A PULSED-POWER ELECTRON ACCELERATOR
USING LASER DRIVEN PHOTOCONDUCTIVE
SWITCHEES

by

Charles Bamber

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Prof. Adrian C. Melissinos

Department of Physics and Astronomy

University of Rochester

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For my wife, Marcia
CURRICULUM VITAE

Charles Bamber is a native of Guelph, Ontario, Canada. He graduated in 1978 with an Ontario Secondary School Honours Graduation Diploma. From 1979 to 1983 he attended the University of Western Ontario where he received his B.Sc. in physics. From 1983 to 1986 he attended McMaster University where he received his M.Sc. in physics. In the fall of 1986, he entered the Ph.D. program in the Department of Physics and Astronomy at the University of Rochester. He has held a research fellowship at the Laboratory for Laser Energetics since 1986, where he performed his Ph.D. thesis research under the supervision of Dr. A.C. Melissinos.
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ABSTRACT

This dissertation documents the experimental investigation of a novel electron accelerator. The characteristics of this device have been studied electrically and its performance has been assessed by measuring the properties of the electron beam produced by it. An understanding of the operation of this device has been aided by extensive modelling of the propagation of the electrical waveform through the structure as well as the response of the electron bunch to this pulse.

The reason for exploring new schemes for accelerating particles is to learn how to produce beams that have higher energy or can be focussed down to a smaller area. Our interest was to determine what maximum accelerating gradient could be achieved in a region where a bunch of electrons would be accelerated from rest. The device that was studied was a pulsed power radial transmission line accelerator. It has been predicted that one should be able to attain extremely high accelerating gradients in such structures. One feature of this device that has been predicted is that there should be an increase in the amplitude of the voltage pulse as it propagates into the center of the structure. In the laboratory we sampled the waveform electro-optically and observed a voltage gain by a factor of 4. This effect was modelled using two independent computer simulations. The electrical pulse was injected into the structure using photoconductive switches. Studies of the production of photoelectrons were carried out in anticipation of generating a beam of electrons from our device.

A series of experiments were carried out where the characteristics of the beam emitted from this accelerating structure were measured. The electron energy and amount of charge per bunch were measured as a function of the accelerating gap. The electron energy as a function of time relative to the accelerating pulse was modelled and the results indicate that the electrical pulse peaks for about 30 ps. The charge per bunch was typically 100 fC. The voltage was increased until the device failed. Failure occurred at a final electron energy of 11 keV after traversing a gap of 0.25 mm. This represents an average accelerating gradient of 44 MV/m.
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CHAPTER 1

Introduction

1.1 Particle Accelerators

Particle accelerators are devices designed to boost particles up to high kinetic energies. These particles are most commonly electrons or protons, but may be ions, positrons or antiprotons. In addition to having a high kinetic energy, the beam should emerge from the accelerator in a well collimated state, at a sufficiently high rate and in a reasonably monoenergetic form. All accelerators are based upon the interaction of charged particles with an electromagnetic field[1].

There is a large variety of acceleration techniques in use in different machines. Electrostatic fields are used in the Cockcroft-Walton or Van de Graaf machines. Circular machines such as Lawrence’s cyclotron or its modern descendent, the synchrotron, use rf fields. There are also linear rf machines as first proposed by Wiedereoe and later realized in the Alvarez linac. In both synchrotrons and linacs the particles are accelerated upon crossing radio frequency cavities resonating in a suitable mode. Another class of accelerators consists of induction machines, such as the betatron and modern linear induction accelerators.

1.2 Laser Accelerators

There are applications where it is desirable to accelerate electrons in extremely high electric fields. In high energy linear accelerators, the overall length of the machine
can be reduced if a higher average electric gradient can be achieved. High gradients are also necessary in injectors, where one wants to minimize space charge effects, by accelerating electrons to relativistic velocities as soon as possible. In the focus of a laser beam the electric field can be very high. It has long been considered attractive to try to use lasers to generate these high fields[2].

The difficulty with laser beams is that their electric field is transverse to their direction of propagation. Several schemes have been proposed and investigated to generate a longitudinal electric field from a laser. These include the grating accelerator[3] and the inverse Cherenkov accelerator[4]. The plasma beat wave accelerator is another approach where lasers generate density waves in a plasma which give rise to longitudinal electric fields. So far, however, none of these schemes has been demonstrated to be a practical method of accelerating electrons.

1.3 Motivation

Most of our understanding of the fundamental particles and forces that make up the physical world has been derived from experiments where a beam of particles scatters off of a fixed target or another particle beam. In recent years it has been accepted that in order to achieve very high center of mass energies two groups of particles must collide head on. This has led to the development of colliders, as opposed to “fixed target” machines. The two particles beams may counter-rotate in the same ring if they have opposite charge (i.e. electrons and positrons, or protons and antiprotons). Two rings must be constructed in the case of proton-proton collisions, as for example in the SSC[5]. The state of the art has progressed to the point where beams
can be stored in the rings with lifetimes in excess of 24 hours, while colliding several times during each revolution.

The event rate in a collider depends critically on the cross sectional area of the two beams at the point of collision.

\[ R_e = \frac{N_1 N_2}{A} f \sigma = \mathcal{L} \sigma \]  

(1.1)

Here \( N_1 \) and \( N_2 \) are the number of particles in each colliding bunch, \( A \) is the area of each beam, and \( f \) is the number of collisions per second. The cross section for the reaction is \( \sigma \). It is convenient to define the luminosity[6], \( \mathcal{L} \), of the collider through equation (1.1). It is clear from this equation that one wishes to pack as many particles as possible into each bunch and to decrease the area \( A \). The latter can be accomplished with suitable magnetic focusing but is limited by the emittance of the beam. The transverse emittance of the beam is the area in phase space in the two transverse coordinates[6]

\[ \varepsilon_x = \pi \sigma_x \sigma_{x'} \quad \varepsilon_y = \pi \sigma_y \sigma_{y'} \]  

(1.2)

where \( \sigma_x \) is the spread in position and \( \sigma_{x'} \) is the spread in angle. The angle of an electron trajectory is given by \( x' = p_x / p_z \). As the electron energy is increased, \( p_z \) increases but \( p_x \) is unchanged, and so the emittance of the beam will decrease. One can define an invariant emittance

\[ \varepsilon_{\text{invar}} = \pi \gamma \sigma_x \sigma_{x'} \]  

(1.3)
which is determined when the beam is first produced and will in general remain constant or grow as the beam propagates through the machine. Here $\gamma$ is defined as the ratio of the total electron energy to its rest energy. Thermionic cathodes in general produce large emittance beams. Recently, laser driven r.f. guns have been shown to produce low emittance beams. Another technique to get low emittance beams is to use damping rings to reduce the emittance by synchrotron radiation.

Currently the largest electron-positron collider in the world is the LEP machine of the European Center for Nuclear Research (CERN). It has a circumference of 28 km and operates in the energy range from 50 to 80 GeV. The large radius is necessary in order to keep the synchrotron radiation to reasonable values so that the energy loss in each turn can be made up by the accelerating cavities. It is therefore agreed that future electron-positron colliders running at energies in the range of 0.5 to 1 TeV will have to be linear machines. Recently it was shown at Stanford that one can collide two linear beams and obtain reasonable luminosity even though it is two orders of magnitude lower than for circular machines. The two mile long SLAC linear accelerator operates at an energy of 50 GeV. The average accelerating gradient is 17 MV/m. It is desirable to operate with gradients of the order of 500 MV/m for future linear accelerators. Much research is being done at present to take us toward that goal[7]. In addition, research is being conducted on how to produce short, high intensity, low emittance beams that will be required for the next generation of accelerators.

One suggestion on how to build a high gradient linac came from W. Willis in 1984[8]. He proposed an accelerating cell composed of a radial transmission line (RTL) which would have a short high voltage electrical pulse injected into the periphery. The beauty of this device is that for short electrical pulses one can obtain a higher voltage at the center than was injected into the edge of the structure. The gain factor can be of the
order of 10 for simple geometries. Further, since the power is pulsed the accelerator should be energy efficient and the accelerating gap should be able to hold off voltages up to the field emission limit.

This thesis is an experimental investigation of this type of device. The voltage is switched into the RTL with a laser driven photoconductive switch. Our laser produced picosecond pulses and photoconductive switches are known to generate electrical pulses with risetimes comparable to the laser pulsewidth. The operation of the Nd:glass laser system and studies of photoconductive switches are discussed in Chapter 2. The radial transmission line and the theory governing the propagation of electrical pulses in the structure as well as the experimental investigation of these phenomena by means of electro-optic sampling are presented in Chapter 3. In Chapter 4 the production of photoelectrons from metal cathodes by absorption of short UV pulses is discussed. These pulses were derived from frequency quadrupling of a portion of the IR pulses from the laser system. The operation of the integrated system leading to the production of an electron beam is presented in Chapter 5. We obtained short pulses of $10^6$ electrons with energies up to 11 keV. These pulses could be focussed down to sub-millimeter spot sizes. The limit on the energy of the accelerated electrons arose from the limitations of the photoconductive switches.
References


CHAPTER 2

Photoconductive Switching and Laser Development

2.1 Introduction

The generation of short electrical waveforms may be controlled by light pulses, by using photoconductive switches. When shielded from light these switches are in their "off" state, but they turn "on" upon the absorption of light. A switch consists of a piece of highly resistive semiconductor placed in contact with two electrodes. When this material is exposed to light, electrons may be promoted out of the valence band into the conduction band. This leaves holes in the valence band as well as electrons in the conduction band, and these charges are free to move around under the influence of an applied electric field and act as carriers. If enough carriers are created, the resistance of the switch can drop to levels where it behaves more like a metal and any voltage drop across it is reduced by the resulting current.

This is the type of switch we decided to use to launch the electrical pulse into the radial transmission line. The switch materials studied were silicon and gallium arsenide. In this chapter, a discussion of photoconductive switching is followed by a description of the laser system that was developed to fire these switches.

2.2 Photoconductive Switching

Consider a simple photoconductive switch connecting two transmission lines as indicated in Figure 2.1. One of these transmission lines is initially charged to voltage
$V_0$. There is a voltage drop across the switch which we will take to be linear from one side to the other. When light is absorbed by the switch it begins to conduct. If the switch is driven well into the saturation regime, i.e. the switch resistance drops to much less than the characteristic impedances of the transmission lines, then an electrical pulse will be launched toward the load, $Z_L$.

Obviously the risetime of the switched electrical pulse will be limited by the risetime of the optical pulse. There are two other factors which must be taken into account which will lengthen the risetime of the electrical pulse. These are the switch geometry and the light pulse energy.

Even in the ideal case where the risetime of the optical pulse is infinitely fast, the risetime of the electrical pulse will be limited by the length of the switch. Before the switch is fired, the electrical waveform will ramp in voltage from 0 to $V_0$ from one end of the switch to the other. When the switch fires, it is this waveform that is launched toward the load. The risetime of this pulse must therefore be given by

$$T_s = L\sqrt{\mu\epsilon}$$

where $L$ is the physical length of the switch and $1/\sqrt{\mu\epsilon}$ is the speed of the electrical pulse through the switch (see Figure 2.1). In general the risetime of the electrical pulse will be the convolution of the risetime of the optical pulse, $T_0$, and $T_s$.

The risetime of the switched pulse may also be degraded if the optical pulse energy is not great enough to drive the switch into saturation. The switch can be considered to be well saturated when the electrical resistance across it is much less than the impedance of the line it is trying to drive. The resistance of the switch scales inversely with the number of charge carriers that are created and therefore, when the
Figure 2.1 Simple Photoconductive Switching
A photoconductive switch of length $L$ connects two transmission lines with impedances $Z_1$ and $Z_2$. The first transmission line is biased to voltage $V_0$; the second terminated in a load $Z_L$. When a light pulse of width $\tau_0$ strikes the switch an electrical pulse is launched along $Z_2$ toward $Z_L$. 
optical pulse is much shorter than the carrier lifetime, it scales inversely with the time integral of the optical pulse energy incident on the switch. The change of risetime as a function of light energy has been theoretically modelled by Mourou et al [1].

It should be noted that on firing the switch we launch not only a pulse toward the load but also a pulse back toward the bias supply. For transmission lines of equal impedances, i.e. $Z_1=Z_2$, these pulses will be equal in magnitude but opposite in sign and so the voltage of the switch will drop to $V_0/2$ and the pulse launched toward the load will also only have half of the applied voltage. In general, the pulse launched toward the load will have an amplitude of

$$V = V_0 \frac{Z_2}{Z_1 + Z_2}$$  \hspace{1cm} (2.2)

Semiconductors are materials which have no conduction electrons but a relatively small band-gap. Usually semiconductors are doped with impurities to increase conduction preferentially by electrons or holes. Intrinsic semiconductors can have high resistivities. In these experiments the materials used were silicon and gallium arsenide. In Table 2.1 are listed the properties of these materials as determined by the manufacturer. These materials are also called semi-insulators. High resistivity

Table 2.1 Switch Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Silicon</th>
<th>Gallium Arsenide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Wacker-Chemitronic GMBH</td>
<td>Litton Airtron</td>
</tr>
<tr>
<td>Dopant</td>
<td>phosphorous</td>
<td>none</td>
</tr>
<tr>
<td>Resistivity (Ω cm)</td>
<td>7000</td>
<td>$4 \times 10^7$</td>
</tr>
</tbody>
</table>
semiconductors may also be manufactured by doping with impurities that create traps deep in the bandgap. These traps capture carriers and thereby increase resistivity.

High resistivity semiconductors are the material of choice for photoconductive switches. These materials can hold off large voltages (~50kV/cm for GaAs) until the photoconductive switching occurs. Typically the voltage is applied as a short high voltage pulse. A switch can hold off a higher voltage if it is applied for a short enough period of time. Breakdown also occurs more readily along a surface rather that through the bulk of the material. When designing a high voltage photoconductive switch it is better to position the electrodes such that the likelihood of surface breakdown is minimized.

Usually for photoexcitation to occur the energy of the photon must be greater than the bandgap. An electron is promoted out of the valence band into the conduction band where it is free to move throughout the lattice. This leaves an unfilled state, or hole, in the valence band which is also free to move around. In Figure 2.2 this type of process is referred to as extrinsic photoproduction. If the photon energy is less than the bandgap, photogeneration will proceed through either extrinsic excitation or two photon excitation. The 1.054 μm light source used in this experiment had a photon energy of 1.17eV which is greater than the bandgap of silicon (1.11eV) but less than the bandgap of GaAs (1.42eV). For undoped GaAs the dominant switching mechanism is due to extrinsic photoproduction from EL2 defects 0.75 eV below the conduction band[2]. The number of carriers created via intrinsic photoproduction is given by

\[ N_e = N_h = \frac{E_{opt}}{E_f} \]  

(2.3)
Figure 2.2 Photogeneration

If the photon energy, \( h\nu \), is greater than the bandgap, \( E_C - E_V \), then photogeneration may be intrinsic. If \( h\nu < E_C - E_V \), then photoexcitation either involves promotion to or from a trap (extrinsic) or by the absorption of two photons. (after Ref. 3)
where $\eta$ is the quantum efficiency, $E_{\text{opt}}$ is the total optical energy absorbed in the switch and $E_\gamma$ is the energy of one photon. In intrinsic photoproduction the quantum efficiency is quite high, often approaching 100%. In extrinsic photoproduction, only one carrier is produced per event. The quantum efficiency varies from sample to sample, since the process depends on the presence of defects or impurities. Two photon excitation will only occur at higher intensities.

