Affecting electronic and wireless devices using low-energy wave-shaped pulses

Abstract: Intentional electromagnetic interference (IEMI) is a threat to modern civilian and military establishments. It is a primary electromagnetic challenge as noted at the *DoD Electromagnetic Environmental Effect (E3) Program Review* conference.[1]

Significant efforts have been devoted to developing high-energy IEMI sources and developing defenses against high-energy IEMI attacks like the electromagnetic pulse (EMP) generated by nuclear weapons.[2] Far less work has been conducted in the area of low-energy IEMI (LE-IEMI). Smaller, low-energy sources, with their higher mobility and lower cost, represent both new opportunities and new threats.

The objectives of the current project are 1) developing a LE-IEMI source and 2) demonstrating that this energy can be coupled via the electric field to disrupt a range of electronic and wireless devices. Specifically, the effects on specific electronic technologies of low-energy wave-shaped pulses will be studied.

This work is a collaboration between Rose-Hulman Institute of Technology, the Air Force Research Laboratory and the EMC Laboratory at the Missouri University of Science and Technology.

Introduction

Disabling electronic devices via electromagnetic pulses is an idea that has been around in military circles for years. However, most of the previous technologies use high amounts of energy which results in high cost solutions with low portability. The aim of this project is to create a low-energy intentional electromagnetic interference (LE-IEMI) solution that will be cheaper and more portable.

Designing the LE-IEMI system described here presents numerous challenges due to having both high voltages involved and the need for coupling and radiation to be broadband. As seen in Figure 1, this particular design employs 60 kV to charge up a bank of capacitors, through a resistor network. The capacitors then release their stored energy through a high-speed relay that is controlled by external circuitry. The pulse released by the capacitors travels down a transmission line to a broadband, directional antenna that transmits the wave into the air toward the target device. Each of these components and subsystems present design challenges that require careful engineering design to implement properly. The following sections outline the main problems and issues that this project has presented as well as the solutions to these problems.

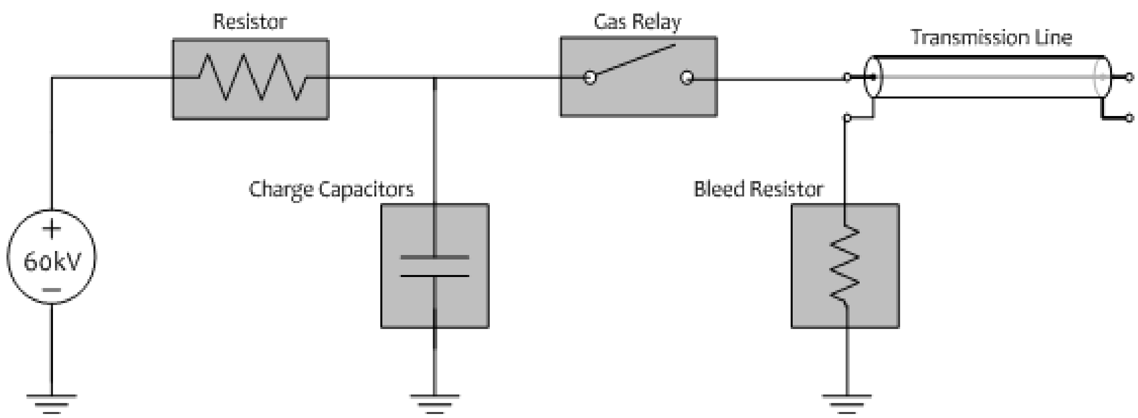

Figure 1: Low-Energy IEMI Schematic

Inductance Reduction

A critical parameter in this project is the rise time of the generated pulse. Without a pulse of sufficiently small rise time, the energy of the pulse would be concentrated at low frequencies which would then require a large antenna to achieve efficient radiation. This would make it difficult to allow the IEMI system to be portable- the antenna should be sufficiently small to fit comfortably aboard an unmanned Aerial Vehicle (UAV). The size of an antenna is directly related to the wavelength of the wave being transmitted. Assuming a wave traveling in air,

$$\lambda = c/f$$

where c is the speed of light in free space. Thus, it is evident having a short rise time for the pulse is a critical factor to allow higher frequency content in the pulse to allow a smaller antenna.

As the system is a series of capacitors being charged up through a resistor network, the rise time can be related to the bandwidth of the system by the equation

$$T_{rise} = 0.35/BW$$

This equation shows the inverse relationship between rise time and bandwidth, so that a small rise time will result in a large system bandwidth.

