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BEAM DYNAMICS, EFFICIENCY AND POWER OF THE SLAC LASERTRON – SIMULATION RESULTS*

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Abstract

In this paper we describe results of the computer simulation of the SLAC proof of principle lasertron device with a conventional single gap output cavity, using the 2D relativistic field and particle code called MASK. The RF to beam power efficiency is calculated for different power levels, DC voltages and optical pulse lengths. The calculated efficiency at the initial operating point of 50 MW beam power, 400 kV, and with 60 picosecond optical pulse duration, is 66%. The maximum RF power at 400 kV is about 50 MW. At 600 kV the maximum power increases to about 110 MW, but the efficiency at low power is not much changed from what it was at 400 kV. The simulation calculation does not take into account loss of RF power due to backscattered electrons nor the full effects of the impedance of the accelerating gap. A calculation of the efficiency of the lasertron with a double output cavity has been carried out by K. Eppley at SLAC, and generally yields efficiencies about 10 percentage points higher than the single cavity simulation.

1. Introduction

The desire for advanced accelerators beyond the SSC has led to an increase in research and developement of high power RF sources. At SLAC we are engaged in an effort to study the possible utility of a photocathode klystron commonly called the lasertron.[1] One of the first steps in this effort was to simulate the beam dynamics and arrive at estimates for efficiency and power. This was first done assuming a conventional output cavity with a single gap, however further calculations[2] show significant gains in efficiency if a less conventional double gap output cavity is used instead. The single gap cavity simulation results are presented here and compared with some of the double gap cavity results.

The simulation used the relativistic particle in cell code MASK. In the code, Maxwell equations are solved on a rectangular mesh to give fields which are used to determine the force on macroelectrons (simulation particles with the same charge to mass ratio as electrons but variable charge). The motion of the macroelectrons is computed and used as input to solve the Maxwell equations, and the process is repeated. The simulation is completely time dependent; steady state behavior can only be studied if the program is run long enough for transients from the initial conditions to decay and for power balance to be achieved. The boundary conditions in the simulation are either metal or port. The port boundary condition divides the fields at the boundary into incoming and outgoing waves. The amplitude and phase of the incoming wave is arbitarily adjusted to give the appropriate voltage across the accelerating gap or across the output cavity gap and is the mechanism by which power is delivered to the beam. The outgoing wave is partially reflected depending on the angle of incidence and an arbitrary reflection coefficient, and therefore provides a mechanism for power to leave the system. Though the port boundary condition is arbitrary and nonphysical, it has been demonstrated that it gives essentially correct results as long as reflections of outgoing waves are not large. The simulation region and dimensions are shown in Fig. 1.

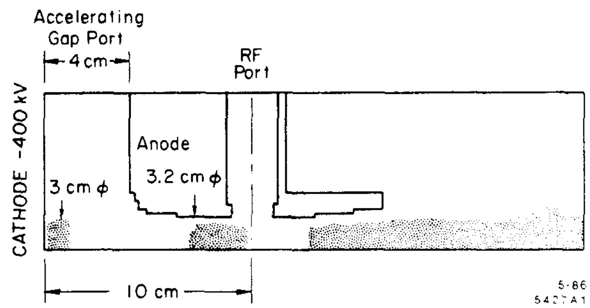

Fig. 1. The MASK simulation of the SLAC lasertron with a single gap output cavity gives the postions of macroelectrons as a function of radial and longitudinal coordinate. This run shows the beam corresponding to the proof of principle parameters for the SLAC lasertron: 50 MW beam power, 400 kV beam voltage, and gives an efficiency of 66%. The initial pulse length is 60 picoseconds fwhm.

The basic geometry of the lasertron focus electrode and anode is shown in Fig. 2. The electrode geometry and the magnetic solenoid focusing scheme were constrained by the available voltage (400 kV) and cathode material (a flat wafer limiting the effective diameter to 3 cm). I chose a defocusing electric field shape in order to increase the electric field on the cathode (10 MV/m), which reduces the debunching in the accelerating gap. A simple ironless solenoid magnet provides a longitudinal magnetic field of about 2000 gauss maximum, and is strong enough that small changes in the geometry of the electrodes have almost no effect on the beam trajectory.

