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CALCULATIONS PERTAINING TO THE DESIGN OF A PREBUNCHER FOR A 150-MeV ELECTRON LINEAR ACCELERATOR

III. COMPARISONS WITH EXPERIMENTAL DATA†

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In a previous paper a ballistic model that included space-charge effects was described and calculated results were presented of the extent to which a current pulse of electrons (approximately 150 keV kinetic energy, approximately 1 μC of charge, and 15 nsec full width at half maximum) could be bunched, i.e., reduced in width without loss of charge, by passing it through a series of gaps on which time-dependent voltages are applied. A prebuncher system similar to the one considered previously has now been constructed, and experimental data on the current at the end of the prebuncher as a function of time have been obtained. Here the calculated current as a function of time, obtained using the model developed previously, is compared with the experimental data. The calculated and experimental data are in substantial agreement for a variety of electron beam and voltage gap conditions.

I. INTRODUCTION

The Oak Ridge Electron Linear Accelerator (ORELA) was designed to produce intense short neutron pulses for the measurement of neutron cross sections by time-of-flight techniques.[1,2,3] The number of neutrons in an ORELA burst of given duration is determined primarily by the total energy of the electrons incident on the target during that time interval and thus the suitability of the machine for time-of-flight measurements would be improved if the total electron energy in a pulse of given duration could be substantially increased. One method for producing this improved performance would be to "prebunch" the electron beam before it entered the accelerator, that is, to reduce the pulse width without substantially changing the charge in a pulse.

In a previous paper,[4] calculated results were presented of the extent to which a current pulse could be bunched by passing it through a series of gaps on which time-dependent voltages are applied. The 150-keV electron pulses considered in Ref. 4 contained approximately 1 μC of charge and had a duration (FWHM) of approximately 15 nsec. The results presented in Ref. 4 were promising, but no experimental confirmation was available. A prebuncher similar to the one considered in Ref. 4 has now been constructed and experimental data for the current at

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the end of the prebuncher as a function of time have been obtained for a variety of initial electron beam and voltage gap conditions. In this paper calculated results obtained using the ballistic model described in Ref. 4 are compared with experimental data. The measured initial current pulse and the measured potential difference as a function of time at each of the voltage gaps have been used as input data for each of the calculations.

In Section II the calculational procedure is briefly described and in Section III the results are presented and discussed.

II. CALCULATIONAL PROCEDURE

The calculational model is the same as that described in detail in Ref. 4 and therefore only a very brief discussion will be given here.

In Fig. 1 a schematic diagram of the prebuncher as it used in the calculations is shown. As indicated in the figure, the model is cylindrically symmetric. The z coordinate is measured along the axis of symmetry, and $z = 0$ is taken to be the exit from the anode of the electron gun and the position where the electron beam from the gun enters the prebuncher. The prebuncher is basically a conducting cylinder (radius = 0.025 m) with a series of gaps across each of which a time-dependent voltage may be applied in such a manner that an electron experiences a change in energy as it crosses each gap. The positions of the gaps are dictated, to a considerable extent, by the equipment required to produce the rapidly varying time-dependent potential difference at each gap. Current as a function of time was measured at the entrance to the prebuncher and just preceding the small collimator (0.00635 m thick, 0.00476 m inside radius) that defines the beam going

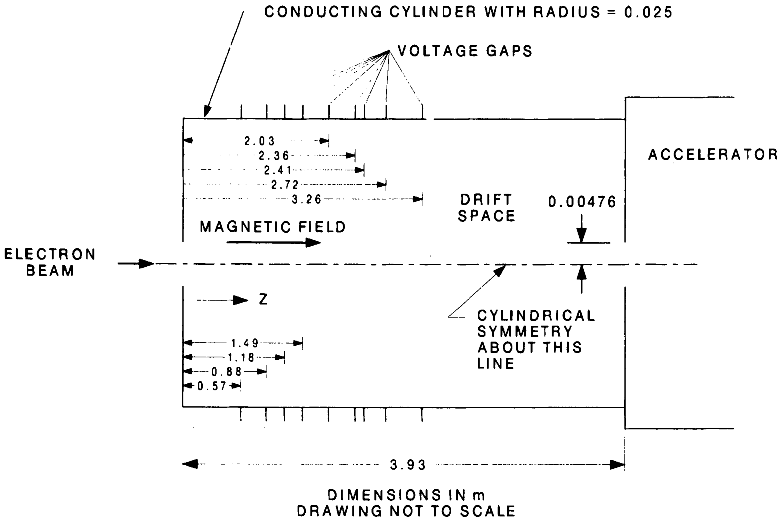

FIGURE 1 Schematic diagram of prebuncher.

