ECE 445

Fall 2023

Team 13 Design Document

Tesla Coil Guitar Amp

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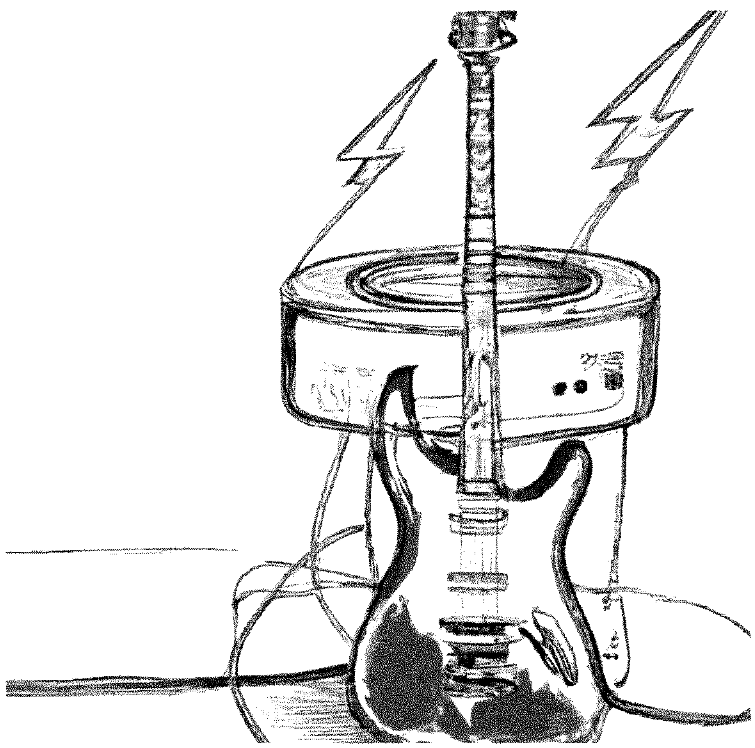
TA Mentor: Jason Paximadas

I. Introduction

Problem:
Musicians are known for their affinity for flashy and creative displays and playing styles, especially during their live performances. One of the best ways to foster this creativity and allow artists to express themselves is a new type of amp that is both visually stunning and sonically interesting. Musical tesla coils have been used for performances in the past, showing there is a market for devices like this [1]. Though, these often use premade music files or are computer-controlled, and do not have the ability to take live input from instruments. Giving these coils the ability to take live input from a musician to create music would open up a new world of possibilities for musical expression and exciting live performances.

Solution:
Our design is a guitar amp that uses a tesla coil to create a unique tone and dazzling visuals to go along with it. The device will take the input from an electric guitar and use this to change the frequency of a tesla coil's sparks onto a grounding rod, creating a tone that matches that of the guitar.

Visual Aid:

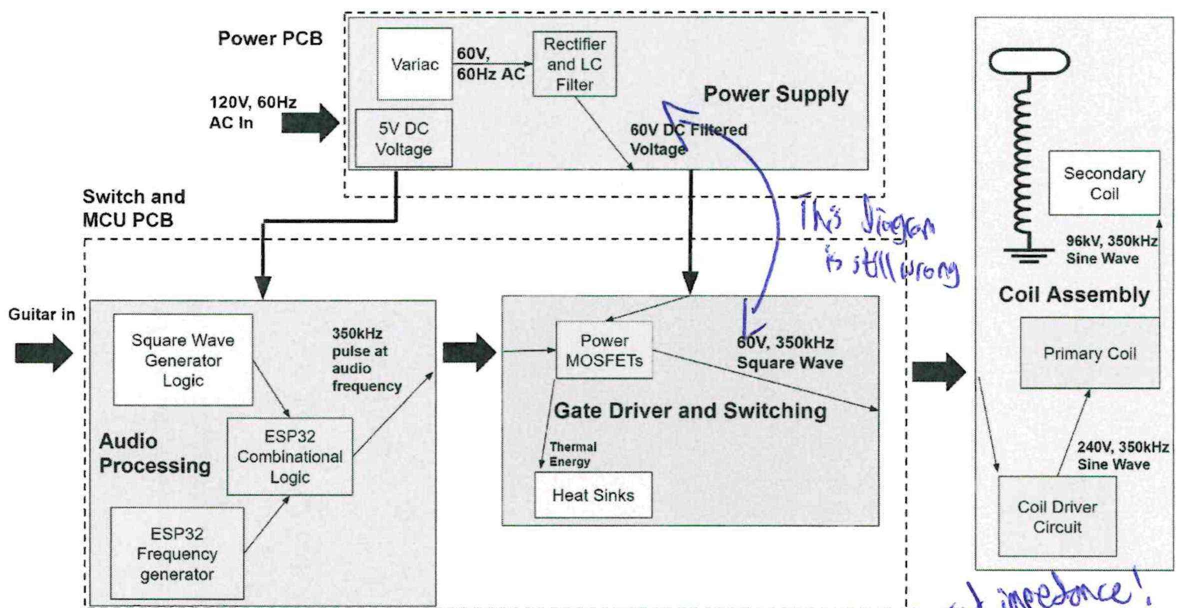


High-Level Requirements:
There are three primary requirements that this design must fulfill in order to be considered successful:

1. The tesla coil can produce visible sparks roughly 5cm in length
2. The coil can produce several different notes and tones
3. The coil can take input from the guitar to determine the notes played

II. Design

Block Diagram:



Specify the input voltage and impedance!

Audio Processing:

The audio processing system will convert the output of the guitar into a pulse wave to be fed as a driver for the tesla coil. This can be done using a network of op-amps. We will also use an LED and phototransistor to separate the user from the rest of the circuit for safety purposes, so that they have no direct connection to any high voltage circuitry. In order to operate our tesla coil, we need to drive it at its resonant frequency. Initial calculations and research have this value somewhere around 100kHz. We have not yet confirmed the microcontroller that we will be using, however we are leaning towards the ESP430 microcontroller, as it can create up to 40MHz, so we will use this to drive our circuit. ~~In~~ order to output different notes, we will use pulses of the resonant frequency, with the pulses at the frequency of the desired note. This output will then be passed to the gate drivers.

where?

Not your MCU

It is not clear from this paragraph that the signal being emitted by the board controls the gate drivers

This sentence should be in the middle

Requirements Table:

put these together

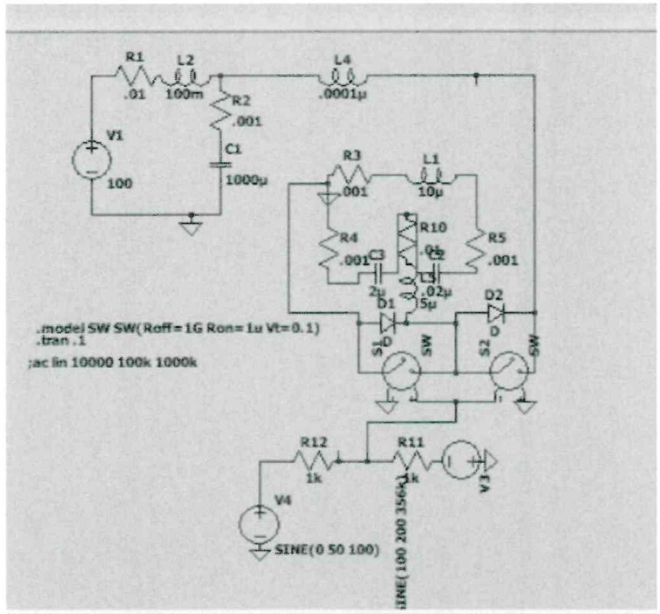
must be list of steps

Criteria:	Tolerance:	Verification:
Microcontroller output variable pulse width wave with frequencies in the range 100-500 kHz	Tolerance is 10 hz e.g. The output signal must achieve a frequency	Measure waveform frequencies
Microcontroller digital signal must be turned to analog to create audible sound and can be done with a digital to analog converter at a resolution of 10mV	Resolution tolerance is + or - 2 mV	Can be done by possibly interpolating to get more data to increase resolution Resolution is nearly a spec of the MCU
Microcontroller needs to employ pulse-width modulation to create a square wave with predetermined amplitude and frequency at a 50% duty cycle	Tolerance is + or - 1% for duty cycle	Duty cycle can be measured with the ratio of the time the circuit is on vs off

Power Subsystem:

