Summary

Radiation pulses 50 ps in duration have been attained at the EG&G/AEC electron linear accelerator by isolation of individual microstructure groups of electrons which normally occur at the fundamental accelerating frequency. Pulse compression by means of velocity modulation techniques has been used to increase the intensity of these pulses from 0.02 nC to 1.5 nC per pulse, or 30 A for the 50-ps pulse length. The injector pulse is synchronized to the RF acceleration frequency with a precision of 30 ps, which results in pulse-to-pulse reproducibility to within a few percent, permitting recurring pulse measurements to be made with sampling oscilloscopes.

These intense short bursts of radiation allow the study of radiation detectors, scintillators, and chemical systems in the subnanosecond time domain. Neutron time-of-flight measurements with a total resolution of 400-500 ps have also been demonstrated.

The calculated charge enhancement resulting from velocity-modulation bunching is compared to measured performance, and the system is described in detail.

Introduction

The EG&G/AEC linac is a single section (2.5 m) L-Band traveling wave electron linear accelerator equipped with beam analysis and beam switching magnets, beam monitors and collimators, radiation monitors, a 25-m neutron flight path, and a fast data-acquisition system. In 1965, the accelerator was modified to generate an extremely short burst (50 ps) of radiation, through injection of electrons into a single cycle of the accelerating microwave frequency (1300 MHz). This short burst of radiation has proven to be extremely useful for investigating fast transient phenomena and for calibrating fast radiation detectors. It has also been used successfully in high resolution neutron time-of-flight measurements.

Since these applications of the single RF burst of radiation require high intensity, a continuing developmental effort is carried on at EG&G's Santa Barbara Division to increase the amount of charge that can be injected into a single RF cycle of the accelerating frequency. Velocity modulation techniques described in this paper, in combination with improved injector optics, have resulted in an increase from 0.02 to 1.5 nC in the 50-ps accelerated charge.

Technical Approach

The maximum charge in a single 50-ps output beam pulse, without allowing satellite pulses in adjacent RF cycles, is determined by the charge that can be concentrated into a single RF cycle. This has been limited by the electron gun and pulser characteristics, whose design is partly determined by low jitter and beam optics considerations.

The electron source consists of a grid-modulated electron gun at 150 kV. The modulation characteristics of the gun require a grid-cathode pulse signal of 800 V to cause its full emission of 4 amperes. This pulse voltage is obtained from a vacuum tube amplifier consisting of several triode tubes in parallel-cascade following an avalanche-transistor pulse generator. These components were chosen for the pulse modulation system because they are capable of the minimum time jitter required for synchronizing the pulse to the accelerating radio frequency. The best obtainable grid-cathode pulse, determined by the vacuum tube capacity, has a half width of 3 ns with a shape as shown in Fig. 1. To inject electrons into only one RF cycle for the short pulse application, it is necessary to superimpose this pulse on a bias voltage, adjusted to allow beam current for the short time that the pulse voltage is above the cutoff potential of the gun. The resulting injected charge within a single cycle is shown in the upper shaded area of Fig. 1.

It was recognized that either sweeping or bunching could reduce the beam-current pulse width at the injection potential (150 kV), allowing reduced bias on the electron gun. Increased charge would thus be injected into one RF cycle at the input of the accelerating section. Velocity-modulation bunching was chosen in order to conserve the charge emitted from the gun, with the resulting improvement indicated by the larger shaded area of Fig. 1.

Since the objective of velocity modulation bunching is to compress a single pulse into a smaller time interval, the ideal modulation voltage is uniformly increasing during the injected pulse length. The most practical way to approximate this ideal voltage is to use the appropriate part of a low-frequency sine wave. The voltage is produced across a gap in the injection region by a high-Q cavity at a subharmonic of the acceleration frequency.

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The injection system, including the subharmonic buncher, is shown in the block diagram, Fig. 2, and the cross-section diagram, Fig. 3.

