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by

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Wireless Power Transfer in the Classroom

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Report

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Abstract

Wireless Power Transfer in the Classroom

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Traditional methods of teaching magnetic induction with lab investigations using a battery, wire and compass are best reserved for demonstration purposes to introduce this particular topic. The modern student who sits in a physics course also lives in a world filled with an increasing number of small portable devices that will eventually be charged wirelessly using some form of magnetic induction. The topic of magnetic induction needs to be placed in the modern context it deserves since the future of transmitting power will eventually be through wireless means. The wireless power transfer kit described in this report is designed to improve student understanding and the application of magnetic induction in an engaging, relevant manner.

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INTRODUCTION

In a traditional high school science class, students are confronted with an array of lab equipment that is designed and purchased to produce a learning opportunity. This is the fundamental reason science classes are filled with an apparatus and timer here, a meter and mass there. Manufacturers of the equipment follow the market demand of their clients – the schools. However, schools ostensibly follow the demand of their own clients – the students. It is safe to say the average high school physics classroom – when compared to a chemistry classroom - does not require a large amount of individual pieces of lab equipment. However each piece is unique to a particular topic and often never used again during the year. A chemistry class has hundreds if not thousands of individual pieces of equipment that are used continuously throughout the year. The chemistry classroom has by far the most numerous, whereas the physics classroom has fewer but retains the widest variety of equipment.

Where biology categorizes Nature's encyclopedia of life, chemistry composes materials that utilize the complex behavior of Nature's elements; we see physics illuminate the fundamental interactions of Nature herself. In order for the physics classroom to provide a deep dive into such broad topics ranging from gravity to diffraction, lab equipment that engages and extracts as much learning as possible is critical.

In all science classes the processes of performing lab investigations are repeated many times throughout the year. One could say that Biology is dominated by the use of

the triple beam balance and the microscope. Chemistry is dominated by glassware and the processes that fill or empty them with various materials. Physics on the other hand has no single piece of equipment that is dominant; most labs require a unique and precise setup that could be used for hundreds of students, but only once a year.

The physics teacher has limited chances to provide major extractions of learning from the equipment, whichever piece it may be. Therefore the equipment in the physics classroom must be of a particular type that has a multiplicity of attributes as to make it engaging enough to conquer the learning goals set forth by the teacher. Not to say that the teacher is only as engaging as their equipment, rather, poorly designed lab equipment could evaporate one of those limited learning chances.

In a traditional physics classroom, the topic of electricity and magnetism is of significant importance. It is safe to assume when teaching this time-consuming topic that every physics teacher in the nation uses some form of lab equipment that includes wires, batteries, switches, light bulbs - or LED's - and perhaps more recently a solar panel of some sort. When the transition comes to introduce the natural relationship between electricity and magnetism, made famous by Faraday's law of induction, the traditional equipment is limited to similar objects – wires, a battery, a compass and perhaps a light bulb to show the 'on' status of a circuit.

The elegance and simplicity of Faraday's law (Faraday, Sec 2, #46., 1855) reveals an invisible yet fundamental behavior of Nature, perhaps the most important application of physics in the modern world – that which utilizes a time-varying magnetic field to induce an electrical current in a conducting wire, bringing electricity to nearly every

corner of the Earth. Faraday's law of induction in its essence is an energy conversion law – mechanical energy to electromagnetic energy - that we use to transfer useful electrical current from one location to another, traditionally via wired connections.

The dark days of transferring energy via wired connections were finished more than 100 years ago – that is, if Nikola Tesla could have had his way. Tesla's 1902 patent for an air-core resonant transformer - the Tesla coil - was able to transmit power that could illuminate light bulbs hundreds of feet away without wires (Tesla, 1902). His vision of a world with free wireless electricity for all was seen as misguided Utopianism; forever reliant upon the shareholder's need for a desirable return on investment. Upon describing this amazing free wireless transfer of energy George Westinghouse - Tesla's million dollar financier - declined to support such a system that could neither be metered nor have a surcharge levied for its use.

Tesla's vision and the Tesla coil have achieved a cult-like following in the past few decades. With the aid of the internet Tesla's wireless power transfer concepts and plans are in the hands of a new generation hungry for innovation and new methods for moving energy efficiently. As of this writing in 2013 only a few consumer products utilize inductive power transfer – resonant or not. The rechargeable electric toothbrush is by far the most recognizable. Future generations will no doubt have an abundance of small devices and home appliances that are either charged or powered by Tesla's discovery of resonant wireless energy transfer.

An educator's goal, no matter what subject, is to hone real world skills that can be applied by all students beyond the classroom. In the process of learning

electromagnetism and the modern world, the traditional lab equipment a physics teacher utilizes to teach this relationship is painfully tangled with wired connections, and sorely disconnected to what students of this generation will be exposed to in their daily lives – a life of portable devices that no longer need wires to communicate and no longer need wires for power.

STATEMENT OF PROBLEM

Making electromagnetism relevant to modern students requires both wired and wireless investigations into Faraday's law of induction. The problem we face as physics teachers is that there are plenty of lab apparatus on the market that can demonstrate wired concepts of induction. However most often we turn to the Tesla coil to demonstrate – not investigate – wireless power transfer and all the other stunning high voltage effects it can harness. When it comes to true scientific investigation of wireless power transfer – the future of energy transmission - there is no lab equipment that provides the following attributes critical to extracting an abundance of student learning:

- 1) Safe to use – even a small Tesla coil can hurt
- 2) Affordable – most Tesla coils are prohibitively expensive
- 3) Engaging – the “wow factor” lures students in to solve the mystery of how it works
- 4) Investigative Science – not just another single piece of demo equipment
- 5) Obvious and Measurable Results – the trend of Nature's secrets are now visible and useful

The traditional combination of wire, battery and magnetic compass are good launching points for merely demonstrating Faraday's law of induction. I feel strongly that this equipment, while good for large scale demonstrations, is a waste of time for students in a lab setting that requires them to utilize outdated and irrelevant modes of energy transfer. I highly suggest a solution to the problem of teaching this topic in a relevant manner for modern students – create a piece of lab equipment that can extract as

much student learning as possible in a safe, engaging and affordable manner. I created such a device that this document will reveal in its entirety for the purpose of improving student learning of real world, and more importantly, modern world applications.

The device is a kit that provides investigative measurement opportunities of wireless power transfer that can be used by teachers and students of secondary and college classes during the E&M portion of an introductory physics curriculum. The wireless power transfer kit - the WPT kit - contains a primary transmitter base and several wireless receiver coils. The primary transmitter and secondary receiver both have on-board “banana” style terminal sockets that allow students to effortlessly plug in a voltmeter or an oscilloscope to take measurements. The design went through various phases of planning, prototyping and numerous iterations of the alpha version to arrive at the current beta kit. Many features were planned, while some features were added along the journey through the various versions. The kit is described largely as two separate components, the transmitter and the receiver.

WPT KIT FEATURES

The major features of the transmitter base will be described in detail in this document; in summary they include:

- safe and easy to use
- an ON/OFF status light
- frequency trim adjustment port
- swappable primary coil

Even though the receiver unit's interior components are relatively simple compared to the transmitter, it too has special features that include:

- durable construction with no moving parts
- unit is small and handheld to mimic small portable devices
- an array of LED's that the user can switch on or off, allowing voltage to be measured:
 - with a load (LED's are on, voltage is held constant when being used by the array)
 - without a load (LED's are off, voltage varies depending on distance from the transmitter)

The kit is operated simply by:

- 1) plugging in the 12V DC plug
- 2) turning the transmitter base ON
- 3) bringing one or several of the wireless receiver units within 10cm of the base

- 4) observing the effects of magnetic induction illuminate the LED array without any wires or batteries.

As the receiver is brought closer to the base, the LED array becomes brighter as the receiver coil encounters an increased time-variation of magnetic flux. With the kit various investigations into the effects of resonant magnetic induction can be made by students in a small lab group setting, or demonstrated by a teacher to an entire classroom:

- Distance versus voltage
- Orientation of receiver versus voltage
- AC Waveform on both transmitter and receiver units
- Materials that allow transfer or block the transmitter signal (shielding)
- Wireless powering of subdermal bionic devices (valves, shunts, batteries)

The WPT kit can also be customized to offer higher level students the chance to investigate resonant magnetic induction by making their own primary and secondary coils. In this activity students must first mathematically solve for a coil's resonant frequency – a property that is largely dependent on accurate measurements of its physical geometry. Students must also adjust the transmitter circuit to match this frequency so as to transfer energy most efficiently. To achieve such customizability the system is designed from the ground up to be modified in several beneficial ways:

- transmitter base frequency is adjustable
- parts such as the primary coil are hot swappable with minimal adjustment
- components on the breadboard can be taken off and on repeatedly and safely

- student-made coils are wound on circular PVC hoops, making construction easy and forgiving to the novice with no experience in winding coils.

The wireless power transfer kit is not meant to replace traditional methods of teaching magnetic induction; rather it is my wish that the kit can be used as an engaging extension that demonstrates clearly the fundamental marriage of electricity and magnetism in a cutting edge, modern context.

NEEDS AND CONSTRAINTS

Faraday's law of magnetic induction is one of the cornerstones of physics taught all over the world. The physics student – from middle school throughout college – is usually introduced to this concept in two steps. First students build a simple circuit composed of a battery, a wire and a magnetic compass. The circuit is closed and the compass is placed near the wire. Students investigate the relationship of the deflection of the compass needle and the direction of current flow. This investigation demonstrates how moving charge produces a static DC magnetic field. Secondly students most often investigate the way a time-varying magnetic field can induce an emf through a conductor by making a generator out of permanent magnets, a nail and some copper wire. The permanent magnets are spun on a rigid axis formed by the nail. The copper wire is made into a large coil perpendicular to the axis of spin. As the magnetic flux rapidly changes direction over time in relation to the coil, an emf is induced in the wire and can be used to do useful work such as illuminating an LED. Both steps allow the student to investigate the invisible magnetic field lines that Faraday himself theorized over two hundred years ago that led him to invent the first electric motor.

These methods should always be introduced; however more modern versions of these investigations need to be implemented into the physics curriculum so that students are challenged to inquire about the mysteries of the mobile technology that is recognizable – and relevant – in their world.

The approach to exactly how this modern version would manifest itself started in its earliest stage as an idea leaning towards making improvements to a high power, yet

safe and customizable desktop Tesla coil. I built a moderate power 270 W Tesla coil in 2012 that shoots out two-foot lightning bolt streamers, so I had experience in making a relatively large-scale coil. This would certainly grab the attention of students as they build and experiment with certain portions of the device on a much smaller scale. The investigation of resonance in magnetic fields – the basis of power interaction of all Tesla coils – was a topic that could saddle waves and electricity units. I knew that desktop Tesla coils existed; I've used small ones as demonstration devices for several years. Small units can be purchased from various science suppliers; however they are not customizable and their streamers are only impressive for a fleeting moment at best. After thinking of possible variations of power and size, the idea started to lose its footing trying to surmount two fundamental goals I had set out to achieve in the design stage.

- Safety: The idea of taking apart and accidentally touching anything containing a high voltage capacitor bank - no matter what discharge frequency - was jettisoned for a device with no chance of physical harm.
- Relevance: Since Tesla coils in the home are incredibly rare, the goal of making something relevant that students see in their daily lives and not just another demonstration device could not be achieved.

While I was searching for safer methods of teaching modern uses of induction, I saw an advertisement for a wireless charging mat online and considered buying one for my cell phone. I was intrigued as to how the device worked and searched for as much background technical information as I could find. I learned that the current technology of wireless charging is still in its infancy, although devices that utilize this phenomenon were invented by Tesla and are most commonly seen in rechargeable electric toothbrushes.

Unlike the single wired electrical power transfer standard found in homes of 120 volts oscillating at 60 Hz, there are multiple competing magnetic resonant wireless power transfer standards of various voltages and various frequencies. Apple, Nokia and Dell are all early adopters and each filed recent patents and produced prototype devices that charge wirelessly even though no standard has been set. On one hand MIT developed Witricity (Aristeidis Karalis, J.D.Joannopoulos, Marin Soljacic., 2008), a wireless standard running on one frequency that has attracted millions of dollars from Toyota. On the other hand The Wireless Power Consortium has developed the Qi standard (pronounced 'chee') running on another frequency, with over 100 members including Samsung, Panasonic and Energizer (Wireless Power Consortium, 2012).

The fact that wireless power transfer is still in its infancy appealed to me immensely; this is truly the future of powering and charging all types of devices. This knowledge is something students could truly use as they will see this feature in many types of devices in their daily lives.

Wireless power transfer is relevant to students in several ways even though market penetration of WPT products is still in the early adopter phase.

- Wireless charging is extremely convenient. Products can simply be placed in proximity of a charging field rather than plugged into a tiny socket.
- Wireless charging reduces waste, a habit that modern students are eager to promote by their purchasing power. Wireless charging means no more wasteful production of incompatible chargers when a phone is upgraded.

- Using the same concepts of wireless power transfer, some products can run on induction alone without any internal power source, thereby reducing the reliance on batteries.

For these reasons, wireless power transfer - resonant or purely inductive - is a far reaching concept that brings Faraday's law of induction into direct contact with a broad range of students. The misguided initial idea of making a dangerous high voltage machine for student use, combined with the modern relevance of wireless power transfer actually helped to crystallize the needs of what I should create in order to teach Faraday's law of induction in a new way.

After coming to the decision that teaching a unit on wireless power transfer would be a major benefit to students in any physical science class, I considered the average high school student to be my client and set out to create a piece of lab equipment that would satisfy the following prioritized needs:

1. Absolutely safe to touch and use while power is on
2. Absolutely safe to modify while power is off
3. Low voltage 12VDC power source from common wall adaptor
4. Harmless and non-interfering output frequency, power and range.
 - Timer oscillations are far above that of human hearing (40 kHz).
5. Durable for classroom use
6. Handheld form factor
7. Obvious, instant, engaging results of resonance and magnetic induction
8. Provide both quantitative and qualitative measurement opportunities:

- LED status lights are powered at a distance of at least 10 cm
 - Voltage measurements are available at a distance of at least 10cm
 - Oscilloscope readings of waveforms can be measured any time
9. Can be built or repaired using commonly available parts
 10. Customizable primary coil
 11. Works with student made receiver coils
 12. Convenient tuning with adjustable frequency settings

ALIGNMENT OF LEARNING STANDARDS

The device needed to have specific physical characteristics but it also needed to satisfy several learning goals that could be aligned to middle school, high school and even early college students. Below is a detailed list of Texas public school learning standards – known as TEKS – that can be reached with the demonstration, use and construction of the device (Texas Education Agency).

Middle school (6th grade)

- 112.18, b (6) Matter and energy. The student knows matter has physical properties that can be used for classification. The student is expected to: compare metals, nonmetals, and metalloids using physical properties such as luster, conductivity, or malleability;
- 112.18, b (7) Matter and energy. The student knows that some of Earth's energy resources are available on a nearly perpetual basis, while others can be renewed over a relatively short period of time. Some energy resources, once depleted, are essentially nonrenewable. The student is expected to:
 - (A) research and debate the advantages and disadvantages of using coal, oil, natural gas, nuclear power, biomass, wind, hydropower, geothermal, and solar resources; and
 - (B) design a logical plan to manage energy resources in the home, school, or community.

High school (grades 9-12)

Integrated Physics and Chemistry 112.38

- (5) Science concepts. The student recognizes multiple forms of energy and knows the impact of energy transfer and energy conservation in everyday life. The student is expected to:
 - (C) demonstrate that moving electric charges produce magnetic forces and moving magnets produce electric forces;
 - (F) evaluate the transfer of electrical energy in series and parallel circuits and conductive materials;
 - (G) explore the characteristics and behaviors of energy transferred by waves, including acoustic, seismic, light, and waves on water as they superpose on one another, bend around corners, reflect off surfaces, are absorbed by materials, and change direction when entering new materials;
 - (H) analyze energy conversions such as those from radiant, nuclear, and geothermal sources; fossil fuels such as coal, gas, oil; and the movement of water or wind; and critique the advantages and disadvantages of various energy sources and their impact on society and the environment.
- (6) Science concepts. The student knows that relationships exist between the structure and properties of matter. The student is expected to:
 - (C) analyze physical and chemical properties of elements and compounds such as color, density, viscosity, buoyancy, boiling point, freezing point, conductivity, and reactivity;

Physics 112.39

- (5) Science concepts. The student knows the nature of forces in the physical world. The student is expected to:
 - (D) identify examples of electric and magnetic forces in everyday life;
 - (E) characterize materials as conductors or insulators based on their electrical properties;
 - (F) design, construct, and calculate in terms of current through, potential difference across, resistance of, and power used by electric circuit elements connected in both series and parallel combinations;
 - (G) investigate and describe the relationship between electric and magnetic fields in applications such as generators, motors, and transformers;
- (7) Science concepts. The student knows the characteristics and behavior of waves. The student is expected to:
 - (A) examine and describe oscillatory motion and wave propagation in various types of media;
 - (B) investigate and analyze characteristics of waves, including velocity, frequency, amplitude, and wavelength, and calculate using the relationship between wave speed, frequency, and wavelength;
 - (C) compare characteristics and behaviors of transverse waves, including electromagnetic waves and the electromagnetic spectrum, and characteristics and behaviors of longitudinal waves, including sound waves;
 - (D) investigate behaviors of waves, including reflection, refraction, diffraction, interference, resonance, and the Doppler effect;
 - (F) describe the role of wave characteristics and behaviors in medical and industrial applications.

Career and Technology courses (CTE, grades 9-12)**Anatomy and Physiology 130.206**

- (7) The student examines the electrical conduction processes and interactions. The student is expected to:
 - (A) illustrate conduction systems such as nerve transmission or muscle stimulation;
 - (B) investigate the therapeutic uses and effects of external sources of electricity on the body system; and
 - (C) evaluate the application of advanced technologies such as electroencephalogram, electrocardiogram, bionics, transcutaneous electrical nerve stimulation, and cardioversion.
- (9) The student investigates environmental factors that affect the human body. The student is expected to:
 - (A) identify the effects of environmental factors such as climate, pollution, radioactivity, chemicals, electromagnetic fields, pathogens, carcinogens, and drugs on body systems;
 - (B) explore measures to minimize harmful environmental factors on body systems.
- (10) The student investigates structure and function of the human body. The student is expected to:
 - (B) evaluate the cause and effect of disease, trauma, and congenital defects on the structure and function of cells, tissues, organs, and systems;
 - (C) research technological advances and limitations in the treatment of system disorders;

Biotechnology 130.363

- (7) The student examines the relationship of biotechnology to the development of commercial products. The student is expected to:

- (D) identify applications of bioinformatics in biotechnology;
- (E) identify the applications of biotechnology in medicine, forensics, and law enforcement;

Electronics 130.368

- (5) The student implements the concepts and skills that form the technical knowledge of electronics using project-based assessments. The student is expected to:
 - (A) apply Ohm's law, Kirchoff's laws, and power laws;
 - (B) demonstrate an understanding of magnetism and induction as they relate to electronic circuits;
 - (C) demonstrate knowledge of the fundamentals of electronics theory;
 - (D) perform electrical-electronic troubleshooting assignments; and
 - (E) develop knowledge of voltage regulation devices.
- (6) The student applies the concepts and skills to simulated and actual work situations. The student is expected to:
 - (A) measure and calculate resistance, current, voltage, and power in series, parallel, and complex circuits;
 - (B) apply electronic theory to generators, electric motors, and transformers;

College introductory E&M class - University of Texas at Austin

PHY 302K • General Physics I—Technical Course—Electricity and Magnetism, Light, Atomic and Nuclear Physics

- is a non-calculus-based technical course sequence for students who need to fulfill a general physics requirement. It serves as an introduction to the mechanics of solids and fluids, heat, and waves.

PHY 309K • Elementary Physics for Non-technical Students

- An introduction to physics for students with a high school-level algebra proficiency who do not intend to do further work in natural sciences, engineering, mathematics, or medicine. It covers topics such as Newton's Laws; Momentum and Energy; Rotational Motion; Gravity; Atomic Nature of Matter; Solids, Liquids, Gases, and Plasma; Temperature and Heat; Heat Transfer; Phase Changes; and Waves and Sound.

PHY 317K • General Physics I

- A calculus-based general introductory physics course sequence. It is especially recommended for premedical and chemistry students and others in the biomedical sciences.

QUANTITATIVE SPECIFICATIONS

In order for the device to provide meaningful learning opportunities that satisfy state standards, the following physical hardware specifications evolved after several months of prototyping and testing. Please see the appendix for circuit diagrams.

