Q Measurement with the AIM4170

revised 7-22-08

Summary: The AIM4170 can be used to determine the Q of coils and of tuned circuits. A function is included in the program to measure the Q of series and parallel tuned circuits. The Q of coils can be determined by noting the ratio of the reactance to the series resistance at any frequency. Q values up to 200 can be measured accurately. A new feature of a future update to the AIM program will be an option to plot Q versus frequency. This is illustrated in graphs in this application note.

The AIM4170 is primarily an instrument for measuring impedance. In addition to its application to antennas, it can also be used to measure components like resistors, coils, capacitors, crystals, resonators, and transformers. The impedance characteristics can be plotted over a wide range to see the effect of frequency.

This application note will show examples of how to use the AIM4170 to measure the Q of coils and tuned circuits and also how to evaluate transformers. The concept of Q ("Quality Factor") relates the loss in a component to the amount of energy stored in the component. Both coils and capacitors store energy but some of this is lost during each RF cycle. The higher the Q, the lower the loss.

There are many different configurations for making coils with special properties for different applications. The AIM makes it possible to study the effect of frequency on various designs to see which coil is better for a particular application.

Toroidal coils are especially interesting to measure with the AIM because they are so frequency dependent. They are quite useful because they allow much higher inductance to be obtained in a smaller volume than a plain air coil. Also, the magnetic field is more closely confined inside the core so there is less interaction between the coil and nearby components. The core material used has to be selected with the frequency range in mind. The AIM can show at a glance if a coil will be appropriate for a particular frequency band. Small construction details, like the turn spacing around the toroid can be evaluated quickly. The AIM can also be used to evaluate large impedances, like the common mode impedance of baluns, which may be several Kohms.

Links:

www.w7zoi.net/coilq.pdf - "Experiments with Coils and Q-Measurements" - by Wes Hayward.
www.g3ynh.info/zdocs/magnetics/index.html - numerous articles on coils

Some key words related to coils that you can look for with Google are:
  Brooks coil – maximum inductance for a given wire length.
  Rooks coil – coils with lower capacitance.
  Wheeler's formula – equations for calculating the inductance of air core coils.
  Litz wire – special wire to reduce coil loss due to skin effect.

Wire gauge awg – general information on wire gauges and properties.

Larry Benko, W0QE, one of the AIM beta testers, has compared Q measurements made with the AIM4170 to the HP4342 Q-meter with good results up to about 200. For Q's greater than 200, the AIM is not as accurate, but the general trend in Q is useful for comparing coils.   Larry has found that tuning out the inductive reactance with a high Q capacitor (air dielectric) gives good correlation with the HP4342 for Q's over 500. The AIM's Q measurement function can be used directly to measure the circuit Q at the resonant frequency.

For more information on the AIM4170, check this website: http://www.w5big.com/

Two of the coils used for this experiment:

Coil A:
#6 wire, 8 turns, diameter=2.65 inches   length=2.4 inches
Inductance=3.1 uH (calculated) = 3.0 uH (measured)
Self-resonant freq =   54.4 MHz (calculated) = 48.6 MHz (measured)

Coil B:
#12 wire, 15 turns, diameter= 1.45 length=1.50
 Inductance=5.5 uH (calculated) = 5.0 uH (measured)
 Self-resonant freq =   54.4 MHz (calculated) = 44.9 MHz (measured)

