CHARACTERIZATION AND APPLICATIONS OF
100-300 MEV ELECTRON BEAMS

by

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DEPARTMENT APPROVAL

of a senior thesis submitted by

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ABSTRACT

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Electron beam characterization methods are discussed for use in a single stage laser-wakefield accelerator. Energy measurements are performed by means of magnetic energy spectrometer, and a program is written to simulate the deflected position and energy of relativistic beams. Divergence of the real electron beam is accounted for and incorporated into the relativistic calculations. The strengths and weaknesses of this method are analyzed. Applications of 100-300 MeV beams are discussed and Radiographic imaging is presented as an important example. In all uses of laser-produced electrons, beam quality and consistency are essential. Quick and reliable characterization techniques are, therefore, discussed and presented.
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Chapter 1

Introduction

The Diocles laser is capable of producing some of the most intense light conditions ever created in a laboratory. These powerful bursts of light are focused onto a gas jet producing energetic electron beams in the 100-300 MeV range. The laser-plasma interaction involved and the subsequent generation of charged particle beams is referred to as laser wakefield acceleration (LWA). The powerful Diocles laser is housed in the sub-basement of the University of Nebraska-Lincoln’s Behlen Hall.

1.1 Extreme Light Laboratory

UNL’s Extreme Light Laboratory is pioneering new methods of generating high energy electrons, which find application in fields ranging from national defense to medicine. Considering that the laser was constructed in 2005, only a few years ago, the Diocles team has made remarkable progress. With a significant power upgrade (1 PW peak) scheduled for the winter of 2008, research is sure to be on the cutting edge.

The lab, itself, was built with the special needs of the laser in mind. The floor is detached from the rest of the building thus preventing excessive vibrations which
would surely lead to misalignment of the laser. The atmosphere in the lab is also closely monitored and controlled. Humidity and temperature are required to stay within set limits to prevent large fluctuations in the laser beam path from day to day. Such misalignments cause beam clipping, which results in a loss of power. The lab is a clean room; and measures are taken to keep dust, dirt and hairs from contaminating the optics. Nearly all lasers in the laboratory are rated as class IV and present a hazard from both specular and diffuse reflections.

1.2 Diocles Laser

<table>
<thead>
<tr>
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<th>Peak Power</th>
<th>Pulse Duration</th>
<th>Repetition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti:Saph</td>
<td>100 TW</td>
<td>30 fs</td>
<td>10 Hz</td>
</tr>
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*Table 1.1 Summary of Diocles laser specifications*

The Diocles laser system is a 100 TW titanium sapphire laser capable of accelerating electrons to energies of several hundred-million electron volts over a distance of about a centimeter. The key to Diocles extreme power is its ultra-short pulse duration, 30 femto-seconds. By expending a moderate amount of energy in a very short time, high power is achieved.

In order to amplify the laser beam beyond normal limiting factors, chirped pulse amplification techniques are used to ramp up the energy without damaging the optical systems. Chirping refers to the temporal stretching of the laser pulse. This stretching is achieved by use of diffraction gratings. Following amplification the process is reversed and the beams are compressed back to the original pulse duration. This takes place in the laser room shown schematically in Figure 1.1. The following is a basic outline of the amplification process employed by Diocles:
1. Pulses are generated in the oscillator with energy greater than 4 nJ, frequency of 75 MHz, and pulse duration less than 10 fs.

2. Diffraction gratings are used to temporally stretch each pulse to more than 300 ps. This step decreases the beam intensity ensuring that no optical damage occurs during amplification.

3. The laser is then amplified by making 9 passes through a Ti:Sapph crystal. This results in beam energy greater than 1.5 mJ with a frequency of 1 kHz.

4. Pulses are then passed through another larger Ti:Sapph crystal 5 times and amplified to more than 70 mJ and frequency of 10 Hz.

5. Next the pulses are spatially enlarged and passed through another even larger Ti:Sapph crystal amplifying the laser to energies in excess of 2 J and the frequency remains at 10 Hz. Note: Each pump laser (Frequency-doubled Nd:YAG)
produces an average power of 12.5 W of 532 nm light - Flashbulbs are set at 10 Hz.

