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Calculated Fraction of an Incident Current Pulse that will be Accelerated by an Electron Linear Accelerator and Comparisons with Experimental Data

R. G. Alsmiller, Jr.
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Engineering Physics and Mathematics Division

CALCULATED FRACTION OF AN INCIDENT CURRENT PULSE THAT WILL BE ACCELERATED BY AN ELECTRON LINEAR ACCELERATOR AND COMPARISONS WITH EXERIMENTAL DATA

R. G. Alsmiller, Jr., F. S. Alsmiller, and T. A. Lewis

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ABSTRACT

In a series of previous papers, calculated results obtained using a one-dimensional ballistic model were presented to aid in the design of a prebuncher for the Oak Ridge Electron Linear Accelerator. As part of this work, a model was developed to provide limits on the fraction of an incident current pulse that would be accelerated by the existing accelerator. In this paper experimental data on this fraction are presented and the validity of the model developed previously is tested by comparing calculated and experimental data. Part of the experimental data is used to fix the physical parameters in the model and then good agreement between the calculated results and the rest of the experimental data is obtained.

1. INTRODUCTION

In a series of previous papers,[1-3] calculated results were presented to aid in the design of a prebuncher for the Oak Ridge Electron Linear Accelerator (ORELA).[4-6] Since the "bunched" electron beam, with its relatively wide spectrum of electron velocities, is useful only insofar as it will be accelerated by the existing accelerator, estimates, upper and lower limits, on the fraction (~50 %) of the bunched beam that would be accelerated were included in Refs. 1 and 2. A series of experimental measurements have now been performed and the data necessary to test the validity of the model used to obtain these estimates have been obtained. In this paper, these data are given and comparisons between the experimental data and calculated results are presented.

The model used to obtain the limits on the time-dependent current that will be accelerated is based on the work of J. C. Slater[7] and requires a knowledge of the amplitude, E_{AO}, of the longitudinal electric field for the dominant mode of the traveling wave in the accelerator and a knowledge of beam loading effects, i.e., the variation of this electric field amplitude with the charge that is accelerated. The upper and lower limits in Refs. 1 and 2 were obtained by neglecting and by overestimating the effects of beam loading. Since there are now experimental data with which to compare, it is more meaningful to have a definite estimate of the current that will be accelerated rather than limits and therefore the model used previously has been modified to provide such an estimate.

The value of the amplitude E_{AO} and of a constant, K, that occurs in the expression for beam loading are not well established for ORELA and therefore they have been determined by comparing calculated results with experimental data. After these quantities are determined, the validity of the model is tested by further comparisons. The values of the constants E_{AO} and K determined here are different from those used in Refs. 1 and 2 and therefore the calculated "pickup" currents, i.e., the time-dependent currents that will be accelerated, given in Refs. 1 and 2, should be modified. To give an indication of the magnitude of the modifications that are required, the pickup currents for one of the cases considered in Ref. 3 are compared with the pickup current that would be calculated using the methodology and constants of this paper.

In Section 2 the geometric configuration of the system is presented, the method of obtaining the experimental data is briefly discussed, and the calculational procedure is described. In particular, modifications in the beam loading model required to obtain a definite estimate of the current as a function of time that will be accelerated rather than limits on this current are described. In Section 3.A, the comparisons with experimental data that are used to determine E_{AO} are given. In Section 3.B, the comparisons to test the validity of the model when beam loading effects are negligible are presented and discussed. In Section 3.C, the comparisons to determine K and to test the validity of the model when beam loading effects are not negligible are presented. In Section 3.D the pickup currents from Case B in Ref. 3 are compared with the pickup current for this case as calculated here.

2. EXPERIMENTAL AND CALCULATIONAL PROCEDURES

A. Geometry and Experiments

A schematic diagram of the geometry of the system is shown in Fig. 1. The z coordinate is measured along the axis of symmetry, $z = 0$ is taken to be the exit of the anode of the electron gun, and $z' = 0$ is taken to be the entrance to the accelerator. The electron beam passes from the anode of the electron gun into a conducting cylinder (radius = 0.025 m) and after traveling a distance of 0.89 m enters the accelerator. Between the electron gun anode and the entrance of the accelerator there is a longitudinal magnetic field of 1000 Gauss to radially confine the beam.

Current monitors were placed as shown in Fig. 1. Monitor 1 is 0.30 m past the electron gun anode; Monitor 2 is 0.02 m in front of the beam scraper; Monitor 3 is 0.02 m past the beam scraper and 0.10 m before the entrance to the accelerator; and Monitor 4 is at 4.40 m past the entrance to the accelerator. The current monitors were single-turn toroidal-shaped inductive loop monitors having square cross sections surrounding ferrite centers. These monitors are similar to those discussed by R. F. Koontz[8] and were developed and calibrated by G. K. Schulze and J. W. T. Dabbs.[9] Each of the monitors gives the current as a function of time as the electron pulse passes.