***When measuring the self-resonant frequency of coils, the equivalent capacity may be
very small. Placement of the coil and the AIM on the bench with respect to other
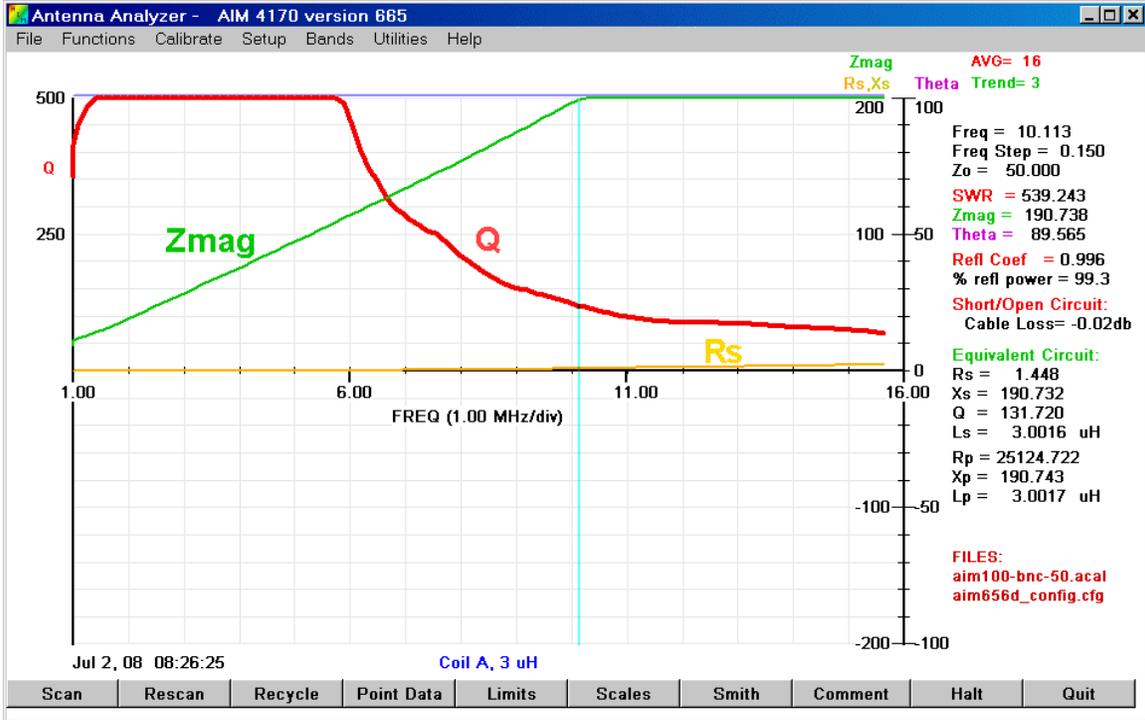objects may affect the resonant frequency by a large percentage.***

The inductance was calculated using Wheeler's formula:

Inductance (uH) = Diameter ^{2} x NumTurns ^{2} / (18 x Diameter + 40 x Length)
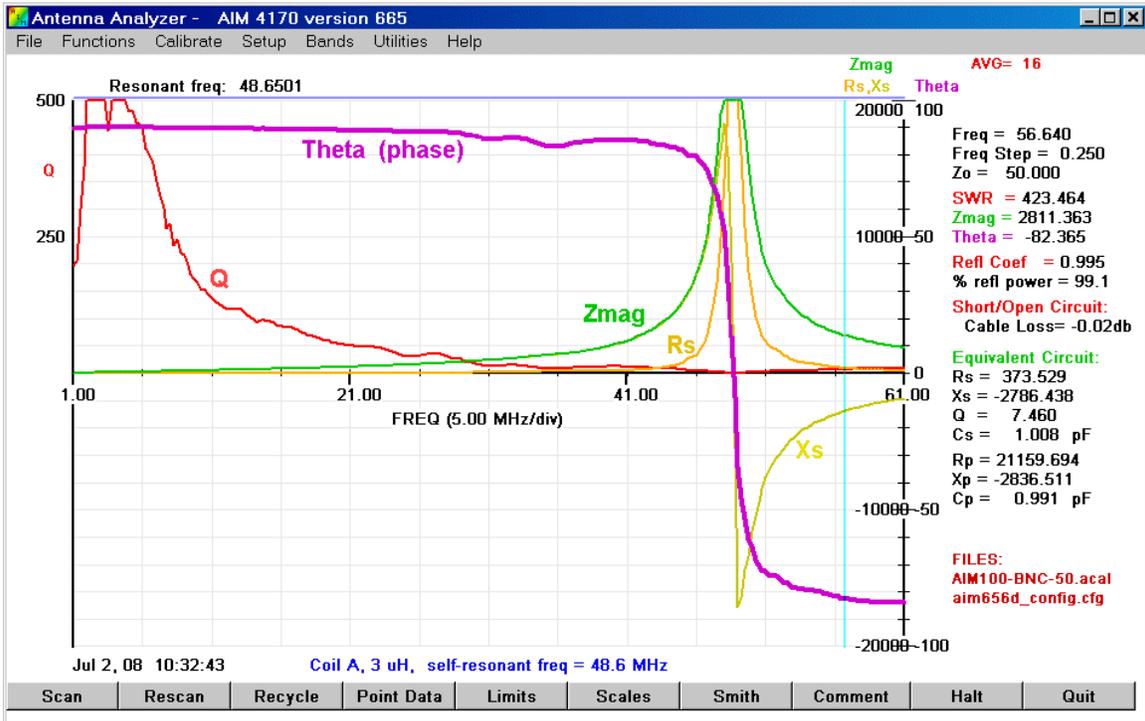
The self-resonant freq is calculated by the formula:

Self-Resonant_Freq(MHz) = 1176x(Length/Diameter)$^{0.2}$ / (NumTurns x Diameter)
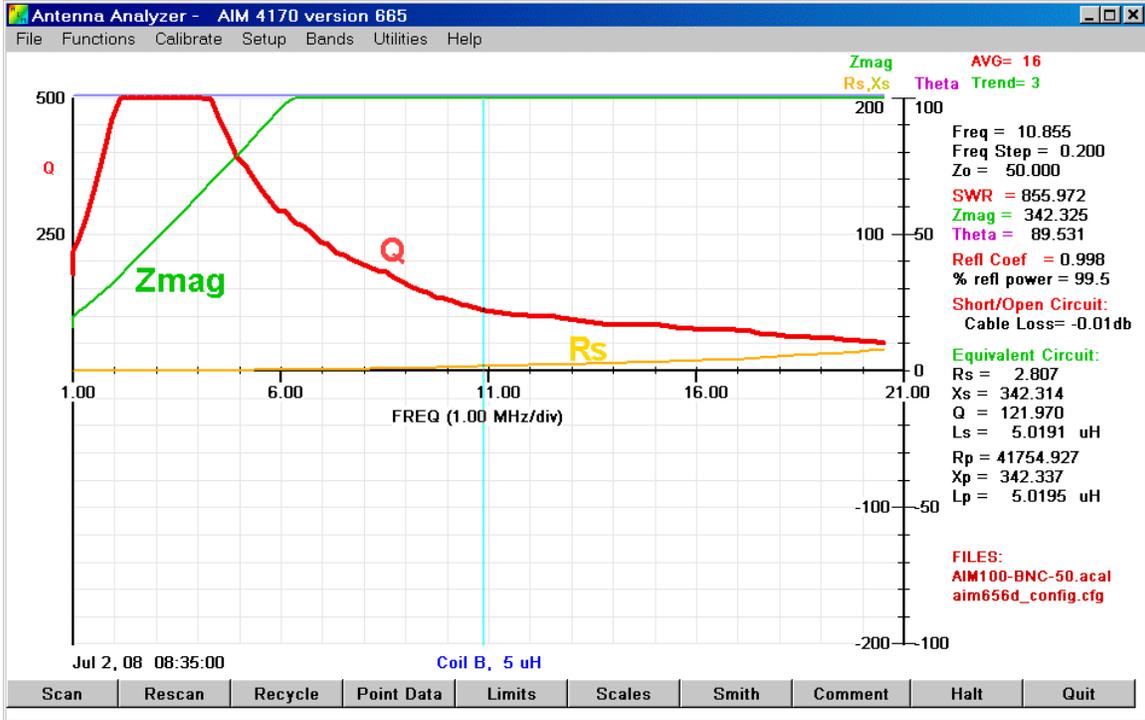
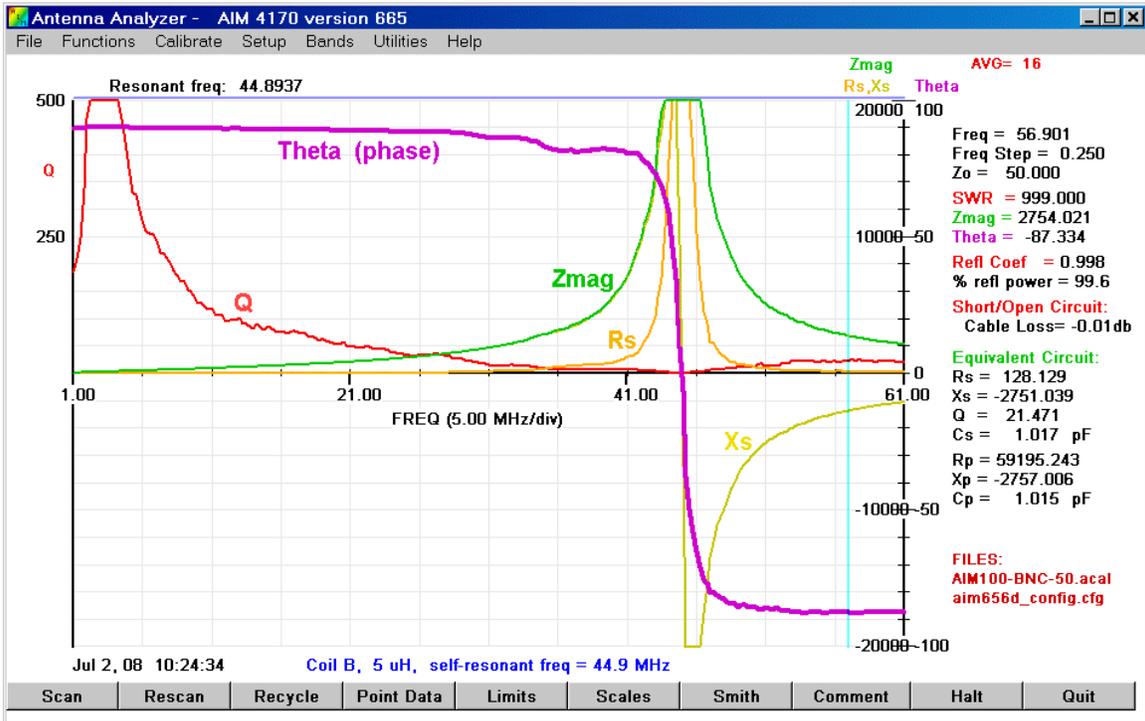*(Dimensions in inches)*

