UltraFlex POWER TECHNOLOGIES

Calculating Magnetic Flux Field Strength for Nanoparticle Applications

Methods of Calculation Magnetic Field Strength

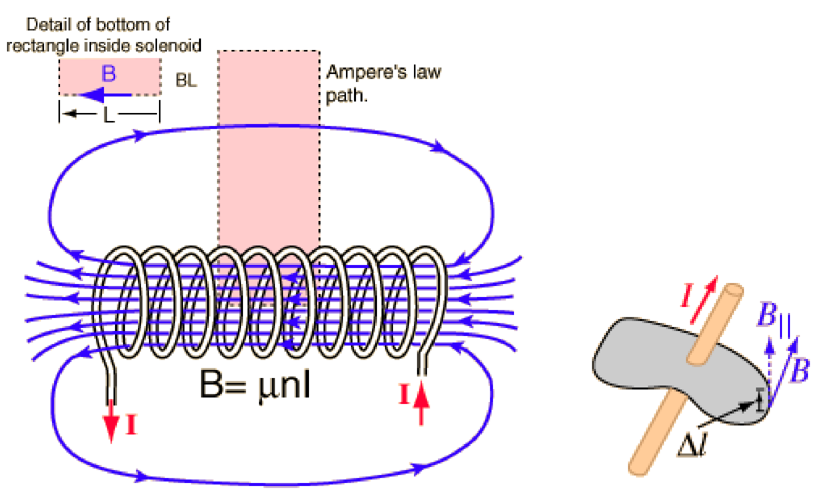
In the nanoparticle application testing, the field strength is an important factor in the experimentation and methods for measurement and calculation seem to vary widely in published research papers.

There are two standard methods used to calculate the magnetic fields generated by RF currents one approximating the coil as an infinitely long coil and the other approximating the coil as a single loop. Each method is appropriate for the right induction coil geometry. In typical induction heating applications with long coils relative to their diameter, Ampere's law provides a convenient method to approximate the field strength of a long coil.

For nanoparticle applications with relatively short induction coils, this paper suggest using single loop approximation to calculate the field strengths is more accurate. Biot-Savart Law is used to approximate the single turn loops.[i]

Long Coils

The field equations based on Ampere's Law for a solenoid, they assume a uniform field within the length of a solenoid. See rectangular section in Figure 1.[ii] The standard formula is an approximation based on a "long" coils where the length >> radius (usually 10x).[iii] For short coils relative to the radius, these approximations will estimate a higher field strength and is not the right method for the typical short coil geometry.



$$\sum B_{||} \Delta l = \mu_0 I$$

Figure 1: Amperes Law Solenoid Coil

Short Coils

A way to approximate a short coil is to assume it is a single turn coil (using the current as the coil current multiplied by the number of turns). It is more convenient to use Biot-Savart law to calculate the field in a single loop.[iv] The calculation should consider both the field at the center of the loop as well as the field at the top of the coil since the field is not constant along the length for a short coil.

This method is suggested to be more appropriate for short coils.

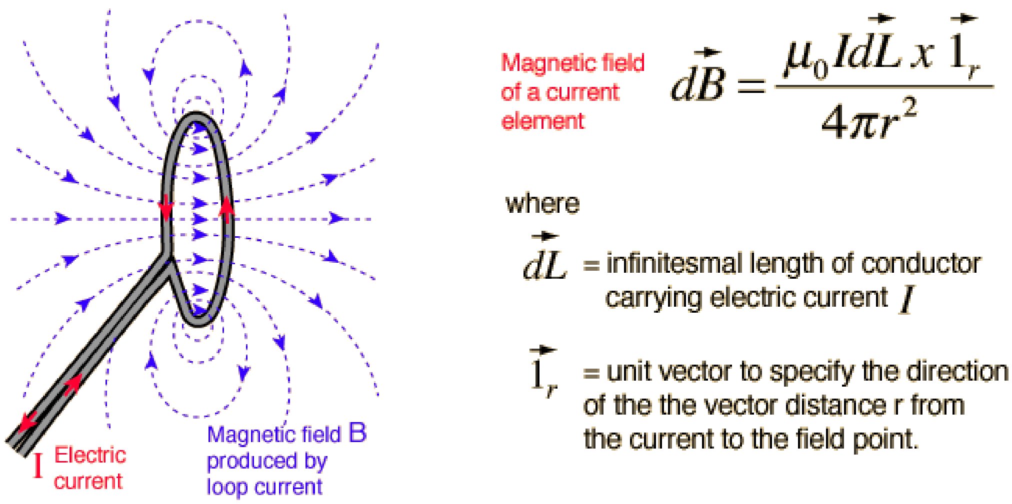


Figure 2: Biot-Savart Law

Comparison of Calculations

A model was created to compare the two methods and then measurements were taken to verify which method is most appropriate for the typical coil geometry used in nanoparticle applications. The coil used is relatively short by Ampere's law method but it is also not really a simple loop.

