

DESIGN OF A 3 AMPERE PEAK STEADY STATE, 0.001 DUTY,  
10 MeV LINEAR ELECTRON ACCELERATOR

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Summary

The centerline design of a 3 ampere steady-state linear accelerator is outlined and theoretical performance given. The techniques used for extending the blow-up threshold are given along with pertinent cold test data. The injection system design is discussed along with methods used for handling high currents while providing  $40 - 60^\circ$  bunches.

Introduction

The AFFRI accelerator is a two-mode device designed to operate with 3 amperes steady state at 10 MeV or 0.75 amperes steady state at 30 MeV. Stored energy operation is also possible in both modes of operation.

The high current and long pulse length ( $10 \mu s$ ) demanded an unusual approach to the design problem. The choice was to build extremely short (12 cavity) sections with highly tapered impedance and high gradient, each powered with 10 MW of RF for the high current mode. In addition, a complex injection system was used to insure that  $40 - 60^\circ$  bunches with negligible inter-bunch base current would be available over the range of steady-state currents. A tapered phase-velocity first section was incorporated into the design as well to provide adiabatic bunching for maximum current. In addition the entire centerline is immersed in a 1 - 2 kg solenoidal field.

The high energy mode is obtained by adding two 1.55 meter sections and rearranging the RF feed. These high gain sections are moved to one side and replaced with a drift tube without losing vacuum for high current operation. A list of pertinent machine specifications is given in Table I.

Injection System

The injection system uses an inflector for transverse video modulation of the beam, an S-band chopper for transverse RF modulation, and two S-band pre-buncher cavities for longitudinal bunching prior to injection. A total of three "crossovers"\* were needed to accommodate this array of components in addition to a fast valve to protect the gun from vacuum failure. See Figure (1) for a block diagram.

The diode electron gun is a standard Varian Mark V, which has a micropervance of .4 so as to deliver 20 amps at 150 kV. This current is required so that with losses incurred in the various operations used in the injection system, the first guide section can still capture and bunch at least 5 amperes, which is the current specified for the stored energy mode.

Subsequent reduction of current is obtained by defocussing the electron beam after it emerges from the gun at the plane of the first and second beam collimators. The defocussing is accomplished by increasing the appropriate thin lens current to reduce the focal length and using space charge spread to widen the spot size at the plane of the collimator. Current reduction is also obtainable by using a cooler cathode.

A thin lens is placed just after the anode to control the position of the first minimum. The shielded design localizes the field so as to prevent flux from cutting the cathode surface, and low impedance with water cooling is used to obtain 2700 ampere turns maximum.

Following this lens is a water cooled tungsten collimator with the 5mm diameter aperture placed some 5 inches from the cathode surface, corresponding to the normal beam cross-over when the gun operates space-charge limited.

Because of the high currents, space charge spreading dictates close spacing of components in order to maintain a beam radius under 1 cm to avoid second order lens aberrations from dominating.

A fast valve is placed next with the capability of closing in 3.5 ms in order to protect the gun from vacuum failures, and following is another shielded thin lens with a set of inflector plates. The deflectors are designed with a field reversal to sweep the beam across the aperture of the high-power collimator, so that pulse heating will be distributed. The plates are driven alternately by hydrogen thyratrons to 20 KV with a 10 to 90% rise time in the order of 5 ns. This provides a sweep of the 150 KV beam of about 25 mm in the plane of the collimator, which was designed with a water-cooled tungsten insert to dissipate up to  $2 \text{ MW/cm}^2$  pulsed and  $6 \text{ KW/cm}^2$  average beam power. During the pulse, surface temperatures of  $1940^\circ\text{C}$  will be reached at this collimator and an average temperature of  $980^\circ\text{C}$ . The purpose of the deflectors is to provide a precise beam pulse over the range of pulse

\* The electron beam is laminar. "Crossover" is used to mean waist or minimum.



The design curves assume a 5% increase in shunt impedance from cold test values due to brazing and a 5% decrease in attenuation. This causes the unloaded voltage to appear somewhat higher than that implied by uncorrected data, but it also causes the load-line to be steeper so that at very heavy beam loading the result is actually more conservative. Corrected design values are then obtained by displacing the load line parallel to itself by 8% of  $V_0$ .

The resulting unloaded uncorrected design voltage with 10 MW incident is 6.1 MeV. At 3 amperes, the design energy gain is 3.2 MeV. The total length is .42 m and the attenuation  $\tau = \bar{I}L = .084$ .

All couplers have their bodies offset from centerline so that the beam sees the maximum electric field and symmetrical magnetic field about the centerline in order to prevent transverse forces from being set up due to the asymmetrical coupler.

The input coupler total bandwidth is 45 MHz; however, the matched bandwidth ( $VSWR < 1.2$ ) is under 3 MHz. Total bandwidth is the frequency difference between the O and  $\bar{A}$  modes as set up in a uniform disc-loaded guide with the same iris as the coupler. The matched bandwidth is smaller than normally seen in Varian guides by a factor of 2 because of the size of the discontinuities used to taper the impedance. Still, the VSWR is under 1.06 at the operating point.

Bead drop data taken on axis with a sapphire bead, after tuning with the standard sliding short and reference guide showed that tuning errors were of the order of  $\pm 2^\circ$ . In addition, it showed that the space harmonic fundamental content was not affected measurably by the steep impedance taper.

