ECE 445

Gentle Giant: A Power-Factor-Corrected Musical Tesla Coil

Design Document

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Introduction

Tesla coils are impressive visual and auditory devices; some can create a surprising range of sounds using arc discharges, and thus have found uses as display pieces in entertainment and STEM education. A particularly large one is permanently mounted to a ceiling inside the Museum of Science and Industry in Chicago. However, for the majority of their existence, they have been crude instruments. Their design and operation typically results in a suboptimal use of AC power, also known as a poor power factor, and even with the advent of "solid-state" Tesla coils (SSTCs) that use power semiconductors, the situation has not improved. Areas with lower-voltage mains like the United States are often at a disadvantage due to details in many of these implementations. Further, when scaling up to large Tesla coils for use in performances, they can place significant strain on electrical grids and suppliers. Addressing these challenges could enhance the efficiency and portability of all Tesla coils, making them more practical for a wider range of applications.

Solution

We aim to build, for a comparatively low cost, a Dual-Resonance Solid State Tesla Coil (DRSSTC) with an active Power Factor Correction (PFC) front end. The combination of these two systems, the latter of which has never been done before on a Tesla coil, puts our design at the very forefront of Tesla coil power electronics technology, and solves several technical issues with other modern designs.

Tesla coils are effectively giant transformers, with a secondary winding that has many times more turns than the primary. Conventional SSTCs operate by first rectifying mains AC to a high-voltage DC, then using a half-bridge or full-bridge of power semiconductors to switch the primary of the Tesla coil. This results in a very large voltage being generated in the secondary, which causes it to release arc discharges. A major benefit that DRSSTCs like ours bring over SSTCs is that it operates more like a resonant converter. In the design phase of the transformer, the primary and secondary must be tuned to have close LC resonant frequencies. During operation, feedback from the primary is used to switch it at its resonant frequency, which results in more energy being built up in the system and more impressive arc discharges. This energy buildup must be stopped intermittently by an external PWM signal called an interrupter (which can simultaneously be used to modulate musical sounds into the arc discharges). The primary feedback also enables zero-current switching (ZCS), reducing thermal losses in the power stage to near zero.

We choose to improve even further by designing a digitally controlled boost-type active PFC to create the high-voltage DC rail. This brings with it several benefits of its own, like improving system power factor and making the system agnostic to mains voltage and frequency. With a higher power factor, larger arcs can be generated for the same apparent power, or arcs of the same size can be generated for less apparent power. This is a great all-around benefit for Tesla coil efficiency and viability at large scale.