Note: the current measured on the generators is rms value, for field calculations we convert this to peak. All field measurements are shown as peak values.

Test Parameters

Coil Parameters are as follows: 3 Turns, 44mm ID, 24mm Height.

The generator used for testing is an Ultraflex UPT-n5 Nanoparticle heating unit[v]. Parameters for the test are below:

Tap Setting	19
Primary Current	27 A, rms
Frequency	186 kHz

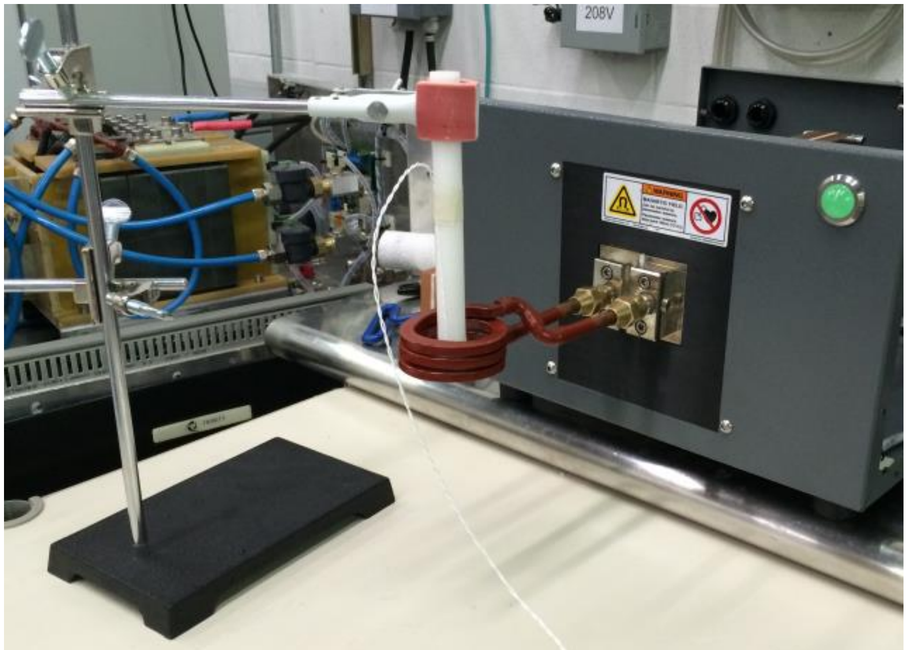


Figure 3: Test Setup

Ampere's Law Calculations

$H := n \cdot Ic$	$H = 9.069 \cdot 10^{4}$	$\frac{A}{m}$
$B := H \cdot \mu \cdot k$	$B = 0.114$	T
$\Phi B := \mu \cdot n \cdot Ic \cdot A$	$\Phi B = 1.733 \cdot 10^{-4}$	Wb
$B := \frac{\Phi B}{A}$	$B = 0.114$	T

Figure 4: Ampere's Law Calculations

Biot-Savart Law Calculations

$$B := \mu \cdot \frac{Ic \cdot Nc}{2 \cdot r} \qquad B = 0.0622 \qquad T$$

$$z := \frac{lc}{2} \qquad z = 0.012 \qquad m \qquad \text{At top of coil}$$

$$Bz := \frac{\mu}{4 \cdot \pi} \cdot \frac{2 \cdot \pi \cdot r^2 \cdot Ic \cdot Nc}{\left(z^2 + r^2\right)^{\frac{3}{2}}} \qquad Bz = 0.042 \qquad T$$

