SLAC – PUB – 3890REV
December 1986
(A)

THE MICROLASERTRON*

AN EFFICIENT SWITCHED–POWER SOURCE OF MM WAVELENGTH RADIATION

R. B. PALMER

Stanford Linear Accelerator Center, Stanford, CA 94305
and
Brookhaven National Laboratory, Upton, Long Island, New York 11973

ABSTRACT

An extension of W. Willis' *Switched Power Linac* is studied. Pulsed laser light falls on a photocathode wire, or wires, within a simple resonant structure. The resulting pulsed electron current between the wire and the structure wall drives the resonant field, and *rf* energy is extracted in the mm to cm wavelength range. Various geometries are presented, including one consisting of a simple array of parallel wires over a plane conductor. Results from a one-dimensional simulation are presented.

INTRODUCTION

The radio frequency power that can be generated by a lasertron is bounded by the beam power, *i.e.*, by the average current times the applied anode voltage. If a suitable cathode can be found then this average current is limited only by space charge considerations. In a simple diode the maximum charge per area (q_{sc}) that can be taken from the cathode is

$$q_{sc} = \epsilon_o \, \mathcal{E} \tag{1}$$

where $\mathcal{E}$ is the accelerating field. The transit time τ to cross a gap g is

$$\tau = \left(\frac{2m}{e}\right)^{1/2} \left(\frac{g}{\mathcal{E}}\right)^{1/2} . \tag{2}$$

Since we cannot start another charge until the first has crossed the gap (if we did, then Eq. (1) would not be valid), the maximum average current per unit area is q_{sc}/τ and the maximum power output is

$$P_{max} = \frac{q_{sc}AV}{\tau} = A\epsilon_o \left(\frac{e}{2m}\right)^{1/2} \mathcal{E}^{5/2} \, g^{1/2} \tag{3}$$

thus there is a strong motivation for using high accelerating fields $\mathcal{E}$.

* Work supported in part by the Department of Energy, contracts DE-AC03-76SF00515 (SLAC) and DE-AC02-76C#0016 (BNL).

Invited talk presented at the Symposium on Advanced Accelerator Concepts, Madison, Wisconsin, August 21-27, 1986

The maximum fields that can be sustained continuously in a vacuum are only of the order of 100 KV/cm (10 MV/m). But for short pulses and small gaps very much higher fields can be obtained. For instance, Warren et al.[3] have reported fields of 160 MV/m across a 1 mm gap for 5 nsec pulses, and Jüttner et al.[4] report 3,000 MV/m across 27 μ for 1 nsec pulses.

The pulse length required for a linac, fall as the wavelength to the 3/2 power; so for short wavelengths long pulses are not required. For instance, at a wavelength of 6 mm the "natural" fill time of an accelerating cavity is only of the order of 5 nsec and thus fields of 100 MV/m could be employed across a gap of the order of 1 mm, without breakdown.

Applying such a field to Eq. (1) implies a maximum power output of the order of a GW per cm^2 of cathode (compared with approximately 10 MW/cm^2 for conventional fields and gaps). This high power per unit area would, however, be offset by the small natural beam area in a lasertron designed for short wavelengths. What is needed is a lasertron design for which the total beam area does not fall with the wavelength. It is the solution to this problem that this paper addresses.

The genesis of the idea is the proposal by Bill Willis[1] for a *Switched Power Linac* (see Fig. 1). In this idea a single burst of electron current is switched by a single pulse of laser light. That burst as it crosses a circumferential gap generates a pulse of electromagnetic radiation which is focussed by the cylindrical geometry and used to accelerate particles on the axis.

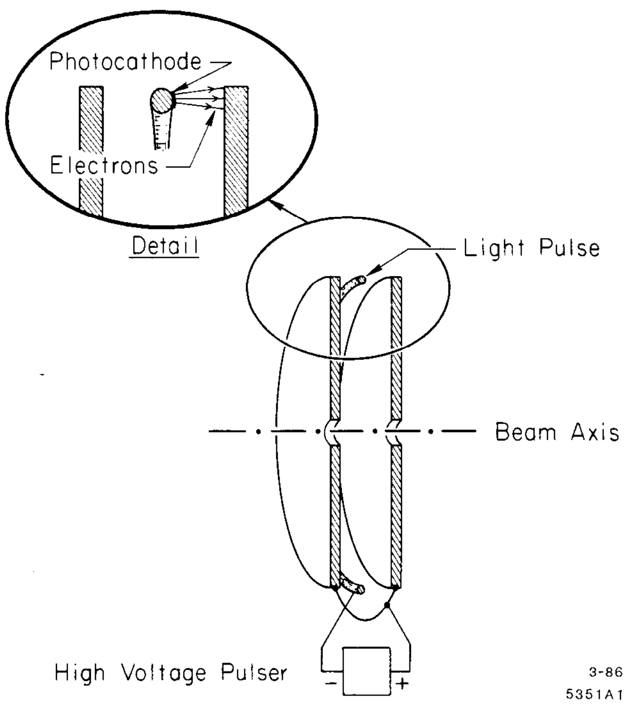


Fig. 1. Switched power accelerator concept as proposed by W. Willis (Ref. 1).

In the present proposal, the same concept is used, except that a train of light pulses is employed, and these are used to excite fields in a resonant cavity (see Fig. 2).

However, unlike in the lasertron, the acceleration of the electron by a dc field, and their deceleration by an RF field is accomplished in a single gap. It is this simplification that allows a multiple linear geometry in which the total photocathode area can remain large even as the wavelength becomes very small.

DESCRIPTION

The basic concept is represented (Fig. 2) by a long, vacuum-filled rectangular cavity with a wire passing down the center. The wire is held at a high potential relative to the enclosure. By illuminating a photocathode on one side of the wire, electron bursts are allowed to pass from the wire to one wall of the box. Repeated pulsing of the photocathode at the cavity resonant frequency results in the excitation of a transverse electric mode within the cavity. Energy can then be extracted by coupling the cavity to a waveguide.

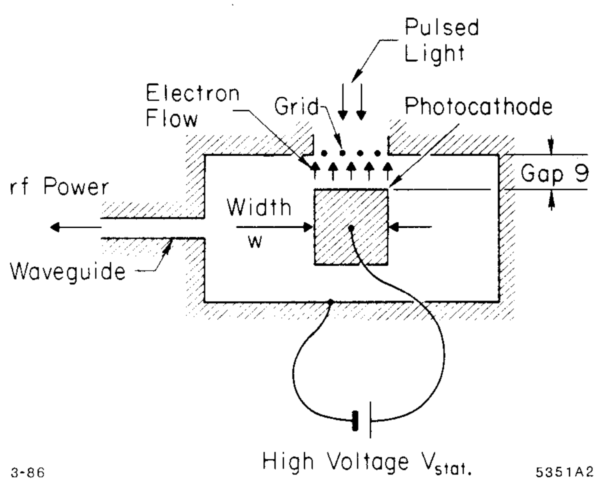


Fig. 2. Microlasertron concept as discussed here.

