# Characterizing Ferroelectric Materials

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*Based on the tutorial at ISAF-ECAPD '10*

# Tutorial Outline

- Introduction
- A device model for non-linear capacitors
- Instrumentation theory
- Definitions of tests
- Fatigue and Imprint
- Conclusion

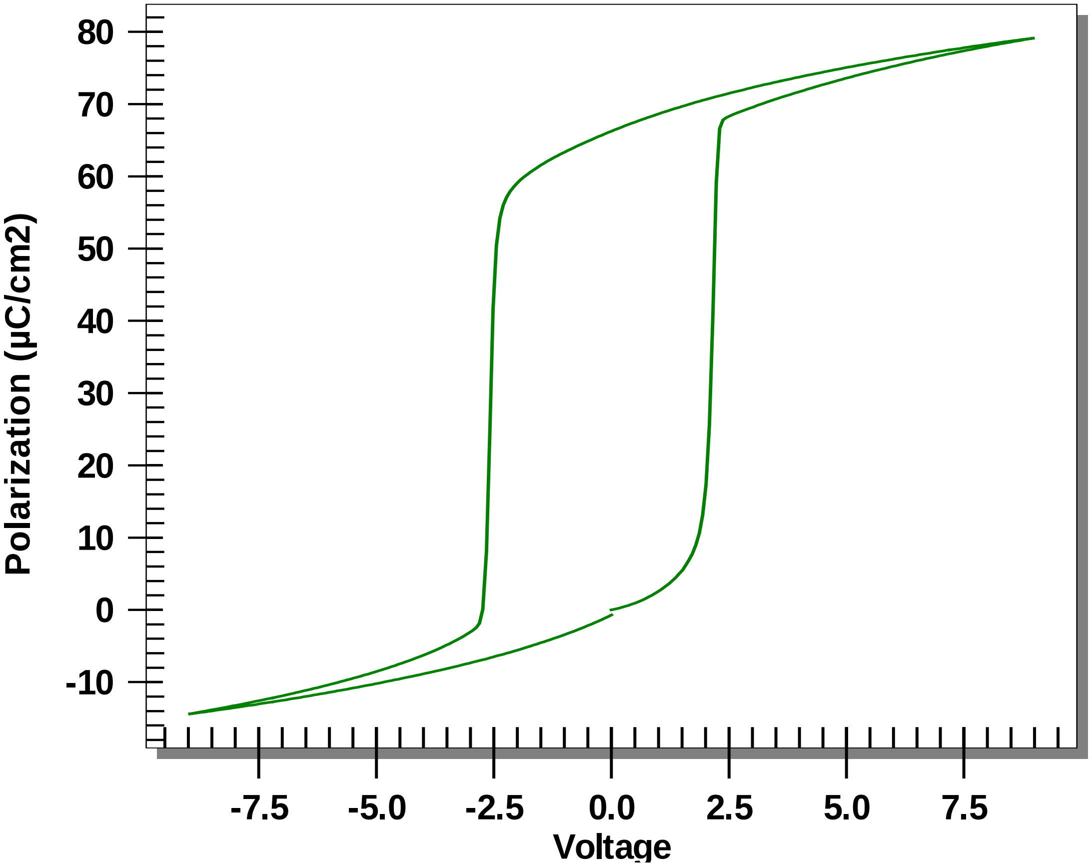
# Radiant Technologies, Inc.

- Radiant Technologies pursues the development and implementation of thin ferroelectric film technology.
  - Test Equipment: Radiant supplies ferroelectric materials test equipment world-wide.
  - Thin Films: Radiant fabricates integrated-scale ferroelectric capacitors for use as test references and commercial products.

# The Presenter

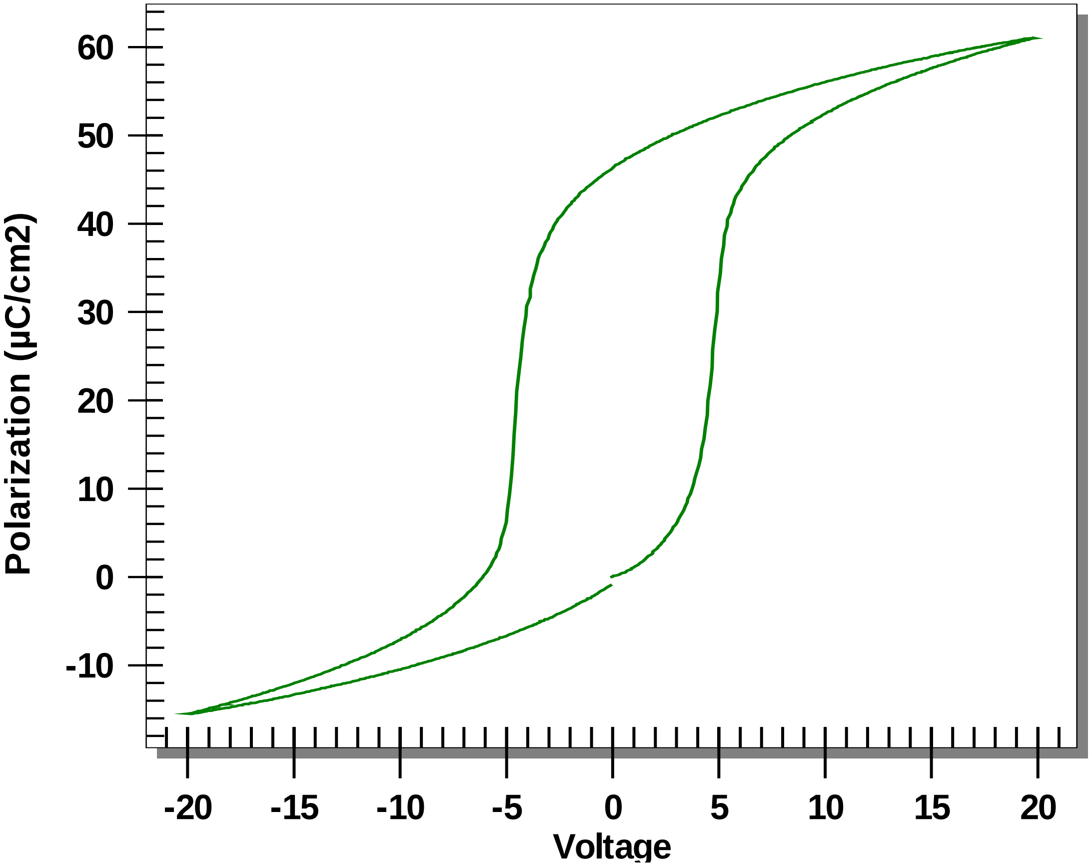
- Joe T. Evans, Jr.
- BSEE – US Air Force Academy in1976
- MSEE – Stanford University in1982
- Founded Krysalis Corporation and built the first fully functional CMOS FRAM in 1987
    - Holds the fundamental patent for FRAM architecture
- Founded Radiant Technologies, Inc in 1988.

# An Excellent Hysteresis Loop



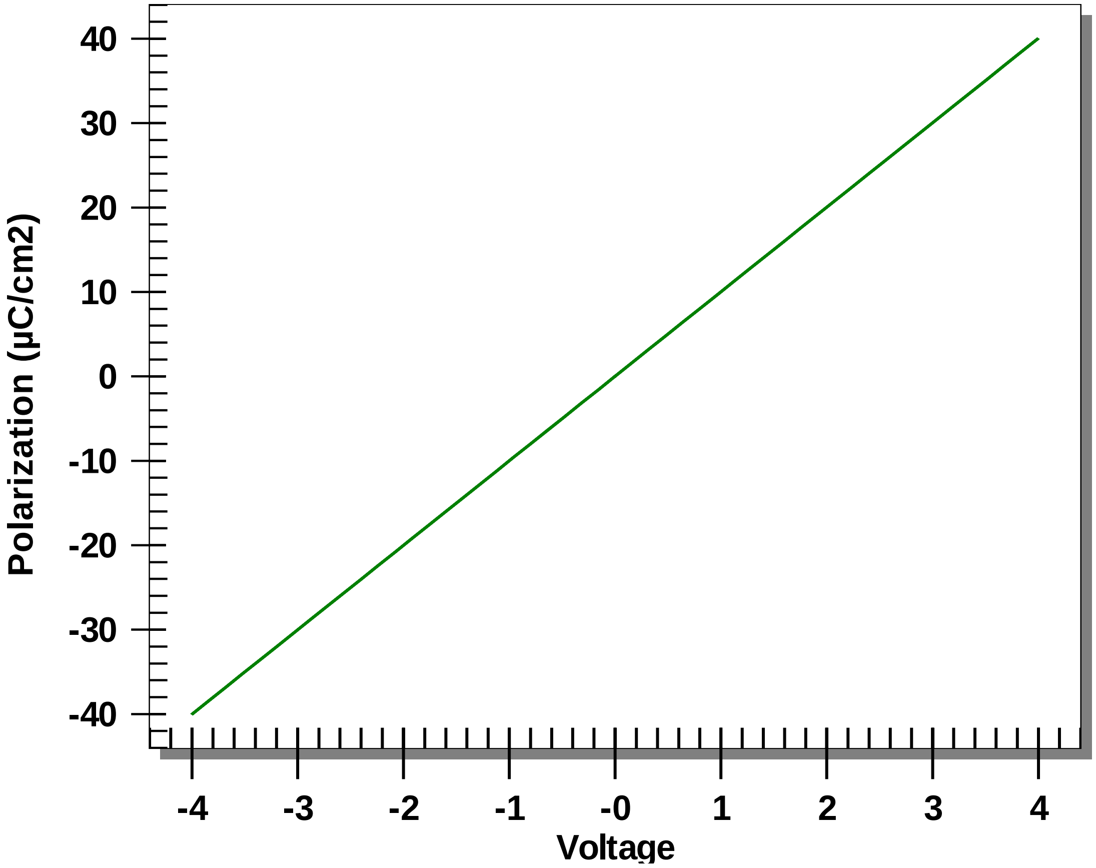
- This loop is nearly “perfect”. Most loops are not. After this presentation, you should be able to discern the difference upon inspection.

# What is this?



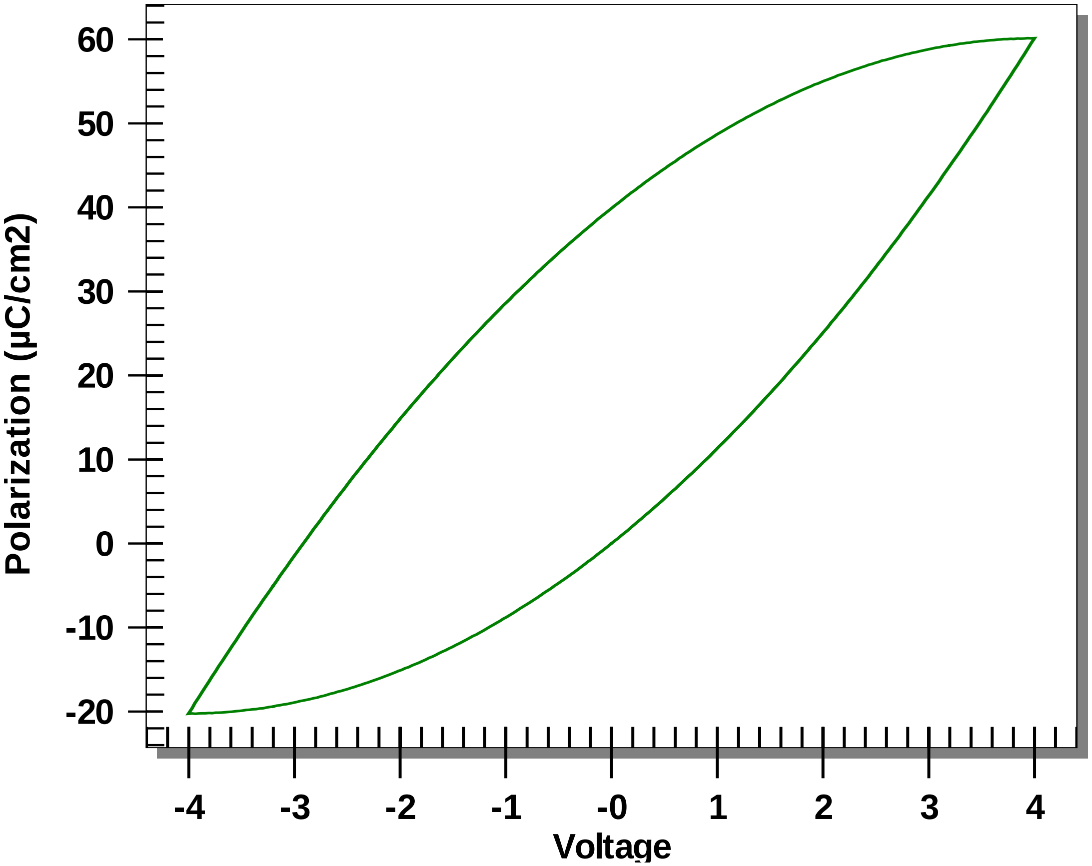
- Is this loop as good as the previous loop?

# What is this?



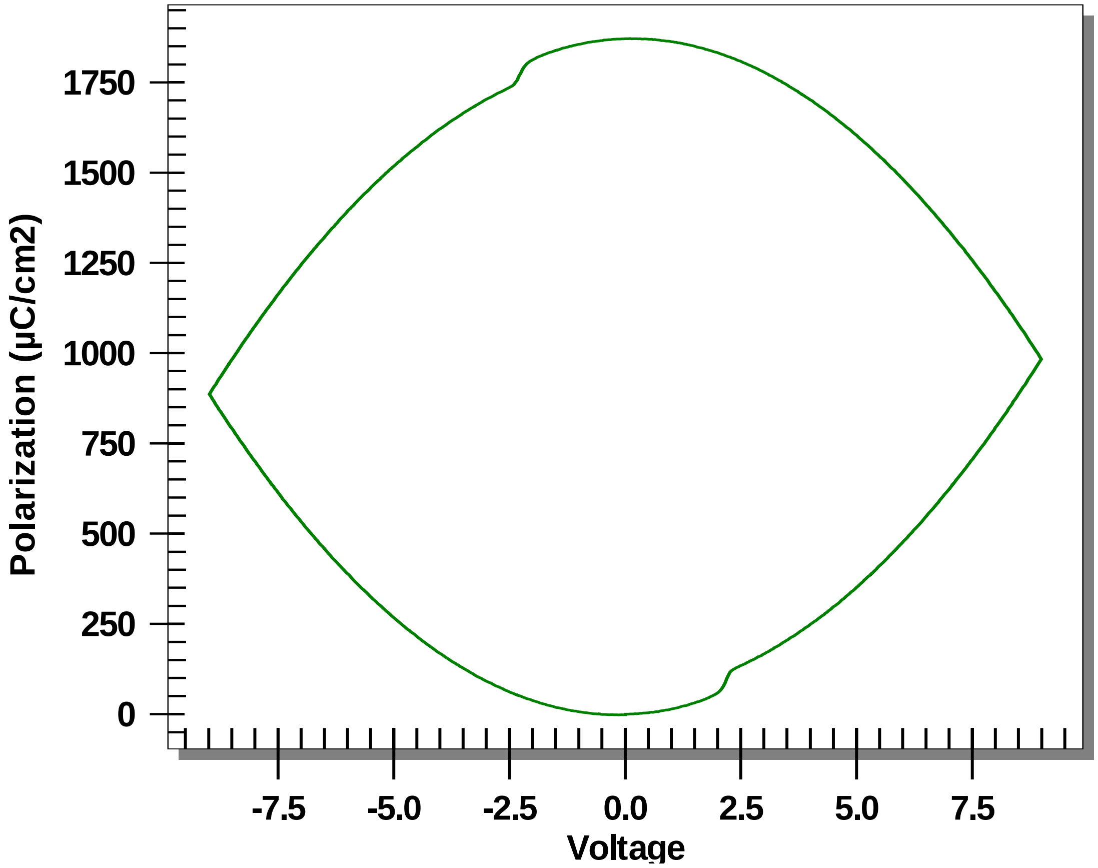
- Real clean.  This one is easy.

# A Harder One

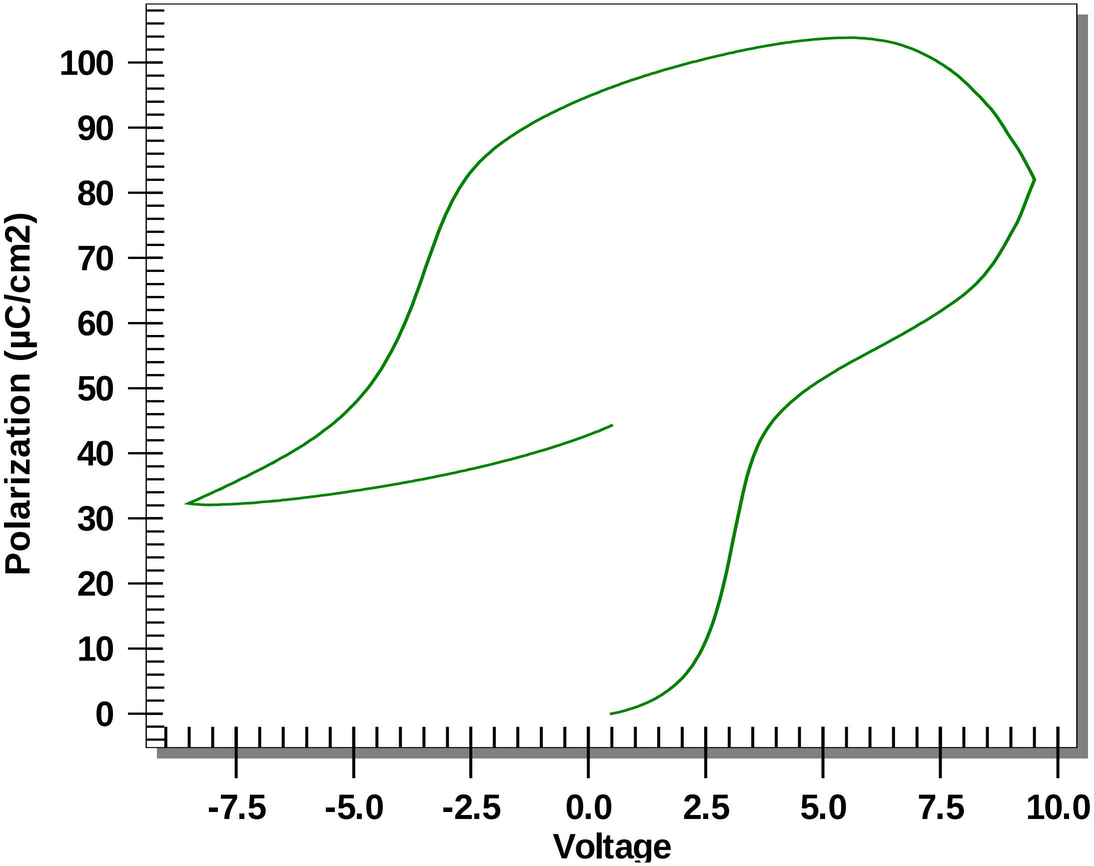


- Quite a few papers include loops that look like this.

# Is this Ferroelectric?



# What Happened Here?



# Modeling Nonlinear Capacitance

- In electrical engineering, a fundamental approach to understanding a system is to break it into components and model each component.
  - Each component responds independently to the stimulus.
  - The output of a component is either the input to another component or is summed with the outputs of other components to form the response of the device.

# The Components

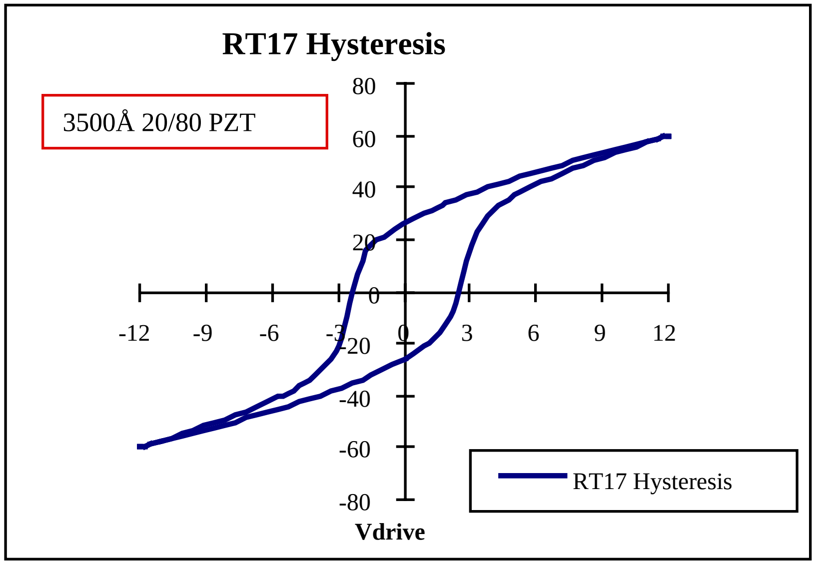
- According to Joe:
  - Linear capacitance
  - Non-linear capacitance
  - Remanent polarization
  - Remanent and nonremanent leakage
  - Remanent and nonremanent small signal capacitance
  - Reverse bias diode electrode interfaces
  - Left-overs

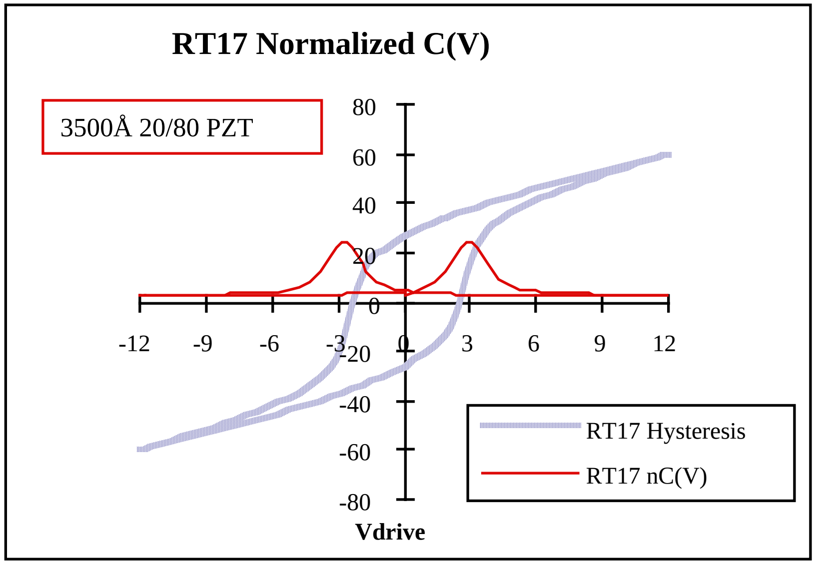
# A Mathematical Tool

The hysteresis loop is polarization responding to applied voltage: P(V). Its derivative with respect to voltage is

$$\delta P/\delta V \Rightarrow (\delta Q/\delta V)/\text{Area}$$

Which equals *Large Signal Capacitance per Unit Area*.


**RT17 Hysteresis**


**RT17 Normalized C(V)**

# Normalized CV

The normalized CV [nCV] has the formula

$$\delta P/\delta V => (\delta Q/\delta V)/\mathrm{Area}$$

and has the units of

$$\mu\mathrm{F/cm}^2$$

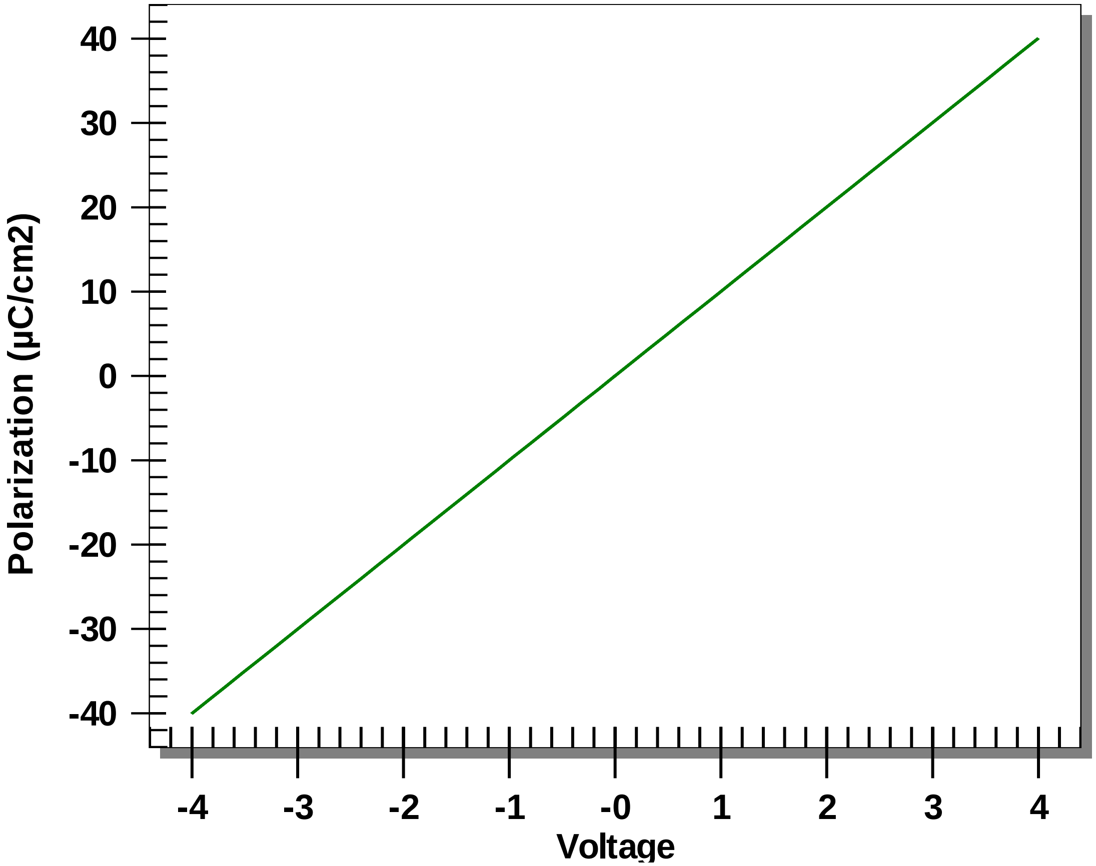
when the derivation is performed on the polarization units of

$$\mu\mathrm{C/cm}^2.$$

# Integration

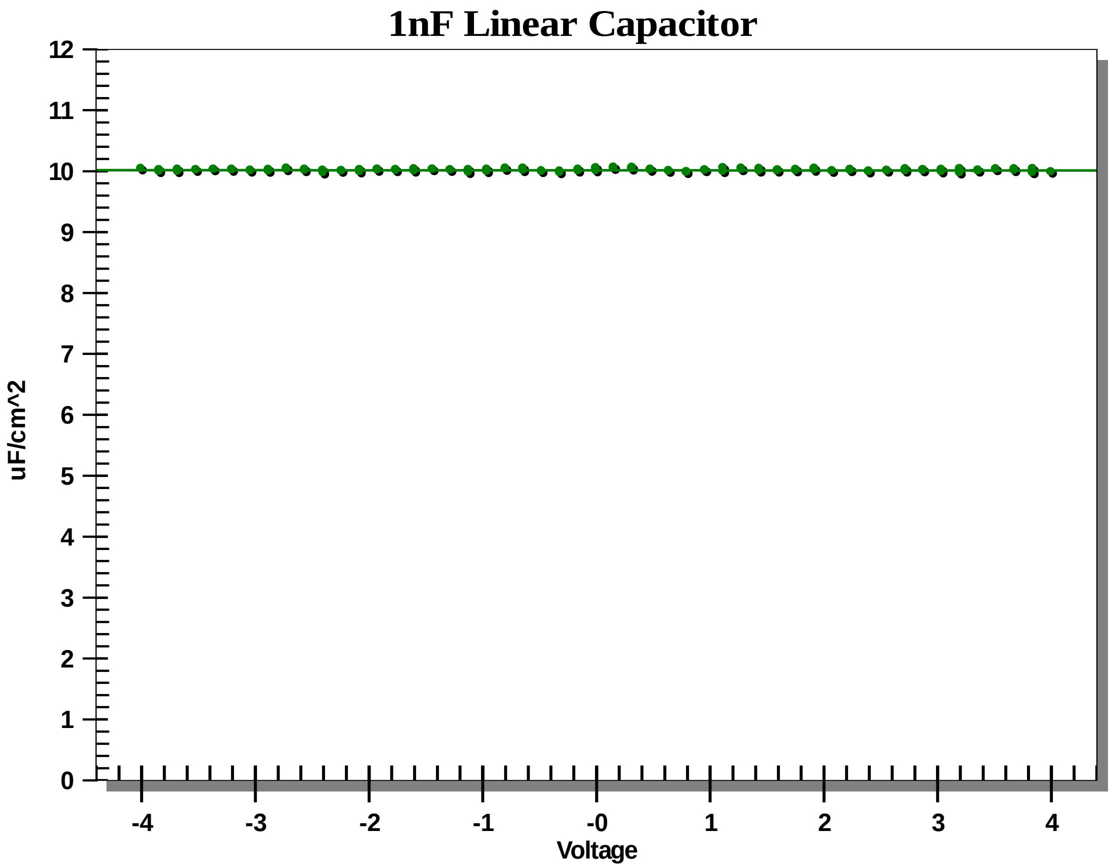
- Some measurements determine capacitance.
  - Small signal capacitance vs. Voltage
- Mathematical integration will convert the capacitance to its equivalent polarization contribution at each voltage.
- This is the inverse operation to the normalized CV function from the previous slide.

# Linear Capacitance



- Q = CxV where C is a constant

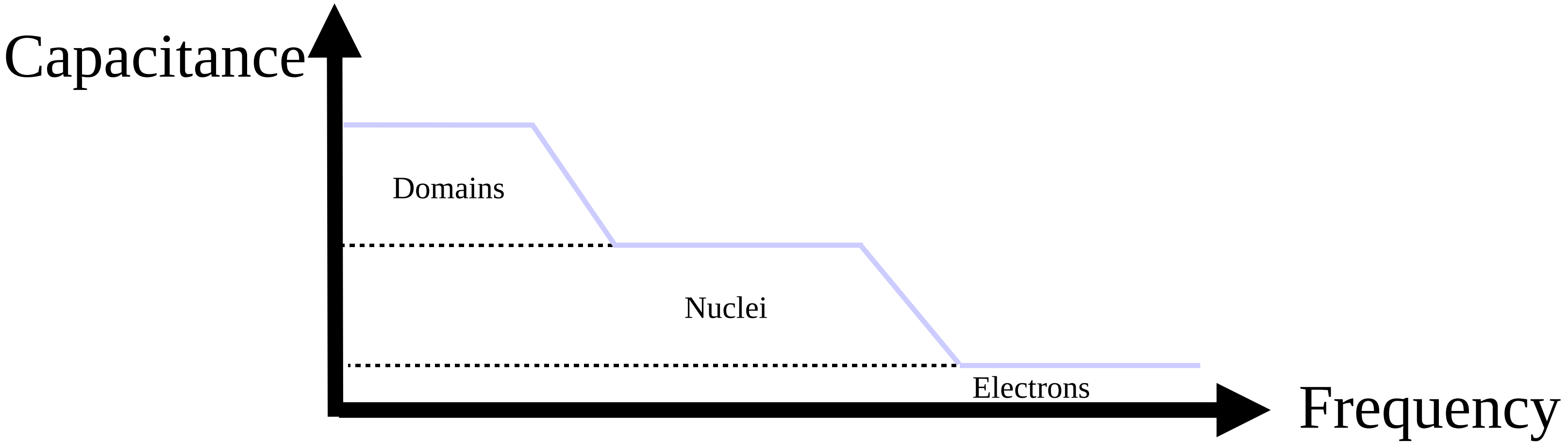
# Derivative of Linear Capacitance



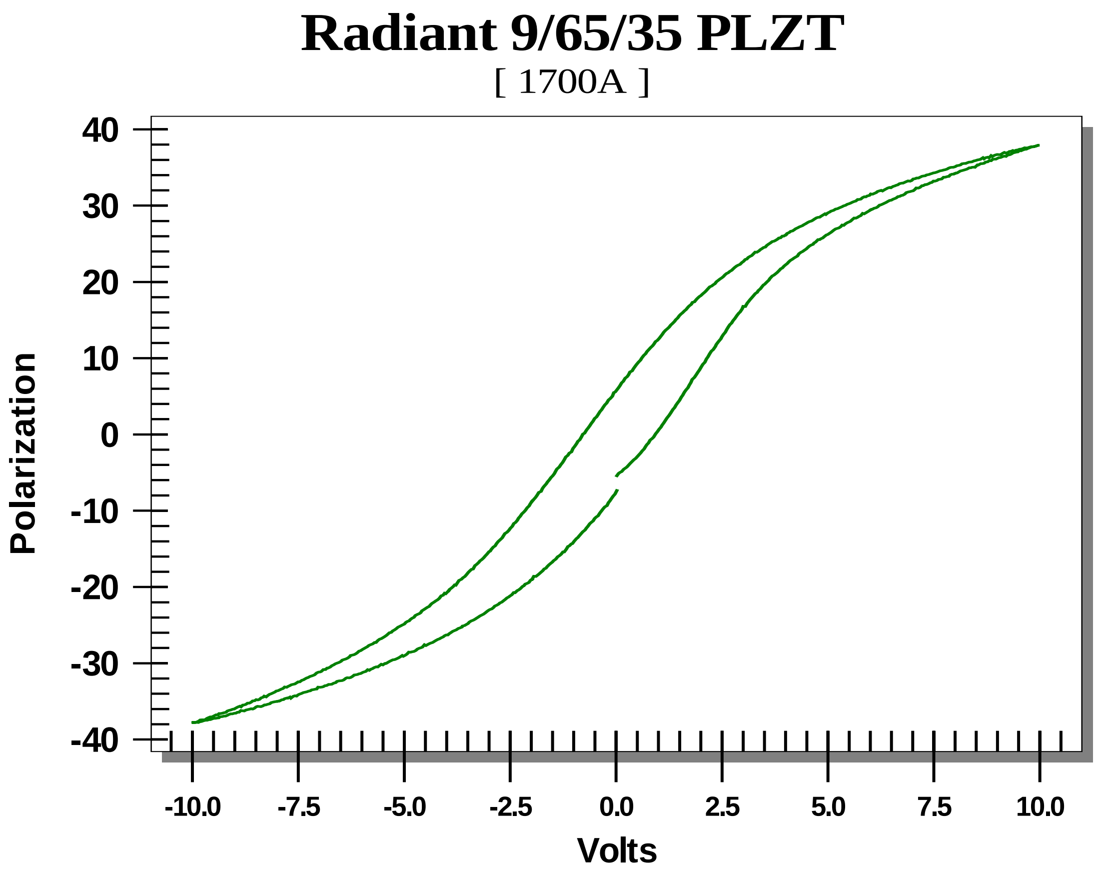
- C is a constant slope so the derivative of linear capacitance is simply a vertical offset on the nCV plot.

# Capacitance vs Frequency

- Capacitance is about *separation* of charge!
  - – Electrons are fast (light speed!).
  - – Atoms are slow!
  - – Domains are *real* slow!

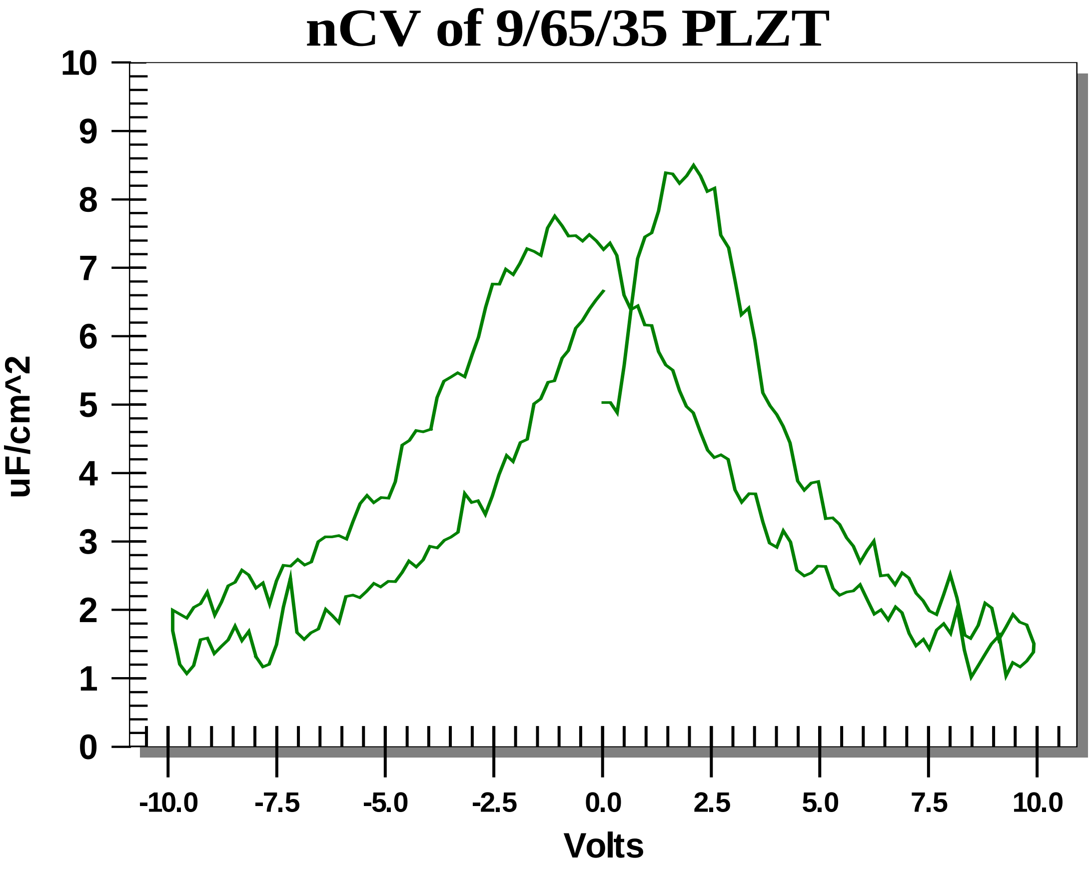


# Non-linear Capacitance



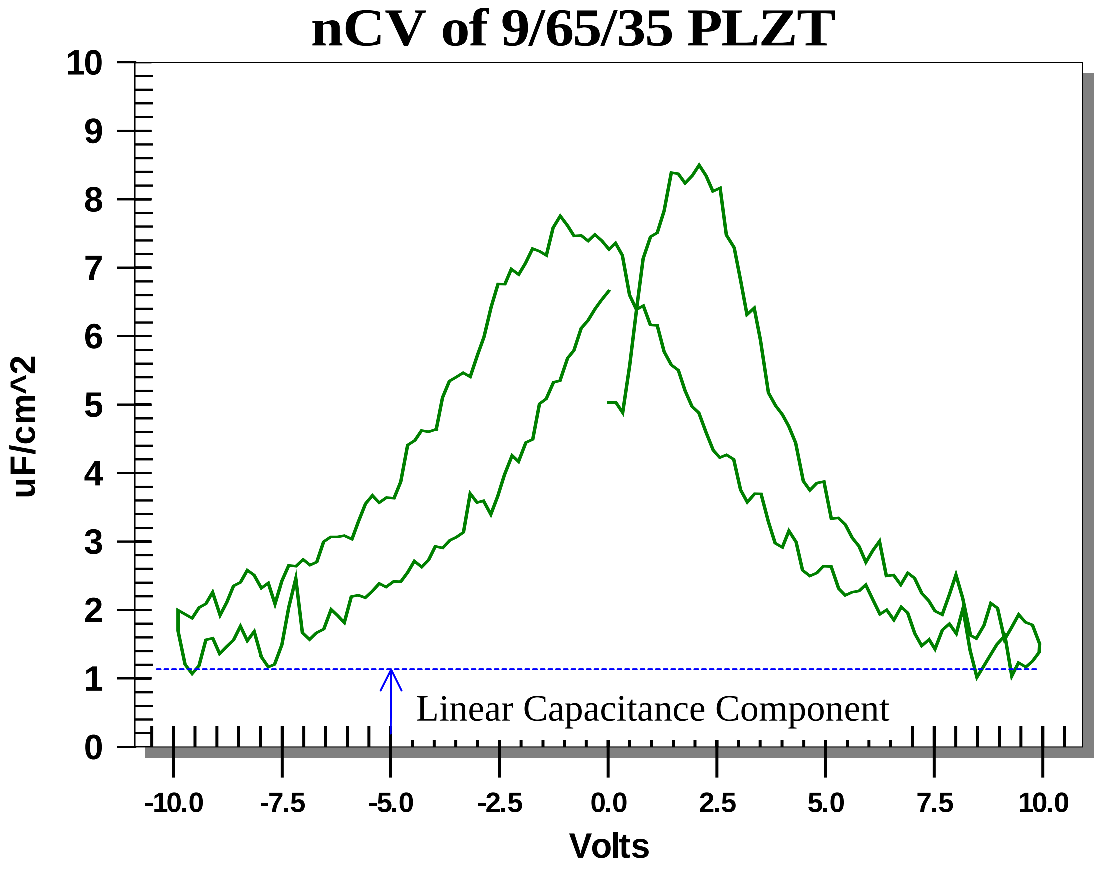
- When the electric field begins to move atoms in the lattice, the lattice stretches, changing its spring constant. Capacitance goes down with increasing voltage

# The Derivative



A non-linear capacitor has decreasing capacitance as the applied voltage increases.

