INJECTOR PULSER FOR LINAC PICOSECOND OPERATION*

R. K. Hanst and N. J. Norris
Edgerton, Germeshausen & Grier, Inc.
Santa Barbara, California

Summary

An injection system is described which modulates the electron beam of the EG&G L-band linear accelerator for a time as short as one rf period. Thus modulated, the accelerated electrons are further grouped into a bunch about 40 picoseconds long. The injected pulse is synchronized with the microwave frequency, producing constant, repetitive beam pulses. The measured pulse width is 100 picoseconds, determined by the response of the sampling oscilloscope.

Introduction

Investigation of short-lived nuclear phenomena, radiation detector development and calibration, and high resolution time-of-flight work are all dependent upon the attainment of a short, intense burst of radiation. At AERE, Harwell, for instance, short pulses from an electron linear accelerator are used in extensive neutron time-of-flight measurements for photonuclear studies. Massachusetts Institute of Technology and General Atomics are also using radiation bursts of a few nanoseconds in their research.

The measurement of fast pulse phenomena has been a primary objective of the EG&G research for many years, and an important part of the research program is associated with the accurate measurement of pulsed radiation. The development and calibration of the radiation detectors is a fundamental research effort of the laboratory. A radiation source whose rise and fall time is short compared to the detector response can materially improve the detector response measurements.

The attainment of pulse widths in the picosecond range results from the inherent bunching action in the traveling wave electron accelerator, wherein pulse compression of about an order of magnitude is obtained from an injected pulse of approximately one radio frequency period. The electron linear accelerator at the Santa Barbara Laboratory of EG&G has been fitted with an injection system to modulate the beam, thus accomplishing the desired picosecond beam pulse.

Accelerator Characteristics

EG&G's linear accelerator laboratory is designed as a flexible research installation, incorporating a single section electron linear accelerator whose important specifications are as follows:

Electron Energy	- 4-21 Mev
Peak Beam Current	- 2 amperes (pulse length =.1 μsec)
	- .6 amperes (pulse length =4.5 μsec)
Repetition Rate	- 1-360 pulses per second
RF Frequency	- 1300 megacycles

The accelerating waveguide is a conventional traveling wave accelerating section with constant phase velocity and constant attenuation throughout its 2.5 meter length. The energy for steady state (long pulse operation) is given by

$$V = 6.76 \sqrt{P} - 14.55\ i \qquad (1)$$

where V is the electron energy (Mev), P is the peak microwave power (megawatts) and i is the peak beam current (amperes).

Injected beam pulses shorter than the filling time are governed by transient considerations. The first electrons of any beam pulse are accelerated to the no-load energy given by the first term of equation (1). Successive electrons also accumulate the energy determined by the integral of the electric field, reduced by the beam loading of the preceding part of the beam pulse.

A loaded waveguide, designed to force the phase velocity to be equal to the velocity of light at a particular frequency, propagates the microwave energy slowly; group velocity (v_g) is 0.0044 c for this accelerator. The resulting filling time (t_f) is 1.9 microseconds.

The stored energy in joules for the fundamental component of the electric field is

$$W = Pt_f\left(\frac{1-e^{-2IL}}{2IL}\right) \qquad (2)$$

where I is the voltage attenuation constant (nepers/meter) and L is the accelerator length in meters. For beam pulses much shorter than the filling time, there is no contribution to the field from the microwave power source, and all of the acceleration is determined by the stored energy, 13.3 joules for a peak power of ten

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megawatts in this machine. Electron energy of about 20 Mev is attained, and the depletion of stored energy is proportional to the accelerated charge.

Typical accelerated beam current for this type of machine has been about 2 amperes, equivalent to 1.5 nanocoulombs per rf cycle. At this beam current, the stored energy is depleted at a rate of .03 joules per cycle, and the electron energy change is about 0.02 Mev (.1%) from one cycle to the next. From stored energy considerations alon , it is seen that the charge per cycle could be 20 nanocoulombs or more for a few cycles of accelerated beam.

The electrons are injected into the accelerating section at 0.63 c (150 kilovolts) after being bunched in a single cavity velocity - modulation buncher. The majority of the electrons are grouped about a central injection phase, approximately 60% within a 60 degree phase angle. During the first part of the acceleration these electrons are further bunched to a phase angle of about 15 degrees, 40 picoseconds, at the end of the accelerator.

One of these beam bunches may be accelerated independently by injecting a pulse that is approximately equal to one rf period, producing a single radiation burst 40 picoseconds in duration. The injection system to be described has accomplished this objective.