The system will draw power from AC mains wall voltage, at 120V. To generate sparks on the coil, we need to drive our circuit at its resonant frequency, which will be around 355kHz. Since the wall power is 120V at a 60Hz frequency, we will use a Variac to step the voltage down to a safer 50V. Then, we will use a DB35-10 full-bridge rectifier to rectify the AC waveform into DC. Then, we will use several ceramic capacitors totaling 1000uF in parallel with the voltage source, and a 100mH inductor in series to filter the to steady 60V DC. Then, we will use our switching circuitry to generate power at the resonant frequency. LtSpice simulations predicted around 10A of current at 60V coming out of the power circuitry and going into the switching subsystem. A circuit schematic with power, filtering, and switching is shown below:

- Input impedance
- Input range
- ~~[illegible]~~ - AFE gain
- AFE bandwidth
- Frequency Max and min
- Frequency accuracy



Requirements Table:

Criteria:	Tolerance:	Verification:
Ripple Voltage	After filtering, limit ripple to 10%	Measure waveform with oscilloscope and observe the min to max voltage variation
Voltage sent to switching	60 ± 10V	Monitor using oscilloscope
Current sent to switching	15 ± 5A	Monitor using oscilloscope
Circuit Protection	Max wall outlet power is 1.5kW[2], so limit power below 1.5kW	Install 30A fuse on Variac output and do not blow outlet breaker

Gate Driver and Switching Subsystem:

The goal of the switching circuitry is to send a square wave to the coil assembly system. The switches will take the rectified and filtered DC voltage from the power subsystem and use two power MOSFETs to turn this 60V 60Hz input signal into a LF or MF square wave (at 100khz-500khz). I thought this was DC! We will use the Infineon BSC050N10NS5ATMA1 due to its high current and voltage ratings of 100V and 100A, respectively, and its low resistance of around 5mΩ. This provides a voltage tolerance within the tolerance limit set for voltage from the power. The MOSFETs will be driven at the resonant frequency, calculated to be around 357kHz according to the LtSpice simulation. The model of FET selected has a 9ns turn-on time and a 7ns turn-off time, which should be suitable for the intended driving frequency. The gate signal will come from the audio processing subsystem, and will trigger the MOSFETs at pulses of the resonant frequency, with the pulse frequency corresponding to the frequency of the desired audio note.

Requirements Table:

component specs! don't include!

Criteria:	Tolerance:	Verification:
MOSFET Current	Current < 20A	Use oscilloscope to ensure operating current does not exceed 20A
MOSFET Voltage	Voltage < 100V	Monitor voltage and use Variac to step down V if necessary
Gate Signal Frequency	Limit signal to under 500kHz	Set limit in microcontroller to ensure frequency does not exceed 500kHz
Power Consumed	$P \leq 5W$	Measure current and voltage into FET with current and voltage probes
MOSFET Temperature	$T \leq 175°C$ lower this value to something reasonable	Use thermocouple to test operating temperature of MOSFETs after 2 minutes of continuous operation

this is not a requirement of this subsystem

Coil Assembly Subsystem:

The final subsystem is the coil assembly. This includes the circuitry used to complete the coil input waveform and the tesla coil itself. The circuit will take an input from the switching, which should be a square wave at the resonant frequency with a voltage around 60V. This square wave will have a number of harmonic frequencies, which can create distortion. In order to remove this harmonic distortion, another LC circuit is included in order to filter the square wave into a sine wave at the resonant frequency. The circuit includes a circuit with two capacitors before the primary coil of the tesla coil. The driver circuit is discussed in further detail in the tolerance analysis, but the goal is to increase the voltage of the system sent to the coil to around 240V by adjusting the ratio of the driver capacitors to 4:1, using 1uF and 250nF capacitors. This voltage will be set across the primary coil, which is then transferred to the secondary coil of the tesla coil assembly. The coils have a turn ratio of around 1:400, which will create around 96kV at the top of the coil. In standard atmospheric conditions, it usually takes around 30kV to bridge a 1cm (John Papiewski), so this voltage is enough to create a spark around 3 cm long. The top of

replace these names with C1, C2, L1...

not IEEE!

add a basic schematic here! with labelled components!

