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## MEASUREMENT AND CHARACTERIZATION OF MICROWAVE TRANSIENT ELECTROMAGNETIC FIELDS GENERATED FROM LASER/MATTER INTERACTION

by

## NICHOLAS BARBIERI B.S. Florida Atlantic University, 2003

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Physics in the College of Arts and Sciences at the University o f Central Florida Orlando, Florida

Fall Term 2005

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#### ABSTRACT

From past experiments conducted with high intensity lasers, it has been known for some time that laser matter interactions result in the emission of short, transient electromagnetic pulses. Previous investigations into laser generated electromagnetic pulses provide basic information regarding frequencies where such pulses may be present, along with the time duration of the pulses. Such investigations have also demonstrated a number of measurement techniques in which basic information on the pulses may be obtained.

The purpose of this current investigation is to obtain a more thorough description and understands of electromagnetic pulses generated for laser matter interaction. To this end, spatial radiation patterns emanating from various laser excited matter sources was predicted using antenna theory for far field radiators. Experimentally, it is the intention of this investigation to gather comprehensive time and frequency domain data on laser matter generated electromagnetic pulses using a number of specific laser targets. Radiation detection techniques using broadband, calibrated EMC horn antennas were devised. A unique measurement system known as an inverse superhetereodyne receiver was designed, tested and demonstrated. An experimental setup using such instrumentation was established. Using the above instrumentation and experimental setup should yield comprehensive time and frequency domain data over a spectra range of 1-40 GHz and with a time resolution of 50 ps. Because the experimental system employed is calibrated, measurements can be corresponded to incident electromagnetic fields.

Several tests were conducted to ensure the proper operation of experimental apparatus. A modulation test was conducted on the inverse superhetereodyne receiver to ensure that the experimentally observed signals appeared when and where predicted within the receiver's bandwidth. The experimental setup was used to measure radiation emitted from an electrostatic discharge source of known distance and discharge voltage. Frequency domain data from the discharges were collected and compiled using a Matlab application ultimately intended to measure laser matter interaction generated electromagnetic pulses, resulting in a compiled frequency domain description comprising 1-17 GHz. The inverse Fourier transform was used to retrieve the time domain response from the compiled data. The discharge gaps characteristics where systematically altered as to allow a parametric study of the compiled data. The discharge measurements demonstrate the measurement system's ability to analyze unknown, short duration; broadband microwave signals.

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## **INTRODUCTION**

Laser produced plasmas are a source of electromagnetic radiation. While this fact has been known for quite some time, little has been done to systematically study the electromagnetic radiation emitted from laser produced plasma. It is therefore desired to begin a detailed a thorough investigation of this phenomenon. To commence such efforts, novel microwave detection instrumentation shall be employed in order to collect detailed temporal and spectral data on laser generated electromagnetic radiation.

### **CHAPTER ONE**

#### Section 1.1

High-power lasers have long provided a means for physicist to investigate matter under otherwise anomalous conditions. Such lasers are a relatively cost effective tool that can readily produce excited ions, electrons, plasmas and other phenomenon of interest. Additionally, the laser-matter interaction used in the course of such investigations often results in the generation of electromagnetic radiation. Not normally intended as part of laser physics experiments, the transient electromagnetic signals often introduce excess noise to measurements being undertaken and disrupt equipment. For this reason, such radiation is considered undesirable, and the normal experimental approach to dealing with the problem is often the introduction of shielding or similar countermeasures. Thus far, little has been done to characterize and understand these transient electromagnetic fields. This will be the focus of our investigation.

State-of-the-art tabletop lasers are currently capable of producing pulses whose energy exceeds 1 J with durations less than 100 fs, generating peak powers in excess of 10 TW. When focused to spot sizes of 40 um, energy densities of  $8 \cdot 10^{18} \frac{W}{cm^2}$  can be achieved, resulting magnetic fields of ~1.8 GigaGauss and electric fields of ~55 GV/cm. Such intense electromagnetic fields are easily capable of removing some or all of the electrons

from atoms. The resulting displacement of electrons and ions should clearly result in transient electromagnetic fields.

#### Section 1.2

There are two particular circumstances of laser generated electromagnetic radiation that are of current interest. The first circumstance is that of laser plasma filamentation in air, in which plasma generated by a laser pulse propagating through the air generates a temporarily stable waveguide that guides the laser pulse intact over significant distance. The second case will be the generation of electromagnetic radiation as a consequence of laser light interacting with solid matter. In both these cases, past experimental observations of electromagnetic radiation has been made, as well as theoretical attempts to describe the mechanism that give rise to such radiation. It is expected that, given the facilities and resources available for this investigation, both these processes will yield detectable levels of radiation.

Plasma filamentation is a novel phenomenon that is the subject of ongoing investigations. Plasma filamentation arises when laser pulses of sufficient peak intensity propagates through the air. Provided the beam has a sufficient Gaussian profile, a Kerr-lens effect caused by nonlinear interaction between the laser pulse and the air focuses the pulse until it is sufficient intense to ionize the surrounding air. The ionization counteracts the Kerrlens focusing allowing for stable, guided pulse propagation. Depending on circumstances, the laser pulse may travel several kilometers before group velocity dispersion disrupts pulse self-channeling.

When a laser pulse is traveling within a self-generated plasma filament, interaction between the laser pulse and the plasma channel produce transient electromagnetic fields. These fields have been observed in past investigations, and theoretical mechanisms for the generation of radiation have been proposed. "In particular, the plasma within the filament is not locally neutral, and may possess dipole and quadruple moments that give rise to transient fields." Proulx(1). It has also been postulated that the ponderomotive forces generated at the focus of the driving ultrafast laser are sufficiently strong to temporarily separate the electrons and ions within the plasma, giving rise to a transient dipole moment that results in radiation (2). These postulates have been experimentally verified by Proulx (1) which measured N2+ ions as a function of distance along the filament. The net charge of the plasma within the filament as a function of distance was inferred from the distribution of nitrogen ions, and the resulting charge distribution demonstrated that the plasma filament formed a definite dipole. In this particular case, the plasma dipole was just over 10 cm in length, divided nearly in half into a single positive and negatively charged region, the positive region occurring after the laser focal point.

A detailed theoretical analysis of plasma filamentation is provided by Cheng (3). Here it is postulated that the intense laser pulse generates electrons through multi-photon ionization, a phenomenon that has been verified by LPL in the past. Once electrons are liberated from their corresponding ions, the Lorentz force associated with the electromagnetic field of the laser pulse separates the electrons from the ions, generating a dipole in the plasma filament. The resulting dipole oscillates at the filaments plasma frequency. For electron densities of  $10^{15} \, 1/cm^3$  this frequency is approximately 200 GHz.

For the second case, electromagnetic radiation is generated when a sufficiently intense laser pulse strikes the surface of a solid. Do to the extreme intensities of the incident laser pulse, plasma, as well as beams of electrons, protons or ions, are violently ejected from the target. Transient electromagnetic fields can then be generated either from charges or currents induced in the target itself, the motion of charged particles ejected from the target, or from induced charge or currents within material that lies within the path of the particles ejected from the original target. The latter case was observed in by Mead (6), an experiment utilizing the Vulcan laser, and may not be relevant for lower energy experiments.

Witte (8) investigated the plasma and electrons generated from the interaction of intense laser pulses with an aluminum target. A Ti:Sapphire laser was used to focus pulses of power  $10^{17} \frac{W}{cm^2}$  on the surface of the aluminum. The laser matter interaction results in the formation of a keV plasma in front of the aluminum and a layer of fast electrons that penetrated into the aluminum target. The resulting plasma last for several picoseconds.

Okano (7) developed a magnetic spectrometer to detect electrons scatter off of irradiated copper targets. Electrons with energies between 80-200 keV where detected using this technique when the target was illuminated by femtosecond pulses.

#### Section 1.3

Past investigations of electromagnetic fields have provided a significant, although not comprehensive, amount of data on radiation resulting from laser plasmas and laser matter interactions. Such data includes limited information detailing the general spectral regions which these fields may be found, as well a rough estimate on the intensities of such fields. Furthermore, such investigations demonstrate a great variety of techniques that may be used to measure such fields, and the relative limitations of such techniques.