Primary Transmitter:

- Case dimensions: 120 mm X 170mm X 63 mm
- Case material: ABS plastic
- Power supply: 12 VDC
- Power output: 12 W max
- Coil frequency: 165 kHz
- Activity distances:
 - Measurable voltage 26 cm
 - Visible light 22 cm
- Voltage port connector type: Banana, color coded
- Main oscillator clock: 555 timer

Secondary Receiver:

- Case dimensions: 80 mm X 142 mm X 38 mm
- Case material: ABS plastic
- Power supply: inductive depending on distance from receiver
- Power output: 12 W max
- Coil frequency: 165 kHz
- Voltage port connector type: Banana, color coded
- Load type: 3- parallel 2V LED array

MODELING THE PROBLEM SYSTEM

After reviewing the needs list, various models were used to focus time, materials and energy into making a good quality functional prototype. Black box models of both the transmitter and the receiver were developed first, then a functional flow was determined. Prior and during circuit construction a software-based circuit model was used to perform virtual measurements for the purpose of experimentation and behavior prediction.

The primary transmitter is designed to produce a resonant oscillating magnetic field using the electrical energy derived from a plug in wall adapter. It is not automated therefore a human needs to physically turn it on to operate it. An alternating current time-varying magnetic field is produced instantly. Since this particular energy conversion emits significant heat due to the relatively high current being pushed through very thin wires of the internal LC coil, a small cooling fan attached directly to the internal power MOSFET can be heard when activated.

BLACK BOX MODELS

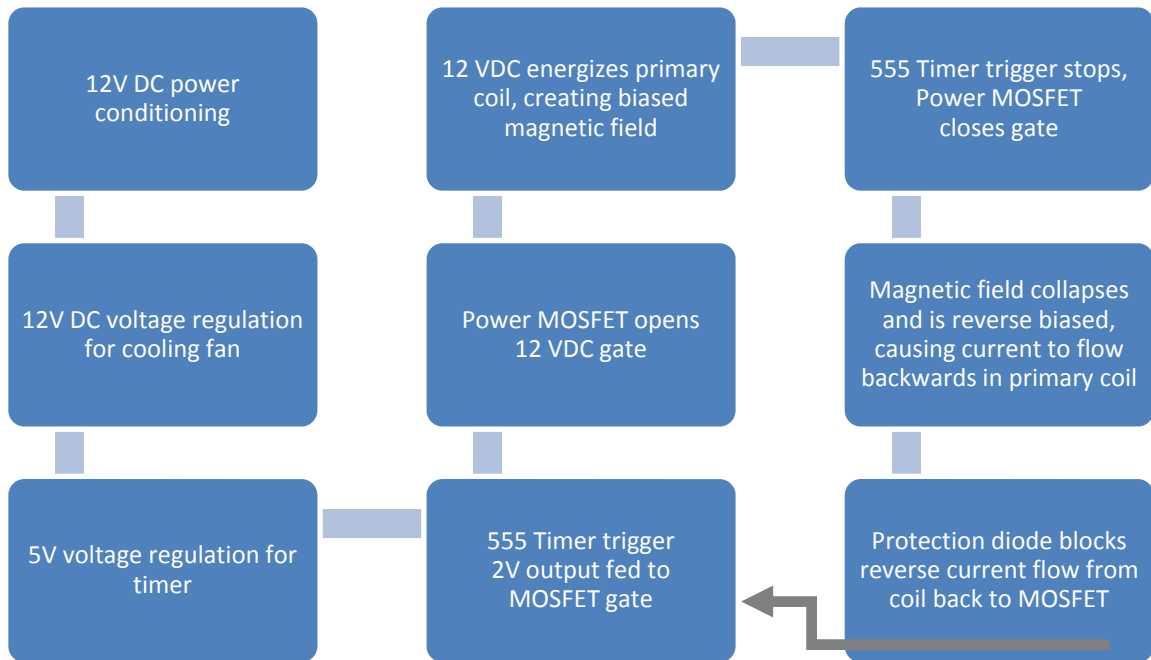
Black box Model for Primary Transmitter		
Inputs	Basic function	Outputs
Material: human to turn on power switch	Produce resonant AC magnetic field	Material: None
Energy: DC electrical power		Energy: AC magnetic field, heat, sound
Information: None		Information: Status LED

The secondary receiver takes on the task of converting the alternating magnetic field back into DC electrical power to drive a load whether it is an LED or a voltmeter. The receiver does not need human intervention to receive power however it does need a human to switch between two load states; with or without the LED array load. Regardless of load state the alternating magnetic field of the transmitter interacts with the receiving coil's internal circuitry to produce AC power which is rectified to DC power.

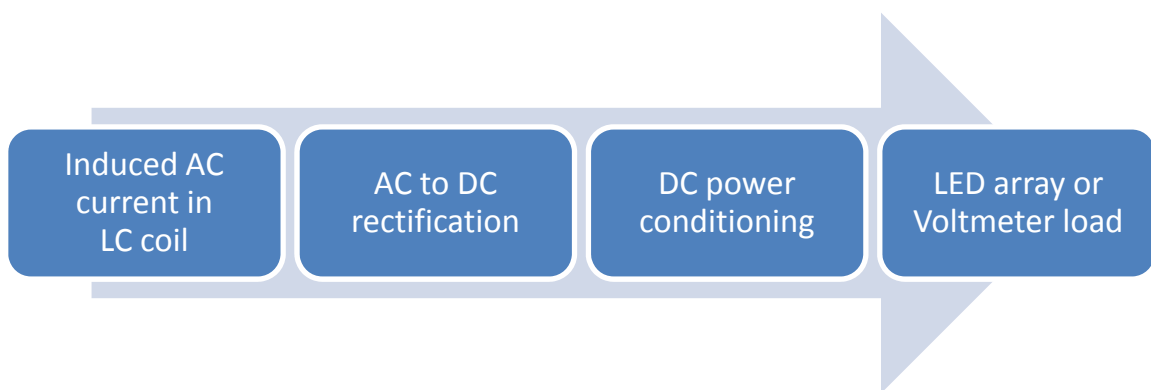
Blackbox Model for Secondary Receiver		
Inputs	Basic function	Outputs
Material: None	Convert resonant AC magnetic field to DC power	Material: None
Energy: AC magnetic field		Energy: light, DC power
Information: None		Information: <u>with load</u> - status light array illuminates <u>without load</u> - status light array is off, voltmeter required to take quantitative measurement

FUNCTIONAL FLOW BLOCK DIAGRAMS

Primary Transmitter



Secondary Receiver



CIRCUIT MODELS AND SIMULATIONS

In designing the kit I chose to model as much of the circuit as possible using predictive circuit analysis software – of which I’ve never used before. There were some major challenges and a lot of time spent adjusting “virtual” components in the modeling software as well as simply trying to find the specifications and physical characteristics of the real components in order to model them better. I chose to use LTSpice from Linear Technologies – a free, open-source circuit modeling software that has an extensible parts library, but out of the box it is mainly specific to LT brand components. My total lack of experience with this package and the limited parts library caused a significant delay since many of the parts I purchased were from Fry’s, Radio Shack, Digikey and Jameco – therefore many parts are not found in the LTSpice library. There are also parts of any prototype that are simply too inconvenient to model at the beginning stages. Parts that were specific to the WPT kit considered to be too inconvenient to model due to software limitations are:

- Cooling fan EMF effect on the coil
- Breadboard internal capacitance
- Jumper wire resistance due to material and length
- Inductance and capacitance of the primary coil umbilical cable

These structural portions of any circuit do add a small measurable difference between the theoretical outputs of model and the actual outputs of a prototype. If the device went into mass production then those items would naturally need to be accounted for and proper models developed if necessary.

After a couple of weeks of learning the software and modifying some of the libraries, I was able to make a circuit that behaved similar to the real alpha and beta designs. I wanted to establish a baseline modeling circuit that was similar to the real alpha circuit I had built on the prototyping deck and from there add components to the model first and see whether or not the addition would improve various sections of my actual circuit. From the model I was able to visually see what was going on in the wires by studying the waveform traces at any portion of the model. From the model I was able to investigate the following behaviors and make improvements upon them. Examples of circuit design iterations are provided in the appendix with details on major changes stemming from the software's predictive model:

- 1) Changing the threshold and discharge resistors in the 555 timing section, finding out lower frequencies produced more current which led me to bring the original operating frequency of around 200-500kHz to around 150-160kHz. The large range in frequency is due to resonant harmonics in the primary coil.
- 2) Previous issues with the MOSFET casing temperature getting extremely hot led me to test the gate voltage from the timer's output pin 3 where I found I was getting very close to the maximum allowed voltage on the gate, near 4.5V. The model showed that placing a current limiting resistor (see appendix primary circuit 1-0) from output pin 3 of the 555 timer section in series before the MOSFET gate lowered the gate voltage enough to drop the gate voltage to 2V. This proved effective in the model, but later on the timer was adjusted with a voltage regulator and smoothing capacitor, as well as a change in operating frequency such that the limiting resistor was not necessary.

- 3) The model showed that a snubber resistor in series with the MOSFET drain cleaned the sine wave signal significantly; however the current became so low as to not be useful, in the range of 10-40 mA. (see appendix primary circuit 1-2b)
- 4) My original circuit for the primary was a simple LC circuit in parallel, however after looking at variations in LCR circuits online I decided to experiment on the model with resistor placement in series and parallel in the LC section. By far the greatest benefit was placing a large 10W 1 Ω resistor in series with the coil itself, but parallel to the capacitor. This cleaned up the signal output as well as allowed enough current, 200-400mA to flow through the primary. (see appendix primary circuit 1-3b and then finally modified in primary circuit 1-5)

Software modeling can only go so far and can only help so much. One must build, test and improve to be functional in the hands of a novice user. One of the goals of the device is for it to be easy to setup and use. The device has minimal parts and requires minimal setup effort such that students given the device for the first time can easily “figure it out”. The basic kit contains the following parts:

1. Primary unit
2. Secondary Receiver
3. Color coded connector wires for voltage ports
4. 12V DC power adapter
5. Magnetic compass

The classroom teacher needs to supply the following materials in order to enhance student learning using the kit:

1. DC Voltmeter

2. Oscilloscope
3. 120V AC power access, “house” power
4. Lab table
5. Ruler
6. Paper
7. Scientific calculator

The user is suggested to follow the steps below in this order for best results.

Quick start operation without meters (simple demonstration):

1. Unpack the kit and separate all parts
2. Place primary unit in the center of the workspace on a flat surface
3. Turn the switch of the secondary receiver to the LED position
4. Place the magnetic compass on top of the primary unit
5. Plug the DC power supply into the primary unit
6. Plug the DC plug into the wall
7. Turn the primary unit switch to the ON position
 - a. the internal fan will start running
 - b. the LED status light will light up
 - c. the magnetic compass needle should deflect from magnetic north. (This can be removed, it is used as an immediate indicator of the magnetic field being generated by the primary coil)
8. User may now pick up the secondary receiver and place it 10 cm above the primary unit and observe the LED’s light up wirelessly at a distance above, below and along the sides of the primary unit.

Enhanced operation with meters (taking measurements):

1. Unpack the kit and separate all parts
2. Place primary unit in the center of the workspace on a flat surface
3. Place secondary next to the primary unit
4. Plug in the color coded connectors into the voltage ports of both the primary and the secondary
5. Attach the voltage connection wires of the primary unit into your own oscilloscope.
6. Attach the voltage connection wires of the secondary receiver to your own voltmeter. Adjust the settings to read under 20V DC.
7. Plug the DC power supply into the primary unit
8. Plug the DC plug into the wall
9. Turn the primary unit switch to the ON position
10. Adjust the oscilloscope to see the sine wave pattern being generated by the primary coil.
11. User may now pick up the secondary receiver and place it 10 cm above the primary unit and observe the LED's light up wirelessly at a distance above, below and along the sides of the primary unit. The voltage reading should be near 2V DC at or near the 10cm mark and should increase to near 15V DC on the top surface of the primary unit.

SOLUTIONS EVALUATED & SOLUTION SELECTED

I went through two alpha stages and several beta stages while developing the WPT kit. Some of the improvements were previously mentioned, but I would like to go into more detail on the technical reasons according the written history of my engineering notebook.

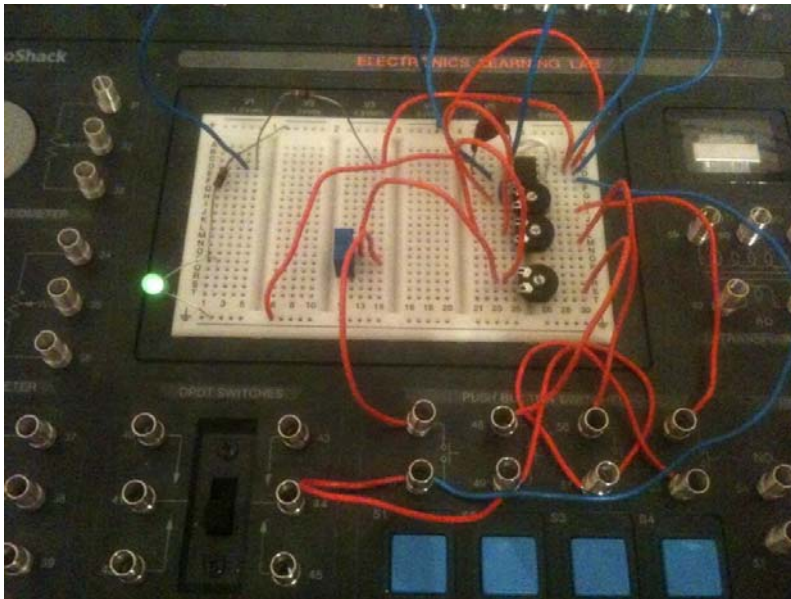
ALPHA 1.0 – THE FREQUENCY KEYBOARD

While researching induction projects in the classroom I saw a video online about wirelessly inducing current in Nitinol memory wire thereby moving a small paper bird's wings using "selective inductive power transfer" – magnetically coupled tuned circuits. At that time this sounded wildly appealing and I set out to build a prototype of a tuned circuit system that could be used in the classroom. I thought of demonstrating modern induction by showing students that a tuned circuit only worked at a certain frequency and that this property could be applied to various applications.

I have built several circuits involving keyboard control of audio signals and I thought that making a pre-tuned keyboard would be a simple way to show that as one "key" is depressed the energy of a specific frequency would transfer to the primary coil. However the power might not transfer efficiently enough to control a device wirelessly at a certain distance, that particular frequency was not resonant. By pressing another "resonant key", the device would work with greatest efficiency and do the most work. By pressing a "harmonic key", the device would work but perhaps not as well.

I set out to build a demonstration device based on a 555 timer that could transmit 4 different frequencies into a small primary coil of these parameters:

- 26 gauge magnet wire
- 8.5 cm diameter
- 10 turns
- 6V input
- 1 variable potentiometer to produce a frequency range
- 3 dedicated “keys”



Alpha Prototype 1.0 - Frequency Keyboard. Three trim pots are used to manually adjust to specific frequencies while three of the blue momentary switch buttons are used as keys.

An identical receiving coil was made and connected to a 2V LED. Both coils were placed inside a plastic CD gel case to protect them and to be able to move them around. This small system transmitted power up to 5mm away as long as the coils

themselves were aligned on top of each other. As written in the notebook I discovered that the signal was able to induce a response in a frequency counter up to 24 cm away. This is the point where I began to take power into consideration, attempting to use distance as a design parameter.

I moved the input voltage to the 9V rail and immediately reached a range of 2 cm which was quickly improved to 4cm. Changing the input voltage I quickly learned that the flow of power throughout the circuit changed as well. This caused a shift in frequencies in the keys of the keyboard since the 555 timer is a voltage controlled oscillator. Changing the input voltage required me to replace the dedicated resistors that went to the keys themselves; every time. After I felt the circuit was stable enough, and the idea somewhat worth pursuing, I found that attaching a 470 uF electrolytic capacitor in series with the LED on the receiving coil would charge the capacitor.

I increased the voltage to 12 V in the circuit and found that the 555 timer can only handle a maximum 200 mA of current. This led to smoking a few timers before I realized it was the current and not the voltage input. I had previously built an audio modulated 555 timer circuit that allowed a high voltage flyback transformer to discharge 20 kV across two leads. This previous experience of powering high voltage portions of a circuit with a low voltage timer gave me the idea I would use to modify the keyboard circuit. I modified the circuit to enable a power switching MOSFET transistor to apply the higher voltage and additional current into the coil instead of the 555 timer. Even with 12 V and the new power routing, I was only able to get the distance increased to 4.5 cm.

I decided to talk to Dr. Ling regarding my progress and my confounding power issues. He explained to me that what I was building was not a tuned circuit, rather I was building a circuit that transferred power only inductively and not via resonance. He stated that I needed to build an LC circuit in both the primary and the receiving coil. My experience in small-scale LC circuits was non-existent and required a lot of studying. My only experience with tuned coils up to this point had been working on my Tesla coil, something that worked using similar properties but was based on a completely different power system.

ALPHA 1.1 – MIGRATING THE CONCEPT TO A TUNED LC CIRCUIT

Tuned circuits require that two coils of wire oscillate at the same resonant frequency. They can be of different physical geometry, but they must be at or very near their resonant frequencies in order to transfer power efficiently – otherwise two coils simply interact with each other inductively at very close distances and low efficiencies. My first step was to decide on a capacitor to use as the C portion of the LC circuit, but most importantly I needed to find the resonant frequencies of the coils I was working with.

At this point the voltage controlled keyboard idea would not be feasible since changing the input frequency to the coil beyond the resonant frequency of the LC circuit would never transfer power in a way I felt good enough to be used to teach this principle. I would need to have made multiple coils with multiple LC drive circuits – I felt this would simply be too confusing to students. I wanted to design the circuit in such a way that a student could change minimal parameters to prove that resonant frequencies were the best to transfer power at, so I decided to use two different capacitors to achieve two different frequencies on both coils so that students could investigate by simply replacing one commonly found component and not dealing with multiple coils or other knobs and switches. I opted to use commonly available high speed low capacitance ceramic 104 and 103 capacitors – 0.1 uF and 0.01 uF respectively.

The method I used to find the resonant frequency of the LC circuit was a common process by which one drives a signal into the LC portion by using a bench function generator instead of the 555 timer. Since I would eventually be using the 555 square

wave DC output to power to the LC circuit, I chose to use the same square wave output of the bench function generator. The point of resonance was detected by attaching an oscilloscope in parallel across the coil and adjusting the input frequency to a point where the peak voltage across the coil is found – this only occurs at resonance and very mildly at certain harmonics. It was determined that the capacitor-coil combination produced resonant frequencies of 126 kHz using a 0.1 uF capacitor and 414 kHz using a 0.01 uF capacitor.

The bench function generator is able to sustain signals up to 1 Mhz. I wanted to see if I could boost the range and performance of my 555 timer circuit by moving into higher frequencies and using a potentiometer to sweep a wide range of frequencies, basically treating the 555 timer as a bench function generator. While changing the circuit I found that the coil was getting hot and the 555 timer chip itself was not quite burning out but nevertheless not functioning. I had reached a point in the build where the backwards EMF coming from the ring down of the coil had become a serious issue. I added a protection diode in series from the output of the timer to the coil. I also found that the 555 timer combined with this set of capacitors and coil could reach a wide range of frequencies, but only be stable among a small cross section of those frequencies. I chose to stay at lower frequencies because the stability spectrum was larger than at those approaching 1 Mhz. This caused me to stay with an LC circuit that utilized a 104 capacitor.

DEVELOPMENT & PROTOTYPE DESIGN DOCUMENTATION

ALPHA 1.2 – TUNED CIRCUIT WITH POWER TRANSISTOR

Once the low voltage LC circuit was established, I increased the power input to 12 V using two 6 V batteries in series on the LC circuit by adding the power MOSFET portion to the main circuit. This improved the AC waveform detected on the receiver as well as improved the accuracy of the signal to the frequency counter. The coils had coupled at a resonant frequency of 141 kHz and a distance of 11.5 cm – however this was without any load, and at very low current.

I found that the bench generator provided much stronger output, and by taking a sweep of the output current it delivered up to 1 Amp. I placed an LED load on the receiving coil and found that the LED responded well to a current above 500 mA. Once on the bench generator the coils coupled strongly at 126 kHz due to increased efficiency of lab equipment and simple coils. It became clear that my circuit was wasting a lot of power and not routing it to where I needed it most – the primary coil.

