DM Radio Magnet Design Campaign

2nd DM Radio Collaboration meeting
August 13th, 2020
Alexander Leder
UC Berkeley

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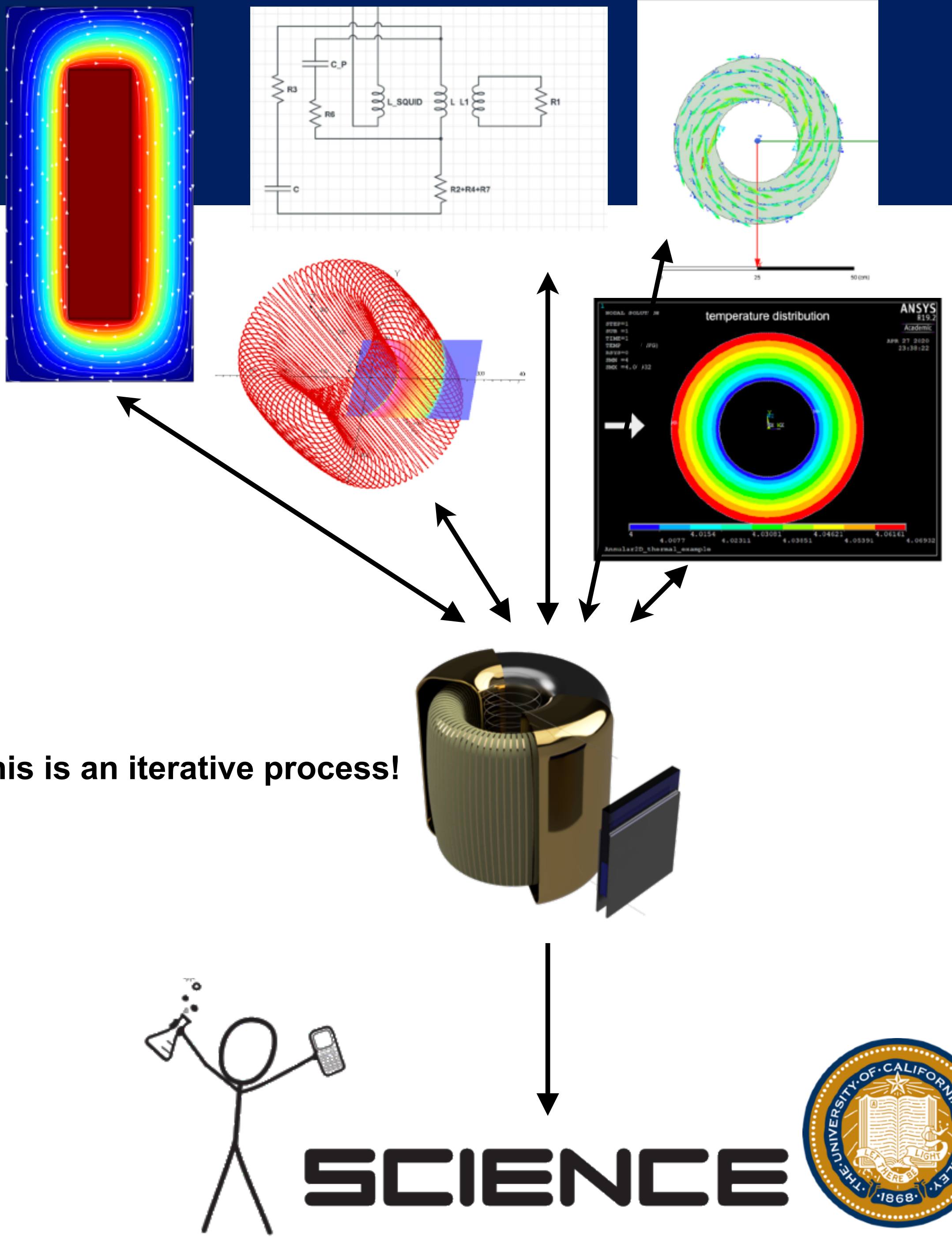
Introduction/Overview

- The goal of this whole magnet campaign is to put together the first design of the DM Radio 50 L experiment for our first end-to-end sensitivity calculation

- At its core we need to design the physical magnet that will provide the coupling to the axion field

- We will examine each magnet parameter keeping it within the range of feasibility while simultaneously maximizing the sensitivity reach

- Finally we discuss the various tie-ins to the other modeling campaigns that will be discussed throughout the morning



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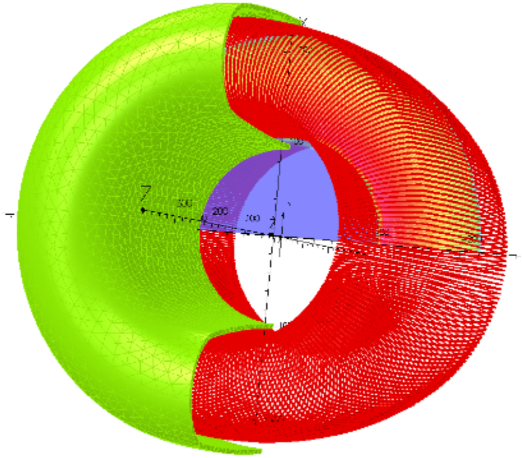
What makes this Magnet Design Difficult?

- The magnet we are designing is atypical in many ways and has a series of design requirements not usually found in accelerator/commercial/medial applications
- What makes this magnet difficult?
  - We want a high field in the largest volume possible
  - Toroid shape in general makes winding difficult
  - We want to install this whole experiment in a cryogenic environment
    - Take into account max current, mechanical vibrations, magnetic forces
  - We have to stick the magnet into a super conducting sheath - field modeling is key
- Design of custom Magnet Designs for axion searches - see Snowmass LOI



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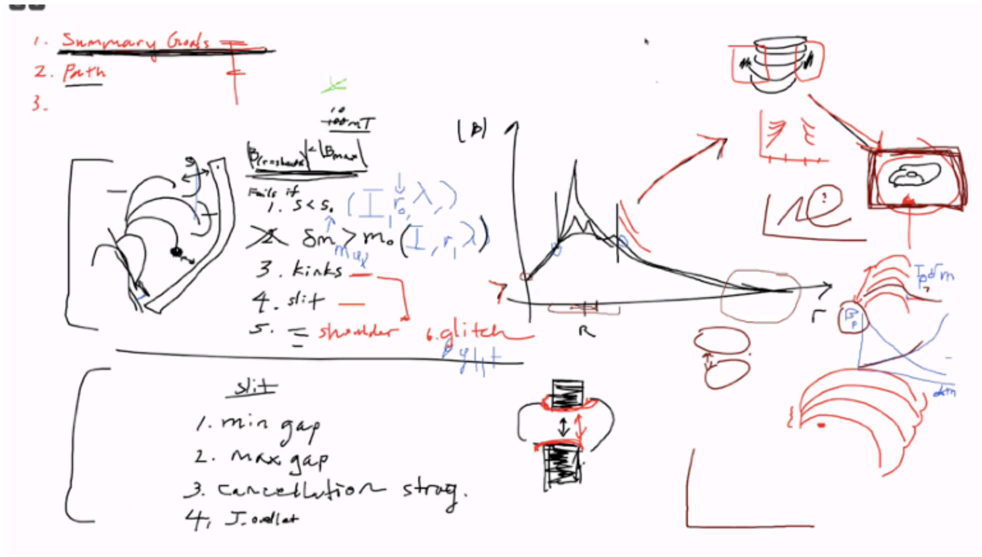
Overview of Design Process