6. Pulses are stretched spatially again and amplified a final time by passing through a 50 mm Ti:Sapph crystal bringing the final energy up to 5 J.

7. The laser pulses are expanded spatially for the final time. The pulses are then compressed temporally from more than 300 ps to less than 30 fs by using large holographic diffraction gratings. Note: This process increases the final power to a whopping 100 TW.
Chapter 2

Laser-Plasma Ion Acceleration

Contained here is a brief overview of theory involved in the production of electron beams by LWA. This is by no means intended to represent a complete summary of the methods and theory. Such a treatment would require a more lengthy volume and can be found elsewhere [3,2,4]. The intent is to provide a few important foundational principles and background.

2.1 Chirped-pulse Amplification

Until the development of chirped-pulsed amplification in 1985, laser systems were severely limited in maximum energy by the quality and size of optics. With the advent of methods to temporally stretch (chirp) a laser pulse with a pair of diffraction gratings [2], higher energies were attained without damaging the optics or producing unwanted non-linear effects.

Amplification is achieved by pumping Ti:Sapph crystals, which act as the gain medium for the 800 nm main beam. The 532 nm Nd:YAG pump lasers obtain their energy from flashbulbs set at 10 Hz. When the main beam passes through the pumped
crystals, it picks up energy stored therein and is thus amplified by stimulated emission. When the desired beam energy is obtained through several stages of multi-pass amplifiers, the main beam is compressed in vacuum back to nearly its original pulse duration of 30 fs and sent on to experimental chambers.

### 2.2 Laser Wakefield Acceleration

During LWA, a fully amplified laser beam is focused by an off-axis parabolic mirror to a spot about 25 microns across. At the focal point, a supersonic gas jet (typically \(\text{He}_2\)) is fired and the laser pulse undergoes self focusing in the medium. The resulting laser-gas interaction produces a relativistic plasma with frequency as follows:\[5,4\]:

\[
\omega_e \left( \text{s}^{-1} \right) = \sqrt{\frac{4\pi n_e e^2}{\gamma m_e}},
\]

(2.1)

where \(n_e\) is the index of refraction, \(e\) is the elementary charge, \(\gamma\) is the relativistic factor, and \(m_e\) is the electron rest mass. As the laser propagates through the underdense plasma media, the relatively small electrons begin to oscillate due to the high frequency electric field \(E(x, t) = E_0 \cos \omega t\). The field is stronger on one side causing a net acceleration perpendicular to the laser axis. The force responsible for this effect is referred to as the pondermotive force, or Miller force \[5,4\]:

\[
F_p = -\frac{e^2}{4m_e \omega^2} \frac{d}{dx} \left( E_0^2 \right),
\]

(2.2)

where \(E_0\) is the electric field amplitude. The displacement of electrons creates a vacated region, or bubble, shown in Figure 2.1. The size of this bubble is on the order of the laser focal spot diameter (25 \(\mu\text{m}\)).

As the electrons begin to fall in behind the wakefield bubble, many become trapped in the laser’s wake. The trapped electrons experience a sharp push forward and are accelerated in a surf-like manner on the plasma waves. This results in electron’s
whose velocities are very near the speed of light and are oriented in exactly the same direction as the laser propogation axis.

The acceleration gradients from LWA are extremely high (100 GeV/m) and occur over a distance of about one centi-meter. One amazing feature of LWA is that it requires no external guiding. When the parameters are properly adjusted and the laser alignment controlled, the end result is a reproducible nearly monoenergetic, low divergence electron beam (5 mrad).

2.3 Electron Beam Characterization

In technological applications electron beam quality is of utmost importance. It is, therefore, necessary to employ reliable characterization methods for electron beam monitoring. These characterization methods can be grouped into four main categories: Imaging, energy anlysis, Charge measurement, and stability.
2.3.1 Imaging

Imaging is performed using a scintillating material, a Kodak LANEX screen, which is placed a short distance behind a magnet mounted on a translational stage. A charge coupled device (CCD) camera is positioned at a view port near the LANEX but not in the beam path (energetic electrons would saturate the camera and cause burn damage). The CCD camera, thus placed, provides a real time image of the electron beam position, shape, and intensity. Operators located in the control room may then view the beam and make necessary adjustments to improve the quality of the electrons.