into the accelerator. Current measurements were actually made just preceding and immediately after the collimator, but here only the measurements preceding the collimator are considered. The z coordinate of the current monitor that is used is 3.93 m, as indicated in Fig. 1. The presence of the accelerator at the end of the prebuncher is indicated in Fig. 1, but the accelerator has no effect on the results presented here. The current measurements were made using single-turn toroidal-shaped inductive loop minitors having square cross sections surrounding ferrite centers. These monitors were developed and calibrated by G. K. Schulze and J. W. T. Dabbs.[5]

Because of the high currents considered, space-charge effects are large and it is necessary to have a longitudinal magnetic field to prevent the beam from spreading radially. The magnitude of the magnetic field that can be produced in the vicinity of the voltage gaps is, however, limited and therefore a different magnetic field magnitude is used in the gap region and in the drift space. In the work reported here, a magnetic field of 1 kG was used between $z = 0.0$ m and $z = 3.35$ m and a field of 2 kG was used between $z = 3.60$ m to $z = 3.93$ m. In the region between $z = 3.35$ m and $z = 3.60$ m the field was assumed to increase linearly. This is an idealization of the field that exists experimentally since measurements indicate that field variations of the order of ±25% exist; however, the calculated longitudinal results presented here are not sensitive to the magnitude of this magnetic field.

Radial electron motion is not considered here, but the rotational motion due to the magnetic field is considered and the change in beam radius due to the change in the magnetic field is taken into account approximately.[4,6] A beam radius of $3.60\ 10^{-3}$ m was assumed at $z < 3.48$ m and $2.5 \cdot 10^{-3}$ m was assumed at $z \geqslant 3.48$ m. These radii were estimated from the results presented in Ref. 6.

The ballistic model described in Ref. 4 is based on representing the current pulse as a number of discrete charged disks. In the work reported here, the distance between the disks initially, which is also the initial disk thickness, was taken to be 1 cm. The time step used in the calculations was determined to be such that at the initial velocity of the electrons one disk entered the prebuncher in each time step.

The initial electron kinetic energy, the initial current, i.e., the current as a function of time at the entrance ($z = 0.0$ m) to the prebuncher, and the potential difference as a function of time at each gap are taken from measurements. These quantities are different for the various cases considered and therefore they are discussed in the next section in conjunction with the results.

III. RESULTS AND DISCUSSION

Input Data for Case A

The initial kinetic energy of the electrons was inferred from the measured potential difference between the cathode and anode of the electron gun and was

128 keV in the case being considered. It is to be expected that there is some variation in the kinetic energy of the electrons from the gun, but this variation has not been measured and was not considered in obtaining the results presented here. The initial current, i.e., the current as a function of time at the entrance to the prebuncher ($z = 0.0$ m) as measured and used in the calculations, is shown at the left of Fig. 2. The experimental data in Fig. 2 and elsewhere in the paper are shown as solid curves. The experimental data were taken from an oscilloscope and therefore curves rather than individual points were measured. It should be noted that in Fig. 2 and throughout the paper, the zero of time is taken to be the time when the first electrons in the initial pulse are at $z = 0$, i.e., when experimentally there is a measurable signal indicating that the initial pulse is entering the prebuncher.