The current as a function of time at Monitor 1 was taken to be the initial current for the calculations. It was determined from the calculations described later in this paper that for the cases considered here the space charge spreading of the electron pulse between the electron gun anode and monitor 1 could be neglected. The current at Monitor 2 is to be compared with the current at Monitor 3 to determine the charge that is lost on the scraper. For the cases considered here, the currents measured at Monitors 2 and 3 agree within experimental error. Monitor 4 is at the end of the first section of the accelerator. The electrons that pass Monitor 4 have already obtained appreciable energy and thus it is assumed here that the integral of the time-dependent current measured by Monitor 4 is a measure of the charge that is actually accelerated by ORELA. This assumption was confirmed experimentally by a current monitor placed at the end of the accelerator. That is, the charge measured by a current monitor (not shown in Fig. 1) at the end of the accelerator was the same within experimental error as the charge measured at Monitor 4. The ratio of the total charge measured by Monitor 4 to that measured at Monitor 3 is defined to be the "pickup fraction", i.e., the fraction of the incident charge that will be accelerated. This pickup fraction will be compared with calculated pickup fractions in Section 3.A to evaluate the amplitude E_{AO} and the current as a function of time measured by Monitor 4 will be compared with calculated time-dependent currents in Sections 3.B and 3.C.

B. Calculational Procedure

All of the electron transport calculations were carried out using the one-dimensional ballistic model described in detail in Ref. 1 and verified by comparison with experimental data in Ref. 3. The geometry used is that shown in Fig. 1. The calculations presented here are, for the most part, simpler than those described in Refs. 1 and 3 because the time-dependent voltages used previously are not present and because the total length of the

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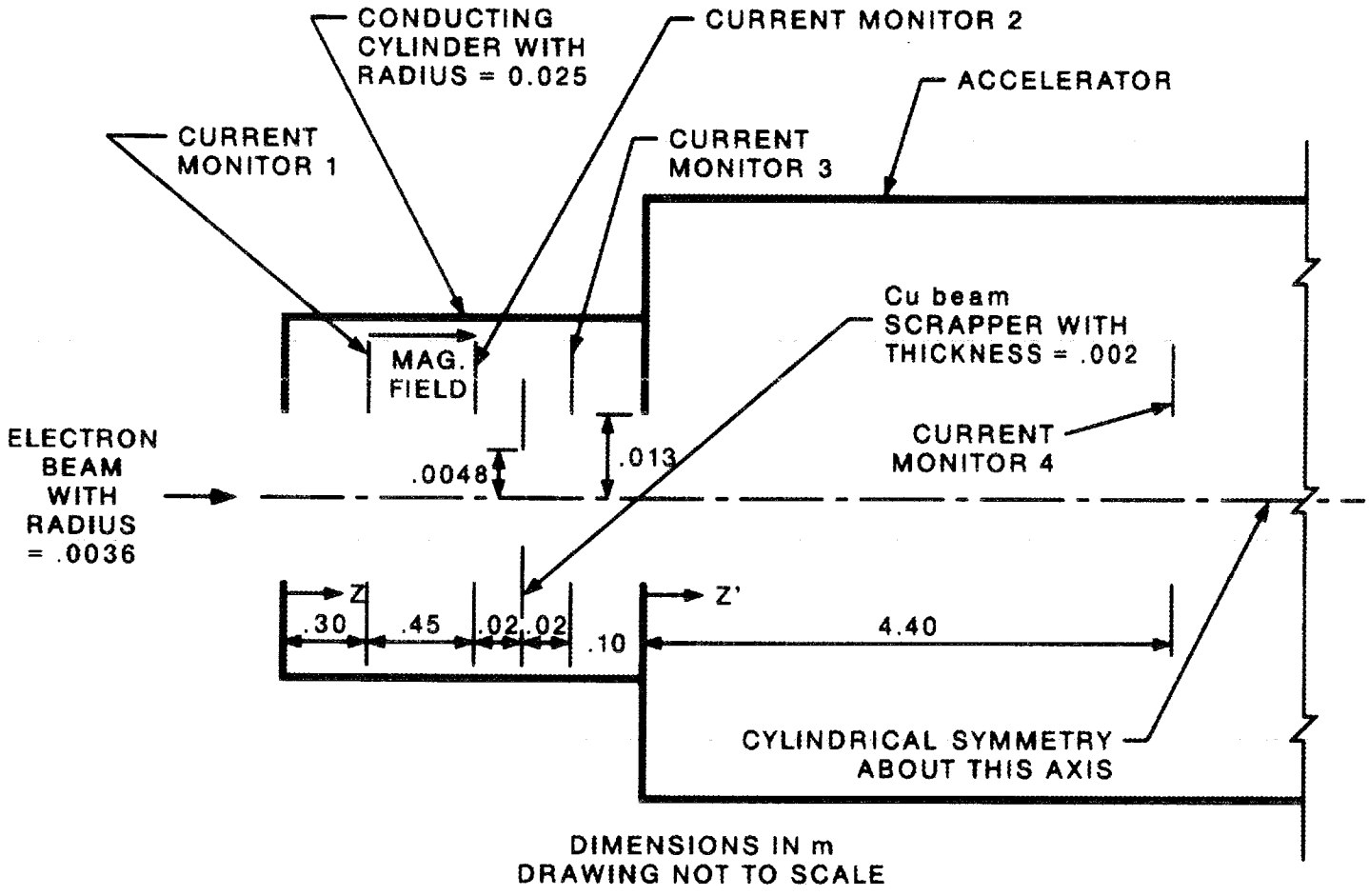

Fig. 1. Schematic diagram of geometry used in the calculations.

system, i.e., the distance from the electron gun anode ($z = 0.0$ m) to the entrance to the accelerator ($z = 0.89$ m) is smaller here than in Refs. 1 and 3. In Section 3.D results from one of the cases considered in Ref. 3 are considered and in this case the distance from the electron anode to the entrance to the accelerator is 3.93 m as in Ref. 3. Radial electron motion is not considered here, but the rotational motion due to the magnetic field is taken into account approximately as described in Ref. 1. A beam radius of 3.60×10^{-3} m is assumed based on the results in Refs. 2 and 3. In the calculations the initial electron kinetic energy was taken from the measurements, and the current as a function of time at $z = 0.0$ was taken to be that measured by Monitor 1.

