EE152: Power Converter!

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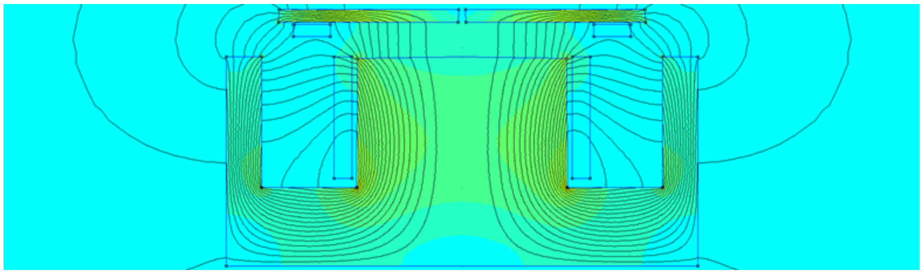

Table of Contents:

Summary

We researched, simulated, and built an inductive power charging device capable of delivering USB power with greater than 50% incremental efficiency.

Inductive power transfer creates a transformer with a large, variable airgap. Alternating current is generally fed into the primary, and the flux couples the secondary and generates a corresponding AC waveform. This waveform is then rectified, filtered, and used to supply the load. For our application, our load is a 5V portable device with a battery. Inductive power transfer as a technology is almost exclusively used for battery charging - and we are no exception - we can successfully charge USB devices wirelessly.

Work Completed

We've broken our project into three steps: simulation, prototyping, and implementation. Details of each are listed below:

Simulation

After we decided to pursue an inductive charging solution, we pursued two separate models. One was a high level SPICE model of the entire inductive charging circuit. The other was a more detailed finite element method magnetics simulation. We decided to use a full bridge topology because that makes best use of the B-H curve and doesn't require large film capacitors (like a half bridge) or involve large, potentially damaging voltage spikes (like a flyback). We were also averse to high-side sensing which would have been necessary for the half bridge alternative. We wanted to use SPICE to determine the dependence of efficiency and power throughput on input voltage and coupling factor [Figure 1]. We discovered efficiency is relatively independent of both of these except for egregiously low voltages, and throughput is highly dependent on both.

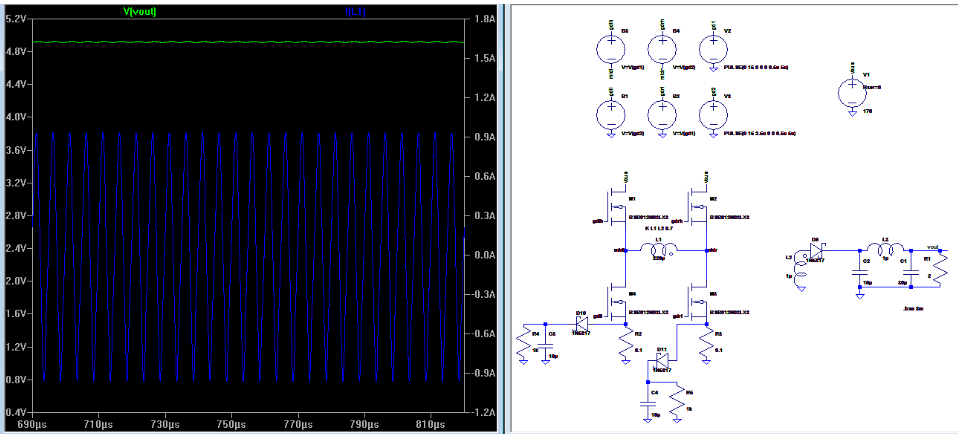

Figure 1: Spice Simulation

The objective of the FEMM simulation was to determine the expected inductance and approximate coupling factor of the air-gap transfer to select components for the drive. The FEMM simulation started with two identical coils, one on top of one another with no magnetic materials other than air. We quickly realized that the flux needed to be shaped in order to get the coupling factor within a respectable range, and condition necessary for an efficient converter. We ended up selecting half of a ferrite pot core as our transmitter. [Figure 2] shows the beginning and end simulations. The figures are rotationally symmetric about the left edge of the simulations.