Semiconductors are classed into two groups, one being direct bandgap material and the other is called indirect bandgap material (see Figure 2.3). In direct bandgap material, an electron promoted from the most energetic state of the valence band to the least energetic state of the conduction band would have no change in momentum. In indirect bandgap material these two states have different momenta. Electron-hole pair creation in indirect bandgap material must be accompanied by the creation or absorption of a phonon to conserve momentum, where typical phonon energies are small (~0.01 eV). GaAs is a direct bandgap material while Si is indirect.

After illumination the photoconductive switch will return to its "off" state by recombination of the charge carriers. In the case of silicon, this recombination process has a characteristic time of several tens of microseconds. This is generally longer than the time it takes to launch the entire charge line toward the load, and so the overall electrical pulse length is limited by the length of the charge line. For GaAs, the characteristic time is of the order of hundreds of picoseconds. For short pulse illumination this type of switch may turn "on" and "off" before the charge line can be depleted.

The conductivity of a material is given by

$$\sigma = (n_e\mu_e + n_h\mu_h)e$$  \hspace{1cm} (2.4)
Figure 2.3 Optical transitions
a) and b) are direct transitions; c) involves the absorption of a phonon and is indirect.
(after Ref. 3)
where \( n_e \) is the density of electrons of mobility \( \mu_e \), and \( n_h \) and \( \mu_h \) are the density and mobility of the holes. If the number of holes and electrons are the same, i.e.

\[
n_e = n_h = n \tag{2.5}
\]

we can write

\[
\mu_e + \mu_h = \mu \tag{2.6}
\]

and

\[
\sigma = n \mu_e \tag{2.7}
\]

At low fields the mobility has a fairly constant value. Silicon has a mobility of 2100 cm\(^2\)/Vsec (1500 cm\(^2\)/Vsec for electrons, 600 cm\(^2\)/Vsec for holes), while for GaAs the mobility is 9100 cm\(^2\)/Vsec (8500 cm\(^2\)/Vsec for electrons, 400 cm\(^2\)/Vsec for holes)[3]. In both cases the greatest part of the mobility comes from the electrons. At fields above 10\(^3\)V/cm the mobilities of these materials begin to change, as is indicated in figure 2.4. The velocity of electrons in silicon reaches a saturation value of \(1 \times 10^7\) cm/sec. For GaAs, the carrier velocity actually begins to decrease with increasing field above 3.2 kV/cm.

At these high fields equation (2.4) no longer applies and the conductivity becomes

\[
\sigma = \frac{(n_e v_e(E) + n_h v_h(E)) e}{E} \tag{2.8}
\]

As an example, let's calculate the "on" resistance of a silicon disk in the radial transmission line to be studied. The silicon wafer was 0.5 mm thick, and the effective
Figure 2.4 Carrier drift velocity vs Electric field

In silicon, at large applied electric field the carrier's reach a saturation velocity. In GaAs, above a field of $3 \times 10^3$ V/cm the velocity of the carriers actually begins to decrease.

(after Ref. 3)
switch area will be taken to be a ring of radius 1.5 cm and width 1 mm. The volume of
the switch is therefore $2.35 \times 10^{-2}$ cm$^3$. The laser switch pulses had approximately 1
mJ of energy, which with a photon energy of 1.17 eV will create $5.3 \times 10^{15}$ pairs of
carriers, if we assume a quantum efficiency of unity. If we assume these carriers are
distributed uniformly in the switch volume the density of carriers is $2.25 \times 10^{17}$ pairs
per cm$^3$. For an applied voltage of 3 kV, we are well into the saturation regime and
calculate the conductivity of the switch to be $6 \ (\Omega \text{cm})^{-1}$. The switch resistance is

$$R_s = \frac{i}{\sigma A}$$  \hspace{1cm} (2.9)

Substituting in our values we calculate the "on" resistance of the switch to be
$1.8 \times 10^{-2} \ \Omega$. The measured "off" resistance was 2 k$\Omega$ and so the resistance changes
by 5 orders of magnitude in just a few picoseconds. The input impedance of the radial
transmission line was calculated to be one ohm, and so the switch should have no
problem launching the pulse into the structure. It is interesting to note that the peak
current switched is 3 kiloamps and the peak power handled is 9 Megawatts.

We have measured the energy of electrons accelerated in a radial transmission
line as a function of the amount of energy in the switch beam. The results are shown in
Figure 2.5. We find that above 1 millijoule of switching energy there is no discernible
increase in the electron energy, and therefore believe that the switch has been driven
into the saturation regime. When the switch resistance is not much less than the line
impedance the switched voltage is no longer given by equation (2.2) but rather by

$$V = V_0 \frac{Z_2}{Z_1 + Z_2 + R_s}$$  \hspace{1cm} (2.10)
where $R_s$ is the "on" resistance of the switch. From Figure 2.5 we see that at an IR energy of 700μJ the electron energy has dropped from 2000 eV to 1900 eV. We know that the sum of the line impedances is 1.3 Ω. Therefore, by taking the ratio of these voltages and solving for $R_s$, we estimate the switch "on" resistance to be 0.07 Ω. This is of the same order of magnitude as the example calculated earlier.

The time response of photoconductors is very fast. Studies have shown that the carriers are created on a subpicosecond time scale[4]. For our purposes, the risetime of the electrical pulse is not limited by the creation time of the carriers.

2.3 Laser Development

The laser system that was developed was required to produce short (< 10 ps) pulses of energy at the millijoule energy level. This laser was used to fire the photoconductive switches and also to produce photoelectrons within the accelerating structure. Photoelectron production was possible only through frequency quadrupling of a portion of the light pulse that had been split off, to a photon energy at which photoelectrons could be produced directly from the gold cathode surface. It was desirable to run this laser at the highest possible repetition rate, in order to facilitate the tuning of optics as well as the collection of data.

Drawing on the experience of the ultrafast group at the Laboratory for Laser Energetics, we chose to develop a system consisting of a mode-locked oscillator followed by a regenerative amplification stage[5]. A schematic of our setup is shown in Figure 2.6.

The first component in the laser system is a mode-locked oscillator. Mode-locking is a common technique for producing short pulses within a laser. Any lasing
Figure 2.5 Optical energy vs Electron energy
The kinetic energy of an electron bunch in a RTL accelerator as a function of the energy of the light pulse that fires the photoconductive switch. The applied voltage was 660 V.
Figure 2.6 Laser System
A short pulse from a mode-locked oscillator is chirped in a fiber, amplified in two stages before being recompressed with a grating pair. The saturable absorber attenuates prepulses and reduces the pedestal.
material has a finite bandwidth and the shortest pulse that can be produced is limited by the reciprocal of this bandwidth. Modelocking is a technique to lock the phases of different frequency components of the laser together in such a way that they interfere constructively to produce a single short pulse. Modelocking can be classified into two groups: phase modulation and amplitude modulation.

Our modelocker worked on the principle of amplitude modulation by acousto-optic methods. It consisted of an approximately rectangular quartz crystal polished on two sides to pass the light pulse that was circulating in the cavity. RF power was coupled into this crystal via a piezoelectric transducer to set up acoustic waves. The RF source was tunable to match the resonant frequency of the crystal and set up a standing wave pattern. The standing wave pattern is made up of alternating regions of compression and rarefaction. The index of refraction of these regions oscillate around a nominal value and light traversing the crystal sees this index modulation as a grating pattern and some of the light will be diffracted off axis. During each RF cycle there are two nodes where, for an instant, the index of refraction is uniform across the crystal and light may pass undiffracted. To make a working modelocked laser it is necessary to set the optical length of the cavity such that the round trip time of a light pulse is one half of the RF period. Then, providing the gain of the cavity is greater than the loss for a finite time window around the RF node, the cavity will lase, and a single short pulse will circulate back and forth between the two end mirrors.

Our modelocked laser consisted of a cavity 1.5 meters long, a krypton lamp pumped Nd:YLF laser rod (Quantronix 116), and a Quantronix modelocker driven with 10 W of RF power at 100 MHz. The pulses emitted from the output coupler had approximately 1 nJ of energy and were spaced by 10 ns. These pulses passed through a 600 m long optical fiber having a core diameter of 7 μm. This did two things to the
light pulse. The first process is self phase modulation: a change in the index of refraction of the fiber that is proportional to the intensity of the light passing through it. At low intensities this effect was negligible but at higher intensities the spectrum became broadened. The bandwidth of the pulse was increased by the interaction of the pulse with the medium; in our case from 2 angstroms to 20 angstroms. The second effect occurring in the fiber was dispersion. The index of refraction of the fiber varies with frequency. Lower frequency light travels faster than higher frequency light. After passage through 600 meters of fiber our pulse, which was initially 35 picoseconds long, grew to 90 picoseconds. The variation of frequency with time is approximately linear. The pulse is said to be “chirped”. A streak camera measurement of the chirped pulse's bandwidth is shown in Figure 2.7.

If the light pulse is now passed through a parallel grating pair spaced as to exactly compensate the negative dispersion of the fiber, it compresses in time down to two picoseconds duration. It is also possible to first amplify the pulse and then compress it with the gratings. The advantage of amplifying before compression is that the peak power in the amplifier is reduced and the chance of optical damage is decreased.

After chirping in the fiber, one pulse was selected out of the pulse train with a Pockels cell. This pulse was amplified in two stages before compression. The first stage was a regenerative amplifier as shown in Figure 2.8. This amplifier consisted of a flash pumped Nd:glass rod (Kigre FC256K) in a laser cavity. The pulse was seeded into this cavity via a Pockels cell and allowed to circulate for approximately 80 round trips. The energy upon extraction from the cavity was 5 mJ. It was not possible to run this amplifier at a repetition rate higher than 5 Hz because of distortion in the beam profile caused by thermally induced stress birefringence (see Figure 2.9).
Figure 2.7 Streak Camera Measurement of the Spectrum of the Chirped Pulse

Optical pulses emerging from the fiber after the modelocked oscillator were spatially dispersed by a grating before being reflected into a streak camera. The nonuniformities in the streak trace are a result of laser speckle.
Figure 2.8 Regenerative Amplifier
A portion of a chirped pulse was reflected off of a glass wedge and Brewster plate (BP) to seed the regenerative amplifier. The KD*P Pockels cell (PC) was slightly tilted to introduce a $\lambda/4$ retardation. After a double pass through the PC, the pulse polarization was rotated $90^\circ$ and the pulse was transmitted through the BP toward the Nd:glass rod. When the pulse was in this part of the cavity a voltage was applied to the PC to cause a $\lambda/2$ rotation on single pass. On double pass the light pulse returned to its original polarization and continued to be transmitted through the BP. The PC voltage was held constant until the light pulse had depleted most of the energy from the rod. At this point the PC bias voltage was adjusted to that the pulse sees $3\pi/2$ rotation on a single pass. After the second pass through the PC the pulse was reflected off the BP. Most of the light passed through the wedge and was sent on for further amplification.
After the pulse was extracted from the regenerative amplifier it was passed through another Pockels cell to remove prepulses from it (see Figure 2.10). The prepulses arise from leakage from the Brewster plate used to extract the pulse. Prepulse reduction was found to be critical for this experiment, since, even a prepulse with a small fraction of the energy (<1%) could partially switch the photoconductive switch.

Next the light pulse was amplified in a two-pass Nd:glass amplifier (Kigre FD-M1065K) running at a repetition rate of 0.36 Hz (again limited by thermal effects). The energy was increased to 30 mJ. All through the amplification stages the chirp of the pulse was maintained. It was now possible to compress the pulse.

The pulse was compressed in a double pass grating pair as shown in Figure 2.11. The gratings were 1800 groove/mm gold coated compression gratings (American Holographic AH-PC-1060-P1), spaced 36 cm apart. An autocorrelation of this pulse is shown in Figure 2.12. The autocorrelation was measured by splitting the pulse into two parts with a partial reflector and recombining these parts in a LiNbO₃ doubling crystal. The crystal was cut for efficient doubling when the two beams crossed at a 15° angle. The path length of one of the beams was variable. The amount of doubled light was measured as a function of the path difference between the beams. The measured curve is the autocorrelation of the beam. The FWHM of this pulse is 1.7 picoseconds. The pulsewidth is critically determined by the spacing between the gratings as is indicated in Figure 2.13.

In Figure 2.12 it is observed that our pulse sits on top of a pedestal extending from -10ps to +10ps. This pedestal arises from frequency components in the pulse which do not have the correct phase relationship and cannot be compressed. We were not able to pinpoint the source of this pedestal, but were able to remove it after the
Figure 2.9 Burn Patterns
The transverse profile of the beam was checked using burn paper. These measurements were taken at different repetition rates of the 10 mm × 8.4 cm amplifier. The amplifier was set up in 2 pass configuration. It was pumped with 260 J/shot. At higher repetition rates, distortion of the beam is apparent.
Figure 2.10 External Pockel's Cell

PIN diode measurement of the pulse after the regenerative amplifier:  
a) with the PC defeated, contrast is 10:1
  
b) with PC operating, contrast is 2000:1
  
c) same conditions as b), vertical scale $\times 500$
Figure 2.11 Double Pass Grating Compression

The early part of the chirped light pulse is red shifted with respect to the later part. In the grating compressor the pulse is dispersed on the first grating and the path of the red shifted portion is longer than the path of the blue shifted part. By adjusting the spacing between the gratings the dispersion of the fiber can be compensated by the negative dispersion of the grating pair and the final pulselength can actually be shorter than the pulselength before the fiber.
Figure 2.12 Autocorrelation of the compressed pulse
Assuming a gaussian profile, this measurement indicates that the pulsewidth is 1.7 picoseconds. Almost half of the energy is in the pedestal.
Figure 2.13 Grating spacing
The minimum compressed pulsewidth can only be achieved if the gratings are separated by an amount which just cancels the dispersion from the fiber. The minimum pulsewidth of 1.7 ps occurs at a spacing of 347 mm.
compression stage. It was found that elimination of the pedestal was necessary for us to observe maximum voltage gain in the radial transmission line structure. The pedestal was removed by passage of our compressed pulse through a saturable absorber (Kodak 9860 dissolved in nitrobenzene at a molar concentration of $1.5 \times 10^{-4}$)[6]. At the proper concentration, the saturable absorber absorbed the pedestal, but was bleached when the main pulse arrived and passed a significant percentage of the energy. An autocorrelation of the pulse after passing through the saturable absorber is shown in Figure 2.14. At the operating concentration the absorber reduced the light pulse energy to 30% of its original value, but since approximately 50% of the energy was in the pedestal, the peak intensity was only reduced to a 60% value.
Figure 2.14 Autocorrelation of pulse after the saturable absorber
Nonlinear absorption attenuates the pedestal much more than the main pulse. The pulsewidth is also shortened to 1.3 ps.
References


Chapter 3

Radial Transmission Lines

3.1 Introduction

Electron accelerators convert energy from an electromagnetic field into the kinetic energy of the electrons. In d.c. accelerators the energy is stored in a static electric field and electrons propagate through this field from a state of high potential energy to one of lower potential energy. The lost potential energy is gained as kinetic energy. Magnetic fields are used in d.c. accelerators as either focussing of steering elements, but the kinetic energy of the electrons is not affected by these components.

