Plasma E Measurement

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ABSTRACT

This senior design project with the Electrical and Computer Engineering department of Colorado State University, AY 2010/2011, was to design voltage and current sensing equipment for an RF plasma system. Working in conjunction with Dr. George Collins in his biomedical research laboratory with the oversight of Sam Choi, this team researched and designed sensing equipment to work in tandem with researchers.

Due to the erratic nature of RF plasma, reliable real-time data about the impedance of the system is almost impossible. Current off-the-shelf solutions are inadequate for sensing voltage/current in the lab’s research due to the probes either being too low impedance or being too large and bulky to get reliable readings while preforming experiments. It was the goal of this team to remedy this situation with custom hardware for the lab to use as to give a competitive advantage against other labs doing similar research. The goal of our design was not only to provide a compact and accurate solution to sense voltage and current in the system, but also to design the equipment in such a way that it would also be easy to use and incorporate into future solutions (if the lab released a commercial product).

After significant modeling and research, two designs were created. The first, what we call a “macro coax” device, emulates Advanced Energy’s Z-Scan. This first device uses a very large coaxial geometry to contain and shield the signal passing through the system to the plasma generator. Between the conductors is an inductor (to act as a current mirror) and a small plate (to act as a capacitor). From these imbedded components, both the E and H fields can be measured. This system also allows for a compact system that can be directly attached into the current system without much problem. Unfortunately, the design to fine tune the capacitive plate and allow for adjustments was a major challenge.

Our second design was an improvement on current equipment, a custom touch-probe. Current off-the-shelf options are too high admittance. The problem is too much energy passes through the probe to keep the plasma flame alive. Also, because of this current passing through the probe, it can damage the components inside, destroying expensive equipment. Our custom probe both provides 1/10th the admittance of current probes, it also seeks to minimize transient effects by incorporating methods from PCB design. Though the probe is only for voltage, the simple design allows for quick prototyping to test and simple implementation to use. The drawback of this component is finding resistors of >10M ohm that will work at the required frequency.
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INTRODUCTION

Plasmas have a wide array of uses in engineering. From silicon fabrication to biomedical applications to entertainment, plasmas are widely used throughout industry. When creating electric plasmas, a gas (typically inert) is excited into a higher state, allowing its electrons to be freed from their orbits. This results in an ionized atom and free electrons [1]. Due to the gas now being in such an energetic state, the now ionized atoms can react in a targeted way. In silicon fabrication, this can be a tuned specificity that can be directed, allowing for deep channels with high aspect ratios (DIRE). In biomed applications, this can be sterilizing equipment or targeting specific molecules.

There are two different methods of creating plasma, either direct current (DC) or using suitably high frequencies (RF). In DC plasmas, a high starting voltage is used to initiate a spark, and then a lower voltage can be used to sustain the plasma. This phenomenon can be seen in the traditional fluorescent light. As shown in figure 1, a high ignition voltage is required to start the reaction, but then drops significantly to standard operating levels quickly.

![Figure 1 Voltage Profile for DC Plasma](image)

DC plasmas allow for less variables when creating a suitable arc. The tradeoff is that much higher power levels must be used to excite the gas being used into a plasma state. For this reason RF is a preferred media for plasma [3].

Though RF plasmas create a higher quality plasma for lower power, there are some significant drawbacks [3]. First, the plasma is dependent on several environmental factors: humidity, pressure and temperature. Due to these factors, many industrial high-volume uses of plasma are performed in vacuum. This is unfortunately unsuitable for the lab we are working with. When it comes to biomedical applications, if plasma is to be used in vivo, a vacuum cannot be used.

Since RF is synonymous with high frequency, signals used to generate plasma cannot be picked arbitrarily. In our experiments, we are using 13.56MHz (HF band), an ISM band. Since transmission on frequencies from 6kHz to 300GHz [4] are regulated (in the US) by the FCC, and signals are generated at significant power (10W), operating frequencies must be chosen carefully. Though it is not the purview of this paper to explain the benefits and drawbacks of each available ISM block as it pertains to plasma generation, it is important to note that the frequencies used are subject to FCC rules. As such, any design of sensing equipment that would be used in conjunction with this system must also conform to FCC regulations for signal emissions.
This leads to irregularities in plasma performance from application to application. Some of this can be combated during experiment setup. The current method of setting up operation of an RF plasma for experiments is as follows.