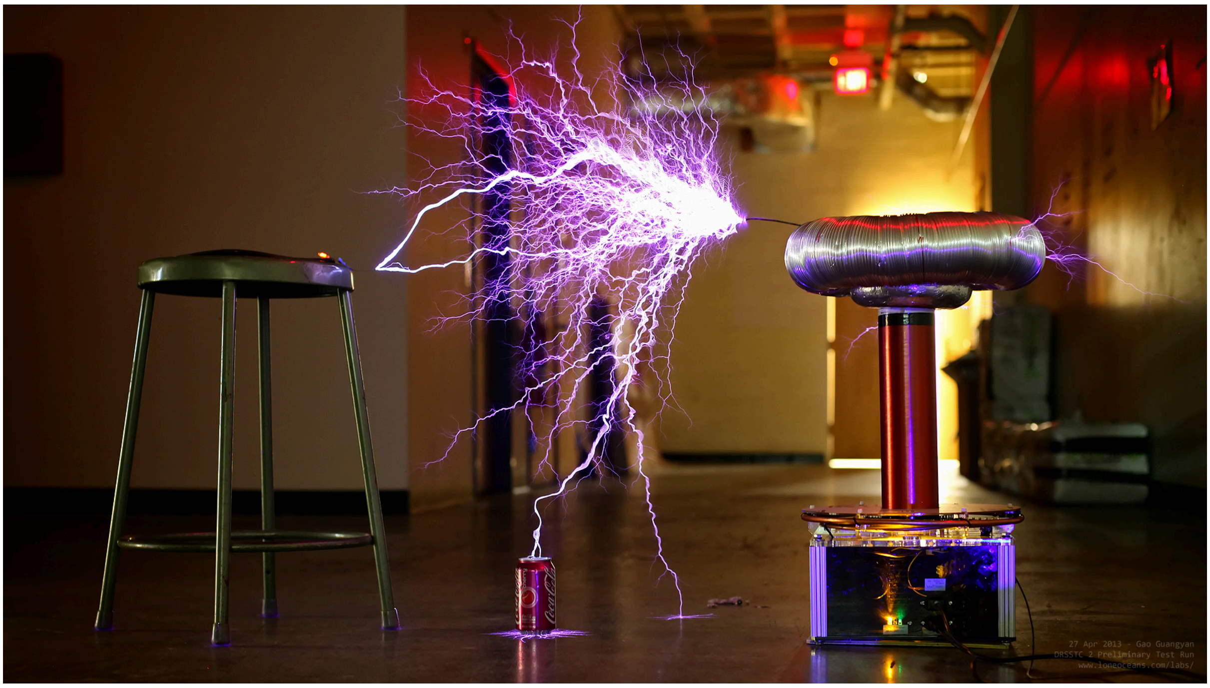


Photo courtesy of Gao Guangyan.

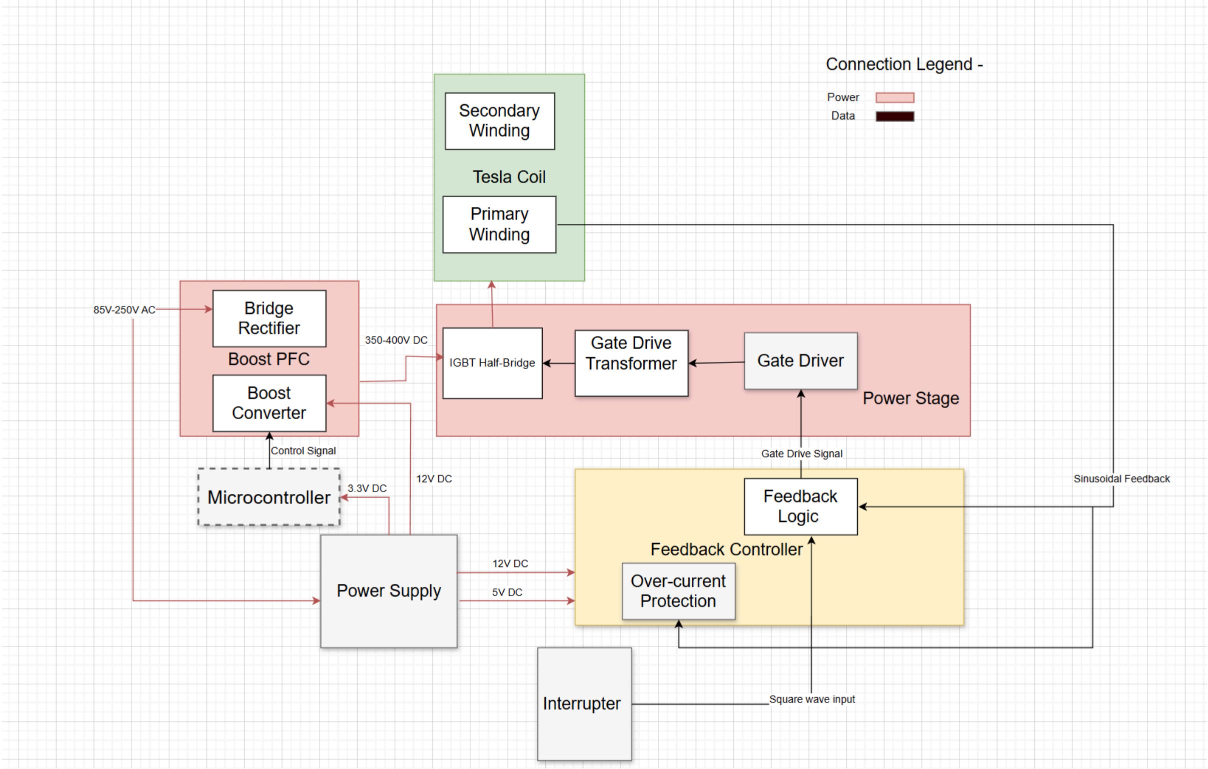
As our main focus will be the boost PFC used in the Tesla coil, users will not immediately see any visual differences from other Tesla coils. However, a measurable metric can be provided in the form of the device's power factor and power consumption.

Project–level Requirements

- The measured power factor has to be above or equal to 0.95 when operating at the US mains level of 120VAC.
- Arc discharge length has to be at least 1 foot, to demonstrate working of the Tesla coil.
- The apparent power drawn during operation should be no more than 1000VA.

