



beehive
ELECTRONICS

135A RF Helmholtz Coil

Operating Manual

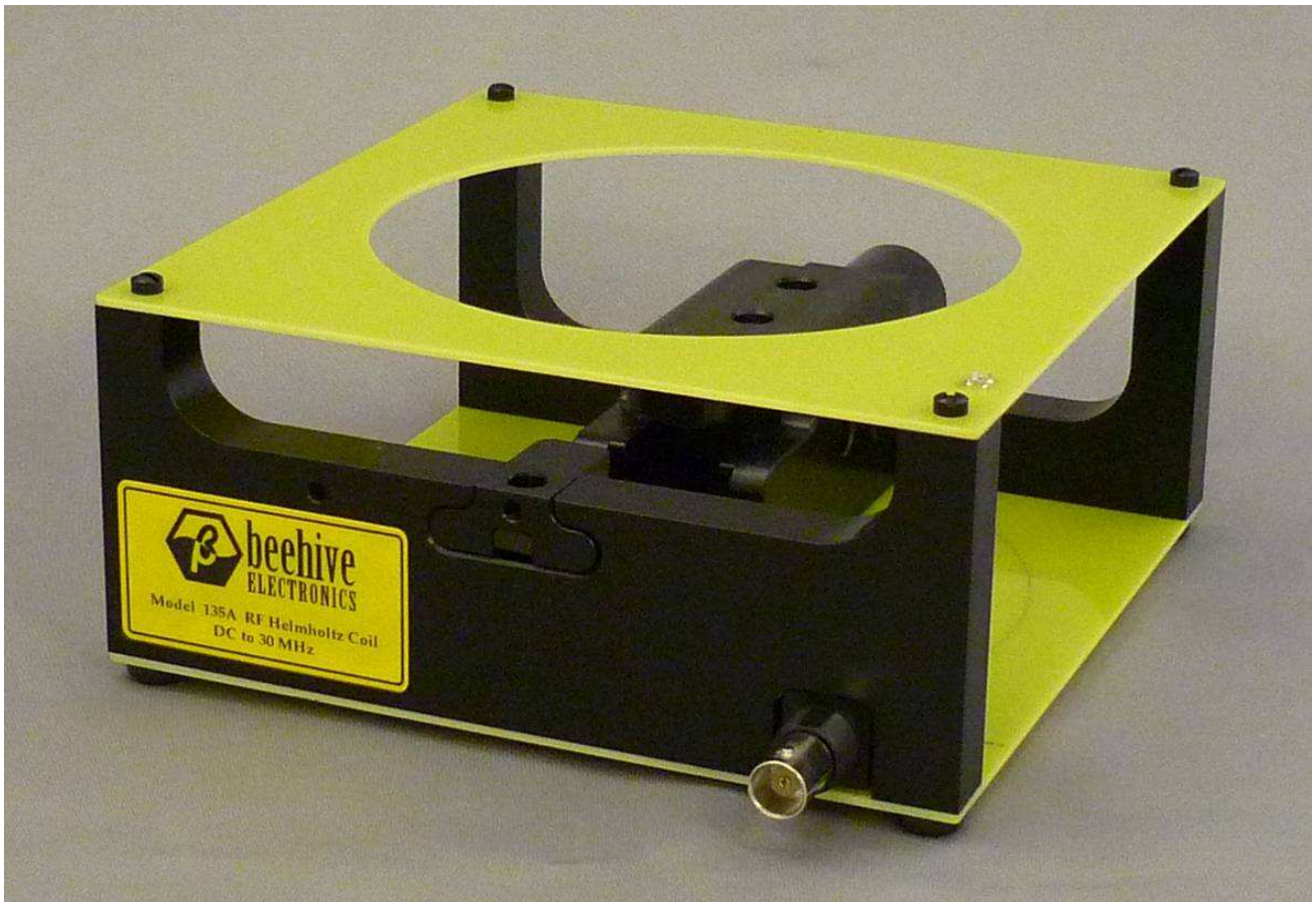


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Description

The 135A RF Helmholtz Coil generates a controlled, well-defined magnetic field between its coils. This magnetic field can be used to calibrate magnetic field probes, or to generate a controlled field for testing other devices.

The 135A is optimized for high-frequency performance, and is usable up to 30 MHz.

The 135A includes fixturing to precisely hold the Beehive Electronics 100A, 100B, and 100C EMC probes so that the user may measure the sensitivity of the probes and calculate their calibration factors. Mounting holes are provided to allow the user to fixture other devices inside the Helmholtz coil.

Features

- Allows the user to calibrate magnetic fields sensors or to subject test samples to controlled, repeatable magnetic fields.
- Wide bandwidth allows operation up to 30 MHz.
- Includes fixtures for use in calibration 100A, 100B, 100C probes.
- Mounting features provided for user-supplied fixtures allow calibration or measurement of many devices.
- Designed for use with standard 50 ohm signal sources.

Specifications

Gain

Expressed as flux density/current

$$1.45 \cdot 10^{-5} \text{ tesla/ampere}$$

Expressed as magnetic field strength/current

$$11.54 \text{ ((amperes/meter)/amperes) or } 11.54 \text{ m}^{-1}$$

Frequency Response

The frequency response of the 135A, expressed as a ratio of output magnetic flux to input current, shows less than 1 dB of variation from DC to 30 MHz:

