

Operating Room Wireless Power Transfer System

6.78 MHz Resonant Inductive WPT using GaN-FET based Class-E Driver

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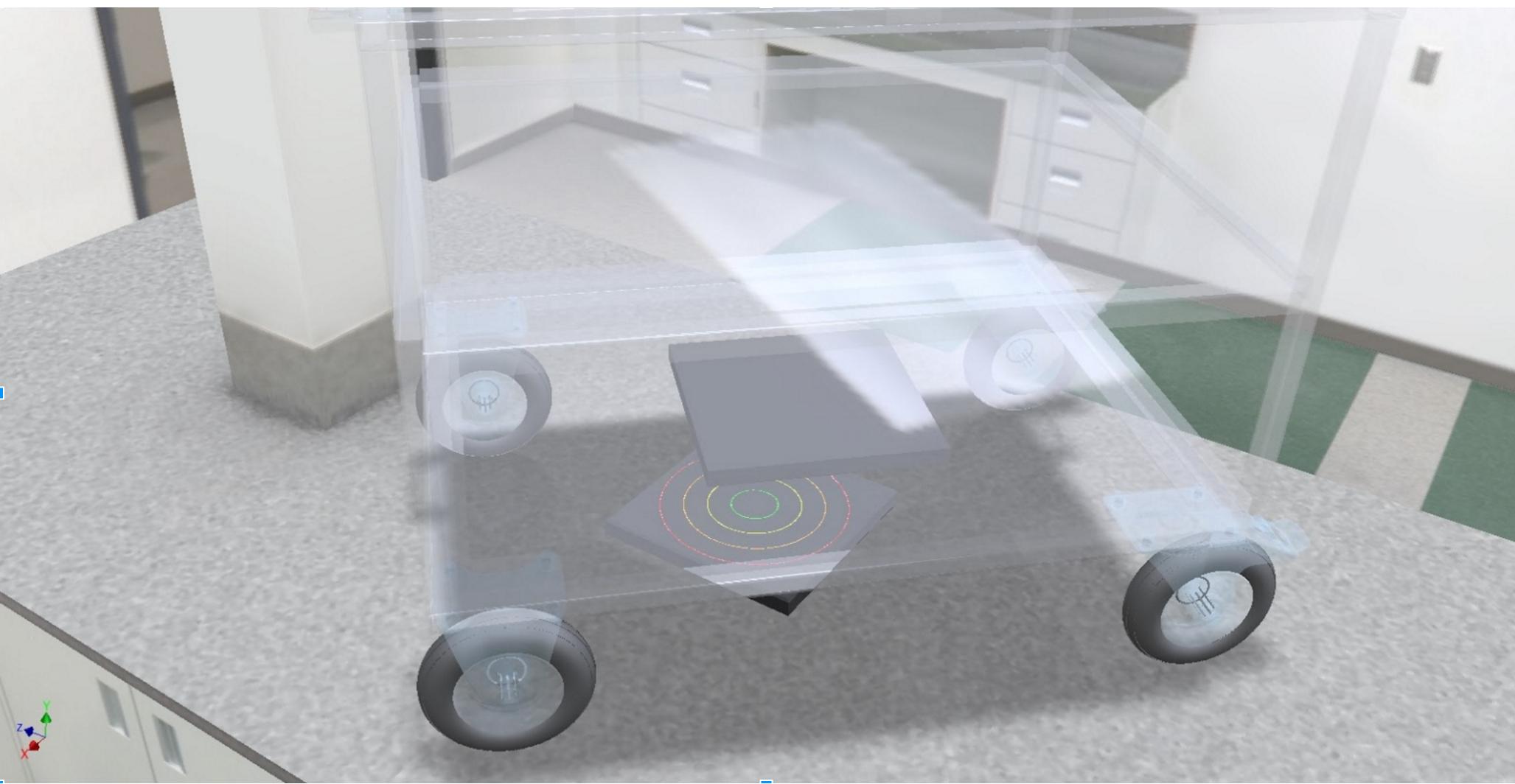


Project Objective

Design a system to eliminate power cables in operating rooms (ORs).

Motivation

Operating rooms (ORs) demand a high cost per minute during surgeries, approaching \$60-300 a minute. To lower costs, OR times should be shortened. Removal of power cables in OR allows this by reducing setup time for equipment such as X-Ray systems. This removal also offers other benefits, including increased mobility of equipment in the OR and improvement of safety by removing a major tripping hazard.



