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RECENT ADVANCES IN HIGH VOLTAGE ELECTRON BEAM INJECTORS

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Summary

A variety of electron gun systems in the 200 to 500 kV range have been placed into linac service during the past five years. These systems were specifically developed to improve the reliability and performance of high power linear accelerators by providing low emittance pulsed electron beams having highly stable flat-top characteristics. Lifetimes considerably in excess of 5000 hours have been achieved through the use of low heater power dispenser cathodes, non-intercepting electrodes for control of beam emission and focusing, all-metal and ceramic high temperature brazed dc accelerating columns, and operational vacuum levels of 10^{-7} to 10^{-8} Torr. The design features and performance of several of these systems, including short beam pulse and high duty factor are discussed, and typical beam waveforms and equipment photographs are presented.

Introduction

The development of a family of HV electron gun injection systems was undertaken to satisfy several important linear accelerator requirements. These included the need for injected electron beams having highly stable flat-top pulse characteristics, high duty factor (up to cw), very low emittance (5×10^{-4} πm_0c-cm), and operational pulse width capability from several nanoseconds to several hundred microseconds.

During the early stages of development, it was decided that in order to satisfy the above requirements,

(a) the injection systems should exploit the beam optics advantages associated with the use of high voltage dc accelerating potentials;

(b) the electron guns should be designed to operate with cathodes of relatively small diameter and high perveance, with non-intercepting extraction electrodes;

(c) the vacuum systems should operate between 10^{-8} and 5×10^{-8} Torr with the full rated dc HV potential applied to the accelerating column, and with the cathode at emission temperature;

(d) efforts should be directed at producing beams of relatively long focal length to allow fast pulse and pulse train inflector systems to be installed externally on the beam pipe at ground potential in a conveniently accessible location instead of with the gun pulser hot deck inside the gun tank; and

(e) the design objective of the cathode median lifetime should be established at between 4000 and 8000 hours when operated under normal conditions.

General Description of System Components

DC Accelerator Columns

The dc accelerating columns are constructed from high purity AL_2O_3 contoured cylinders and OFHC copper electrodes which are hydrogen furnace jig brazed to form integral stacks. The electron gun housings and high vacuum flange connections are then TIG welded to the stacks to form overall assemblies as shown in Figure 1. Shaping of the ceramic and electrode surfaces, including the re-entrant beam apertures and external corona rings, was influenced by computer generated contours which were optimized to reduce electric field enhancement factors and avoid scattered electron and ion back bombardment of the ceramic insulators.

Figure 1. Typical all Metal-ceramic brazed Accelerating Columns (300 kV and 550 kV) showing Electron Gun Housing and OFHC Copper Electrode Corona Rings.

Electron Gun

Figure 2 shows an early design, low emittance, 500 mA electron gun cathode and focusing electrode assembly and base plate. A view looking into the gun housing showing the extraction electrode and annular ceramic insulator is shown in Figure 3.

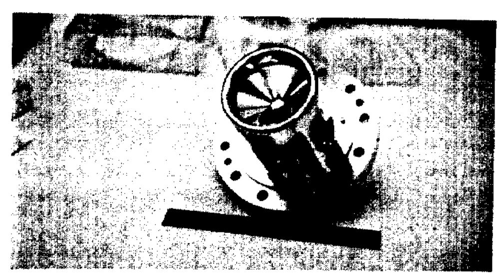

Figure 2. Cathode and Focus Electrode Assembly of a 500 mA, Low Emittance Electron Gun.

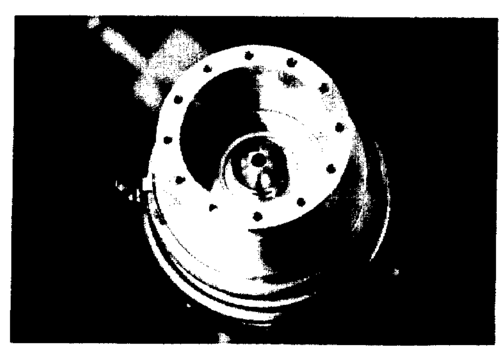

Figure 3. Prototype design, Non-intercepting Extraction Electrode Assembly.

