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THE SLAC LASERTRON PROJECT*

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ABSTRACT

SLAC has a program underway to develop an efficient high power microwave source for accelerator applications employing a photoemission cathode, the so-called lasertron. After a brief discussion of the lasertron idea, the various elements of the current program are reviewed. A proof-of-principle experiment to build a 35 MW, 70% efficiency, S-band microwave source is nearing completion. Actual RF power testing is expected to begin in late 1986 or early 1987.

INTRODUCTION

Many accelerator physicists believe that the next, if not the ultimate, higher energy electron accelerator will involve feeding an axially symmetric, room temperature copper accelerating structure with externally generated microwave power. Such an accelerator would likely operate at a higher frequency than is currently conventional, perhaps 10 to 15 GHz. Since the desired beam energy is about one order of magnitude greater than the current SLAC linac, and since high accelerating gradients are desirable to make a machine of practical size, a large amount of high frequency, high peak power microwave energy will be required. Currently, no suitable microwave power sources exist. The lasertron project at SLAC is an experimental and theoretical program to investigate one candidate technology for such a microwave power source.

The lasertron is basically a very simple device. It employs a photoemission cathode, illuminated by an optical pulse train of the proper microwave structure, to produce a bunched electron beam directly at the cathode. This beam is accelerated to high voltage and immediately passed through an RF output structure to produce microwave power. In a high peak power device, there will be considerable charge in each bunch, requiring that the beam be contained transversely by an axial magnetic field and that it be rapidly accelerated to a relativistic velocity to limit the longitudinal spreading. As in all microwave power tubes, the spent beam is dumped in a collector.

The attractiveness of a photoemission cathode for this application stems from the ease of directly modulating the emission at high frequency and the very high current densities which can be readily obtained. To date, however, photoemission has been used only as a detector of photons, rather than as a source of high power electron beams. Much of the lasertron program involves learning to prepare robust high current density photocathodes capable of operating for long periods in the environment of a high power microwave tube.

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There are a number of reasons why the lasertron is an interesting candidate for microwave power production. For example, computer simulations indicate that very efficient conversion of beam power to microwave power should be possible. The basic simplicity of the device gives hope that a relatively inexpensive unit can be produced. Since the photocathode emits only while illuminated, only a DC power supply or a very simple modulator is required, as opposed to the complex and expensive modulators necessary for devices with thermionic emission cathodes. It appears feasible to scale the lasertron to power levels and frequencies currently of interest for future high energy electron linacs. The phasing of multiple lasertrons should be very straightforward and stable, given the constant velocity of light. Finally, it may ultimately be possible to eliminate the laser by using a directly modulated cold cathode, thus producing a laser-less lasertron.

These potential advantages do not come for free, however. Photoemission cathodes are typically far more sensitive than thermionic cathodes to degradation or destruction by residual gases. Thus, in general, a better vacuum system is required. Activation of photocathodes requires the use of various alkali metals, which makes the operation of high voltage guns more difficult. The laser itself is a complex system, and is far more costly than a filament transformer. The necessity of getting the illuminating light to the cathode can add significantly to the complexity of the basic device. In general, photoemission cathodes operating in actively pumped UHV systems have not shown very long lifetimes, and the ability of these cathodes to deliver the large total charge required over the operating life of a microwave power source has not been demonstrated. A lasertron proof-of-principle investigation must address all of these issues.

It is worth noting that the lasertron idea was patented some years ago by Tallerico and Wilson at Los Alamos.[1] A small lasertron has been built and operated briefly by a Japanese group.[2]

THE LASERTRON PROOF-OF-PRINCIPLE EXPERIMENT

A schematic view of the SLAC lasertron is shown in Fig. 1. The basic simplicity of the complete experiment is presented in Fig. 2. The entire experiment is assembled in a small, detached building, the former hydrogen target test cell, now converted to dedicated lasertron test lab.

The relevant parameters for the proof-of-principle device are given in Table I. The choices made in developing this parameter list were based upon a number of considerations. The frequency chosen, 2856 MHz, though lower than desirable for a next generation linac, matches the current SLAC operating frequency. Thus a good selection of components and test equipment at this