Numerous techniques have been used to measure the transient fields resulting from laser plasma filaments. Among the most primitive technique, used by Proulx (1), was the use of a stripped coaxial cable 0.5 cm from a plasma filament resulting from a 220 fs laser pulse. A 1 GHz impedance matched scope was able to measure a 30mV, ~100ps pulse, which pushed the limit of the 2ns/div scopes capability. The measured field intensity of the filament varied with distance from the focus of the driving laser.

A more sophisticated technique employed by Tzortzakis (4) utilized a heterodyne microwave receiver system. This system employs a corrugated horn and microwave focusing optics to measure the electromagnetic field associated with laser plasma

filament. The captured signal is then mixed to DC and filtered to 1 GHz and rectified, and the resulting output displayed on an oscilloscope. Do to limited mixing frequencies, only the 93-95 GHz and 117-119 GHz bands where measured. The technique provided finite measurements of this above portion of electromagnetic spectra (measurements where reported in arbitrary units).

Another simple technique developed by Hosseini (5) used simple monopole and loop antennas attached to coaxial cable to measure the electromagnetic fields resulting from the filament. These antennas where attached to rails running parallel to the filament, allowing field measurements as a function of distance along the filament. The measurements where recorded by a 1 GHz oscilloscope with 50 ps time divisions. Each antenna was used to measure transient electromagnetic fields as a function of time, and a graph averaging of 20 laser generated filaments was reported A -0.25 V, 2 ns pulse was measured with the linear antenna probe and a -0.5 V, 1 ns pulse was measured with the linear probe.

Mead (6) used the Vulcan laser to generate a strong Electromagnetic Pulse. The pulse was measured using standard EMC antennas for measurements between 1 kHz – 1 GHz, as well as a moebius loop antenna. The Vulcan laser was fired at aluminum and copper foil targets. The resulting electric fields contained spectra centered about 59 MHz and lasted for durations of ~100 ns. It is claimed that the reason the field is centered at 59 MHz is that 59 MHz represents a natural resonant mode of the chamber being used, the chamber being excited by electrons ejected from the copper and aluminum targets.

From previous investigations, the properties of the electromagnetic pulses that will be generated in the course of our experiments can be anticipated. It is clear that such pulses will last for relatively short periods of time, with durations that will be no greater than 1 ns under most circumstances. Furthermore, such pulses are comprised of extremely broad range of frequencies, ranging from 10 MHz to the X-Ray spectrum. The spectral compositions of such pulses, especially for sub-THz frequencies, are partially dependent upon the parameters of the material used as the radiation source. This includes plasma frequency for filamentation and physical dimensions for solid targets. Other spectral components, specifically the ones associated with the laser fundamental and harmonic frequencies, are directly dependent on the laser used to excite the source of radiation. Likewise, field intensity is also dependent upon the properties of both the driving laser and the target.

#### Section 1.4

The large spectral range of the transient electromagnetic fields resulting from laser irradiation presents a major technical challenge. A large portion of the spectrum in question exist in frequency ranges were detection technology required to meet the needs of this investigation is highly underdeveloped or lacking all together. In particular, adequate detection systems in the THz and sub-THz range are lacking. Furthermore, detection systems for the microwave range, while available, are cumbersome and expensive. It is, however, the sub-THz and microwave range that is of the greatest interest, as radiation at these frequencies would prove disruptive to electronic equipment. Ultimately, however, it would be desirable to investigate the entire spectrum of the laser plasma generated radiation, but such broad investigation is beyond the scope of this experiment.

For this experiment, investigation will be confined to the spectral range of 1-40 GHz. Currently, 1 GHz represents the minimum frequency that is anticipated from the laser plasma source, while 40 GHz represents the highest frequency economically achieved with the approach devised for this experiment. The 40 GHz limit also represents the highest frequency at which the transient electromagnetic fields will be measured in complete temporal and spectral detail. Other methods have been investigated for future experiments that will extend into different ranges of the electromagnetic spectra, but this experiment will act as a starting point

This investigation will proceed as follows. First, a literature search shall be conducted to obtain the most complete an accurate description of laser generated electromagnetic pulses currently available. Once sufficient information has been obtained, instrumentation will be developed to conduct detailed analysis of such electromagnetic fields. The physical mounts for the experimental setup will then be installed. Two sets of experiments will be run. The first will measure the radiation resulting from irradiating solid targets with intense laser pulses, while the second will involve measuring the fields associated with an airborne laser plasma filament. The data collected will then be

compensated for experimental artifacts introduced by measurement instrumentation. Compensated data will then be compiled to recreate the measured electromagnetic pulse.

#### **CHAPTER TWO**

#### Section 2.1

The laser plasma dynamics and laser matter interaction whose mechanics ultimately dictate the characteristics of the resulting transient electromagnetic fields is not entirely understood. While insightful, the modeling of such detailed phenomenon is beyond the scope of this investigation. However, it is desired to predict the behavior of the resulting transient electromagnetic fields with at least limited accuracy. As such, it is desired to employ simple but reasonable models to predict the behavior of the laser generated electromagnetic fields.

To this end, it is desired to construct a model that provides a simple but reasonable physical description of the phenomenon in question. Because of the detection methods that will be employed, particular emphasis shall be placed on describing mechanism that would give rise to far-field electromagnetic radiation. For this reason, the plasma radiation sources shall be modeled as antennas with geometric and electric properties similar to that of the plasma in question. Because the characteristics and behavior of laser plasma filaments and laser interaction with solid media are different, different models shall be used in each scenario.

It has been observed and calculated from previous investigations that in the case of laser plasma filamentation, electrons are separated from their respective ions creating a dipole that is macroscopic in scale. Thanks to previous work from Proulx (1), it is known that the dipole can be at least as long as 10 cm in length. In general, plasma filaments are approximately 100 um in diameter. These facts, when taken in conjunction with the fact the laser pulse generating the filament separates the dipole axially implies that the net motion of charge along the filament as well as the average electric field along the filament should be in the direction of the plasma filament axis. A "thin wire" approximation for the laser filament radiation characteristics can be reasonably justified from these characteristics. A classically wire antenna radiation model supporting a superposition of different frequencies will therefore be used.

When intense laser pulses interact with solid media, there are several methods of radiation that must be accounted for. Pulse lasers are capable of ejecting electrons from, or driving electrons into the surface of the irradiated media. Such burst of electrons should result in sharp, transient magnetic fields that should induce short duration electromagnetic pulses. Laser pulses also create plasma immediately outside to material surface irradiated. Often this plasma is accompanied by electrons being forced into the material surface as described above. Such plasma quickly cools and recombines with the material, creating a momentary dipole. Finally, for conducting targets, any residual charge left within the material will result in current to the surrounding region. Provided Mead's (6) explanation, conductive material effected thusly should radiate at one or more of its resonant modes.

An additional special case of laser matter interaction will also be considered. If, instead of irradiated bulk media, small targets several tens of micrometers are irradiated. In this particular case, a sufficiently intense laser will vaporize the target entirely. Under such conditions, the resulting plasma should be separated by a Lorentz force in a manner similar to that of a plasma filament, forming a dipole. The scale of such a dipole should be significantly smaller than that of the filament. Therefore, micrometer scale solid targets will be treated as infinitesimal dipoles for the purpose of predicting radiation emissions.

#### Section 2.2

For this analysis, the far field approximation, as commonly used in antenna theory, shall be employed. In general, the radial dependence time harmonic electric and magnetic fields generated by a source localized in space can be expressed as a series of powers 1/r with 1/r as the lowest ordered term. In the infinite limit of r, all higher order terms vanish, resulting in a field with radial dependence 1/r. Furthermore, the radial vector components of both the electric and magnetic fields can have terms of order no lower than  $\frac{1}{r^2}$ , and thus vanish in the far-field approximation. Therefore, only the transverse components of the electromagnetic field remain.

In antenna theory, distances satisfying the relation  $d > \frac{2l^2}{\lambda}$ , where *d* is the distance from the radiator, *l* is the largest dimension of the radiator, and  $\lambda$  is the wavelength, is

conventionally considered to be far-field. This relation is only valid for  $l > \lambda$ . For sources substantially smaller in scale than the radiation wavelength, the far-field relationship for an infinitesimal dipole is instead applicable. This relation is given by  $d > \lambda$ . These conventions have been provided by Balanis(9).

