THE ASTRON LINEAR ACCELERATOR*

J. W. Beal
Lawrence Radiation Laboratory, University of California
Livermore, California

Abstract

The design features of a linear induction electron accelerator, for use in experiments with the Astron, are described. The parameters of the accelerator are: beam energy—4.23 MeV, beam current—1000 A, beam pulse length—0.3 μsec. The design beam emittance is 10π mr-cm in both transverse dimensions and an energy spread of 2% full-width-half-maximum. The accelerator consists of an increasing gradient gun with an output beam energy of 562 keV, followed by two constant gradient injector sections each adding 220 keV to the beam energy. The remainder of the accelerator is made up of 17 identical accelerator sections, each supplying 190 keV to the beam energy. Solenoidal focussing magnets are positioned with a particular magnetic field strength to provide phase-space matching between the various sections of the accelerator. Steering magnets are placed so as to compensate for the earth ambient magnetic field and possible stray fields.

Introduction

One of the primary requirements of the Astron[1] controlled thermonuclear reactor experiment is an intense beam of relativistic electrons. An accelerator to produce such a beam has been in operation at the Lawrence Radiation Laboratory, Livermore site, for several years.[2] The accelerator operates on the principle of magnetic induction as applied to a linear accelerator.

The present, operating accelerator is discussed and its operating characteristics are noted. The present accelerator is being redesigned and rebuilt to increase the output beam current to a nominal 1000 A, to increase the beam energy to approximately 4.23 MeV, and to improve the quality of the output beam. For economic reasons, as much of the existing hardware was retained as was practical for the modified accelerator.

Magnetic Induction Principle

The Astron accelerator is a linear machine, utilizing the principle of magnetic induction to produce the accelerating fields. The geometry applying this principle to a linear accelerator is shown diagrammatically in Fig. 1. In this approach, a toroidal ring of magnetic material surrounds the accelerating column, and the change in flux in the magnetic core induces an axial electric field.

The volt-seconds available to this system for a given magnetic material depends upon the cross-sectional area of the toroidal ring. The requirement for energy uniformity during the beam pulse makes it necessary for some provision to be made in the pulsing system to maintain a constant dB/dt during the useful part of the pulse. This may be done by proper shaping and control of the current pulse to the primary.

The magnetic core material is 0.001 in. thick, 50%-50% Ni-Fe tape wound to the proper dimensions.

Linear Induction Accelerator

The electron gun used for this accelerator is a high-perveance, increasing gradient gun capable of producing approximately 1200 A of beam current at about 650 keV. This amounts to an average emission current density of 4.8 A/cm^2 at a perveance of 2.58 μperv. The increasing gradient approach is used to provide radial beam focussing.

A cross section of the gun assembly is shown in Fig. 2. The required field gradient is obtained by adjustment of electrode spacing and the number of cores between successive gaps. Each gun core contributes an average of 14.4 keV to the beam. The cathode is a conventional oxide cathode on a carbonyl nickel base, and is heated by radiation.

The entire gun assembly is installed in a pressure tank which is pressurized to 30 psig of freon to minimize sparking and corona. A blower circulates this gas through a heat exchanger to remove the heat generated in the system. The vacuum tube and electrodes are constructed of 14-in.-diam, metal-ceramic seals.

The accelerator sections are uniformly accelerating and hence have no electric focussing properties other than those due to end effects. Each accelerator section has a diameter of approximately 10 cm and has an accelerating column about 100 cm long. Each section adds about 500 keV to the beam energy.

Figure 3 shows an overhead view of the Astron accelerator as it appears today. The entire accelerator is enclosed with a 7-ft-thick, concrete-walled room. Nominal beam energy is 3.8 MeV with an energy spread of 4% (FWHM) over the entire beam pulse. Figure 4a shows typical cathode emission current, and Fig. 4b shows the resultant output beam current. These results correspond to a transmission efficiency of about 78%. The beam pulse width is approximately 0.3 μsec.

The accelerator generally operates at a continuous rate of 5 pulses/sec. This would cor-

*Work performed under the auspices of the U.S. Atomic Energy Commission.

respond to a duty cycle of 1.5×10^{-6} with an average beam current of about 6×10^{-4} A. The accelerator can operate in a burst mode at a maximum pulse rate of 1440 pulses/sec. This rate would correspond to a duty cycle of 4.3×10^{-4} with an average beam current of 0.17 A over the burst period.

Space-Charge Limited Beam Current

Experiments with the present accelerator showed that the maximum transmittable beam current is approximately 425 A. These experiments indicate that this value of current is the nominal space-charge limit, and that any further increase in the input beam current results in beam particle loss to the accelerator chamber walls. This space-charge limit has been verified to some extent by computation made with the computer program EXPORT.[3] This computation yielded a result for the maximum transmittable beam current of approximately 500 A for an injection energy of 1.0 MeV into the first accelerator section. In view of the approximations inherent in the computation and the random errors in the accelerator itself, this appears to be reasonable agreement.

To increase the beam current, it was necessary to raise the space-charge limit. Several means to this end are possible: (1) increase the injection beam energy; (2) increase the aperture of the accelerating structures; (3) increase the accelerating gradient; or (4) increase the focusing per unit length by decreasing the length of the accelerator sections. Simultaneously the economic requirement was to be considered, namely that of using as much of the existing hardware as possible.