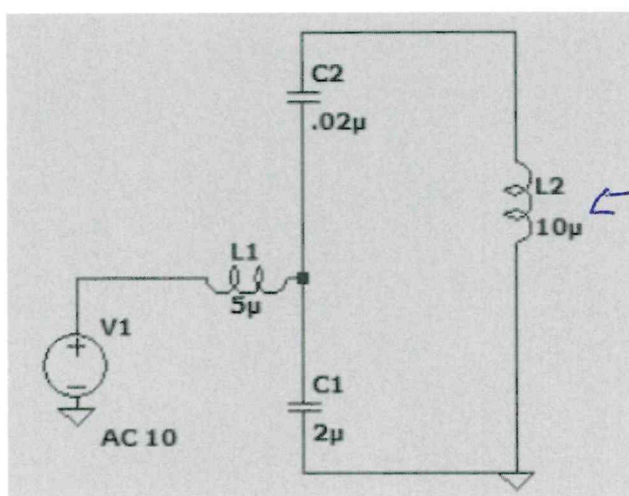
the coil is not in the traditional toroidal loop, it is instead concentrated to a point. The coil will only ever be operated outside with all bystanders keeping at least 10 ft distance away from the coil. A grounding rod will be installed 3 cm away from the coil in order to direct the sparks and give a clear path for the secondary coil to discharge.

Requirements Table:

don't need tolerance here, ≤ 240 is fine

Criteria:	Tolerance:	Verification:
Primary Coil Voltage	Limit to 240 ± 20V	Measure with voltage probe
Spark Length	Limit to 3 ± 1cm >2cm is fine here	Measure if sparks reach grounding rod or if they break off in the wrong directions
Circuit Protection	All sparks are directed to grounding rod, no arcing to surroundings or the rest of the system	Visual inspection during coil operation

Tolerance Analysis:
The most critical block in our diagram is the coil driving assembly. This assembly is a resonant circuit, which can be modeled as such:



where is the secondary here?

L2?

The AC input will be a pulse wave, generated by the MOSFET half-bridge connected to voltage rails. L7 is the primary winding of the tesla coil, estimated to be about 10 uH. The frequency response of this circuit is such that when

$$w_o = \sqrt{\frac{c_1 + c_2}{c_1 \cdot c_2 \cdot l_2}} \qquad \text{then:} \qquad v_{out} = v_{in} \cdot \left(\frac{c_1}{c_2} + 1\right)$$

In addition, in this scenario, input current is 0. This means that in a lossless circuit, power consumption is 0, and this current just sloshes around the tank. Note that none of these values depend on the inductance of L1. This will become important in a moment. There are two practical concerns when implementing a circuit like this. The first is to do with the fact that the input signal is a square wave, not a sine wave, and the second has to do with parasitic resistances.

~~you barely touched~~ ~~be specifi~~ be explicit about the primary benefit of this design: switches do not conduct tank current

Note that if we pick the fundamental frequency as we do above, and have an inductance of 0 for L1, as we raise the frequency, the circuit will behave more and more like a short to the input. Thus, if we input a square wave into this circuit, the efficiency at the fundamental will be very high, but harmonic distortion will cause an extremely high DC current to come from the power source, all of which is wasted. This is where L1 comes into play. Note that in ideal circumstances, no matter what the value of L1, the voltage gain is the same, as is the input current (0) and the frequency with this property. If L1 is high (or at least non-zero), higher harmonics contained in the square wave just won't pass through. In this way, input current will be very low.

