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New Induction

Supplement #3
CRIM
Current Ramp Induction Metering circuit

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Current Ramp Induction Measuring Circuit

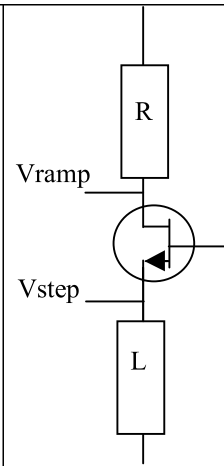
The Current Ramp Induction Measuring Circuit (CRIM) is capable of measuring very small self-inductances. Self-inductance is a combination of intrinsic inductance and the interfragment linkage across the shape of the inductor. This supplement is supported by software algorithms found in NEW_IND.TBK.

The Current Ramp Induction Measuring Circuit (CRIM) measures inductance by applying a voltage step to an inductor. The equation relating the voltage across an inductor to the current through it is $V = -L\frac{di}{dt}$. If the voltage is held constant, then the rate of current change through the inductor will be constant. Therefore, the inductance is found by rearranging the above equation as follows: $L = -\frac{V_{step}}{\frac{\Delta i}{\Delta t}}$.

The CRIM circuit measures the current through the inductor by a voltage drop across a resistor; therefore, $\frac{di}{di}R = \frac{dv}{dt}$. Substituting this equation into the above equation yields:

$$L = -\frac{RV_{step}}{\frac{\Delta V_{ramp}}{\Delta t}}$$

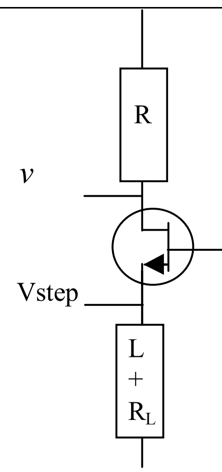
- Equation 1



Accounting for the resistance of the inductor increases the accuracy of the measured value. In the following equation, the voltage at two different points (t0 and t1) is used instead of a slope. The value of R_L is computed from standard wire tables.

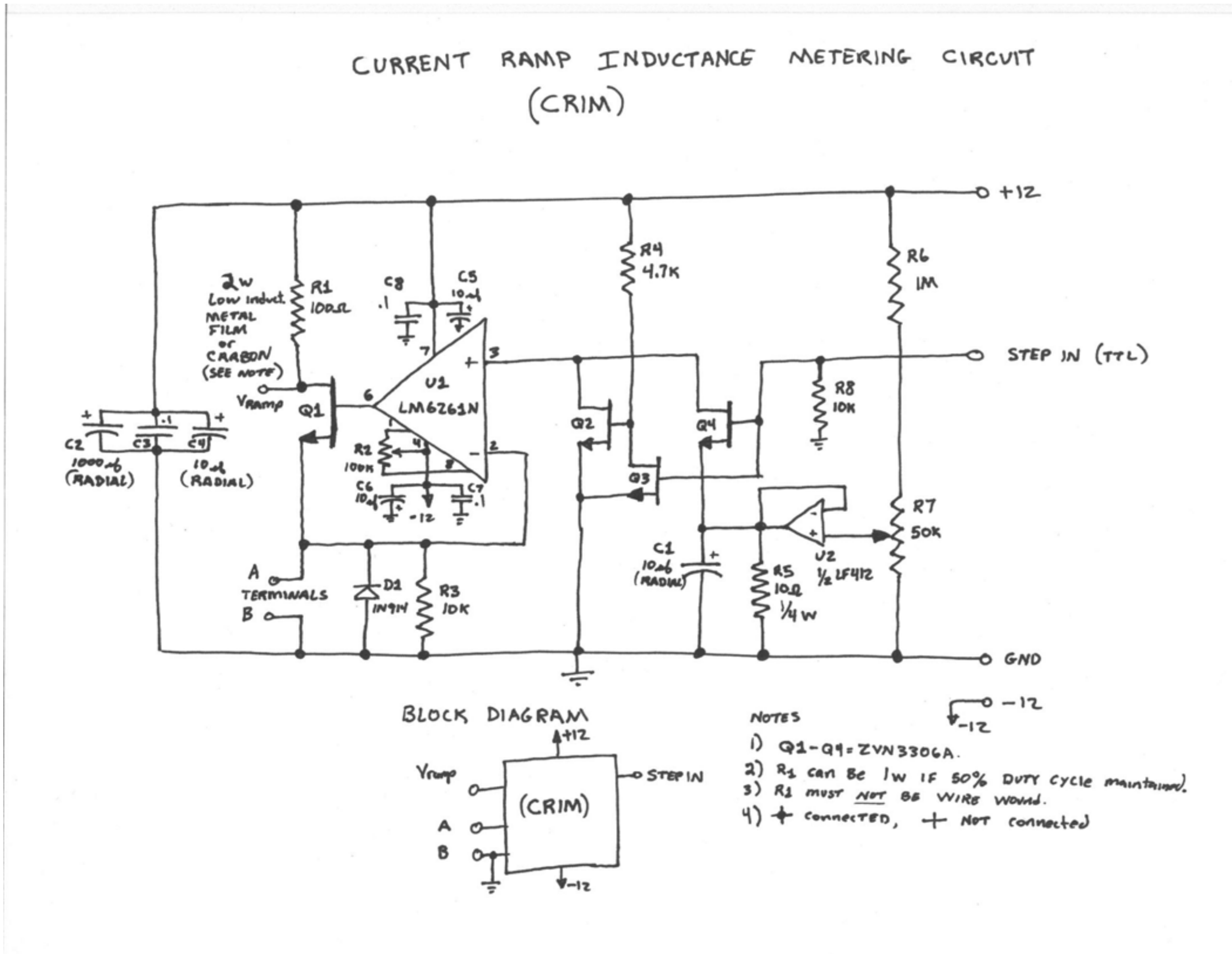
$$L = -\frac{R_L(t_1 - t_0)}{\ln(1 - R_L(\frac{v_0 - v_1}{RV_{step}}))}$$

- Equation 2



Included in the software package "NEW_IND.TBK" is a screen (titled "CRIM Inductance") that computes inductance values for data using the above equation. The use of this screen is detailed in a later section.

The complete schematic of the CRIM circuit



• Figure 0-1 CRIM schematic

The circuit description:

1) The Inductor to be tested is attached to terminals A and B.