This simple concept may be compared to that of the lasertron (Fig. 3) in which the pulsed photocathode is used to generate a bunched accelerated beam. The energy is then extracted as the beam is decelerated passing one or more ring cavities. Since the beam's kinetic energy will be lost when it hits the anode, high efficiency is only obtained if the beam is decelerated to as near rest as possible.

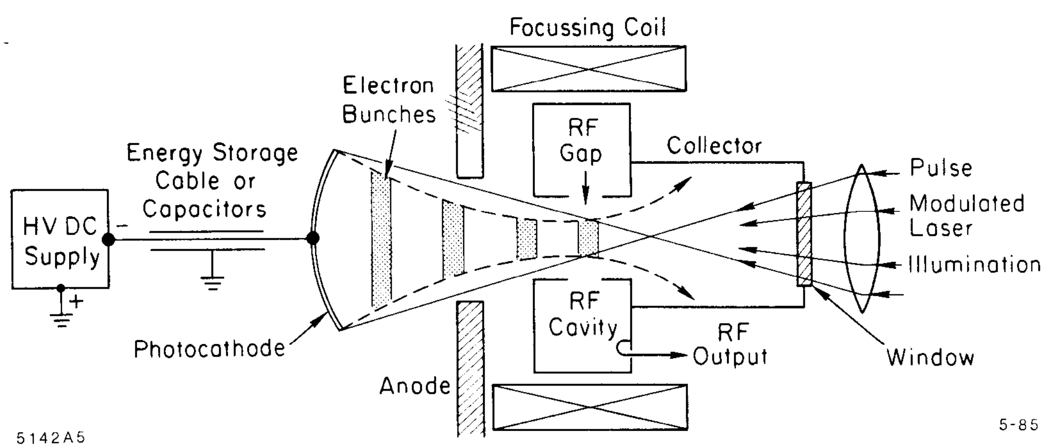


Fig. 3. The conventional lasertron concept.

In the microlasertron, the acceleration and deceleration occur within the same gap. High efficiency is again obtained when the electrons are brought nearly to rest as they arrive at the anode. But the processes of acceleration and subsequent deceleration are controlled by the phase of the field rather than the position along the beam.

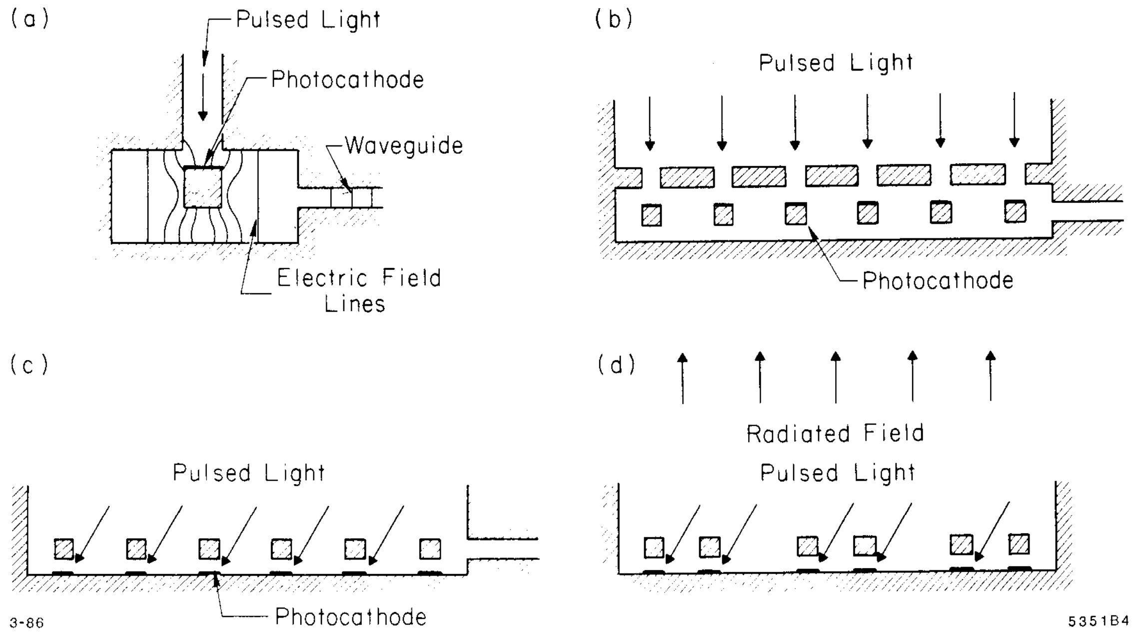


Fig. 4. Realizations of the microlasertron: a) single cavity, b) multi cavity, c) grating cavity, d) modification to grating cavity to couple to outgoing wave.

The grid indicated in Fig. 2 may not be practical in a short wavelength realization of the idea. One finds, however, that the grid can be omitted so long as a relatively deep slot is enclosed between conducting walls (see Fig. 4a). An extension of this idea has an array of parallel wires under a single slotted cover (see Fig. 4b). In this case we find that the slots do not need to be deep. A drive frequency is chosen so that the distance between wires is approximately one half wavelength and the light pulses entering alternate slots we arranged to be 180° out of phase. At all finite angles radiation from the slots cancel. Even in the direction parallel with the plane the fields do not sum because the loading from the wires causes the phase velocity in the cavity to be less than the speed of light. Fields leaking through the slots will also have a phase velocity less than the speed of light and will thus be evanescent waves, falling exponentially from the slotted wall.

The above observation leads to a further extension of the idea (see Fig. 4c). Now the upper cover of the cavity has been removed, the photocathodes placed on the remaining surface and the pulsed light brought down at an angle between the wires. Again, because of the presence of the wires, the phase velocity along the surface is less than the speed of light, and the field excited will be evanescent, falling exponentially from the surface.

As in the single wire case, electromagnetic energy could be taken out of the multiwire cavities by coupling them to waveguides. However, it is possible, and perhaps more convenient, to arrange that they couple to plane parallel waves emanating from the surface. In case of Fig. 4c, this can be achieved by disturbing the periodicity of the wires (see Fig. 4d).

In the above discussion we have not mentioned how the cavities would be ended at the end of the wire. In order to investigate this question a radio frequency model was made at a wavelength of 5 cm. It was found that if the cathode plane was terminated well before the wire ends (see Fig. 5) then the fields were effectively constrained to the area above this plane and no loss of power occurred along the wires beyond it.