Q of Coil A vs frequency

Coil A self-resonant frequency is 48.6 MHz

Plot of Q vs frequency for Coil B

Coil B self-resonant frequency is 44.9 MHz

In actual practice, the stray capacity tends to lower the measured resonant freq. For Coil A, the effective self-capacity at the parallel resonant frequency of 54.4 MHz is **2.85** pF (assuming the inductance=3 uH).

At 44.9 MHz, the total effective capacity in parallel with the coil is **4.19** pF, a difference of **1.34** pF which is due to the connector and wires. When making a measurement like this, the coil should be spaced several coil-dimensions away from any metal object.

For Coil B, the effective self-capacity at 54.4 MHz is 1.71 pF (assuming the inductance=5 uH).

At 44.9 MHz, the total capacity is 2.51 pF, a difference of 0.8 pF due to the connector and wires.

Notice how the **phase angle** passes quickly through zero at the resonant point and the reactance, Xs, changes from a positive value (inductive) to a negative value (capacitive). At the cursor position of 56.9 MHz (Coil B) the component looks like a 1 pF capacitor. The maximum impedance of both coils is greater than 20K ohms at the frequency of parallel resonance.

Tuned Circuits

Larry Benko, W0QE, has found that large Q measurements at high frequencies are more accurate when the reactance of the coil is canceled with a high Q capacitor. This reduces the error caused by trying to measure a small resistance in series with a large inductive reactance. At the resonant frequency, the positive reactance of the coil is canceled by the negative reactance of the capacitor and the residual resistance and the phase angle can be determined more accurately. The Q measurement function can then be used to directly read the Q at the resonant frequency. Note that there should be at least 10 or 20 scan points in the transition region where the phase angle (theta) changes from -90 to +90 for a series (or parallel) tuned circuit.

For measuring the Q of a tuned circuit, an air core coil was made with 38 turns of 24 gauge magnet wire (enamel) on a ½ inch polystyrene tube. The inductance measures 7.8 uH at 3.0 MHz and the coil Q peaks there at 155.

A tuned circuit was made by putting a 1000 pF NPO ceramic capacitor in series with the coil.
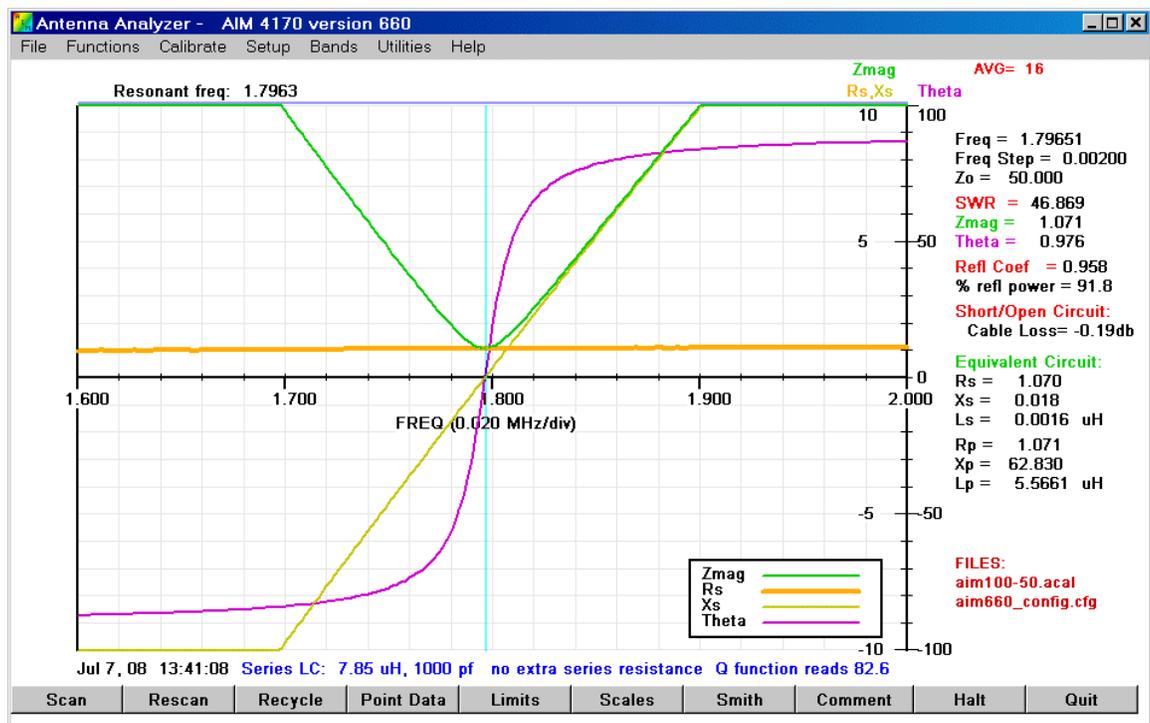
The purple trace is the **phase angle**. This starts off negative because at low frequencies the circuit looks like a capacitor (the reactance of the coil is relatively low and the reactance of the cap is relatively high). As the frequency approaches resonance, the phase angle changes to a positive value indicating the circuit is now inductive (the reactance of the capacitor is now lower than the reactance of the coil).