More recently, high current electron guns have been constructed in which the extraction electrode is attached to and removed with the cathode base plate. These assemblies permit the gun perveance to be readily adjusted for experimental purposes while maintaining the tight mechanical tolerances which are necessary to ensure a high degree of beam laminarity. A 2A electron gun of this type is shown in Figure 4.

Figure 4. Integral Assembly 2A Electron Gun being Installed in a 300kV Accelerating Column.

The dispenser type, indirectly heated, removable cathode assemblies which are used in these guns have been designed to facilitate easy field replacement, and considerable effort has been directed at achieving space charge limited operation at relatively low levels of heater power. Typical operating temperatures of 1050°C are achieved, for example, using 45 watts of heater power with 16 mm diameter cathodes operating in excess of two amperes.

Prototype Performance

Figure 5 shows an early prototype 175 kV electron gun installed in the gun tank of a 60 MeV linear accelerator. This gun went into active service in 1971, and is still (March 1975) operating at full performance with the originally installed cathode after 5300 hours of service, despite several failures of the accelerator's vacuum system.

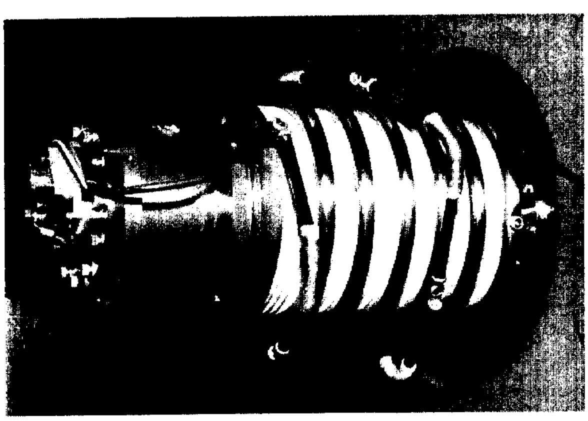

Figure 5. View of 500 mA, 175 kV Prototype Electron Gun with Terminal Spinning Removed.

The gun extraction electrode is switched ON and OFF by a dual, UHF planar triode, switch tube hot deck pulser which is triggered via fiber optic light links from a ground level logic chassis. The entire hot deck assembly, including bias and filament supplies, is suspended on tubular lucite insulators from the gun tank cover, as shown in Figure 6. Initial performance of this prototype system was evaluated by inserting a water cooled beam collector into the accelerator waveguide input coupler through the rectangular waveguide coupling iris.

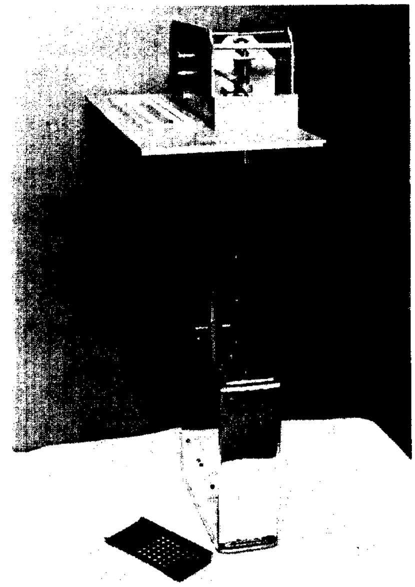

Figure 6.

Fiber Optic Light Link Triggered Hot Deck Pulser Assembly.

Figure 7 shows a typical beam waveform as obtained with the inserted collector at the injection plane of the first accelerator waveguide, i.e., after beam traversal through the injection system collimators and lenses. Subsequent full scale tests of the linear accelerator indicated that the spectrum of the accelerated beam had improved dramatically[1] (a 60% increase in analyzed beam through 0.3% slits), which was attributed directly to the very stable flat-top beam pulses and low emittance of the new injector.

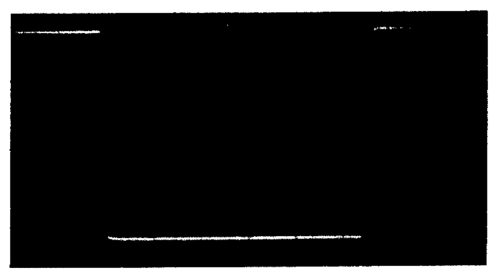

Figure 7. Typical Flat-Top Beam Waveform. (Injection Potential 175 kV, 100mA/div., 1μs/div.)