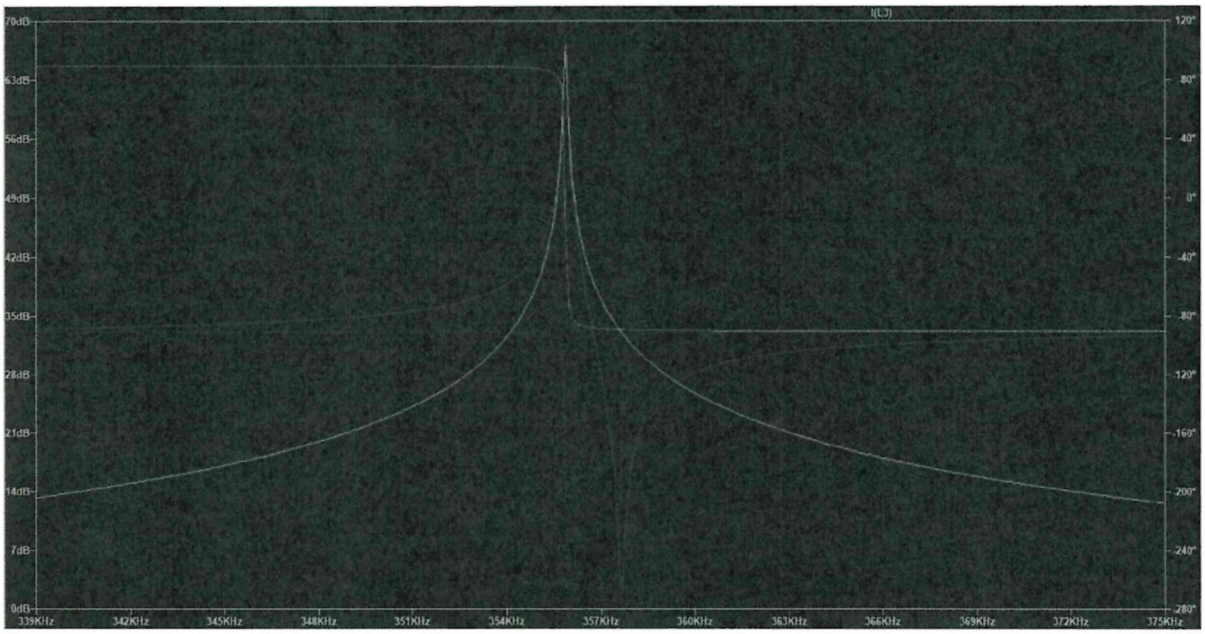
The second consideration here is parasitic resistances. Due to these resistances, the input current isn't really zero, and after L1 reaches a certain size, voltage gain becomes non ideal. The important part, though, is that all of these components have high tolerances for exact value. Resonant frequency should be calculated by the microcontroller. how? Basically, L1 can't be too big, and the ESR for C1 and C2 should be as small as possible. Another consideration here is voltage tolerances for the capacitors. The capacitors can experience very high voltages, if for a short period of time. Thus, these capacitors must be able to manage at least 1kV AC voltage without breaking.

why?

how did you get this figure?

The inductors in this circuit will be hand wound, they're only a couple of turns. They will also be handling high current, so thick wire must be used. This wire should be able to handle at least 100 why? amps of current without breaking. Due to the properties of this circuit, the tolerances of the MOSFETs can be a little more flexible. Current gain is astronomic, so in an ideal scenario, there could be no more than 30 amps, possibly much less flowing through the mosfets. They must be rated for this current level. These MOSFETS must also have DC blocking levels much higher than voltage rails, double would be preferable, so for 60V rails, that would mean a blocking voltage of around 120V. On resistance of mosfets is also less important with this circuit topology, because comparatively low current is flowing into the tank.

The most important tolerance to support this circuit, however, is the microcontroller's granularity of output. This circuit is extremely frequency dependent. Below is a frequency response curve of the tank circuit with l1 removed, and parasitic resistances included. Blue is current in, green is voltage out. Note how current in has a minimum at ~358 kHz, and a maximum at ~354 kHz. These extremes are alleviated slightly with the inclusion of l1, but still remain. With Q values this high, the microcontroller needs to be able to output a variable pulse width wave with frequencies in the range 100-500 kHz with granularity of ~10 hz. This is probably the most important specification of any element in our circuit. this is only a product of no ESR in the circuit



III. Cost and Schedule:

High Level Cost Analysis: Include a cost analysis of the project by following the outline below. Include a list of any non-standard parts, lab equipment, shop services, etc., which will be needed with an estimated cost for each.

Part(Expense)	Part Link	Cost
Single-Phase Diode Bridge Rectifier	https://www.mouser.com/ProductDetail/Diotec-Semiconductor/DB35-10?qs=OlC7AqGiEDlsV5lyy2qneA%3D%3D	$4.93
Cartridge Fuses (2x)	https://www.mouser.com/ProductDetail/Bel-Fuse/5SF-10-R?qs=sGAEpiMZZMsIz3CjQ1xega8hXO6fltfAeiYzrw%25	$0.48

	2BuPvFneRZxI6B8gg%3D%3D	
Circuit Breaker	https://www.mouser.com/ProductDetail/Qualtek/QLB-103-11B3N-3BA?qs=vbU4ZYfMnUr53F0RHGXmWA%3D%3D	$2.45
Capacitors (10x)	https://www.mouser.com/ProductDetail/Panasonic/ECQ-UAAF473MA?qs=sGAEpiMZZMsh%252B1woXyUXj02IBd6%2FO481IVRjtbUwo8s%3D	$4.85
Gate Driver	https://www.mouser.com/ProductDetail/Monolithic-Power-Systems-MPS/MP1924AHR-LF-P?qs=BHWkRorfSmV7dQcJzSRQBw%3D%3D	$2.91
MOSFETs (2x)	https://www.digikey.com/en/products/detail/stmicro/STW65N65DM2AG/	$22.24
Tesla Coil (provided)		Estimated $40
Msp430 microcontroller are you using this?	https://www.digikey.com/en/products/detail/texas-instruments/MSP-EXP430G2ET/9608004	$11.99
TL074 op amp	https://www.mouser.com/ProductDetail/Texas-Instruments/TL074CNE4?qs=odmYgEirbwzZM%2F3R%2FF4zPw%3D%3D	$0.65
Circuit Boards		~$30
Labor		Approximately $16,800
Total		$16,920.50