The block diagram above (figure 2) is how equipment is set up in this lab. A signal generator and amplifier create the RF signal. The Z-Scan is then used to tune the matching network impedance to achieve maximum power transfer. Then the energy arrives at the plasma probe, where gas is flowing through, and creates the plasma flame. Though it is easy to tune the matching network to get maximum power transfer, it is impossible to tune the impedance of the matching network further to reach voltage resonance. If resonance could be achieved, plasma from experiment to experiment could be more standardized, allowing for better results. Unfortunately, figuring out the impedance of the plasma, to tune the matching network to, is not possible with current equipment.

There are a few off-the-shelf options to be able to sense voltage and current in high frequency systems such as this, but each comes with significant drawbacks. Options include; touch probes, current transformers and devices such as Advanced Energy’s Z-Scan.

Though touch probes are easy to use and a vital piece of an electrical engineer’s tool kit, picking a suitable probe for a plasma system is not trivial. First, a probe with enough bandwidth must be chosen. Also, suitable voltage ratings are key, since the system will start at a very high voltage then drop to a more reasonable voltage. Lastly, admittance is a very large part of any probe’s performance. Unfortunately, getting an optimal mixture of all three elements is not possible from current probe manufacturers. The major drawback in current touch probe design is admittance. If the admittance is too high, energy will flow through the probe and scope rather than the plasma generator. This causes expensive and sensitive equipment to fail because too much power is flowing through the probe.
A second sensing option is current transformers. These work off similar principles as a general transformer. As seen in figure 3, an oscillating magnetic field inside a coil induces a current in the coil. This then can be fed through a resistor to read a voltage. As per the properties of a transformer, current and voltage are linked by the turns ratio. Though the principle works without overloading in this situation, most of the commercial offerings are poorly suited for the application. The first problem is the low current being used in the experiment. Though the voltages may be very high (500V to 1000V or more), the currents are very small (100mA). If a current transformer has too many turns, the current can become too miniscule to measure. Second, if the ring (Figure 3, 1B) holding the coil is thicker than the plasma flame, the readings on the scope are not actually those of the plasma flame (the goal of the readings). Also, in very high frequency applications, a magnetic core may not be suited for holding the coil, as the material may not be able handle the high frequency, therefore not transmitting flux into coil. Also, traditional current transformers are meant to be placed around the plasma flame (in substitute for the wire in figure 3). This could also be cumbersome to researchers and may not be a good design for future commercial products.

The third sensing option is to use a device like Advanced Energy’s Z-Scan. The actual Z-scan itself cannot be used in this system. Z-Scan requires a 50 ohm input impedance. Since the matching network is tuned to allow maximum power transfer into the plasma system, the impedance out the back side of the matching network cannot also be tuned to 50 ohm (See figure 2). Though the exact Z-Scan device cannot be used as a sensor in the required region, a device similar to it can be designed and implemented. The Z-Scan is like a very large coaxial cable. Inside the outer shielding, where a traditional coax would have dielectric, an inductor and capacitor (plate) are placed around the inner conductor. This allows for a sensing package self-contained inside one simple in-line application. This design will be explored in depth in chapter 3.

1 SYSTEM INTEGRATION AND PROPOSED SOLUTIONS

As covered in the introduction, there are a lot of off-the-shelf solutions that come close, but fail on some level to provide the results required. To combat these issues, this project seeks to improve upon these commercial offerings by taking the original concept and redesigning it to suit our needs. Touch probes are too high admittance, current transformers are not sensitive enough (and bulky), and AE’s Z-Scan cannot be utilized in the region required. As such, the following cartoon is a simple diagram of intended operation.
Though the block diagram in figure 4 doesn’t paint the whole picture, it gives a reasonable outline of expected setup. Not pictured above is the tissue sample the plasma flame would be pointed at and ground sensors to measure outgoing current. These other elements are not part of the scope of the project because they are either already solved by off-the-shelf equipment, or not relevant to solving the problem.

