

THE ASTRON LINEAR ACCELERATOR*

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Summary

One of the primary requirements of the Astron¹ controlled thermonuclear reactor experiment is an intense beam of relativistic electrons. An accelerator to produce such a beam with currents of the order of several hundred amperes has been in operation at the Lawrence Radiation Laboratory, Livermore, for several years.² The accelerator operates on the principle of magnetic induction as applied to a linear accelerator.

The original accelerator has been redesigned and rebuilt in order to increase the output beam current, to increase the beam energy, and to improve the quality of the output beam. Given in Table I is a comparison between the original machine and the design parameters for the new machine.

Table I. Parameters of Astron Electron Accelerator.

	Original	Redesign
Beam energy	3.7 MeV	4.2 MeV
Beam current	350 A	800 A
Pulse length	0.3 μ sec	0.3 μ sec
Repetition rate	0-60/sec	0-60/sec
Momentum spread	< 3% FWHM	< 2% FWHM
$\Delta p/p$		
Emittance	$\sim 50 \pi$ mr-cm	$\sim 25 \pi$ mr-cm

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.

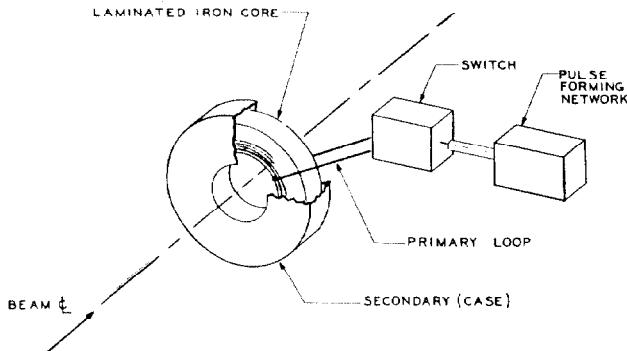


Fig. 1. Induction accelerator principle.

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The volt-seconds available to this system for a given magnetic material depend upon the cross-sectional area of the toroidal ring as given by the expression

$$\oint \vec{E} \cdot d\vec{l} = - \int_s \frac{d\vec{B}}{dt} \cdot d\vec{s} \quad (1)$$

where the accelerating particle performs the integration on the left side and the surface integral is taken over the cross section of the ferromagnetic material.

It should be noted that the beam pulse length influences the energy gain. Furthermore, since it is the cross section that determines the energy available, it is desired to minimize the diameter for two reasons. The first is to minimize the total weight of magnetic material and hence its cost, and the second is to minimize the power for magnetization which is proportional to the volume.

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 is done by proper shaping and control of the current pulse to the primary.

The magnetic core material is 0.001 inch thick, 50% Ni-50% Fe tape wound into cores of the proper dimensions.

Space-Charge Limited Beam Current

Experiments with the original accelerator showed that the maximum transmittable beam current was approximately 425 A. These experiments indicated that this value of current was the nominal space-charge limit, and that any further increase in the input beam current resulted in beam particle loss to the accelerator chamber walls. This space-charge limit was verified to some extent by computations made with the computer program EXPORT.³ EXPORT is a paraxial ray calculation with electric and magnetic self-fields included as well as external vacuum fields.

In order 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 original hardware in the new machine as possible.

Since the space-charge and self-magnetic forces are a strong function of the beam energy, it is expected that a significant increase in beam current could be gained by a relatively small increase in injection energy. If the accelerator sections remained as they were in the original

accelerator, namely a uniform gradient accelerating column 102 cm long with an aperture of 10.2 cm and an accelerating gradient of 4.53 kV/cm, computation showed that an increase in the injection energy to 1.67 MeV would be required to pass a 1000 A beam. This would represent an increase of 67% in injection energy. 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 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. Computation showed that in this case in order to transmit a 1000 A beam, a beam radius of approximately 7.5 cm would be required. This represents an increase in the accelerator aperture of almost a factor of two over its original value. Since the inner diameter of the existing cores sets the maximum aperture at 10.2 cm, this method of increasing the beam current was rejected.