To increase the final energy of the electrons it is either necessary to increase the terminal voltage of the machine, or to increase the its overall length. The maximum gradient is limited by electrical breakdown across the electrodes (about 10 MeV/m) for d.c. machines); the maximum length is limited by economics. The first generation of accelerators were d.c. machines but to get to higher electron energies the technology changed to machines that used radio frequency power. Typically the electrons travel together in bunches crossing a number of electrode gaps. In the case of a cyclotron or synchrotron, these bunches travel in a closed loop crossing the same gaps a number of times. When the electron bunch is in a gap between electrodes it is forward biased and gains energy. The gap voltage will then reverse until the next bunch is ready to cross. In such a device it is possible to increase the accelerating gradient beyond the d.c. limit, since at frequencies greater than 10 MHz the breakdown limit increases[1]. Also, for
circular machines, the final energy does not depend on length, since the electrons may travel for many orbits, but usually depends on synchrotron radiation. The synchrotron power radiated by an electron beam passing through a bending magnet is

$$P = \frac{88 E^4 I}{R}$$

(3.1)

where $P$ is in kilowatts, $E$ is the electron energy in GeV, $I$ is the electron beam current in amps, and $R$ is the radius of curvature in meters. In an electron linac the electromagnetic wave has a travelling component with a phase velocity equal to the electron velocity. In this case the electrons can just "surf" along on the wave.

The accelerator we have studied is a pulsed power device. The idea is to store electrical energy in a large volume at low field and then to switch it into a structure where it will be concentrated in a small volume at high field. The electron bunch, when introduced into this high gradient region, will be accelerated during the short period of time that the field is peaked. If this time period is short enough, the electrical breakdown limit will be quite high[2]. This concept was explored by Hartwig[3] in 1968.

3.2 Simple Theory

The structure we have explored is a radial transmission line (RTL). In 1984 Willis [4] suggested that extremely high gradients could be generated using this type of structure. It consists of two parallel circular conducting plates (see Figure 3.1). A short electrical pulse is applied to the circumference with the two plates originally grounded. If the length of this pulse is much shorter than the radius of the structure,
Figure 3.1 Radial Transmission Line

The anode is grounded; negative voltage is switched onto the cathode. The cathode is a gold coating evaporated onto the semiconductor wafer. Voltage is applied to a gold ring evaporated onto the other side of the wafer. Switching is initiated through the bulk of the wafer by absorption of the IR laser pulse. This pulse is focused onto the annular region between these two electrodes.
the pulse will propagate in toward the center as a wave. As the pulse passes through shorter radii, it occupies a smaller volume, and by a simple conservation of energy argument, the field must increase as the inverse of the square root of the radius. Numeric simulations of the energy gained by a relativistic electron passing through this structure predict the average accelerating voltage seen by the electron to be [5]

\[ V = 2V_0 \sqrt{\frac{2R_0}{g + c \tau}} \]  

(3.2)

where \( g \) is the gap spacing, \( \tau \) is the rise time of the pulse, \( R_0 \) is the outside radius of the RTL, and \( V_0 \) is the voltage applied at the edge. The electrical impedance of this device at a radius of \( R_0 \) is given by

\[ Z = 377 \, \Omega \cdot \frac{g}{2\pi R_0} \]  

(3.3)

where \( g \) is the gap.

It was necessary to connect the anode and cathode together with a short copper strip approximately 3 mm wide and 4 cm long. This prevented the cathode from floating up to a voltage \( V_0 \) before the switch was fired. After the pulse was launched the inductance of this strip was high enough not to have a significant effect on the pulse propagation.

An analysis of the performance of a RTL can be made by calculating the differential equation describing the propagation of an electromagnetic wave in this structure. One may then determine a set of normal modes and, by finding a suitable linear combination of them to describe the initial conditions, calculate the time evolution
of the field in the structure. We start with Maxwell's equations and the boundary conditions that describe our situation. In the absence of media Maxwell's equations are

\[ \nabla \cdot \mathbf{E} = 0 \quad (3.4a) \]

\[ \nabla \cdot \mathbf{B} = 0 \quad (3.4b) \]

\[ \nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = 0 \quad (3.4c) \]

\[ \nabla \times \mathbf{B} - \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} = 0 \quad (3.4d) \]

For simplicity we will find the solutions for the fundamental TEM modes,

\[ \mathbf{E} = E_z(\rho, t) \hat{z} \quad (3.5a) \]

\[ \mathbf{B} = B_\phi(\rho, t) \hat{\phi} \quad (3.5b) \]

and assume axial symmetry, i.e. no \( \phi \) dependence of any field component. Note that the boundary conditions are already satisfied; the electric field is normal at the surface of the disks and the magnetic field is parallel.

From equation (3.4c)

\[ \frac{\partial E_z(\rho, t)}{\partial \rho} = \frac{1}{c} \frac{\partial B_\phi(\rho, t)}{\partial t} \quad (3.6) \]
From equation (3.4d)

\[ \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( \rho B_\phi(\rho, t) \right) = \frac{1}{c} \frac{\partial E_z(\rho, t)}{\partial t} \]  

(3.7)

From equation (3.6)

\[ \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( \rho \frac{\partial E_z(\rho, t)}{\partial \rho} \right) = \frac{1}{c^2} \frac{\partial}{\partial t} \left( \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( \rho \frac{\partial B_\phi(\rho, t)}{\partial \rho} \right) \right) \]  

(3.8)

Substituting equation (3.7) into (3.8)

\[ \frac{\partial^2 E_z(\rho, t)}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial E_z(\rho, t)}{\partial \rho} - \frac{1}{c^2} \frac{\partial^2 E_z(\rho, t)}{\partial t^2} = 0 \]  

(3.9)

Given an initial waveform, \( E_z(\rho, t=0) \), equation (3.9) describes how the TEM mode will propagate through the structure.

Some physical insight can be gained by finding solutions to equation (3.9) that form a complete set of orthogonal functions. Let's look for solutions that have the form

\[ E_z(\rho, t) = R(\rho) \ T(t) \]  

(3.10)

Substituting into equation (3.8) and dividing by \( R(\rho) \ T(t) \)

\[ \frac{R''(\rho)}{R(\rho)} + \frac{R'(\rho)}{\rho R(\rho)} - \frac{1}{c^2} \frac{T''(t)}{T(t)} = 0 \]  

(3.11)
This equation is separable into two parts

\[ \frac{1}{c^2} T''(t) + k^2 T(t) = 0 \]  
(3.12)

which has simple sinusoidal solutions, and

\[ R''(\rho) + \frac{1}{\rho} R'(\rho) + k^2 R(\rho) = 0 \]  
(3.13)

This equation can be reduced to

\[ R''(x) + \frac{1}{x} R'(x) + R(x) = 0 \]  
(3.14)

where we have substituted \( x = kp \). This is Bessel's equation of order zero with solutions

\[ R(\rho) = J_0(k\rho) \]  
(3.15)

So

\[ E_2(\rho,t) = J_0(k\rho) \left( A \sin(kc t) + B \cos(kc t) \right) \]  
(3.16)

is one solution of equation (3.9).

We know that if \( k = \frac{\chi_{0n}}{R_0} \), where \( \chi_{0n} \) are the zeros of \( J_0(\chi_{0n}) = 0 \), that

\( \left\{ J_0 \left( \frac{\chi_{0n} \rho}{R_0} \right) \right\} \) form a complete set on the range \( 0 < \rho < R_0 \). Then any arbitrary waveform, \( F(\rho) \), may be represented by
\[ F(\rho) = \sum_n A_n J_0 \left( \frac{x_{0n} \rho}{R_0} \right) \]  

(3.17)

\[ A_n = \frac{2}{R_0^2 J_0^2(x_{0n})} \int_0^{R_0} \rho F(\rho) J_0 \left( \frac{x_{0n} \rho}{R_0} \right) d\rho \]

To solve for the propagation of a TEM pulse into a RTL we solve for the coefficients, \( A_n \), corresponding to the initial waveform and then the solution as a function of time is given by

\[ E_z(\rho, t) = \sum_n A_n J_0 \left( \frac{x_{0n} \rho}{R_0} \right) \cos \left( \frac{x_{0n} c t}{R_0} \right) \]  

(3.18)

if we assume that the waveform was originally static at \( t = 0 \). We chose the cosine part of the time dependence since this sets the magnetic field to zero at \( t = 0 \).

The alternative approach to solving for the propagation of the electric field is to integrate equation (3.9) numerically. Since the TEM solutions are one dimensional, this was very simple to do. Our simulation divided the disk into 100 space cells with equal radial step sizes. Time was incremented in 0.1 ps step sizes. In Figure 3.2 electric field profiles are plotted at different times after the launch of a pulse into a RTL of radius 3.1 cm. The rise of the voltage was taken to be a linear ramp from 0 to \( V_0 \) over 20 ps. The leading edge of the pulse can be seen to increase in amplitude as it
Figure 3.2 Electric Field Profiles in an RTL
These curves are the calculated electric field gain profiles at 25 ps intervals after injection of the electrical pulse. The RTL is assumed to have a 3.1 cm radius. The calculation also assumed the voltage was increased linearly from 0 to $V_0$ at the outside edge.
propagates in toward the center of the structure. After reaching the center it reflects and reverses direction.

In another set of simulations the electric field at the center of the structure was calculated as a function of time. The time evolution of the electric field at a radius of 0.5 mm for a 3 cm RTL is plotted in Figure 3.3 for 3 different risetimes. The field peaks upon arrival at the center and falls off as the pulse reflects back toward the edge of the disk. The peak gains calculated by this method are in good agreement with equation (3.2) which was calculated by Villa. Villa’s calculation was performed by integrating a Bessel function representation of the field (i.e. equation (3.16)).

3.3 Electro-optic Sampling

Electric field measurements were made at the center of a RTL using an electro-optic sampling technique. The electric pulse was switched into the structure at its periphery with a photoconductive switch. The radius of the structure was 3.1 cm and the gap spacing was 2 mm. The electro-optic effect is a phenomenon exhibited in certain crystals when exposed to an external electric field. These crystals have a birefringence which varies as a function of the magnitude and direction of an applied electric field. The electric field in the vicinity of the crystal can be determined by passing a beam of polarized light through this crystal and measuring the amount of optical rotation that is introduced by the birefringence. This can be accomplished by simply passing the beam through a second polarizer and measuring the variation in intensity of the component of polarization perpendicular to the original direction. The electro-optic effect is intrinsically fast and has been used to measure waveforms with a sub-picosecond resolution[6]. This is much faster than measurements that can be made
Figure 3.3 Voltage at the Center of a RTL
These numerical simulations of the voltage at the center of a 3.1 cm RTL were calculated for electrical risetimes of 1, 20 and 50 ps. The voltage at the edge is assumed to rise linearly.
using conventional electronic means. In Figure 3.4 the experimental setup for this sampling measurement is indicated. A portion of the IR switch beam was frequency doubled to the green and split off to probe the electro-optic crystal. The crystal was located at the center of the RTL between the two plates. There were 1 mm holes in either plate to pass the probe beam. The green probe pulse was polarized and passed through a crossed polarizer after exiting the RTL. The electro-optic crystal was KD*P with dimensions 10 mm \times 10 mm \times 2 mm. The IR pulse was used to switch a photoconductive switch that was distributed around the edge of the RTL. The IR beam was upcollimated and then passed through a lens to focus the light into a ring. This lens, shaped roughly like a donut, was specially fabricated for this purpose. When the photoconductive switch was fired an electrical wave was launched into the structure. By varying the path length of the IR switch beam with a translation stage, the relative timing of the probe beam and the IR beam could be set. Thus it was possible to sample the electrical waveform at different times as it propagated through the structure. After the second polarizer, the rotated portion of the green pulse was measured with a PIN photodiode. This signal was averaged by a boxcar integrator (SRS model SR250). The transmitted intensity is given by [7]

\[ I_0 = I_i \sin^2 \left( \frac{\pi}{2} \frac{V}{V_\pi} - \phi \right) \]  \hfill (3.19)

where \( I_i \) is the input intensity, \( V \) is the voltage across the crystal, and the phase offset \( \phi \) is determined by the amount of static birefrigence introduced by the KD*P crystal. \( V_\pi \) is the half wave voltage, which when applied to the crystal induces a retardation of \( \pi \) radians of the polarization along one axis with respect to the other. For KD*P the half wave voltage is 5500 volts for a wavelength of 1 \( \mu \)m. Our measurement was made
Figure 3.4 Electro-optic Sampling Set-up
In this set-up the short light pulse is responsible for both firing the photoconductive switch and sampling the electric field at the center of the RTL with an electro-optic crystal. The temporal structure of the waveform was measured by varying the path length of the IR beam.
with $\phi = 0$, i.e. very little static birefrigence. To be able to convert the measured signal to an actual voltage across the crystal, a calibration was performed. A set of measurements were made with a static DC voltage applied across the crystal. This calibration was used during the sampling phase of the experiment to convert the measured signal to an actual voltage. The calibration is plotted in Figure 3.5. The signal was measured with and without the voltage applied. The relative effect is the difference in signals divided by the signal with voltage off. The shape of the curve in Figure 3.5 is nonlinear, since we are biased close to the minimum of the sine squared function.

The pulselength of the probe beam will affect the time resolution of this sampling technique. A streak camera measurement revealed that the length of the IR pulse was about 20 ps. Another factor influencing the resolution is the transit time of the probe pulse through the crystal. The crystal was 2 mm thick, with an index of refraction of 1.5, so the transit time was 10 ps. Convolving these two factors together gives us a resolution of about 22 ps. The delay between the switching beam and the probe beam was varied in 10 ps steps. Results [8] for a 500 V pulse applied to a 3.1 cm radius RTL with a 2 mm gap are plotted in Figure 3.6. The time structure of the voltage across the center of the crystal appears to consist of a series of peaks spaced with a period of $150 \pm 20$ ps. The interpretation of this data is that the electrical pulse is travelling in from the edge of the disk and some of it is reflecting when it reaches the crystal. The ratio of the electric field that is transmitted through a dielectric interface is given by

$$T = \frac{2n_1}{n_1 + n_2}$$ (3.20)
Figure 3.5 Electro-optic Calibration
This calibration was determined by measuring the optical rotation of the light with, and without voltage applied to the crystal. The relative effect is taken to be the difference of these signals normalized by the signal for no applied voltage. The crystal was tilted such that the static rotation was very small.
Figure 3.6 Electro-optic Sampling Curve
Results from an RTL of 3.1 cm radius and 2 mm gap. This device was switched photoconductively by a laser pulse of 20 ps FWHM. The applied voltage was 500 V.
where $n_1$ is the index of refraction before the interface and $n_2 = \sqrt{\mu\epsilon}$ is the index after the interface. KD*P has a dielectric constant of 49 and index of refraction of 7 in this high frequency range and so we expect that 25% of the pulse will be transmitted in toward the center. The remaining 75% will be reflected back toward the edge of the RTL. The peak of the initial pulse transmitted into the crystal was determined to be 470 volts. Since this represents only 1/4 of the voltage, the gain of the RTL is 4. The energy that was reflected off of the crystal will reflect again at the edge of the structure and return to the center. Thus the periodic nature of the sampling curve is just the ringing of the pulse in the structure. The 150 ps period should equal the time it takes for the pulse to travel from the crystal to the edge of the structure and back again. A TEM electrical pulse will travel at the speed of light in this region, so this round trip time should be 160 ps.