With this setup, the project worked on three different solutions. First was a “touchless” solution, providing for minimum admittance. The second was a design similar to AE’s Z-Scan. The final, a touch probe specifically designed for this project. In the following chapters, each design will be explored and explained.

2 TOUCHLESS PROBE DESIGN

Our initial inclining was to design antenna devices to allow for sensing emitted field without causing power loss from the system. This relied on applying Poynting’s theorem. If what was entering the system could be measured as well as what was emitted from the plasma flame as well as energy leaving the system through ground, the plasma flame could be modeled from the resulting differences.

\[ P_g = P_J + Q + P_{Poynting} \]

Since \( P_g \) is known, from energy entering the matching network, and \( P_{Poynting} \) can be derived from sensing \([\text{Energy Radiated by System}]+[\text{Energy Leaving Through Ground}]\), the complex power \( P_J+Q \) can be inferred from \( P_g-P_{Poynting} \). Using this basic principle of E&M, we set out to design an antenna system to measure the emitted energy.

Unfortunately, designing an effective antenna to collect full-wave information about the system was going to be monstrously large. With the wavelength of the 13.56MHz signal being near 22m, designing an antenna to handle that would have been difficult and very large. Using traditional dipole designs would have still required at least a size of 1/2 the wavelength. Also, this design was abandoned due to a lack of expertise and belief that deadlines would not be met.
This did not make us abandon a touchless approach, but did change our approach to gather the data.

Remaining with a touchless design, we set out to create a pair of touchless probes; a voltage probe, a plate to act as a capacitor, and a specially designed current transformer to be used in tandem to measure the system more directly.

![Diagram of proposed touchless design](image)

**Figure 5 Proposed Touchless Design**

We believed the real challenge in this system was the capacitive voltage sensor, due to the complex emitted fields. Due to this challenge, we set out to design this part first. It was assumed that from the same modeling data could be used to better create a current transformer after the voltage probe was finished.

![Radiation data](image)

**Figure 6 Radiation Data, HFSS**

Using HFSS, a 3-D model of the plasma probe was built and tested to see emission patterns. This data would be used to match a capacitive plate to the emitted fields so a known capacitance could be found. This energy would then be fed into a custom voltage divider (using the capacitance between the probe and plate as C1) to then be read by the oscilloscope. As shown in figure
6, the emitted fields are much more complicated than originally expected. In fact, the complex fields pictured above also provided a challenge in shielding the divider to only see the emitted field we wanted, rather than pick up ambient fields. Due to this, the touchless voltage probe was passed on due to being too messy to design in a reliable package.

3 MACRO-COAXIAL DESIGN

Since we found our approach to touchless design was not going to work for this project, we took another direction. In trying to keep the benefits of a touchless design, we took inspiration from AE’s Z-Scan. This device is a very large coaxial structure (compared to standard coax transmission lines) allows the same benefit of our previous designs, explained in the previous chapter, in a sleek package. Also, because the device is in essence a coaxial cable, it can easily be shielded. This way we could continue on a similar design strategy as our original research, but in a much more effective package.

When setting out to design this device, there were a few key parts to take into effect. First, the ratio between the diameter of the inner conductor and the outer conductor had to be designed. Second, make sure the pieces are thick enough to properly shield the equipment. Lastly, pick the right components for inside the space between. Also, with designing the innards of the device, allow for easy maintenance.

When choosing the ratio of inner conductor diameter to outer conductor diameter, frankly the choice is rather trivial. There are methods to ensure maximum voltage tolerance or maximum power transfer, but since the cabling will be sized more like a waveguide than a coax cable, these considerations were skipped. The goal was to set the ratio so the device would be 50 ohm input impedance (like the transmission line feeding the device). This way we could insure maximum transmission into the system and not worry about reflecting energy inside the matching network, or not delivering power to the plasma probe. To make this choice easy, we picked an inner conductor of \( \frac{3}{4}'' \) (6.35mm) because it was easy to get a hand of. With that initial assumption, the inner diameter of the outer conductor was set at 14.6mm.

