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A WIDE DYNAMIC RANGE 10 MeV HIGH CURRENT ELECTRON LINEAR ACCELERATOR

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Summary

The salient features of a new high power linear accelerator system are described. This machine combines a 300 kV dc accelerator, constructed for operation with pulsed currents in excess of 2A, with a single section 10 MeV accelerator waveguide so that given levels of high peak current may be maintained over a wide range of beam energies. (Previous technology required RF phase and/or power adjustment to a second accelerator section.) The accelerator waveguide incorporates a suppressed phase oscillation buncher designed so that a loss of terminal electric field strength, caused by a large reduction of input RF power to reduce beam energy, may be accurately compensated by an increase in potential of the dc accelerator, thus maintaining the capture efficiency of the waveguide. Reduction of space charge forces due to HV injection, and avoidance of dual section operation, prove to be major operational advantages. The 20 MW RF transmitter and the overall beam centerline are described; and operating performance and equipment photographs are presented.

Introduction

This single section linear accelerator system was designed to provide a high level of beam power over a wide range of beam energies and, more specifically, to produce a 10 MeV, 1.1A peak current beam with a high degree of long term stability and reliability. To fully exploit the now established excellent operational history (and the economic and technical advantages) of the SLAC-type 20 MW klystron,[1] a frequency of 2856 MHz was chosen for the accelerator RF system. The accelerator waveguide was designed to meet the immediate beam specifications with a peak RF input power of only 16 MW and a beam loading of less than 30%, so that future uprating of the system to peak current levels in excess of 2A could be readily achieved.

Although a variety of special components were incorporated in the accelerator system, three specific subsystems contributed principally to meeting the above objectives. These were, (a) a high potential injection system which provides highly stable, well focused, prebunched beams adjustable in energy over the range 180 to 275 kV; (b) a high power transmitter system containing solid state de-Q-ing circuitry, water cooling for all major dissipative elements, and a 20 section PFN which operates at a peak charge voltage of less than 28 kV; and (c) a high group velocity bunching and accelerating structure with a total fill time of only 190 ns, a 92% theoretical maximum conversion efficiency of RF to beam power, and a very insensitive dependence of beam phase position with respect to changes in system frequency (or temperature), e.g., a change in frequency of 14.5 kHz (or 0.31°C) produces less than 1 degree of phase shift at the end of the accelerating structure. These innovations and the results of initial beam tests are described in the sections which follow.

Description of Linear Accelerator

Injection System

The injection system consists of an HRC Model 275/2250 electron gun,[2] a short beam pulse video deflection system, a single cavity, high current prebunching system, and a set of magnetic lens and steering assemblies. The electron gun comprises an indirectly heated dispenser cathode and focusing electrode assembly, a biased non-intercepting extraction electrode (which is triggered from a hot deck pulser via fiber optic light links) and an all metal-ceramic brazed, compensated gradient, 300 kV dc accelerating column. A view of the electron gun assembly is shown in Figure 1. In this accelerator system, high quality transformer oil was chosen as the insulating medium for the electron gun and its HV dc power supply.

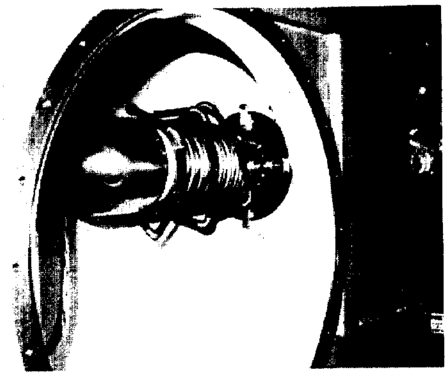

Figure 1. High Potential Electron Gun and DC Accelerating Column Viewed Through Tank Access Port.