Figure 5: Biot-Savart Law Calculations

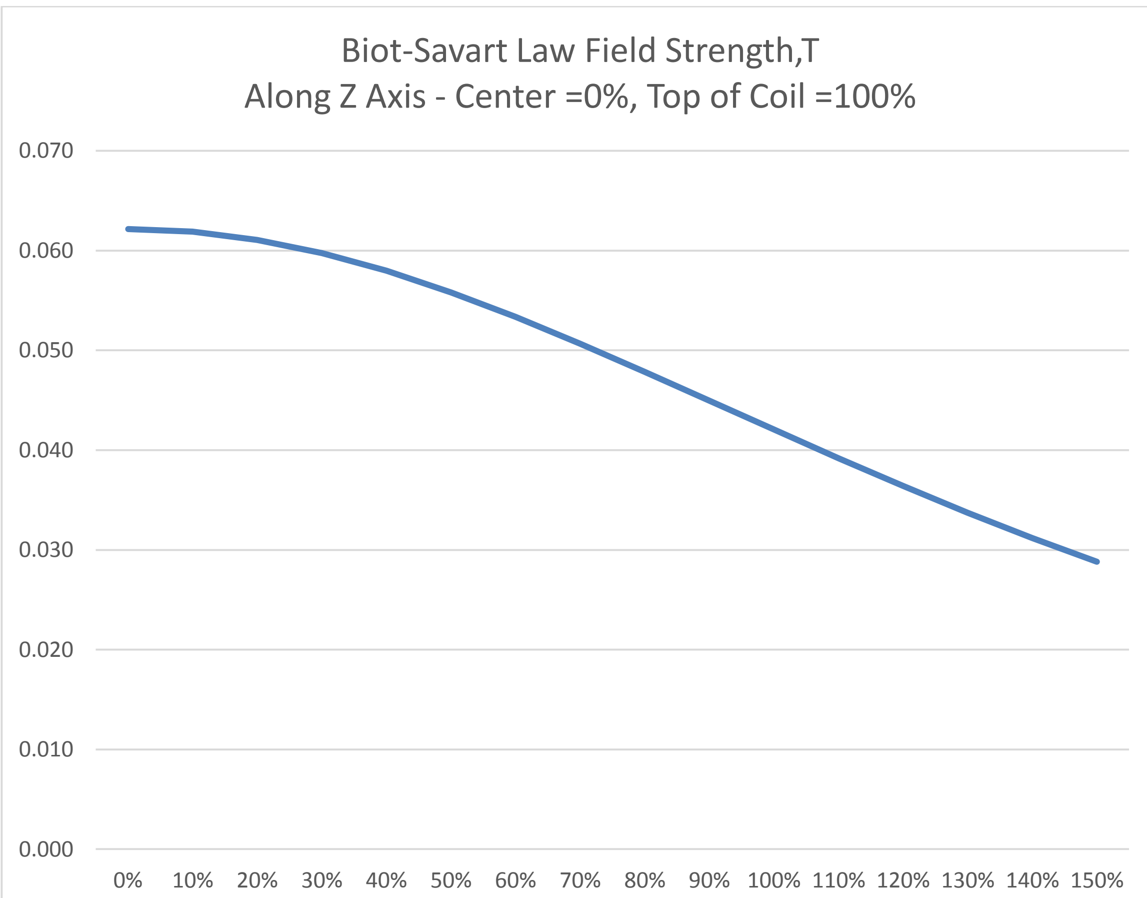


Figure 6: Biot-Savart Field Strength Along Z Axis

Measured Results and Comparison

We used a simple two turn coil (16.5 mm ID) using a small gauge wire as a field pick up coil. We took a measurement at the center of the coil (along Z axis) and at the top of the coil and compered to the two methods of calculation. We use the following formula to calculate the B field from the measured peak voltage induced in the pickup coil[vi]. r1 is the pickup coil radius, n1 is the number of turns of the pickup coil, and Vp is the peak voltage measured on pickup coil

$$B := \frac{Vp}{2 \cdot \pi \cdot f \cdot \left(\pi \cdot r1^2\right) \cdot n1}$$