The second consideration is making the walls of the outer conductor thick enough to not allow background radiation into the system as well as not let energy leak out (instead of being delivered to the system). With this, the assumption was made to pick an appropriate number of skin depths, then double it. Using the assumption for \( \delta_{Cu} \), \( \delta_{Cu} = \frac{66}{\sqrt{f}} \ [mm] \) \[6\], \( \delta_{Cu} \) at \( f=13.56\text{MHz} \) is 17.9um. Using the approximation that at 5\( \delta \) the energy in the conductor will be less than 1\% \[6\], the thickness of the outer conductor can be set to two times that. That sets the outer conductor thickness to approximately 0.2mm. Using that number plus the inner conductor diameter, a rod of at least 15mm needs to be found. For this reason, \( \frac{3}{4}'' \) diameter solid copper was chosen.
For both inner and outer pieces, appropriate grade copper is required. For this purpose, C110 solid rods were chosen for both inner and outer conductors. The outer conductor would then be machined to the desired inner diameter, leaving it hollow. Also, by choosing a thicker outer conductor, the hope was to add some strength to the device. This did cause budgetary concerns, which will be discussed in the Budget chapter.

The last step was one of our toughest. We ended up picking similar components to AE’s Z-scan as a base line, namely the inductor. But due to modeling challenges, we had a lot of trouble settling on a plate design. Also, to mount the components inside the device, we needed a reliable way to set their location and be able to measure that location readily (since it would change the values/behavior of readings). We decided the best option was to settle with a coated inner conductor to allow for a uniform distance to place parts on, and allows for easy estimation of both desired values and parasitics.

The final step in this design was to create the appropriate physical designs. This was challenging, because we needed to not only hold elements in place, but also needed to support the inner conductor. Also, due to the size of the components, it was expected that we would “pinning” the wires to the leads, rather than traditionally soldering them. It was feared that soldering would end in melting the components.

Due to budgetary constraints, this device was not prototyped in this phase of the project. These issues will be discussed further in the Budget chapter.

4 TOUCH PROBE

Due to budgetary constraints, and the desire to have a finished product by the end of the project, a third design was pursued. After spending considerable resources researching RF circuit design (outlined in the RF Design chapter), it was deemed feasible to make a simple divider circuit and build a design around that simple concept.
The original problem with commercial touch probes was the problem of high admittance. This caused power to flow through the probe tip, rather than the plasma probe. This caused the system to be inaccurate, and lead to damage of components. To achieve this design, a very large input impedance was desired to mitigate the problems of energy flowing down the wrong components.

Further in our design, we found that the “simple” divider circuitry was not as simple as we expected. First, there was the trouble of picking components. It turns out high valued resistors at RF frequencies are not trivial. Another challenge we faced was achieving enough bandwidth to get the system work appropriately at 13.56MHz. These challenges with circuit design and parts are explained in depth in the RF Design chapter.

The circuit itself is pretty straightforward.

The goal was to create a probe with 10x the impedance of current commercial offerings. This resulted in a goal of 100M ohm / .2pF input impedance. Along with this, we set out to design a shielded box to place the board inside. The last goal was to make sure the system did not have similar heat issues to the commercial probes we had worked with in initial testing phase.
In this design, we picked a very wide and reasonably thin probe “tip”. This would allow us to mitigate a significant portion of the lead inductance. Also, due to using very small components (chip capacitors and chip resistors), the divider box could be designed to be extremely small as well. In fact, the dominant size constraints would come from the coax connector to the oscilloscope and the wide piece of copper for the sensor probe.

With this design, a simple component could be built and tested. This way not meant to be the final product, but it does provide a baseline to compare against our original control tests (outlined in the Testing chapter). The other benefit is this design is relatively cheap to produce. Very limited machining skill is required to build the enclosure and the components for the most part are very cheap and easy to acquire. This will be further discussed in the Budget chapter.