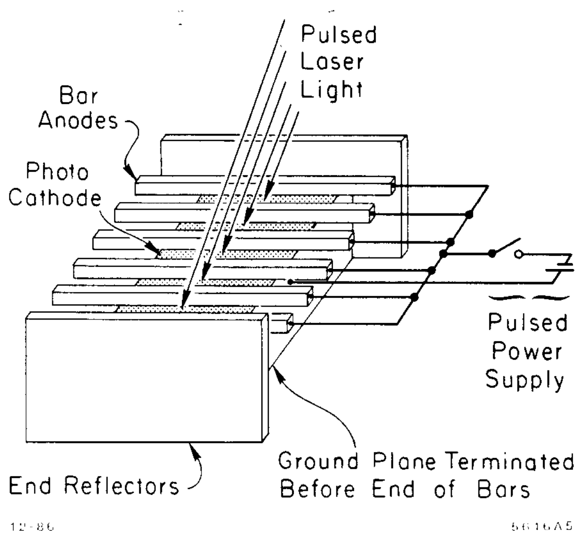


Fig. 5. Microlasertron geometry, including cavity end design.

The attraction of the microlasertron is its simplicity, and thus the possibility of scaling it down to produce very short wavelengths. It also appears from the following analysis that very high powers and efficiencies may be obtainable.

ANALYSIS

EQUIVALENT CIRCUIT

Under the conditions where

$$g \text{ (gap)} \ll w \text{ (gap width)}$$
$$v \text{ (electron velocity)} \ll c \text{ (vel of light)}$$
$$w \text{ (gap width)} \ll \lambda \text{ (wavelength)}$$

then the device of Fig. 2 may be thought of as separate diode gap coupled to a resonant circuit (see Fig. 6).

For our purposes we can think of L_2 as an infinite inductance that allows a dc current i_{DC} to flow from the high voltage supply V_{stat}. C_2 may be thought of as an infinite capacitor that isolates the dc from the resonant circuit.

In the following discussion we will consider an equivalent circuit which will allow us to make approximate calculations of performance. The analysis is strictly applicable only to the plane parallel examples of Figs. 2, 4c and 4d although similar results are probably obtainable for the cases of Figs. 4a and 6.

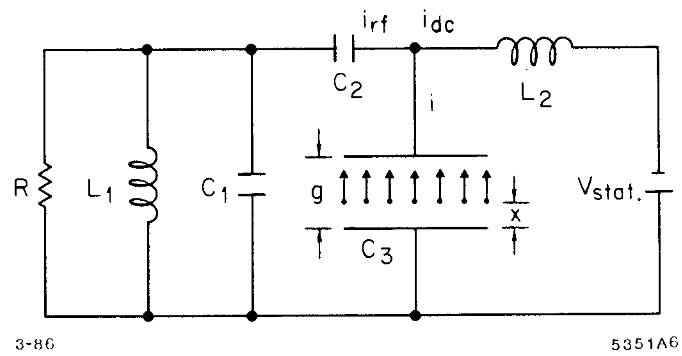


Fig. 6. Equivalent circuit of microlasertron.

The current i may be divided:

$$i = i_{res} + i_v$$

where i_{res} is a resonant oscillatory current associated with the resonant circuit of L_1 and $(C_1 + C_3)$; and i_v which is associated with motion of charges in the gap.

$$i_v = q\ v/g$$

where q is the charge in the gap and v the velocity of that charge across the gap.

With these definitions we have

$$i_{RF} = I_{RF} \sin(\omega t + \theta) + q\ v/g \quad . \tag{4}$$

The voltage V across the gap will again have two components:

$$V = V_{RF} \cos(\omega t + \theta) + V_{stat} \quad . \tag{5}$$

V_{RF} may, of course, vary if there is a net transfer of energy to the system. The energy transferred per cycle will be

$$\Delta E = \frac{\Delta (V_{RF})^2}{Z} = \int_{0}^{\lambda/c} i_v(t) V_{RF} \cos(\omega t + \theta)\ dt \tag{6}$$

where Z is the impedance of the resonant system. The phase θ may also be perturbed. The change in phase per cycle will be:

$$\Delta\theta = \frac{2\pi}{Q} \tan\chi \tag{7}$$

where

$$\tan\chi = \frac{\int_0^{\lambda/c} i_v(t)\sin(\omega t)dt}{\int_0^{\lambda/c} i_v(t)\cos(\omega t)dt} \quad . \tag{8}$$

If driven at the resonant frequency ω_0, then clearly χ must be equal to zero. But if the driven frequency is off the resonance, then we have

$$\omega - \omega_0 = \Delta\theta \cdot \frac{\omega}{2\pi} = \frac{\omega}{Q} \tan\chi \quad . \tag{9}$$

EFFICIENCY

The energy used from the dc source per cycle will be

$$\Delta E_{dc} = \int_0^{\lambda/c} i_v V_{stat}\, dt = q\, V_{stat} \quad ,$$

the difference between this and ΔE_{res}, the energy going into the rf field, is lost as heat in the anode as electrons give with finite kinetic energy. Thus,

$$\Delta E_{dc} - \Delta E_{res} = \frac{q}{2} \frac{m}{e} v_f^2$$

where v_f is the velocity with which the electrons hit the anode, m is the electron mass and e its charge. Thus the efficiency ϵ of transferring energy from the dc source to the resonant circuit is

$$\begin{aligned} 1 - \epsilon &= \left[\left(\frac{mc^2}{e}\right) \cdot \frac{v_f^2}{2\, c^2\, V_{stat}}\right] \\ 1 - \epsilon &= \left[.51\ 10^6\ \frac{v_f^2}{2\, c^2\, V_{stat}}\right] \text{(mks)} \end{aligned} \quad . \tag{10}$$

To get v_f we obtain first the acceleration of a charge in the gap which will be

$$\frac{dv}{dt} = \frac{e}{m}\left[\mathcal{E}_s + \mathcal{E}_{RF}\cos(\omega t + \phi)\right] \tag{11a}$$

where $\mathcal{E}_s = V_{stat}/g$, $\mathcal{E}_{RF} = V_{RF}/g$ and ϕ is introduced as an arbitrary phase so that we can define $t = 0$ as the time when the charge is initially released from the cathode. Integrating Eq. (11a) we obtain the velocity of the electrons at time t:

$$v(t) = \frac{e}{m}\left[\mathcal{E}_s\, t - \frac{\mathcal{E}_{RF}}{\omega}\ \sin(\omega t + \phi) + \frac{\mathcal{E}_{RF}}{\omega}\ \sin\phi\right] \quad . \tag{11b}$$

Integrating again we obtain the distance traveled:

$$x = \int_0^{\tau} v(t)dt = \frac{e}{m}\left|\frac{\mathcal{E}_s t^2}{2} - \frac{\mathcal{E}_{RF}}{\omega^2}\ \cos(\omega t + \phi) + \frac{\mathcal{E}_{RF}}{\omega}\ \sin\phi\right|_0^{\tau} \quad . \tag{11c}$$

Setting $x = g$ in Eq. (11c) will give the transit time $\tau = t$ which when substituted into Eq. (11b) gives the final velocity v_f and thus the energy loss and efficiency using Eq. (10).

