MAY15-30:
Fast, Compact, High Strength Magnetic Pulse Generator

Team Members

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Communication Leader

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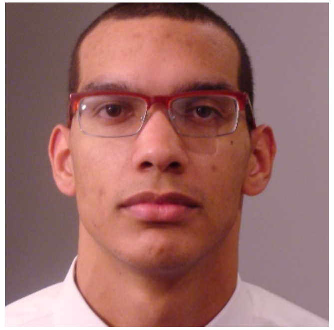
Systems Leader & Commissioner



Brandon Dixon
Layout Designer

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Coil Designer

Advisors
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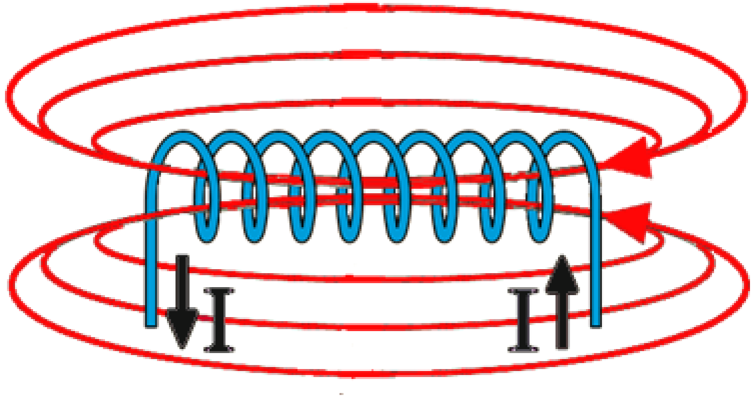
Client
Iowa State University High Speed Systems Engineering Lab

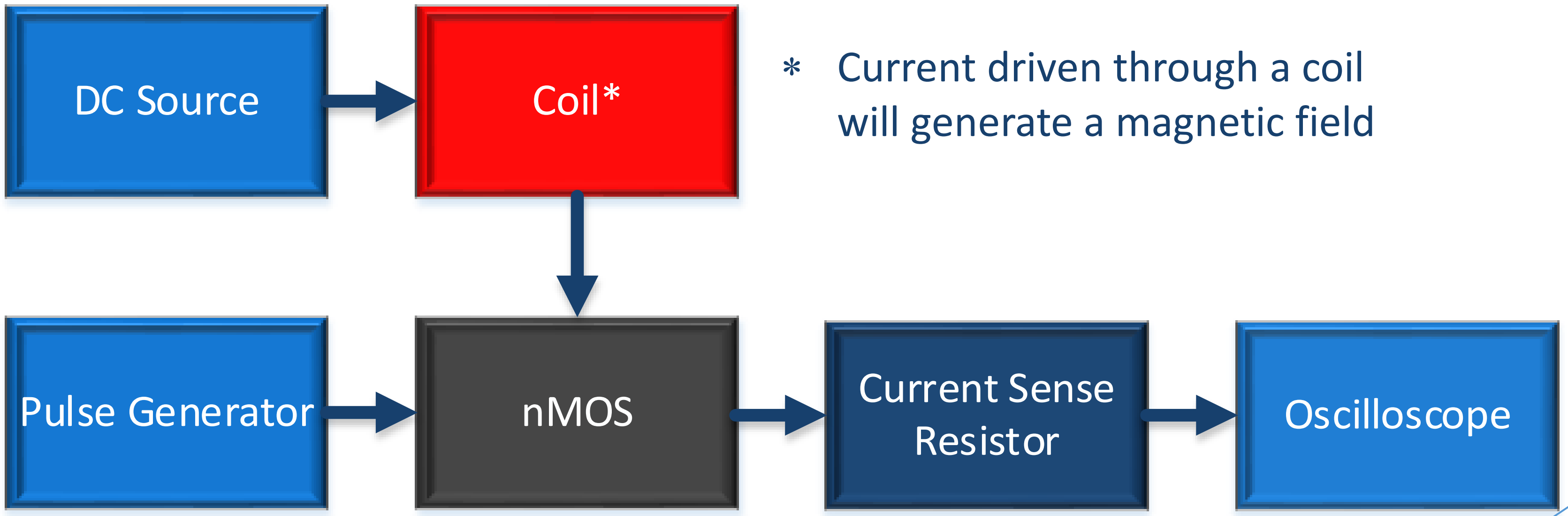
Presentation Outline

- Project Scope
- Design Cycle
  - Coils
  - Schematics
  - Layouts
- Test Plan
  - Electronics Test Plan
  - Optics Test Plan
- Results
- Challenges

Project Scope

- Deliverables
  - Fast (1µs)
  - Compact (3.5” x2”)
  - High Strength (500 G)





DC Source

Coil*

* Current driven through a coil will generate a magnetic field

Pulse Generator

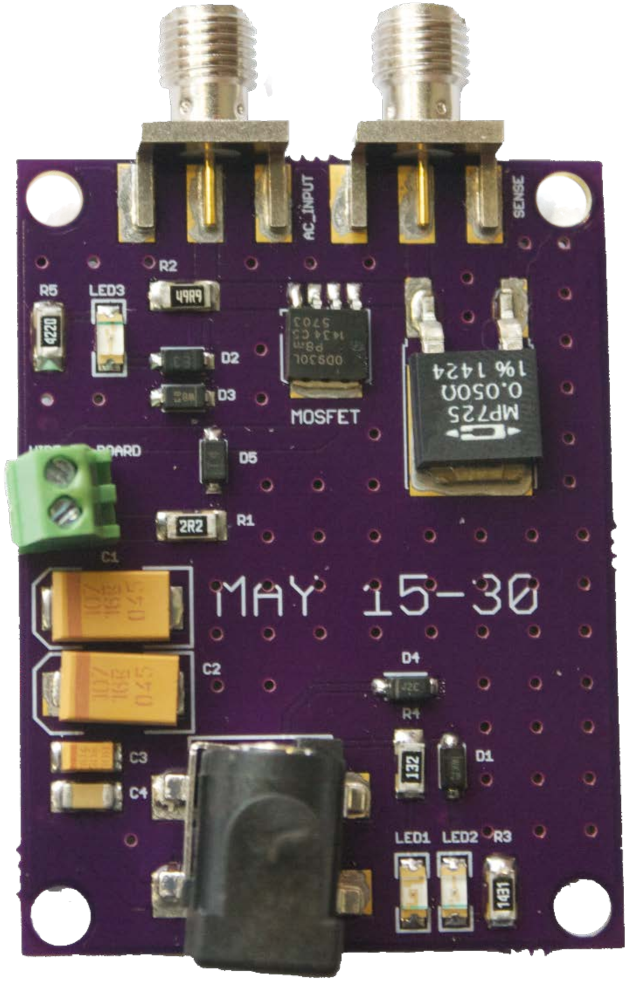
nMOS

Current Sense Resistor

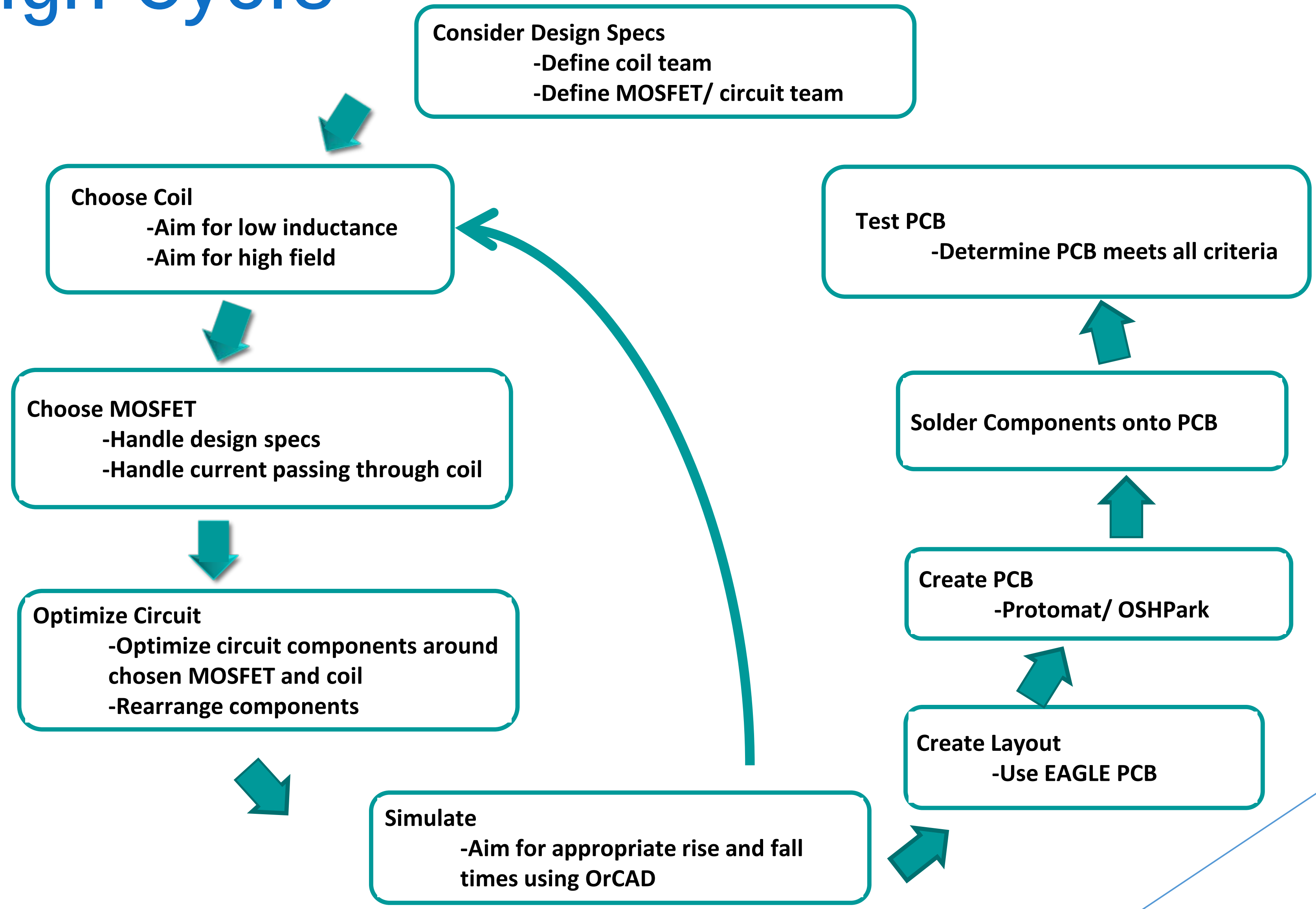
Oscilloscope

Project Scope

- Functions
  - Generates a magnetic field with strength ≥ 500 gauss
  - Able to generate a magnetic field using a 1μs pulse width
- Features
  - Barrel jack for ≤ 15 V DC source
  - SMA port for pulse generator
  - SMA port for 0.050 Ω current sense resistor
  - Wire to board connection allows for interchangeable coils
  - Indicator LEDs for user friendly functions and protective circuitry
  - Dimensions: 3.5" x 2”



Design Cycle



Consider Design Specs
- Define coil team
- Define MOSFET/ circuit team

Choose Coil
- Aim for low inductance
- Aim for high field

Choose MOSFET
- Handle design specs
- Handle current passing through coil

Optimize Circuit
- Optimize circuit components around chosen MOSFET and coil
- Rearrange components