Since the space-charge and self-magnetic forces are a strong function of the beam energy, it was expected that a significant increase in beam current could be gained by a relatively small increase in injection energy. Figure 5 shows this relationship between injection energy and maximum transmittable beam current through an accelerating section. The accelerating section was defined as a uniform gradient accelerating column, 102 cm long with an accelerating gradient of 4.53 kV/cm. The figure shows that in order to transmit the desired 1000-A beam, an injection energy of 1.67 MeV would be required. This represents an increase in the injection energy of approximately 67% over its present value. This method of increasing the beam current was rejected because it was not economically feasible to increase the injection energy by this required amount.

The second possible method of increasing the beam current was to increase the beam radius. Since the self-forces vary inversely as the beam radius, it is expected that by increasing the beam radius more total beam current could be accommodated. Figure 6 shows the relationship between beam radius and maximum transmittable beam current. The curve in Fig. 6 is for the case with an injection energy of 1.0 MeV, and with a uniform gradient accelerating column 102 cm long with an accelerating gradient of 4.53 kV/cm. Figure 6 shows that to transmit the desired 1000-A beam would require a beam radius of approximately 7.5 cm. This represents an increase in the accelerator aperture of almost a factor of two over its present value. Again this method of increasing the beam current was rejected since it was not economically practical to increase the accelerator aperture by this amount.

The third possibility of increasing the beam current was to increase the accelerating gradient in the accelerator structures themselves. Figure 7 shows the relation between maximum transmittable beam current and accelerating gradient for an injection energy of 1.0 MeV, an initial beam radius of 4.0 cm, an initial beam slope of -0.04, and a uniform gradient accelerating column 102 cm long. The curve shows a relatively weak dependence of the beam current on the accelerating gradient. Extrapolating the curve in Fig. 7 to the desired 1000-A beam current yields a resultant accelerating gradient of approximately 9.7 kV/cm. This represents an increase in the accelerating gradient of approximately 70% over its present value. Such an increase in the accelerating gradient was not practical from economic and electronic considerations; therefore, such a means as this to increase the beam current was rejected.

The fourth and final means of increasing the beam current was to increase the focusing per unit length by reducing the length of the accelerator sections. For an injection energy of 1.0 MeV, an initial beam radius of 4.0 cm, an initial beam slope of -0.04 and a uniform gradient accelerating column at 4.53 kV/cm, the question was to determine the length of an accelerator section that would pass 1000 A. Figure 8 shows the relationship between the length of the accelerating column and the maximum transmittable beam current. From Fig. 8 it is seen that in order to pass 1000 A of beam current, an accelerator section length of approximately 53 cm or shorter would be required. For our consideration, this was the most practical method of increasing the beam current since all that is required is to rebuild the accelerator sections into shorter modules. This approach was, therefore, chosen as the method to increase the beam current.

As designed, these short accelerator modules have an overall length of 20 in., with a 4-in. clear aperature. The active accelerating length is 16.50 in., with an accelerating gradient of 4.53 kV/cm. Figure 9 shows a cross section of newly designed accelerator modules.

Accelerator Layout

The next question to be answered was that of placement of the various accelerator elements with respect to each other in order to transmit the desired beam and to provide for the phase-space matching requirements. To investigate this question, computer calculations were made using the code TRANSPORT.[4]

TRANSPORT was originally developed at the Stanford Linear Accelerator Center and has been modified for use on the LRL Octopus-6600 computer system. TRANSPORT is basically a program for applying the matrix transformation of beam optics to the desired transport system. In its current state, TRANSPORT can trace a beam through the given system to first or second order, adjust parameters of the system (i.e., field strengths, drift lengths, etc.) to fit specific conditions, evaluate the effects of misalignment of magnets, and execute various other instructions that may be given. A variety of constraints are available (such as beam spot-size at a target, location of a beam waist, etc.) by which the properties of the system may be defined. In general, constraints are available to specify any condition upon the system that can physically be obtained. Where the program is instructed to fit system parameters, it uses a general least-squares parameter fitting procedure to compute first-order corrections to the variables. The correction process is repeated until the system is adjusted to given tolerances, or until the program acknowledges that it cannot find a solution. With the speed of the CDC-6600 computer, a solution requires only 5-10 sec.

TRANSPORT is particularly suitable for phase-space matching studies. For space-charge limited beams, it is desirable to have a converging beam at the entrance to an accelerator section diverging at the exit, with a beam waist at the center of the section. In terms of a phase-space, matrix calculation such as TRANSPORT, a beam waist means that the off-diagonal elements of the transfer matrix are zero and the phase ellipse is upright. Simultaneously, it is required that the beam envelope be contained within the aperture of the accelerator sections. This maximum beam envelope radius was taken to be 3 cm, giving a clearance of 2 cm between the beam envelope and the accelerator walls, thus allowing for the beam drift off axis due to the ambient earth magnetic field, stray magnetic fields, and the like. A minimum beam envelope radius was also chosen. Since the magnitude of the space-charge forces varies inversely with the beam radius, as the beam radius decreases the space-charge forces increase and the beam diverges more rapidly. With this in mind, a minimum beam envelope radius of 1 cm was chosen. These constraints then define the phase-space matching requirements; that is, the beam radius is to be $1 \leq R \leq 3$ cm and a beam waist is to be at the center of each of the accelerating sections.