- For starters we were looking at designs that could achieve 1 Tesla peak field with the 11-22-44 cm proportions discussed at the first collaboration meeting

- From there we took into account as many of the engineering constraints as possible while still maximizing the science reach

- We will look into each one of these constraints and see how they are addressed in our proposed 50 L design which I am calling “Sputnik”

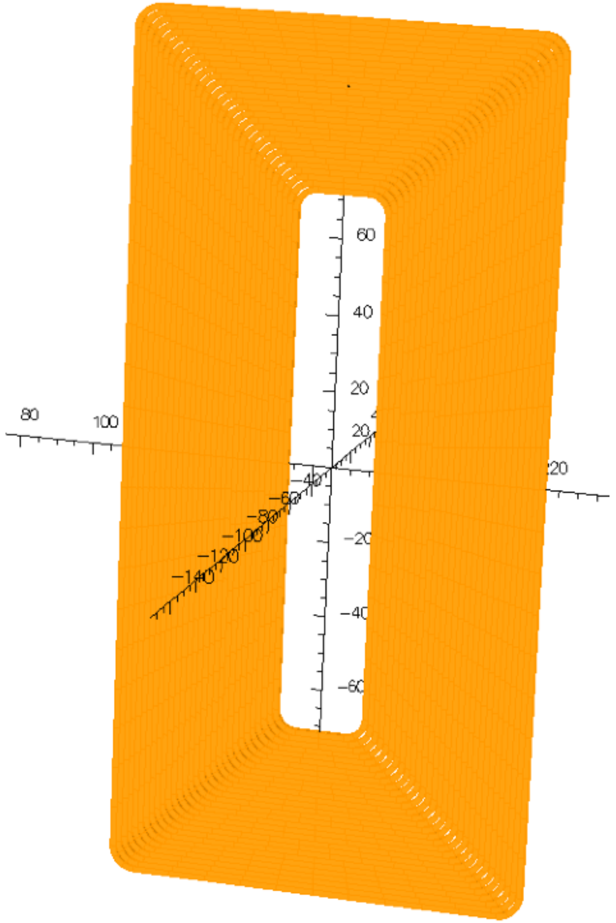


Original Design Doodles by Leder/Li
I will be selling originals in the gift shop

Maximizing the Peak Field

Maximizing the Science Volume

- We want high field in large volume with low current/high density of individual wires
- To reach 1 Tesla you have to increase the number of current wires contributing to the field
  - More turns with smaller wires/less layers
  - More layers with larger wires/less turns
- Rule of thumb: Loss of 1 L in Science Volume for each additional layer of wire
- For all designs considered: 2 layers minimum



Stronger Field ⟹ Smaller Science Region

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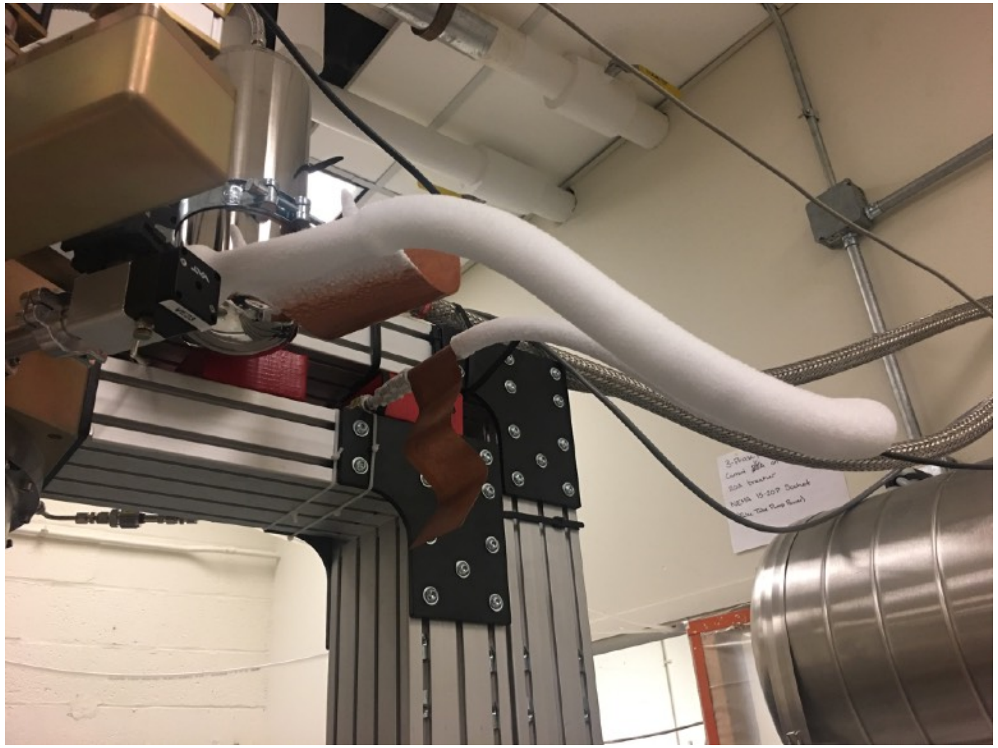
Cryogenic Constraints

Cryogenic Constraints

- We have to cool this whole experiment to superconducting temperatures
- We will run the wires at **60% of maximum listed critical current at 3 Tesla**
    - Make sure that nothing is going normal/safety consideration
- Ties in with Maria's work on maximum current allowed through wires



Cryogenic Budget

- We have to balance the need for more/smaller wires (less layers) with the maximum current that can be safety supported by those wires

- 54S33 wire model and its corresponding 1 Tesla design offers a low total mass while keeping the current density per wire reasonable