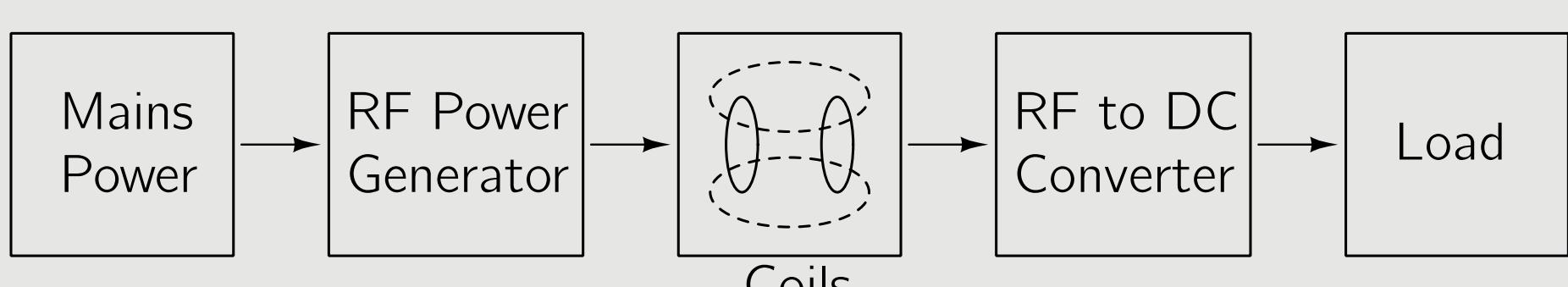
Solution & Goals

Our solution is a resonant-inductive wireless power transfer system which consists of the following features (pictured above):

- Transmitting coil array embedded in OR floor
- Receiver coil mounted to cart, 4-8 inches from floor
- 125 W power transfer ideal, >25W for demonstration
- Compact (<1 ft²)
- Over power detection and shutdown
- High-efficiency design
- Compliance with government regulation (FCC)

Technical Approach - Architecture

Shown is the overall system architecture implemented.

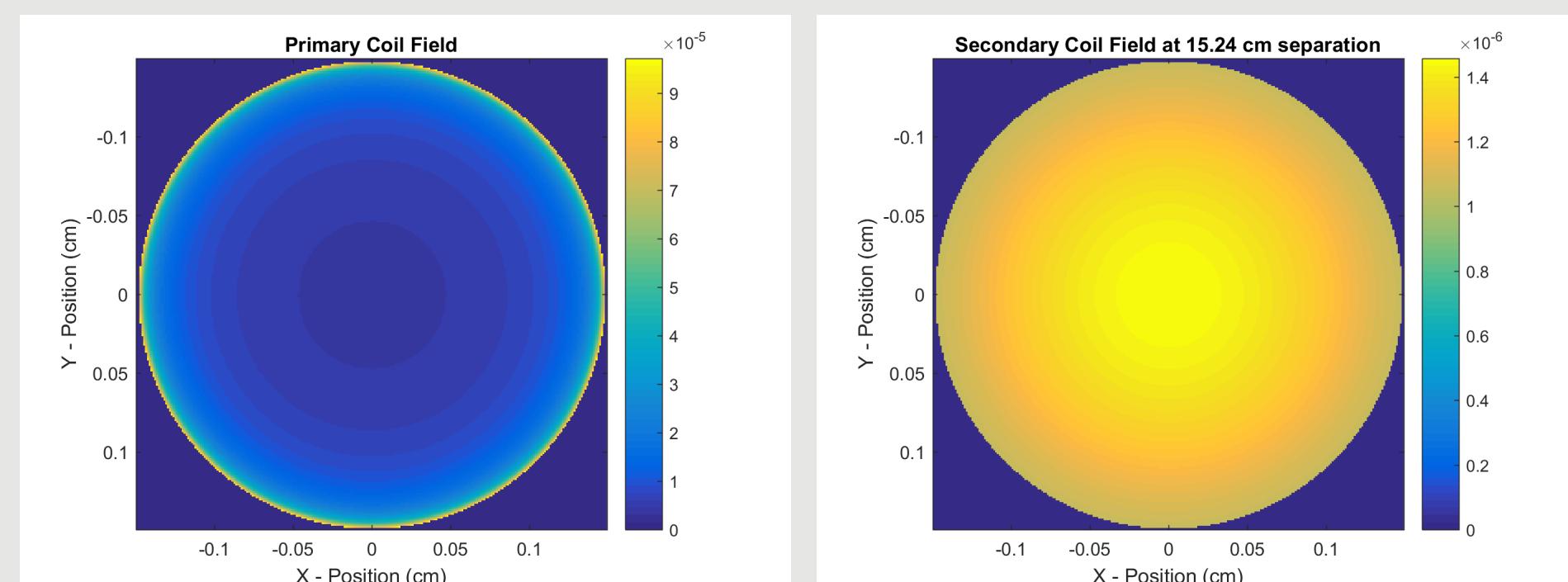


Major systems are:

- RF generator: 6.78 MHz GaN Class-E power amplifier
- Coil system: 4 coil resonant-inductive structure
- RF to DC converter: Schottky bridge rectifier

Technical Approach - Coils

For high power transfer, a resonant-inductively (RI) coil system was chosen. Direct inductive coupling was found to have too low coupling in the desired range and coil size. Coupling and inductance were found using numerical integration of the Biot-Savart law over separated single turn coils. The results for two 12" coils separated by 6" with a 1A coil current is shown:

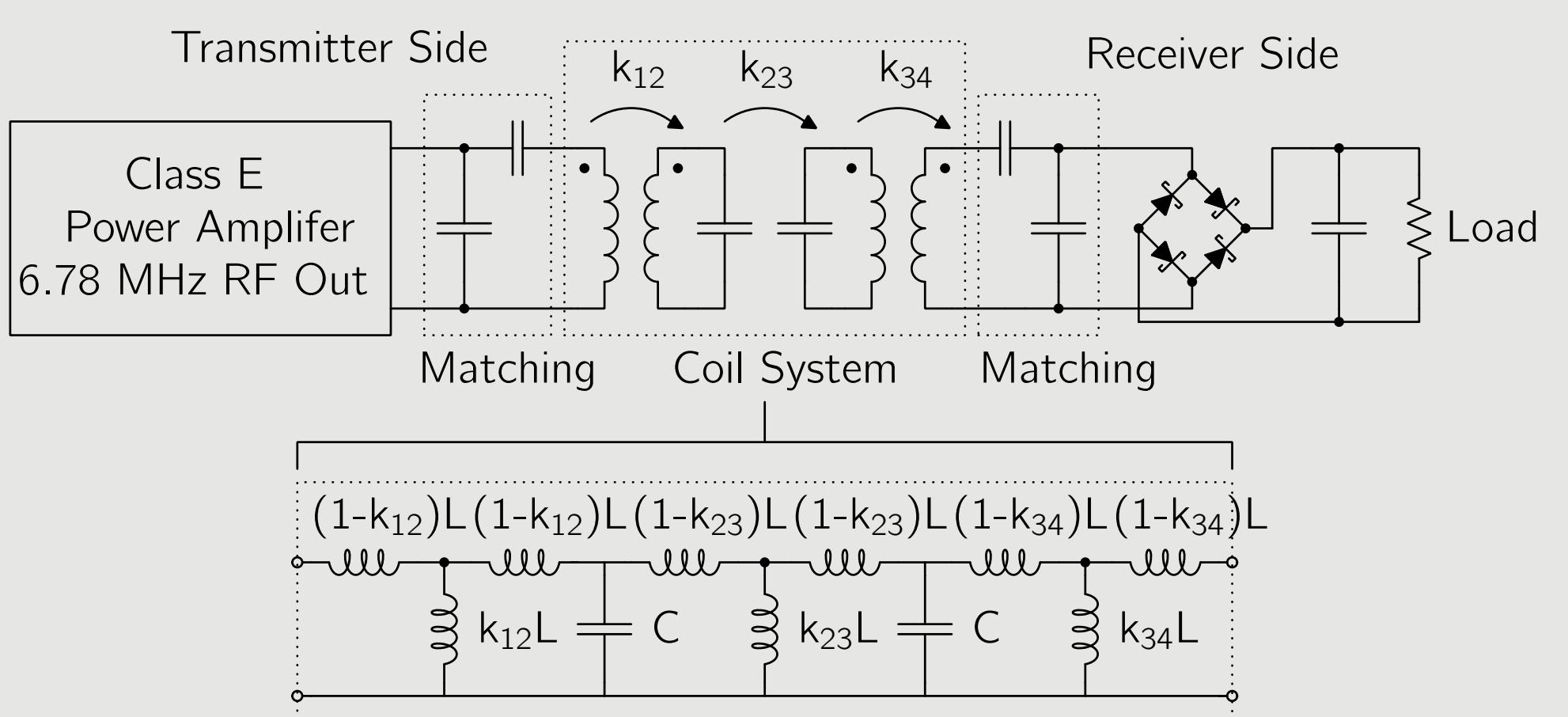


The above coil geometry was selected to be implemented for this project, with the addition of two closely coupled resonator coils to implement a RI system. The extracted inductance and coupling parameters from the simulation are below:

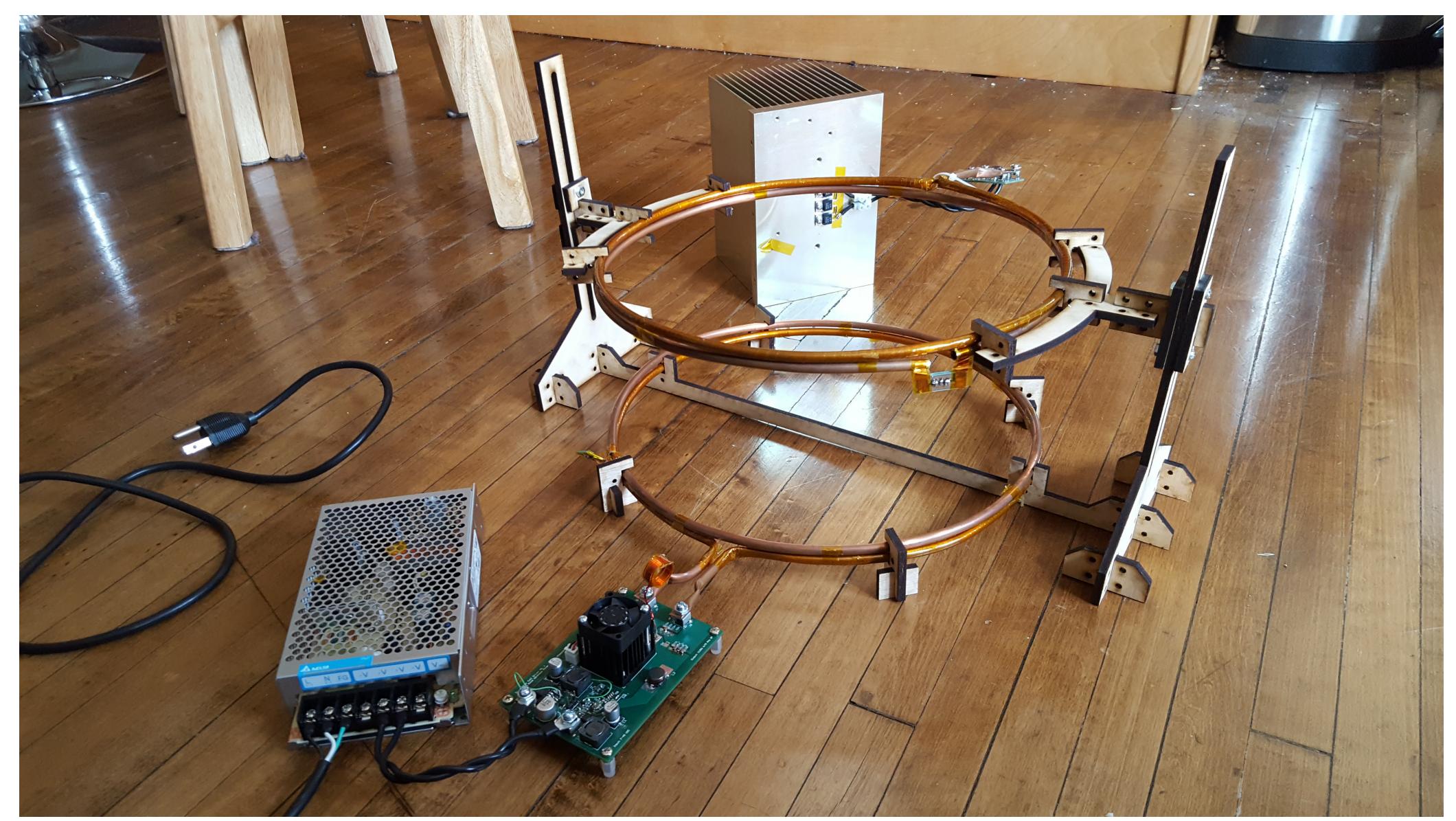
$$k_{23} = 0.843 \quad k_{12} = k_{34} = 0.0909$$

$$L_{coil} = 944nH$$

The diagram below illustrates the structure of the 4-coil RI system, and the circuit model used for the coil system. Coil 1 is separated from 4 by 6", coil 2 is held within 0.25" of coil 1 as is coil 3 from coil 4.