# Linear vs. Non-linear Capacitance



This device has both linear and non-linear capacitance. The linear capacitance is the vertical offset of the nCV plot so that the non-linear capacitance does not reach zero.

# Math Model for Non-remanent Capacitance

Non-remanent capacitance is the sum of linear capacitance (C•V) plus a non-linear capacitance which decreases with increasing voltage. The non-linear capacitance may be adequately modeled with a Gaussian distribution with a mean of zero volts.

$$P_{NR} = \left[C_L \bullet V\right]_{linear} + \left[P_{nlc}\left(\frac{1}{\sqrt{2\pi\sigma^2}}\right)e^{\frac{V^2}{2\sigma^2}}\right]_{non-linear} \qquad \text{Eq(1)}$$

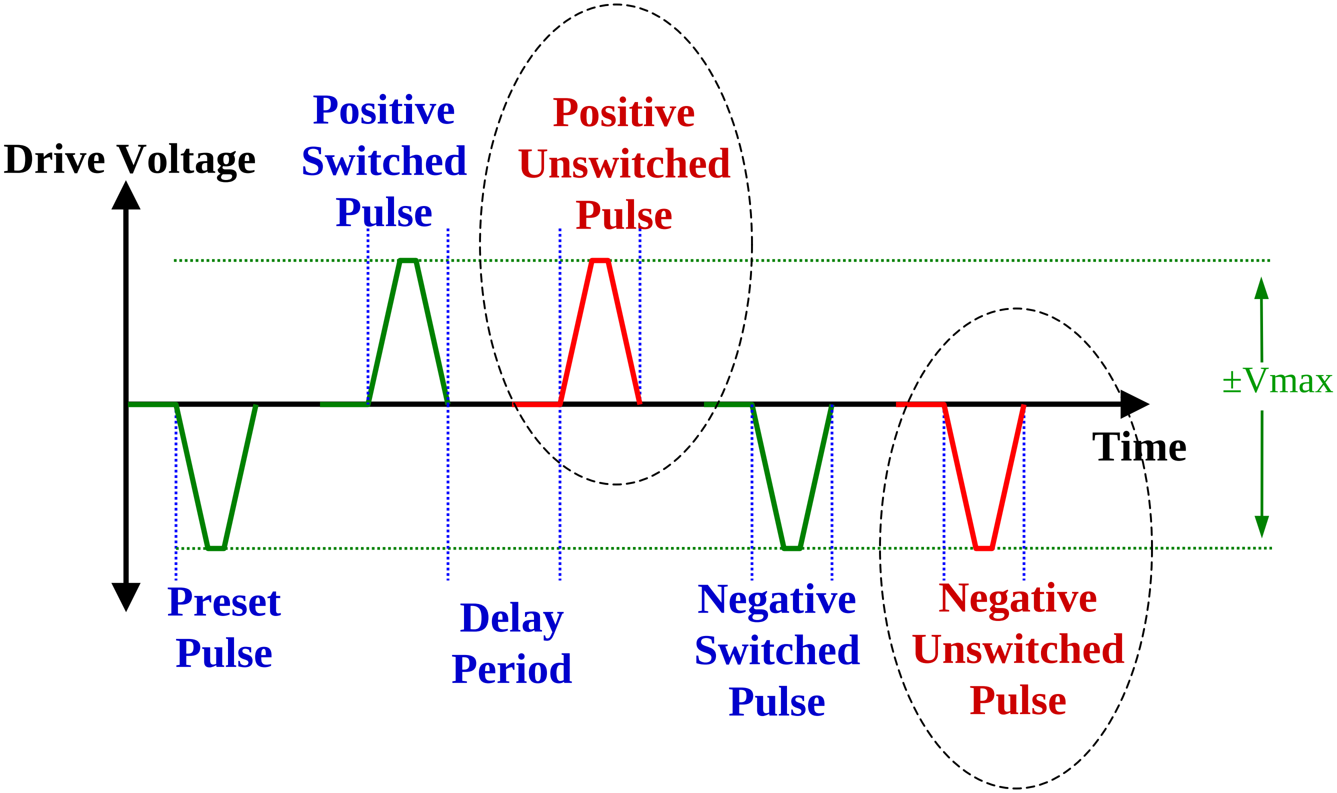
- $P_{NR}$ is the non-remanent component.

- $P_{nlc}$ is the polarization contributed by the non-linear capacitance.

- The rate at which the non-linear capacitance decreases with voltage is set by the variance parameter $\sigma$.

# Remanent Polarization

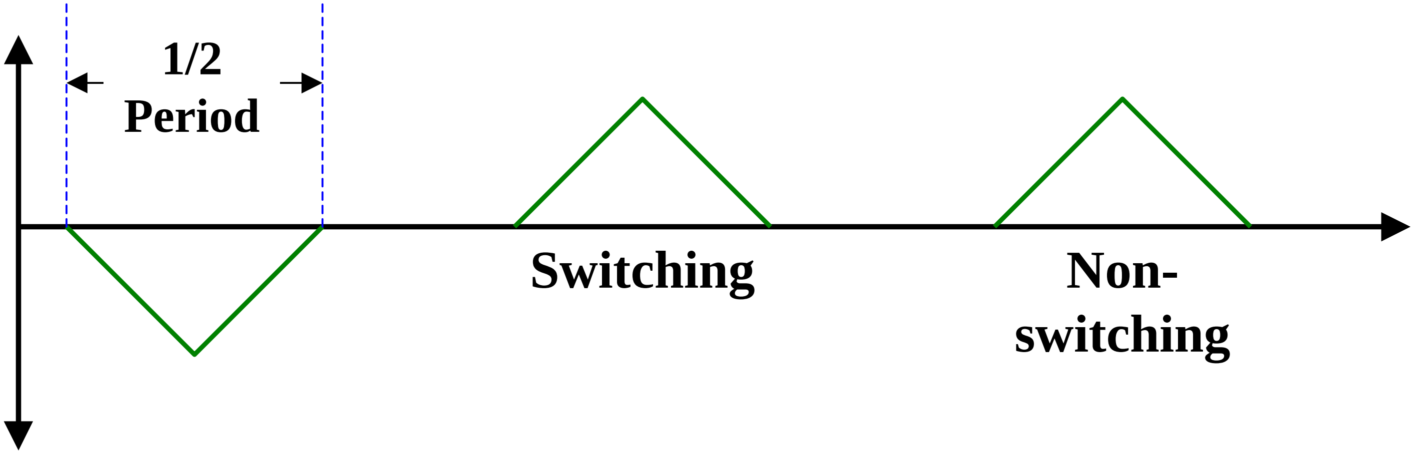
- The PUND test is a familiar measurement:



- Any matched pair of switched and non-switched pulses may be subtracted from each other to get the remanent (spontaneous) polarization.

# Remanent Hysteresis

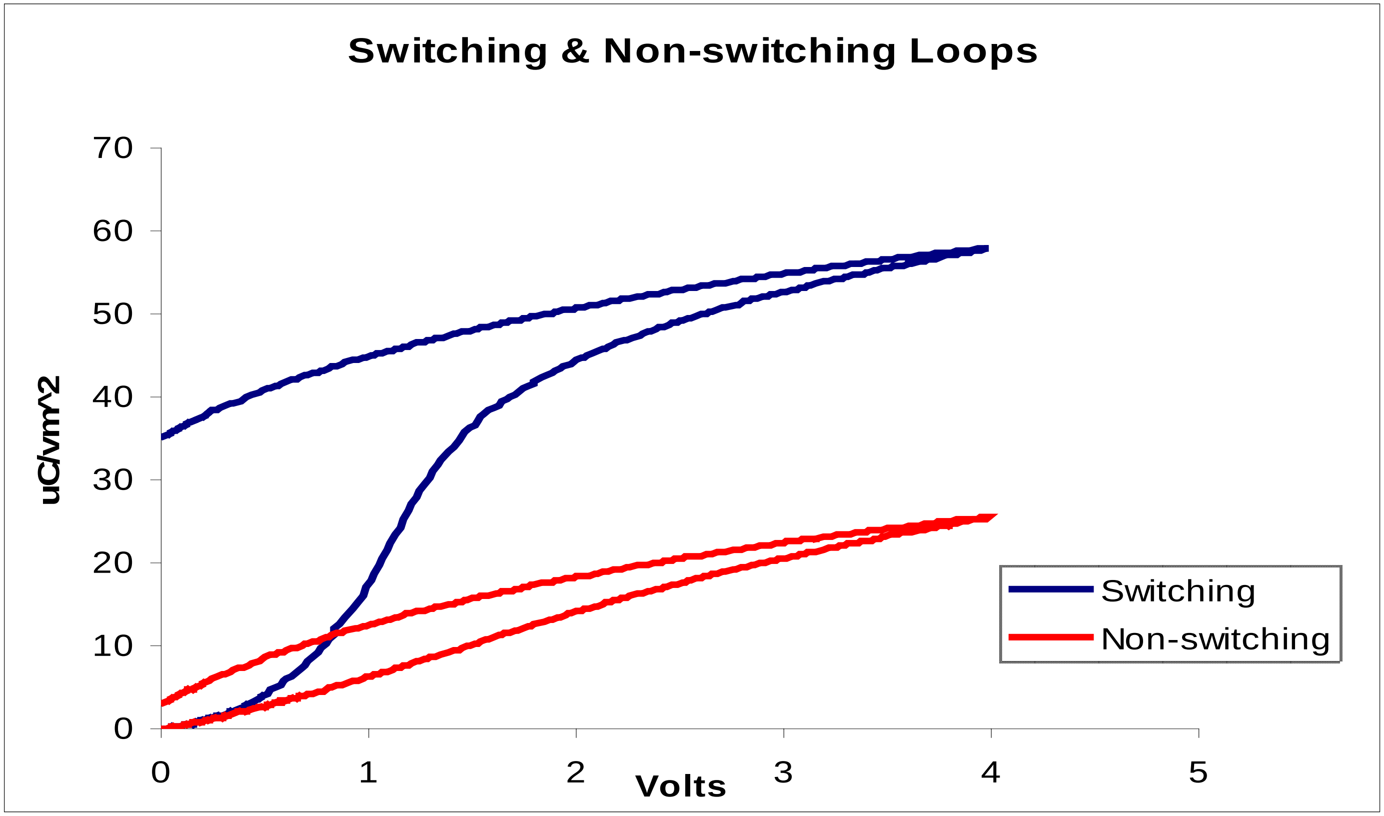
- The same measurement may be made using *half-hysteresis loops* instead of pulses:



- The difference between the switching and non-switching measurements will give the Remanent Polarization vs Voltage function *loop*.

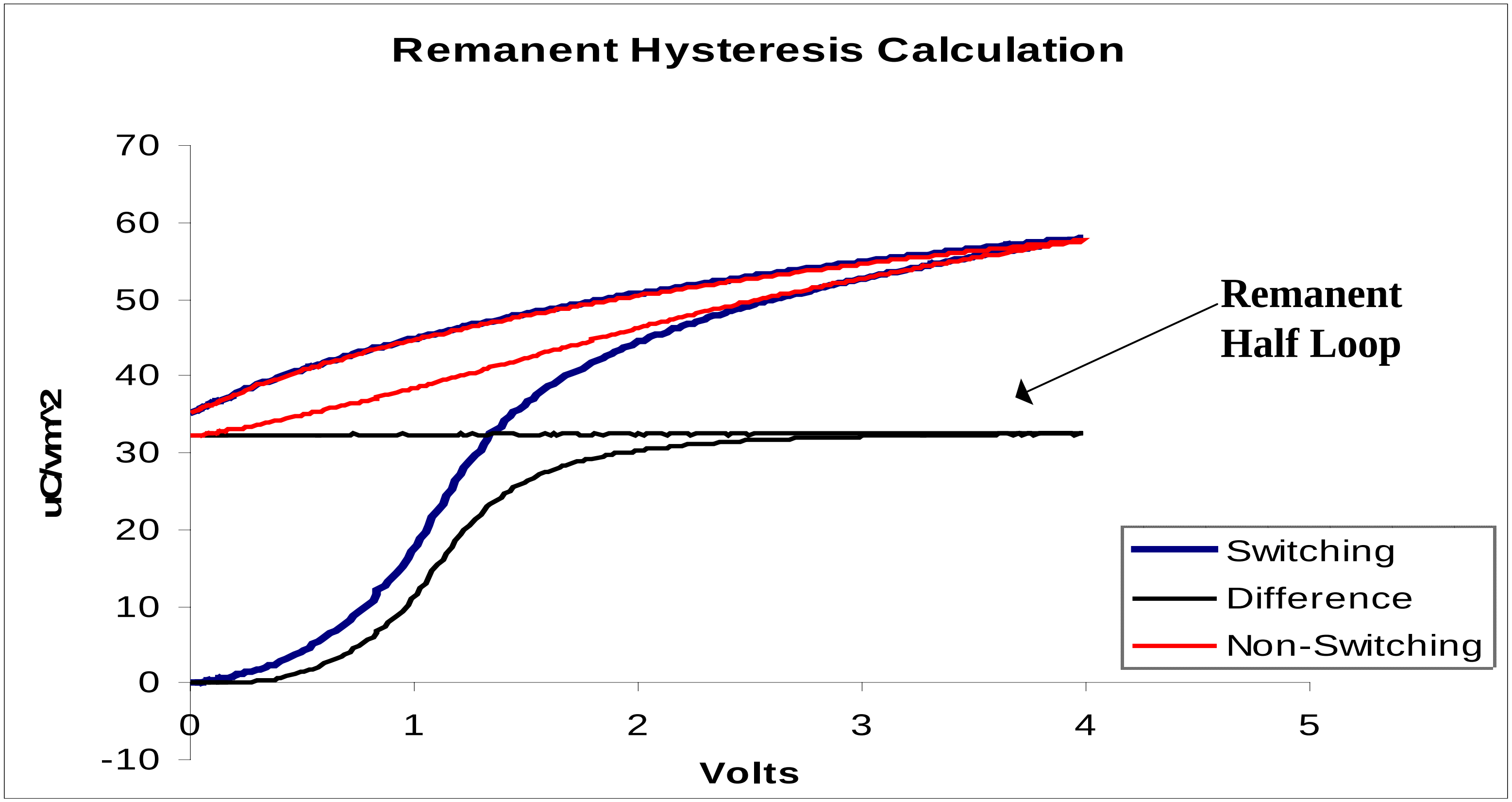
# Remanent Hysteresis

Switching and Non-switching half loops:



# Remanent Hysteresis

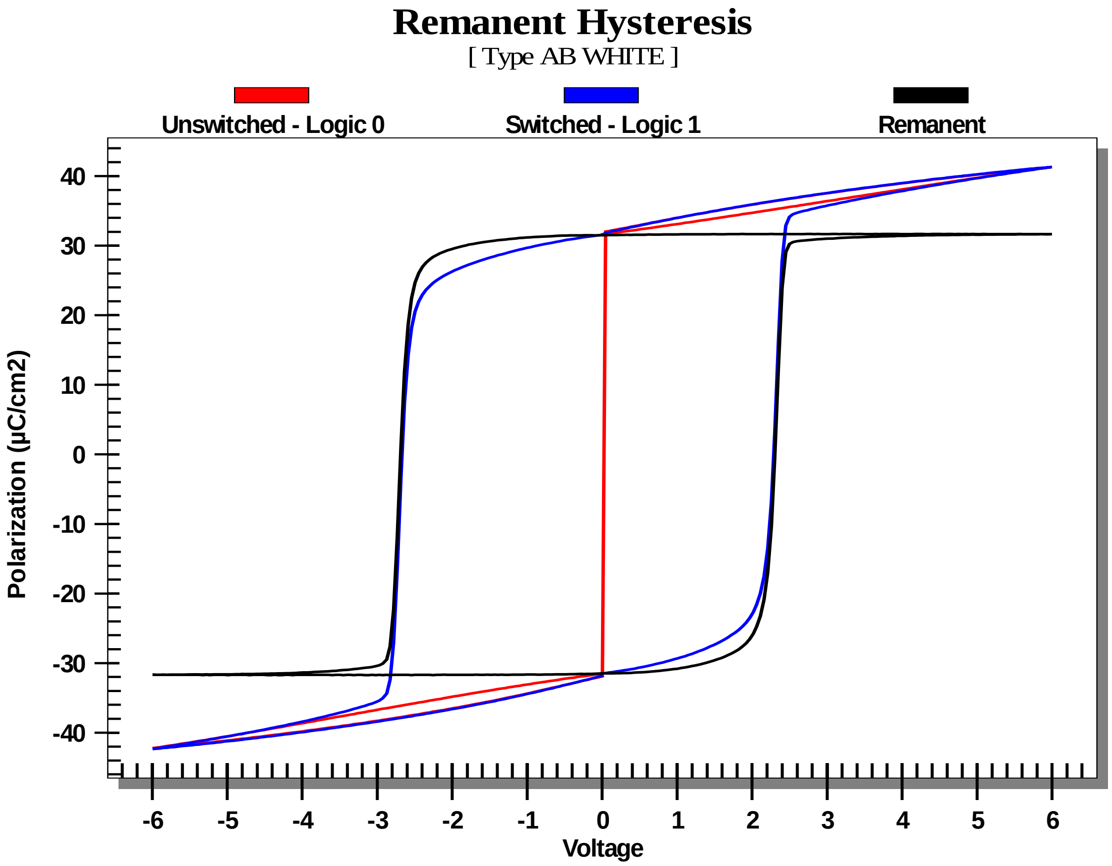
- PUND: P*r - P^r = dP = Qswitched
- Hysteresis: Switching - Non-switching = Remanence



- Note in the graph that the non-switching measurement was moved to align with the top of the switching measurement.

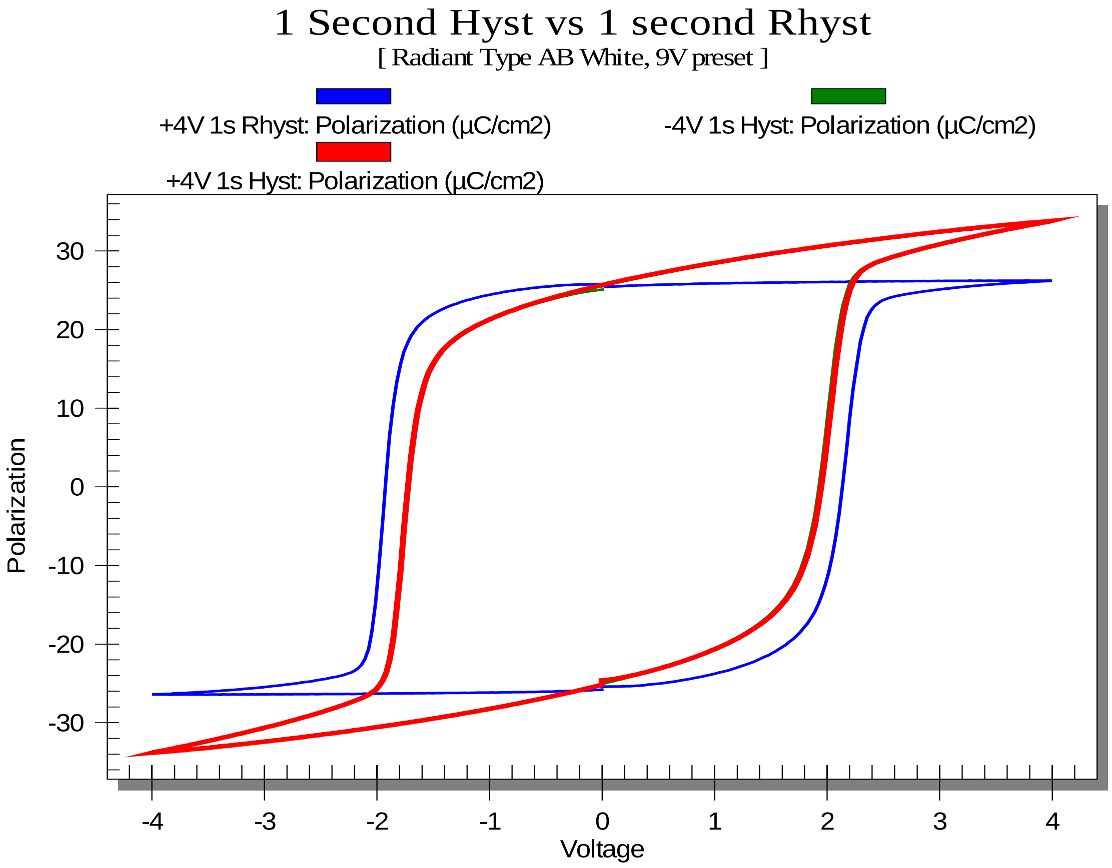
# Remanent Hysteresis

- The test may be executed in both voltage directions and the two halves joined to show the switching of the remanent polarization that takes place *inside* the full loop.

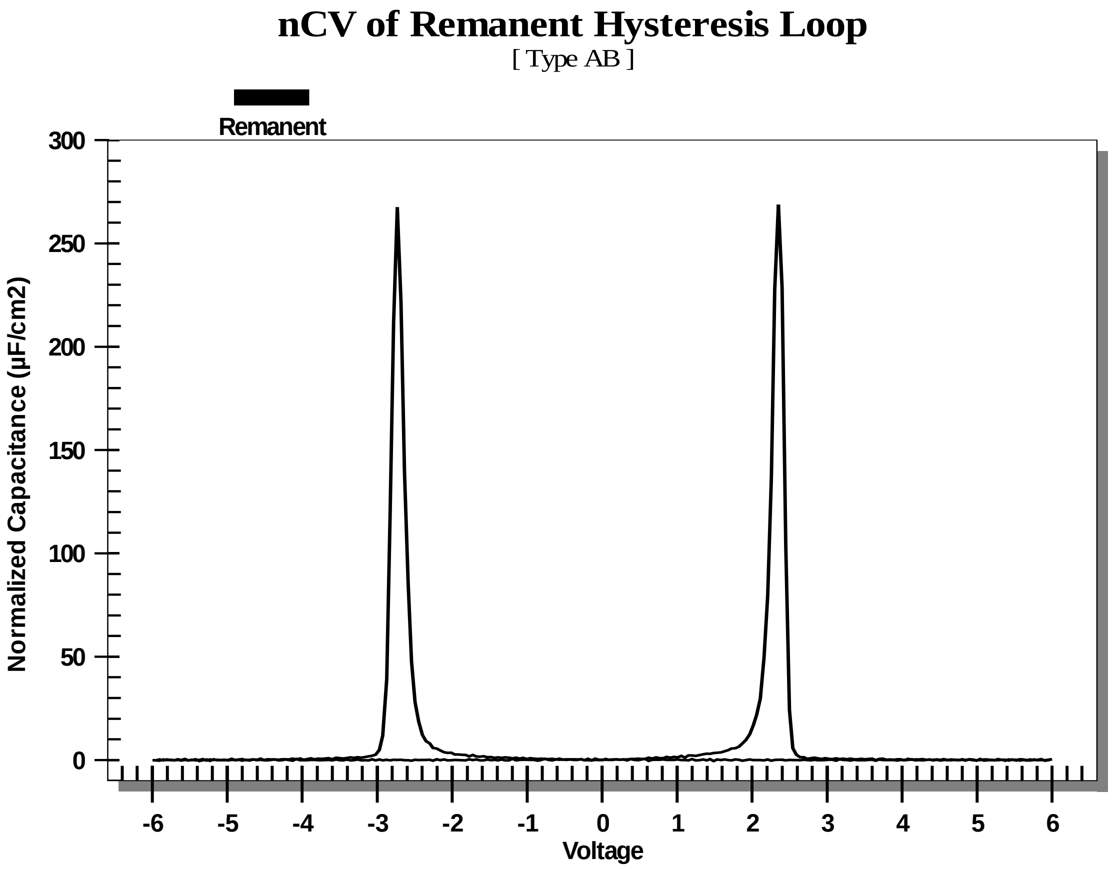


# Remanent vs. Normal Hysteresis

- The remanent hysteresis is in blue.
- The standard hysteresis loop is in red.
- The Vc of the remanent loop lies outside that of the normal loop. Why? (Hint: the reason is purely mathematical.)
- The Vc of the remanent loop is the true coercive voltage.



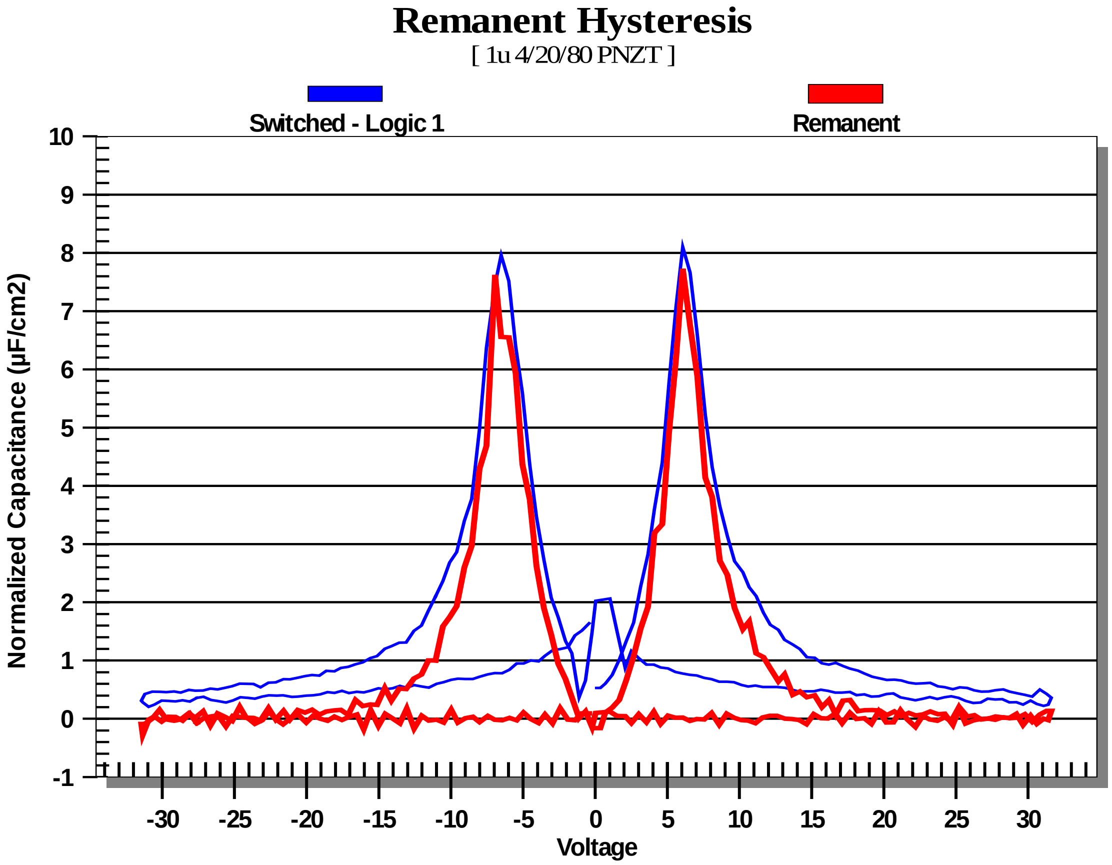
# The Derivative



- The nCV of the remanent polarization loop rests on the X-axis because it has *no capacitance* on its re-trace.

# The Perfect Capacitor

- A perfect capacitor combines non-linear capacitance with remanent polarization.  The blue line is the standard loop.



# Math Model for Remanent Polarization

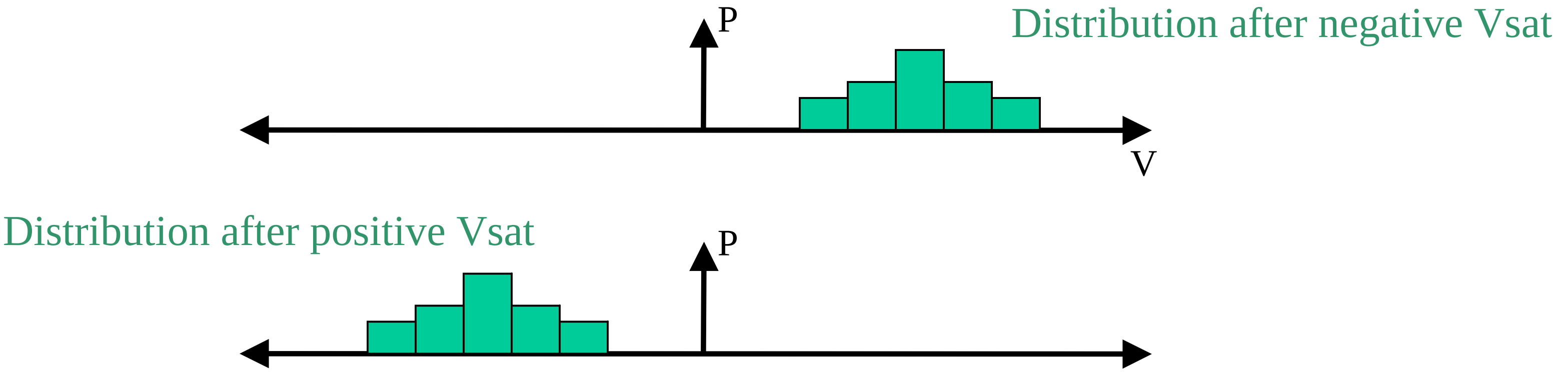
Remanent polarization may be adequately modeled as a normal distribution of small discrete remanent polarization units where each unit has its unique switching voltage threshold.

$$P_R = P_s\left(\left[\left(\frac{1}{\sqrt{2\pi\sigma_+^2}}\right)e^{\frac{\left(V - V_c^+\right)^2}{2\sigma_+^2}}\right]_+ - \left[\left(\frac{1}{\sqrt{2\pi\sigma_-^2}}\right)e^{\frac{\left(V - V_c^-\right)^2}{2\sigma_-^2}}\right]\right)_-$$

- $P_R$ is the remanent polarization.
- $P_S$ is the maximum switchable spontaneous polarization.
- The width of the switching peaks in the nCV is set by the $\sigma$ parameters.

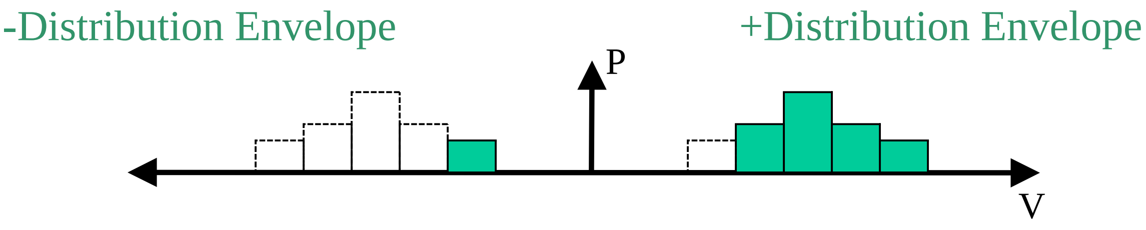
# Math Model for Remanent Polarization

- Define the remanent polarization as consisting of small units of polarization where each has its own switching threshold which defines where it sits under either of the ±distribution curves in Eq(2).
- $P_S$ is the sum of all remanent polarization units.
- All of $P_S$ fits under *one distribution curve* but can be divided between the two distribution curves by the action of applied voltages.



# Math Model for Remanent Polarization

- When a voltage increases under a portion of one or the other of the distribution curves, any polarization units *under that curve at that voltage at that time* will switch polarity, that is, jump to the other distribution curve.
- $P_R$ is the *difference* of the population of polarization units under each distribution curve.



Distribution after negative Vsat followed by voltage < +Vc

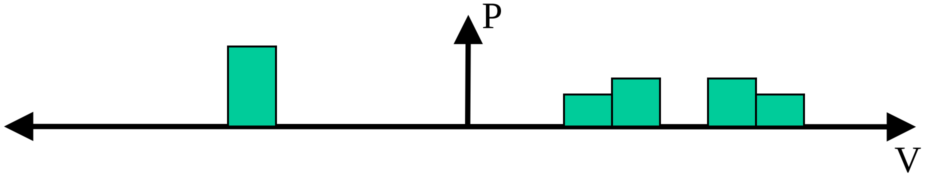
# Math Model for Remanent Polarization

- It is possible using custom voltage profiles to create unique distributions of remanent polarization units between the two curves.
- As an example, given a ferroelectric capacitor with symmetrical switching in both directions having the following parameters:

  $\sigma = 0.5\text{v}$
  $V_c = 2\text{v},$

  99% of the remanent polarization will switch between 0.5v and 3.5v.

  - Applying the following voltage sequence, [-5,+2.5,-1.5] will leave the remanent polarization distribution looking as below:



# Hysteresis in other Properties

- It is reasonable to assume that the remanent polarization state will affect other properties of the capacitor, giving those properties hysteresis as well.
- This is true for small signal capacitance and DC leakage.
- The effect of remanent polarization on these two properties are described in the following panels.

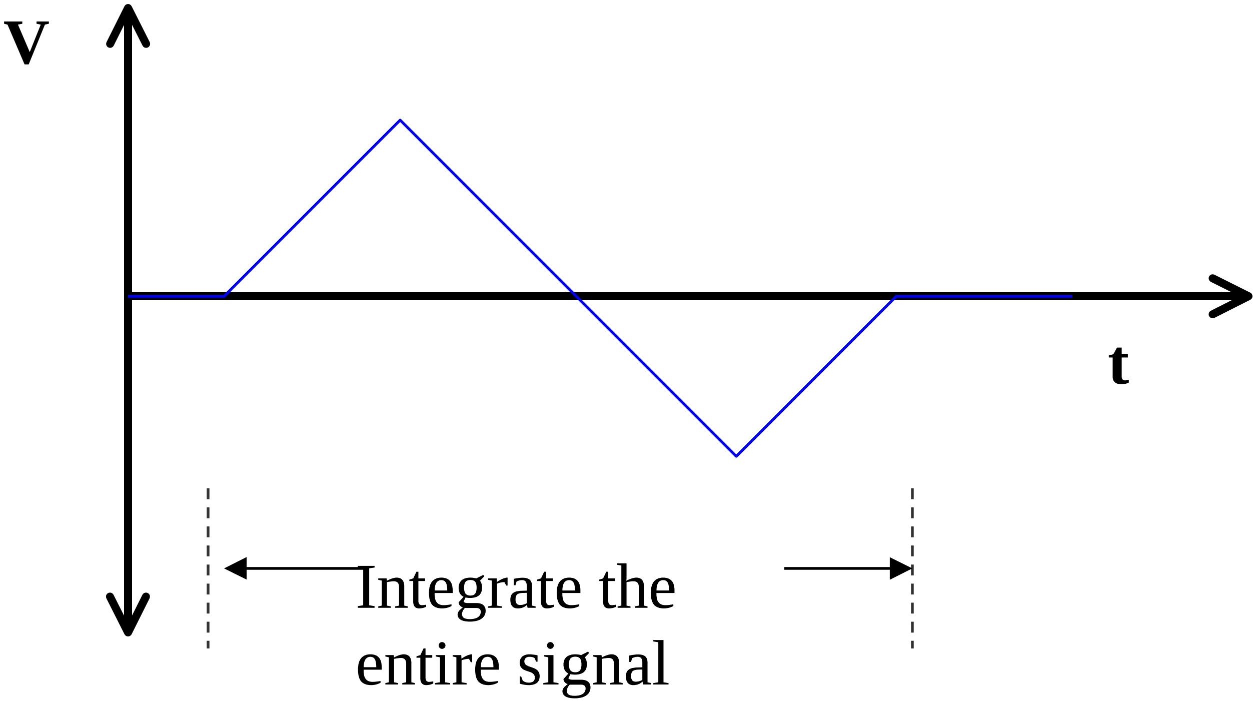
# Hysteresis in Small Signal Capacitance

- The small signal capacitance versus bias voltage is determined by measuring the sample capacitance with a low amplitude signal at a series of bias voltages.
  - Theoretically, the signal amplitude should be small enough that it does not disturb the state of the capacitor.
- While this is a noble effort, it cannot be ignored that the remanent polarization modulates the small signal capacitance.
- The state of the remanent polarization must be managed during measurements of small signal capacitance.

# Small Signal vs Large Signal

- The ferroelectric hysteresis measurement is defined at Radiant as a "large signal" measurement of the polarization properties of the sample.
- "Large signal" means that the test waveform has a large enough amplitude to switch dipoles in the ferroelectric material.
- As well, the "large signal" measurement captures and integrates <u>all</u> changes the sample experiences during the test waveform, showing its entire trajectory.
- The measurement result contains contributions from all components of the sample, including the remanent polarization and parasitics.

# Small Signal vs Large Signal



Integrate the entire signal

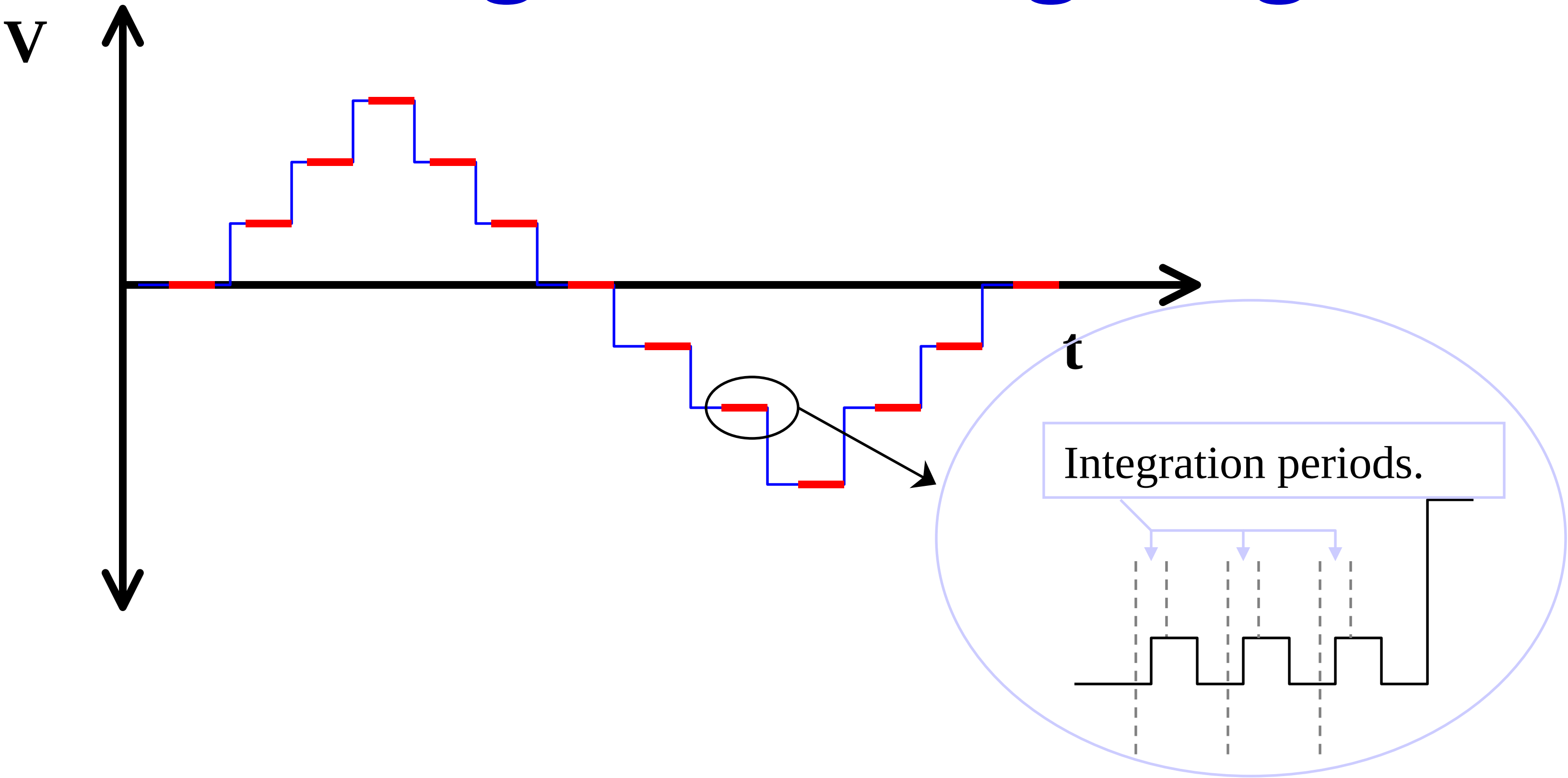
- A “large signal” measurement captures every electron that moves into or out of the capacitor during the stimulus waveform.