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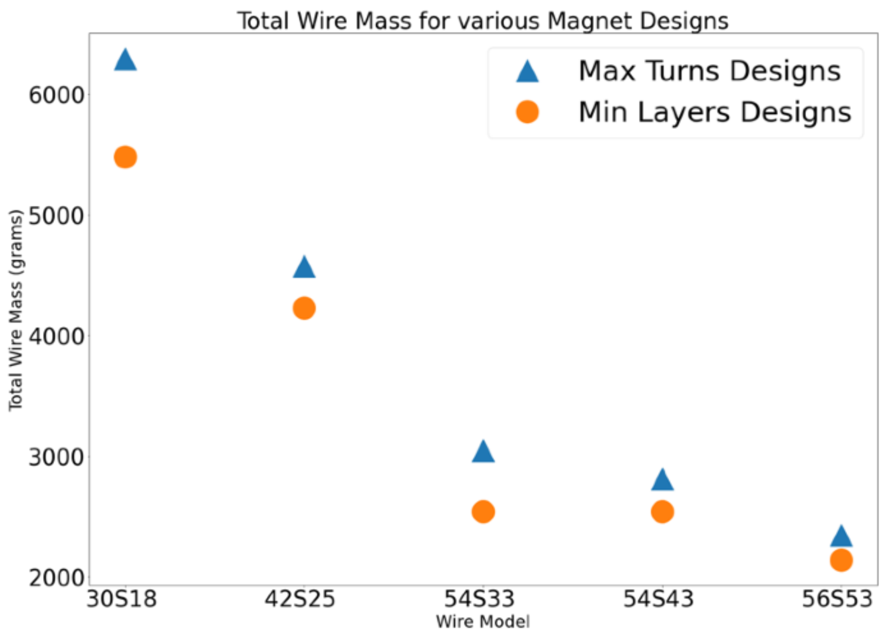
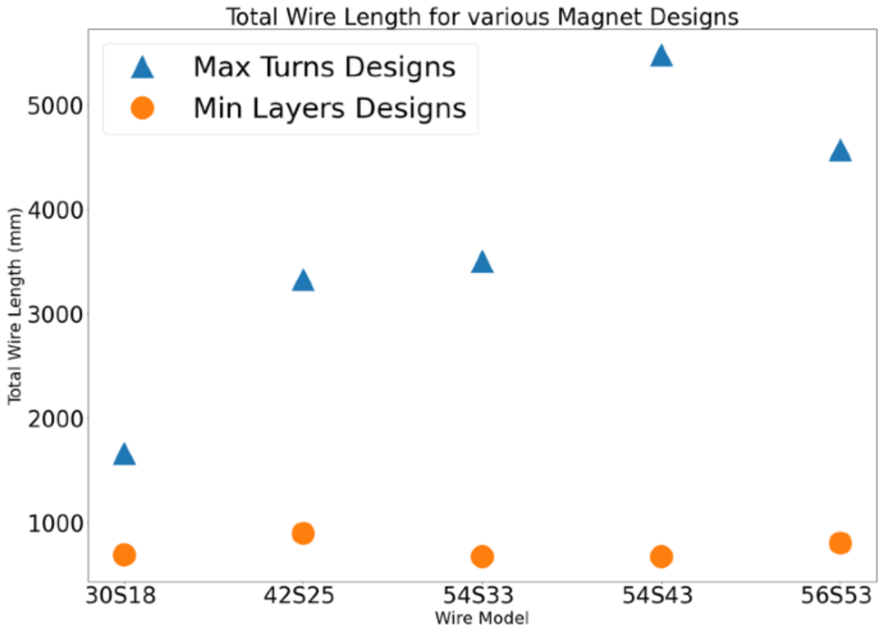


Larger individual wires/more layers/ lower current density ⟷ Lots of tiny wires/ less layers/higher current density



Machining/Building a Toroidal Magnet

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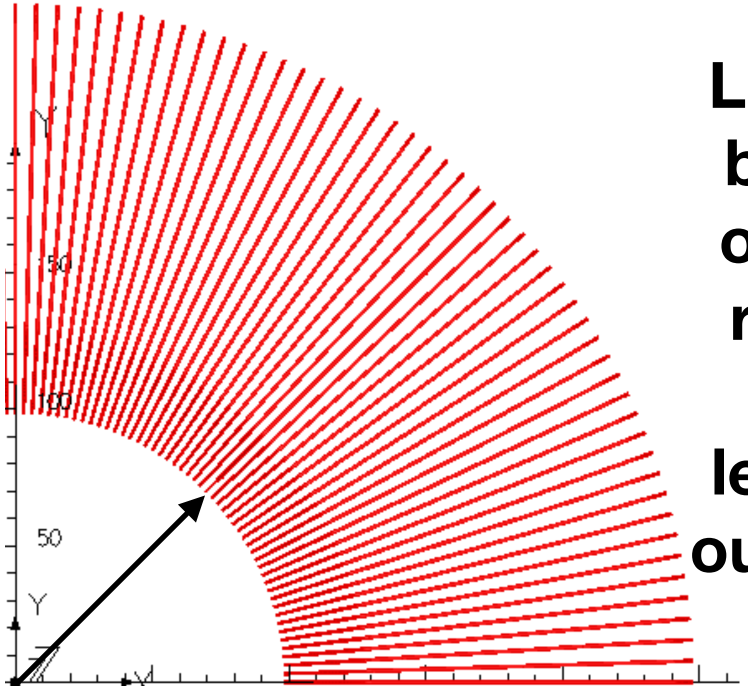
Machining the Toroid

- Note that given a toroidal design the maximum packing of the wires (N) will be determined by the inner radius of the magnet coils and the diameter of the wires
- We are looking at designs where we are packing in the wires at **80% of maximum packing density**
    - This is a machining tolerance
- We assumed a uniform spacing of wires along the entire magnet half



Larger spacing between coils on the outside radius means more field leakage on the outside curve of the magnet

R = 110 mm   a = Wire Diameter

$$N_{total}^{max} = \frac{\pi}{arcsin[\frac{a}{2R}]}$$

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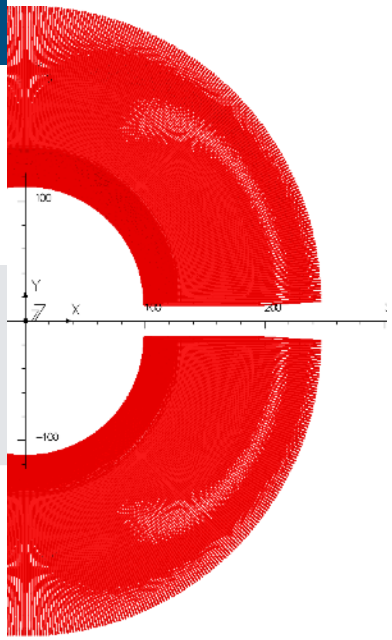
50 L Magnet Design - Force Calculations

- In order to allow for the wire/ mandrel to be installed we have to spilt the magnet into two halves
- This means we now have to content with the two toroid halves wanting to pull each other together
- Our spacers and wire packing will have to be able to deal with these forces

Parameter	Value/per magnet half
Force (normal) across the gap	74.4 Newtons
Force (parallel) across gap	235.6 Newtons
Total across gap	247.0 Newtons
Peak Magnetic Pressure on wires	58 psi / 4.0 atm



Fringe Field Considerations

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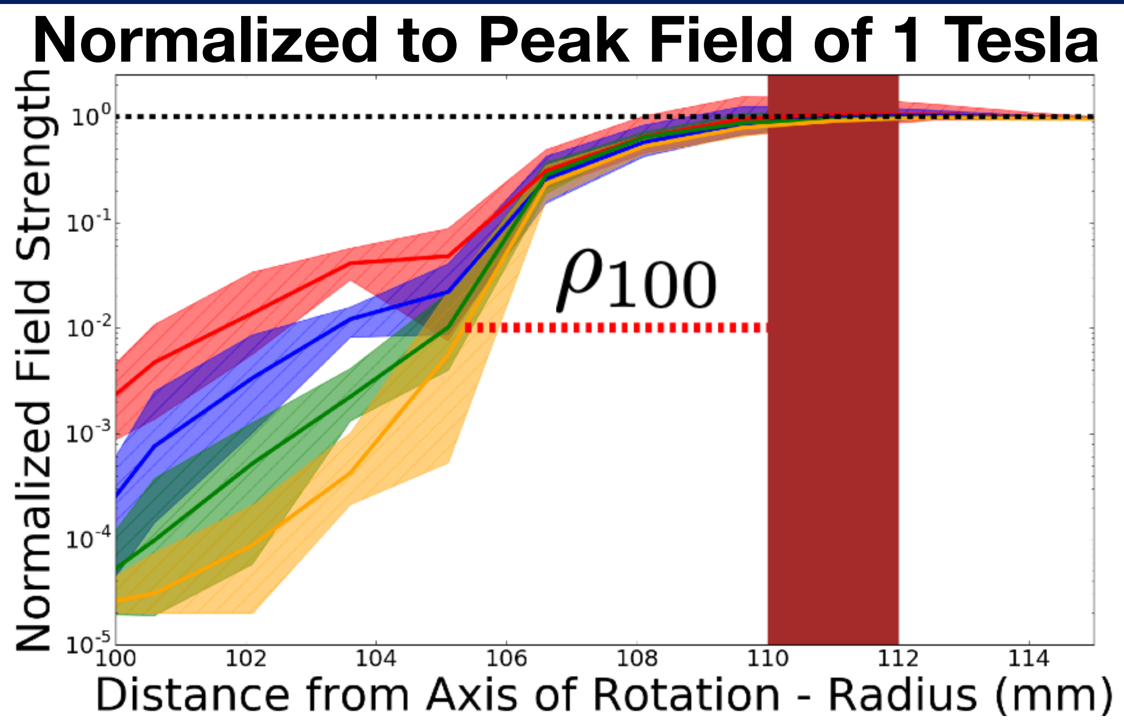
Fringe Field Width