In the simulation, a bunch of macroelectrons is formed every 350 picoseconds – the period of the fundamental mode of the output cavity. The current pulse shape is believed to follow the optical pulse shape initially and is given in Fig. 3. The bunches are accelerated in the cathode anode gap by the electric field which derives from the port boundary condition as well as fields induced by the passage of previous bunches. The bunches spread out considerably by the time they reach the output cavity. At 50 MW of beam power, the bunches in the simulation spread from an initial fwhm of 60 picoseconds to about 135 picoseconds.

The electric field amplitude and phase in the output cavity are adjusted to minimize the final kinetic energy of the macroelectrons subject to the constraint that none are reflected, by changing the RF port boundary condition. Reflected electrons

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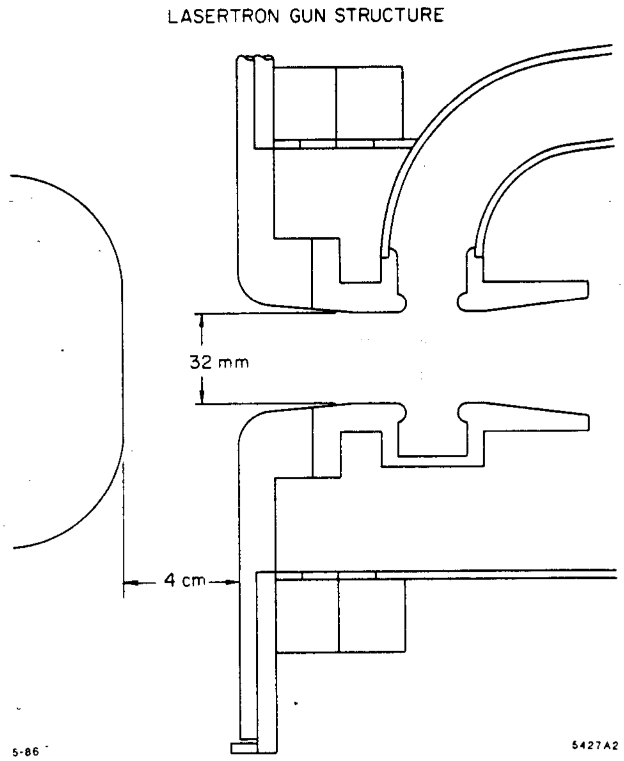

Fig. 2. The lasertron gun structure. The beam is confined against defocusing electric fields from the gun geometry and space charge by a longitudinal magnetic field of about 2000 gauss. The field on the cathode is about half the field at the cavity center causing a radial compression of the beam.

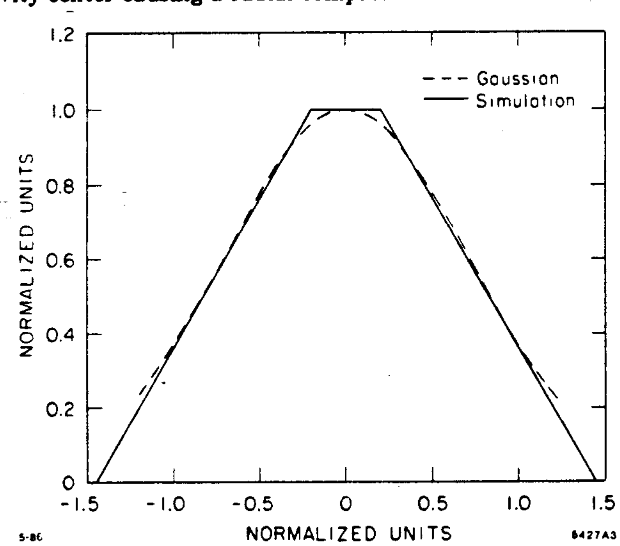

Fig. 3. The simulation profile of the optical pulse shown against the expected gaussian pulse shape from the laser.

cause two problems: they drain power from the output cavity reducing efficiency, and they can strike the output cavity or drift tube when their velocity gets near zero and the magnetic focusing becomes ineffective causing excessive gas desorption.