Design

Block Diagram



Feedback controller

Subsystem Requirements	Verification requirements and method
Electrical Isolation: The interrupter signal receiver must provide complete electrical isolation between the interrupter device and the Tesla coil. An Industrial Fiber Optics IF-D95T fiber optic receiver is used for this purpose.	No measurable conduction (0 Ω) between the interrupter device and the Tesla coil, verified using a multimeter.
Total propagation delay: The feedback logic must be fast enough to ensure a zero-crossing detection propagates quickly enough to the power stage drivers for it to	Total propagation delay must be less than 2 μs to ensure proper synchronization with the Tesla coil's resonant frequency.

be effective. This is primarily down to the comparators and logic chips.	
Zero-Crossing Detection: The feedback controller must accurately detect zero-crossing events to ensure smooth operation of the Tesla coil. A ferrite core current transformer provides the feedback itself.	Zero-crossing detection accuracy must be within ±2 μs.

This subsystem implements a simple ZCS feedback controller using comparators and digital logic chips, and utilizes a long cable to safely and remotely play simple musical notes via PWM (this is the interruptor signal). There must be absolutely no conduction measurable with a multimeter between the interrupter device and the Tesla coil. Thus, the interrupter signal receiver we use will be an Industrial Fiber Optics IF-D95T, which is an inexpensive fiber optic device that has been highly proven in Tesla coil design history. Though in theory the microcontroller could also perform the logic task, we felt that it would not have low enough latency. The feedback itself is provided by a current transformer made of a ferrite core, which feeds into a burden resistor. A second current transformer's output is used to calculate an average current, which is then used for overcurrent protection (OCP. Texas Instruments LM311 comparators perform the zero crossing detection and 74HCT logic chips manipulate the signal, combine it with the interruptor signal, and create gate drive waveforms for the power stage.

Power stage

Subsystem Requirements	Verification requirements and method
Voltage Handling: The IGBT half-bridge must withstand a minimum input voltage of 400 VDC (the expected maximum output of the PFC) with sufficient headroom.	We will probe the HV bus with a multimeter during a low-power operation mode. Additionally, we have picked IGBTs that can handle a maximum voltage of 650 VDC (as per the FGA60N65SMD datasheet).
Switching Frequency: The IGBTs must operate at a minimum switching frequency of 300 kHz without excessive switching losses.	Quantitative: Turn-on time (t_on) and turn-off time (t_off) must be less than 200 ns each.

Gate Drive: The gate drive transformer (GDT) must provide sufficient drive signals to the IGBTs	Measured gate drive voltage must be between 15 V and 20 V, with a rise time of less than 100 ns.

The power stage simply consists of a half-bridge of two power semiconductors to which the primary LC is connected. The switches are driven by a gate drive transformer (GDT) to save cost and complexity versus developing a solution with isolated gate drive ICs. GDTs have been by far the leading solution to drive SSTC power semiconductors, and there is little incentive to do otherwise. Its gate drive signals are provided by the feedback logic, and it should drive the primary at its resonant frequency. In order to achieve smooth operation with the PFC and Tesla coil, the IGBT half-bridge must withstand at least a 400 VDC voltage input with headroom to spare, and the IGBTs must have a t_{on} and t_{off} low enough to operate at a minimum of 300kHz without excessive switching loss. We choose to use 60N65 IGBTs, and a UCC27423 to drive the GDT which then drives the half-bridge.

Transformer/Tesla coil

Subsystem Requirements	Verification requirements and method
Capacitor Protection: Capacitors should not be destroyed under normal operating conditions.	The capacitors should be visually observed to not have failed.
Coupling Coefficient: The coupling coefficient between the primary and secondary windings must be kept low (< 0.3) to ensure a slow and safe ramp-up.	This can be verified by putting the physical dimensions of the transformer into JavaTC and checking the coupling coefficient.
Resonant Frequency: We should be able to adjust the resonant frequency of the primary without issue by adding or removing windings from the primary.	Using the stated adjustment method, we should be able to measure a change in the primary's resonant frequency. This can be done by observing its reaction to a sinusoid sweep from a waveform generator through an oscilloscope, with the waveform pictures put in the lab notebook for reference.