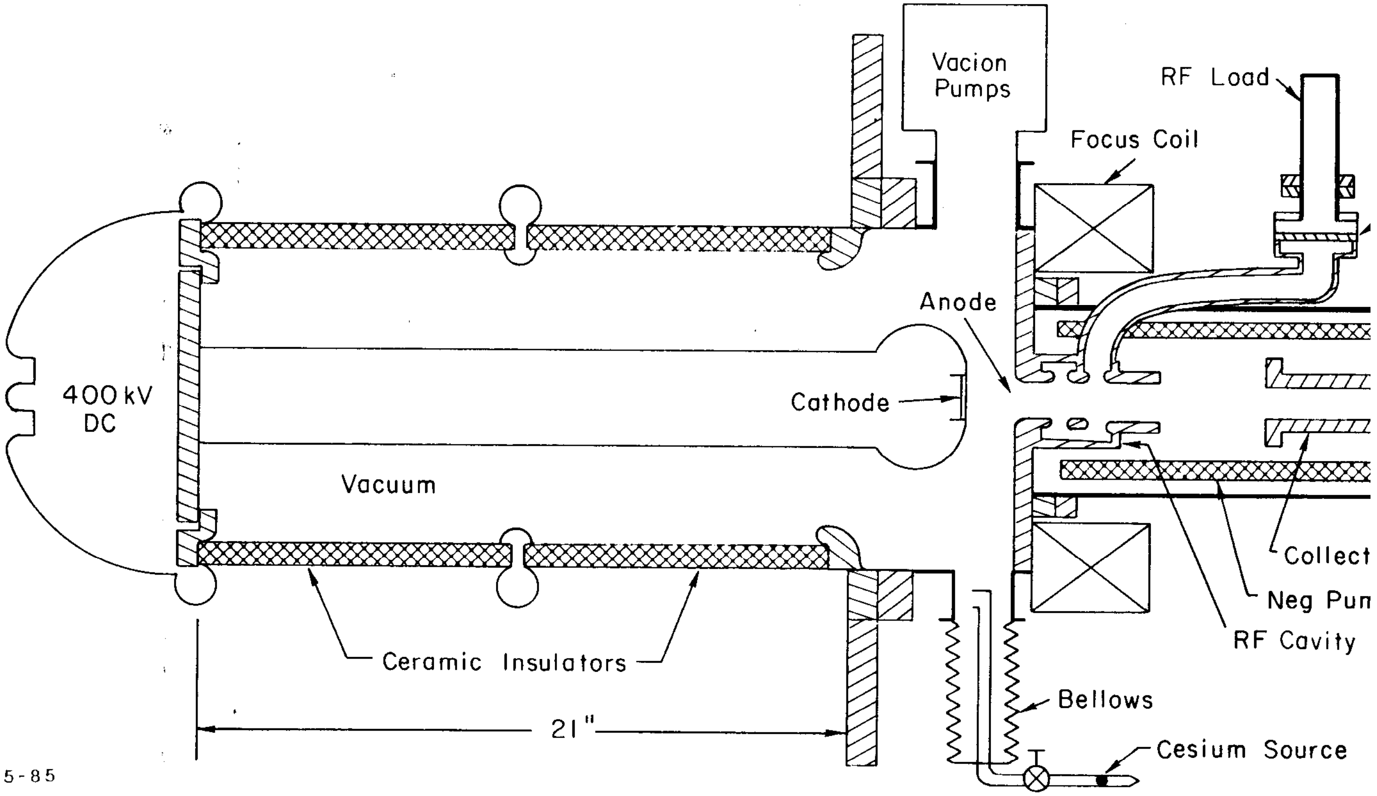

Fig. 1. A schematic view of the SLAC lasertron.

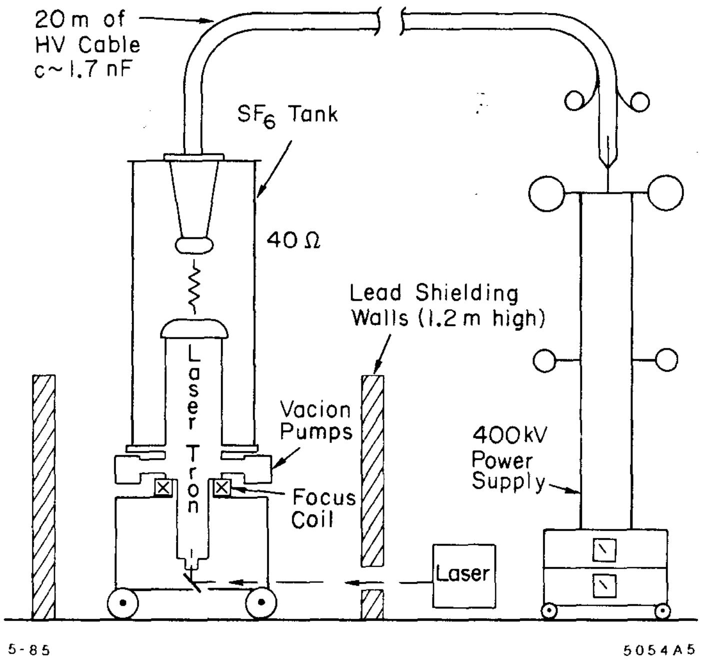

Fig. 2. The lasertron proof-of-principle experimental setup.

frequency is readily available. Furthermore, it will be feasible to have the developmental lasertron actually power a section of SLAC accelerating structure.