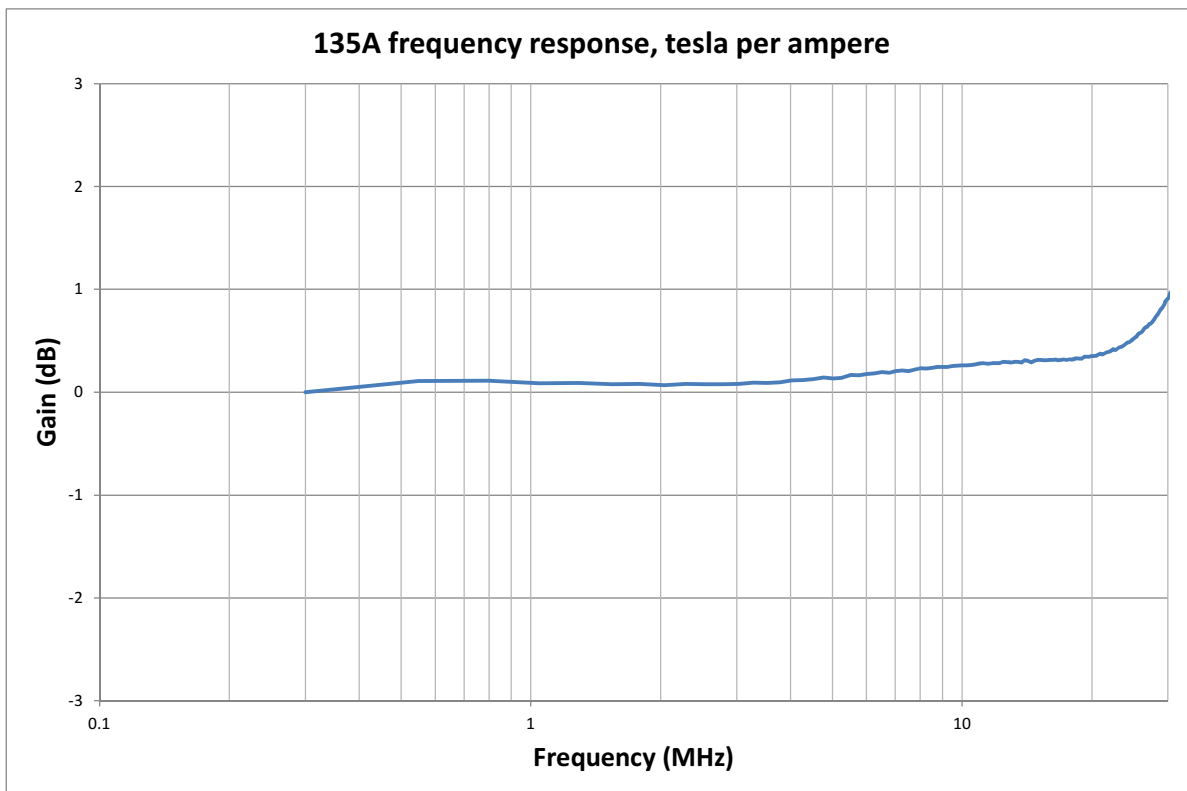


Figure 1

When driven from a 50 ohm source, more frequency response rolloff will be observed because the Helmholtz coil's input impedance increases with frequency, reducing the current drawn from the 50 ohm source. When driven from 50 ohms, this effect results in the frequency response shown below in figure 2. This effect can be easily compensated for, if desired, as shown later in this manual.

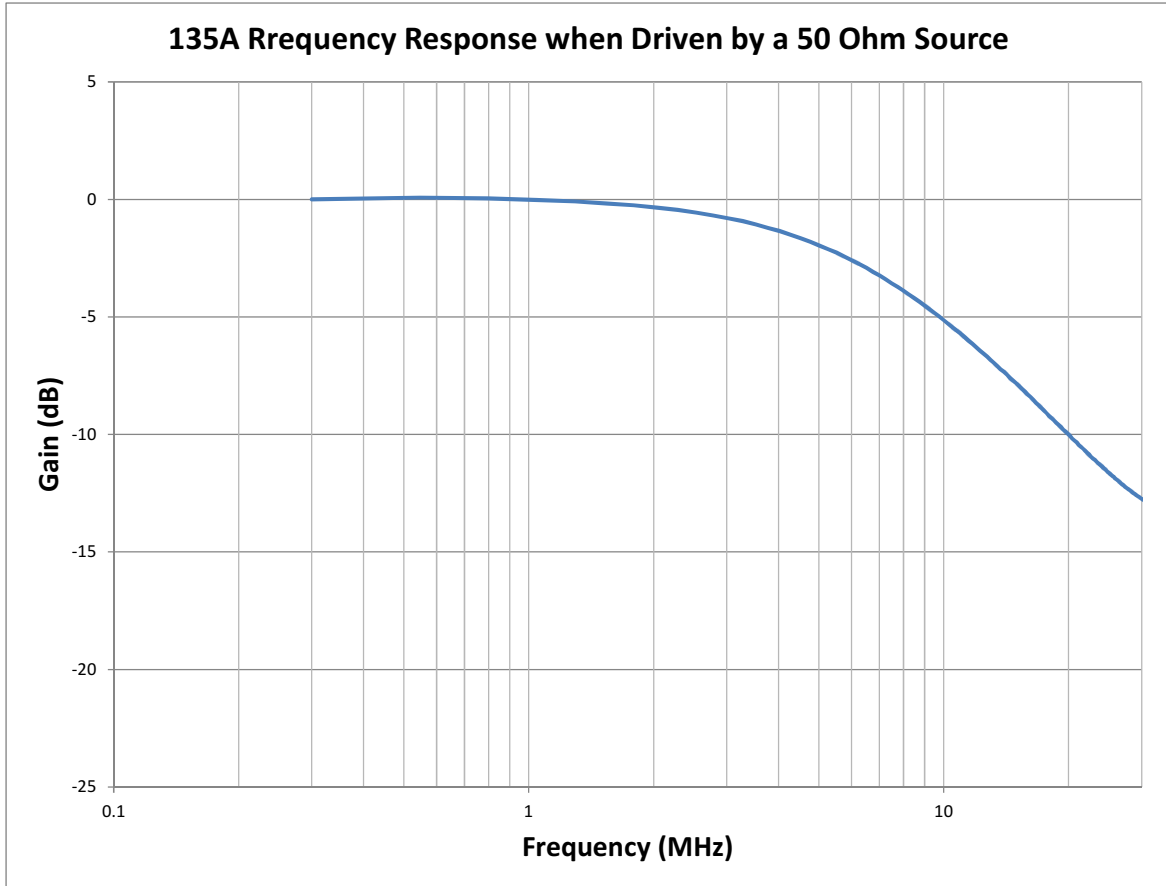


Figure 2

Maximum Input Current

0.5 amperes peak, 0.35 amperes rms

Maximum Input Voltage

240 volts peak, 170 volts rms

Maximum Input Power

When using a 50 ohm source to drive the Helmholtz coil, the power limits shown in figure 3 below guarantee that neither the maximum input current or maximum input power will be exceeded.

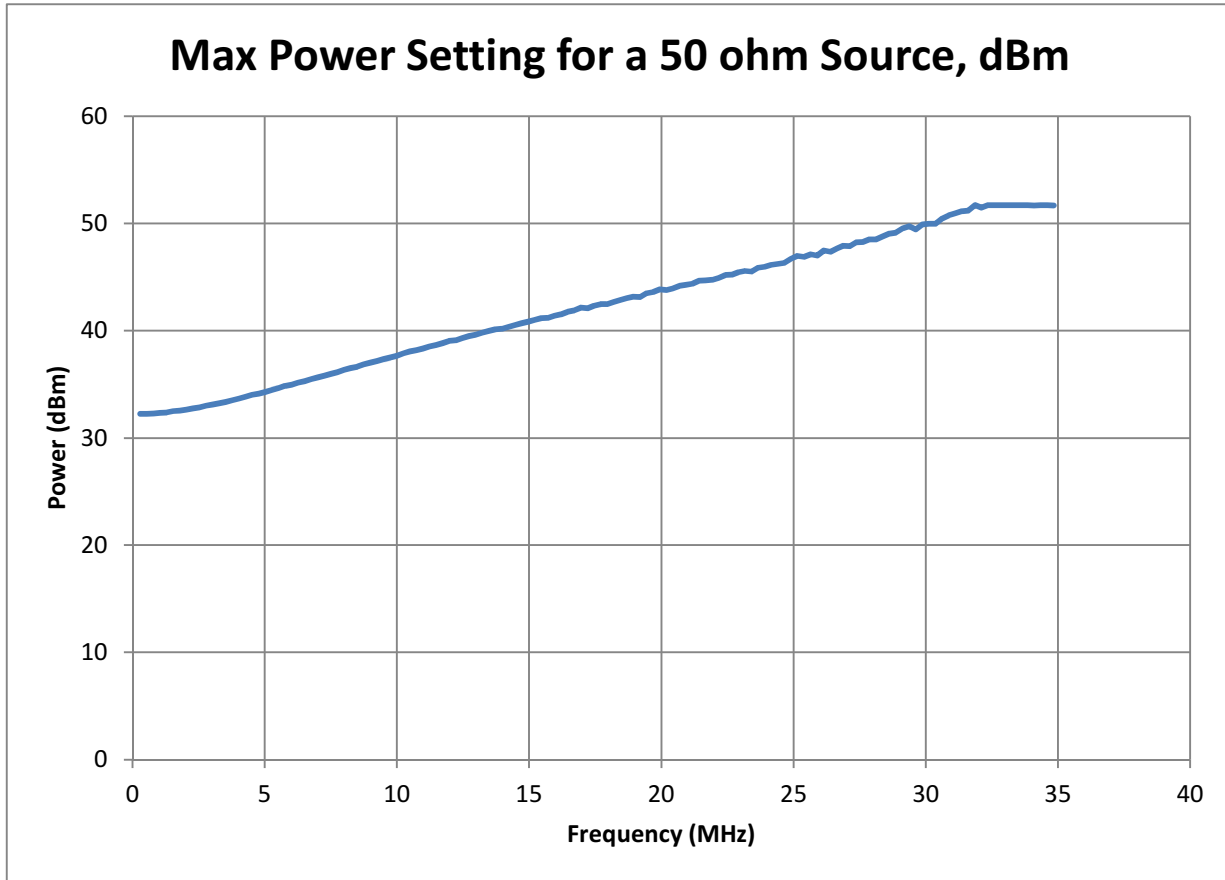


Figure 3

Port Characteristics

Impedance

Inductance: 1.25 uH +/- 10%, test frequency 1 MHz

Typical impedance versus frequency is shown in figure 4 below:

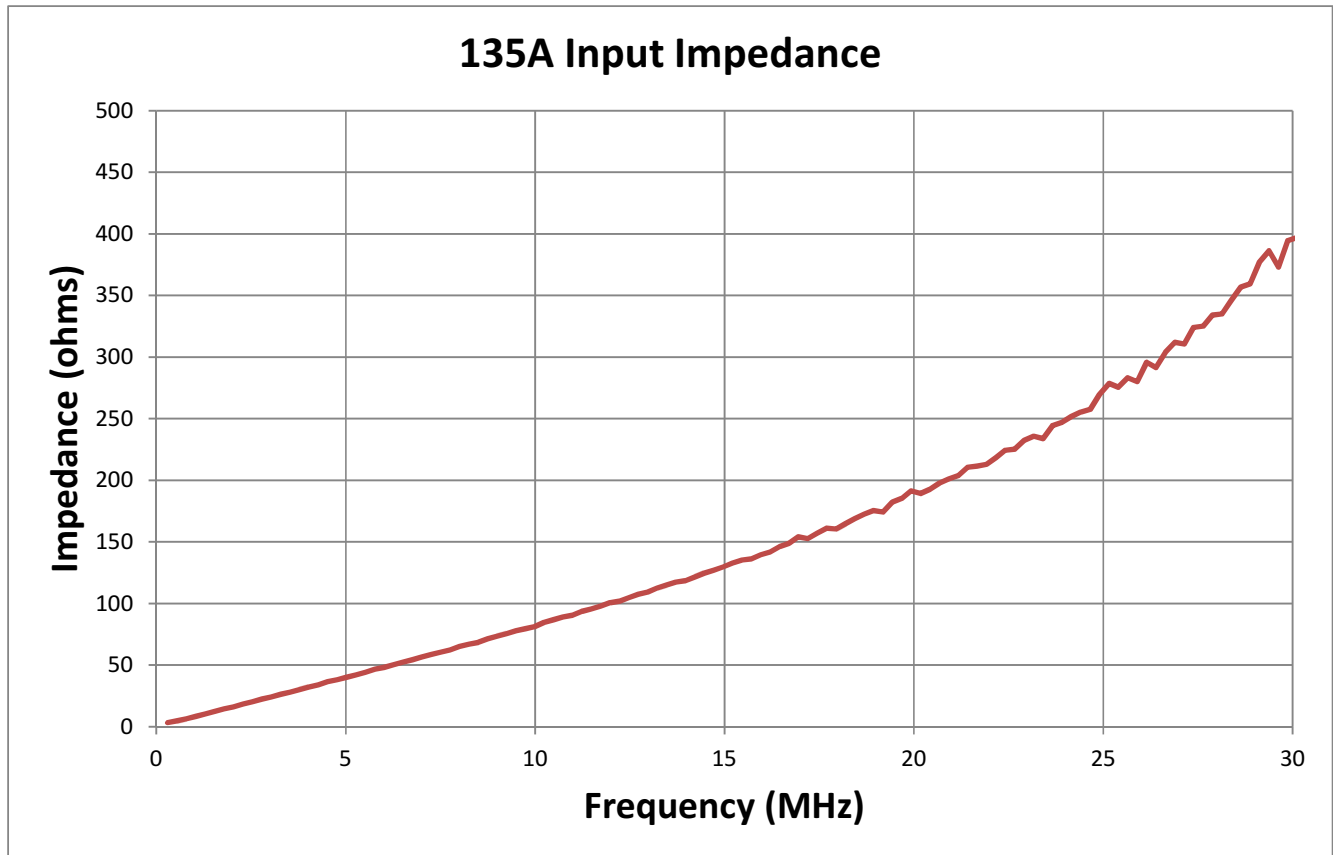


Figure 4

Connector

BNC female

Environmental

Operating temperature: 0C to 55C

Storage temperature: -20C to 70C

Dimensions

Loop dimensions

Loop diameter	4.88" (123.9 mm)
Loop spacing	2.44" (62.0 mm)

Overall dimensions

Height:	2.5" (63 mm)
Width:	6" (152 mm)
Depth:	6" (152 mm)

Warranty

- 1 year warranty
- 30 day unconditional return policy

Theory of Operation

A Helmholtz coil consists of two loops of wire (solenoids) aligned on a common axis. The two solenoids are wired in series and connected to a common input. When a signal is applied to the input, the same current flows in both solenoids, contributing to the magnetic field established.

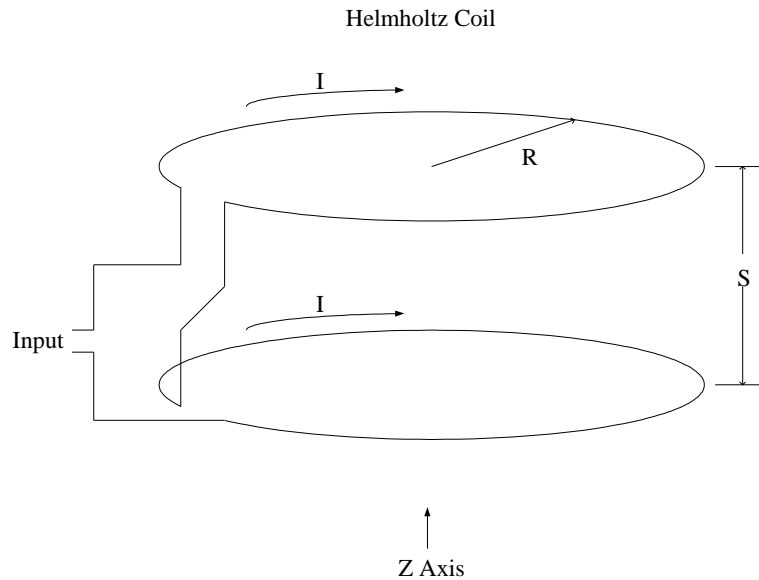


Figure 5

The spacing between the loops affects the shape of the magnetic field. For a Helmholtz coil, the spacing between the coils is set to be equal to the coil radius. When this condition is met, the following conditions are met:

The first derivative of the on-axis magnetic field is zero in the center of the coil:

$$dB / dz = 0$$

The second derivative of the on-axis magnetic field is zero at the center of the coil:

$$d^2 B / dz^2 = 0$$

As a result, a relatively uniform magnetic field is created in the center of the coil. The flux density is:

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 n I}{R}$$

Where I is the current in the coil, n is the number of turns in each solenoid, and R is the coil radius. For the 135A, these values are:

$$n=1$$

$$R=2.44'' (0.0620 \text{ m})$$

Most Helmholtz coils use a large number of turns in each solenoid to create the largest flux density possible. This works fine at DC, but it results in a large solenoid inductance. This makes the impedance of the Helmholtz coil increase rapidly with frequency, restricting their use to very low frequencies.