At this point in the build while experimenting with the device and the 8.5 cm thin coils, I was fortunate to have come across a used LCR meter of which I immediately measured the inductance of the coils. The measured value was 19 uH. I wanted to test this measured value against a calculated value based on the bench generator produced 126 kHz resonant frequency. Since calculations in the classroom will normally be done

first and then measured for accuracy, I myself need to go through this process and refine it so that students would see moderate success in their coil construction.

INDUCTANCE - DEFINITION

Inductance (L , measured in Henries) is an electromagnetic property of all conductors when they experience a pulse of current of any magnitude and of any oscillation. As current passes through a conductor, a magnetic field builds up along the conductor at right angles to the direction of current; the more intense the current the greater the flux of the magnetic field surrounding the conductor. As the current is cut off, the magnetic field collapses in sync pushing current backwards as it rushes to return to equilibrium – this is called “back emf” incidentally. If we were to catch this collapsing energy with a capacitor and feed it back into the conductor we have an LC circuit that has a property of oscillating back and forth from capacitor to conductor until they both reach equilibrium.

If we take a straight line conductor and make circular windings to produce a coil, the magnetic field does not collapse so easily since a magnetic field will induce an electric current in the coil wrapped tightly next to, above it and below it. This constant creation and collapse in three dimensions slows down the back EMF from reaching equilibrium. Therefore geometry of a coil plays an extremely critical role in a coil's inductance and overall performance in any circuit application. If a coil has slightly too much or slightly too little inductance, the collapse of the magnetic field might be out of

sync with the capacitor it is attached to and therefore won't oscillate at the frequency one would desire.

CALCULATING INDUCTANCE – THE GEOMETRY METHOD

Winding a coil without the ability to predict its inductance is useless; therefore students will use a table of formulas that correspond to various coil winding geometries. The best table that I found that would be easily understood by students is located at this website using their calculator for the multi-layer solenoid:

http://www.pulsedpower.eu/toolbox/toolbox_inductances.html

The web page hosts a calculator that inputs variables the students place into the fields in that section. The multi-layer solenoid formula is:

$$L = \frac{\mu_0}{4\pi} \left(FN^2 2R - \frac{12.57}{10^4} N^2 R \frac{w}{l} (0.693 + B) \right)$$

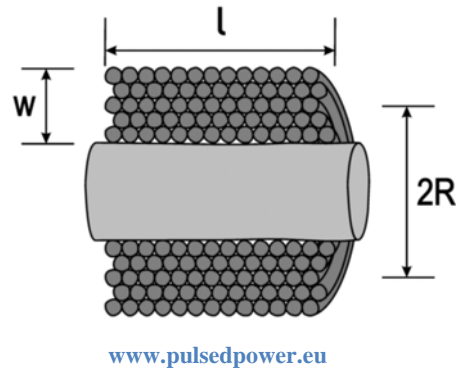
www.pulsedpower.eu

L = inductance, μ_0 = magnetic permittivity of free space, F = a factor related to the diameter and length of the coil, N = number of turns in coil, R = radius, w = width, l = length, B = correction factor due to thickness from increasing turns

I would consider this equation and its various constants to be slightly tedious and perhaps beyond many students in a regular physics classes to do repeatedly while building a coil.

I purchased and began winding a coil around a 2 inch inner diameter PVC coupler. To find the inductance of the geometry demonstrated in the kit, students must measure precisely the following parameters of their coil:

- Inner diameter
- Layer vertical width
- Length of windings on the form
- Outer diameter
- Number of turns
- Wire gauge



The 2 inch original coil that I wound had the following parameters:

- | | |
|----------------------------------|-------|
| • Inner diameter | 69 mm |
| • Layer vertical width | 3 mm |
| • Length of windings on the form | 15 mm |
| • Outer diameter | 75 mm |
| • Number of turns | 19 |
| • Wire gauge | 20 |

Using the web-based calculator, the inductance of the coil was 38.77 μH . Using the LCR meter, the measured value was 39 μH – extremely close and well within useful classroom tolerances. This method was tested twice with an identical coil achieving 40.7 μH calculated, 39 μH measured; as well as a completely different coil geometry calculated at 225.3 μH and measured at 228 μH . These results confirm that both measured value and formula will provide relatively error free results in the classroom even with the loosest of student hands.

CALCULATING INDUCTANCE – RESONANT FREQUENCY METHOD

It is important for students to understand the property of inductance and be able to calculate it using various methods. An alternate method is to first find the resonant frequency of their LC coil circuit using a bench function generator, then working backwards to solve for the inductance using the following formula:

$$2\pi f_{res} = \frac{1}{\sqrt{LC}}, \quad \text{rewritten to solve for L,} \quad L = \frac{1}{C(2\pi f_{res})^2}$$

$$L = \frac{1}{(1 \times 10^{-6} \text{ uF})(2\pi(1.26 \times 10^5 \text{ Hz}))^2} = 15.97 \text{ uH}$$

The above value is for the early 8.5 cm coils from the alpha prototype. This value came very close to the measured value of 19 uH mentioned previously. The math itself does not seem to be overly complex as long as the resonant frequency can be manually attained with a classroom oscilloscope.

Once the inductance can be calculated using the geometry method, the resonant frequency can be easily ascertained by using the previously mentioned formula in its standard form. The coils I wound at this point are labeled “A” and “B”, they are 2 inch PVC forms and are somewhat identical with inductances 39.1 uH and 40.7 uH respectively. The “A” coil is considered to be the primary, the “B” coil will be the new receiver. The calculated resonant frequency of these coils were both extremely close to 254 kHz, with the actual resonant frequencies close to 258 kHz.

BETA 1.0 – ENCLOSURE, COIL FORMS AND ORIENTATION STAND

The driver circuit was modified (see Appendix WPT Primary 1.0) in two ways to improve power and cool the over-heating MOSFET:

- 1) A switch operated 13.4 V (12 V DC) wall power supply with a 3A fuse was added
- 2) A 12 V DC cooling fan was placed near the MOSFET

It was discovered that the protection diode was causing a great deal of interference and producing a lot of heat in the MOSFET. Removing it cooled down the MOSFET significantly and made tuning a lot easier. In a later version of the circuit the protection diode was put back into the circuit after other portions had been corrected (see Appendix WPT 1.2b).

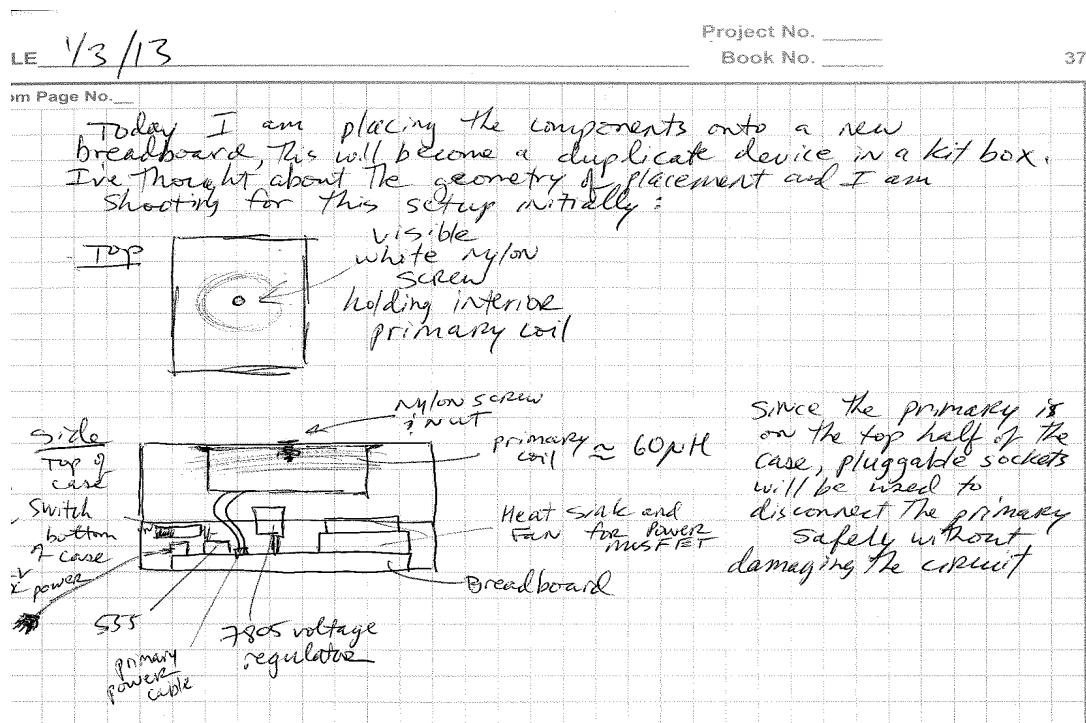
After completing a reliable beta primary circuit I bought a Serpac brand #173 enclosure to place it in. The enclosure has a small form factor but enough room inside for students to add and remove parts comfortably from an internally mounted breadboard. The enclosure was made of durable ABS plastic with areas available to install switches, controls and a status light.

Considering the small success of the two coils wound around the previously mentioned 2-inch PVC couplers, I went to Home Depot again and chose a selection of other PVC pipe connectors according to the criteria:

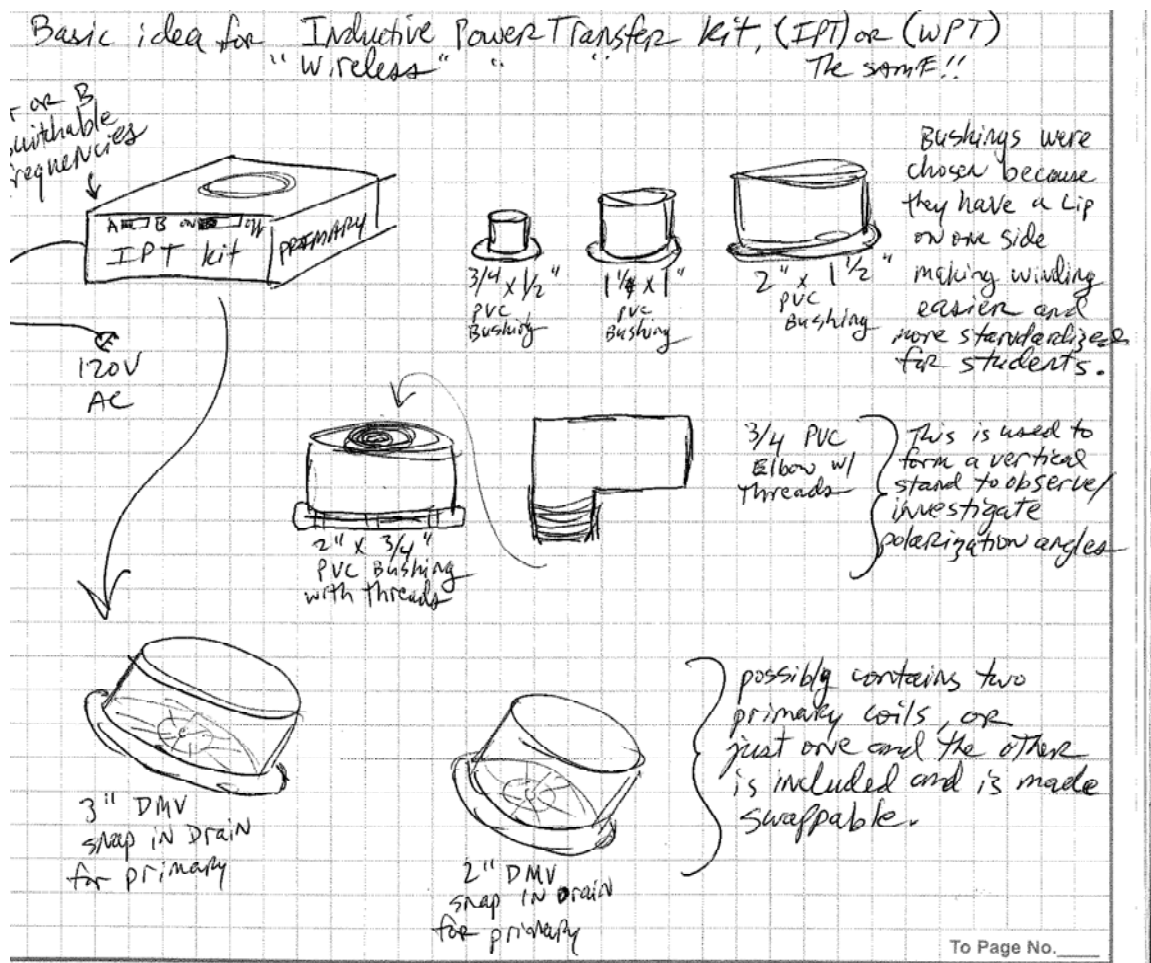
- Ease of winding for students
- High error tolerance, small mistakes are somewhat acceptable

- Easy to find and replace (PVC is ubiquitous and reusable)
- Little to no learning curve in winding
- Easy to calculate theoretical values and measure actual values
- Highly repeatable results
- Allows students freedom to predict and experiment

Not only did the students need a form upon which to wind coils, they also needed the forms to be easily installed in a “plug and play” manner into the primary and secondary to be used for various experiments. The primary coil forms that fit best were Sioux Chief brand 2” and 3” shower floor drains. These were chosen for their size, shape and ease at which they would be mounted into the primary enclosure’s interior top with a non-conductive nylon screw.

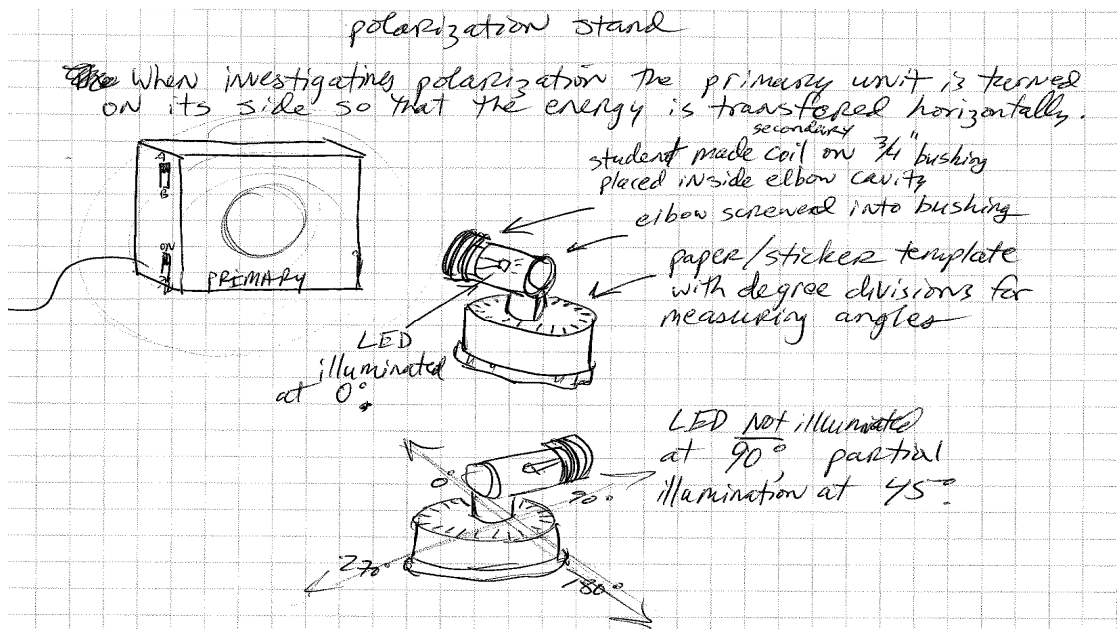


The secondary coil forms were based on PVC bushings as opposed to the couplers I had previously purchased. Bushings have a lip on them that allows students a good starting place upon which to wind the coil easily. A selection of bushings was chosen ranging in diameter from $\frac{3}{4}$ ", $1\frac{1}{4}$ " to 2".



An important part of learning about magnetic induction is the orientation at which magnetic flux is best received by a coil. Energy propagated via a time-varying magnetic field is most efficiently transferred to a secondary coil that is oriented parallel to the

primary coil. It is least efficient when it is oriented perpendicular to the primary coil. In order to study this effect scientifically in the classroom a device must be made to hold the student wound secondary coil at various measurable angles. Since the coil forms themselves were made of PVC, I decided to use a PVC threaded elbow to make an armature with a right-angle to hold a coil in place – an “orientation stand”. The right-angle elbow piece is threaded onto a base so that it stands up and can be rotated to specific angles. The student made secondary coil is plugged into the remaining end and then placed near the primary box where measurements can take place. The primary box can easily be placed on its side to perform these measurements.



PROTOTYPE TEST DATA WITH EVALUATION

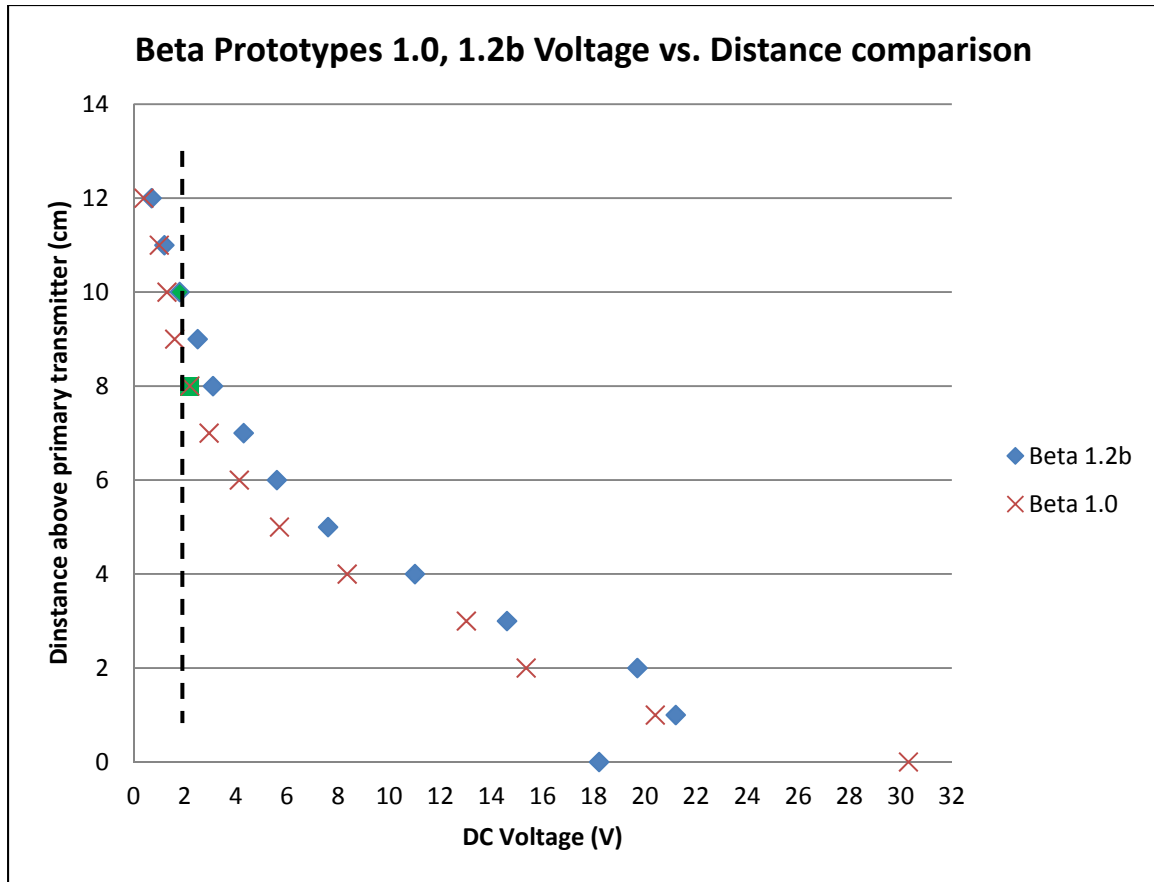
BETA 1.2B – IMPROVING POWER TRANSMISSION DISTANCE

I invited Jim Carpetas, a local HAM radio hobbyist, to my house to give me advice regarding power transmission and alternating current signal stability. He suggested some power conditioning modifications to the primary circuit as well as bringing up the frequency into the 200 kHz range. The secondary coil was also remade to better match the primary coil's inductance. Previous measurements of voltage vs. distance with the earliest alpha coils were noticeable at a maximum distance of only 4 cm at best. With the improvements in the circuit and coils the following data were obtained and compared to Beta 1.0.