In this case no voltage was applied to any of the gaps and thus the comparison in this case is primarily intended to test the space-charge calculations in the model. However, with no applied voltage at a gap, the gap structure acts as a resistance in the system and the electrons lose energy when they pass through a gap. In Fig. 3 the energy change at a gap as the beam for the case being considered passes through is shown as a function of time. The time t_i is the time when the first electrons in a pulse reaches gap i. Since the electron current as a function of time at the various gaps is slightly different, due to space-charge spreading the energy loss at each gap is also slightly different, but the effect is small. The data in Fig. 3 are an average over the measured energy loss as a

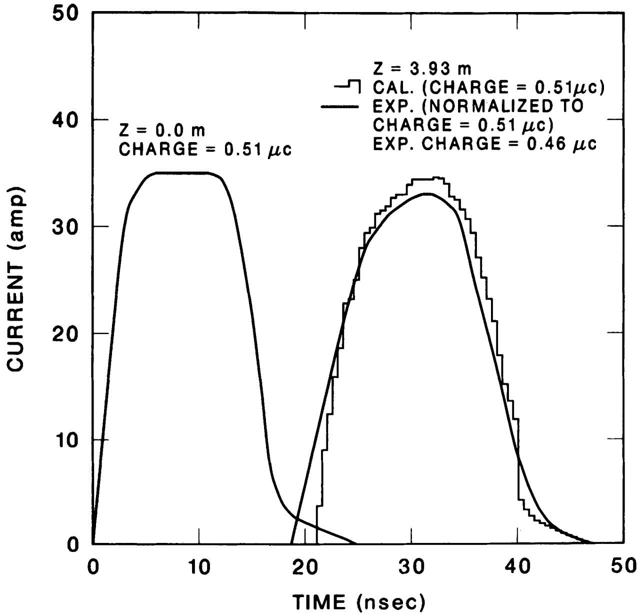

FIGURE 2 Current vs. time (Case A). The current at the left of the figure is the measured current at the beginning of the prebuncher that was used in the calculations, and the currents at the right are those at the end of the prebuncher.

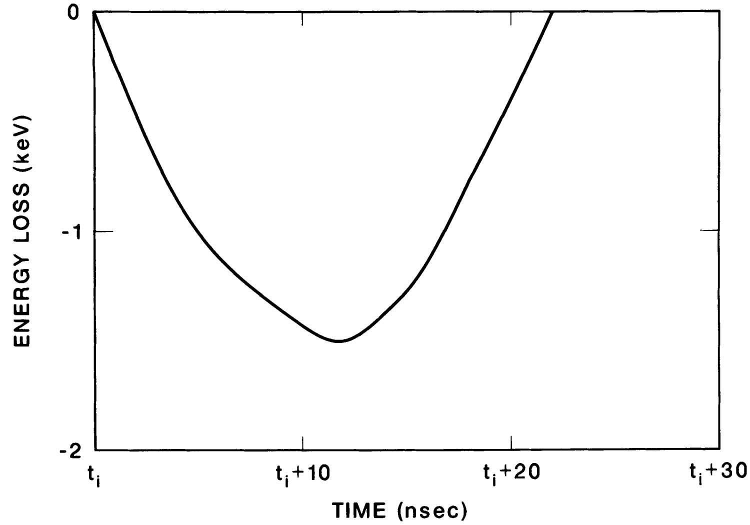

FIGURE 3 Energy change vs. time of an electron as it passes through a voltage gap in which there is no externally applied voltage. The time t_i is the time when the first electrons in a pulse arrive at gap i.

function of time at each gap. The energy losses were obtained from measurements of the voltages by direct coupled resistive dividers through approximately 300 m of RG 214 coaxial cable, which limits the rise time to approximately 7 nsec or greater. Because of this limitation on the rise time, the shape of the energy loss may not be very accurate, but because the energy losses are small, no correction for this effect was made. In obtaining the calculated results, the average energy loss shown in Fig. 3 was utilized at each of the nine gaps.

Comparison of Experimental and Calculated Currents in Case A

The experimental and calculated currents as functions of time are compared at the right of Fig. 2. The data shown are at $z = 3.93\, m$, i.e., at the end of the prebuncher just before the entrance to the accelerator. Note that for purposes of comparison the experimental current shown at the right of Fig. 2 has been normalized to have a charge that is equal to the charge in the incident pulse. In the model used in the calculations, charge is conserved, so the charge in the current pulse at the end of the prebuncher is equal to the charge in the current pulse at the beginning of the prebuncher. Experimentally, however, 12% of the charge was lost from the electron beam as it passed through the prebuncher. The experimental error on the measured total charge is estimated to be 10%, so the measured charge loss is approximately within the expected measurement error.