- Advantage of the max turn design is that the fringe field will change as a function of the number of turns
- We defined the width at which the field falls off to 1/100th its peak value (10 mT) as ρ_{100}
- More coils = tighter fringe field



Number of Coils	Fringe Field Width
80	8.3 mm
120	6.6 mm
180	4.9 mm
240	4.6 mm

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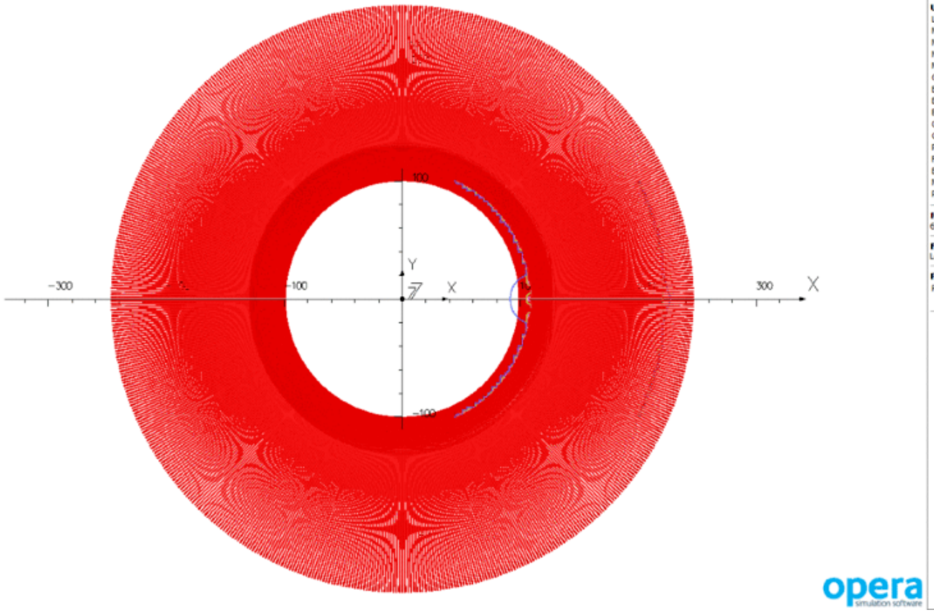
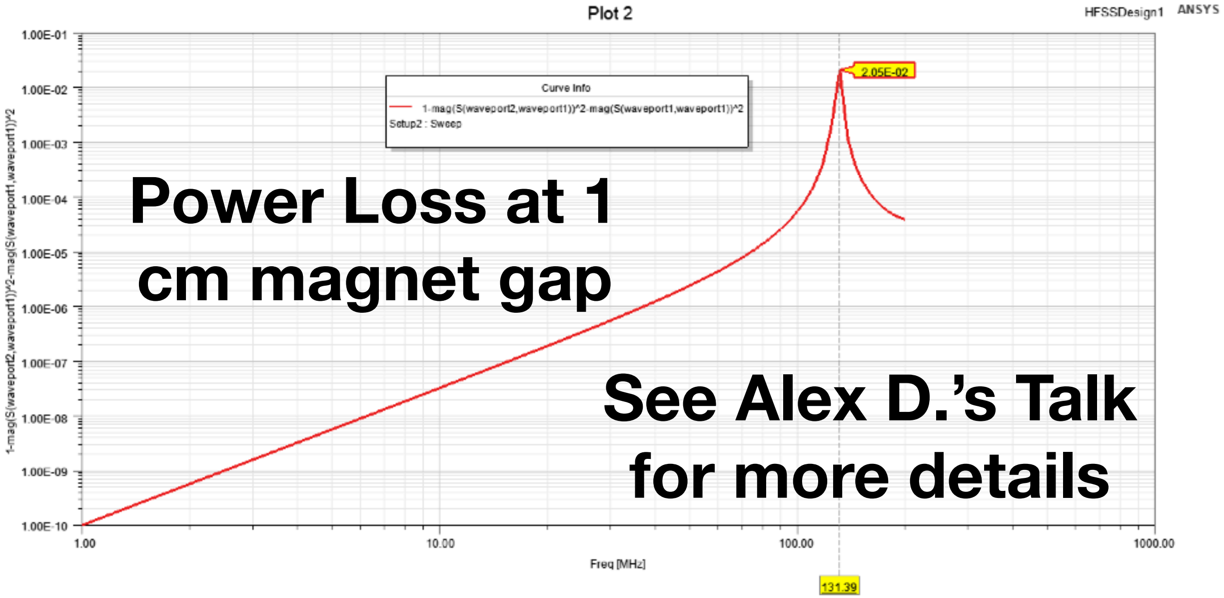
Magnet Gap

- One of the biggest contributions to the fringe field profile comes from the size of the magnet gap
- Gaps simulated range 3 mm - 200 mm
- From Alex D.'s calculations we saw that for 1 cm magnet gap size we would not cause acceptable losses in the frequency ROI



