the acceleration of ions in the lower half of the periodic table, and consequently the new resonators will be designed for the relatively high velocity $\beta \geq 0.135$. On the other hand, because of the modular nature of the cryostats, it would be feasible at a later time to extend the mass range by adding more low-β sections and by moving the various sections to the locations required to give the desired ion-velocity profile. The dashed extension of the upper curve illustrates the performance that could be achieved for an addition expenditure of about $1.2 million.

One of the most interesting aspects of ATLAS is the fact that it will be able to provide two beams without loss of the effective beam current to either. This is possible because, when the second stripper is at the entrance of the booster (as it will be), the booster accelerates all charge states above some critical value to about the same energy and with the same beam quality. Thus, at the 40° bend in the ATLAS linac one can form two beams, one of which is directed into Target Area II and the other into the second stage of linac acceleration. The maximum energies of the two beams are given in Fig. 14 by the curves labelled Area II and Area III. Because of the flexibility provided by independent phasing of the resonators, the energies of the beams going into Areas II and III can be independently varied.

As remarked earlier, one of the attractions of the superconducting approach to heavy-ion linacs is that there is a potential for substancial improvements in the technology, which is still in an early stage of development. An example of the unplanned benefits that can result from such advances in the technology is provided by a comparison of the curves labelled "original proposal" and "booster" in Fig. 13. In our case, the big unplanned technical advance was the conception of a new accelerating structure (the split ring) and the development of new techniques for resonator fabrication and control. There is every reason to believe that similar pleasant surprises remain in store for the future.

ACKNOWLEDGEMENTS

This paper would not have been possible, of course, without the hard, inovative work of the authors of references 1 through 9, my associates in the superconducting-linac project at Argonne. I am also grateful to P. Paul of Stony Brook and H. Ingwersen of Heidelberg for up-to-date information about the status of their respective projects.

REFERENCES

1. L. M. Bollinger, R. Benaroya, B. E. Clifft, A. H. Jaffey, K. W. Johnson, T. K. Khoe, C. H. Scheibelhut, K. W. Shepard, and T. P. Wangler, in Proc. 1976 Proton Linear Accelerator Conf., Chalk River Report AECL-5677, p. 95 (1976).

2. K. W. Shepard, IEE Trans. Nucl. Sci. NS-26, 3659 (1979).

3. J. Aron, R. Benaroya, L. M. Bollinger, B. E. Clifft, W. Henning, K. W. Johnson, J. M. Nixon, P. Markovich, and K. W. Shepard, to be published in Proc. 1979 Linear Accelerator Conf. (1979).

4. The most complete description of some aspects of the ANL superconducting-linac technology is given in the proposed document for ATLAS (February 1978) and in the Addendum to that proposal (December 1978). Copies may be obtained from the author of the present paper.

5. F. J. Lynch, R. N. Lewis, L. M. Bollinger, W. Henning, and O. D. Despe, Nucl. Instrum. Methods 159, p. 245 (1979).

6. R. N. Lewis, Nucl. Instrum. Methods 151, p. 371 (1978).

7. K. W. Shepard, C. H. Scheibelhut, P. Markovich, R. Benaroya, and L. M. Bollinger, IEE Trans. Mag. MAG-15, 666 (1979).

8. J. M. Nixon and L. M. Bollinger, to be published in Advances in Cryogenic Engineering.

9. A. H. Jaffey, R. Benaroya, and T. K. Khoe, in Proc. 1976 Proton Linear Accelerator Conf., Chalk River Report AECL-5677, p. 102 (1976).

10. J. W. Noé, P. Paul, G. D. Sprouse, G. J. Dick, and J. E. Mercereau, IEE Trans. Nucl. Sci. NS-24, 1144 (1977).

11. J. R. Delayen, G. J. Dick, J. E. Mercereau, J. W. Noé, P. Paul, and G. D. Sprouse, IEE Trans. Nucl. Sci. NS-26, 3664 (1979).

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

13. E. Jaeschke, H. Ingwersen, R. Repnow, Th. Walcher, B. Huck, and B. Kolb, IEE Trans. Nucl. Sci. NS-26, 3667 (1979).

14. E. Jaeschke, H. Ingwersen, R. Repnow, Th. Walcher, B. Huck, and B. Kolb, Nucl. Instrum. Methods 157, 195 (1978).

Table I. Ion beams accelerated by the ANL superconducting linac during June 1979.

Ion	Tandem Energy (MeV)	Max. Linac Energy (MeV)
^{16}O	61	128
^{28}Si	76	166
^{32}S	85	204

Resonator Performance:

$\bar{E}_a = 3.3$ MV/m

$\Delta V_R = 1.16$ MV

$\Sigma \Delta V_R = 9.3$ MV

Table II. Comparison of the technologies involved in tandem-linac heavy-ion accelerators for resonators with $\beta \approx 0.10$.

	Argonne	Stony Brook	Heidelberg
Resonator	Split Ring	Split Ring	Spiral
rf frequency	97	152	108
Conductor	SC Niobium	SC Lead	Copper
Acceleration (MV) per resonator	1.5	0.7	0.35
Design Emphasis	High-performance resonators	Cryogenic and resonator simplicity	Minimum rf power
Primary Problems	Resonator cost	High rf frequency	Cost of rf equipment
	Need for flowing LHe	Large No. of units	Cost of power

Table III. Comparison of costs for heavy-ion linacs. The number of asterisks associated with each item gives a rough measure of the relative cost of the item. The quantity "cost per MV" is intended to be the cost for reproducing the hardware of an existing design, including everything except the building.

	Argonne	Stony Brook	Heidelberg
Resonators	****	**	**
RF Power and Controls	**	***	***** ***** *****
Cryogenics	***	****	
Vacuum	*	*	*
Cost per MV	$125,000[a]		500,000 DM[b]

[a] In 1979 dollars.

[b] Cost reported by E. Jaeschke at the Symposium on Post Accelerators, held at Munich in September, 1978.