This is the Tesla coil itself; electrically, it is an air-core transformer. It will stand at around three feet tall once completed, and we estimate that the frequency will be around 200kHz. It has no electronic components, but its physical design places some constraints on the power stage and boost PFC. The physical placement and shape of the windings determines the coupling coefficient, which must be kept low (below 0.3) for a slow ramp-up. A coupling coefficient that is too high can result in real damage to the Tesla coil by causing a phenomenon called “racing sparks”, where the voltage induced in the secondary is so high that it destroys the enamel coating of the wire and arcs begin to jump between adjacent windings. Also, calculating the stray capacitances in both the primary and secondary is necessary to keep the real resonant frequencies close. The math behind this is rather indeterminate due to how the plasma in the arcs affects the secondary’s capacitance, so it is difficult to come up with strict requirements or formulas for this subsystem, but we will be using a popular community tool called JavaTC to help us meet commonly accepted specifications.

Boost PFC stage

Subsystem Requirements	Verification requirements and method
Output Voltage: The PFC stage must output a DC voltage between 350 V and 400 V for the power stage.	Output voltage must be regulated within ±5 V of the target voltage at steady state as monitored by our STM32F103 microcontroller.
Switching Frequency: The boost converter must operate at a switching frequency of roughly 100 kHz.	Switching frequency must be accurate within ±1 kHz of the target frequency as verified by an oscilloscope.
The gate driver must provide sufficient drive signals to the IGBT in the boost converter.	Measured gate rise time must be less than 100 ns, as measured by an oscilloscope.

The PFC stage will ideally output between 350-400 V DC for use in the power stage’s DC rail. It is digitally controlled using an STM32F103 microcontroller, which allows it to compensate for different mains voltages and frequencies.

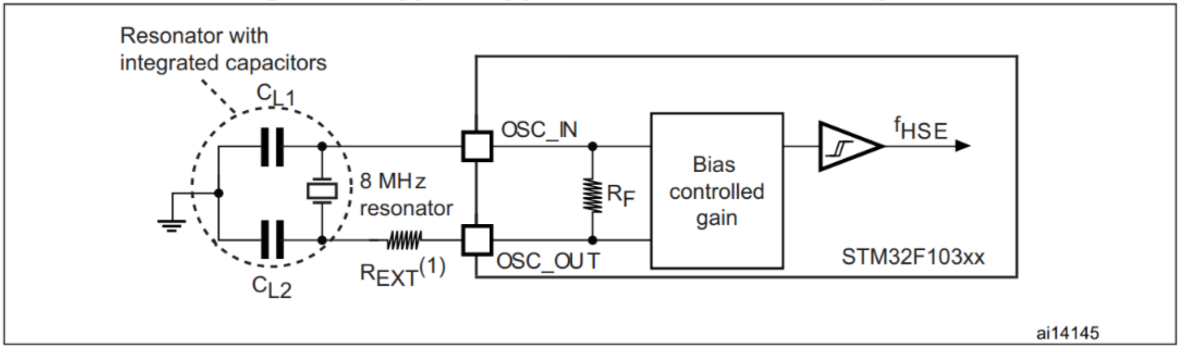
This subsystem consists of a bridge rectifier and a boost converter structure (which can be further broken down into an input inductance, an output capacitance, a FET and a diode). Specifically, we plan to use a Diodes Incorporated GBJ bridge rectifier, the same 60N65 IGBT as the power stage, and an STMicroelectronics STPSC12065D SiC diode. A Texas Instruments UCC5710x gate driver powered from the 12V supply can be used to allow the STM32F103 to drive the FET, and it must be able to operate at a switching frequency of 100kHz.

Tolerance Analysis

Programming the embedded microcontroller to perform the PFC is one of the main challenges we expect to face, as digital power is a relatively new technology. We plan on getting started early to familiarize ourselves with the microcontroller’s functions, and building a small-scale test bed to experiment with lower voltages.

We start by ensuring that the STM32F103 microcontroller has an accurate and consistent clock source; this is critical both for proper code execution, accurate interrupt timing and PWM frequency. This means utilizing an external clock source, known on the STM32 platform specifically as the HSE (High Speed External). We chose to use the CTS ATS080B-E 8MHz crystal, a common and highly performant crystal, along with several passive components. We then followed the STM32F103 datasheet and the AN2867 application note to pick the rest of the component.

Figure 24. Typical application with an 8 MHz crystal



A crystal needs several components to function properly: a load capacitance on each leg, here C_L1 and C_L2, an external resistance R_ext, and a feedback resistance R_F. On the STM32F103, R_F is already chosen for us: a typical value of 200kΩ is internal to the microcontroller. This is slightly too strong according to the app note, which recommends a range of 1-5MΩ for a 10MHz crystal, but there is not much we can do about it, and its role is more related to the oscillator than the crystal itself.