Simulate
- Aim for appropriate rise and fall times using OrCAD

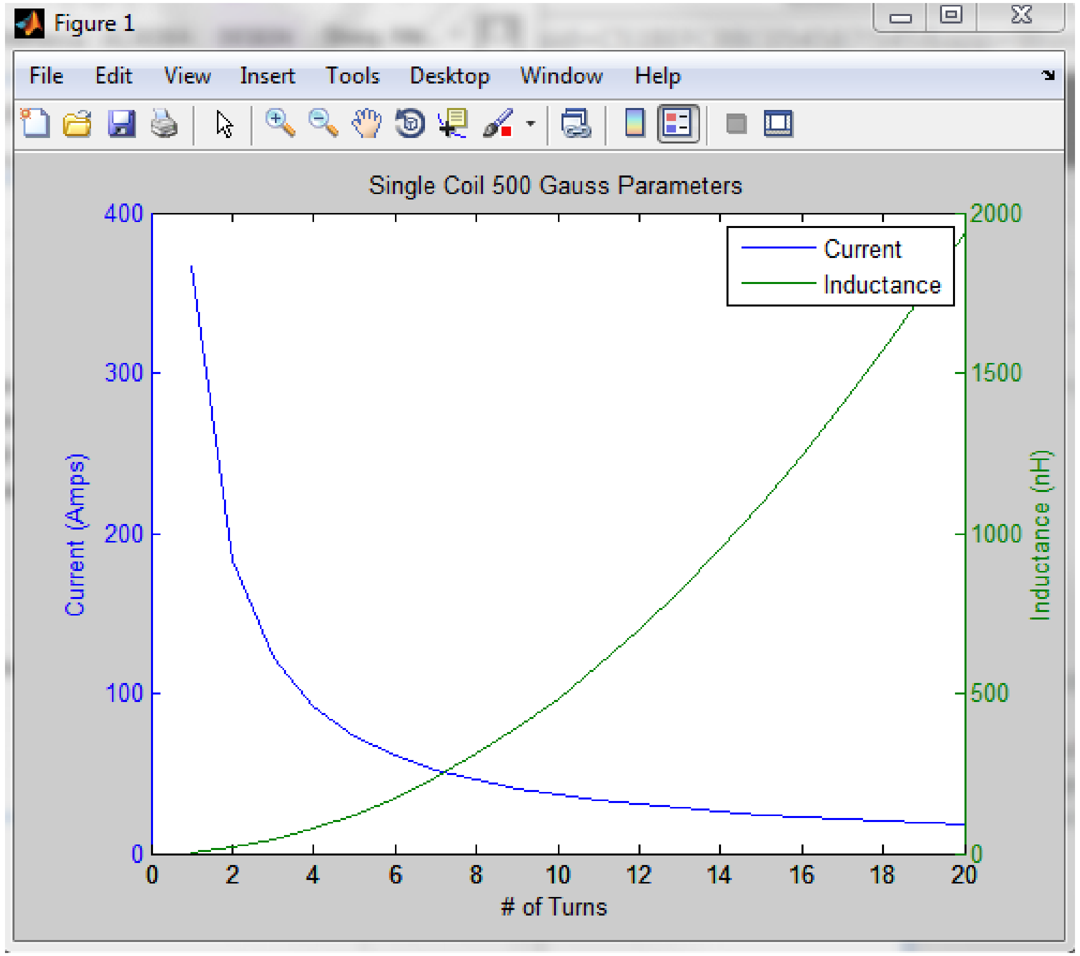
Create Layout
- Use EAGLE PCB

Create PCB
- Protomat/ OSHPark

Solder Components onto PCB

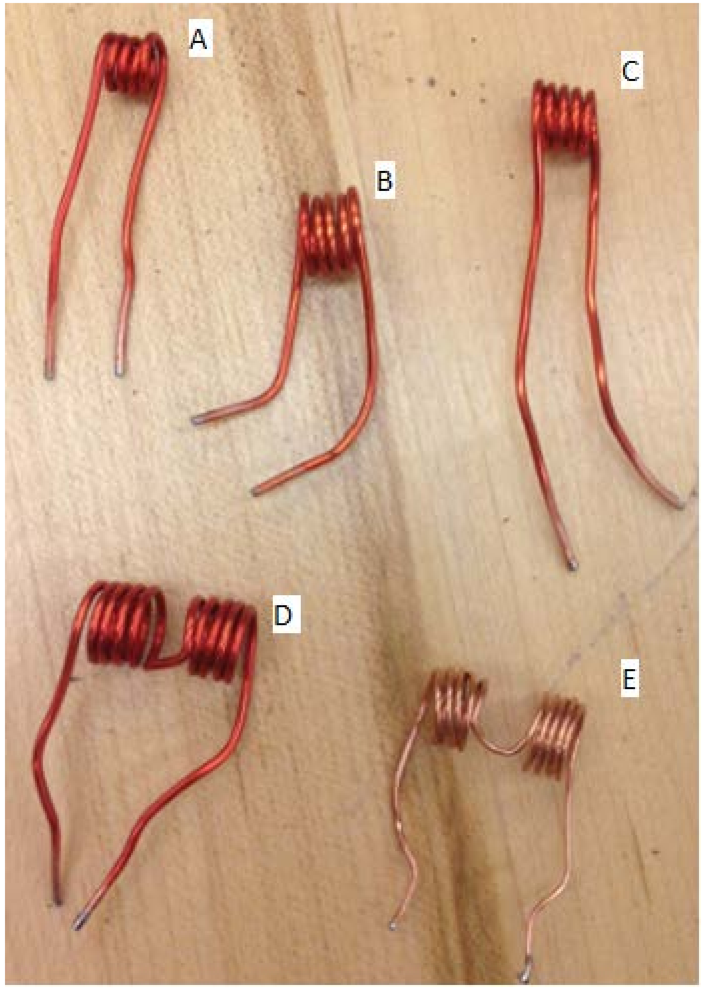
Test PCB
- Determine PCB meets all criteria

Coils

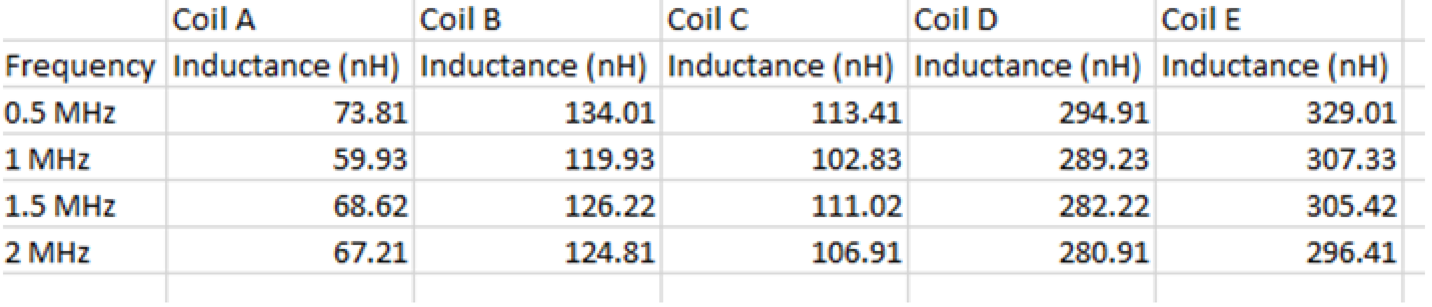


- Lower inductance → faster rise time
  - Lower inductance requires higher current to maintain field strength

Coils Continued…

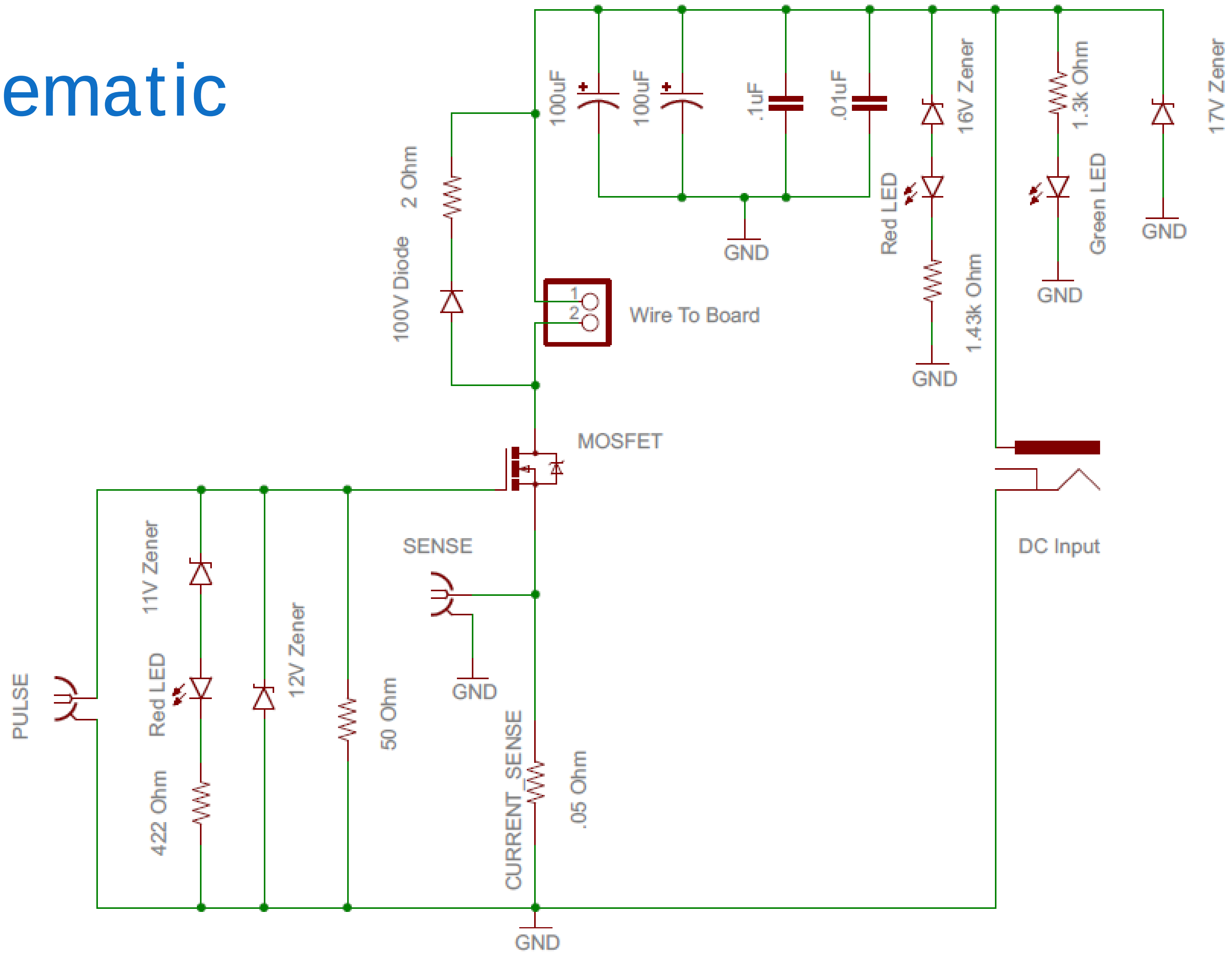


- Helmholtz coils give a stronger magnetic field for similar parameters
- Single coils give lower inductance for similar parameters



	Coil A	Coil B	Coil C	Coil D	Coil E
Frequency	Inductance (nH)	Inductance (nH)	Inductance (nH)	Inductance (nH)	Inductance (nH)
0.5 MHz	73.81	134.01	113.41	294.91	329.01
1 MHz	59.93	119.93	102.83	289.23	307.33
1.5 MHz	68.62	126.22	111.02	282.22	305.42
2 MHz	67.21	124.81	106.91	280.91	296.41

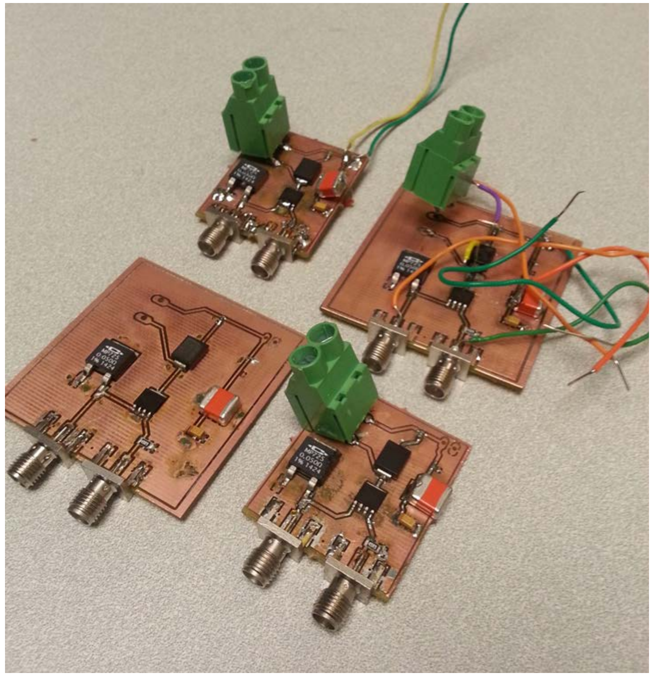
Schematic

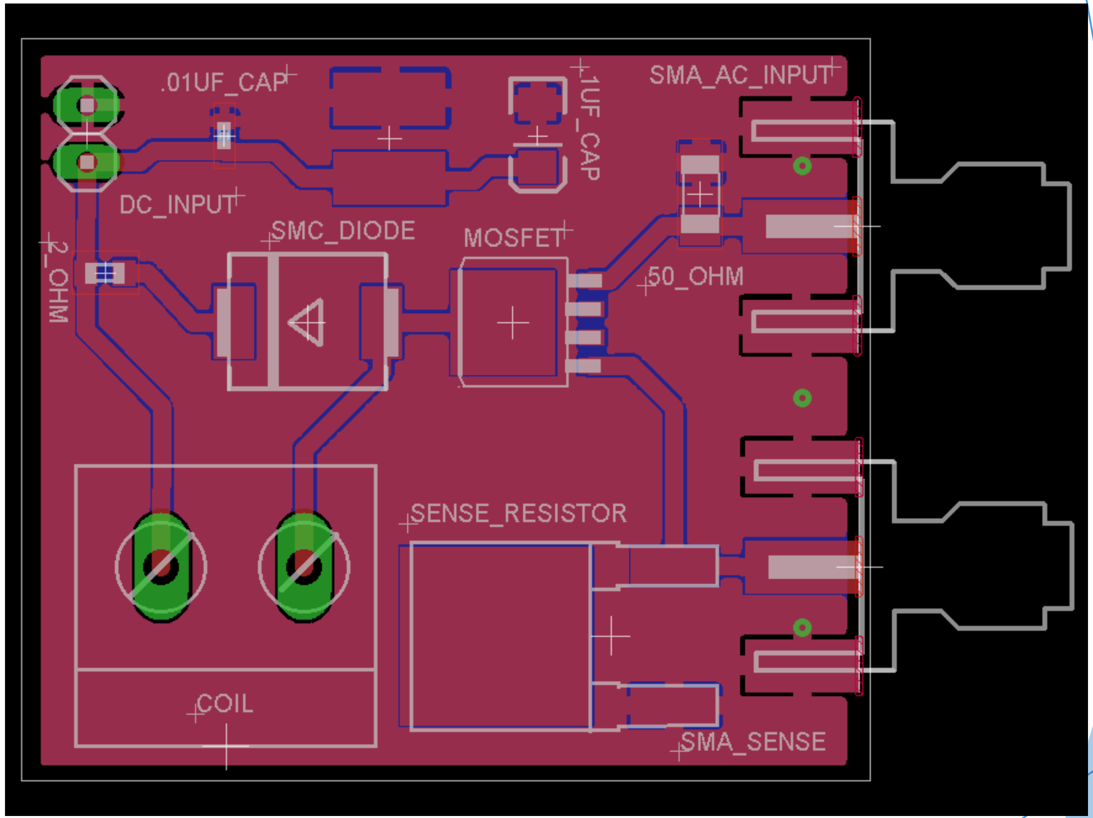


100uF
100uF
.1uF
.01uF
16V Zener
1.3k Ohm
17V Zener
2 Ohm
100V Diode
GND
Red LED
Green LED
GND
GND
1
2
Wire To Board
1.43k Ohm
GND
MOSFET
DC Input
SENSE
11V Zener
12V Zener
GND
PULSE
Red LED
50 Ohm
422 Ohm
CURRENT_SENSE
.05 Ohm
GND