The microwave output power and efficiency were chosen at a level deemed impressive but still within the confines of a reasonable first effort. No microwave power source at this frequency and power level has ever approached the 70% efficiency level. The microwave pulse length is comparable to the SLAC structure filling time, and is reasonable for the laser to provide. It is likely longer than what would be required at higher frequency.

The cathode voltage is that obtainable from an inexpensive, air insulated voltage multiplier power supply. The cathode current density is about half that which we have already demonstrated with a high current test gun.[3] We are employing GaAs cathodes initially, but similarly large current densities have been reported for other types of photocathode, particularly the common and readily fabricated Cs_3Sb[4].

A flat cathode with a high, nearly uniform electric field is necessary to limit debunching, which would reduce the beam power to RF conversion efficiency. We chose a field on the photocathode of 10 MV/m. The highest field on the cathode electrode structure is somewhat less than 15 MV/m. These fields are somewhat higher than common practice, but we believe that we can operate with these fields through a choice of high quality electrode material and careful fabrication techniques. We have reliably processed several sets of large area electrodes to fields of about 45 MV/m in a test system, though the interelectrode

Table 1. Parameters of the proof-of-principle lasertron.

MICROWAVE FREQUENCY	2856 MHz
MICROWAVE PULSE LENGTH	0.3 to 1.0 microseconds
MICROWAVE OUTPUT POWER	35 MW
EFFICIENCY	$> 70\%$
CATHODE VOLTAGE	400 kV D.C.
BEAM POWER DURING PULSE	50 MW
AVERAGE BEAM CURRENT DURING PULSE	125 A
PEAK CATHODE CURRENT	750 A
MICROPULSE DURATION	60 picoseconds
CATHODE AREA	7 cm^2(3 cm dia)
CATHODE LOADING	108A/cm^2 instantaneous 18 A/cm^2 average during pulse
CATHODE ELECTRIC FIELD	10 MV/m
PEAK ELECTRIC FIELD	< 15 MV/m
MAGNETIC GUIDE FIELD	2000 gauss
VACUUM	10^{-10} torr, nominal

gap for these tests was only 2 mm, rather than the 4 cm of the actual lasertron. In addition, it is well known that certain coatings can reduce the pre-breakdown currents by several orders of magnitude. We have been studying the use of diamond-like carbon coatings in this application, and the early results are very promising. It may be possible to eliminate the need for high voltage processing at the field strengths used in the lasertron by this technique, and a cathode electrode to test this hypothesis will be fabricated soon.

It is worth noting that since the electron bunch is significantly shorter than the anode-cathode gap, conventional ideas about space charge limited flow, perveance, and Pierce type electrode structures do not apply. In fact, Pierce type electrode geometry is detrimental to the bunch length. The beam instead must be transversely constrained by an external solenoidal magnetic field.

The goals of the proof-of-principle experiment are to demonstrate high efficiency RF power production, and to show that the cathode can survive with a reasonable lifetime in the operating vacuum environment of a high power device. Ultimately, we expect to compare the actual performance of the lasertron with computed performance generated by the program MASK over a wide range of operating conditions. This comparison should allow confident extrapolation to future, more interesting lasertrons.

THE LASER SYSTEM

A laser system to produce an optical pulse train with the required microwave structure is not, as such, commercially available. However, a reasonable synthesis of demonstrated laser techniques can satisfy our requirements. The parameters of the laser system for the proof-of-principle experiment are given in Table II. These parameters are a reasonable match to both current photocathode performance and to the microwave goals of Table I.

A system meeting the specifications of Table II is under construction for us by the XMR Corporation. It employs a CW mode-locked Nd:YAG oscillator to produce a continuous train of narrow (80 - 90 psec) infrared optical pulses. A single one of these pulses is selected and injected into a regenerative amplifier with a cavity length chosen to produce an optical pulse comb at 357 MHz. The amplitude and width of the pulse comb produced are controlled by an electronically programmed Pockels cell polarization rotator. The 357 MHz pulse train, up to one microsecond in length, is amplified further in a power amplifier. Following this, the infrared beam is frequency doubled into the green (532 nm) and passed through an 8-fold optical multiplexer to produce the final 2856 MHz pulse train.

Table 2. Parameters of the laser system for the lasertron proof-of-principle experiment

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1. Pulse Train of 60 psec Wide Pulses at a 2586 MHz Rate.
2. Pulse Train Width Variable Between 0.3 and 1.0 μsec.
3. Wavelength - 532 nm.
4. Spectral Analysis:

   Δf of 2856 MHz Peak $\leq$ 25 MHz.