2) R1, R2, Q1, U1 and the Inductor attached between the terminals form the current ramp. The components must be placed as close together as possible to minimize intrinsic inductance and capacitance.

3) R1 must be a low inductance resistor with good heat stability such as a metal film type. It should be a 2 watt resistor; however, since this circuit will be cycled to a 50 % duty cycle, a 1 watt resistor will do if the user is cautious. R1 must NOT be a wire wound resistor.

4) The capacitors C2 – C4 should be mounted as close to the ramp section as possible. All electrolytic capacitors should be of radial lead construction to minimize inductance.

5) Since this circuit switches an inductive load, the diode D1 protects the circuit from the inductive kick when Q1 is switched off.

6) The resistor R3 provides a minimal pull down in order to settle the output when Q1 is switched off or when no load is attached.

7) The potentiometer R2 nulls the offset of the high speed OP-AMP U1.

8) R6, R7, U2, R5, and C1 comprise a stable reference voltage. R5 loads down the OP-AMP U2 in order to minimize any switching transients. R7 sets the step voltage. The step voltage can be set from 0 to 0.6 volts.

9) Q2, Q3, Q4, R4, and R8 comprise a high-speed analog switch responsive to the STEP input. When the STEP input is grounded (or unconnected), Q3 and Q4 are turned off. This enables the pull up resistor R4 to activate Q2, which connects the non-inverting input of U1 to zero volts. When the STEP input is driven to a logic high (TTL), both Q3 and Q4 are activated. Q4 connects the non-inverting input of U1 to the reference voltage while Q3 deactivates Q2. Because of the 100mv offset on the source of Q4, Q3 turns on slightly ahead of Q4.

10) When the STEP input goes high, the non-inverting input of U1 is connected to the reference voltage. This forces the OP-AMP U1 to drive the transistor Q1 in such a manner to obtain the same voltage on its inverting input. This causes a falling voltage ramp to be observed at the Vramp output.

Calibration : The 100mv calibration scheme

The following steps calibrate the CRIM circuit.

1) **WARM UP**: Apply power, allow the circuit, and power supply to warm up for at least 10 minutes. The STEP input should be disconnected.

2) **OFFSET NULL**: With the STEP input disconnected and nothing attached to the terminals, adjust R2 until the voltage between the terminals A and B is zero.

3) **MEASURE FIXTURE INDUCTANCE**: This step is only required for those who desire to use the circuit to measure absolute inductances. This step is not required for those running the rhombus experiment. To measure the fixture inductance, see the section titled “CRIM Fixture Inductance.”

4) **ADJUST STEP VOLTAGE**: Place a 1-ohm resistor across the terminals A and B. Connect the STEP input to +5 volts and adjust R7 until the voltage across the 1-ohm resistor reads as close to 0.100 volts as possible. Record the voltage you were able to obtain. This is your Vstep voltage. NOTE! If you are using a 1-watt resistor for R1 instead of a 2-watt resistor, you should perform this operation as quickly as possible to avoid damage to R1 from overheating. Disconnect the STEP input as soon as possible and remove the 1-ohm resistor.

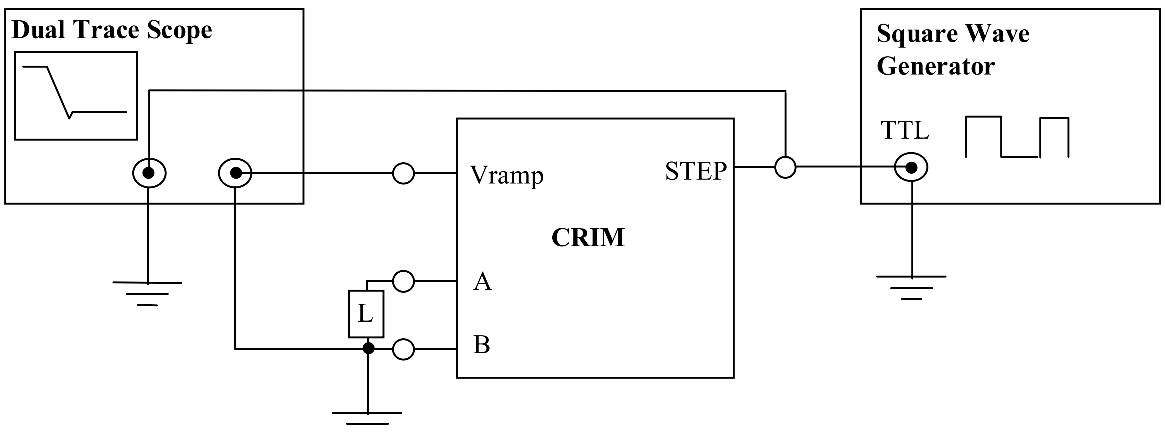
5) **MEASURE R**: Turn off the power and measure the resistance of R1. Record this value, this is the value of R in the equations above. For best accuracy, measure R1 after measuring the desired inductances.

CRIM Operation

The following steps detail the use of the CRIM to obtain inductance measurements.

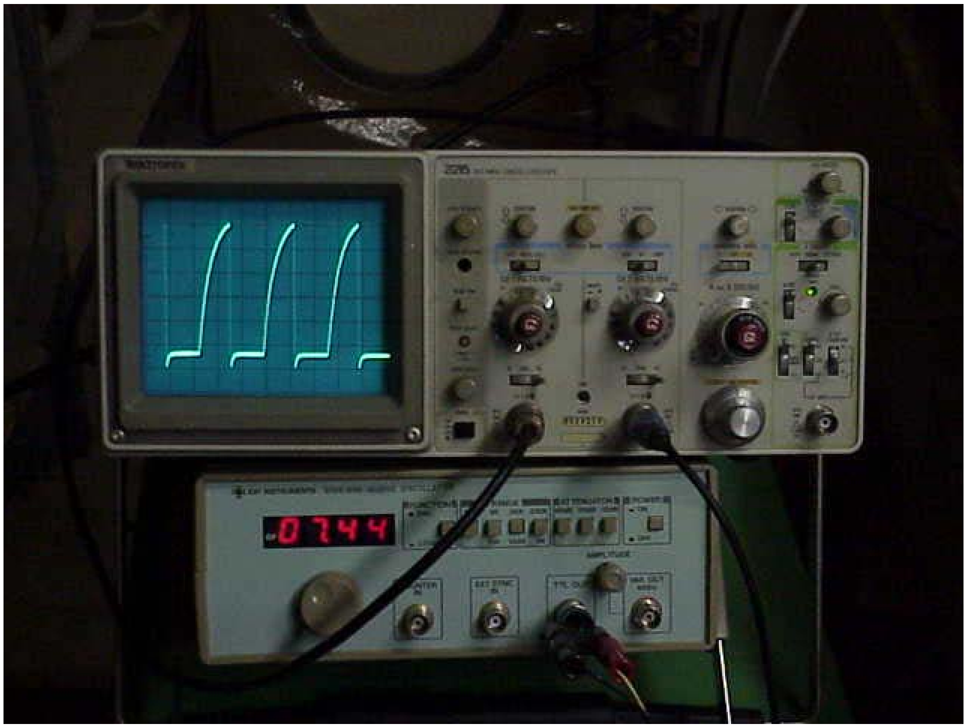
1) **CALIBRATE**: Calibrate the CRIM as detailed in the calibration section.