Layout Process Version 1

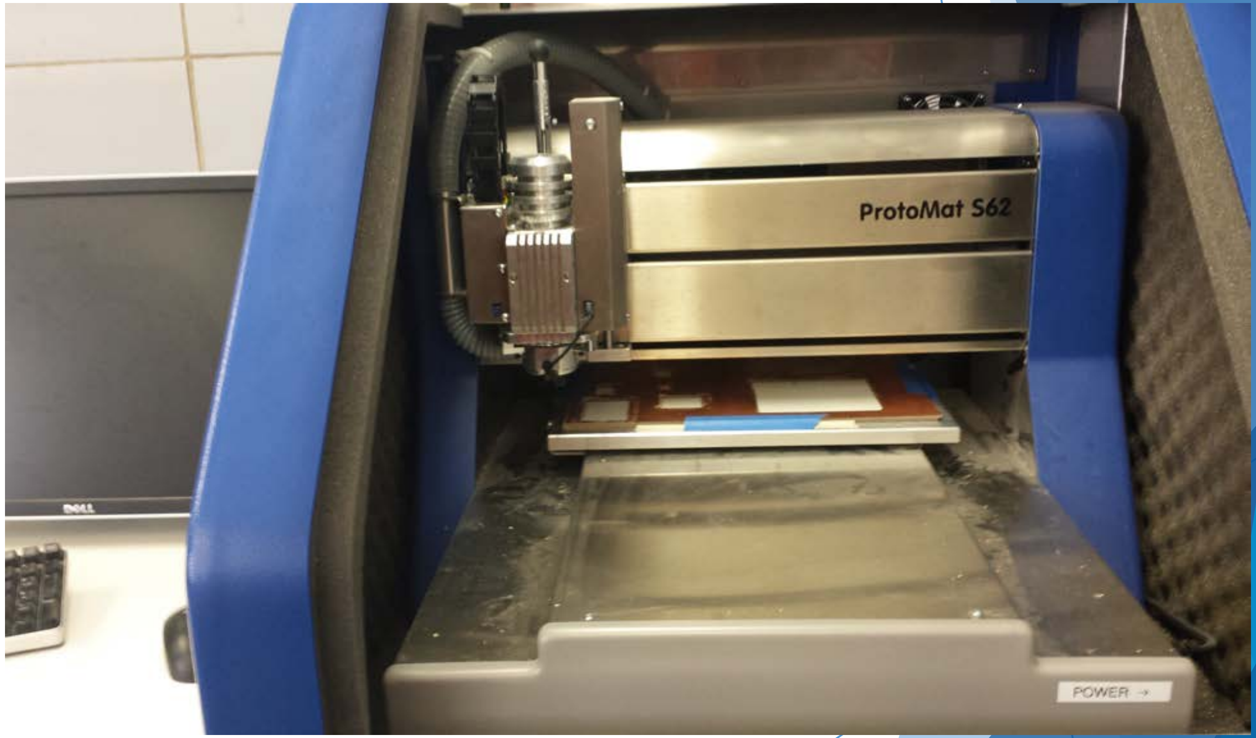
- Designed in EaglePCB
- Created on ProtoMat S62





Layout to Protoype

- ProtoMat S62
- Export Layout in GERBER file
- Each file indicates a particular layer
- Copper top(GTL) and bottom layer(GBL)
- Drill size(TXT)
- Create Isolation around the line

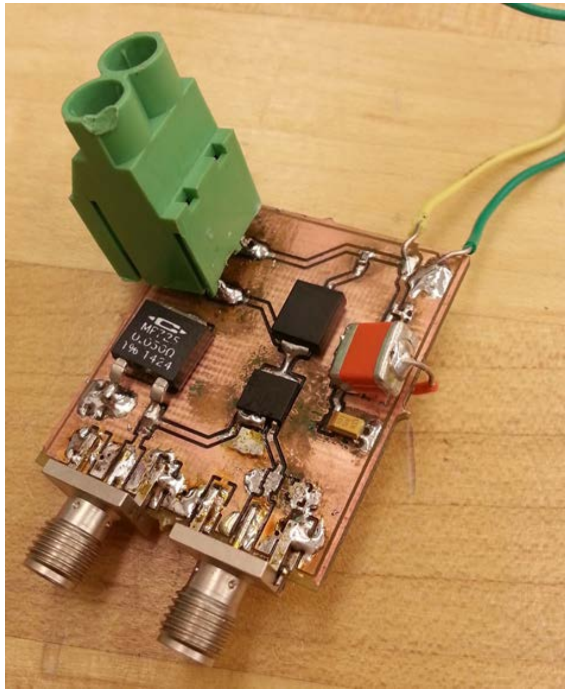


Protomat S62

Video Here

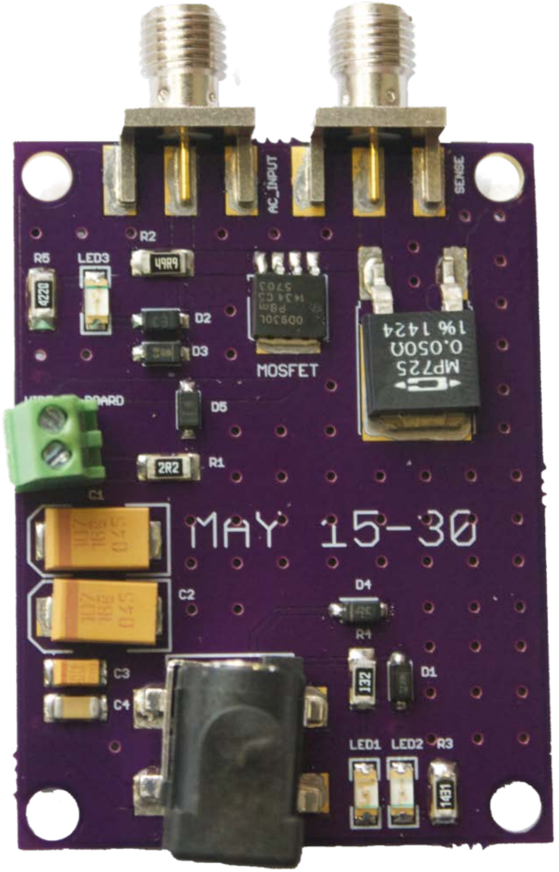
Soldering Challenges

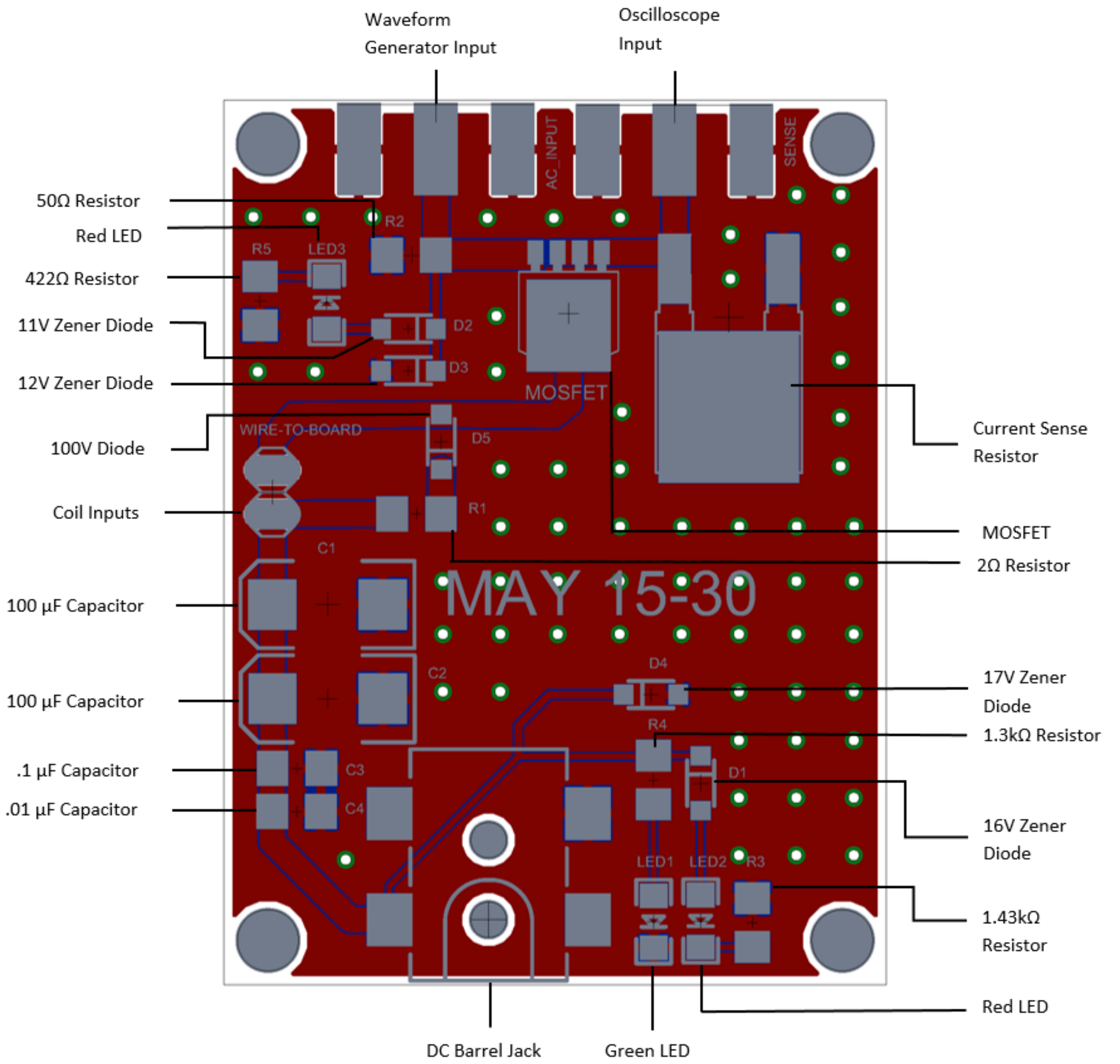
- Size of components
- Size of board
- Weak traces



