COMPUTER SIMULATION OF THE LASERTRON WITH A RING MODEL*

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Abstract

The lasertron is more efficient, lighter, and smaller than a klystron, especially at outputs below 2 GHz. Higher peak output powers are possible with the lasertron, and a separate modulator is not required. These advantages are useful for rf accelerators and linear colliders. The electron dynamics are simulated to estimate the device performance limits and to design an experimental lasertron. The relativistic electron dynamics are followed from the photocathode through the acceleration region and through the output region. The total fields are the sum of the space-charge, external magnetic, and acceleration or output-cavity fields. Wake fields are ignored, and the steady-state output fields are found. Lasertron performance as a function of acceleration field, charge per pulse and frequency is calculated, showing its advantages and limitations. A preliminary design for the first Orsay lasertron experiment is presented.

Introduction

The lasertron is a device to transform high-voltage power to microwaves, and it is much like a klystron with a photocathode. The beam is bunched in the lasertron by the laser light that is modulated at the microwave frequency. The photoelectrons are produced at a cathode (see Fig. 1) and accelerated to a fairly high voltage in the gun region by an electric field. These electrons produce microwaves in the output section, which is one or more cavities that decelerate the beam with the microwave fields. With the present availability of powerful lasers with picosecond light pulses, there is little doubt that this device can be an efficient microwave generator at frequencies below 1 or 2 GHz, but the debunching electron dynamics are quite complicated, so the upper frequency limits are not well defined. This paper discusses a computer model of the lasertron. This model can be used to predict general trends in lasertron performance on the device parameters, and the model be used to design lasertrons for particular applications.

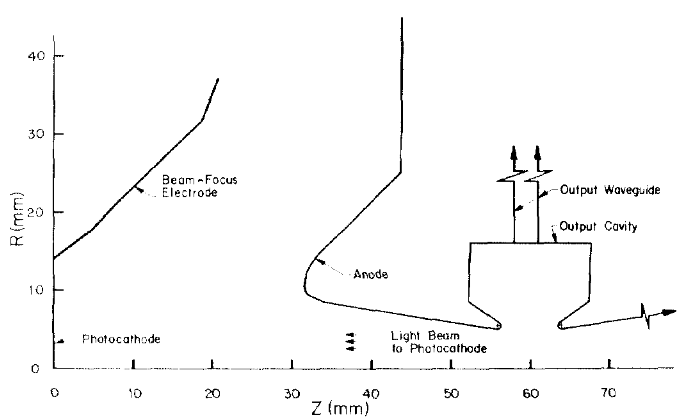

Fig. 1. Schematic diagram of the 6-GHz Orsay prototype lasertron.

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The relativistic electron dynamics of a set of particles are followed from the photocathode through the gun region and through the output region, with time as the independent variable. The fields are summed by superposition to find the total field at each electron's position. The model is two and one-half dimensional because r and z are tracked for each particle, but v_ϕ is obtained from the relativistic form of Busch's theorem. Wake fields and the transient filling of the output cavity are ignored. A single bunch of electrons is followed through the lasertron, but the code can easily be modified to calculate the dynamics of a small number of bunches at the expense of computer time.

The program is modular and flexible; many of the fields can be approximated in several ways to alter the accuracy and time requirements to perform the simulation. In this paper, only the most accurate methods of calculating the fields are described, and the details, as well as faster but less accurate approximations, are described in a longer paper.*

The particles all have the same charge; the laser light pulse is assumed to be rectangular. This restriction can be removed fairly easily to allow a time-varying light pulse to be simulated. All processes in the photocathode are instantaneous. The beam model is a central disk suroundcd by rings. This combination starts at the cathode in a plane and is repeated many times over the length of the laser pulse. Typically, between 20 and 200 particles are followed, and it takes between 0.5 and 50 minutes of VAX 11/785 cpu time to do a simulation. A separate graphical output program may be run to obtain the pictures of the interaction. The static electric fields in the gun region have both E_r and E_z components, and the static magnetic fields have B_r and B_z components. Both the space charge and the output cavity fields have E_r, E_z, and B_ϕ components.