BETA PROTOTYPES 1.0, 1.2B VOLTAGE VS. DISTANCE COMPARISON

Beta 1.2b	Beta 1.0	Distance (cm)	% improvement
0.7	0.4	12	42.9%
1.2	1	11	16.7%
1.8	1.3	10	27.8%
2.5	1.6	9	36.0%
3.1	2.2	8	29.0%
4.3	2.95	7	31.4%
5.6	4.13	6	26.3%
7.6	5.7	5	25.0%
11	8.35	4	24.1%
14.6	13.01	3	10.9%
19.7	15.35	2	22.1%
21.2	20.4	1	3.8%
18.2	30.3	0	-66.5%

Green areas indicate the voltages at which the LED load was illuminated. The data show that Beta 1.2b illuminated the load a distance of 10 cm above the transmitter; achieving at 2 cm improvement over Beta 1.0.



The data show that Beta 1.0 displays a very smooth curve of decreasing voltage as distance is increased. Beta 1.2b shows a similar curve with improved higher voltage at most points up until “near-contact” with the transmitter base. At this close near-contact range the voltage dropped significantly - although this anomaly was not investigated

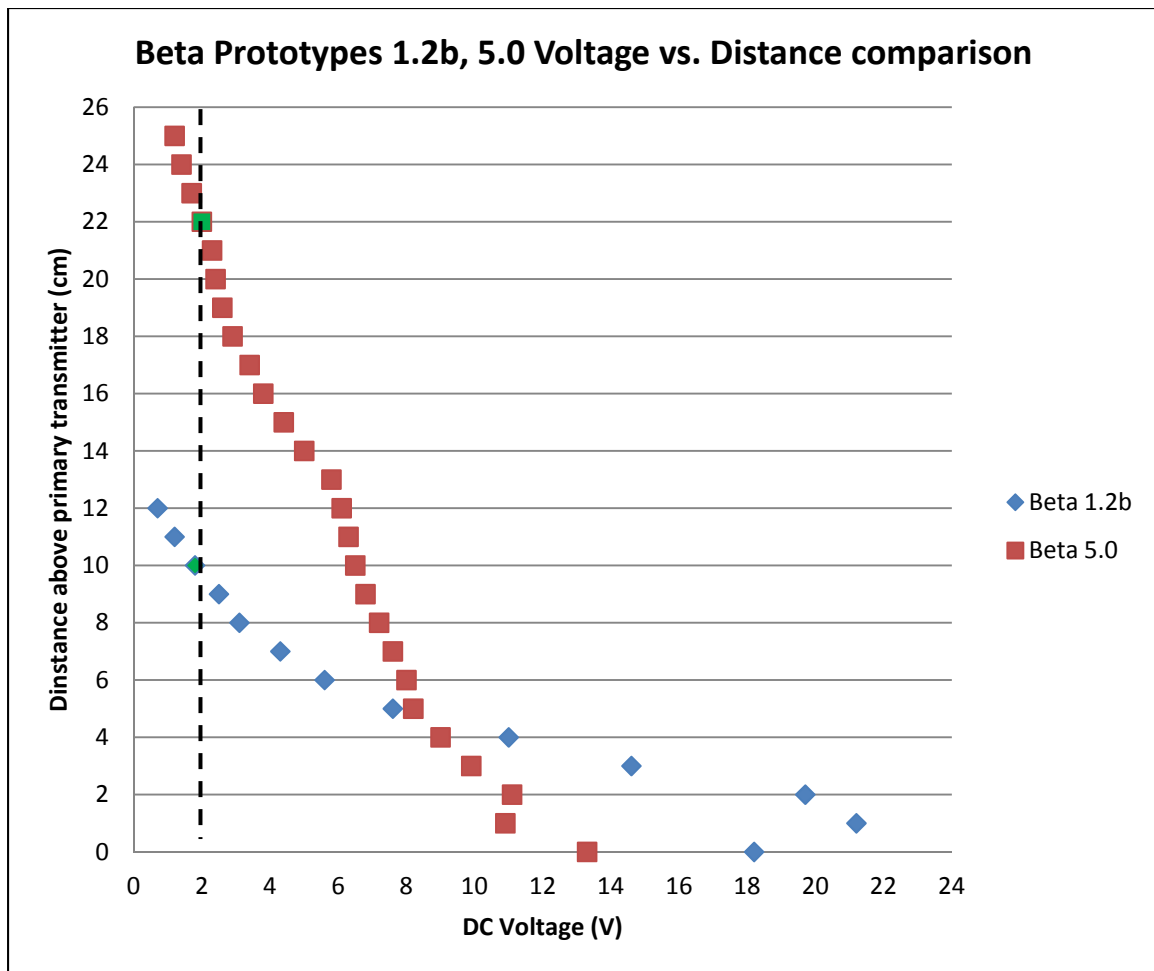
further I feel that this drop in voltage is yielding an increase in the induced current of the receiving coil due to its extremely close proximity. Although voltage above the primary transmitter is a critical metric that will appeal to teachers who want quantitative measurements in the discovery process of a student lab, the most striking effect is illuminating LED's at increasing distances from the transmitter. Due to the LED's voltage requirements, they begin to illuminate when the voltage approaches 2V. The Beta 1.0 design caused LED illumination at 8 cm above the transmitter as noted in green in the data table. The improvements of the Beta 1.2b design caused the LED load to illuminate nearly 2 cm further away than the previous design, a full 10 cm away as shown by the vertical line in the graph.

After discussing ways to improve the signal strength with Dr. Hao Ling, a new set of data was taken to demonstrate the improvements in the power received at higher vertical distances. The major improvement that was suggested was to make a secondary receiver unit that had stronger magnetic coupling by better matching the primary transmitter coil's geometry – its diameter being the major change.

BETA PROTOTYPES 1.2B, 5.0 VOLTAGE VS. DISTANCE COMPARISON

Beta 5.0	Beta 1.2b	Distance (cm)	% improvement
1.2	0	25	
1.4	0	24	
1.7	0	23	
2	0	22	
2.3	0	21	
2.4	0	20	
2.6	0	19	
2.9	0	18	
3.4	0	17	
3.8	0	16	
4.4	0	15	
5	0	14	
5.8	0	13	
6.1	0.7	12	88.5%
6.3	1.2	11	81.0%
6.5	1.8	10	72.3%
6.8	2.5	9	63.2%
7.2	3.1	8	56.9%
7.6	4.3	7	43.4%
8	5.6	6	30.0%
8.2	7.6	5	7.3%
9	11	4	-22.2%
9.9	14.6	3	-47.5%
11.1	19.7	2	-77.5%
10.9	21.2	1	-94.5%
13.3	18.2	0	-36.8%

Green areas indicate the voltages at which the LED load was illuminated. The data show that Beta 1.2b illuminated the load a distance of 10 cm above the transmitter. With improvements in the internal circuitry, Beta 5.0 illuminated the LED load at a distance of 22 cm; more than double.



The graph shows two interesting trends in the comparison of early to more recent iterations of the device. Firstly, improvements in the internal circuitry of both primary

and secondary units led to doubling the distance that the LED load was illuminated, noted in the graph by the dashed vertical line. This has exceeded my initial requirements of at least 10 cm. Secondly, the maximum voltage reached at the contact point of 0 cm by Beta 5.0 is much lower than that reached by previous versions – this was unexpected however I feel it is due to the secondary unit’s coil having a larger diameter that matches more closely to the primary coil than the previous version of the secondary unit; thus avoiding the transformer step-up effect where coils of fairly different geometries convert more accessible current to higher voltage. The results conclude that the device’s improvements produced useful power at larger distances at the expense of decreasing the voltage at the point of contact between the transmitter and receiver.

REVISIONS

BETA 2.0 – CLEANING THE SIGNAL, IMPROVING CURRENT

The amount of voltage I was working with was plenty to illuminate the low current needs of the LED load, but I wanted a way to have as much power transfer in both voltage and current as possible so as to increase the various receiver loads that students might create. I attached an ammeter to both coils of the kit and found that the induced current received was a paltry 20 mA compared the 400 mA of output current. This was less than 10% and completely unacceptable. My new goal was to seriously boost the induced current. It was discovered that a combination of applied gate voltage to the MOSFET, the timing capacitor, the duty cycle of the timer (the percentage of time the circuit is allowing current to flow to the primary) and the actual LC circuit configuration itself was causing far too many harmonics near the 214 kHz resonant frequency.

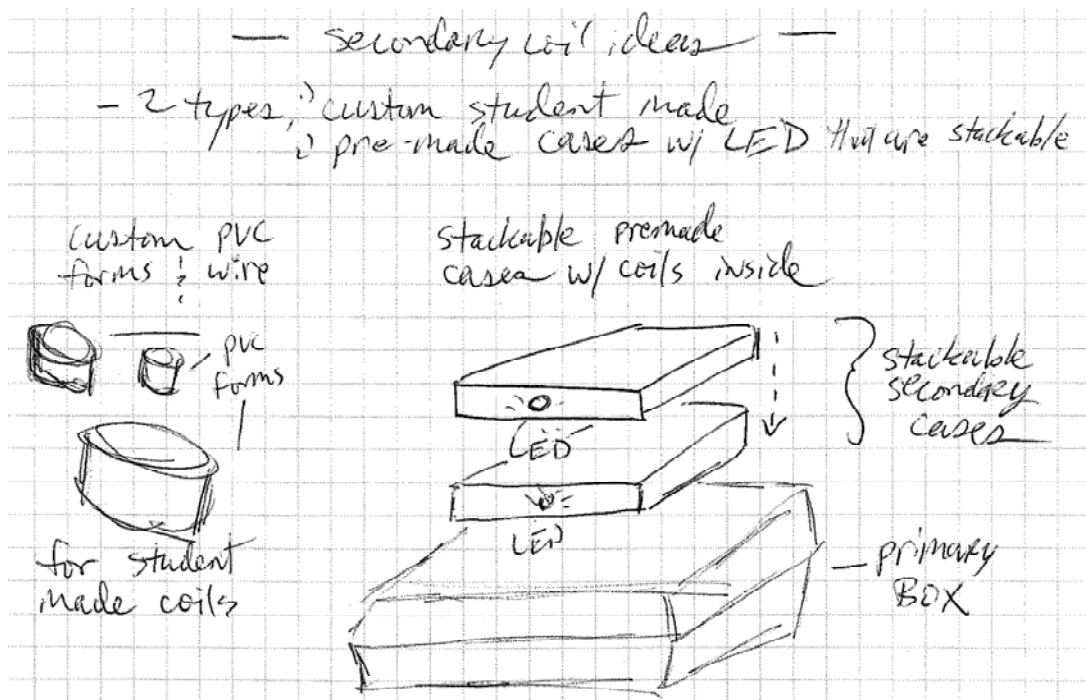
I started this improvement goal by adding power conditioning capacitors to the 12V power rail to eliminate most interference from the naturally unstable power supply itself. I investigated various LC configurations and found that an LCR configuration might be worth trying – adding a low resistance “snubber resistor” from the MOSFET drain output to the primary coil raised the duty cycle of the device which allowed more current to flow into the coil before switching off. This also improved overall stability of the device by allowing smooth increases in frequency from 100 kHz to 170 kHz with only a few harmonics.

By experimenting with various resistances of this iteration, it was discovered that the waveform of the primary was most sinusoidal when a 1.2 k Ω resistor was applied. The output waveform showed a duty cycle of 49.1% at 214.6 kHz with an output voltage of 12.32 V. A perfectly timed sine wave would require a duty cycle of exactly 50% at resonance - meaning that the coil is energized with input current for exactly half the time and switched off. As the magnetic field in the primary coil collapses, the current reverses and stops. At that instant the coil is energized again by the timing circuit and the process is repeated hundreds of thousands of times each second. Resonance is all about timing and nothing else. Power can still be transmitted without resonance, but it is vastly inefficient.

Another complication in the transference of power is that the receiving coil must also be resonant with the primary coil. I remembered back when designing my Tesla coil that I should have started with the secondary tower first, determined the resonant frequency of it and then design the primary coil. At this point in the design I paused and tried various receiving coils made with different inductances and connected to several different capacitors to achieve a frequency range of 57 – 261 kHz, wide enough to cover resonance and any powerful harmonics. Up to this point I had been making relatively small diameter receiving coils.

SECONDARY RECEIVER 1.0 – ENCLOSURES AND INITIAL FEATURES

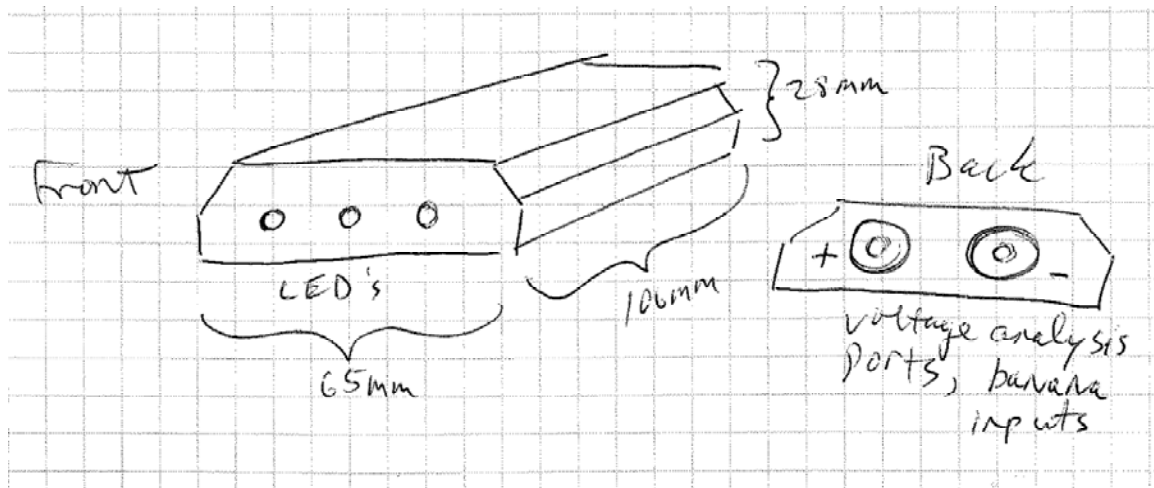
I purchased several small enclosures that would eventually become the handheld secondary receivers. I would be able to comfortably fit a maximum 46 mm diameter coil inside any of them. I decided to make a 100 uH coil that would resonate at 160 kHz with a 103 capacitor. I came to this value because it seems to be an easy target for students to approach in various ways that doesn't use too much or too little raw materials.



The secondary receivers themselves went through several iterations in their design and features. My original needs list required:

- Units to have a small “handheld” form factor

- Units to be robust and durable since this part will be handheld and most prone to being dropped
- Units can be stacked on top of each other to demonstrate wireless transfer through multiple units
- Units wired in a manner in which they are always “on” when near the resonant magnetic field, no switches to turn “on”
- Units to be pre-tuned to work with the primary transmitter unit
- Units will have three LEDs in parallel, both for good visualization and to demonstrate a load
- Units will have voltage analysis ports for making measurements of distance vs. voltage with an active load (this changed in version 1.2 to have a switch allowing “load / no load” voltage measurements)



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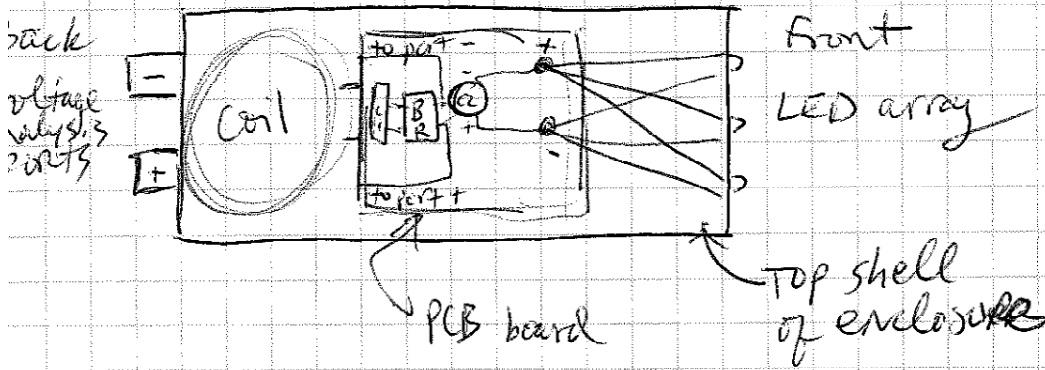
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Receiver Board:

Minimum components:

- 103 capacitor (0.01 μF)
- 50 - 60 μH coil
- 1A 4-pin Bridge rectifier diode
- 10 μF electrolytic capacitor, for smoothing
- LED

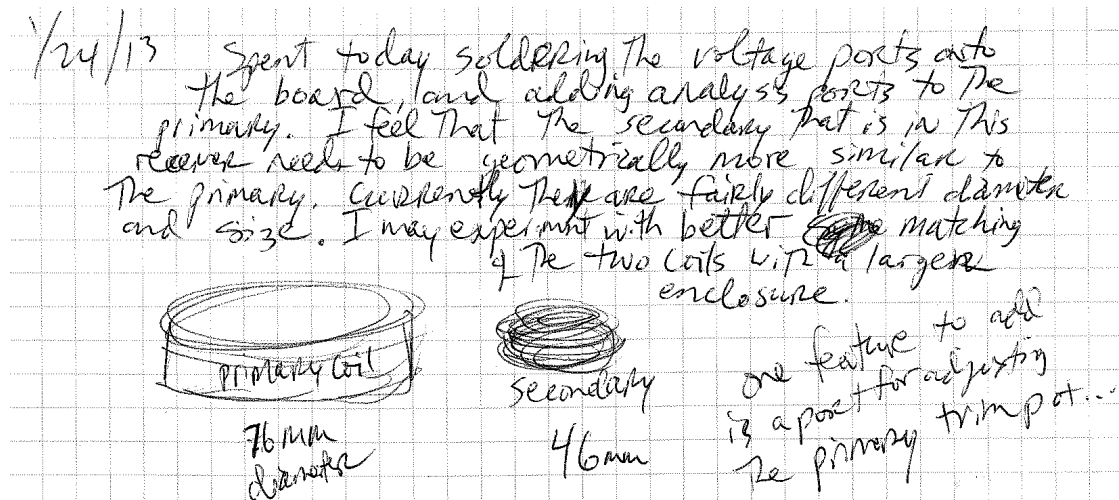


The enclosure was measured and mapped out with holes for the LEDs and ports

Secondary Receiver 1.0	
	
Front LED mapping	Rear voltage analysis ports mapping
	
Interior front	Interior top
	
> 5 cm wireless power transfer distance to LED array in parallel orientation	No power transfer when oriented perpendicular to field flux

SECONDARY RECEIVER 1.1 – LARGER ENCLOSURE

The secondary receiver configuration (Appendix WPT Secondary Receiver 1.0) worked and fulfilled all the requirements listed; however after the actual build I felt it was too small. The diminutive size limited the experience in learning about the interior circuit - it wasn't "learner friendly". The small coil size in the secondary receiver was also a major factor. The primary coil at this point was 76 mm in diameter and seemed to be operating well enough to leave alone. Version 1.0 of the secondary receiver contained a coil that was only 46 mm in diameter. Both coils were in resonance at this point, however the windings were vastly different and were not performing as well as I had intended. I decided to look for another larger, yet still handheld enclosure.



The new enclosure I found could hold a 2 inch diameter PVC form and still have room for other components all around it. To build a 100 uH coil as I had decided earlier, the diameter turned out to be 64 mm – much closer, although not identical, to the diameter of the primary coil. After installing all the initial components for the larger

enclosure and minimally revising the timing of the primary coil I was able to match the resonance of the new secondary receiver and achieve bright LED illumination at a full 16 cm, the best distance so far.