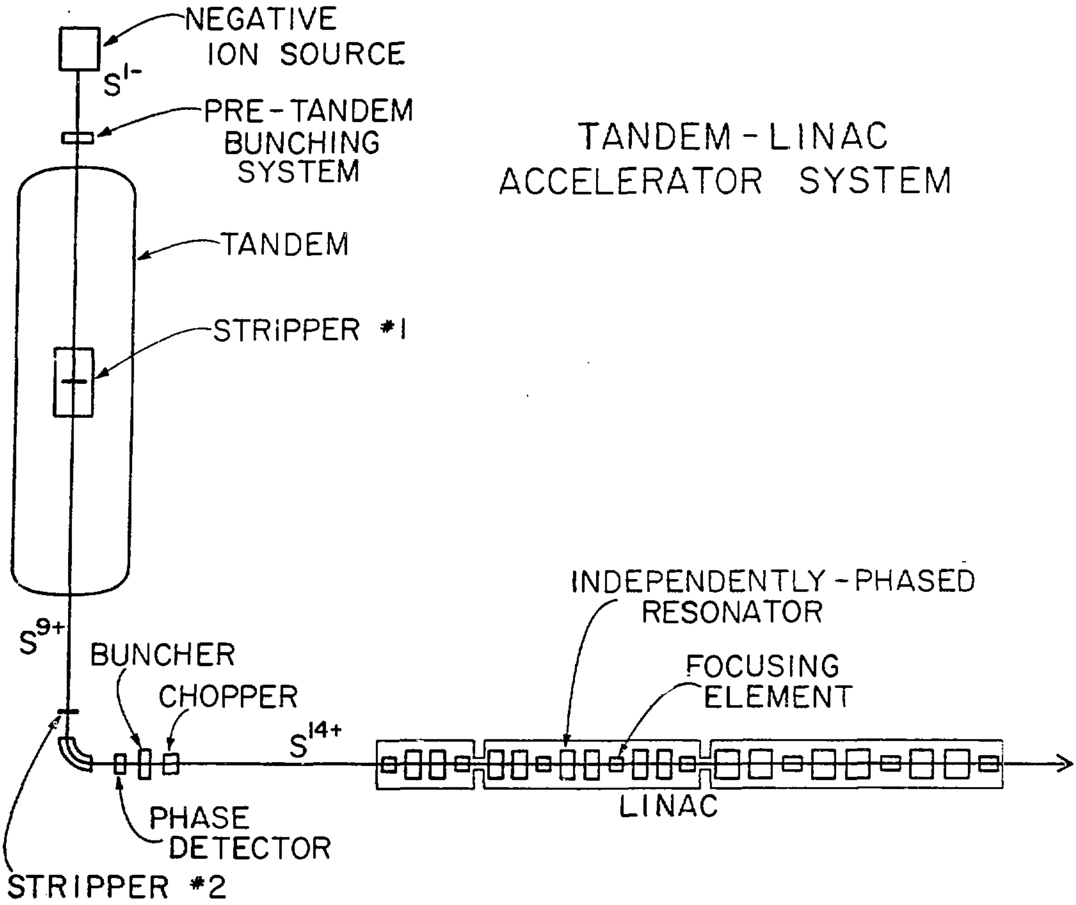

Figure 1. Schematic representation of a tandem-linac accelerator system, as used for the acceleration of ^{32}S ions.

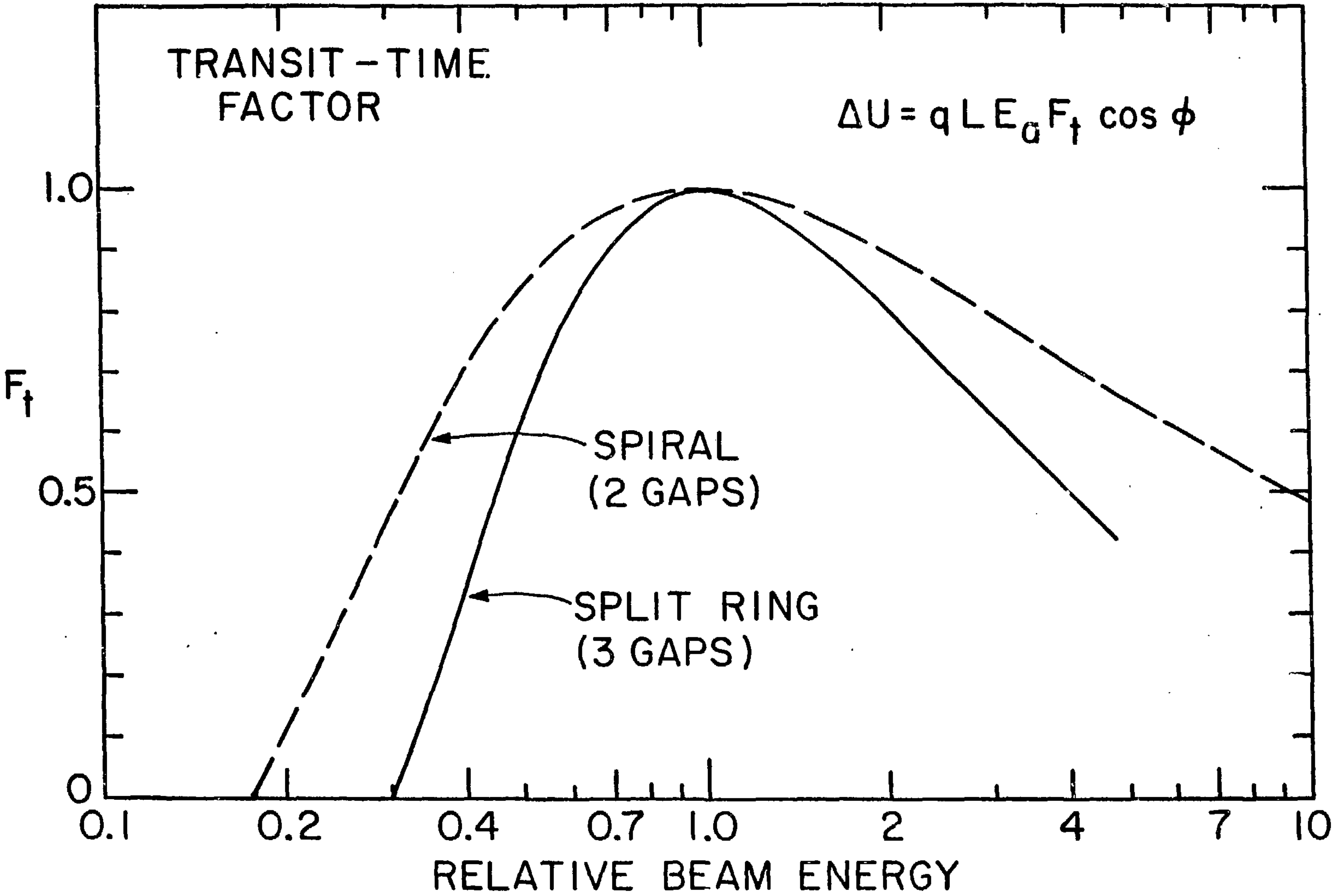

Figure 2. Transit-time factor F_t of 2-gap and 3-gap accelerating structures. The transit-time factor gives the relative accelerating voltage as a function of ion velocity.