Since the 135A uses a single turn in each solenoid, its inductance is much lower, allowing operation as high as 50 MHz. The tradeoff for this wide bandwidth is that it results in a low flux density. In typical applications, such as when calibrating a magnetic field probe, the output signal from the probe will be relatively low. We recommend the user connect their probe to a spectrum analyzer or network analyzer, since these have good sensitivity.

Operating Instructions

General measurement recommendations

When making magnetic field measurements, it is important to be aware of items in the environment that might affect the magnetic fields. When testing with a DC magnetic field, this is easiest. Only high-permeability materials, such as iron, steel, ferrite, and nickel, will distort field patterns. Plastics and wood will not affect the magnetic field, nor will low-permeability metals like aluminum or copper.

However, when testing at high frequency, the rules change slightly. Non-conductors such as plastic and wood are still safe – they will not affect the magnetic fields. But any conductor, regardless of its permeability, will change the magnetic fields around it. So, when you're trying to measure AC magnetic fields, it's important to clear the measurement area of conductors as well.

This is because AC magnetic fields will generate AC currents in nearby metal objects. Those currents generate their own magnetic fields, disturbing the overall field pattern.

When using the Helmholtz coil, you should clear the area around it of metal objects. In particular, the Helmholtz coil should not be set on a metal surface. We recommend that you set it on a wood or plastic surface. If these are not available, you can place the Helmholtz coil on an empty cardboard box.

As a general recommendation, we suggest that you keep all metal objects at least 12'' (0.3m) away from the Helmholtz coil when in use.

When routing cables to the Helmholtz coil or the probe under test, be sure to route the cables directly away from the Helmholtz coil and the probe. Do not let the cables loop through the measurement area.

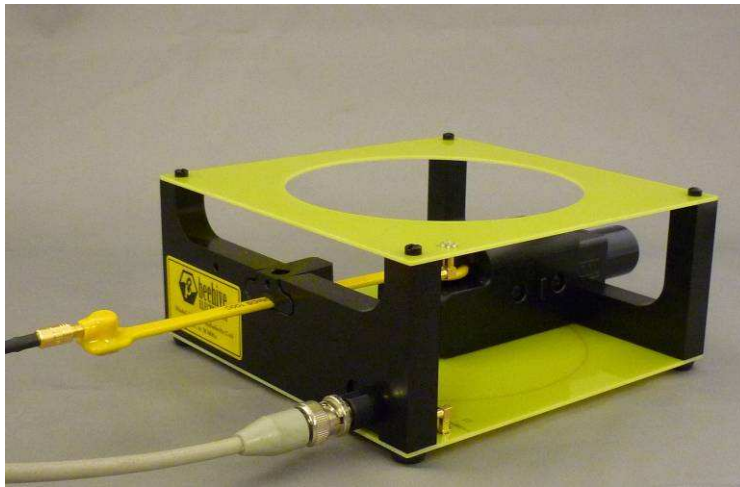


Figure 6
Good cable routing

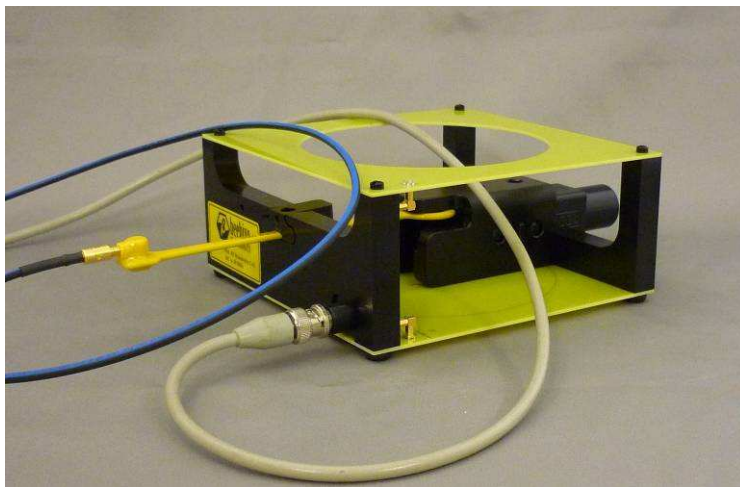
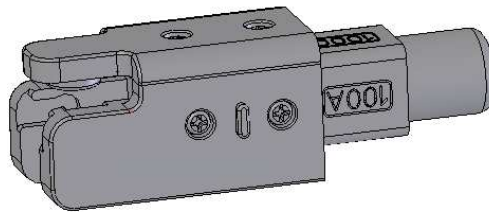


Figure 7
Bad cable routing

Testing of Beehive Electronics 100A/B/C probes

Aligning the probe fixture

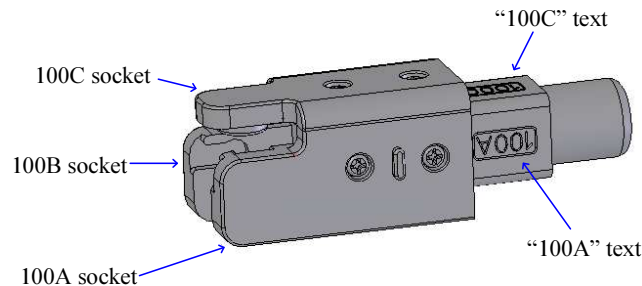
If you are testing a Beehive Electronics 100A, 100B, or 100C probe, you can use the included probe fixture to properly place the probe's sensor in the center of the Helmholtz coil. If you're testing another type of device, skip this step.



Probe fixture

Figure 8

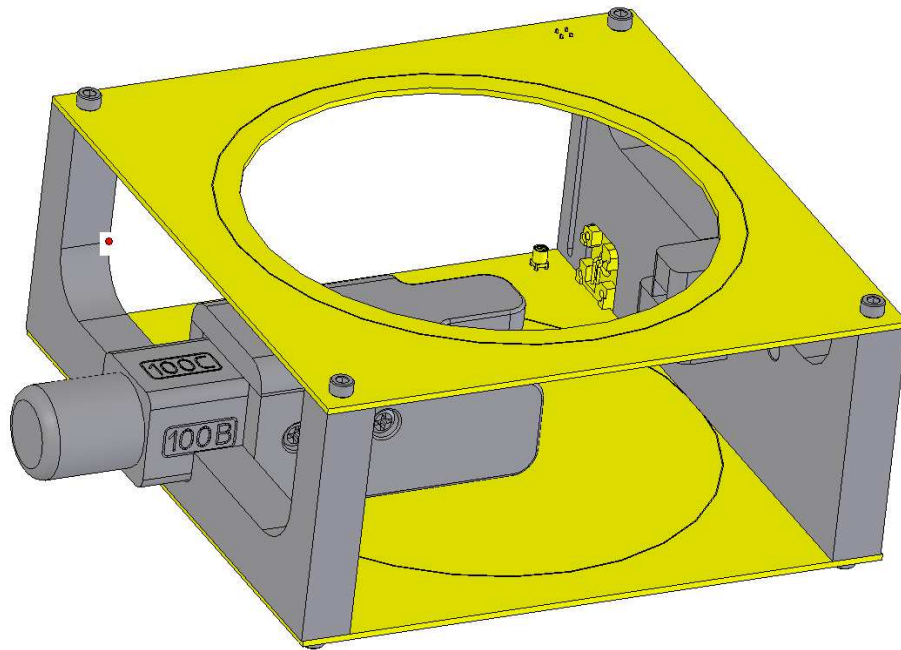
The probe fixture has three sockets machined into its body, designed to accept the probe tip of the 100A, 100B, and 100C. When the probe is rotated so that, for example, the text "100A" is on top, the socket for the 100A will be on top as well.