The 1-40 GHz bandwidth in question dictates  $7.5mm \le \lambda \le 300mm$ . For this investigation, the scale of micrometer targets, as well as the plasma and electron jets generated from such targets, should be less than 7.5mm under all conditions. Therefore, such experiments dictate a distance of at least 300mm. As currently configured, measurements conducted on these targets will be done at a distance of approximately 500mm therefore validating the assumption used.

In the case of bulk targets, target geometry dictates rectangular dimensions of 25-30mm with a mount containing conductive material of dimensions 50mm. Splitting far-field criterion into two cases for  $l > \lambda$  and  $l < \lambda$  respectively, it is necessary to ensure that d > 240mm for radiation emanating from the bulk targets and d > 667mm for the mount in the first case. For the second case, d > 300mm for both target and mount radiation. While the radiation targets remain complaint with this assumption for all cases, the target mount will exhibit near field behavior for frequencies below 7 GHz.

For laser plasma filamentation, a radiator scaling 100mm can be expected. For  $\lambda > l$  farfield begins at 300mm as in the previous two cases. For  $l > \lambda$ , a distance of at least 2.7m is required to achieve far-field behavior under all circumstances. Because laser filamentation experiments will not be conducted within Target Chamber #1, measurement antennas can be placed sufficiently far from the filament to ensure the far-field conditions are met.

With far-field conditions established, antenna radiation theory can be used to analytically predict radiation patterns from the corresponding models of laser plasma radiators. Furthermore, the horn antennas used for this experiment are specifically designed for analysis of radiators under these conditions. This should allow the use of experimental data for detailed reconstruction of model parameters.

#### Section 2.3

In the previous to sections, the radiator model and applicable measurement region were identified and justified. Using these two pieces of information, an antenna radiation pattern will be derived.

For the case of plasma filamentation, the radiator in question is a dipole of finite length horizontal to the ground plane. To begin, the radiation pattern for finite dipole of arbitrary length l resonating at angular frequency w shall be taken from Balanis (9). To start, the pattern multiplication formalism will be used. Here, a finite dipole is constructed using a continuum of infinitesimal dipoles of identical orientation. This allows a scalar distribution of current to be integrated over space for each point in space,

and then simply multiplied by the radiation pattern of the infinitesimal element. This is expressed as *antenna pattern* = (*element factor*) x (*space factor*) as per (9).

The antenna pattern for an infinitesimal dipole as directed along the z-axis in free space is given by Balanis (9) as:

$$\vec{E} = j30 \frac{kI_0 l e^{-jkr}}{r} \sin(\theta) \hat{\theta} \frac{Volts}{Amp}$$

Where the dipole is assumed to be driven by a current of  $I_0 e^{jwt}$ .

The space factor for a "thin wire" finite length dipole is given from (9) as:

$$I_{0} = \int_{\vec{r}'} I(\vec{r}') e^{jk|\vec{r}'|} d\vec{r}'$$

Unlike ordinary antennas that require standing waves with nulls at the endpoint when driven when resonating at a single frequency, the filament is deformable plasma driven by a laser. The laser separates charges in the plasma about its focus, forcing to spatial current distribution of the dipole to have a peak at the laser focus, which is approximately in the center of the dipole. Therefore, the constraint of having nulls at the dipole endpoints will be replaced by the constraint of having peak current at the center of the dipole (for some frequencies, these constraints may be identical). If such a current distribution is directed along the z-axis, the following space factor is obtained for a time harmonic current:

$$I_{0} = \int_{-l/2}^{l/2} \cos(kz') e^{jkz'\cos(\theta)} dz'$$

Solving:

$$I_0 = \frac{2\cos(\theta)}{k\sin^2(\theta)} \left[ \sin\left(\frac{kl}{2}\right) \cos\left(\frac{kl}{2}\cos(\theta)\right) - \cos(\theta)\cos\left(\frac{kl}{2}\right) \sin\left(\frac{kl}{2}\cos(\theta)\right) \right]$$

Simplifying a substituting yields the electric field:

$$\vec{E} = j60 \frac{kle^{-jkr}}{r} \cot(\theta) \left[ \sin^2\left(\frac{\theta}{2}\right) \sin\left(kl\cos^2\left(\frac{\theta}{2}\right)\right) + \cos^2\left(\frac{\theta}{2}\right) \sin\left(kl\sin^2\left(\frac{\theta}{2}\right)\right) \right] \hat{\theta} \frac{V}{A}$$

The resonant responses of the filament at particular frequencies can now be collected to form a spectral profile as a function of w and  $\theta$ .

$$\vec{E}(w,\theta) = j60I(w)\frac{wle^{-j\frac{r}{c}}}{cr}\cot(\theta)\left[\sin^2\left(\frac{\theta}{2}\right)\sin\left(\frac{wl}{c}\cos^2\left(\frac{\theta}{2}\right)\right) + \cos^2\left(\frac{\theta}{2}\right)\sin\left(\frac{wl}{c}\sin^2\left(\frac{\theta}{2}\right)\right)\right]\hat{\theta}\frac{V}{A}$$

Where I(w) is an arbitrary spectral profile of the current in the filament.

And band limited signal limited to  $\varpi_{low} \le w \le w_{high}$  can be constructed using the step function.

$$I_{\rm lim}(w) = I(w) \cdot \left[ u \left( w - w_{low} \right) - u \left( w - w_{high} \right) \right]$$

Taking the inverse Fourier Transform of  $\vec{E}(w,\theta)$ :

$$\bar{E}(t,\theta) = j\frac{60l}{cr}\cot(\theta)\left[\sin^2\left(\frac{\theta}{2}\right)\frac{d}{dt}\left(I(t_d - \tau_1) - I(t_d + \tau_1)\right) + \cos^2\left(\frac{\theta}{2}\right)\frac{d}{dt}\left(I(t_d - \tau_2) - I(t_d - \tau_2)\right)\right]\hat{\theta}\frac{V}{A}$$
  
where

$$t_{d} = t - \frac{r}{c}$$
  
$$\tau_{1} = \frac{l}{c} \cos^{2}\left(\frac{\theta}{2}\right)$$
  
$$\tau_{2} = \frac{l}{c} \sin^{2}\left(\frac{\theta}{2}\right)$$

For a phase synchronized spectrum of uniform spectral density bandlimited to  $w_{\min} \le w \le w_{\max}$ :  $I(w) = I_0 [u(w - w_{\min}) - u(w - w_{\max})]$  Which yields a radiated field of:

$$\vec{E} = -j\frac{l60}{cr}\cot(\theta)I_0 \left[\sin^2\left(\frac{\theta}{2}\left(\frac{1}{(t_d - \tau_1)^2} - \frac{1}{(t_d + \tau_1)^2}\right) + \cos^2\left(\frac{\theta}{2}\left(\frac{1}{(t_d - \tau_2)^2} - \frac{1}{(t_d + \tau_2)^2}\right)\right]\sin\left(\frac{w_{\max} - w_{\min}}{2}t\right)e^{j\left(\frac{w_{\max} + w_{\min}}{2}t\right)}\theta\frac{W_{\max}}{A}$$

#### Section 2.4

In the case of laser matter interaction most of the radiation sources in question, the electron jets, the momentary plasma, and the vaporization of micro scale targets, can be treated as infinitesimal dipoles. The radiation pattern of such structures being as listed before:

$$\vec{E} = j30 \frac{kI_0 l e^{-jkr}}{r} \sin(\theta) \hat{\theta} \frac{Volts}{Amp}$$

For electrons jets accelerating or charged plasma that is being accelerating away from the surface of a laser target, emitted radiation clearly takes place within the presence of the target itself. Therefore, the laser target acts as a ground plane, the dipole modeled radiation source being vertical with respect to this plane. This geometry implies that the z-axis used as a reference for a spherical coordinate system will be normal to the plane of the laser target, and parallel to the earth. As such, the space factor for a vertical dipole above a ground plane will be used. The space factor, as given by Balanis (9), is:

$$SpaceFactor = e^{jkh\cos\theta} + R \cdot e^{-jkh\cos\theta}$$

Where *R* the reflection coefficient is:

$$R = \frac{\eta_0 \cos \theta_i - \eta_1 \cos \theta_t}{\eta_0 \cos \theta_i + \eta_1 \cos \theta_t}$$

where

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$
$$\eta_1 = \sqrt{\frac{jw\mu_1}{\sigma_1 + jw\varepsilon_1}}$$