# Small Signal vs Large Signal

- The “small signal” measurement is defined as one where the test amplitude is small compared to that required to switch remanent polarization in a ferroelectric capacitor.
- Since the response of a non-linear sample changes with the absolute value of the voltage applied and the remanent polarization state, the “small signal” measurement must also have a steady state voltage component as well as a remanent polarization pre-set procedure to put the sample in the appropriate state.
- Therefore, the “small signal” measurement captures and integrates only those changes the sample experiences during a small amplitude stimulation of the sample at a specified voltage and polarization state.

By definition, the “small signal” measurement contains no contribution from switching dipoles!

# Small Signal vs Large Signal



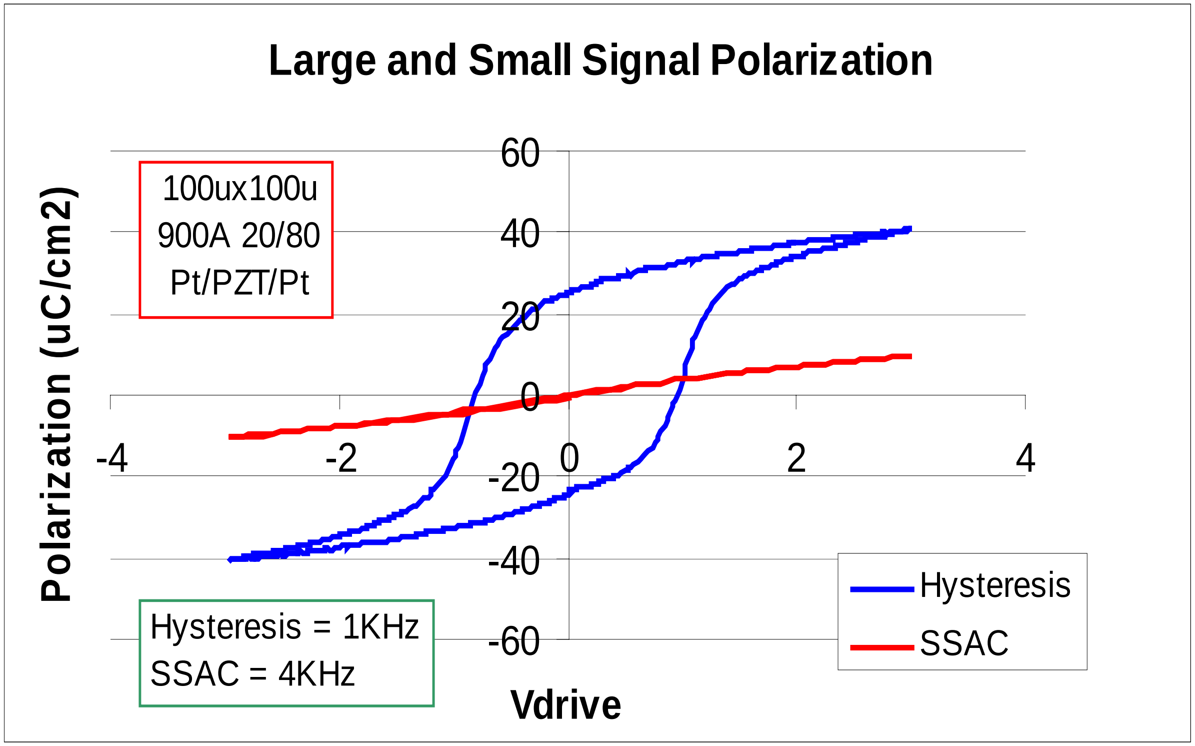
- In “small signal” measurements, many small measurements are taken that capture only the small changes associated with small stimuli.
- In a “small signal” measurement, the sequence of DC bias values is the same as the voltage profile used for hysteresis so the two can be compared directly.

# Small Signal vs Large Signal

- Radiant testers execute both standard “large signal” hysteresis and “small signal” capacitance measurements.
    - “large signal” hysteresis results are normally given in units of polarization (µC/cm$^2$) but can be converted to capacitance using the CV or Normalized CV plotting functions of the Hysteresis Task or the Hysteresis Filter.
    - “small signal” measurements are normally given in units of capacitance (nF or µF/cm$^2$) but can be converted to equivalent polarization using the appropriate plotting function of the Advanced CV measurement task.

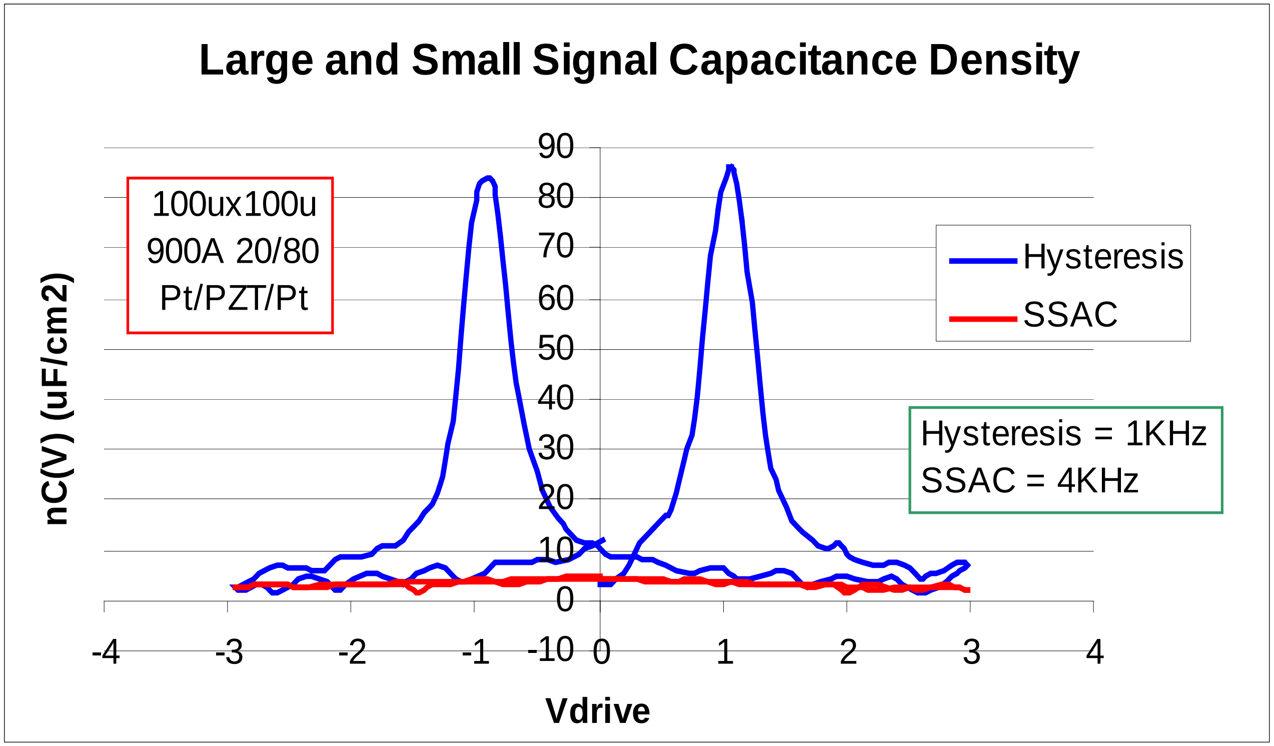
# Small Signal vs Large Signal

- Comparison of the Hysteresis and Polarization of the Small Signal Capacitance is shown below:

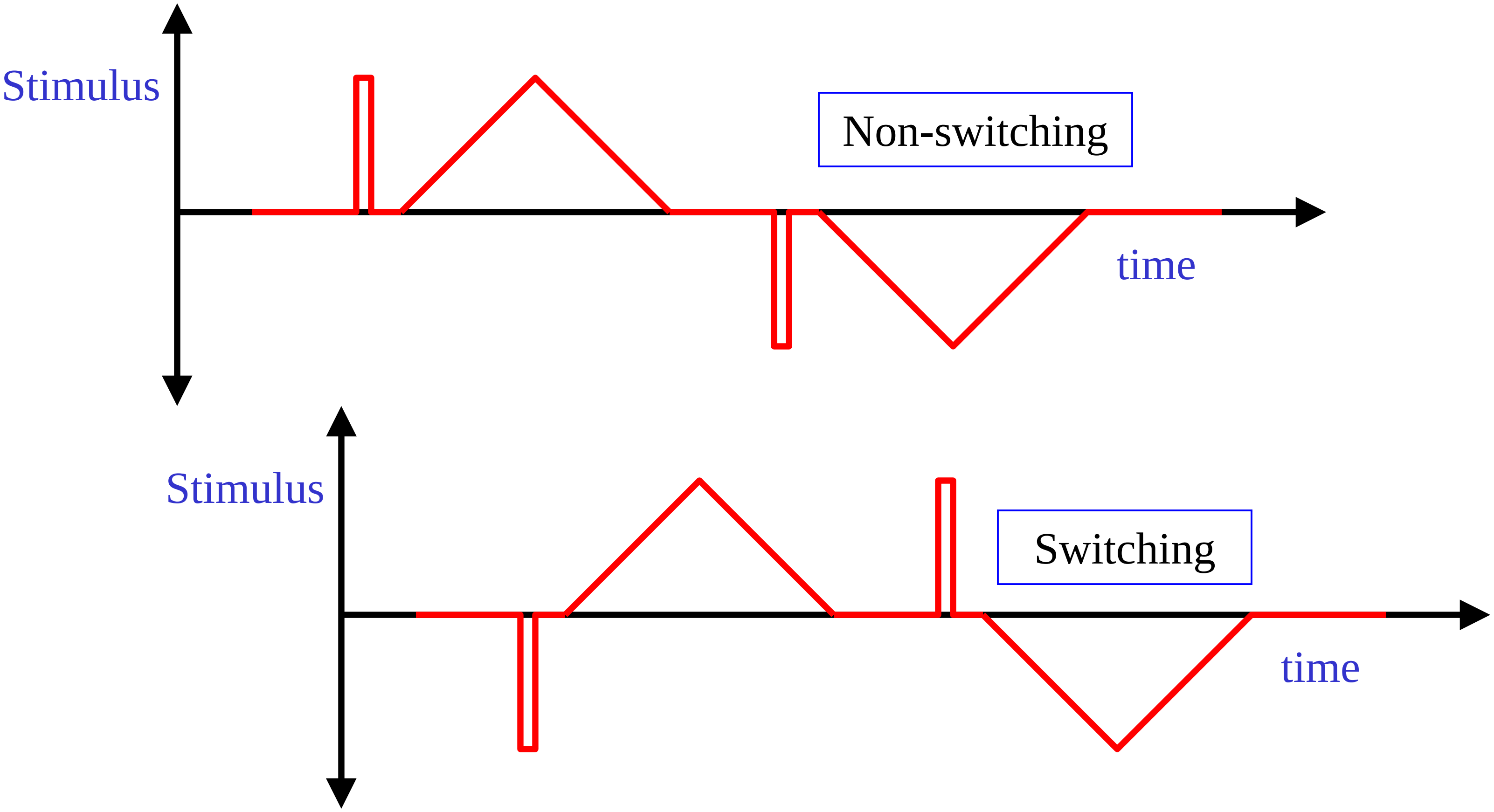


# Small Signal vs Large Signal

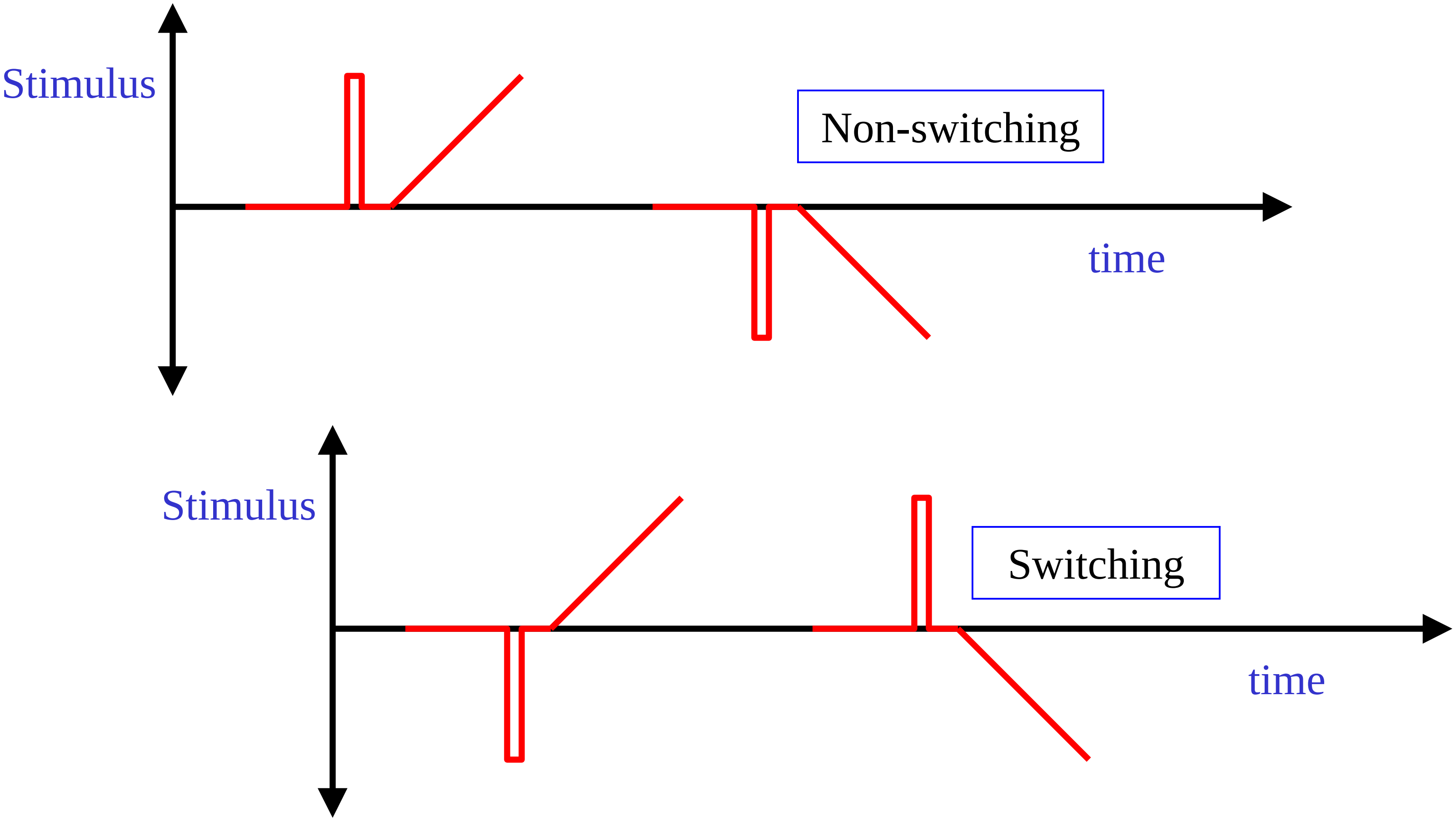
- Comparison of the Large and and Small Signal Capacitance is shown below:



# Hysteresis in Small Signal Capacitance

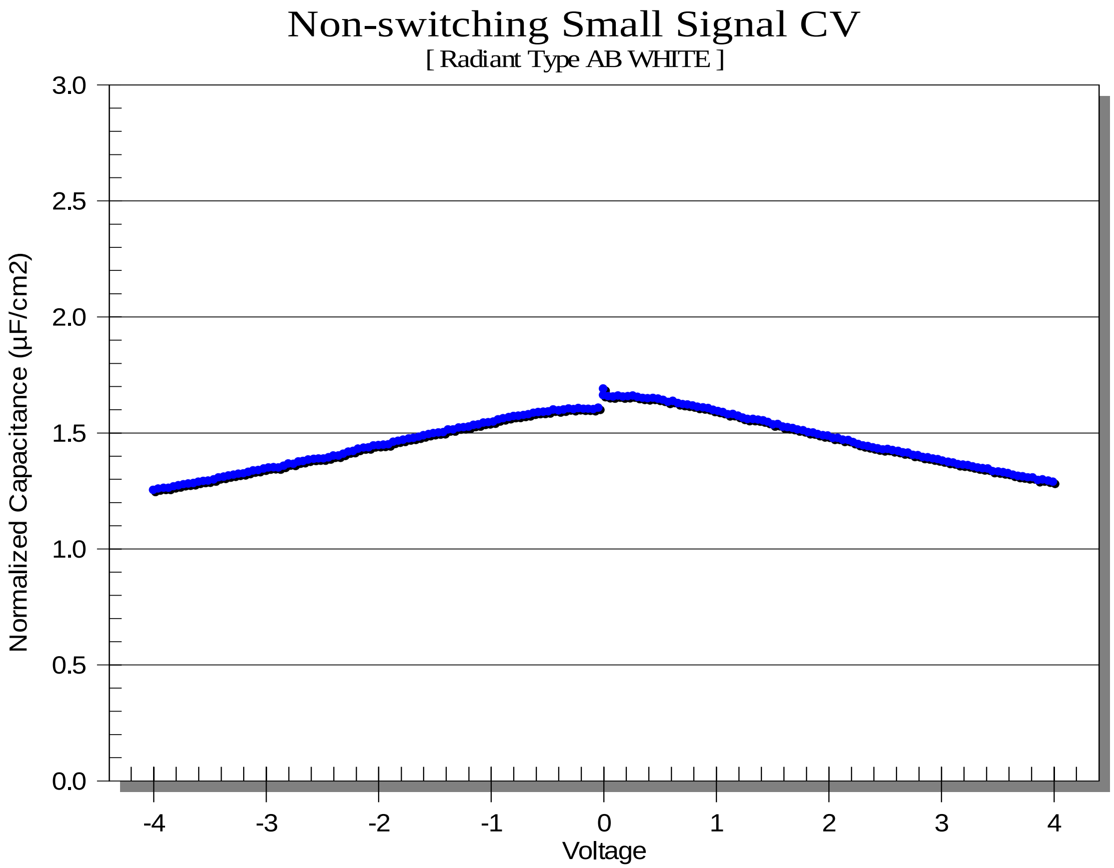


# Hysteresis in Small Signal Capacitance



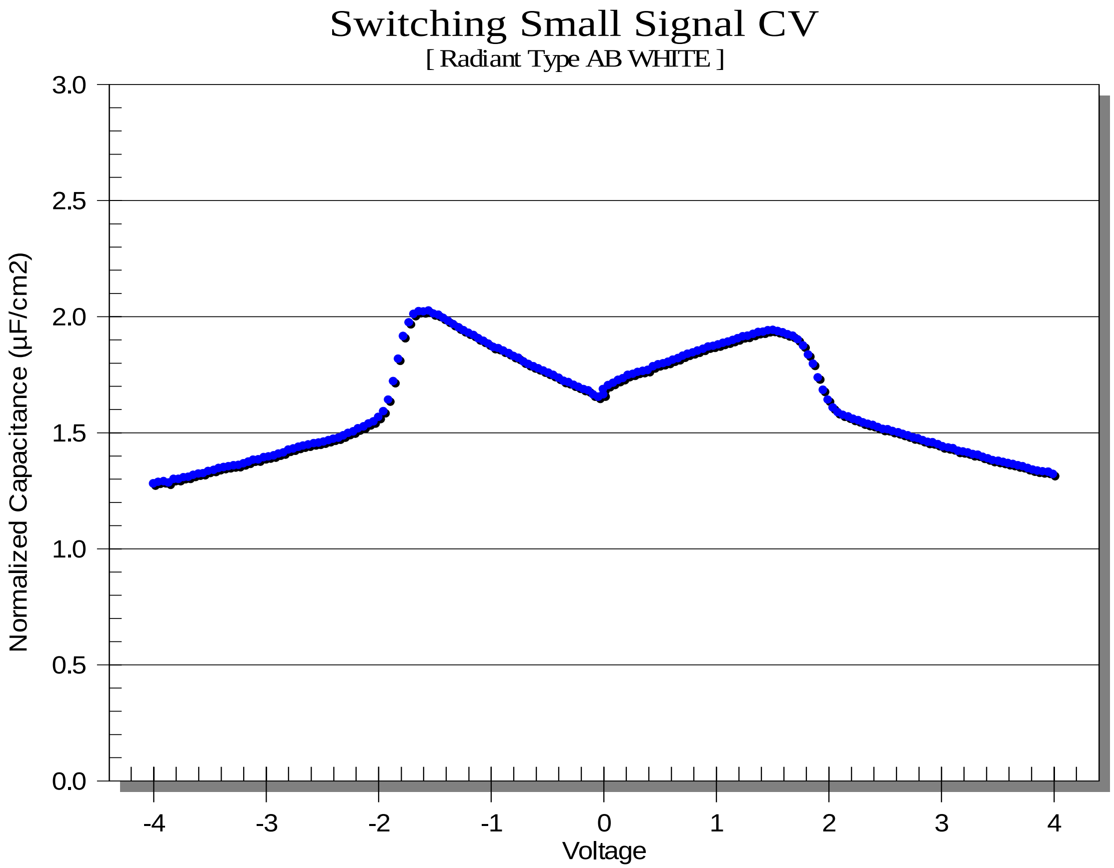
# Non-switching CV for the Sample under Test

- 1KHz 0.2V test with 182 points



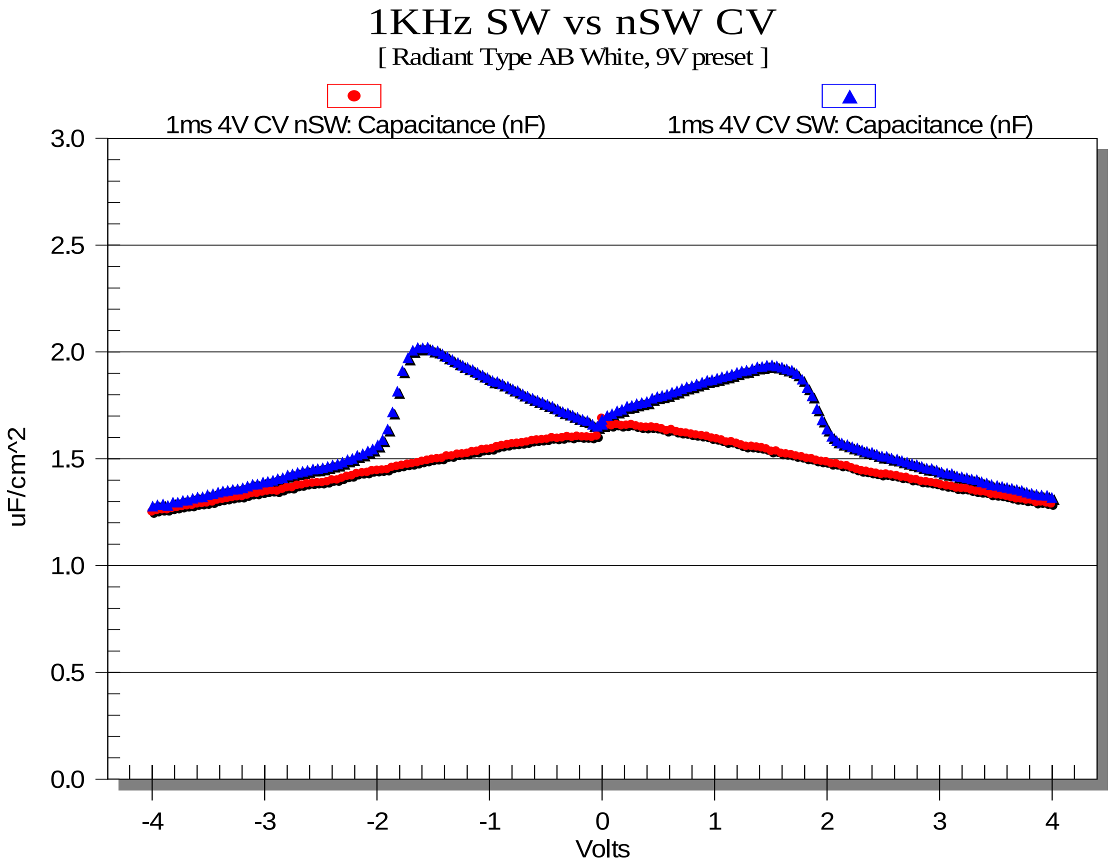
# Switching CV for the Sample under Test

- 1KHz 0.2V test with 182 points



# Non-switching vs Switching CV

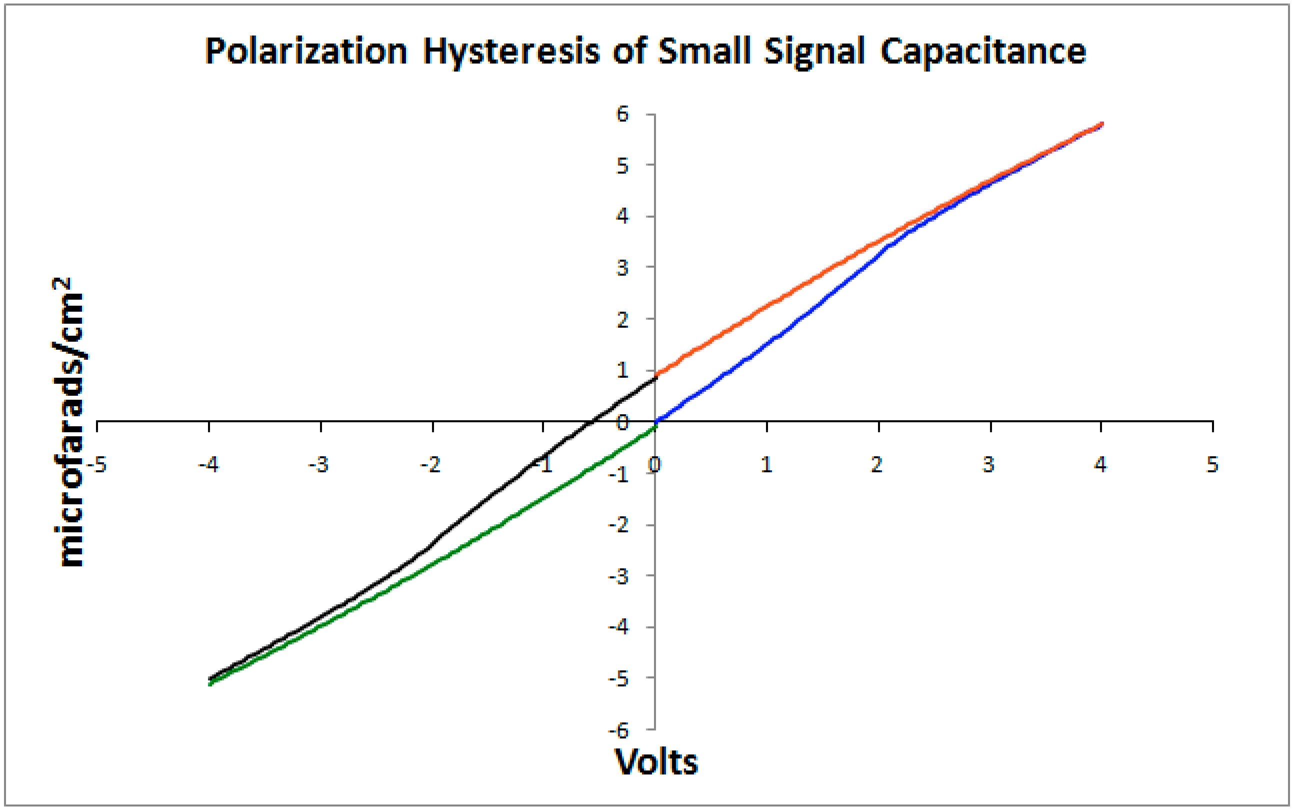
- 1KHz 0.2V test with 182 points



# Q vs V from Small Signal Capacitance

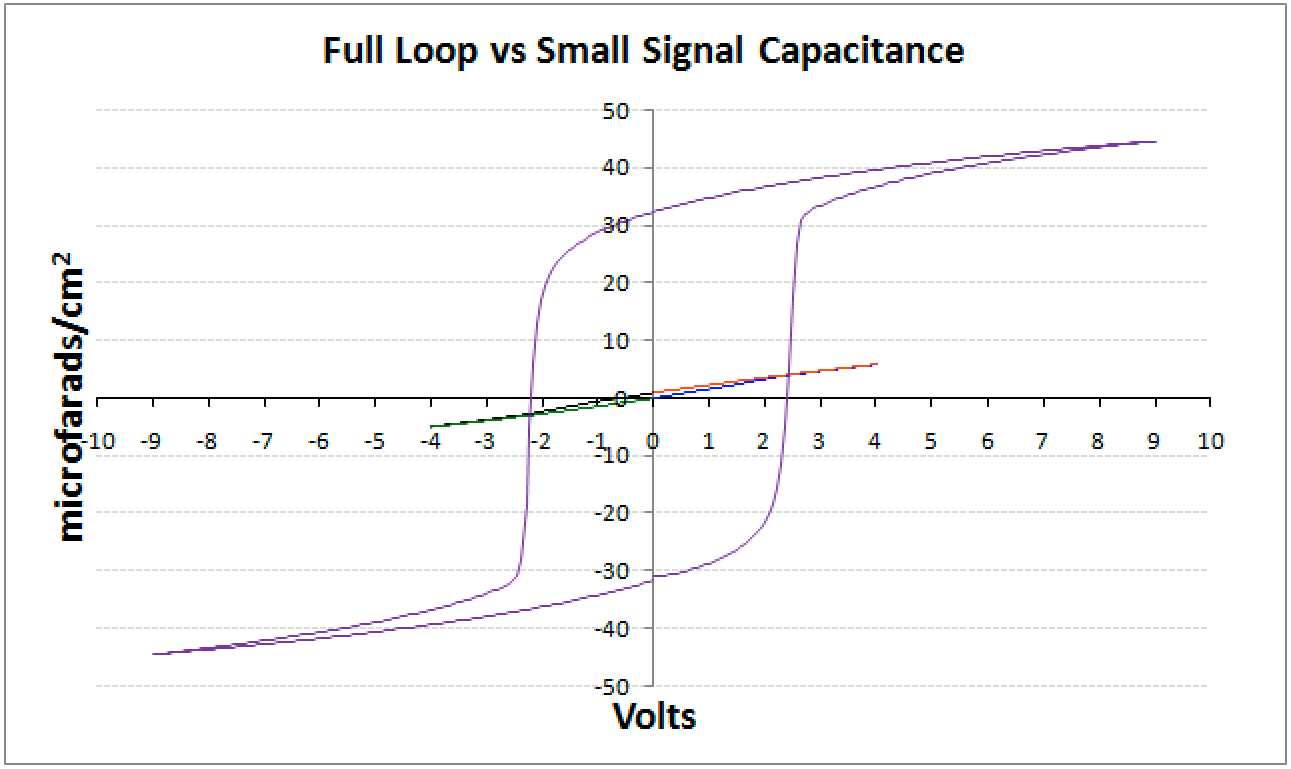
- The small signal capacitance can be multiplied by the dV to get the dQ per test step.
- The dQs may be integrated to see the polarization hysteresis contributed by the modulation of small signal capacitance by remanent polarization!

# Small Signal Capacitance Polarization



- Small signal capacitance forms a hysteresis of its own.

# Small Signal Capacitance Polarization



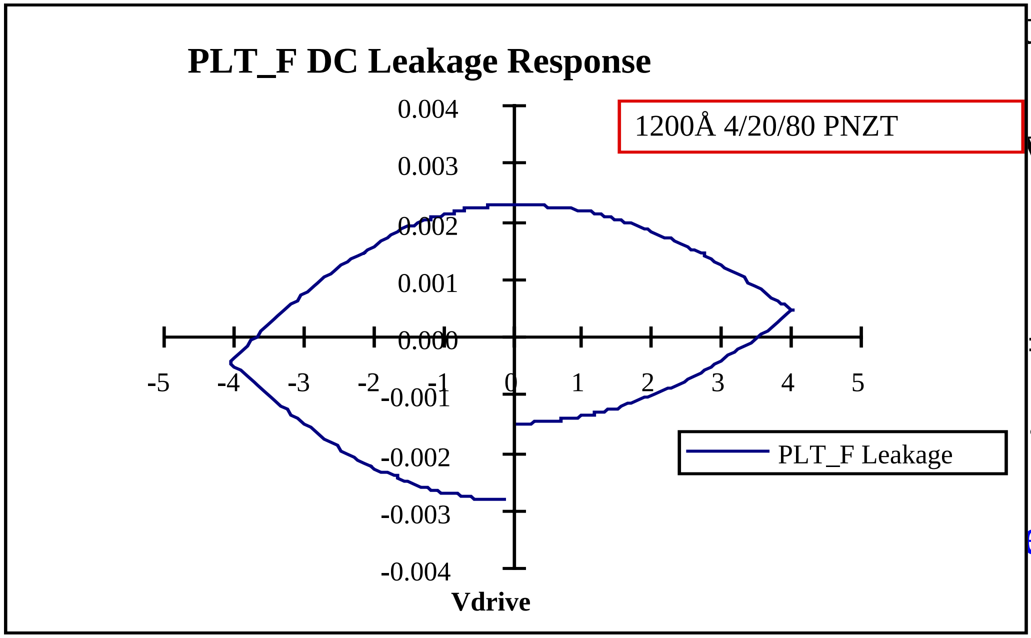
- The contribution of small signal capacitance hysteresis to the overall loop is small in this case.

# Resistive Leakage in a Hysteresis Loop

***Linear*** resistance is easy for a triangle wave:

$$\Delta P = (\text{Current} \bullet \Delta\text{time})/\text{Area}$$

$$\therefore P_i = (\Sigma^k_{n=0}\ n \bullet \Delta V/R_\pm \bullet \Delta t)/\text{Area}$$



time=time step per point

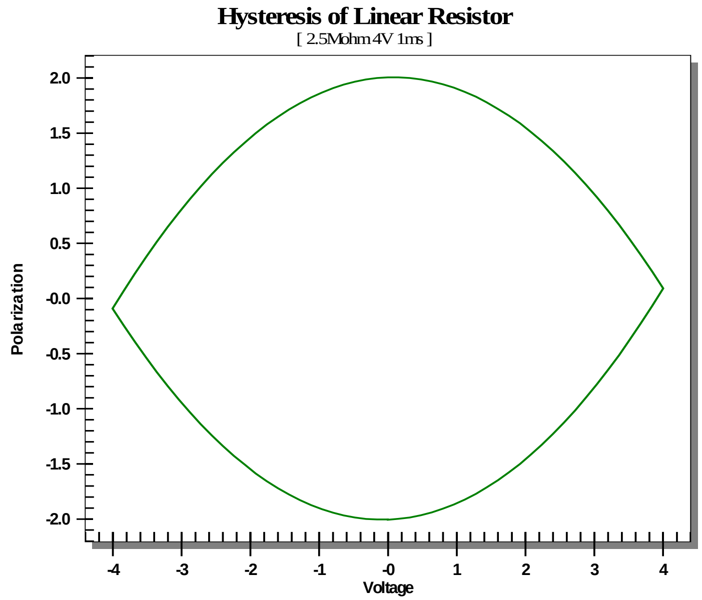
V=fixed voltage step of

= point number of
gitized triangle wave

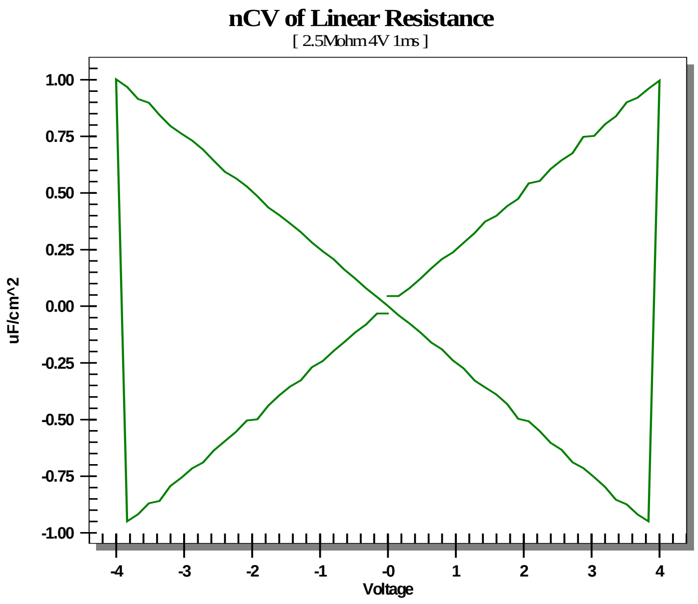
esult = “Football”
( $R_+ \neq R_-$ )

# Resistive Leakage in a Hysteresis Loop

The derivative of pure resistive leakage is an “X”.

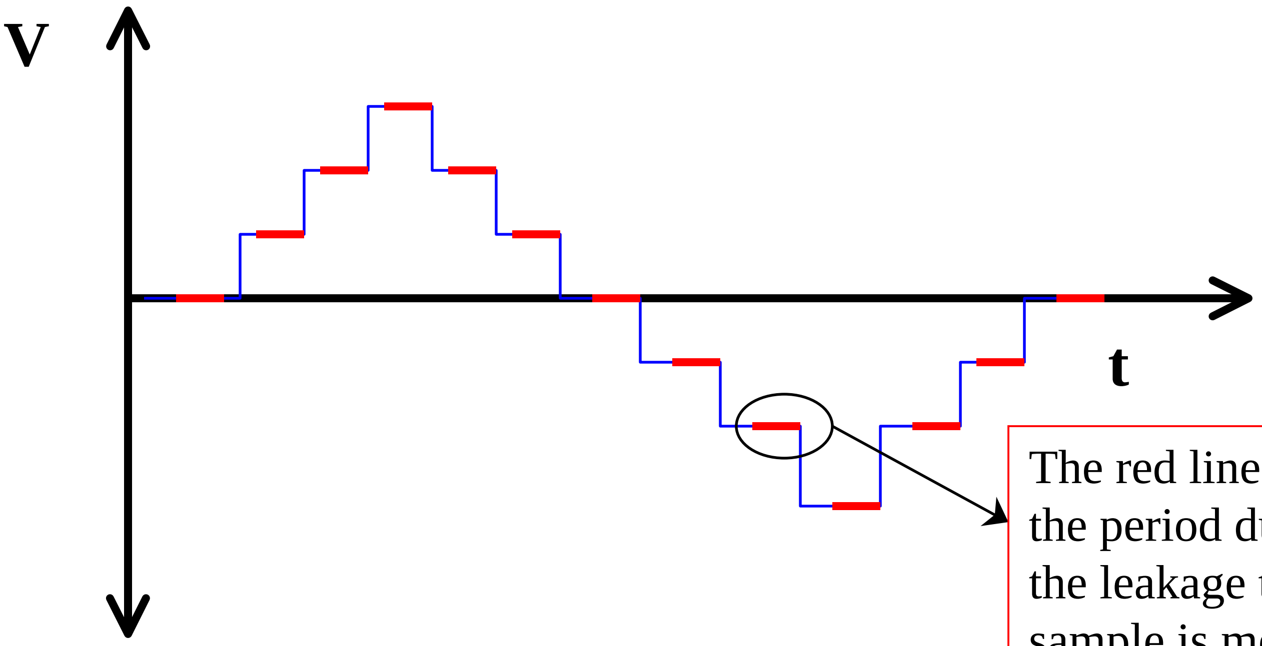

Hysteresis of Linear Resistor

[ 2.5Mohm 4V 1ms ]


nCV of Linear Resistance

[ 2.5Mohm 4V 1ms ]

# IV Test

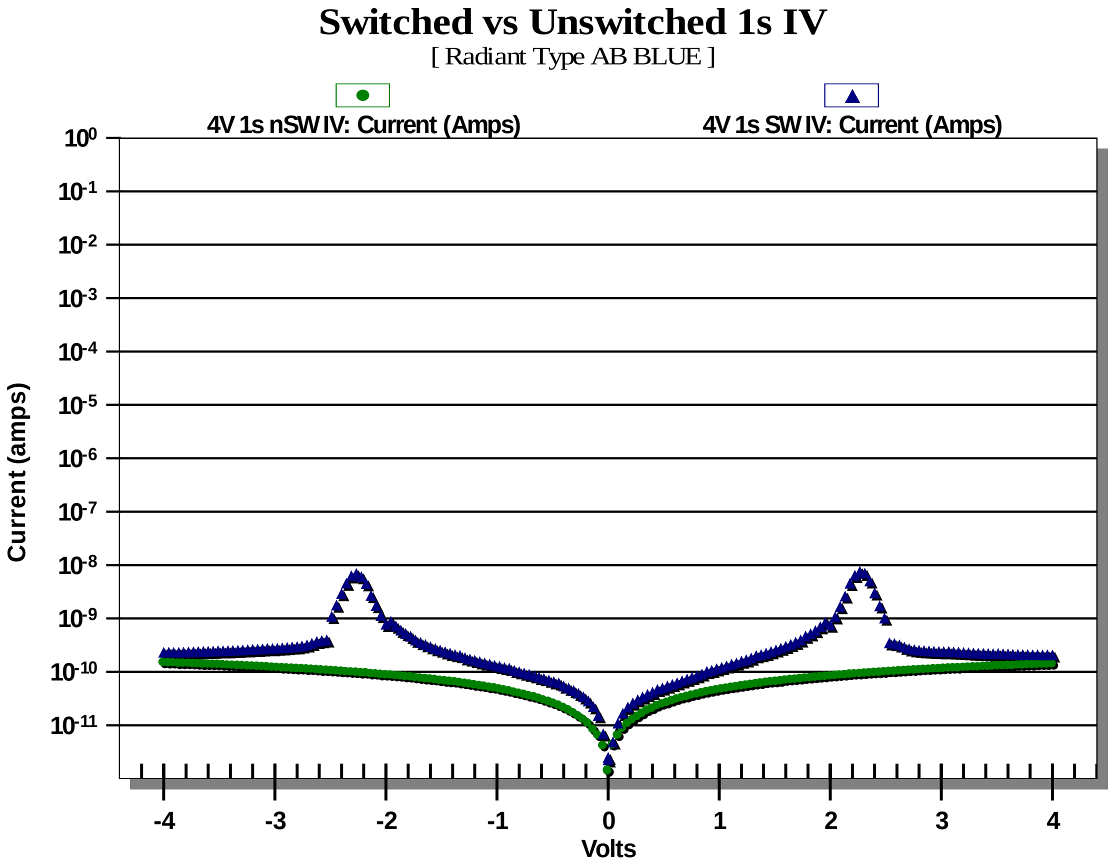


The red line indicates the period during which the leakage through the sample is measured after a soak period.