LOW RF FIELD CASE

If $\mathcal{E}_{RF} \ll \mathcal{E}_{stat}$, then

$$g \approx \frac{e}{2m}\ \mathcal{E}_{stat}\ \tau_0^2$$

and

$$\tau_0 \approx \left(\frac{2m}{e}\right)^{1/2} \left(\frac{g}{\mathcal{E}_{stat}}\right)^{1/2} \quad .$$

This may be compared with the cycle time λ/c and we define this ratio as:

$$F_\tau = \frac{\tau_0}{\lambda}\ c = \left(\frac{2mc^2}{e}\right)^{1/2} \left(\frac{1}{V_{stat}}\right)^{1/2} \left(\frac{g}{\lambda}\right) \quad , \tag{12a}$$

$$F_\tau = 1.01\ 10^3 \left(\frac{1}{V_{stat}}\right)^{1/2}\ \frac{g}{\lambda}\ \text{(mks)} \quad . \tag{12b}$$

We will continue to use this definition of F_τ even when $\mathcal{E}_{RF}$ is not less than $\mathcal{E}_{stat}$. F_τ then becomes a useful scaling fact or rather than an actual ratio of transit time to cycle.

SHORT TRANSIT TIME APPROXIMATION

If we assume

$$F_\tau \ll 1 \tag{13}$$

then $\omega\tau \ll 1$ and Eq. (11c) reduces to

$$g \approx \frac{e\tau^2}{2m} \left(\mathcal{E}_s - \mathcal{E}_{RF} \cos\phi\right) \tag{14a}$$

and

$$v_f \approx \frac{e}{m}\,\tau\,\left(\mathcal{E}_s - \mathcal{E}_{RF} \cos\phi\right) \quad . \tag{14b}$$

Maximum efficiency is realized if v_f is minimum, *i.e.*, the least kinetic energy is dumped on the anode. This will occur for $\phi = 0$. Referring to Eq. (6) and noting that throughout the transit $\omega t \approx \phi$, we see that this maximum efficiency condition also implies $\chi = 0$, *i.e.*, that the structure is driven on resonance: $\omega = \omega_0$.

So for $\phi = 0$, and remembering that $\tau = F_\tau \lambda / c$ we obtain

$$1 - \epsilon \approx \frac{mc^2}{e} \left(\frac{g}{\lambda}\right)^2 \frac{1}{F_\tau^2\, V_{stat}} \quad , \tag{15a}$$

$$1 - \epsilon \approx 1.02\; 10^6 \left(\frac{g}{\lambda}\right)^2 \frac{1}{F_\tau^2\, V_{stat}} \quad \text{(mks)} \quad . \tag{15b}$$

If for example we chose $\lambda = 6$ mm, $g = .5$ mm, $\epsilon = 50\%$ and $F_\tau = .38$, then we require

$$V_{stat} \approx 50{,}000 \text{ V}$$

and

$$\mathcal{E}_s \approx 100 \text{ M V/m} \quad .$$

Now from the references quoted by Willis,[1] we note that[3] for times less than 5 nsec, voltages as high as 160,000 V have been held over 1 mm—2 mm gaps ($\mathcal{E} = 160$ MV/m) and for times less than 1 nsec,[4] 80,000 volts could be held across a 27 μ gap (3000 MV/m). Thus, although the values of our example are high, they are by no means unreasonable for times less than 5 nsec.

However, the above example assumed an efficiency of only 50%. Higher efficiencies would seem to imply even higher fields. It also assumed a transit time rather long (.38) compared with the cycle time. This hardly satisfies condition (13). Clearly we should calculate the effect of finite transit times.

ONE–DIMENSIONAL SIMULATION

To study this problem for finite transit times, a small computer program was written that would emit and track the electrons as a function of time in the varying fields. Initially, we consider short pulses and ignore space change effects.

WITH SHORT PULSES $\chi = 0$ (ON RESONANCE)

Keeping the driving phase $\chi = 0$, *i.e.*, driving at a frequency equal to the cavity resonant frequency, we calculate the efficiency as a function of the ratio of $\mathcal{E}_{RF}/\mathcal{E}_{stat}$. The results are shown in Fig. 7a for the case where F_τ (defined by Eq. (12)) is 0.38 (*e.g.*, for V = 50,000 v, g = .5 mm). As expected, the efficiency 1) rises as the RF field rises and 2) is somewhat less than that expected for $F_\tau \rightarrow 0$ (dotted line). (Due to the finite transit time, the electrons do not feel the maximum deceleration field over their full transit.) What is surprising however is that the efficiency remains finite even when $\mathcal{E}_{RF}$ is greater than $\mathcal{E}_{stat}$.

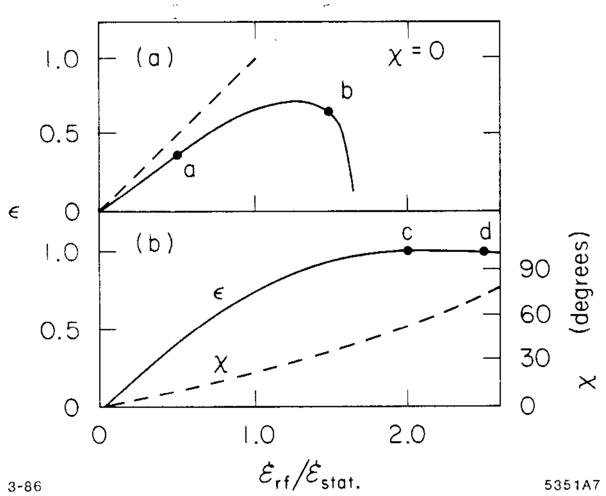


Fig. 7. Efficiency vs. strength of RF field a) for phase advance $\chi = 0$ and b) phase advance adjusted to give maximum efficiency.

If we examine the variation of electron velocity (and thus current) as a function of the RF phase for a case of low RF field (*e.g.*, $\mathcal{E}_{RF}/\mathcal{E}_s = .5$, see Fig. 8a), then we see the velocity rising more or less linearly and hitting the anode at its maximum. This then is much as predicted by Eq. (14b).

For higher values of the RF field the situation becomes more complicated (Fig. 8b for $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.5$). Now the particles are started at a phase when the RF field is helping the static field. The electrons are thus initially accelerated, then decelerated for awhile, and finally accelerated again to arrive at the anode at a phase which again corresponds to the $\mathcal{E}_{RF}$ helping the $\mathcal{E}_{stat}$.