Since the proposed accelerator is to handle a relatively low-rigidity beam, adequate beam steering must be provided. As mentioned above, there is at least 2 cm clearance between the theoretical beam envelope and the accelerator walls. Therefore, steering magnets should be placed at positions where the accumulated beam displacement due to the ambient earth magnetic field and stray fields add to approximately 2 cm. Since the rigidity of the beam is increasing down the length of the accelerator, the steering magnets may be spaced farther apart at the high-energy end than at the low-energy stage. For small angle deflection, the relation is

$$\Delta y = \frac{z^2}{2\rho}$$

and

$$B\rho = \text{magnetic regidity,}$$

where Δy is the beam displacement, z is the distance through which the beam travels through the magnetic field B, and ρ is the radius of curvature of the trajectory. A value of B = 0.45 G was chosen corresponding to the earth's ambient magnetic field as measured at the accelerator. This field strength was assumed to be uniform over the length of the accelerator. By determining the deflection as a function of beam energy (rigidity), it was possible to determine the positions of the steering magnets consistent with the beam parameters. In practice, the steering magnets are cosine-type air-core windings with a maximum field strength of approximately 5 G.

Using EXPORT as in the previous section, the beam envelope through the increasing gradient gun was determined. Figure 10 shows the calculated beam envelope for the increasing gradient gun for an emission of 1200 A at 562.5-keV output energy. These calculations are in qualitative agreement with some rough experimental measurements made on the gun itself. The parameters describing the beam output from the gun were then chosen as:

Beam radius at beam waist	R = 2 cm
Horizontal and vertical emittance	$\mathcal{E}_x = \mathcal{E}_y = 50\pi$ mr-cm
Beam current	1200 A
Beam energy	T = 562.5 keV
Momentum spread	$\Delta p/p = 10\%$

Additionally, each injector section yields an energy gain of 220 keV/section, and each accelerator section adds 190 keV/section as determined by engineering tests. The parameters of the focusing solenoids were chosen consistent with previously reported measurements.[5]

The resultant machine layout is shown in Fig. 11. In the figure the gun is positioned as noted; the two injector sections are denoted by I1 and I2 respectively; and the accelerator sections are denoted by A1-A17. Steering magnets are located at the positions labeled S, and focussing magnets are denoted by F. As can be seen, the accelerator as designed is approximately 97 ft long.

Assuming that approximately 20% of the beam particles are lost between the gun and the accelerator output, the accelerator will yield approximately 1000 A beam current at 4.23 MeV. The emittance would be adiabatically damped as 1/p to a value of approximately 10π mr-cm. The final momentum error would be $\Delta p/p = 2\%$ FWHM.

In the design, space has been provided for diagnostic equipment such as current monitors and beam position monitors. In this manner, it is hoped to have better monitoring and control of the accelerated beam and therefore have a more reproducible beam. The drift space between the end of the accelerator and the entrance to the Astron vacuum chamber will also be used to diagnose and prepare the beam for injection.

Throughout the design, a requirement was that the various parameters be somewhat conservative. To this end the focusing magnets are simple, iron-shrouded solenoids with a maximum field strength of approximately 1000 G. The steering magnets are air-core, cosine-type windings with a maximum field strength of 5 G. The accelerating gradients in the injectors and the accelerators are 4.77 and 4.53 kV/cm respectively. These gradients and voltages are well below the sparking limit for vacuums in the region of 10^{-5} - 10^{-6} **torr.**

In addition, it was desired that this accelerator design be compatible with possible future expansions of the accelerator to higher energy. While no detailed work exists regarding this question, it appears from preliminary studies that it is a straightforward matter to add more accelerator sections at the output end to obtain the desired energy.

References

[1] N. C. Christofilos, Proc. Second U.N. Intern. Conf. Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1958, Vol. 32, p. 279.

[2] N. C. Christofilos et al., Rev. Sci. Instr. 35, 886 (1964).

[3] J. W. Beal, Beam Trajectories Under the Influence of Self-fields and External Focusing Elements, UCRL-14194, Lawrence Radiation Laboratory, Livermore, May 1965.

[4] C. Moore, S. Howry and H. Butler, Special Stanford Linear Accelerator Center report, TRANSPORT—A Computer Program for Designing Beam Transport Systems.

[5] W. A. Sherwood, IEEE Trans. Nucl. Sci., NS-14, 928 (1967).

DISCUSSION

(J. W. Beal)

PERRY, ANL: Was the accelerating tube constructed of ceramic with metalized bonds?

BEAL, LRL: Yes, this is correct.

LOEW, SLAC: When are you going to start making electron rings with this injector?

BEAL, LRL: According to present plans, we will start the ERA experiment in August.

GODLOVE, NRL: In the early days, did you ever consider an accelerator like (Phermex) at Los Alamos for this application? What was the outcome of that comparison?

BEAL, LRL: There was a comparison done. At that time (8 years ago), any kind of a wave accelerator they thought, could not produce the required 150 amperes of beam due to loading problems.

GODLOVE, NRL: I think perhaps nowadays it may be possible to get these currents from a stored energy machine.

BEAL, LRL: The other requirement was that we have an output energy spread of only a few percent.

LEFEBVRE, SACLAY: What is the actual field along the gun?

BEAL, LRL: It is variable and has a maximum value of 75 kV per centimeter.

LEFEBVRE, SACLAY: Do you have any sparking problem at that value?