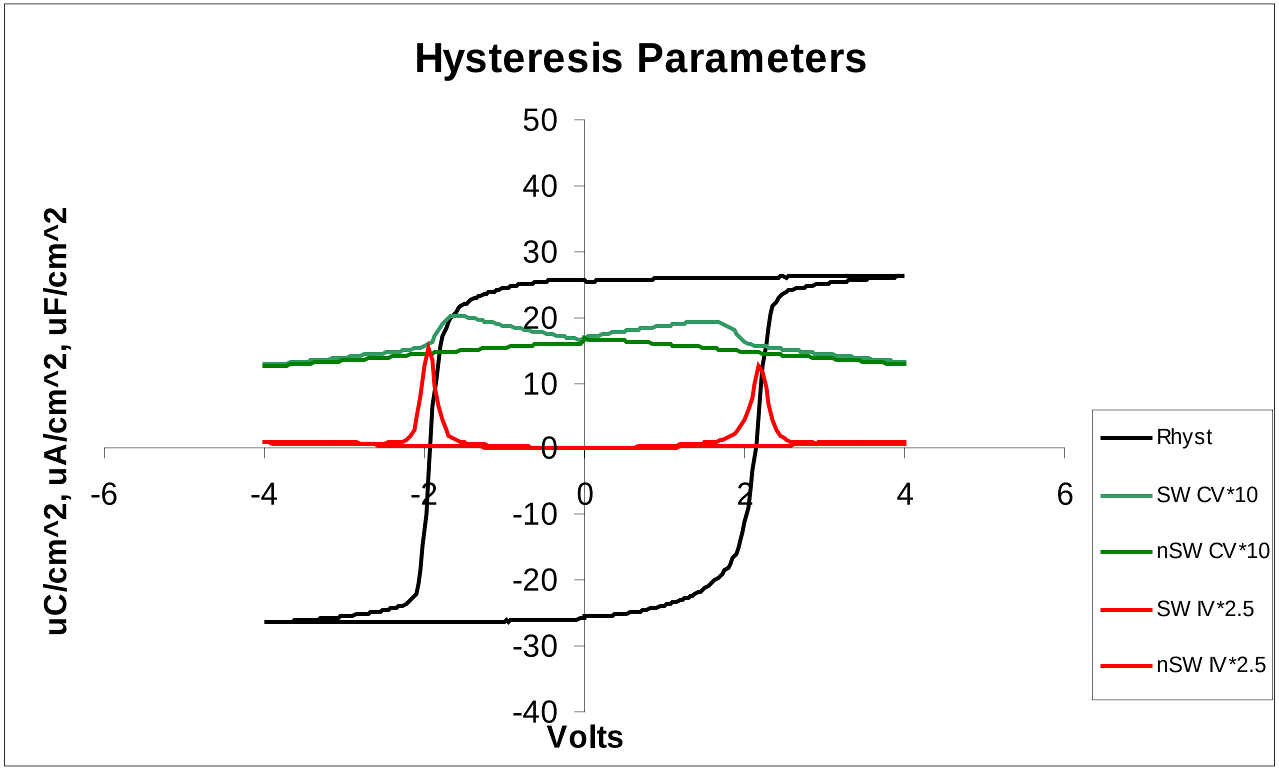
- The IV, or Current vs Voltage, test is a series of leakage tests executed over the voltage profile used for the traditional hysteresis loop.

# Hysteresis in Leakage

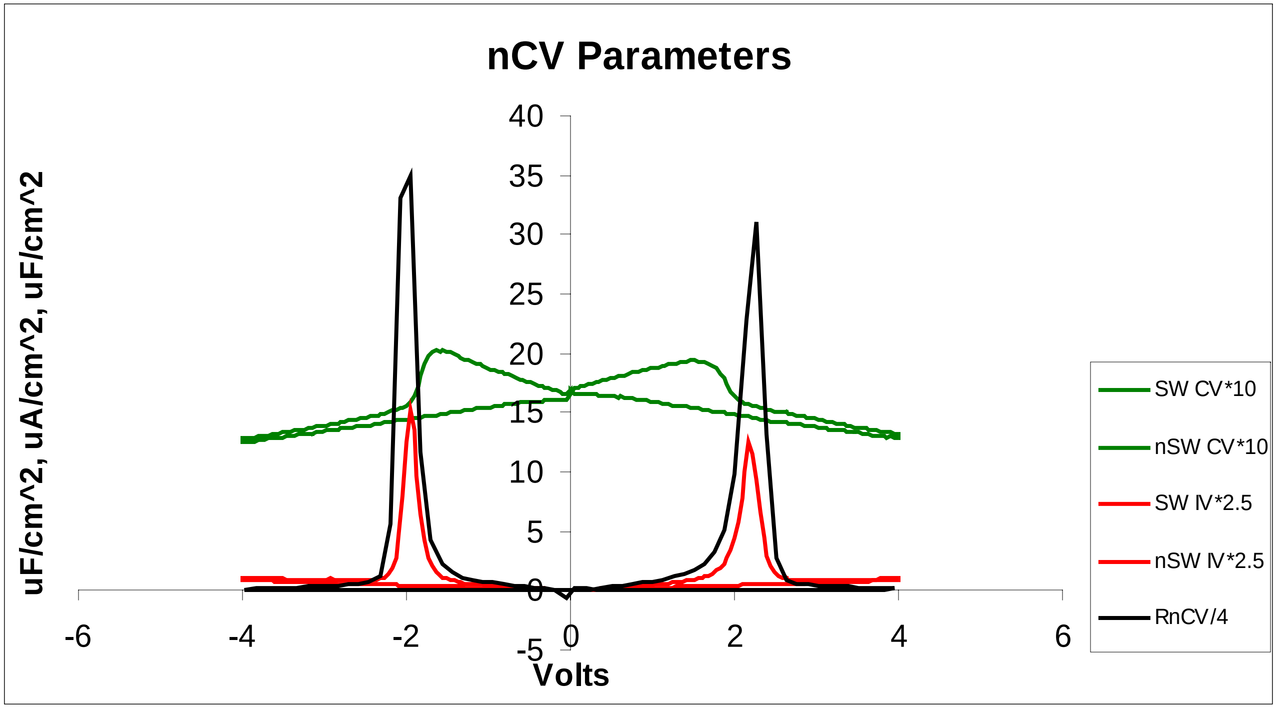
- Leakage in ferroelectric materials does not have to be linear.
- Leakage can have its own hysteresis modulated by remanent polarization.



# Leakage vs CV vs Remanent Polarization

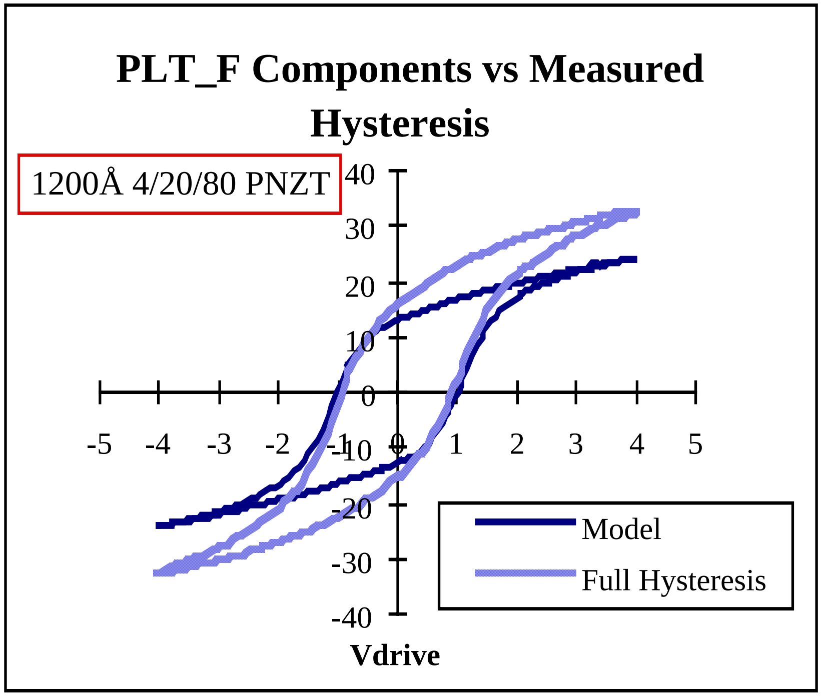


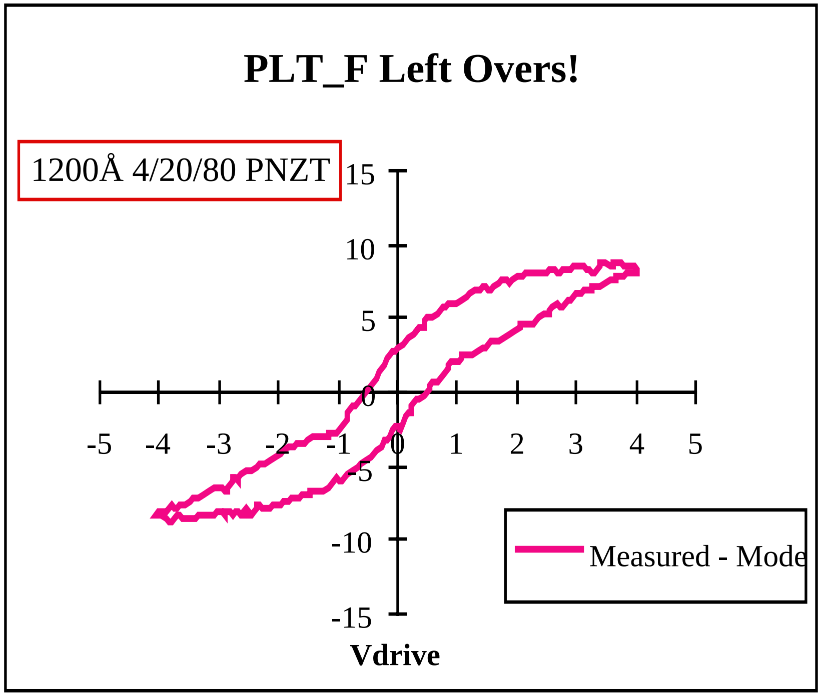
# Leakage vs CV vs Remanent Polarization



# Something Left Over

If we measure the remanent polarization, small signal capacitance, and leakage and then subtract them from the full loop, something is left over: *(Note the change in Y-axis scales in the graphs below.)*





This is the source of the "gap" in the hysteresis loop!

# Reversed Bias Diodes

- A platinum-electrode-based capacitor has two opposing diodes at the ferroelectric/platinum interface, one of which is always turned off.
- In reverse bias, a diode has a constant current *independent of applied voltage*. See the ideal diode equation below.

$$I_D = I_S\left(e^{\frac{V_D}{V_T}} - 1\right) \qquad \text{Eq(3)}$$

where

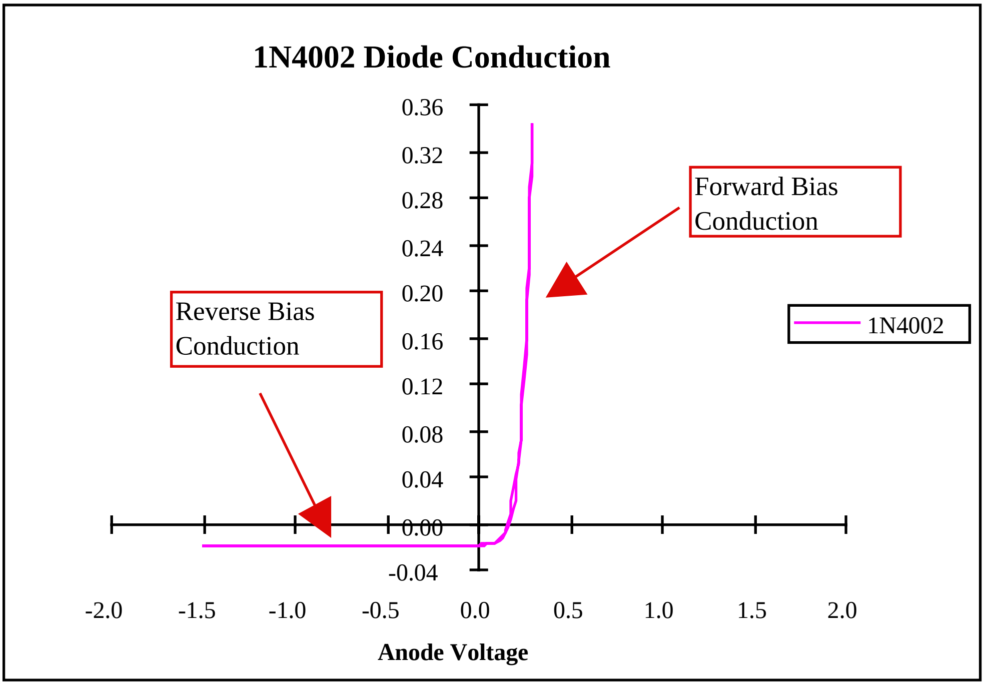
$V_D$ = the voltage across the diode
$V_T$ = the Boltzmann thermal voltage
$I_S$ = the diode saturation current

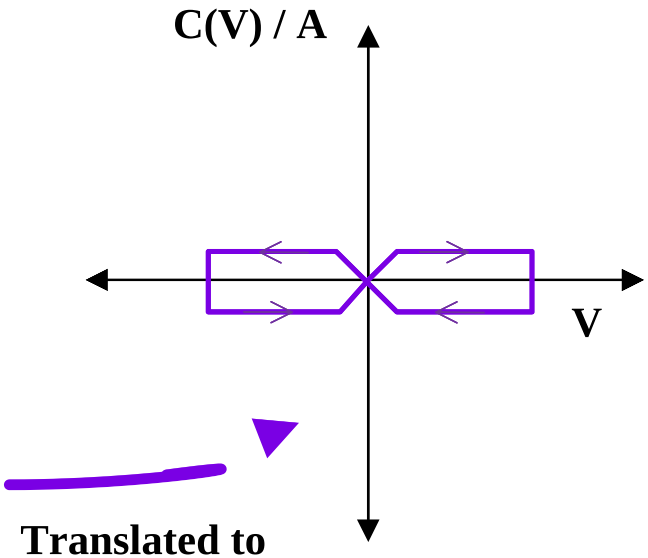
When $V_D$ is negative, the equation reduces to

$$I_D = I_S(0 - 1) = -I_S$$

# Reversed Bias Diodes

- The constant current delivers the same amount of charge per unit time to the test instrument independent of the voltage.
- When tested with a triangle wave where ΔV/ Δt is constant, the reverse-biased diode thus looks like a capacitor when voltage is increasing and a *negative* capacitor when the voltage is decreasing!



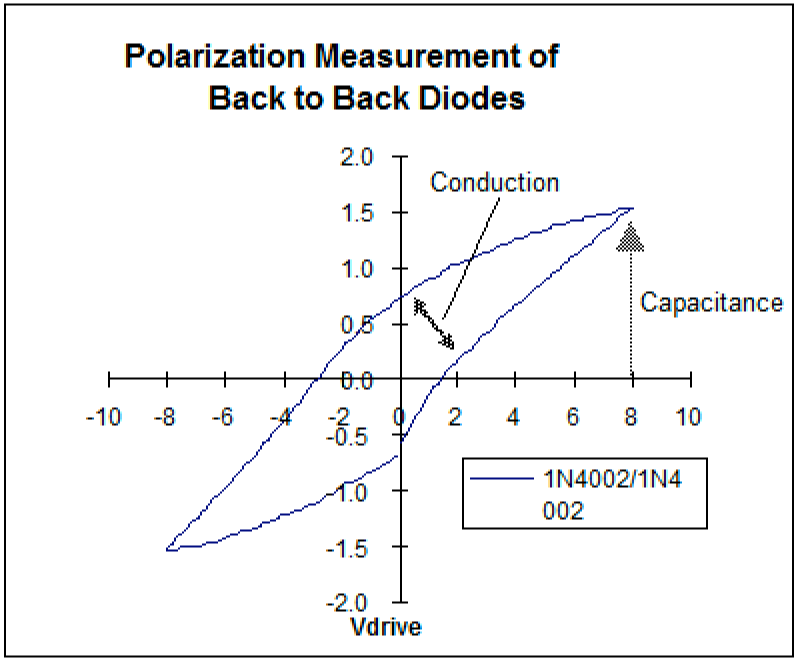


**Translated to C(V) plot**

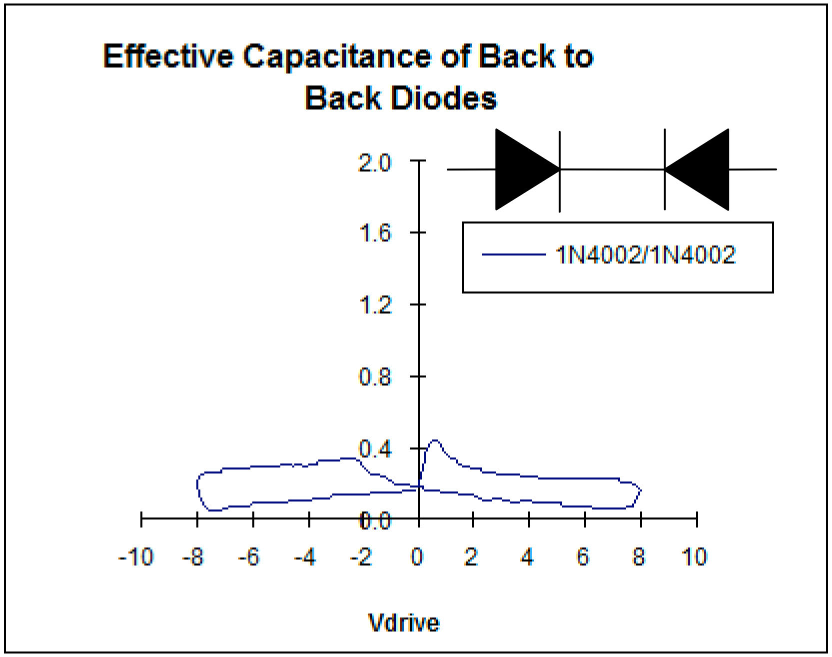
# Reversed Bias Diodes

- The hysteresis and nCV of two back-to-back 1N4002 diodes are plotted below.

- The nCV shows the *positive/negative capacitance signature* of the diodes translated up by the capacitance of the diodes.



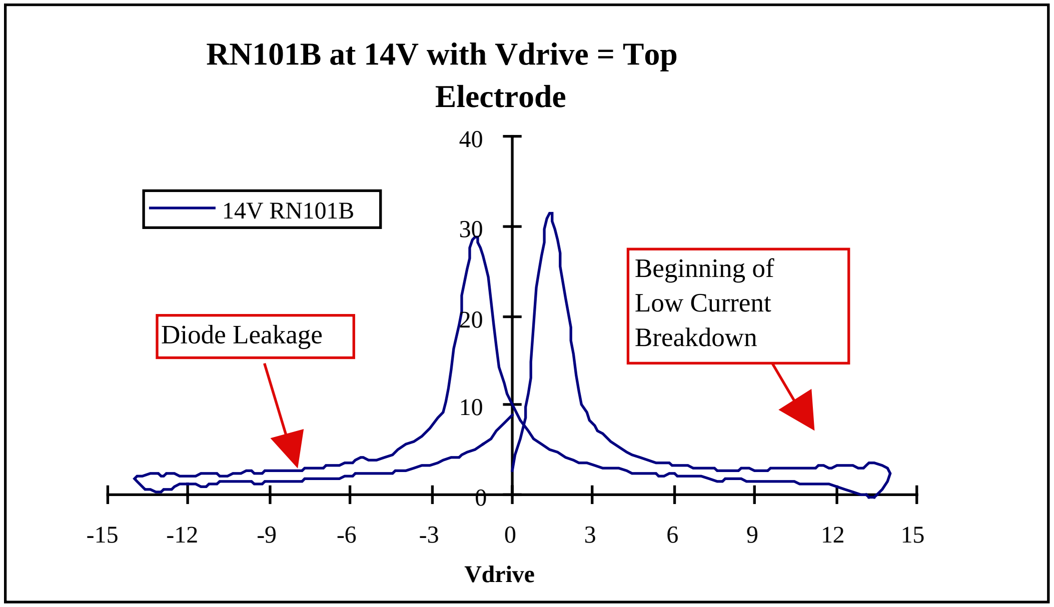
**Polarization Measurement of Back to Back Diodes**



**Effective Capacitance of Back to Back Diodes**

# Reversed Bias Diode Breakdown

- The derivative of a polarization hysteresis loop clearly shows the contact diode reverse-biased leakage effect and breakdown of the contact if it is present.



- The leakage of diode reverse-biased breakdown is marked by exponentially increasing current. This produces a “trumpet flare” instead of the “X” of linear leakage.

# The Components

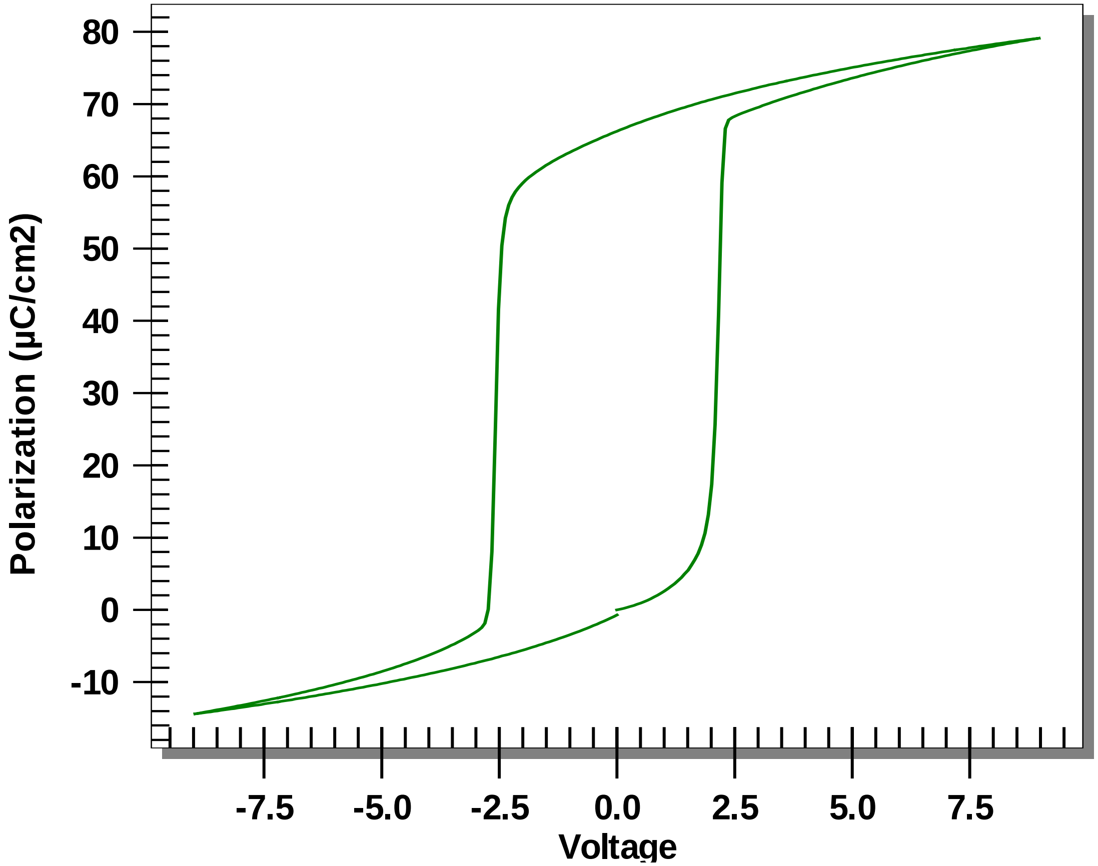
- Remanent polarization
- Linear small signal capacitance (dielectric constant)
- Nonlinear small signal capacitance (dielectric constant)
- Hysteretic small signal capacitance (remanent polarization modulation)
- Linear resistive leakage
- Hysteretic resistive leakage
- Electrode diode reverse-biased leakage
- Electrode diode reverse-biased exponential breakdown

All of these components are visible in the derivative of the polarization hysteresis loop!

# What is this?

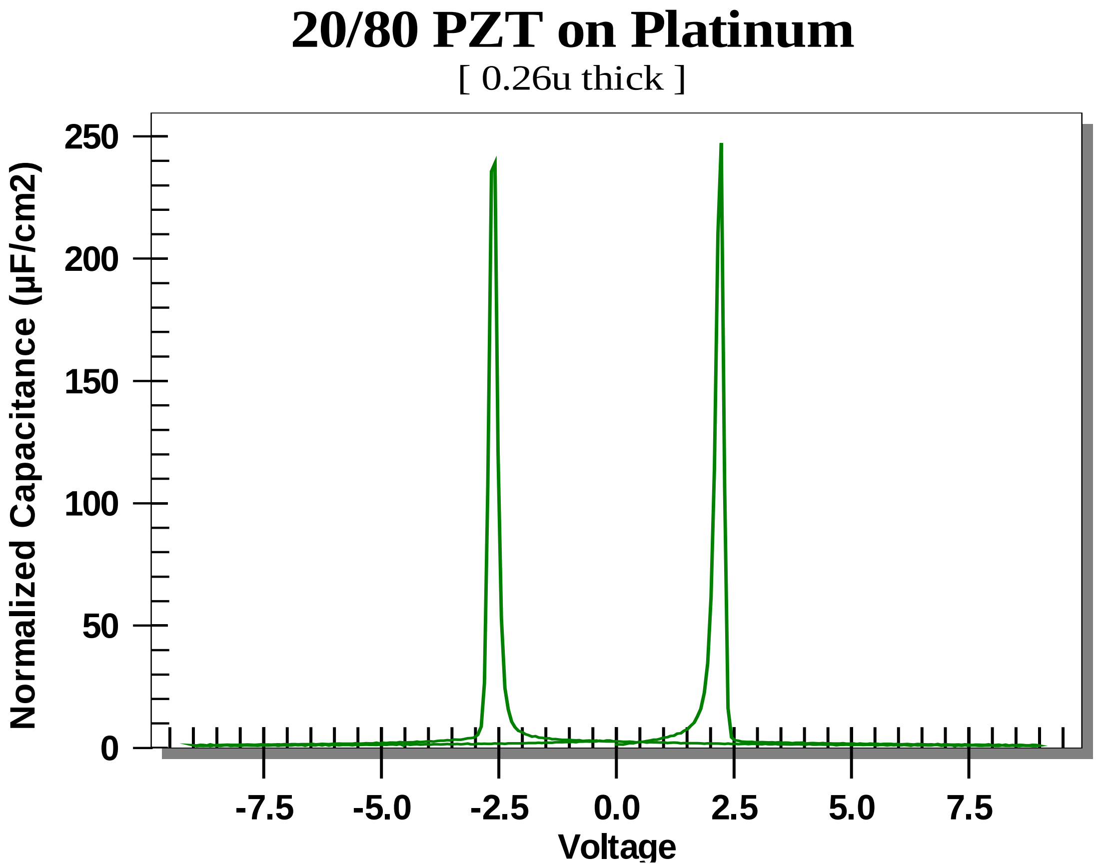
Now let’s analyze some capacitors!

# An Excellent Hysteresis Loop



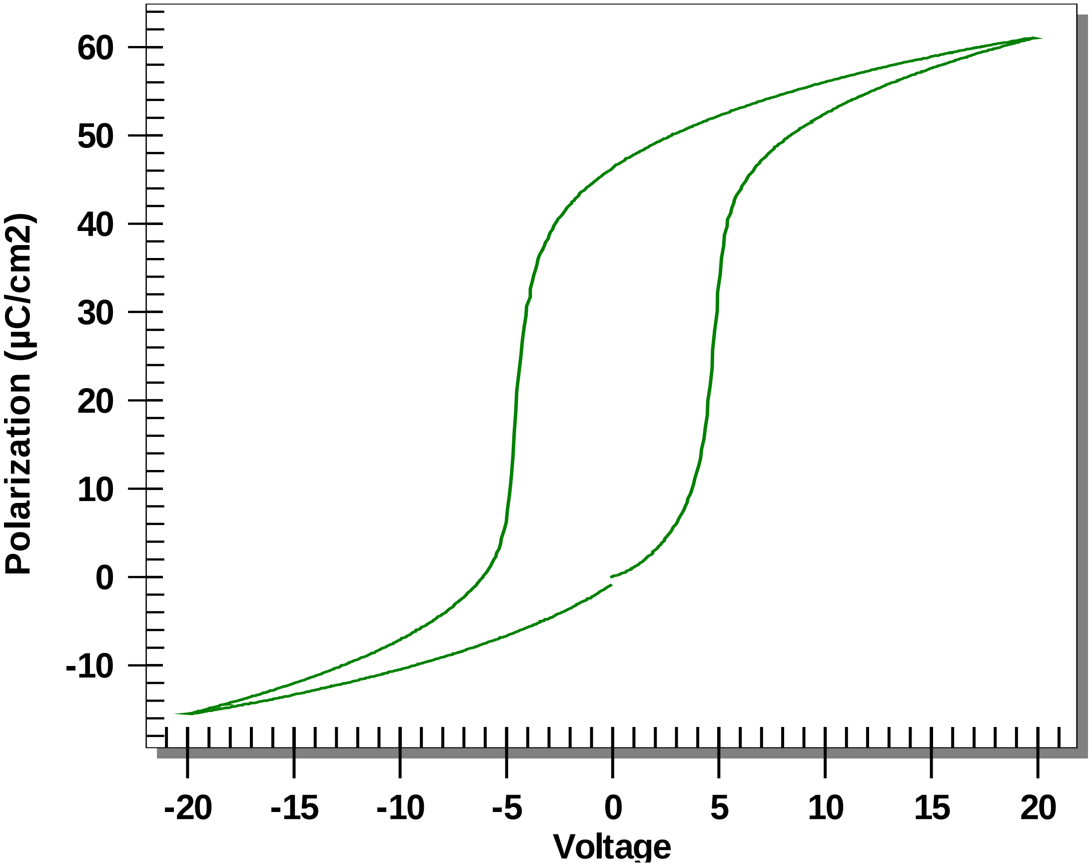
- The nearly “perfect” loop. 20/80 PZT on platinum.

# An Excellent Hysteresis Loop



- The 20/80 PZT on platinum is so square that the instantaneous capacitance increases by x250 or more during switching.

# What is this?

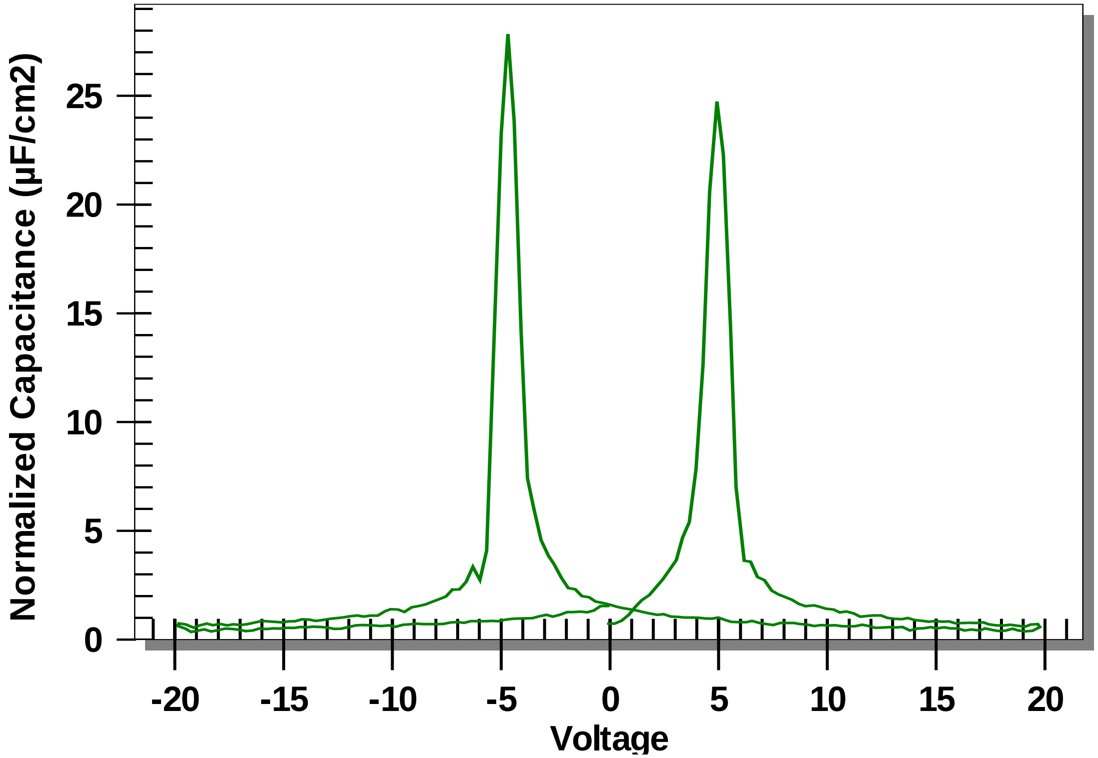


- Is this loop as good as the previous loop? Yes! It is 4/20/80 PNZT, a different composition from 20/80 PZT. So, it has a different shape.

# What is this?

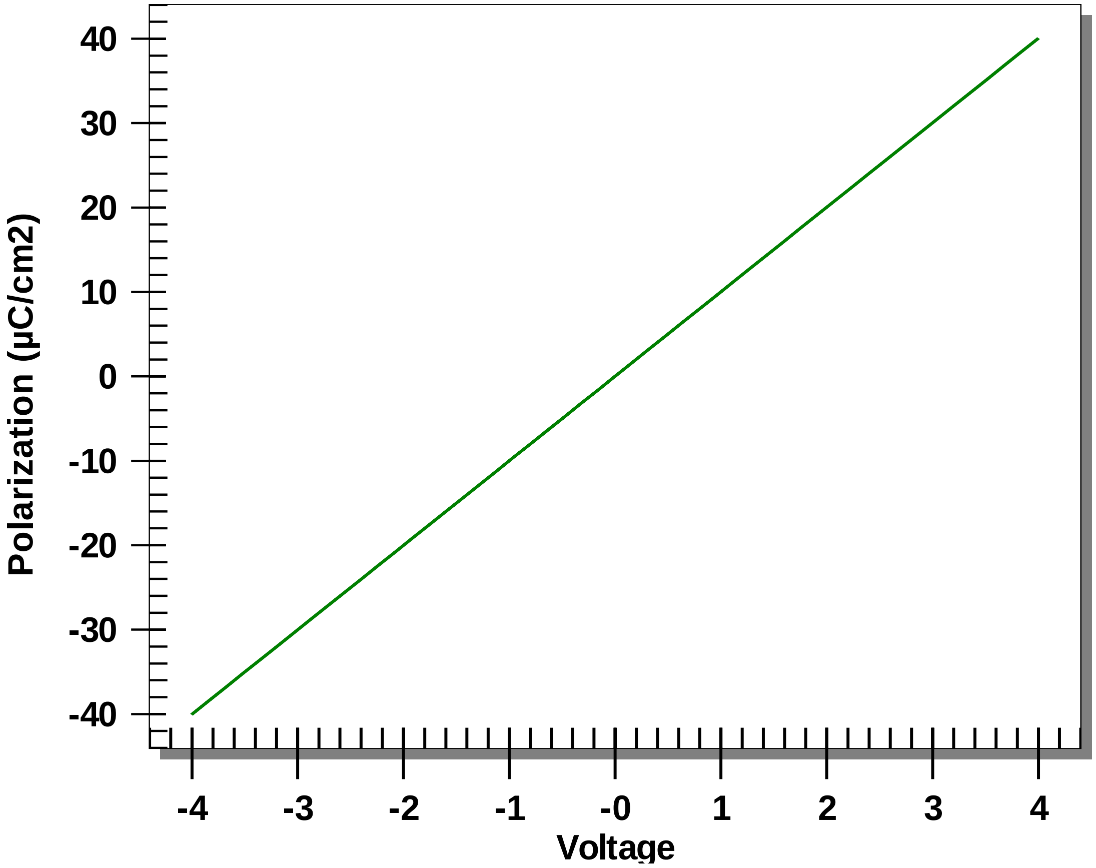
**4/20/80 PNZT**

[ 1u thick ]



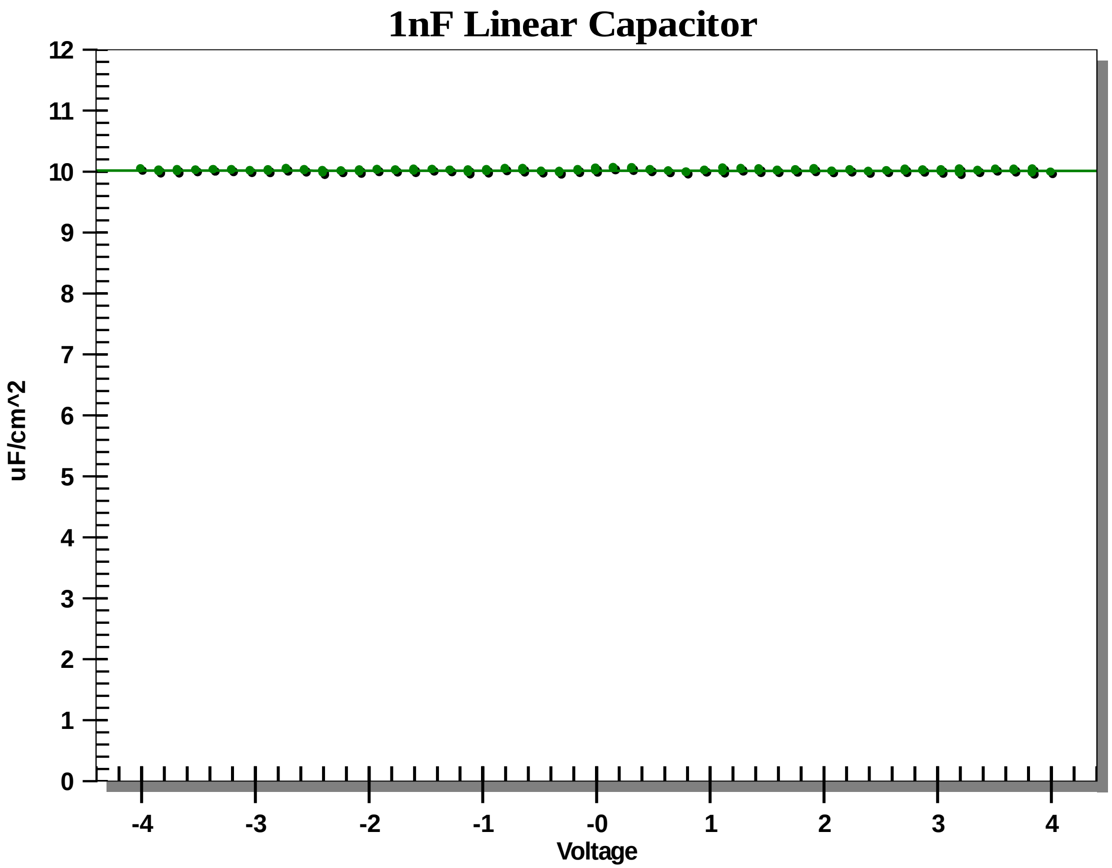
- This loop is good for 4/20/80 PNZT but it is less square than 20/80. Note the extra "diode" leakage in the tails that make the saturated tips of the loop open up. This is the effect of the niobium doping.