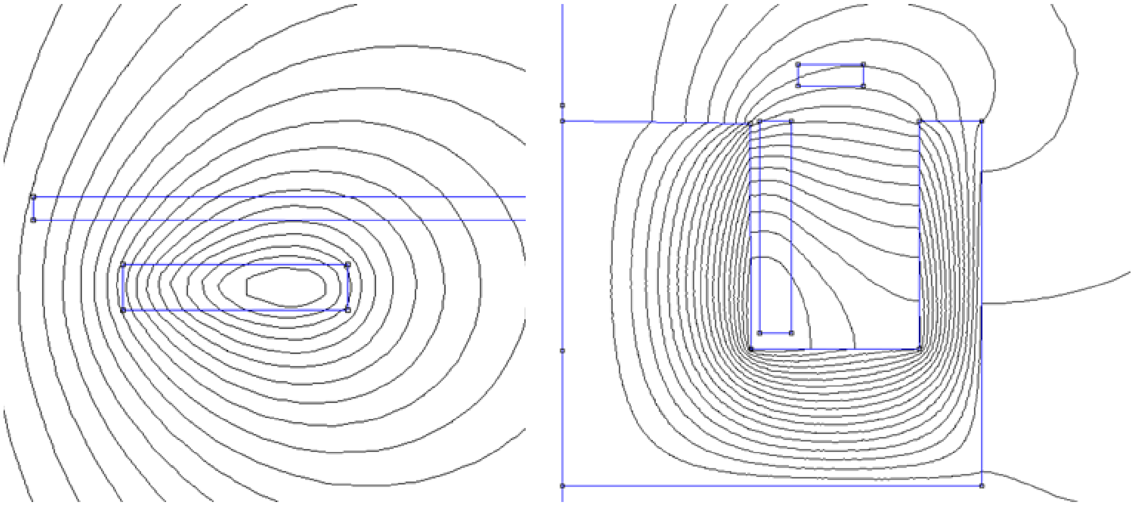

Figure 2: FEMM simulation showing the first iteration and last iteration. Better coupling factors result from more field lines captured by the secondary (shown on top). The configuration on the right has a theoretical coupling factor of .53 and measured value of about .61, which is quite good.

Ferrite Sheet

In order to capture more of the flux on the receiver, we decided to put a ferrite film on the top of the receiver coil. Since maximum thinness, and occasionally flexibility, is preferred for the secondary, we used a film normally used for EMI suppression. The film serves to straighten the flux traveling through the secondary, and markedly improves the coupling factor [Figure 3].

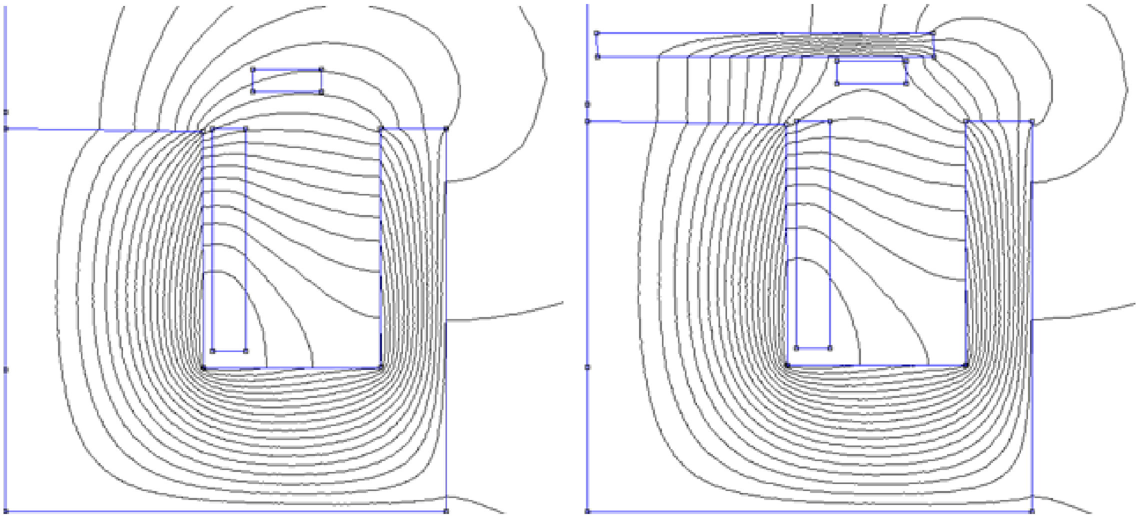

Figure 3: The FEMM simulation on the left shows the transformer without the ferrite sheet. The simulation on the left adds a ferrite sheet that channels the flux around the receiver coil.