Probe fixture socket locations

Figure 9

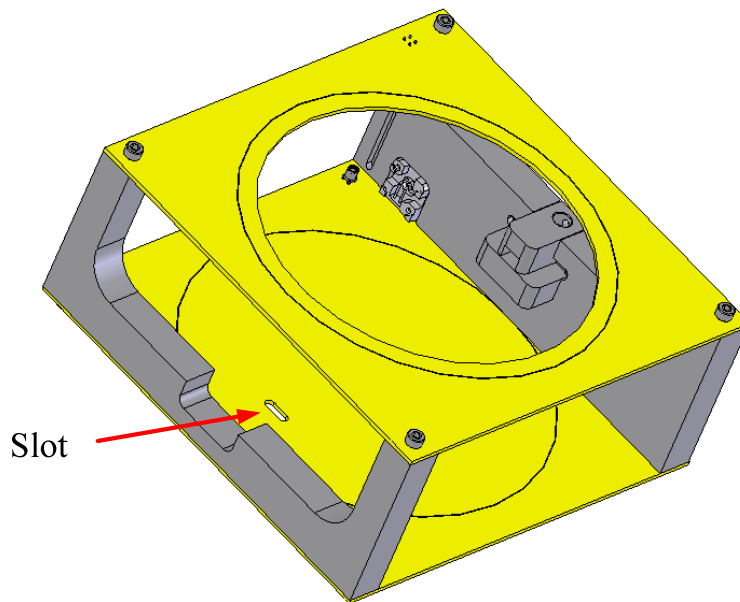
Place the probe fixture into the Helmholtz coil with the correct text facing up. For example, if you're testing a 100C probe, the "100C" text should be on top, as shown in figure 10.



**Probe fixture in Helmholtz coil,
“100C” upwards**

Figure 10

Note that underneath the probe fixture, in the Helmholtz coil baseplate, there is a slot designed to mate with the probe fixture:



Mouting slot in Helmholtz coil baseplate for probe fixture

Figure 11

There is a corresponding protrusion on the bottom of the probe fixture that fits in this slot. The probe fixture should be mounted with its protrusion in the baseplate slot.

Mounting the probe in the probe fixture

Important note regarding probe fit

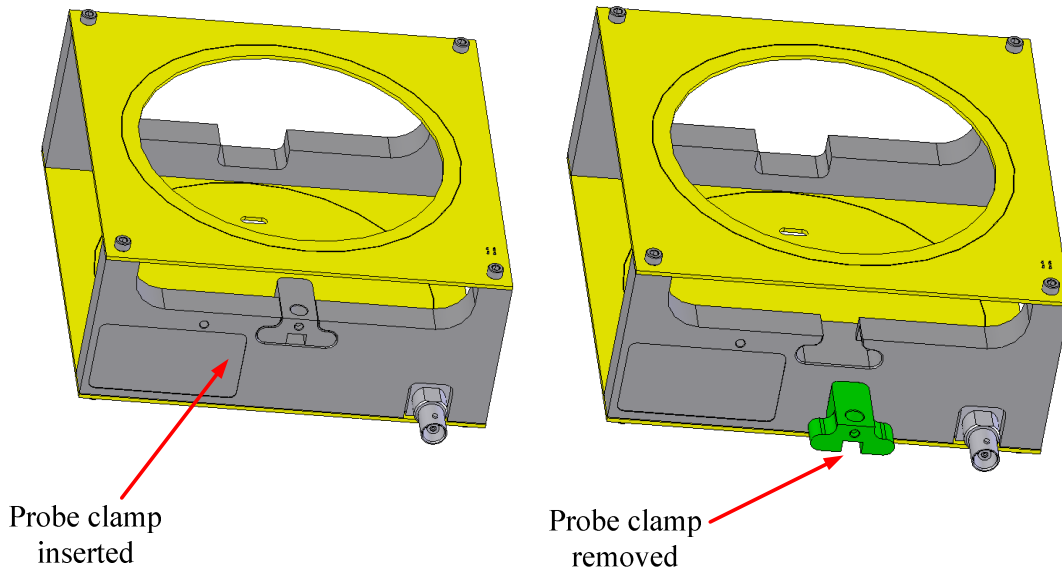
The 100 A/B/C probes are coated with a yellow vinyl coating that covers the antenna inside. This coating can vary in thickness from probe to probe. As a result, if you have a probe with a thicker coating than normal, you may find that the probe won't fit in the socket.

If this is the case, you will need to trim the yellow vinyl coating back with an Exacto knife or something similar.

This sounds risky, but there is no risk to the probe in doing this. Trimming the yellow vinyl back will not damage the probe, affect its performance, or void your warranty.

This section can also be skipped if your device under test is something other than a Beehive Electronics 100A, 100B, or 100C probe.

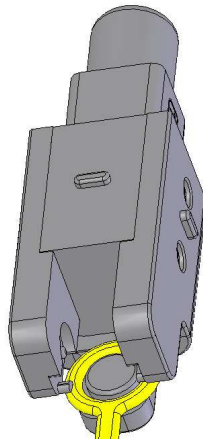
1. Slide the probe clamp out of the Helmholtz coil front panel.



Probe clamp insertion and removal

Figure 12

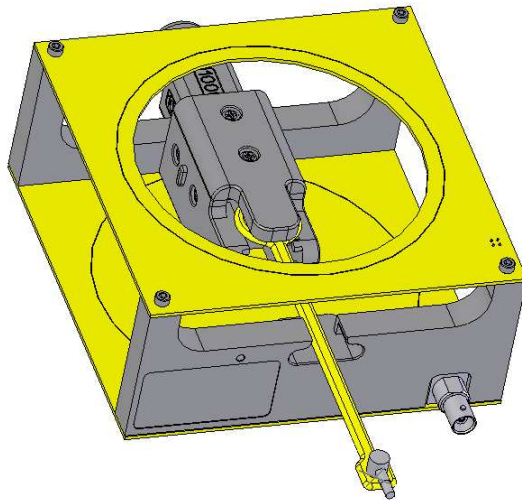
2. Insert the tip of your probe into the appropriate socket on the probe fixture. The sockets are designed to be a relatively snug fit with the probe tip to aid in centering the probe in the Helmholtz coil accurately.



**100C probe in probe fixture,
Bottom view**

Figure 13

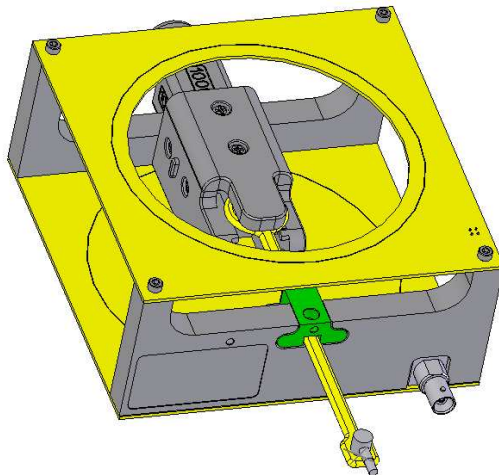
The connector end of the probe should be sticking out the front of the Helmholtz coil as shown in figure 14.