Equations Of Motion

Starting with the Lorentz force and the energy conservation equations[1]

$$\frac{d}{dt}(m_0\gamma\vec{v}) = e(\vec{E} + \vec{v}\times\vec{B}) \tag{1}$$

and

$$\frac{d}{dt}(m_0\gamma c^2) = e\vec{v}\cdot\vec{E}\ , \tag{2}$$

with the following normalizations; $\tau = \omega t, \vec{V} = \vec{v}/u_0, u_n = u_0/c, \eta = |e|/m_0, R = \omega r/u_0, Z = \omega z/u_0$, one finds that the force equations in cylindrical coordinates are

$$\frac{dV_z}{d\tau} = \frac{-\eta}{\omega\gamma}\left\{\frac{E_z}{u_0}[1-(u_nV_z)^2] - V_\phi B_r + V_r(B_\phi - u_nV_zE_r/c)\right\} \tag{3}$$

and

$$\frac{dV_r}{d\tau} = \frac{-\eta}{\omega\gamma}\left\{\frac{E_r}{u_0}[1-(u_nV_r)^2] + V_\phi B_z - V_z(B_\phi + u_nV_rE_z/c)\right\} + V_\phi^2/R, \tag{4}$$

* P. J. Tallerico and J. P. Coulon, "A Ring Model of the Lasertron," Los Alamos National Laboratory report, to be published.

where u_0 is the velocity of an electron on the axis and at the anode voltage. The equation for the conservation of angular momentum is

$$V_\phi = \frac{\eta R B_z}{2\omega\gamma}\left(1 - \frac{R_c^2 B_{zc}}{R^2 B_z}\right), \qquad (5)$$

and the energy equation is

$$\frac{d\gamma}{d\tau} = -\frac{\eta u_n}{c\omega}(E_r V_r + E_z V_z). \qquad (6)$$

The γ's are calculated by both Eq. (6) and the definition $\gamma = [1 - u_n^2(V_r^2 + V_\phi^2 + V_z^2)]^{-1/2}$; the difference is used to estimate the integration errors. The new positions are integrals of the velocities. The equations of motion are numerically solved by Euler's method with τ as the independent variable.

There is a variable number of particles in the program. After the beam is injected, there are N_z axial slices, with N_r rings in each slice. At each time step within the laser pulse, a subroutine determines if a new set of N_r particles should be emitted at the cathode. When the laser pulse is over, a total of $N_r N_z$ particles will have been emitted. These electrons all start with zero velocity and are positioned on the cathode so that each particle represents equal charge. Thus, thermal velocity effects are neglected, and the beam initally has zero emittance.

Electromagnetic Fields

Because the bunch changes its shape so quickly in the lasertron, the space-charge forces must be evaluated at every time step. The first action taken by the space-charge routine is to set the five field components E_r, E_z, B_r, B_z, and B_ϕ to zero. Then the ring-model Green's functions[2] are calculated, and the computation time varies as the square of the number of particles. One expects that the use of a finite-difference or finite-element computation and a fast Fourier transform method would significantly reduce the space-charge computation time for a large number of particles because this type of computation takes a time proportional to n log n. The Green's function method involves a Lorentz transformation using the source particle's z velocity, and is relativistically exact only when all the particles have the same velocity. The total space-charge fields are found by integrating the Green's functions times the charge density over the volume occupied by the beam.

$$\vec{E}_{sc}(r,z) = \int\int\int \rho'(V')\vec{E}(r,z,;r'z')dV',$$

where $\rho'(V')$ is the charge density in the beam. The Green's functions for the zero-volume sources become infinite as one approaches the singularity, so it is better to use a finite volume source as the Green's function; therefore, Carlsten's finite-valued Green's functions[3] are used.

The electrostatic fields in the gun region may be approximated as constant and one-dimensional. A more accurate approximation is to run Herrmannsfeldt's electron gun code[4] for the actual lasertron geometry, but for a very small beam current, and to write the potential to a disk file. This data file is then reformatted with a simple program and used as input data in the lasertron program. The static focus field is piecewise linear, and it may have 10 breakpoints from the cathode to the end of the output cavity. The axial field is constant before the first breakpoint and after the last breakpoint. To use this option, a small table of the breakpoint fields and positions are read as input data.