The beam power to RF power conversion efficiency is defined as

$$\eta = \frac{E_{initial} - E_{final}}{E_{initial}} \qquad (1)$$

where $E_{initial}$ is taken to be the bunch charge Q multiplied by the applied voltage, and E_{final} is kinetic energy of the macroelectrons when they reach the right boundary in figure 1, approximately where the collector would be located. If Q is large, then the initial kinetic energy of the bunch is less than $QV_{applied}$ since the beam would load down the accelerating gap and reduce the accelerating voltage. This effect is small for the parameters we are currently dealing with and in any case, only affects the conversion efficiency to second order. For maximum efficiency from a 400 keV beam, the peak RF field in the cavity is about 20 MV/m and the corresponding cavity voltage is 450 kV. The efficiency obtained in this way is not sensitive to small changes in phase or amplitude and the values given in the figures which follow are probably within 5% of the maximum.

It is possible using MASK to simulate the entire output cavity without using the RF port boundary condition by sending many bunches through a completely metal cavity which is resonant at the bunch frequency. The electric field strength in the cavity will build up with the passage of each bunch until the power lost to reflected electrons equals the power absorbed from electrons which pass through the cavity. When the electric field in the cavity gives the maximum conversion efficiency as defined above, the amplitude and phase will be the same as that in an optimally coupled cavity. This occurs after about 10 to 15 bunches from a 50 MW beam. The efficiency calculated in this way is insensitive to the number of bunches needed to build up the fields, but does require a careful adjustment of the cavity dimensions and fairly long computer runs. This method gives almost the same results as obtained using the port boundary condition. The efficiency of a 50 MW beam at 400 kV was 66.1% when computed without the port approximation and 66.3% when the port approximation was used. Bunches from a 100 MW beam gave an efficiency 46.5% without an RF port compared to 42.5% with. At this time MASK has no provision for adjusting the coupling of a cavity to the outside world, nor for measuring the RF power removed from a cavity directly.

2. Simulation Results

Runs were made with two optical pulse lengths, corresponding to gaussian laser pulses of 30 and 60 picoseconds fwhm. Figure 4 summarizes MASK simulation results for the SLAC lasertron at the design voltage of 400 kV. At modest beam power there is little difference in RF output power between the two optical pulses. At 100 MW of beam power, the 30 picosecond pulse gave about 10 MW more RF than the 60 picosecond pulse. The design parameters for the proof of principle device include a an efficiency of 70% at 50 MW of beam power, but MASK predicts we should get only 66% efficiency or 32 MW of output power using a single gap output cavity.

I have performed a series of runs at 600 kV using the same cathode anode geometry as in the 400 kV runs thereby increasing the cathode electric field to about 15 MV/m. We might be able to convert our 400 kV DC supplies into a 600 kV supply with only minor changes. It is not known yet whether or not the lasertron structure can support 600 kV DC or even 400 kV DC for that matter. It is fairly certain that the lasertron would hold off these or possibly higher voltages if we used short pulses, on the order of 10 microseconds long.

The data from the 600 kV runs is added to the data from the 400 kV runs and efficiency versus beam power is plotted in Fig. 5. The leftmost data point, 81% at almost zero beam power, represents the best efficiency I could obtain using a

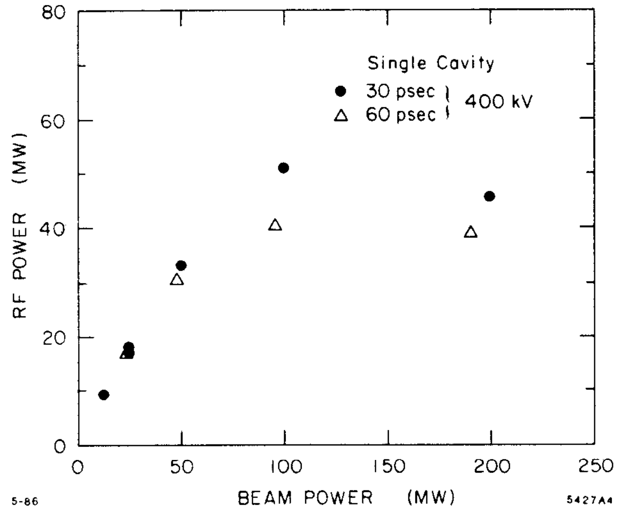

Fig. 4. The MASK calculated SLAC lasertron output power for various beam powers and for two optical pulse lengths. These results were obtained using a model with a single gap output cavity.