In Ref. 1 a model was described in detail for calculating the fraction of the time-dependent current entering the accelerator that will be accelerated to high energy. This model did not give a definite estimate of the current, but gave upper and lower bounds. For a linear accelerator such as ORELA[4,5] the electric field amplitude is not a constant, but varies with the amount of charge that is accelerated. Basically electrons that are accelerated remove energy from the field in the wave guide and electrons that enter the accelerator after some electrons have been accelerated therefore experience a smaller accelerating field. This effect is called beam loading and in Ref. 1 the upper and lower bounds on the accelerated current were obtained by underestimating and overestimating the effects of this beam loading. Here, because there are experimental data with which to compare, it is desirable to have a definite estimate of the accelerated current and therefore the model used previously has been modified to give such an estimate. The model used here is similar to that used previously so only the differences will be described here.

The approximate relation concerning beam loading that was derived and used in Ref. 1 is

$$E_A \Big|_{z'_i} = E_{AO} - KQ_i \qquad \text{(i)} \tag{1}$$

where

z'_i = the position, measured from the entrance to the accelerator, of the ith electron to enter the accelerator as it travels down the accelerator,

$E_A \Big|_{z'_i}$ = the amplitude of the longitudinal electric field of the dominant mode of the traveling wave evaluated at the position z'_i,

K = constant

Q_i = the charge that is accelerated ahead of the ith electron in the current pulse,

E_{AO} = the amplitude of the longitudinal electric field of the dominant mode of the traveling wave if no charge has been accelerated,

and it is to be understood that Eq. (1) holds for all i. The term dominant mode in the above definitions is used to express the fact that only a single frequency component of the RF fields in the wave guide is utilized in the theory of J. C. Slater[7] that is used here. Since there are many other field components whose effect on the electrons is neglected, i.e., is assumed to average to zero, the quantities E_{AO} and E_A should be considered effective field amplitudes that occur in the model used here and that must be determined from experimental data.

If E_{AO}, K, and Q_i for all i are assumed to be constant, then the electric field amplitude at the position of the ith electron as it travels in the accelerator is a constant. The derivation of Eq. (1) is strictly valid only at sufficiently large values of z'_i that Q_i is reasonably constant and is not valid at small values of z'_i where a large amount ($\sim$50%) of the charge that enters the accelerator is lost. It is, however, at the smaller values of z'_i where the electric field amplitude, E_A, is needed to determine whether a particular electron will be accelerated. In Ref. 1, Eq. (1) was used at small z'_i and it was argued that a lower limit on the electric field amplitude and consequently on the current that will be accelerated could be obtained by assuming that Q_i was the total charge that entered the accelerator before the ith electron. That is, it was assumed that all electrons that enter the accelerator, even those that will ultimately not be accelerated, remove substantial energy from the fields in the accelerator. On the other hand, if in Eq. (1) the quantity Q_i is taken to be zero, the electric field amplitude is a maximum and an upper limit on the current that will be accelerated is obtained. This is the manner in which the bounds that were presented in Ref. 1 were obtained.

Here, however, since experimental data are available for comparison, a less conservative assumption concerning the quantity Q_i (for each i) in Eq. (1) is made and a definite estimate of the current that will be accelerated is obtained. Equation (1) is retained but the quantity Q_i is taken to be only the charge that is accelerated ahead of the ith electron rather than the total charge that enters the accelerator ahead of the ith electron. That is, electrons that are lost from the beam are assumed to be lost very near the entrance to the accelerator so that these electrons remove essentially no energy from the accelerator fields before they are lost. The Q_i obtained with this assumption is intermediate between the two values of Q_i used in Ref. 1 to obtain the upper and lower bounds. The calculations of the current that will be accelerated are not appreciably different from those in Ref. 1, except that now an iteration must be performed. That is, for a given value of E_{AO}, Q_i for all i is assumed and from the calculation a revised estimate of the Q_i's is obtained, etc., until self-consistency is obtained. No such iteration was required in Ref. 1 because the limiting values of the Q_i's used did not depend on the actual current that was accelerated.

Here, as in Ref. 1, the calculations of the current that will be accelerated are carried out on the basis of general consideration of the equations of motion of electrons in the electromagnetic field of the accelerator[7] and not by explicitly integrating the time-dependent equations of motion for various incident particle boundary conditions. Nevertheless, it will be of interest in Sections 3.B and 3.C to compare the experimental and calculated time-dependent currents at Monitor 4. To do this the assumption will be made that all of the electrons that reach Monitor 4 spent the same amount of time in traveling from the entrance of the accelerator to Monitor 4. That is, it is assumed that the time-dependence of the current that is accelerated is the same at Monitor 4 as at the entrance to the accelerator.