General Approach

After analyzing the different means of modulating the electron beam, it was decided to modulate the cathode-grid potential of a fast electron gun with a vacuum tube amplifier. Briefly, the reasons for this decision are:

1. The only promising alternative to the gun modulation, deflection of the injected beam across a slit, requires a very rapid rate of change of large voltages across the deflection plates, which is extremely difficult to attain. The beam optics problems of a deflection system are very complex, and some deterioration of beam quality would be expected with this method.

2. Much of the research equipment using the picosecond radiation burst will produce fast, low amplitude signals. To allow sampling oscilloscopes to be used, it is necessary that the output beam pulse be stable and repetitive, requiring that the injected beam pulse be phase-synchronized to the rf accelerating frequency. This dictates that the overall time jitter of the pulser electronics must be small compared to an rf period (0.77 nanoseconds). The vacuum tube modulating amplifier was the only practical choice over the several alternatives (spark gaps, thyratrons, etc.). The time jitter of the ionization types of devices prevented the synchronization of the injected pulse to a particular phase of the rf accelerating wave. Solid state switches (avalanche transistors, etc.) were considered, but all have insufficient voltage to modulate the electron gun selected.

System Design

A diagram of the injection system designed to accomplish the objectives is shown in Figure 1. A special electron gun, designed for fast pulse work, is used as the source of the injected beam into the accelerator. The grid-cathode voltage is supplied by a vacuum triode pulse amplifier which determines the amplitude and pulse shape of the injected beam. The rise time of this pulse is determined by the characteristics of the amplifier, which is driven by an avalanche transistor stage. These pulse amplifiers are mounted on the high voltage terminal of the power supply, operating at the 150 kilovolt injection acceleration potential. The trigger signal is coupled to the equipment at the high voltage by a very small capacitor from the synchronizing circuits at ground potential.

Methods for detecting and measuring the pulse shape of the accelerated beam are also required, and a Faraday Cup with excellent frequency response has been designed and used in the present experiments.

Electron Gun

The electron gun and accelerating electrodes are shown in the cross-section view (Figure 2). The electron gun (ARCO Model 10) is similar to the gun furnished with the accelerator except that the grid and cathode connections are designed with low capacity and inductance to make them suitable for fast pulse modulation.

The grid and cathode connections are coaxial (the grid terminal being the outer conductor) and have an impedance of 33 ohms at the flanges. A tapered coaxial adapter connects the gun flange to standard 50-ohm coaxial fittings with minimum discontinuity. The structure and amplifier circuits are compatible for a negative cathode pulse with respect to the grid. The gun filament leads were brought out through the cathode connector using inductances to isolate the filament transformer circuit from the pulse voltage.

The grid is a square mesh molybdenum with openings of approximately 0.1 inches. It is spaced approximately .050 inches from an indirectly-heated matrix cathode about .750 inches in diameter. The internal connections to the grid and cathode are also coaxial and not longer than 3 inches.

The input capacity between grid and cathode flanges, important in determining the rise time of the voltage between grid and cathode, was measured to be 15 picofarads, primarily in the support structure. The input impedance of the cathode-modulated gun varies from infinite to 150 ohms with increasing cathode voltage requiring a 75-ohm loading resistor mounted at the cathode flange of the gun to match the 50-ohm driving impedance of the amplifier to the gun.

Gun characteristic curves (Figure 3), plotting the injected current as a function of accelerating voltage and grid potential, show that the gun perveance is nearly constant at 6 x 10^{-8} and that injected currents of 5 amperes can be expected for a pulsed cathode voltage of 700 volts.

Pulse Amplifier

The desired pulser output is determined by the gun characteristics. In order to yield the full current capability of the gun, a cathode-grid pulse of approximately 700 volts is necessary, and the pulse width must be as short as possible, approaching .7 nanosecond.

Jitter requirements determined that the pulser must be a vacuum tube amplifier, and gun and output capacity required that the load impedance of the amplifier be low, resulting in very high current demands on the output amplifier tubes. The best vacuum tubes for this use have been the planar triode Machlett ML7698, where individual tubes are capable of currents as high as 18 amperes and have a small output capacity.

The amplifier output pulse rise time can be made as small as 1.5 nanoseconds. The pulse fall time cannot be made equally fast by grid modulation however, and a shorted coaxial stub "clipping line" in the output has been used to produce the shortest pulse presently attained. Pulse clipping reduces the amplitude to about half the applied pulse however, so two paralleled output tubes are necessary. A representative pulse, before and after clipping, is shown in Figure 4.