We could model the system more accurately using Maxwell which supports 3D non-symmetrical geometries. Maxwell indicated a coupling factor of 0.45 between the coils given our geometry with final distance [Figure 4].

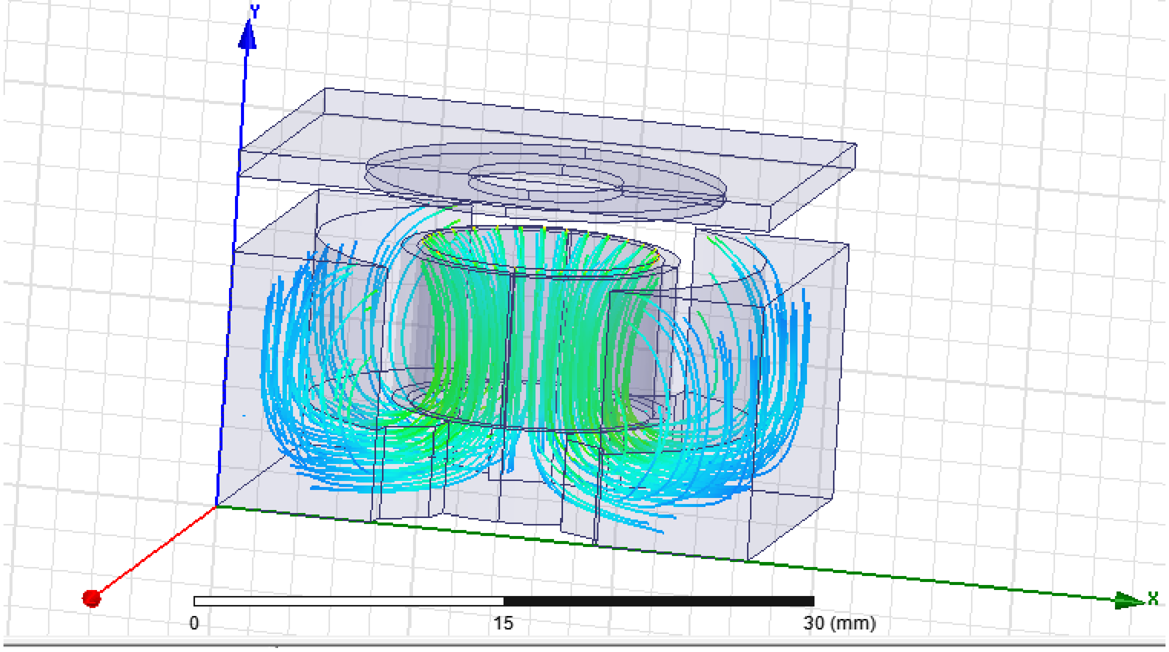

Figure 4: ANSYS Maxswell simulation

Prototyping

We prototyped the inductive charger with the EE152 Lab Setup. We used the processor to generate a 47 kHz square wave, which we then used to switch 12V. We made the receiver coils by winding 28 ga magnet wire around a thin mandrel coated in release agent [Figure 5].

By tightly controlling the thickness of the slot, we could get very precise winding configurations (1 or 2 layers). The coil shown in [Figure 6] has 20 turns and is .5mm thick.