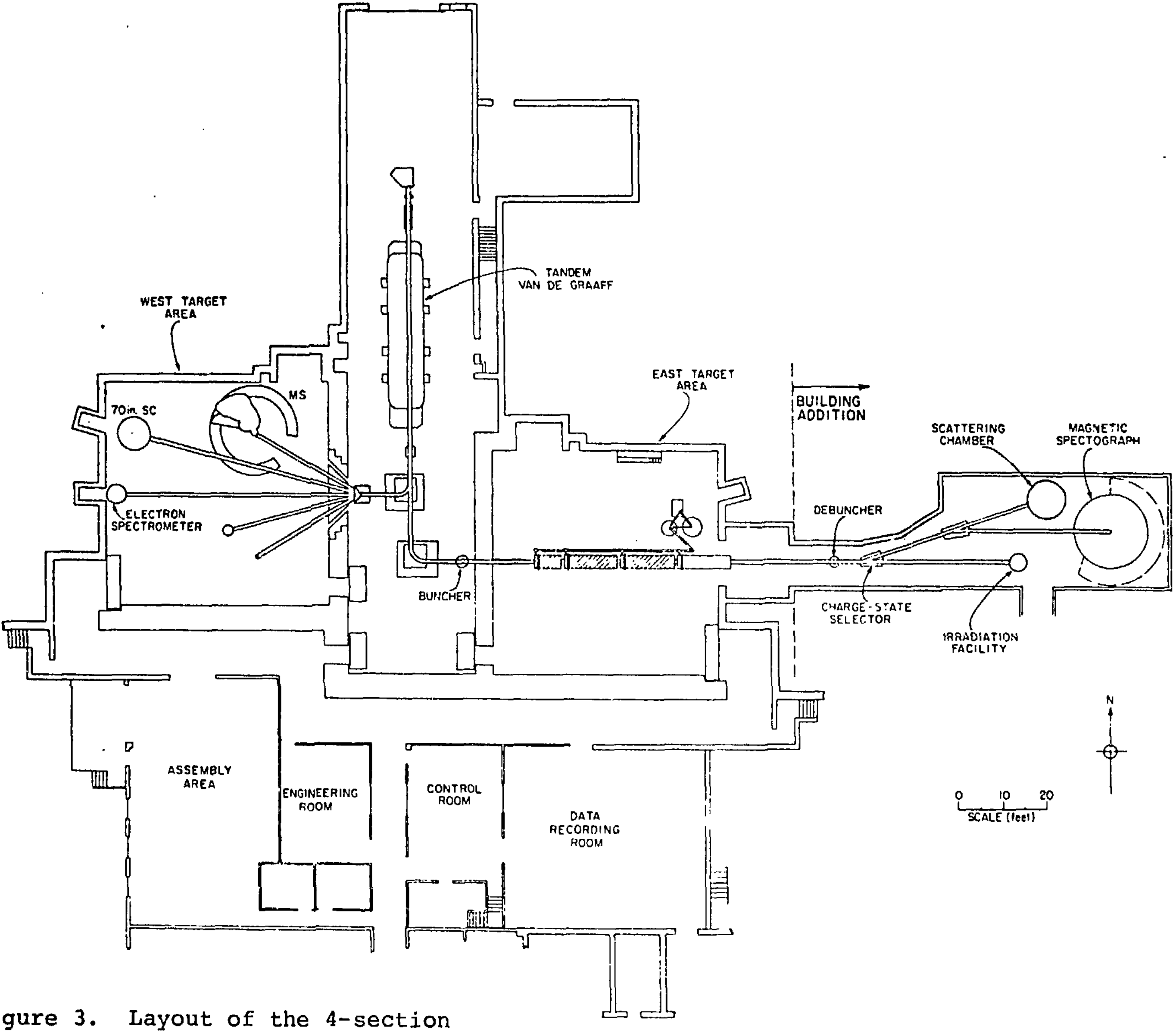

Figure 3. Layout of the 4-section Argonne tandem-linac accelerator system now being assembled.

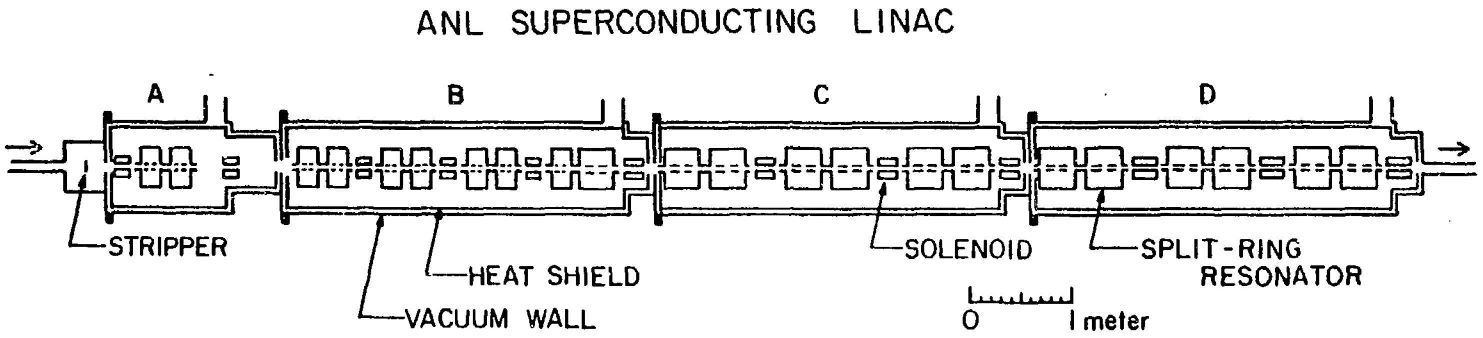

Figure 4. Schematic representation of the superconducting-linac heavy-ion energy booster at Argonne.