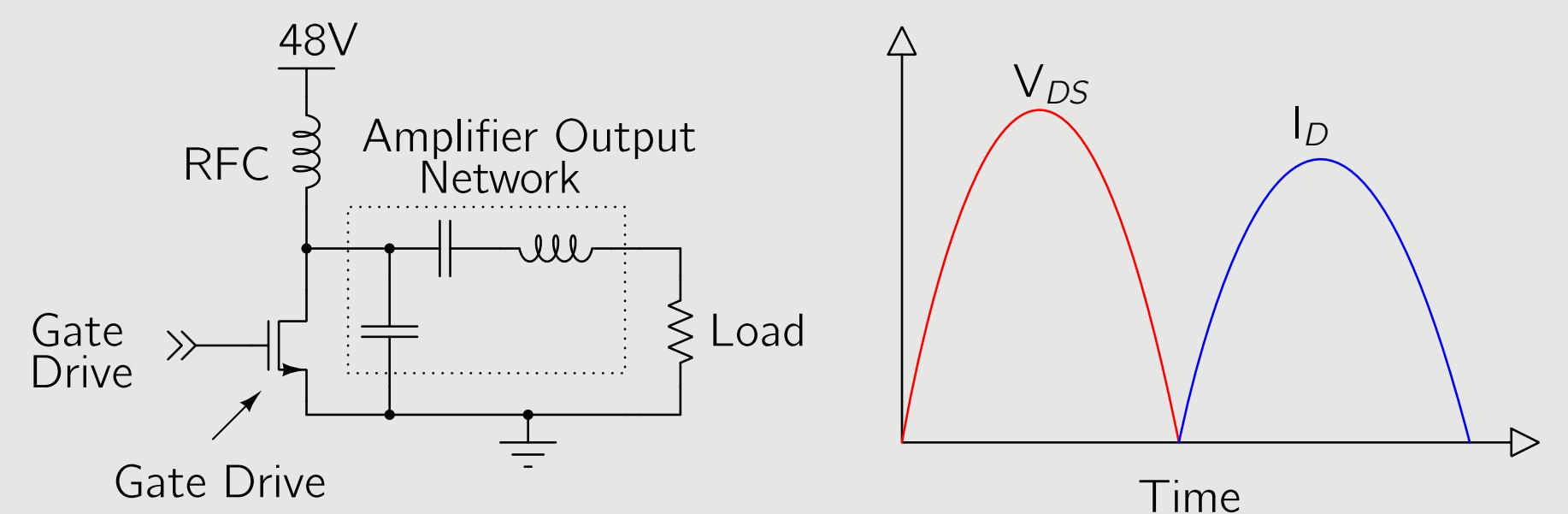


Matching is performed using symmetric series-shunt capacitor networks on each side of the coil system, designed to present a real impedance on the primary side that equals that loading the secondary side (for this system $Z_L = 10 \Omega$ was used). Below is an image of the constructed coil system and supporting systems.