3. RESULTS AND DISCUSSION

A. Determination of the Electric Field Amplitude E_{AO}

A direct measure of the electric field amplitude E_{AO} in Eq. (1) is not feasible but experimental data were obtained that enabled E_{AO} to be determined by comparing experimental and calculated data of the pickup fractions, i.e., the fraction of the incident current pulse that will be accelerated, as a function of E_{AO}.

Experimental measurements of the pickup fraction were obtained for incident electron energies of 125 keV, 100 keV, 73 keV and 48 keV. For these incident energies, calculated results were obtained for a range of values (5 to 10 MV m^{-1}) of E_{AO}. The total charges in the incident current pulses in these experiments were chosen to be small (~0.010 μC) so that the effects of space charge and beam loading would be minimal. In this way it was hoped to avoid errors in the determination of the electric field amplitude due to any failure of the calculational procedure to accurately include these effects.

The calculated and experimental pickup fractions are shown in Fig. 2. The calculated results are shown by the plotted points and the experimental value for each incident energy is shown by the dashed horizontal lines. The solid curves join the corresponding plotted points. The plotted points for E_{AO} = 7.0 MV m^{-1} are not shown so as not to obscure the intersections between the horizontal lines and the solid curves. An estimate of the value of the electric field amplitude is obtained from the abscissa value in Fig. 2 corresponding to the intersection of the horizontal line and solid curve for each incident energy. Thus, from Fig. 2, four estimates of the amplitude are obtained. There is some small variation in the amplitude estimates, due to experimental error and calculational uncertainties, but in general, the results in Fig. 2 provide good confirmation of the assumption used in the calculational model that only one value of the electric field amplitude of the dominant mode of the traveling wave need be considered. The estimated expected errors of the experimental data in Fig. 2 are ± 3 to 5%, and the variations of the amplitude values are within this experimental range. A linear average of the four amplitude estimates obtained from Fig. 2 provides a value of E_{AO} of 7.0 $\pm$ 0.1 MV m^{-1} and this is the value used in obtaining the results in the remainder of this paper. This value is somewhat smaller then the value 10.0 MV m^{-1} that was used in Refs. 1 and 2. This value of 10.0 MV m^{-1} was determined from the measured value of 170 MeV for the highest energy electron out of ORELA and the fact that ORELA is 17 m in length. Thus, the value 10.0 MV m^{-1} corresponds to an average over the complete accelerator while the value 7.0 MV m^{-1} is an effective electric field amplitude that is to be used in the model (discussed briefly in Section 2.B and in detail in Ref. 1) employed here to calculate, near the entrance of the accelerator, the current that will be accelerated.

B. Comparison of Calculated and Experimental Data in the Case of Negligible Beam Loading

To obtain the data needed to test the calculational model when beam loading effects are small, an experiment was conducted for 125-keV incident electrons and for a charge of 0.027 μC in the incident current pulse.