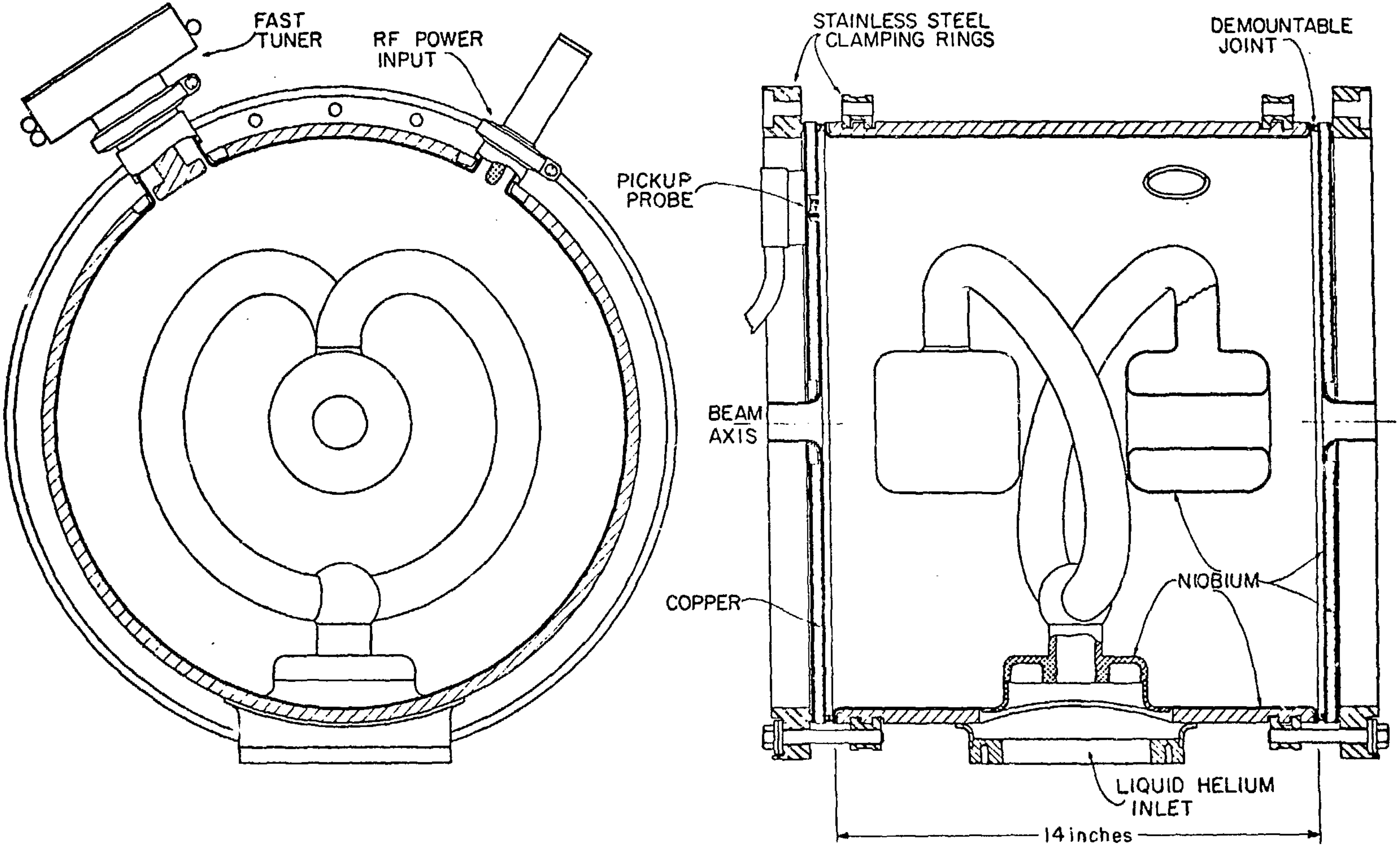

Figure 5. The Argonne high-β superconducting resonator.

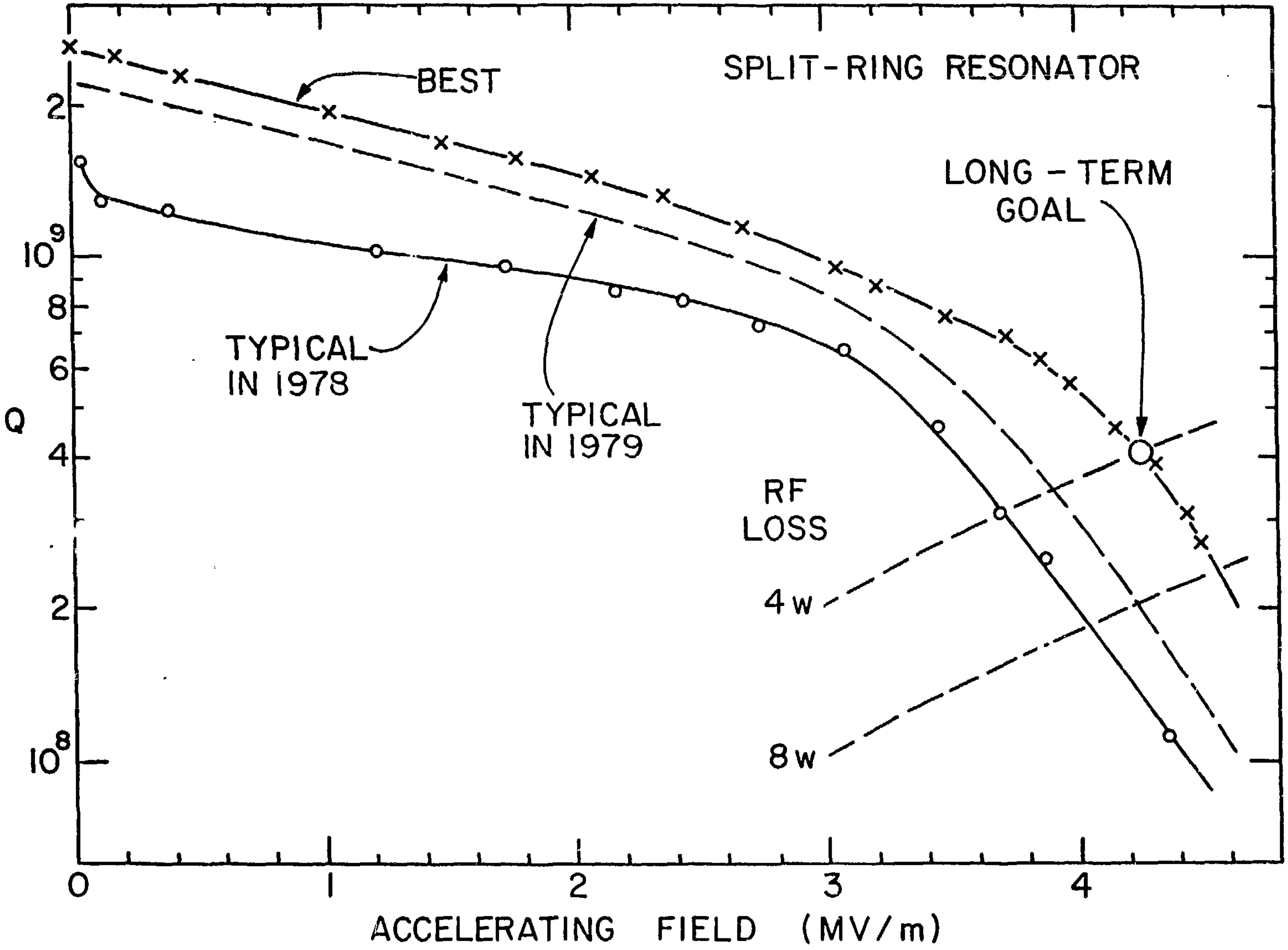

Figure 6. Performance characteristic of the Argonne high-β resonator.