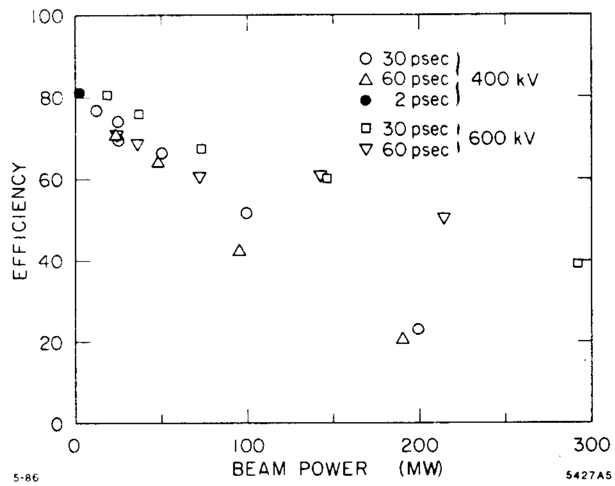

Fig. 5. The MASK calculated efficiency of the SLAC lasertron using a single gap output cavity. Note the maximum efficiency is 81%.

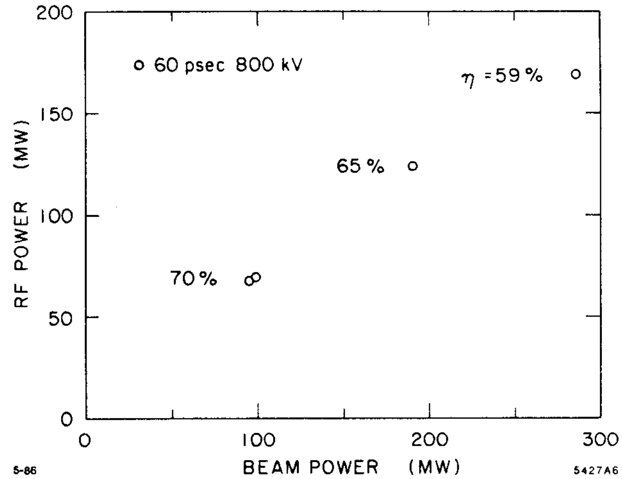

Fig. 6. Calculated power and efficiency for the SLAC proof of principle lasertron at 800 kV. This is too high a voltage for the electrode structure to hold off DC, but it may be possible to hold off using a short pulse.

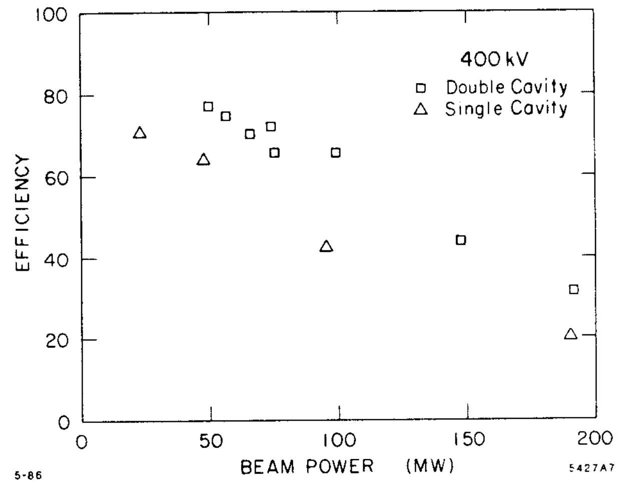

Fig. 7. Calculated efficiency versus beam power of the SLAC lasertron with a single gap cavity and with a double gap cavity, at 400 kV and using a 60 picosecond fwhm optical pulse. The double gap cavity efficiencies are typically about 10 percentage points higher at the same beam power.