Layout Process Version 2

- Designed in EaglePCB
- Sent to OSHPark





Waveform Generator Input

Oscilloscope Input

50Ω Resistor

Red LED

422Ω Resistor

11V Zener Diode

12V Zener Diode

100V Diode

Coil Inputs

100 µF Capacitor

100 µF Capacitor

.1 µF Capacitor

.01 µF Capacitor

Current Sense Resistor

MOSFET

2Ω Resistor

17V Zener Diode

1.3kΩ Resistor

16V Zener Diode

1.43kΩ Resistor

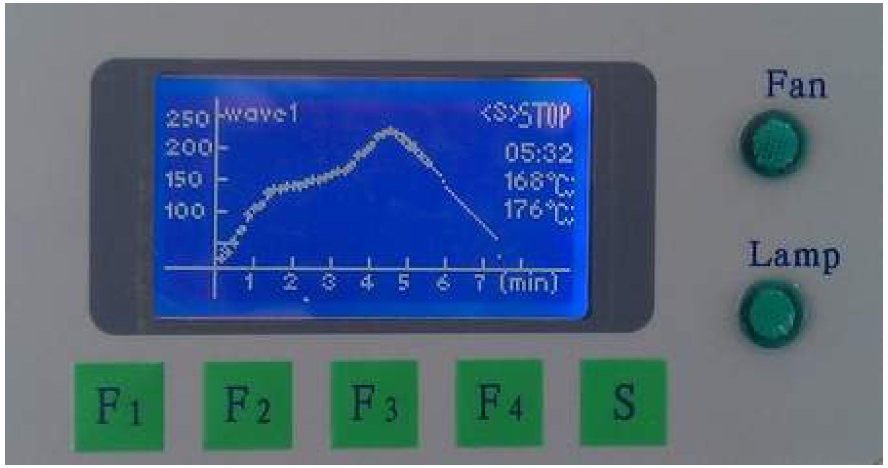
Red LED

DC Barrel Jack

Green LED

Reflow Soldering

- Solder Paste
- Reflow Oven
- Thermal Profile
- Check Connection



Electronics Test Plan

Test Circuit Continuity

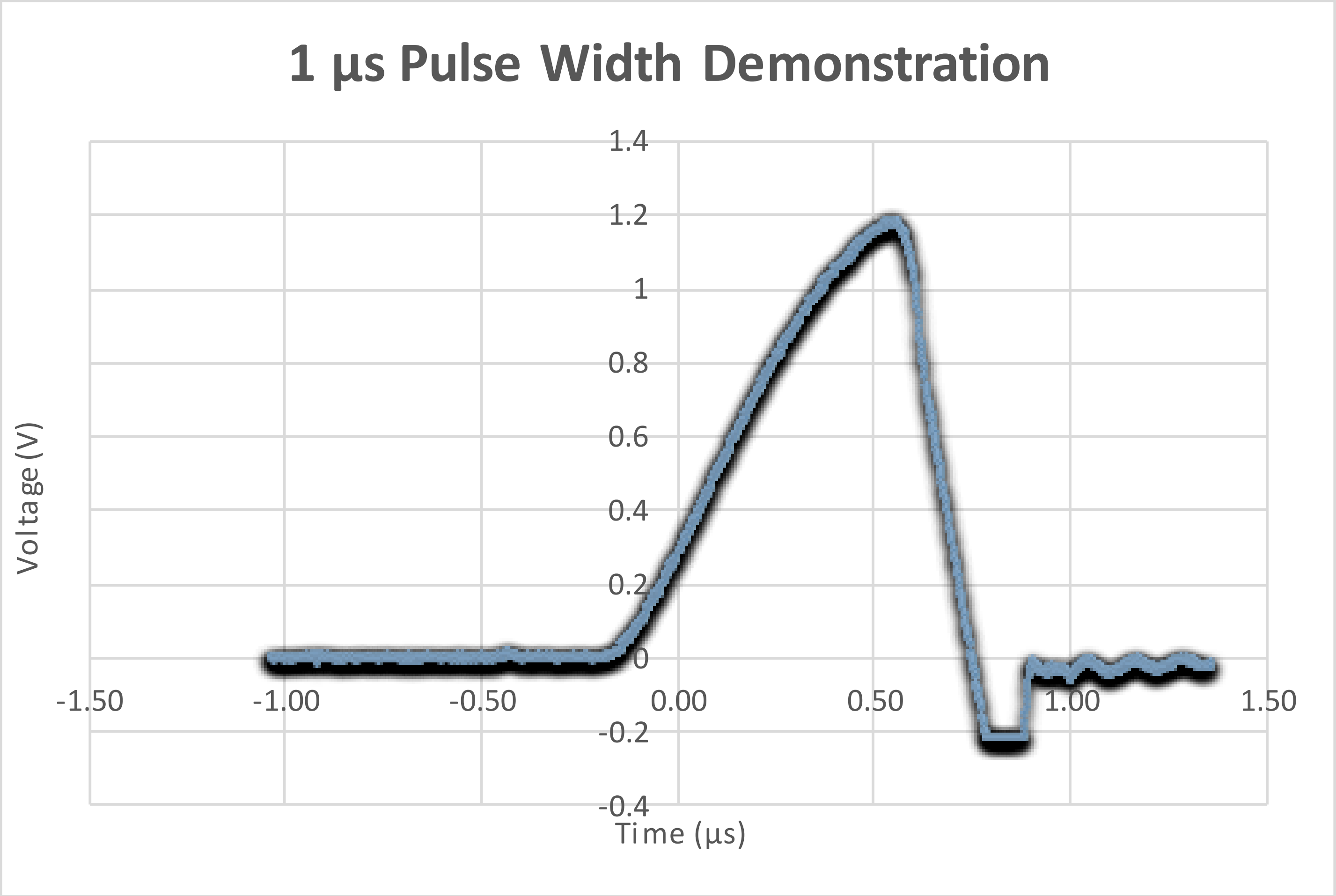
Measure Source Voltage

- 1 µs pulse

Evaluate Current

- Magnetic Field strength met?

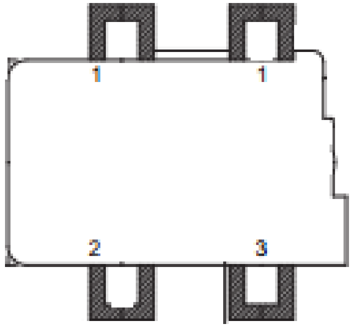
Preliminary Results

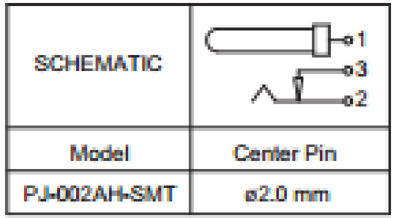


- 15 volts DC input
- 1 µs pulse width input
- 2 V amplitude peak-to-peak
- Measured pulse width of 930 ns

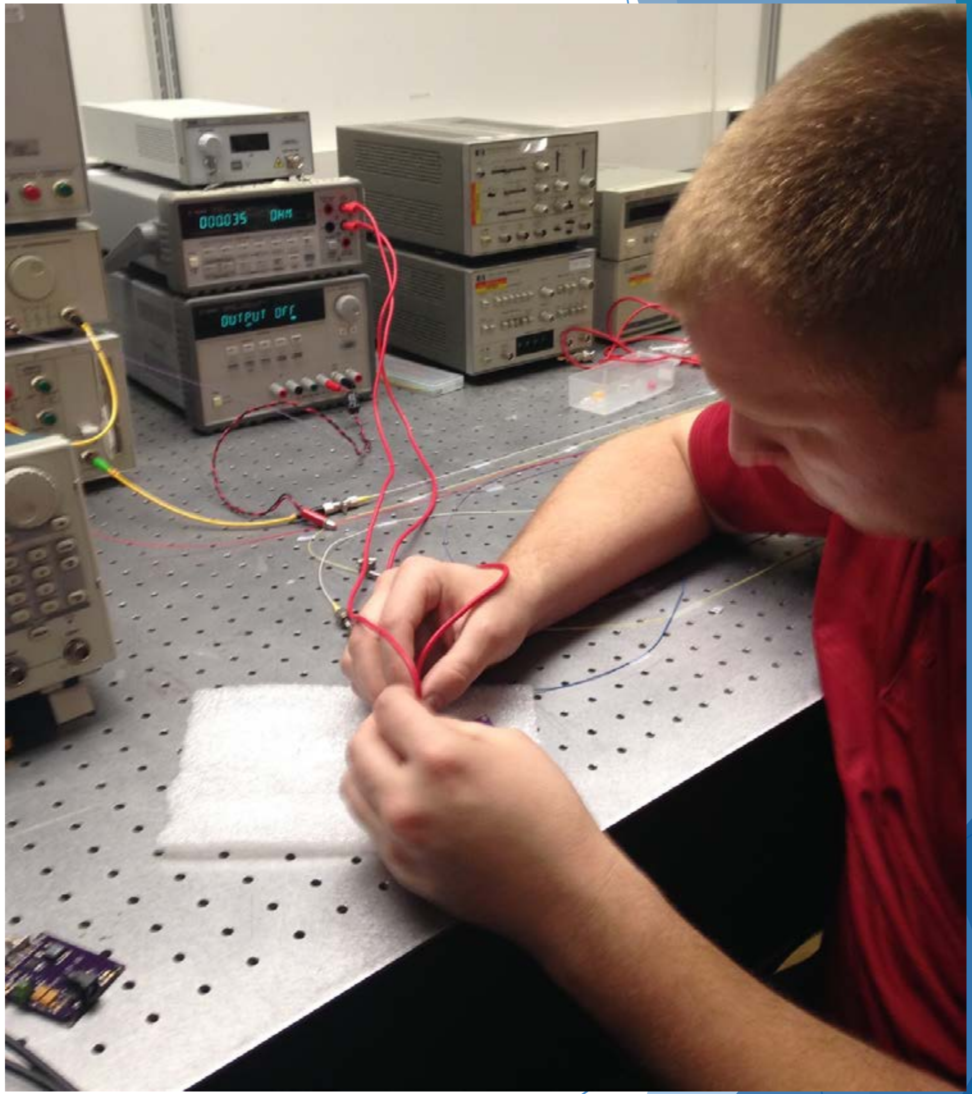
Technical Challenges

- Bad Cables
- “Cold Solder”
- Duty Cycle Considerations
- DC Barrel Jack layout incorrect
- Measuring magnetic field