   Sidebands Down $\geq$ 15 db from Central Peak.
5. Energy in 1 μsec Pulse Train $\geq$ 15 mj.
6. Pulse to Pulse Energy Variation $\leq$ 5% RMS Over 1 Hour Period.
7. 60 Hz Repetition Rate.

The most difficult aspect of this laser system is the generation of the long, uniform amplitude pulse comb from the regenerative amplifier. The 8-fold multiplexing proved to be straightforward. The alignment of this multiplexer is done by observing the output beam with a fast photodiode and a spectrum analyzer. The individual optical delays and amplitude division components are then each tuned to eliminate sidebands on the central peaks at 714, 1428, and 2856 MHz. The spectral purity of the optical pulse comb is better than that required by the relatively low loaded Q of the lasertron output cavities.

The total optical output energy of 15 mj per one microsecond pulse comb is sufficient to produce the full microwave output power with a photocathode of 2% quantum efficiency, well below the standard for either GaAs or Cs_3Sb photocathodes. Were it necessary, an additional increase in output energy by a factor of 1.8 would be feasible from this laser by adding a second frequency doubling crystal and beam combining optics. Increasing the repetition rate of this laser to 180 Hz involves only the addition of power supplies.

While the 60 psec micropulse width from the laser is adequate for production of S-band microwaves, a shorter pulse is required for higher microwave frequencies. Micropulses of duration 15 - 20 psec may be prepared by flattening the gain spectrum of the Nd:YAG oscillator with an intracavity etalon.[5,6] Even shorter pulses may be prepared with fiber - grating optical pulse compressors.[7] It would appear that extension of the existing laser system to operation at X-band frequencies is indeed practical.

The laser system represents by far the most expensive aspect of the lasertron project. For a multiple RF source installation as would be required for a real accelerator, the laser cost per RF source would be dramatically reduced. One would, in this case, employ a single very high quality oscillator, and select a small portion of this output to be amplified, frequency doubled, and multiplexed at each RF station. Depending on the overall economics of this situation, one might elect to amplify and double a fully multiplexed oscillator output. In either of these schemes, the phase stability from RF station to RF station is easy to maintain.

PHOTOEMISSION CATHODE STUDIES

Well before the start of the lasertron proof-of-principle experiment, we have had a program to learn to prepare long lived, high current density photoemission cathodes. Our efforts have concentrated on negative electron affinity (NEA) GaAs photocathodes for several reasons. These cathodes offer a very high quantum efficiency, and they can be restored in situ many times, without breaking the vacuum. They can be fabricated as part of a cold cathode assembly making it possible, in principle, to make electrically modulated, rather than optically modulated, cathodes. Finally, we have had a great deal of experience with this cathode type from our work on polarized electron sources. Other photocathodes might be used in a lasertron as well. The common cesium antimonide cathode (Cs_3Sb) is perhaps the most obvious candidate, and it has the advantage of somewhat lower sensitivity to the vacuum environment than the NEA cathodes. NEA photocathodes have been most recently reviewed by Escher.[8]

At SLAC, we have resurrected a different method for the fabrication of NEA GaAs photocathodes with excellent results. This process,though published and patented,[9,10] has been widely neglected by manufacturers of NEA cathodes, for reasons not entirely clear. Conventional NEA cathodes are prepared by exposing an atomically clean semiconductor surface to monolayer quantities of cesium and oxygen. The process we are using employs cesium and nitrogen trifluoride, the latter serving as a source of fluorine. Using this Cs plus NF_3 process, we have prepared cathodes with lifetimes under continuous, low level illumination exceeding our measurement capabilities, or greater than 10^4 hours. We have compared the sensitivity of Cs-NF_3 cathodes and Cs-O_2 cathodes to measured exposures of pure gases which are common residual gases in UHV systems, *e.g.*, CH_4, CO, and CO_2. Typically the Cs-NF_3 cathodes are an order of magnitude less sensitive to such exposures than the Cs-O_2 cathodes. Both cathodes are quite sensitive to CO_2 exposures, and it is worth noting that the system in which the long lived cathodes were prepared had an exceptionally low level of CO_2.

Exactly why the NF_3 cathodes are more stable than the O_2 ones is not clear, but several points may be made. First, cesium forms only one compound with fluorine, CsF, while there are a number of suboxides of cesium known as well as the common Cs_2O. The formation of these suboxides is known to be important in the formation of photocathodes.[11] Secondly, the gas O_2 is very reactive, and sticks readily to most surfaces in a clean UHV system. NF_3 by contrast is basically inert at room temperatures, though it is readily cracked and thus pumped by ion pumps. In the presence of cesium, NF_3 loses a fluorine atom to form CsF. One might imagine that the introduction of NF_3 into a cathode preparation chamber results in the formation of CsF in areas where cesium is present, and that otherwise the inert gas is simply pumped away. With oxygen introduction, one or more of the cesium-oxygen compounds are formed in the areas with cesium present, and the active oxygen molecules stick to any other areas in the vacuum system. Over the long term, this captured oxygen is able to be desorbed and reach the cathode, where it causes deterioration. While hypothetical, this model is the one proposed in the patent of the Cs-NF_3 process, and is consistent with our results.