Another powerful method of imaging involves use of phosphor image plates (IP) \[6\]. The IP is first exposed to ionizing radiation and then transferred, in a dark envelope, to an IP scanner. This process, though time consuming (5 minutes to develop), provides a low cost and convenient way of imaging electron bunches at a distance.

2.3.2 Energy measurements

Energy measurements are performed by means of a magnetic spectrometer. Figure \[2.2\] represents a typical electron bunch dispersed through a magnet. The lack of a trailing low energy tail indicates that this electron bunch is monoenergetic. When electrons originate from the same wakefield bubble, the result is a monoenergetic beam ideal for applications requiring specific energies. Further discussion of magnetic spectroscopy will be the focus of Chapter 3.
2.3 Electron Beam Characterization

2.3.3 Charge measurements

An integrating current transformer (ICT) is used to measure the total current contained in a single pulse. This device sums over the current induced in a transformer due to charged particles passing through it. ICTs are designed for use in applications with very short pulse durations; however, little has been done to ensure the accuracy of the instrument for current pulses on the order of femtoseconds [7, 8]. Because the amount of charge induced in a coil is independent of particle speed, ICTs remain an integral part of laser accelerator facilities.

2.3.4 Stability

Pointing stability refers to the consistency of the laser beam position from shot to shot. A lower number for pointing stability corresponds to a more stable beam. Figure 2.3 shows results from Diocles measurements indicating that the average centroid position varies by \( x = \pm 6 \ \mu m \) and \( y = \pm 7.5 \ \mu m \) or about 40\% of the beam size. With a distance of 1 meter to the objective, pointing stability was found (by taking the inverse tangent) to be (6,7.5) \( \mu \)radians [1]. High laser pointing stability corresponds to consistent electron bunches.

Figure 2.2 Monoenergetic electron beam with energy scale [1]
Figure 2.3  Pointing Stability [1]
Chapter 3

Magnetic Energy Spectrometer

Electrons can be thought of as point charges, which when passed through a uniform magnetic field follow a circular path. For a first approximation to a real beam we make a few assumptions. It is assumed that the magnetic field is uniform. This approximation becomes more accurate if the field distance, $L_1$, is large compared with the distance between the magnet’s poles.

![Figure 3.1 Schematic of electron energies dispersed by a magnet](image)

The electron beam is also assumed to have a gaussian distribution of energies. When passed through the magnetic region shown schematically in Figure 3.1, the energies are dispersed and lie in predictable locations on a screen.
3.1 Geometric Approach

If the central position is known, two additional points in space define a circle. The Z coordinate of the circle’s center is constrained to equal the Z coordinate of the field entrance position. Given the equation for the relativistic Larmour radius \[6\],

\[
R = \frac{m_0c}{eB} \sqrt{\left(\frac{E + m_0c^2}{m_0c^2}\right)^2 - 1}
\]  

(3.1)

the field exit point and electron trajectory can be defined. Note that the entrance point and field length, \(L_1\), are known quantities as shown in Figure 3.2. The trajectory of the exiting electron is given by the negative reciprocal of the slope between points \(C\) and \(P_2\).

The geometric approach, although a good first approximation, is limited to the case of a perfectly collimated beam and fails when angular divergence is considered. This is due to the fact there is not enough information to reach a solution for the case when the propagation axis of an electron is shifted by some arbitrary angle.