The Q measurement function included with the AIM4170 program measures the frequencies at which the phase angle is + and – 45 degrees. Let's call these frequencies F1 and F2. These correspond to the traditional 3dB points. Then the Q of the tuned circuit is calculated as:

$Q = F_{RESONANCE}$ / Bandwidth $= F_{RESONANCE}$ / (F2 – F1)

This is the net **Q of the circuit and includes the capacitor as well as the coil**.

For this tuned circuit the Q function reads **82.6**.

Note the heavy orange line in the above graph. It's the series resistance, Rs, of the tuned circuit. It's relatively flat between 1.6 and 2.0 MHz because the loss in the circuit is relatively constant. The cursor data on the right side of the graph shows that Rs= 1.07 ohm.

At 1.8 MHz, the coil has a reactance of 88.6 ohms.

If we calculate Q= X_L/Rs = 88.6/1.07 = **82.8,** this is very close to the value obtained by dividing the resonant frequency by the bandwidth (82.6, shown above).

To verify that the value of Rs is reasonable, we can connect an extra 1 ohm resistor in series with the coil. The trace below shows that Rs now has increased from 1.07 to 2.04 ohms, an increase of 0.97 ohm, as expected, and the software Q function reads **43.4** :
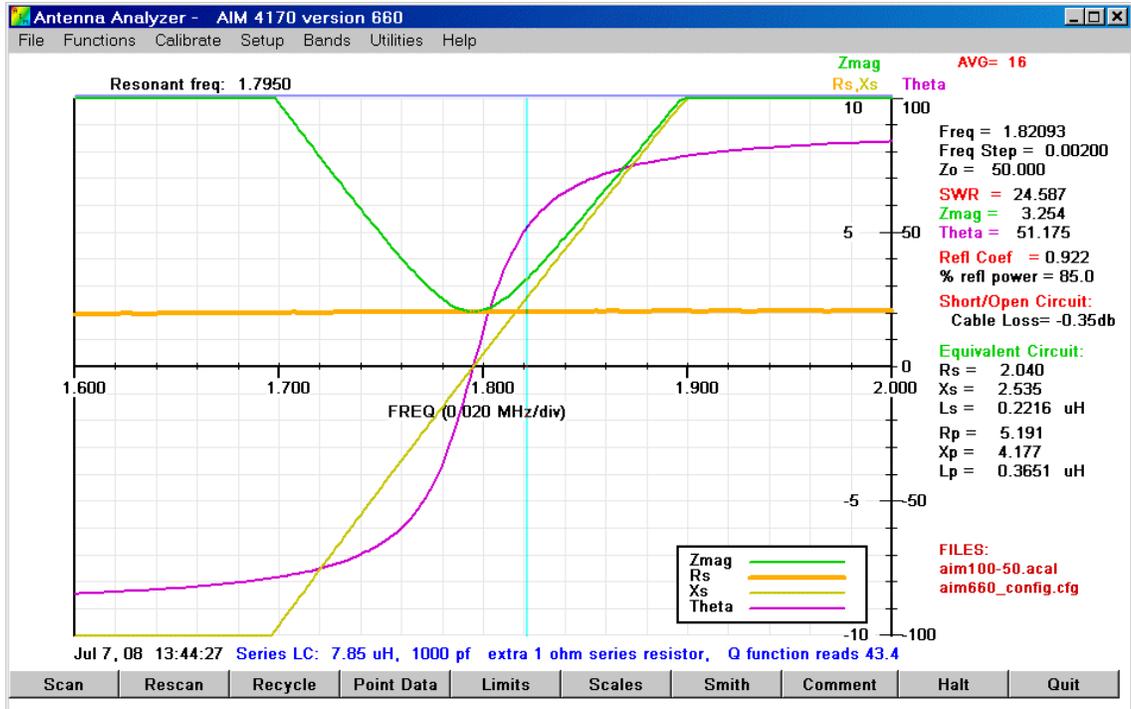
Calculating Q using X_L /Rs = 88.6/2.04 we get Q= **43.5**. Again, the two methods agree closely.