According to equation 3.1, the gain in this structure should be 5.6 if we assume an electrical risetime of 20 ps. A gain of 4 is consistent with a risetime of 45 ps. The risetime of the electro-optic measurement of the initial pulse is 50±20 ps, clearly longer than the IR pulsewidth. Either the risetime of the switched pulse is lengthened at the switch or the pulse is spreading out as it propagates toward the center. In Chapter 2 the geometry dependent risetime of the switch was shown to be

$$T_s = L \sqrt{\mu\epsilon}$$  \hspace{1cm} (2.1)

$$= 5.3 \text{ ps}$$

This will have little effect since our IR pulsewidth is 20 ps.

Passage through the KD*P crystal will also smear the electrical pulse. This arises because the crystal is square and not axially symmetric. The portion of the
wavefront that is transmitted through the corner of the crystal will be slowed down by the larger index of refraction earlier than the portion that enters through the middle of the side. The index of refraction of KD*P for this frequency range is 7. There is a 40 ps range of propagation times through a crystal of this size. This spread in propagation times will result in a broader pulse by the time it arrives at the center of the crystal.

It is also possible that our pulse is dispersing as it propagates through the RTL. It is not obvious from equation (3.18) but our numerical simulations predict that the pulse will travel at the speed of light, c. Dispersion occurs when different frequency components have different phase velocities. In our idealized model, all frequency components travel at c, but we have made some assumptions which, if incorrect, may invalidate this model. The first assumption is that the conducting plates have zero electrical resistivity. If the electrical resistance is non-zero equation (3.9) is no longer valid. The equations governing the propagation of the pulse must be reformulated. A treatment of pulse propagation through the RTL which includes resistive losses is developed in the next section.

3.4 The RTL with Resistive Losses

Consider the propagation of an electrical pulse through an infinitesimal length of transmission line as shown in Figure 3.7. A TEM electrical pulse may be uniquely described as a voltage pulse and an associated current pulse. The differential equation describing the propagation of the voltage pulse through the structure is [9]

\[
\frac{\partial^2 V}{\partial x^2} - (R C - L G) \frac{\partial V}{\partial t} - L C \frac{\partial^2 V}{\partial t^2} - R G V = 0
\]  

(3.21)
Figure 3.7 Equivalent Circuit of a differential length of transmission line (after Ref. 9)
This equation is of limited validity for our situation since \( R, C \) and \( L \) are all functions of \( x \). However providing we keep \( \partial x \) small, we may assume that \( R, C, \) and \( L \) are constant and calculate the local attenuation coefficient and propagation speed for a pulse through this element. We assume a travelling wave solution

\[
V = V_0 e^{-\gamma x - i \omega t} \tag{3.22}
\]

where \( \gamma = \gamma_0 + i \gamma_t \). The attenuation is governed by the factor

\[
e^{-\gamma_0 t}
\]

while the phase velocity is given by

\[
v = \frac{\omega}{\gamma_t} \tag{3.23}
\]

If we substitute (3.22) into (3.21) and divide by \( e^{i \omega t} \) we get

\[
\gamma^2 - i \omega (RC - LG) + LC \omega^2 - RG = 0 \tag{3.24}
\]

In our case \( G=0 \) since we have no current leaking from one plate to the other. The resistance per unit length is given by

\[
R = \frac{R_m}{H} \oint_{S_1 + S_2} B \mathbf{B}^* \, dl \tag{3.25}
\]
where the high frequency surface resistance $R_m = 1/\sigma \delta_s$. The skin depth 
$\delta_s = \sqrt{2/\omega \mu \sigma}$. Here $S_1$ and $S_2$ are the circular paths of constant $\rho$ on either electrode.

In our case

$$B = \frac{1}{2\pi r}$$

$$R = \frac{R_m}{\pi r}$$  \hspace{1cm} (3.26)

The capacitance per unit length is given by

$$C = \frac{\epsilon}{VV^*} \int_S E E^* ds$$  \hspace{1cm} (3.27)

where $S$ is the cylindrical surface of constant $\rho$ extending from the anode to the cathode. The electric field is simply

$$E = \frac{V}{g}$$

So in our case

$$C = \frac{2\pi r \epsilon}{g}$$  \hspace{1cm} (3.28)

The inductance per unit length is
\[ L = \mu \frac{i}{i^*} \int_B B \cdot ds = \frac{\mu g}{2\pi r} \] (3.29)

Therefore equation (3.24) becomes

\[ \gamma = \sqrt{-\mu \varepsilon \omega^2 + i \omega \frac{2\varepsilon R_m}{g}} = \gamma_0 + i \gamma_i \] (3.30)

From equation (3.29) we can calculate

\[ \gamma_0 = \sqrt{\frac{1}{2} \left( \left( \omega^2 \mu \varepsilon \right)^2 + \omega^2 \left( \frac{2R_m \varepsilon}{g} \right)^2 - \omega^2 \mu \varepsilon \right)} \] (3.31)

and

\[ \gamma_i = \sqrt{\frac{1}{2} \left( \left( \omega^2 \mu \varepsilon \right)^2 + \omega^2 \left( \frac{2R_m \varepsilon}{g} \right)^2 + \omega^2 \mu \varepsilon \right)} \] (3.32)

If the conductivity of the metallic disks is high (i.e. \( R_m \) is small) we may approximate

\[ \gamma_0 = \frac{R_m}{g} \sqrt{\frac{\varepsilon}{\mu}} \] (3.33)

\[ \gamma_i = \omega \sqrt{\mu \varepsilon} + \frac{R_m^2}{2\omega \mu g^2} \sqrt{\frac{\varepsilon}{\mu}} \] (3.34)
From the real part, $\gamma_0$, we see that the higher frequencies are attenuated more strongly than the lower frequencies since $R_m$ is proportional to $\sqrt{\omega}$. The conductivity of aluminum is $3.5 \times 10^7 \, (\Omega \, \text{m})^{-1}[10]$. Take, as an example, a wave with a frequency of 1 THz. The characteristic range of this wave, $1/\gamma_0$, is calculated to be 2 m. This wave would have a skin depth of only 92 nm. Lower frequencies will propagate with even less attenuation, and so we expect that resistive losses should not cause serious attenuation of the pulse in our structure.

From equation (3.34) we can calculate the velocity of the frequency components of our wave

$$v = \frac{\omega}{\gamma_1} = \frac{1}{\sqrt{\mu \varepsilon} + \frac{R_m^2}{2\omega^2 \mu^2 \varepsilon \sqrt{\mu}}}$$

(3.35)

for $\omega = 2\pi \times 10^{11} \, \text{Hz}$

$\sigma = 3.5 \times 10^7 \, (\Omega \, \text{m})^{-1}$

$g = 1 \, \text{mm}$

we calculate

$$v = (1 - 1 \times 10^{-7}) \, c$$

We may conclude that resistive losses will have no appreciable effect on the propagation speed or dispersion of the pulse in our structure.
3.5 TM Modes of Propagation

Another mechanism that may be responsible for the risetime degradation of our electrical pulse is the dispersion that occurs between different frequencies in a non-TEM mode of propagation through the RTL. For a TM mode the electric field has a component in the \( \rho \) direction. We must modify equation (3.5) to reflect this

\[
E = E_\rho(\rho,z,t) \hat{\rho} + E_z(\rho,z,t) \hat{z}
\]  
(3.36)

\[
B = B_\phi(\rho,z,t) \hat{\phi}
\]

The field must have a \( z \) dependence since \( E_\rho(z=0) = E_\rho(z=g) = 0 \), if we assume the electrodes are perfect conductors. Substituting these expressions into Maxwell's equations and solving for the differential equation describing the propagation of the \( z \) component of the electric field we get

\[
\frac{\partial^2 E_z(\rho,z,t)}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial E_z(\rho,z,t)}{\partial \rho} + \frac{\partial^2 E_z(\rho,z,t)}{\partial z^2} - \frac{1}{c^2} \frac{\partial^2 E_z(\rho,z,t)}{\partial t^2} = 0
\]  
(3.37)

Again using "separation of variables" we find

\[
E_z(\rho,z,t) = J_0(\kappa \rho)(X \sin(\omega z) + Y \cos(\omega z))(A \sin(\omega t) + B \cos(\omega t))
\]  
(3.38)

The \( E_\rho \) components may be calculated from equation (3.4a)
\[
\frac{1}{\rho} \frac{\partial}{\partial \rho} (\rho E_\rho) = - \frac{\partial E_z}{\partial z}
\]

At the metallic boundaries the \( \rho \) component must vanish, which requires \( \frac{\partial E_z}{\partial z} = 0 \) at \( z=0 \) and \( z=g \). In equation (3.38), this requires that \( X=0 \) and \( h=\frac{m\pi}{g} \), where \( m \) is an integer. We can set \( Y=1 \) since the coefficients \( A \) and \( B \) can absorb any normalization. The coefficients \( k, h \) and \( \omega \) are related by

\[
k^2 - h^2 - \left( \frac{\omega}{c} \right)^2 = 0
\]

(3.39)

Since \( h \) is already defined we see that equation (3.39) relates \( k \) to \( \omega \). As we saw earlier, \( k \) will be determined by the radius over which we wish to define the electric field

\[
k = \frac{\chi_0 n}{R_0}
\]

Therefore \( \omega \) is given by

\[
\frac{\omega}{c} = \sqrt{\left( \frac{\chi_0 n}{R_0} \right)^2 - \left( \frac{m\pi}{g} \right)^2}
\]

(3.40)

If \( \frac{m\pi}{g} > \frac{\chi_0 n}{R_0} \), we find that \( \frac{\omega}{c} \) is pure imaginary and this component will not propagate through the structure but will decay by \( \frac{1}{c} \) over a characteristic distance of
\[
\frac{z_1}{e} = \frac{2g}{m} \left[ 1 - \left( \frac{gX_{de}}{m \pi R_0} \right) \right]^{\frac{1}{2}}
\] (3.41)

For a 3.1 cm radius and a 2 mm gap even for \(m=1\) the first 15 modes are non-propagating. A simulation of the voltage seen at the center of a RTL of radius 3.1 cm and gap 2 mm, was run using the "sum of bessel functions" computer model for a first order TM mode. This is compared with a calculation for a TEM mode in Figure 3.8. Both waveforms had an instantaneous risetime at the edge of the RTL. The peak gain of the TM mode is less than one while the TEM mode peaks at a gain factor of 12. In our structure we expect that the waveform injected into the edge will be a combination of TEM and TM modes. Before the switch is fired, some of the field will "fringe" into the gap. The \(\rho\) components from this fringing will contribute to the TM mode of propagation. The energy in this mode will be attenuated before it can reach the center, lowering the gain of the structure.

3.6 Summary

We have observed voltage gain in a RTL. The voltage waveform injected into our structure was measured electro-optically. The measured gain is consistent with an electrical pulse rise time of 45 ps which agrees with the observed risetime of 50 ps. The optical pulse was measured to be 20 ps FWHM. We have calculated that resistive effects should not cause broadening nor attenuation of the electrical pulse. Coupling into TM modes will result in a loss of electrical energy but not a distortion of the electrical waveform.
Figure 3.8 Comparison of TM1 and TEM modes
Calculations of the electrical waveforms at the center of an RTL arising from TEM and TM1 modes. The risetime at the edge is assumed to be instantaneous. The RTL was assumed to have a 3.1 cm radius and a 2 mm gap.
References


CHAPTER 4

Photoelectron Production

4.1 Introduction

The sources of electrons for particle accelerators have traditionally been thermionic cathodes. These cathodes are heated to a temperature where a substantial number of electrons have a kinetic energy higher than the potential energy that binds them to the cathode. The electrons then "boil off" spontaneously and may be injected into the accelerator. Nowadays, many modern injectors for high energy electron accelerators employ photocathodes to generate electron bunches. The electrons are produced when the cathode absorbs photons in the appropriate frequency range. The photons must have enough energy to overcome the work function of the material. Photocathodes have the advantage that the production of electrons can be controlled by light pulses, and very short bunches can be generated. Also photocathodes can produce extremely bright electron bunches (where brightness is defined as the number of electrons per unit area per solid angle per unit time). These high brightness electron injectors use photocathodes consisting of semiconductor materials, such as GaAs and Cs\(_3\)Sb\([1]\). These materials are used because they have a low work function and a high quantum efficiency. Quantum efficiency is defined as the ratio of the number of photoelectrons produced to the number of photons illuminating the surface. The photocathode materials we have studied are gold and niobium. The material used in the
radial transmission line accelerator is the same gold surface that was evaporated onto the semiconductor wafer to guide the electrical wave.

In our case we wanted to create a bunch of electrons in our structure just as the electrical pulse was arriving at the center. A portion of the light pulse was split off and frequency quadrupled to illuminate the region of the cathode at the center of the radial transmission line structure and generate photoelectrons. The path length of this UV pulse could be adjusted to set the time of arrival at the photocathode to coincide with the arrival of the electrical pulse very precisely.

In this chapter, a discussion of frequency doubling in nonlinear crystals is followed by a section dealing with photoelectron production and yields.

4.2 Frequency Conversion

Certain classes of crystals have a nonlinear dielectric response which upon passage of light of one frequency can give rise to light at the second harmonic. For this to occur the crystal must lack an inversion symmetry and the applied field must produce a component of polarization that is proportional to the square of the field. If the crystal is inversion symmetric, dipoles in it can only oscillate at odd multiples of the field frequency. For maximum efficiency it is important that the fundamental and first harmonic travel at the same speed in the crystal. This ensures that the correct phase relationship between the two waves is maintained and energy is transferred only from the fundamental to the second harmonic and not back. The natural birefringence of some crystals can be exploited to maintain this phase relationship. By choosing the orientation of the crystal with respect to the beam axis, it is sometimes possible to find
an angle where both the fundamental and the harmonic see the same index of refraction, and propagate at the same speed. This angle is called the phase matching angle.

Second harmonic generation was first observed by passing the beam from a ruby laser through a quartz crystal[2]. The conversion efficiency was only 10^{-8}. Since that time many new crystals have been developed and much higher efficiencies are possible.