2 picosecond optical pulse with 70 A peak beam current at 400 kV. The efficiency of the 30 picosecond 600 kV runs approaches but does not exceed that value. From the figure, it can be seen that there is a large premium to be gained by going to higher voltages provided that it is acceptable for the efficiency to fall below about 68%. For example, at 60% efficiency, the 600 kV beam puts out twice as much RF as the 400 kV beam. At beam power less than about 75 MW, and high efficiency, the advantage of higher voltage is minimal.

A few runs were made at 800 kV, again using the same geometry as in the 400 kV runs, and are plotted in Fig. 6. An 800 kV device brings the RF power levels well into the range of 100 to 200 MW at greater than 50% efficiency.

Some results from the double gap cavity simulation by Eppley are plotted together with the single cavity simulation results in Fig. 7. The double cavity simulation used the same electode geometry, optical pulse and a somewhat longer solenoid with the same current density in the magnet coil. The double cavity efficiencies are about 10 percentage points higher than the single gap cavity efficiencies. The same results are plotted differently in Fig. 8. The double gap cavity simulation results provide as much as 20 MW more RF than the single gap cavity at the same beam power, and with efficiencies around 65%. At the design value of 50 MW beam power, it gives 8 MW more RF power. For these reasons and because the design parameters called for more than 70% efficiency at 50 MW beam power, we chose to build a double gap cavity for the lasertron.

Some mechanisms by which efficiency and power are lost that are not taken into account in the MASK simulation are listed below.

1. Backscattered electrons from the collector will be directed by the magnetic field to the output cavity where they will act as a current drain on the cavity. This effect is particularly large for the lasertron because the backscattering coefficient is large (0.3 to 0.6) and because the magnetic field is strong even in the collector, and can easily direct backscattered electrons to the output cavity.

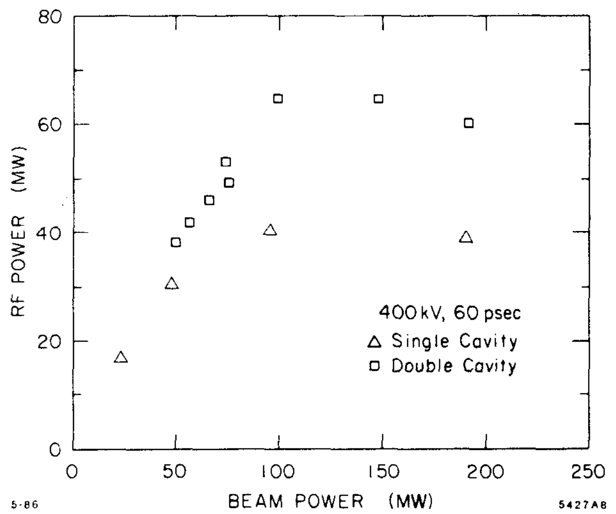

Fig. 8. Calculated RF power dependence on beam power for the SLAC proof of principle lasertron with a single gap cavity and with a double gap cavity.

2. Multiple reflections of the optical pulse from the electrode to the anode and then to the cathode, or from surfaces of the vacuum window, cause emission at the wrong phase.
3. Current loading effects will lower the beam voltage so the cavity will no longer be optimized. Also, bunches induce RF power in the accelerating gap which is lost in the power supply and energy storage system. The induced RF may act back on the beam and cause a flucuation in the arrival time of the bunches at the output cavity and a flucuation in the energy of the bunches and therefore a loss of efficiency.

These losses depend in detail on the particular design of the lasertron and in some cases can be completely eliminated. Nevertheless, they will have a significant effect on the beam power to RF power conversion efficiency, thus the calculation of the efficiency by the MASK simulations may be regarded as an upper limit on the actual device performance.

References

1. E.L. Garwin *et al.*, SLAC-PUB-3650 (April 1985).
2. K.R. Eppley, SLAC/AP-48 (February 1986).