SCHEMATIC	
Model	Center Pin
PJ-002AH-SMT	ø2.0 mm



Optics Test Plan

- Sagnac Interferometer

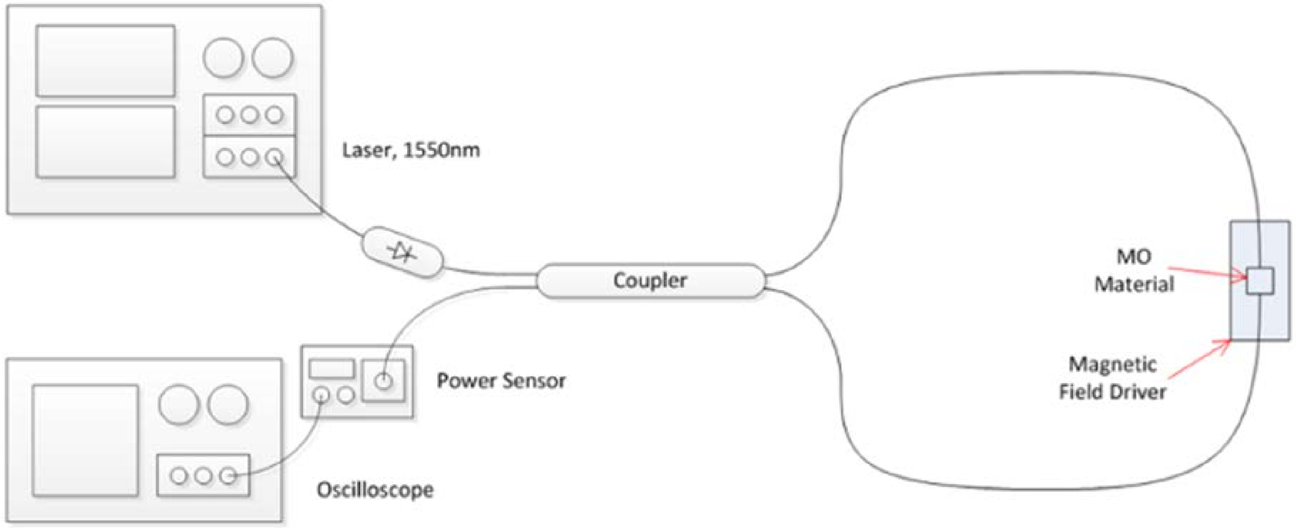
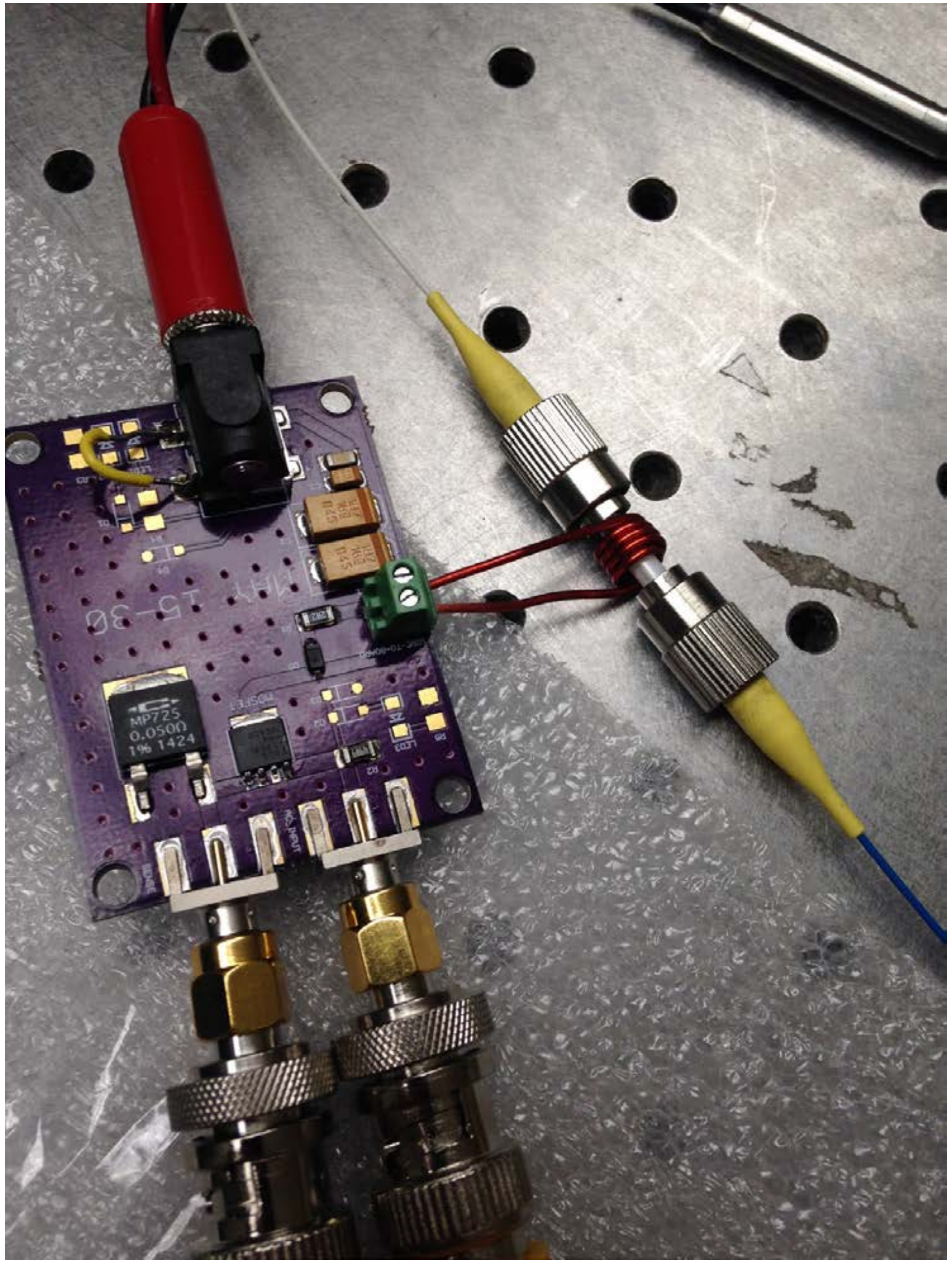
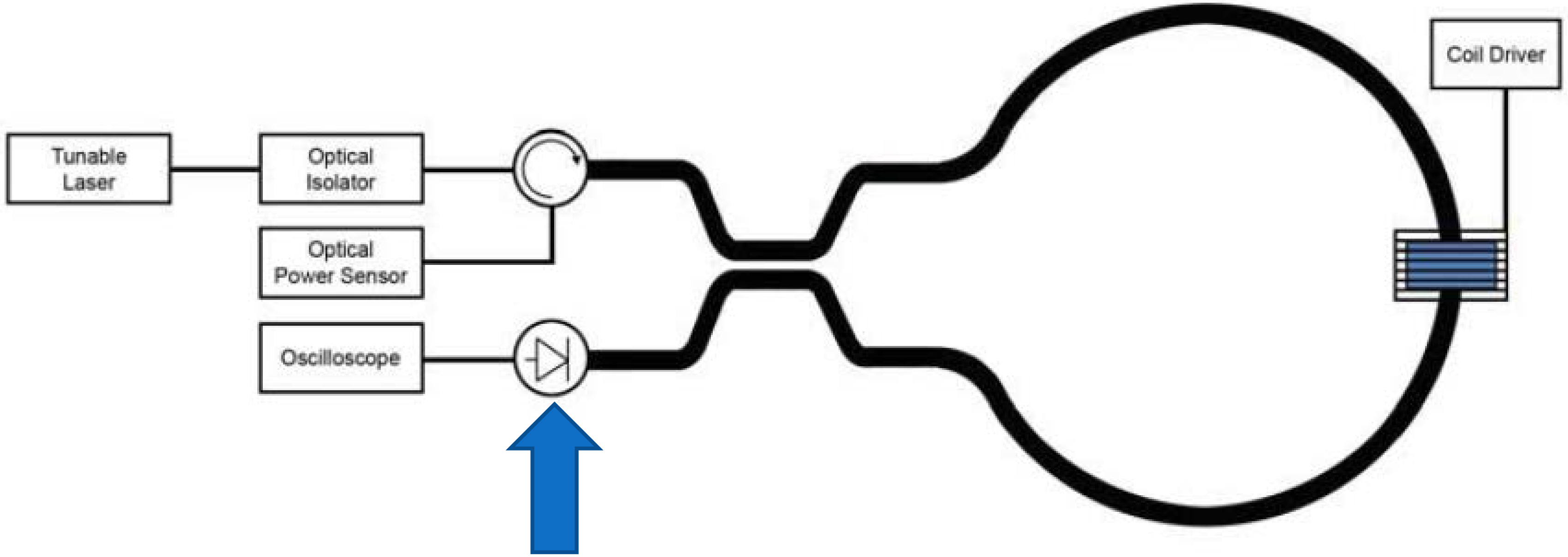


Photo Courtesy of Dr. John W. Pritchard

Client's Experiment



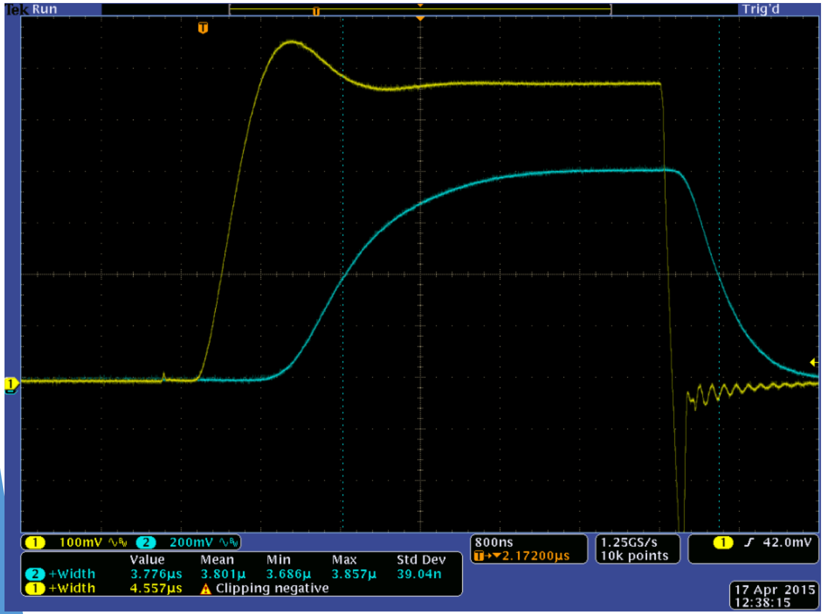
New Test



Transimpedance Amplifier

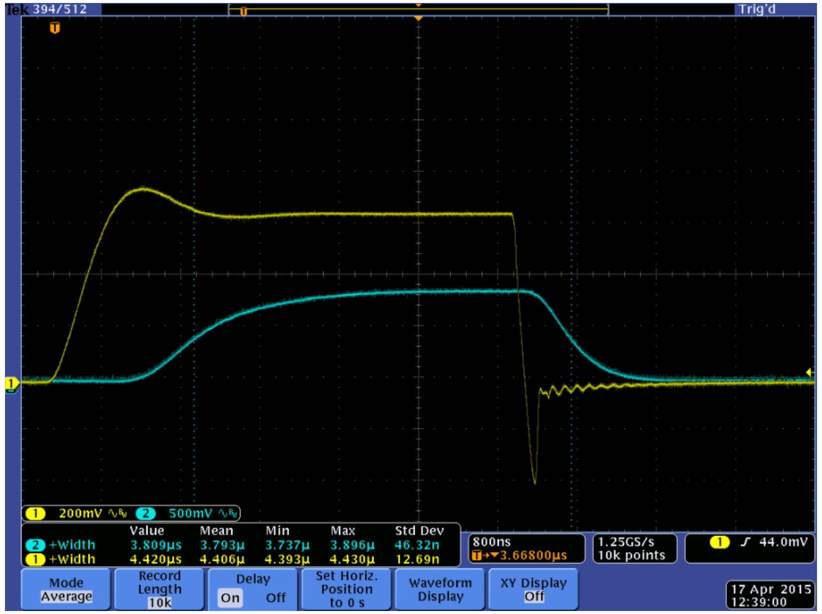
Tioh, Jin-Wei, "Interferometric switches for transparent networks: development and integration" (2012). *Graduate Theses and Dissertations.* Paper 12487.

New Test Results



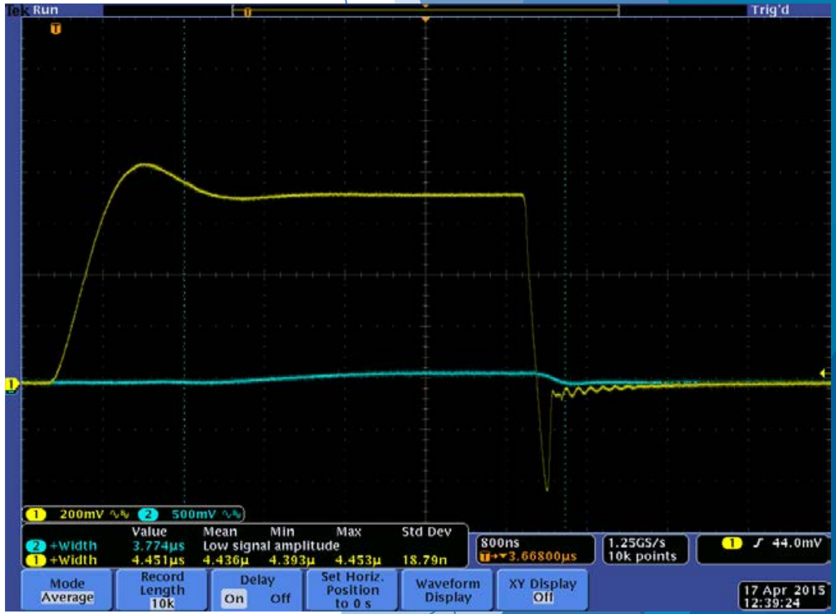
```
1  100mV  2  200mV
              Value     Mean     Min      Max      Std Dev
2 +Width      3.776µs   3.801µ   3.686µ   3.857µ   39.04n
1 +Width      4.557µs   ⚠ Clipping negative
800ns
T→▼2.17200µs
1.25GS/s
10k points
1 ƒ 42.0mV
17 Apr 2015
12:38:15
```

2.8 V Input



```
1  200mV  2  500mV
              Value     Mean     Min      Max      Std Dev
2 +Width      3.809µs   3.793µ   3.737µ   3.896µ   46.32n
1 +Width      4.420µs   4.406µ   4.393µ   4.430µ   12.69n
800ns
T→▼3.66800µs
1.25GS/s
10k points
1 ƒ 44.0mV
17 Apr 2015
12:39:00
```

2.9 V Input



```
1  200mV  2  500mV
              Value     Mean     Min      Max      Std Dev
2 +Width      3.774µs   Low signal amplitude
1 +Width      4.451µs   4.436µ   4.393µ   4.453µ   18.79n
800ns
T→▼3.66800µs
1.25GS/s
10k points
1 ƒ 44.0mV
17 Apr 2015
12:39:24
```

3.0 V Input

Theoretical Results vs Actual Discrepancy Speculation

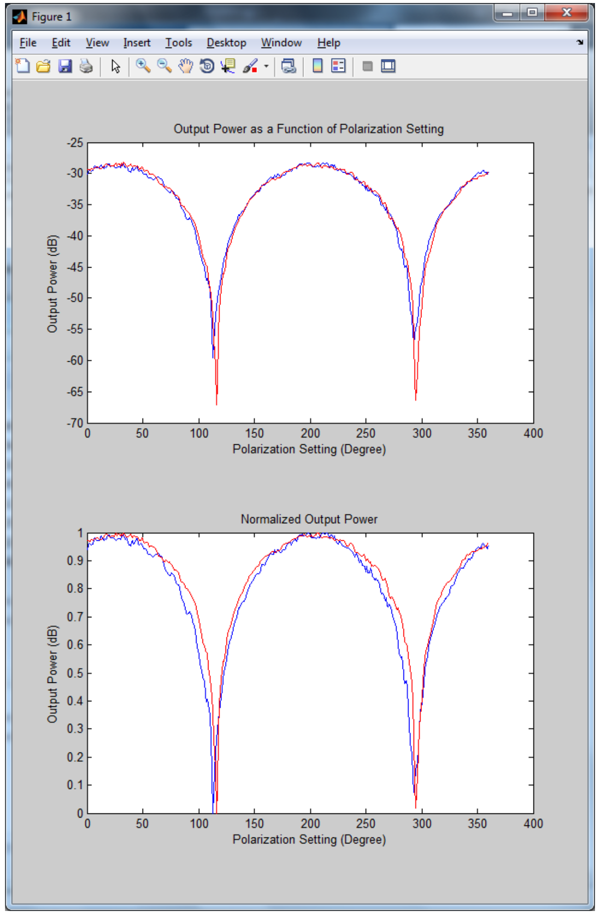
- Magneto-optic material saturated at 225 G
- Current sense resistor voltage ≈ 750 mV
  - Current through coil ≈ 15 A
    - B ≈ 112 G
- Many factors could be responsible
  - Magnetic permeability
  - Imperfect coil
  - Sensitivity of the MO material
  - Human error
- Ongoing investigation