C_L1 and C_L2 are commonly set to be of equal value, and there is no reason for us to deviate from this, so we will refer only to C_L1 from here on out. According to the crystal’s datasheet, it has an internal load capacitance C_L = 18pF, a shunt capacitance C_0 = 7pF, and an ESR of 60Ω. Substituting C_L1 = C_L2 into formula 3.3 from the app note gives us a formula to find C_L1:

$$C_L = \frac{C_{L1}}{2} + C_S$$

Substituting in our value for C_L and assuming the stray capacitance C_S = 5pF gives us C_L1 = C_L2 = 26pF. We then verify this against the gain margin formula in section 3.4:

$$g_{mcrit} = 4 * ESR * (2\pi F)^2 * (C_0 + C_L)^2$$

We get a g_mcrit = 0.379 mA/V. The g_m specified in the STM32F103 datasheet is 25 mA/V, and dividing g_m by g_mcrit gives us about 66. The application note specifies that the ratio must be at least 5, so we know the crystal will oscillate properly.

The external resistor is chosen by

$$R_{ext} = \frac{1}{2\pi F C_{L1}},$$

and we get a recommended value of R_ext = 765 ohms.

Labor Breakdown and Cost Analysis -

Part	Quantity	Part link	Cost
P-N combo for GDT drive	2	https://www.digikey.com/en/products/detail/vishay-siliconix/SQJ560EP-T1-GE3/9462337	$4.06
560μF Bulk Capacitor for DC rail	1	https://www.digikey.com/en/products/detail/panasonic-electronic-components/EET-UQ2G561EA/483502	$4.16
Film Decoupling Capacitor for DC rail	3	https://www.digikey.com/en/products/detail/wima/MKP4J041006D00KSSD/9370504	$9.03
Ferrite cores for CTs and GDT	5	https://www.digikey.com/en/products/detail/epcos-tdk-electronics/B64290L0674X830/1830199	$26.65
Schottky diodes	10	https://www.digikey.com/en/products/detail/stmicroelectronics/1N5819RL/1037327	$1.69
GDT gate driver	1	https://www.digikey.com/en/products/detail/texas-instruments/UCC27423P/603260	$1.21
Fiber transmitter for interrupter	1	https://www.digikey.com/en/products/detail/industrial-fiber-optics/IF-E96E/3461614	$6.66
Fiber receiver for interrupter	1	https://www.digikey.com/en/products/detail/industrial-fiber-optics/IF-D95T/243780	$8.91
Plastic optic fiber for interrupter	5 meters	https://www.digikey.com/en/products/detail/industrial-fiber-optics/GH4001/22535727	$8.34

IGBTs for power stage and PFC	3	https://www.digikey.com/en/products/detail/onsemi/FGA60N65SMD/3137189	$19.62
SiC Schottky for PFC	1	https://www.digikey.com/en/products/detail/stmicroelectronics/STPSC12065DY/6051095	$4.29
Bridge rectifier for PFC	1	https://www.digikey.com/en/products/detail/diodes-incorporated/GBJ2006-F/815150	$2.76
Gate driver for PFC switch	1	https://www.digikey.com/en/products/detail/microchip-technology/MCP1407-E-P/1228640	$1.25
74HCT flip-flop	1	https://www.digikey.com/en/products/detail/texas-instruments/SN74HCT74N/277271	$0.61
74HCT AND gate	1	https://www.digikey.com/en/products/detail/texas-instruments/SN74HCT08N/277252	$0.64
Schmitt-trigger inverter	1	https://www.digikey.com/en/products/detail/texas-instruments/SN74HCT14N/376852	$0.66
LM311 comparator for OCP	1	https://www.digikey.com/en/products/detail/texas-instruments/LM311P/277038	$0.41
Differential comparator for feedback	1	https://www.mouser.com/ProductDetail/Texas-Instruments/TL3116IDR?qs=odmYgEirbwwN4qt6U49uyg%3D%3D	$3.46
HSE crystal	1	https://www.digikey.com/en/products/detail/cts-frequency-controls/ATS080B-E/2292902	$0.21
STM32F103C8 Microcontroller		https://www.digikey.com/en/products/detail/stmicroelectronics/STM32F103C8T6TR/2122442	$6.08

With each person putting in about 17-18 hours of work in a week - amounting to about 175 hours per person throughout the project - we expect our team to have the following distribution of hours across the project -

	Ali	Kartik
Circuit Design and debug	100	80
Microcontroller Setup, Interfacing and Debugging	65	80
Documentation and Writing	10	15

Setting the average wage to 35$/hr over a 2.5-month period, we obtain our cost of labor -

Wage	Total Labor Hours (monthly)	Labor Cost
35$/hr	140	$12,250

And given the cost of parts and labor, the total cost for our project comes out at **$12,360.70**.