SHORT PULSE DRIVEN OFF RESONANCE

As we noted above (Eq. (7)), it is not necessary to operate at $\chi = 0$. If we drive the photocathode at a frequency ω different from the resonant frequency ω_0, then the stable phase χ is finite. If we adjust ω and thus χ to give maximum efficiency (*i.e.*, minimum arrival electron velocity), then we obtain efficiencies as plotted on Fig. 7b.

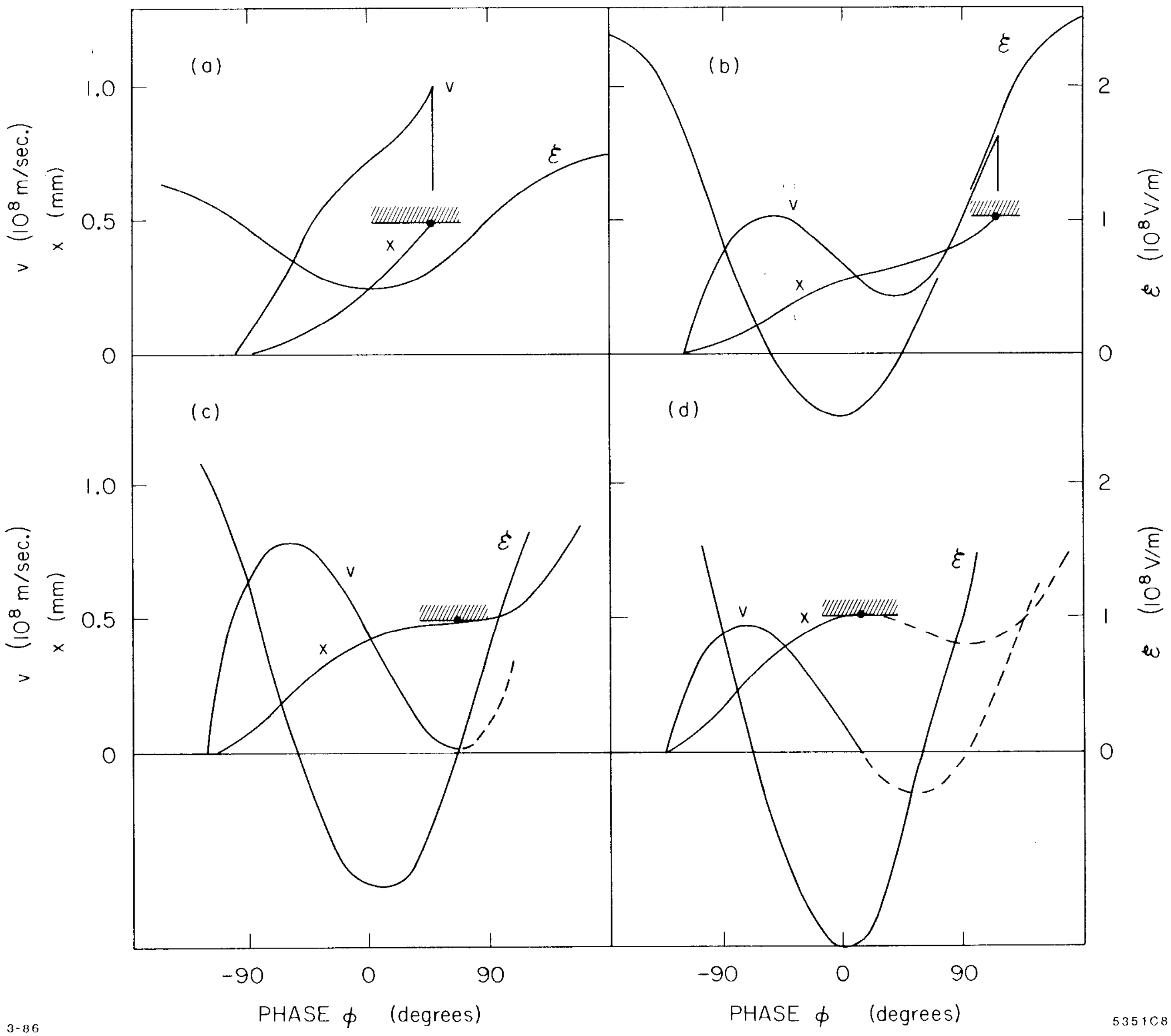
Fig. 8. Motion of electrons in the gap as function of RF phase, with electric field and electron velocity also shown:

a) for $\mathcal{E}_{RF}/\mathcal{E}_{stat} = .5$ and $\chi = 0$;

b) for $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.5$ and $\chi = 0$;

c) for $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 2$ and χ adjusted for maximum efficiency. This represents the 'magic' condition;

d) $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 2.5$ and χ adjusted for maximum efficiency.



Now we observe that efficiencies of a 100% are achieved as $\mathcal{E}_{RF} \approx 2\mathcal{E}_s$. We examine this case in Fig. 8c. The particles are again initially accelerated and then decelerated. The parameters, however, are such that the electrons come to rest just as they arrive at the anode. We note further that for this "magic" case the electrons are not only at rest as they touch the anode but that their acceleration is also zero. This situation should be contrasted with that obtained at an even higher RF field (*e.g.*, $\mathcal{E}_{RF}/\mathcal{E}_s = 2.5$, Fig. 8d). In this case the electrons are also at rest as they approach the anode, but they are at that point being decelerated. An electron that just missed the anode would move away from it and only arrive some time later and at a finite velocity. This is a less desirable operating point than the "magic" one of Fig. 8c.

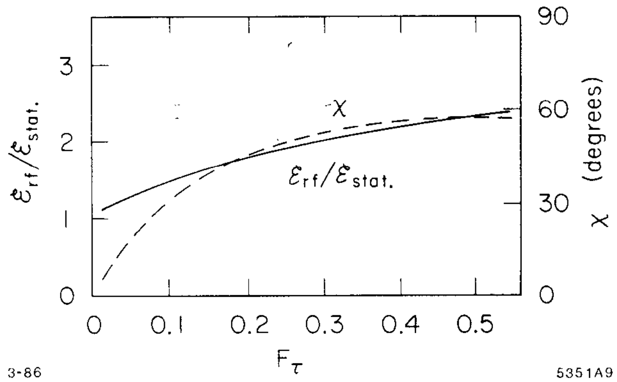


Fig. 9. Values of $\mathcal{E}_{RF}/\mathcal{E}_{stat}$ and the phase advance χ to give the 'magic' condition for different transit time factors F_τ.