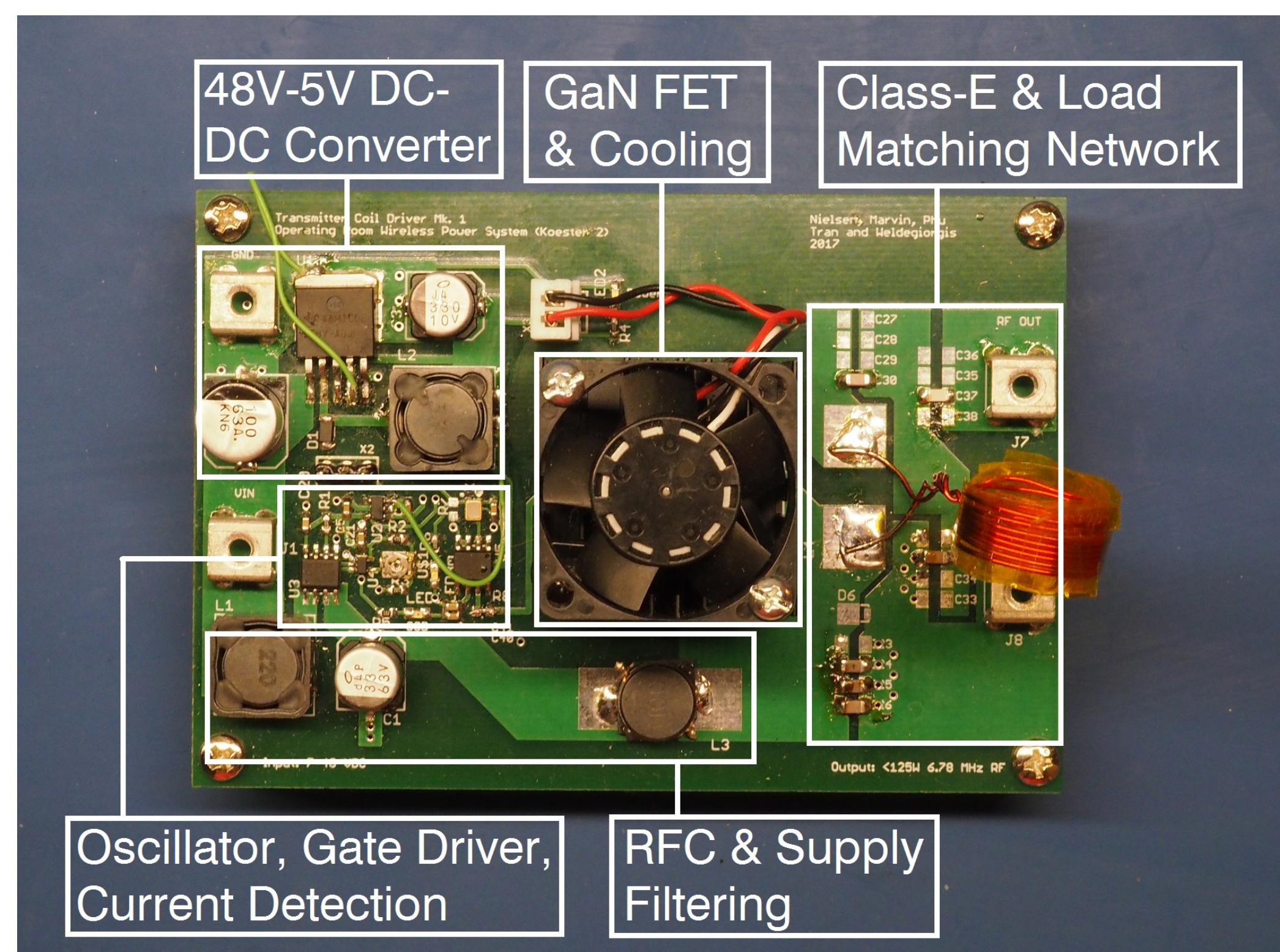


Technical Approach - Driver

For high efficiency, a Class-E power amplifier was designed to drive the coil system. Class-E amplifiers utilize zero voltage switching (ZVS) to minimize losses in the amplifier. The structure of a Class-E PA is shown below. The plot demonstrates ZVS operation, namely where the FET V_{DS} and I_D are exclusive, implying $P_{FET} = I_D V_{DS} = 0$.



The above structure was implemented utilizing a Gallium Nitride (GaN) FET as the switch. GaN was chosen due to the relatively high 6.78 MHz system frequency (done to take advantage of relaxed FCC regulation of ISM bands), low loss required and high switching node voltages, of which only GaN devices can satisfy. The FET is driven by a high speed gate driver fed with a highly stable 6.78 MHz crystal oscillator. The load in this circuit would be the coil network. The below image shows the Class-E power amplifier board constructed for this project.