In order to generate photoelectrons it was necessary to frequency convert the IR beam all the way to the ultraviolet. This was accomplished by doubling the beam from the IR (1054nm) to the green (527nm) and then doubling the green in a second crystal to the UV (263nm). Our experimental setup is shown in Figure 4.1. The first doubling crystal was a Type I beta-barium borate (BBO). The conversion efficiency from IR to green was about 30%. The second crystal was also a Type I BBO but was cut at a different angle. The conversion efficiency from green to UV was about 10%. We split off about 300 μJ of IR from the main beam and after these two conversion processes ended up with about 10 μJ of UV. BBO is very sensitive to correct tuning of the phase matching angle and the beam had to be very well collimated to achieve these efficiencies. We found that 10 μJ of UV was enough to generate a beam of electrons of the required intensity.

After conversion to the UV, the beam had to be transported to the photocathode and this involved the use of many aluminum mirrors. These mirrors had a magnesium fluoride coating to enhance the reflection of UV, and had a reflectivity at our wavelength of 90%. Only 15% of the original UV beam energy was delivered to the photocathode. The beam was focussed with a 1 meter lens, positioned 1 meter away from the photocathode. The beam size was measured by scanning a razor blade across
Figure 4.1 Frequency Conversion
IR light is frequency quadrupled to produce UV. The frequency conversion occurs in two stages: doubling from IR to green, and doubling from green to UV. Overall efficiency is 3%.
the beam and measuring the beam energy. The results, shown in Figure 4.2, indicate a FWHM of 106 μm.

4.3 Photoelectron Emission

The photoelectric effect was first observed by Hertz in 1887 [3]. During his experiment on the transmission of electromagnetic waves he observed that the length of a spark gap could be increased if the electrodes were illuminated from the ultraviolet light from a nearby sparkgap.

In the following year Hallwachs published a study [4] showing that a zinc plate connected to an electrometer would discharge an applied negative charge when illuminated by UV. If the charge applied was positive, the electrometer would not discharge when illuminated. He concluded that negative charges were being emitted by the plate during illumination. Next, Lenard [5] and J.J. Thomson [6] showed that the negative charges being emitted in these experiments were in fact electrons. Lenard also showed that the total number of electrons emitted was proportional to the intensity of the light but that the kinetic energy of the electrons was independent of this intensity. These results seemed to be irreconcilable with the wave nature of light.

In 1905, Einstein [7] conjectured that light could be regarded as coming in discrete units, or quanta. Each unit would have an energy, hv, where ν is the frequency of the light and h is Planck's constant. The kinetic energy of a photoelectron was the difference between the photon energy and the energy required to extract that electron from the surface.

\[
E_k = \frac{1}{2} m v^2 = hν - e\phi
\]  

(4.1)
Figure 4.2 UV Spot Size

Results of a measurement of UV energy as a razor blade was scanned across the beam at the position of the photocathode. The data was fitted with an error function and indicate a FWHM of 106 μm.
where the potential, $\phi$, is called the work function of the metal.

Experimental measurements have confirmed Einstein's theory and provide another method for determining Planck's constant, $h$. In practice it is very difficult to measure the work function of a material definitively. Cleanliness and contaminants may greatly influence the measured value. Changes in the work function of several tenths of an eV have been observed for very slight contamination[8]. Usually the work function decreases upon contamination.

The photocathode materials used in our accelerator were either gold, or a 88:12 mixture of gold and germanium. The gold coating was evaporated onto the silicon wafer to a thickness of 6000Å while under continuous argon ion bombardment. The argon ion beam was used because it was found to greatly increase the adhesion of the gold coating to the silicon substrate. The working pressure during the evaporation was $3 \times 10^{-5}$ torr.

Eastman[9] reports a work function of 5.1±0.1 eV for a polycrystalline gold film which had been evaporated onto a Cr plated quartz substrate. Our UV photon energy was only 4.7 eV yet we observed photoelectron production from our gold surface. Clearly either something must be acting to depress the work function of our sample or we are photoexciting electrons which already have a few tenths of eV of kinetic energy. Another possibility is that the photoelectrons are being produced by 2 photon absorption.

We are not the only group to report photoelectron production from gold with UV energies below 5 eV. Fischer and Srinivasan-Rao [10] report photoelectron production from a gold surface using frequency quadrupled light from a Nd:YAG laser. Their photon energy is slightly less than ours. They measured photoelectron yields of other metals and calculate the quantum efficiencies. They found that plotting the square
of the energy excess, \((h\nu - e\phi)^2\), against the quantum efficiency yielded a straight line for most of the materials studied. Several materials were displaced off of this line, gold being one of them. To get the gold measurement to fall on the line they calculate that its actual work function should be 4.2 eV. They measured a quantum efficiency of \(4.7 \times 10^{-5}\) for gold.

At low intensities we have observed that the electron yield is simply proportional to the intensity of the light falling upon the sample. This is consistent with photoproduction from single photon absorption. At higher intensities there is a departure from this behavior as we get into the regime where the photocurrent is limited by space charge.

Space charge limiting is the phenomenon where the cloud of electrons that have already been emitted impede further photoelectron production because of the electric field generated by them. When it is first created we expect our electron cloud to be roughly pancake shaped, i.e. a thin disk hovering just off of the photocathode surface. (see Figure 4.3). The radius of this distribution will be determined by the UV spot size, usually 50 to 500 \(\mu m\) for our experiments. The thickness will be depend on the initial velocity distribution the accelerating gradient and the UV pulsewidth. For a 2 ps UV pulse, assuming a maximum initial electron energy of 1 eV and an accelerating gradient of 10 MV/m, the maximum distance a photoelectron may have moved by the end of the pulse is just 4 \(\mu m\). This charge distribution will give rise to an electric field that will tend to be directed perpendicular to its flat surfaces. This approximation will not be valid close to the edges of the distribution. But close to the center, the field can be approximated by the field of an infinite charge plane. For an infinite plane of charge in free space, the electric field is perpendicular to it with a magnitude of
Figure 4.3 Initial Photoelectron Distribution
Calculations indicate that the photoelectrons created by a short (2 ps) laser pulse will be distributed in a thin disk close to the cathode.
\[ E = \frac{\lambda}{2\varepsilon_0} \quad (4.2) \]

where \( \lambda \) is the charge per unit area. This field will exist on either side of the plane and has a constant value independent of the distance from the plane. In our case we also need to take into account the "image charge" that arises because the cathode surface is a conducting plane. In the region between the charge distribution and the cathode, this will add another equal contribution to the electric field so, in this region the total electric field will be

\[ E = \frac{\lambda}{\varepsilon_0} \quad (4.3) \]

Note that this approximation is only valid close to the axis of the distribution and in the gap between the distribution and the cathode. An electron in this region will experience a force which will push it back toward the cathode. It is this force which accounts for the limitation of photocurrent by space charge.

The space charge limited current density of a parallel plate diode in steady state has been calculated [11]

\[ J = \frac{4\varepsilon_0}{9} \sqrt[3]{\frac{2e}{m}} \frac{V_0^2}{g^2} \quad (4.4) \]

This equation is known as the Langmuir-Child Law. The derivation of this equation assumes a continuous current flow from one plate to another in a steady state of equilibrium.
A simple diode experiment demonstrates this effect (see Figure 4.4). The photocathode is located parallel to a charge collecting anode with a variable bias supply connecting them. A picoammeter was in series with this bias supply. The gap between the electrodes was 5 mm. UV (253nm) pulses were brought into the gap from the side and struck the photocathode at grazing incidence (<10°). By measuring the average current flowing in the circuit, we were able to determine the number of electrons generated per pulse as a function of the bias voltage. The results are plotted in Figure 4.5 for gold and niobium. The UV energy was 50 μJ per pulse. The spot size at the photocathode was approximately 1 mm². For 50 pC of charge, this represents a surface charge density of 5×10⁻⁵ C/m². In the region between the charge distribution and the cathode we calculate a field

$$E = 5.6 \frac{MV}{m}$$

assuming we are close to the center of the spot. As we increased the bias, we were able to extract more electrons but it appears that these curves are starting to saturate as the field increases. The maximum quantum efficiencies are (5.5±0.1) × 10⁻⁶ for gold and (4.7±0.1) × 10⁻⁶ for niobium.

It is interesting to compare this measurement with the maximum current density predicted by the Langmuir-Child Law, equation (4.4). We observed about 50 pC of charge emitted by the gold cathode at a field of 1 MV/m. The gap was 5 mm, so the applied voltage was 5 kV. The Langmuir-Child Law predicts a maximum current density of 3.3 × 10⁴ A/m². We observed a charge density of 5 × 10⁻⁵ C/m², and in a 2 ps pulse this represents a current density of 2.5 × 10⁷ A/m². One can argue that the
Figure 4.4 Measurement of Electron Yield at Near Grazing Incidence

The charge per bunch of photoelectrons was determined by measuring average current with a pico-ammeter, or by measuring the voltage rise on the input capacitance of an oscilloscope. The gap between the anode and cathode was 5 mm. The UV struck the cathode at 80° off axis.
Figure 4.5 Electron Yield as a Function of Applied Field at Near Grazing Incidence

Results from Gold and Niobium photocathodes. The voltage was varied from 1 to 7 kV dc across a gap of 5 mm. UV (263 nm) pulses with 50 μJ energy struck the photocathode at near grazing incidence (80° off axis).
Langmuir-Child Law does not apply in our case since our electron bunch is pulsed and the system will not be in a steady state.

In Figure 4.6 the setup of a similar experiment is indicated. Here the UV pulse entered the gap through a 0.5 mm hole and struck the gold photocathode at near normal incidence. The gap was 0.5 mm. The emitted photoelectrons escaped through the hole and were collected in a MCP based Faraday cup. Here the UV spot size was focussed down to 106 µm FWHM. The UV pulse energy was 1.7 µJ. The results of this measurement are shown in Figure 4.7. We see the transition from the space charge limited regime to a constant photoelectron yield begin at around 2 MV/m. At a charge density of .09 pC over our UV spot size we can calculate an electric field intensity of 1.2 MV/m, again consistent with our measurement. The quantum efficiency for applied fields greater than 4 MV/m is \((2.4\pm0.1)\times10^{-7}\).

An alternative way of studying this phenomenon is to set the accelerating field constant and vary the UV intensity. At low UV intensities we expect that the electron cloud will not be dense enough to generate a field larger than the applied field and so no space charge limiting behavior should be observed. As we increase the UV intensity we will enter a regime where space charge fields are larger than applied fields and the quantum efficiency will drop. The results of such an experiment are shown in Figure 4.8. The setup is the same as shown in Figure 4.6. The curves were measured at 2 different fields: 3 MV/m and 8MV/m. In both curves we see the presence of 2 regimes: a sharp increase followed by a more gradual increase. The fast rise portion has a fairly constant slope and passes through the origin, indicating a constant quantum efficiency. For the data taken at 3 MV/m we find a quantum efficiency of \((1.4\pm0.1)\times10^{-7}\); for the 8 MV/m data the quantum efficiency is \((3.0\pm0.4)\times10^{-7}\). No space charge effects are present in this regime. Note however that the higher gradient field has twice the
Figure 4.6 Measurement of Electron Yield at Near Normal Incidence
Set-up for the measurement of photoelectron yield with UV incident 5° off axis. Photoelectrons were focussed into the MCP based Faraday cup. The charge was determined by measuring the voltage rise on the input capacitance of the oscilloscope.
Figure 4.7 Photoelectron Yield as a Function of Applied Field at Near Normal Incidence
Results for the measurement of photoelectron yield for a gold surface. The UV was incident at approximately 5° off axis with 1.7 μJ per pulse.
Figure 4.8 Photoelectron Yield as a Function of UV Energy at Near Normal Incidence

Results from measurements at two applied fields: 3 MV/m and 8 MV/m from a gold surface.
quantum efficiency of the lower one indicating that the field is enhancing the photoelectron production. The applied fields may be influencing the yields due to the Schottky effect. Schottky showed [12] that the work function of a conducting surface will be reduced by a factor of

\[ \Delta \phi = \sqrt{\frac{eE}{4\pi \varepsilon_0}} \] (4.6)

For a field of 8 MV/m this reduction is calculated to be 0.10 eV.

At higher UV intensities the slope of the line changes but continues to rise. In the simple space charge model used so far, one would argue that once the space charge field exceeds the applied field, any extra photoelectrons will just be turned around by the net electric field and reabsorbed by the cathode. Thus one would expect the electron yield should approach a constant value. However we need to take note of the fact that our UV spot does not have a sharp edge but falls off rather gradually (see Figure 4.2). Space charge blocking will limit photoelectron production at the center of the spot much sooner than at the edge. As we enter the space charge limited regime, the contribution from the edge of the spot will continue to increase even after the central region has saturated. Thus the yield will continue to increase, albeit at a slower rate, since the rms radius of electron production continues to increase.

This leads us to another feature of Figure 4.8 that must be explained. When we increased the field from 3 MV/m to 8 MV/m, the electron yield increased 20%. If the electron yield is being limited only by space charge, the electron yield should scale proportionately with the applied electric field. Naturally, this can not be so. There are other limits to the number of electrons that can be removed from the surface. There will
be a finite density of electrons in the metal which will be available for photoexcitation. Only conduction electrons can be emitted. These electrons will have a Fermi distribution of velocities. There will be some of the electrons which will have their momentum directed inward from the surface and will be unlikely to be emitted, even if they absorb a photon. Indeed Fowler[13] has shown that photoproduction from a gold surface is strongly dependent on temperature, especially when the photon energy is close to the workfunction limit.

Remember as well that gold is a good reflector of light. At 263 nm, 40% of the light is reflected. The portion that is transmitted only penetrates into the first 50 monolayers or so[14].

4.4 Summary

With frequency quadrupled light from our laser system we were able to produce photoelectrons from a variety of metallic surfaces. We have studied photoproduction at near normal and near grazing incidence. The design of our accelerator calls for photoelectron production from a gold cathode at near normal incidence. If our applied field is great enough to overcome space charge effects we measure a quantum efficiency of $3.0 \times 10^{-7}$ for this case. This value is low compared to measurements made by other groups. Fischer and Srinivasan-Rao have measured gold quantum efficiencies of $4.7 \times 10^{-7}$[10]. The low value of our measurement may be attributable to differences in cleaning of the photocathode and well as a higher operating pressure in our vacuum system. We operated at a base pressure of $1 \times 10^{-6}$ Torr, while Fischer and Srinivason-Rao operated in the $10^{-9}$ Torr range. Our photocathode was cleaned with organic solvents in atmosphere before it was introduced into the vacuum chamber. They also cleaned with solvents, but in addition had a provision to clean the photocathode in situ.
by irradiation with their laser. They claim that the quantum efficiencies could be increased by up to 4 orders of magnitude with this second stage of cleaning.