Our team's tentative schedule is as follows

Week n#	Task	Team Member Roles
8(3/10)	Breadboard Demo, Send Finalized heatsink design to machine shop and work on board design	Whole team will demo the breadboard, Kartik on board design and Ali working on linking the STM32F103 microcontroller to the Boost PFC. Team works to tackle any safety issues with the board
9(3/17)	Spend time reviewing board design, tesla coil assembly	Ali reviewing board design, Kartik ordering selected components. Test and verify every subsystem of current design before porting to SMD.
10(3/24)	Finish working iteration of the tesla coil for testing, along with board design.	Team begins setting up a testbench for the tesla coil, Kartik programming the STM32 and Ali finishing the circuit layout.
11(3/31)	Individual progress reports,	Team solders SMD layout,

	test first version of the final layout. Finish setting up testbench and STM32 for the PFC..	start testing and debugging the entire circuit. Sort out faulty parts.
12(4/7)	PCB revision (if required), Debug	Work on ironing out possible bugs with the microcontroller, continue debugging.
13(4/14)	Debug, prep for mock presentations, team contract assessment.	Prepare for mock presentation, debugging.
14(4/21)	Debug, mock presentation	Team presentation, sorting out any bugs, prepare for final demo.
15(4/28)	Final Demo	Team presentation, fine-tuning design and, preparing for the final presentation
16(5/5)	Final Presentation	Team Final Presentation

Ethics and Safety

Responsibility to Public Welfare (IEEE/ACM Code of Ethics)

This project involves high-voltage electricity, which poses risks of injury or fire if not properly designed and controlled. Misuse or accidental exposure could harm individuals or damage property. To mitigate this, we will adhere to the IEEE Code of Ethics principle of prioritizing public safety and welfare by ensuring the design includes safety features such as grounding, insulation, and fail-safes to prevent accidental harm. In addition, clear labels on the device with warnings will provide sufficient instruction for safe operation.

Transparency and Honesty (IEEE/ACM Code of Ethics)

Misrepresenting the capabilities or safety of the Tesla coil could lead to misuse or overconfidence in its safety. We aim to be transparent about the risks and limitations of the device, and will document all design choices, safety measures, and potential hazards.

Environmental Impact (IEEE/ACM Code of Ethics)

High-voltage discharges generate ozone and other byproducts, potentially harming the environment or human health. The Tesla coil should and will only be operated in well-ventilated areas.

Preventing Misuse (IEEE/ACM Code of Ethics)

The Tesla coil could be intentionally misused to cause harm, such as by interfering with electronic devices or creating public panic. It will be kept out of reach of children, and any instructions for use will be accompanied by warnings of the ethical and legal implications of its misuse.

Electrical Safety

High-voltage discharges pose risks of electric shock, burns, or even death, so in order to minimize injury we will adhere to the following electrical safety standards and best practices.

NFPA 70 (National Electrical Code): Ensure proper grounding, insulation, and circuit protection.

OSHA Standards: Use personal protective equipment (PPE) such as insulated gloves and safety goggles during testing.

Campus Policies: Adhere to university lab safety protocols, including supervision (presence of at least one other person in the lab) and restricted access to high-voltage equipment.

FCC standards for Electromagnetic Interference (EMI): A Tesla coil is, by nature, a large emitter of broadband EMI, potentially disrupting nearby electronic devices or communication systems. We will operate a safe distance from any sensitive electronics.

Auditory and Visual Safety: Loud noises and bright flashes from the Tesla coil could cause hearing damage or eye strain. We will maintain a safe distance during operation to mitigate any potential harm.

Legal Responsibilities

Failure to comply with state or federal regulations could result in legal liability. We will review and adhere to:

State and Local Regulations: Take Illinois Electrical Equipment - General admin code and Champaign noise ordinance laws into consideration while building and testing the coil.

Federal Regulations: Ensuring compliance with the aforementioned FCC and OSHA standards.

Industry Standards: We will follow guidelines from organizations like the IEEE for high-voltage circuit design, particularly with respect to safe clearances.

References -

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