The same L and C were rearranged to form a **parallel resonant circuit**. The graph below shows the results:
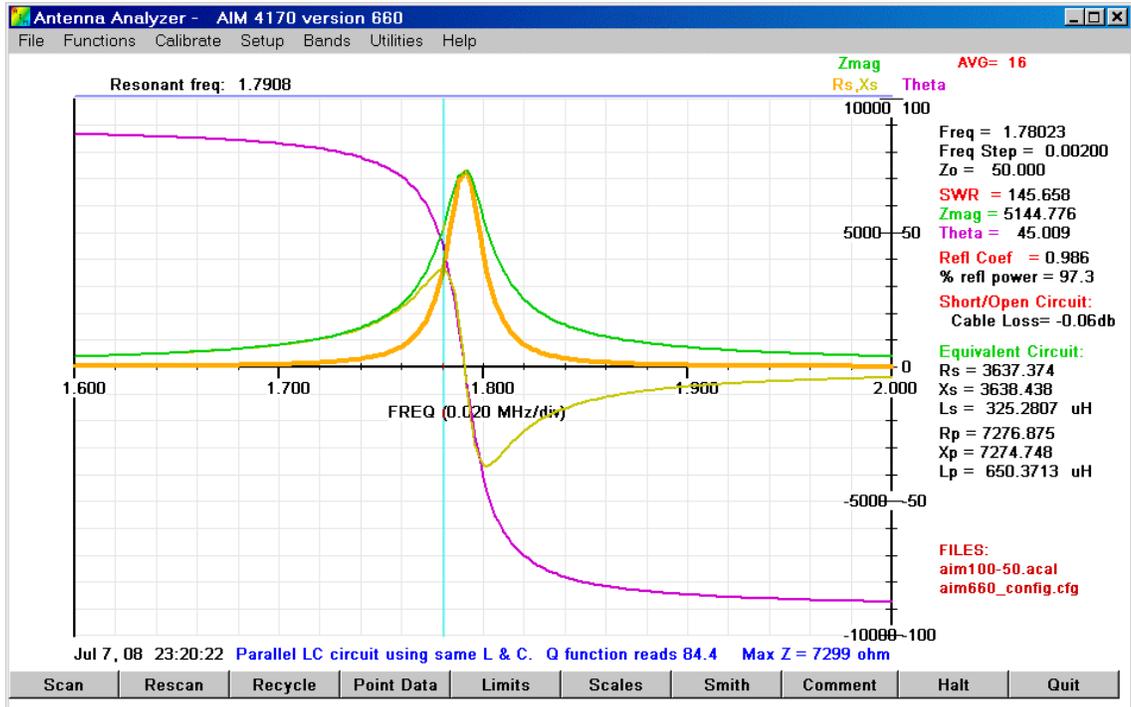
The maximum impedance is 7299 ohms. The 3 dB bandwidth is 0.0212 MHz. This gives us:

$Q = F_{RESONANCE}$ / Bandwidth = 1.7908 / 0.0212 = **84.5**

The software Q function reads **84.4** based on the points where the phase shift is +/-45 degrees.

Transformer Evaluation

To illustrate how the AIM can be used to evaluate a transformer, an FT50-43 core was used to make a 2:1 transformer. The primary has 10 turns and the secondary has 20 turns.