Conclusion

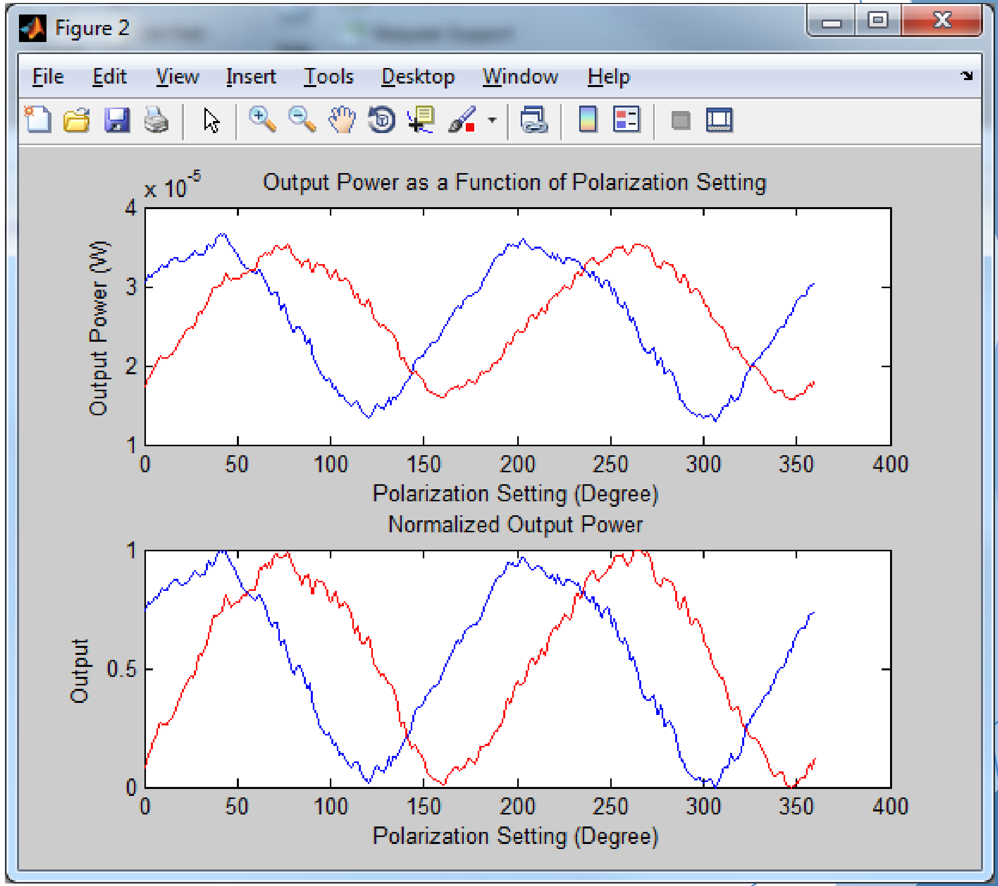
- Achievement of requirements demonstrated to client
- Wire-to-board connector allows various coils to be used for other applications such as
    - Megawatt Q-switched laser systems
    - Research in biomagnetism
    - Small solenoid systems

Questions?

Test Results



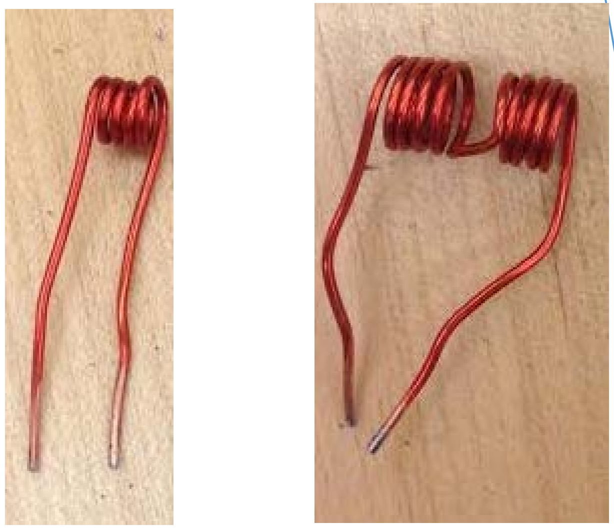
Obtained Results



Expected Results

Coil Equations

Single Coil Calculations



$$B = \frac{\mu N I}{\sqrt{l^2 + 4R^2}} = \frac{(4\pi\ x\ 10^{-7})(5)(48.41)}{\sqrt{(1\ x\ 10^{-3})^2 + 4(3\ x\ 10^{-3})^2}} = 0.050005\ Teslas = 500.05\ gauss$$

$$L = \frac{\mu N^2(\pi R^2)}{\sqrt{l^2 + 4R^2}} = \frac{(4\pi\ x\ 10^{-7})5^2(\pi * (3\ x\ 10^{-3})^2)}{\sqrt{(1\ x\ 10^{-3})^2 + 4(3\ x\ 10^{-3})^2}} = 146nH$$

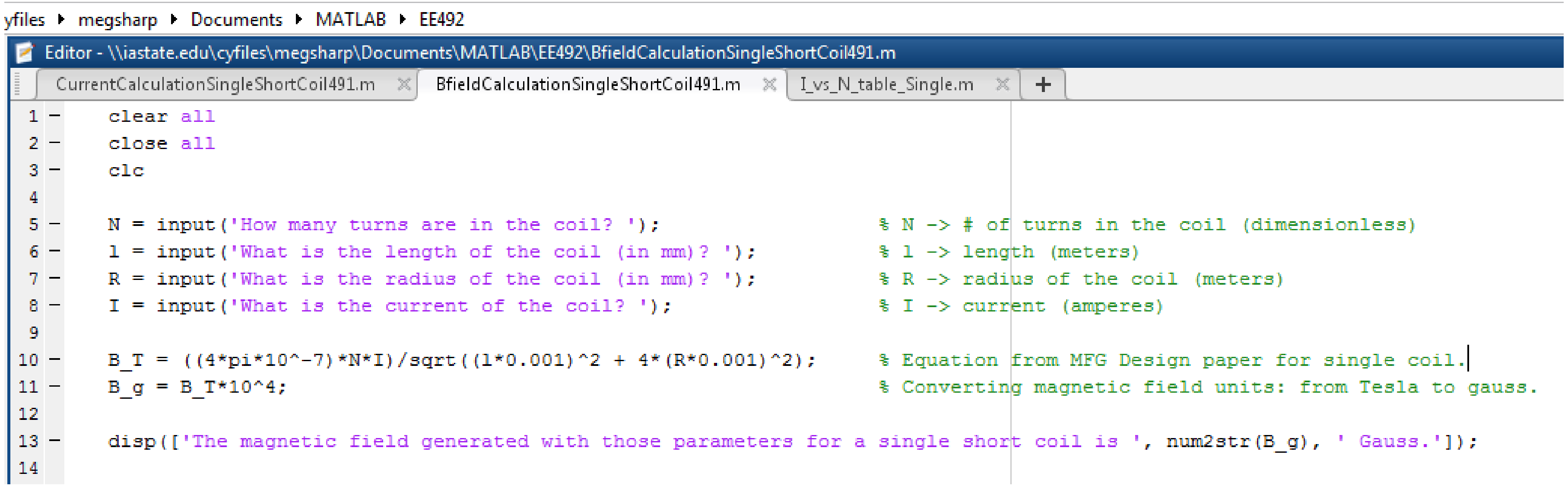
Helmholtz Coil Calculations

Note: Here are relevant variables for this section:
μ: permeability of free space ($4\pi\ x\ 10^{-7}$)
N: number of turn of a coil (dimensionless)
R: radius of a coil (meters)
l : length of a coil (meters)
L : inductance of a coil (Henries)
B : magnetic field of a coil (Teslas. 1 tesla=10,000 gauss)
I : current through a coil (amperes)

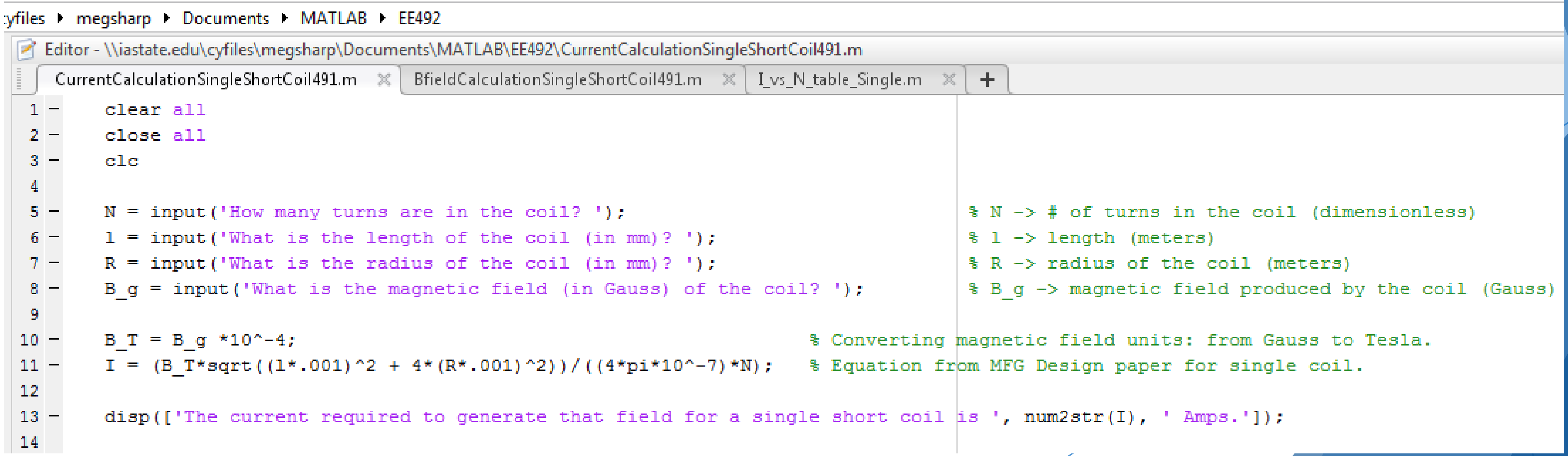
$$B = \frac{\mu(0.7155)NI}{R} = \frac{(4\pi\ x\ 10^{-7})(0.7155)(5)(33.37)}{(3\ x\ 10^{-3})} = 0.050006\ Teslas = 500.06\ gauss$$

$$L = 2\mu(0.7155)N^2\pi R = 2(4\pi\ x\ 10^{-7})(0.7155)5^2(\pi(3\ x\ 10^{-3})) = 423.7nH$$

MATLAB CODE – Single Coil

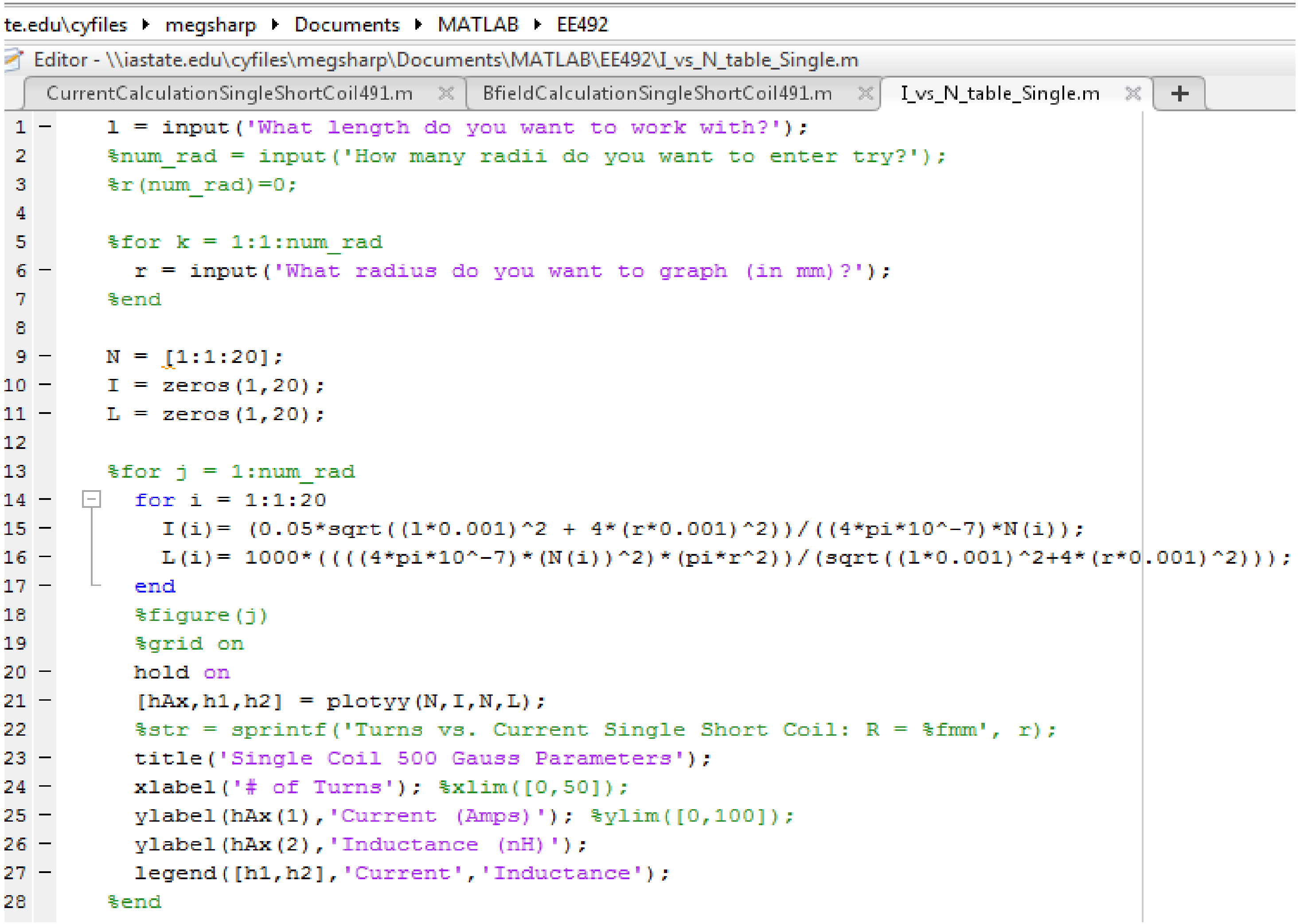


```matlab
clear all
close all
clc

N = input('How many turns are in the coil? ');                  % N -> # of turns in the coil (dimensionless)
l = input('What is the length of the coil (in mm)? ');          % l -> length (meters)
R = input('What is the radius of the coil (in mm)? ');          % R -> radius of the coil (meters)
I = input('What is the current of the coil? ');                 % I -> current (amperes)

B_T = ((4*pi*10^-7)*N*I)/sqrt((l*0.001)^2 + 4*(R*0.001)^2);     % Equation from MFG Design paper for single coil.
B_g = B_T*10^4;                                                 % Converting magnetic field units: from Tesla to gauss.

disp(['The magnetic field generated with those parameters for a single short coil is ', num2str(B_g), ' Gauss.']);