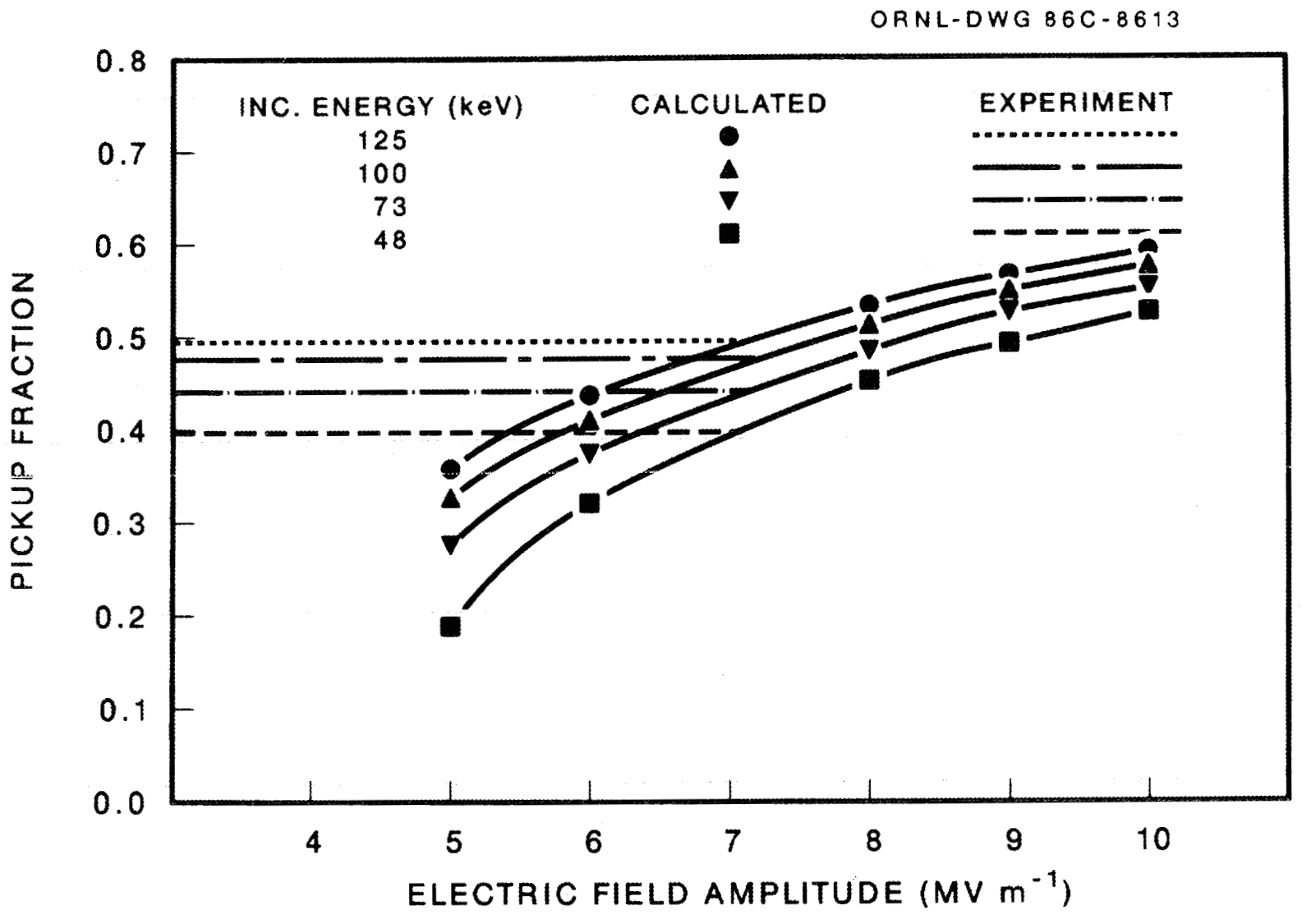

Fig. 2. Pickup fractions vs. electric field amplitude. The calculated points for the electric field amplitude = 7.0 MV m^{-1} are not plotted in order not to obscure the intersections between the horizontal line and the solid curves.

The initial current that was taken from the experiment and was used in the calculations is shown by the dashed line in Fig. 3. Also shown in Fig. 3 are the calculated and experimental currents as functions of time at Monitor 4. The calculated results are given by the histogram and the experimental results are given by the dash-dot curve. The experimental results are shown as a curve rather than plotted points because the experimental results were taken from an oscilloscope and thus a curve was obtained. The time when the first charge reached Monitor 4 is not obtained in either the experiment or the calculations, so the histogram and the dash-dot curve have been made to agree at the zero of time in Fig. 3. The calculated values in Fig. 3 were obtained using the beam loading model, but the calculated results with and without beam loading are so nearly the same that the differences can not be shown in the figure.

The calculated histogram and experimental curve in Fig. 3 agree to within the estimated experimental error of $\pm 5\%$ and the calculated and experimental charges at Monitor 4, i.e., the integrals of the currents, are also in very good agreement.

C. Comparison of Calculated and Experimental Data in the Case of Significant Beam Loading

To further test the model and, in particular, to obtain a test of the beam loading model, an experiment was conducted with an electron energy of 125 keV and a charge in the initial pulse of 0.88 μC. The measured initial current as a function of time that was used in the calculations is shown by the dashed curve in Fig. 4. In order to obtain as large an initial charge as possible the pulse width in this experiment is considerably longer than the pulse width in the experiment discussed in Section 3.B. The charge of 0.88 μC in the initial pulse is, approximately at least, the largest pulse charge that can be obtained with ORELA.

The measured current at Monitor 4 is shown by the solid line in Fig. 4. The dashed histogram in Fig. 4 shows the calculated current at Monitor 4 when beam loading is neglected, i.e., when the second term, KQ_i, on the right-hand side of Eq. (1) is neglected for all electrons that enter the accelerator. Here, as before, the time when the first charge reaches Monitor 4 is not measured or calculated so all results at monitor 3, both experimental and calculated, have been made to agree at the zero of time in Fig. 4. The differences between the solid curve and the dashed histogram in Fig. 4 indicate the magnitude of the effects of beam loading on the current that is accelerated and thus, even though a large incident charge is used, the effects of beam loading are not large.

To carry out the calculations with beam loading included it is necessary to know the value of K in Eq. (1). Since this value is not known it was determined by requiring that the charge in the calculated current pulse at Monitor 4 agree with the measured charge at Monitor 4. The solid histogram in Fig. 4 shows the calculated current at Monitor 4 with a value of $K = 2.68$ MV $(\mu C)^{-1}$ m^{-1}. Even though this value of K was determined by making the experimental and calculated charges at Monitor 4 equal, the shapes of the calculated and experimental data must still be compared. At small times (<6 to 7 nsec) the solid histograms and the dashed histograms coincide because beam loading effects are, of necessity, negligible for the early charge that is accelerated. The early charge that is