10 mT field line 55 mT field line 100 mT field line



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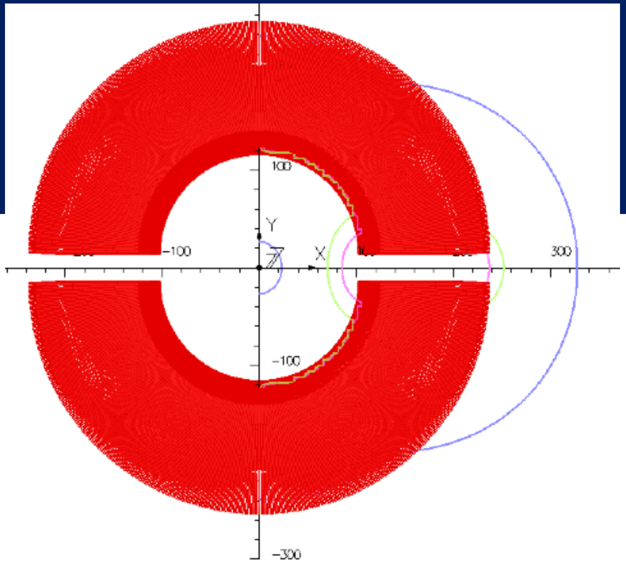
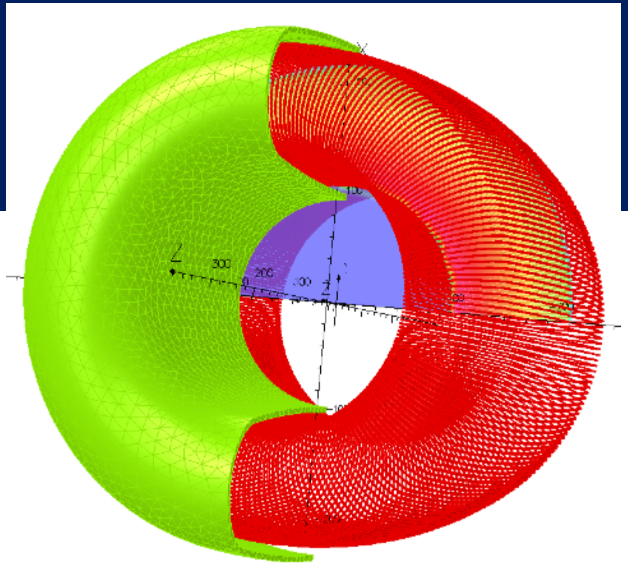
Fill Factor





- We want to place the sheath as close as possible to the magnet coils without having any part of the sheath going normal

- Given the 1 cm gap size we can now generate a sheath-to-wire spacing that has a high fill factor while ensuring everything is still superconducting

  - 1 cm wire offset ~ keeps entire sheath < 100 mT

10 mT field line 55 mT field line 100 mT field line

Fill Factor (10 mT contour)	0.7630
Fill Factor (55 mT contour)	0.8985
Fill Factor (100 mT contour)	0.9195

*** for a 1 cm gap size**

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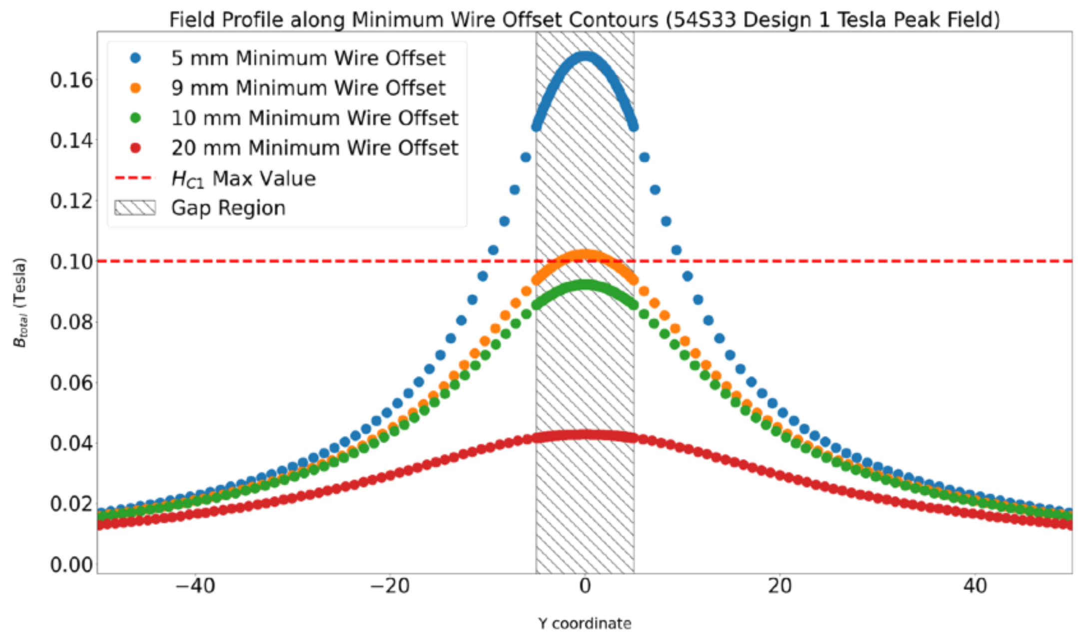
Tie-ins with Other Modeling Campaigns

- Current caps from Maria's thermal calculations
- Min/Max Range of magnet gaps sizes from Alex D.
- Designing a sheath contour for maximum pickup that makes sure that no part of the sheath gets above H_{C1} - Input into Chiara's Studies



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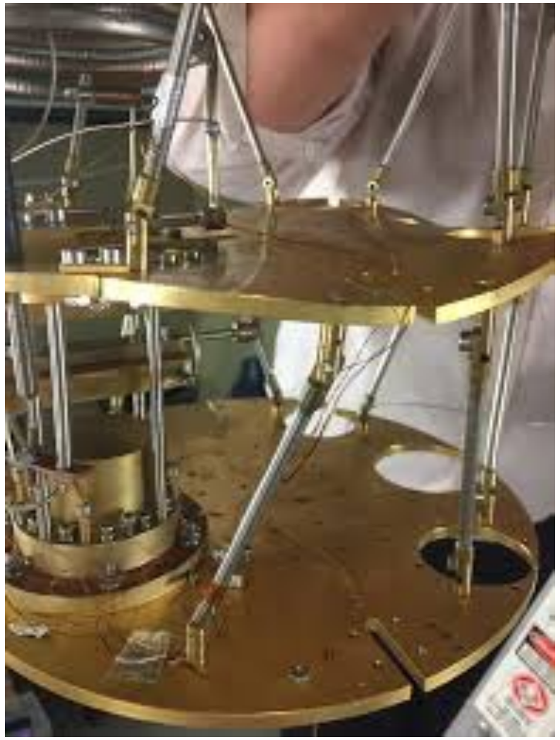
Future Studies

- Iterate Sputnik design based on input from other modeling campaigns with end-to-end sensitivity for example:
    - Maximum current we can handle
    - Sheath pickup considerations
- Look at effect of coil shape on magnetic force/pressure on individual wires
- Effect of mechanical vibrations on individual coils - tie in with Kaliroe's work
- Start to look at time dependent phenomena:
    - Quenching studies
    - Ramp up rate studies



We want to avoid this!

DM Radio 50 L - “Sputnik” Design Parameters

- DM Radio Sputnik design reaches 1 Tesla peak field taking into account various engineering constraints while maximizing the science reach
- We can iterate off this design based on the input from the other modeling campaigns
- Many thanks to Lucas and the LBL magnet team for their help in this effort

Property	Value	More Details can be found on Slide X
Number of Turns	617 Turns	6
Number of	2 Layers	6
Wire Diameter	0.896 mm	Fixed by Manufacturer
Current/wire	438 Amps	8
Science Volume	48.12 Liters	6
Total Wire Mass	2542.04 grams	9/28
Total Wire Length	671.9 meters	9/28
Fill Factor (100 mT)	0.9195	16
Max Field	.998 Tesla	Design Goal
SU:CU Ratio	1:2	27
Minimum Bending Radius	5 mm	Discussions with Machinists

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Additional Questions/Comments?