# What is this?



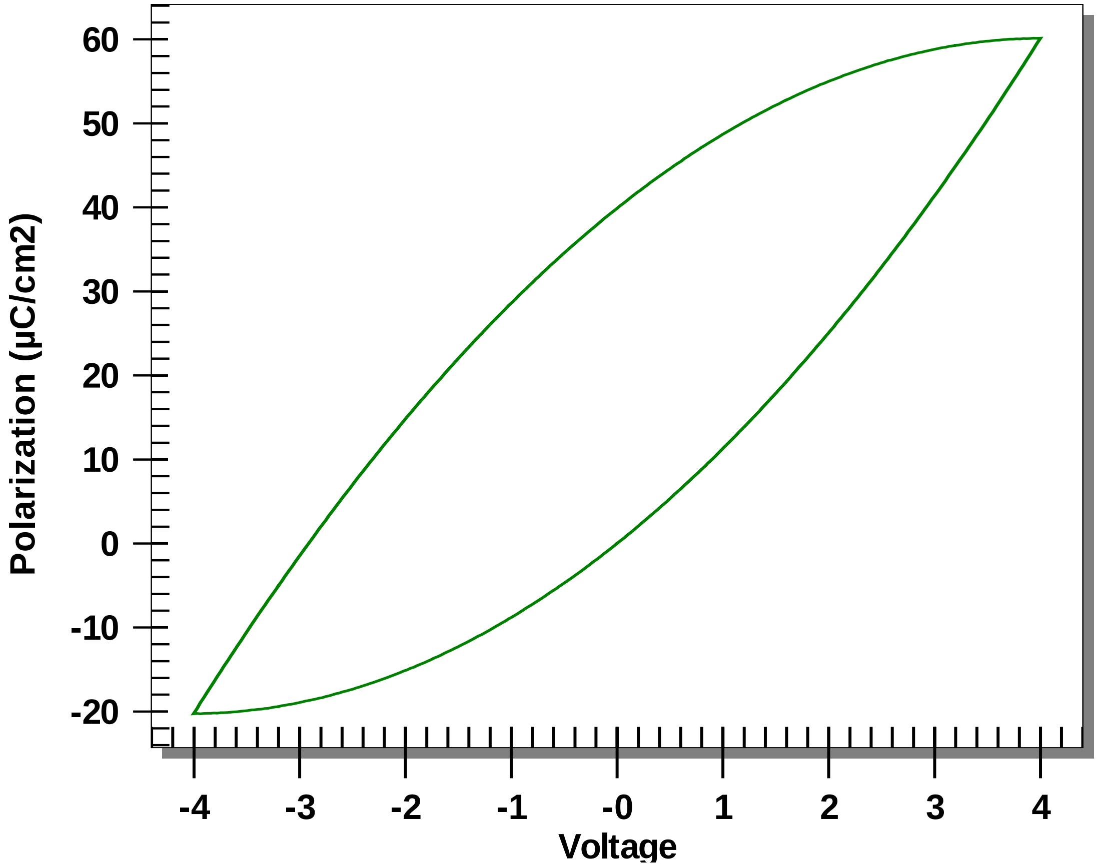
- A 1nF linear capacitor assigned an arbitrary $10^{-4}$ $cm^2$ area.

# What is this?



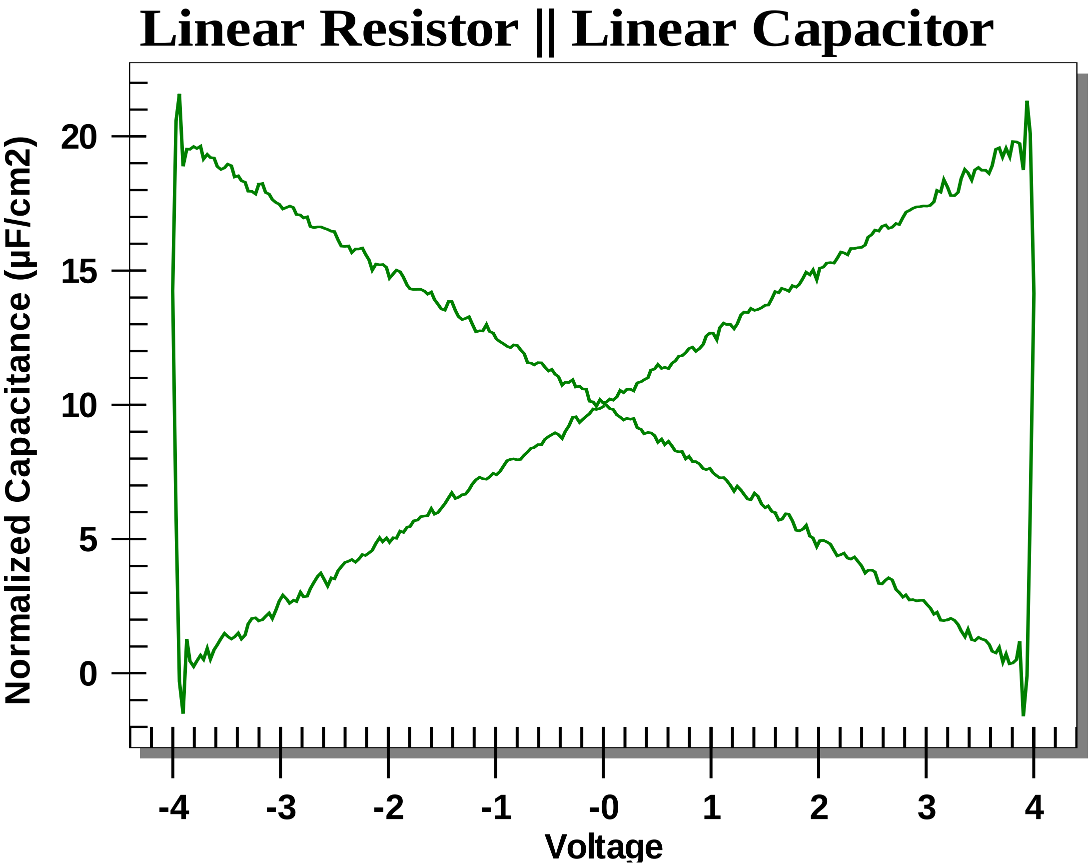
- The linear capacitor in nCV format! 1nF with an area of $10^{-4}$ cm$^2$ yields a capacitance density of 10$\mu$F/cm$^2$.

# A Harder One



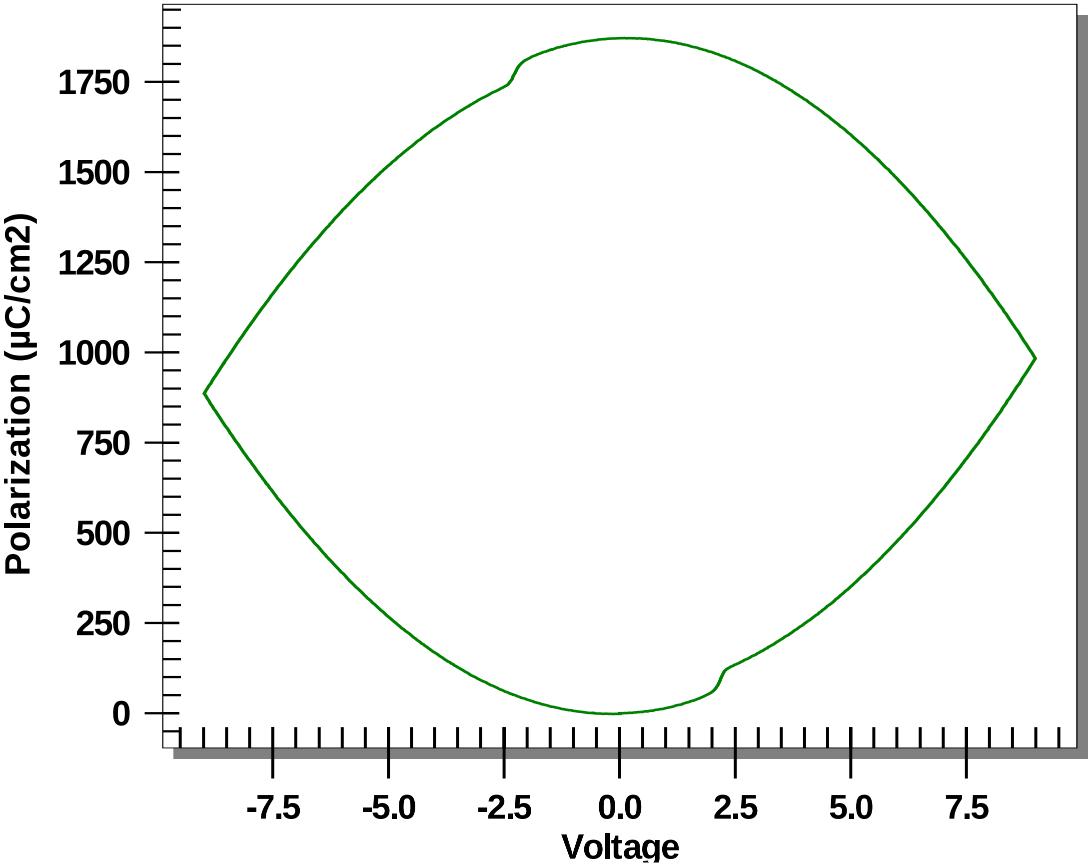
- Quite a few published papers include loops that look like this.

# A Harder One

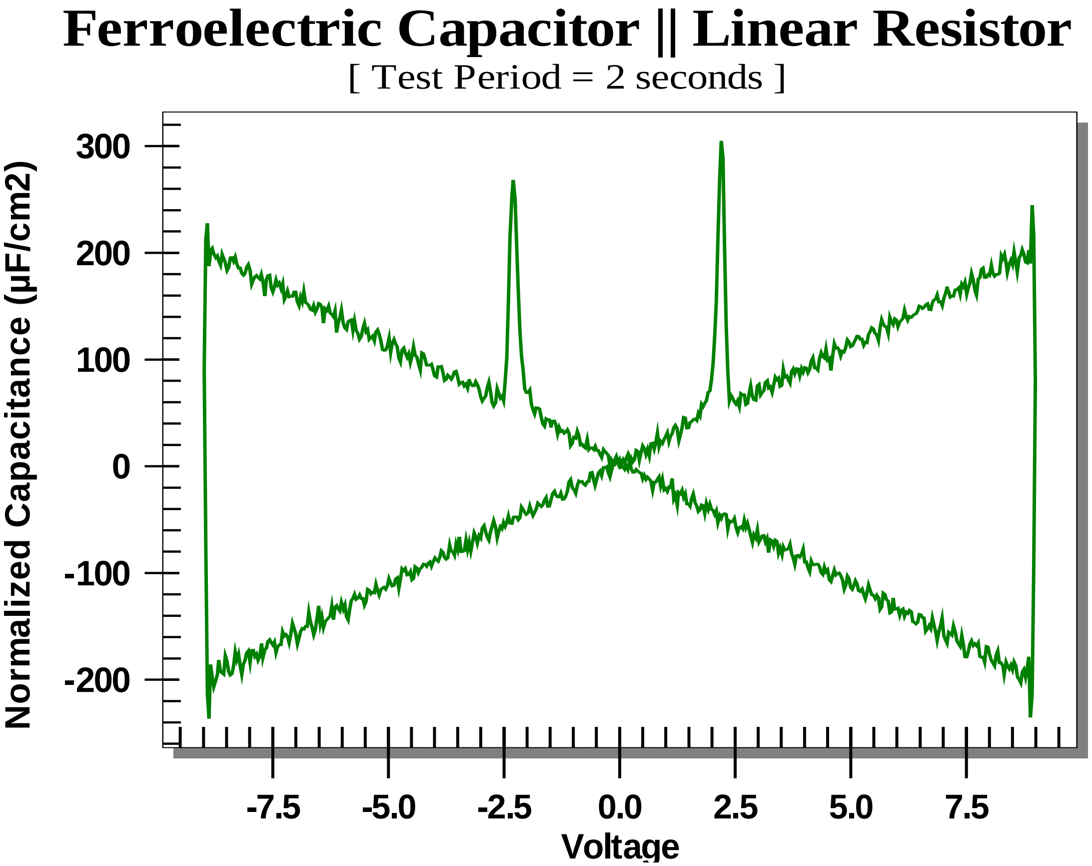


- It is *only* a resistor with a linear capacitor in parallel.

# Is this Ferroelectric?

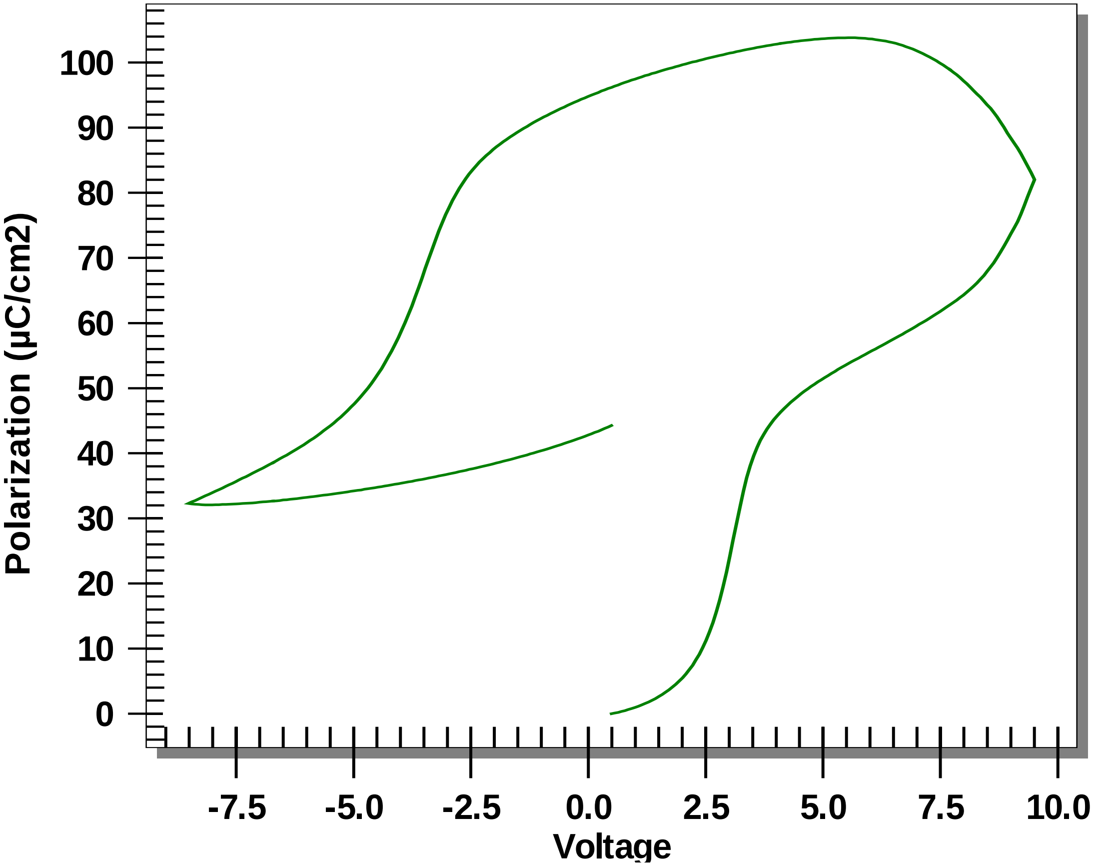


# Is this Ferroelectric?



- Yes, it is! See the ferroelectric switching peaks sticking out of the resistive leakage “X”.

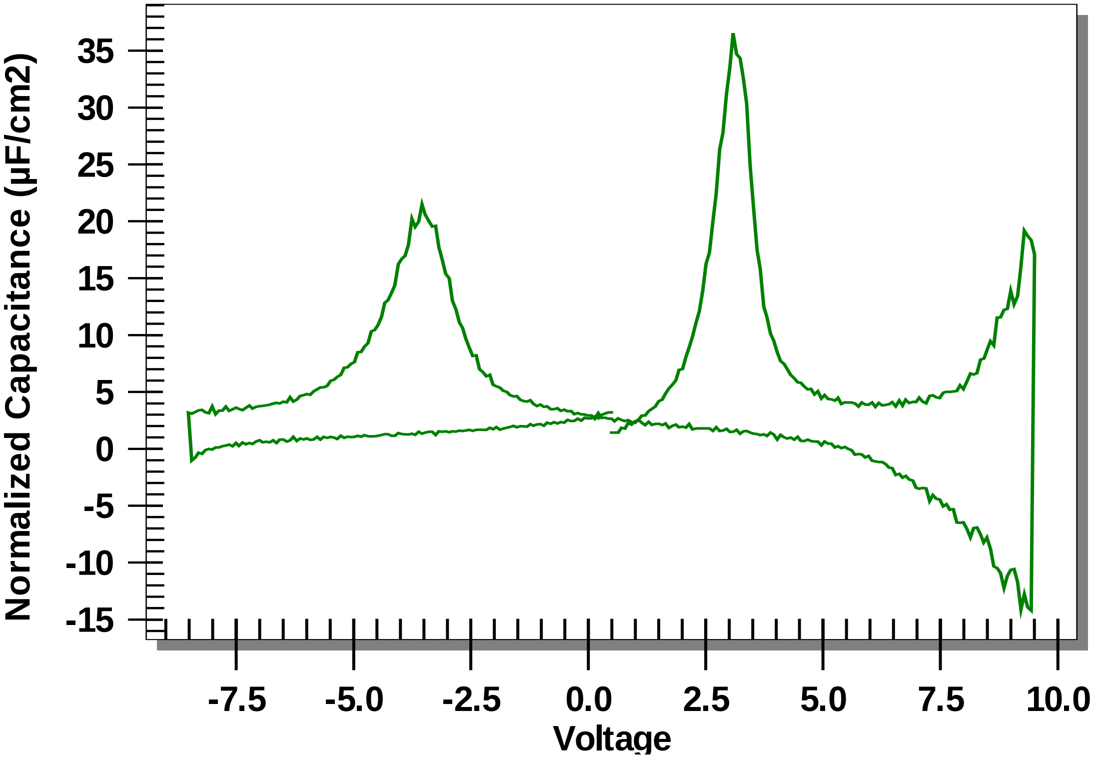
# What Happened Here?



# What Happened Here?

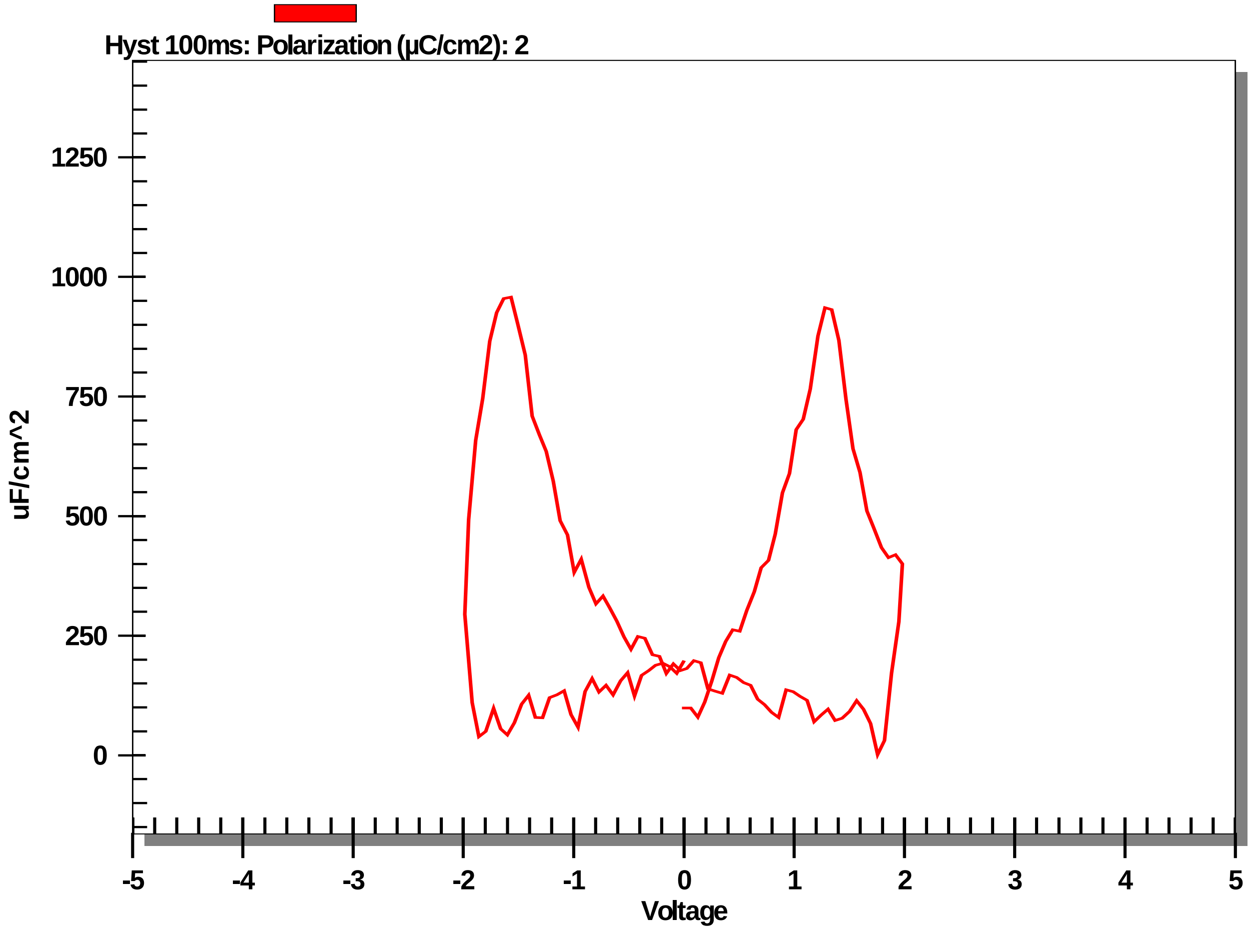
**PZT on Nickel Lanthanate - 300ms Period**

[ EXP09BQ Rev A ]



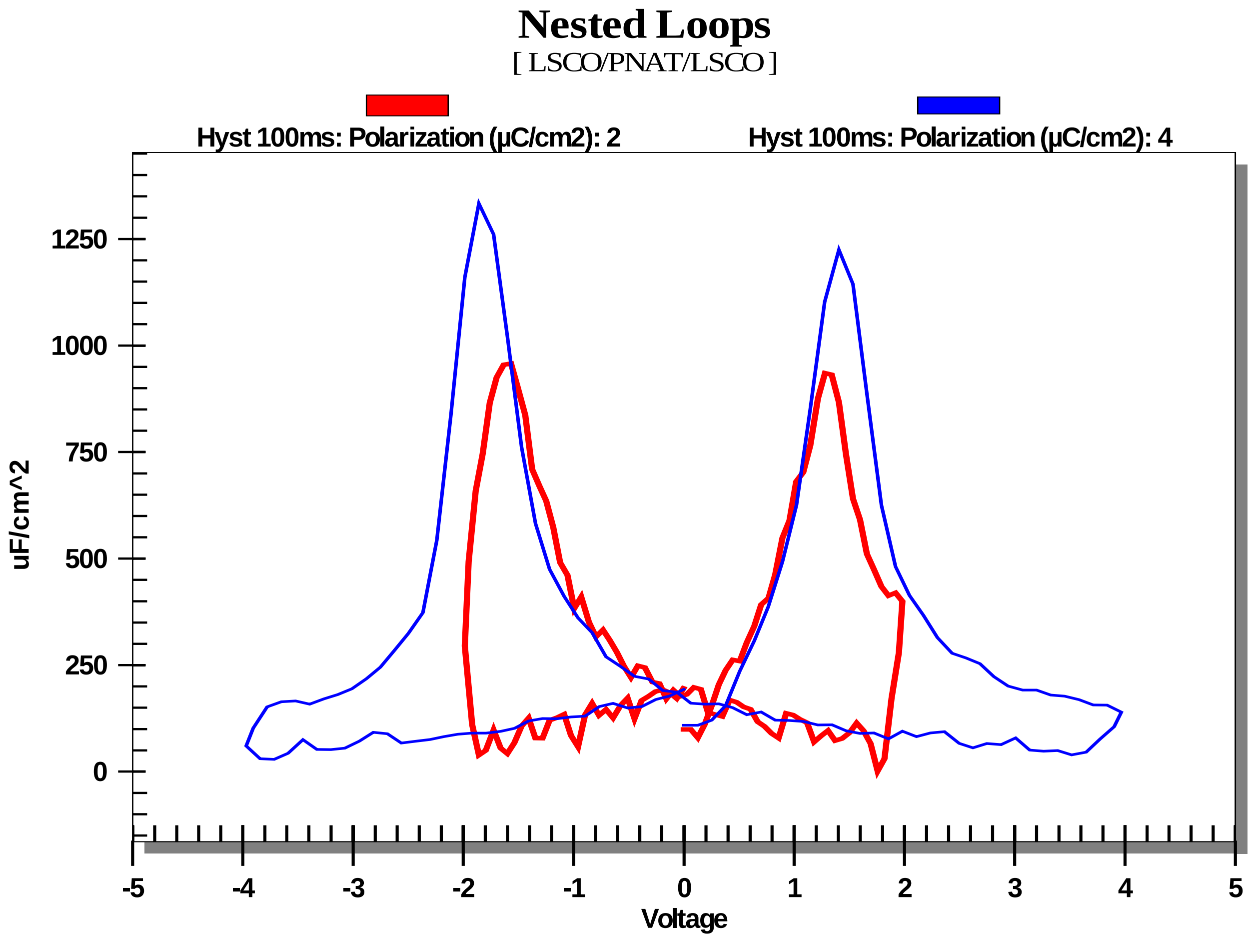
- Different electrodes on each interface means a different switching characteristic with direction. No linear leakage but classic back-to-back diode leakage. Surface diode breakdown occurred at one of the electrode/ferroelectric interfaces.

# Gotcha!



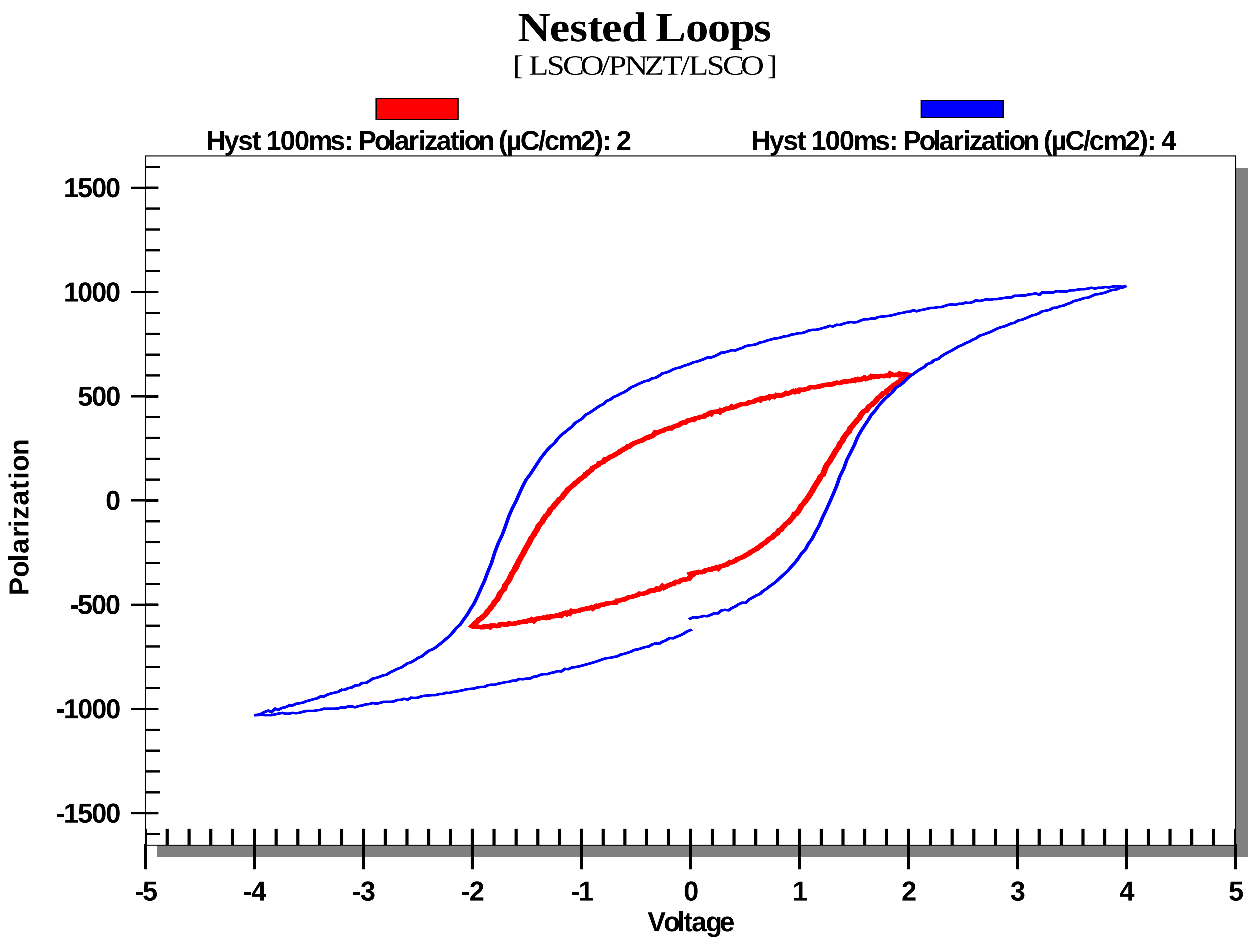
- What is this??? Is it some kind of breakdown???

# Partial Switching!



- It is a sub-saturated loop which can sometimes look like breakdown.

# Partial Switching!



- Here are the hysteresis loops.

# Triangle Wave

- All of the modeling described above is dependent upon using a triangle wave to stimulate the sample.

- $\Delta V/ \Delta t$ is constant.
    - $nCV = \Delta Q/ \Delta V$
    - $I = \Delta Q/ \Delta t \approx \Delta Q /k\, \Delta V = k\ x\ nCV$

- This is the reason that Vision on Radiant testers always defaults to the triangular test profile!

# Conclusion of Components

- Geometry is everything, well almost.
- The ferroelectric hysteresis loop may be broken down into independent components.
- The mathematical derivative of the PE loop is a tool that allows identification by inspection of the components contributing to the response of the sample.
- Practice makes perfect.

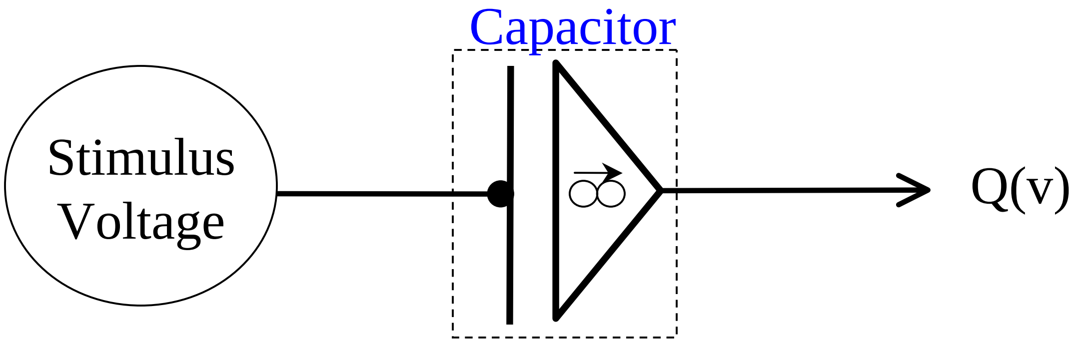
# Instrumentation

- The capacitor under test is never alone.
- It is part of a larger circuit that includes the tester stimulus and measurement circuitry.
- The measurement results *include* contributions by the stimulus circuit, the measurement circuit, the fixture, or all three.
- The next section discloses how to recognize the tester's contribution.

# The DUT Model of FeCaps

- The non-linear capacitor under test generates a new charge state for every new voltage state.

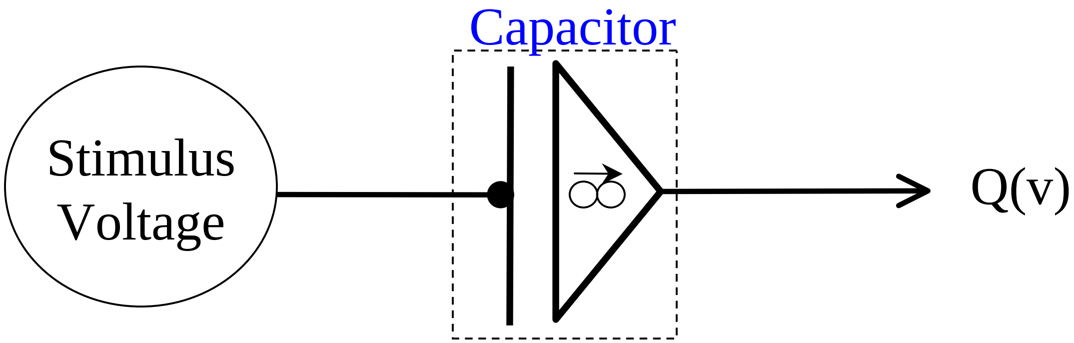
- The device may be modeled as a *voltage controlled charge source*.



- Infinite impedance may be considered to exist between the voltage input and charge output of the Device Under Test.

# The DUT Model of FeCaps

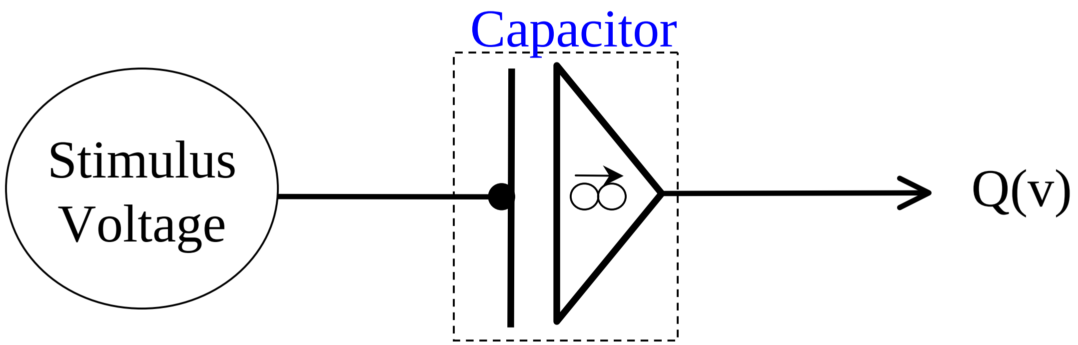
- Any electrical device may be modeled in this manner but its output must be mapped into *polarization space* as described earlier in the modeling section of this tutorial.



- NOTE: Since an *infinite impedance* exists between the input of this DUT model and its output, the input *has no knowledge of the output*! It could be 2 volts or 1500 volts or a magnetic field. *The input only sees changes in the charge state*.

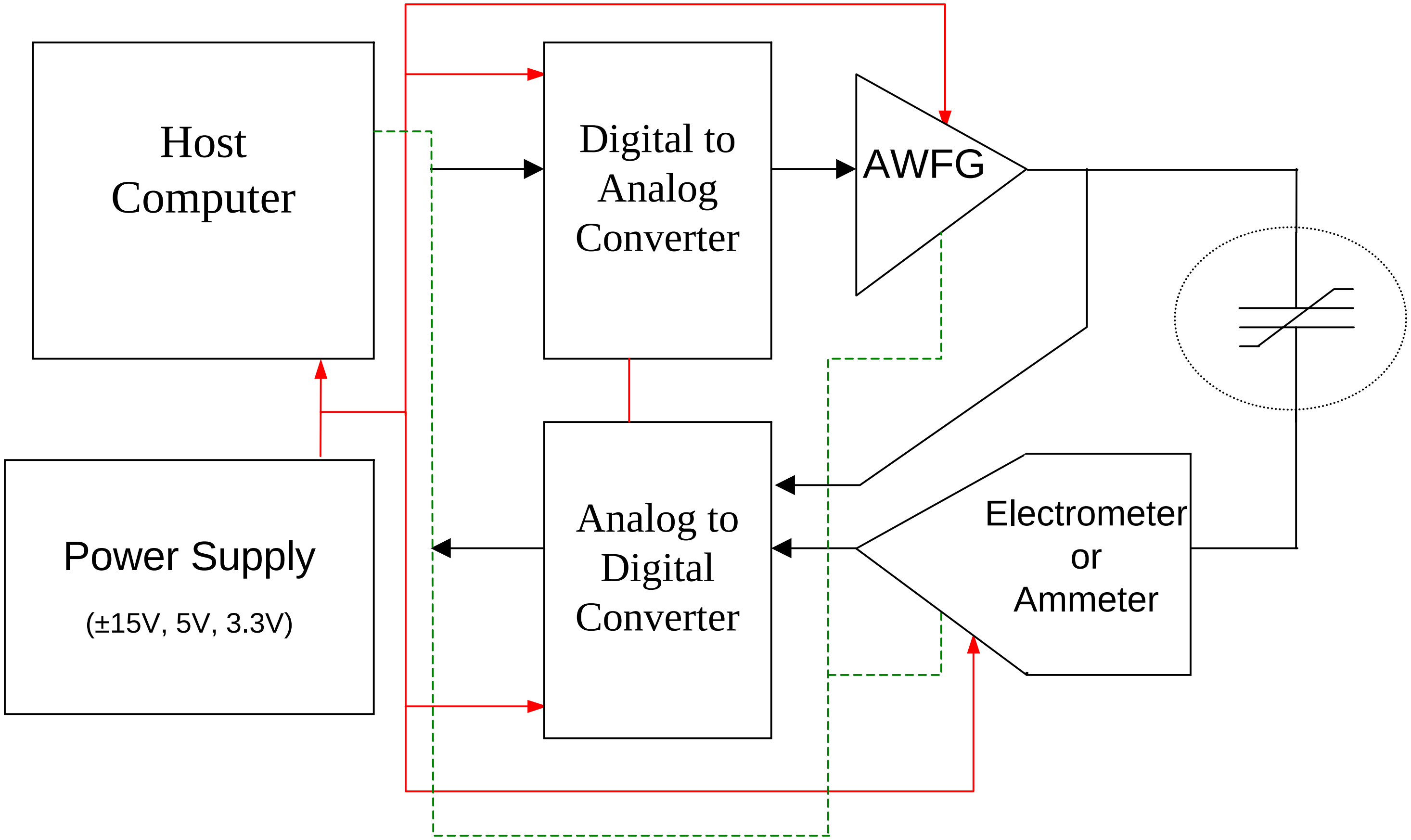
# The DUT Model of FeCaps

- To test this device, a test instrument must have
  - ➢ An arbitrary waveform generator to stimulate the DUT.
  - ➢ A charge measurement circuit to capture the charge state.



- That architecture is shown on the next page.