Because of the low emittance, long focal length beam produced by the electron gun (high beam quality is obtained by using high injection potentials and small cathode dimensions, by avoiding the use of a grid, and by using a plurality of electrostatic focusing lenses along the dc accelerating column), a stepped potential video deflection system of only 3.5 kV is sufficient to produce beam pulse widths of less than 5 ns when operating at injection potentials of up to 250 kV. The injection system beam optics is arranged so that a beam waist is produced 40 cm beyond the exit plane of the gun tank and, after traversal through the video deflector, is re-imaged by a special lens system to a 2 mm diameter at a chopping collimator located 110 cm from the gun tank exit plane. After traversal through a prebuncher cavity and a drift space lens, the beam is again re-imaged to a small diameter at the injection collimator located at the accelerator waveguide entry plane. Figure 2 shows the unusually long dimensions and the conveniently open layout of this high potential injection system.

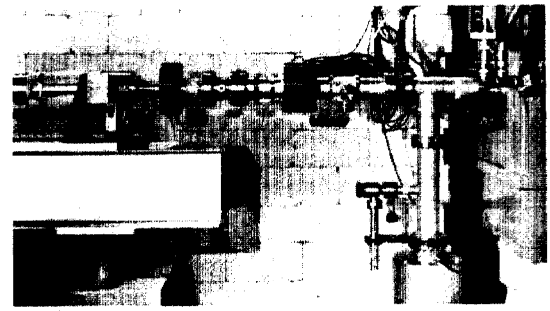

Figure 2. Injection System Drift Space Containing Short Beam Pulse Video Deflector, Prebuncher, Collimators and Lenses.

Transmitter

The transmitter comprises a high voltage power supply which converts ac line power to 1% regulated 18 kV dc; a charging transformer and solid state de-Q-ing system; a modulator consisting of a low impedance pulse forming network (PFN) with resonant charging; a step-up pulse transformer; a RCA/ITT 8568 2856 MHz klystron with electromagnetic focusing coils; and a stable solid state RF driver having a dual triode output stage. A view of the transmitter cabinet is shown in Figure 3.

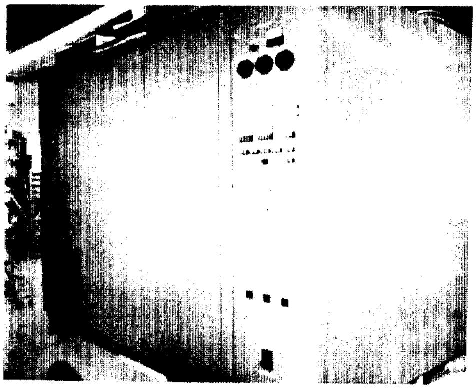

Figure 3. 20MW/20kW RF Transmitter Cabinet Showing Local Control Panel.

AC line power is applied to the primary of a delta-wye high voltage plate transformer by means of a unique combination of a variable transformer bank and series bucking transformers. This arrangement allows control over a range of 70 to 100% of the output voltage, and it limits the in-rush current during switch-on. Another feature of this combined transformer system is that, for diagnostic purposes, a zero to 100% range of voltage may be obtained, at reduced duty, by a simple re-connection. To insure reliability and long life, the three phase plate transformer and associated full wave all-solid state rectifier bridge network are immersed in a sealed oil-filled, water-cooled tank which is provided with access ports for inspection and service. The HV dc output is automatically adjustable between 13 and 18 kV, consistent with the desired de-Q-ing level and klystron pulse voltage.

The dc resonant charging line modulator controls precisely the charging voltage to the pulse forming network. This is accomplished by de-Q-ing the charging transformer (which is housed in a small water-cooled oil tank) at the exact moment the PFN obtains the desired charge for the klystron pulse. The charging transformer has a low voltage de-Q-ing winding which is controlled by an all-solid state circuit. The unused energy in the charging transformer is dissipated in a water-cooled power resistor (see Figure 4), thereby avoiding a large contribution to the ambient temperature within the transmitter cabinet. To conserve energy, for high efficiency pulse regulation, the de-Q-ing reference circuit also controls the regulator for the HVPS so that the ratio of dc power supply voltage to PFN charging voltage is optimized. High current stacks of compensated controlled avalanche diodes are used for the charging hold-off and shunt diode circuits. These diodes are capable of withstanding full short circuit faults without damage. The PFN sections (refer Figure 5) are mutually independent; and to obtain the desired pulse shape and flatness, each section may be tuned while the transmitter is operating at full voltage. A high power ceramic thyratron discharges the PFN, through a low impedance circuit, to the primary of the klystron pulse transformer. This pulse transformer and the associated monitoring equipment are housed in a water-cooled oil tank which is fitted with an oil recirculating and filtering system.