Probe installed in Helmholtz coil

Figure 14

3. Re-install the probe clamp. Note that the probe clamp has a foam shim inside it so that it can firmly hold the probe in place. You will need to press down on the clamp as you insert it to compress the foam.



Clamp installed in Helmholtz coil

Figure 15

Measurement

When using the Helmholtz coil, two pieces of test equipment are required:

1. A signal source, such as a signal generator or function generator. A 50 ohm source is recommended, but not required. This will supply the signal to the Helmholtz coil.
2. A receiver to measure the output of the probe under test.

A network analyzer has both a source and receiver, and can be used alone for this measurement. Alternatively, a signal generator can be used as a source, and a spectrum analyzer as the receiver.

Note on the use of oscilloscopes with the measurement

In principle, an oscilloscope can be connected to the probe under test and used as a receiver, in place of the network analyzer or spectrum analyzer. However, the sensitivity of oscilloscopes in general is not nearly as good as these other instruments. In most cases, the oscilloscope will have insufficient sensitivity for the measurement.

However, there is a way to improve the sensitivity of the oscilloscope. Many newer oscilloscopes have an FFT (fast Fourier transform) mode that display the Fourier transform of the input signal. In this frequency-domain display, the noise floor will be significantly lower than in the time domain display. For this reason we recommend using FFT mode if you're trying to use an oscilloscope.

Also, be sure to set your oscilloscope's input impedance to 50 ohms. If you leave the probe input impedance at 1 Megohm by accident, you will get very inaccurate results.

Connections when using a network analyzer

Most network analyzers have two ports:

Port 1, usually on the left side, which is the source

Port 2, usually on the right side, which is the receiver

Connect the Helmholtz coil to port 1 and the probe output to port 2, as shown below

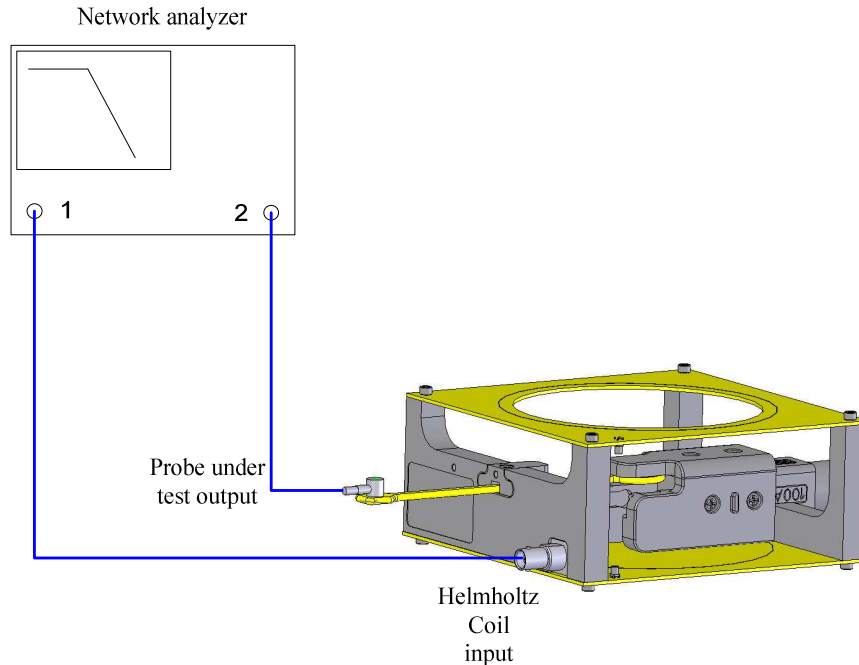


Figure 16

Measure gain of the test setup. On most network analyzers, the gain will be called “S21”.

Tips on network analyzer setup:

- Vector network analyzers are preferred over scalar network analyzers because they have much higher sensitivity as well as their higher accuracy.
- Any good quality vector network analyzer will work in this application. An example would be the Keysight Technologies E5061 series.
- For best sensitivity reduce the resolution bandwidth to the lowest practical value.
- For best sensitivity set the source output power to the maximum level.

Connections when using a signal generator and spectrum analyzer

Connect the signal generator to the Helmholtz coil input and connect the spectrum analyzer to the output of the probe under test, as shown in figure 17.

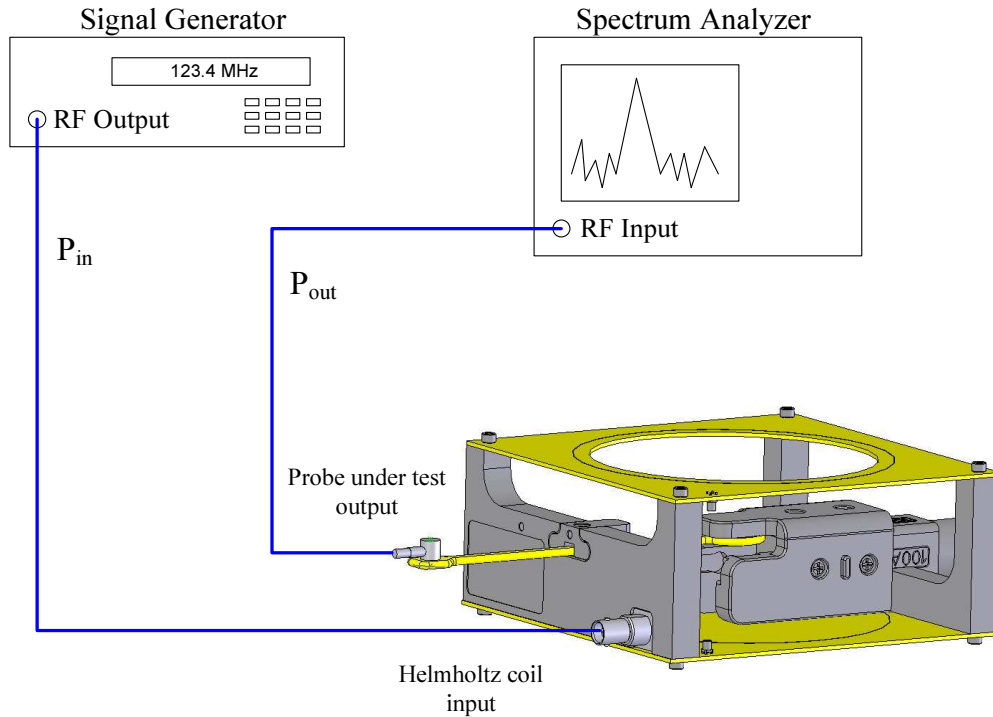


Figure 17

Tips on setup of signal generator/spectrum analyzer measurements

- Any good-quality spectrum analyzer can be used in this application. Examples are the Tektronix MDO4000 series and the Rigol DSA1000.
- For best sensitivity reduce the resolution bandwidth of the spectrum analyzer to the lowest practical value. Note that as the resolution bandwidth is decreased, the sweep time increases. Reduce the resolution bandwidth until the measured signal is at least 10 dB above the noise floor.
- Video averaging can also be used to reduce trace noise.
- For best sensitivity set the spectrum analyzer input attenuator to 0 dB.
- Set the signal generator output power to its maximum value.

Testing other devices in the Helmholtz coil

The Helmholtz coil can be used to test other devices than the 100 series probes. Any device that can fit between the coils can be placed inside.