BEAL, LRL: Yes.

SLUYTERS, BNL: What type of vacuum do you have?

BEAL, LRL: 10^{-5} to 10^{-6} torr.

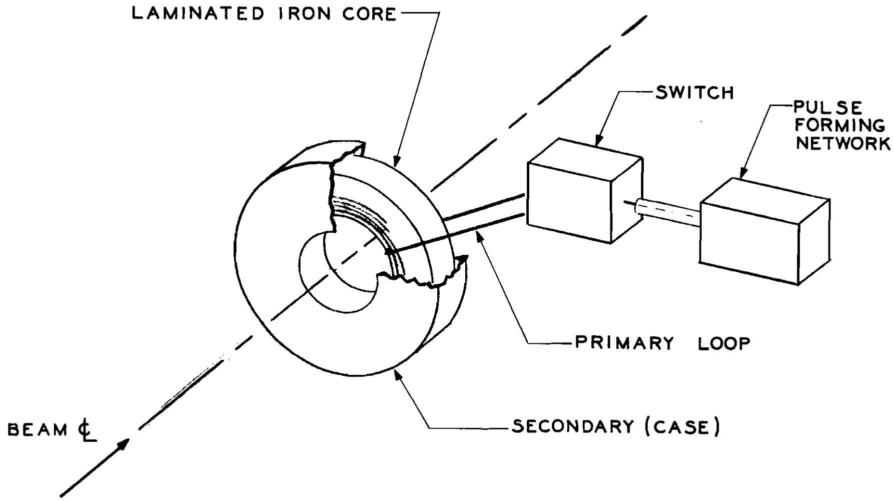


Fig. 1. Induction accelerator principle.

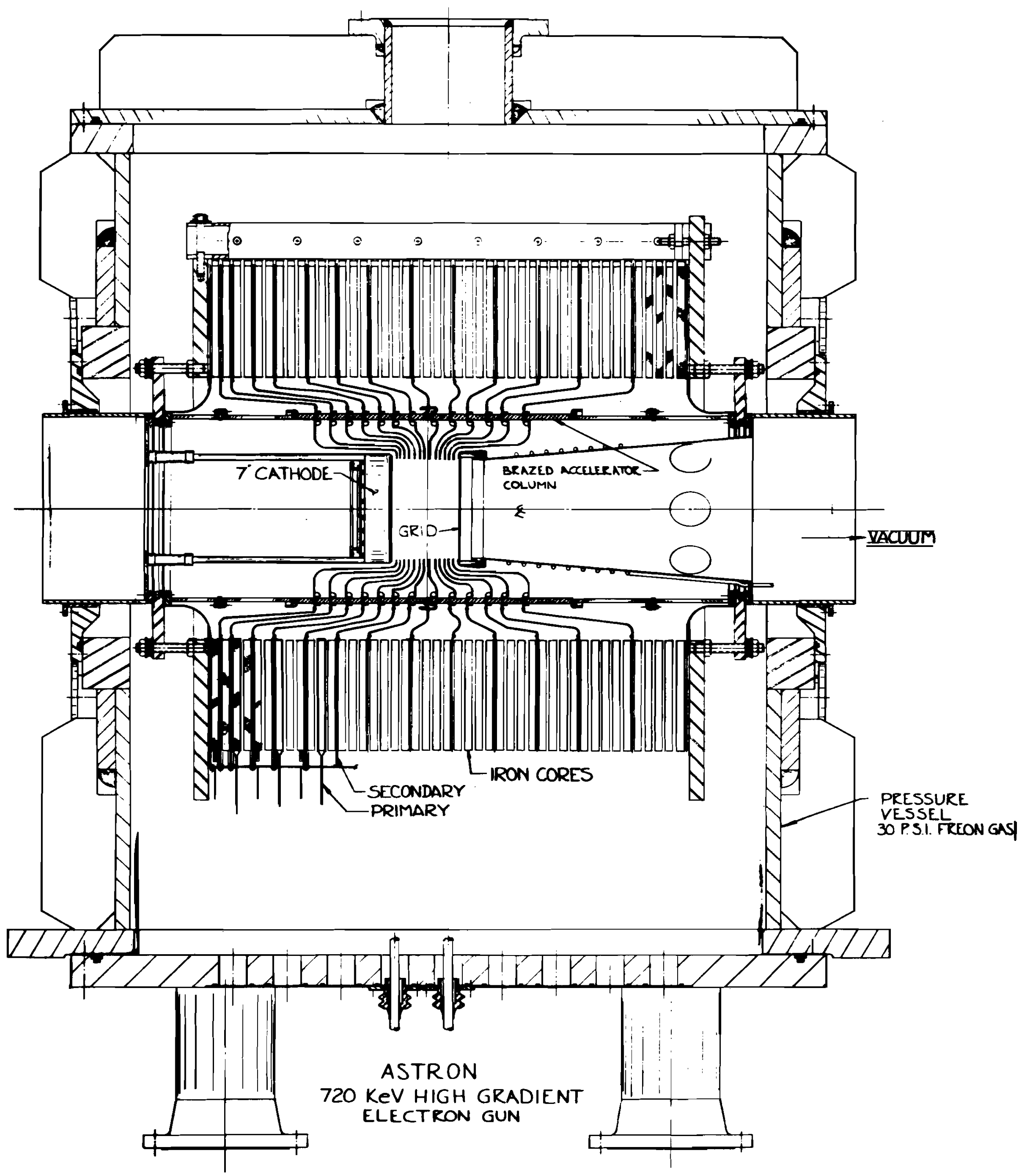


Fig. 2. Astron electron gun section.