From Fig. 2 it can be seen that experimentally the first electrons arrive at the end of the prebuncher at 18.7 nsec, while the calculations indicate that the first electrons arrive at the end of the prebuncher in 21.1 nsec. The estimated error in the measurements is ±0.5 nsec so the discrepancy is not within the error estimate. Since the prebuncher is 3.93 m long, the first electrons experimentally travel with an average kinetic energy of 204 keV, while calculationally they travel with an average kinetic energy of 140 keV. Space charge should increase the kinetic energy of the leading electrons, but the average kinetic energy of 204 keV seems to be too large for space-charge effects alone. If space-charge effects were this large, then the agreement in Fig. 3 at the later times would not have been obtained. In general, the calculated results in Fig. 2 are in fair agreement with the experimental data. In particular, it should be noted that the "tail" on the initial current pulse appears as a tail on both the experimental and calculated current pulses at the end of the prebuncher.

Input Data for Case B

The initial kinetic energy and the initial current for this case is the same as that in Case A. The initial current is repeated on the left of Fig. 4 for comparison purposes. The difference between Cases A and B is that in Case B external voltages are applied to many of the gaps.

In Fig. 5 the measured potential differences as functions of time at the various gaps are shown. The potential differences were measured as before. Here, however, the rise times are relatively slow and therefore the shape of the measured curves should be reliable. The estimated error in the potential differences is ±5%. The gaps are number 1 to 9 beginning at the left in Fig. 1. A

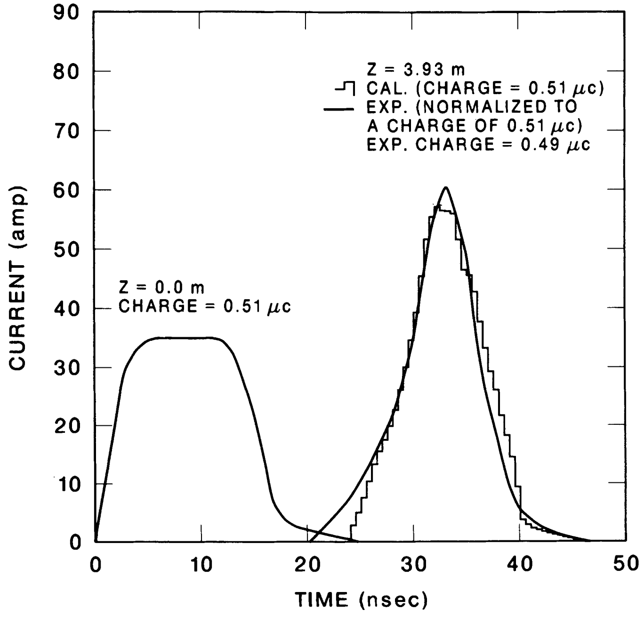

FIGURE 4 Current vs. time (Case B).

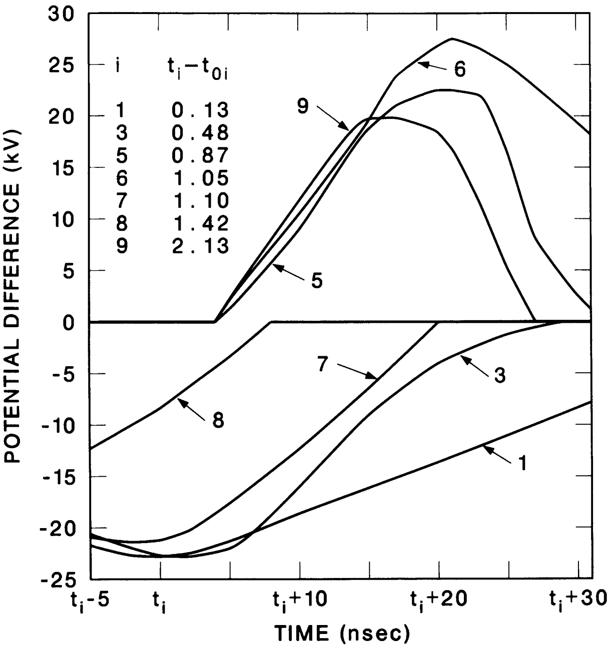

FIGURE 5 Potential difference vs. time at the various gaps for Case B. The times t_i and t_{0i} are defined in the text.

negative potential difference means that the kinetic energy of an electron is decreased as it crosses the gap. In Fig. 5

t_i = the time when the first electrons in a pulse arrive at gap i,

t_{0i} = the time when the first electrons in a pulse arrive at gap i when no external voltage is applied on any of the gaps. (These times of arrival are those from Case A.)