The major rise time limitation of the amplifier is imposed by the input capacitance of the amplifier stage, approximately 15 picofarads including Miller capacity and strays. A compromise between driving impedance and stage gain has determined that 50-ohm coaxial inverting transformers be used for the interstage coupling. With this configuration, the voltage gain is approximately two per stage. The present amplifier consists of six amplifier tubes, using two stages in cascade driving a paralleled stage which drives two output tubes in parallel.

The driving pulse for the vacuum tube amplifier is supplied by an avalanche transistor stage. Two transistors (National Semiconductor Corporation - NS1116) in series generate a pulse of approximately 150 volts with a 1.5 nanosecond rise time into 50 ohms. This pulse generator, whose pulse length is determined by a 50-ohm coaxial "charge line," is triggered with a fast two-volt pulse. This pulse is supplied from another avalanche transistor through the small coupling capacitor across the 150 kilovolt accelerating potential.

The time jitter of the entire amplifier and driving transistors was measured to be about 40 picoseconds. The timing drifts, caused by changes in voltage and temperature, are not serious, and the overall system stability is excellent.

Synchronization Circuits

An important system objective, which has now been achieved, was the attainment of injector pulse synchronization with the microwave accelerating field at 1300 megacycles. This was accomplished with the synchronization system, shown in block diagram in Figure 5. All of this circuitry was constructed using the EG&G M100 logic modules.

The cw master oscillator at 108.36 mc is the 12th subharmonic of the acceleration frequency. This variable oscillator is phase-locked to the output rf frequency and is stable to better than 1 part in 10^7. The 108.36 mc is counted down to 13.58 mc, shaped and compared with the injector trigger pulse in a coincidence circuit. The resulting output pulse occurs synchronized with one of the rf cycles. This synchronized trigger pulse fires the avalanche driver stage.

In order to eliminate the random pulses due to the finite pulse width of the synchronization pulse, an anti-coincident circuit was also included. It senses the occurrence of the input pulse during a synchronization pulse and vetoes any incorrectly-synchronized output pulse.

The jitter of the synchronized pulse output has been measured to be 50 picoseconds or less, allowing the observation of single beam pulses on the sampling oscilloscopes.

Faraday Cup

Detection of the short beam pulses produced taxes the frequency response of the best detection systems. Two models of coaxial Faraday Cup have been designed to couple the electrical signal from the accelerated electrons into a 50-ohm coaxial cable of high quality. These designs use an insulated target in vacuum to absorb the electrons. The target is the center conductor of a 50-ohm coaxial line, tapering over several inches to the dimensions of standard 50-ohm air-insulated coax. The frequency response of the better Faraday Cup has been investigated and proven to be capable of resolving individual beam pulses with a measured half width of 100 picoseconds.

Experimental Results

The results of the measurements of the accelerated electron beam have shown 1) that the individual beam pulses at the rf frequency can be resolved, 2) that a single beam bunch can be accelerated and detected, and 3) that beam synchronization to the rf frequency can be accomplished.

The injection system, without the synchronization to the rf frequency, was used for the first experiments (December, 1964). The fast Faraday Cups were used on the direct beam port and on a magnetically-deflected 45 degree port. The Faraday Cup signals were transmitted through cables designed for the best available frequency response to the fastest traveling wave oscilloscopes available, Tektronix 519 and EG&G OS-12.

Electron gun conduction time and beam current amplitude were determined by the amplifier pulse output and the applied gun bias superimposed on the cathode terminals. Typical voltage pulses on the gun are shown in Figure 4 where the short, triangular pulse was used for the single rf bunch experiments by biasing the gun cathode far beyond the cutoff potential of the gun. Varying the bias changed the pulse amplitude above the conduction point of the gun. Due to the triangular pulse shape of the amplifier output pulse, the relationship between amplitude and pulse length is nearly linear, attaining 100 volts in 1 nanosecond and 700 volts in 3 nanoseconds. The output beam pulse shape followed the same relationship, modulated by the rf frequency, proving that neither the injector gun nor the accelerating process affected the beam pulse envelope.

Individual beam pulse cycles were observed as fine structure of the envelope of 1.5 ampere pulses (averaged over several cycles). As the bias is increased, the amplitude and pulse length decrease together, producing a single cycle beam pulse with the charge equivalent to a current of about 0.2 ampere. The apparent pulse width of an individual cycle is determined by the frequency response of the detection equipment and oscilloscope.