The cathode of a lasertron operating as an RF power source for an accelerator would have to supply on the order of 10^7 coulombs per year of operation. The delivery of such a large total charge from a photoemission cathode has never been demonstrated. Never-the-less, there is no good reason to presume that the act of emitting electrons does anything to degrade the photocathode.

A small UHV system to test the ability of our photocathodes to deliver large total charges at average currents and current densities exceeding those of the proof-of-principle lasertron has been constructed.

This system uses a CW argon-ion laser, and is capable of delivering over 100 mA continuously over long periods of time. To date, this system has been used only in short runs of a few coulombs total delivered charge, with no detectable photocathode degradation. Minor modifications are necessary to enable the system to operate at its full ratings, and this is planned for the near future. The absence of noticeable degradation in delivering even a small number of coulombs indicates that many hundreds of coulombs should be deliverable, a number substantially exceeding the performance reported for any photocathode. We expect any degradation associated with emission from the cathode is due to gases desorbed by the electron beam, rather than any process occurring in the cathode surface itself.

COLLECTOR MATERIAL DESORPTION TESTS

One of the most prominent sources of potentially damaging residual gases in the lasertron is electron stimulated desorption from the surfaces of the spent beam collector. It was suggested to us that a collector surface of non-evaporable getter (NEG) material might well have a lower desorption than the conventional collector material, OFHC copper. Since the NEG layer might be very thin (25 to 100 microns) the collector would be expected to have all of the thermal properties of the underlying copper.

To test this idea, we constructed a small UHV system to measure the electron induced desorption from a small area sample. The operating conditions were chosen to closely approximate the actual operating conditions in the proof-of-principle lasertron. As noted earlier, CO_2, and to a lesser extent, CO, were found to be the most harmful gases to the cathode, so our measurements concentrated on these gases.

Two different samples of NEG coated OFHC copper,[12] and two samples of the highest quality vacuum degassed OFHC copper were measured. This latter material is used in the collectors of the SLAC klystrons for the SLC. The results, presented in Figs. 3a and 3b, for desorption of CO and CO_2, respectively, indicate quite clearly that the NEG coated material has superior gas desorption characteristics. The first lasertron collector has already been fabricated with OFHC copper, but a second unit is being fabricated for coating with the NEG material. This NEG coated collector will be used in later work with the lasertron. If these initial results continue to hold true, this type of beam collector will be important for conventional microwave tubes with thermionic emitters as well as for lasertrons. This work is discussed in more detail elsewhere.[13]

COMPUTATIONAL RESULTS

An extensive series of computations has been completed, using the program MASK, to simulate the performance of the lasertron. The MASK program is