Selection of Subharmonic Frequency

Several factors affect the optimum frequency for best accelerator operation. At 150 kV, the electron velocity, \( \beta \) (normalized to the velocity of light, \( c \)) is 0.63. The velocity modulation, \( \Delta \beta \), must be small to limit the accelerated energy spread due to the injection energy variation. This \( \Delta \beta \) limit requires that the modulation voltage be kept small and the drift distance large. Of course, the frequency must be a subharmonic of the acceleration frequency, so it was convenient to choose a frequency which is easily obtainable from the master oscillator-multiplier chain. Lower bunching frequencies approximate the ideal ramp voltage better, but as the frequency is decreased, the drift distance and peak RF voltage must be increased. Lower frequencies with their correspondingly long drift distances also impose more serious beam focusing and containment problems. In addition to the short pulse operation, our objective was to design an injection system that would permit much higher currents in the 5 to 50 nanosecond pulse-length range and remain compatible with the normal long-pulse (4 us) operation.

It would have been possible to use a distributed bunching wave-guide or combination of several frequencies whose net effect would closely approximate the ideal sawtooth velocity modulation voltage. However, when the added expense, complication, and mechanical problems of such complex systems were compared with their advantages, it was decided to use a two-cavity velocity modulation arrangement of a fundamental frequency cavity (required for normal operation) and a single subharmonic-frequency cavity.

Computer Calculations

The optimization of the several parameters involved was greatly assisted by a computer analysis. This calculation applied the sinusoidal accelerating voltages with variable amplitudes, frequencies, and phases to the current pulse available from the electron gun. With certain of the parameters as independent variables, the computer program optimized the total charge \( Q_0 \) within 60 degrees of the accelerating frequency, while not allowing any charge to be within the acceptance angle of adjacent cycles. The variables to be determined were as follows:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>Subharmonic number</td>
</tr>
<tr>
<td>( V_s )</td>
<td>Subharmonic voltage</td>
</tr>
<tr>
<td>( V_f )</td>
<td>Fundamental voltage</td>
</tr>
<tr>
<td>( \phi_s )</td>
<td>Phase of subharmonic frequency with respect to accelerating frequency</td>
</tr>
<tr>
<td>( \phi_f )</td>
<td>Phase of fundamental frequency with respect to accelerating frequency</td>
</tr>
<tr>
<td>( \phi_i )</td>
<td>Phase of injection pulse with respect to accelerating frequency</td>
</tr>
<tr>
<td>( D_s )</td>
<td>Distance of subharmonic cavity from fundamental cavity</td>
</tr>
<tr>
<td>( D_f )</td>
<td>Distance of fundamental cavity from input coupler</td>
</tr>
<tr>
<td>( V_b )</td>
<td>Bias voltage</td>
</tr>
</tbody>
</table>

For this calculation the following parameters were fixed:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_i )</td>
<td>Injection voltage, 150 kV</td>
</tr>
<tr>
<td>( \Delta \beta )</td>
<td>Allowed peak to peak velocity modulation, 0.1c</td>
</tr>
<tr>
<td>( f )</td>
<td>Fundamental frequency, 1300 MHz</td>
</tr>
<tr>
<td>( \Delta \phi_f )</td>
<td>Input acceptance phase, 60° (of 1300 MHz)</td>
</tr>
<tr>
<td>( \phi_m )</td>
<td>Maximum phase limit, 360° (of 1300 MHz)</td>
</tr>
<tr>
<td>( i )</td>
<td>Current vs. time relationship (experimentally determined)</td>
</tr>
</tbody>
</table>

The charge \( Q_0 \) within the \( \Delta \phi_f \) was optimized for each set of the input parameters, where the program was allowed to vary \( n \), \( V_s \), \( \phi_s \), \( \phi_f \), \( V_f \) and \( V_b \) in a prescribed pattern for each set of the other input parameters. A table was then generated which listed \( Q_0 \) for each practical value of \( n \) and \( V_s \), allowing the comparison of different parameters.