5 RF CIRCUIT DESIGN

Designing high impedance circuitry at high frequencies is not trivial. Beyond the concerns of bandwidth with standard parts, every design choice starts to become important. First, wires and traces must be taken into account due to their capacitance/inductances. Second, parts must be analyzed to make sure they are behaving as intended. Last, interference from phenomena such as cross talk must be taken into account.

Wires

Wires act primarily as inductors at high frequencies. Round wire, the type typically found in most low frequency applications, can cause significantly high inductances that will cause ringing in components. This ringing will cause devices such as the voltage probe we are designing to give poor readings. Behavior of a wire in RF is mainly determined by the wire’s diameter and length. If an AC current is present, the alternating magnetic field surrounding the conductor is expanding and contracting. This produces a voltage on the wire which opposes any change in current flow. The opposition to the change is called self-inductance and anything that has this quality can be modeled as an inductor. The inductance of a wire is found by:
\[ L = 0.002l[2.3ln(4l/d - (0.75))] \mu H \] [7]

\( l \) = length of wire in cm.
\( d \) = diameter of wire in cm.

With the above equation, a 1 cm length of 22AWG wire would have an inductance of 21.4nH. This will be significant in the Modeling subchapter.

A lot of these wire inductances can be mitigated with the use of flat traces like those in PCB’s. These inductances tend to be significantly smaller, making it easier to achieve higher bandwidths. Using a similar trace to the above example of 22AWG wire and the following equation:

\[ L = 0.2l \left( 0.5 + \ln \left( \frac{2l}{w+h} \right) \right) + 0.11 \frac{w+h}{l} \text{ nH} \] [7]

\( l \) = length of trace [mm]
\( w \) = width of trace [mm]
\( h \) = thickness of trace [mm]

Using similar values from the 22AWG example as it would apply to a standard PCB trace, the inductance becomes 3.8nH. Almost a 10x reduction. By applying PCB techniques, parasitics between components can be dramatically reduced.

**Resistors**

![Resistor Model with Paracitics][8]

![Chip Resistors (With Dime for Scale)][8]

Even though the resistor can be considered the simplest component in circuit design, the element does not behave simply at RF. Just as outlined in the previous section, the leads on a stereotypical resistor will cause inductances. Also, the metal caps on the ends of the resistor will act as a capacitor. As seen in the following figure, the humble resistor will be modeled as such at these higher frequencies:

There is very little that can be done to minimize the capacitance between leads on the resistor. But the lead inductances can be minimized, as with wires, by making them rectangular. This is why most PCB components (especially high frequency ones) will tend to have wide flat leads, rather than round ones. For our project, the trouble was finding a suitable chip resistor that was large enough to suit the application. Regardless of which design we
pursued, large high frequency resistors would need to be used to provide the divider. This is part of the key to low probe admittance.

Unfortunately, purchasing these high resistance high frequency resistors has caused some trouble. This will be further explained in the Budget section.

**Capacitors**

![Figure 13 Capacitor Model with Parasitics](image)

Just as with wires and resistors, capacitors have their own parasitics. There are several reasons for losses in a capacitor. The main two are $R_s$, the energy lost to heat dissipation and $R_p$, the current through the dielectric. Also, just as with the resistor, there are lead inductances.

Since we are using chip capacitors, the lead inductance is negligible. But the rest of the losses are modeled as Effective Series Resistance (ESR). This simplifies the circuit to just a capacitor and resistor in series. Though the resistance will not cause ringing or inaccuracies, as with the parasitic inductances, the resistance can cause trouble with resonating or power loss inside the capacitor.

**Modeling**

As said in the previous sections, modeling each component is not as trivial as putting together an RC circuit in PSpice. Each component must also consist of relevant parasitics. Furthermore, second order effects may need to be added into the model to account for nonlinearities. Most part providers will provide PSpice models with their components, but due to the specific nature of our particular components, we were unable to obtain manufacturer models. Instead, all parts were modeled with their relevant parasitics.
With only these values set, the design runs into problems. As seen in the AC sweep below, there is a pole around 1MHz, causing the frequency response to not lay flat. This is problematic since we want a flat response between 10MHz and 100MHz. This rise also causes problems in the transient analysis, causing loud ringing on the step response.