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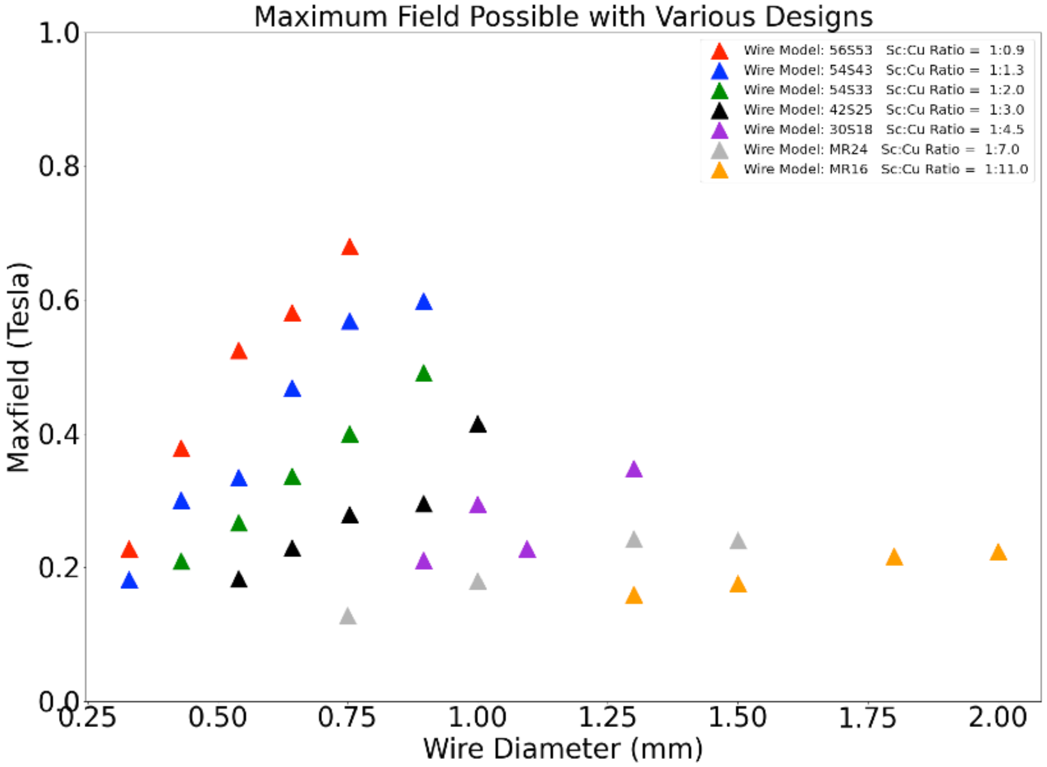
Backup Slides

SC:Cu fraction

- Spoke with Lucas regarding picking a SC:Cu fraction
- As a good starting point he suggested that we pick a ratio of 1:2 to 1:3
  - Models 54S33 and 42S25 respectively
- This is tied to quench protection which is a discussion best left to the professionals



Kitty Hawk Design - Min Layers Proposed Design

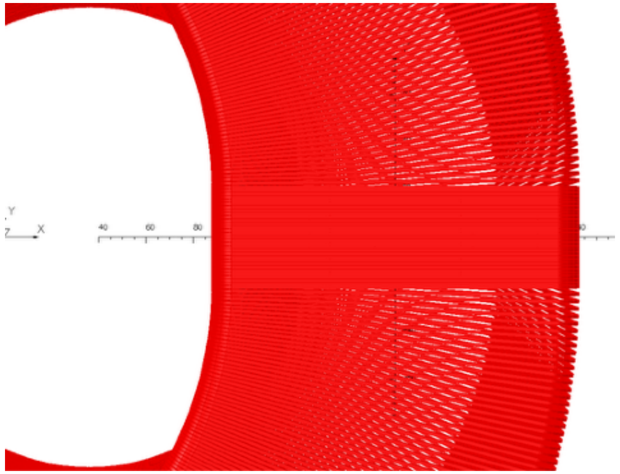
- Design 54S33 with the minimum number of layers fits the bill on all counts
- There is still some amount of wiggle room in these parameters based on the assumptions discussed earlier
- This is a starting point for the design studies
- From here we can map out the change to any one parameter and plug it into the end-to-end sensitivity calculation

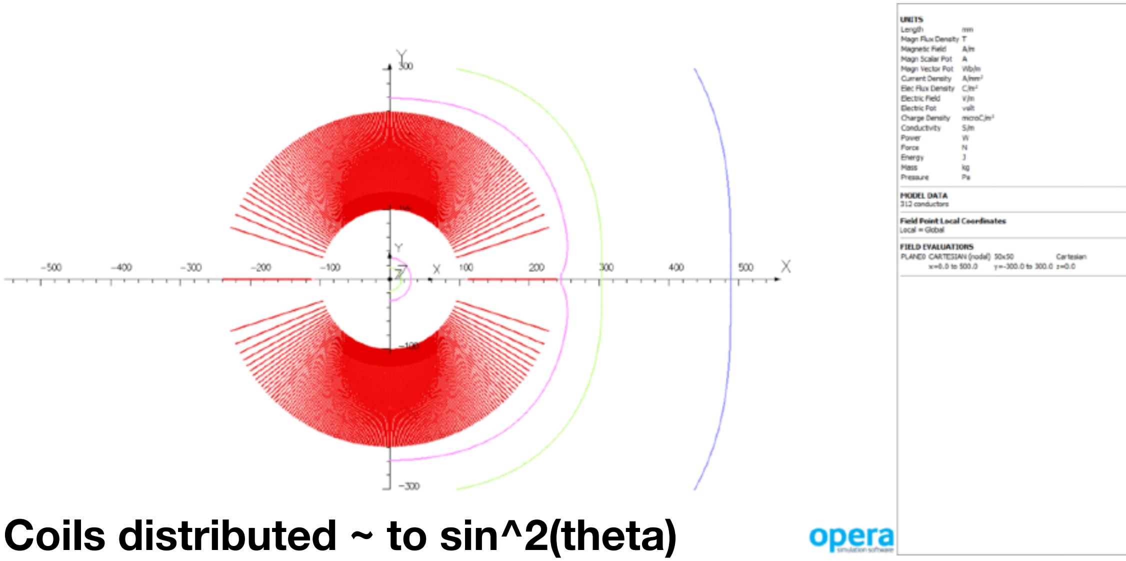
Property	Value
Number of Turns	617 Turns
Number of Layers	2 Layers
Wire Diameter	0.896 mm
Current through each wire	438 Amps
Science Volume	48.12 Liters
Total Wire Mass	2542.04 grams
Total Wire Length	671.9 meters
Max Field	.998 Tesla
SU:CU Ratio	1:2
Minimum Bending Radius	5 mm

Plugging the gap

- With the 54S33 design I generated a new set of simulations where the gap is maximally filled with equivalent coils
- The packing density is determined by the inside curve of the toroid design
- Larger gap between the filler coils and the toroid coils on the outside
- At the same time looked at varying the coil distribution to try and shape the fringe field
- Overall, for small gap sizes (<15 mm) the effect on the fringe field is small at the overall cost of the overall magnetic field

Max Filler Coils with 30 mm gap in 54S33 Design





Coils distributed ~ to sin^2(theta)