2) **CONNECT**: Connect a Dual Trace oscilloscope and Square wave generator as shown in Figure 0-2. In this circuit Channel 1 is connected to the Square Wave Generator and used to trigger the scope in the delayed sweep mode. Channel 2 is connected to the Vramp output and used to display the ramp.

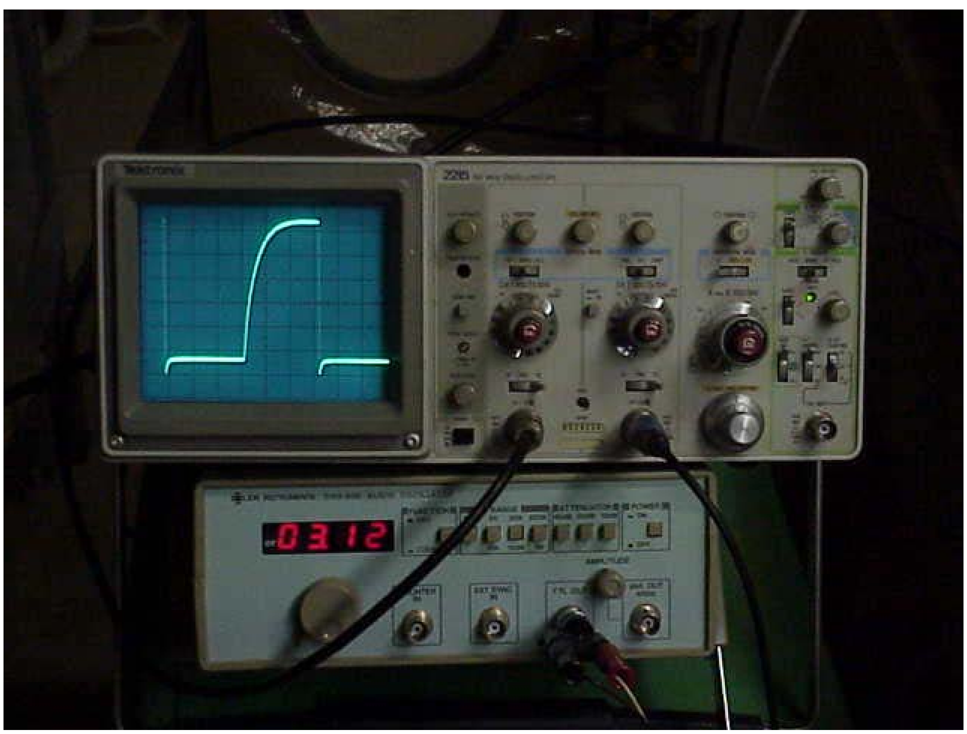


• Figure 0-2

3) **ADJUST FREQUENCY**: Power up all of the components, then adjust the period of the Square Wave Generator such that the rise in the Vramp signal has time to sufficiently saturate before going low. The next picture shows insufficient period while the picture following shows sufficient saturation.