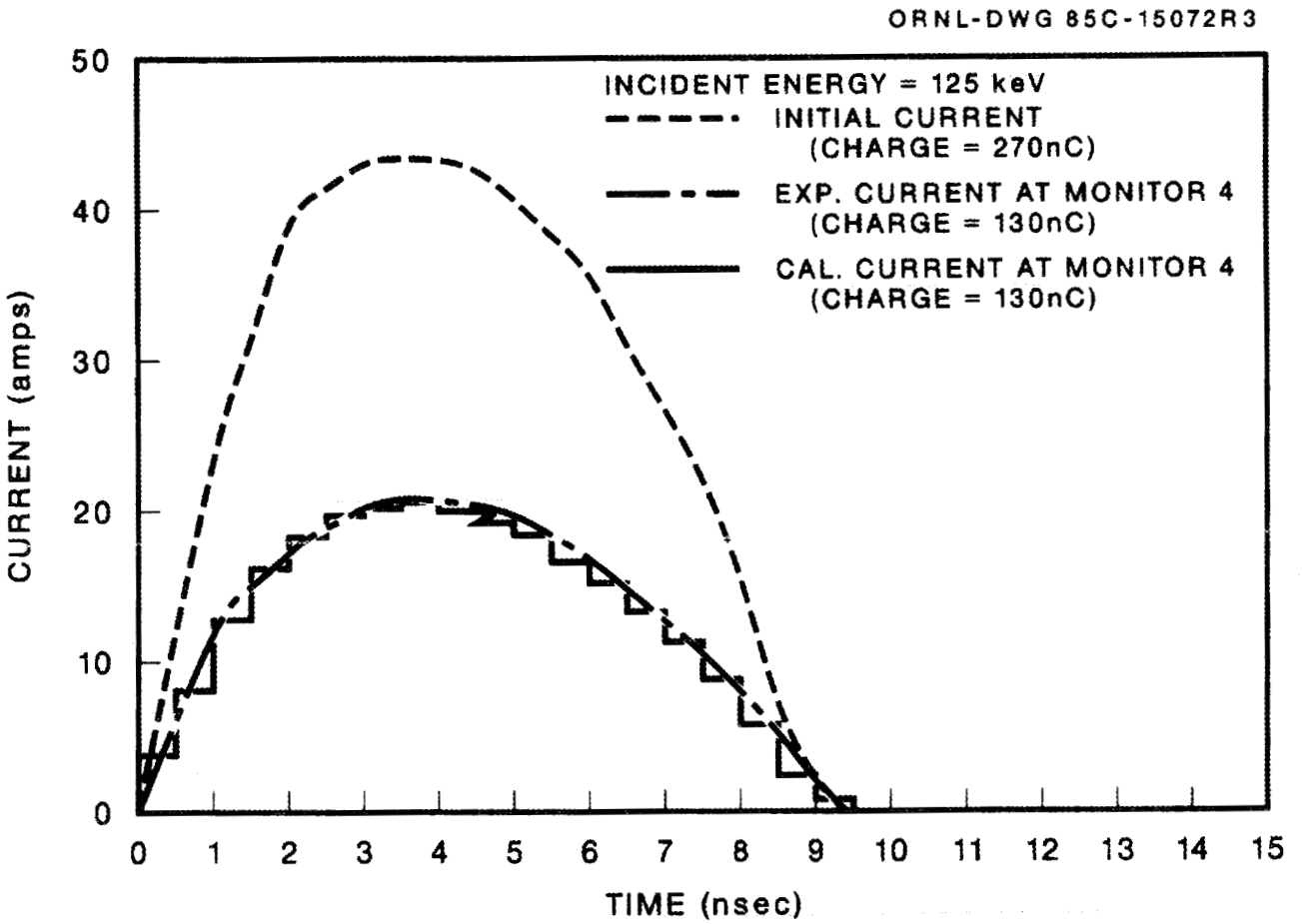

Fig. 3. Current as a function of time for a given initial current. The charge in the initial current is small so beam loading effects are negligible.