One strategy to reduce the rise time of the transmitted pulse is by reducing the inductance in the system. Inductance is a function of geometry and material properties. For non-magnetic materials, the inductance is purely a function of geometry[3].” In the case of the LE-IEMI system, excess inductance was present where there was a large separation between the inner and outer conductors within the system. This separation allowed a significant amount of area for magnetic flux to flow and ultimately lead to an increase in the total inductance. The two solutions to this problem were to decrease the distance between the conductors by making a more compact design and to make the inner conductors thicker so that they were closer to the outer conductor. The tradeoff that comes with making the design more compact by reducing the area between the inner and outer conductors is that arcing becomes a concern with the high voltages that the system requires. This problem will be discussed more thoroughly in a later section. By making the current-carrying conductors thicker, the team tried to maximize the reluctance of the flux path. This tends to reduce the flux density, and the combination of lower flux density and lower area for the flux to link acts to minimize the inductance, which is to minimize the flux linked per unit-current.

Short Circuit Tuning Stub

After substantially lowering the system inductance to get a suitable rise time, the energy of the pulse will still be centered on DC. The system employs a short circuit tuning stub optimized to remove the DC content of the transmitted pulse and shift that energy to a higher frequency. A model of the tuning stub was created and simulated in CST by last year's team at Rose-Hulman. This model is shown below in Figure 2 and provides a visual breakdown of what the tuning stub accomplishes.

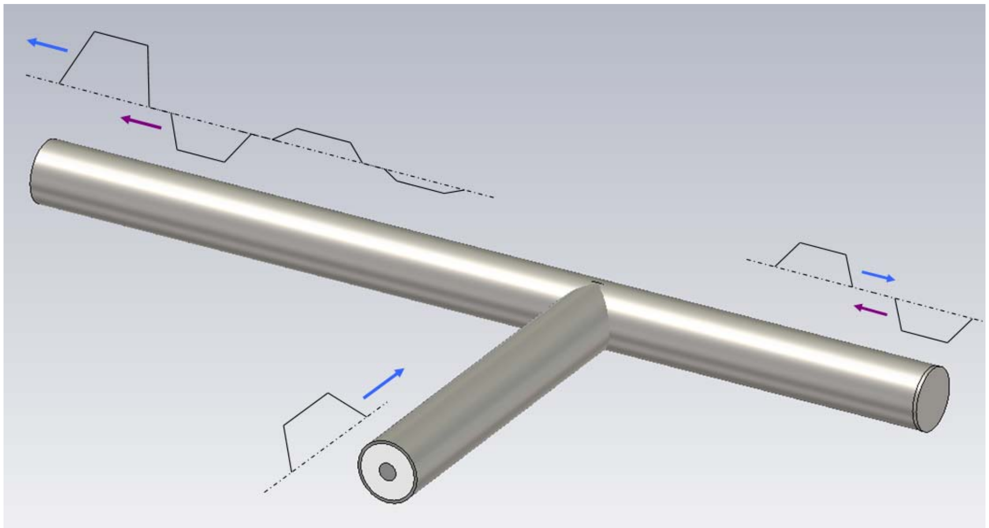

Figure 2: Tuning Stub CST Model

The tuning stub works by splitting the transmitted signal via a T-splitter and sending one signal down the transmission line to the antenna. The other signal travels away from the antenna for a short period of time before hitting a short circuit load that reflects the pulse back toward the antenna. The short circuit, having a reflection coefficient of -1, results in the pulse traveling back toward the antenna having the opposite polarity of the incident pulse. Using the lengths of the cable and the speed of the wave in the transmission line, the total time it took for the reflected pulse to get to the antenna was calculated and optimized so that it arrived back at the transmission line to combine with the first pulse to largely remove the DC content of the pulse transmitted to the antenna (upper left in figure 2). The results of the CST simulation utilizing a 50 cm stub are shown in Figure 3 in both the time and frequency domain. The frequency domain plot makes it clear that the tuning stub is shifting the energy of the transmitted pulse away from DC and toward higher frequencies. Also, a screen shot of the actual transmitted pulse with the tuning stub attached to the system is found in Figure 4. The pulse of figure 4 had a spectrum whose energy was centered at around 400 MHz.