Figure 3.2 Geometry for a circle - \(P_1\) and \(P_2\) are B field entry and exit points
3.1 Geometric Approach

3.1.1 Maple 11 Code for the Geometric Method

This program was written for the simple case of a perfectly collimated electron beam. It is included here for comparison to Section 3.2 which addresses the more complicated case. The simplicity of the calculations in the geometric method allow for much faster computing time without loss in accuracy, but rather only the restrictions mentioned above.

```
restart

Constants

m := 0.91093897e−30 :
c := 2.99792458e8 :
e := 0.160217733e−18 :
B := 0.6 :
L0 := 0.125 :
L1 := 0.025 :
L2 := 0.200 :

Relativistic Larmour Radius with energy conversion for MeV input

Radius := \frac{m·e·B}{m·c^2} \sqrt{\left(\frac{E·c^6 + m·c^2}{m·c^2}\right)^2 - 1} :

Center of circle and exit position

cx := L0 :
cy := Radius :
ex := L0 + L1 :
ey := Radius − \sqrt{Radius^2 − L1^2} :

Find slope tangent to circle at exit point

Yslope := -\left(\frac{cy−ey}{cx−ex}\right)^{-1} :

Define total deflection in Y direction as a function of energy
```
\[ Y_{\text{Position}} := (Y_{\text{slope}} \cdot L_2 + e_y) \cdot 1000 : \]
\[ Y := \text{unapply}(Y_{\text{Position}}, E) : \]

Calculator and plotting
\[ Y(100) \]
\[ \text{with(plots)} : \]
\[ \text{loglogplot}(Y_{\text{Position}}(E), E = 50..500) : \]

![Figure 3.3 Log-Log plot of deflection vs. energy](image)

Select only the positive energy (MeV)
\[ \text{with(Statistics)} : \]
\[ \text{SelectInRange}([\text{solve}(Y_{\text{Position}}(E) = 6, E)], 0..10000) \]
\[ [179.4262426] \]

### 3.2 Differential Equation Method

Because the real electron beams in the laboratory have some angular divergence, I wrote an algorithm to account for these factors. The program considers the relativistic deflection of diverging electrons in a magnetic field and simulates the expected location on an imaging screen. The program also allows the user to input experimental parameters to obtain the energy spectrum of the beam. This program aids in
quick determination of beam energy and is a useful resource to laser operators working from control room computers. While in the magnetic field region, \( L_1 \), electrons follow a circular path given by
\[
\frac{d\vec{p}}{dt} = \gamma m \frac{d\vec{v}}{dt} = e \left[ \vec{v} \times \vec{B} \right].
\] (3.2)

The result of the cross product in Equation 3.2 is the following:
\[
e [\vec{v} \times \vec{B}] = e \left[ (0) \hat{x} + (V_z B) \hat{y} - (V_y B) \hat{z} \right].
\] (3.3)

This corresponds to the following system of ordinary differential equations. The solutions to this system (given in section 3.2.1) describe the position and velocity of an electron moving in circular motion within a uniform magnetic field.
\[
x'(t) = V_x(t)
\]
\[
y'(t) = V_y(t)
\]
\[
z'(t) = V_z(t)
\]
\[
b \cdot V'_x(t) = 0
\]
\[
a \cdot V'_y(t) = V_z(t)
\]
\[
a \cdot V'_z(t) = -V_y(t)
\]
Where $a = \frac{me\gamma}{eB}$ and $b$ drops out of the equations. The following initial conditions apply to this setup:

$$x(0) = X_o, \quad y(0) = Y_o, \quad z(0) = 0,$$

$$V_x(0) = V_{xo}, \quad V_y(0) = V_{yo}, \quad V_z(0) = V_{zo}$$

### 3.2.1 Maple 11 Code for the Differential Equation Method

This program was written to account for the real case of a diverging beam. The beam is assumed to propagate along the positive $z$-axis. The electrons pass through a region of uniform magnetic field (oriented along the $X$-axis) and are deflected. $X$ and $Y$ coordinates on a detector screen are found by specifying values for the electron energy and angle. Given a measured value for the deflected position, beam energy is calculated.

```maple
restart
Basic Equations with energy conversion for MeV input
v := \frac{c}{E} \cdot \sqrt{E^2 - m^2 \cdot c^4} :
\gamma := \frac{E}{mc^2} :
a := \frac{m\gamma}{eB} :
E := En \cdot 10^6 \cdot e + m \cdot c^2 :
ODE solutions for Equations of motion
x := t \rightarrow V_{xo} \cdot t + X_o :
y := t \rightarrow a \cdot V_{yo} \cdot \sin(\frac{t}{a}) - a \cdot V_{zo} \cdot \cos(\frac{t}{a}) + a \cdot V_{zo} + Y_o :
z := t \rightarrow a \cdot (V_{yo} \cdot \cos(\frac{t}{a}) + V_{zo} \cdot \sin(\frac{t}{a}) - V_{zo}) :
V_x := t \rightarrow V_{xo} :
V_y := t \rightarrow V_{yo} \cdot \cos(\frac{t}{a}) + V_{zo} \cdot \sin(\frac{t}{a}) :
V_z := t \rightarrow -V_{yo} \cdot \sin(\frac{t}{a}) + V_{zo} \cdot \cos(\frac{t}{a}) :
```