The equations used in the calculation assumed that the beam is on the axis and that space charge forces in both radial and longitudinal directions are negligible. The relativistic velocity is important and these effects were included. The injected current was divided into segments, and each element of the total charge was calculated through the cavities and drift distances to the input point of the accelerating waveguide. The phase and velocity of each element was plotted and the charge, if it was within \( \Delta \phi_f \) (60°), was summed into \( Q_0 \). Typical results showing energy \( \beta \) and charge \( q \) plotted as a function of phase are shown in Figs. 4 and 5, respectively. These plots allowed us to check the computer calculation of total charge and charge distribution.

Calculated subharmonic bunching parameters, including \( Q_0 \) within the 60° acceptance angle, are shown in Table 1. Consideration of the improvement in total charge and other design factors resulted in the choice of the 6th subharmonic (216 MHz) for the velocity modulation frequency.

Subharmonic Bunching Cavity

Various cavities capable of producing the desired beam modulation voltage were investigated. The most convenient geometry is a coaxial structure (Fig. 6) that resonates at the 216-MHz frequency in the TM mode.

We decided to place the insulator and the vacuum seal near the gap. The alternative method, an evacuated cavity, is much more difficult to fabricate, since the cavity, coupling loop, and
### Table 1. Comparison of subharmonic bunching parameters.

<table>
<thead>
<tr>
<th>Total Charge, $Q_s$ (pC)</th>
<th>Harmonic Number, $n$</th>
<th>Cavity Separation, $D_s$ (m)</th>
<th>Final Drift Distance, $D_f$ (m)</th>
<th>Subharmonic Voltage, $V_s$ (kV)</th>
<th>Fundamental Voltage, $V_f$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1054.7</td>
<td>4</td>
<td>1.0</td>
<td>0.425</td>
<td>34</td>
<td>5.0</td>
</tr>
<tr>
<td>1175.2</td>
<td>4</td>
<td>1.2</td>
<td>0.350</td>
<td>32</td>
<td>6.5</td>
</tr>
<tr>
<td>1124.4</td>
<td>5</td>
<td>1.0</td>
<td>0.525</td>
<td>36</td>
<td>7.0</td>
</tr>
<tr>
<td>1251.3</td>
<td>5</td>
<td>1.2</td>
<td>0.475</td>
<td>34</td>
<td>7.0</td>
</tr>
<tr>
<td>1354.3</td>
<td>6</td>
<td>1.0</td>
<td>0.575</td>
<td>40</td>
<td>6.5</td>
</tr>
<tr>
<td>1376.9</td>
<td>6</td>
<td>1.2</td>
<td>0.525</td>
<td>38</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Tuning means must be vacuum tight. Also, the possibility of multipactor in the low-voltage coaxial region would probably be a serious limitation.

The high RF voltage initially caused sparking across the outer surface of the insulator, which was eliminated by adding a corona shield and Freon gas inside the cavity. The shunt impedance and $Q$ are about 100,000 and 2,000 respectively, and only about 5-kW input power is required to obtain optimum bunching.

The end plate can be moved to adjust the resonant frequency, and the input coupling loop can be rotated for optimum match to the coaxial line. A small monitor loop installed in the cavity permits pulse shape and relative buncher voltage to be measured at the console. An independent absolute measurement of buncher gap voltage has not been made, due to detuning and losses introduced by any probe. Adjustment of the input subharmonic power and phase to obtain optimum performance is not difficult.

When first installed in the axial magnetic field, the cavity would occasionally multipactor, especially at the lower RF voltages. The cavity's internal surfaces near the gap have apparently improved in such a way that the secondary emission is reduced, since multipactor in this cavity is no longer a problem.

### 216-MHz Power Amplifier

The subharmonic buncher cavity requires a phase-coherent amplifier to supply power. The characteristics of this power amplifier are as follows:

- Center frequency: 216 MHz
- Bandwidth: 3-5 MHz at 3 dB points
- RF-pulse width: $10 \pm 0.5$ μs
- Pulse repetition rate: $0.360$ pps
- RF-pulse rise time: 1 μs
- RF-pulse fall time: 2 μs

RF-pulse flatness: 3%
Phase modulation: 8°
RF input power: 100-mW CW
RF power output: 12 kW peak

The amplifier consists of four planar-grid triode stages in cascade driving a high-power tetrode stage. Power output is controlled by manually adjusting a continuously variable attenuator in series with the amplifier input. The 216-MHz buncher frequency phase is continuously adjustable at the control console by means of a line stretcher.