Each winding can be evaluate separately, as shown by the next two graphs:
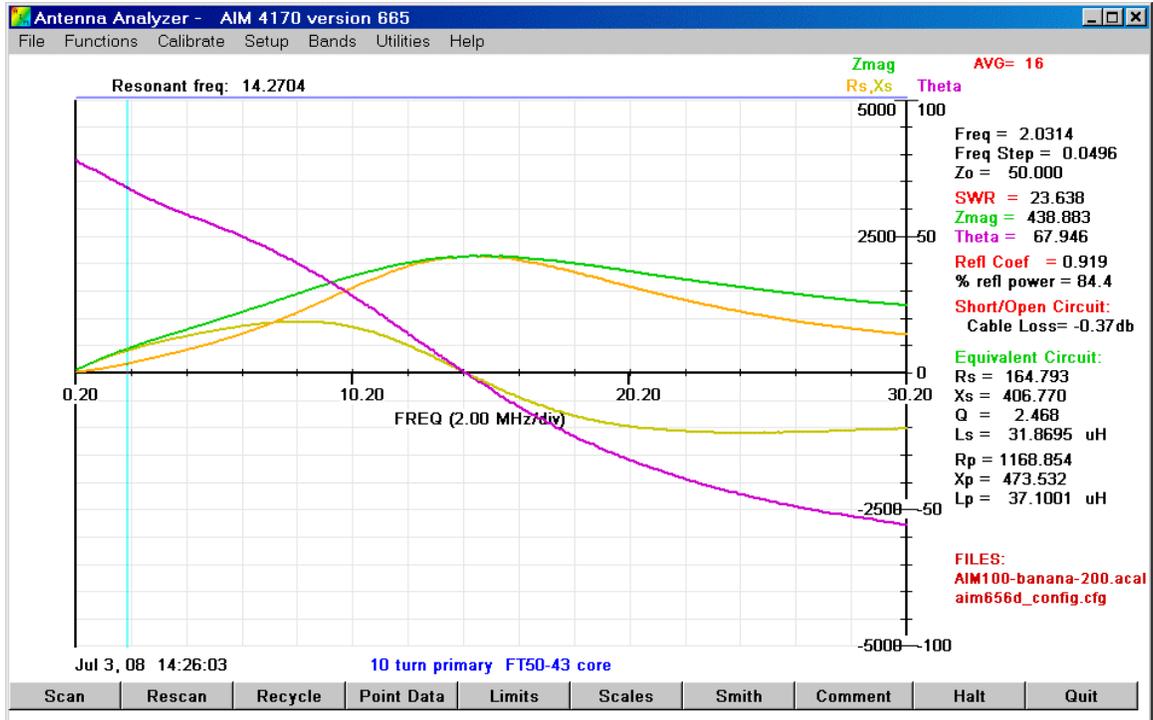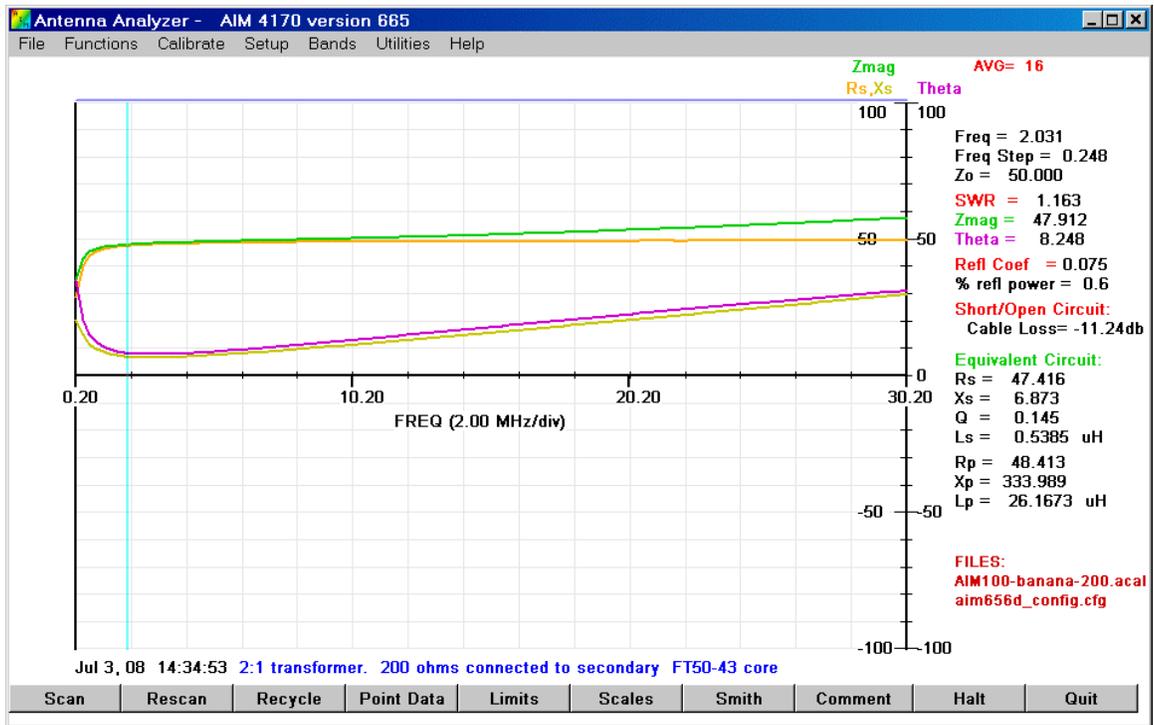