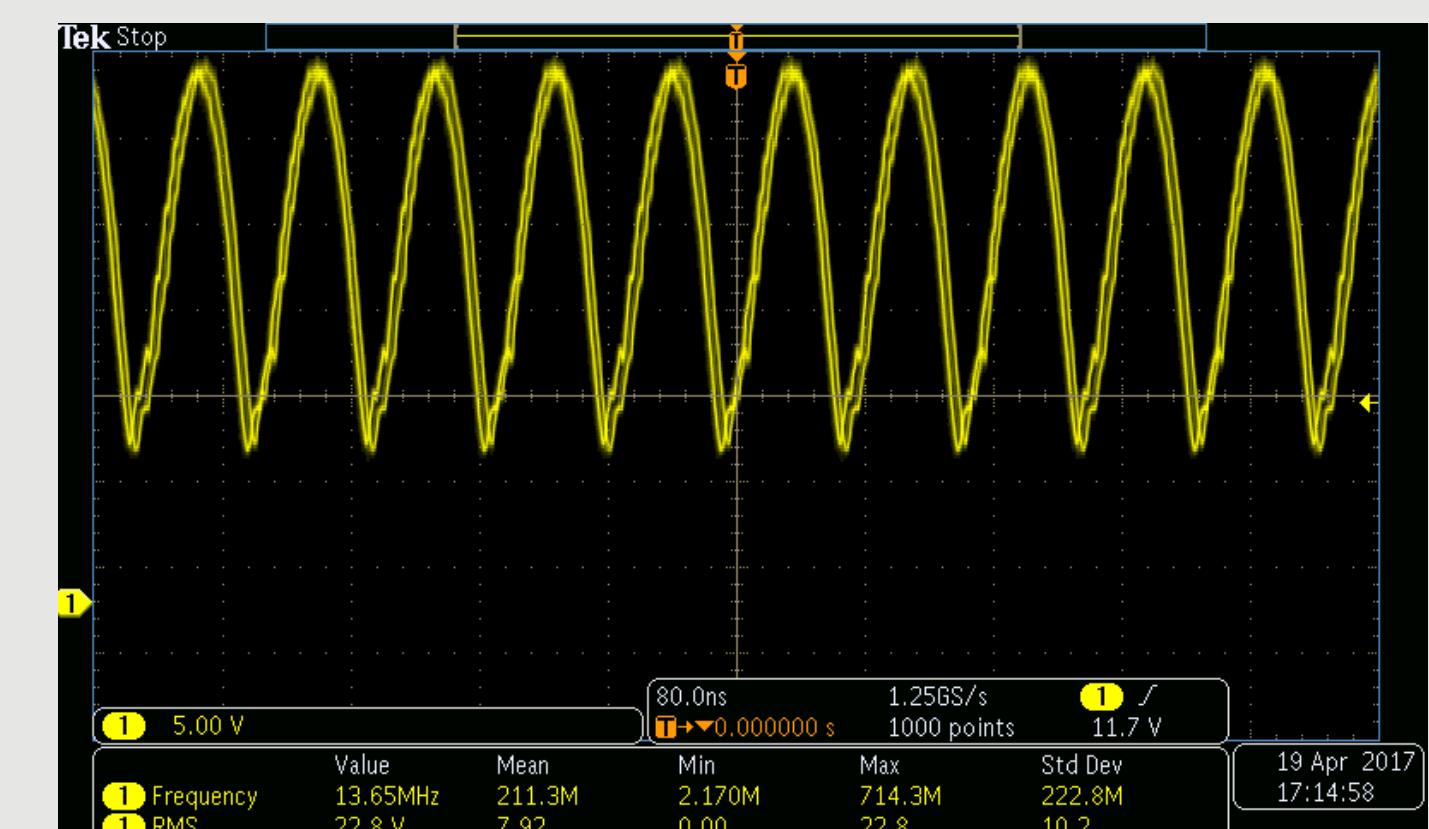
Implementation

The described system was implemented as shown in the images above and to the left. The power amplifier and receiving side rectifier were implemented on their own PCBs respectively, the coils were constructed out of 0.25" copper tubing and mounted into a custom laser cut testing stand, adjustable in coil separation.

A 10 Ω load was constructed for testing out of three 3.3 Ω thin film resistors on a large heatsink, permitting up to 150W of power dissipation with minimal parasitic capacitance.

