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SI-Traceable RF Nano-Henry Inductor

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Abstract

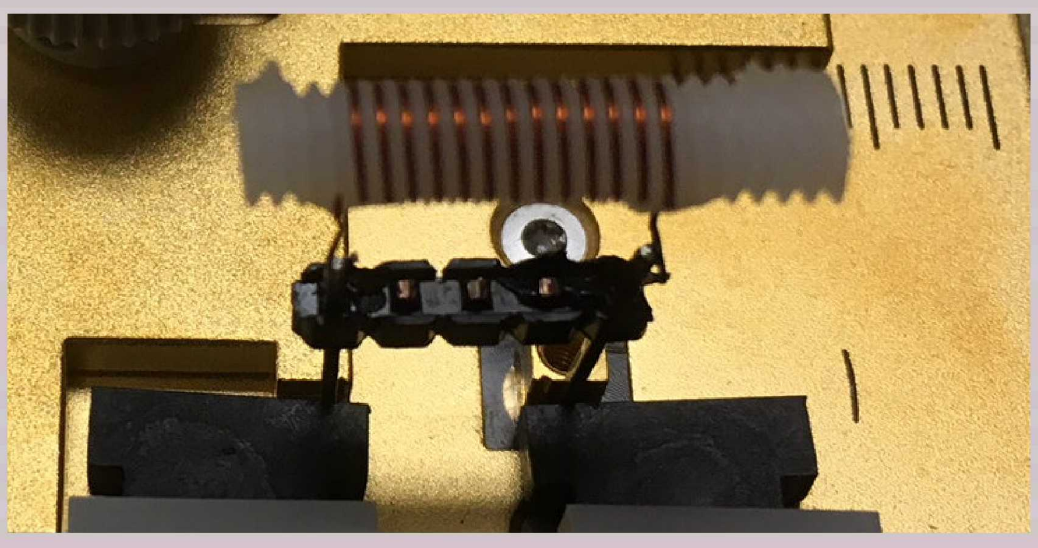
The reliability and accuracy of electrical components, which are ensured based upon measurements traceable to the fundamental SI units through Sandia's Primary Standards Laboratory (PSL), is vital to our nation's defense and scientific endeavors. The traditional equation for finding inductance ($L = \mu A N^2 / \ell$) works at lower frequencies because the length of wire used to make the coil is much shorter than the wavelength, but at higher frequencies, where the wavelength decreases, it is no longer accurate. The lumped model is unsuitable as the phase of the wave is different than that upon entry. In the RF field with higher frequencies there is an increase in undesirable effects and parasitics (the difference between ideal passive components, and real-life hardware). According to Knight (2016), in a coil the permittivity is modified, as electromagnetic waves must follow the winding electrical conductor path due to its geometry. A coil is a waveguide or transmission line that allows for a longer path, which allows it to store more energy by trapping and detaining electromagnetic radiation that would otherwise have made a much shorter journey. The PSL has an SI-traceable 100 nH inductor for 100 kHz and 1 MHz with uncertainties on this standard between 3 and 5 percent. The goal was to improve this standard by increasing the range for traceability. The frequency range from 1MHz to 200MHz was used for analysis. This was done by fabricating inductors and measuring them in the lab, then comparing them to theoretical results computed in Python as well as Comsol modeling. This research is still a work in progress. Inductor fabrication is ongoing as measurements are compared with models of varying complexity.