The beam energy was measured as the no-load energy of the accelerator, attaining 21.5 Mev for full microwave power in agreement with Equation (1). The energy decay during a 6 nanosecond pulse was 0.2 Mev or 0.025 Mev per cycle at 1 ampere beam current, substantially as predicted.

Dramatic improvements of beam pulse measurements (Figure 6) resulted from the operation of the injection system with the synchronization circuits during recent tests (February 1965). The beam pulse, being synchronized to the rf accelerating wave, remained the same from pulse to pulse, allowing sampling oscilloscopes to be used in examining the output beam. Figure 6B shows the beam pulse on a sampling scope triggered by the injection trigger pulse, proving that the time jitter was less than 0.1 nanosecond.

Figures 6A and 6B were taken with the sampling oscilloscope separated from the faraday cup by 100 feet of ½ inch Foamflex coaxial cable. The frequency response of these 100 foot cables limited the response of the transmitted signals however, and a Hewlett-Packard sampling oscilloscope in the radiation area was used to record the signal shown in Figure 6C. The oscilloscope was connected to the Faraday Cup through a short length of the semi-rigid coax, and the low frequency output of the sampling scope was monitored in the control room. The resulting pulse width of 100 picoseconds and rise time of 70 picoseconds may be expected from the sampling scope response alone. This indicates that the beam pulse is approaching its theoretical value as nearly as it can be measured and that the Faraday Cup does not contribute significantly to the pulse shape.

Continuing Program

Additional tests of the accelerated beam to investigate beam-loading and energy variations are planned for the near future. The frequency response of the Faraday Cup and cables will also be measured in more detail.

The prototype equipment used for these measurements is being replaced by permanent hardware, physically compatible with the new (long pulse) injector pulser now under construction. The combination will permit the selection, from the control console, of pulse lengths from picoseconds to 4.5 microseconds.

Amplifier rise time will be improved, if possible, by a continuing program. Several possibilities exist, including new amplifier tubes with lower input capacity.

Injector gun development at several commercial companies has continued to emphasize the high current for short pulses. An ideal gun for our purposes would have high current, high transconductance, and good geometry for fast pulse applications.

An improved injector gun for this accelerator is planned, although the detailed approach has not yet been determined.

Conclusions

The demonstration of the synchronized beam pulse with time durations as small as a single rf bunch have improved the time resolution of the radiation source by nearly two orders of magnitude. Radiation detector response function measurements have been made with an accuracy previously impossible using this source as a "delta function" of radiation.

Time-of-flight experiments on fast neutrons are now possible with an energy resolution about an order of magnitude better than previously obtained. The EG&G facility is being fitted with a 25-meter time-of-flight path to make use of this linac capability. Fast neutron detectors are now the limiting factor on the neutron energy resolution in this energy range.

Accelerator physics investigations are expected to gain new information regarding the transient acceleration processes. The ability to directly measure the beam bunch profile (approximately) and to study the energy and spatial correlation of these bunches will allow many of the theoretical calculations to be tested. Increased current capability from fast injector systems is necessary for investigations of the maximum accelerated charge.

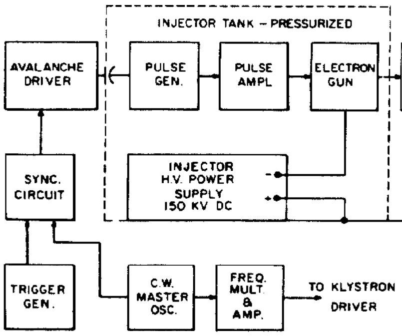


Fig. 1. Injection System Block Diagram.