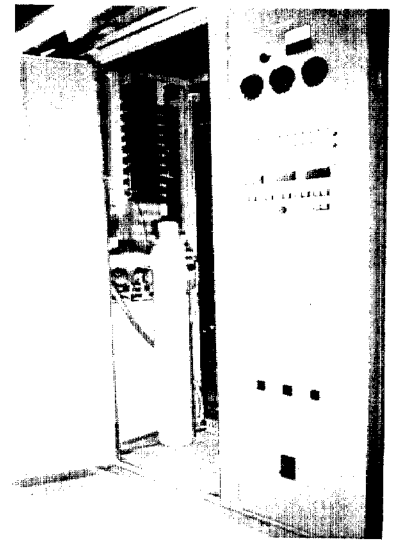

Figure 4. Water cooled de-Q-ing Power Resistor and Resonant Charging Transformer Viewed through Inspection Doorway.

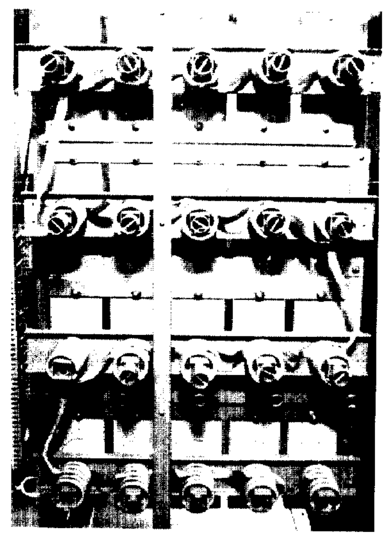

Figure 5. 20 Section, 5 μs Tunable PFN Assembly Showing Low Inductance, Low Profile Bushing, Pulse Capacitors.

Accelerator Waveguide

The accelerator waveguide for this high current machine comprises, (a) a reduced phase velocity "offset" cavity input coupler which is designed to initially retard,[3] bunch and then accelerate the prebunched beam prior to entering the second cavity; (b) a tapered phase velocity traveling wave structure having a constant group velocity and designed to ensure adiabatic bunch compression[3] of the prebunched high current beam and to suppress longitudinal phase oscillations; (c) a short transition section which provides phase compensation and impedance matching between the buncher structure and the subsequently located phase velocity of light cavities; (d) a non-uniform impedance velocity of light structure; and (e) an offset output coupler which transforms the accelerating TM_{01} mode to a TE_{01} mode to allow the residual RF power to be monitored, and then absorbed external to the vacuum system in a water-cooled high power RF load. Photographs of the accelerator structure before and after installation of the solenoid coils, and the evacuated rectangular waveguide components, are shown in Figures 6 and 7, respectively.

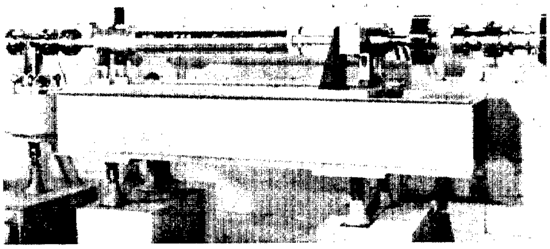

Figure 6. View of Accelerator Waveguide Prior to Installation of Solenoid Focusing Coils.