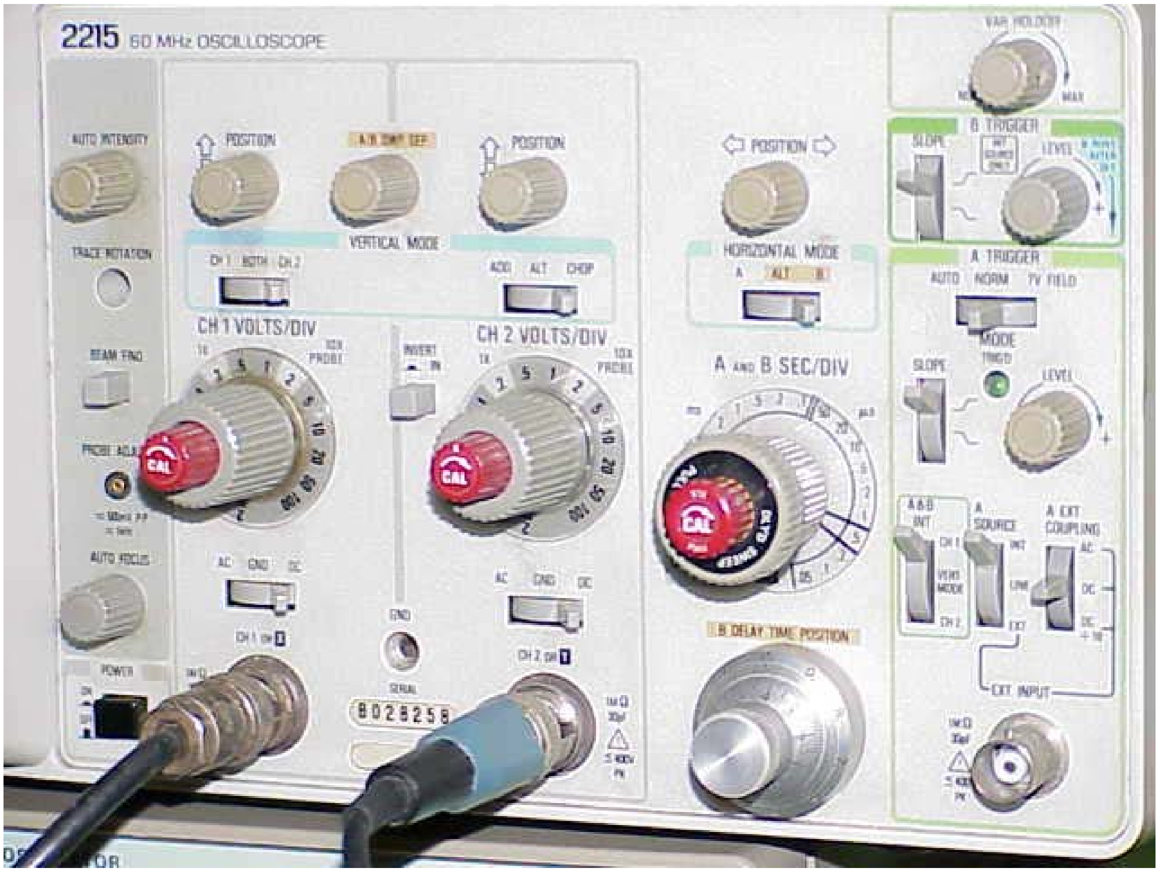


• Figure 0-3 Insufficient Saturation



• Figure 0-4 Sufficient Saturation

4) Set up the dual trace scope for delayed sweep operation with channel 1 as the trigger input. The following picture records the setup of the scope for delayed sweep operation to measure the 22-AWG rhombus. Not discernible from the photo are the following: A) CH2 probe is a x10 probe. B) The B TRIGGER LEVEL knob is turned all the way to the right. C) The A time base is 500ns/div and the B time base is 200ns/div. D) All red knobs are in calibrated positions and the X10 time base multiplier is not used (right red knob pushed in).



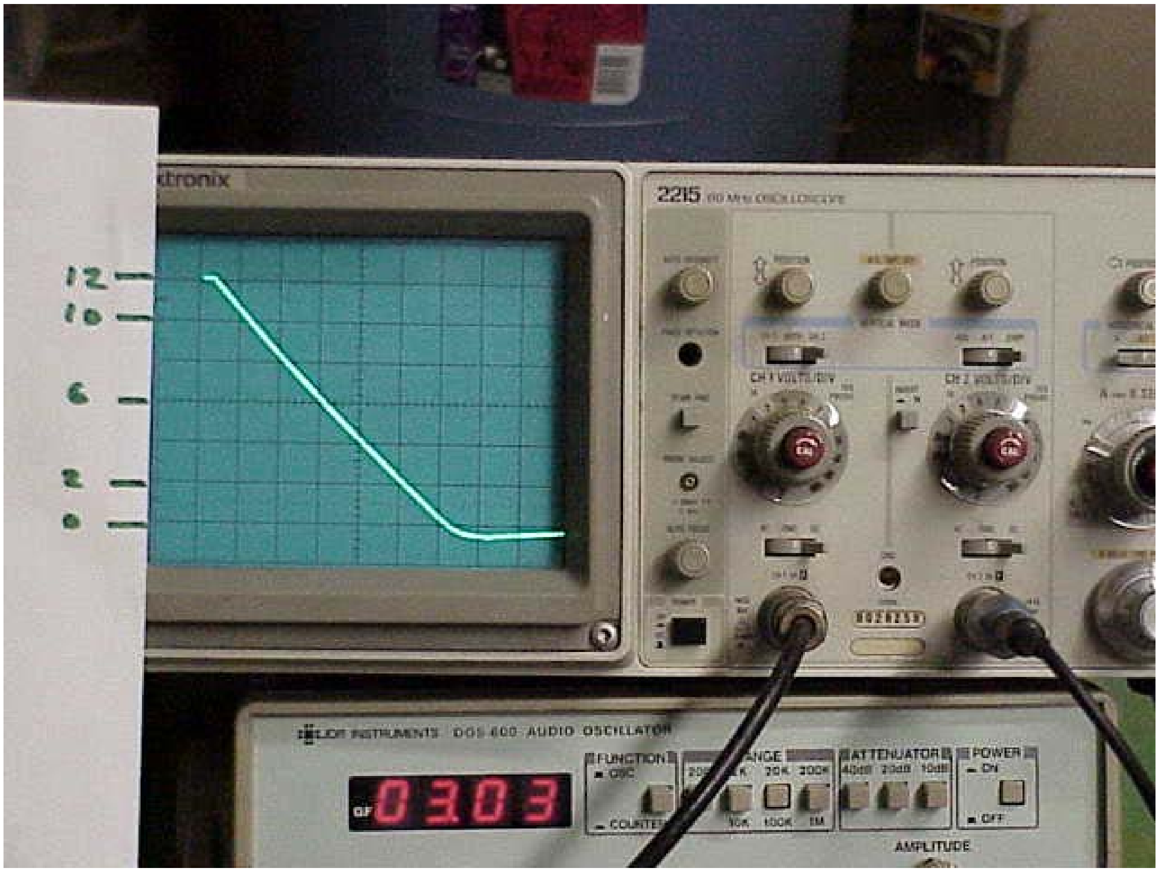
5) The settings in the photo are a good starting point. The following steps align the scope trace and obtain the correct time base for whatever you are measuring. If you are doing the rhombus experiment, you should arrive at the same time base settings.

6) Set the horizontal mode switch to A.

7) Attach the largest inductance (of the set being measured) to the CRIM terminals (rhombus fully open to form a square).

8) Use the vertical position knob to align the trace top to the designated 12-volt line. See photo following next step.

9) Adjust the A time base for the smallest setting that is able to contain the 10 volt to 2 volt section of the ramp within 9 horizontal divisions. See following photo. The value 9 is based on the fact that the B TIME DELAY POSITION of this scope can only traverse 9 full divisions.