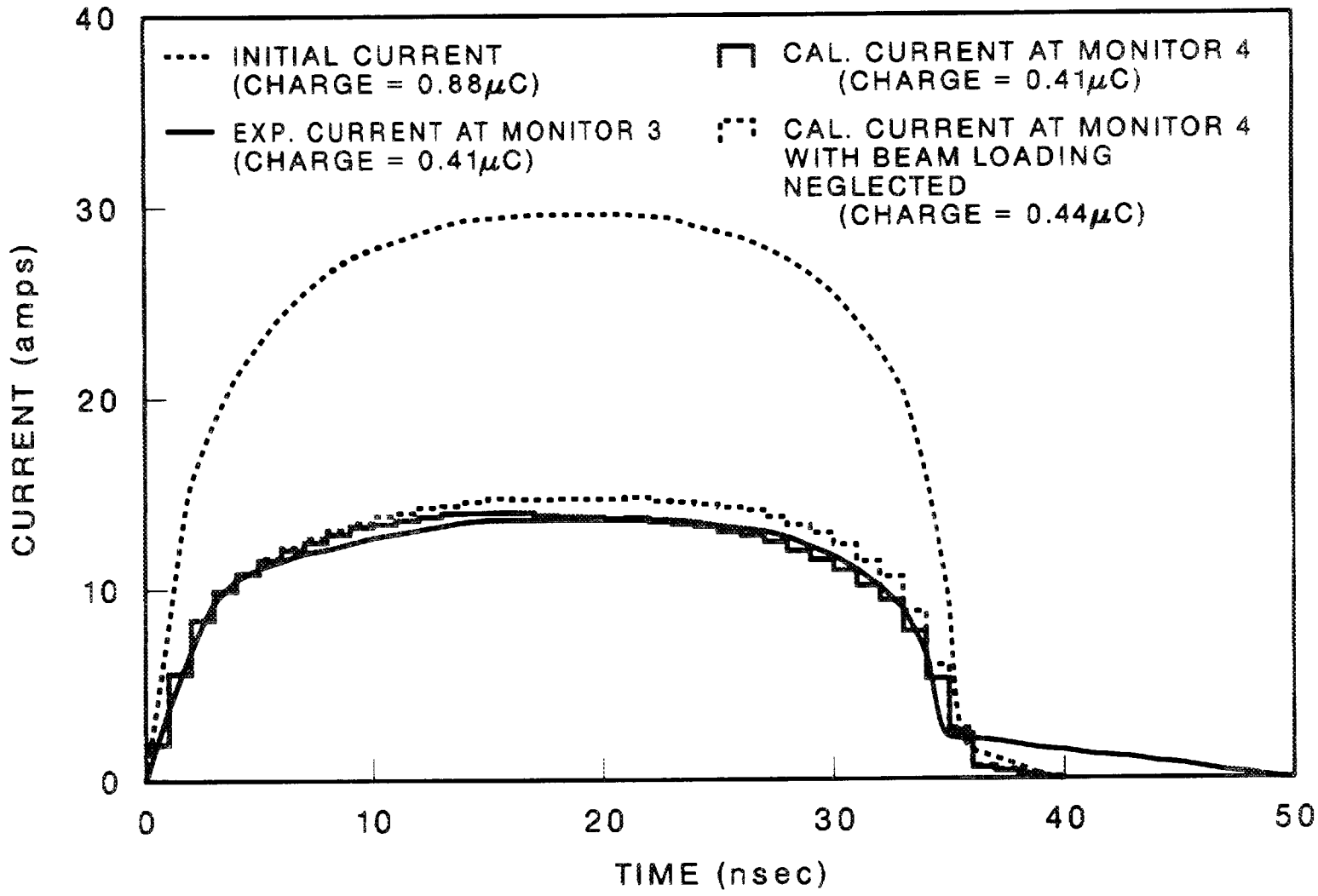

Fig. 4. Current as a function of time for a given initial current. The charge in the incident current pulse is large so beam loading effects are not negligible.

accelerated removes energy from the field in the accelerator, but the effect is cumulative, and only as more and more charge is accelerated does this loss of energy have an appreciable effect. The fact that the calculated histogram and measured curve agree at small times is further confirmation that the electric field amplitude of 7.0 MV m^{-1} determined previously is applicable in the present experiment. For times between approximately 7 and 20 nsec the calculated histogram overestimates slightly the experimental data and between times of approximately 25 and 32 nsec, the calculated histograms underestimates the experimental data slightly. However, the estimated error on the experimental data is $\pm 5\%$ and all of the differences are within this error except at times greater than approximately 35 nsec where the experimental data show a small tail that is not present in the calculated results. In general, the agreement between the calculated and experimental results in Fig. 4 is satisfactory and provides a validation of the beam loading model, although the value for ORELA of K = 2.68 MV $(\mu C)^{-1}$ m^{-1} that must be used in the model is somewhat less than the value K = 7.18 MV $(\mu C)^{-1}$ m^{-1} that was used in Refs. 1 and 2. The value of K used in Refs. 1 and 2 was determined from the measured energy distribution out of ORELA.[4] On the basis of the comparisons in Fig. 4, it appears that the value of K determined from the electron energy distribution at the end of the accelerator is not the appropriate value of K for use in the model used here to calculate, near the entrance to the accelerator, the current that will be accelerated.

D. The Effect of the Revised Values of E_{AO} and K on the Current That Will Be Accelerated

On the basis of the comparisons in Ref. 3 and in the present paper, it has been established that the model developed in Ref. 1 to carry out prebuncher design calculations for an electron linear accelerator provide results that are in agreement with experimental data. However, the quantities E_{AO} and K that are needed in the model require values that are different from those used in Ref. 1 and therefore the calculated values of the current that will be accelerated in Ref. 1 must be modified. To obtain an estimate of the magnitude of the required modifications, the time-dependent current from one of the previous cases — Case B of Ref. 3 — will be compared with the current for this case that is calculated with the methodology and constants of this paper.

The case considered here is described in detail in Ref. 3 so only a few of its features will be given here. The incident electron kinetic energy was 128 keV and the initial current pulse had an incident charge of 0.51 μC and a full-width-at-half-maximum of approximately 14 nsec. The prebuncher was 3.93 m in length and substantial voltages were applied at the various gaps in the prebuncher so appreciable bunching (full-width-at-half-maximum of the bunched pulse equals approximately 7.6 nsec) was achieved. Experimental results on the pickup current for this case are not available, but in Ref. 3 calculated and experimental time-dependent currents at the entrance to the accelerator are compared.

The calculated time-dependent pickup currents are compared in Fig. 5. The zero of time in Fig. 5 was taken to be the time when the first charge entered the accelerator. The dashed histograms show the upper and lower limits on the pickup current as a function of time when the values of E_{AO} and K used in the previous papers are used. The solid histogram shows the results when the methodology and values of E_{AO} and K of the present paper are used.