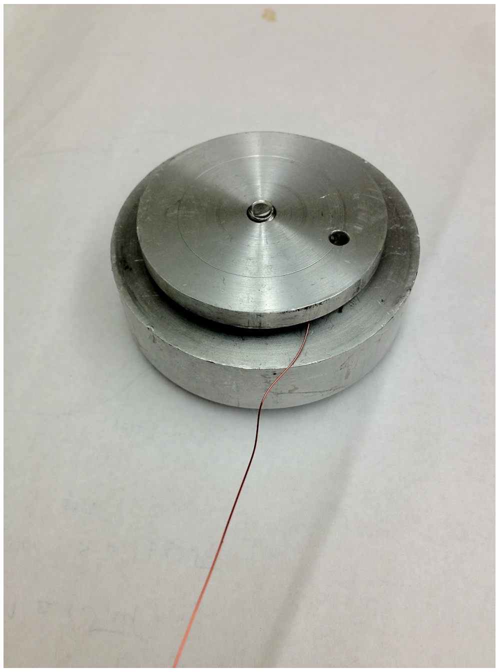

Figure 5: Receiver Coil Winging Mandrel

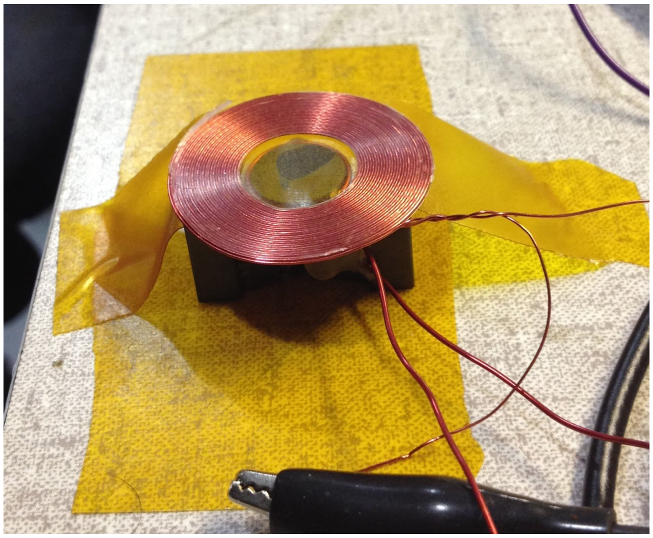

Figure 6: Test Setup. We were able to validate our FEMM simulations by using the EE152 hardware to generated a 12V square wave of small duty cycle.

During our prototype test, we gradually unwound the receiver coil to generate a series of data points. We also re-ran the simulation with the same parameters, and generated a coupling factor plot [Figure 7].

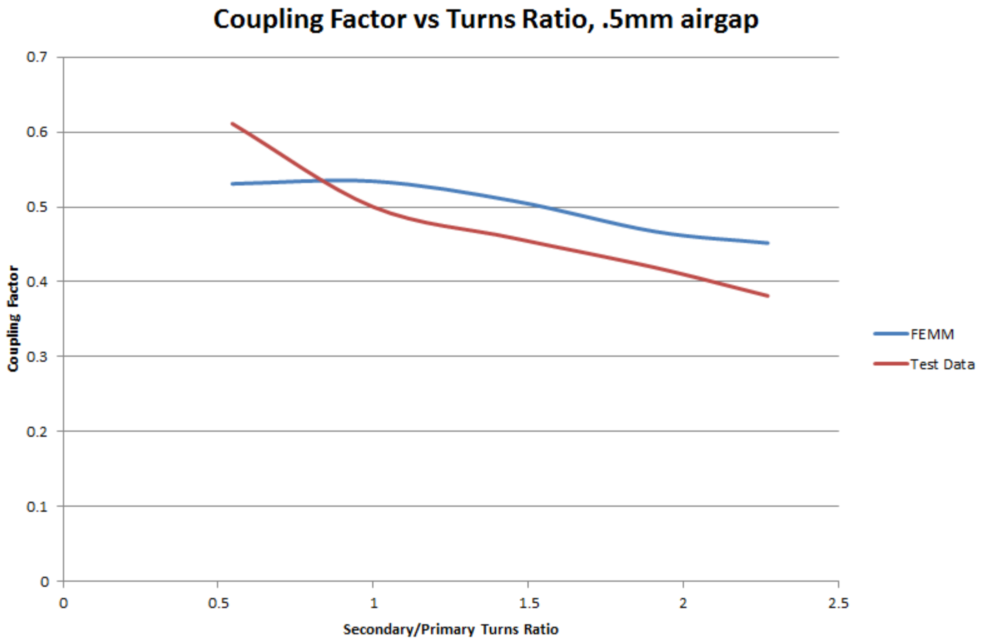

Figure 7: Showing the simulated coupling factor versus the real coupling factor for several different turns ratios. Since the secondary was a single-winding platter, the coupling factor improved as the secondary got smaller and more of the flux lines encircled the loop. See Figure 3 for a visualization.

Implementation

Our objective in building the final prototype was to wirelessly charge a USB powered device. We chose a kindle as the target - it readily accepts 5V, displays when it is being charged, and is relatively cheap to replace if damaged. Our objective was to make the secondary as thin as possible (in the fashion of wireless smartphone charging). Therefore, we built a full-bridge converter in an enclosure, with the transmitter facing upwards.