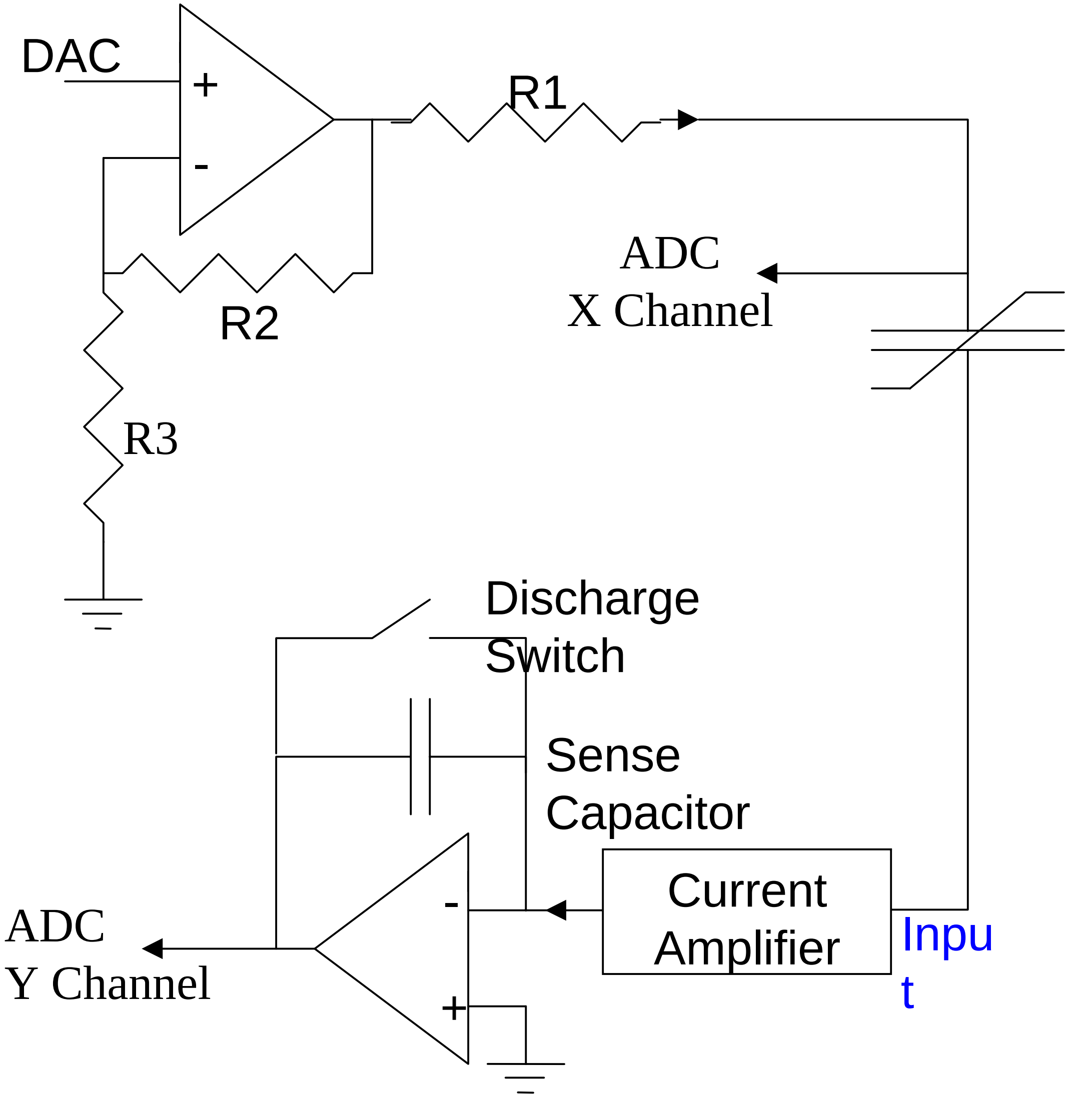
# Test System Diagram



# The Subsystems

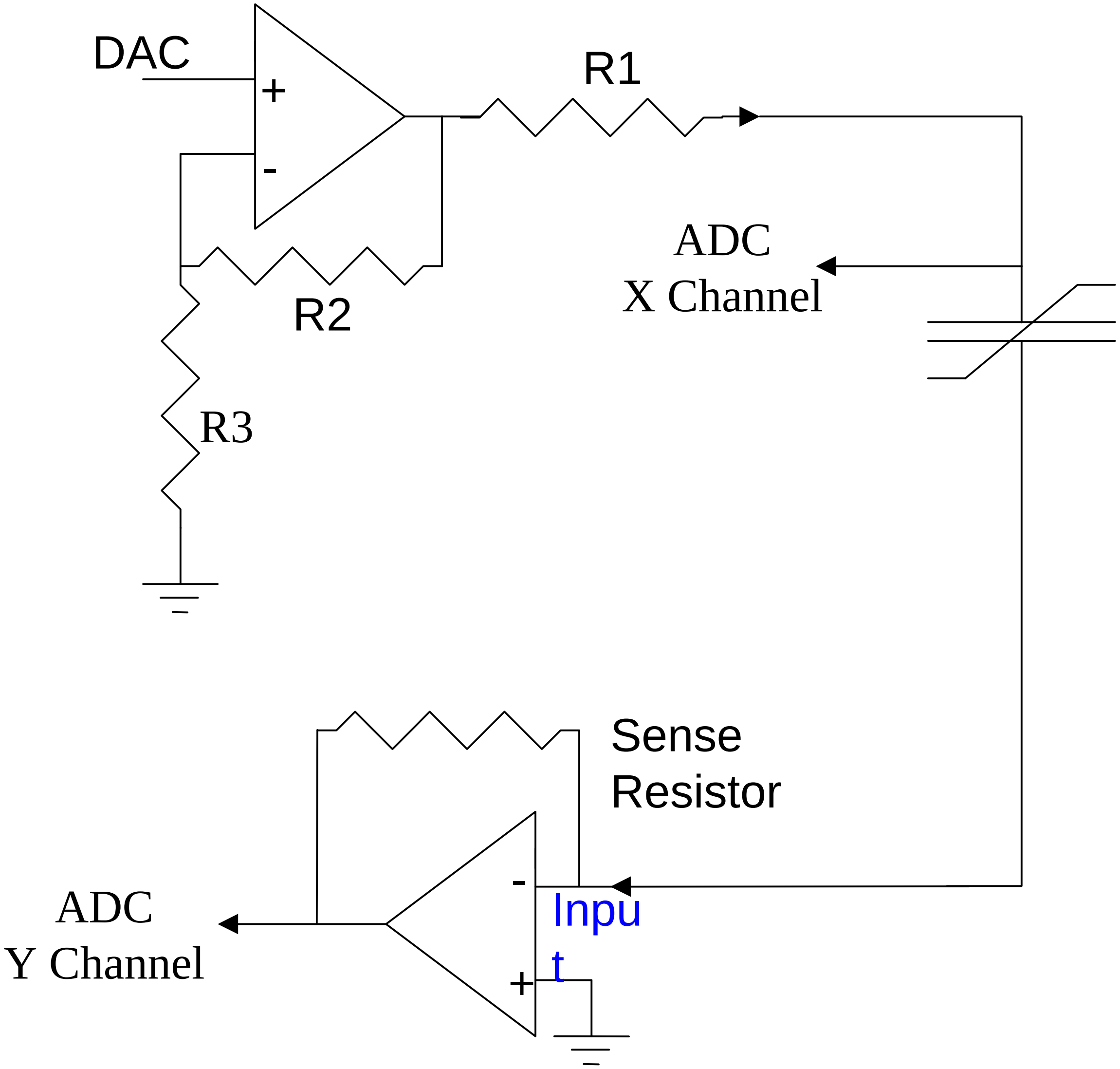
- Host computer
- Communications channel
- DAC (bits, speed)
- Output circuit (current limit and frequency)
- Cable
- Fixture
- Cable (virtual ground)
- Input circuit (current limit and frequency)
- ADC ( bits, speed)
- Memory (width, depth, bits, location)

# The Test Circuit



- To the left is one example of a test path for a ferroelectric tester.
- This is the circuit for the Radiant EDU, a very simple tester.
- The EDU uses an *integrator circuit* to collect charge.

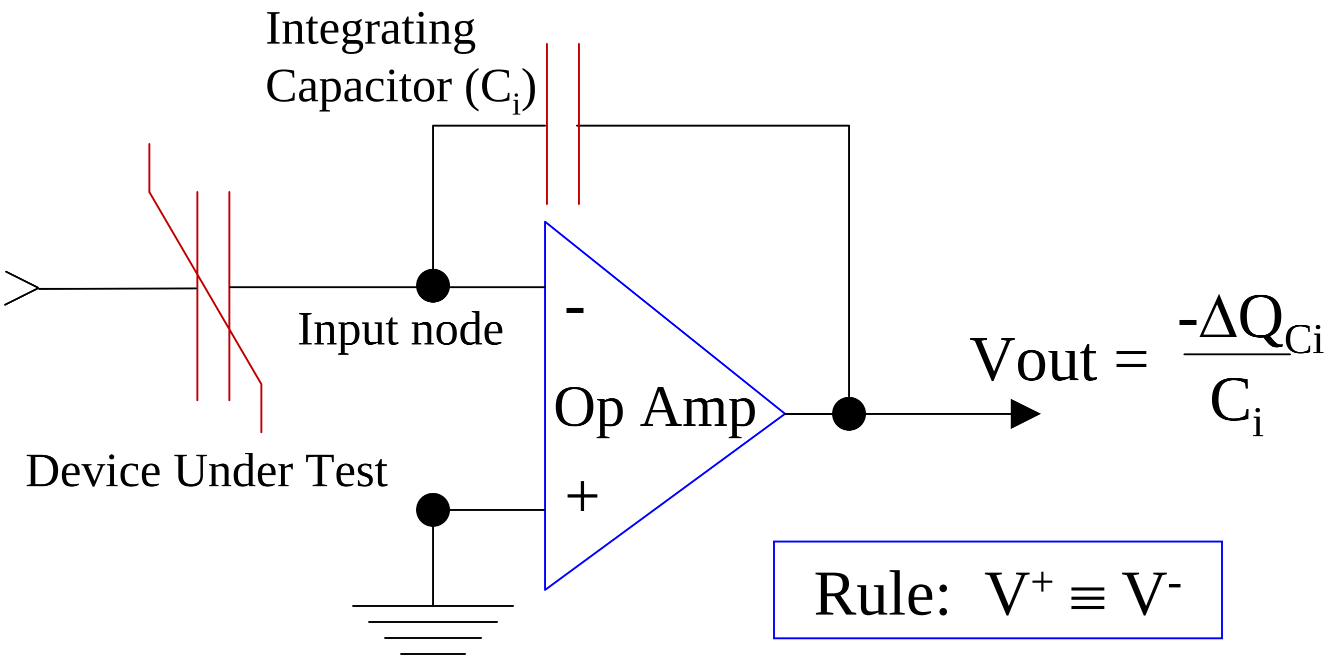
# Another Test Circuit



- This circuit uses a *transimpedance amplifier* to create the virtual ground.

- On both this circuit and the EDU circuit the input amplifier forces the input to remain at ground.

# Virtual Ground Circuit

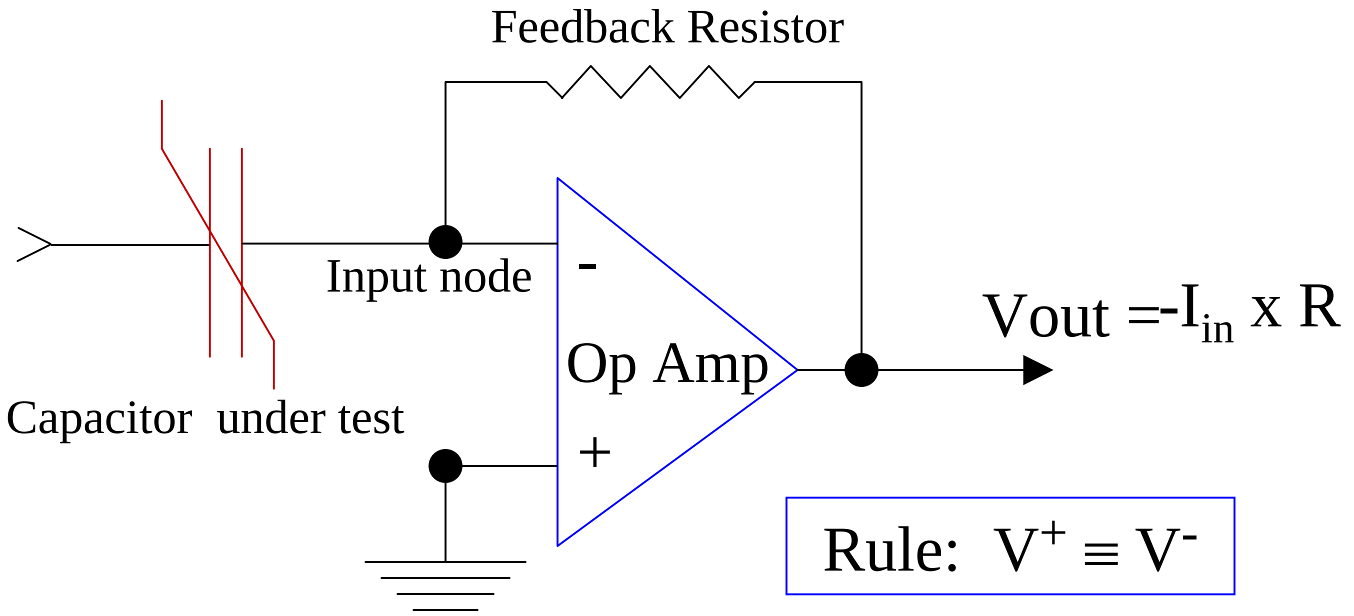


$$\text{Vout} = \frac{-\Delta Q_{Ci}}{C_i}$$

Rule: $V^+ \equiv V^-$

- The charge amplifier in the figure above generates an output voltage proportional to the amount of charge that has flowed into or out of its input node.
- The output of the amplifier always acts to force the "-" node to equal the "+" node, or ground. Hence, the name "virtual ground".

# Virtual Ground Circuit



$V_{out} = -I_{in} \times R$

Rule: $V^{+} \equiv V^{-}$

- The transimpedance amplifier in the figure above generates an output voltage proportional to the current flowing into or out of its input node.
- This circuit also maintains a "virtual ground" on its input node.

# The Virtual Ground

- Electrons in the wire connected to the virtual ground input move freely into or out of that node in response to outside forces.

- The virtual ground input has no blocking force to that movement, i.e. *it has zero impedance*.

- The transimpedance amplifier measures the *flow* of electrons into or out of its input node.

- The integrator, or charge amp, *counts electrons* moving into or out of its input node.

# Mathematics

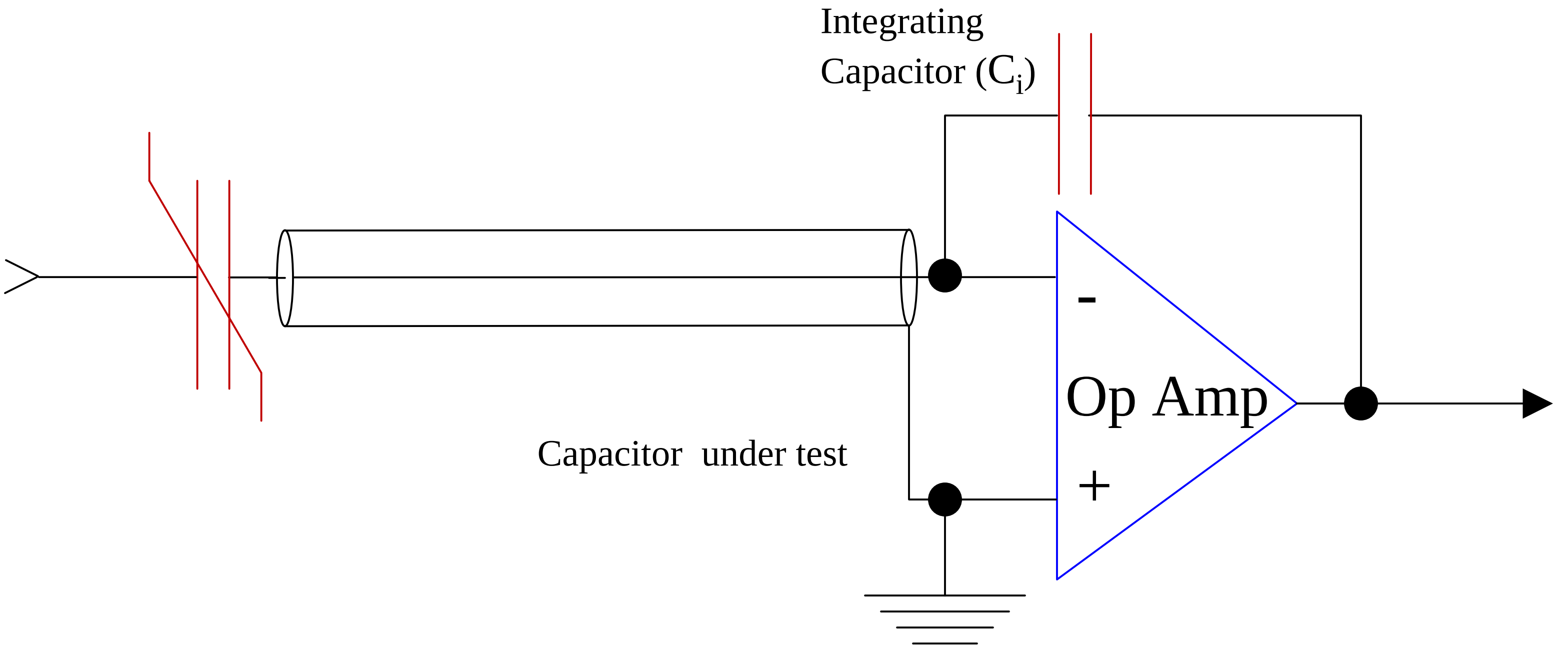
- Transimpedance amplifier:
  - Measures "I"
  - Integrate "I" to get charge: $P = \int I \, \delta t / \text{Area}$
- Integrator:
  - Measures "Q"
  - Divide by area to get "P"
  - Derivative yields current density "J":

$$J = [\, \delta Q / \delta t \,] / \text{Area}$$

# Cables

- Ferroelectric testers usually have BNC connectors for attaching coaxial cables.
- Coaxial cables consist of a center wire conductor surrounded by plastic which itself is covered with a wire braid.
- The center conductor carries the signal.
- The outside braid is usually connected to the tester ground.

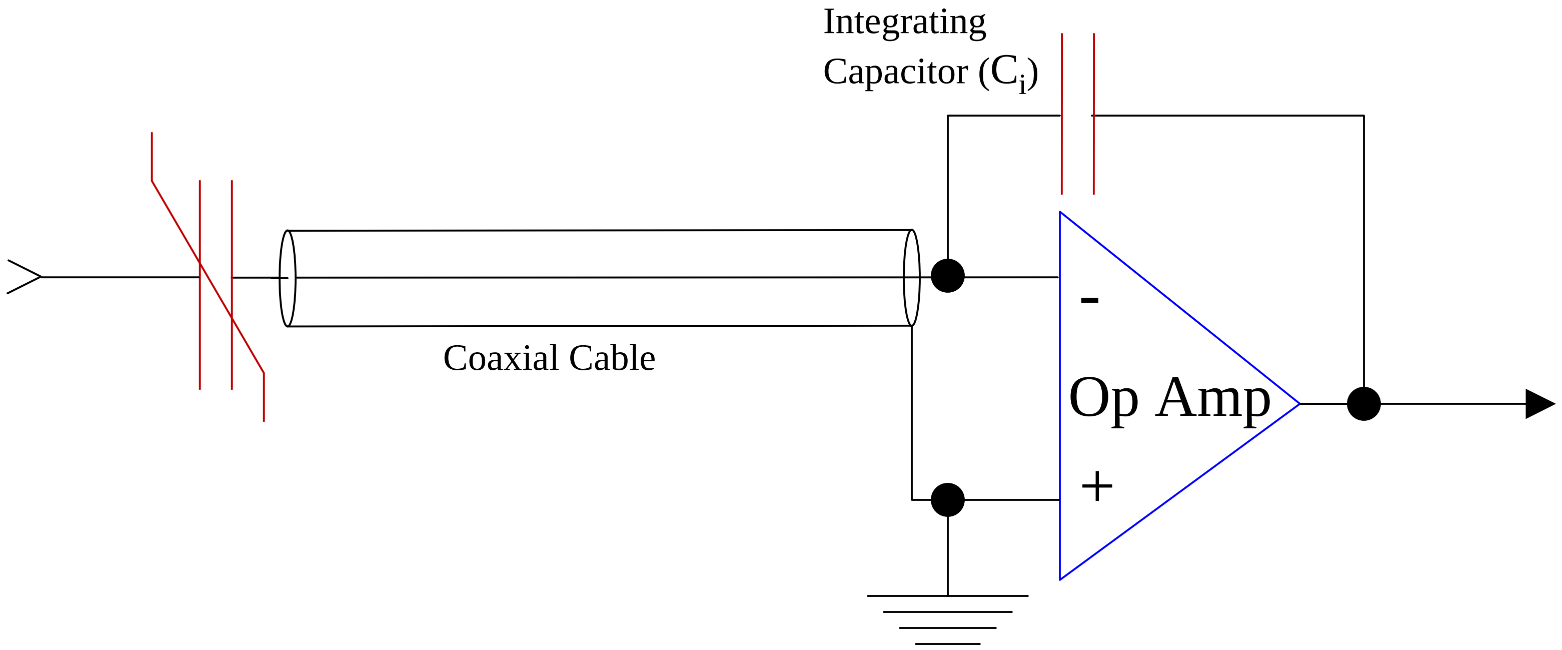
# Cables



- Op amps amplify the *difference* between their input nodes.

- If the coax braid is connected to the ground node, then the test circuit ground *extends* to the sample!

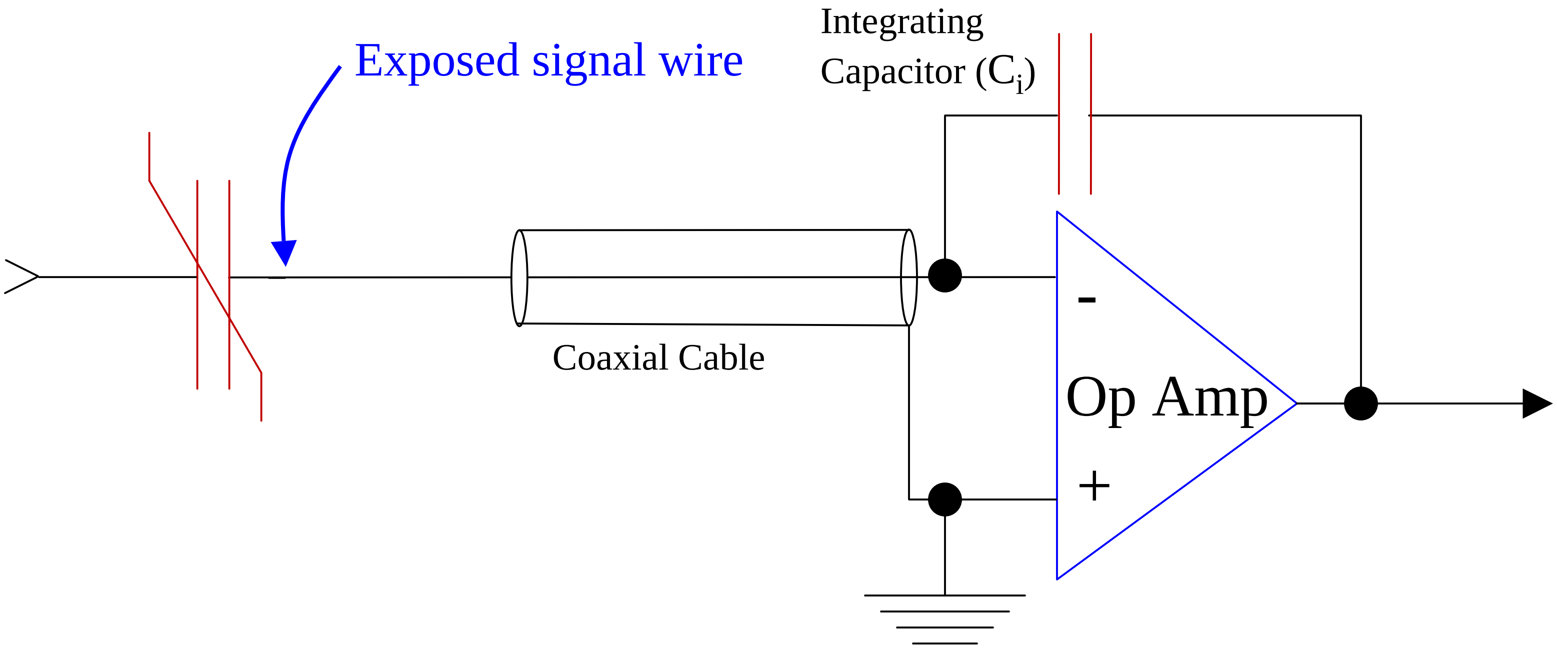
# Cables



- Any ambient electrical noise picked up by the cable braid becomes part of the ground reference of the op amp.

- If the same noise is picked up by the signal wire, it is subtracted out!

# Cables



- Where the center signal wire *extends beyond* the cable braid, it can pick up noise the braid does not see.
- This noise is *not common mode* and is not subtracted out.

# Cables

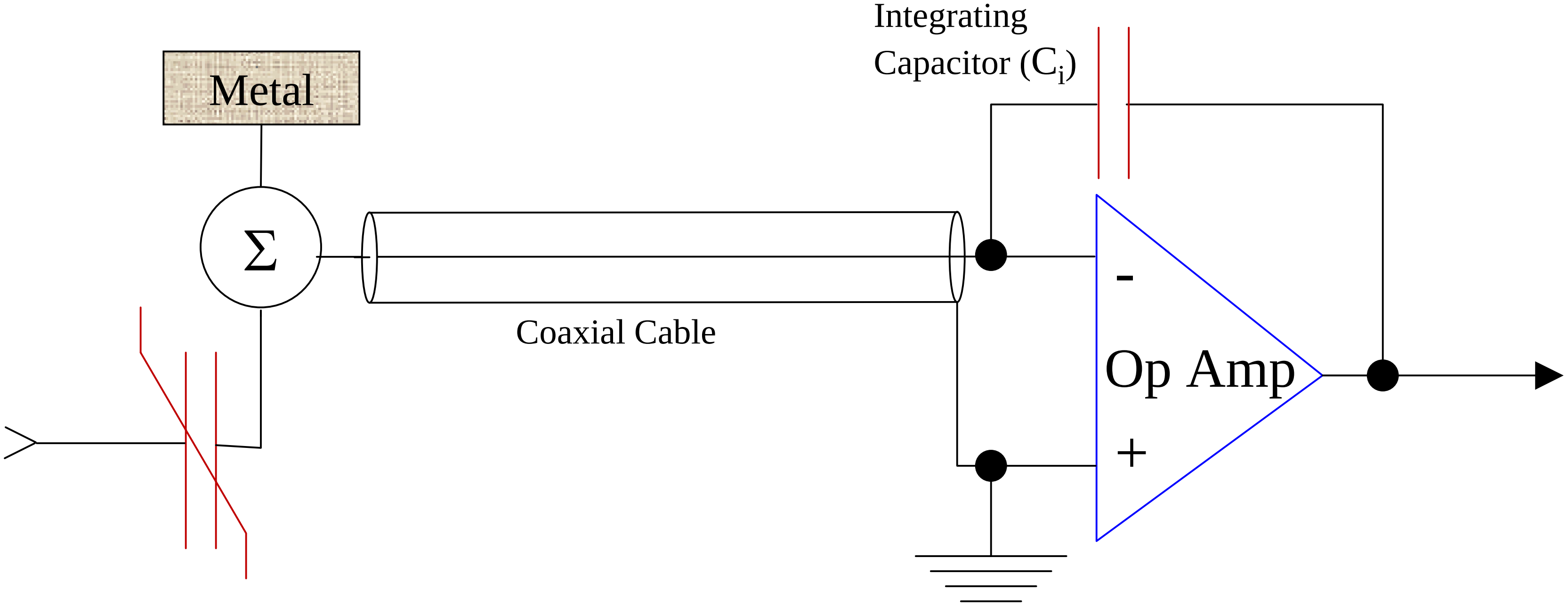
- Use coaxial cable as much as possible.
- Leave as little exposed signal wire a possible.

# Test Fixtures

- The test fixture is an intimate part of the test circuit including the ferroelectric capacitor.
- It can affect the results of your tests.
- The temperature and lighting of the test fixture are two sources of variance.
- Two little known issues:  current injection and noise.

# Current Injection

- A tester *counts* electrons or *meters* current flow.
- Any low impedance connection to the virtual ground input can add electrons to that cable.



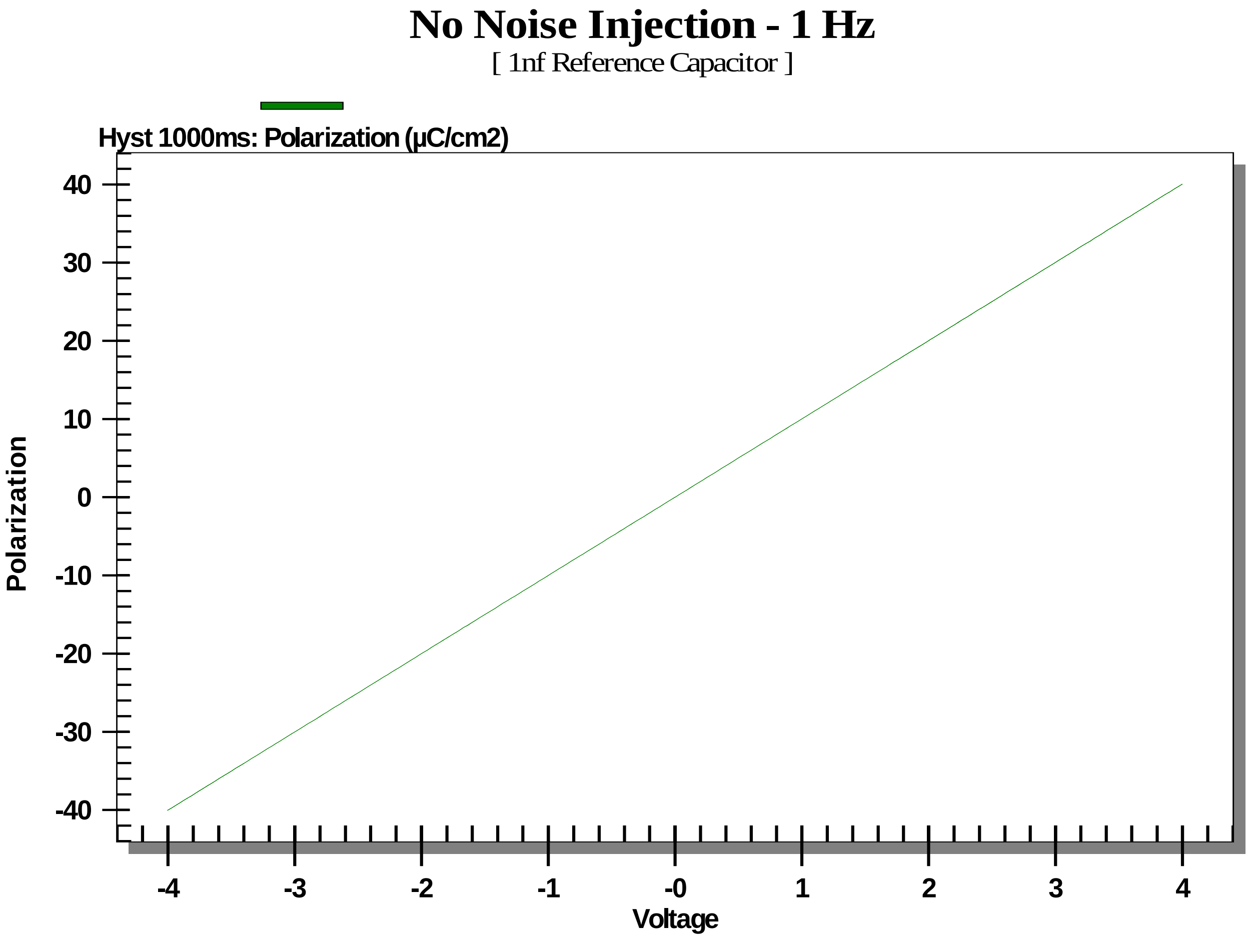
- The sample must be *insulated* from the test fixture.

# Noise Injection

- Any metal in a test fixture is an antenna.
- Any EMF signals near the test fixture will oscillate the free electrons in that metal.  The electrons in turn re-radiate the signal towards the sample.
- The sample will pick up the electric field, injecting that EMF signal into the measurement.
- Solution:  *Make the noise signal common mode.*

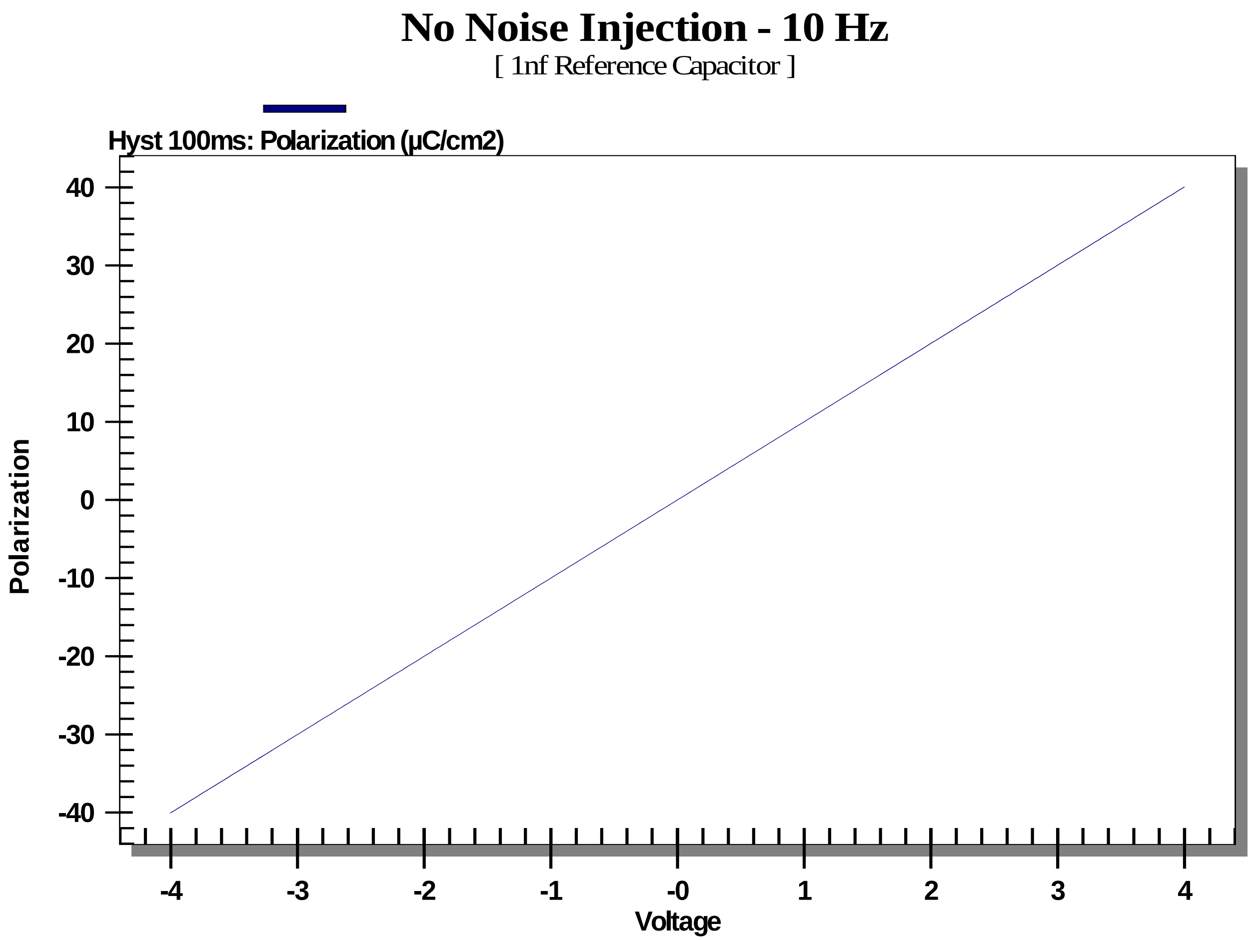
  ➢ Connect all of the metal parts of a test fixture to the ground connection of the tester.

# No Noise Injection – 1 Hz



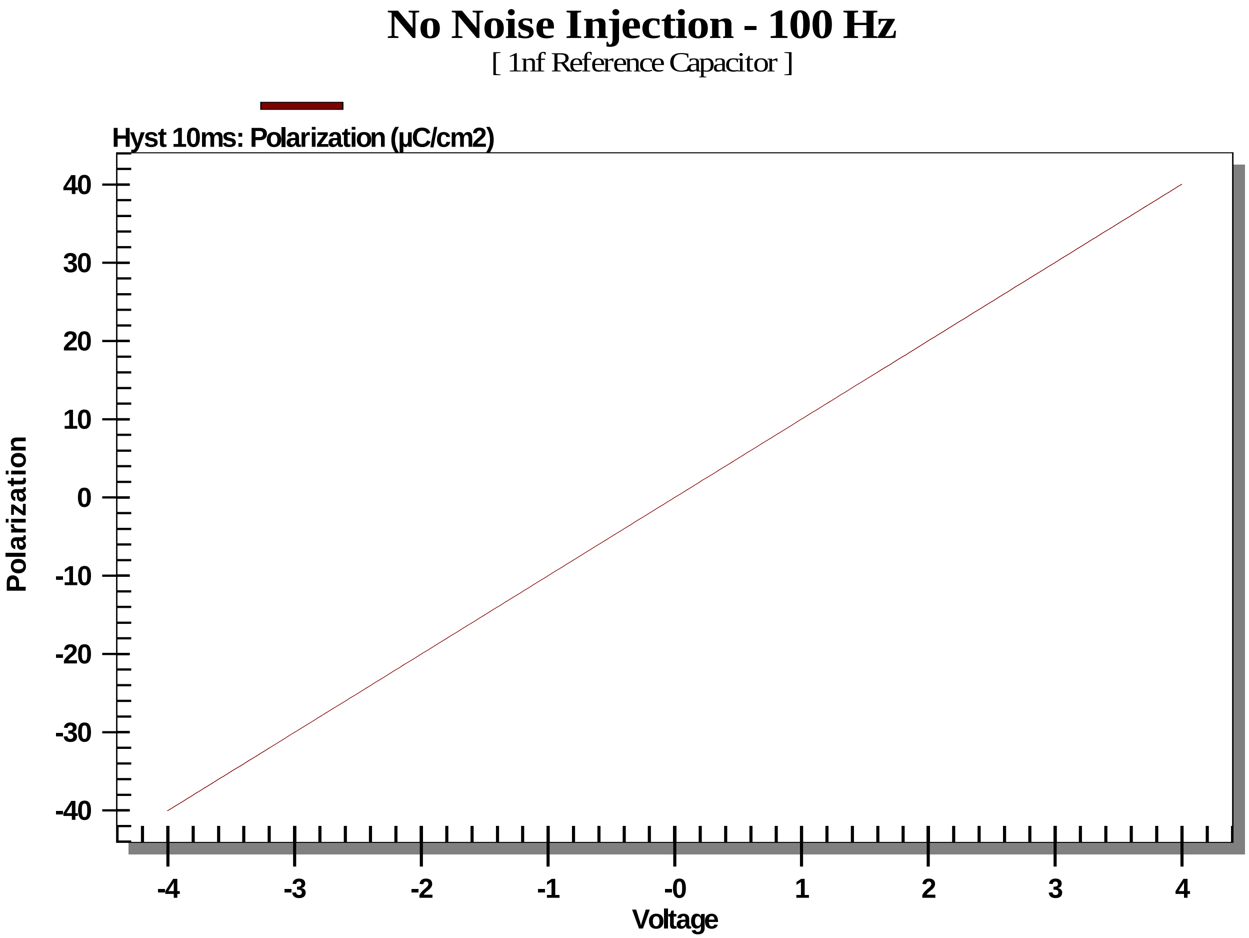
- The tester with no external cables or test fixture attached.

# No Noise Injection – 10 Hz



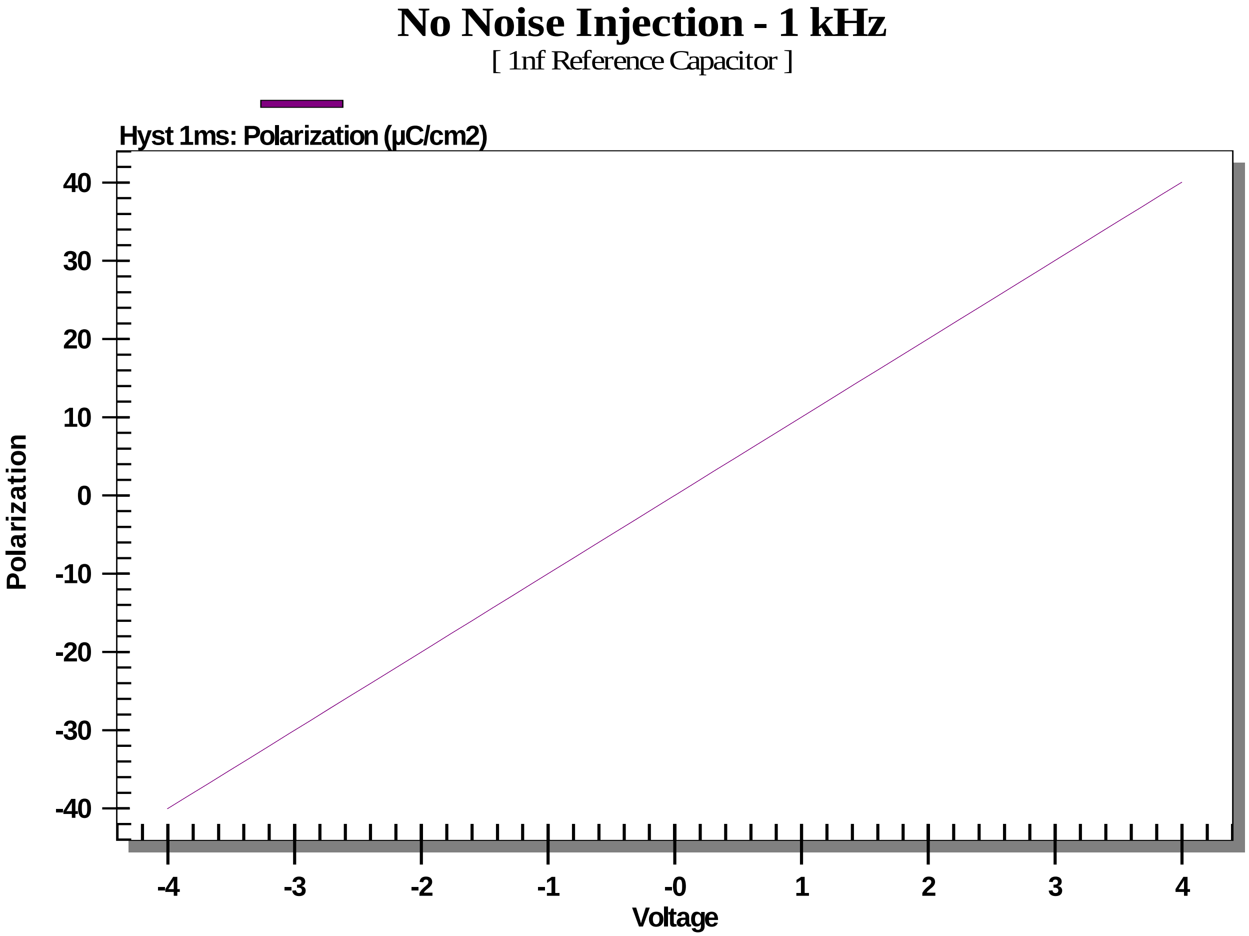
- The tester with no external cables or test fixture attached.