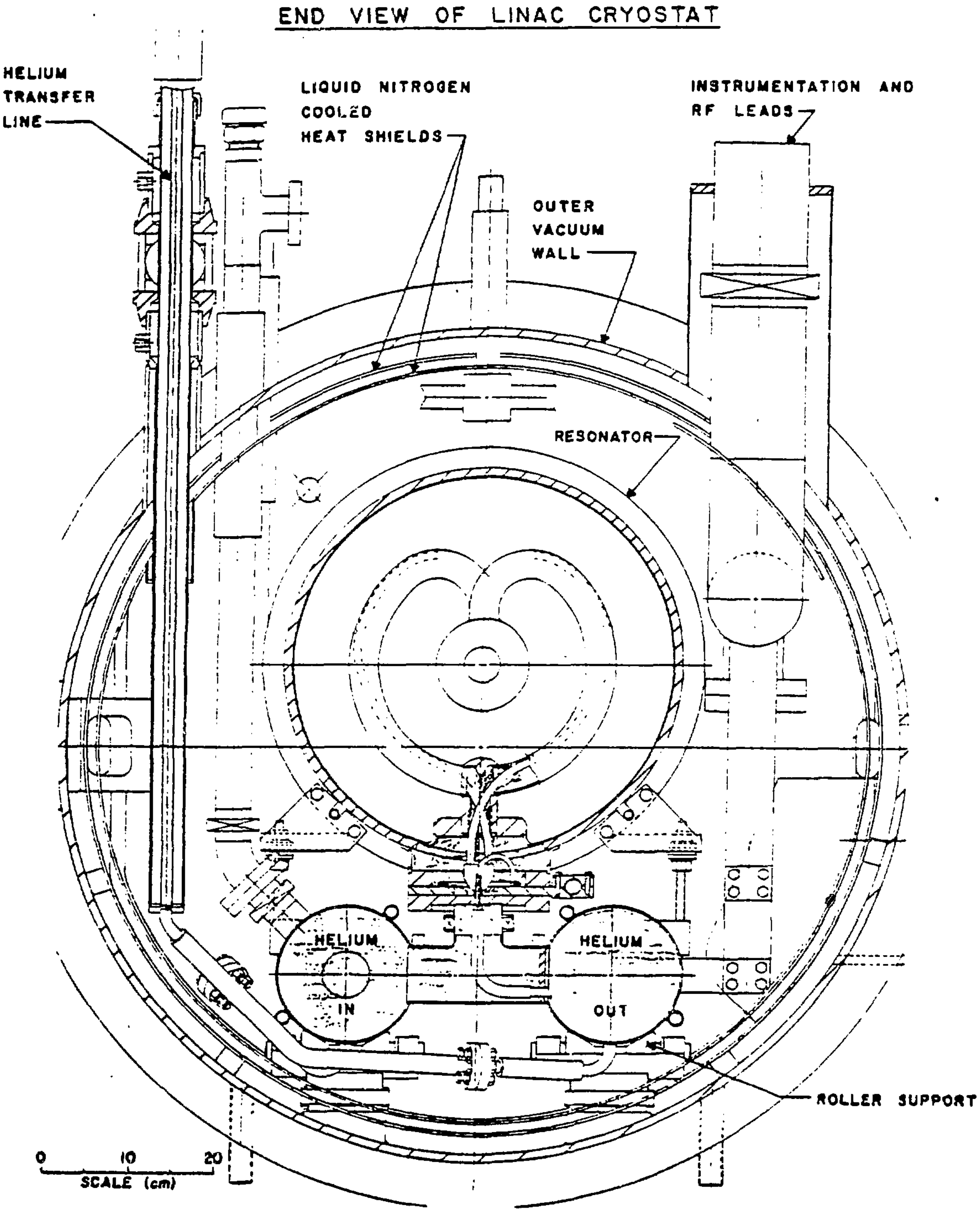

Figure 7. End view of a beam-line cryostat with a resonator in place.

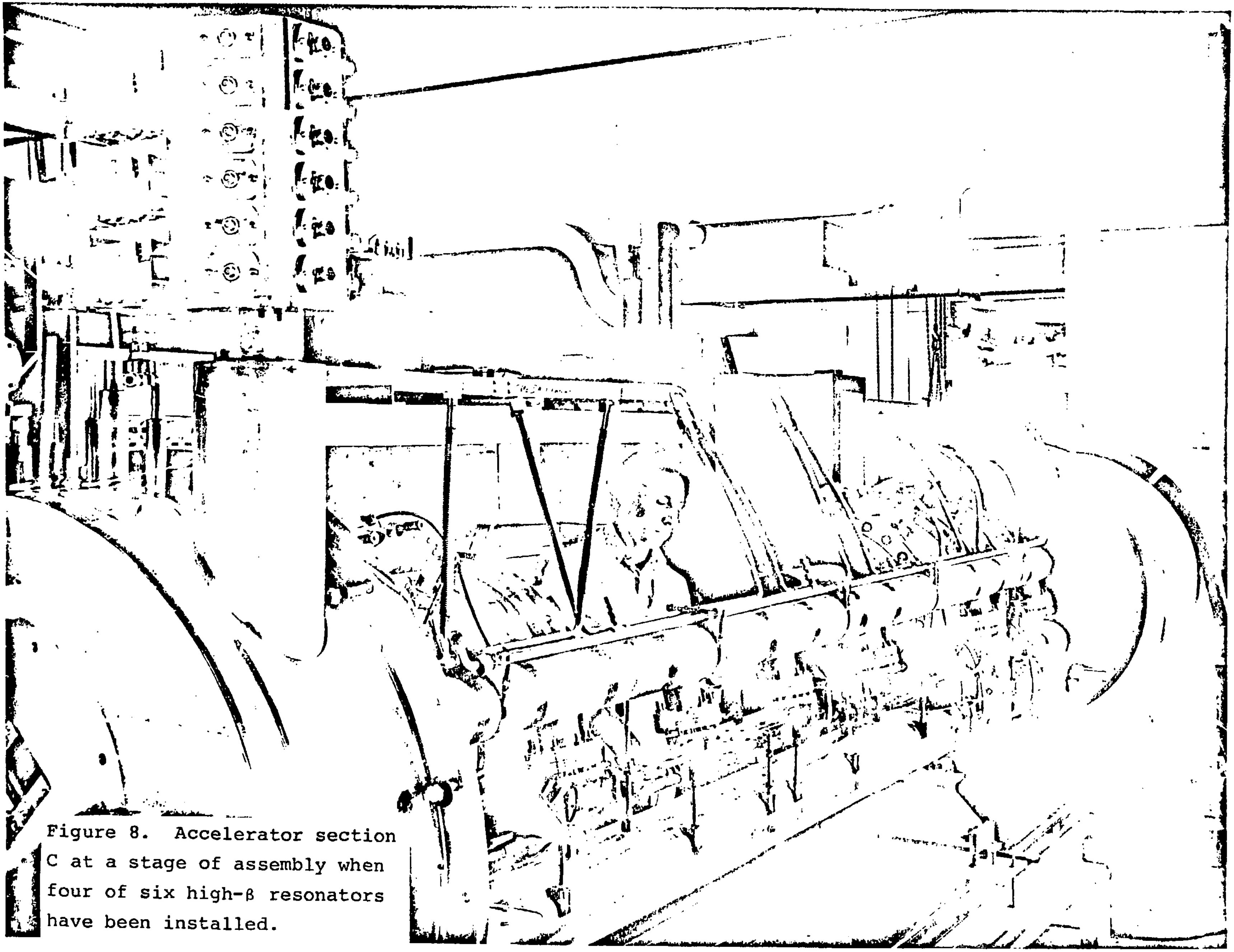

Figure 8. Accelerator section C at a stage of assembly when four of six high-β resonators have been installed.