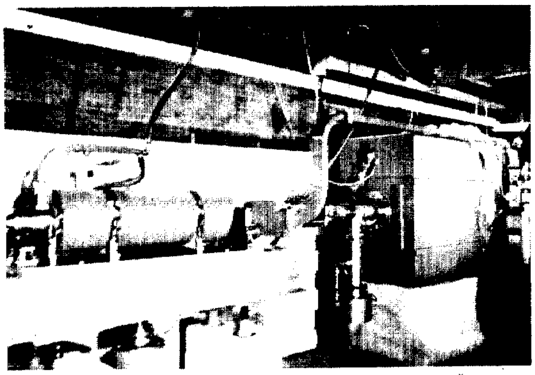

Figure 7. View of Completed Centerline Assembly Showing Electron Gun Tank and Klystron.

Both the input and output couplers have offset cavities which are designed to minimize radial momenta contributions to the beam. The couplers are of the side-wall, iris coupled type for high electric field operation and are of novel design in that the water cooling header, the vacuum pumping port, and the high power RF connections are all integrally machined from a single ingot of 300 series stainless steel into which the OFHC copper terminating cavities are vacuum brazed. The accelerator waveguide proper was constructed from interlocking OFHC copper components which were stacked and brazed with copper-gold alloys in a hydrogen furnace. The internal surfaces of the copper cavities were final machined with a surface finish of less than 10 microinches using diamond tipped tools in a tracer lathe under tight temperature controlled conditions. After brazing, borescopic inspection, TIG welding, and helium leak testing, the waveguide structure was nodal tuned so that the phase shift of each cavity was within ±1° of the 120° design value. A fixed $2\pi/3$ mode configuration was maintained for the entire length of the waveguide, and the HEM_{11} BBU modes were made highly dispersive so as to elevate the starting current threshold level above 3A. Additional waveguide design information is listed in Table I. A comparison of the high power RF waveforms at the input and output of the accelerator waveguide, confirming the very short filling time of this high group velocity structure, is shown in Figure 8.

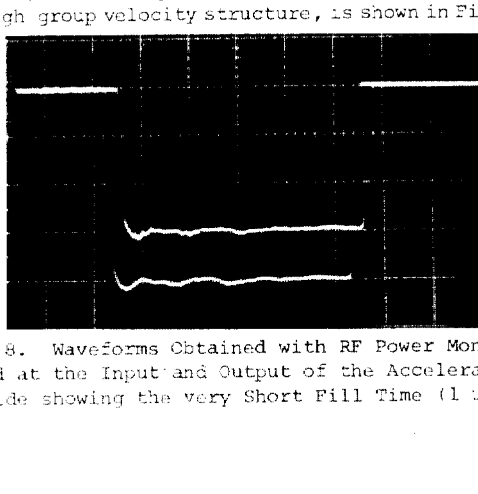

Figure 8. Waveforms Obtained with RF Power Monitors Located at the Input and Output of the Accelerator Waveguide Showing the Very Short Fill Time (1 μs/div).

Initial Measurements and Beam Performance

A non-intercepting, low Q RF monitor and an evacuated Faraday cup were used to measure the straight ahead beam. A second high power evacuated Faraday cup and an analyzing slit assembly were manufactured and installed in the 30° arm of a magnetic spectrometer to measure beam energy characteristics. The beam analyzing equipment is shown, during installation, in the Figure 9 photograph. A waveform of the first high current beam pulse obtained during the initial beam tests is shown in Figure 10.

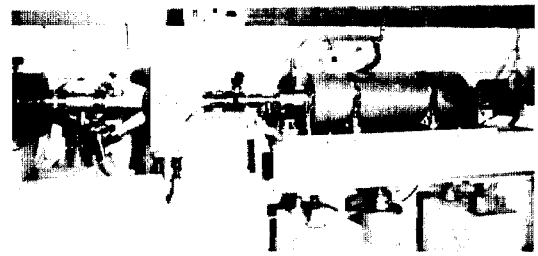

Figure 9. View of Accelerator Waveguide and Beam Analyzing Equipment.