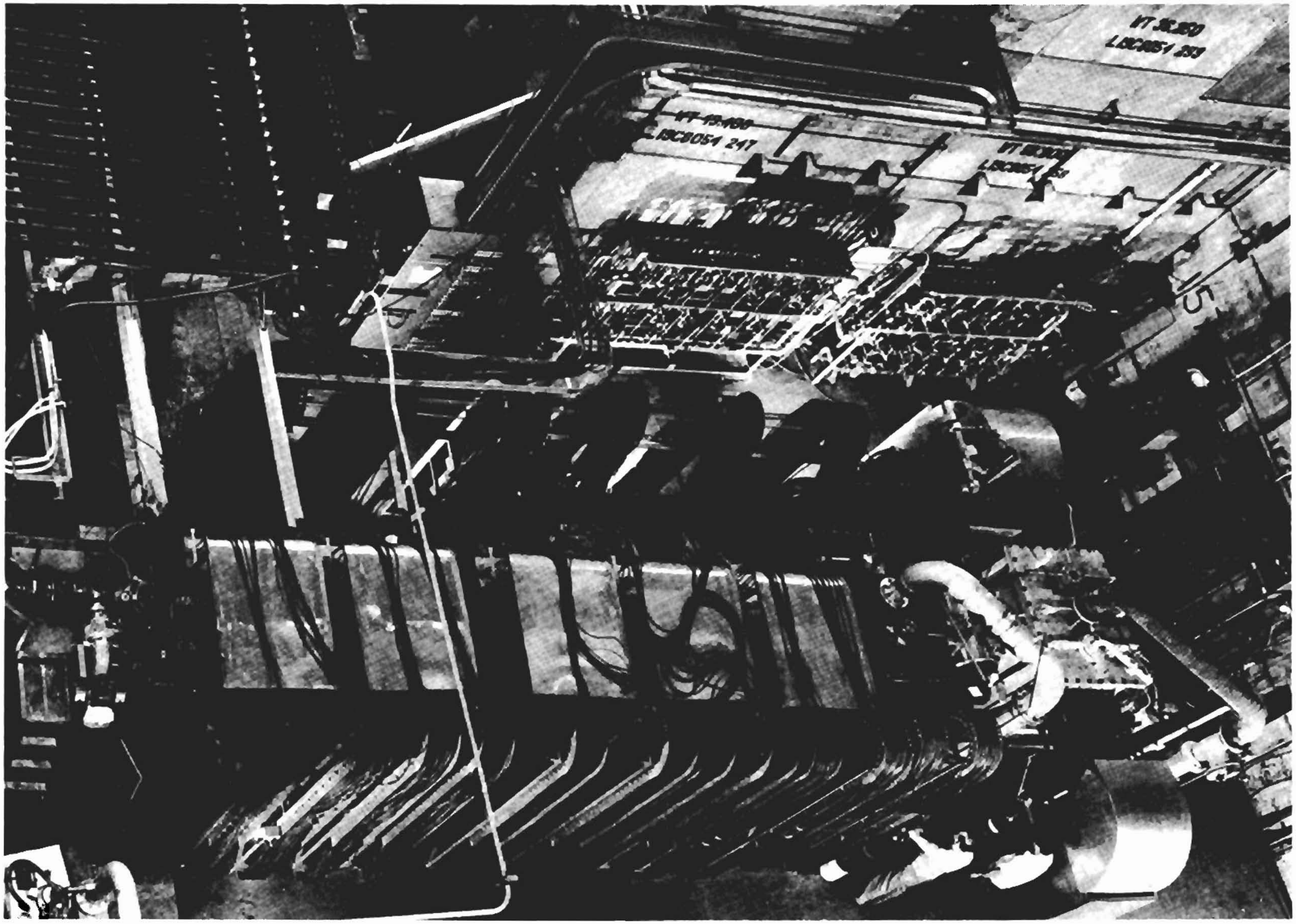
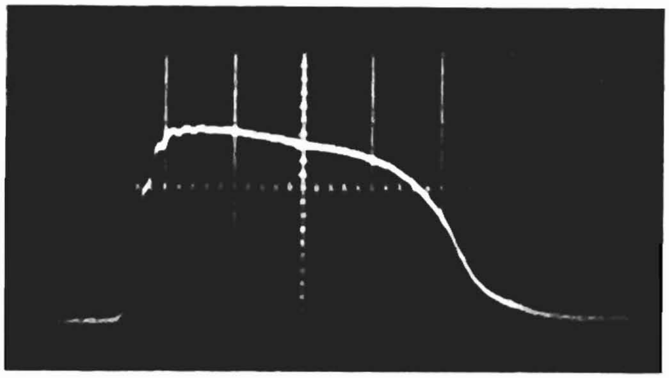
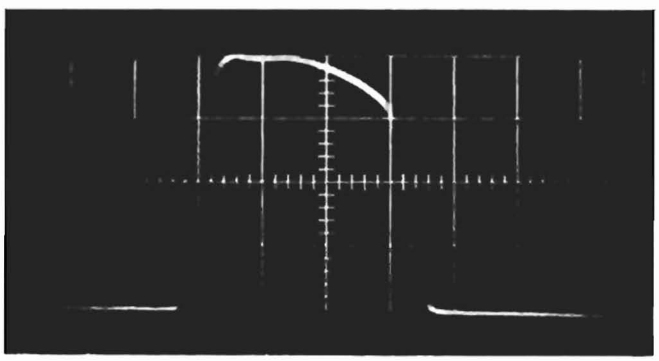


Fig. 3. Overhead view of Astron accelerator.