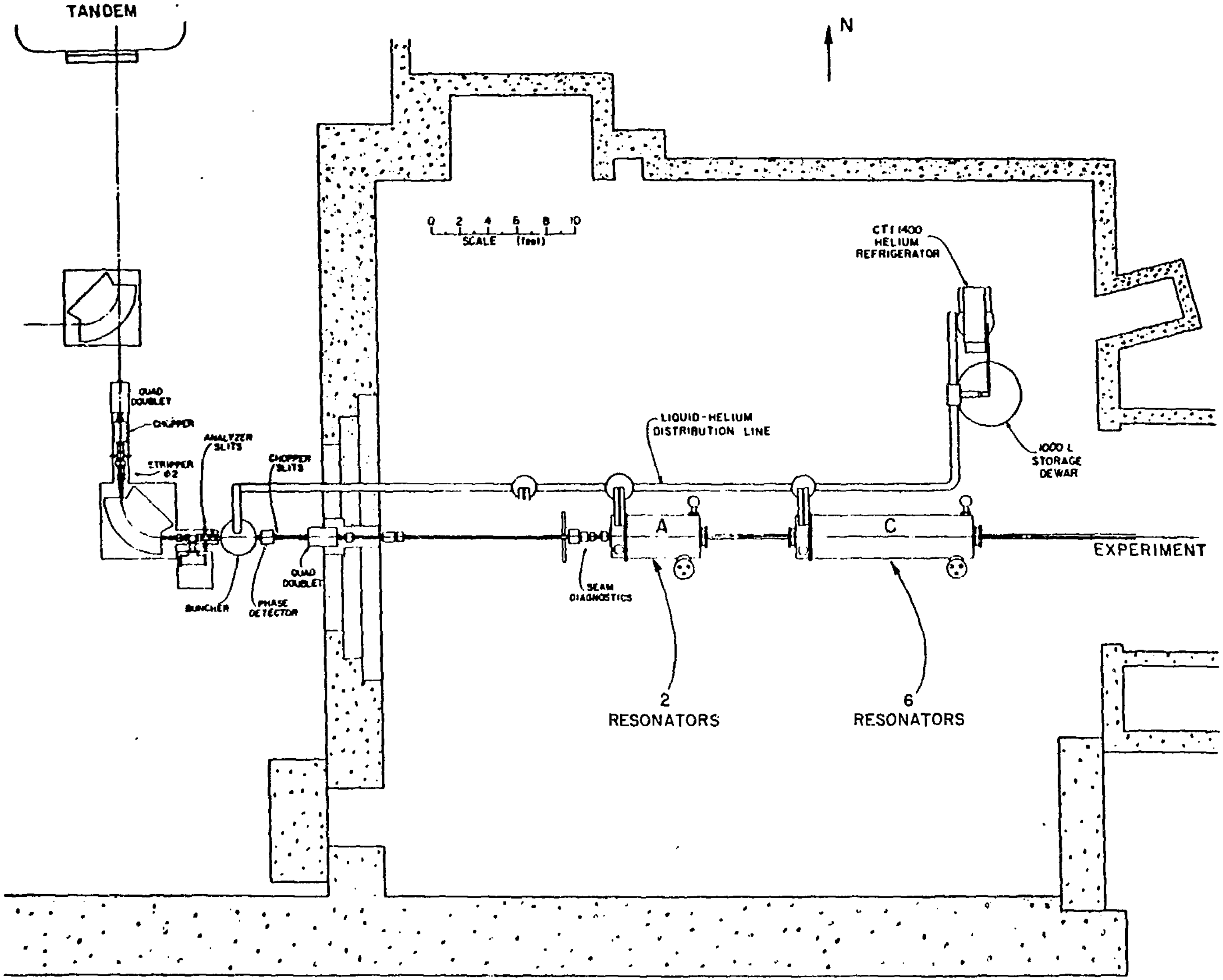

Figure 9. Configuration of the 8-resonator booster used during June 1979.