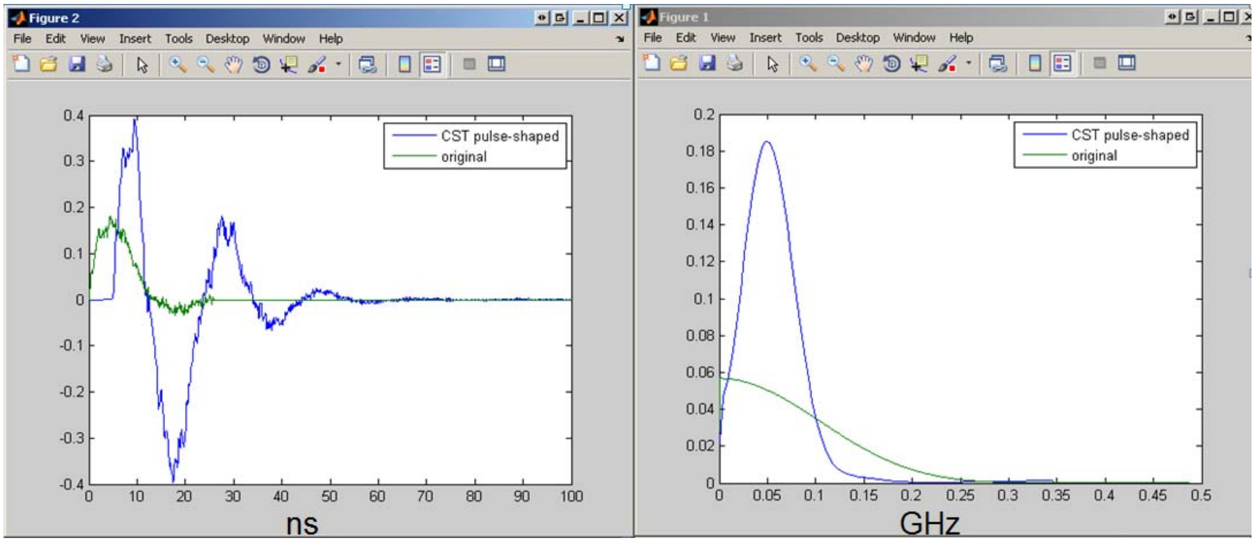

Figure 3: Time and Frequency Domain Plots of the Pulse with and without Tuning Stub

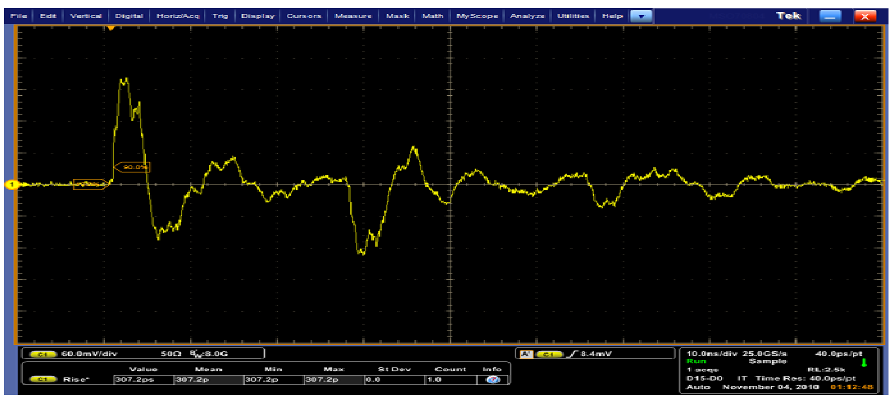

Figure 4: Transmitted Pulse with Tuning Stub Attached

A frequency of 400 MHz results in a wavelength of 0.75 meters, or a half-wavelength of around 0.4 meters. Building an antenna based on these lengths is much more practical for a LE-IEMI system. Apart from size, the other parameters to consider in designing an antenna for this application are directionality and achieving a broadband match. The next section discusses antenna design options and tradeoffs that had to be considered when designing a broadband, directional antenna.

Antenna Design

The first antenna that was looked at as the delivery system for the high-voltage pulse was the discone antenna, which is made up of a disc attached to a cone and fed by a coaxial cable. The inner conductor or the coax cable is attached to the disc, and the outer conductor is attached to the cone. The discone antenna was chosen because of its broadband characteristics, meaning that it is both an efficient radiator and can be impedance matched over a large range of frequencies. A weakness of the discone antenna is its poor directionality – the energy is dispersed along a 360-degree radiation pattern originating from between the inner and outer conductors.[4]