Labor Cost Analysis:

Assuming 12 hours per week per person, each individual would be doing 12 * 14 = 168 hours of labor over the duration of the project.

Category	Estimated Hours per person		
	Griffin	David	Aditya
Circuit Design and Construction	67	67	67
Testing and Debug	100	100	100
Logistics/Documentation	15	15	15

Assuming an average hourly rate of $40 and that each person is doing 168 hours of work, then the total labor cost would come out to be approximately $16,800.

Schedule:

- Week of 9/25 (Week 6)
    - Finish all Schematics and the Simulation, Design Document, Ordering Power Components, Select Transistors and Switching ICs, Review and Feedback
        - David will look into the schematics and simulation before discussing it all amongst our team
        - Order components and design document all together
- Week of 10/2 (Week 7)
    - Review of the Design document, Rough draft of the power board(PCBWay)
        - Work split equally amongst team members
- Week of 10/9 (Week 8)
    - First PCB Order for the Power board, Test Power board upon arrival, Teammate evaluation #1
        - Work split equally amongst team members
- Week of 10/16 (Week 9)
    - Design the Audio Processing board, Test Power board, Order another power board if deemed necessary
        - Work split equally amongst team members
- Week of 10/23 (Week 10)
    - Order Audio Processing board, Finish Individual progress report
        - Work split equally amongst team members
- Week of 10/30 (Week 11)
    - Test Audio Processing board with Power board, Debug, Review

Equally amongst team? Is that really how you have split it?

        - Aditya will work more closely with the audio processing, but overall testing will be done together as a group
- Week of 11/6 (Week 12)
    - Audio Processing, Test Tesla Coil Amp holistically, Debug, Review
        - Work split equally amongst team members
- Week of 11/13 (Week 13)
    - Debug, Review, Prepare for Demo, Mock Demo, Prepare for final presentation
- Week of 11/27 (Week 14)
    - Debug, Review, Prepare for Final Demo, Final Demo, Prepare for final presentation
- Week of 12/4 (Week 15)
    - Final Presentation

IV. Discussion of Ethics and Safety:

Ethics:

Our group will act in accordance with the IEEE code of ethics. We understand that the technologies and parts that we are working with have the ability to affect one's life. In our group, we have established a process to review and revise all software and hardware designs that will take everyone's considerations into account. We will make sure to follow course guidelines for feedback and work with the head TA, Jason, closely. One ethical consideration that we need to take is not necessary with regards to our project, but with regards to making sure we treat everyone we work with with respect. We have taken steps to address this with open communication amongst our group members as well as our lead TA. Additionally, we have created a google drive with all of our research and design ideas, as that way everyone can access it and always give open feedback without the fear of their ideas not being taken into consideration. There aren't too many ethical concerns with this project, but there are some concerns with the use cases of this project. We outlined that we expect this tesla coil to be used in a live music performance setting, and not in other industries such as the military. Other ethical concerns with this project involve user safety, however in the next section we outline our safety concerns and guidelines to make sure there is no harm or injuries.

Safety:

Reference asc safety standard

We have considered potential safety issues regarding the use and design of the Tesla Coil, and have outlined below precautions and safety measures that we will take in order to prevent any potential risks. We will be following the Safety Guidelines set on the ECE 445 web page, as we have already all completed the Safety Training, and all plan to complete the extra training that is required for working with high currents. We have looked at the previous group to make a Tesla Coil, and are incorporating safety measures they took as well.