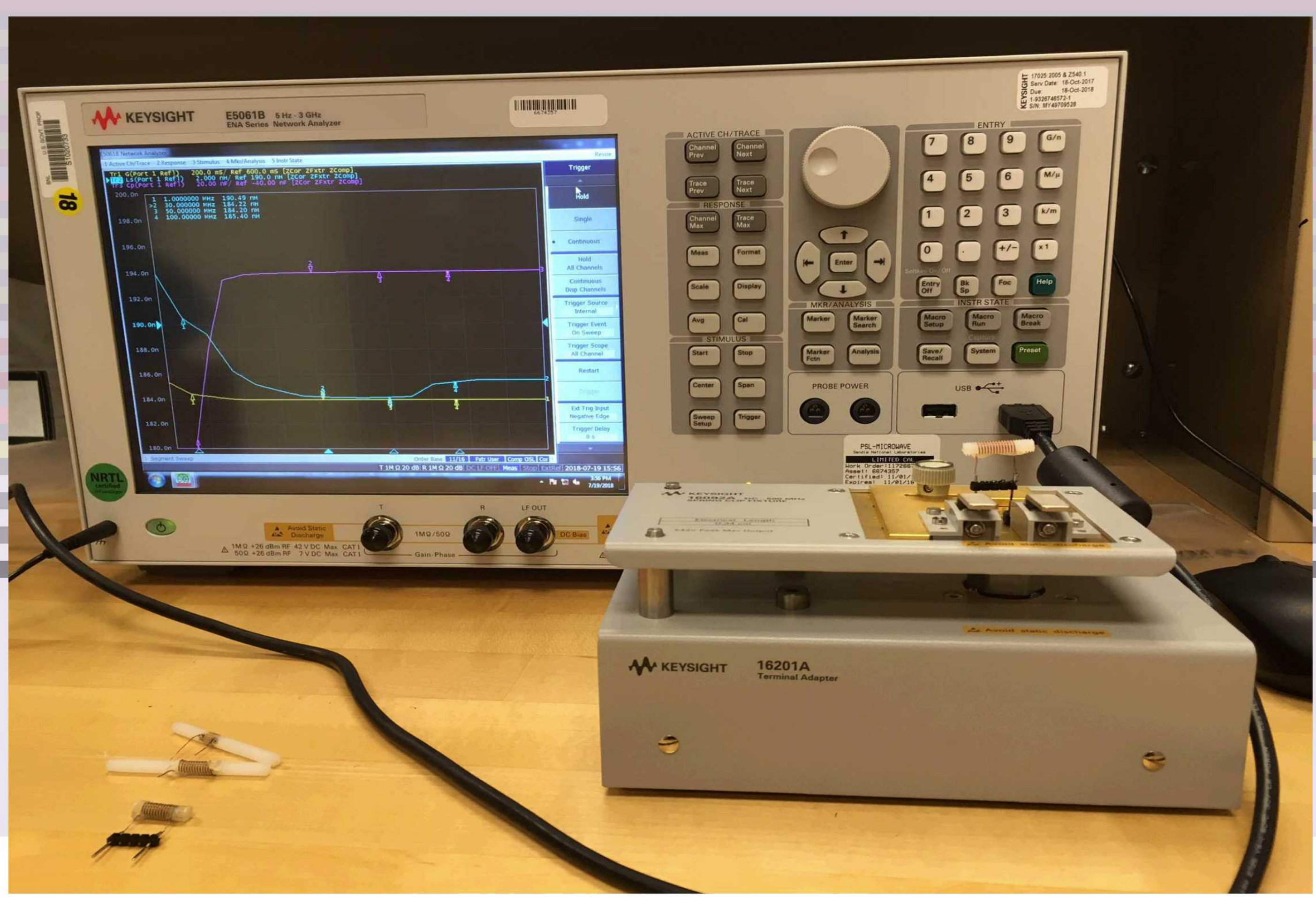
Introduction

Determining an inductance standard at higher frequencies for nH inductors is challenging. The traditional equation for finding inductance ($L = \mu A N^2 / \ell$) works at low frequencies, but at higher frequencies, where the wavelength decreases, it is no longer accurate and the increased complexity of solenoid's behavior isn't fully understood. As the frequency increases, current diminishes and redistributes itself within wires, causing the inductance to diminish as well. The redistribution of current leads to the effective area being considered instead as well as the development of proximity and skin effects. Measurements of solenoid core dimensions and wire diameters that determine A and ℓ must be adjusted to predict the inductance. Several equations for inductance have been developed for higher frequencies, which this research examine to determine if they can be used or modified to establish an SI standard. This was done by fabricating inductors, measuring them in the lab, then comparing to theoretical results computed in Python as well as Comsol modeling from 1 MHz to 200 MHz. The uncertainty is determined from measurements of physical dimensions.

