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° 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 μs) 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° 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 prebuncher 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 electron beam is laminar. "Crossover" is used to mean waist or minimum.

The diode electron gun is a standard Varian Mark V, which has a microperveance 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 inflectors 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 MW/cm^2 pulsed and 6 KW/cm^2 average beam power. During the pulse, surface temperatures of 1940°C will be reached at this collimator and an average temperature of 980°C. The purpose of the inflectors is to provide a precise beam pulse over the range of pulse lengths used: from 10 ns for stored energy to 10μs for long-pulse steady state.

A short drift space with adjustable steering and thin lens No. 3 separates the high power collimator and the chopper. This thin lens is unshielded so as not to short out the bias coil fields, and it operates at a high current so as to be effective as a lens. The result is that components both upstream and downstream have to be rotated azimuthally to compensate for the additional beam rotation. The chopper cavity is operated at S-band in the TM_{120} mode and has its shape optimized for maximum deflection for a given power input. The beam is biased off axis with a dc magnetic field superimposed on the cavity field, and the cavity is used to return the beam to the axis for the appropriate phase window. A waveguide feed drives the chopper with about 18 kW of r-f to provide 180° chopped injection per cycle, dumping the unwanted portion on the chopper collimator, which absorbs up to 800 watts of beam power. The chopper is not used for the stored energy mode.

Because of the wide range of currents, two slotted prebunchers are used to obtain a 40-60° bunch length at the midplane of guide No. 1 input coupler. Only one is used at a time and a changeover will be made during mode change. Up to fifty kilowatts of RF power is made available through waveguide feeds to provide the variety of gap voltages needed for correct bunching. The maximum current case will deliver 8 amperes to the accelerator in a 60° bunch. A gap voltage of about 75 kV and a drift space of 15 cm is required for this mode of operation.

The drift space and second prebuncher are immersed in a solenoidal magnetic field for beam confinement before reaching the final collimator and injection into the accelerator.

Section No. 1A

Accelerator guide No. 1A is made up of an eight-cavity tapered impedance buncher followed by seven velocity-of-light cavities. The phase velocities are increased gradually from an initial value of .66C to unity in the bunching region. Average field strengths with 10 MW incident at zero loading vary approximately linearly from 103 kV/cm in the input coupler to 150 kV/cm in the last cavity.

The use of a tapered phase velocity buncher is mandatory for high currents[1] for several reasons. One is that the input coupler is shorter and the injection potential reduction due to interaction with the standing wave region of the input coupler is reduced, so that the space charge effect is not as severe. Another is that interaction with higher order space harmonics during bunching is reduced because the RF phase velocity is matched approximately with electron velocity.

The design approach used was to minimize phase excursions while providing distributed bunching. The injected electrons have an orbit centroid around a phase point 15°-30° in front of the crest for the first few cavities, so that bunching is gradual and energy gain high. This reduces space charge debunching at high currents. Electrons from injection angles varying from 60-80° in front of the crest to 20-30° behind the crest are compressed adiabatically. Electrons injected more than 90° in front of the crest are not used for they have experienced a retarding field in the input coupler, and their lower energy increases space charge forces. These initial angles are avoided by proper use of the injection system.

The results of this design approach have been proven in tests at high currents.[2]

Sections 1B, 2A, 2B

These sections were designed to operate in the high current steady state mode. The approach used was to slice the accelerator into a number of short sections to increase the regenerative blow-up threshold to above 2.6 amperes at 10μs. A known regenerative threshold (Bonn Synchrotron Injector) of 800 mA at 5μs with a 2.83m guide having a uniform front end at 17 MeV/m was scaled using $(TlZ/E)^{1/3}$ as an invariant.

This resulted in the .42 m length per section. Subsequent evaluation of the design with the simple asymptotic equation for transverse modulation derived by Helm[3] shows that a multi-section (or SLAC-type) blow-up threshold without focusing exists in the vicinity of 1 ampere at 10μs.

The use of short sections to avoid regenerative blow-up is well-known. The only advantage of this approach with regard to the SLAC-type blow-up, however, is that the higher impedance taper available in the short sections can be used to decrease the interaction length. The estimated decrease in interaction length for the AFFRI design is about 70% .

The problem of elevating this one-ampere threshold to 3 amperes is considered solvable with the use of strong focusing.

The iris diameter over the twelve cavities of each section varies from an initial .9365 inch to a final .8225 inch with a corresponding range of group velocity divided by C of .0145 to .0089. At 10 MW the unloaded gradient increases from 13.3 MeV/Meter in the input coupler to 16.2 MeV/m in the last cavity. With 3 amperes of beam, the gradient ranges from an initial value of 12.8 MeV/m to a final .8 MeV/m. At .75 amperes the guide is approximately constant gradient with an average electric field of 12.8 MeV/m. The gradient referred to is the peak of the fundamental space harmonic, which represents some 80% of the total harmonic content.

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 Vo.

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 = $\overline{I}L$ = .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 π 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 ± 2°. 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).

<u>Operation in Mode A</u>

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.

<u>Guides 3A and 3B</u>

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).

Acknowledgement

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References

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2. Haimson, J., Pering, N., "A High Current Investigation of a 10 MeV S-Band Electron Linear Accelerator," DASA 1523, June 1964.