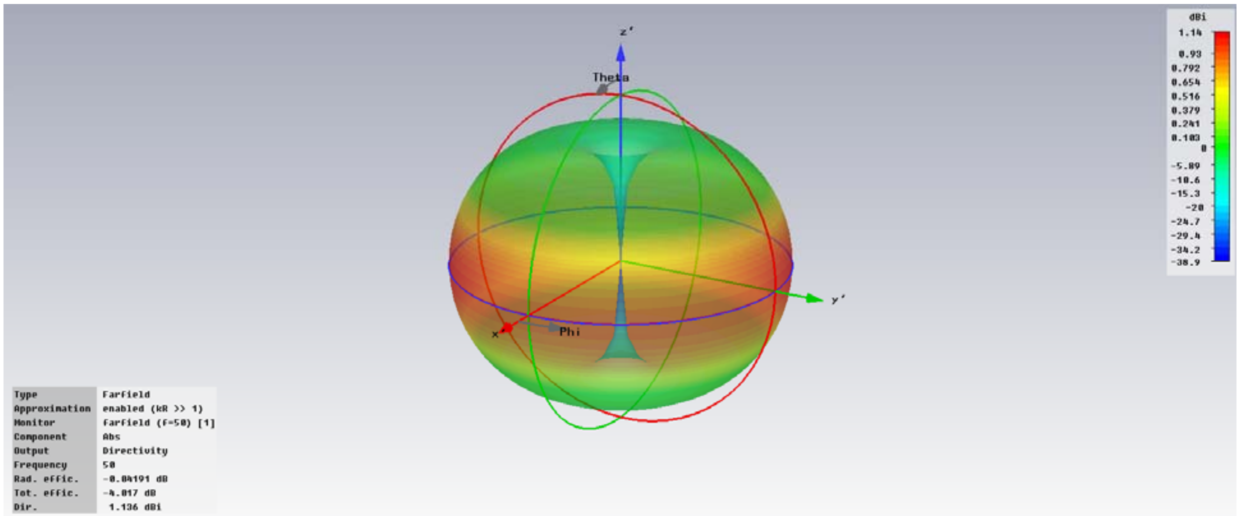

Figure 5: Radiation Pattern of Discone Antenna

Another antenna, which was investigated for this project is the multi-turn, circularly polarized radiating line antenna. This antenna works similarly to a standard helical antenna. However, rather than being effective at a narrow band of frequencies, the multi-turn, circularly polarized radiating line antenna achieves a broadband match by varying the radius of each turn of the helix, thereby changing the necessary wavelength of a wave that can propagate through the antenna.[5]

In both of these designs, the size of the antenna was an important figure of merit. Since the energy of the pulse created by the pulser system is concentrated at frequencies in the 100MHz range, this corresponds to a wavelength of about 3 meters. In general, antennas are designed to be at least one-fourth of a wavelength, making these antennas each at least 75 centimeters long. In order to reduce this size, a strategy of embedding the antennas in a high-permittivity medium is being investigated. This would reduce the speed at which the waves travel, shortening the wavelength, allowing for a smaller antenna. This is illustrated by the following equation:

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} = \lambda f$$

Where v is the speed of the electromagnetic wave, ε_r and μ_r represent the relative permittivity and relative permeability in the material through which the wave is traveling, c is the speed of light in free space, and λ and f are the wavelength and frequency of the wave.

The high-permittivity medium investigated was a suspension of barium titanate in paraffin wax. Barium titanate has a relative permittivity ranging from 1200 to 10,000, depending on the temperature and other factors from its manufacturing stage. By mixing this material with paraffin wax, a dielectric with a relative permittivity of 16 can be created with minimal loss for the frequencies involved in this application. This would allow the antenna size to be reduced by a factor of four.

One major obstacle to overcome with these antennas is the problem of impedance matching them to the transmission line which carries the high-voltage pulse to the antenna. Any geometrical or material properties of the antenna that disturb the steady-state characteristics of the wave will result in a non-zero reflection coefficient and a less-than-ideal match. The goal is to create a seamless transition from transmission line to antenna. This problem is complicated by a tradeoff between good matching and small antenna size – because of the dielectric introduced to the surrounding area of the antenna, waves travelling from the coax cable to the antenna are disturbed and a match is made difficult to realize. This problem is being investigated using computer simulations in CST to create a plot of input impedance over a frequency range of 1MHz to 500MHz. Once this is obtained, the coax cable can be properly matched to the antenna over the specific frequency range that the energy of the pulse is contained in (around 100MHz). Matching can be accomplished by creating a gradual change in impedance along the transmission line. The characteristic impedance of the coaxial transmission line is given by the following equation:

$$Z_c = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{D}{d}\right)$$

Or equivalently:

$$Z_c = \frac{138}{\sqrt{\varepsilon_r}} log_{10}\left(\frac{D}{d}\right)$$

Where $\frac{D}{d}$ is the ratio of the radius of the outer conductor of the coax cable to the radius of the inner conductor.