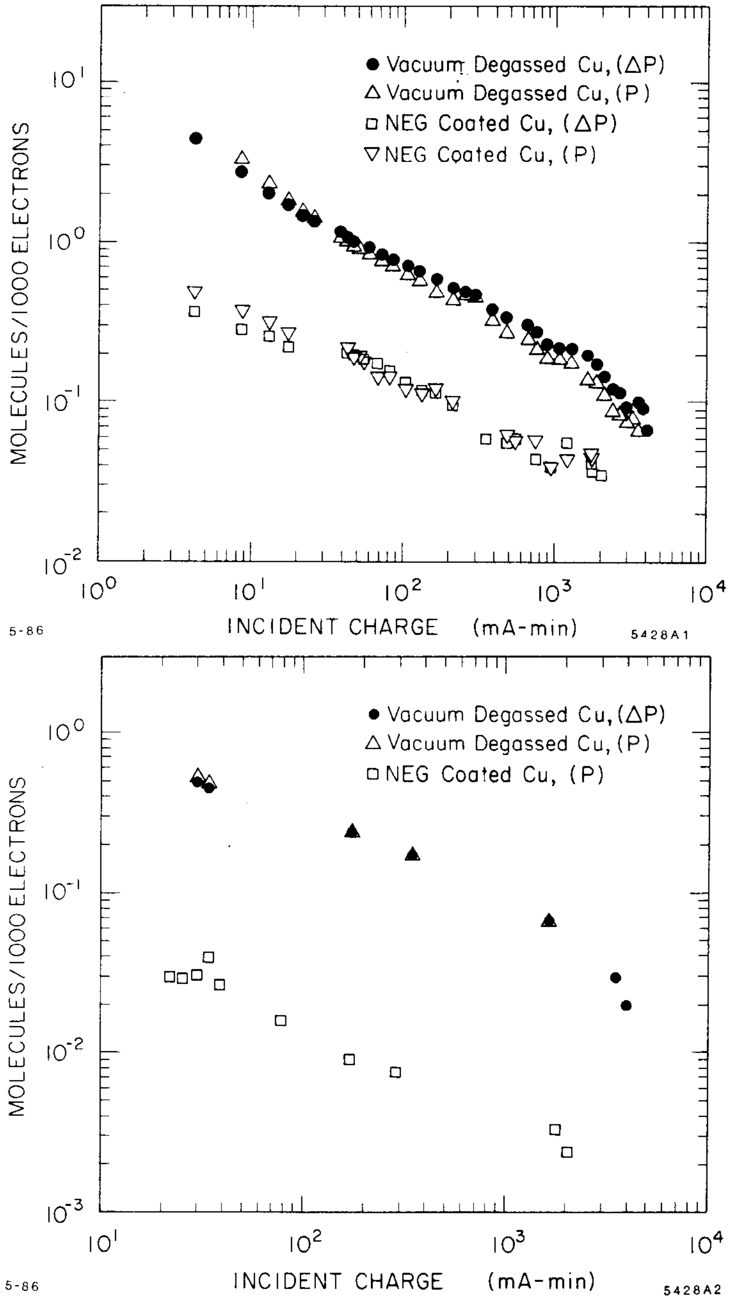

Fig. 3. CO and CO_2 desorption from NEG coated copper and vacuum degassed OFHC copper.

a fully relativistic particle-in-cell code for following charged particle motion in electromagnetic fields. In our case, the fields and boundaries are restricted to having axial symmetry, while the charged macroparticles are moved in three dimensions, leading to the description of the MASK program as "$2 + 1/2$ dimensional." While the program could in principle follow each electron burst from the cathode through the output structure and calculate the build up of the RF fields to steady state, the so-called port approximation is often used to shorten the computation time. In this procedure, assumed RF fields are imposed across a gap to represent the cavity, and an iterative procedure is used to determine the steady state operating conditions. The port approximation has been found to give results in good agreement with the measured behavior of SLAC high power klystrons.[14] In addition, for the case of a single gap output cavity on the lasertron, the full computation allowing the fields to build up to steady state has been done, and compared with the results from the port approximation. The agreement was again very good.

While a major goal of the proof-of-principle experiment is to compare the lasertron performance with the computational results over a range of operating parameters, our initial computations have been done to explore lasertron parameters to reach a reasonable device design. Many calculations were done for the basic 400 kV lasertron gun driving either a single or double gap output structure. While it appears possible to approach the goals of the proof-of-principle experiment with a single gap cavity, the double gap cavity clearly provides a higher efficiency over a broader range of experimental parameters. It appears possible to keep the efficiency above 70% with a beam power well above the 50 MW planned for our first lasertron, using the double gap output cavity.

The effects of varying the beam voltage and the laser micropulse width have also been calculated for both the single and double gap cavity cases. As expected, both higher beam voltage and shorter micropulse widths give improved performance. Particularly for the case of the double output gap cavity, it appears possible to reach 70% efficiency with somewhat lower beam voltage

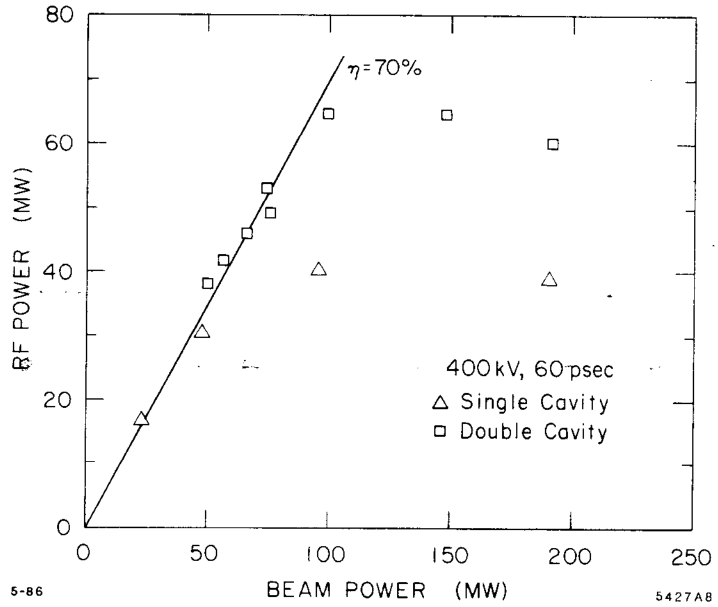

Fig. 4. RF output power versus Beam Power with single and double gap cavities.