Secondary Receiver 1.1 (Larger enclosure)



Interior front



Version 1.0 on left, larger 1.1 on right



Improved performance of wireless power transfer distance



Wireless power transfer through multiple stackable units. Version 1.0 on bottom, version 1.1 held above

SECONDARY RECEIVER 1.2 – LOAD SWITCH

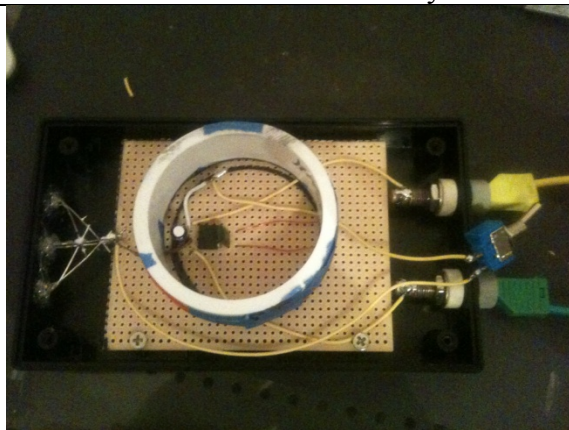
During the very earliest builds I found that removing the LED load and directly measuring voltage vs. distance proved to be very important in determining performance and understanding the geometry of the magnetic flux field interactions of the two devices. For example in previous measurements I removed the LED and instead attached the voltmeter across the open junction. Lifting the secondary receiver above the transmitter would decrease the voltage until there was no voltage to be measured. With the LED load “on”, the secondary circuit voltage measurements do not fluctuate, they remain relatively constant (~3 V) when in direct contact with the transmitter all the upwards to the distance at which the LEDs lack the necessary minimal voltage to illuminate them.

The reason for this “constant voltage” effect when a load is attached is that LEDs themselves are a low voltage device and when wired in parallel they share the same voltage, in this case, around 3 V. To keep the LED array from suddenly turning on and suddenly off, an electrolytic smoothing capacitor of 100 uF is placed in parallel with the array and the DC output of the rectifier (Appendix WPT Secondary Receiver 1.2). When measuring voltage across the LED array or the capacitor, the draw will always only be around 3 V. However, when shorting the parallel connection between the DC output of the rectifier and the load with a voltmeter, one can obtain the changing voltages that are actually happening to the coil as its distance is changed with respect to the transmitter.

I did not want students to measure something that was constant and then suddenly dropped to zero, as this can be frustrating if not understood. I also did not want students

to use only brightness as a quantitative measurement since this is subjective and largely inaccurate. To solve this problem I installed a switch on the secondary receiver at the site of the aforementioned short such that students, when guided with a lesson, can use to bring the LED load into the circuit where voltage measurements are mainly constant (3 V), or take it out of the circuit – allowing a range of voltage measurements (0 ~ 20 V) .

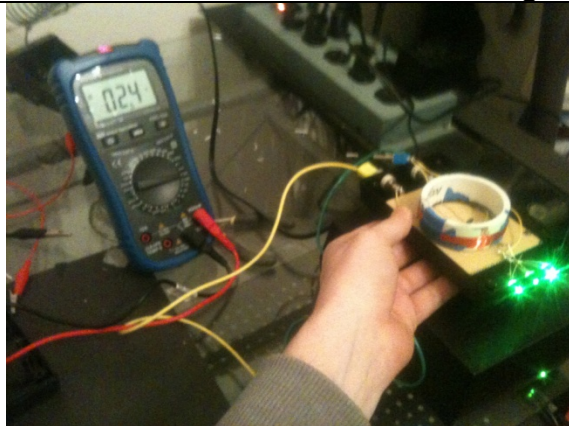
Secondary Receiver 1.2 with Load Switch



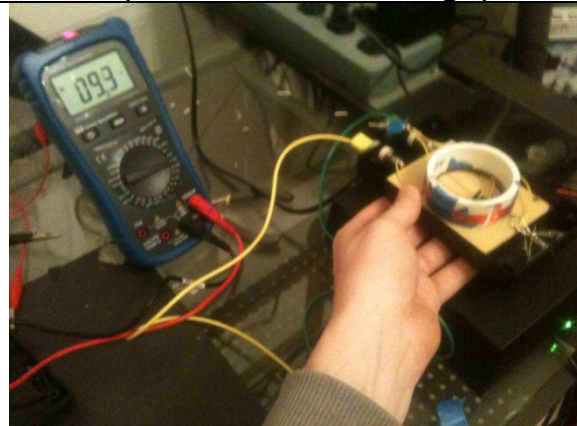
Interior receiver coil with switch wiring



Switch placement between voltage ports



Load “on”, constant voltage ~ 3 V with a few cm of distance above transmitter



Load “off”, demonstrating changing voltage at same distance above transmitter

BETA 3.0, 3.0B – LOWERING LCR RESISTANCE

The snubber resistor was removed in order to allow more current to flow directly into the coil. Various resistor configurations in series and parallel were inserted into the LC portion of the primary to make it an LCR circuit with a lower resonant frequency than previous iterations. Decreasing the resistance of the $\frac{1}{4}$ W resistor in the LCR portion of the circuit from 1000 Ω , 500 Ω to 270 Ω improved stability and signal quality, however overheating of the resistor became a serious safety issue due to its power rating – touching the resistor would easily scald fingertips and leave a visible burn. This was obviously unacceptable. The signal quality near 160 kHz seemed to prefer lower and lower resistances – but without the heat.

It was discovered that two 10 Ω resistors in parallel with the LC circuit - one resistor in front of the coil, one resistor in front of the capacitor - stabilized the primary waveform and illuminated the LED's very brightly in the receiving coil. A distance of 10 cm was reached, however the heat was starting to melt the bodies of these tiny $\frac{1}{4}$ W components. Taking the resistor out of the circuit would have seemed like a good idea since resistance is considered an obstruction to current flow, however in this case of high frequency oscillations, fixed coil inductance and the lack of a tunable capacitor - adding a small amount of resistance was obviously improving resonance and allowing large amounts of current to flow due to synchronization of both incoming current to the coil and the collapsing magnetic field.

I decided to invest in some much higher wattage resistors with low resistances. A 10 W 10 Ω resistor was placed in series with the inductor coil with immediate positive results both in distance increase and heat dissipation.

BETA 5.0 – A SAFE, USABLE AND MEANINGFUL PROTOTYPE

After seeing the results for the 10 Ω resistor, I decided to push further and see the effects of a single 10 W 1 Ω resistor. I had considered putting several of these large wattage resistors in parallel with each other to drop the resistance even further but this would simply take up too much space, and in my opinion, be confusing to students. This tiny amount of resistance was as low as I felt the device should have considering that I want students to be able to replace minimal components and understand the device at-a-glance. Each time resistance was changed the timing circuit of the primary would have to be adjusted over and over again since a change in resistance would affect the flow of current in and out of the coil. The receiver with its 100 μH secondary coil and 0.01 μF capacitor (103) had a fixed resonant frequency of 160 kHz; this was the target frequency to reach each time the primary circuit was adjusted.

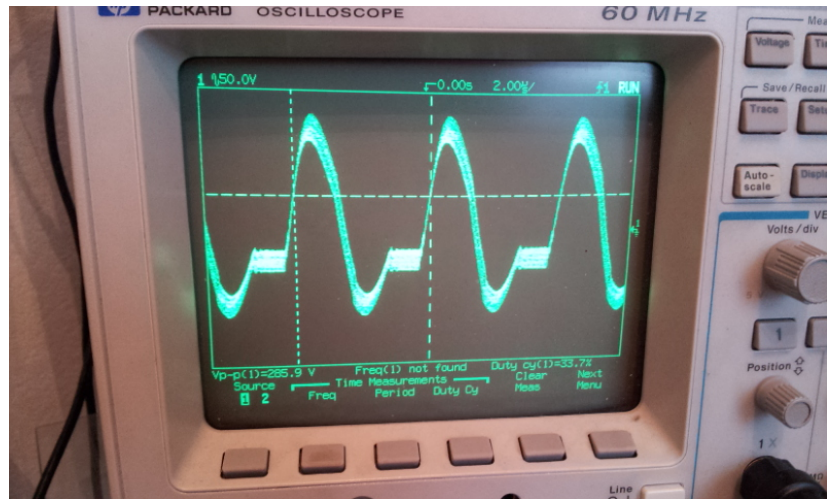
With the primary retuned and the single 1 Ω resistor installed; the distance was improved to 19.5 cm, nearly double the previous best configuration. With so much more current flowing in and out of the coil, heat dissipation inside the primary box became a higher priority than in previous iterations. Actually the heat across the 1 Ω resistor was minimal, making it low enough to be safe to handle now if a student were to run the device and then use their fingers to replace this component. The primary box has several punctures made in the plastic casing for the DC power jack, voltage and timing ports, power switch and the status LED. I decided not to add more punctures to the plastic because I felt that the cooling fan would move enough external air in and out through those punctures. What I felt was most important was to increase the amount of airflow around the primary coil itself. The PVC coil form itself was sitting down on the

breadboard and surrounding the power MOSFET's heat sink. This design decision was made to reduce the overall size of the device, knowing all along that the heat generated by the heat sink would be rising into the coil. However all previous iterations were relatively "cool" since the coil itself was not very warm. This current version brought me to the point of dealing with both the heat emanating vertically from the heat sink and horizontally from the surrounding coil. I decided to drill three evenly spaced 5 mm airflow holes in the PVC form of the primary coil. The cooling fan now would draw lower temperature air across the heat sink, push hot air up into the coil PVC form, and finally out through the airflow holes – relieving the heat of both the power MOSFET and the coil itself.

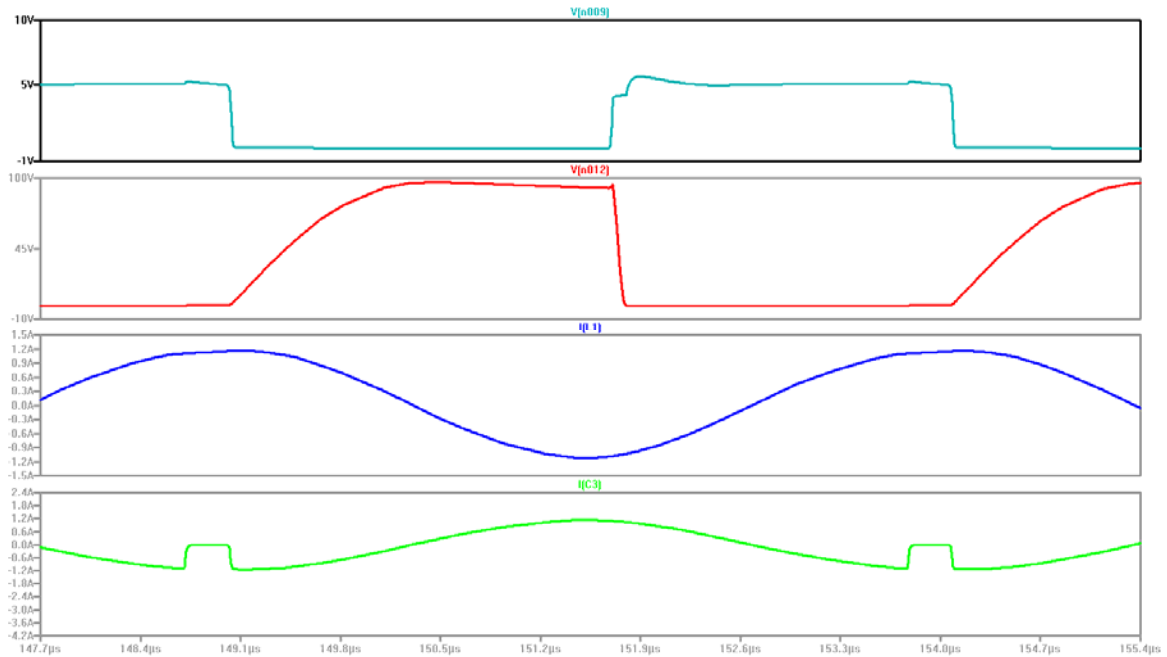
EFFORT TO IMPROVE WAVEFORM

The Beta 5 version has yielded a stable platform, however the outgoing AC waveform emitted by the primary is not a perfect sine wave. This minor imperfection in the outgoing signal shows that there is still some form of inefficient timing between the drive circuit and the resonance of the LCR coil. Ideal efficiency is found at resonance and would yield a perfect sine wave of equal peak to peak amplitude with a 50% duty cycle as mentioned before.

The Beta 5 version has a waveform with a strange “shelf” that I hypothesize indicates an electrical “pause” either between the MOSFET gate to the LCR coil or the protection diode that stops the reverse EMF. To investigate the problem without defeating my progress to this point, the circuit was modeled again using LTSPICE software and several virtual components were updated to reflect changes I had made. The LTSPICE waveform showed a similar shelf in the voltage reading across the protection diode, but what intrigued me the most was that the shelf appears at the same time as a “flat topped spike” in the discharging of the LCR capacitor. It seems that the capacitor discharges and then is suddenly charged instantaneously and at a constant value for a very brief amount of time.



Beta 5.0 waveform of Voltage vs. Time showing a near perfect sine wave with the “shelf”, to be improved as of writing.



Waveform traces in LTSPICE – The bottom trace is the current through the capacitor of the virtual LC circuit. The pillar that is rising above the sine wave I feel is a model of the problem I’m experiencing.

I brought this problem up to my advisor Dr. Ling and he suggested that since the resistance was so low already, the capacitor might be the best component to adjust at this point. In his experience with RF transmission, antenna design and enhancement, a “tuning capacitor” is often used to maximize the efficiency of power transfer into a coil and thereby place it into an ideal resonant state. A tuning capacitor is simply a variable capacitor with a very low capacitance range.

Variable capacitors come in a large variety of shapes, sizes and values. They are not commonly available; therefore adding one to the kit would require some forethought in planning for this. It is a design compromise at this point – to build a functional device with common parts that reaches nearly all goals knowing that it is not ideal, or add components to the device that make it work nearly perfectly but students may find it difficult to reach perfection due to the availability of parts.

Either way, at this point I needed to see if a variable capacitor would solve the waveform problem. I had never worked with variable capacitors previously. I looked online to see what range these were available in and what physical size they were more commonly available as. I found that most were of very low capacitance and of relatively small range. I ordered one that had what I thought was most common from Digi-key at considerable expense compared to other components (\$20 with shipping) and the shipping time would be a 10 full days.

I did not want to wait that long so I disassembled an old AM radio and experimented with its tuning capacitor since the AM band was closer along the RF

spectrum to my primary coil. The capacitance range of the pins on the variable capacitor was measured using an LCR meter. The widest range found in the AM variable capacitor was 10 – 80 pF from pins E – F. This range falls far too short when considering that the primary coil's capacitor is a 103 (0.01 uF, or 10,000 pF). A range that only changes from 10 – 80 pF isn't going to be noticeable in this particular configuration. A variable capacitor with a sweep range of perhaps 5000 – 15,000 pF would be a much better starting point. Unfortunately that is not what I ordered from Digi-Key; lesson learned.

The variable capacitor from Digi-Key arrived however as I thought the sweep range falls much too short for what I felt was necessary. The waveform on the oscilloscope still had the shelf however it was marginally improved, but far from what I hoped to achieve. Further edits to the circuit yielded little to no improvement as far as voltage vs. distance was concerned; however after having discussions with other electronics hobbyists on the All About Circuits forum, it was discovered that I had not been saturating the gate of the power MOSFET with enough voltage to open it fully. This led to a small redesign of the circuit whereby several parts were removed and a new power path was implemented utilizing only one 12V voltage regulator (see Appendix: WPT Primary 8.0).

LAB ACTIVITIES AND DESIGN CHALLENGES FOR STUDENTS

In the process of building the device and consulting with Dr. Ling, Electricians and teachers, I feel confident that the following design challenges will provide secondary school students with opportunities beyond simply watching LED's illuminate at a distance. Teachers and students are encouraged to try the following experiments outlined below.

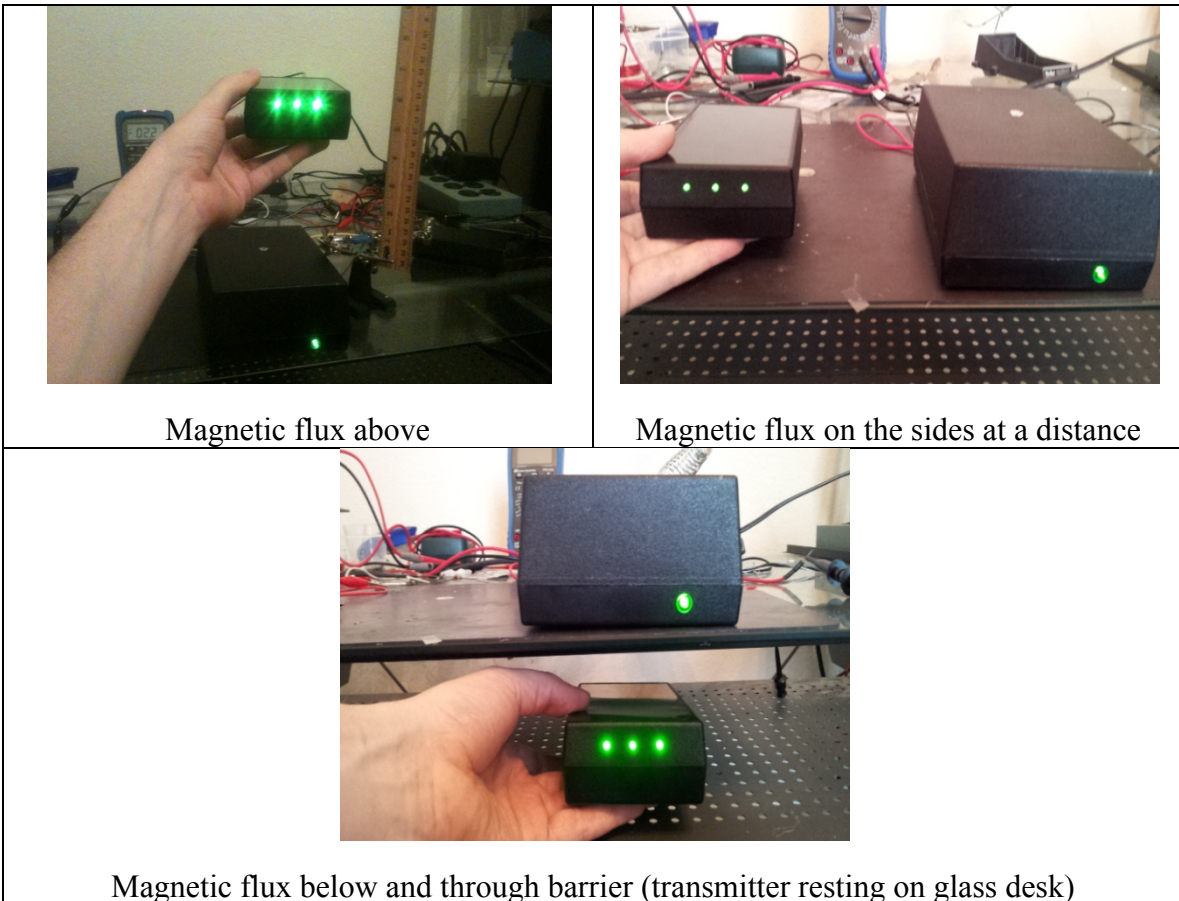
DEMONSTRATING RESONANT FREQUENCY

Using a small flat head screwdriver, students can adjust the internal frequency control resistor of the primary unit to see the effects of frequencies above and below that of the resonant frequency. Students can attach an oscilloscope to the ports on the rear of the primary case to see the various patterns in the waveform including erratic oscillations, stable harmonics and stable resonance.



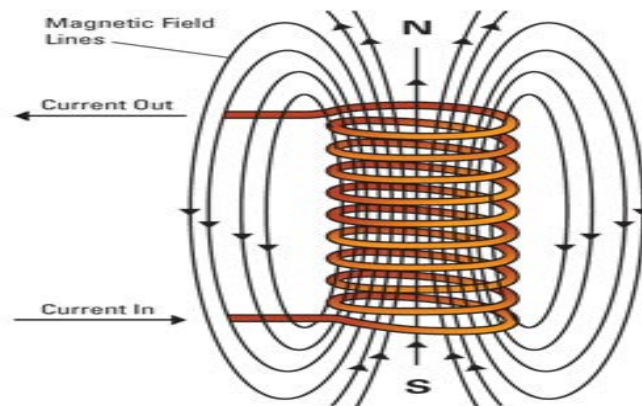
MAPPING THE MAGNETIC FLUX FIELD

The transmitter generates a directional magnetic field that is bound to regional field lines emanating in three dimensions from the primary coil. Students can take both quantitative voltage measurements or flip the load switch “on” and transpose brightness cues from the illuminated LED array to paper, in essence drawing a “map” of the flux field geometry and relative strength.