3.2 Differential Equation Method

Times (T1 is time in B field and T2 is time from field to screen)

\[ T_1 := \text{solve}(z(t) = L_1, t) : \]
\[ T_2 := \frac{L_2}{V_z(T_1)} : \]

Initial values

\[ X_o := r \cdot \cos(\theta) : \]
\[ Y_o := r \cdot \sin(\theta) : \]
\[ V_{zo} := v \cdot \sin(\alpha) \cdot \cos(\theta) \]
\[ V_{yo} := v \cdot \sin(\alpha) \cdot \sin(\theta) \]
\[ V_{zo} := v \cdot \cos(\alpha) : \]

Define the deflection functions

\[ x := \text{simplify}(x(T_1) + V_x(T_1) \cdot T_2) : \]
\[ y := \text{simplify}(y(T_1) + V_y(T_1) \cdot T_2) : \]
\[ X := \text{unapply}(x, En, \theta) : \]
\[ Y := \text{unapply}(y, En, \theta) : \]

Constants: Match with experimental parameters. Note: if d (undeflected beam diameter) is changed press enter on \( \alpha \) (beam divergence angle) too.

\[ m := 0.91093897e - 30 : \]
\[ c := 299792458. : \]
\[ e := 0.160217733e - 18 : \]
\[ B := 0.6 : \]
\[ L_0 := 0.125 : \]
\[ L_1 := 0.025 : \]
\[ L_2 := 0.200 : \]
\[ d := 0.005 : \]
\[ \alpha := \arctan(d/(2 \cdot (L_0 + L_1 + L_2))) \]
\[ r := L_0 \cdot \tan(\alpha) : \]
Deflection Calculator (mm)

Change the colored values below and hit enter for deflection coordinate on screen for Y, and X respectively. Note: function of Energy (MeV) and Angle (radians)

\[
1000 \cdot \text{evalf}(Y(303, 35 \cdot (1/180) \cdot \pi))
\]

\[
1000 \cdot \text{evalf}(X(303, 35 \cdot (1/180) \cdot \pi))
\]

Energy (MeV) calculator for a given displacement (mm)

Note: This will take about one minute to compute

\[\text{with(Statistics)}:\]
\[\text{SelectInRange([solve(evalf(1000 \cdot Y(En,0) = 3.6), En)], 0..10000)}:\]

Plot of Y-axis deflection (mm)

Note: values for \(-\pi\) to \(\pi\) are plotted beneath those for 0 to \(\pi\)

\[
\text{with(plots)}:\]
\[\text{plot3d([1000 \cdot Y(En,\theta), 1000 \cdot Y(En,\theta - \pi)], En = 50..500, \theta = 0..\pi, axes = boxed)}\]

Plot of X-axis deflection (mm)

Note: Independent of energy as expected
3.3 Accuracy

The results from both the geometric method and the differential equation method match and confirm one another. The geometric method proved to be computationally simpler and required much less computer time: a few seconds vs. a minute. For most practical purposes, one is interested in the central location of the electron bunch and the geometric method is sufficient. However, if one is concerned about beam divergence, the differential equation method must be used. Note that small shot to shot variation in electron beam position creates some uncertainty in these energy measurements.