(a)

Cathode Emission Current
188 A/div
0.1 μsec/div



(b)

Output Current
102 A/div
0.1 μsec/div

Fig. 4. (a) Cathode emission current. (b) Accelerator output current.

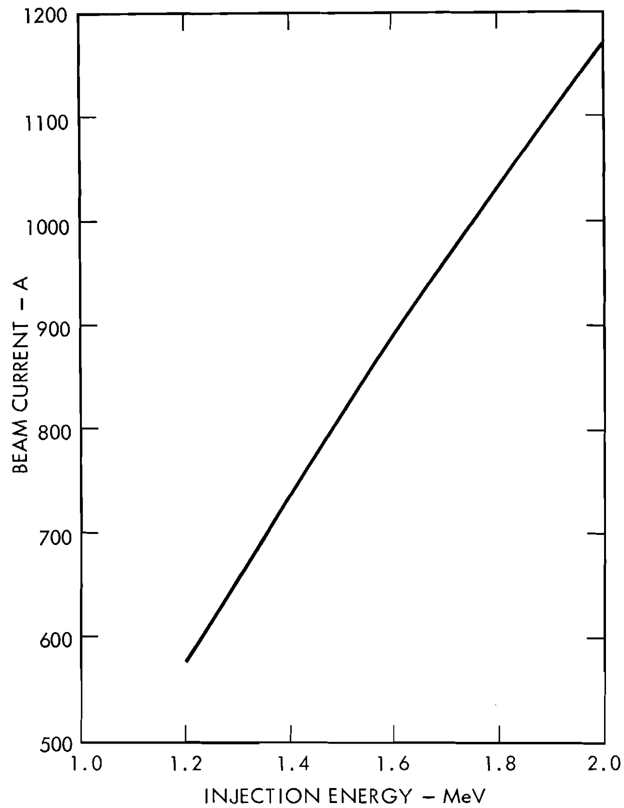


Fig. 5. Transmitted beam current vs injection energy.

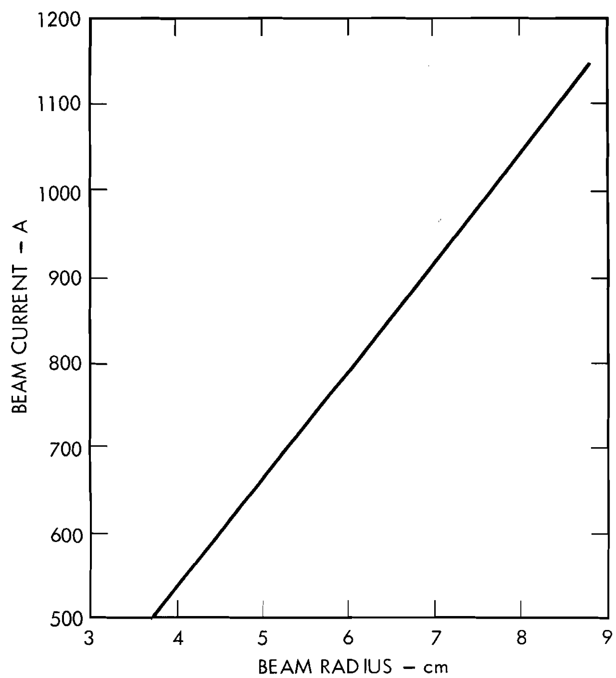


Fig. 6. Transmitted beam current vs beam radius.

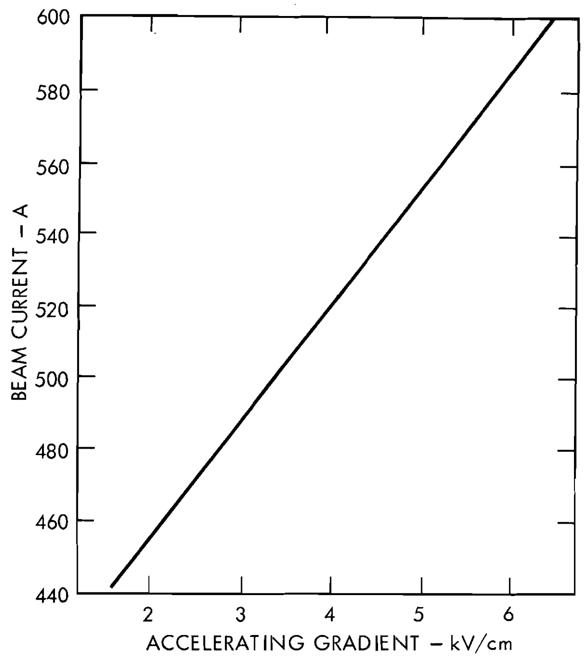


Fig. 7. Transmitted beam current vs accelerating gradient.