We found that even working with less than 1 pC of charge per pulse was satisfactory for making measurements of the beam characteristics. We were able to measure the beam energy and charge, as well as focus the beam down to sub-millimeter spot sizes. The next stage of the experiment was to extract the beam from the RTL in pulse biased mode.
References


[9] ibid


CHAPTER 5

Accelerator Results

5.1 Introduction

The electro-optic measurement of voltage gain in an RTL, together with the observation of photoelectron production from gold cathodes, demonstrated that we had the ingredients necessary to construct a switched power linac based on these technologies. To incorporate these two processes together we had to take note of the dynamics of accelerating electrons with a pulsed electromagnetic field. In this chapter a nonrelativistic model of the motion of the electrons in a pulsed electric field is developed. In the following sections, the experimental setup and the results of the electron energy measurement are discussed. Following is a description of the measurement of the amount of charge in each electron bunch and a discussion of the data.

5.2 The Acceleration Model

The final energy of electrons accelerated in a pulsed power device depends critically on the gap size, the electric field gradient, and the duration of the pulse. The phase relationship between the creation of the photoelectrons and the arrival of the electrical pulse also has an effect on the final energy.
The electrons are produced with very little kinetic energy (<1 eV) compared to their final energies (>1 keV), so we may consider the electrons as starting essentially from rest ($v_i=0$). Consider the simple model of a short electrical pulse, $V_0$, applied to an accelerating gap, $g$, for a time $\tau$. The acceleration an electron feels during the application of the pulse is simply

$$a = \frac{F}{m} = \frac{e}{m} \frac{V_0}{g}$$

(5.1)

If the electron starts from rest, the distance it travels during the time, $\tau$, is

$$\Delta x = \frac{1}{2} a \tau^2 = \frac{eV_0 \tau^2}{2g m}$$

(5.2)

providing the electron does not exceed the gap, i.e. $\Delta x < g$. We are using non-relativistic kinematics throughout this discussion, which is justified since the final energy of the electrons never exceeds a few tens of keV. The energy gained is

$$T = F \Delta x = \frac{1}{2m} \left( \frac{eV_0 \tau}{g} \right)^2 \text{ for } \Delta x < g$$

(5.3)

$$= eV_0 \quad \text{ for } \Delta x > g$$

In order for the electron to receive the maximum kinetic energy, it must completely traverse the gap during the application of the electric pulse. Once out of the gap we assume the electric field is zero and no more kinetic energy is gained by the electron. Equation (5.2) provides us with a criterion for determining the maximum gap.
size that the electron will be able to traverse during a time \( \tau \). By setting \( \Delta x = g \), this critical gap is determined to be

\[
g_c = \sqrt{\frac{eV_0\tau^2}{2m}}
\]

(5.4)

As an example, for 1 kV applied for 10 ps, the critical gap is determined to be 0.09 mm. From a practical standpoint, it would be desirable to build structures with larger gaps than this. That would mean operating at higher voltages and longer pulses.

A computer program was written to simulate the propagation of an electron across the gap for an arbitrary electrical waveform. This program assumed a discrete set of electric field values as a function of time and calculated electron position and energy for each time iteration. The time spacing of each iteration was 0.1 ps. The iterations continued until the electron traversed the gap, at which point the final kinetic energy was determined. The kinetic energy gained by an electron is calculated to be

\[
T_r = \sum_{i=1}^{f} eE_i v_i \Delta t
\]

(5.5)

where \( E_i \) is the field at time \( t_i \). At each iteration the electron velocity is recalculated

\[
v_i = \sqrt{\frac{2T_i}{m}}
\]

(5.6)

as well as the incremental change of position

\[
\Delta x_i = v_i \Delta t
\]

(5.7)
The increments were continued to be summed up until the electron left the gap, i.e.

\[ \sum_{i=1}^{f} \Delta x = g \]  

(5.8)

By starting the electrons at different times with respect to the electrical pulse, the effect of varying the time of arrival of the UV pulse with respect to the IR pulse could be modelled. In Figure 5.1 the results of a simulation for a gap size of 0.5 mm for 3 different voltages are shown. The voltage pulse is assumed to be gaussian with a FWHM of 30 ps. The peak of the electric field occurs 100 ps into the simulation. In Figure 5.1a the applied voltage is 1 kV, but the maximum electron energy is only 370 eV. The reason for this is that the electrons cannot get all the way across the gap while the electrical pulse has any significant amplitude. If we use equation 5.4 as an approximation, we note that \( g_c = 0.3 \) mm, which is less than our gap. Notice the shape of this curve. If the electrons are produced much before the peaking of the electric field \( (t_i < 70 \text{ ps}) \), the amount of energy gained is constant. This is expected since in the model they all start with \( v_i = 0 \) and may spend different amounts of time at the cathode, but will all eventually see the same field structure. If they are produced after the field has peaked, they gain less energy because the electric pulse has left the center before the electrons can traverse the gap. The simulation in Figure 5.1b corresponds to a peak voltage of 3.5 kV. Again using equation 5.4 as an approximation we find \( g = g_c \). Indeed our maximum final electron energy is about 80% of the maximum of the applied voltage. The shape of the curve is similar to that of Figure 5.1a indicating that electrons created early are remaining at the cathode until the pulse arrives. In Figure 5.1c the applied voltage is 10 kV and using equation 5.3 we see that \( g < g_c \). This means that the electron can cross the gap in much less time than the width of the pulse. Notice a
Figure 5.1 Simulations of Electron Energies from a Pulsed Electric Field
The electric field is assumed to have a gaussian profile with a FWHM of 30 ps. The motions of electrons across the gap of 0.5 mm are calculated numerically. Peak voltages are a) 1 kV, b) 3.5 kV, c) 10 kV with peaks at $t = 100$ ps.
new feature to the shape of this curve: the peak in the electron kinetic energy at $t = 89$ ps. This corresponds to an electron starting time 11 ps before the peak of the electric field. The peak electron energy is 95% of the maximum value of the applied voltage. Assuming a constant voltage of 10 kV across a gap of 0.5 mm we can calculate a traversal time

$$\Delta t = \sqrt{\frac{2g^2m}{eV}}$$  \hspace{1cm} (5.9)$$

$$= 16.8 \text{ ps}$$

Electrons started at earlier times will not gain as much kinetic energy because the force they experience in the early stages of their traversal is lower. Thus the early energy increments they gain will be lower. Electrons started later than $t = 89$ ps will see higher initial energy gains, but as they approach the end of the gap, the field gradient and the corresponding energy increments will be less. An initial starting time of $t_i = 89$ ps, 11 ps before the peak of the electric field, is optimum for extracting the maximum kinetic energy from the field. Electrons started before $t_i = 60$ ps gain only about 7550 eV of energy; 80% of the maximum. The simulation indicates that they leave the gap at $t_f = 100$ ps.

The final energy of the electrons scale as the mean electric field they feel averaged over space, not averaged over time.
5.3 Experimental Set-up

A series of experiments were conducted where photoelectrons were accelerated in a RTL and their energies were measured. The experimental setup is shown in Figure 5.2. The laser pulse was partially converted to UV to create the bunch of photoelectrons, while the remaining IR portion fired a photoconductive switch which launched the electrical wave into the RTL. The path length of the UV pulse was variable so that the final electron energy could be determined as a function of the relative time of photoelectron generation to the arrival of the electrical pulse. The RTL was housed in a vacuum chamber held at $1 \times 10^{-6}$ Torr. The IR pulse passed through a saturable absorber before being up collimated and focussed into a ring using the "donut" lens. The focal length of the "donut" lens was long enough to allow these focussing elements to sit on the optical table outside of the vacuum chamber. The IR light entered the chamber through an 8" glass viewport. The UV entered through a separate 1" quartz viewport. Adjustments to both of these beams was possible outside of the chamber. A schematic of the inside of the chamber appears in Figure 5.3. The UV was reflected off of a mirror slightly off-axis toward the accelerator. The UV beam entered through a hole in the anode and illuminated the cathode at near normal incidence. The accelerated electron beam exited the accelerator through the same hole and travelled about 50 cm before striking a single stage imaging MCP. Behind the MCP was an image intensifier with a fluorescent screen and the beam profile was either viewed directly or recorded with a CCD camera. Before striking the MCP the electrons passed through a stopping grid which could be biased by a variable high voltage power supply. By adjusting the bias on the grid it was possible to determine the electron
Figure 5.2 Operation of the RTL Accelerator

Four percent of the IR beam was used to make UV to create photoelectrons. Most of the remaining IR was used to fire the photoconductive switch, which launched the electrical wave into the RTL. A fraction (4%) of the IR beam was split off and delayed 2 ns to fire a switch which discharged the accelerator. The relative timing of the IR and UV beams was varied with a delay line in the UV line.
Figure 5.3 Setup in the Vacuum Chamber
The electron beam emitted from the RTL accelerator was focussed by an axial solenoid onto an imaging MCP.
energy. Electrons were prevented from passing through the grid when the bias was set to a potential greater than their kinetic energy. The stopping grid was tested with a DC electron gun. It was possible to set the stopping potential to within 30 V of the electron energy. The calibration was found to be 1 V : 1 eV up to a voltage of 4.5 kV. Above 4.5 kV field emission from the grid was great enough to obscure the electron signal from the gun. One drawback of using a stopping grid is that it measures the maximum electron energy but does not give a measurement of the energy spread.

To obtain a small spot on the fluorescent screen it was necessary to focus the beam. This was achieved by using a thin solenoid with an axial field which, as is known, provides a point to point focus for a monochromatic beam. The focussing solenoid was positioned half way between the accelerator and the imaging MCP. The electrons passed through the center of the solenoid with the magnetic field parallel to the beam axis. Refer to Figure 5.4 for a review of the theory governing the focussing of a beam of electrons. The source and focal point are at equal distance from the solenoid. A typical electron trajectory is shown in the figure. The longitudinal component of the electron momentum is not affected by the magnetic field. The transverse component will be rotated by the magnetic field. Focussing occurs when the magnetic field is set to a value where the momentum component of the electron perpendicular to the field will be turned around 180° by the field. If this is the case the transverse momentum will carry the electron back to the axis after it passes a distance equal to the distance from the source to the solenoid.

We will now derive the equations governing the focussing of the solenoid. An electron with transverse velocity \( v_\perp \) will orbit in a circle of radius \( r \) when the magnetic field is
Figure 5.4 Focussing Solenoid
An electron emitted at the source will be focussed back onto the axis at an equal distance from the solenoid, if the magnetic field \( B \) is set to the correct value for the electron’s longitudinal component \( p_z \). This will happen regardless of the transverse momentum, \( p_{\perp} \).
\[ B = \frac{m v_\perp}{e r} = \frac{m \omega}{e} \]  \hspace{1cm} (5.10)

where \( \omega \) is the cyclotron frequency. To reverse the direction of the transverse velocity it is necessary that

\[ \omega \Delta t = \pi \]  \hspace{1cm} (5.11)

where \( \Delta t \) is the time the electron spends in the magnetic field. This time will depend on the length of the solenoid, \( \ell \), and the velocity of the electron parallel to the field, \( v_z \). From this we may determine the field to be

\[ B \ell = \frac{\pi m_e v_z}{e} \]  \hspace{1cm} (5.12)

or more generally

\[ \int B d\ell = \frac{\pi p_z}{e} \]  \hspace{1cm} (5.13)

Note that this formula depends only on the momentum of the electron parallel to the field. Providing \( p_\perp \) is much less the \( p_z \) the electrons will all focus at the same point. The magnetic field is proportional to the current flowing through the solenoid. It is possible to calibrate the solenoid by measuring the focussing current as a function of the kinetic energy of the electrons. This calibration should have a square root relationship since the kinetic energy is proportional to the square of momentum. In Figure 5.5 a calibration of the solenoid used in our experiment is shown. The solenoid was 4 cm long with an inner diameter of 1.5 inches and approximately 1200 turns. The
Figure 5.5 Solenoid Calibration
The solenoid was calibrated by measuring the current required to focus an electron beam from a dc gun. A least square fit to this data gives a calibration, $I_{\text{focus}} = 5.1 \sqrt{\text{mA/}\sqrt{\text{eV}}}$
electron source used in the calibration run was a parallel plate accelerator with a gap of 0.5 mm and a hole of 0.5 mm. It was biased with d.c. voltage and the solenoid current was adjusted to give the best focus for a range of electron energies from 0.4 to 4.4 keV. The calibration is very well fit by the relationship

$$I = 5.1 \frac{mA}{\sqrt{eV} \sqrt{T}}$$

(5.14)

A digitized image of the focussed electron spot is shown in Figure 5.6. It was possible to focussed down to 2 mm² sizes. The focussing solenoid could also be used to measure the kinetic energy of the electrons. We can also calculate what the coefficient relating the solenoid current to the square root of the electron energy should be. We start with Ampere’s Law

$$\oint Bdl = \mu_0 NI$$

(5.15)

Substituting into equation (5.13) we find

$$I = \frac{\pi p_{\infty}}{\mu_0 Ne} = \frac{\pi \sqrt{2mT}}{\mu_0 Ne}$$

(5.16)

Substituting in the values for our solenoid we find

$$\frac{\pi \sqrt{2m}}{\mu_0 Ne} = 7.0 \frac{mA}{\sqrt{eV}}$$

(5.17)

in good agreement with our measurement.
Figure 5.6 Electron Spot Size

The axial solenoid focused the beam to a 1.5 mm diameter. The diameter of the MCP is 25 mm. This image was digitized with a CCD camera.
Low energy electron beams are susceptible to deflection by weak magnetic fields. For instance the displacement off axis for an electron beam of kinetic energy $T$, in a region of length $L$ is

$$
\Delta x = \frac{eBL^2}{2\sqrt{2}Tm}
$$

(5.18)

For $T = 1 \text{ keV}$, $L = 0.5 \text{ m}$ and $B = 1 \text{ gauss}$ we find $\Delta x = 12 \text{ cm}$. Considering the scale of this deflection we decided to eliminate stray magnetic fields as much as possible by magnetically shielding the path of the electrons.