# No Noise Injection – 100 Hz



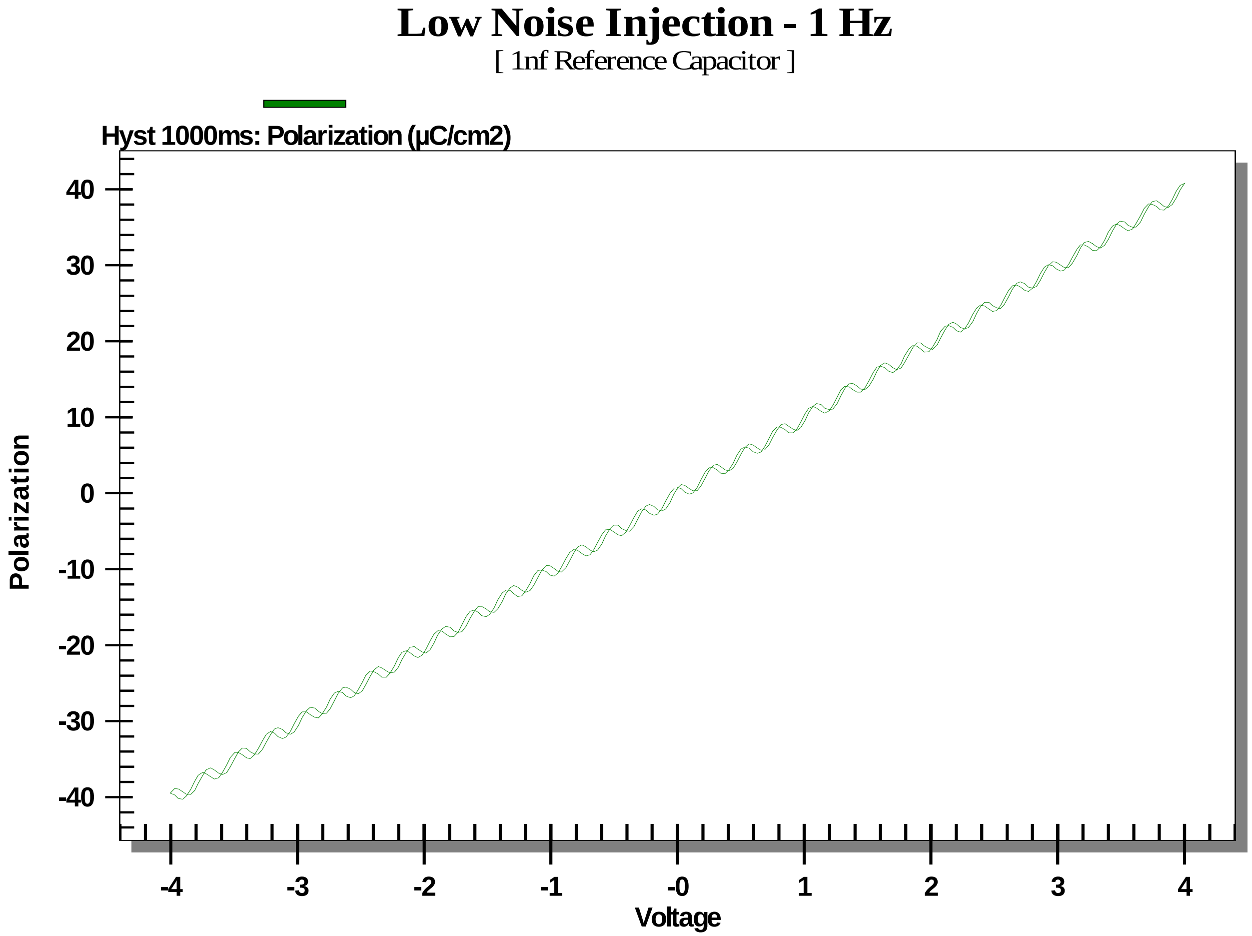
- The tester with no external cables or test fixture attached.

# No Noise Injection – 1 kHz



- With no external connections, the measurement is clean, indicating that the tester itself is injecting no 60Hz noise.

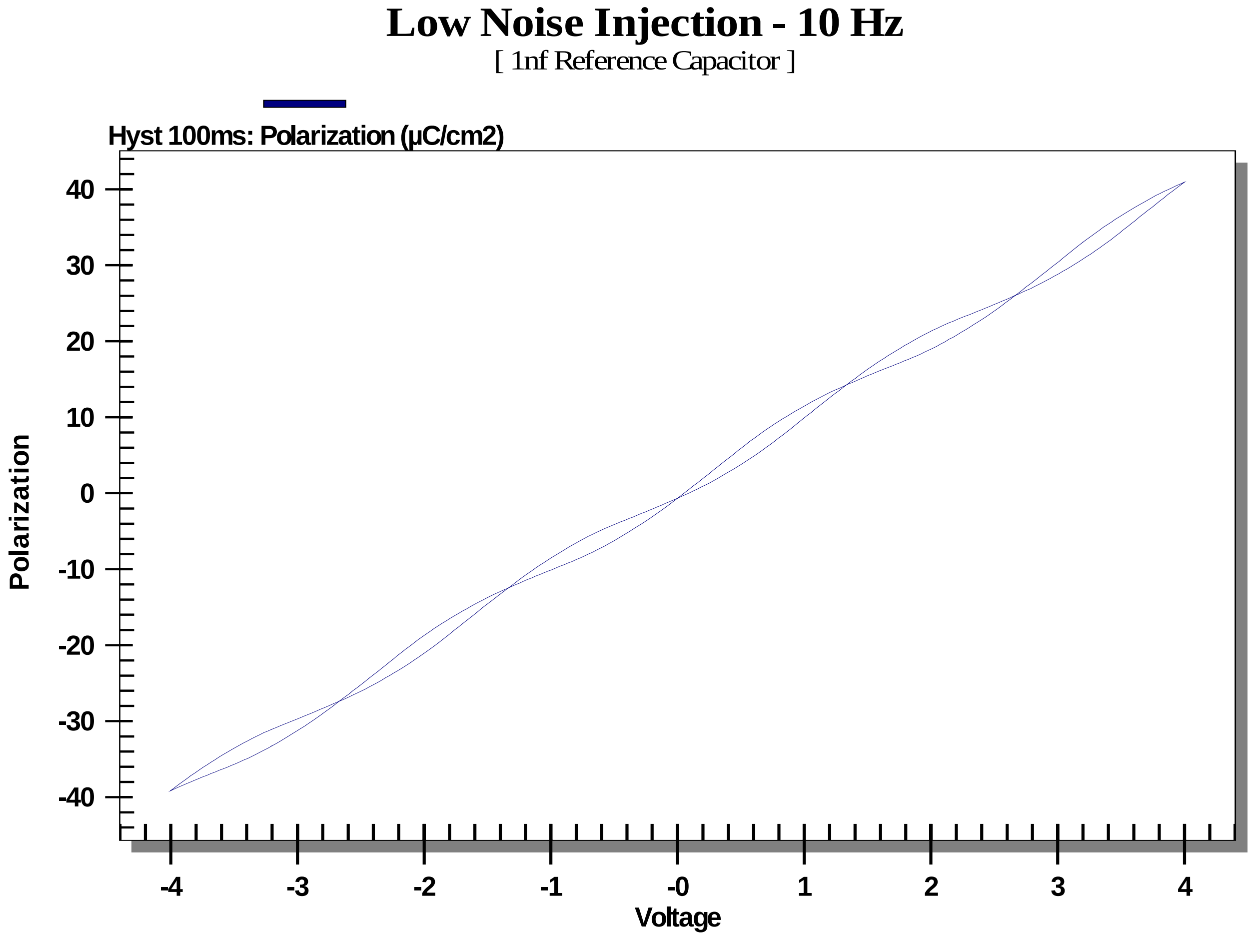
# Low Noise Injection – 1 Hz



- 1 second test period = 60 noise cycles!

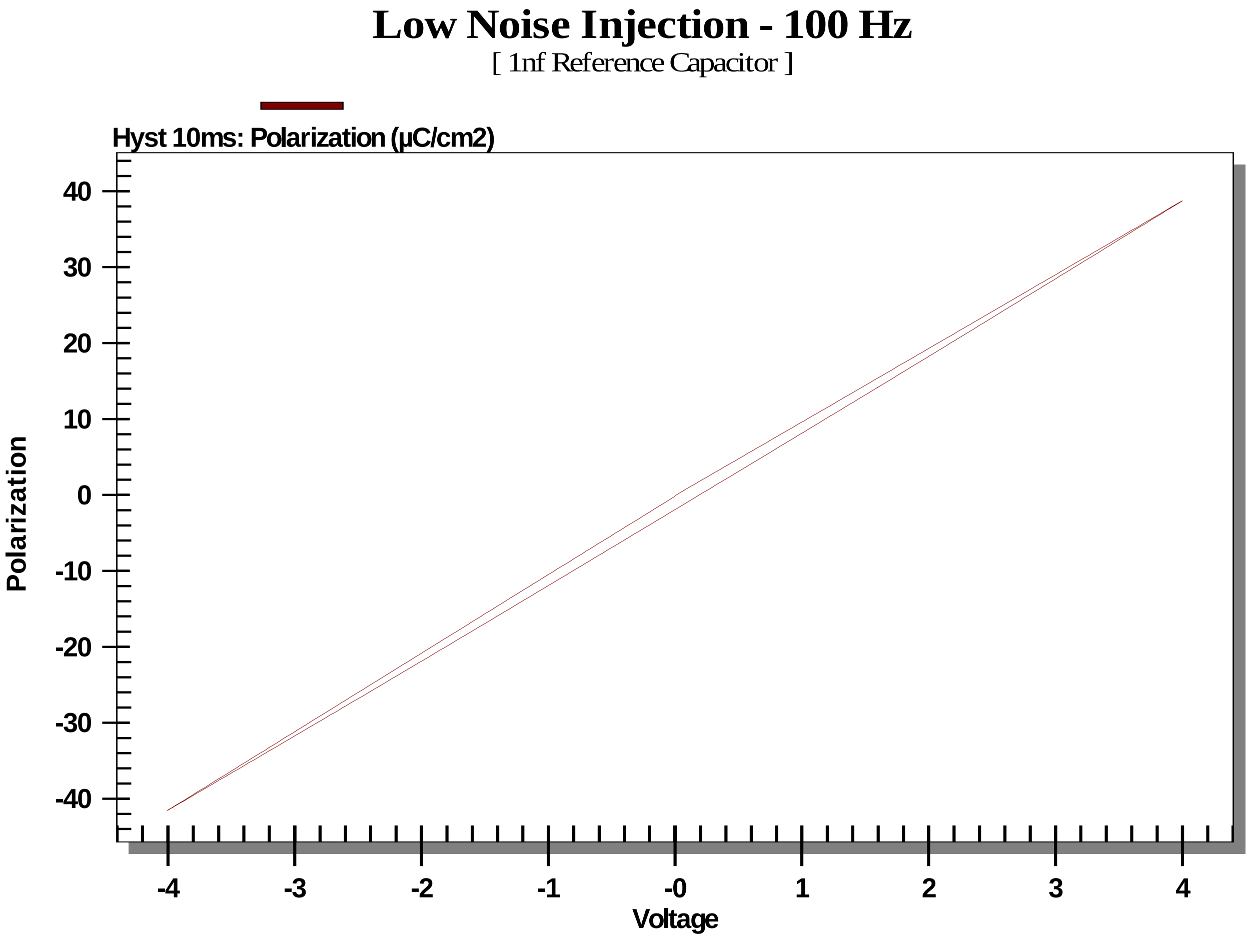
Radiant Technologies, Inc.

# Low Noise Injection – 10 Hz



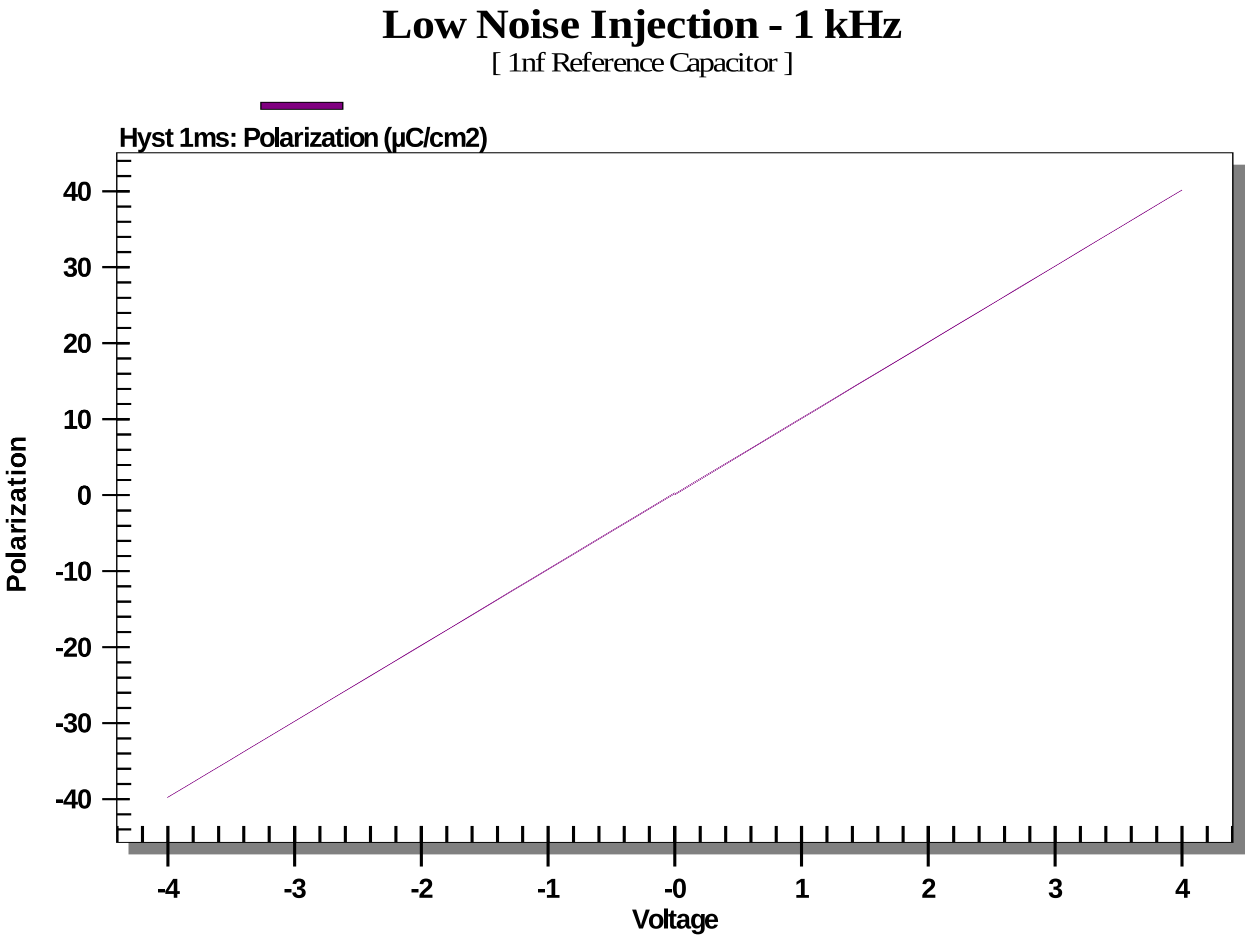
- The tester with virtual ground shield connected to probe station table.

# Low Noise Injection – 100 Hz



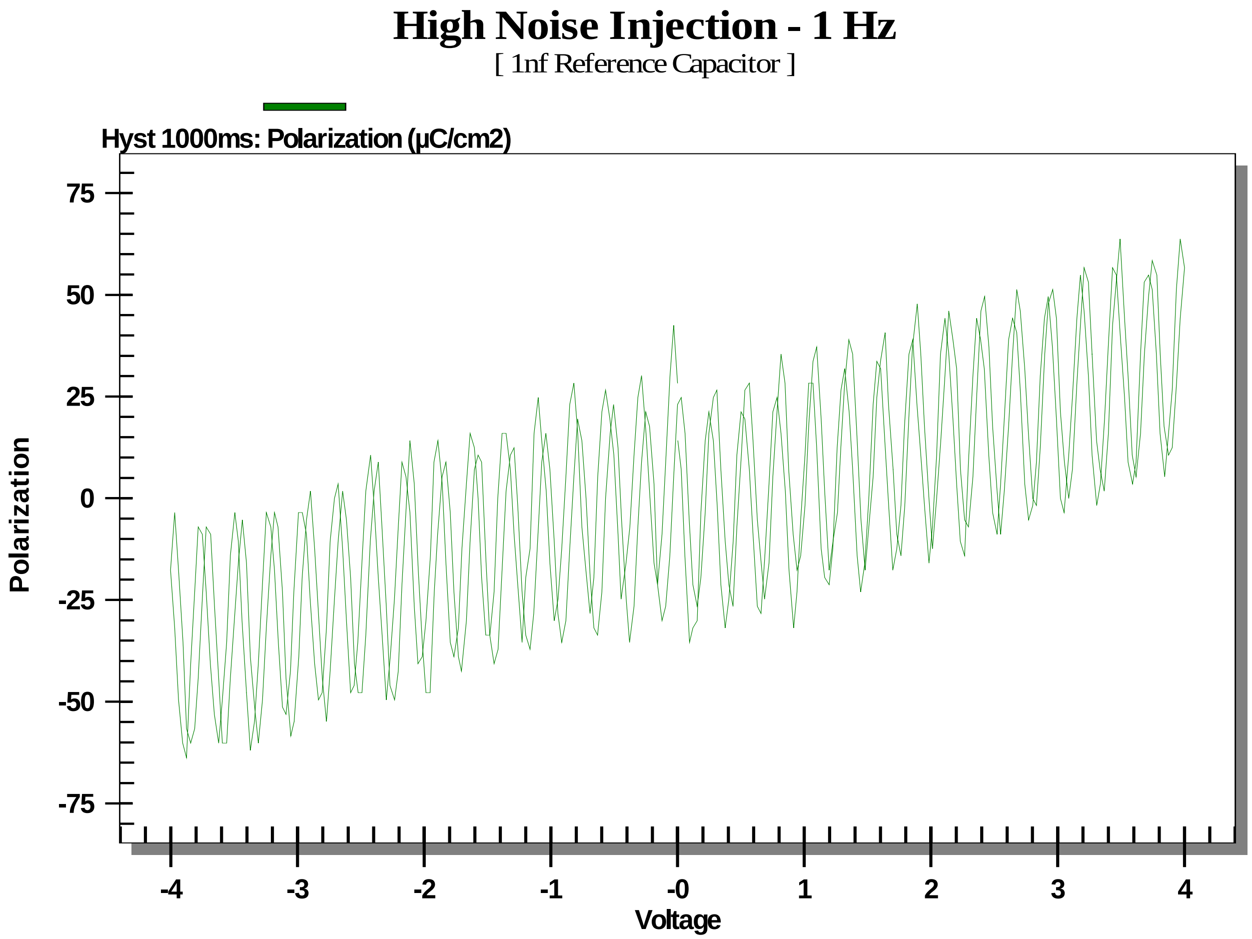
- The 60Hz injected noise makes this loop look like a lossy capacitor.

# Low Noise Injection – 1 kHz



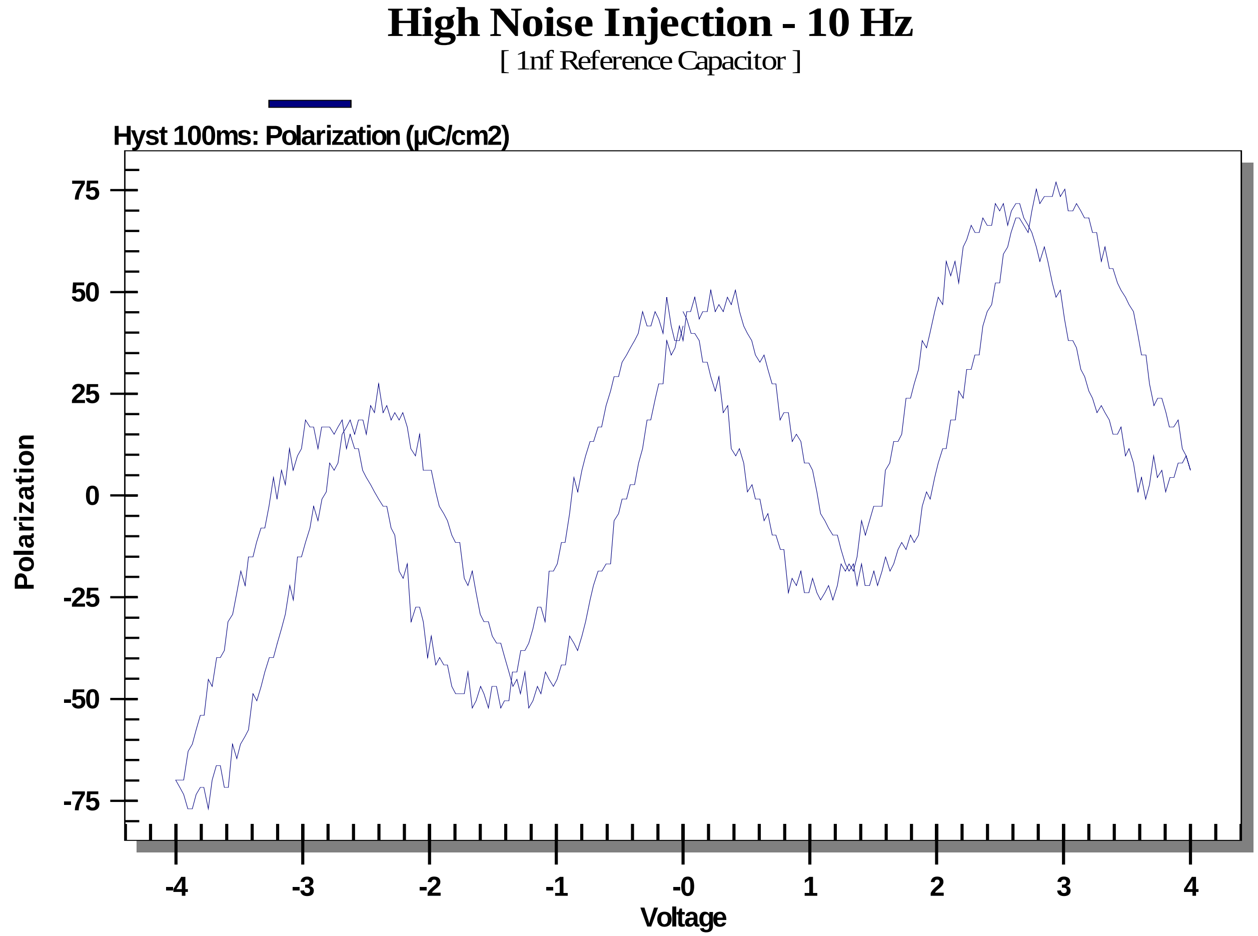
- With low amplitude noise, there is little apparent effect at speeds much higher than the period of the noise.

# High Noise Injection – 1 Hz



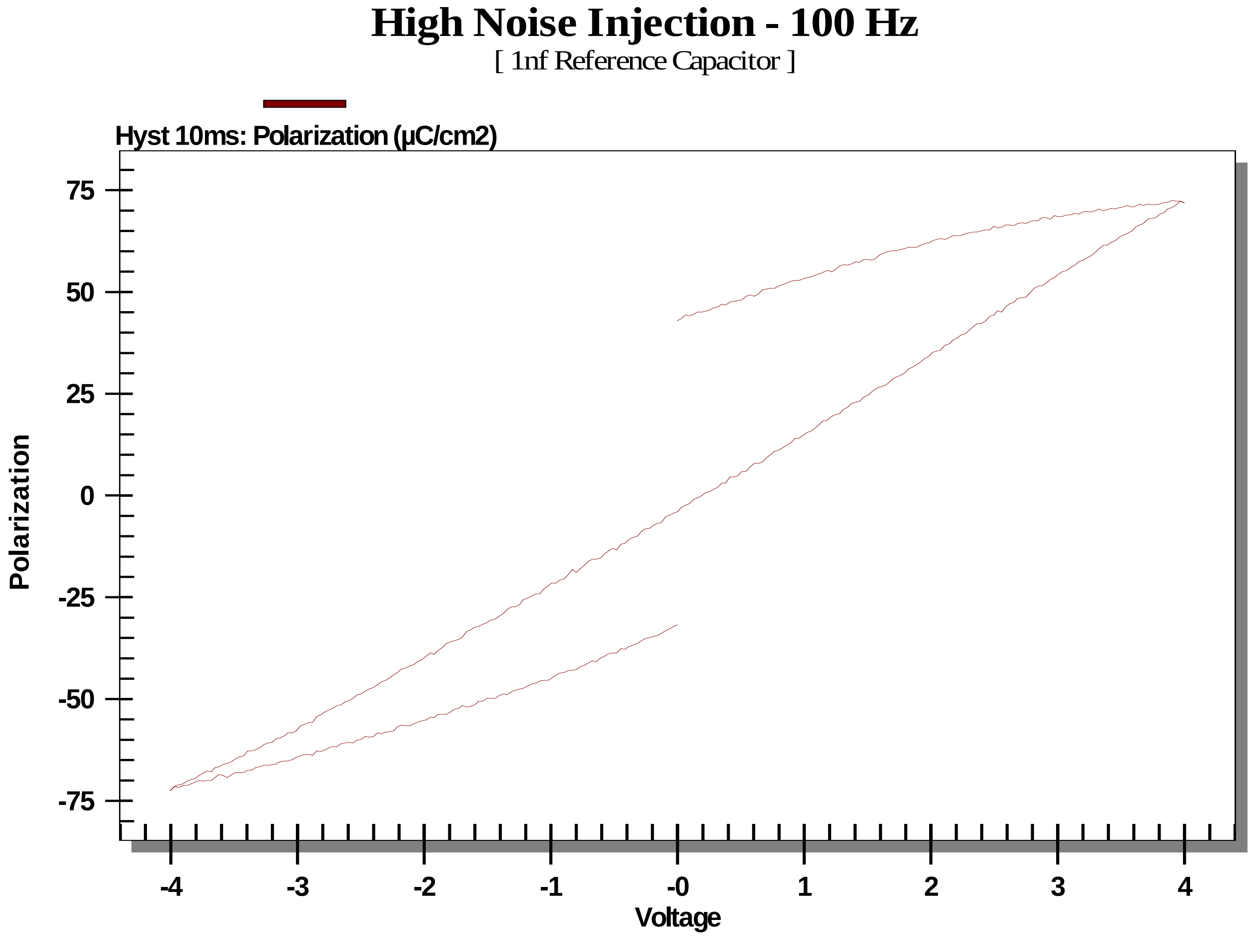
- The tester with virtual ground signal connected to probe station table.

# High Noise Injection – 10 Hz



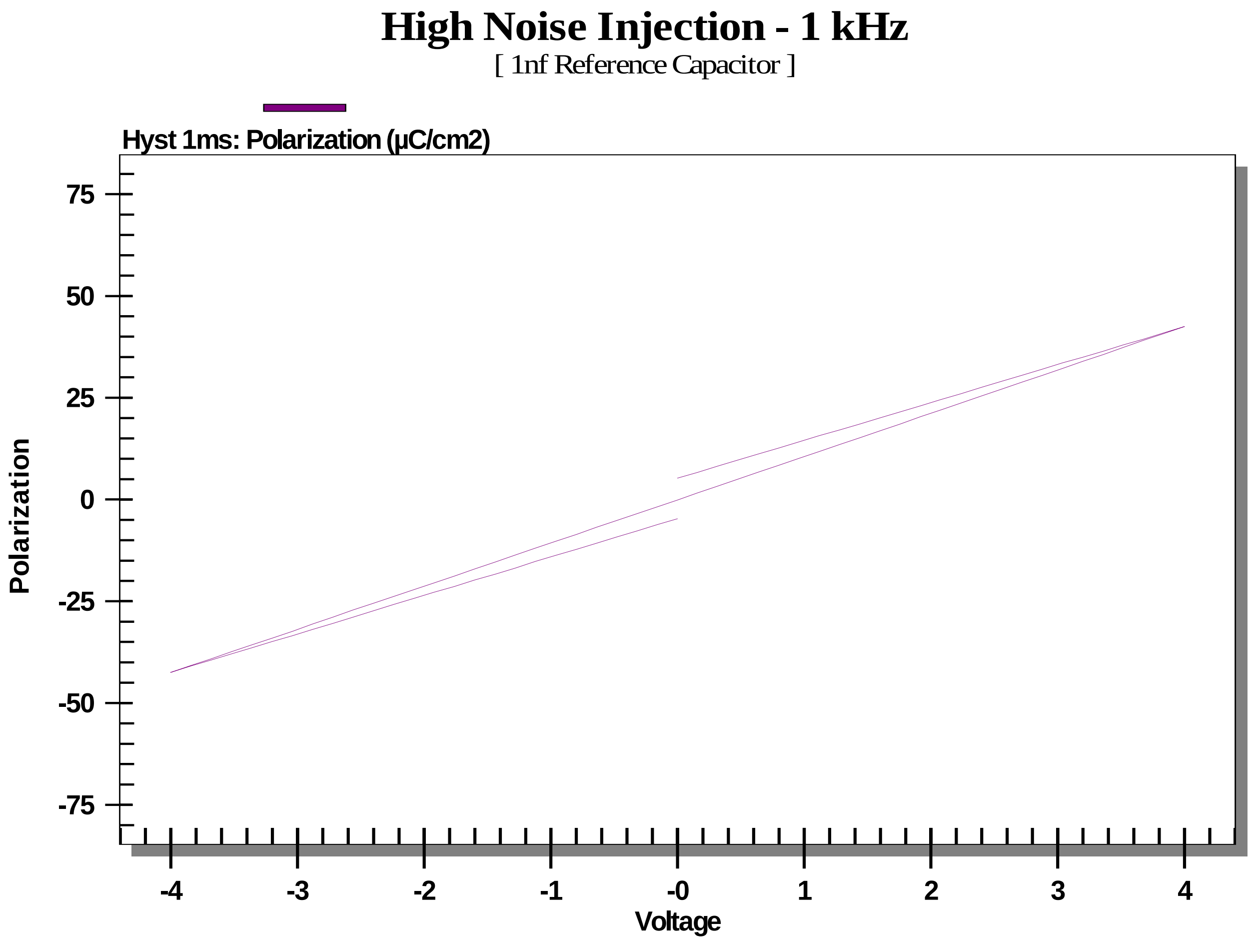
- Six noise cycles in 100ms ≈ 16.7ms period (60Hz)

# High Noise Injection – 100 Hz



- The test period (10ms) is just over half of the noise period (16.7ms).

# High Noise Injection – 1 kHz



- This type of result at a fraction of the period of the injected noise is a classic indication of external noise injection.

# Noise Injection

- Recognize the signature of external noise injection.
- Ground the probe station to the tester frame.
- Use coaxial cable as much as possible.

- The metal table above was the “antenna” I used to inject 60Hz.

# Output circuits

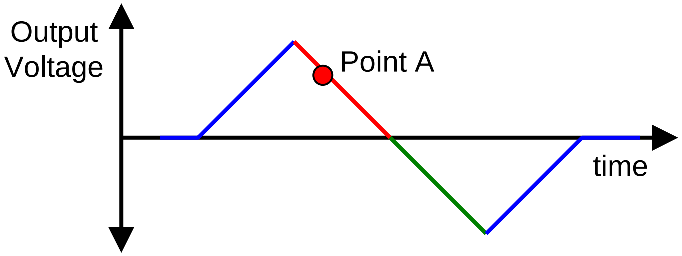
- A digital-to-analog converter (DAC) accepts digital words from the computer and converts them into voltages.

- The DAC is cycled by a master clock, also set by the host computer.

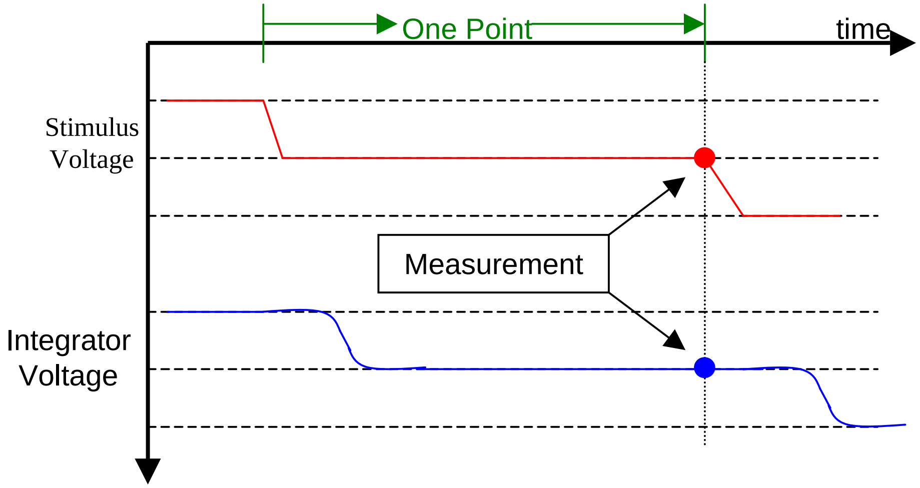
- No test cannot run any faster than one output voltage step per clock tick.

# Output Stimulus

The stimulus waveform



consists of a series of discrete steps



where each step is one tick of the clock.

# Current Limit

- The output amplifier can only generate a specified current while maintaining the assigned voltage.
- The sample *area* determines how much current is needed during the test.

$$I = ( \Delta P \times \text{Area} ) / \Delta t$$

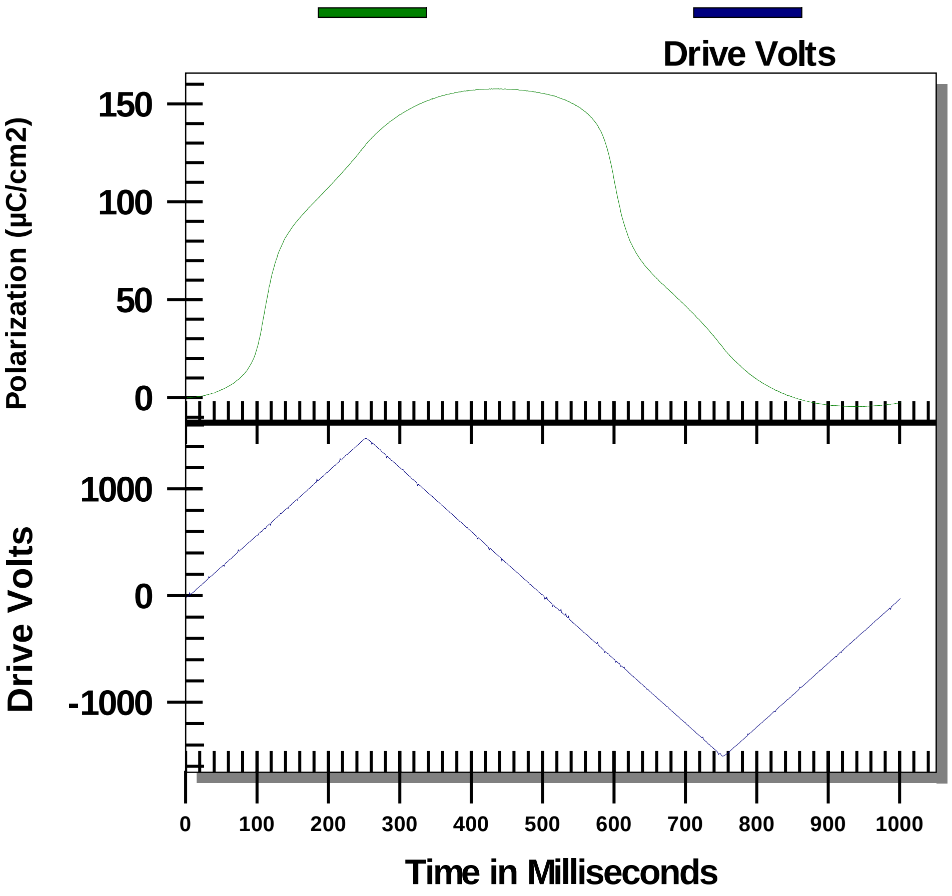
- Examine the measured stimulus waveform for distortion. Any variance from the triangle wave shape indicates current starvation.

# Current Limit

- To see if the current limit is exceeded, look at the output waveform:

## One Second Test

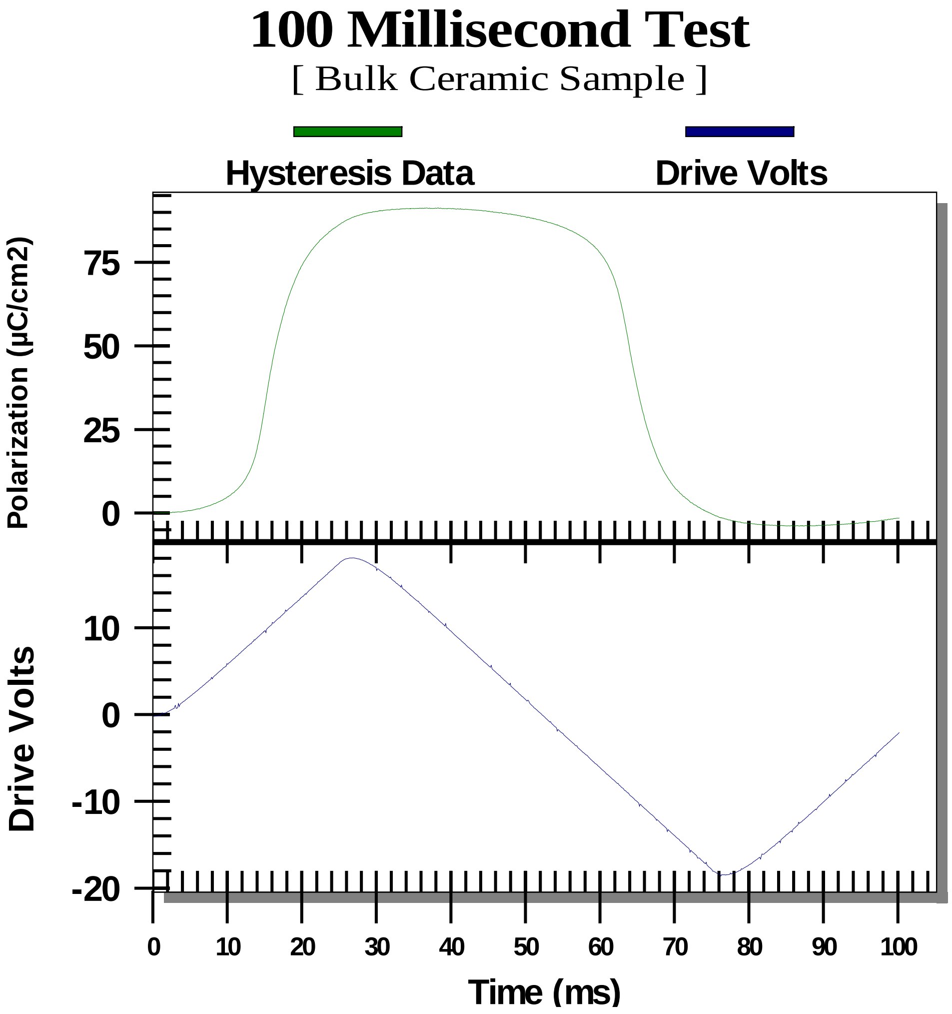
[ Bulk Ceramic Sample ]



*Radiant Technologies, Inc.*

# Current Limit

- The same sample tested with a shorter period.
- The current demand on the output amplifier is too high!



# Input circuits

- An analog-to-digital converter (ADC) converts an input analog voltage to a digital word on each clock pulse.
- The ADC is also cycled by a master clock, usually the same one clocking the DAC.
- No test cannot run any faster than one input voltage measurement per clock tick.