The device under test (DUT) should be placed in the center of the Helmholtz coil, both horizontally and vertically. Mounting holes are provided in the Helmholtz coil base plate so that a user-provided fixture can be mounted to the Helmholtz coil. The hole pattern is shown in figure 18:

Mounting hole locations
Units: Inches

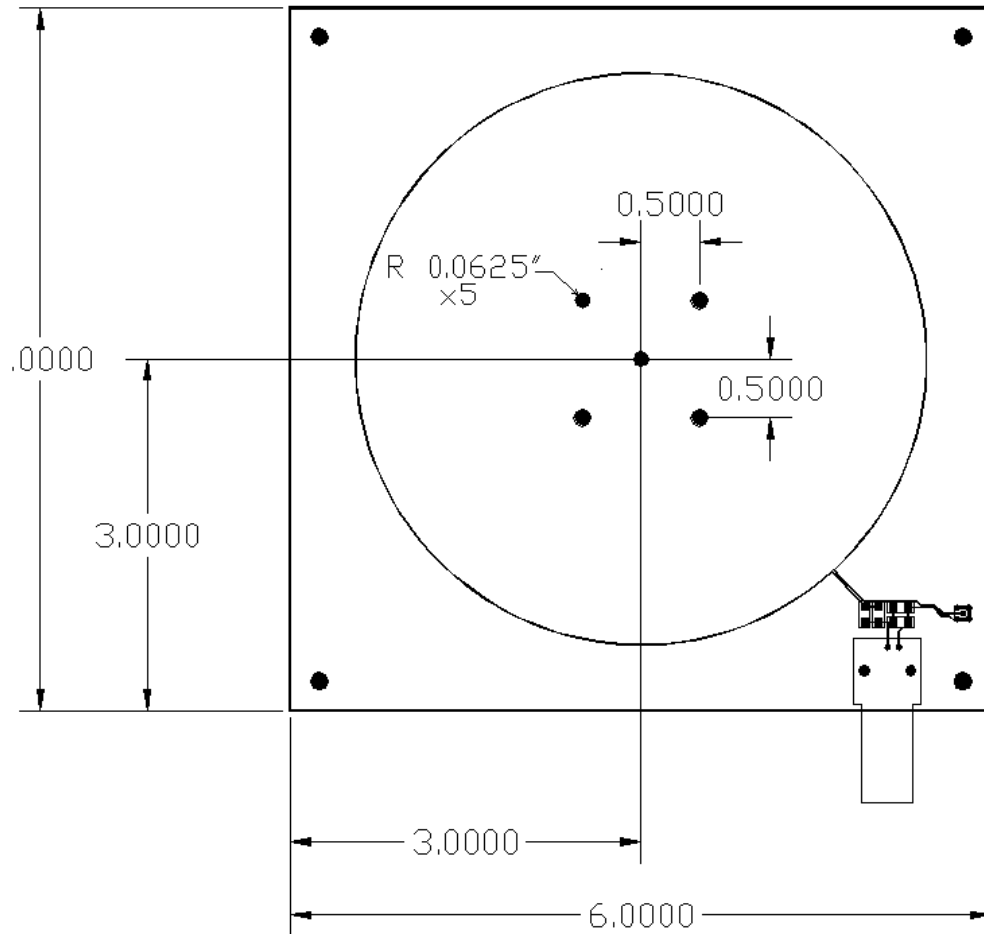


Figure 18

Calculating the sensitivity of the device under test

Calculating sensitivity with network analyzer measurements

When measuring a device under test (DUT) in the Helmholtz coil using a network analyzer (figure 16), we measure the combined gain of the Helmholtz coil and the device under test. Gain is measured as the S-parameter S21, typically expressed in decibels. For the calculations below, G_{meas} , the measured gain of the Helmholtz coil / DUT combination is equal to S21.

Calculating sensitivity with signal generator/spectrum analyzer measurements

When measuring a device under test (DUT) in the Helmholtz coil using a signal generator and spectrum analyzer (figure 17), we measure the combined gain of the Helmholtz coil and the device under test. This gain is calculated by subtracting the

power into the Helmholtz coil (P_{out}) from the signal power into the spectrum analyzer (P_{load}). Both are typically in units of dBm.

G_{meas} , the measured gain of the Helmholtz coil / DUT combination is equal to:

$$G_{meas} = P_{out} - P_{in}$$

When all are expressed in decibels.

Calculating the gain of the device under test

In order to calculate the gain of the device under test, we need to consider these things:

- The measured gain of the Helmholtz coil and the device under test
- The voltage the source would deliver into an open circuit
- Inductance of the Helmholtz coil
- Gain of the Helmholtz coil
- Gain of the device under test

As an example, we'll assume that we measured a total gain (G_{meas}) of -70 dB on the network analyzer at a frequency of 1 MHz.

An equivalent circuit of the measurement setup is shown below:

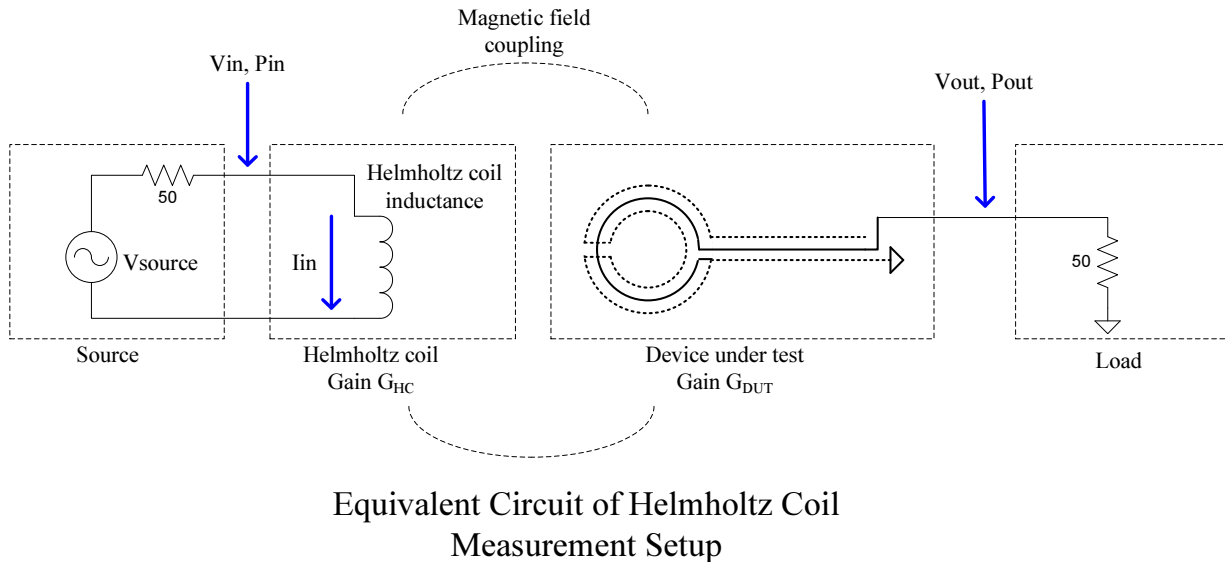


Figure 19

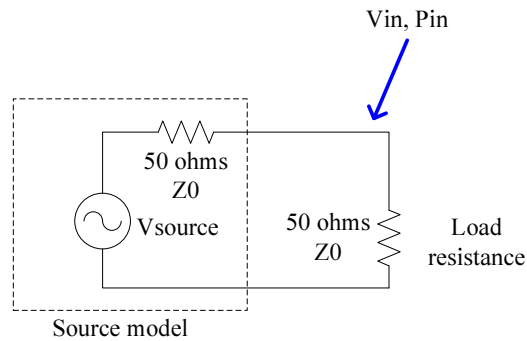
Step 1: Calculate V_{out}/V_{in}

The ratio V_{out}/V_{in} is the measured gain of the system expressed as a ratio of voltages. The measured gain G_{meas} is typically expressed in dB; we'll convert it to a linear voltage gain:

$$G_{meas,v} = \frac{V_{out}}{V_{in}} = 10^{G_{meas,dB} / 20}$$

Step 2: Calculate V_{source}

In both the spectrum analyzer and network analyzer scenarios, the signal source will typically have an output impedance of 50 ohms, which we'll call Z_0 . If we consider this source connected to a 50 ohm load,