Fast Pulse Operation

Several injection systems with higher current and voltage ratings than the prototype unit have been constructed to provide short beam pulse (and programmable pulse train) injection capability. Figure 8 shows the larger size gun and hot deck pulser typically used for this type of beam application.

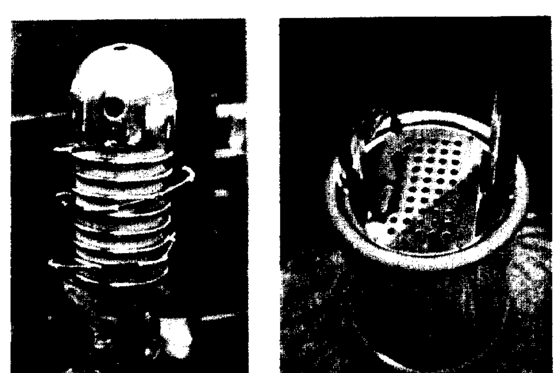

Figure 8. View of 225 kV, 1250 mA Electron Gun and Associated Hot Deck Pulser Assembly.

The relatively long focal lengths that can be achieved with these electron gun systems permit the installation of video and RF deflection equipment at convenient positions along the beam centerline. Injected beam pulse widths of less than 5 ns have been readily demonstrated using simple video deflection systems which operate at step pulse potentials of less than 3½ kV. Also, by arranging for continuous adjustment of the video deflection start and stop triggers, the width of beam pulses having very fast rise and fall times can be extended continuously outward from several nanoseconds to several microseconds. For example, Figure 9 shows a 200 kV beam pulse of 1200 mA which has been "gated" to 6 μs by a video deflector.

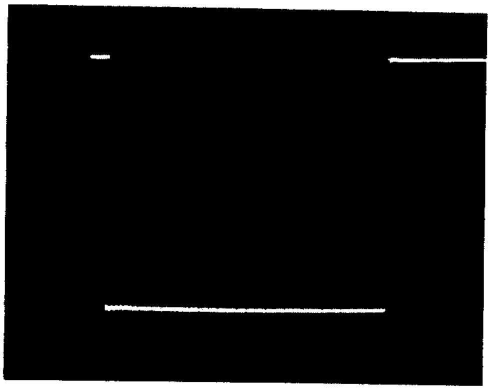

Figure 9. 200 kV Beam Pulse "Gated" by a Fast Video Deflector System (225 mA/div., 1 μs/div.).

By combining an RF deflector with a video deflector, beam pulse rise and fall times of 2 ns have been achieved. (Increased RF power can produce even shorter pulses.) With this technique, a fast scanning RF transverse electric field deflector is located between the video deflector and the chopping collimator. The zero field crossing of the RF field is synchronized with respect to the video scan so that the beam is subjected to a rapid single RF scan during a short interval of time within the video scan. Thus, by suitable choice of RF frequency and by simple adjustment of the video deflector pulse length, individual beam pulses or a series of pulses can be selected for injection into the accelerator. Figure 10 shows a dual deflection system incorporating a 10 MHz RF deflector and a 3.5 kV stepped video deflector which provides short beam bursts of 1 ampere (and/or a train of short beam bursts with 50 ns separations). The RF deflector is pre-triggered 10 to 15 μs before the electron gun pulse to allow build-up of the transverse electric field. A typical video envelope of the 100 ns cycles during field growth and decay within the RF deflector is shown in Figure 11.

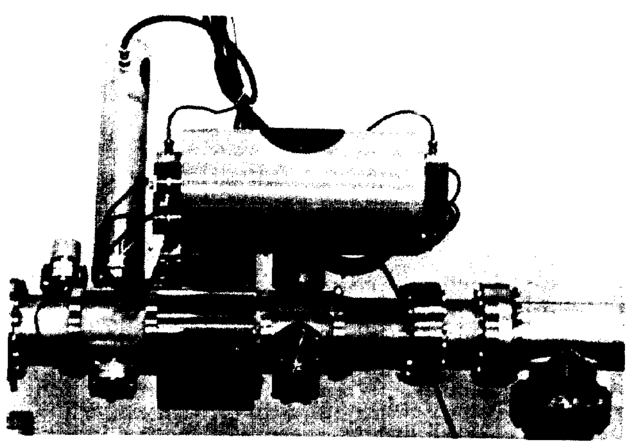

Figure 10. Dual RF and Video Deflection System to Produce 2 ns Beam Rise and Fall Times.