All of the above analysis was done for $F_\tau = .38$. We find a different magic point for each value of F_τ and these are plotted on Fig. 9. Remember that F_τ is the fractional cycle time taken for transit in the absence of an RF field. $F_\tau \to 0$ corresponds to very high fields and a small gap. In that case 100% efficiency is obtained at $\mathcal{E}_{RF}/\mathcal{E}_s = 1$ and no phase lag χ is needed. For larger transit times a phase lag is required and larger RF fields are needed to obtain the magic condition. In our following studies we will assume

$$F_\tau = .38 \quad .$$

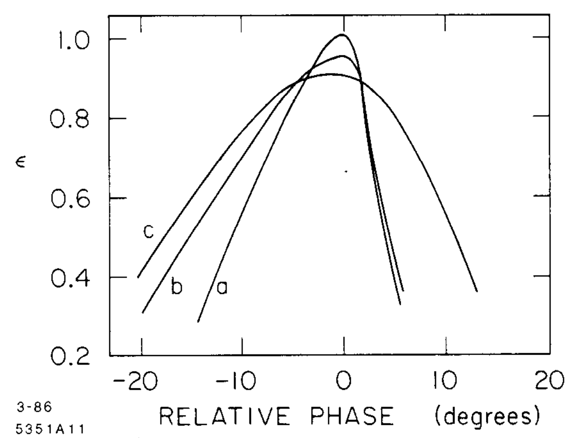


Fig. 10. Efficiency vs. relative phase for a) the magic condition with $\mathcal{E}_{RF}/\mathcal{E}_{stat} =$ 2.0; b) $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.5$; c) $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.0$.

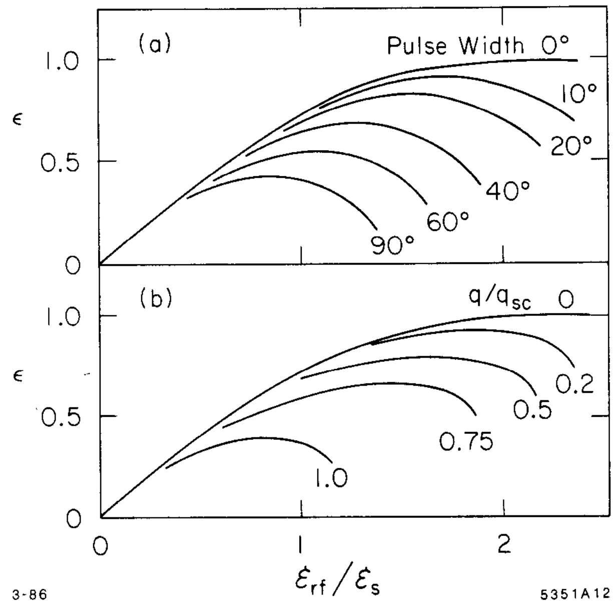


Fig. 11. Efficiency vs. $\mathcal{E}_{RF}/\mathcal{E}_{stat}$ for a) different pulse lengths and b) different ratios F_{sc} of charge q to the space charge limit q_{sc}.

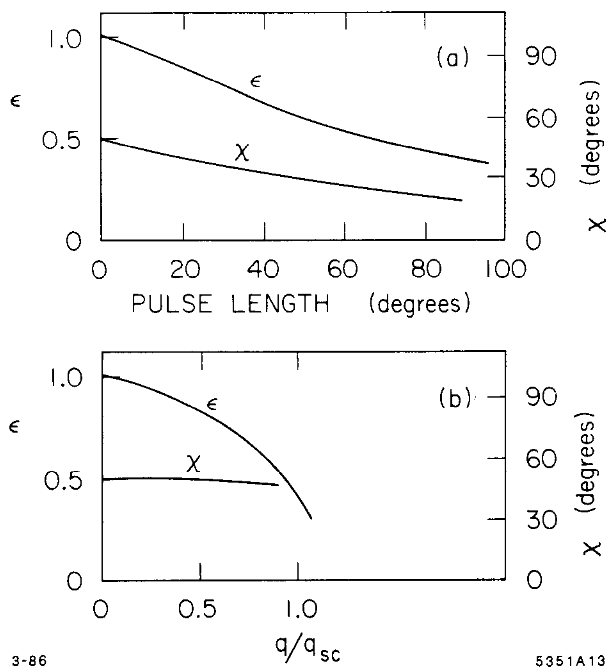


Fig. 12. Maximum efficiencies and corresponding phase advances χ as a function of a) pulse length and b) charge.

condition (Curve a) the variation is very rapid with the efficiency dropping to 50% when the phase is wrong by only $+ 4°$ or $- 10°$ from the magic value. At lower values of the RF field, although the maximum efficiency is less, the sensitivity to phase is weaker (Curves b and c). As a result a plot of efficiency vs $\mathcal{E}_{RF}$ for finite pulse lengths (Fig. 11a) shows maximum efficiencies being obtained at progressively lower values of $\mathcal{E}_{RF}$. Figure 12a shows the maximum efficiencies as a function of pulse duration ($\Delta\phi$) in degrees. For an example we will consider a pulse duration ($\Delta\phi$) of 18°, for which the efficiency would be $\approx 90\%$.

SPACE CHARGE EFFECTS

If a charge density q in coulombs/m^2 exists just above the cathode surface then the induced electric field behind this charge $\mathcal{E}_{sc}$ is given by

$$\mathcal{E}_{sc} = \frac{q}{\epsilon_o}$$

where ϵ_0 is the dielectric constant of free space in mks units ($8.855\ 10^{-12}$).

The maximum charge that can be accelerated with a given static field $\mathcal{E}_{stat}$ is then

$$q_{sc} = \mathcal{E}_{stat}\ \epsilon_0$$

and we define a scale invariant fraction F_{sc}

$$F_{sc} = \frac{q}{q_{sc}} = \frac{q}{\mathcal{E}_{stat}\ \epsilon_0} \quad .$$

Clearly if $F_{sc} \ll 1$ the effect of space charge will be negligible. As F_{sc} increases the earlier charges will be accelerated more and the later charges less than in the small charge case. As a result it again becomes impossible to bring all charges to rest at the anode and the efficiency suffers.

Figure 11b shows the efficiency for different amounts of charge F_{sc} and different $\mathcal{E}_{RF}$. As with the long pulse case, maximum efficiency occurs at fields less than the magic value. Figure 12b shows maximum efficiencies as a function of the charge.

At first it would seem natural to pick a charge of the order of .4 times the space charge limit, for which the efficiency would still remain above 70% even with a pulse length of 18°. Such a large charge however would have two difficulties:

(1) The current density in our example ($V = 50$ KV, $g = .5$ mm, $\lambda = 6$ mm) would be 44 KA/cm^2 which may be excessive.

(2) The instantaneous voltage drop of the wire would be large. In a closed device as illustrated in Fig. 4a or 4b, assuming equal gaps above and below the wire, then the fractional voltage drop would be $q/(2\ q_{sc})$ or 20%. In the open structure case of Fig. 4c or 4d the capacity is only half and the voltage drop would be 40%.

Thus for an example we will chose a somewhat smaller value of q/q_{sc}, such as 0.1, for which the resulting inefficiency is very small.