3. Helm, R. H., Proc. of the 1966 Linear Accelerator Conference, "Computer Study of Wave Propagation, Beam Loading and Beam Blowup in the SLAC Accelerator", p 254.

TABLE I

AFFRI SPECIFICATION

Frequency 2856 MHz

Mode 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 μs
Energy Spread at 50% Integrated Current at 10 MeV	± 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 μs
Energy Spread at 50% Integrated Current at 30 MeV	±0.6 MeV

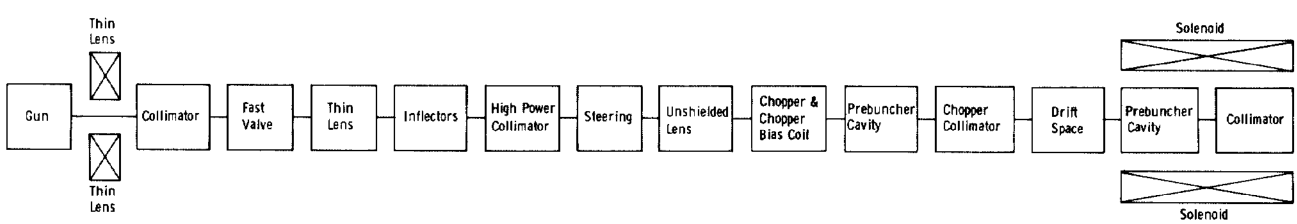

Fig. 1. Block Diagram of AFFRI Injection System.

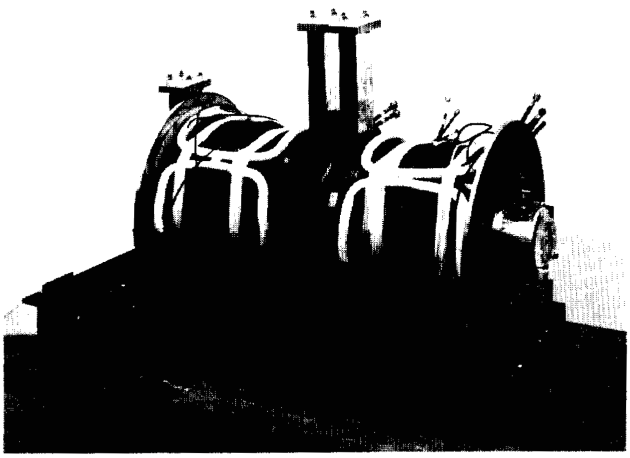

Fig. 2. Accelerator Guides Number 2A and 2B.

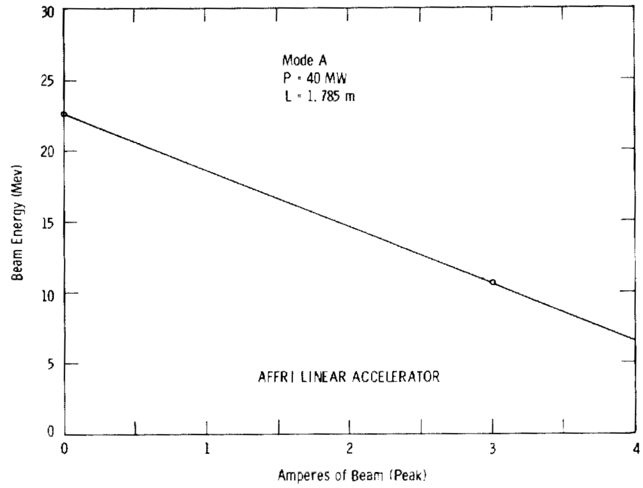

Fig. 3. Load Line for Mode A.

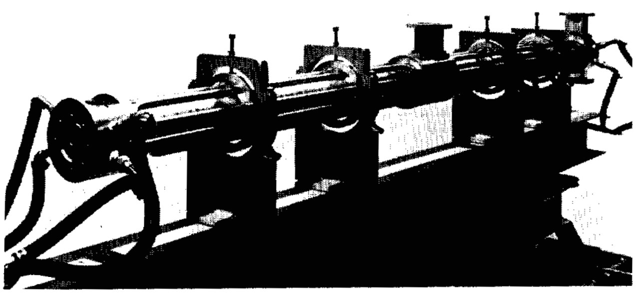

Fig. 4. Accelerator Guides 3A and 3B During Tuning.

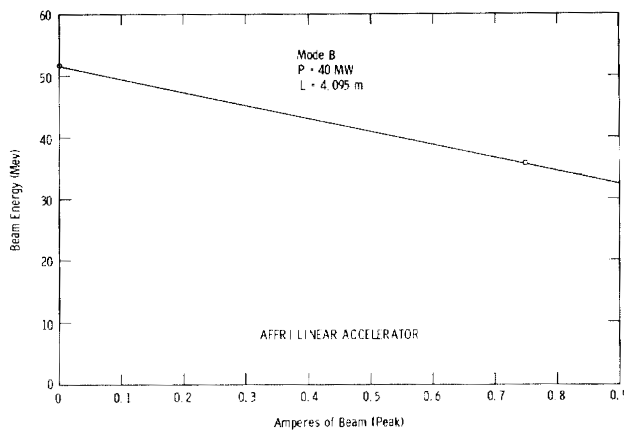

Fig. 5. Load Line for Mode B.