From the above equation, it is apparent that the characteristic impedance can be changed gradually by changing the ratio of outer to inner conductor in the coax cable gradually using a custom adapter. Another matching strategy would be to introduce dielectric of increasing permittivity into the transmission line near the antenna rather than the sudden change to a relative permittivity of sixteen.

Simulation Techniques

CST Microwave Studio was used to investigate more complicated aspects of the antenna designs, including farfield radiation patterns, directivity, and input impedance.

Discone Antenna

The geometry of the discone simulation is shown below. By changing various geometrical parameters such as the width of the torus shapes around the edges of the disc and the cone, a voltage standing wave ratio (VSWR) plot shown below was obtained. It is desirable to have a VSWR as close to 1 as possible. This corresponds to a reflection coefficient of 0, which means all of the energy in the pulse that runs into the antenna is actually transferred to the antenna rather than being reflected back into the transmission line. A VSWR of 2 corresponds to a reflection coefficient of 0.33, which results in 11% of the energy being reflected and 89% sent to the antenna.

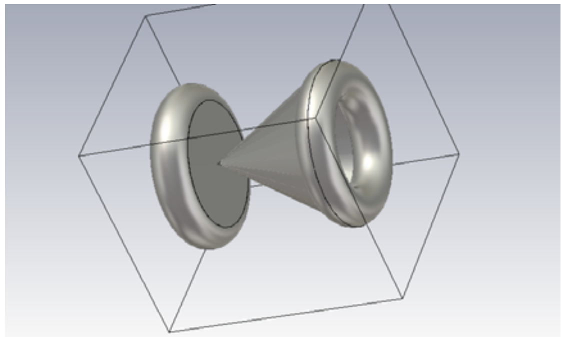

Figure 6: Discone Antenna in CST[5]

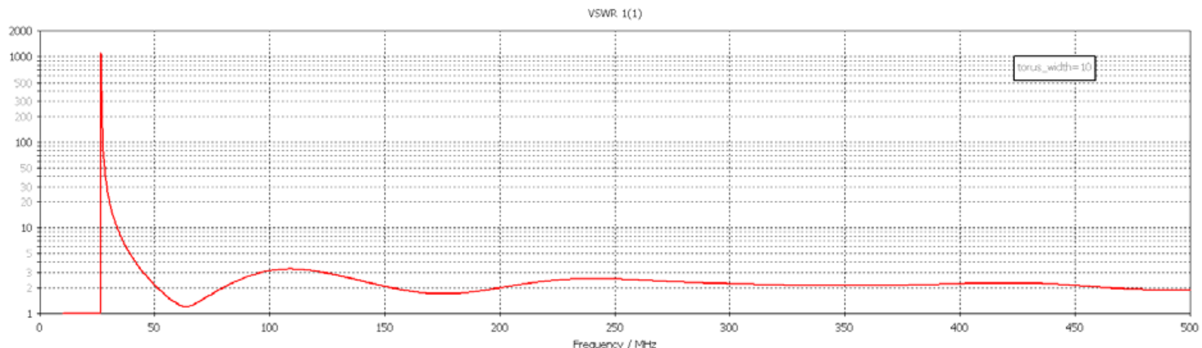

Figure 7: VSWR of Antenna from Figure 3[5]

Originally, the diameter of the disc was 65 cm and the cone length (along the cone) was 110 cm. However, since these dimensions are much larger than the desired antenna size, a new simulation was created by filling the area between the disc and the cone with a dielectric with relative permittivity of 16. This allows for an antenna with a similar radiation pattern but that is 4 times smaller than the originally antenna. This antenna is pictured below along with a graph of the resulting VSWR.

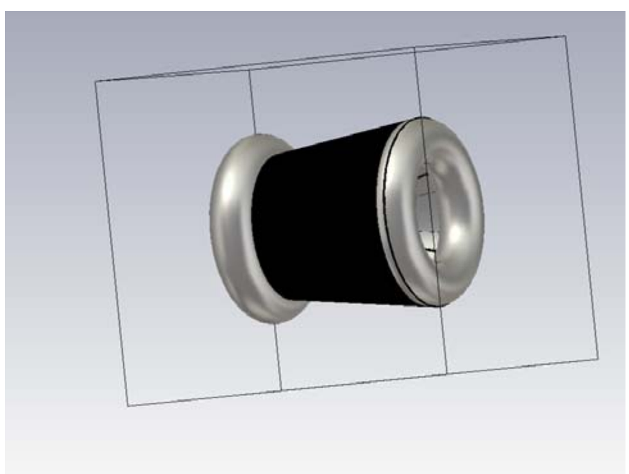

Figure 8: Discone Antenna with Dielectric Added[5]