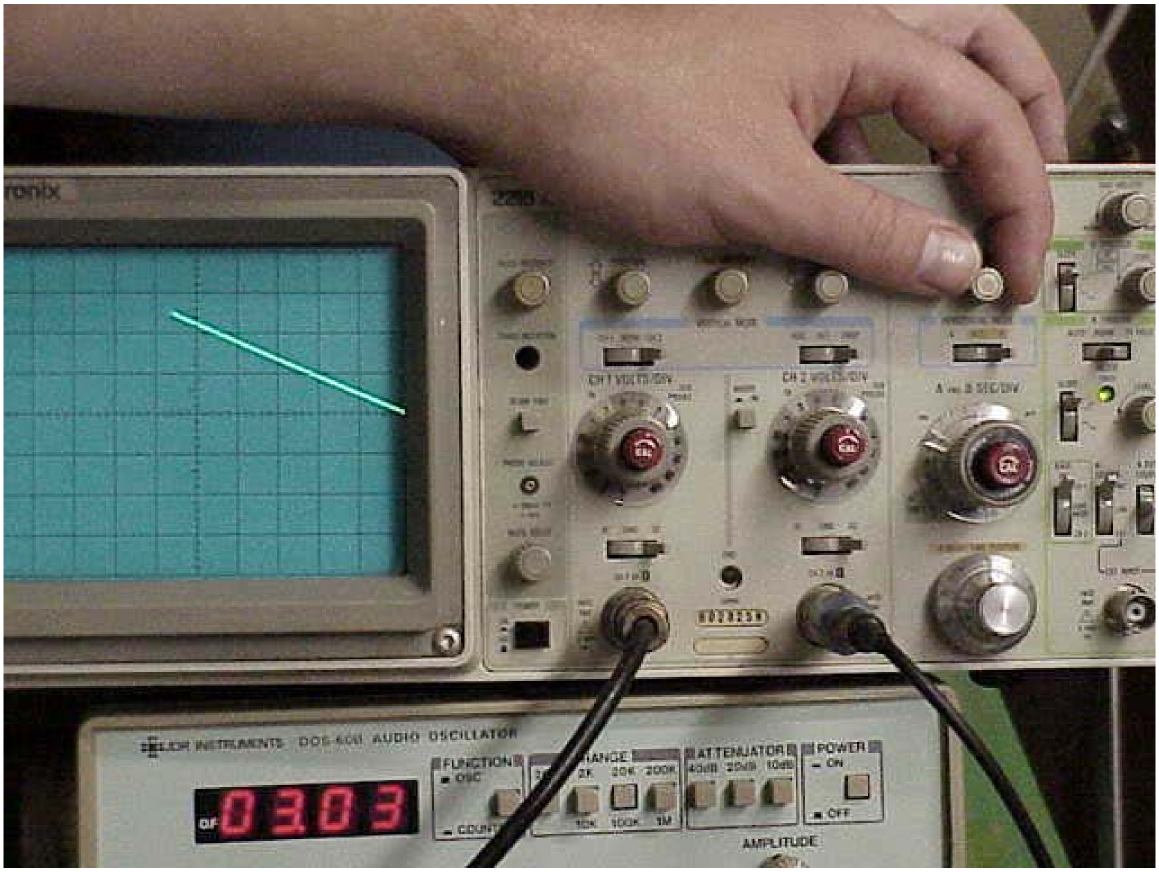
The reader will notice the ramp is not perfectly strait; it “sags” slightly. The resistance of the inductor causes this sag. The accompanying software accounts for the sag using Equation 2 in conjunction with wire tables.

10) Adjust the B time base to the next lower settings and move the horizontal mode switch back to B.

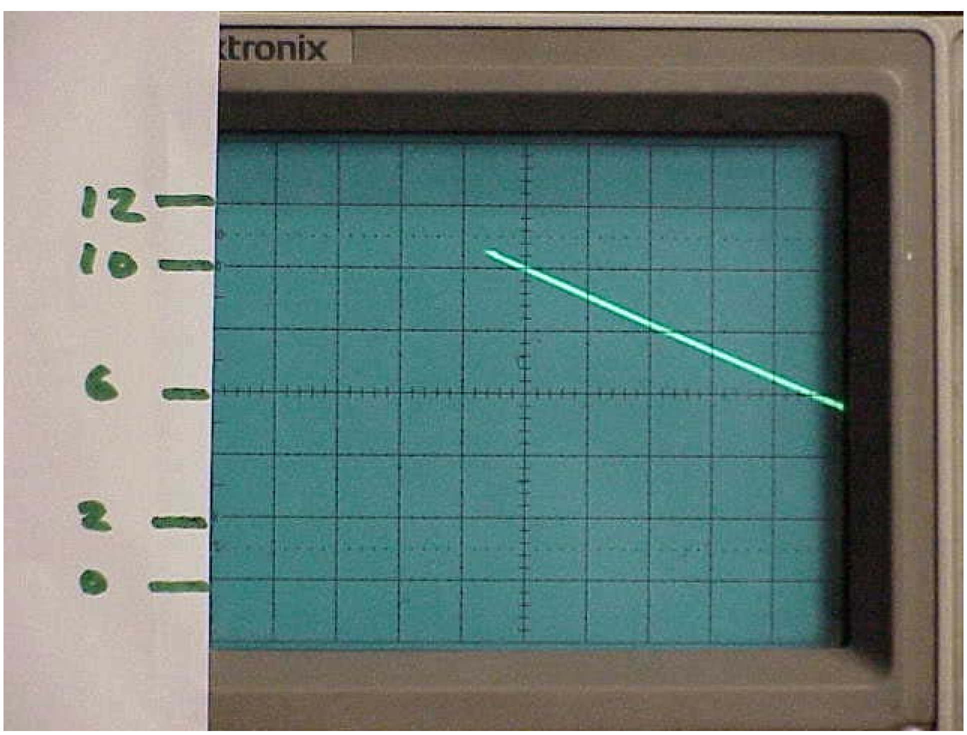
11) Turn the B DELAY TIME POSITION knob counter-clockwise to the smallest setting possible.