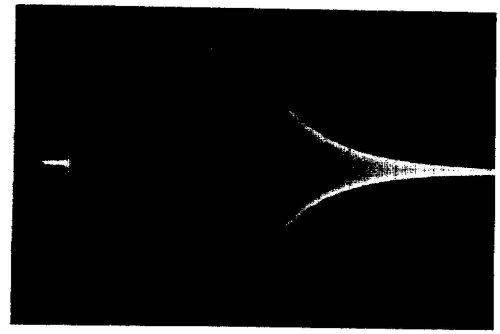

Figure 11. Growth and Decay of 10 MHz Field Pattern in RF Deflector (5μs/div.).

The required 1A, 2 ns beam operation was achieved with a peak transverse electric field of 3 kV/cm produced with approximately 2.5 kW of 10 MHz power. The 200 kV electron gun tank and prebuncher drift space assemblies, which comprise the remainder of this injection system, are located to the right and left, respectively, of the view shown on Figure 10.

For injection potentials up to 300 kV, high quality transformer oil has been the logical choice for gun tank insulation. The gun tanks are constructed with generous clearances, and, where possible, the gun and hot deck pulser terminal spinnings are located contiguously to minimize transient effects and permit the use of unshielded quick disconnects. As an example, Figure 12 shows a view looking into the injector gun tank of a recently constructed high current 10 MeV linear accelerator.[2] This oil-insulated electron gun system operates over a wide range of injection potentials, from 200 to 275 kV, to match the accelerator waveguide acceptance requirements as the peak RF input power is varied from 20 to 8 MW.

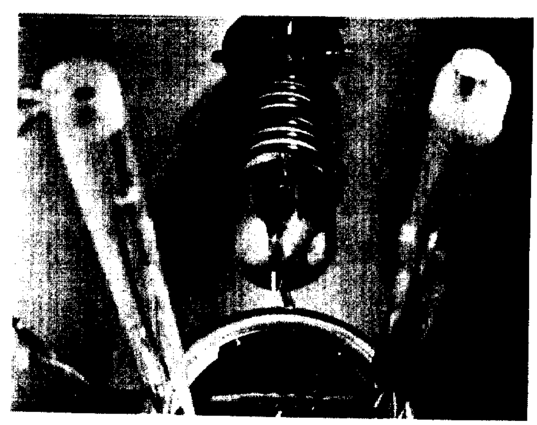

Figure 12. 10 MeV Linear Accelerator Injector Tank Showing Layout of the 275 kV, 2250 mA Electron Gun and Hot Deck.

High Duty Factor and CW Systems

By their very nature, high duty and cw RF accelerators are denied the accelerating and bunching advantages associated with the high peak RF fields of conventional machines. The advantages[3] of a high injection potential can, however, more than compensate for the absence of high RF fields because of the opportunity to produce injected beams of very low longitudinal and transverse phase space.[4] This, clearly, is of particular significance for low RF field machines (e.g., cw accelerators[5]) which are based on beam recycling concepts.

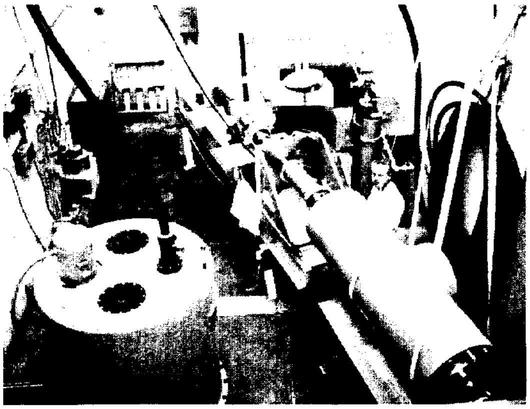

Figure 13. View of a 6 MeV High Duty Factor Accelerator and 500 kV Electron Gun System during Construction.