Figure 7: Equation for Measuring B Field with Pickup Coil

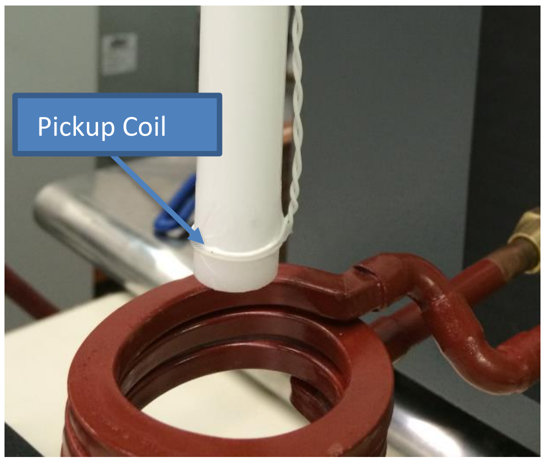


Figure 8: Pickup Coil used for Measurements

Magnetic Field Calculator

Primary Current	Pickup Coil Voltage (Center)	Pickup Coil Voltage (Top)	Frequency	Pickup Coil ID	Pickup Coil Turns	Transformer Ratio	Coil Inside Diameter	Coil Length	Coil Turns	Coil Current, peak	Ampere's Law Flux Density, B	Biot-Savart Law Flux Density, B (Center of Loop)	Measured Field (center)	Biot-Savart Law Flux Density, B (Top of Coil)	Measured Field (Top of Coil)
Arms	Vp	Vp	kHz	m			m	m		A	T	T	T	T	T
4.0	3.4	3.0	186	0.0165	2	19	0.044	0.024	3	107.48	0.017	0.009	0.007	0.006	0.006
6.0	5.9	5.1	186	0.0165	2	19	0.044	0.024	3	161.22	0.025	0.014	0.012	0.009	0.010
8.3	8.4	7.2	186	0.0165	2	19	0.044	0.024	3	223.02	0.035	0.019	0.017	0.013	0.014
10.9	10.9	9.4	186	0.0165	2	19	0.044	0.024	3	292.88	0.046	0.025	0.022	0.017	0.019
13.5	13.5	11.6	186	0.0165	2	19	0.044	0.024	3	362.75	0.057	0.031	0.027	0.021	0.023
16.1	17.1	13.6	186	0.0165	2	19	0.044	0.024	3	432.61	0.068	0.037	0.034	0.025	0.027
18.8	20.2	16.4	186	0.0165	2	19	0.044	0.024	3	505.16	0.079	0.043	0.040	0.029	0.033
21.6	23.0	18.8	186	0.0165	2	19	0.044	0.024	3	580.39	0.091	0.050	0.046	0.034	0.038
24.3	25.8	20.8	186	0.0165	2	19	0.044	0.024	3	652.94	0.103	0.056	0.052	0.038	0.042
27.0	28.4	23.2	186	0.0165	2	19	0.044	0.024	3	725.49	0.114	0.062	0.057	0.042	0.046

Figure 9: Measured Vs. Calculated Values for Field Strength

As you can see from the measured results, the calculations based on Biot-Savart law for these shorter coils produces more accurate results than relying on Ampere's law.