Equivalent Circuit of 50 Ohm Source and Load

Figure 20

we see that the equivalent ideal voltage source, V_{source} , is:

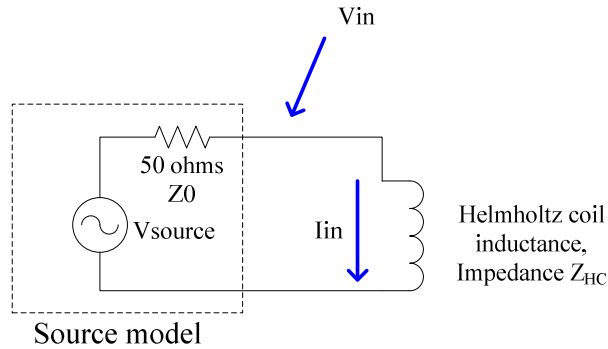
$$V_{source} = 2 * V_{in}$$

V_{source} is the voltage that would be delivered into an open circuit.

Step 3: Calculate the current into the Helmholtz coil

The input impedance of the Helmholtz coil is essentially zero ohms at low frequencies – it's just a few loops of wire, after all. At higher frequencies, the input impedance increases due to the inductance of the Helmholtz coil. Thus, at higher frequencies, the Helmholtz coil impedance affects the total system gain. At frequencies above 1 MHz, we should correct for this effect.

When the source is connected to the Helmholtz coil, the equivalent circuit looks like this:



Equivalent Circuit of Helmholtz Coil Connected to 50 ohm Source

Figure 21

The impedance of the coil is:

$$Z_{HC} = 2 * \pi * L_{HC} * F$$

Where F is the frequency of the source and L_{HC} is the inductance of the Helmholtz coil.

The magnitude of the current into the Helmholtz coil is

$$I_{in} = \frac{V_{source}}{\sqrt{Z_0^2 + Z_{HC}^2}} = \frac{2 * V_{in}}{\sqrt{Z_0^2 + Z_{HC}^2}}$$

Where Z_0 is the output impedance of the source. For most signal generators and function generators this will be 50 ohms.

Step 4: Calculate the Helmholtz coil flux density

Referring to the specifications for the 135A, we see the gain G_{HC} of the Helmholtz coil is $1.45 * 10^{-5}$ tesla/ampere. The flux density B is:

$$B = I_{in} * G_{HC}$$

Note that the units of G_{HC} are tesla/ampere, so the flux density B is expressed in tesla.

Step 5: Calculate the voltage out of the device under test

G_{DUT} , the gain of the device under test, is in units of volts/tesla. The voltage out of the DUT is therefore

$$V_{out} = B * G_{DUT} = I_{in} * G_{HC} * G_{DUT}$$

$$V_{out} = \frac{2 * V_{in} * G_{HC} * G_{DUT}}{\sqrt{Z_0^2 + Z_{HC}^2}}$$

Step 6: Calculate the gain of the device under test from the measured gain

We will call the measured linear voltage gain of the Helmholtz coil and device under test together $G_{meas,v}$.

$$G_{meas,v} = \frac{V_{out}}{V_{in}} = \frac{2 * G_{HC} * G_{DUT}}{\sqrt{Z_0^2 + Z_{HC}^2}}$$

$$G_{meas,v} = \frac{2 * G_{HC} * G_{DUT}}{\sqrt{Z_0^2 + (2 * \pi * F * L_{HC})^2}}$$

$$G_{DUT} = \frac{G_{meas,v} * \sqrt{Z_0^2 + (2 * \pi * F * L_{HC})^2}}{2 * G_{HC}} \quad \text{volts / tesla}$$

Note that we used V_{in} , not V_{source} , for this calculation. Practically speaking, when we measure the gain of the Helmholtz coil and device under test together, the units of the gain measurement will be decibels. To use the equation above, we will need to convert this to a linear voltage gain. If we define the measured gain in decibels as $G_{meas,dB}$, then:

$$G_{meas,v} = 10^{G_{meas,dB} / 20}$$

An excel spreadsheet is included with the 135A documentation that automates the above calculations. The file name is “135A RF Helmholtz coil gain calculations.xls”. It can also be downloaded from the Beehive Electronics website.

Example

For this example, we will assume a network analyzer was used for the measurement. We’ll assume that we measured a total gain (G_{meas}) of -70 dB on the network analyzer at a frequency of 1 MHz. Since this is expressed in decibels, we’ll call it $G_{meas,dB}$.

The Helmholtz coil parameters are found in the specifications table. We need the gain of the Helmholtz coil, G_{HC} , and the Helmholtz coil inductance, L_{HC} . These are:

$$G_{HC} = 1.45 * 10^{-5} \text{ tesla / ampere}$$

$$L_{HC} = 1.25 * 10^{-6} \text{ henries}$$

We measured the gain of the Helmholtz coil and device under test together as -70 dB. We need to convert this gain from units of decibels to linear voltage gain:

$$G_{meas,v} = 10^{-70/20} = 3.16 * 10^{-4}$$

Using the equation from step 6, we can calculate the gain of the device under test:

$$G_{DUT} = \frac{(3.16 * 10^{-4}) * \sqrt{50^2 + (2 * 3.14 * 10^6 * (1.25 * 10^{-6}))^2}}{2 * (1.45 * 10^{-5})}$$

$$G_{DUT} = 552 \text{ volts / tesla}$$

Comparing measurement results with 100 series probe data

The datasheet and calibration certificates for the Beehive Electronics 100 A/B/C probes specify their gain as output power with an input of 1 microtesla. It might be useful to show how to convert the probe data into the same units, volts per tesla, that we've used above.

The datasheet for the 100 series probes provides a formula for calculating the probe output power in dBm based on a flux density expressed in tesla. The formula for probe gain from the datasheet is:

$$P_{out} = X + 20 * \log_{10}(B) + 20 * \log_{10}(F) , \text{ or alternatively,}$$

Where

B is the magnetic flux density, in tesla

F is the frequency of the received signal, in megahertz

Pout is the probe output power into 50 ohms, in dBm

X is a model-specific cal factor. For example, X=85.1 for the 100C probe

As an example, let's assume a frequency of 1 MHz and a flux density of 1 tesla. The output power of the 100C, in dBm is:

$$P_{out} = 85.1 + 20 * \log_{10}(1) + 20 * \log_{10}(1 * 10^6) = 85.10 \text{ dBm}$$

A probe output power of 0 dBm corresponds to a probe output voltage of 0.2236V, or -13.01 dBV. Therefore,

$$V_{out} = 85.10 - 13.01 = 72.09 \text{ dBV}$$

$$V_{out} = 10^{72.09/20} = 4022 \text{ volts}$$

Thus, the sensitivity of the 100C probe at 1 MHz is 4022 volts/tesla.

For further information

Visit our web site for applications notes and the latest versions of the 135A's documentation.