Physically, the distance *h* from the target plane is near zero, the resulting plasma and electron jets having no separation for the surface. The only actual contribution to h would be the distance from the edges of the phenomenon to the center, likely 10s of um. The value *k* for the spectral values to be measured has a maximum of .84 per *mm* at 40 GHz, the highest frequency that will be measured in this experiment. Therefore *kh* can be taken to be approximately 0, reducing the space factor to (1+R). In the case of a perfect conductor,  $\eta_1 = 0$ , further reducing the space factor to a value of 2. This yields a corresponding field of :

$$\vec{E} = j30(1+R)\frac{kI_0le^{-jkr}}{r}\sin(\theta)\hat{\theta}\frac{V}{A} \cong j60\frac{kI_0le^{-jkr}}{r}\sin(\theta)\hat{\theta}\frac{V}{A}$$

In terms of  $w, \theta$ :

$$\vec{E}(w,\theta) = j30(1+R)\frac{wI(w)le^{-j\frac{w}{c}r}}{cr}\sin(\theta)\hat{\theta}\frac{V}{A}$$

Again,  $I_0 = I(w)$  is used to represent the excitation of the dipole as an arbitrary spectral profile.

Applying the inverse Fourier Transform yields:

$$\bar{E}(t,\theta) = 30(1+R)\frac{l}{cr}\sin(\theta)\frac{d}{dt}I(t_d)\hat{\theta}\frac{V}{A}$$

In the case where the dipole is formed as a result of a monopole outside of the target and its image within target, the system as a whole can simply be treated as an infinitesimal dipole. This case can be expressed by setting R = 0.

For conductive targets, laser matter interaction will result in a region of localized charge center at the laser focus. Such momentary charge will cause the target to resonate. The actual radiated mechanism in this case will be assumed to be current resulting from the temporary laser induced charge in the conductor. The planar conductor is assumed to be sufficiently thin to disregard current travel normal to the planar surface. The z-axis will be taken to be normal to the planar target, while the x and y axis shall be taken to be parallel with the target edges. The current density within the target will be described by a superposition of currents traveling in the x and y directions. Because this phenomenon is a resonance phenomenon, only currents that results in standing wave modes shall be considered.

To begin resonating currents shall be described as:

$$\vec{J} = \sum_{m=1}^{\infty} J_x(m) \sin\left(\frac{\pi m x}{l_x}\right) e^{j\frac{\pi c m}{nl_x}t} \hat{x} + \sum_{p=1}^{\infty} J_y(p) \sin\left(\frac{\pi p y}{l_y}\right) e^{j\frac{\pi c p}{nl_y}t} \hat{y}$$

Exploiting the square geometry:

$$\vec{J} = \sum_{m=1}^{\infty} \left[ J_x(m) \sin\left(\frac{\pi m x}{l}\right) \hat{x} + J_y(m) \sin\left(\frac{\pi m y}{l}\right) \hat{y} \right] e^{j\frac{\pi c m}{nl}t}$$

And substituting:

$$\vec{J}_{m} = J_{x}(m)\sin\left(\frac{\pi mx}{l}\right)\hat{x} + \vec{J}_{y}(m)\sin\left(\frac{\pi my}{l}\right)\hat{y}$$
$$w_{f} = \frac{\pi c}{nl}$$

Yields:

$$\vec{J} = \sum_{m=1}^{\infty} \vec{J}_m(x, y) e^{jmw_f t}$$

And the Fourier Transform:

$$\vec{J} = 2\pi \sum_{m=1}^{\infty} \vec{J}_m(x, y) \delta(w - mw_f)$$

Using the expression from Balanis (9) to express the radiated field in terms of an arbitrary current density:

$$\vec{A}(\vec{r}) = \frac{\mu}{4\pi} \iiint_{V} \vec{J}(\vec{r}') \frac{e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} dV'$$

Using far field assumptions and the fact that all currents lie on the z=0 plane, the integral can be simplified to:

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi |\vec{r}|} \iint_{x',y'} \vec{J}(x',y') \exp\left(-jk\sqrt{(x-x')^2 + (y-y')^2 + z^2}\right) dx' dy'$$

Expanding the square root term in a series and applying the far-field conditions:

$$\vec{A} = \frac{\mu_0}{4\pi r} e^{-jkr} \iint_{x,y} \vec{J}(x',y') e^{-jkx'\sin\theta\cos\varphi} e^{-jky'\sin\theta\cos\varphi} dx' dy'$$

$$A_{x} = \frac{\mu_{0}}{2r} e^{-jkr} \sum_{m=1}^{\infty} \delta\left(w - mw_{f}\right) \int_{0}^{l} dx' \int_{0}^{l} dy' \left[J_{x}(m)\sin\left(\frac{\pi mx'}{l}\right) e^{-jkx'\sin\theta\cos\varphi} e^{-jky'\sin\theta\sin\varphi}\right]$$
$$A_{y} = \frac{\mu_{0}}{2r} e^{-jkr} \sum_{m=1}^{\infty} \delta\left(w - mw_{f}\right) \int_{0}^{l} dx' \int_{0}^{l} dy' \left[J_{y}(m)\sin\left(\frac{\pi my'}{l}\right) e^{-jkx'\sin\theta\cos\varphi} e^{-jky'\sin\theta\sin\varphi}\right]$$

Solving:

$$A_{x} = j\frac{\mu_{0}}{2r}e^{-j\frac{w}{c}r}\sum_{m=1}^{\infty}J_{x}(m)\delta(w-mw_{f})\frac{\sin\left(\pi\frac{w}{c}\sin\theta\cos\varphi\right)\sin\left(\pi\frac{w}{c}\sin\theta\sin\varphi\right)}{2\frac{w}{c}\sin\theta\sin\varphi\left[1-\left(\frac{2wl}{\pi mc}\sin\theta\cos\varphi\right)^{2}\right]}e^{-j\pi\frac{w}{c}\sin\theta(\sin\varphi+\cos\varphi)}$$

$$A_{y} = j\frac{\mu_{0}}{2r}e^{-j\frac{w}{c}r}\sum_{m=1}^{\infty}J_{y}(m)\delta(w-mw_{f})\frac{\sin\left(\pi\frac{w}{c}\sin\theta\cos\varphi\right)\sin\left(\pi\frac{w}{c}\sin\theta\sin\varphi\right)}{2\frac{w}{c}\sin\theta\cos\varphi\left[1-\left(\frac{2wl}{\pi mc}\sin\theta\sin\varphi\right)^{2}\right]}e^{-j\pi\frac{w}{c}\sin\theta(\sin\varphi+\cos\varphi)}$$

In far field,  $\vec{E}$  is related to  $\vec{A}$  by the relation:

$$\vec{E} = -jw\vec{A}$$

Yielding:

$$E_{x} = \frac{\mu_{0}}{2r} w e^{-j\frac{w}{c}r} \sum_{m=1}^{\infty} J_{x}(m) \delta(w - mw_{f}) \frac{\sin\left(\pi \frac{w}{c}\sin\theta\cos\varphi\right)\sin\left(\pi \frac{w}{c}\sin\theta\sin\varphi\right)}{2\frac{w}{c}\sin\theta\sin\varphi\left[1 - \left(\frac{2wl}{\pi mc}\sin\theta\cos\varphi\right)^{2}\right]} e^{-j\pi \frac{w}{c}\sin\theta(\sin\varphi + \cos\varphi)}$$
$$E_{y} = \frac{\mu_{0}}{2r} w e^{-j\frac{w}{c}r} \sum_{m=1}^{\infty} J_{y}(m) \delta(w - mw_{f}) \frac{\sin\left(\pi \frac{w}{c}\sin\theta\cos\varphi\right)\sin\left(\pi \frac{w}{c}\sin\theta\sin\varphi\right)}{2\frac{w}{c}\sin\theta\cos\varphi\left[1 - \left(\frac{2wl}{\pi mc}\sin\theta\sin\varphi\right)^{2}\right]} e^{-j\pi \frac{w}{c}\sin\theta(\sin\varphi + \cos\varphi)}$$