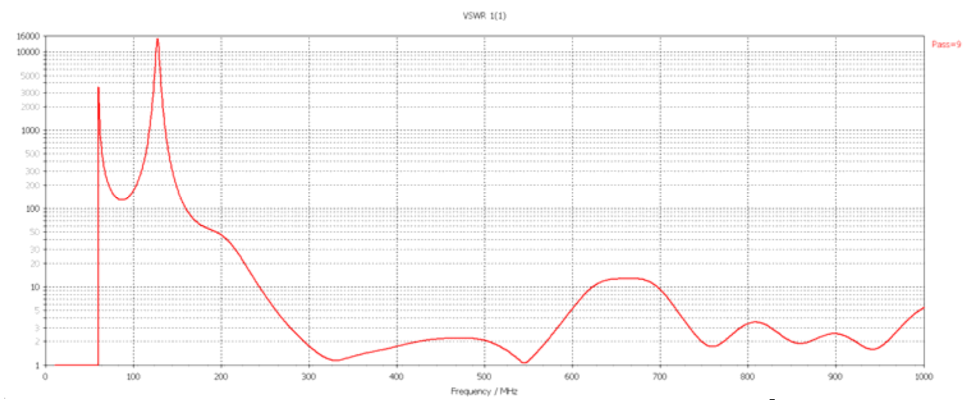

Figure 9: VSWR of Antenna from Figure 5[5]

Spiral

To investigate the multi-turn radiating line antenna, Matlab was used to create the spiral geometry, and the curves were imported into CST.

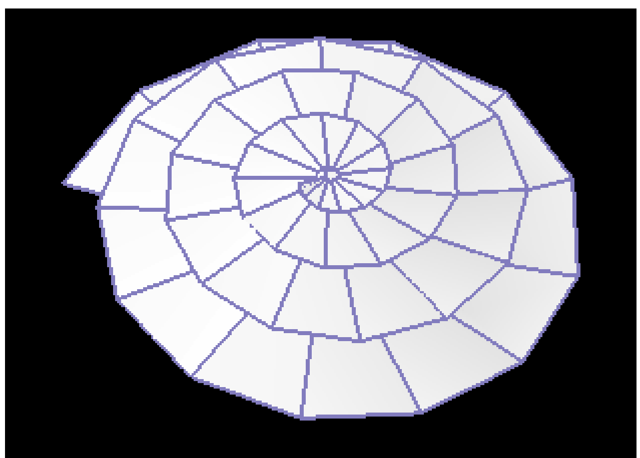

Figure 10: Multi-turn Radiating Line Antenna[5]

This antenna originally results in the following VSWR plot.

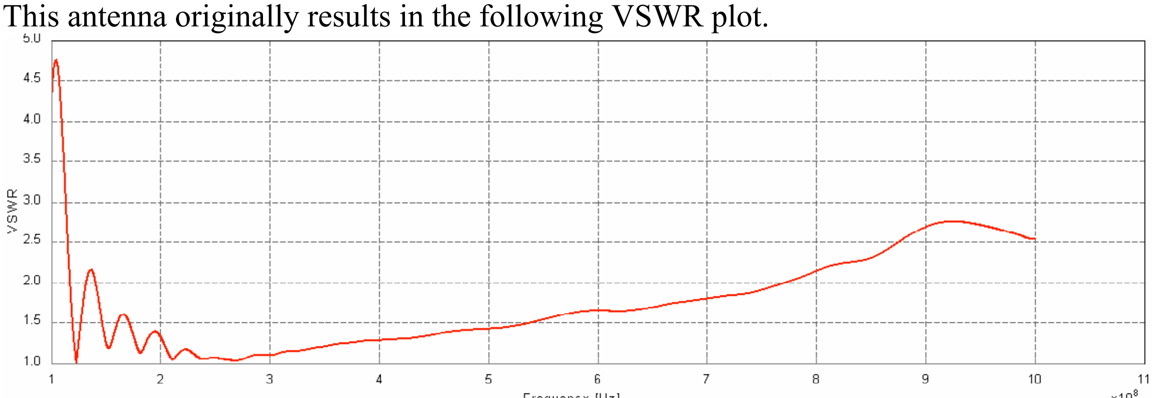

Figure 11: VSWR of Antenna from Figure 7[5]

Since this antenna deals with the same wavelength as the discone antenna, its dimensions are also larger than desired – the antenna is roughly 1.5 meters in diameter. A proposed design using a parabolic reflector filled with dielectric results in a much smaller antenna – roughly 40 cm in total diameter. This antenna is shown below along with a VSWR plot showing quality of matching.