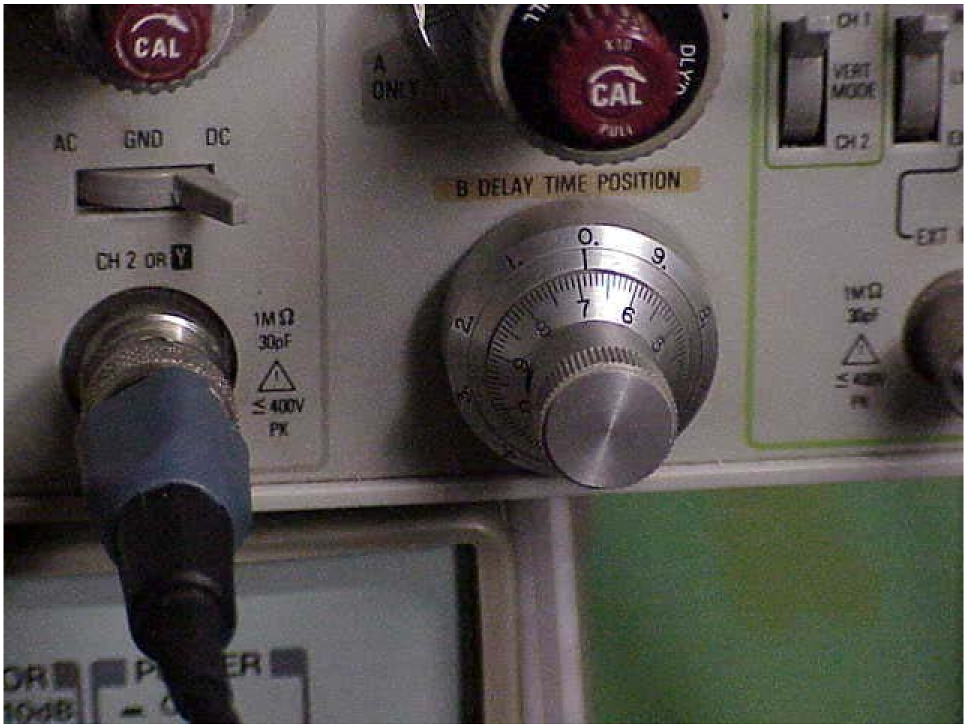
12) At this point, the circuit is ready for taking inductance measurements. The next steps are repeated for each inductance value measured. The user should not adjust any other controls or settings during the measurements.

13) Use the Horizontal position knob to move the 10 volt intersect point just to the right of the vertical centerline. See the following picture.



14) Adjust the B DELAY TIME POSITION knob until the ramp intersects the 10 volt line at the center vertical line. Set the following pictures.





15) Record the delay time position of the 10-volt intersect. In this case, the reading is 0.68. Because of the camera angle, the photo shows a slightly higher setting (0.685) than when the knob is observed strait on.

16) Record the delay time position of the 6 volt intersect and the 2 volt intersect.

17) Attach the next inductor to the terminals and repeat steps 11 to 16.

18) After collection data for the entire set, the next section will show you how to use the software to offset the effect of inductor resistance.

Computing the Inductance from the measurements

As stated in the previous section, the inductance must be computed from the measurements. The inductance can be computed by hand using Equation 2 where the resistance of the inductor is computed from wire tables. Alternatively, you can use the accompanying software titled “NEW_IND.TBK” to do this for you. The following steps

1) If you have not done so already, install the software according to the instructions found in this document.

2) From the main screen, click on the “CRIM input form” button. This will bring you to a screen that will allow you to enter your experimental data.

3) After you have entered the data, click the “Save Data” button. The will prompt you for a filename that will be created with your data.

4) Enter a standard 8 character with 3-character extension filename. Example =”DATA.IND”.

5) Your data is saved in a CRLF delimited ASCII file that you may edit with notepad.exe if you wish.

6) Click the button “CRIM inductance” to get to the actual screen that will compute the inductance values.

7) On the “CRIM inductance” screen click the button “Load Data” and select the file you created in the previous steps. The click OK.

8) Your data will be loaded into the form as required.

Click the “Compute” button. This will compute the resistance based on the shape and number of turns in the loop. Then it will compute the Inductance based on the ramp measurements and the resistance. The “+/-L” column gives the tolerance of the inductance based on Vaccuracy. Vaccuracy is the accuracy of the ramp voltage measurements. The default given by the CRIM input form is ½ the width of a typical oscilloscope trace in volts (0.05 volts) when the vertical scale is 2 volts/div. “+/-L” is the change in the computed inductance for an error of Vaccuracy in the measurement.

CRIM accuracy

A few terms must be defined in order to understand and appreciate the results from this version of the CRIM:

1) K_C: The calibration constant. This is the ratio of the true inductance to the CRIM inductance. This factor is due to circuit design. The Kc is constant among the measurements made. Kc may also be introduced by non-calibrated test equipment.

2) L_F: Fixture Inductance. The difference between the true inductance and the CRIM inductance due to the additional inductance of the terminals. The fixture inductance is constant among measurements made.

3) L_E: The error introduced by experimental procedure. The amount of error is random among the measurements made. There are two ways to approximate the amount of error in your measurements. The first is from the tolerance described at the end of the previous section. With good experimental procedure, your error will be less than the tolerance of the previous section. For those who are running the Rhombus experiment, the second approximation is to note the “RMS error” and “max error” results for geometry #5,0,0,8.

The following equation relates the manner in which the above factors relate the true inductance to the results obtained from the CRIM.

$$L_{TRUE} = K_C L_{CRIM} - L_F - L_E$$

The Hash-Search engine was designed to find a correlation between measured data and geometric combinations using an over-determined system. Because the algorithm is fed more sets of experimental data than there are unknowns in the equations, Kc and Lf are factored out. This will occur as long as you have at least 5 (the more the better) sets of CRIM measurements and your error is minimal. With good experimental procedure, your error should be no greater than ½%.

Because of the over determined nature of the Hash-Search engine, it is not required that Kc and Kf be determined for the rhombus experiment. Fo those who are interested, the next sections discusses Kc and Kf.

Kf CRIM Fixture Inductance

The inductance measured using the CRIM circuit includes the inductance of the CRIM circuit and the leads ("pig tails") that connect the CRIM to the inductor being measured. This inductance is called Fixture Inductance. The Fixture inductance should be subtracted from the measured inductance to obtain the most accurate value.