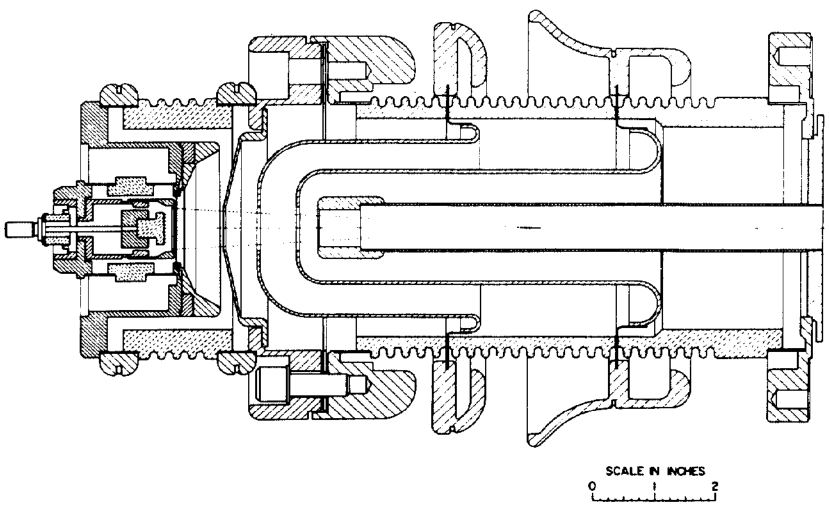


Fig. 2. Electron Gun.

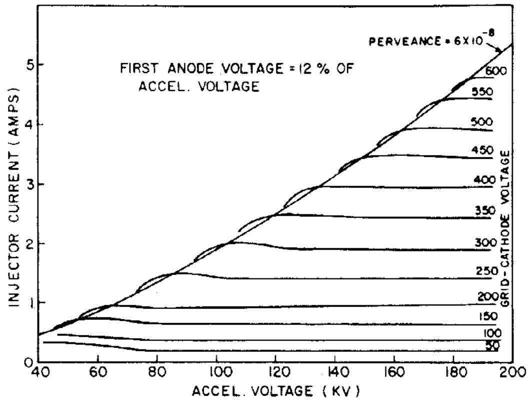
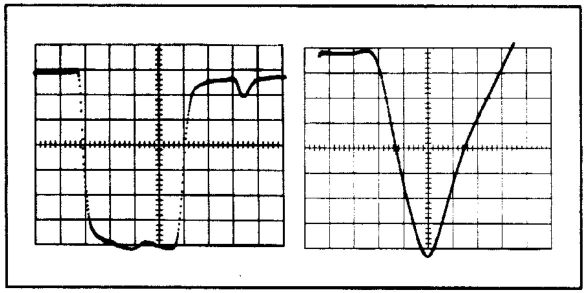


Fig. 3. Gun Characteristic Curves.



200 v/cm 5 ns/cm 100 v/cm 1 ns/cm

Fig. 4. Amplifier Output Pulses. 200 v/cm, 5 ns/cm; 100 v/cm, 1 ns/cm.

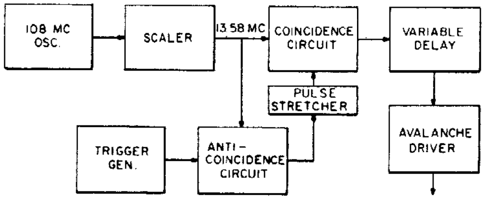
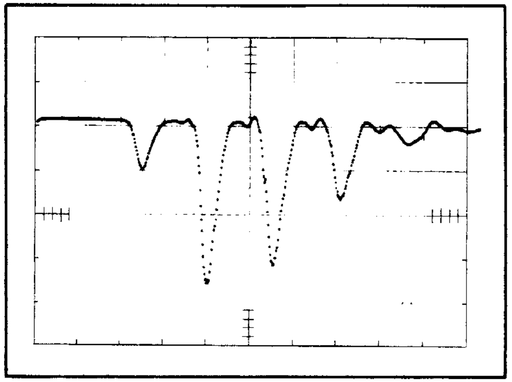
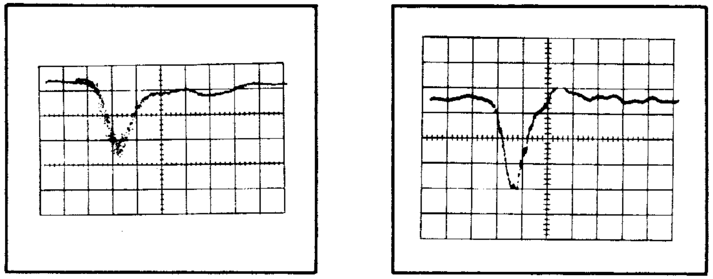


Fig. 5. Synchronization Circuit Block Diagram.



a. 20 v/cm 0.5 ns/cm



b. 50 mv/cm 200 ps/cm

c. 200 mv/cm 100 ps/cm

Fig. 6. Typical Output Beam Pulses. (a) 20 v/cm, 0.5 ns/cm. (b) 50 mv/cm, 200 ps/cm, (c) 200 mv/cm, 100 ps/cm.