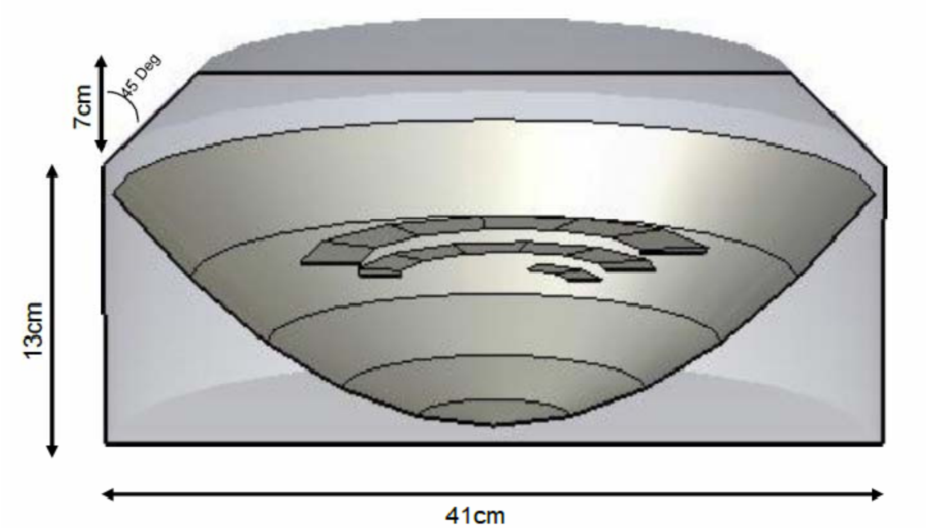

Figure 12: Dimensions of the Multi-turn Radiating Line Antenna filled with Dielectric[5]

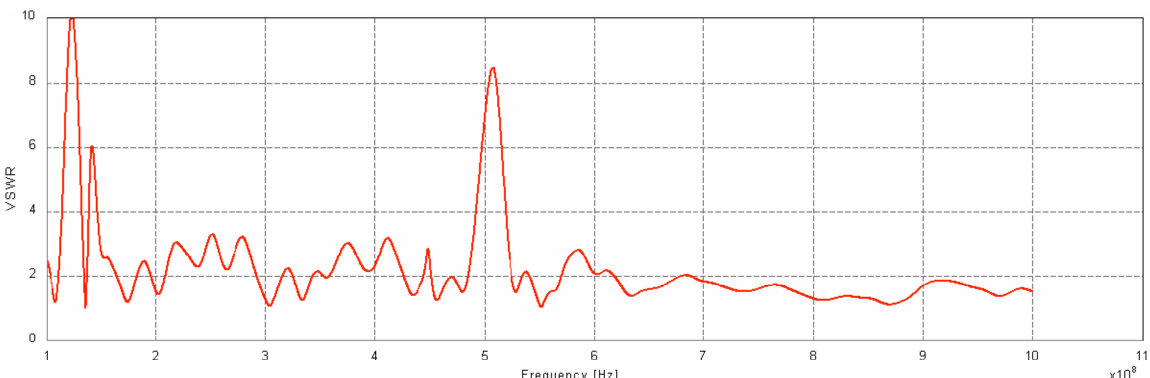

Figure 13: VSWR of Antenna from Figure 9[5]

This smaller antenna results in a slightly worse wide-band match than the original 1.5-meter antenna. However, a VSWR hovering around 2 in the frequencies of concern will still only reflect 11% of the pulse back through the transmission line.

Arcing Issues

In a high voltage system in which portability is a goal, an important problem that arises is arcing. In the context of this project, the extreme voltages caused very high electric fields that were sufficient enough to ionize the air around any exposed conducting material having too great a curvature (points or edges especially). If another conducting material was located close enough to the exposed conductor, the ionized air would provide a channel for a very high current from one conductor to the other. Such arcs represent a substantial loss of energy available to be delivered to the antenna, making it important that they be eliminated from the system. There were numerous parts of the original system in sufficiently close proximity for arcing to be possible, but as overall system size is decreased in the second design such arcing could become very serious.