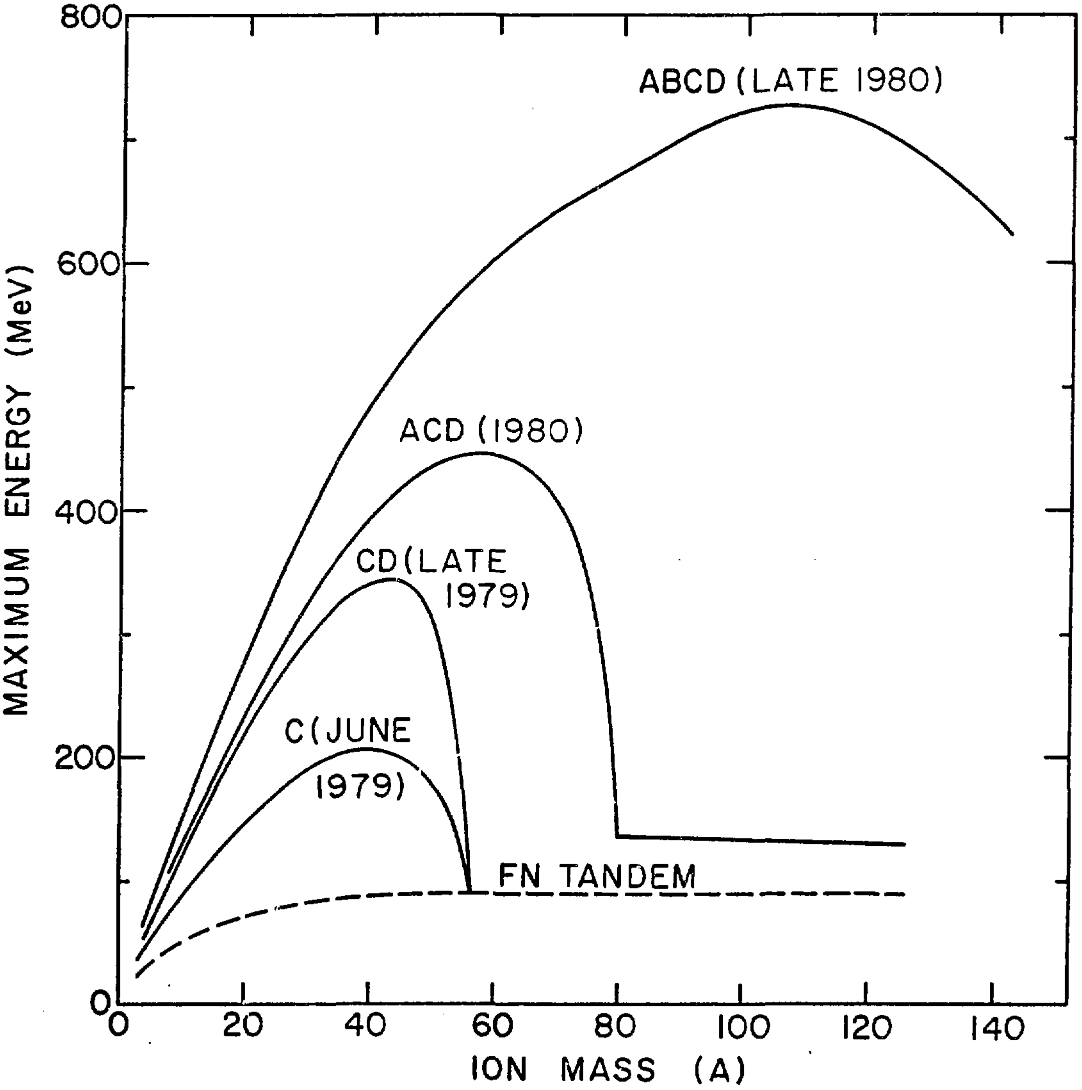

Figure 10. Energy performance of the booster at several stages of completion.

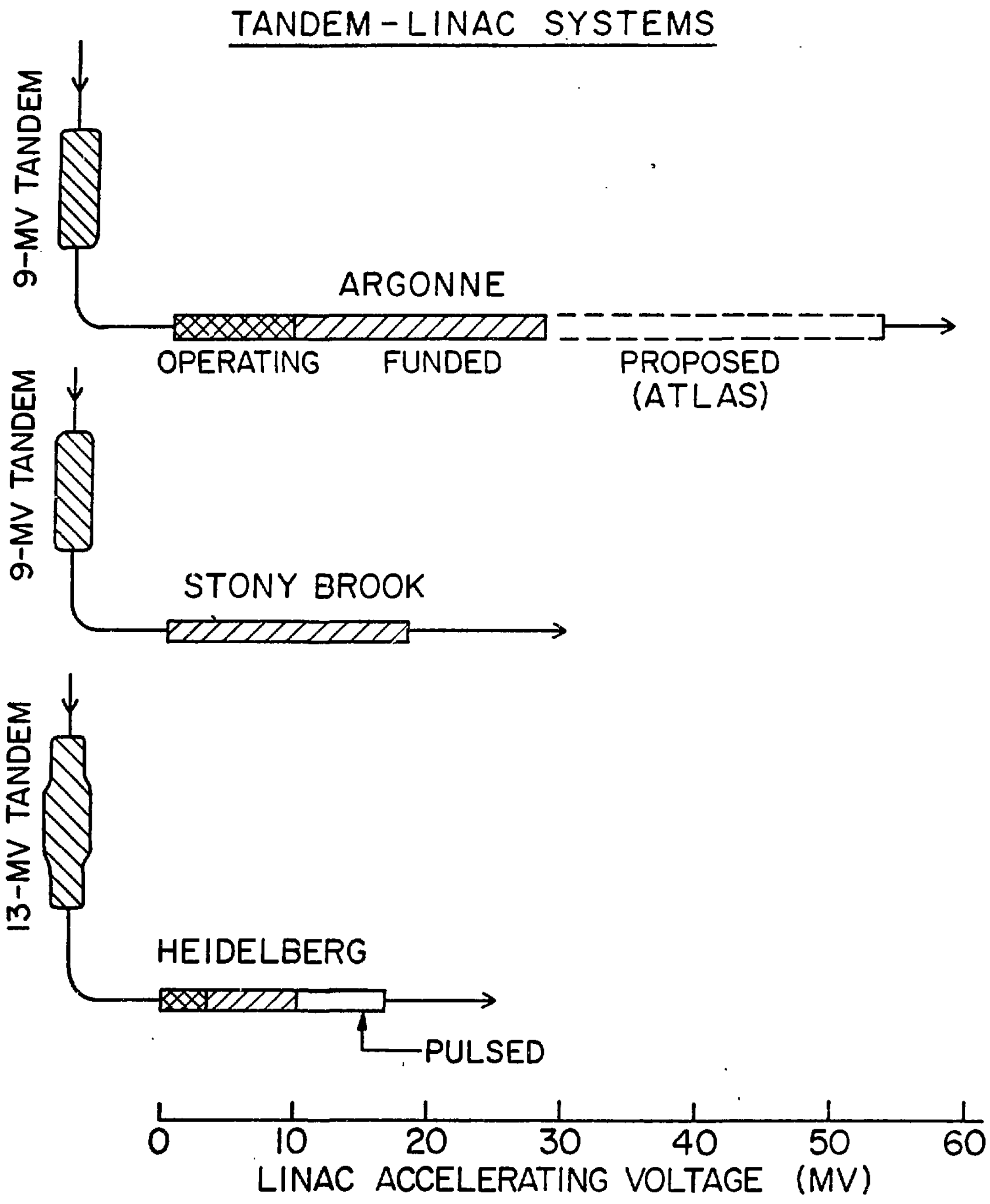

Figure 11. Schematic of tandem-linac systems now being built.