Methods

- Theoretical work with equations of inductance work were coded in Python. A great deal was work done by Knight (2016), who concentrated on methods for HF and described some measurements at low HF frequencies. This work should apply to higher frequencies.
- An inductor was designed in Comsol v.5.3a to calculate inductance for comparison to theoretical inductance using the RF and ACDC physics modules.
- Several helical inductors were fabricated for measurement. Early inductors were fabricated by hand using a nylon screw for the core and wire ends attached with epoxy glue. Later solenoid models were made using a Fortus 400mc 3D printer for the core and a Meteor M22 coil winder. The initial solenoid cores were made of .16, .2 inch diameter polycarbonate rod without grooves. The number of turns varied from 12, 13, 14, 15, 20. The wire used was either 29 or 40 AWG copper wire. The pitch also varied from either 0.4 or 0.08 inches.
- Measurements of inductance of fabricated coils were taken with a Keysight Network Analyzer E5061B and a Keysight 16092A fixture in a frequency range of one 1MHz to 200 MHz.





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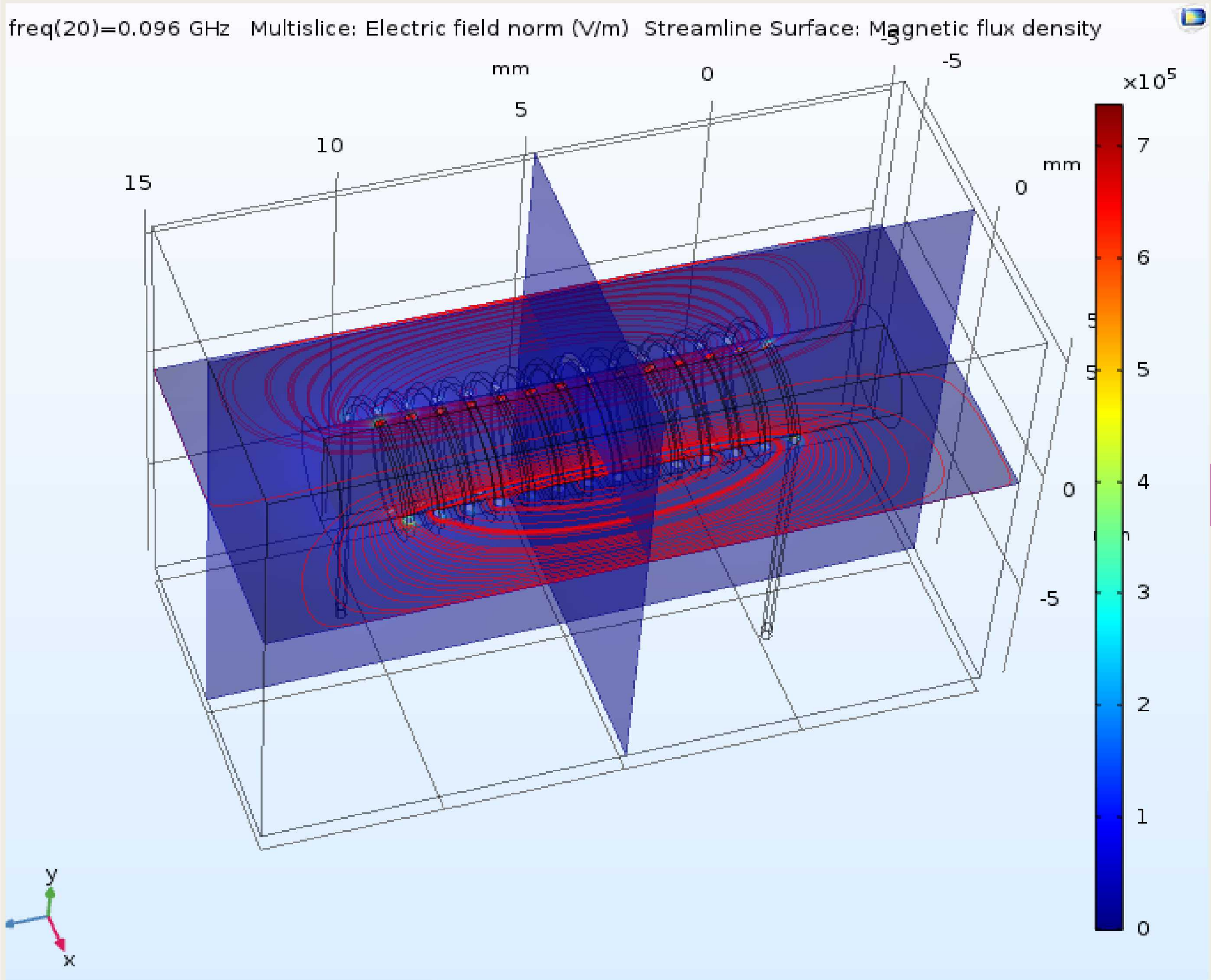
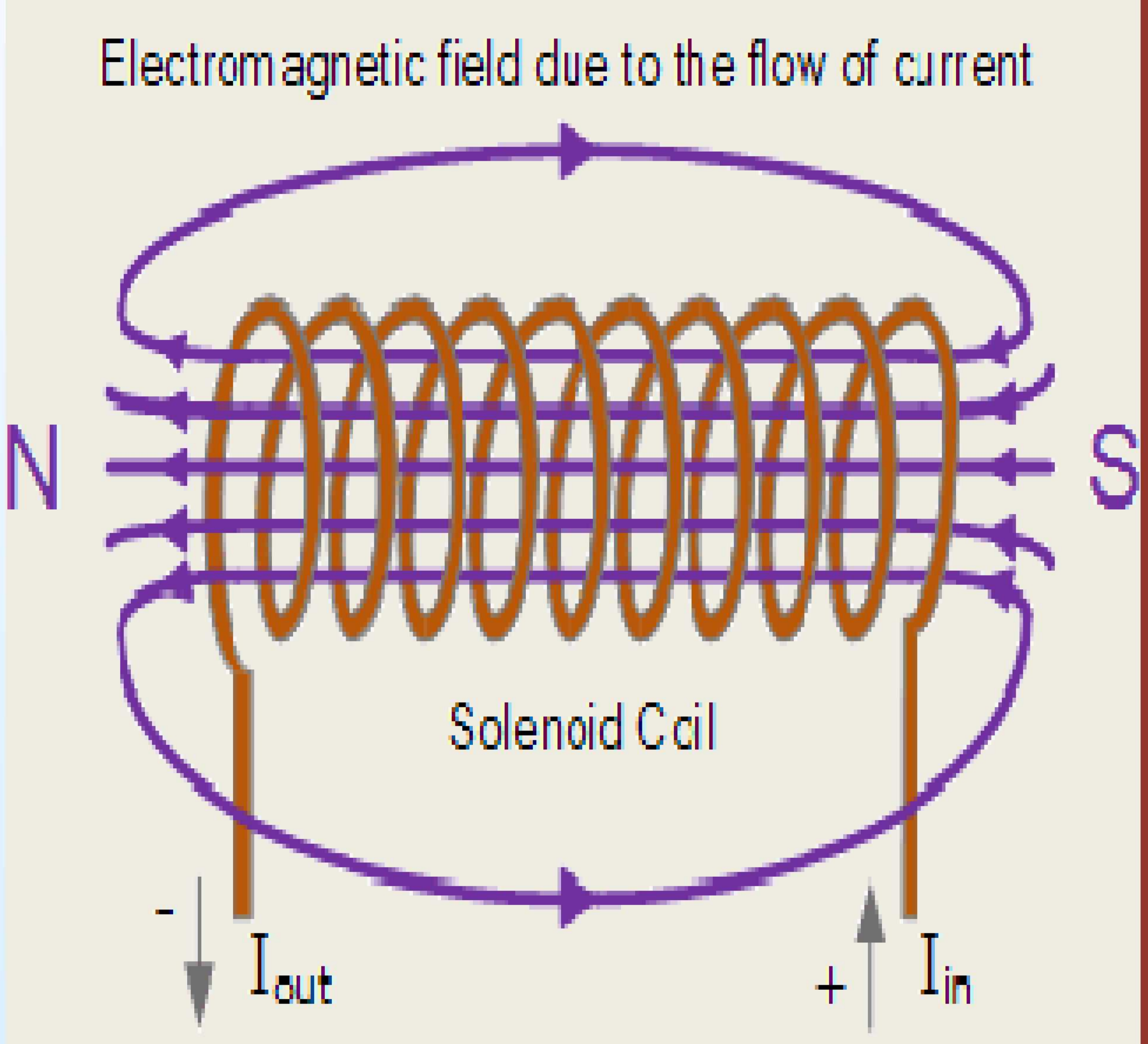
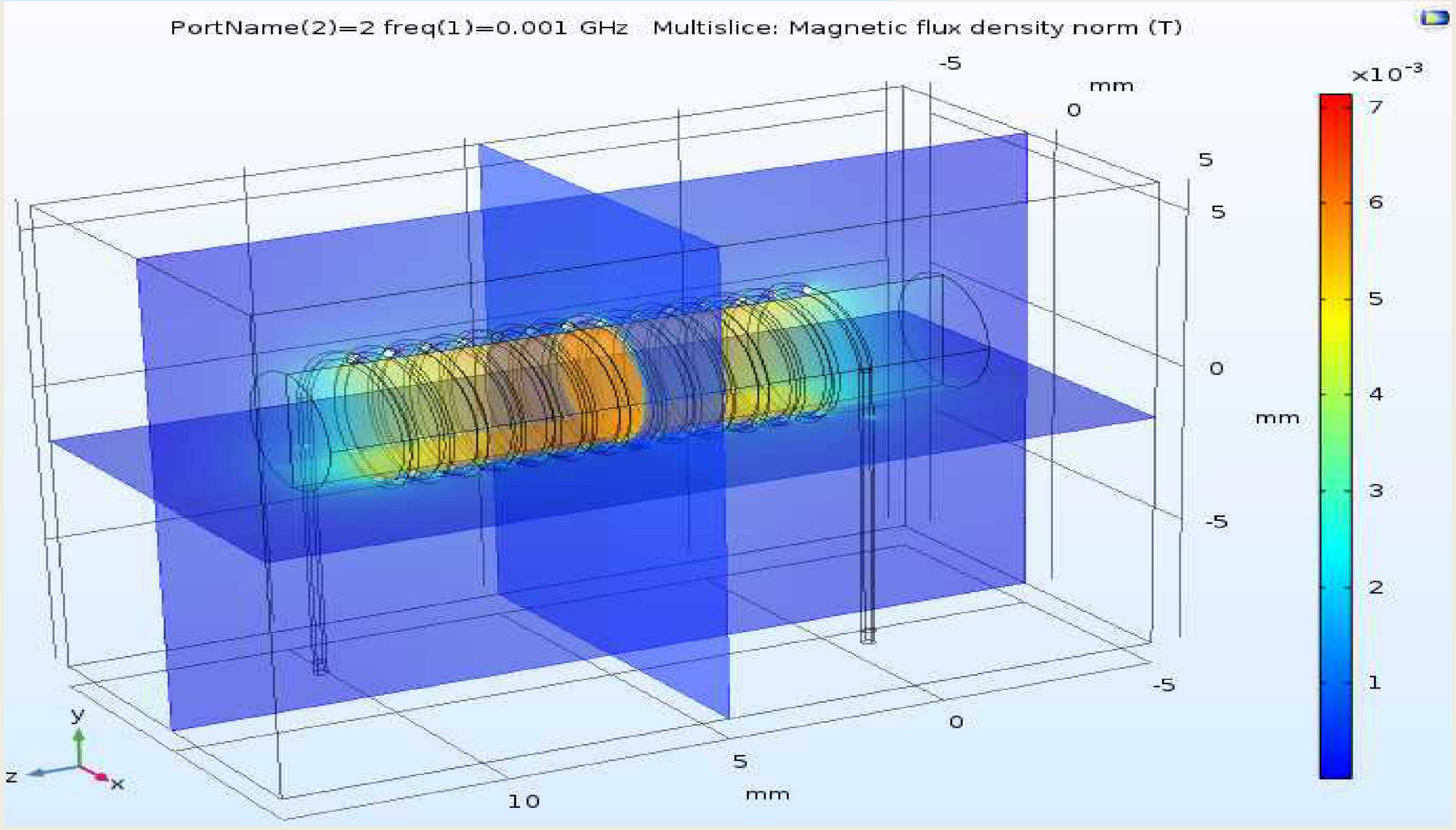
Results