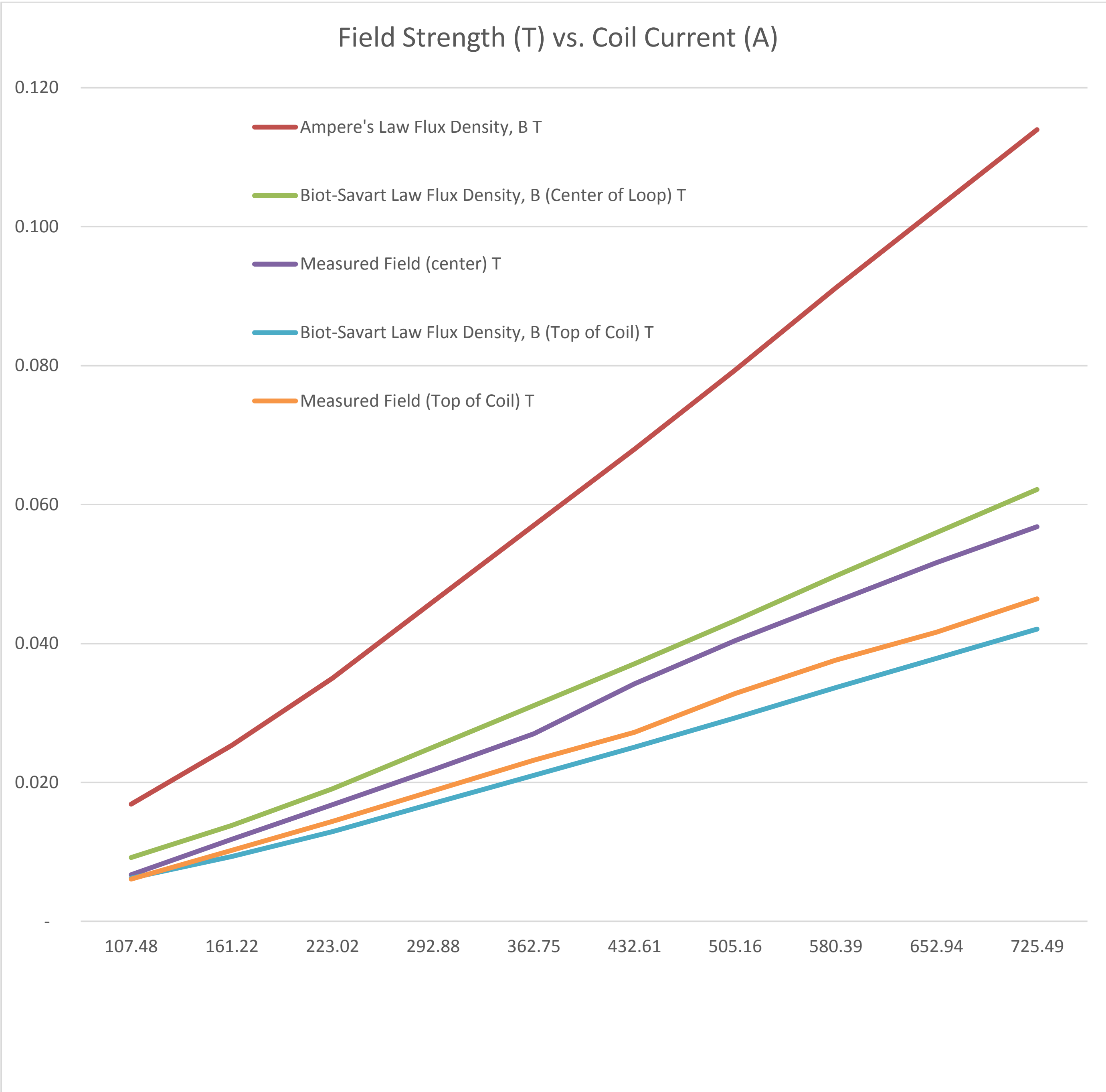


Figure 10: Field Strength Calculation Vs. Measured

Summary

Consideration of the coil geometry is important for determining the most appropriate method for calculating field strength. The typical induction heating coil used in nanoparticle applications is considered a short coil relative to its diameter. The standard long coil equations based on Ampere's law can significantly overestimate the field strength for these coil geometries and it is more appropriate to use the short coil method. This holds true for coils with length <= diameter, and as coils begin to get longer using the long coil method does tend to be more accurate. Measured results for the shorter coils used in nanoparticle applications compare favorably to the calculated results from short coil method discussed above.

Based on an informal survey of research papers on nanoparticle heating, there seems to be a wide variety of methods of calculation and measurement methods used for field strength. It is recommended to verify the actual calculation methods used by other researches to ensure proper methods for estimating field strength for any comparison purposes.

UltraFlex Power Technologies provides the Ultraflex UPT-n5 Nanoparticle heating unit, http://www.ultraflexpower.com/upt-n5/ with frequency range from 50 kHz to 500 kHz and the ability to generate magnetic fields in excess of 100 mT, offering the researcher a wide range of settings for their nanoparticle experiments.

An excel worksheet used in this paper is available for your own calculations. Contact Ultraflex Power Technologies for more assistance in selecting the proper generator and coils for your nanoparticle applications.

References

[i] In their exact forms Ampere's Law and Biot-Savart Law are equivalent. For Long coils it is more convenient to use Ampere's law and single turn coil is more convenient from Biot-Savart law. http://en.wikipedia.org/wiki/Biot%E2%80%93Savart_law

[ii] http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/amplaw.html#c1

[iii] http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html#c1

[iv] http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/curloo.html, http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/biosav.html#c1

[v] http://www.ultraflexpower.com/upt-n5/

[vi] http://physics.nyu.edu/~physlab/GenPhysII_PhysIII/MagFieldCoil.pdf