The B_ϕ component for a single eigenmode of a given cavity is calculated with SUPERFISH[5] for the empty cavity, and this field is written as a data file that is read by the lasertron program. These data are interpolated, and the appropriate derivatives are taken to find the fields for each electron in the output section for each time step. The amplitude and phase of these fields are input data. The simplest method is to adjust these values to obtain the maximum energy conversion efficiency, but the corresponding cavity impedance may not be physically realizable. The self-consistent method[6] of calculating the gap voltage and phase is clearly better, and it is implemented in the lasertron code.

DC-to-RF Conversion Efficiency

The simplest procedure to estimate the dc-to-rf conversion efficiency is to ignore the output gap and calculate the fundamental harmonic current and the axial momentum spread in the beam at the center of the output gap. If a gap were correctly placed and coupled to the bunched beam, Mihran[7] has shown that the quantity

$$MF = \frac{i_1}{2I_0}\frac{(\gamma v_z)_{slow}}{(\gamma v_z)_{avg}} \qquad (7)$$

is a good estimate of the interaction efficiency. In Eq. 7, i_1/I_0 is the first Fourier component of the beam current, and the axial momentum is evaluated both for the slowest electron and for the average electron.

It is more accurate to actually calculate the electron dynamics through the output gap with realistic, self-consistent gap fields and to estimate the efficiency as

$$\eta = \frac{1}{N_z N_r(\gamma_0 - 1)}\sum_i(\gamma_i - 1), \qquad (8)$$

where γ_0 is the relativistic factor for the dc anode voltage. This efficiency is the fraction of the kinetic energy that is transfered to the microwave fields. Some of this field energy is then lost as ohmic heating of the output cavity, but this is a small fraction for high output power.

The Computer Program

A computer program has been written in FORTRAN to solve the equations presented above. Euler's method is used to step the velocities forward in time, and the trapezoidal method is used to increment the positions. In the gun region, a time step of 1.0 ps usually is a good value. The rf time step must generally be about 1° of rf phase; thus, it depends on the frequency. The program is written in a modular fashion, therefore it can be altered as the requirements change. The program is interactive, and it requires several data files to produce a good simulation, with accurate dc, rf, magnetic, and space-charge fields. Output data files are written for the code DESSIN,[8] which produces the graphical output.

Merit-Figure Results

The electron dynamics of the lasertron are similar to those of the microwave triode, in that the bunching is good initially, but grows worse as time goes on. The general conclusion is that the lasertron is an excellent microwave device at the lower frequencies, and that it is more difficult to obtain good efficiency as the frequency is increased. High acceleration gradients improve the conversion efficiency at any frequency. In Fig. 2, the merit figure is plotted for two frequencies versus the fraction of the maximum charge extracted per pulse, q_{max}, where

$$q_{max} = \pi r_c^2 \epsilon_0 E_a/d, \qquad (9)$$

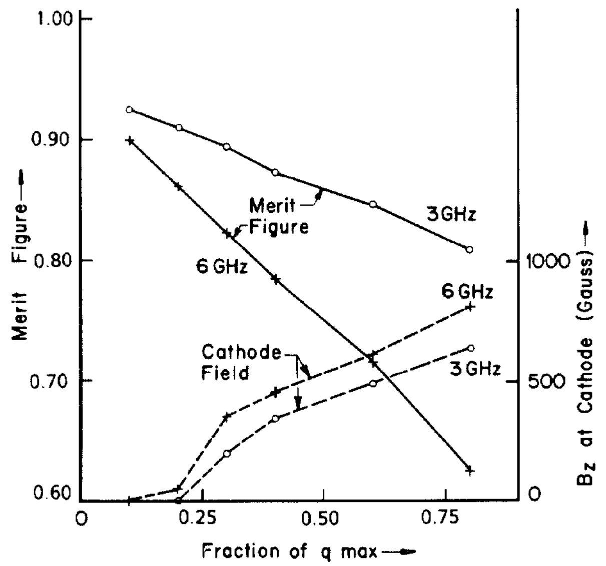

Fig. 2. Merit-figure estimate of efficiency and magnetic-focus field versus fraction extracted of q_{max}: planar acceleration fields, Bessel function space-charge fields, $r_c = 15$ mm, frequency = 3 and 6 GHz, $V_0 = 300$ kV, anode-cathode distance = 30 mm.