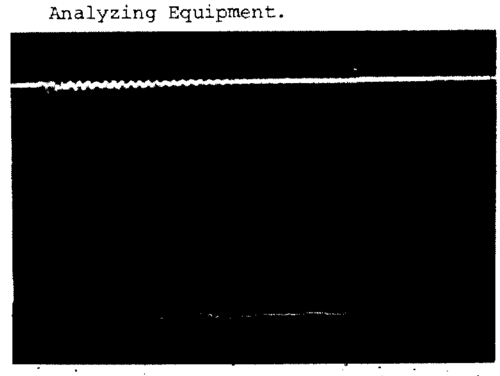

Figure 10. First High Current Beam Pulse — Injector Pulsed at ¼ of the Transmitter Pulse Rate; Noise due to Scope being Located Temporarily alongside Transmitter. (210 mA/div, 1 μs/div).

Measured values of several of the important waveguide parameters are shown listed in Table I, together with beam performance data as obtained with two widely different values of peak RF input power (P_0). At P_0 = 16 MW and an injection potential of 220 kV, a beam energy of 8½ MeV was obtained at a peak current of 1500 mA. The wide dynamic range of this single section accelerator was confirmed when P_0 was lowered to 8 MW and, with the injection potential raised to 260 kV, a peak current of 1500 mA was delivered to the Faraday cup at a beam energy of 4½ MeV.

TABLE I

Accelerator Waveguide Microwave Parameters and Preliminary Beam Performance Data

Description	Measured Value
Accelerator Waveguide Attenuation Parameter*	0.128 Np
Accelerator Waveguide Quality Factor ($\bar{Q}$)	13130
Accelerator Waveguide Fill Time (T_F)	190 ns
Phase-Frequency Sensitivity Parameter ($\partial\delta_a/\partial f$)	67.4°/MHz
Zero Current Energy Gain at 16 MW Input RF Power	14.1 MeV
Energy Gain at 1100 mA and 16 MW Input RF Power	10.2 MeV
Energy Gain at 1500 mA and 16 MW Input RF Power	8.5 MeV
Zero Current Energy Gain at 8 MW Input RF Power	10.1 MeV
Energy Gain at 1100 mA and 8 MW Input RF Power	5.9 MeV
Maximum RF Conversion Efficiency (η_m)†	87.5 %
Peak Current (i_m) for η_m	1400 mA

*Design Value = 0.124 N_p
†Theoretical Value = 92 %

These beam measurements were obtained with a 6 mm diameter, water-cooled, collimator located at the end of the accelerator section and with a drift distance of 2 m to the Faraday cup. Figure 11 shows actual measured values of electron energy versus peak current collected in the Faraday cup for the two different conditions of operation. No allowance has been made for back scatter or output collimator interception losses.

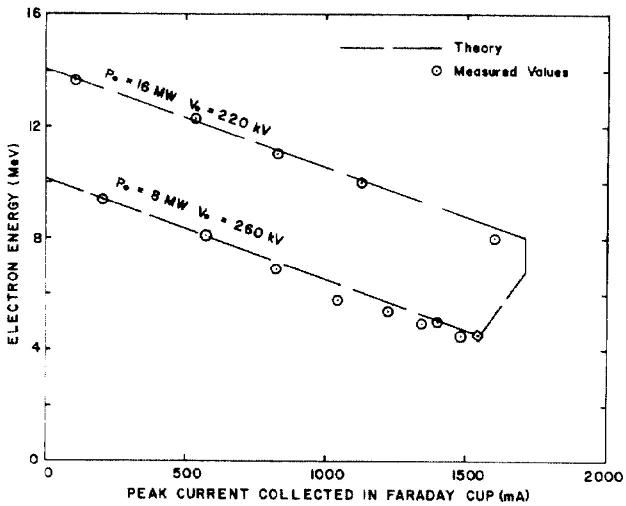

Figure 11. Electron Energy vs Peak Current Collected in Faraday Cup (Positioned 2 m beyond the 6 mm diameter Accelerator Output Collimator) for a 2 to 1 Change in RF Input Power.