The strategy the team has deemed most effective is to encase the system in a medium which does not lend itself to arcing. A material's dielectric strength is a measure of its ability to resist the formation of an electric field, so to prevent arcing a material with a high dielectric strength is necessary. To accomplish this goal and to allow for greater ease of construction, a readily available material called Paraffin was selected. Paraffin is a type of wax with a broad range of commercial uses from candle making to surf board waxing, and is well suited for the task of preventing arcing with a dielectric strength on the order of 200-300 kV/inch (as much as ten times the dielectric strength of air alone).

Capacitor Charge Experiments

In order to test the feasibility of the new design, the team had to figure out whether the capacitors in the system could hold a voltage for an extended period of time. This was important because the plan is to charge the capacitors at a specified "base station" before deploying the system on its "mission". By excluding the power supply from the physical system, a significant amount of weight and space would be saved, allowing the system to be lighter, smaller, and more portable.

To perform these experiments, the desired capacitor configuration (two capacitors in series) was connected to a spark gap to measure the voltage. The capacitors were charged to the specified voltage level and then left undisturbed until the prescribed amount of time had passed. The team expected the voltage level of the capacitors to decay at an exponential rate, so they took measurements after ten minutes, one hour, and four hours. The results of these experiments, carried out at varying initial voltage levels, are summarized in the table below.

	1 Capacitor	2 Capacitors	2 Capacitors	2 Capacitors	2 Capacitors
0 min	20 kV	10 kV	20 kV	30 kV	40 kV
10 min	19 kV	8 kV	16 kV	27 kV	30 kV
60 min	18 kV	5 kV	15 kV	23 kV	25 kV
240 min	10 kV	4 kV	9 kV	12 kV	18 kV

Table 1: Results of Capacitor Experiments

The decay observed during these tests has to be mostly due to corona discharge effects between the capacitors and the air surrounding them. In the final system design, the capacitors will be embedded in paraffin wax which will mitigate corona effects. Once the final design is completed, similar capacitor tests will be conducted in which one could expect a dramatic decrease in voltage decay. The fact that there is still charge on the capacitors after four hours in an air environment is an encouraging sign for the final system design.

Testing Methods

To test the viability of the LE-IEMI system, a Transverse Electromagnetic Cell (TEM Cell) was used. A TEM cell is a device that resembles a box and acts as an expanded coaxial cable. The walls of the box act as an outer conductor and an inner conductor goes through the box with a spot where electronics can be tested inside the box. Using a TEM Cell, the electronic device under test could receive most of the energy released from the system, with little or none of the energy being transmitted in other directions. A diagram of the TEM cell testing setup can be found in Figure 3.

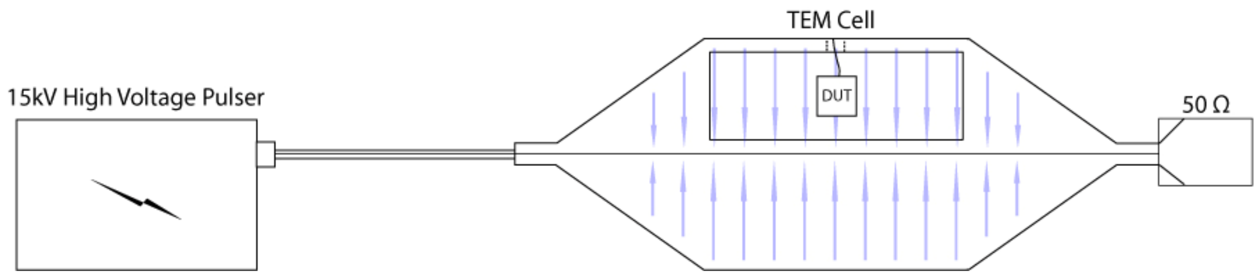

Figure 14: TEM Cell Testing Setup

The problem with this type of testing is that it does not model real world conditions accurately. In real world conditions, an antenna would have to be created as directional as possible and would have to transmit energy through air at the targeted device. The actual amount of energy received by the targeted device would depend on a number of factors, including the distance from the antenna and the angle the antenna is incident on the target. The final goal for this project is to complete open air testing with the system to determine its overall viability.

TEM Cell testing has been conducted with the original pulse source, which was successful in disrupting targeted electronic devices at 30kV. A list of the disabled electronics can be found in Table 2.

Items Disabled in TEM Cell
Cell Phone
GPS
Alarm Clock
Answering Machine
Radio
CD Player
Pedometer

Table 2: List of Electronics Disabled in TEM Cell

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