In the experimental set-up shown in Figure 5.3 there is a Faraday cup mounted onto a manipulator which could be moved into the beam to measure the amount of charge per electron pulse. This Faraday cup consisted of a single stage microchannel plate (MCP, Galileo EO Chevron 6025) in front of a charge collecting flat copper anode. The MCP was 1" in diameter, grounded on the front surface and biased to +900 V on the back. The purpose of this MCP was to amplify the number of electrons to a level where they were detectable over the noise in the laboratory. There were many sources of noise, but most was generated by the firing of the Pockel's cells and the HV pulser. The gain of the MCP, $G_{\text{MCP}}$, was 6320 for an applied voltage of 900 V. This was enough to amplify our signals to the 100 mV level, well above the noise. The current collecting anode was a copper disk 1" in diameter biased to 1350 V. This bias was necessary to draw the electrons from the back of the MCP into the anode. The anode was connected to an oscilloscope through a 1 nF blocking capacitor. The capacitor passed the fast signal that was generated by the electron bunch but isolated the oscilloscope from the dc bias. The signal measured at the oscilloscope was a decaying exponential. Conversion of the signal to the amount of charge was dependent on the
capacitance of the scope input, of the connecting cables, and other stray contributions. This capacitance was determined by observing the decay time of the signal across the 1 MΩ input impedance of the scope. It was found to be \( C_{\text{eff}} = 60 \) pF. The conversion from signal amplitude, \( V_{\text{obs}} \) in volts, to charge in the electron pulse absorbed, \( Q \), is

\[
Q = \frac{V_{\text{obs}} C_{\text{eff}}}{G_{\text{MCP}}} = 9.5 V_{\text{obs}} \text{ (fC)} \tag{5.19}
\]

The electrons were focussed onto the Faraday cup by the solenoid. The Faraday cup was positioned as close to the central axis of the solenoid as possible. It was not possible to position the Faraday cup exactly on axis because its mounting hardware would clip the UV beam. Setting the current of the solenoid correctly was critical to maximizing the signal measured at the Faraday cup. A study was done to compare the amount of charge collected to the solenoid current for a dc accelerator. The results are given in Figure 5.7 for a 1 keV beam. As the focussing current was increased, the amount of charge collected increased, presumably since the radius of the focal spot was decreasing and more charge was being concentrated into the detector. At a current of 200 mA, there is a sharp decrease in the charge collected. This is because the charge has been focussed down to a small area on the axis of the solenoid, which is small enough that little charge is hitting the MCP located slightly off axis. As the current is increased further, the focal spot grows, since the transverse momentum is being rotated by more than 180°. Initially the charge collected will rise since the spot will start to overlap the MCP again but later it will drop and reach a minimum when the momentum is rotated a full 360°. This occurs around a current of 450 mA. As the current continues to rise the electrons will again begin to focus, reaching the tightest focus when the transverse momentum is rotated by 1 1/2 revolutions, 540°, as can be
Figure 5.7 Charge Collected as a function of Solenoid Current
The charge emitted from a dc gun was measured as a function of the current flowing through a focussing solenoid placed halfway between the gun and the Faraday cup. The dc gun was operated at 1 kV.
seen in the figure. The calculated value of the current for the first focus is 160 mA. The MCP should be fairly efficient at collecting electrons with keV energies. The manufacturer's estimate of the efficiency of this MCP is given in Figure 5.8. For 1 keV the estimate is between 50% and 75% efficient. We take the best estimate of the MCP's efficiency to be 62%. If we also note that since the edge of the MCP is off axis the most optimistic overlap between the focussed electron spot and the front of the MCP is 50%. This gives us a revised conversion efficiency of signal amplitude to charge of the bunch of 31 fC/V.

Data were taken for different gap widths, and for a series of applied voltages for each gap. For each configuration, the energy and current of the electron pulse were measured as a function of the relative delay between the IR and UV pulses. The electron energy varies with this relative timing and so the solenoid current was adjusted at each point to maximize the signal. Energy and current could not be measured simultaneously, but had to be determined from different runs. Most of the data was obtained with the laser pulsewidth less than 2 ps and with 10 mJ in the IR and 20 µJ in the UV. The repetition rate was typically 0.36 Hz. It was discovered that good radial gain in the accelerator was only observed when the pedestal and prepulses were removed from the IR switch beam. The most effective way to accomplish this was by passing this beam through a saturable absorber of the proper concentration. In order to minimize the possibility of electrical breakdown across the switch a second switch was added to the circuit which discharged the applied voltage 2 ns after the main switch should have fired. In case the main switch misfired, this would prevent the energy stored in the charge line from being dissipated in the RTL. The UV pulse was focussed down to 100 µm on the photocathode.
Figure 5.8 MCP Efficiency

This is the manufacturers estimate of the range of efficiencies that the MCP may operate at. We have taken the best estimate of 62% for a 1 keV beam of electrons.
5.4 Electron Energy Measurements

Most of the electron energy measurements were made using the stopping grid described in the last section. The electron energy as a function of the relative delay for four gap spacings are shown in Figures 5.9 through 5.12. As in the case of the electro-optic sampling data there are multiple peaks due to the reflection of the electric pulse from the center to the outside edge and back. As can be seen from the data, the structure of these reflected peaks is strongly dependent on the gap width. In this section, only the details of the first peak are discussed. A treatment of the reflections occurs in the next section.

If one considers the initial part of each curve, up to the first peak, the qualitative resemblance to the computer simulation is apparent. The flat energy in the early part of the curves was observed in the simulation to occur because the electrons remain at the cathode until the electrical pulse arrives. Electrons produced nearer the peak of the pulse gain more energy since they are traversing the gap while the field is close to its maximum value. The gains are highest for the smaller gaps as would be expected for a short electrical pulse. In Table 5.1 the ratios of electron energy to applied voltage for different gaps are listed. The average gradient seen by the electron bunch is also listed in this table. The computer simulation was used to extract the shape of the electric field from the data. This was accomplished by fitting the output of the simulation with a set of experimental data points. The shape of the electric field was assumed to be gaussian in time and the amplitude and width were adjusted to give the best least squares fit. A fit of the initial peak of Figure 5.10 is shown in Figure 5.13. The electric field in the simulation was gaussian in time with a peak amplitude of 2560 V and a FWHM of 39
ps. The voltage applied in the experiment was 757 V so the voltage gain in the RTL structure was 3.38 according to this fit. The risetime of the electric field in the simulation is 46 ps (10% to 90%). From equation 3.2 we would expect a gain of 4.16 for this risetime in an RTL with dimensions corresponding to the structure in the experiment. These values are consistent with our electro-optic measurement of the electric field.

Table 5.1 First Peak

<table>
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<th>0.25</th>
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<td>3.37</td>
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<tr>
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</tr>
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<td>5.1</td>
<td>1.1</td>
<td>0.6</td>
</tr>
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<td>48±8</td>
<td>52±10</td>
</tr>
<tr>
<td>pulsewidth (ps)</td>
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</tbody>
</table>

It was discovered that the final electron kinetic energy had no dependence on hole size over the range of holes we tried (0.5 to 2.0 mm).

The role of the switch was explored by comparing the electron energy sampling data using two different photoconductive materials. In each case the RTL had a 0.5 mm gap and a 3.1 cm radius. The results are plotted in Figure 5.14. The data indicates that the effect of the switch is very small; most of the features of the curve appear to depend on the geometry of the RTL. There is a slight difference in the period of ringing of the pulse in these two measurements. The period for the structure with a

106
Figure 5.9 Electron Energy Sampling Curve for a RTL with a 0.25 mm gap
The ratio of electron energy to applied voltage as a function of the delay between the IR switch and UV electron-generating pulses. The errors in the energy are equal to the size of the points. The applied voltage was 658 V.
Figure 5.10 Electron Energy Sampling Curve for a RTL with a 0.5 mm gap
The ratio of electron energy to applied voltage as a function of the delay between the IR switch and UV electron-generating pulses. The errors in the energy are equal to the size of the points. The applied voltage was 757 V.
Figure 5.11 Electron Energy Sampling Curve for a RTL with a 1.0 mm gap
The ratio of electron energy to applied voltage as a function of the delay between the IR switch and UV electron-generating pulses. The errors in the energy are equal to the size of the points. The applied voltage was 666 V.
Figure 5.12 Electron Energy Sampling Curve for a RTL with a 2.0 mm gap
The ratio of electron energy to applied voltage as a function of the delay between the IR
switch and UV electron-generating pulses. The errors in the energy are equal to the size of
the points. The applied voltage was 688 V.
Figure 5.13 The Model Fit to the Data
The data points are taken from the first peak of the data displayed in Figure 5.10. The model assumed a gaussian voltage pulse of amplitude 2560 V and FWHM of 39 ps. These parameters were derived from a least squares fit to the data.
Figure 5.14 Comparison of Switch Materials
The data in these two curves were collected from two RTL accelerators with the same dimensions: 0.5 mm gap and 3.1 cm radius. The only difference was the switch materials: silicon vs. gallium arsenide.
silicon switch is about 240±15 ps while the GaAs based structure has a period of 250±15 ps.

A sampling set of data was collected where the electron energy was measured by determining the solenoid current necessary to focus the electron spot, as well as using the stopping grid. This data is displayed in Figure 5.15. The electron energies based on the solenoid current were calculated using equation 5.17. The agreement between the two sets of data gave us confidence that this technique could be used to determine electron energies that were beyond the reach of the stopping grid. The focussing current technique also gave an indication of what the electron energy spread was. It was noted that variations in the focussing current of 3% did not significantly affect the focussed spot size. This is consistent with an energy spread of about 6%.

With this new method of measuring the electron kinetic energy it was possible to increase the voltage applied to the structure up above what had previously been possible. The RTL was set up with a 0.25 mm gap and a 3.1 cm radius. The switch material was GaAs. The advantage of using GaAs is that it has a higher "off" resistance and so less power is dissipated in the switch while the HV pulser was ramping up to maximum voltage. With a Si switch it was found that the resistance of the switch (~ 2 kΩ) was low enough to load down the HV pulser at higher voltages. GaAs has also been found to have a higher hold-off voltage, i.e. it can be pulsed to higher voltages before breaking down. The translation stage for the path length of the UV pulse was set such that the electron energy was maximized. The electron energy at this point was measured as a function of the applied voltage. The ratio of the electron energy to the applied voltage for this structure remained in the range of 3.3 as the voltage was increased gradually up above 3 kV. These data are shown in Figure 5.16. At a voltage of 3.4 kV applied to the outside of the RTL the switch failed. The
Figure 5.15 Comparison of Electron Energy Measurement Techniques
These two data sets were taken during the same run. The RTL had a 0.25 mm gap and a 3.1 cm radius. The measurements were made using both the stopping grid and the focusing solenoid. Agreement is excellent.
Figure 5.16 Electron Energy vs. Applied Voltage
These data were collected from a RTL with a 0.25 mm gap. The slope is $3.33 \pm 0.06$ eV/V.
previous measurement was made at an applied voltage of 3.33 kV. The measured electron energy was 11.1 keV. Across a 0.25 mm gap this represents an average accelerating gradient in excess of 44 MeV/m. The failure of the device was not reversible. Microscopic examination of the switch revealed that an arc had punched a hole through the GaAs wafer. There was no evidence of arcing having occurred across the gap which separated the electrodes.

5.5 Reflections, Pulse Propagation and Impedance Matching

The reflections or “ringing” of the electrical pulse is observed in all of the data sets. In the data from the electron energy studies it is observed that the gap spacing strongly affects the structure of these reflections. The time interval between reflections is around 250 ps corresponding to a speed of propagation $v = 0.8 \, c$ for the round trip distance of 6.2 cm.

The reflected power at the outer edge of the RTL depends on the mismatch between the impedance of the feed structure and the RTL impedance. The impedance of the RTL is given by

$$Z_2 = 377\Omega \frac{g}{2\pi r}$$  \hspace{1cm} (3.3)

The impedance of the feed structure is not so straightforward to calculate. The region beyond the switch is loaded with G10 and the semiconductor substrate. The impedance can be estimated by assuming the effective gap is given by the sum of the thicknesses of these layers divided by their dielectric constants. For a 0.5 mm thick region of Si ($\varepsilon = 11.8$), on top of a 0.5 mm layer of G10 ($\varepsilon = 4.6$) the effective thickness is 0.15 mm
and the effective impedance is 0.29 $\Omega$. The reflection coefficient at the interface between these two regions is

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2} \quad (5.20)$$

Successive pulses should be attenuated by the factor $R$. We can use the ratio of electron energies from the first and second peaks to estimate $R$ and the value of $Z_2$ calculated from equation (3.3) to find an empirical value of $Z_1$ from equation (5.20). In Table 5.2 these values are listed for the four gaps studied. The values we determine for

<table>
<thead>
<tr>
<th>Table 5.2 Reflection Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap (mm)</td>
</tr>
<tr>
<td>$R$</td>
</tr>
<tr>
<td>$Z_2$ ($\Omega$) (calculated)</td>
</tr>
<tr>
<td>$Z_1$ ($\Omega$) (empirical)</td>
</tr>
</tbody>
</table>

$Z_1$ are all consistent and average to $Z_1 = 0.29 \pm 0.06 \Omega$. An interesting conclusion of this analysis is that, except for the smallest gap there is a significant impedance mismatch into the RTL which inhibits the amount of power transferred when the switch is fired. At the matched condition, maximum power is transferred but only half of the voltage and this may explain why the electron energy did not increase in going from a 0.5 mm gap to 0.25 mm. In Chapter 2 it was noted that the voltage switched was

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\[ V = V_0 \frac{Z_2}{Z_1 + Z_2} \]  

(2.1)

We have determined an empirical value for the impedance outside of the switch, \( Z_1 = 0.29 \pm 0.06 \, \Omega \). The RTL impedance, \( Z_2 \), has been calculated from equation 5.11. For the 0.5 mm gap we find that 78\% of the applied voltage is injected into the RTL. For the 0.25 mm gap, the value is only 63\%. An estimate of the voltage gain in the RTL can be made if we assume that the electron energy is an indication of what the voltage at the center was. This is a good approximation at small gaps. The voltage injected into the RTL at the edge is related to the applied voltage by equation (5.20). The estimated voltage gain is the ratio of the electron energy to the calculated injected voltage. These values are tabulated in Table 5.3. The estimated gain for the 0.25 mm gap is 5.1. Using Villa's formula, equation (3.2), we find that this value is consistent with a electrical risetime of 31 ps consistent with our fit of the pulsewidth of the electrical pulse.

<table>
<thead>
<tr>
<th>gap (mm)</th>
<th>0.25</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>V/V_0</td>
<td>0.63±0.05</td>
<td>0.78±0.04</td>
<td>0.87±0.02</td>
<td>0.93±0.01</td>
</tr>
<tr>
<td>estimated voltage gain</td>
<td>5.08</td>
<td>4.32</td>
<td>2.00</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table 5.3 Impedance Mismatch

We are now in a position to tie together several aspects of our model of the operation of this accelerating structure. We can calculate an estimate of the ratio of the final electron energy to the applied voltage based on just a few parameters. These
parameters are the geometry of the RTL, the applied voltage, the estimated electric pulsewidth that was determined from the data and is listed in Table 5.1, and our estimate of the impedance of the feed structure. From the impedance mismatch we have calculated the fraction of the voltage, $V/V_0$, that is launched into the RTL when the switch is fired. Next we calculated the gain factor of the RTL from equation (3.2) and multiplied by the mismatch factor and the applied voltage to get an estimate of the peak voltage at the center of the structure. This peak voltage and the pulsewidth were then used in the program that simulates the propagation of the electron bunch across the gap. The electric waveform was assumed to be gaussian. From this simulation we calculated what the maximum electron kinetic energy should be. These calculations are summarized in Table 5.4. The estimated electron energies compare well to the measured

<table>
<thead>
<tr>
<th>Table 5.4 Final Energy Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap (mm)</td>
</tr>
<tr>
<td>estimated electrical pulsewidth (ps)</td>
</tr>
<tr>
<td>$V/V_0$ (Table 5.3)</td>
</tr>
<tr>
<td>radial gain (eqn. 3.2)</td>
</tr>
<tr>
<td>applied voltage (V)</td>
</tr>
<tr>
<td>estimated peak voltage (V)</td>
</tr>
<tr>
<td>maximum kinetic energy from model (eV)</td>
</tr>
<tr>
<td>measured kinetic energy (eV)</td>
</tr>
</tbody>
</table>
values at small gap sizes. At large gap sizes the model predicts that the energy of the electrons should have been higher than what was observed.