Component Selection

Switching Frequency

The switching frequency (180khz) was chosen to minimize the size of the filter required on the receiver. We implemented the entire receiver with only surface mount components less than 2mm tall. The largest output filter we could design, a single-pole pi filter, had the following frequency-domain characteristic:

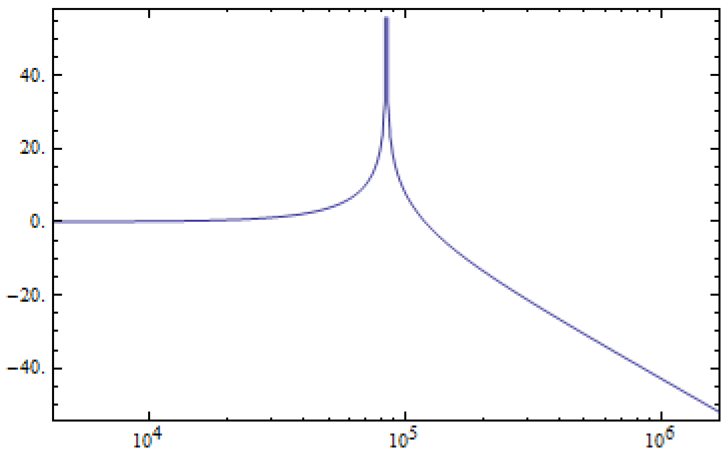

Figure 8: Frequency response of the output filter

Processor

Given the low maximum pwm frequency of the EE152 boards (47 kHz), we used an STM32F107 Discovery Board to generate PWM with hardware enforce dead time. Hardware dead-time greatly reduces the chance of shoot-through and makes the code very simple.

Switches

We used 200V 70A FETs. These were rated for mains voltage and have an avalanche rating to deal with the back EMF produced by the primary side inductor.

Core

We chose the largest PQ core that we could easily find. The selection of core was not especially critical, except that it be large in order to deal with the flux and misalignment of the secondary.

Turns ratio

We used 11 turns on the primary and 40 turns on the secondary. This was to promote a high voltage on the secondary which we subsequently bucked down to 5V.

Output Switching Power Supply

We used an LTC3600 Buck Switcher to switch 15V down to 5V. Since the geometric alignment of the transmitter and secondary determines the effective turns ratio, being able to charge the USB device with an input voltage from 5V to 15V was preferred. By using an efficient switcher designed for fast transients, we increased the tolerance to error and misalignment of the charger by a wide margin.

Circuit diagram

The most difficult aspect of the circuit was the gate drive, especially since we were forced to use a single-layer board and etch it ourselves; we modified the DRC to enforce high minimum trace width and clearance. We used a STM32F4 discovery board because we could use a DIP footprint (easier to etch and solder) rather than the small 64LQFP package. Each gate drive pair looks like this:

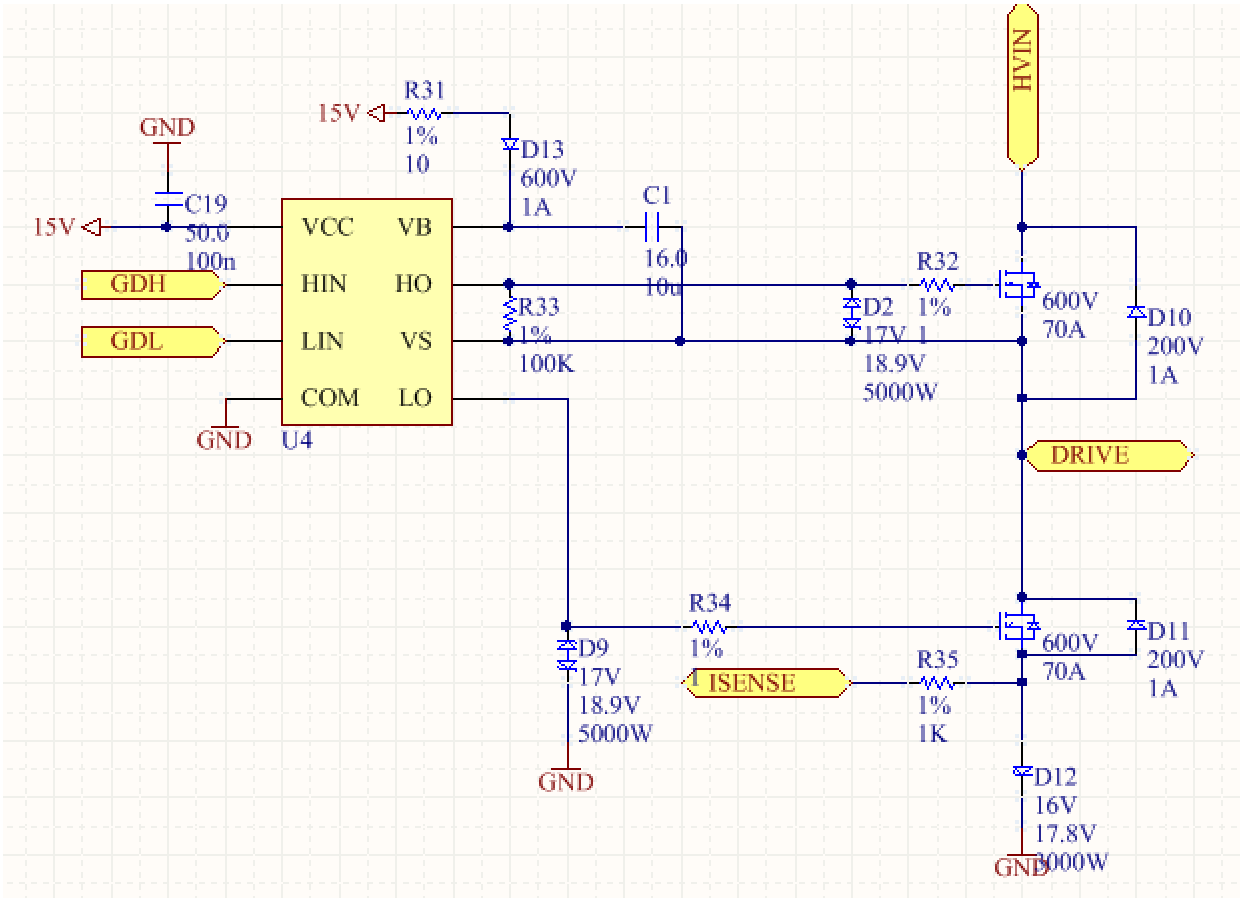

Figure 9: Custom Half-Bridge Driver

We made extensive use of protection circuitry such as zener diodes, fast diodes in parallel with the FETs' body diodes, and series resistors to dampen ringing and voltage spikes.

We decided not to run primary side off 170V. The circuit worked well at 35V input, but we observed large (though very short-lived) approximately 90V voltage spikes on the switch nodes. We were concerned that increasing the voltage further would cause overvoltage faults in the FETs since the clamping diodes were evidently not turning on fast enough, which could have resulted in the destruction of our MCU. Given we reached this stage the weekend before the deadline and did not have enough spare parts to rebuild the critical parts of the circuit (gate drives, MCU, FETs), we made the defensive decision of not increasing the input voltage further.

What We Learned

To put it shortly, inductive power transfer can be made to work well over very short distances, but the falloff with distance is extremely fast. Also, we learned that magnetic fields do not follow intuition and are very sensitive to materials placed next to the active magnetics - even placing your hand near the transmitter would affect performance.

In more detail, we gained familiarity with SPICE, FEMM, ANSYS Maxwell, hand-etching circuit boards, and the importance of getting DIP footprints correct. Furthermore, we learned about advanced deadtime timers on the STM32F107. When debugging the full bridge transmitter, we learned how to get useful data out of current probes. Finally, from messy power lines on our receiver pcb, we learned about routing power, ground, and the proper use of bypass capacitors.

Results

We were able to charge an Amazon Kindle at 1.5W at a coil-coil distance of approximately 3mm. The charging current holds for +2mm in the vertical direction and +/- 4mm.

The circuit switches 20V across the primary inductor at 180KHz. From this we were able to produce voltages exceeding 15V on the secondary that were clamped to 15V by the zener.