3.3.1 Resolution

When attempting to measure higher energies, the problem of resolution arises. As energy, $E$, increases the difference in position from one energy to the next decreases. When this distance, $d$, is less than one pixel on the CCD camera, the limit has been reached. The resolution between one energy and the next is defined as the following:

$$Resolution = PixelLength \left( \frac{\Delta E}{\Delta d} \right).$$

Increasing distance to the screen and or adding additional magnets would improve resolution by increasing the image size.
3.3.2 Power Radiated

The power radiated by an accelerated point charge moving with velocity near light speed is given by Lienard’s generalization of the Larmor formula [9]:

\[
P = \frac{\mu_0 q^2 \gamma^6}{6\pi c} \left( a^2 - \frac{\vec{v} \times \vec{a}}{c^2} \right),
\]

where \( \gamma \equiv \left( 1 - \frac{v^2}{c^2} \right)^{-1/2} \) is the relativistic factor. For a 300 MeV electron the power radiated is 12.34 GeV/s and the time required to traverse the magnetic field region is 70.05 ps. The product of these two numbers or 0.86 eV is the total energy radiated. For a 500 MeV electron this total jumps up to a measly 2.40 eV, a tiny fraction of the original energy. The energy radiated due to acceleration of the electrons in such a magnetic energy spectrometer is negligible.
Chapter 4

Application and Conclusions

Applications of laser-produced electron bunches range from homeland security to medicine. Specific applications include the detection of clandestine nuclear material in cargo containers, production of MeV X-rays by counter-propagating Thomson scattering, and radiographic imaging for the detection of microscopic cracks embedded in rotary turbine blades. Because the beams are actually very short femtosecond pulses, they might even be used to resolve the processes involved in ultrafast chemical reactions. Protons, which might also be accelerated by means of LWA, are useful in treating cancer patients because heavy particles do not damage healthy tissue in the same manner as other types of radiation. These applications and more make laser-ion acceleration an important area of research.

Although electrons produced by other methods might also be useful in similar applications, laser-accelerated electrons prove to have many advantages. One advantage is the compact nature of laser systems as compared to synchrotrons or RF linear accelerators. Laser facilities have much higher acceleration gradients: 100 GeV/m as opposed to 50 MeV/m. This allows laser accelerators to fit on a table top or even on a truck, which makes them suitable for a wide range of mobile applications [10,2].
Lower cost (about $1 million), shorter pulse duration, and high repetition rate (10 Hz) are other notable benefits.

4.1 Radiography

Radiographic imaging is an important technique used in several of the above mentioned applications. In this process phosphor plates are used to record images of electron bunches after attenuation in various materials. In figure 4.1 the clear image on the left is an unblocked, whereas the one on the right has been shielded by a dense medium. The intent of Figure 4.1 is to simulate hidden nuclear material inside a cargo container. The density ratio between aluminum and steel is similar to that of steel to uranium making it a good first approximation. Contrast and features can be analysed to determine possible threats. Once a potential hazard is detected, high energy electron bunches can be used to partially activate the material for determination of its elemental composition.

Another use of radiography is to detect small internal cracks in turbine blades or other mechanical parts. Such detection could improve safety and could also save a great deal of money by avoiding unnecessary early decommission of military vehicles.
4.2 Conclusion

Radiographic imaging is a nondestructive method of analyzing the interior of solid objects.

4.2 Conclusion

Reliable characterization methods aid in the development of high quality femtosecond electron bunches. Applications of LWA electrons span a wide variety of fields and show much promise for technological advancement [11]. Energy measurements by use of a magnetic spectrometer were performed, and programs were written to calculate the energy spectrums of realistic beams. The Maple code allows laser operators to quickly obtain the energy spectrum of an electron beam observed on a LANEX screen. With these tools to aid in the production of consistent monoenergetic beams, many exciting applications lie within reach.

4.2.1 Future Work

There are many ways this research could be extended. Several possible projects that might grow out of this work are the following:

- Modify the spectrometer program to include the two magnet case.
- Modify the program to allow for different orientations of the detector screen.
- Create a graphical user interface for operator convenience and efficiency.
- Explore laser shadowgraphy techniques to obtain images of the plasma channel.
- Perform an absolute calibration of energy measurements using activation techniques.
Bibliography