Taking the inverse Fourier Transform:

$$E_{x} = j \frac{\mu_{0}}{4\pi r} \sum_{m=1}^{\infty} mw_{f} J_{x}(m) \frac{\sin\left(\pi \frac{mw_{f}}{c} \sin \theta \cos \varphi\right) \sin\left(\pi \frac{mw_{f}}{c} \sin \theta \sin \varphi\right)}{2 \frac{mw_{f}}{c} \sin \theta \sin \varphi \left[1 - \left(\frac{2}{n} \sin \theta \cos \varphi\right)^{2}\right]} \exp[jmw_{f}(t_{d} - \tau(\theta, \varphi))]$$

$$E_{y} = j \frac{\mu_{0}}{4\pi r} \sum_{m=1}^{\infty} mw_{f} J_{y}(m) \frac{\sin\left(\pi \frac{mw_{f}}{c} \sin \theta \cos \varphi\right) \sin\left(\pi \frac{mw_{f}}{c} \sin \theta \sin \varphi\right)}{2 \frac{mw_{f}}{c} \sin \theta \cos \varphi \left[1 - \left(\frac{2}{n} \sin \theta \sin \varphi\right)^{2}\right]} \exp[jmw_{f}(t_{d} - \tau(\theta, \varphi))]$$

Where:

$$\tau(\theta, \varphi) = \frac{\pi}{c} \sin \theta (\sin \varphi + \cos \varphi)$$
$$\vec{E} = E_x \hat{x} + E_y \hat{y}$$

From particle-in-cell code calculations, it is estimated that Terawatt can induce current densities of  $\vec{J} = 10^{15} A/cm^2$  by forcing electrons into the laser target. For a cross-section of 10 um, this implies peak currents of ~1 GA. Assuming that the resulting stream of electrons is at least as long as the laser pulse generating them, the stream will form a dipole of at least 1 mm. Using the equation for an infinitesimal dipole, peak electric fields at a distance of 500mm from the event should result in peak electric field intensities of:

$$E = 30 \frac{1^9 A \cdot 30um}{0.5m} (3.33 - 133) 1 / m \frac{V}{A} = (6.0 - 240) \frac{MV}{m}$$

Such field intensities are far in excess of the sensitivity of the detectors that will be employed in this experiment. An electromagnetic field with an electric field component of at least 1 V/m is sufficiently strong to be detected in all proposed detector configurations. Working backwards, a minimum detectable current can be estimated:

$$I = \frac{\left|\vec{E}\right|r}{30lk}\frac{A}{V} = \frac{1\frac{V}{m} \cdot 0.5m}{30 \cdot 1mm \cdot (3.33 - 133)1/m} = (125mA - 5A)$$

Which, for uniform current density 40um diameter, corresponds to current densities of:

$$J = (10 - 400) \frac{kA}{cm^2}$$

Or, for current density 10um in diameter:

$$J = (160 - 6,400) \frac{kA}{cm^2}$$

Provided that 50% of the laser energy is converted to high energy electrons with average energy of 100 keV that propagate from the target in a collimated beam, a rough estimate of the necessary laser energy can be determined. Using the antenna model developed for this phenomenon, electrons that are measured should endure for approximately the inverse of the frequency of radiation they admit. Using these estimates, the necessary laser pulse energy required is:

$$E = \frac{100 keV \cdot I \cdot \tau}{.5 \cdot e \cdot \gamma} = \frac{100,000J(125mA - 5A)(25ps - 1ns)}{.5\gamma C} = \frac{1}{\gamma} (0.625uJ - 1mJ)$$

Where  $\gamma$  represents the total percentage of energy found within the spectrum being investigated.

Another estimate can be made by using the time the electrons are required to transverse 1mm. Here, the velocity is given by

$$v^{2} = \left[1 - \frac{m_{0}^{2}c^{4}}{E}\right] = .55c$$

If instead the time duration  $\tau$  is set to  $\tau = \frac{d}{v} = \frac{1mm}{.55c} = 6ps$ , then the required laser pulse

energy is:

$$E = \frac{100,000J(125mA - 5A) \cdot 6ps}{.5\gamma C} = \frac{1}{\gamma} (.1.5uJ - 6uJ)$$

#### Section 2.5

For antennas operating in far-field, the effective aperture may be used to ascertain the incident electromagnetic field provided the output to the antenna is known. The effective aperture is the ratio of received antenna power to incident radiation power. The expression for effective aperture is:

$$A_e = \frac{P_{antenna}}{W_{em}}$$

Using Poyntings' Theorem:

$$W_{em} = \frac{\vec{E} \times \vec{B}}{\mu_0} = \frac{EB}{\mu_0} = \frac{E^2}{\mu_0 c}$$
$$\vec{E} = \sqrt{\mu_0 c \frac{P}{A_e}} \hat{p} = \sqrt{377 \frac{P}{A_e} \frac{V}{A}} \hat{p}$$

Where  $\hat{p}$  is a unit vector in the direction of the antenna's polarization.

### Section 2.6

To separate instrumentation artifacts from desired data when taking measurements, it is necessary to understand the operation of instrumentation used. Do to the relative sophistication of the instrumentation for this investigation, communications theory shall be employed to predict and devise countermeasures for instrumentation generated signal distortion.

The magnitude spectral response has been characterized for all devices in the receiver to be used. Such responses are cataloged using the spectral scale, allowing the magnitude response of the system as a whole to be ascertained by taking the sum of the responses of the individual components. Actual computations have been done in Microsoft Excel.

Do to the enormous bandwidths involved in these experiments susceptibility to noise is of particular importance. In general, noise power increases with bandwidth, so predicting and designing against excessive noise is of paramount importance. Because the detection instrumentation to be used in this experiment already has documented noise characteristics, noise performance of the instrumentation can readily be described a calculated using noise figure characterization.

Noise figure is defined for any two-port device as the ratio of signal to noise at the input of the device as compared the signal to noise at the output of the same system. This ratio is always equal or greater than 1, where values in one indicate degradation of signal to noise performance. The signal to noise ratio of a series of characterized devices is given by the following relation as provided by Chang (11):

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots$$

Where F is the noise figure G is the gain, ordered such that the first device is the first receiver component in series and each sequential parameter is the sequentially corresponding device in the receiver.

Specific characteristics of the receiver can be found in Section 3.7.
# **CHAPTER THREE**

## Section 3.1

For this experiment, the Laser Plasma Laboratory Terawatt Laser Facility at CREOL will be used. Terawatt is a tabletop Femtosecond chirped-pulse amplification laser capable of generated laser pulses of 1 J with duration of less than 120 fs. It utilizes a mode-locked Ti:Sapphire laser oscillator to generate the initial pulse and Cr:LiSAF for the amplifiers necessary to increase the pulse energy to 1 J. The resulting output pulse is centered at 850 nm.

In general, Terawatt will fire single laser pulses at a rate of 1 Hz. Terawatt is also capable of burst mode, where several pulses can be fired with ~10 ns spacing.



Figure 1: Terawatt Laser System Configuration

In the first set of experiments, transient electromagnetic fields resulting from laser irradiation of solid targets will be investigated. These tests will be conducted in target chamber #1. Initially, homogeneous sheets of copper and aluminum will be investigated. Upon completion of the initial investigation, more sophisticated targets will be analyzed if allowed by circumstances. The purpose of using multiple targets is to determine the effect target composition and geometry has on the resulting electromagnetic field.

For these test, laser pulses from Terawatt shall be routed in Target Chamber #1. A precision 3-axis translation stage is located within the center of Target Chamber #1, at a height of 8.5". This translation stage can be operated remotely from controls outside the chamber. Target samples will be mounted in a non-conductive, non-magnetic delron arm that will suspend the sample directly in the center of Target Chamber #1. A lens or off-axis parabolic mirror will be used to focus the laser beam onto the surface of the target with a spot size as small as 40 um in the case of the lens or <40 um in the case of the parabolic mirror.

To allow radiating plasma and hot electrons to form, Target Chamber #1 will be evacuated using both displacement and turbo pumps. Pressures of at least 10<sup>-6</sup> torr will be attained before proceeding with the experiment.