A 6 MeV high duty factor linear accelerator which will be used as the injector for a 500 MeV, 250 μA electron linear accelerator is shown, during construction, in Figure 13. This injector comprises a 500 kV electron gun system, an RF chopping and prebunching assembly and a 6 MeV variable phase velocity buncher section designed to operate over a range of input RF peak power from 1.8 to 3.6 MW and with an input RF average power of 90 kW. The design objectives of this injector are greater than 75% rated current in $5 \times 10^{-4}\ \pi m_o c$-cm emittance and 1° longitudinal phase space with an input RF phase stability of ±1° at 2856 MHz. To meet the 10% beam duty specifications, (with 50 μs pulse widths), all the beam centerline microwave components have been designed for 15% duty operation, and the HV electron gun system for 100% duty operation. At an operational injection potential of 400 kV, the chopper prebuncher assembly is designed to produce a 6° bunch at the entry plane of the 6 MeV buncher waveguide.

SF_6 gas was chosen for the electron gun insulating medium, and a view of the dc accelerating column and hot deck, with the aluminum gun tank in the background, is shown in Figure 14. The metal-ceramic brazed HV column supports a 40 kg hot deck pulser, and the entire assembly is cantilevered from a rigid stainless steel base plate which is attached to the main support channels on linear ball bearing assemblies.

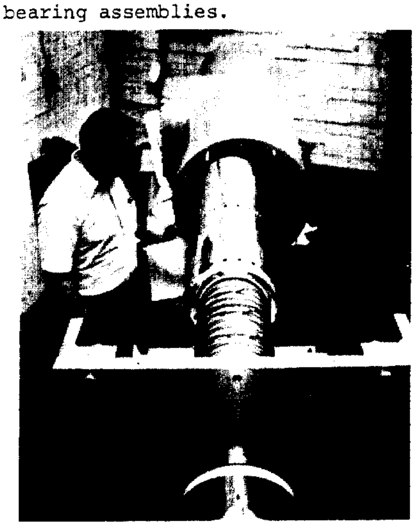

Figure 14. 500 kV Electron Gun Showing Metal-ceramic Brazed Accelerating Column and Hot Deck Pulser Spinning.

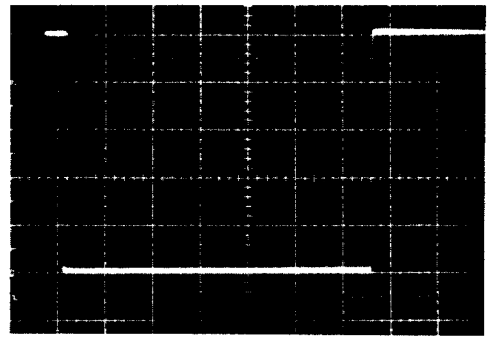

Figure 15. Faraday Cup Beam Waveform with Injection System Operating at a Potential of 440 kV (40 mA/div., 10 μs/div.).

The relatively small cathode used in this electron gun operates under space charged limited conditions with 40 watts of heater power, and the electrostatic and magnetic lens systems are arranged to produce beam minima at the RF chopping collimator and the buncher injection collimator. A vacuum of better than 5×10^{-8} Torr is maintained in the dc accelerating column at full applied potential and with the cathode at full emission temperature.

A typical beam waveform as obtained with an evacuated high power Faraday cup located downstream after transversal of the lenses and collimators is shown in Figure 15. Although this 200 mA, 65 μs extremely flat beam pulse was demonstrated at 440 kV, it is characteristic of the quality of the injected beam over the full range of energy, current and duty cycle. (The beam pulse width can be adjusted smoothly and continuously from the control console over a range of 40 to 1 without any detectable change in pulse amplitude.)

The high intensity and quality of the 400 kV injected beam when operating at a duty factor of 18.75%, is shown by the Figure 16 (50 μs/div.) Faraday cup waveform.

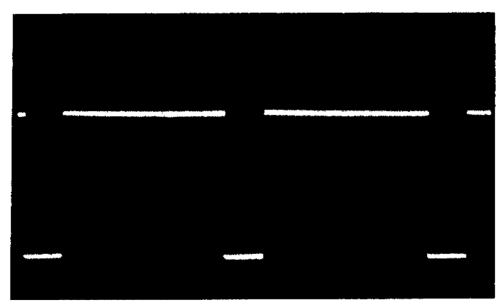

Figure 16. Faraday Cup Beam Waveform with Injection System Operating at a Potential of 400 kV, a Pulse Repetition Rate of 4686 pps and a Duty Factor of 18.75% (10 mA/div., 50 μs/div.).

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