Figure 14 Probe Model with Parasitics

Figure 15 Frequency Response of Fig 14 Circuit
Furthermore, as more first-order effects are added in, the circuit changes considerably. The major problem being the capacitance of the coaxial line between the divider and the oscilloscope changes the circuit significantly. To counteract this new shunt capacitance, the divider needed to be adjusted. The capacitor in the divider needed to be changed to 1.1pF and a compensating variable capacitor added to the end of the line to allow for further tuning.

After fine tuning the divider, the frequency and transient responses are much more desirable.
Though figure 19 still shows ringing on the step signal, the resonations are close to 1GHz. Since operation is within 13.56MHz, this noise is negligible. If required, a harmonic trap could be added to counteract the 1GHz peak.
6 BUDGETARY CONCERNS

Unfortunately, for our project, budget was a major sticking point. In fact, budget was the major contributor to design criteria. Even though the project settled on two viable options, budget and lead time to get parts became major roadblocks to completing physical designs.

Macro Coax Budget

Though most of the individual parts were not terribly expensive, there were a few pricey parts that inhibited building prototypes. Most of the cost trouble was due to the outer shielding.

Unfortunately, we could not obtain hollow tubing that was close to the desired dimensions. This meant we needed to buy solid copper rods. The C110 copper we were interested in using was going to cost 25USD per foot, plus shipping for either several small orders (for each prototype) or a large bulk order for several attempts that would burn most of our budget.

Also, due to the need to order solid copper tubing, professional machining would be required. Though we contacted several shops and able metalworkers, we could not get a reasonable quote (or donation) which pushed the price of producing a single prototype to over 150USD.

Due to the budgetary concerns and lack of sponsor or donations to be able to quickly and cheaply produce prototypes, this design was placed on hold. More information as to why the macro coax design was not pursued in this iteration can be found in the Macro Coax chapter. Future intentions for this design can be found in the Continuation chapter.

Touch Probe Budget

The touch probe designs were proposed and completed with an eye on budget concerns and to better take advantage of available resources that could be used for free or cheap. The costs of the touch probe build can be broken into the following sections; PCB, resistors, capacitors, housing.

Due to working with a research laboratory, the resources to etch our own PCB’s are at the project’s disposal for free. Also, if desired, PCB prototypes can be designed and built for 100USD per board. This allows for reasonably cheap final build of components.

The second cost, which turned out to be the major hurdle on this design, was acquiring the resistors we needed. The 100M ohm Venkel HMCR0402-16W-1006FT requires a minimum order. Though we would only need a dozen resistors, we are required to order in 5000 reels. This requires 110USD plus shipping. We worked with our lab to help split that cost between the senior project budget and the lab budget.

Thankfully, the lab we are working with has a large storeroom of capacitors of the appropriate ratings. These have been donated to complete the touch probe prototype.
The last portion, the housing for the divider, we intend to build from 3003 Aluminum. This has a reasonable cost of 10USD for the material to build two housings. Since the machining of the box is very simple, we have donated machine time lined up to build the box for us at no charge.

**Budget Breakdown**
See Appendix B.

### 7 PROJECT CONTINUATION

This project still has a ways to go to be finished. It is our belief that this work is important and vital to not just CSU researchers, but also to others in the RF plasma realm. The following are our recommendations for this project moving forward.

**Macro Coax Device**

We believe this device is worth researching further. But to do so, the project scope will need a reworking.

**TEAM SIZE:**

No more than two people. May need to consult with mechanical engineers, but not advocating a mechanical engineer member.

**BUDGET:**

For this project to work, a reasonable budget needs to be acquired at the start. We are advocating at least $500 in sponsorship, though up to $1000 is advised. Also, consulting with students in the mechanical engineering department for the first semester is recommended so that physical properties such as layout and structural strength can be properly designed. We also highly suggest an industry partner to help facilitate research (preferably AE).

**SKILLS:**

Strong skills in HFSS (or similar E&M modeling software) as well as 3-D CAD software will go far in this project. Also, machinist skills/certifications to build the physical prototypes would be useful (but not required). Furthermore, strong grounding in subjects such as ECE341/ECE342 and RF design should be required. Lastly, a strong interest in biomedical research and/or plasma applications would be useful.