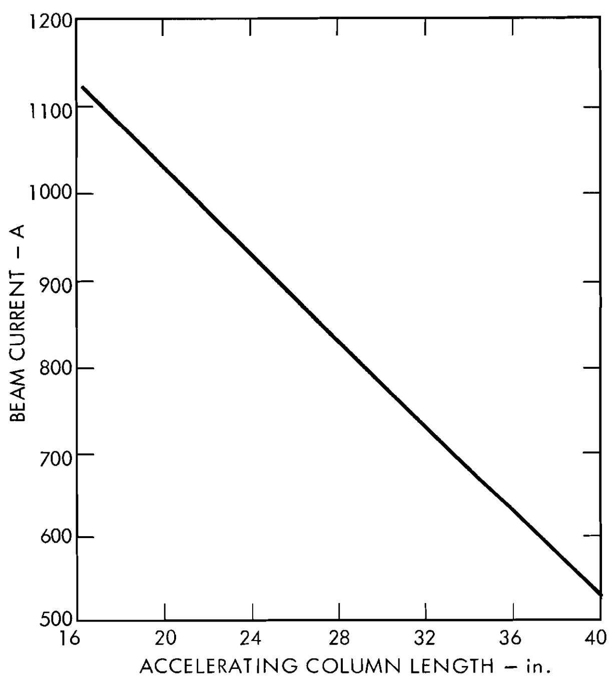


Fig. 8. Transmitted beam current vs accelerating column length.

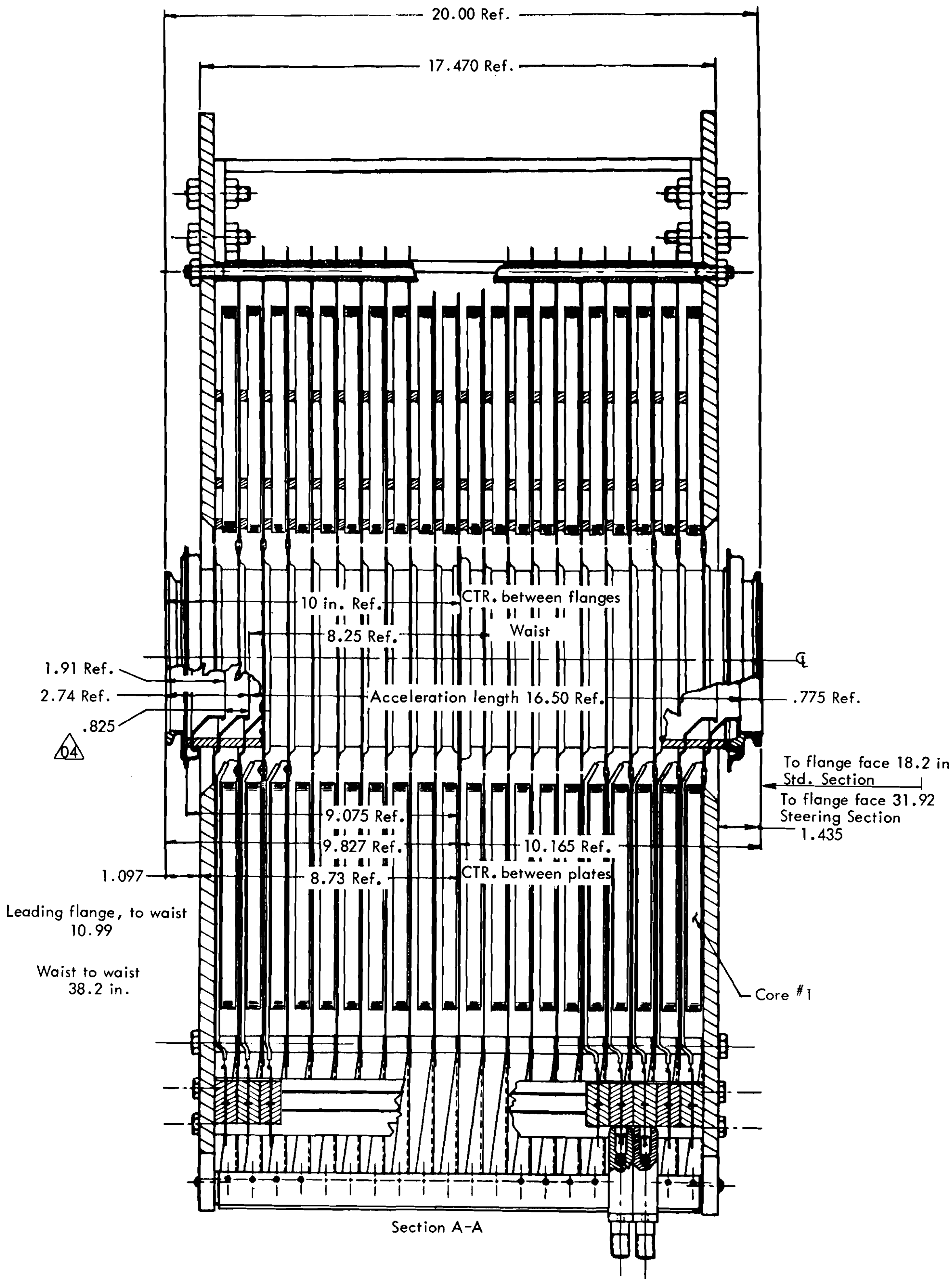


Fig. 9. Cross section of accelerator sections.