The tuning frequency was chosen to compensate for the change from room to operating environment and the phase error due to beam-induced fields at  $i = im/2$ , so that a minimum phase error deviation is seen over the entire operating range. The water circuit design minimizes phase error due to thermal detuning over the range of current and repetition rate. Evaluation of available water circuits was made using a cavity-by-cavity analysis of guide heating and thermal sensitivity. Guide 1B is cooled using 20 GPM and 8 tube counterflow; whereas guides 2A and 2B use unidirectional, front fed flow at 40 GPM.

The first two sections are immersed in 2000 gauss solenoidal magnetic fields and the rest of the centerline uses 1000 gauss on axis to confine the beam. The resulting transfer of transverse momentum to helical motion confines the beam to a diameter of 1.0 cm under normal beam loading. Steering is provided to correct for various sources of position error so that the beam trajectory is maintained as closely as possible to machine centerline.

A picture of guides 2A and 2B with vacuum jacket, solenoids, and steering coils in place is shown in Figure (2).

#### Operation in Mode A

Mode A is a high current mode of operation in which sections 3A and 3B are moved off beam centerline using a sled arrangement inside a large solenoidal magnetic field. A drift tube replaces these accelerator guides.

The Guides 1A, 1B, 2A, and 2B are fed with 10 MW each from the four arms of two 24 MW (Thomson-Varian 2014) klystrons. High power phase shifters are used between guides.

The resulting load line is shown in Figure (3).

The use of external water loads with intervening RF windows allows for flexibility in changing modes of operation of the machine. During mode change, the guides do not have to be brought up to air, and a great variety of connections are possible.

#### Guides 3A and 3B

The high energy gain sections are used only in Mode B operation. They are each composed of 33 cavities which approximate constant gradient by means of uniform sections followed by short, low-reflection transitions.

With 10 MW incident, the unloaded, uncorrected design energy is 16.3 MeV. At a peak beam current of .75 ampere the uncorrected energy gain is 10.5 MeV. The fundamental component of electric field without beam varies from 12 to 14.8 MeV/m down the guide. With  $i = .75$  ampere, the gradient at the input coupler is 12.4 MeV/m and at the last cavity it is 3.5 MeV/m.

An 18 inch inside diameter solenoid around sections No. 5 and No. 6 concentric with beam centerline allows these sections to be moved to one side and be replaced with a drift tube without losing vacuum.

The tuning frequencies for each of the guides was chosen carefully to compensate for a variety of sources of phase error. Among these are beam induced electric field for asynchronous loading at high currents, and varying repetition rates. The attempt is made to tune the guides for zero phase error at one typical operating point and design for minimum deviation in phase error for operation away from this point. The choice of unidirectional flow for the water circuit was based on this and on computer analysis of the temperature profile of the guides and the phase sensitivity of the cavities. A picture of guides 3A and 3B during tuning is shown in Figure (4).

Operation in Mode B

The entire six lengths of accelerator guide are used, and plumbing is rearranged so that Guide 1A is fed with 10 MW from one arm of a klystron. Guide 1B is fed with the output of Guide 1A through a high power phase shifter. A similar arrangement is used to feed Guide 2A and use its output for Guide 2B. The high gain guides 3A and 3B use the other two available klystron arms individually. Load lines are shown in Figure (5).

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References

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TABLE I

AFFRI SPECIFICATIONFrequency 2856 MHzMode A

Loaded Beam Energy at 2.6 Amps	10 MeV
"Unloaded" Beam Energy at 0.001 Amp	20 MeV
Peak Beam Current at 10 Mev	2.6 Amps
Beam Pulse Length	0.01 - 10 $\mu$ s
Energy Spread at 50% Integrated Current at 10 MeV	$\pm$ 1 MeV

Mode B

Loaded Beam Energy at 0.75 Amp	30 MeV
"Unloaded" Beam Energy at 0.001 Amp	50 MeV
Peak Beam Current at 10 MeV	0.75 Amp
Beam Pulse Length	0.21 - 10 $\mu$ s
Energy Spread at 50% Integrated Current at 30 MeV	$\pm$ 0.6 MeV

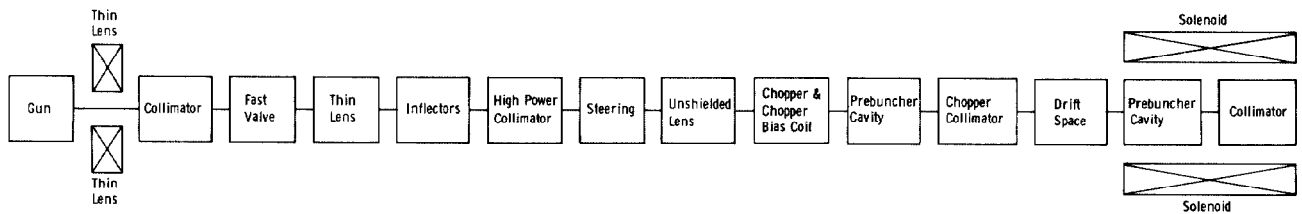


Fig. 1. Block Diagram of AFFRI Injection System.