Magnet Variables

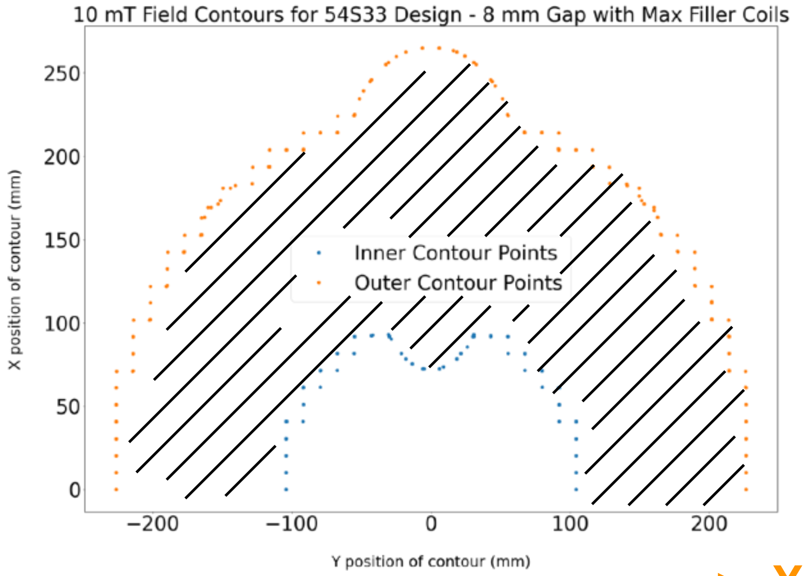
- Starting with the kitty hawk design this is the effect you have when you move things in particular directions

Effect of raising each of these parameters

Parameter	Pros	Con
Total Number of Wires	Larger B field, less amps per wire	More mass, longer total wire length
Number of layers	Less amps per wire, fringe field gets reduced	Reducing the science volume, more more mass
Wire Diameter	More maximum current	Less total number of wires
Coil Shape	Change in total force felt by individual wires (future studies)	
Superconductor:conductor fraction	Quench protection considerations (beyond the scope of this talk)	

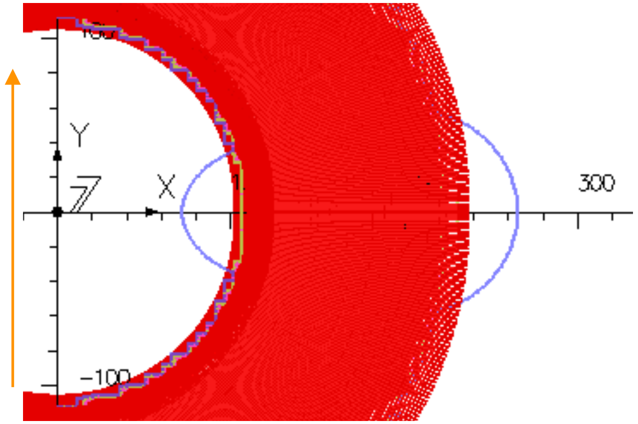
Calculating the Fill Factor

- For each simulation I then exported the contour points for further analysis
- I could then calculate the cross sectional area contained by the inner/outer contour
- Hashed region = area contained by the contours



Y axis

Y axis



N.B. the x/y orientations of each plot

SC:Cu fraction

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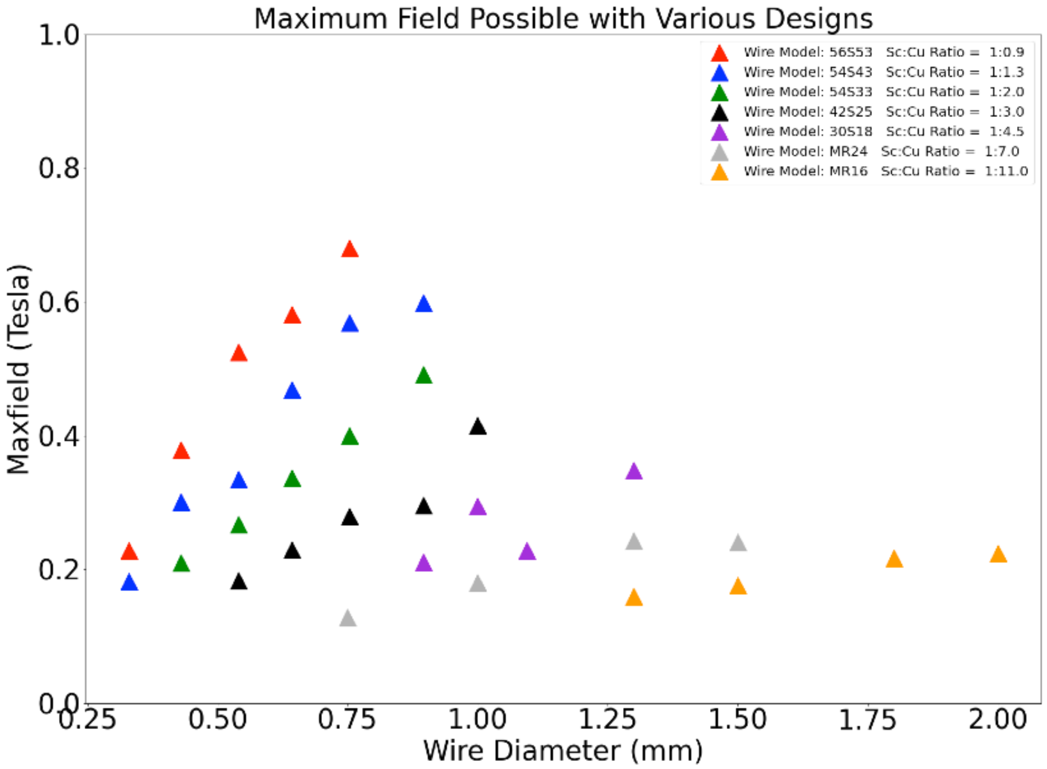
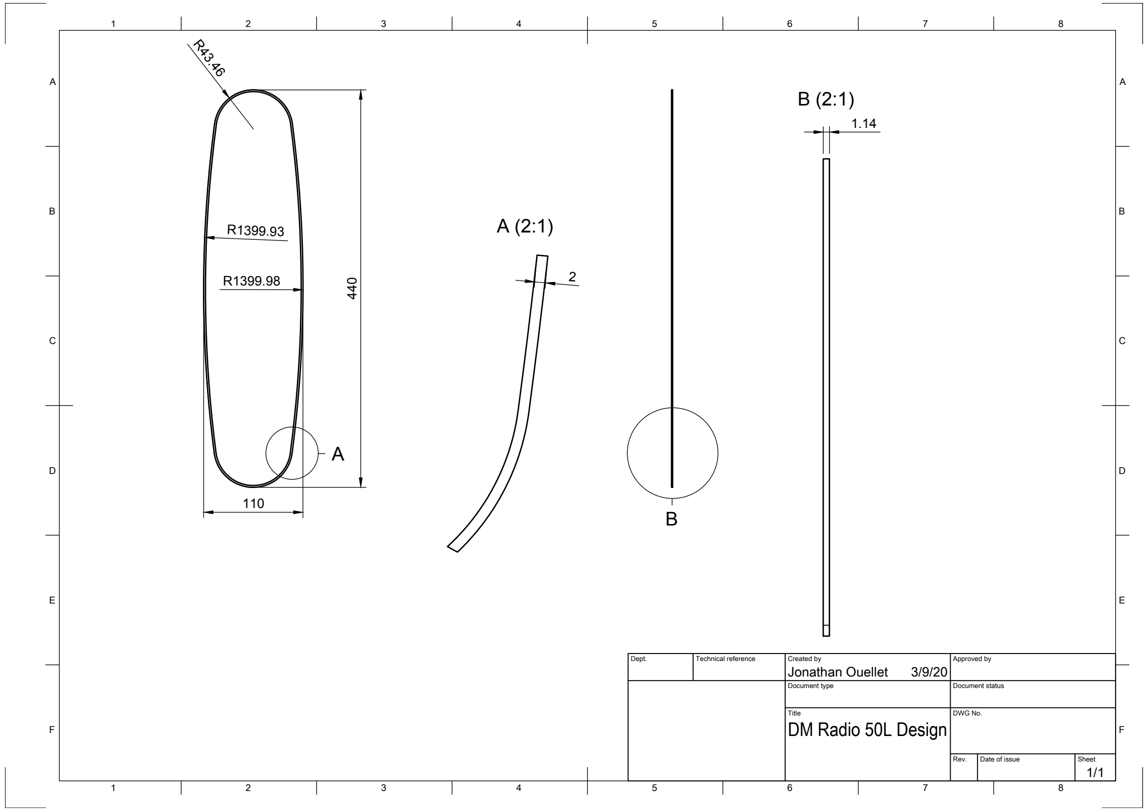