CRITICAL ANGLE OF POWER TRANSFER

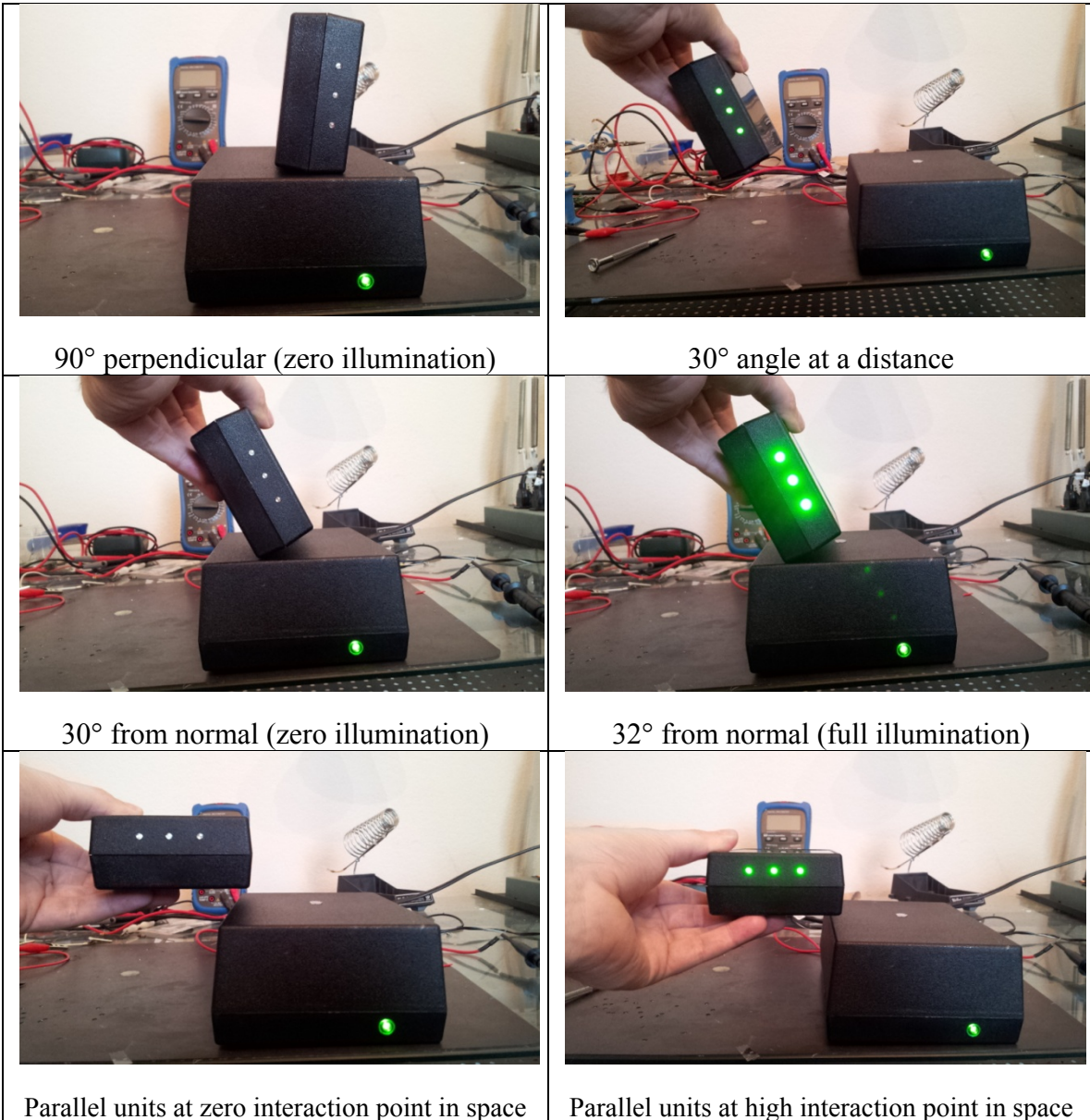
As current flows through a wire, the magnetic field is curved in a circular geometry at right angles to this flow. In the case of this device, a coil wound with many turns of individual strands of wire is used to create a time-varying magnetic field similar in geometry to a common permanent magnet. The shape of the field flux surrounding the transmitter is described as being “toroidal” whereby certain points in space around the coil have a higher density of flux lines and therefore are able to move more charge inside the receiver due to the fundamental effect of induction. Not only are the number of lines of flux per unit area critical to producing induction in the receiver, the orientation at which those flux lines interact with the receiver is also very important.



<http://thefutureofthings.com/news/5926/los-alamos-magnet-lab-explores-superconductivity.html>

Students can place the secondary receiver at various angles on, or near, the primary transmitter while making voltage or brightness measurements. The device is sensitive enough that in certain discrete points in space surrounding the transmitter extremely slight changes in the angle of orientation will reveal the flux to be highly

interactive or non-interactive such that full or zero illumination is observed. Students can effortlessly investigate maxima and minima of flux directionality and density as relates to the angle of orientation; thereby gaining a much more detailed picture of the invisible field they are working within.



SHIELDING CHALLENGE

Cell phones, car stereos, televisions and even Wi-Fi routers all have some sort of shielding material inside of them for various purposes of reinforcement or blocking of energy emanating and radiating from those devices in an effort to reduce or eliminate electromagnetic interference – sometimes even for human safety. Even though this beneficial component of electrical engineering has appeared silent yet diligent in nearly all electronic devices manufactured for the past 100 years, the topic of “shielding” is very rarely mentioned in a high school or college level introductory physics course.

The device allows students to experiment with various conductive and non-conductive shielding materials in an effort to reduce or completely block the transmission of power to the secondary receiver. The device can be used in a challenge whereby students design, build and test a shield that blocks most of the power using the lowest mass of shielding materials. In this challenge students are encouraged to research materials-cost so they learn that during the design process engineers must both achieve a primary functional goal while also taking into account the cost of materials.



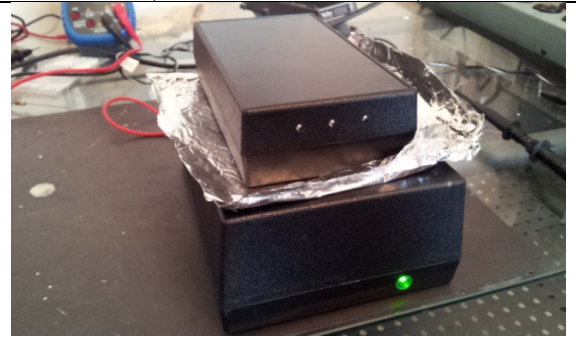
Three small foil pieces of similar diameter to the transmitter (good illumination)



One large diameter single sheet of foil (moderate illumination)



Two large diameter sheets of foil (dim illumination)



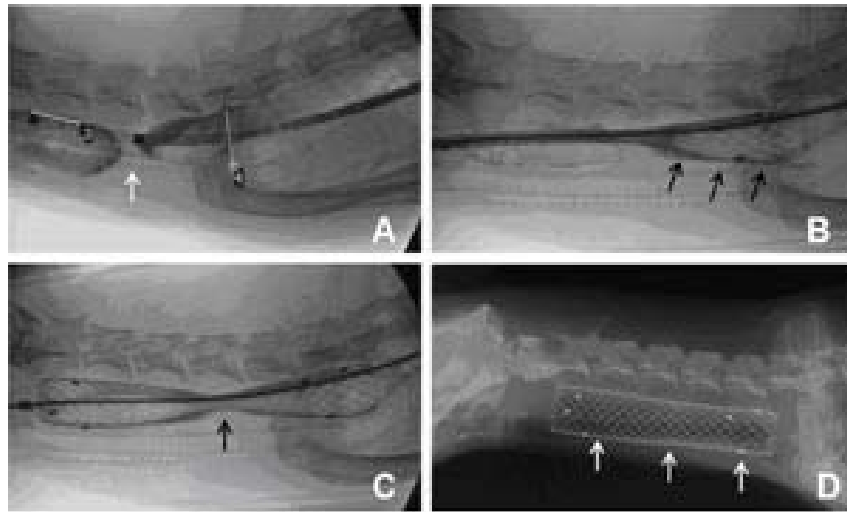
Three large diameter sheets of foil on contact (zero illumination)

BIOTECH CHALLENGE

Bionics is an exciting advancement in the medical industry where high tech hardware aids the human body internally or externally. Some of the earliest forms of bionic technology are found in pacemakers, cochlear hearing aids and electronic heart valves. Devices that require energy to send a signal, drive a motor, charge a battery or pull a muscle wire inside the body can all be integrated with a wireless power transfer source.

Nitinol wire is also an exciting modern advancement in metallurgy. Nitinol, just like any metal, is heat sensitive and conductive. When normal metal is heated it expands mostly in all dimensions. When Nitinol wire is heated its physical geometry changes by expanding only its diameter while contracting in length. Since the wire is incredibly thin, the growth in diameter is negligible; whereas the contraction in length is highly useful for flexing small objects. Nitinol can be heated by external temperature changes or by sending DC current through the wire itself.

In this challenge students will explore internal bionics by designing a flexible paper heart valve, a soda straw coronary stent or other paper muscle using Nitinol shape memory alloy wire in an effort to model real-world applications of subcutaneous wireless power transfer in medicine.



Palliative Stenting for Benign Stenoses, Penn Veterinary Medicine - Image B shows a “partial deployment of Nitinol stent” that could eventually be manipulated with the help of a wireless power source.

APPLICATIONS TO PRACTICE

DEVELOPING KNOWLEDGE FOR AND OF ENGINEERING TEACHING

My UTeach Engineering experience has been nothing less than a game-changer in my life both inside and outside the classroom. Three years later, I have been privileged to learn from amazing engineering professors and support staff. In my opinion it is the people of UTeach Engineering and their passion for educating others that has made the program so uplifting and effective. Since I feel I've been trained well in engineering fundamentals, I have the confidence necessary to bring engineering concepts into my classroom at any point in time. I feel confident nearly all traditional assignments can be modified to express one or more engineering concepts.

Since the first semester of the ESIT summer I have taken several traditional lessons and adjusted them give students many engineering opportunities. The UTeach Engineering methodology combined with the Legacy Cycle is both extremely portable in many ways - not just in content but also affordability. I have been using both of these for the past three years because they are so easy to inject into my existing physics curriculum. I feel that my students get the most out of being able to improve and retest a product they've developed as a group. Whether the product is a car bumper, rocket fin

or audio speaker design; students become naturally motivated when a challenge faces them regarding a product they built on their own.

DEVELOPING ENGINEERING HABITS OF MIND

My students over the past three years have become quite used to design projects that are combined with their lessons. I bring in design projects in an effort to add more relevance to what is normally considered dry algebra-based analysis of the laws of nature. I feel that planning with the end in mind to achieve learning by open-ended design is the best way to deliver engineering content.

I feel that the single biggest retained skill that my students have acquired is to slow down and analyze what is going on in the system rather than simply take data and turn it in. If a student has the habit of being able to critically think deeper than the surface of a system, I feel this will give them a better chance for success later on in life. As teachers we are charged with producing not just successful students, but productive citizens. I feel that engineering offers another way for students to develop an appreciation for product, process and social purpose.

DEVELOPING AN UNDERSTANDING OF THE DESIGN PROCESS

I have been creating small electronic gadgets for several years with no real intention other than the challenge of making a particular circuit work as intended. During those years I rarely documented anything, had no particular problem to attack; I simply dove into the process of building. After having gone through the MASEE program, I feel that I need to go back to all of those devices and give them a new look through the lens of engineering and improve them.

The construction of the wireless power transfer kit relied heavily on having the proper training and adequate time to invest in so many aspects of product development. I learned early on that the product I wanted to build would require consultation from my supervising professor as well as other people in industry. This is in total contrast to my former life spent isolating myself while building gadgets. It is priceless to discuss problems and successes with a wide variety of people. Without consulting others, I would have never discovered a relevant problem in the physics classroom. I know now that it can only serve to improve the final creation.

I learned that documenting even the slightest modification proved critical to solving problems later on in development. Admittedly I caught myself chasing my tail on two occasions due to inadequate documentation. Utilizing the engineering notebook as well as an enormous amount of circuit diagram and waveform photos was essential to

keeping track of small variations in the prototype. My documentation skills evolved as I found examples of good documentation in my search for similar projects. I tried to adhere to the well-written examples I found and applied certain elements to the goal of my own construction – for others to be able to recreate the device on their own with off-the-shelf parts.

By far the most important aspect I learned of engineering was that a product will always be in a state of beta. There is never a finished product; there is always room for improvement, innovation, new audiences, new materials and new opinions. I found myself adding new features as I moved from the high school to the college audience. The entire concept of hot swappable coils and capacitors was aided by the use of new plastic connector materials I had never worked with previously.

LITERATURE REVIEW

Faraday's discoveries of several fundamental electromagnetic phenomena are essential concepts that are taught in the high school and college physics classrooms throughout the world. Faraday's law of induction provides the basis for the electrified modern world. Modern students are exposed to a myriad of electronic devices - all rely on various applications of the law of induction. It would seem with so much exposure to devices that exploit this law, students would have total mastery of its paramount concept - moving charge in a conductor produces a magnetic field. On the contrary, this topic has traditionally eluded mastery of struggling students; even those in their first year of college physics.

The concept of Faraday's magnetic and electrostatic lines of force are a critical learning component that can easily be taught with the wireless power transfer kit; however challenges still exist and improvements in teaching methods can be made to enhance mastery in the topic at any level – even for teachers. An innovative technique detailed by Terhi Mäntylä called Didactical Reconstruction of Processes was applied to teaching the law of induction to pre-service Physics teachers because “it was important to select a topic with which students are known to struggle”. Using the DRP “students drew flow charts for representing how the law of electromagnetic induction is formed” (Mäntylä T. 2012).

Struggling physics students aren't just found in the high school setting. In a 2002 study of 39 first-year college engineering students, Pocovi and Finley demonstrate a "confusion between trajectory and lines of force" students manifest because they tend to believe "the lines of force are real entities or paths of transmission" (Pocovi M. Cecelia and Finley F., 2002). In this example qualitative misconceptions in the visual aid are to blame; quantitative calculations based on poor mastery of the law can also manifest at the college level.

Faraday's law of induction relies on 1) a constant flow of current through a conductor such as a DC source fed through a wire or 2) a current that is variable in time or direction such as that found in AC generators and motors. Motors and generators - two vital components of modern life - have motional emf; there is a force interaction when magnetic lines of force are crossed at certain orientations. In a study of 102 first-year engineering students and 36 third-year physics students the researchers state "interpreting Faraday's laws and its relationship with motional emf presents consistency challenges for teaching electromagnetic phenomena." They found that most textbooks gave students a limited scope of situations in which to quantitatively describe induction through a conductor in a magnetic field whereby one is moving relative to the other. When asked to explain situations which were out of this scope or to explain situations considered to be exceptions often the Lorentz force - where a point charge moving through a magnetic field experiences a force - and not Faraday's law of induction is chosen to find solutions to these problems. They proposed broadening the scope of

situations where motional emf is present – one of which was a Maglev train – to explain that “Faraday’s law is useful in any situation, as much as the Lorentz force strategy” (Zuza K., Guisasola J., Michelini M., Santi L., 2012).

Even though Faraday’s law of induction is taught in regular high school physics classes across the globe, misconceptions still occur at the college level among students that are majoring in engineering or physics. This speaks of a complex topic; one that is in need of more support to foster student mastery early on, perhaps even at the middle school level. The wireless power transfer kit combined with research-based learning successes can be used in numerous ways to challenge students of any level.

APPENDIX

BILL OF MATERIALS

Items sourced directly from Fry's, Home Depot and Radio Shack

ITEMS	QTY	Unit Cost	Total	ID
Primary Transmitter				
Timing Circuit				
471, 0.00047 uF ceramic capacitor	1	\$0.89	\$0.89	C1
Electrolytic capacitor 10 uF	1	\$0.89	\$0.89	C4
Electrolytic capacitor 100 uF	1	\$0.89	\$0.89	C5
7805 5vDC voltage regulator	1	\$3.00	\$3.00	U2
NTE 955 timer (or standard 555 timer)	1	\$3.00	\$3.00	U1
10k variable resistor, 3 pin, 28 turn, board mount	2	\$2.00	\$4.00	R1
NTE 403 metal heat sink set	2	\$3.00	\$6.00	
103, 0.01 uF ceramic capacitor	1	\$0.89	\$0.89	C2
Miscellaneous Power, Structure and Control Parts				
Electrolytic capacitor 470 uF	1	\$0.89	\$0.89	C6
Electrolytic capacitor .47 uF	1	\$0.89	\$0.89	C7
LED 2 - 3V	1	\$0.25	\$0.25	D1
1k resistor (for status LED)	1	\$0.25	\$0.25	R3
7812 12VDC voltage regulator (for fan)	1	\$0.25	\$0.25	U3
DPDT switch	1	\$2.00	\$2.00	
120VAC / 12V DC wall adapter	1	\$15.00	\$15.00	
2.1 mm DC barrel pin jack Size K	1	\$2.00	\$2.00	
2.1 mm DC power plug Size K	1	\$2.00	\$2.00	
Breadboard 6" x 2"	1	\$5.00	\$5.00	
Jumper wires, various sizes (depends on layout)	10	\$0.01	\$0.10	
Binding posts, insulated	2	\$2.00	\$4.00	
Serpac 173 Black kit box	1	\$11.99	\$11.99	

Sioux Chief brand 3" snap in PVC floor drain	1	\$3.00	\$3.00	
#10-32 Nylon screw	1	\$0.55	\$0.55	
#10-32 Nylon nut	1	\$0.62	\$0.62	
NTE 587 high speed switching diode 1A	2	\$2.00	\$4.00	D2
NTE 2390 (or comparable) power mosfet	1	\$3.99	\$3.99	M1
Pactech PA-4FANZ fan cooled heat sink	1	\$9.95	\$9.95	

Primary LC Coil Parts

#20 AWG vinyl insulated solid copper wire 1 LB	1	\$10.00	\$10.00	
103, 0.01 uF ceramic capacitor	1	\$0.89	\$0.89	C3
1 Ohm, 10 Watt ceramic resistor	1	\$2.00	\$2.00	R4
Link Depot 12" Fan power extension cable M-F	1	\$4.00	\$4.00	

Total: \$103.18

ITEMS	QTY	Unit Cost	Total	ID
Secondary Receiver Coil				
LC Coil Parts				
103, 0.01 uF mylar capacitor	1	\$0.89	\$0.89	C1
2" x 1-1/2" PVC bushing (large form) for coil	1	\$1.80	\$1.80	L1
#26 gauge magnet wire (one spool)	1	\$2.00	\$2.00	L1
AC to DC conversion				
Electrolytic capacitor 1 uF or 10 uF, for conditioning	1	\$0.89	\$0.89	C2
NTE 5332 Bridge rectifier, or similar diode configuration	1	\$1.59	\$1.59	D1-D4
8 pin socket mount for rectifier IC	1	\$1.99	\$1.99	

Miscellaneous Power, Structure and Control Parts				
LED 2 - 3V	3	\$0.25	\$0.75	D5,D6,D7
SPST switch	1	\$2.00	\$2.00	S1
Jumper wires, various sizes (depends on layout)	10	\$0.01	\$0.10	
Serpac a151i kit box 3"x5.5"x1.5"	1	\$9.00	\$9.00	
Binding posts, insulated	2	\$2.00	\$4.00	
Perfboard for receiver components	1	\$5.00	\$5.00	

Accessories for Experiments				
3/4" PVC elbow with threads	1	\$0.74	\$0.74	
2" x 3/4" PVC bushing with threads	1	\$1.99	\$1.99	
3/4" x 1/2" PVC bushing (small form)	1	\$0.44	\$0.44	
1-1/4" x 1" PVC bushing (medium form)	1	\$0.97	\$0.97	

Total: \$34.15

HELPFUL WEBSITES

These sites proved priceless in helping to construct, maintain and ideally teach others about wireless power transfer.