Transformer Primary

The primary inductance is about 32 uH at low frequencies. It decreases steadily with frequency.

This basic measurement technique can be used to measure an ordinary coil made with a core. In this case, we see the phase angle decreases steadily from 200KHz, so this coil is not a very good approximation to an ideal inductor (ideally, the phase shift would be 90 degrees). Other core materials are better at high frequencies. With the AIM4170, it's possible to quickly evaluate different core materials and different windings to find what is most suitable for the desired frequency range. The AIM can also be used to help sort a collection of cores that are not marked.
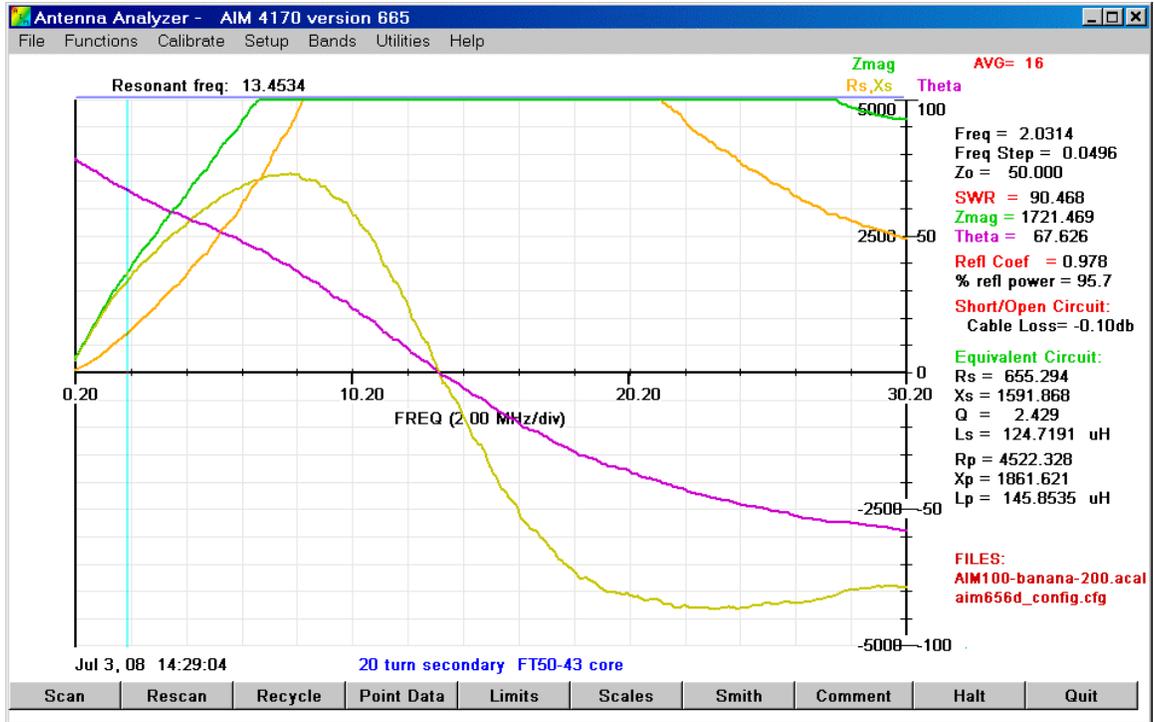
Transformer Secondary

The inductance of the secondary is about 125 uH at low frequencies. As expected, this is about four times the primary inductance since the turns ratio is 2 to 1.

200 ohms transformed to approximately 50 ohms

When the secondary is connected to a 200 ohm resistor, the impedance seen at the primary side would ideally be 50 ohms and the phase shift would be zero. The actual result is about 47.4 ohms and there is some loss even at 2 MHz. The impedance transformation is reasonably flat up to 30 MHz but the loss increases steadily, as indicated by the increasing phase shift (purple trace) and reactive component (yellow trace).