Coil Mass calculations

- Went through the SSI designs again and calculated the total length of wire per coil: 981.1 mm
- This corresponds to a mass of 13.4 grams/coil
- 600 coils ~ 8 kg of wire
- Using a wire density of ~ 6e-6 kg/mm^3
- For the rectangular coils this corresponds to between 4-12 grams/coil and 1-1.6 meters/coil



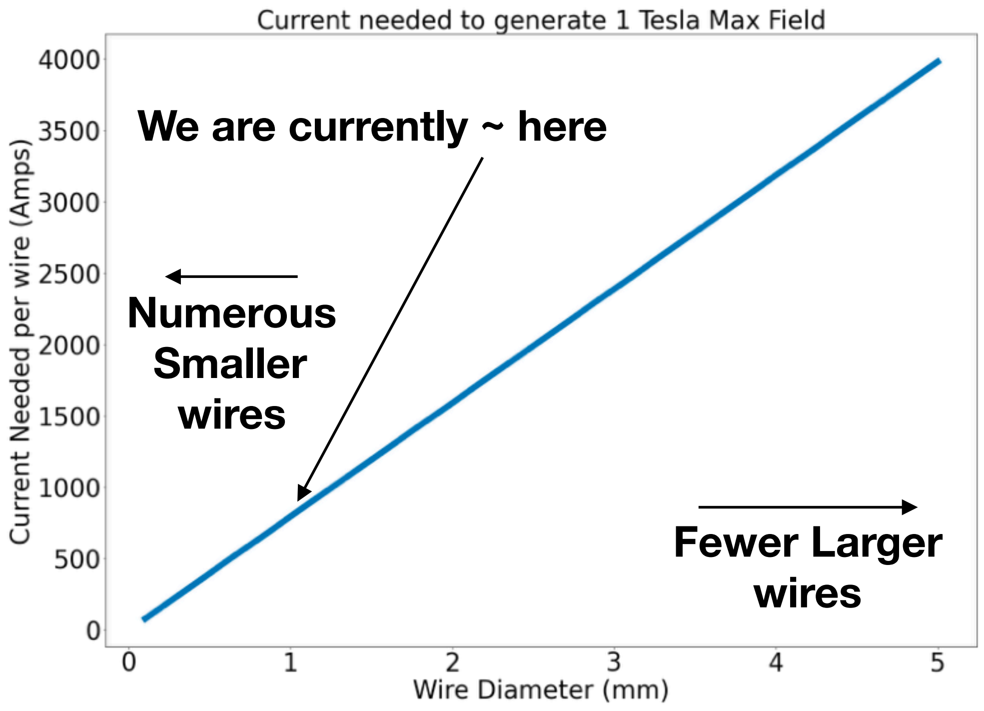
Target Design

- Design goal: generate a design that can achieve a 1 Tesla peak field and evaluate the “goodness” of said design

- Now there are two ways to get to that B field:

  - Go with lots of smaller wires each carrying a little bit of current -> Max Turns

  - Go with less wires, but each wire carries more current -> Min Layers



Maximum Fields

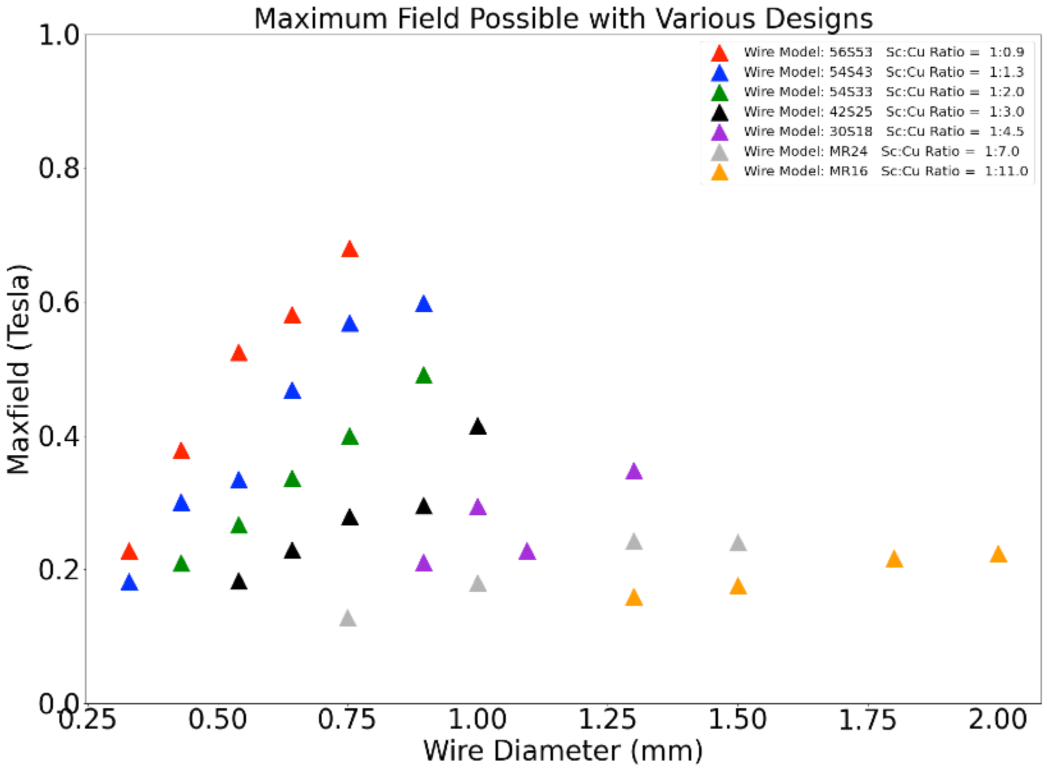
- For starters, given all the various wires that we have been considering, what is the maximum field that we could generate

- First calculate the maximum number of wires that you could fit in the inside curve of the toroid for a given wire diameter

- To give some buffer margin I made two assumptions:

    - **We are running at 80% of max packing fraction**

    - **For a given wire we are running at 60% of critical current**



$$N^{Total}_{Wires} = \frac{\pi}{arcsin[\frac{a}{2R}]}$$

a = Wire Diameter

R = Inside Radius of the Toroid = 11 cm here