To collect data in the 1-18 GHz range, a DRH-118 ridged waveguide horn as been installed in one of the flanges, ~1.5 ft from the target sample mounted. The center of the

aperture will be located at a height of 8.5". The aperture of the horn antenna will be placed immediately outside of the flange so as to minimize coupling between the antenna and the chamber. The aperture will be pointed directly at the target to maximize antenna gain and to attenuate signals reflected off the side of the chamber. The antenna will be oriented such that it is polarized in the horizontal direction. The antenna is connected to a 40 GHz vacuum feedthrough via an Astrolab Minibend K series microwave cable, ensuring the received signal is extracted with minimized and documented distortions.

Data collected in the 18-40 GHz range will be collected in a manner identical to that in the 1-18 GHz range, except a Q-Par Angus QSH-180K Broad Band Horn Antenna will be used in place of the DRH-118.



Figure 2: Target Chamber Configuration



Figure 3: Alternate Target Chamber Configuration

Of particular concern when conducting chamber experiments are the distortions that reflected waves and antenna chamber coupling will have on the data of interest. The experimental setup as detailed above should ensure antenna chamber coupling is minimized. Reflected waves are of a greater concern. Fortunately, horn antennas are highly directive end fire antennas that are insensitive to radiation incident from above, below, or on the sides of the antenna. This ensures only waves deflected directed at the front of the antenna will effect measurements. Such waves are required to scatter off the walls of the chamber opposite the antenna, requiring a 3 ft round trip relative to the desired signal, resulting in a 3.3 ns delay. Under no circumstance is the pulse emanating from the target expected to exceed 2 ns in duration. It is therefore believed that the desired signal can be temporally separated from undesired reflections.

Initial test will employ a thick sheet of copper as the laser target. Do to the targets thickness and lack of internal geometry, the laser may be fired continuously at the target. This allows continual monitoring of laser generated EMP while the laser is focused on a single point on the target or while the laser focus is translating across its surface. For this reason this target design will provide both a diagnostic tool and a source of EMP for our investigation.

A thin sheet of aluminum foil will provide the second type of laser target. Here the foil shall be suspended across a metal frame. Here the laser may only be fired continuously while the focus is translating, otherwise single shot mode must be used.

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The third target design will be a specially designed, equally spaced, array of thin gold disc. The gold disk will be suspended above a silica substrate on specially etched silica columns, effectively creating a small floating target. A single laser pulse should immediately destroy the target, converting it entirely into plasma. Disk in the array will be spaced 300um apart in both directions, and each disk will vary from 10um-30um in a systematic manner. Immediately outside the array will be a gold alignment region, where the laser focus may be alignment with the height of the disk and the focus checked for translation drift. A simple LabView program will be used to compensate for focus drift during translation. Bare substrate in a cross pattern will be placed in the alignment region in line with the gold target disk, so that they laser focus may be alignment with the two dimensional grid. The array and alignment strip combined will occupy a 1"x 1" area, each alignment strip being 0.2" in thickness. Substrate shall extend as far as 1.5"x1.5" so that the target may be physically suspended.



Figure 4: Microtarget Array



**Figure 5: Array Features** 

The second set of experiments will investigate the electromagnetic fields generated by a laser plasma filament in air. These experiments shall be conducted in the utility chaseway within CREOL. Here, Terawatt will be used to produce laser plasma filaments that will extend for several meters.

For these test, both microwave antennas shall by mounted on a precision two-axis tripod within the utility chaseway. The antenna shall be located at a distance of 3 m from the laser filament column for initial testing. The antenna will be manually rotated about the filament maintaining the uniform distance to measure a rough approximation of the laser filament radiation pattern. Additional test at different distances shall be used if more detailed investigation into spatial dependence of radiation is required.

In order to conduct the experiments described, an innovative system for measurement had to be developed. The instrumentation in question needed to meet several stringent requirements simultaneously. Because Terawatt can only fire at a rate of 1 Hz, detection instrumentation cannot be dependent upon reconstructing a measurement by sampling a continuous series of similar signals, a technique often employed in many modern digital sampling oscilloscopes. Instead, it is necessary that a complete set of data can be measured from a single laser trigged electromagnetic pulse. Because of the incredibly short duration of the electromagnetic pulse, the system must have extremely high time resolution, preferable in the range of tens of picoseconds. Due to the relatively unknown nature of the electromagnetic field to be measured, a large dynamic range is desired, so a wide range of varying intensities can be measured simultaneously. Finally, it is required that the measurement instrumentation be readily able to probe any frequency within a 1-40 GHz range. If taken individually, meeting these requirements may not be difficult, but when taken together, they require a unique approach. To meet these demands, a unique array of microwave antenna and microwave circuitry will be employed.

Radiation resulting from laser plasma shall be measured using a horn antenna located at a specified distance from the laser target. To measure the fields, a pair of EMC broadband antennas is employed. Both antennas are calibrated horn antennas with known coupling characteristics, including antenna gain and effective aperture across their operating frequencies. Because no antenna with a 1-40 GHz bandwidth exist, it was necessary to employ two antennas to cover the bandwidth range of interest.

For frequencies of 1-18 GHz, a Sunol Sciences DRH-118 ridged waveguide horn antenna will be used. When making measurements in the 18-40 GHz range, a Q-Par Angus QSH180K broad band horn antenna will be used.

### Section 3.6

It is our intent to provide detailed time domain and frequency domain of such laser generated electromagnetic radiation. To achieve this end, the Tektronics CSA7404 Communication Signal Analyzer shall be employed. The CSA7404 is a single shot oscilloscope, which is capable of reconstructing an electrical event after only a single observation. This is in contrast to commonly available digital sampling oscilloscope, which requires a periodic signal to reconstruct an electrical event by taking samples over several periods. The CSA7404 allows real time measurement of signals that fall within DC-4 GHz analog bandwidth. It has a 20 GS/s sample rate, 50 ps resolution, and a vertical resolution within 2mV(operating in a 50 ohm system).

The received antenna signal will be interpreted and analyzed using the CSA7404. Under normal circumstances, a low-noise amplifier would be sufficient to analyze the electrical output of the antenna. For this experiment, however, it is desired to probe up to 40 GHz. Furthermore, it is required that the receiver, while extending the frequency range of the system, should not degrade the systems time resolution, so that events as short as 50 ps can still be measured. To achieve this end, and ultra-broadband inverse superhetereodyne receiver shall be employed. This system is a unique receiver designed by the Laser Plasma Laboratory for the specific purpose of measuring laser generated transient electromagnetic fields.

The inverse superhetereodyne receiver used for these experiments is a purely microwave analog electronic system capable of demodulating select 4 GHz portions of the spectrum with a time response that should only be limited by its analog bandwidth. It can be tuned from 1-40 GHz so as to be consistent with experimental requirements. Depending on configuration a spectral range, the system has a gain of 3.70 - 7.26 dB, a noise figure of 9.99-10.75 dB, a minimum sensitivity of 0.04-0.82 V/m and a dynamic range of 30 dB.

The purpose of the inverse superheterodyne receiver is to demodulate frequencies from 1 to 40 GHz to DC while filtering all but 4GHz of the received signal to match the CSA7404's bandwidth limitation and to eliminate overlap of the measured signals spectral components in the Fourier domain. To achieve this end, the signal in question will be passed through a 1-40 GHz pre-amplifier for noise suppression. A 1-50 GHz mixer will then be used shift its spectra in a manner such that bottom of the 4 GHz window that is intended to be measured will coincide with 16 GHz after being shifted(mixing will be driven by a local oscillator that can be tuned from 2-40 GHz). Depending of the frequency range of interest, this frequency shift could be either positive or negative. The signal will then be passed through a low noise amplifier to increase gain and suppress noise contributed by latter stages. A bandpass filter with a passband of 16 to 20 GHz with 80 dB out of band attenuation 2 GHz from the passband will filter out all unwanted frequencies below the intended window (which was mixed so as to start at 16 GHz). The resulting filtered signal will then be mixed with a fixed 16 GHz local oscillator signal so that the bottom of the intended 4 GHz window corresponds with DC. A lowpass filter with 4 GHz cutoff shall then be to eliminate any remaining signal above 4 GHz.

A microwave signal synthesizers shall be used as variable oscillator to drive the first mixer in the system. A Spacek Labs AKKa2X frequency doubler will be used to extend the DC-20 GHz range of the signal synthesizer to 40 GHz.