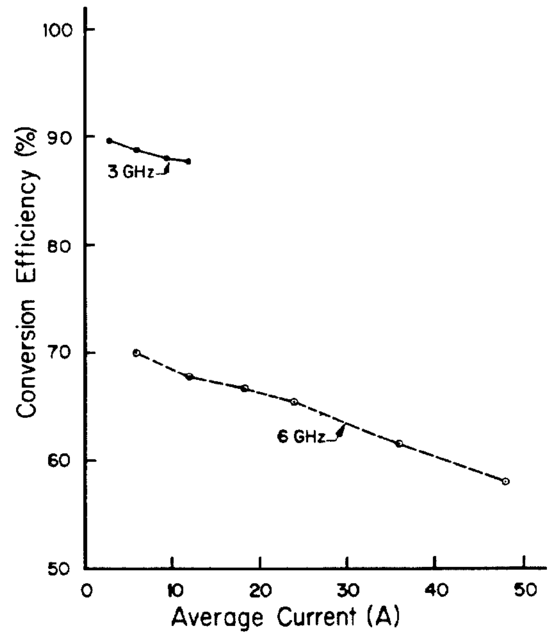

Fig. 3. Calculated dc to rf conversion efficiency versus peak beam current for the Orsay prototype lasertron at 3 and 6 GHz and 300 kV.

E_a is the acceleration field at the cathode, r_c is the cathode radius, and d is the anode-cathode spacing. When a charge of q_{max} is emitted in a bunch, the acceleration field at the cathode is completely cancelled by the simplest approximation to the space-charge field. These calculations were made with one-dimensional acceleration fields, no rf output gap fields, and the Bessel function space-charge fields. The cathode radius is 15 mm, the anode is 30 mm from the cathode, the drift tunnel radius is 20 mm, and the voltage is 300 kV. The average current is 187.8 A at $q_{max} = 1$ and 3 GHz; it is proportional both to frequency and to q_{max}. The center of the output gap is 65 mm from the cathode, and 3 radial and 16 axial subdivisions are used in the calculations. The electron pulse length at the cathode is 60 and 30 ps for the two frequencies. The predictions are very encouraging because the case at 3 GHz, and a fraction of 0.6, for example, indicates an efficiency of 86% and an output power of 29 MW with only a 900-G peak magnetic confining field. The results for 6 GHz are lower, with an efficiency of 71.5% at a fraction of 0.6, but the output power is 48 MW and the peak magnetic focus field is 2400 G.

Calculations On The 6-GHz Orsay Prototype

The first detailed calculation made with this code is for the 6-GHz laserton designed at Orsay for linear collider applications. A sketch of this lasertron is shown in Fig. 1. The results of the calculations for both 3 and 6 GHz are shown in Fig. 3. These are complete calculations in that the electrostatic fields are computed with Herrmannsfeldt's code, the output cavity fields are calculated with SUPERFISH, and the space-charge fields are calculated with the Green's functions. Only the self-consistent amplitude and phase calculations are not made. The results are quite encouraging for both frequencies. The beam voltage is 300 kV, and the gradient in the gun region is conservative, with an average of 10 kV/mm. The performance is quite sensitive to this gradient and even higher conversion efficiencies are calculated with 15 kV/mm, which is still an achievable, but difficult, acceleration gradient. Thus, efficiencies of over 80% at 3 GHz and over 70% at 6 GHz are calculated for the lasertron with the present code. This is in general agreement with the past calculations using other codes and is significantly better than the klystron case. Thus, the lasertron is expected to be an excellent rf generator for accelerator applications.

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