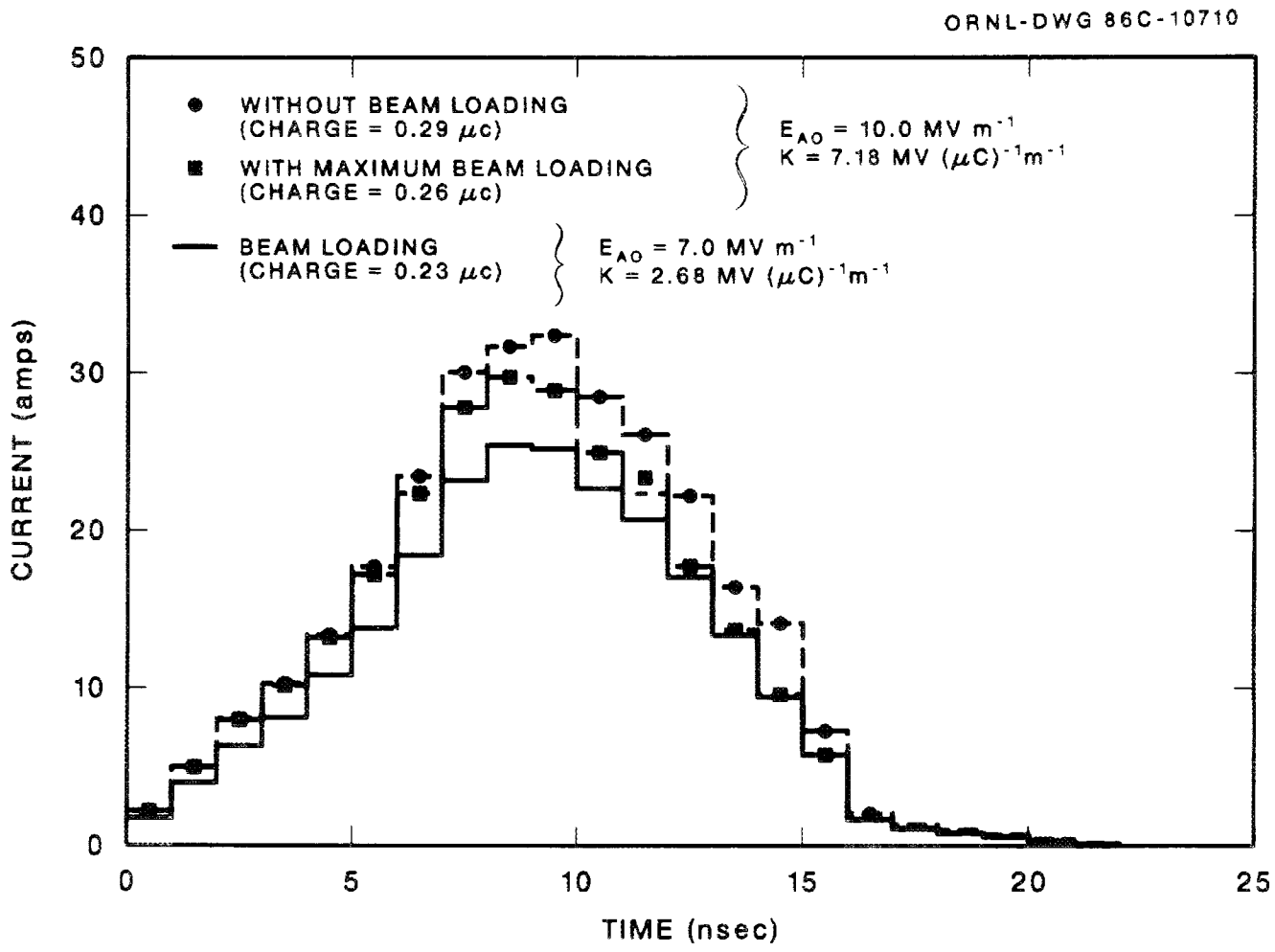

Fig. 5. Current as a function of time based on different values of the quantities E_{AO} and K. (The case considered is that designated Case B in Ref. 3.)

A smaller value of E_{AO} reduces the pickup current and a smaller value of K reduces the effects of beam loading. The solid histogram is less than or equal to the dashed histograms at all times in Fig. 5 indicating that the accelerated current as calculated here is less than that calculated in Refs. 1 and 2. The magnitude of the differences vary with time and depend on whether the upper or lower limit values are used, but very approximately the reduction is of the order of 20%.

4. SUMMARY

A revised Slater[1,7] theory for calculations of the "picked up" current inside the Oak Ridge Electron Linear Accelerator, including a realistic calculation of beam loading effects, is based on the electric field given in Eq. (1). The parameter E_{AO} was obtained by comparison of the pickup fractions computed from integrals of calculated currents with fractions obtained from measured currents near the end of the first section of the accelerator and at its entrance. Low initial charge was used. The parameter K was found by another charge comparison at high initial charge.

The theory was verified by the fact that four values of E_{AO} for initial small charge pulses with energies from 48 to 125 keV were in close agreement. Further verification was obtained with a larger charge by detailed comparison of the shapes of the measured and calculated time-dependent currents. Finally, a case with the maximum pulse charge available at ORELA was used. In this case, beam loading was not negligible and the value of K was found by making the integrals of the currents agree. Good agreement of the shapes was again found.

The close agreement of E_{AO} values at different energies indicates that the same value can be used for current calculations involving a beam with varying electron energies obtained with a prebuncher. Comparison, using the new beam loading model, with previous limiting cases[3] using rather different values of E_{AO} and K determined by averaging over the entire accelerator, shows a difference of approximately 20%.

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