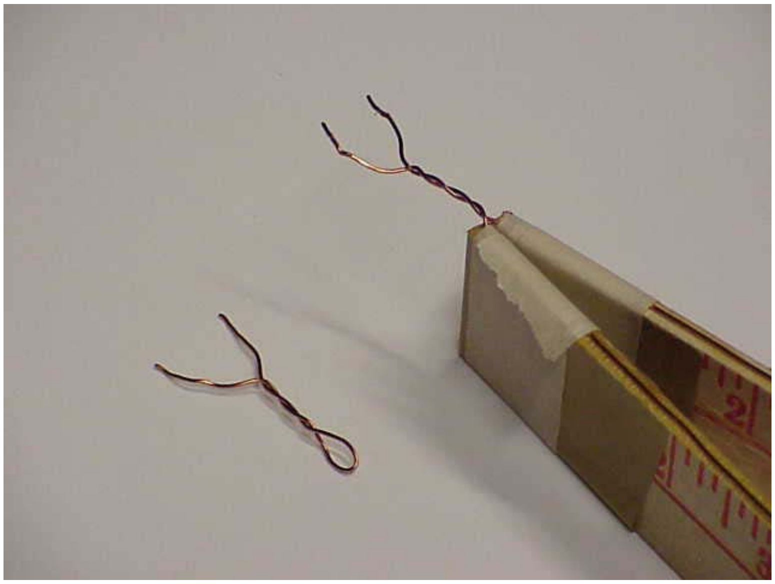
NOTE: At the end of certain steps below, you will find numbers in parenthesis. These are the measurements made with my circuit. They are included as an example.

The intent is to find the inductance of the CRIM circuit and pigtail combined. This is called the fixture inductance. Since the fixture inductance is much smaller than the loops measured in the experiments, we will use a smaller step voltage between 15 and 30 millivolts. To measure the fixture inductance, the following steps are performed:

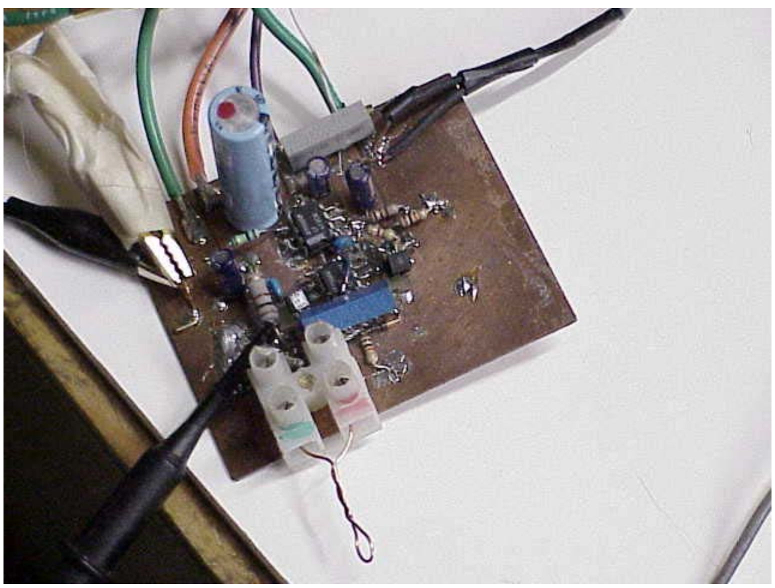
1) **WARM UP**: Apply power, allow the circuit, and power supply to warm up for at least 10 minutes. The STEP input should be disconnected.

2) **OFFSET NULL**: With the STEP input disconnected and nothing attached to the terminals, adjust R2 until the voltage between the terminals A and B is zero.

3) **CREATE PIGTAIL**: Using wire that matches the leads of the inductor to be measured, create a "Pigtail" that approximates as closely as possible the construction of the leads of the inductance of possible. Referring to the following picture, the pigtail is shown to the left, while the inductor to be measured is on the right.

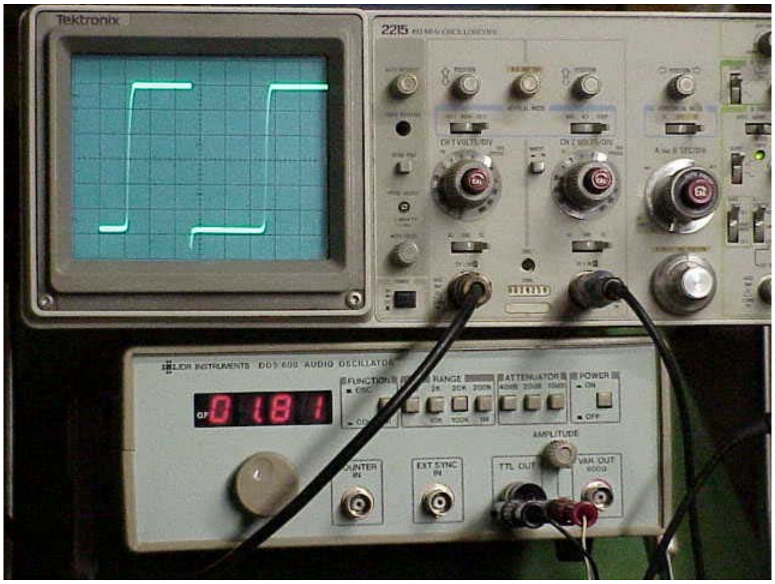


4) **ATTACH PIGTAIL**: Attach the pigtail to the terminals of the CRIM.



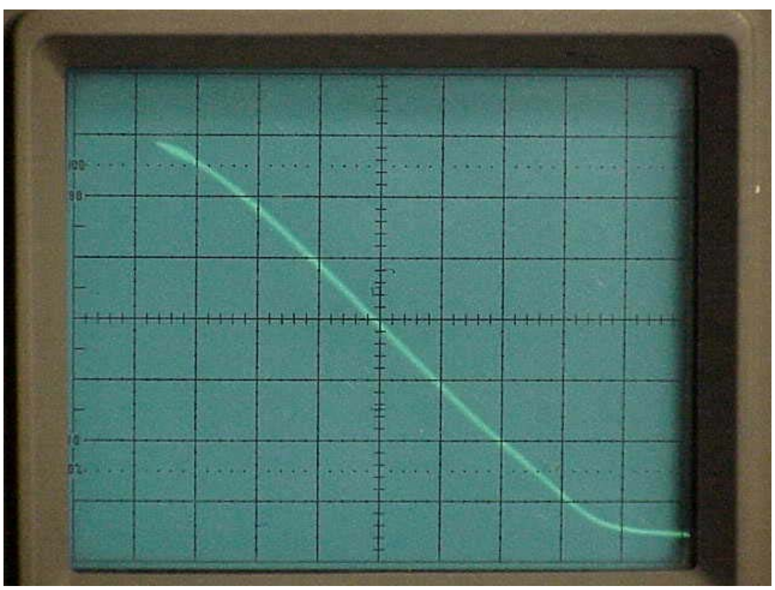
5) **CONNECT**: Attach instruments as shown in Figure 0-2.