Testing & Performance Results

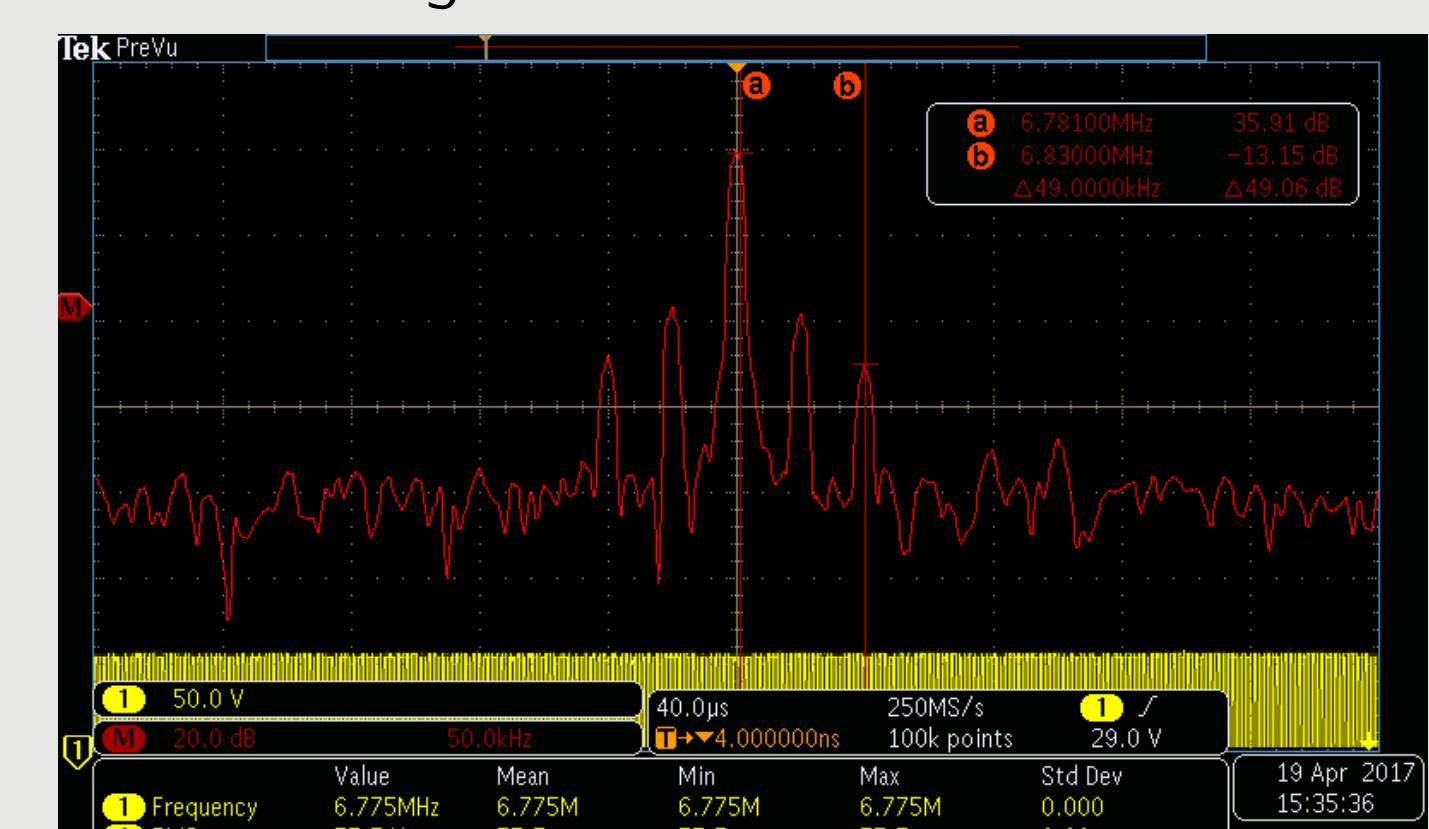
Power transfer and efficiency was measured by varying the supply voltage to the PA while measuring the RMS voltage across the load. Power at the load is simply $P = \frac{V^2}{R}$, and input power just the product I/V observed at the power supply. The best result for power transfer is shown below:



The RMS voltage was measured at 22.8V_{RMS} into a 10.3 Ω load, while drawing 2.16A at 36V from the supply. This corresponds to:

$$P_{transfer} = 50.5W \quad \eta = 64.6\%$$

This satisfies >25W power transfer. The spectrum of the output of the driver board was also measured to verify compliance to FCC regulations for the 6.78 MHz ISM band.



As seen in the above plot, the signal is centered at 6.78 MHz with visible sidebands extending to ± 5KHz. This is well within the 6.78 MHz ± 15 KHz allocated by the FCC in the first ISM band.

Conclusions

A prototype wireless power system was successfully developed demonstrating non-trivial (>50W) power transfer wirelessly. The system also maintained dimensional constraints and compliance to government regulation. These factors combined imply the success of the project in addition to its viability to be further developed in future semesters.

Future Work

Given the possibility of the continuation of this project, numerous aspects of this design can yet be improved and expanded upon. For example:

- Development of a receiver-side power converter to deliver 120 VAC to devices
- Development of a multi-transmitter coil array
- Receiver integration onto medical cart