A POSSIBLE PARAMETER LIST

THE CAVITY

I will consider an open structure of the type illustrated in Fig. 4d, with 1 mm square wires and a total area of 10 cm by 10 cm. For a wavelength of ~ 6 mm the wires would be placed about 2.5 mm apart. Thus there would be ~ 40 wires. The total photo cathode area is about 40 cm^2. I will consider a pulse length of 18° and $q/q_{sc} = 0.1$. I then obtain:

$$
\begin{aligned}
V_{stat} &= 50 \text{ KV} \\
g &= .5 \text{ mm} \\
\mathcal{E}_{stat} &= 100 \text{ MV/m} \\
\lambda &= 6 \text{ mm} \\
\lambda/c &= 18 \text{ p sec} \\
t_{pulse} &= .9 \text{ p sec } (18^\circ) \\
q_{sc} &= 8.8\ 10^{-4} \text{ c/m}^2 \\
F_{sc} &= .1 \\
q &= 8.8\ 10^{-5} \text{ c/m}^2 \\
Q_{pulse} &= 3.5\ 10^{-7} \text{ coulombs} \\
\mathcal{E}_{RF} &= 150 \text{ MV/m} \\
\epsilon &= 80\% \\
\phi &= -130^\circ \\
\chi &= -\ 38^\circ \\
peak\ i_{photo\ cathode} &= 10 \text{ KA/cm}^2 \\
ave.\ i_{photo\ cathode} &= 500\text{A/cm}^2 \\
W_{output} &= .78\ 10^9 \text{ watts} \quad .
\end{aligned}
$$

The time for the microlasertron to fill requires knowledge of both the stored energy in the structure and the average efficiency during the fill, neither of which we have. Rough estimates suggest:

$$\tau_{las\ fill} \approx .8 \text{ nsec} \quad .$$

If this power source is to fill a semi-conventional accelerating cavity then the pulse duration must be less than the natural "fill time" of that cavity. If we scale from SLAC's $\tau_{fill} = .8\ \mu$sec at $\lambda = 10$ cm then for $\lambda = 6$ mm:

$$\tau_{acc\ fill} = 12 \text{ nsec} \quad .$$

Reference 3, however, suggests that breakdown could occur after about 5 nsec and thus the pulse length and energy per pulse would have to be reduced to:

$$\begin{aligned} \tau &\approx 5 \text{ nsec} \\ n_{cycles} &\approx 250 \\ J_{output} &\approx 3.9 \text{ Joules} \quad . \end{aligned}$$

This still represents a large total energy output for such an apparently simple device.

LASER AND PHOTOCATHODE REQUIREMENTS

The laser would be required to deliver 1 psec pulses approximately 18 psec apart for trains lasting of the order of 5 nsec. The optic frequency and power required would depend on the photo cathodes. If a conventional S 20 type of cathode could be employed and if $\epsilon_q = 10\%$ quantum efficiency is assumed at a wavelength of the order of 500 n meters ($V_\nu = 2.5$ volts) then the power required would be

$$\begin{aligned} J_{opt} &= \frac{J_{RF}}{\epsilon}\,\frac{V_\nu}{V_{stat}} \cdot \frac{1}{\epsilon_q} \\ &= 2.4\ mJ/ \text{ train of pulses} \quad (c.f.\ 3.9 \text{ Joules output}) \\ &= .06\ \%\ J_{RF} \quad . \end{aligned}$$

Such a train of pulses could, for instance, be generated by multiplexing a single psec pulse generated by a mode locked dye laser. If the whole train were finally amplified by a X_eF laser the overall efficiency might be expected[9] to be about 2%. In this case the power going to the laser would be negligible compared to that going to the electrical supply ($\sim$ 3%).

However, it is unlikely that a conventional photocathode could carry the required current or survive long in the expected environment. A more rugged photocathode would be required and lower quantum efficiencies are to be expected. If the power to the laser is to remain less than half the total then a quantum efficiency of the order of 1% is needed.

It has been reported[5] that a C_sI photocathode can give the required current densities and quantum efficiency if UV light is used, but its lifetime is not known. Very high current densities and quantum efficiencies[6] have also been reported from a brush like photocathode but the time response and mechanism in this case is yet to be determined. Lanthanem hexaboride is another possible cathode. At low fields and UV light it has been observed to give a quantum efficiency[7] of 10^{-3} and may be expected to have higher efficiency at the field levels employed in our example.

Perhaps the most promising approach would be to use a metal photocathode and UV light. It is observed[8] that the quantum efficiency of most metals peaks at about 2500 Å and that this efficiency is given very approximately by the relation

$$\epsilon \approx 3 \times 10^{-3} (V_\mu - W_{eff})^3$$

where $V_\mu \approx 5$ V for 2500 Å and W is the work function of the metal. Table I gives some examples. It is reasonable to assume that the quantum efficiency would be raised in a high field due to the Schottky reduction of the effective work function

$$W_{ef} = W - \left(\frac{e}{4\pi \ \epsilon_o} \right)^{1/2} \mathcal{E}^{1/2} \quad .$$

On this assumption values are given in Table I for expected quantum efficiencies for some values of surface fields.

Table I. Work functions W in volts and quantum efficiencies for $\approx$ 2500 Å light at different surface fields. The zero field values are measured and the others extrapolated.

		Percentage Quantum Efficiency for $\mathcal{E}\,(MV/m) =$					
Metal	W (Volts)	0	50	100	200	500	1000
Na	2.1 – 2.5	6	7.9	8.9	13.6	13.6	18
Ce	2.8 – 4.2	2	2.9	3.5	4.2	6.1	8.8
Tw	3.4 – 3.6	1.2	1.9	2.3	2.8	4.3	6.5
Zr	3.7 – 4.3	.3	.6	.8	1.1	1.9	3.2
Ta	4.0 – 4.2	.15	.35	.48	.68	1.3	2.4
Cn	4.4	.08	.22	.32	.47	1.0	1.9

If we take a Zirconium photocathode then with a field of 100 MV/m we can assume a quantum efficiency of .8%. The optical power then required for our example is 60 mJ/train of pulses which is a significant fraction of the output power (1.5%).

However, a *KrF* Exemer laser at a frequency of 2480 Å could be used and such lasers have given[9] 15% intrincic efficiency.If we assume an overall laser efficiency of 9% then the electrical power required for the laser is still only 17% of the output power.

SCALING

BREAKDOWN

In order to discuss the scaling of the microlasertron, we need a theoretical model of the electrical breakdown. In Table II we give published values for the breakdown fields for different gaps and times (τ). In all cases listed the electrodes were of copper or brass. For comparison we give also the transit time (t) for a copper ion and the ratio n of the breakdown time to this transit.