The clock cannot run any faster than the maximum speed of the ADC or the DAC, *whichever is slower!*

# Amplifier Circuits

- There will be one amplifier chain and DAC to generate the output stimulus from the tester.

- There will be multiple amplifier chains and ADCS for the signals to be measured:
  - The output stimulus
  - The virtual ground input
  - The output of an external high voltage amplifier
  - Independent external voltage signals
    - Displacement sensor
    - Thermocouple
    - Force sensor

# Amplifiers!

- The amplifier stages are the most difficult part of the design of a non-linear materials tester.
- To use a tester properly and to have confidence in the results, *you must understand how amplifiers affect your results.*

# Amplifier Characteristics

- All amplifiers *delay the signal from the input to the output.*
- All amplifiers *reduce the amplitude of the signal from the input to the output.*
- Distortion is the difference between 1) the *true shape* of the property being measured and 2) the *measured shape* of that property.
- Right now, *it is impossible to prove after the measurement of a non-linear material that the result of the measurement is the true shape.*

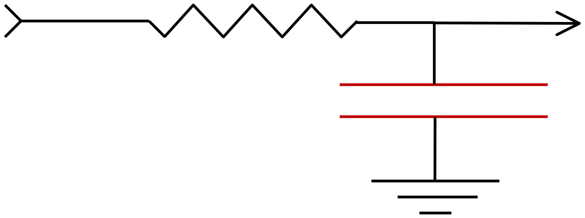
# Amplifier Characteristics

- The delay and amplitude reduction introduced by the amplifier is a continuous function of
  - the instantaneous frequency content of the signal,
  - the output voltage amplitude of the amplifier, and
  - the current demand on the amplifier output.

- You control these factors when you select the area of the sample and set the period of the hysteresis loop.
  - These two factors establish the current demand during the test.

# Amplifier Characteristics

- The simplest model for amplifier effects is the Resistor/Capacitor low pass filter.



- Voltage out = Vin ( 1 – $e^{-t/RC}$)
  - RC can be considered the unity gain frequency of the amplifier.
  - 99.9% = 6.9 RC time constants
  - To have near perfect stimulus and response, each output clock tick should be longer than 7 RC time constants.
  - *A 1000 point test thus should run 7000 times slower than the unity gain bandwidth of the amplifier!*

# Amplifier Characteristics

- In short, run your tests as slow as you can tolerate.

- The slower you go, the “sharper” and “squarer” the loop will appear.
  - Some of the change will be due to the tester.
  - Some of the change will be due to the sample changing its response with frequency.
  - It is difficult to separate the two effects out accurately.

# Instrumentation Conclusion

- Know the limits of your test equipment.
- Minimize noise pick-up from the cables and test fixture.
- Choose the properly sized sample for the test that you want to run:
  - Larger samples give better signal-to-noise.
  - Smaller samples lower the current demand on the test equipment, lowering distortion.

# Test Definitions

- **Hysteresis** – the polarization curve due to a continuous stimulus signal. The signal can have any shape.
- **Pulse** – the polarization change resulting from a single step up and step down in voltage. Essentially a 2-point hysteresis loop.
- **Leakage** – the current continuing to pass from or through the sample after the polarization has quit switching.
- **IV** – Individual leakage tests conducted over a voltage profile.

# Tests

- **Small Signal Capacitance** – The polarization response of the sample when stimulated by a voltage change smaller than that required to move remanent polarization.

- **CV** – small signal capacitance measured over a voltage profile.

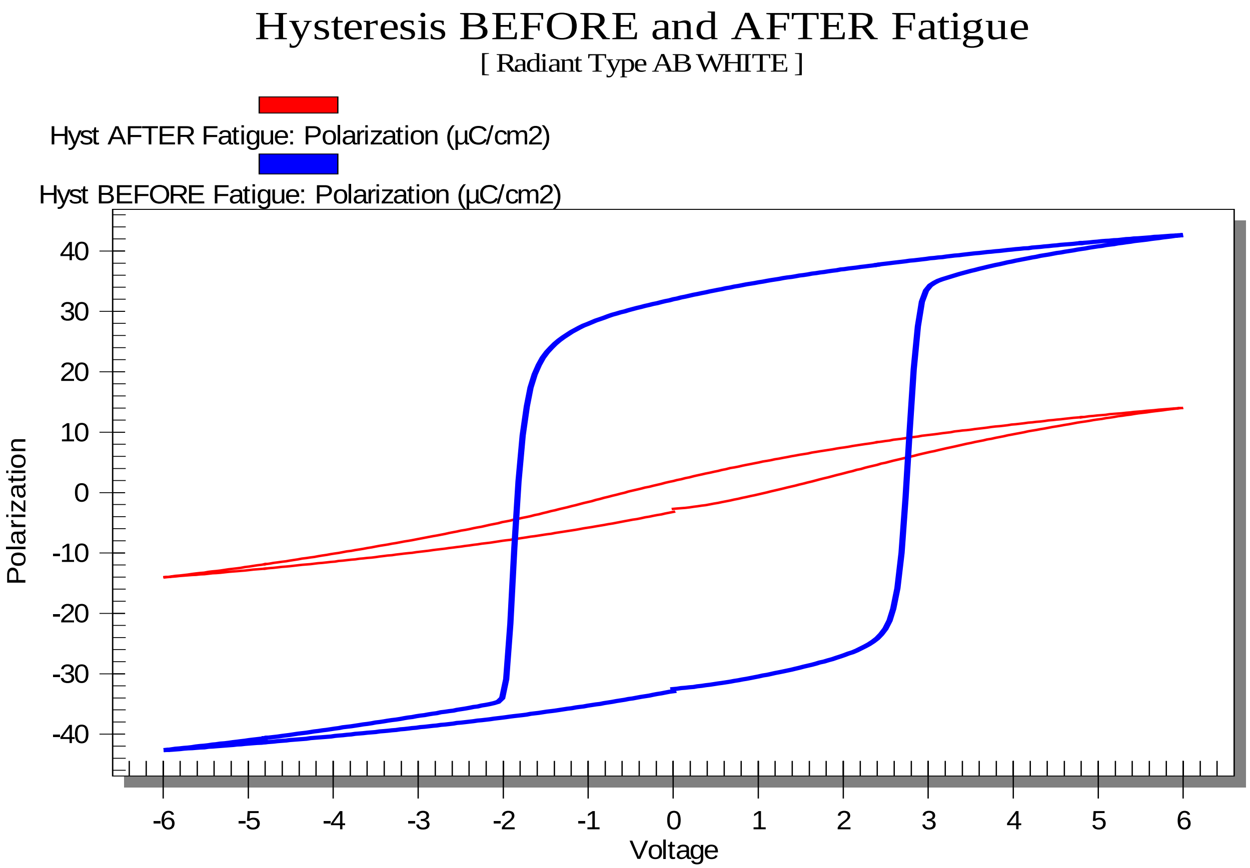
- **Piezoelectric Displacement** – the change in dimensions of the capacitor during voltage actuation.  Each test listed above has its counterpart measurement of piezoelectric displacement.

# Reliability

- **Fatigue** – The loss of a property of the capacitor with repeated cycling of the capacitor *around* its polarization loop.  Non-switching signals may not fatigue the capacitor.

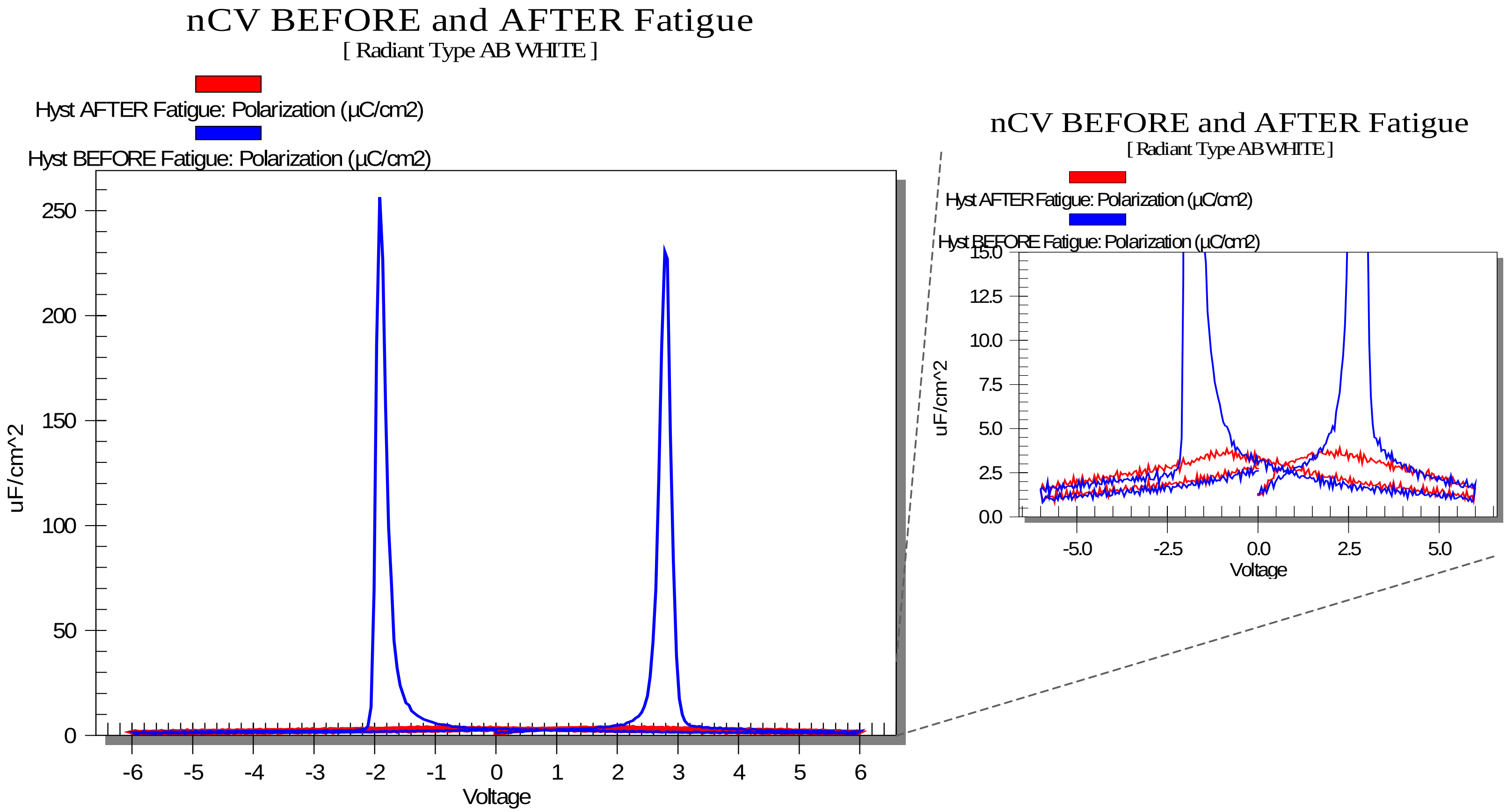
- **Imprint–** Changes in the hysteresis loop with *time in state*. It starts the instant after the first voltage is applied and never stops.
  - The changing property can be any property of the capacitor, not just polarization.
  - Our model at Radiant is that memory ***imprint*** in FeRAMs and traditional capacitor ***ageing*** are the ***same*** mechanism.

# Fatigue



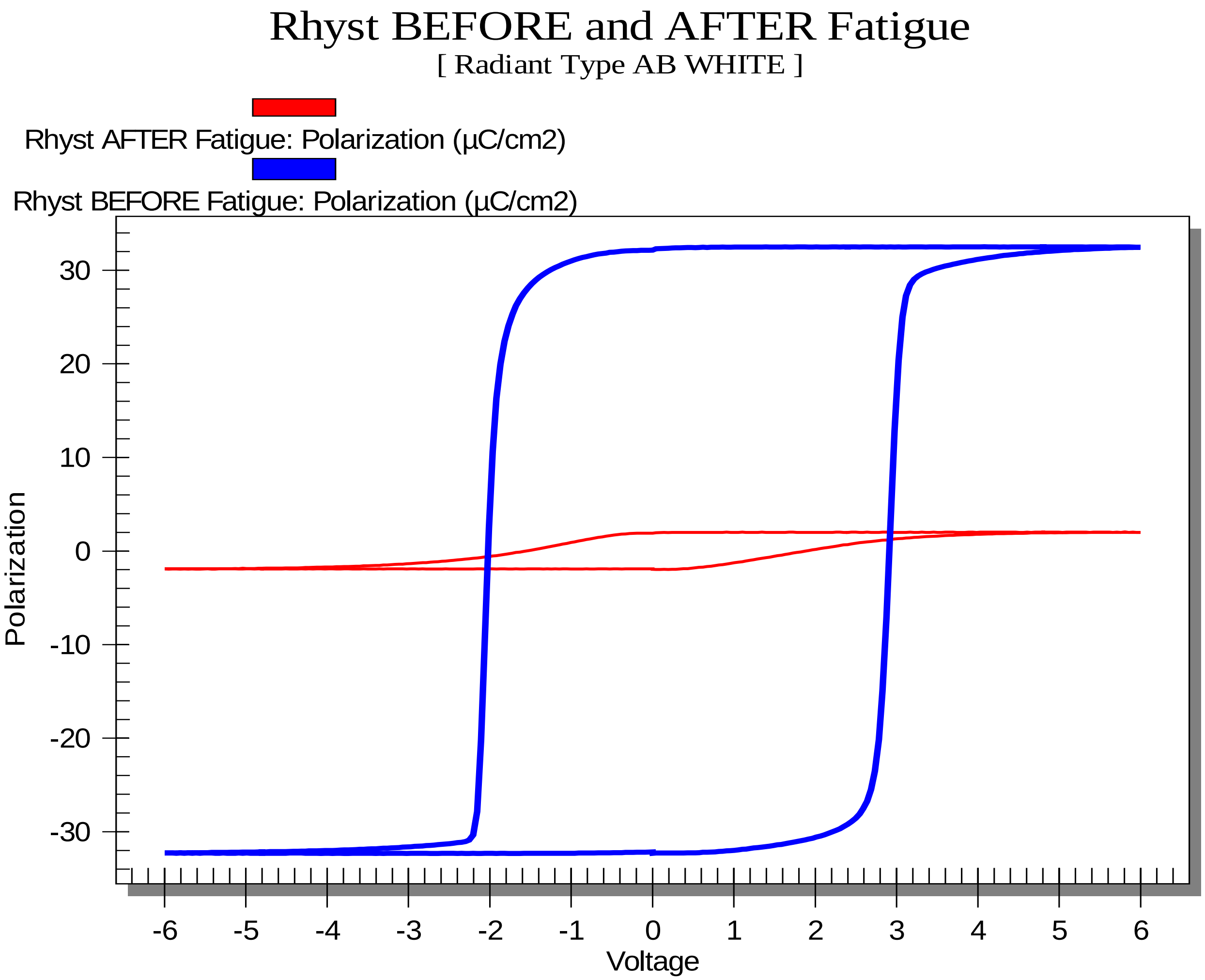
Fatigue causes a loss of polarization from repeated cycling of the capacitor around its loop. Experience indicates that polarization must switch direction for fatigue to occur.

# Fatigue



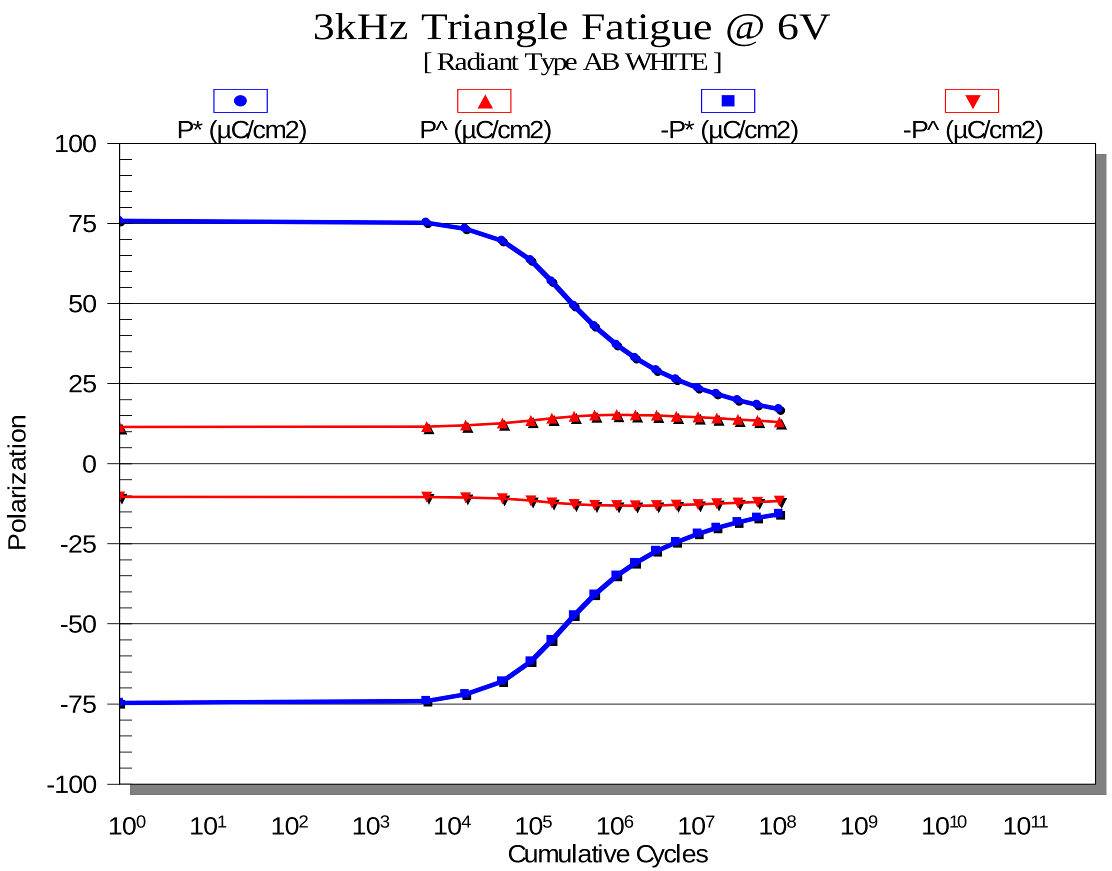
It appears that the switching peak evaporates as fatigue progresses. The linear capacitance and leakage, already small before the test began, change little.

# Fatigue



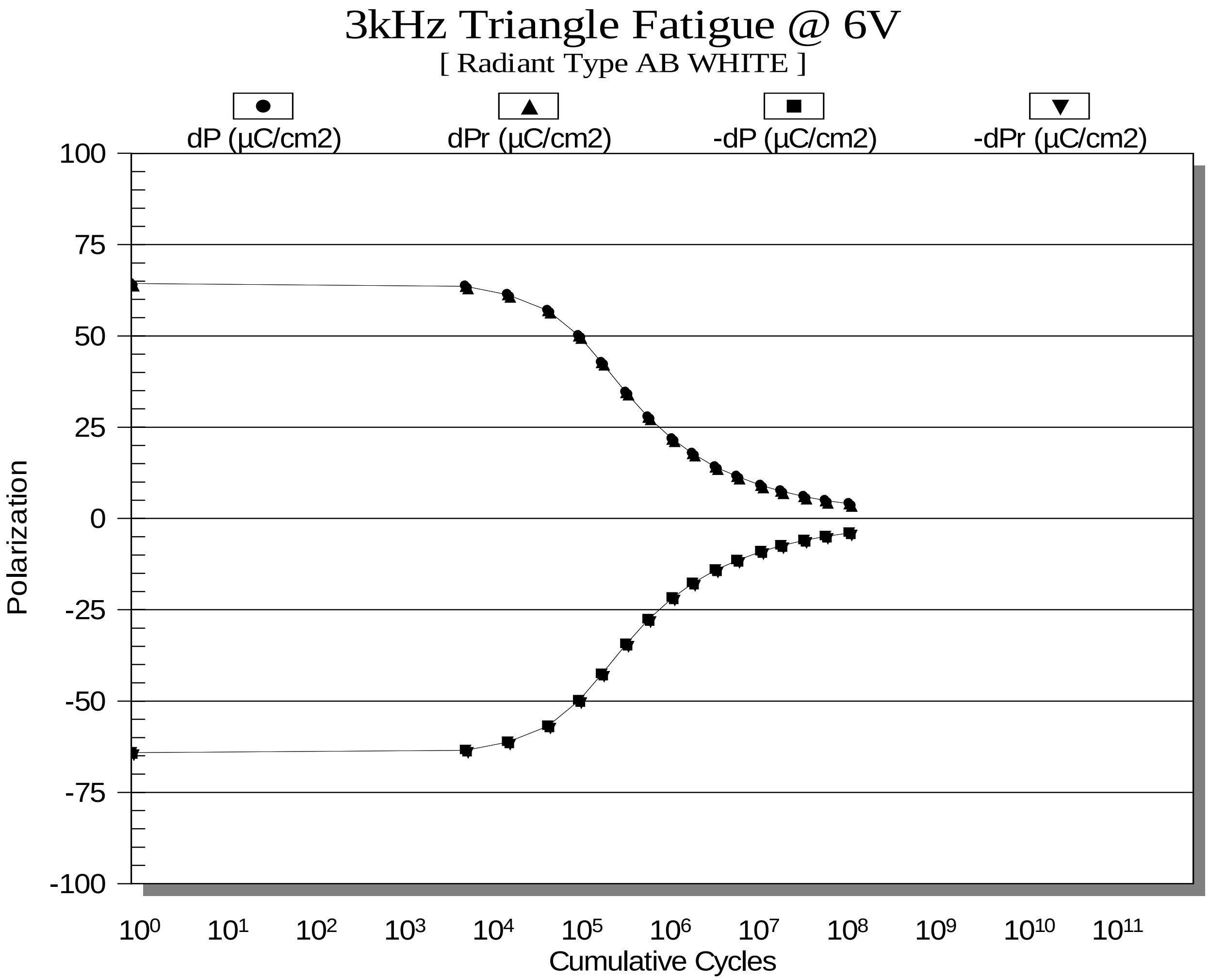
The remanent hysteresis before and after fatigue indicates that remanent polarization decreases substantially but some still exists after fatigue.

# Fatigue



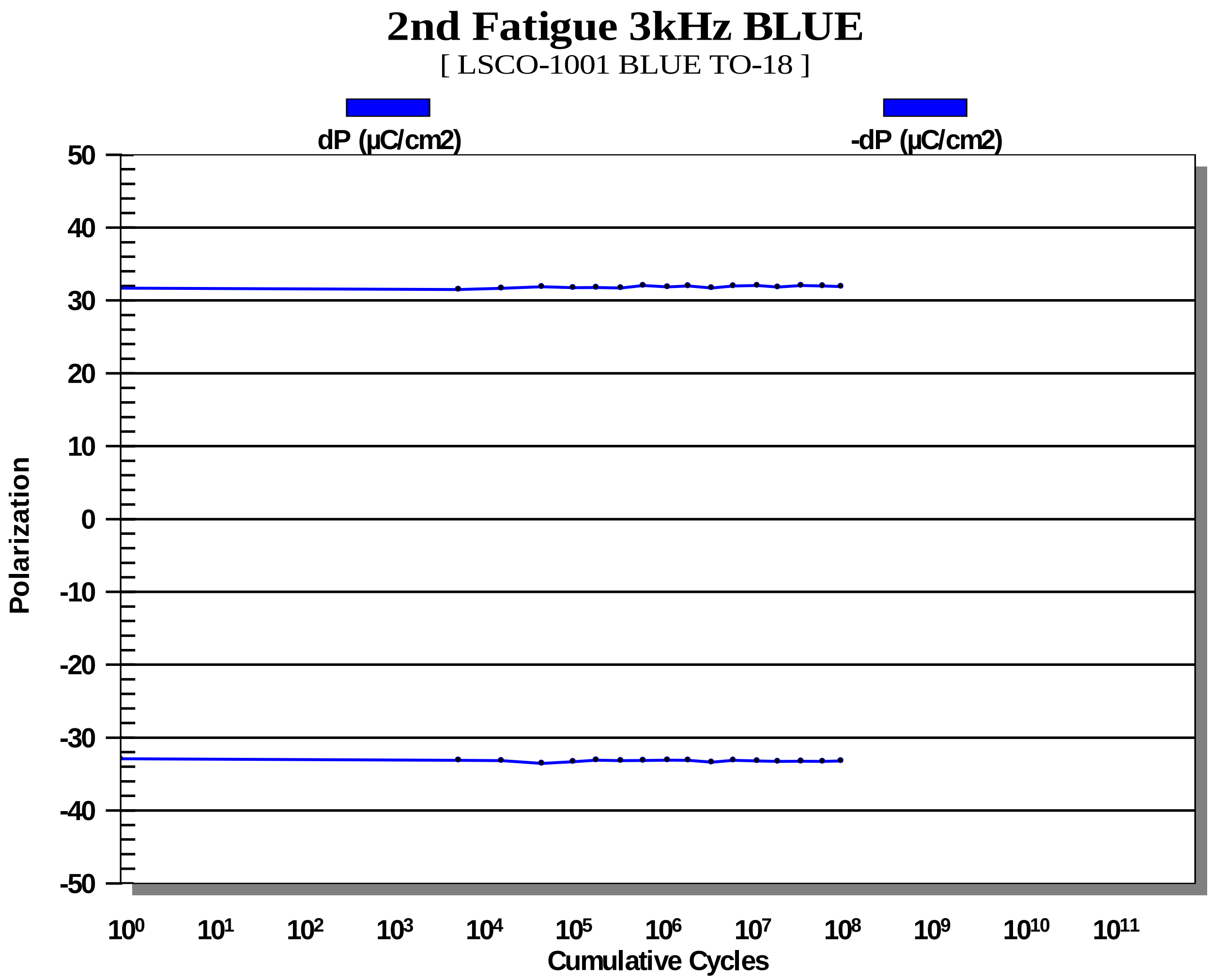
The classic fatigue test monitors the PUND values as a function of cycles. This capacitor was cycled with a 3kHz triangle wave at 6V to produce the fatigue effect. Switched and non-switched polarization (P* & P^) are plotted above.

# Fatigue



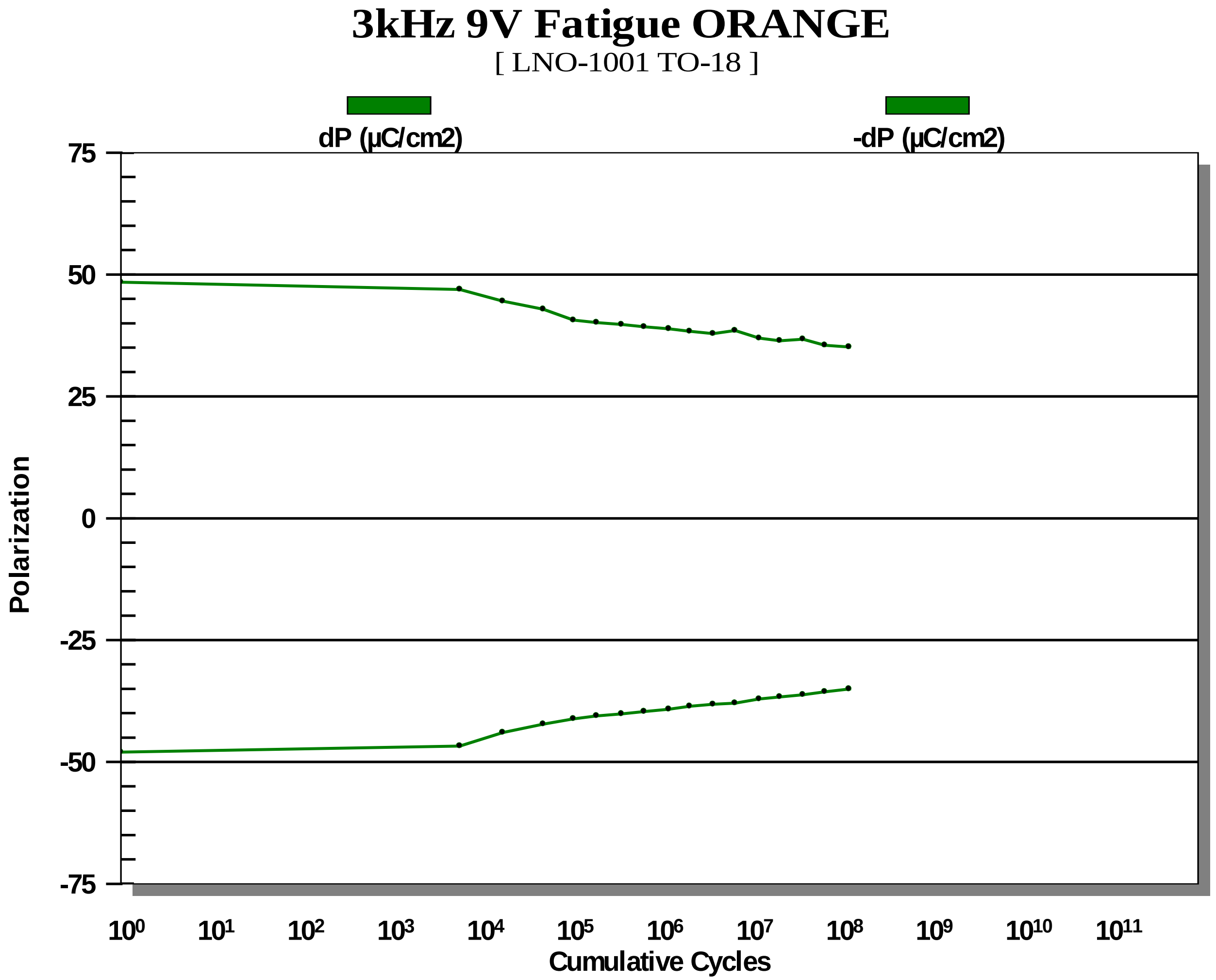
It is the remanent polarization (P*-P^) that fatigues. *The capacitor in this test has PZT on platinum electrodes which is known to fatigue strongly.*

# Fatigue-Free



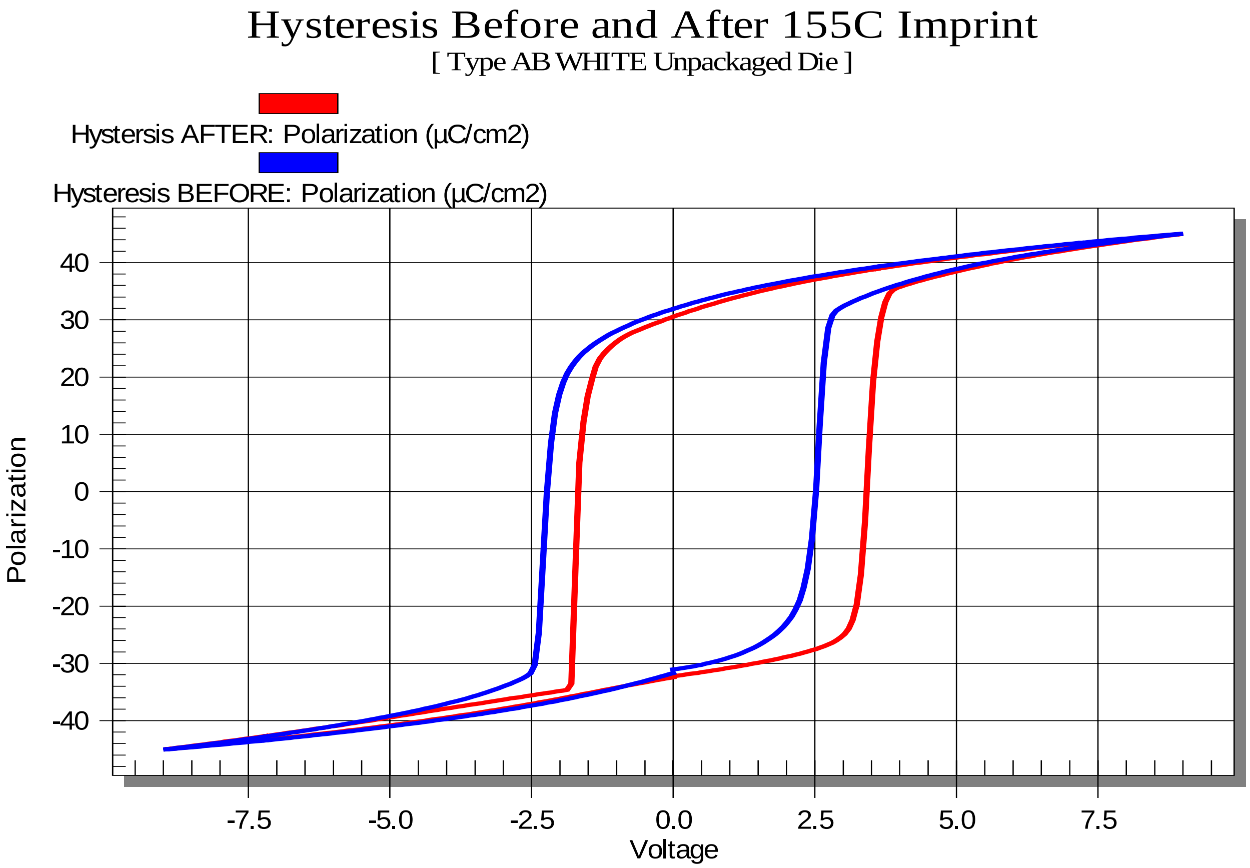
Radiant PZT with LSCO electrodes does not fatigue!

# Low Fatigue



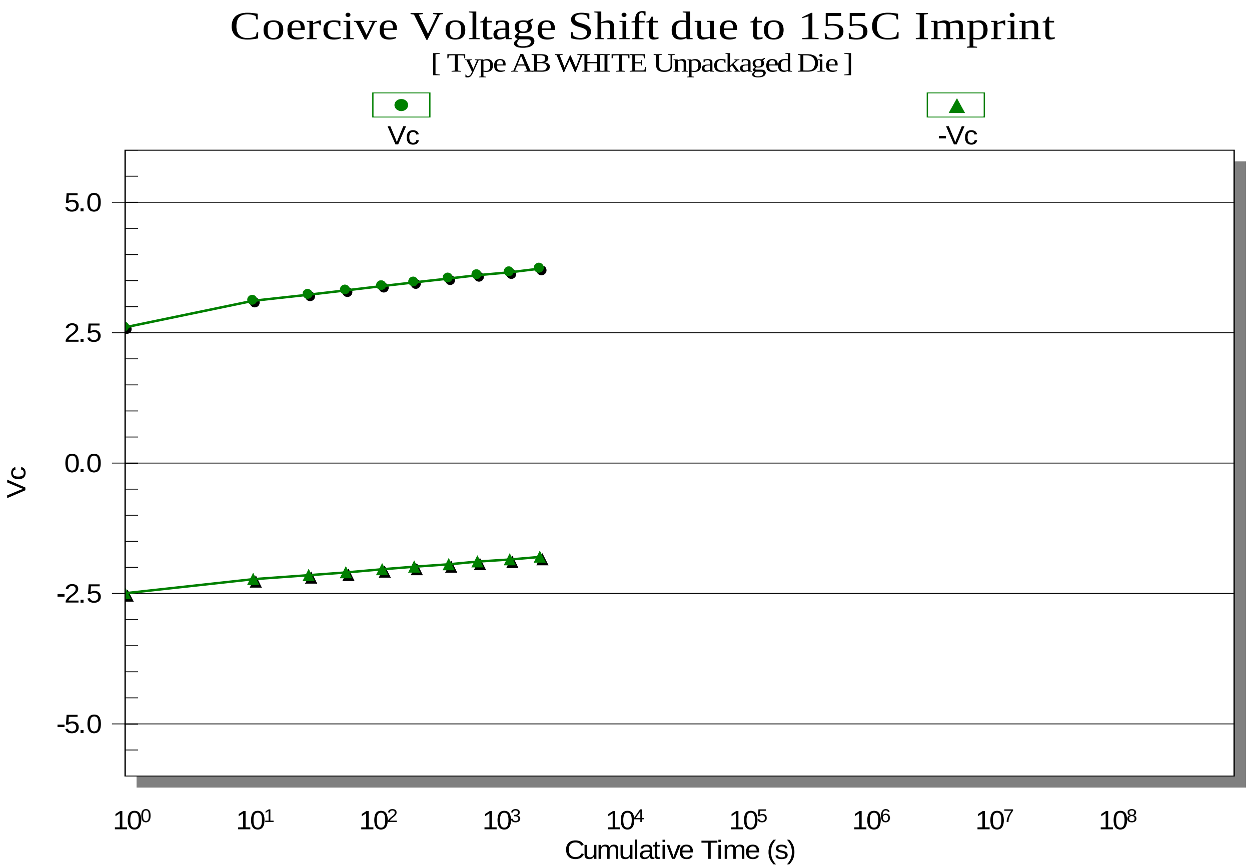
Radiant PZT on LNO electrodes fatigues slowly.

# Imprint



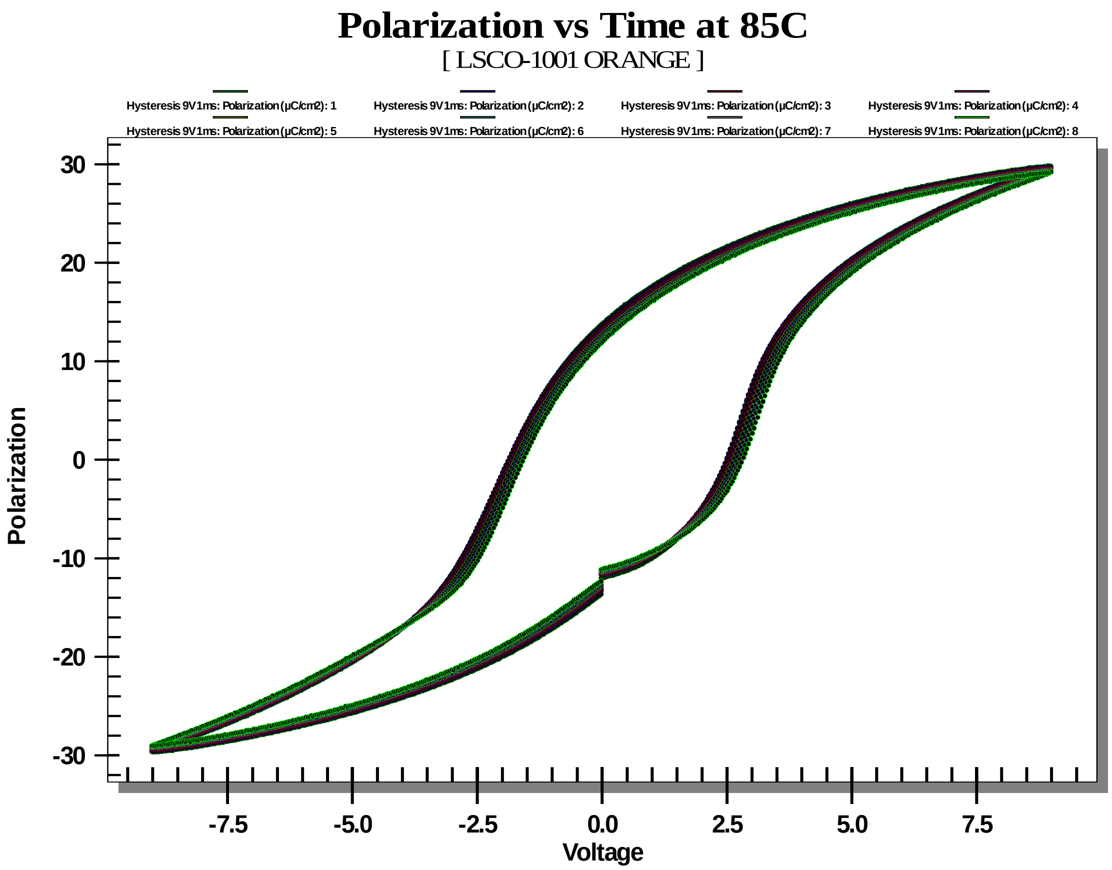
The primary mechanism is the gradual growth of an internal DC bias over time that shifts the hysteresis loop horizontally on the voltage axis. It is accelerated by temperature. The capacitor above saw 2300 seconds at 155°C between the blue loop and the red loop.

# Imprint



1x$10^9$ seconds is equal to 30 years. The imprint drift occurs constantly as long as the capacitor remains in the same remanent polarization state. *This data is of PZT on platinum electrodes, known to imprint strongly.*

# Imprint on LSCO


Polarization vs Time at 85C

[ LSCO-1001 ORANGE ]

The addition of LSCO electrodes to Radiant’s PNZT results in a very low imprint rate below 85°C. The plot above shows eight loops measured over 10,000 seconds at 85°C.

# Conclusion

- This presentation has only touched the surface of the test environment.
- Tests may be run as a function of time, temperature, pressure, history, frequency, voltage, rise time, and preset values.  Other stimuli such as temperature or magnetic field may be used.  Many properties have not been adequately examined to date.
- Each and every test must be executed within the limits of the test equipment to prevent distortion.
- Visit Radiant's web site periodically to see application notes on test procedures or test results.