Several good plots of electromagnetic and electrical fields in Comsol match the hypothesis.

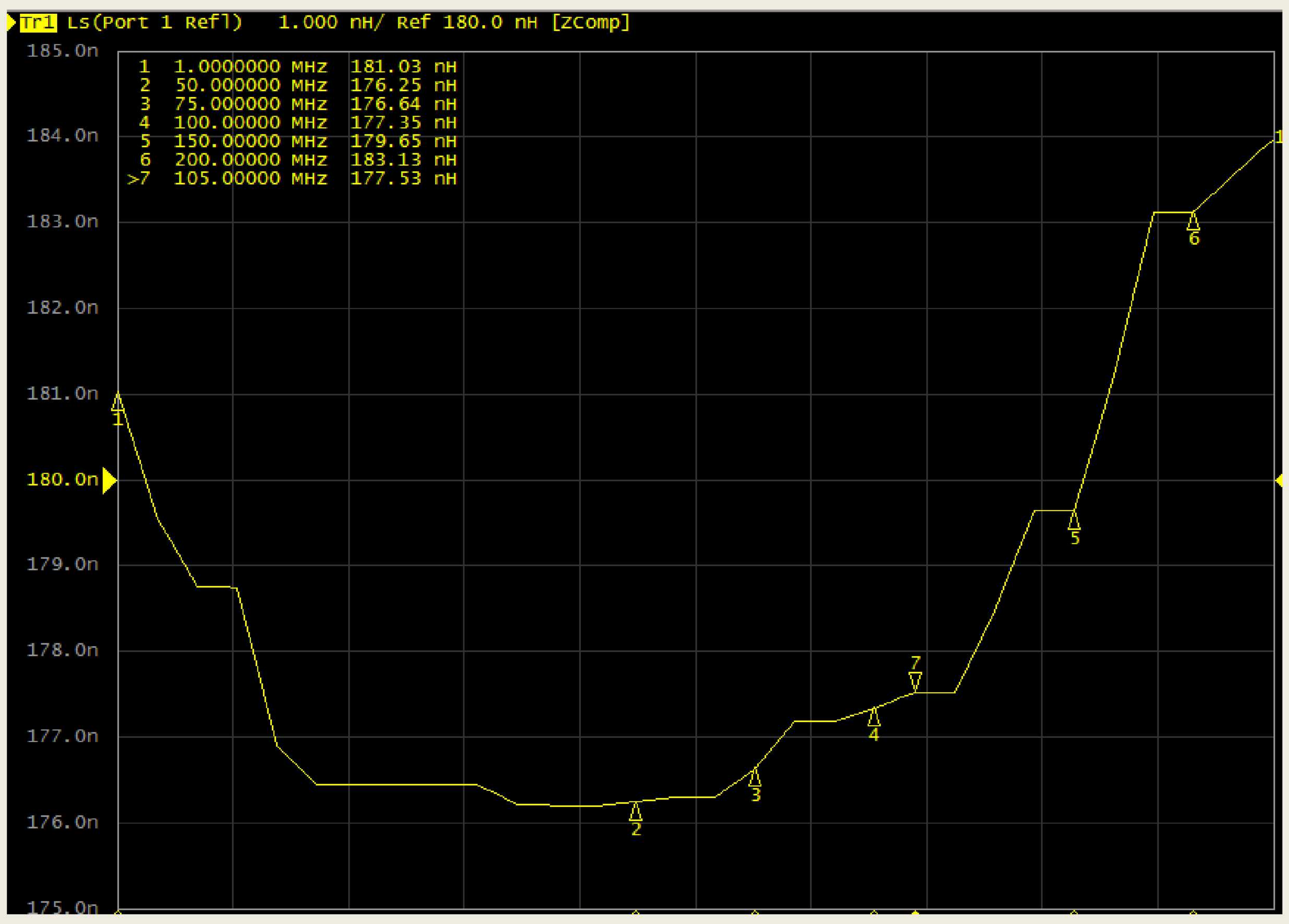






The final results are still in progress. There is a concern with the accuracy of the solenoid's fabrication and mounting and their effects on the results.

Measured Inductance b/t 1MHz-200MHz for 12 turn coil.



Conclusions

This research is still in progress. The graph of magnetic flux shows promise for Comsol work. For conclusive results, however, future work is required.

Future work

- Model the geometry of the solenoid in Comsol more accurately. The values of the inductance are off. In Comsol, s-parameters and inductance remain to be solved over a range of frequencies. Another software more commonly used in RF and electromagnetic work, such as CST, might be better suited.
- Iron out any fabrication concerns.
- Finish fabrication of coils and measurements for comparison to theoretical inductance.
- Calculate the uncertainties of the inductor and the measurement method.

References

Knight, David. (2016, February 4). An introduction to the art of Solenoid Inductance and Impedence Calculation [online]. Available: http://g3ynh.info/zdocs/magnetics/SolenoidZ.pdf