The velocity of propagation across the RTL is also dependent on the gap width. Table 5.5 summarizes the observed speeds of propagation. The decrease in group velocity due to resistive effects can be calculated from equation 3.55. This effect turns out to be negligible compared to the observed decrease in velocity. Clearly some other mechanism must be responsible.

Table 5.5 Pulse Propagation Velocity

<table>
<thead>
<tr>
<th>gap (mm)</th>
<th>0.25</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>period (ps)</td>
<td>273±20</td>
<td>250±15</td>
<td>238±15</td>
<td>233±10</td>
</tr>
<tr>
<td>velocity (c)</td>
<td>0.76±0.06</td>
<td>0.83±0.05</td>
<td>0.87±0.06</td>
<td>0.89±0.04</td>
</tr>
</tbody>
</table>

One approach is to return to the transmission line analysis developed in Chapter 3. The velocity of a pulse in a transmission line is given by

\[ v = \frac{1}{\sqrt{LC}} \]  

(5.21)

In Chapter 3 the capacitance and inductance per unit length were determined to be

\[ C = \frac{2\pi r e}{g} \quad \text{and} \quad L = \frac{\mu g}{2\pi r} \]  

(3.28, 3.29)

Substituting into equation 5.12
\[ v = \frac{1}{\sqrt{\mu \varepsilon}} = c \]  \hspace{1cm} (5.22)

Let us modify the definitions of \( L \) and \( C \). We will add a correction term to each of these properties.

\[ L_{\text{corr}} = \frac{\mu g}{2 \pi r} + L'(r,g) \]  \hspace{1cm} (5.23)

\[ C_{\text{corr}} = \frac{2 \pi r \varepsilon}{g} + C'(r,g) \]  \hspace{1cm} (5.24)

Then the velocity of the pulse is given by

\[ v = \frac{1}{\sqrt{\mu \varepsilon + \frac{\mu g}{2 \pi r} C' + \frac{2 \pi r \varepsilon}{g} L' + L'C'}} \]  \hspace{1cm} (5.25)

The pulse will travel slower than the speed of light when \( L' \) and \( C' \) are positive values. Rather than work from equation 5.25 it is easier to assume a more general form and then use equation 5.25 to relate our form to \( C' \) and \( L' \). We assume the relationship between the velocity and gap to be given by

\[ v = \frac{1}{\sqrt{1 + f(g)}} c \]  \hspace{1cm} (5.26)

Empirically it was found that a good fit to the data could be made if we assume a form,
\[ f(g) = \frac{1.088 \times 10^{-2}(m)^{\frac{1}{2}}}{\sqrt{g}} \]  

(5.27)

Values for the velocity of the pulse calculated from this assumed form are compared with the measured values in Table 5.5. The form \( f(g) \) can be related to the functional forms \( L' \) and \( C' \) from equation 5.25. If we assume \( C' = 0 \) we find that the correction to the inductance per unit length is given by

\[ L' = \frac{1.088 \times 10^{-2}\sqrt{g}}{2\pi re c^2} \]  

(5.28)

If we assume \( L' = 0 \) we find that

\[ C' = 1.088 \times 10^{-3} \frac{2\pi r}{\mu c^2(g)^{\frac{3}{2}}} \]  

(5.29)

Note that these corrections are both related to their nominal values given in equations 3.28 and 3.29 by

\[ \frac{L'}{L} \text{ or } \frac{C'}{C} = \frac{1.088 \times 10^{-2}(m)^{\frac{1}{2}}}{\sqrt{g}} \]  

(5.30)

The ratios of these values is also included in Table 5.6.
Table 5.6 Impedance Correction Terms

<table>
<thead>
<tr>
<th></th>
<th>gap (mm)</th>
<th>0.25</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{\text{calc}}$ (c)</td>
<td>0.77</td>
<td>0.82</td>
<td>0.86</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>$v_{\text{obs}}$ (c)</td>
<td>0.76</td>
<td>0.83</td>
<td>0.87</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>L'/L or C'/C</td>
<td>0.69</td>
<td>0.49</td>
<td>0.34</td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

We also note that the width of the peaks in the electron energy increase with each successive reflection. This indicates that the electrical pulse is broadening as it reflects back and forth in the RTL. Broadening can either occur due to frequency dispersion (i.e. different frequencies having different phase velocities) or due to attenuation of the high frequency components of the pulse. In Figure 5.17 a simulation of the effect of the loss of high frequency terms is shown. In one curve the simulation consists of a summation of the first 27 bessel function modes describing a pulse with an instantaneous risetime at the edge. In the second curve only the first 5 modes are summed; the higher mode coefficients are all set to zero. Not only is the peak amplitude decreased but the overall width of the pulse is broadened. There is no dispersion introduced in this simulation, the broadening is due solely to the loss of the high frequency components.

The electromagnetic pulse propagates in the RTL dominantly in the TEM mode. Coupling to TM modes, as well as energy loss at the center of the structure due to radiation from the hole are also possible causes of attenuation and distortion of the electrical pulse in the structure.
Figure 5.17 Loss of the High Frequency Components
These simulations were made for a 3.1 mm radius RTL. The time evolution of the field at the center of the structure is plotted for Bessel's series solution of a pulse with an infinitely fast risetime. In one case the series was truncated at the 27th mode; in the other case the series was truncated at the 5th mode.
5.6 Charge Measurement

Measurements of the electron yields for the four gap spacings were made by moving the Faraday cup into the path of the electron beam. The data were collected by varying the relative delay between the IR and UV pulses. The electron energy varies with this relative timing and so the solenoid current was adjusted at each point to maximize the signal. The UV pulse was focussed down to 100 μm on the photocathode. The results of these measurements are shown in Figures 5.18 to 5.22 for the four gap spacings. The ringing of the electrical pulse in the structure is of course reproduced by these data. The peaks in the curve indicate that when photoelectrons are produced in the presence of the electric field the quantum efficiency is higher. This is explained by the field overcoming the space charge effects. In this measurement we find that the photoelectron production follows the electric field with a response time of less than 10 ps. In the set of kinetic energy measurements it was noted that the damping of the electric field pulses is greater for the smaller gaps. Again we note this behavior in the charge data: the amount of charge produced during the reflections in the electric field falls off faster for the shorter gaps. Note that there is more charge measured from the structures with large gaps than for the smaller gaps. There was up to 183 fC of charge measured from an accelerator with a 2 mm gap. For a pulse length of 2 ps and a spot of radius 50 μm, the current density is 1.2 kA/cm². Since the structures with larger gaps will have a lower electric field one would expect that these structures should produce less charge. The fact that we observe the opposite of this indicates that the geometry of the structure is influencing the amount of charge
Figure 5.18 Electron Charge Measurement for a RTL with a 0.25 mm gap and 0.25 mm hole
A measurement of the charge of the emitted electron bunch as a function of the relative time between the IR switch pulse and the UV electron-generating pulse. The hole size was 0.25 mm diameter.
Figure 5.19 Electron Charge Measurement for a RTL with a 0.25 mm gap and 0.5 mm hole
A measurement of the charge of the emitted electron bunch as a function of the relative time between the IR switch pulse and the UV electron-generating pulse. The hole size was 0.5 mm diameter.
Figure 5.20 Electron Charge Measurement for a RTL with a 0.5 mm gap
A measurement of the charge of the emitted electron bunch as a function of the relative time between the IR switch pulse and the UV electron-generating pulse. The hole size was 0.5 mm diameter.
Figure 5.21 Electron Charge Measurement for a RTL with a 1.0 mm gap
A measurement of the charge of the emitted electron bunch as a function of the relative time between the IR switch pulse and the UV electron-generating pulse. The hole size was 1.0 mm diameter.
Figure 5.22 Electron Charge Measurement for a RTL with a 2.0 mm gap
A measurement of the charge of the emitted electron bunch as a function of the relative time between the IR switch pulse and the UV electron-generating pulse. The hole size was 2.0 mm diameter.
measured. The effect of the hole size is not as pronounced as the effect of the gap although we do measure slightly more charge from structures with larger holes.

We can calculate what the maximum current density is predicted by the Langmuir-Child law for this geometry and voltage from equation (4.4). For an applied voltage of 1.2 kV and a gap of 2 mm, this law predicts a maximum current density of $2.4 \times 10^4$ A/m$^2$. We estimate our current density to be $1.2 \times 10^7$ A/m$^2$. This discrepancy is due to the fact that the Langmuir-Child Law is not valid for a pulsed cathode.

It is interesting to note the effect of the amount of UV striking the photocathode. In Chapter 4 it was noted that the electron yield increased for increasing UV for a dc accelerator (see Figure 4.9). In Figure 5.23 we see the measurement of electron yield from a pulsed RTL with a 0.5 mm gap and a 0.5 mm hole at three different UV levels. The UV was attenuated by passing the beam through filters. The yield does increase with increasing UV, but only when the electrical pulse is peaking at the center of the structure. At earlier times the three curves are indistinguishable. With no applied electric field to compensate for space charge the number of photoelectrons emitted is sharply limited. From the kinetic energy data, it was argued that when the photoelectrons are created before the arrival of the first pulse, they wait in the gap between the electrodes until the electrical pulse arrives, and are then accelerated by the electrical pulse. From this data it is apparent that not all of the electrons wait for the pulse, but some are either being reabsorbed by the cathode or diffuse away from the region where they can effectively be accelerated. During these early times the applied electric field is zero and so the electron dynamics should be dictated by the space charge fields. In Figure 5.24 the yields for a variety of gap sizes are plotted on a semi-log scale. The loss of photoelectrons can be fit well with an exponential decay. The decay
Figure 5.23 The Effect of UV energy
The electron yield from a RTL accelerator with a 0.5 mm gap. The unfiltered UV pulse energy was 0.8 μJ. This energy was reduced by factors 0.65 and 0.36 with filters in the other two measurements.
Figure 5.24 Charge Decay Times
These measurements of the amount of charge emitted from RTL accelerators were made at times when the UV pulse arrived before the arrival of the electric pulse.
time is a function of the RTL geometry. Larger gaps mean longer decay times. This type of behavior suggests that the electron cloud is redistributing itself during the time no applied field is present. One would expect the cloud to expand because of the space charge fields. We calculated in Chapter 4 that these fields may be of the order of 1 MeV/m. Electron may be pushed into regions where the electric pulse, when it arrives, will not accelerate them in such a way that they will be delivered to the Faraday cup. The decay constants have been fit to the data and values are tabulated as a function of gap in Table 5.7. For an electron to move 0.25 mm in 200 ps its kinetic energy would

<table>
<thead>
<tr>
<th>gap</th>
<th>0.25</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>decay time (ps)</td>
<td>170</td>
<td>220</td>
<td>290</td>
<td>850</td>
</tr>
</tbody>
</table>

be 18 eV. The electrons on the outside of the charge pancake may be picking up enough energy from the space charge field to be blown out of the accelerator before the electrical pulse arrives. At a field of 1 MeV/m electrons only need to travel 18 μm to gain 18 eV of energy.
CHAPTER 6

Conclusions

We have demonstrated that short electron pulses can be accelerated by pulsed power and that the radial compression gain predicted for radial transmission lines can be achieved under the proper circumstances. We were able to obtain an accelerating gradient as high as 44 MV/m. The pulsed bias voltage had to be kept below 3.5 kV to avoid breakdown across the 500 μm thick GaAs wafer. To support higher voltages a different switching configuration will have to be adopted.

We observed a degradation of the risetime of the electrical pulse from that of the incident laser pulse by a significant factor. From 2 ps in the laser pulse, the risetime of the electrical pulse arriving at the center of the RTL was measured as 30 ps. It is possible that with better impedance matching and attention to details in the construction of the RTL structure the dispersion of the electrical pulse could be reduced.

With an RTL of larger dimensions, engineering tolerances could be relaxed and one could expect higher compression gains. However we believe that the dimensions of our prototype are optimal in terms of the laboratory lasers available. Even under those conditions maintaining the performance of the system was not trivial.

The accelerator was operated at applied voltages of less than 3 kV for 3 months without any apparent degradation of performance. The photoconductive switch was fired at a repetition rate of 2.5 Hz for a period of several hours on a daily basis during these studies. Failure of the GaAs switch only occurred when the bias voltage was
increased to 3.4 kV and was irreversible. Optimum electron kinetic energy was very susceptible to the quality of the IR light pulse. Tuning of the laser was critical to maintaining this quality. The reliability of the laser was mixed. Some days the laser would require adjustment as often as every 20 minutes. On other days, the laser would run reliably for a period of several hours with no adjustment necessary. The use of a saturable absorber to reduce the prepulses in the laser pulse was absolutely necessary. Energy loss in the absorber was quite high. The saturable absorber was housed in a static cell and needed to be replaced on a weekly basis.

It was desirable to work with very small gaps in the RTL because of the problem of electron traversal time as discussed in Chapter 5. We were also using all of the IR energy after the saturable absorber to fire just a single stage. Cutting the IR energy by a factor of 10 would result in a significant loss in the final electron energy. The average power in the electron beam is of the order of a few nW. Most of the power consumed in the laboratory was used by the laser system. This amounted to about 15 kW of power. Overall the electrical efficiency of the system is very small, of the order of $10^{-13}$. It is interesting to note that the peak power in the electrical pulse is about 10 MW, although the average power is less than 1 mW.

A multistage device based on this design would require 50 stages to bring the electron kinetic energy up to 0.5 MeV. The logistics of bringing in the IR energy to fire all of the stages with the correct relative phase is a difficult enough problem. The optical energy produced by the laser would have to be correspondingly higher. One drawback of the RTL design is that the switch is distributed around the periphery of the disk and so the light from the laser must be spread out to cover this area. An alternative design would be to fire a simple switch to turn on one or a series of small area diodes and to accelerate the electron beam across their gaps. This device would not have the voltage
gain of the RTL, but by increasing the switch gap a higher voltage could be applied directly from the pulser.

The electrical characteristics of the RTL were measured with picosecond resolution and are in general agreement with expectations. Both the electro-optic sampling technique and the measurement of the energy of the accelerated electrons confirm the voltage gain resulting from the radial compression process. The results are in agreement with our computer simulation.

No great effort was made to maximize electron emission from the gold surface. This depends on surface cleanliness and requires ultra-high vacuum which was not available for these studies. Furthermore semiconductor or cesiated cathodes would be a better choice to incorporate into a practical design.

We observed a dependence of the electron yield on the gap size. The lifetime of the photoproduced plasma is also strongly dependant on the gap size. If we extrapolate to zero gap size we find a lifetime of about 150 ps. This suggests that if the electrons are confined close to a gold surface they may be reabsorbed with this characteristic time.

While the electron beam produced is not yet competitive with the yield from laser rf guns, it is the first demonstration of acceleration by pulsed power at the picosecond level. The data and the experience obtained are a necessary step in any further development of similar acceleration schemes.