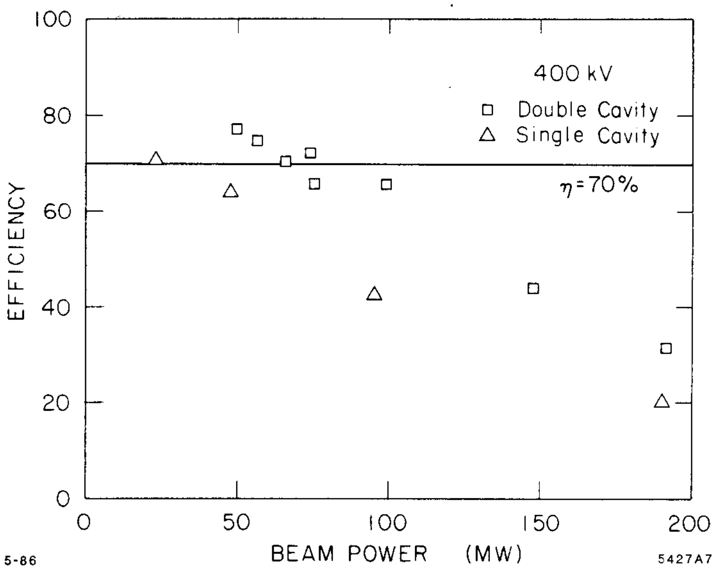

Fig. 5. Efficiency with single and double gap cavities at 400 kV.

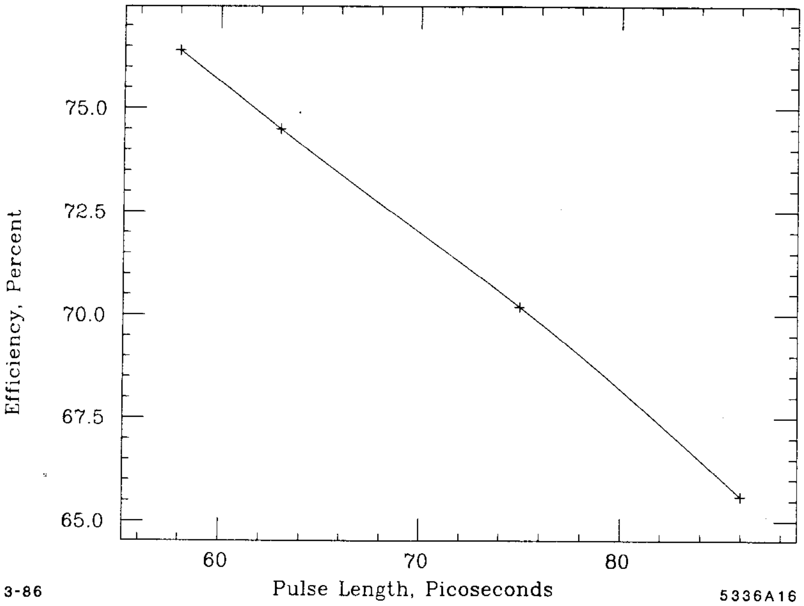

Fig. 6. Efficiency with a double gap cavity as a function of laser micropulse length.

and somewhat longer micropulse width. Some of these results are presented in Figs. 4 through 7. All of these results are part of a much larger body of computations done by Welch,[15] Eppley,[16] and Herrmannsfeldt.[17]

As the general results are far more favorable with a double output gap cavity, an optimized double gap cavity has been incorporated into the lasertron design. Similar double gap cavities have been demonstrated to improve the performance of high power klystrons by over 18%, though in the case of the lasertron the improvement is more like 10%. There are a number of reasons why the double output gap improves the performance, but basically the first gap extracts a fair fraction of the RF power while improving the bunch entering the second gap.

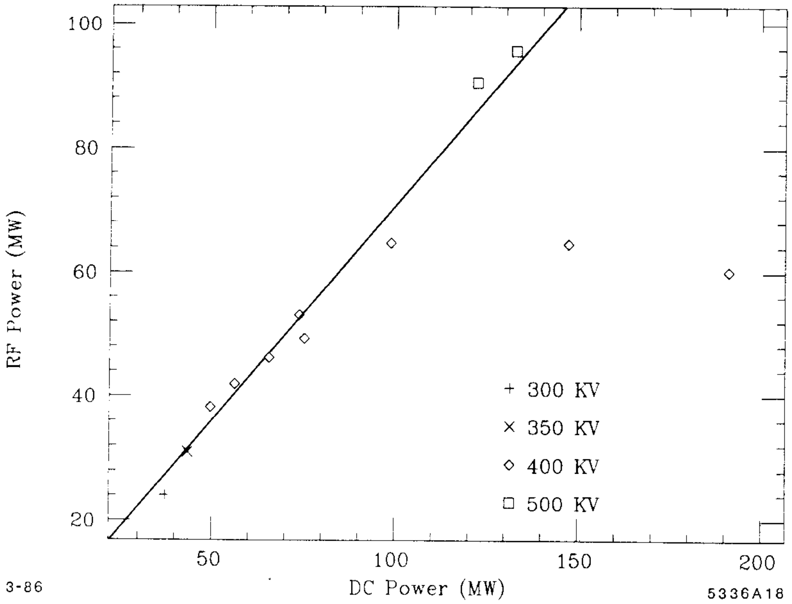

Fig. 7. RF output power versus beam power with a double gap cavity, for various beam voltages.