The third possibility of increasing the beam current was to increase the accelerating gradient in the accelerator structures themselves. Computation showed a relatively weak dependence on the maximum transmittable beam current and the accelerating gradient. In order to transmit a 1000 A beam through the geometry of the original accelerator sections, an increase in the accelerating gradient of approximately 70% would be necessary. Such an increase in the accelerating gradient was not practical without a major change in the existing electronics.

The fourth means of increasing the beam current was to increase the focusing per unit length by reducing the length of the accelerator sections. Computation showed that in order to pass a 1000 A beam current, an accelerator section length of 53 cm or shorter would be required. This would be approximately one-half as long as the accelerator sections in the original machine. For our consideration, this was the most practical method of increasing the beam current since all that was required was to rebuild the accelerator sections into shorter modules and insert additional focusing elements between these shortened accelerator sections.

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. In order to investigate this question, computer calculations were made using the computer 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 for the desired transport system.

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 approximately 2 cm between the beam envelope and the walls. This clearance allows for the beam drift off-axis due to the ambient earth magnetic field, stray magnetic fields, error 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 $1 < R < 3$ cm and a beam waist is to be at the center of each of the accelerating sections.

Since the accelerator is to handle a beam of relatively low rigidity, 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. By determining the deflection as a function of beam energy (rigidity), it is possible to determine the positions of the steering magnets consistent with the beam parameters.

Accelerator Hardware

The designed machine layout is shown in Fig. 2. 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 to A17. Steering magnets are located at the positions labeled S, and focusing magnets are denoted by F. As can be seen, the accelerator as designed is approximately 97 ft long. Figure 3 is a photograph of the machine looking back down the accelerator toward the gun.

The electron gun used for the Astron accelerator is a high-perveance, increasing gradient gun capable of producing 1200 A of a beam current at approximately 550 keV. This corresponds to a perveance of 2.9 μ perv. The increasing gradient approach is used to provide radial beam focusing.

A cross section of the gun assembly is shown in Fig. 4. 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 12.5 keV to the beam. The cathode is a flat disk 17.8 cm in diameter, and is a conventional oxide cathode on a carbonyl nickel base. The cathode 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 1.5-in.-diam, metal-ceramic seals.

The two injector sections are uniformly accelerating, with grids on the input and output to terminate the electric field. Each injector section has an active accelerating length of 46.1 cm with a clear aperture of 20.3 cm. The accelerating gradient in the injectors is 4.77 kV/cm.

The accelerator sections are uniformly accelerating and hence have no electric focusing properties other than those due to end effects. Each accelerator section has an overall length of 50.8 cm, with a 10.2-cm clear aperture. The active accelerating length is 41.9 cm with an accelerating gradient of 4.53 kV/cm. Figure 5 shows a cross section of the accelerator sections.

The focusing magnets are simple, iron-shrouded solenoids with a field strength of approximately 265 gauss/ampere. The steering magnets are air-core, cosine-type windings with a maximum transverse field strength of approximately 5 gauss. Figure 6 shows a typical focusing magnet section. The aluminum boxes on either side of each and every solenoid throughout the machine are designed to house beam diagnostic equipment. In particular, one diagnostic box houses a current transformer to measure the beam current; and the other diagnostic box houses x and y beam displacement loops. These diagnostics allow the monitoring of the beam position and current approximately every 3 ft down the machine.

Base vacuum is provided by a number of mercury diffusion pumps distributed throughout the length of the machine. Typical operating pressure is 1 to 3×10^{-6} torr.

Power for the accelerator is provided by resonant charging of energy storage coaxial cables in a pulse-forming network. Several milliseconds before the pulse forming networks are charged, each core is taken into saturation in the negative direction by a reset pulse. The pulse-forming network is then charged and a thyatron switch delivers the current pulse to the primary straps surrounding each core. A pulse shaper is used to produce the desired current ramp for each core. Operation of the accelerator requires the simultaneous operation of 496 of these thyatron switch chasses and pulse forming networks.

The electronics is such that the accelerator generally operates at a continuous rate of 5 pulses/sec. This would correspond to a duty cycle of 1.5×10^{-6} with an average beam current of 1.2×10^{-3} A. Electronics are available which allow the accelerator to operate in a burst mode at a maximum rate of 1440 pulses/sec. This rate would correspond to a duty cycle of 4.3×10^{-4} with an average beam current of 0.34 A over the burst period.