The shapes of the potential difference pulses in Fig. 5 and the timings of the pulses with respect to t_{0i} were measured, but the timings of the pulses with respect to t_i were not measured. In the calculations, however, the value of the potential difference at gap i at the time t_i is needed as input. To overcome this difficulty the time differences $t_i - t_{0i}$ were estimated from the calculations. In principle, this required some iteration, but in practice, it was not at all difficult because the results are not very sensitive to the time differences $t_i - t_{0i}$. The values of $t_i - t_{0i}$ used are given in Fig. 5.

Potential differences as a function of time for gaps 2 and 4 are not given in Fig. 5 because in the present case there was no applied voltage on these gaps. However, the gaps were included in the prebuncher during the measurements and thus the electrons did lose energy when they passed through these gaps. These small lossess of energy were taken into account in the calculations using the measured energy losses. The measurements at gaps 2 and 4 could be made during the Case B experiment so no correction for the difference betwzen t_i and t_{0i} (see above) was necessary. The energy losses at gaps 2 and 4 used in the calculations are very similar to those shown in Fig. 3. These losses are small compared to the applied voltages in Fig. 5 and thus they have no appreciable effect on the final results.

Comparison of Experimental and Calculated Currents in Case B

The experimental and calculated currents as functions of time are compared on the right in Fig. 4. The data shown are again at the end of the prebuncher. The peak current of the final pulse in Fig. 4 is substantially larger than the peak current in the incident pulse and the full width at half maximum (7 to 8 nsec) is considerably less than that approximately (14 nsec) of the initial pulse. Thus, there has been substantial bunching in this case.

As in the previous case, the experimental curve in Fig. 4 has been renormalized so that the charge for the experimental curve is the same as the charge for the calculated histogram. The experimental charge loss in this case is only 4% so the renormalization is not very significant. Since the experimental error on the measured total charge is ±10%, the charge loss is well within the error.

The agreement between the calculated and experimental current in Fig. 4 is moderately good. The time of arrival at the end of the prebuncher of the first electrons is considerably shorter (approximately 4 nsec) experimentally than calculationally. This discrepancy is similar to that found in Case A, but here because of the energy gains and losses at the various gaps the situation is more complex. The calculated and experimental results in Fig. 4 have their peaks at approximately the same time, but beyond the peak the experimental curve decreases more rapidly than the calculated histogram. The estimated experimental error is ±0.5 nsec, as before. The tail at the back of the experimental current pulse is reproduced rather well by the calculated results.

Input Data for Case C

The initial kinetic energy for this case is 80 keV, but the other input quantities are similar to those used in Case B. Thus, the purpose of the comparison in this case is to determine if the calculational model gives reliable results at rather low kinetic energies.

At the left of Fig. 6 the measured initial current pulse that was used in the calculations for this case is shown. The initial charge in this case is somewhat smaller than that used in the previous cases and the initial pulse in this case has no "tail."

In Fig. 7 the measured potential differences on the gaps as functions of time are shown. Voltages for gaps 2 and 4 are not shown in Fig. 7 because in this case no applied voltages on these gaps were used. The small energy loss as the beam passed through these gaps was taken into account in the calculations using

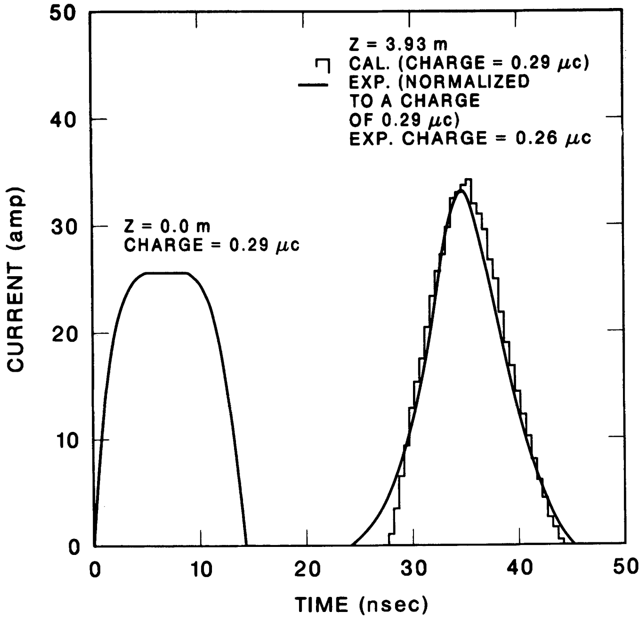

FIGURE 6. Current vs. time (Case C).