**TIMELINE:**

We believe more modeling is required before a first prototype can be built. We expect the first 2 months to be dedicated to building models of the system. Once modeling is completed, building a first prototype should be relatively simple, but we expect the project to
take 2-3 months from material ordering to final product. Lastly, and most importantly, testing is required. We expect that to take no more than 1-2 weeks to gather the required data to apply toward either a final product, or further prototyping. It is our hope that, at the very least, designs for a final product would be completed by the end of the next project year. With those final designs, the lab should be able to order the final product built for their research.

**Touch Probe Design**

We expect to have almost everything built for the first touch probe design by the end of the semester. We are advocating continuation of this project, though not as strongly as the Macro Coax project.

**TEAM SIZE:**

One member. ECE only

**BUDGET:**

The given budget (as long as components such as resistors remain inexpensive) should be adequate to finish this project. We are only expecting that only one more prototype for the device should be built. We also highly suggest an industry partner to help facilitate research (preferably LeCroy or AE).

**SKILLS:**

A strong grounding in circuit design and RF design. Basic understanding of component parasitics. Strong in PSpice simulation. Skill in PCB design desired (but not required).

**_TIMELINE:**

Since this project should be near complete by the end of SP2011, we expect the actual work to last no longer than one semester. The purpose for completing this project is to act as a baseline for the coax project. Though, if further research after the preliminary prototype is required, we expect the timeline to look as such.

- 2 months to finish testing and research on current prototype. (if redesign is required) 2 months to rework the divider circuit and find new components. 1 month to assemble new prototype. 2 months for additional testing and decide if another redesign is required.
REFERENCES


APPENDIX A: List of Abbreviations

AE: Advanced Energy
PCB: Printed Circuit Board
RF: Radio Frequency
USD: United States Dollars

ECE: Electrical and Computer Engineering (In reference to Colorado State University’s program)
CSU: Colorado State University
FCC: Federal Communications Commission
APPENDIX B: Budget

Table 1 Macro Coax Cost per Prototype

<table>
<thead>
<tr>
<th>Part or Process</th>
<th>Price</th>
<th>Lead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Conductor (1/4” C110 copper rod)</td>
<td>$3.50/ft</td>
<td>1wk shipping</td>
</tr>
<tr>
<td>Outer Conductor (3/4” C110 copper rod)</td>
<td>$25.00/ft</td>
<td>1wk shipping</td>
</tr>
<tr>
<td>Machine time</td>
<td>$75.00/hr</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Circuit Components</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>TOTAL/prototype</td>
<td>$120.00</td>
<td>&gt;1 month</td>
</tr>
</tbody>
</table>

As shown in the table above, each prototype would cost a significant amount (in comparison to the available budget of $300). Without sponsorship, the design gets prohibitively expensive.

Table 2 Touch Probe Cost per Prototype

<table>
<thead>
<tr>
<th>Part or Process</th>
<th>Price</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB Board</td>
<td>Donated</td>
<td></td>
</tr>
<tr>
<td>PCB printing</td>
<td>Donated (or $100/board)</td>
<td>3wk</td>
</tr>
<tr>
<td>Capacitors</td>
<td>Donated</td>
<td></td>
</tr>
<tr>
<td>Housing (aluminum box)</td>
<td>$10</td>
<td>1wk</td>
</tr>
<tr>
<td>Machining</td>
<td>Donated</td>
<td></td>
</tr>
<tr>
<td>Resistors</td>
<td>$110 (one time)</td>
<td>Unknown</td>
</tr>
<tr>
<td>TOTAL/prototype</td>
<td>$50</td>
<td>3wk</td>
</tr>
</tbody>
</table>

Unlike the coax device, which costs over 100USD per prototype, the costs and time for prototyping the touch probe are much less. Also, there are several costs that can be kept down by doing prototyping in different stages. For instance, each prototype doesn’t need a brand new housing. Also, to make a final finished product, the process is relatively straightforward and also not too expensive.
ACKNOWLEDGEMENTS

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