Accelerator Operation

The original Astron accelerator operated for approximately 5-1/2 years before being dismantled in the fall of 1968. This accelerator produced a nominal 250-300 A beam at 3.7 MeV. Momentum spread was measured by a magnetic analyzer to be of the order of 2% FWHM, and by appropriate tuning the momentum error could be made less than 1% FWHM. The emittance was measured⁵ to be of the order of 54π mr-cm.

The rebuilt Astron accelerator was turned on in mid-December 1968. To date, the accelerator has produced approximately a 500-A beam at approximately 95% of full energy. While no quantitative measurements regarding beam emittance and momentum spread have been made during this initial debug and tune-up phase, operation to date has been within expected limits in this respect.

The beam current has been limited due to a form of the beam breakup instability.⁶ Preliminary investigations indicate that the instability is of the cumulative, multisection amplifier type whereby a transverse, deflecting mode is generated in some of the identical structures housing the beam diagnostics down the length of the machine. At the exit of the first small-bore accelerator, the beam current is 650 A. After passing through the next 9 small bore accelerator sections, the beam current is 520 A at approximately 3 MeV. The beam breakup occurs rather abruptly in the following unit. Modifications to the structures are proceeding so as to remedy this situation.

References

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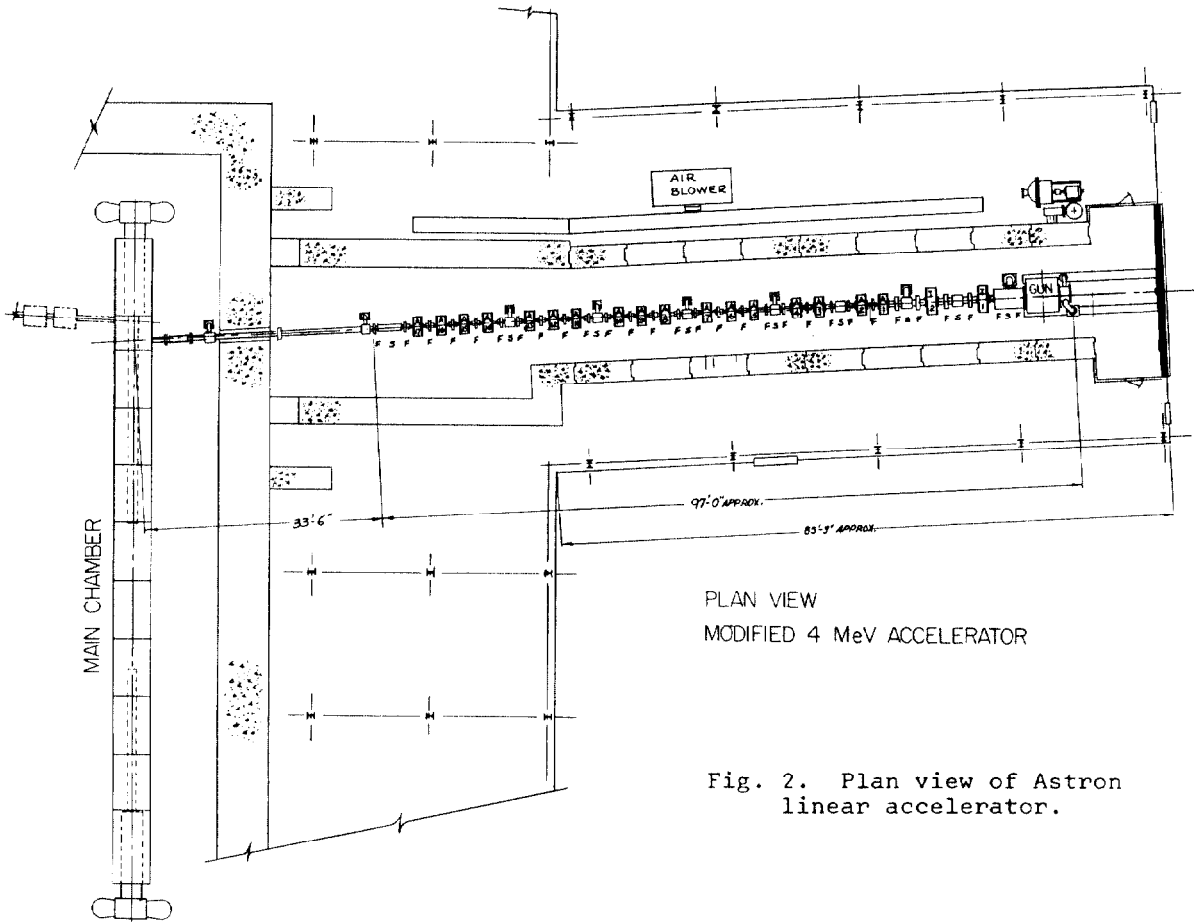