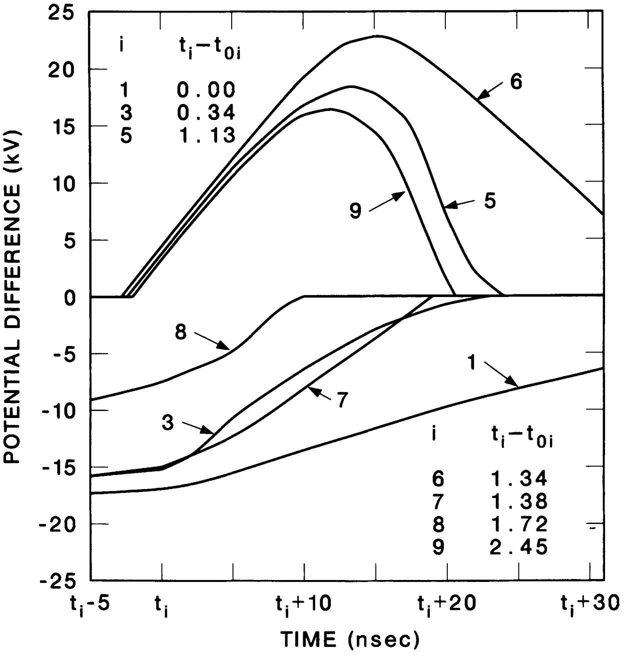

FIGURE 7. Potential differences vs. time at the various gaps for Case C. The times t_i and t_{0i} are defined in the section titled "Input Data for Case B."

measured data as before. The potetial differences are similar to those in Fig. 5, but the peak potential differences are smaller in Fig. 7 than in Fig. 5. The definitions of t_i and t_{0i} are the same as before.

Comparison of Experimental and Calculated Currents in Case C

The experimental and calculated currents as functions of time at the end of the prebuncher are given at the right in Fig. 6. The charge loss in this case was 10% and, as indicated in Fig. 6, the experimental curve shown has been renormalized for comparison with the calculated histogram. The charge loss is approximately within the estimated error of the measurements. The calculated and experimental data are in moderately good agreement in this case, but the experimental time of arrival of the first electrons at the end of the prebuncher is, as in the previous cases, earlier than the calculated time. Note that because the incident electron kinetic energy is lower in this case than in the previous cases, the time of arrival of the first electrons at the end of the prebuncher is later. In addition, there was no tail on the initial current pulse in this case and there is no appreciable tail on either the experimental or calculated current pulse at the end of the prebuncher.

Input Data for Case D

The initial kinetic energy for this case is 128 keV, as in Cases A and B, but the initial current pulse is narrower (FWHM = 7.8 nsec in Case D and = 14 nsec in Cases A and B) and the applied voltages on the gaps are somewhat different from those used previously.

At the left of Fig. 8 the measured initial current pulse that was used in the calculations is shown. The initial charge in this case is approximately 50% of that in Cases A and B, but because the pulse is narrower the peak initial current is 80% of that in Cases A and B.

The potential differences as functions of time on the various gaps are shown in Fig. 9. As before, no potential difference was applied to gaps 2 and 4. The potential difference on gaps 5, 6, and 9 are similar to those used previously on these gaps. The potential differences applied to gaps 1, 3, 7, and 8 are quite different from those used previously. In the previous cases, these gaps, i.e., 1, 3, 7, and 8, were used to provide substantial deceleration of the electrons at the front of the current pulse. Here, on the other hand, these gaps have positive potential differences that vary only slowly with time. One of the consequences of this is that the quantities $t_i—t_{0i}$ given in Fig. 8 are negative rather than positive as in the previous cases. Also, as a consequence of these voltages, it is to be anticipated that the bunching will not be nearly as appreciable as the previous cases. As before, the energy loss of the electrons as they passed through gaps 2 and 4 was taken into account using measured data for this case.