A variable attenuator will be used to align the dynamic range of both amplifiers in the receiver system. This should ensure an optimal dynamic range of 30 dB regardless of system configuration.

The resulting signal should be a selectable 4 GHz window located anywhere between 1 and 40 GHz, that has been amplified by approximately 5 dB (system gain depends on frequency). This signal will then be feed into the CSA7404, enabling thorough time domain and frequency domain analysis over the desired 1-40 GHz range.



Figure 6: Inverse Superhetereodyne Receiver Specifications

Do to the range of experiments to be conducted, the system can be arranged in several configurations depending on circumstances. In particular, for each experiment, at least two setups must be used, one utilize the DRH-118 for low frequencies and the other using the QSH180K for high frequencies. Despite its design limitations, the DRH-118 is sensitive to frequencies greater than 18 GHz, unfortunately it is not calibrated for this range and the additional bandwidth can interfere with other signals being demodulated for measurement. A lowpass filter is therefore placed between the pre-amplifier and the

rest of the inverse superheterodyne to suppress to unwanted bandwidth. Both the DRH-118 and the QSH180K act as natural lowpass filters, and frequencies in excess of 40 GHz simple do not interfere with the inverse superhetereodyne receiver, eliminating the need for additional filters.

For measurements taken within Target Chamber #1, the addition of a vacuum feedthrough is required. Otherwise, no additional modifications are necessary. The feedthrough has minimal and documented distortions and should have little effect on the experiment.

Ultimately, there are four specific configurations that shall be used for this investigation. Using manufacturer component specifications, and calculations made in section 2.5, the magnitude spectral response of the system has been fully characterized.

Configurations A and B refer to the receiver configurations without and with the vacuum feedthrough respectively. Configuration 1 is for 1-18 GHz measurements using the DRH-118, Configuration 2 is for 18-40 GHz using the QSH180K. The Intermediate Stages represent stages that affect the signal regardless of system configuration. Such stages exist after the first mixer, where a 4 GHz window to be measured has been select. Therefore, the 0-4 GHz represented in the intermediate stage gain must be taken relative to the lowest frequency in the 4 GHz window to ascertain the actual frequency they are applied to.

System gain as a function of configuration and frequency, this gain relates incident radiation power density to measured power at the oscilloscope.



Figure 7: System Front End Gain, Low Frequency Band



Figure 8: System Front End Gain, High Frequency Band



Figure 9: Intermediate Stage Gain

To allow for quick and comprehensive analysis of multiple magnitude and phase plots generated while using different modulation frequencies, a Matlab application has been developed. This program will automatically compile and compensate data for instrumentation artifacts.

The Matlab application will be able to read a predefined sequence of .xls data files, which can be generated from the .csv data files recorded by our measurement system. Three arrays of magnitude, phase, and background measurements can be feed into the program simultaneously along with an array of the respective starting frequency for each window the data describes. The program automatically subtracts background signals from the spectra, then compensates for system distortion using an additional file describing the spectral gain of the inverse superhetereodyne receiver. Compensated data is then compiled into a single larger spectrum, spectrally overlapping regions of the data being averaged in the process. Compiled data is then combined with phase and converted to free space electric field intensity. An inverse fast fourier transform algorithm can then be used to retrieve the new time domain signal.

#### **CHAPTER FOUR**

#### Section 4.1

Before initiating experiments, the system was tested against known signals to ensure proper demodulation. Because spectral gain of system components were already provided by the system component manufacturers, and do the lack of a controlled signal source spanning 40 GHz, magnitude response of the system was not determined experimentally. Rather, manufacturer specifications were used to calculate the systems magnitude response.

Instead, signal modulation was investigated for the 1-18 GHz regime. Here, a microwave synthesizer and a simple antenna were used to generate continuous wave signals at integer GHz frequencies. Signals were observed by the CSA7404 set to magnitude spectrum analysis, with a center frequency of 2.5 GHz and span of 5 GHz, and with a resolution bandwidth of 80 MHz. When the inverse superhetereodyne receiver is properly configured, the continuous wave signals will appear as sharp peaks on the oscilloscope.

For 1-18 GHz, the variable mixer signal will actually modulate the calibration signal up by the selected amount to be passed through the 16-20 GHz passband filter. This signal will be then be mixed with 16 GHz, reducing the frequency back to DC-4 GHz, provided it did not get rejected by the passband filter. Therefore, the observed signal should appear on the oscilloscope with an apparent frequency given as follows:

Apparent Frequency = Actual Frequency + Mixer Frequency – 16 GHz

If the apparent frequency does not lie within DC-4 GHz, the signal should not be observed at all.

For the test in question, the microwave synthesizer was set to a variety of values between 1 and 18 GHz, including each integer value. For each of these values, the mixer frequency was set to values that where the apparent frequency would appear on the oscilloscope, to ensure that the apparent frequency was accurately determined by the equation above. Furthermore, the mixer frequency was also set to values where the apparent frequency should not appear. In both cases the system performed as expected, yielding only a single peak corresponding to the calibration signal and the apparent frequency predicted, or yielding no peak for apparent frequencies outside the DC-4 GHz band.

Unfortunately, the calibration signal peak was not the only signal present. For mixer frequencies 10 GHz and less, harmonics from the M2-0250 mixer can appear in the output. Fortunately, the location of these harmonics can be predicted. The apparent frequency of each harmonic is simply the appropriate integer multiple of the fundamental frequency reduced by 16 GHz. As with the desired signal, harmonics only appear if their apparent frequency falls within DC-4 GHz. For mixer frequencies of 4 GHz and below, multiple harmonics can appear.

Because there harmonics are predictable, the spectra they occupy can be disregarded or the harmonic can be removed by subtracting a background spectral plot taken at the same frequency. The data analysis program mention in Section 3.8 automatically performs that latter operation. While it has not been test, an additional method of suppressing these harmonics would be to analyze the negative half of the Fourier spectra, which would allow analysis of spectra that would ordinarily require mixer signals 10 GHz or below to instead require mixer signal well above 10 GHz. This would eliminate harmonics but would also invert the spectra. If such a scheme working correctly, the spectra could be corrected using simple computer script.

### Section 4.2

Before measuring laser generated EMP, the inverse superhetereodyne receiver and data analysis software were employed to measure the radiation emanating from a simple spark gap. The spark gap is powered by a 10 kV power supply placed in series with a large resistor which fed a 3300pF doorknob capacitor. The capacitor was then placed in parallel with the spark gap and with a leakage resistor to ensure the safe discharge of the capacitor when the device is not in use. The spark gap is formed by a pair of 8-32 screws whose tips have been ground to form sharp electrode tips. The distance may be adjusted to form sparks of different lengths and voltage.

For an initial test, the spark gap was adjusted to 1.5 mm. At this distance, the gap discharges several times per second. The voltage reached before discharging averaged to approximately 4 kV. Discharge radiation could easily be discriminated from background radiation and system harmonics, and simply oscilloscope triggers could capture the radiated signals immediately after discharge. The discharge gap was placed ~1 ft in front of the receiver antenna. For these experiments, the gap discharge was polarized with respect to the antenna, so that the discharge traveled along the antennas polarization sensitive axis.

Both time and frequency domain data was collected on this discharge using the inverse superheterodyne receiver. Frequency domain data included both the magnitude and the phase, and both types of data where recorded from the same event. However, data from different spectral windows necessarily corresponded to different events. Analyzing data on electrostatic discharge lead to another modification in how data was interpreted. Raw time domain data for a particular spark discharge is on the left in figure 10, while the resulting inverse Fourier transform of the compiled spectra from the same sequence of discharges is on the right. The logical approach in comparing the compile data to the raw data is to truncate the second half of the compiled time domain data, which results the signal that appears in figure 11. It is apparent that figure 11 corresponds well to the time domain data. Modifications to the Matlab based data interpretation program have been made to automatically perform this truncation.



Figure 10: Respective Raw(left) and Processed(right) time domain data



Figure 11: Truncated Processed Data

Using these modifications a complete reconstruction of the discharge may be created my measuring the spectra across multiple, contiguous 4 GHz windows. The reconstructed time and frequency domain data for a 4.1kV discharge over a 0.08" air gap is listed below in figures 12, 13 and 14.