Fig. 2. Plan view of Astron linear accelerator.

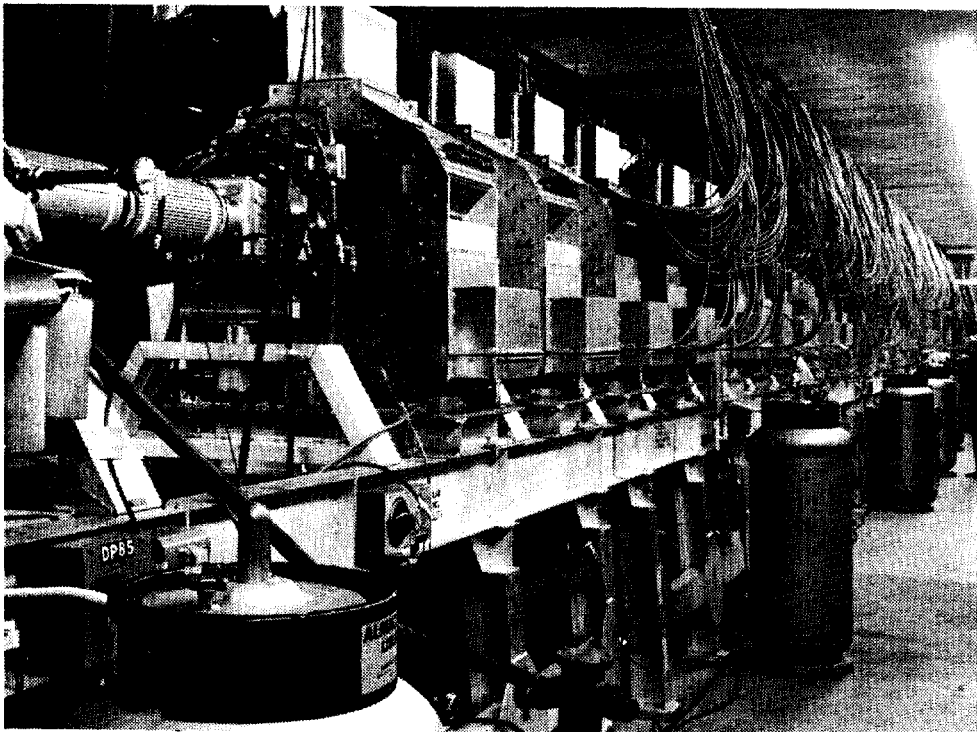


Fig. 3. View of Astron accelerator.