```



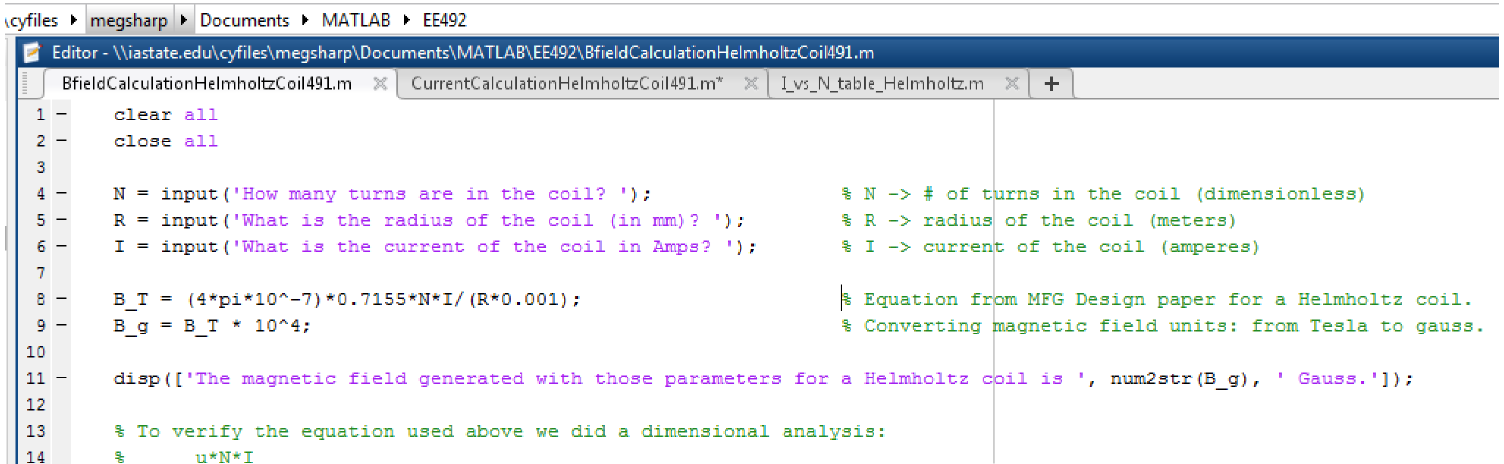
```matlab
clear all
close all
clc

N = input('How many turns are in the coil? ');                                   % N -> # of turns in the coil (dimensionless)
l = input('What is the length of the coil (in mm)? ');                           % l -> length (meters)
R = input('What is the radius of the coil (in mm)? ');                           % R -> radius of the coil (meters)
B_g = input('What is the magnetic field (in Gauss) of the coil? ');              % B_g -> magnetic field produced by the coil (Gauss)

B_T = B_g *10^-4;                                                  % Converting magnetic field units: from Gauss to Tesla.
I = (B_T*sqrt((l*.001)^2 + 4*(R*.001)^2))/((4*pi*10^-7)*N);        % Equation from MFG Design paper for single coil.

disp(['The current required to generate that field for a single short coil is ', num2str(I), ' Amps.']);

```

MATLAB CODE – Single Coil Continued…

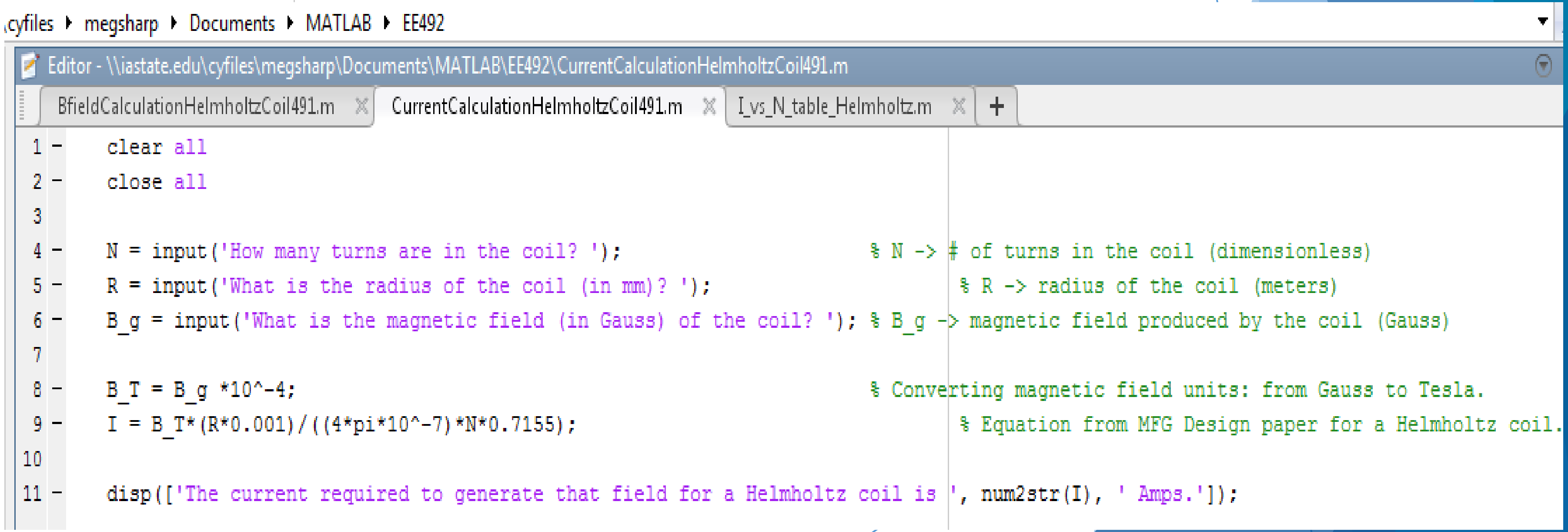


```matlab
l = input('What length do you want to work with?');
%num_rad = input('How many radii do you want to enter try?');
%r(num_rad)=0;

%for k = 1:1:num_rad
  r = input('What radius do you want to graph (in mm)?');
%end

N = [1:1:20];
I = zeros(1,20);
L = zeros(1,20);

%for j = 1:num_rad
  for i = 1:1:20
    I(i)= (0.05*sqrt((l*0.001)^2 + 4*(r*0.001)^2))/((4*pi*10^-7)*N(i));
    L(i)= 1000*((((4*pi*10^-7)*(N(i))^2)*(pi*r^2))/(sqrt((l*0.001)^2+4*(r*0.001)^2)));
  end
  %figure(j)
  %grid on
  hold on
  [hAx,h1,h2] = plotyy(N,I,N,L);
  %str = sprintf('Turns vs. Current Single Short Coil: R = %fmm', r);
  title('Single Coil 500 Gauss Parameters');
  xlabel('# of Turns'); %xlim([0,50]);
  ylabel(hAx(1),'Current (Amps)'); %ylim([0,100]);
  ylabel(hAx(2),'Inductance (nH)');
  legend([h1,h2],'Current','Inductance');
%end
```

MATLAB CODE – Helmholtz Coil

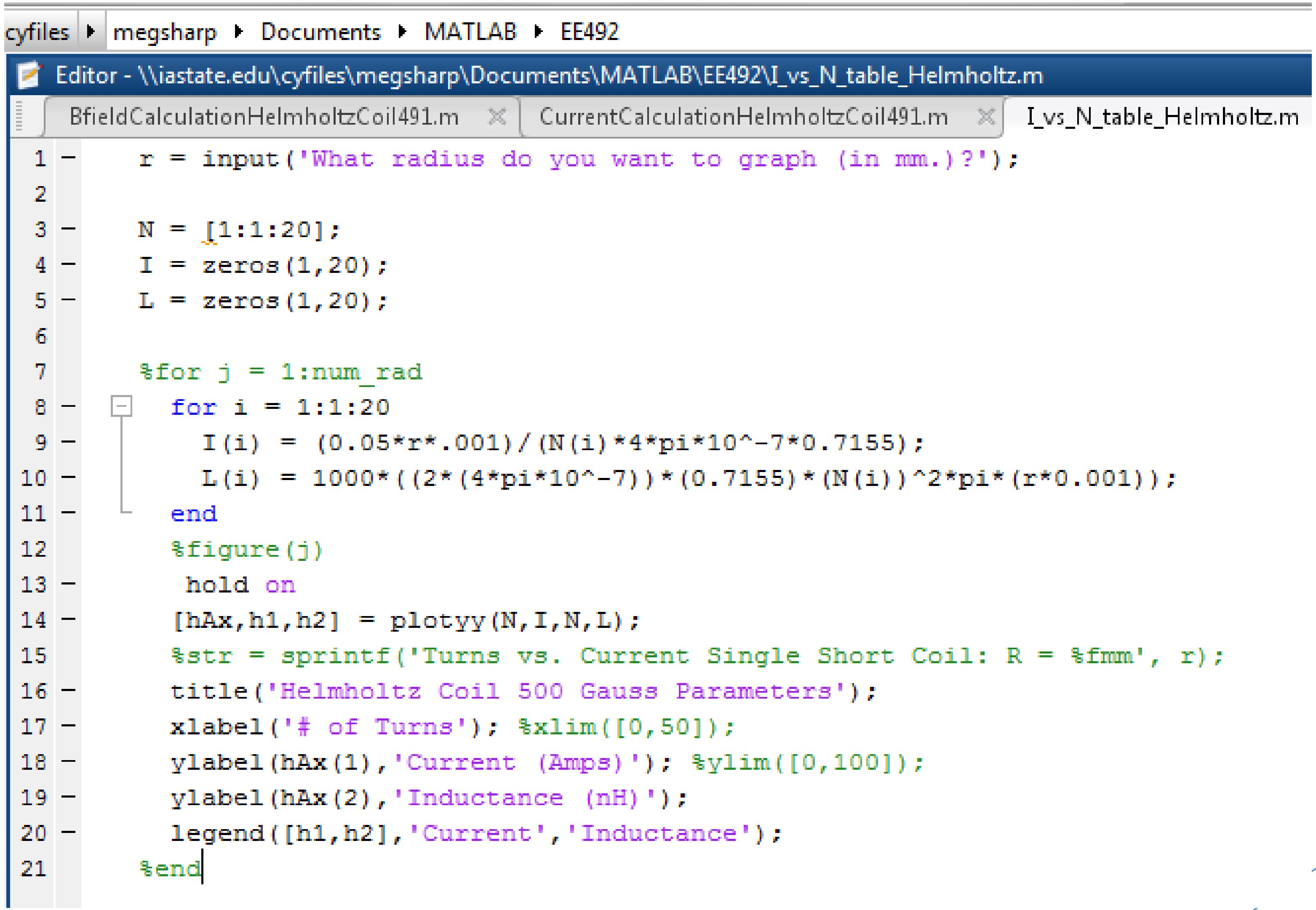


```
clear all
close all

N = input('How many turns are in the coil? ');                % N -> # of turns in the coil (dimensionless)
R = input('What is the radius of the coil (in mm)? ');        % R -> radius of the coil (meters)
I = input('What is the current of the coil in Amps? ');       % I -> current of the coil (amperes)

B_T = (4*pi*10^-7)*0.7155*N*I/(R*0.001);                      % Equation from MFG Design paper for a Helmholtz coil.
B_g = B_T * 10^4;                                             % Converting magnetic field units: from Tesla to gauss.

disp(['The magnetic field generated with those parameters for a Helmholtz coil is ', num2str(B_g), ' Gauss.']);

% To verify the equation used above we did a dimensional analysis:
%      u*N*I
% B =  -----
%        R
% UNITS:
% B -> Tesla(T) -> V-s/A*m
% u -> H/m -> Wb/A*m -> V-s/A*m
% N -> dimensionless
% I -> Amperes(A)
% R -> radius(m)
% V-s   V-s/A*m * A   V-s/m   V-s
% --- = ----------- = ----- = ---
% m^2       m           m     m^2

% Then we found that 1 Gauss = 0.0001 Tesla
```