Figure 12: A complete time a frequency domain description of a spark discharge measured for 50ns.



Figure 13: A complete time and frequency domain description of a spark discharge measured for 100ns.



Figure 14: Complete time and frequency domain description of a spark discharge measured for 100ns. For this measured, the spark gap was cross-polarized with respect to the horn antenna.

For reference, the corresponding raw data for both polarized cases is provided in figures 15 and 16.



Figure 15: Raw time domain data for the 50ns measurement.



Figure 16: Raw time domain data for the 100ns measurement.

An important observation can be made in regard to the raw data listed in figure 15 and 16. When changing the duration of which the pulse is measured from 50 to 100 ns, the pulse duration in each of the listed frequency regimes appears to approximately double. This implies that the measured pulse length is dependent on the duration of time over which the pulse is measured. The measurement artifact is undesired, but its cause is not yet known.

Once a reliable means of measured of the electrostatic discharge source were established, a parametric study of radiation emanating from the discharge gap as a function of the coupled parameters of gap voltage and distance was conducted. Furthermore, different electrode configurations were used, changing the coupling relation between the gap voltage and distance, as well as the resulting discharge radiation.

Initially, the gap was employed in which both electrodes terminated at sharp points, as illustrated in the figure below.



#### Figure 17: Discharge Gap Depiction

Discharge voltage was adjusted by changing the length of the air gap between electrodes. The relation between distance and voltage is given in the following table.

Discharge Voltage	Gap Distance
2.6kV	0.035"
4.1kV	0.08"
8.0kV	0.10"
9.4kV	0.14"

Table	1
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Figure 18: Discharge Spectra, the left spectrum is for a 2.6kV discharge while the right spectrum is for a 4.1kV discharge. The spectra were measured over a 50ns interval.



Figure 19: Discharge Spectra, the left spectrum is for an 8.0kV discharge while the right spectrum is for a 9.4kV discharge. The spectra were measured over a 50ns.

From figures 18 and 19, two major spectral components comprising the pulse can be observed. One such component is at 1 GHz while the other component resides at 13 GHz. As discharge voltage is increased, the 1 GHz component diminishes leaving the 13 GHz component to dominate the spectrum.



Figure 20: Discharge Spectra, the left spectrum is for a 2.6kV discharge while the right spectrum is for a 4.1kV discharge. The spectra were measured over a 100ns.



Figure 21: Discharge Spectra, the left spectrum is for an 8.1kV discharge while the right spectrum is for a 9.4kV discharge. The spectra were measured over a 100ns.

When measured over 100ns, it is clear that the pulse description has a greater number of spectral components than the corresponding 50ns measurements. The pattern of diminishing 1 GHz components remain, although in this case the 1 GHz component diminishes from being the dominant component to being of equal intensity with other major spectral components.



Figure 22: Reconstructed discharge time domain plots, the left plot is for a 2.6kV discharge while the right plot is for a 4.1kV discharge.



Figure 23: Reconstructed discharge time domain plots, the left plot is for an 8.1kV discharge while the right plot is for a 9.4kV discharge.

In all four of the above cases, the pulse duration remains approximately constant while the pulse intensity appears to decrease with increase gap distance and voltage.



Figure 24: Reconstructed discharge time domain plots, the left plot is for a 2.6kV discharge while the right plot is for a 4.1kV discharge.



Figure 25: Reconstructed discharge time domain plots, the left plot is for an 8.1kV discharge while the right plot is for a 9.4kV discharge.

When measured over 100ns instead of 50ns, the pulse duration approximately doubles with reference to the 50ns case, although all 100ns measured pulse durations are approximately the same. This indicates the measured pulse duration is dependent on the time in which the pulse is measured, which demonstrates a flaw in the experimental methodology currently used. Again intensity decreases with increase gap distance and voltage as in the previous case.

In the second spark gap configuration, the original anode was replaced by an anode the terminated at a plane instead of a point, while the cathode is still terminated at a point.



Figure 26: Discharge Gap Depiction with Planar Anode

Table 2

Discharge Voltage	Gap Distance
3.2kV	0.025"
3.6kV	0.05"
8.0kV	0.09"
9.3kV	0.115"



Figure 27: Discharge Spectra, the left spectrum corresponds to a 3.2kV discharge while the right spectrum corresponds to a 3.6kV discharge. The spectra were measured over 50ns.



Figure 28: Discharge Spectra, the left spectrum corresponds to an 8.0kV discharge while the right spectrum corresponds to a 9.3kV discharge. The spectra were measured over 50ns.

For this second spark gap configuration, the same two spectral components observed in the original configuration, those at 1 and 13 GHz, are also found in the above set of 50ns spectral graphs. Here, the situation regarding the 1 GHz spectral component appears to be reverse, it increases relative to the 13 GHz component with increase gap distance and voltage.



Figure 29: Discharge Spectra, the left spectrum corresponds to a 3.2kV discharge while the right spectrum corresponds to a 3.6kV discharge. The spectra were measured over 100ns.



Figure 30: Discharge Spectra, the left spectrum corresponds to an 8.0kV discharge while the right spectrum corresponds to a 9.3kV discharge. The spectra were measured over 100ns.

When measured over 100ns, the discharge spectra of the second gap configuration do not seem to share the spectral richness of the original configuration, with the possible exception of the 3.2kV discharge. Instead, the spectra seem to be dominated by a 1 GHz spike and a 1-5 GHz continuum, with weak spectral components for frequencies greater than 5 GHz.

# CONCLUSION

Due to the success of the modulation test, the inverse superhetereodyne receiver has been demonstrated to operate as intended, at least for the purposes of demodulating the correct portion of the spectra. The spark gap discharge test demonstrates that the receiver system operates under realistic operating conditions. In addition, the tests seem to demonstrate that the receiver system is more sensitive than theoretical characterization would indicate.

Various observations can be made about the measured electrostatic discharge time and frequency domain data. The measured electromagnetic fields appear to be unusually weak, never exceeding 1 V/m. Furthermore, the radiated intensity of such discharges becomes even weaker as the gap discharge voltage is increased. It is likely that such discharges radiate at frequencies well below 1 GHz, so that the measurement instrumentation is insensitive to much of the incident radiation. The decrease in intensity with increase in discharge voltage might indicate that for higher voltage discharges, more of the radiation is located out of the measurement band, likely below 1 GHz.

The duration of the measured discharge pulses appear to be dependent upon the length of time in which the pulse is measured, so that a pulse measured over 100ns has a duration approximately of twice that of a pulse measured for 50ns. This is clearly an experimental artifact resulting from the measurement techniques employed, and needs to be investigated in the future.
The measured spectra of the spark discharges appear to be dependent on the duration over which the pulse is measured. It is readily apparent that discharge pulses measured over 100ns have spectra which are comprised of a significantly greater number of components that those measured over 50ns. Spectral components comprising the 100ns measured pulses include all spectral components that comprise 50 ns measured pulses. It is evident that it requires additional spectral information to describe pulses when measured over 100ns. This implies that the pulses when measured over 100ns are more detailed, despite a loss in resolution proportional to the change in time scale, and therefore require more spectral components to describe.

As was the intent of the parametric analysis of the spark discharge, discharge spectra where found to be dependent upon both the spark gap voltage and the electrode configuration. For discharge measured over 50ns, the spectra had two predominate components at 1 and 13 GHz. For a pair of sharp electrodes, the 1 GHz components decrease relative for the 13 GHz components with increased discharge voltage. Replacing the sharp anode with a planar anode reversed this behavior causing the 1 GHz component to increase relative to the 13 GHz component with increasing voltage.

Analogous behavior was observed in for 100ns measurements. Here high frequency components increased in strength relative to the discharge spectra's 1 GHz component when discharge voltage was increased for the original gap. When a planar electrode was employed, the high frequency components of the spectra diminished with increased voltage relative to the 1 GHz component instead.

When 100ns and 50ns measurements are taken together, it can be concluded that high frequency components begin to dominate a discharge voltage increases when a sharp anode is employed, while the 1 GHz component of the spectra dominates for high discharge voltage when a planar anode is employed. At this point in time, the reason for such behavior has not been ascertained, but it definitely merits the subject of future investigations.

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