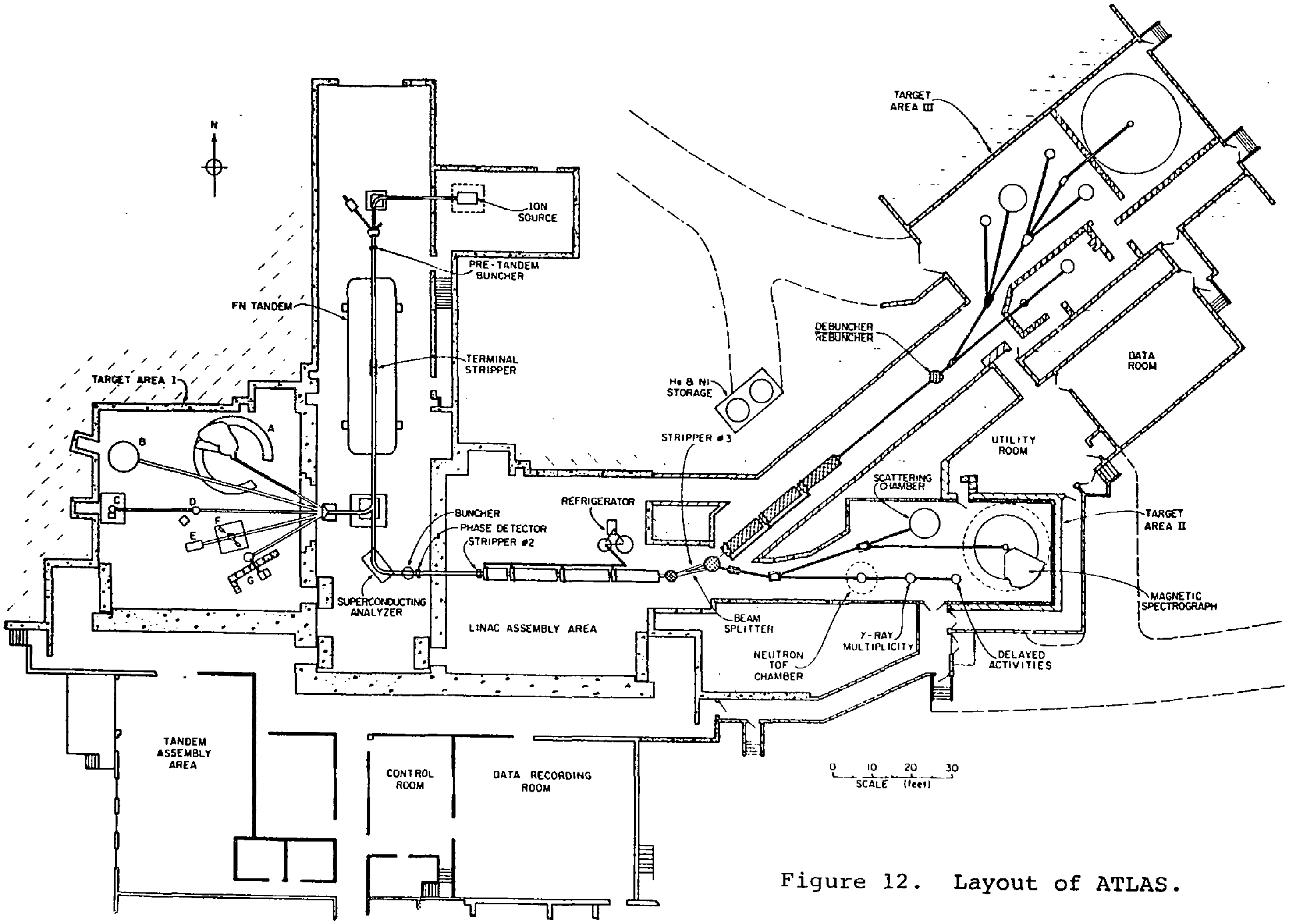

Figure 12. Layout of ATLAS.

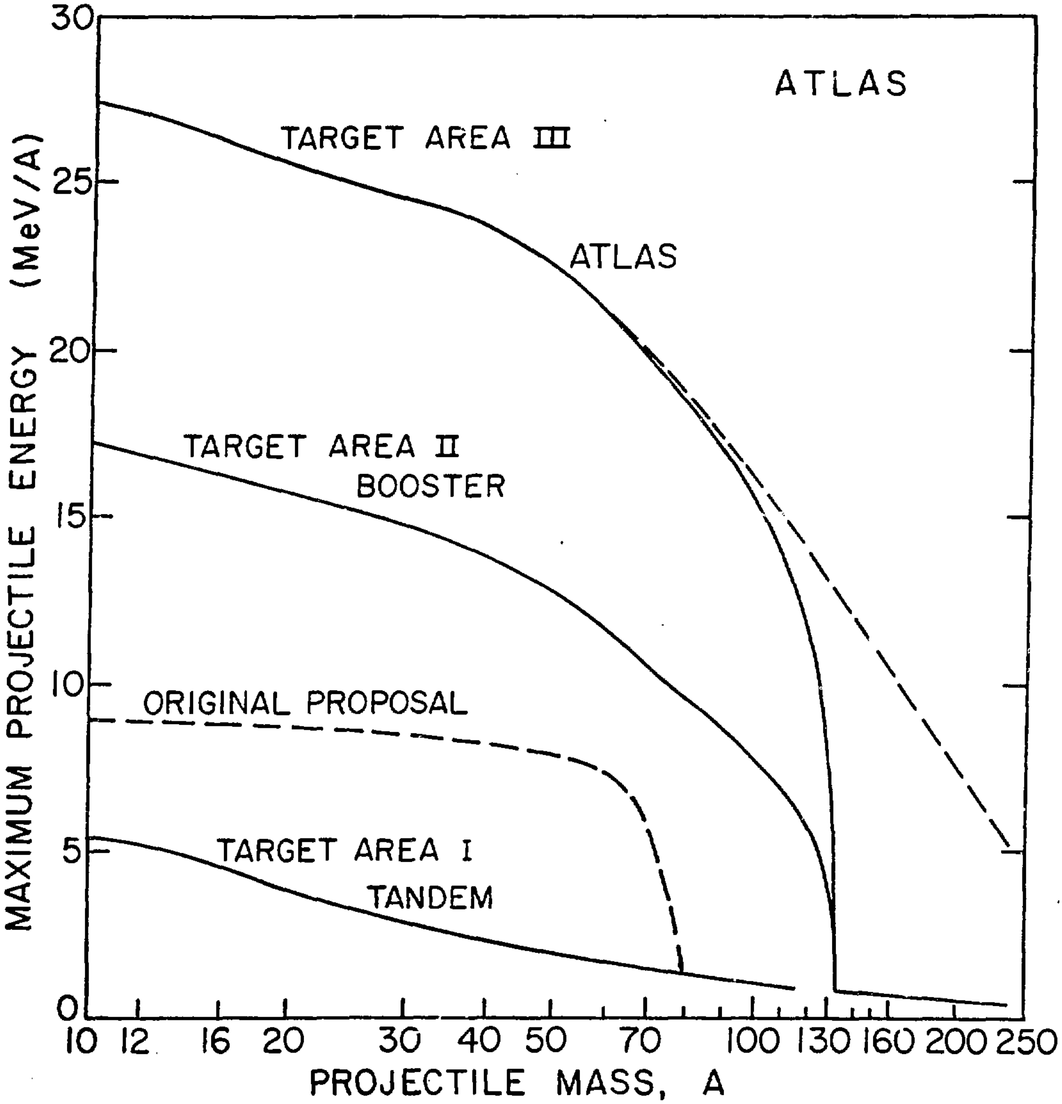

Figure 13. Beam energies available from various parts of ATLAS.