6) **ADJUST FREQUENCY**: Power up all of the components, then adjust the period of the Square Wave Generator such that the rise in the Vramp signal has time to sufficiently saturate before going low. For optimal thermal performance, a near 50% duty cycle is desirable. See the following picture:



7) ADJUST STEP VOLTAGE: Attach a **2.7**-ohm resistor to the terminals. With the STEP input connected to +5 volts, quickly adjust the voltage across this resistor to approximately 25 millivolts. Disconnect the STEP input.

8) With the scope set at 2v/div, adjust the time base to obtain a trace of approximately -45-degrees (do not break calibration or use X10 setting to do this). Adjust R7 to obtain an exact -45-degree angle near the center of the trace. The scope in the photo below is set to 2 volts/div and 50ns/div. (slope = 2 / 0.00000005).



9) Remove the power and the pigtail and immediately measure the resistance of R1. (R=99.3 ohms)

10) With the power off, clamp a **2.7**-ohm resistor into the terminals and place a voltmeter across the resistor set up to measure millivolts.

11) Attach the STEP input to the +5 volt terminal of the power supply and turn the power on. When the voltmeter stabilizes, record the value, then deactivate the power and remove the resistor. (Vstep=25.8 millivolts)

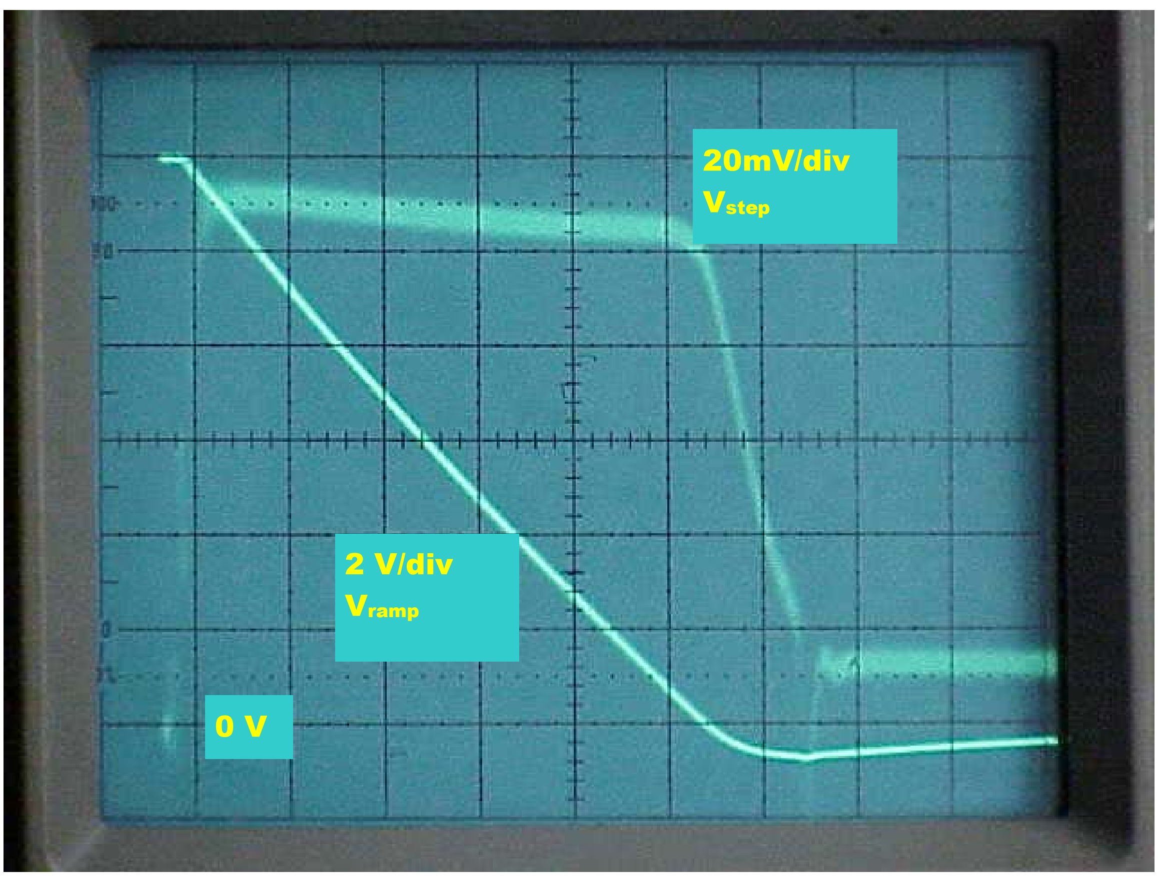
12) The Fixture inductance is computed using Equation 1. The values obtained from my circuit are used as an example:

$$L = \frac{\frac{(99.3)(0.0258)}{2}}{0.00000005} = 64nH$$

Note: There are other ways to measure the Fixture Inductance more accurately. This is the simplest procedure.

Kc CRIM calibration constant

The following picture shows that the step output voltage has not quite settled across the inductor being measured. The picture shows that the step is approximately 12mv higher at the point where the 10v measurement is taken.



The picture also shows that the step voltage is about 5mv higher where we take the 2v measurement.

The overshoot during measurements will cause the ramp to fall faster. The faster falling ramp means that the L_{CRIM} result is smaller than L_{TRUE}.

The following list shows some ways to correct the CRIM readings for the overshoot:

1) Use a Vstep that is the average of Vstep at the 10v crossing and Vstep at the 2 volt crossing.

2) Re-derive the equations for the CRIM for a trapezoidal Vstep.

3) Improve the circuit design.

4) Adjust the CRIM reading with a constant (Kc) that adjusts for the overshoot.

There are many ways to correct for the overshoot; however, because correcting for the overshoot is not required for the rhombus experiment, a procedure was not devised.

Instead, a value Kc has been approximated by comparing CRIM measurements using smaller Vsteps to the 100mv results. This procedure yields an approximate value for Kc of 1.14. Care should be taken when using Vstep lower than 100mv as it seems that intrinsic inductance increases with lower values of Vstep. This observation is still under investigation.