We note that for a fixed voltage V the ratio n is relatively insensitive to the gap and thus the field. For lower voltages n is higher, and for higher voltages n seems to tend towards 1. This observation clearly suggests that the breakdown in these cases was a result of a cascade process involving the release, by electron impact, of ions at the anode, their movement back to the cathode and release there of more electrons. The number of ion transits required for breakdown would be dependent on the numbers of ions and electrons released by the impacts, and these would depend only on the voltage. This is as observed. For scaling purposes, therefore, we assume that the time for breakdown is a fixed multiple of the ion transit times at fixed voltage V.

Table II. Observed breakdown times for copper or brass electrodes and different gaps and voltages.

V (KV)	g (mm)	$\mathcal{E}$ (MV/m)	τ (nsec)	t (nsec)	n	Ref.
40	1	40	24	5.7	4.2	3
80	2	40	22	8	2.8	3
80	1	80	11	4	2.8	3
80	.057	1400	.57	.23	2.5	4
160	2	80	5	5.6	.9	3
160	1	160	5	2.8	1.8	3

WAVELENGTH SCALING

It is reasonable to keep the relative geometry constant, *i.e.*,

$$\frac{g}{\lambda} = \text{const } (.083)$$

$$F_\tau = \frac{\tau_0 c}{\lambda} = \text{const } (.38)$$

$$\Delta\theta = \text{const } (18^\circ)$$

$$\frac{q}{q_{sc}} = \text{const } (.1) \quad .$$

Then from Eq. 126

$$V_{stat} \approx 10^6 \, \frac{g}{\tau_0 c} = \text{const } (50KV)$$

From the breakdown scaling of Sec. 6.1 we obtain the time before breakdown to be

$$\tau_{\text{breakdown}} = n_{bd} \left(\frac{2M}{e} \, \frac{g}{V} \right)^{1/2} \quad \propto \lambda$$

and the number of RF cycles before breakdown (n_{RF})

$$n_{RF} = n_{bd} \, \frac{3 \; 10^5}{V^{1/2}} \, \left(\frac{g}{\lambda} \right) = \text{const } (\approx 400) \quad .$$

Since the gap g is proportional to λ the field, for fixed voltage

$$\mathcal{E} \propto \frac{1}{\lambda} \quad ,$$

the space charge limit per unit area

$$q_{sc} \propto \frac{1}{\lambda}$$

and the average current per unit area

$$i_{ave} \propto q_{sc}\omega \propto \frac{1}{\lambda^2} \quad ,$$

and thus the average power per unit of cathode area

$$W \propto i \, V \propto \frac{1}{\lambda^2}$$

and the output energy in Joules

$$J \propto W\tau \propto \frac{1}{\lambda} \quad .$$

Using these relations we obtain for a 10 cm $\times$ 10 cm device as described in Sec. 5, but with different wavelengths.

λ	$\mathcal{E}$	i_{ave}	W_{out}	$\tau_{breakdown}$	J_{out}
3 cm	20 MV/m	20 A/cm^2	30 MW	36 n sec	.8 Joules
1 cm	70 MV/m	200 A/cm^2	300 MW	10 n sec	2.3 Joules
3 mm	200 MV/m	2 KA/cm^2	3 GW	3.6 n sec	8 Joules

The advantages in going to short wavelengths is remarkable. It will be limited, presumably, by cooling, photocathode, or nonscaling breakdown phenomena.

CONCLUSION

The above analysis has shown that a microlasertron might be a source of powerful mm radiation but there are many assumptions that need to be demonstrated:

(1) Firstly we have assumed that a gradient of the order of 100 MV/m can be maintained over a .5 mm gap for 5 nsec. This is consistent with extrapolations from experimental results using metal electrodes but may not be possible if one of the electrodes has a low work function surface (photocathode). Experimental work is required.

(2) We have assumed current densities of the order of 10 K amps/cm^2 for 1 psec pulses, and average currents of the order of 500 A/cm^2 for the order of 5 nsec. Both values are higher than observed with a conventional photocathode. Values of the required order have been observed from metal photocathodes, but with low quantum efficiency.

(3) The analysis ignores the finite width of the diode gaps and also ignores the direct radiation from the electrons into the cavity. Full two-dimensional numerical calculation is required.

(4) Details of switching the primary current have not been discussed. Laser activated solid state switches may be suitable, but much work remains to be done.

(5) Details of RF windows, heat removal and a thousand other questions have not yet been addressed.

Despite these questions the potential of the proposed device seemed to justify its presentation now. Work on many of these problems is being pursued at various labs and future publication will hopefully answer some of the questions.

I would like to thank W. Willis whose original idea started this work and whose continued interest and suggestions have nurtured it. I also wish to thank J. Clause, U. Stumer, V. Radeka, T. Rao, and many others for their contributions.

REFERENCES

1. W. Willis, *Switched Power Linac,* Laser Acceleration of Particles (Malibu, 1985), AIP Conf. Proc. **130,** p. 242.
2. E. L. Garwin *et al., An Experimental Program to Build a Multimegawatt Lasertron for Super Linear Colliders,* 1985 Particle Accelerator Conf. (to be published in IEEE Trans. Nucl. Sci. NS–32); also SLAC–PUB–3650. Y. Fukushima, *et al., Lasertron, a Photocathode Microwave Device Switched by Laser,* 1985 Particle Accelerator Conf. (to be published in IEEE Trans. Nucl. Sci. NS–32).
3. F. T. Warren, *et al., Current Evolution in a Pulsed Overstressed Radial Vacuum Gap,* IEEE Trans. Elec. Insulation **EI–18** No. 3, p. 226 (1983).
4. B. Juttner, *et al., Zerstörung und Erzeugung von Feldemittern auf ausgedehnten Metalloberflächen,*[1] Beitrage für Plasmaphysick **10,** p. 383 (1970).
5. F. Villa (SLAC), private communication.
6. M. Boussoukaya, *et al.,* LAL (Orsay) internal report LAL–RT/86–04.
7. M. Bergenet, *et al.,* (Orsay) internal report LAL–RT–84-10.
8. *Ultraviolet Radiation,* Lewis R. Koller, John Wiley & Sons.
9. C. B. Edwards, *et al.,* Applied Physics Letters, **36,** 617 (1980).

SLAC – PUB – 3890REV
July 1987
(N)

ERRATA

THE MICROLASERTRON*

R. B. PALMER

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

and

Brookhaven National Laboratory
Upton, Long Island, New York 11973

This manuscript was submitted to three different Conferences:

Invited talk presented at the Seminar on New Techniques for Future Accelerators, Erice, Italy, May 11–17, 1986

Invited talk presented at the 1986 Symposium on Advanced Accelerator Concepts, Madison, Wisconsin, August 21–27, 1986

and also

Presented at the 1987 Workshop on New Developments in Particle Acceleration Techniques, Orsay, France, June 29 – July 4, 1987

⋆ Work supported in part by the Department of Energy, contracts DE–AC03–76SF00515 (SLAC) and DE–AC02–76C0016 (BNL).