### Fundamental Frequency Buncher

The modified accelerator injector uses the original buncher cavity with a 1.1-inch beam-aperture diameter. It has a $Q$ of 1000 and adequate modulating voltage capability for the single RF pulse mode. An increase of beam aperture to 2 inches would be desirable to match other high-current gun equipment, but mode and coupling problems could be serious. The drift distance is less than it was previously, requiring increased RF power to the fundamental cavity, which is supplied by a variable coupling loop from the klystron output. A remotely variable phase shifter is used to empirically adjust the phase.

The most serious problem has been multipactor breakdown in this cavity, which is completely evacuated and, with the present focusing arrangement, is enclosed in an axial magnetic field. The combination of this field and the internal RF electric field made the cavity susceptible to multipactor breakdown even though there was no problem with it before. When the cavity was first used in this revised configuration, the problem was very serious and prevented the simultaneous use of optimum focusing fields and buncher power. However, the range over which satisfactory operation can be obtained has increased because of surface conditioning, and the cavity now performs well at the levels required for the present electron gun.
Magnetic Focusing

The additional drift distance required for the subharmonic bunching increased the total distance from the electron gun to the injection point considerably. An additional objective was to make an injection system capable of injecting much higher current (~40 A) for pulse lengths of 5 to 50 ns.

These considerations required a redesigned magnetic focusing system to replace the two magnetic lenses previously used. After considering various alternates and calculating beam trajectories through the injection region, we decided to use a series of air core solenoids and one magnetic lens, as shown in Fig. 3. These coils are powered from several separate power supplies, allowing considerable flexibility in the field shape, and the capability to produce a nearly constant field in excess of 500 gauss along the injector drift region.

The revised focusing system has contributed to the increased charge within the single RF pulse.

System Performance

The improvement of the charge in the 50-ps pulse due to the subharmonic bunching system and the injection focusing has increased the charge per pulse from 0.02 to 1.4 nC. In the computer calculations the charge without the subharmonic buncher was 0.1 nC, increasing to 1.4 nC with the optimum subharmonic parameters. These values are in substantial agreement with the experimental measurements, where the charge per pulse, measured by average current in a Faraday cup, is 1.5 nC under optimum conditions. Without the subharmonic buncher, the charge is from 0.08 to 0.1 nC with optimum adjustment of the focusing parameters.

A representative pulse, measured in a 50-Ω Faraday cup, is shown in Fig. 7. This pulse has a peak pulse amplitude of 12 A, a half width of 60 ps, and a total charge of approximately 0.8 nC. The measured shape is almost independent of intensity, but the pulse width can be influenced by tuning, especially the buncher phase relationships.

Continuing Enhancement Programs

Means to further increase the intensity of the single short pulse are also being developed. The present pulse contains about 0.03 joules of energy per cycle, and one pulse is therefore a very small reduction of the 13.3 joules of microwave energy stored in our machine. Since the bunch is much smaller than the individual cavity dimensions, all electrons in the bunch have only the energy variation due to their phase angle, without energy spread due to beam loading. We estimate that the accelerating guide could accelerate a beam two decades larger if this beam can be injected. Space charge will probably be the ultimate limit in the charge per cycle at this frequency, but a factor of 10 to 20 improvement is within the demonstrated capability, since 15 ampere beams of several nanoseconds duration have been produced.

The present program for increasing linac pulse intensity is aimed primarily at development of guns with higher transconductance and the generation of higher amplitude pulses with reduced half width. Both techniques are promising and are being pursued vigorously.

Acknowledgement

The assistance of Dr. W. C. Anderson in the computer analysis of the velocity modulation techniques is gratefully acknowledged.

References


Fig. 1. Cathode voltage pulse.

Fig. 2. Injection system block diagram.

Fig. 3. Injection system cross section.
Fig. 4. Electron energy distribution.

Fig. 5. Charge distribution.

Fig. 6. Subharmonic buncher cavity.

Fig. 7. Output beam pulse.