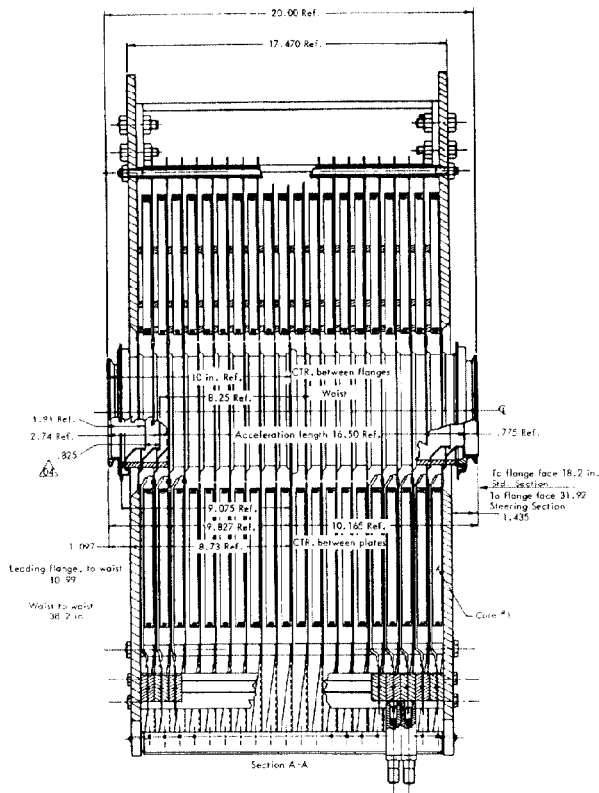


Fig. 4. Astron electron gun section.

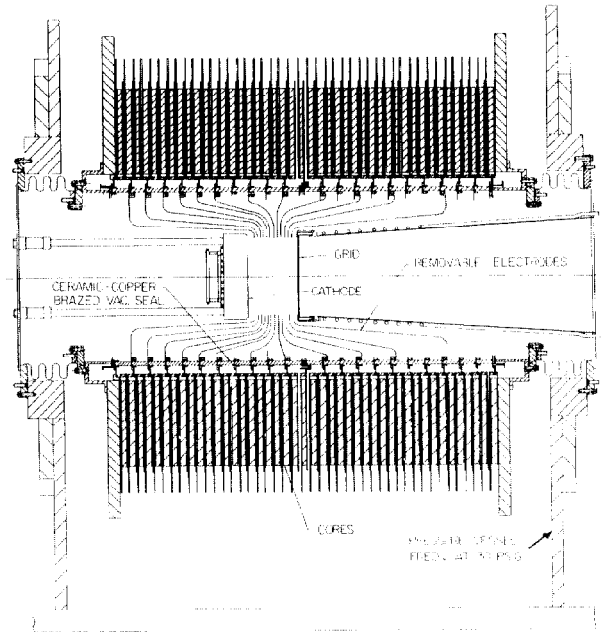


Fig. 5. Cross section of accelerator sections.

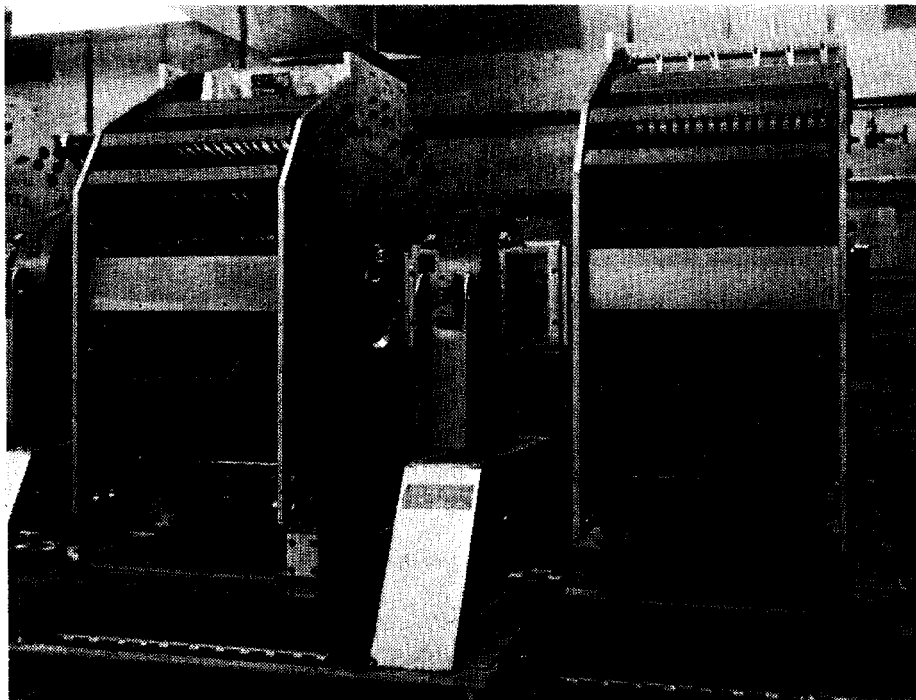


Fig. 6. View of focusing solenoids and beam diagnostic boxes.