We will be able to vary the beam voltage, the laser micropulse width, and the beam power at fixed beam voltage over limited ranges with the first lasertron, and thus will be able to verify the computational predictions for the proof-of-principle lasertron. As there are several small effects which are not included in the calculations (*e.g.*, dissipation in the 40 ohm resistor, beam voltage variation during the beam pulse, etc.) it is important to study the efficiency variation with changes in the operating parameters.

CURRENT STATUS AND SCHEDULE

At the present time (early October, 1986) the proof-of-principle lasertron has been assembled as a diode, i.e. the complete UHV system with the photocathode electron gun, the external beam containing solenoid, and the collector. The initial assembly, lacking only a few small components, was baked in a vacuum oven to 450 C. Subsequent bakeouts have been in air at 250 C. Currently after a 250 C bakeout the ultimate pressure is 2×10^{-11} torr, as measured by a nude Bayard Alpert gauge in the cathode-anode gap region. The residual gas spectrum shows only small peaks of H_2 and CO, at levels which should not be detrimental to good photocathode lifetime. The NEG pumps surrounding the beam collector are sufficiently activated by the 250 C bakeout that no further activation is required.

The diode has been processed to 400 kV with a series resistor of 10^9 ohms, and to somewhat lower voltages with a 10^4 ohm series resistor, before the introduction of cesium for cathode activation. A number of cathode activations have been made on several GaAs wafers. The highest quantum efficiency achieved to date in this system is 3.5%. This level, though well below what we have obtained on smaller wafers in other UHV systems, is well above the level required to reach the full performance goals of the proof-of-principle experiment. It should also be noted that these are the largest GaAs photocathodes prepared to date. Currently both the cathode activation process in the lasertron vacuum system, and the high voltage processing after cesium introduction are being studied in some detail with the assembled diode.

Small continuous beam currents produced by a 2 mW He-Ne laser, and larger pulsed currents from a frequency doubled, Q-switched Nd:YAG laser, have been produced. While the average current in each of these cases is only a few microamperes, a number of coulombs have been delivered to the beam collector. On the basis of these results, it does not appear that there is any difficulty from charge buildup on the laser entrance window, which is in a direct line with the electron beam. It should be noted that without the RF cavity installed, the beam striking the collector is at the full gun voltage.

The laser has yet to be delivered, and is several months behind schedule. It has yet to produce a sufficiently stable flat-topped one microsecond long pulse comb. As a number of laser systems have been built which meet this specification, the problem is not fundamental. Aside from this difficulty, the laser has met all of its other specifications in laboratory operation, and has operated stably and continuously for extended periods in the manufacturer's lab, leading us to anticipate an ultimately reliable and stable system.

A double gap output cavity was designed to provide the optimum impedances specified by the MASK runs. After cold testing and some minor modifications, the cavity came very close to the optimum parameters. The initial cold testing was done with a full height output waveguide, while the actual cavity will have to drive a half-height waveguide for space reasons. The final cavity assembly with half height waveguide will be once again cold tested before final assembly on the lasertron.

We anticipate that the RF cavity will be completed and ready for installation sometime in November, and we hope to have laser delivery by that time. If this proves to be the case, we should be able to begin RF testing very late this year, or very early in 1987.

ACKNOWLEDGEMENTS

My very able collaborator in this work, Jim Welch, has made essential contributions to virtually every aspect of this program. Tim Siggins has provided exceptional assistance with the UHV work, the photocathode studies, and the setup and operation of the lasertron laboratory. Bill Herrmannsfeldt and Ken Eppley have done a large part of the computational work. Terry Lee did the design and cold tests on the double gap output cavity. The XMR Corporation, of Santa Clara, CA, has worked very hard to produce the laser system. The encouragement and support of Matt Allen, Ed Garwin, Kaye Lathrop, Burt Richter and Perry Wilson has been much appreciated. Dave Sutter of DOE has maintained a continuous interest in this work, and provided very substantial additional support for the purchase of the laser. Finally, the support of the SLAC machine shops, Vacuum Group, and Physical Electronics Group has been invaluable.

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