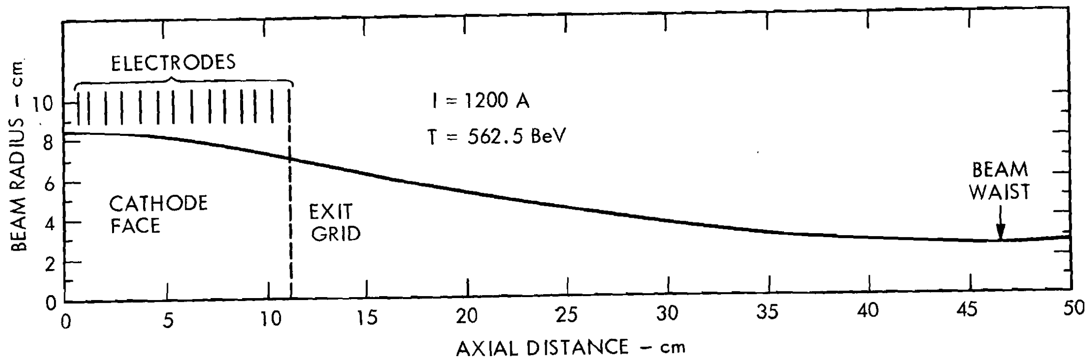


Fig. 10. Computed beam envelope for gradient gun for beam current of 1200 A and at 562.5-keV output energy.

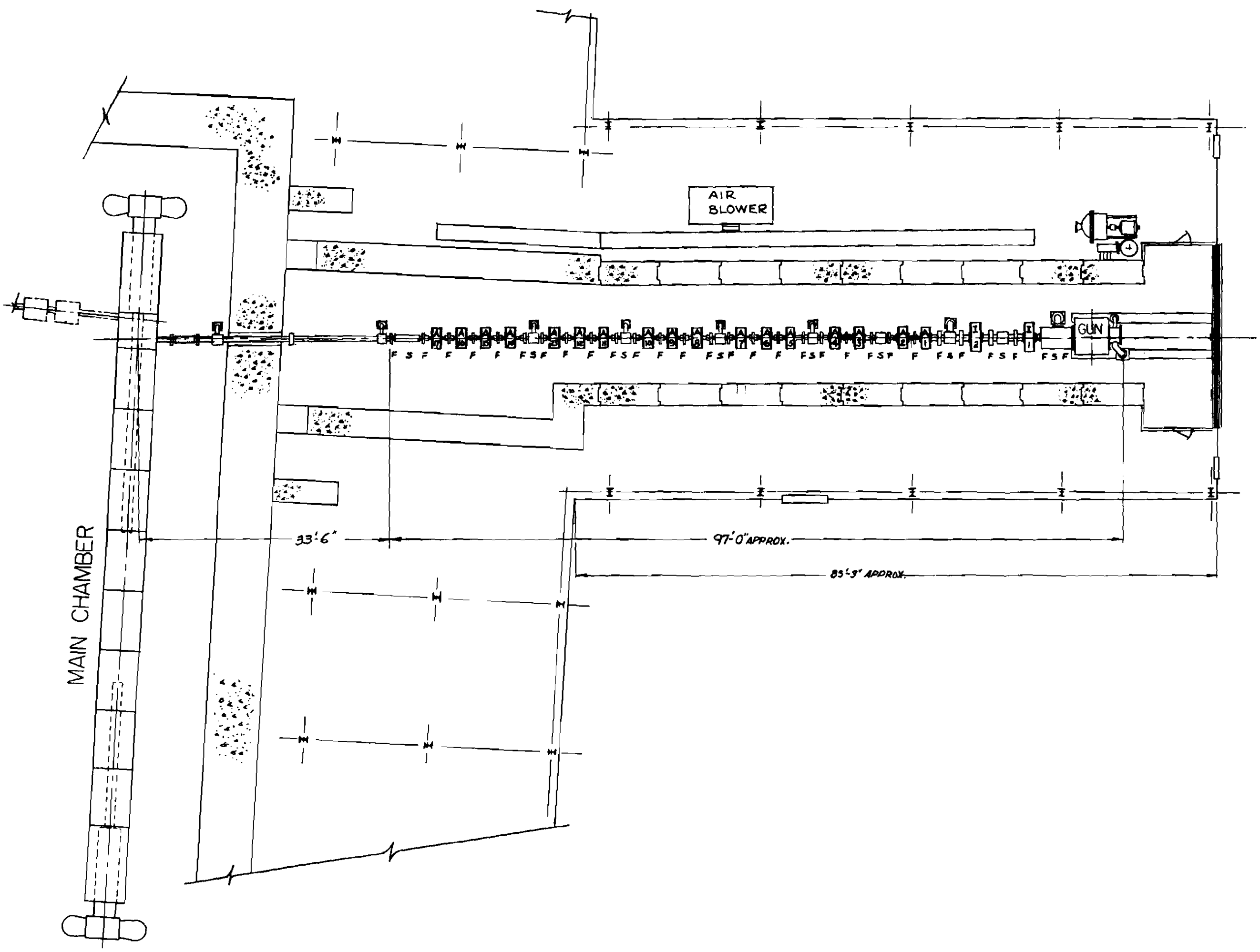


Fig. 11. Plan view of modified Astron 4-MeV accelerator.