- The tesla coil will never be turned on indoors, it will be tested outside with multiple group members present using an outdoor wall outlet, with cones to create a circle of safety to keep bystanders away.
- We will keep everyone at least 10 ft away while the coil is active.
- The voltage can reach up to 100kV (albeit low current) so all sparks will be directed onto a grounding rod 3-5 cm away, as a general rule of thumb is each 30kV can bridge a 1cm gap.
- The coil will have an emergency stop button and a fuse at the power supply.
- The cable from the guitar will use a phototransistor so that the user is not connected to a circuit with any power electronics.
- We will have a grounding rod, so that we can ground the tesla coil after use so that it will be safe to handle after grounding
- In order to take extra precautions because we are working with high power and voltage, we will be using gloves when working with the Tesla Coil

V. Citations:

Jones, Edwin; Wright, Andrew. *How Many Watts Can an Outlet Handle?* Galvin Power. 1 Sep 2023. Accessed 26 Sep 2023.

Papiewski, John. *How to Calculate Voltage by Spark Gaps.* 13 Mar 2018. Accessed 26 Sep 2023.

Long, Jason; et al. *Improving the Musical Expressiveness of Tesla Coils with Software.* 1 Oct 2015. Accessed 27 Sep 2023.

Project #: NM 13 Semester: FA23 Reviewer: Jason Paximadas

Design Document Evaluation Sheet

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Introduction: 5 pts 5/5	Max Score ----------		Min Score
Problem and Solution	**(2)** - clearly defined problem and solution	**(1)** - one of prob./sol. unclear or missing	**(0)** - prob. + sol. both unclear or missing
Visual Aid	**(1)** - pictorial representation of how the final solution is used in the context of the problem		**(0)** - visual aid unclear or missing
High-level Requirements	**(2)** - three clear, comprehensive, and quantitative (where applicable) reqs.	**(1)** - at most one req. unclear or missing	**(0)** - more than one req. unclear or missing

Design: 24 pts 14/24			
Block diagram (+ optional physical design) -1	**(2)** - complete, modular design with all important details	**(1)** - design incomplete or lacks important detail	**(0)** - lacking multiple important details or missing
Subsystem Descriptions -2	**(5)** - complete description of all subsystem functions and interaction with other subsystems	**(3)** - more than one subsystem description lacking detail	**(0)** - all subsystem descriptions lacking detail or missing
Subsystem Requirements -3	**(5)** - reqs. are for student design - not for off-the-shelf parts - comprehensive, detailed, quantitative (with tolerances), and relevant	**(2)** - half of reqs. are off-the-shelf parts, missing, lacking detail, irrelevant, or non quantitative	**(0)** - most of reqs. are for off-the-shelf parts, missing, lacking detail, irrelevant, or non quantitative
Subsystem Verifications -3	**(5)** - test procedure and success criterion are unambiguously presented	**(2)** - half of verification procedures are lacking detail or missing	**(0)** - majority of verification procedures are lacking detail or missing
Supporting Material -0	**(3)** - supporting figures and data effectively communicate technical details of design	**(1)** - supporting material occasionally omitted or ineffective	**(0)** - supporting material often omitted or ineffective
Tolerance Analysis -1	**(4)** - feasibility of a critical subsystem function proven through mathematical analysis or numerical simulation 3	**(2)** - analysis is unsound or fails to demonstrate the feasibility of the subsystem function	**(0)** - missing tolerance analysis

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Cost & Schedule: 4 pts	2/4		
Cost -1	**(2)** - all parts and required information included	**(1)** - some parts of required information missing	**(0)** - most parts or required information missing
Schedule -1	**(2)** - specific, with one task assigned per week/member	**(1)** - schedule is unsound or some information missing: division of labor, specificity	**(0)** - missing information: division of labor, specificity

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Ethics & Safety: 4 pts	1/4			
Considers all ethical & safety issues of project Explains how to address these issues ✓ (eg. danger mitigation procedures) References appropriate ethics code References to relevant safety or regulator standards (e.g. OSHA, FCC) Justifies design decisions for project safety & ethics	**(4)** - includes all elements where applicable	**(2)** - one incomplete or missing element where applicable	**(1)** - two incomplete or missing elements where applicable	**(0)** - more than three incomplete or missing elements where applicable

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Writing: 3 pts	2/3			
Final report formatting guidelines Title page: title + group members ✓ Figures + tables labeled and captioned. Equations explained in accompanying text. ✓ IEEE formatted references; Citations throughout document No typos or grammatical errors ✓ ***Text is consistent and flows logically from one paragraph to the next***	**(3)** - at most one invalid element	**(2)** - two invalid elements	**(1)** - three invalid elements	**(0)** - more than three invalid elements

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Total: 24 / 40