Because of the unusual opportunity to demonstrate a new maximum RF conversion efficiency with this high group velocity microwave structure, a series of heavy beam loading tests were conducted at the 8 MW peak RF input power level. Figures 12(a) through (d) show the ratio of accelerator residual RF power level with and without beam loading for successively increased levels of accelerated current. The corresponding beam energy and RF conversion efficiency values are shown plotted in Figure 13. It can be noted that the residual RF power was reduced to zero at approximately 1200 mA loading [refer Figure 12(c)], that the maximum RF conversion efficiency was achieved at a somewhat higher[4] value of beam loading (1400 mA), and that a further increase in beam loading resulted in the beam transferring RF power back into the structure, i.e., RF regeneration.[5] These beam tests proved that a conversion efficiency of RF power to beam power as high as 87.5% can be successfully demonstrated with a suitably constructed linear accelerator system and that, with some design modifications, actual operational efficiencies of 90% could be achieved. (The waveguide structure used in this accelerator has a theoretical maximum RF conversion efficiency of 92%.)

A detailed beam measurement program has now commenced, including investigation of beam spectra, prebunching efficiency, and acceptance versus injection potential, etc., and publication of this test data is planned for the future.

Acknowledgement

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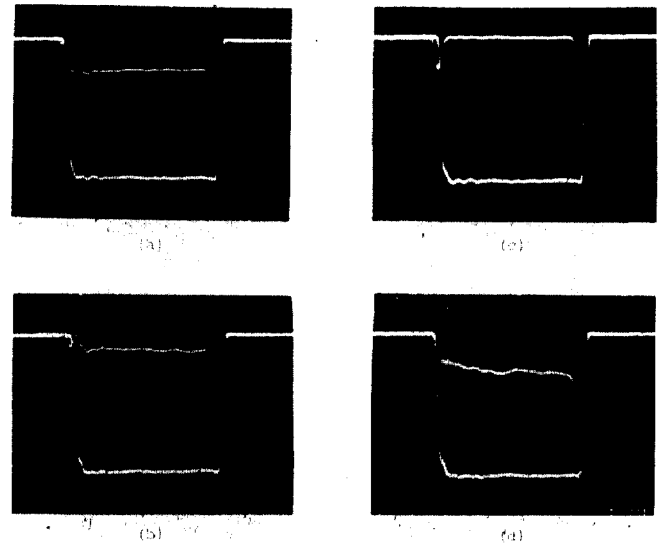

Figure 12. Accelerator waveguide Residual RF Power with Successively Increased Values of Beam Current [(a): 750 mA, (b): 1000mA, (c): 1200 mA, (d): 1500 mA]. Each Waveform shows Remnant RF Power with and without Beam Loading. (These dual waveforms were obtained by pulsing the injector at ½ of the transmitter pulse repetition frequency.)

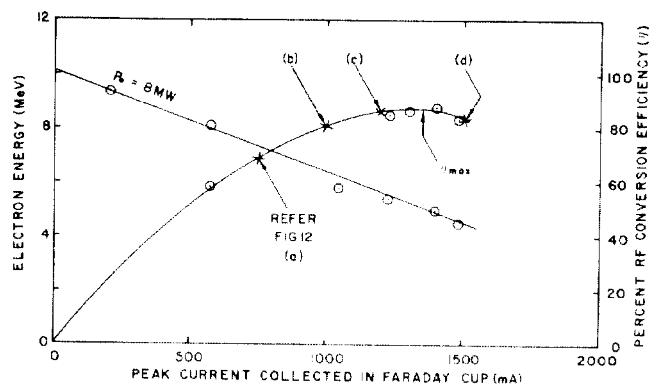

Figure 13. Electron Energy and RF Conversion Efficiency vs Peak Current Collected in Faraday Cup (Positioned 2 m beyond the 6 mm diameter Accelerator Output Collimator) showing Achievement of Maximum RF Conversion Efficiency of 87.5%.

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