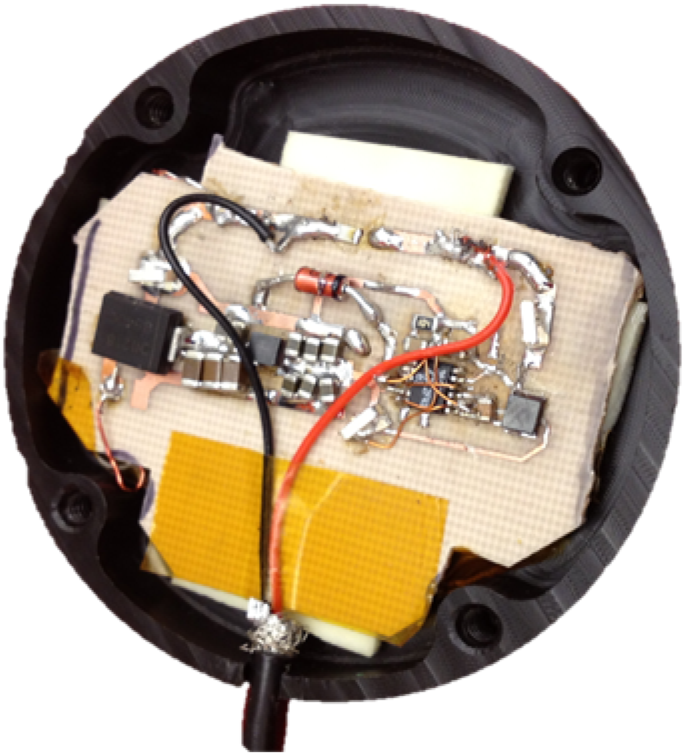

Figure 10: Receiver PCB. The receiver coil is underneath.

Figure 11: Transmitter

We also tested the dependence of output voltage on distance:

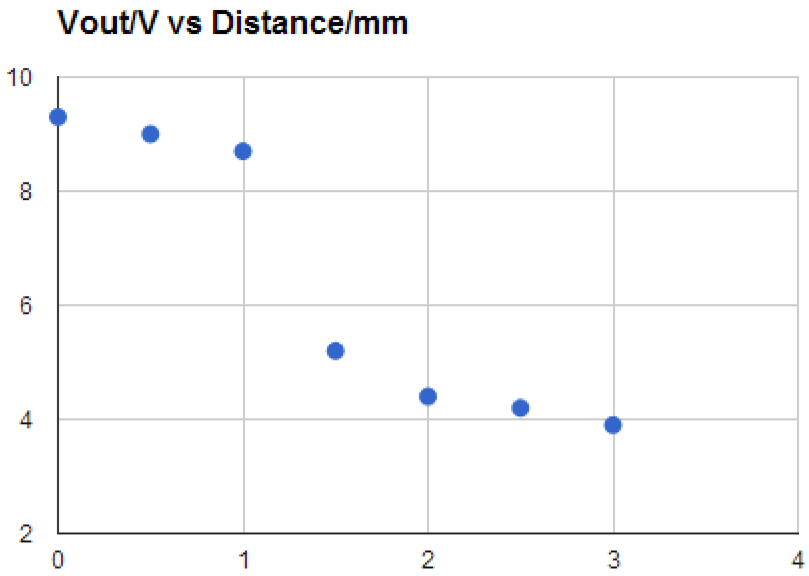

Figure 11: Output voltage (coupling factor) varies with distance as fewer field lines are captured by the receiver coil.

The discontinuity can be accounted for by considering that the buck turns off at around 6V input.

This table summarizes the results of the prototype:

Results	**Project Proposal**	**Finished Project**
Input Voltage	170V	20V
Output Voltage	5V	5V
Efficiency	50% total	50% marginal efficiency (not including switching losses). 20% total system efficiency. Most of this loss is due to the gate capacitance of the large FETs selected (c. 250nC).
Charges USB Device	Yes	Yes

What's Next

If we had more time we would have experimented with a more advanced feedback mechanism. Our original sensing strategy was to detect the asymmetry in current on each half of the full bridge switching cycle using half wave rectification on the output but this proved prohibitively difficult owing to a low signal/noise ratio. We discovered that it was very easy to determine whether the secondary was drawing power by observing the current supplied to the full bridge. We therefore could have full wave rectified the output instead of half wave.

Resonance would have resulted in more sinusoidal looking current waveforms through the coils - if we had more time we would have experimented with introducing capacitance to the system and determining its effect on efficiency.

Another interesting idea we had but which we never got to test out was a system for spreading the primary over a large area. Instead of using a very large primary coil, we thought of placing multiple primaries in an alternating arrangement to promote alternating B-field lines in and out of the table. This would be interesting to experiment with given more time since it scales linearly with area (the alternative--the single enormous coil--scales approximately quadratically).

The performance gain that we saw (5-10%) from adding the ferrite film on top of the receiver coil was unexpected. Another possible avenue for experimentation would by changing the shape of the ferrite film on the top and/or bottom of the coil, further focusing the field. It’s possible that encasing the coil in a block of ferrite might have the best properties, but more modeling and testing would be required to conclude that there would be better ways of focusing field lines.