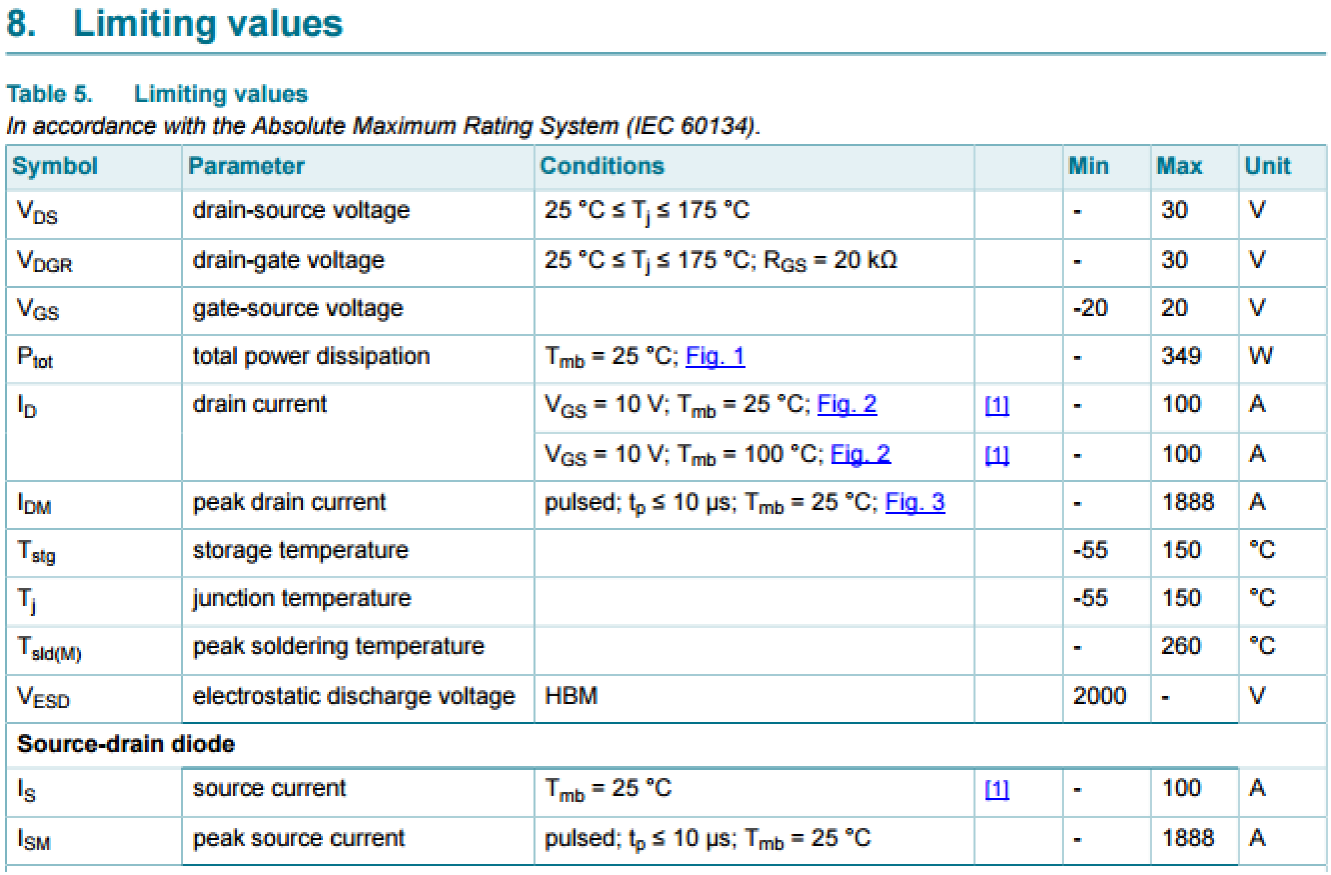
```
clear all
close all

N = input('How many turns are in the coil? ');                     % N -> # of turns in the coil (dimensionless)
R = input('What is the radius of the coil (in mm)? ');                     % R -> radius of the coil (meters)
B_g = input('What is the magnetic field (in Gauss) of the coil? '); % B_g -> magnetic field produced by the coil (Gauss)

B_T = B_g *10^-4;                                                  % Converting magnetic field units: from Gauss to Tesla.
I = B_T*(R*0.001)/((4*pi*10^-7)*N*0.7155);                                 % Equation from MFG Design paper for a Helmholtz coil.

disp(['The current required to generate that field for a Helmholtz coil is ', num2str(I), ' Amps.']);
```

MATLAB CODE – Helmholtz Coil Cont…



```
r = input('What radius do you want to graph (in mm.)?');

N = [1:1:20];
I = zeros(1,20);
L = zeros(1,20);

%for j = 1:num_rad
  for i = 1:1:20
    I(i) = (0.05*r*.001)/(N(i)*4*pi*10^-7*0.7155);
    L(i) = 1000*((2*(4*pi*10^-7))*(0.7155)*(N(i))^2*pi*(r*0.001));
  end
  %figure(j)
   hold on
  [hAx,h1,h2] = plotyy(N,I,N,L);
  %str = sprintf('Turns vs. Current Single Short Coil: R = %fmm', r);
  title('Helmholtz Coil 500 Gauss Parameters');
  xlabel('# of Turns'); %xlim([0,50]);
  ylabel(hAx(1),'Current (Amps)'); %ylim([0,100]);
  ylabel(hAx(2),'Inductance (nH)');
  legend([h1,h2],'Current','Inductance');
%end
```

MOSFET



8. Limiting values

Table 5. Limiting values

In accordance with the Absolute Maximum Rating System (IEC 60134).

Symbol	Parameter	Conditions		Min	Max	Unit
V_{DS}	drain-source voltage	25 °C ≤ T_j ≤ 175 °C		-	30	V
V_{DGR}	drain-gate voltage	25 °C ≤ T_j ≤ 175 °C; R_{GS} = 20 kΩ		-	30	V
V_{GS}	gate-source voltage			-20	20	V
P_{tot}	total power dissipation	T_{mb} = 25 °C; Fig. 1		-	349	W
I_D	drain current	V_{GS} = 10 V; T_{mb} = 25 °C; Fig. 2	[1]	-	100	A
		V_{GS} = 10 V; T_{mb} = 100 °C; Fig. 2	[1]	-	100	A
I_{DM}	peak drain current	pulsed; t_p ≤ 10 µs; T_{mb} = 25 °C; Fig. 3		-	1888	A
T_{stg}	storage temperature			-55	150	°C
T_j	junction temperature			-55	150	°C
$T_{sld(M)}$	peak soldering temperature			-	260	°C
V_{ESD}	electrostatic discharge voltage	HBM		2000	-	V
Source-drain diode						
I_S	source current	T_{mb} = 25 °C	[1]	-	100	A
I_{SM}	peak source current	pulsed; t_p ≤ 10 µs; T_{mb} = 25 °C		-	1888	A

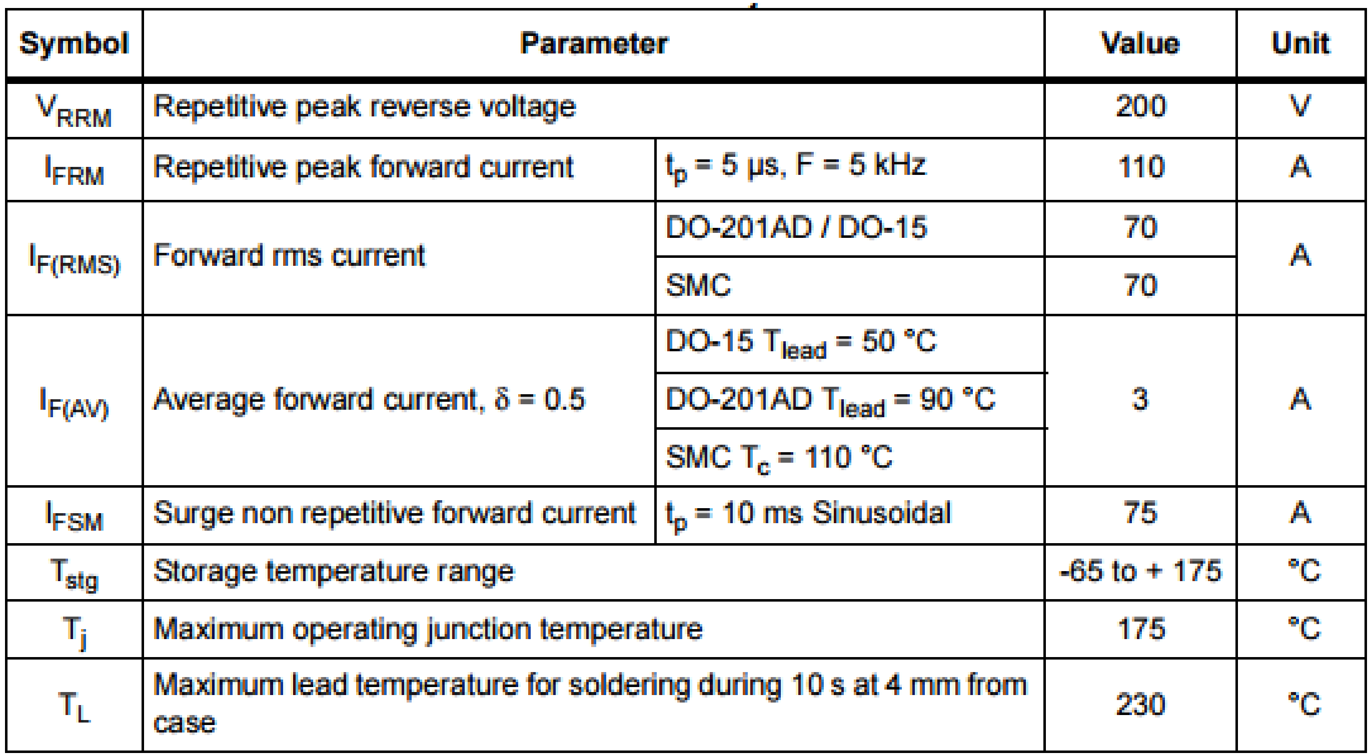
- http://www.nxp.com/documents/data_sheet/PSMN0R9-30YLD.pdf

Current Sense Resistor

Model No.	Power Rating	Dielect. Strength V_{RMS}AC	Max. Voltage	Resistance		Terminal
				Min.	Max.	
MP725	25 Watts *	1,500	200	0.020 Ω	1.00K	Solderable

- http://www.caddock.com/Online_catalog/Mrktg_Lit/MP725.pdf

Diode



Symbol	Parameter		Value	Unit
V_{RRM}	Repetitive peak reverse voltage		200	V
I_{FRM}	Repetitive peak forward current	t_p = 5 µs, F = 5 kHz	110	A
$I_{F(RMS)}$	Forward rms current	DO-201AD / DO-15	70	A
		SMC	70	
$I_{F(AV)}$	Average forward current, $\delta = 0.5$	DO-15 T_{lead} = 50 °C	3	A
		DO-201AD T_{lead} = 90 °C		
		SMC T_c = 110 °C		
I_{FSM}	Surge non repetitive forward current	t_p = 10 ms Sinusoidal	75	A
T_{stg}	Storage temperature range		-65 to + 175	°C
T_j	Maximum operating junction temperature		175	°C
T_L	Maximum lead temperature for soldering during 10 s at 4 mm from case		230	°C

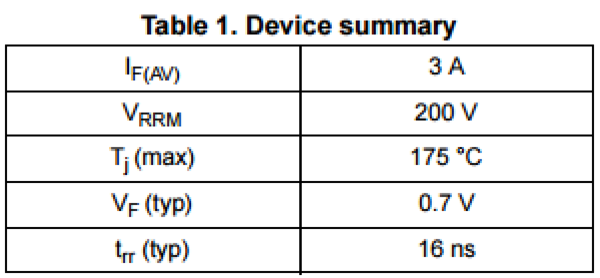


Table 1. Device summary

$I_{F(AV)}$	3 A
V_{RRM}	200 V
T_j (max)	175 °C
V_F (typ)	0.7 V
t_{rr} (typ)	16 ns

- http://www.st.com/web/en/resource/technical/document/datasheet/CD00110333.pdf