<http://forum.allaboutcircuits.com/>

<http://events.ccc.de/congress/2009/Fahrplan/events/3696.en.html>

<http://www.vk2zay.net/article/253>

<http://www.electronics-tutorials.ws/accircuits/parallel-resonance.html>

http://www.w0qe.com/Technical_Topics/inductor_Q_tests.html

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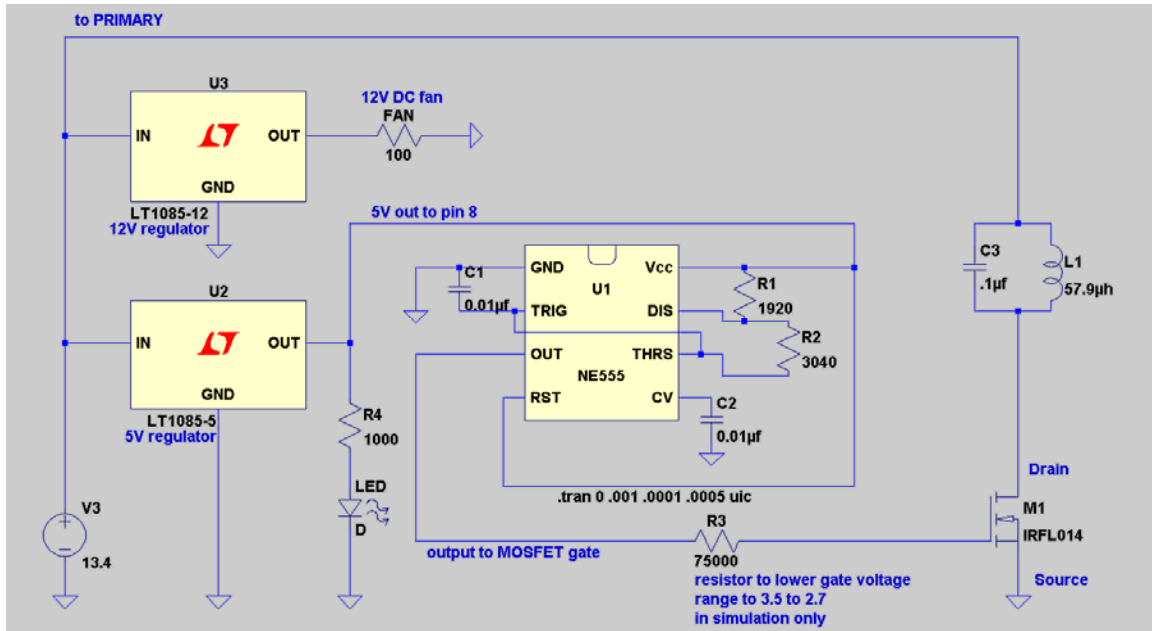
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<http://www.deephaven.co.uk/lc.html>

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CIRCUIT DIAGRAM - WPT PRIMARY 1.0

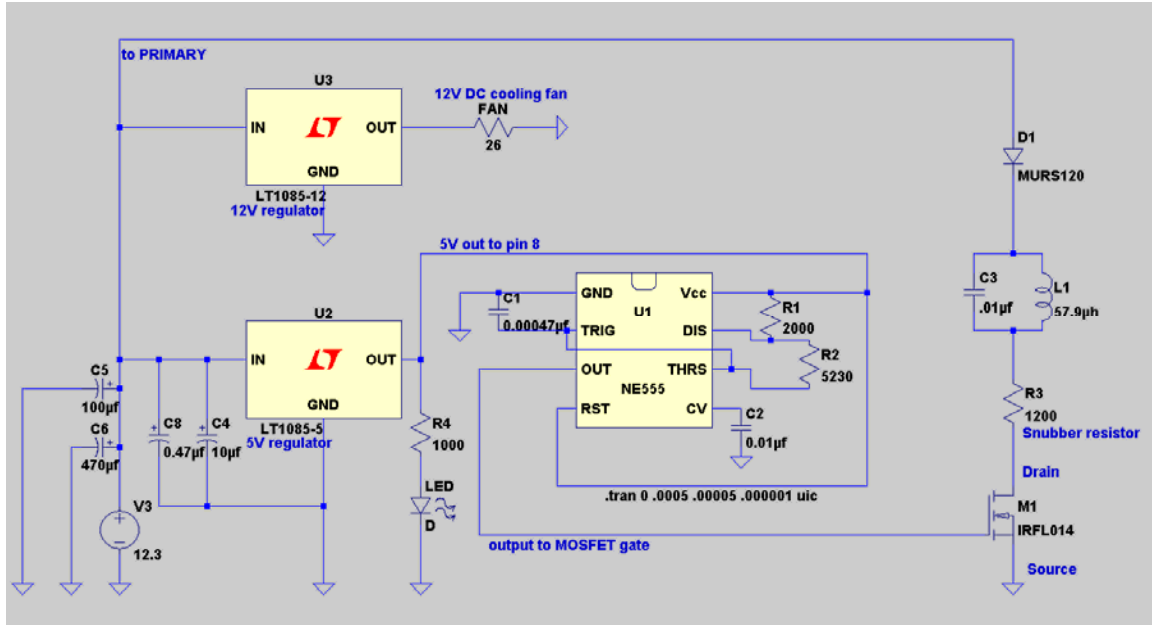


Above:

This circuit came from the alpha prototyping board on the electronics learning lab and went to the board of the actual primary unit itself.

<ul style="list-style-type: none"> • V3 – DC input voltage • S1 – Power switch • U1 – 555 timer • U2 – 5V regulator to 555 timer • U3 – 12V regulator to cooling fan • R1 – Threshold resistor • R2 – Discharge resistor 	<ul style="list-style-type: none"> • R3 – Resistor to lower gate voltage • R4 – Protection resistor for status LED • C1 – Timing capacitor • C2 – Discharge capacitor • C3 – LC capacitor • L1 – Primary inductor coil • M1 – Power MOSFET
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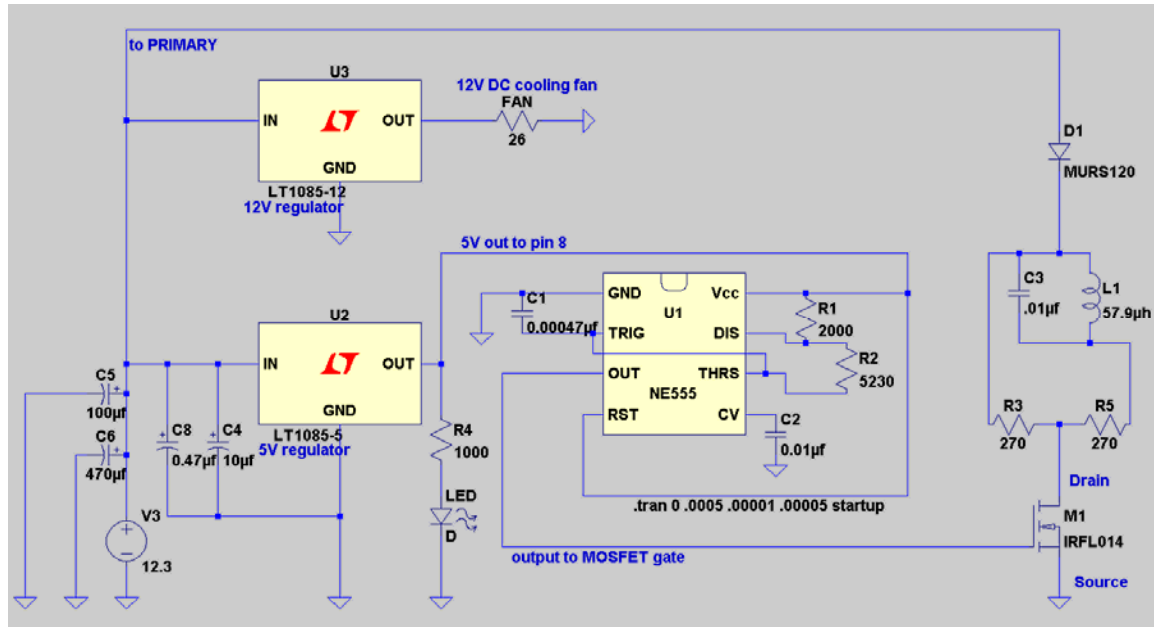
CIRCUIT DIAGRAM - WPT PRIMARY 1.2B



Above:

- Input voltage now 12.3 VDC.
- Added power conditioning capacitors (C4, C5, C6, C8) to high voltage rail as well as the 555 timer voltage regulator.
- Added protection diode from high voltage input to the LC section – D1.
- Changed the timing capacitor on the 555 timer section – C1.
- R3 is no longer the current limiting resistor to MOSFET gate.
- Added snubber resistor in series from MOSFET drain to LC section – R3.
- Adjusted threshold and discharge resistors on timer.

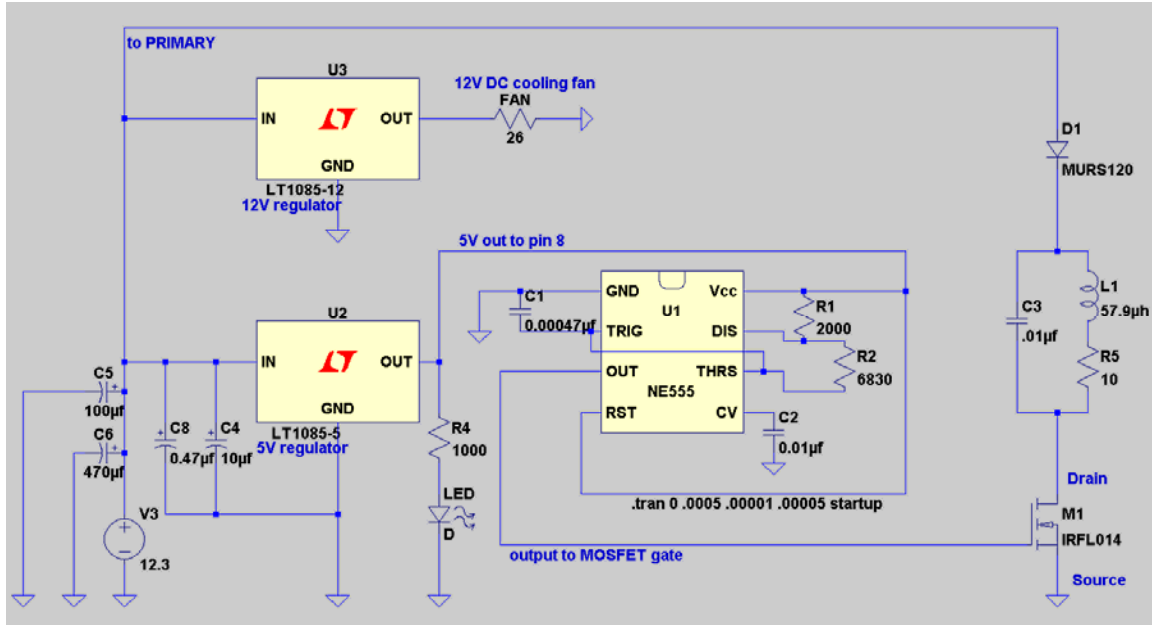
CIRCUIT DIAGRAM - WPT PRIMARY 3.0



Above:

- Snubber resistor was removed and is no longer R3.
- Added two 270 Ω resistors from the MOSFET drain in parallel to the capacitor and series to the inductor in the LC section – R3, R5.

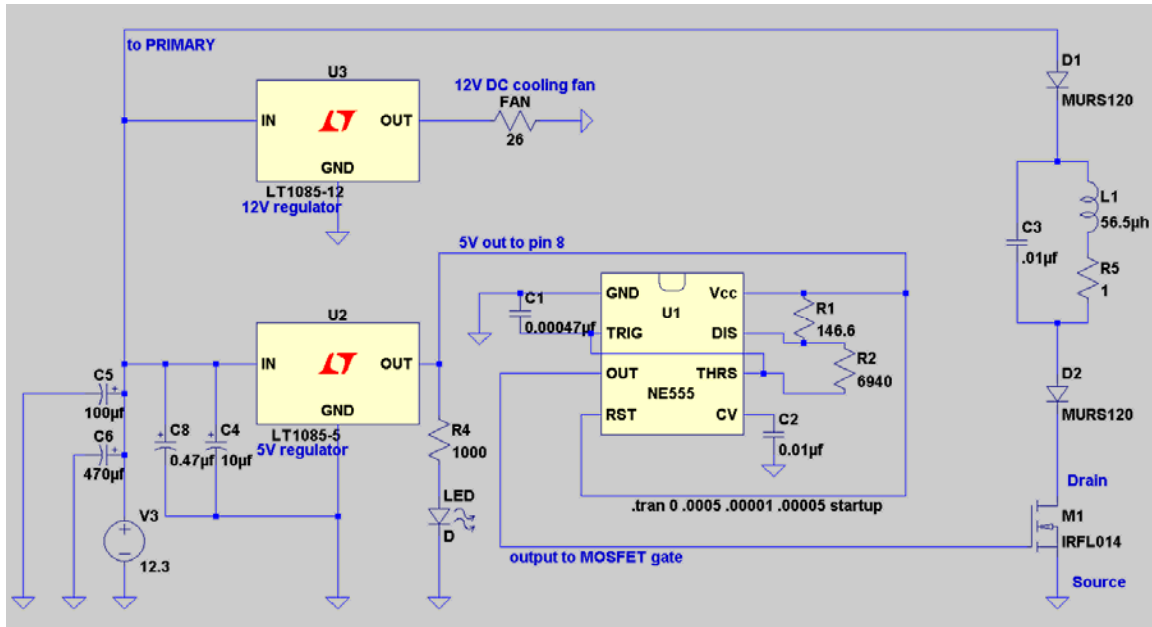
CIRCUIT DIAGRAM - WPT PRIMARY 3.0B



Above:

- Removed R3 and R5 from previous version.
- Revised the LC section to become an LCR circuit with a 10W 10 Ω resistor in series with the inductor coil – R5.

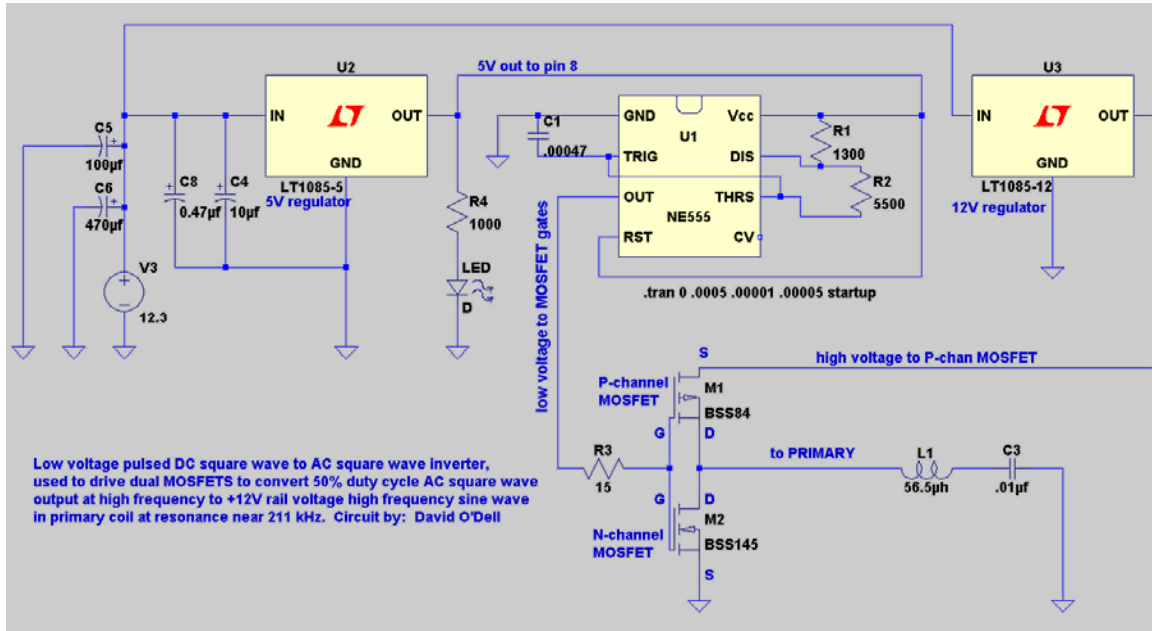
CIRCUIT DIAGRAM - WPT PRIMARY 5.0



Above:

- Resonant frequency = 211 kHz, however this is tuned to 159 kHz to match the resonant frequency of the Secondary version 1.2.
- Protection resistor for status LED is now R3.
- Changed the LCR section with a 10W 1 Ω resistor - R4.
- Adjusted threshold and discharge resistors on timer to meet the new timing requirements for resonance.

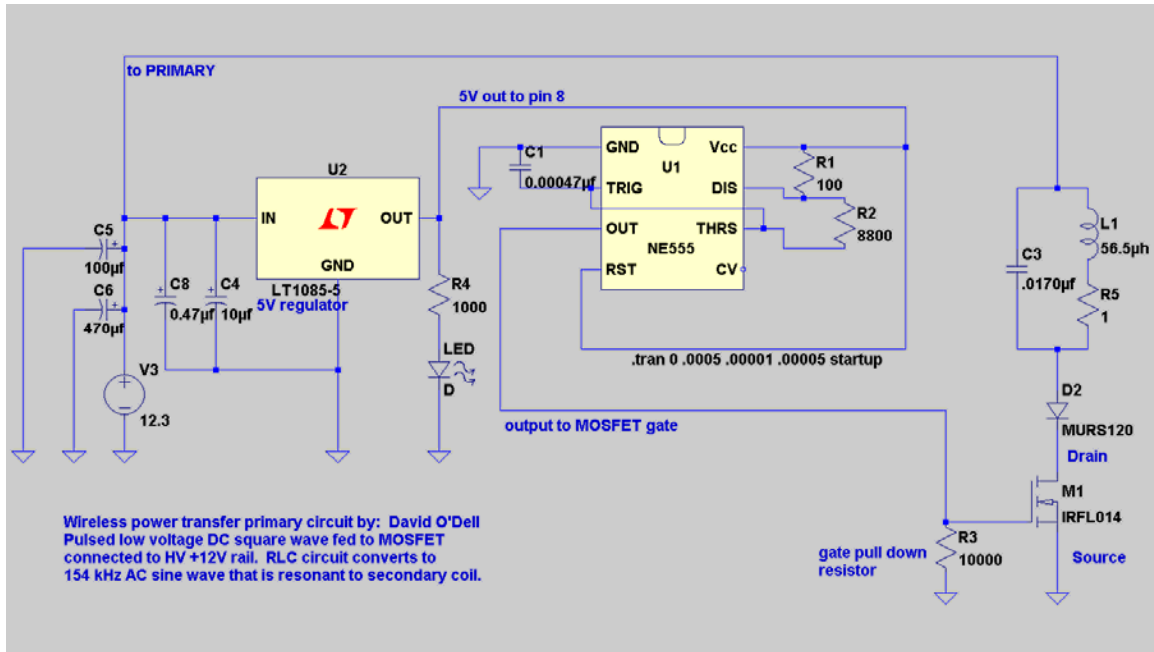
CIRCUIT DIAGRAM - WPT PRIMARY 6.0



Above:

An attempt to make an AC square wave inverter in order to feed oscillating current into the LC circuit. The circuit worked and both an AC square wave and an AC sine wave were created, however even at resonance the power dissipation was too great and very little power was transferred wirelessly. The decision was made to go back to the 5.0 circuit and improve upon it.

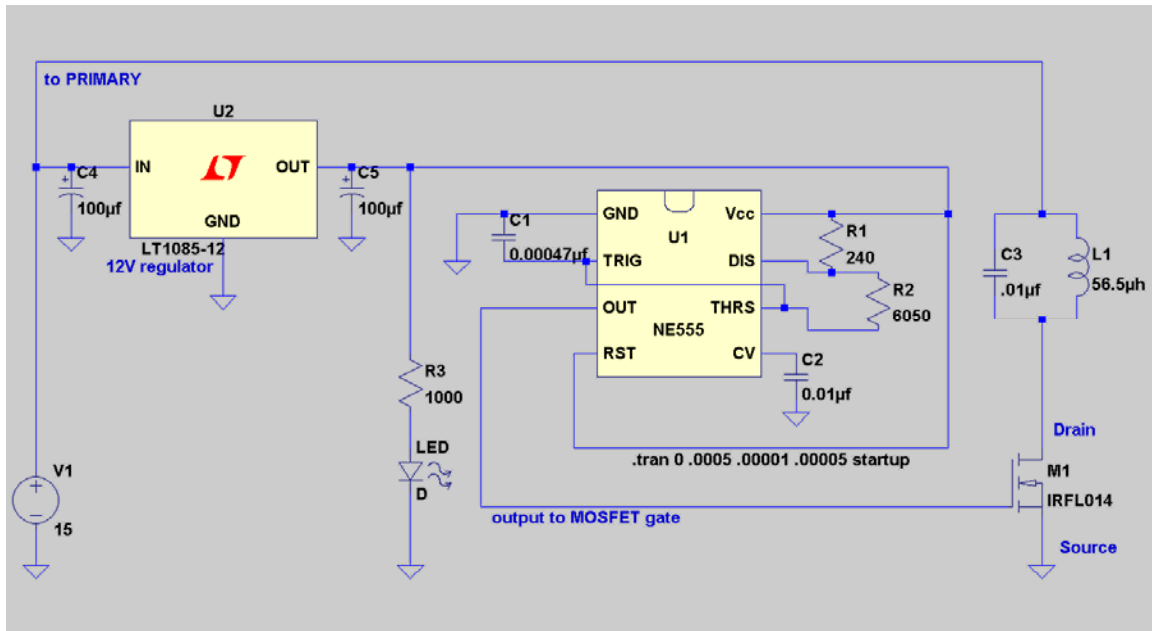
CIRCUIT DIAGRAM - WPT PRIMARY 7.0



Above:

- This circuit is very similar to the 5.0 circuit with only some fine tuning of the LC capacitor (L3) and the timing resistors (R1 & R2).
- The power supply protection diode was removed since this is constant 12 VDC output at resonance.