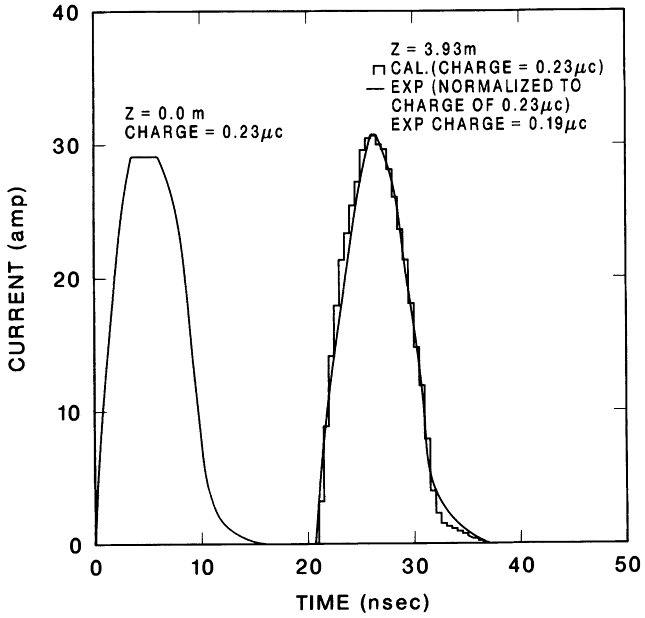

FIGURE 8. Current vs. time (Case D).

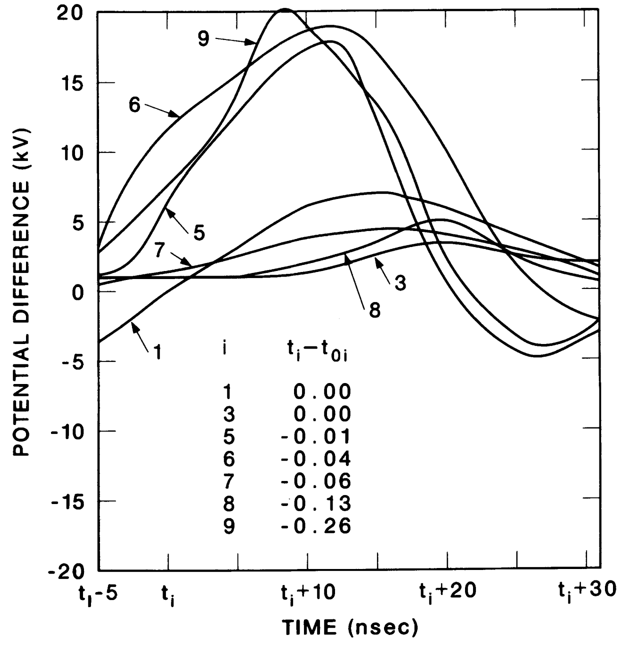

FIGURE 9. Potential difference vs. time at the various gaps for Case D. The times t_i and t_{0i} are defined in the section titled "Input Data for Case B."

Comparison of Experimental and Calculated Currents in Case D

The experimental and calculated currents as functions of time are compared at the right of Fig. 8. The agreement is satisfactory, but there is, as in the previous cases, a discrepancy between the calculated and experimental times of arrival of the first electrons at the end of the prebuncher, but in this case the discrepancy is not large. Because no appreciable decelerating voltages were used in the gaps, no appreciable bunching occurred.

SUMMARY

Results obtained with the calculational model described in Ref. 4 have been compared with experimental data for several different conditions, i.e., initial current, applied voltages, etc. Moderately good agreement has been obtained but, in all cases considered, differences (a few nsec) exist between the experimental and calculated times of arrival at the end of the prebuncher of the early electrons in a pulse. On the basis of the results, it is concluded that the model is sufficiently reliable to be used for many design purposes. In the model used in the calculations, charge is conserved; i.e. the charge in the pulse at the end of the prebuncher is the same as the charge in the initial pulse. Experimentally, a small amount of charge (approximately 10%) is lost. The estimated experimental error on the measured charge is also of the order of ±10% so no firm conclusion can be drawn concerning the charge loss.

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