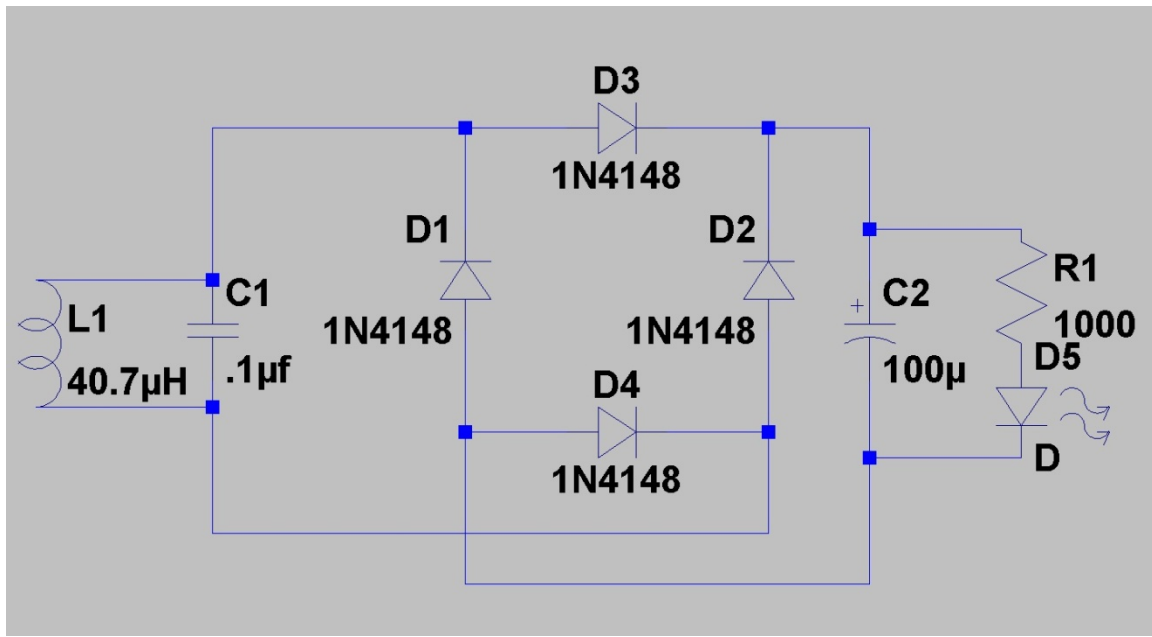
CIRCUIT DIAGRAM - WPT PRIMARY 8.0



Above:

- It was discovered that I had not been saturating the gate of the power MOSFET with enough voltage to fully activate it. This circuit is simplified to bare minimum components with the new power requirements.
- Since the gate is wide open with around 10V DC from the 555 timer, the cooling fan is not needed; the aluminum block heat sink is sufficient.
- The diodes surrounding the LC portion were also removed as they proved after all to have no purpose in the overall performance.

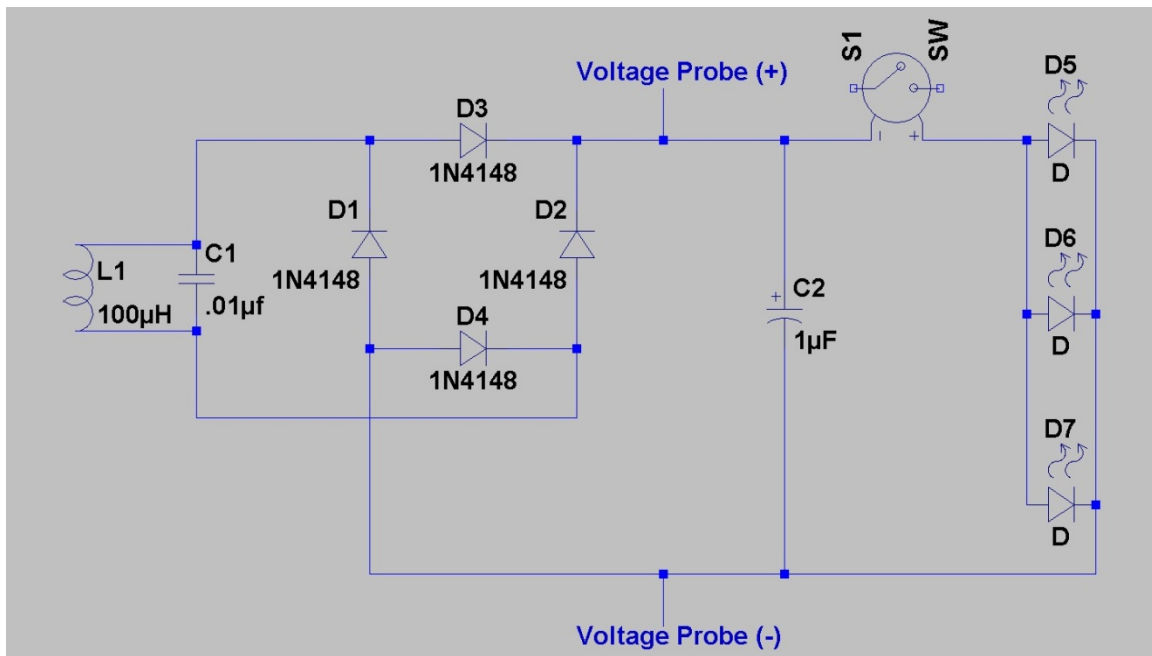
CIRCUIT DIAGRAM - WPT SECONDARY RECEIVER 1.0



Above:

- The original circuit for the secondary consisted of a receiver coil that would feed a bridge rectifier AC and output DC to power an LED.
- Resonant frequency = 78 kHz
- L1 - Inductor
- C1 - LC Capacitor
- D1 – D4, Rectifier diodes
- C2 - Smoothing capacitor
- R1 - Protection resistor
- D5 - LED diode

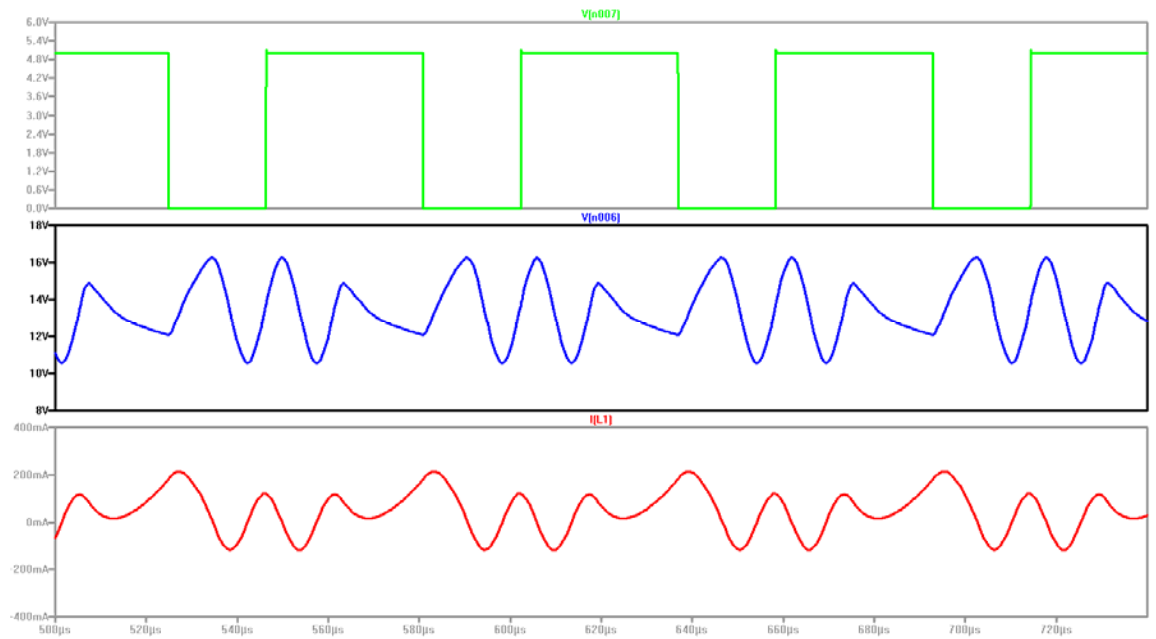
CIRCUIT DIAGRAM - WPT SECONDARY RECEIVER 1.2



Above:

- Calculated resonant frequency = 159 kHz, actual best brightness around 154 kHz.
- Added voltage probe ports.
- Added load switch.
- Added tri-LED array.
- Changed smoothing capacitor - C2.
- Changed LC capacitor - C1.

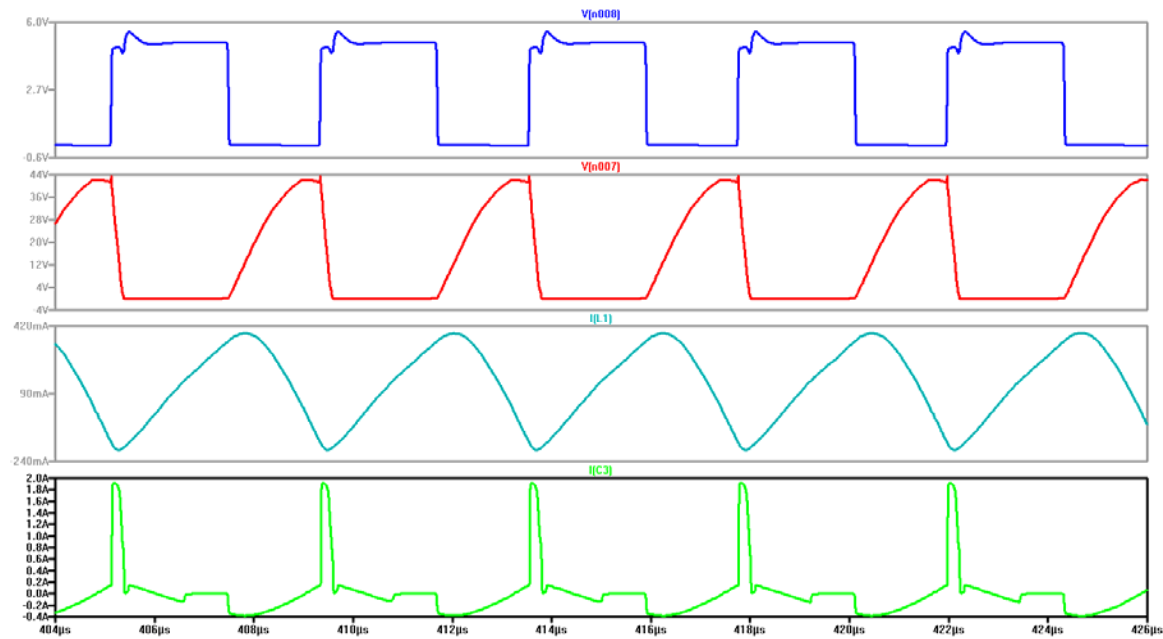
SIMULATION TRACES - WPT PRIMARY ALPHA 1.0



From top to bottom.

- Trace 1 shows the voltage output of the 555 timer pin 3.
- Trace 2 shows the voltage from the drain of the MOSFET to the LC section.
- Trace 3 shows the AC current through the inductor.

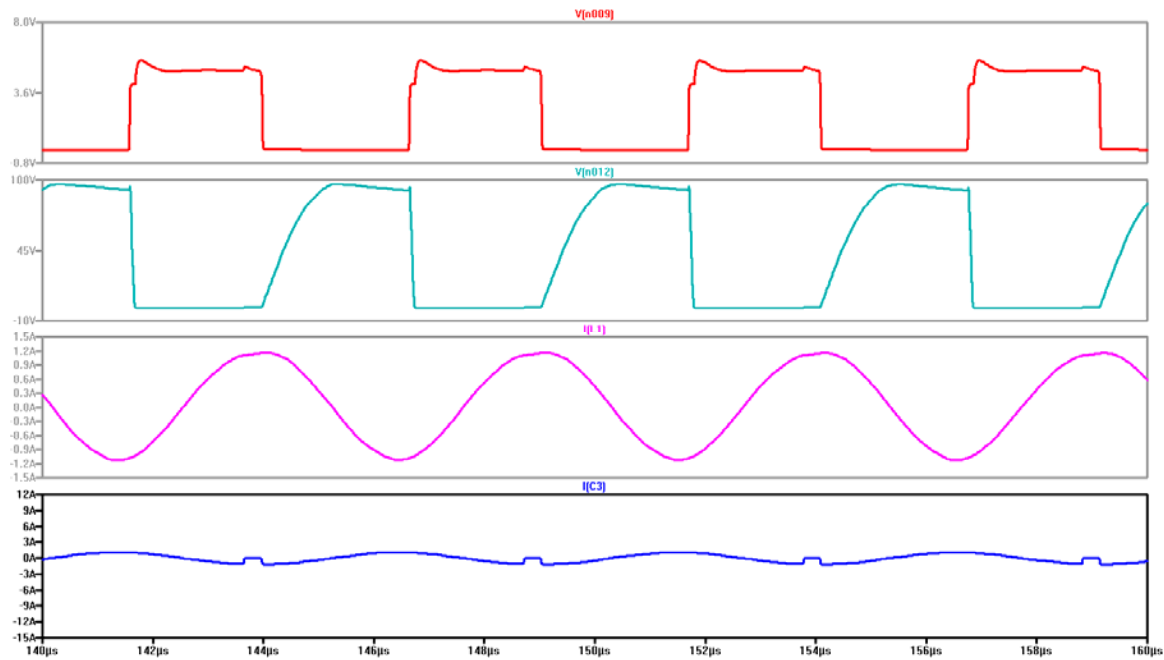
SIMULATION TRACES - WPT PRIMARY BETA 1.1



From top to bottom:

- Trace 1 shows the voltage output of the 555 timer pin 3.
- Trace 2 shows the voltage from the drain of the MOSFET to the LC section.
- Trace 3 shows the AC current through the inductor.
- Trace 4 shows the current through the LC capacitor.

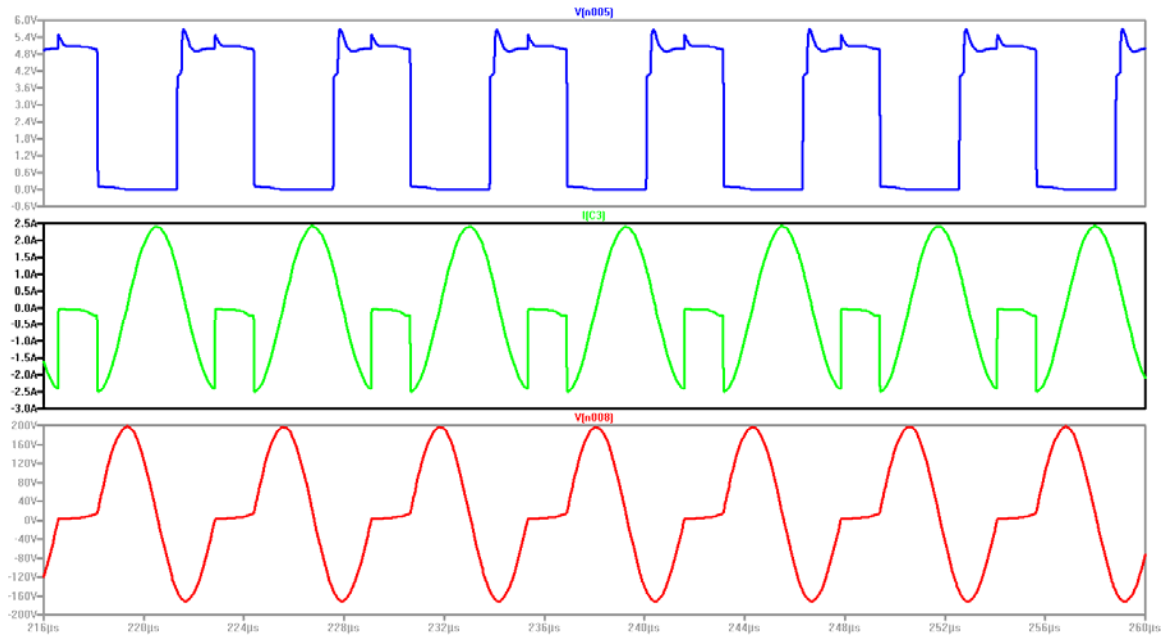
SIMULATION TRACES - WPT PRIMARY BETA 5



From top to bottom:

- Trace 1 shows the voltage output of the 555 timer pin 3.
- Trace 2 shows the voltage from the drain of the MOSFET to the LC section.
- Trace 3 shows the much improved AC current through the inductor due to the LCR configuration.
- Trace 4 shows the current through the LC capacitor with what looks to be the cause of the “shelf” problem I’ve been experiencing with the actual circuit.

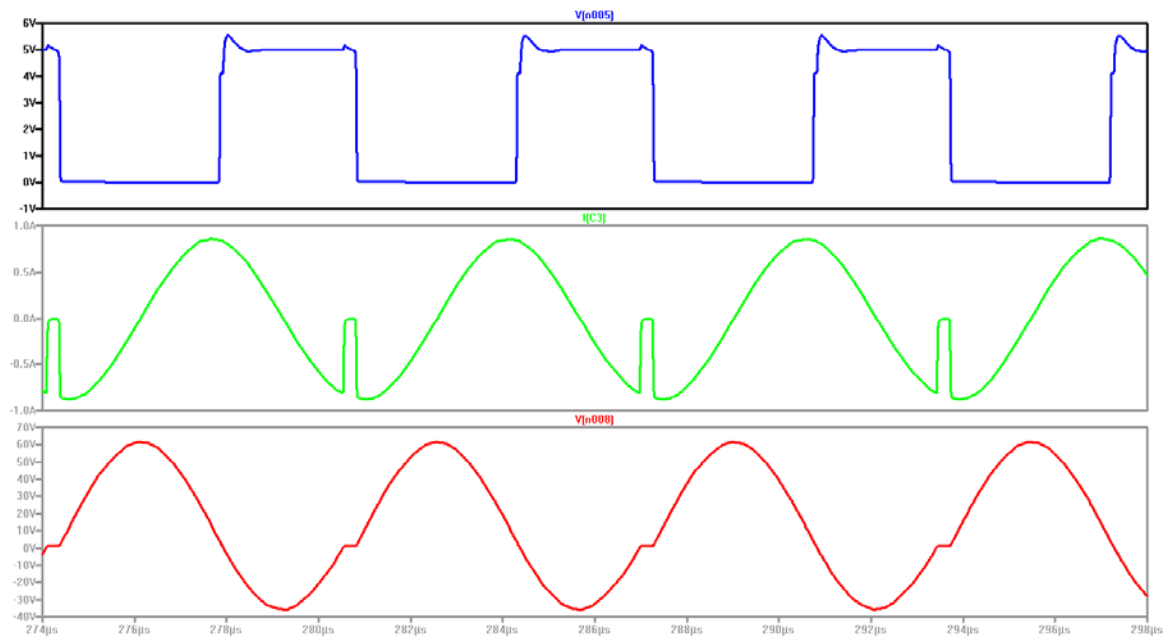
SIMULATION TRACES - WPT PRIMARY BETA 7



From top to bottom:

- Trace 1 shows the voltage output of the 555 timer pin 3.
- Trace 2 shows the current oscillating inside the LC capacitor (0.01 uF)
- Trace 3 shows the voltage across the LC circuit and the characteristic “shelf” that is nearly identical to actual, and is what is trying to be improved. Ideally this is a sine wave.

SIMULATION TRACES - WPT PRIMARY BETA 7.1



From top to bottom:

- Trace 1 shows the voltage output of the 555 timer pin 3.
- Trace 2 shows the current oscillating at 153 kHz inside the adjusted LC capacitor (0.0170 uF) and resistances changed on the timer to $R1 = 100$, $R2 = 8800$.
- Trace 3 shows the voltage across the LC circuit with the simulated shelf partially corrected.

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