The Effect of the Delay Between Pulses on the Remanent Polarization of the PUND test

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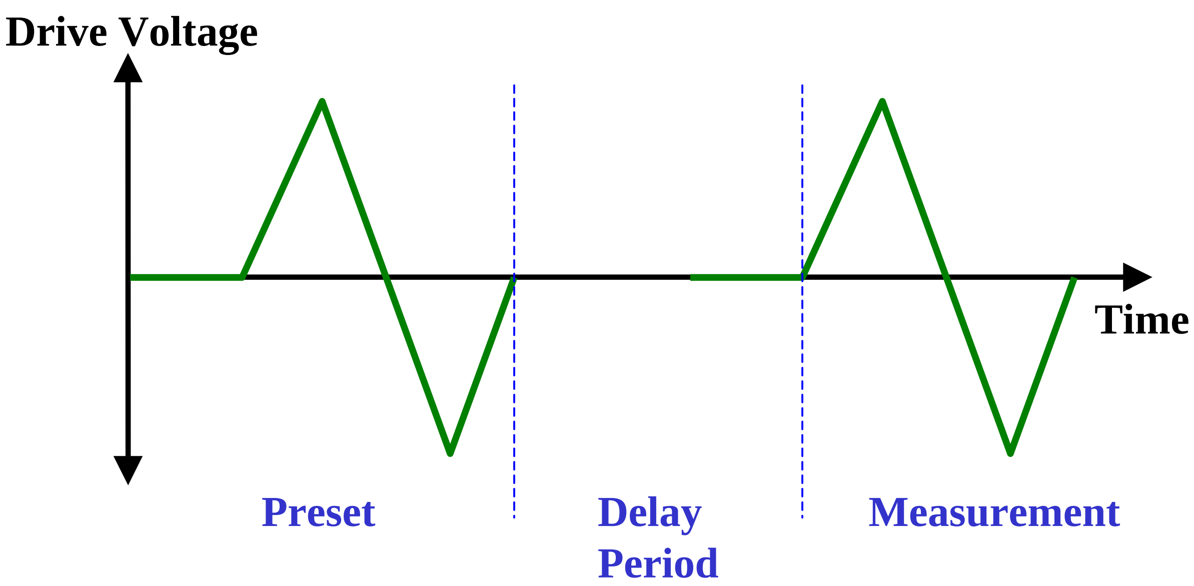
Introduction

- What are we seeing when we measure polarization hysteresis?
- Models say it should be only switchable remanent polarization plus dielectric polarization.
- What we do measure has a decay even down to the microsecond range.
- Does domain polarization decay or is it something else?
  - It is something else!

Samples

- Unless otherwise stated, all data was measured from a single capacitor.
  - 1200Å of 4% Niobium doped 20/80 PZT
  - Bottom electrode = global layers of 1500Å Platinum on 400Å titanium
  - Top electrode = 1500Å Platinum patterned into 110µ x 110µ squares
- The other capacitor had the same structure but used 900Å of undoped 20/80 PZT.

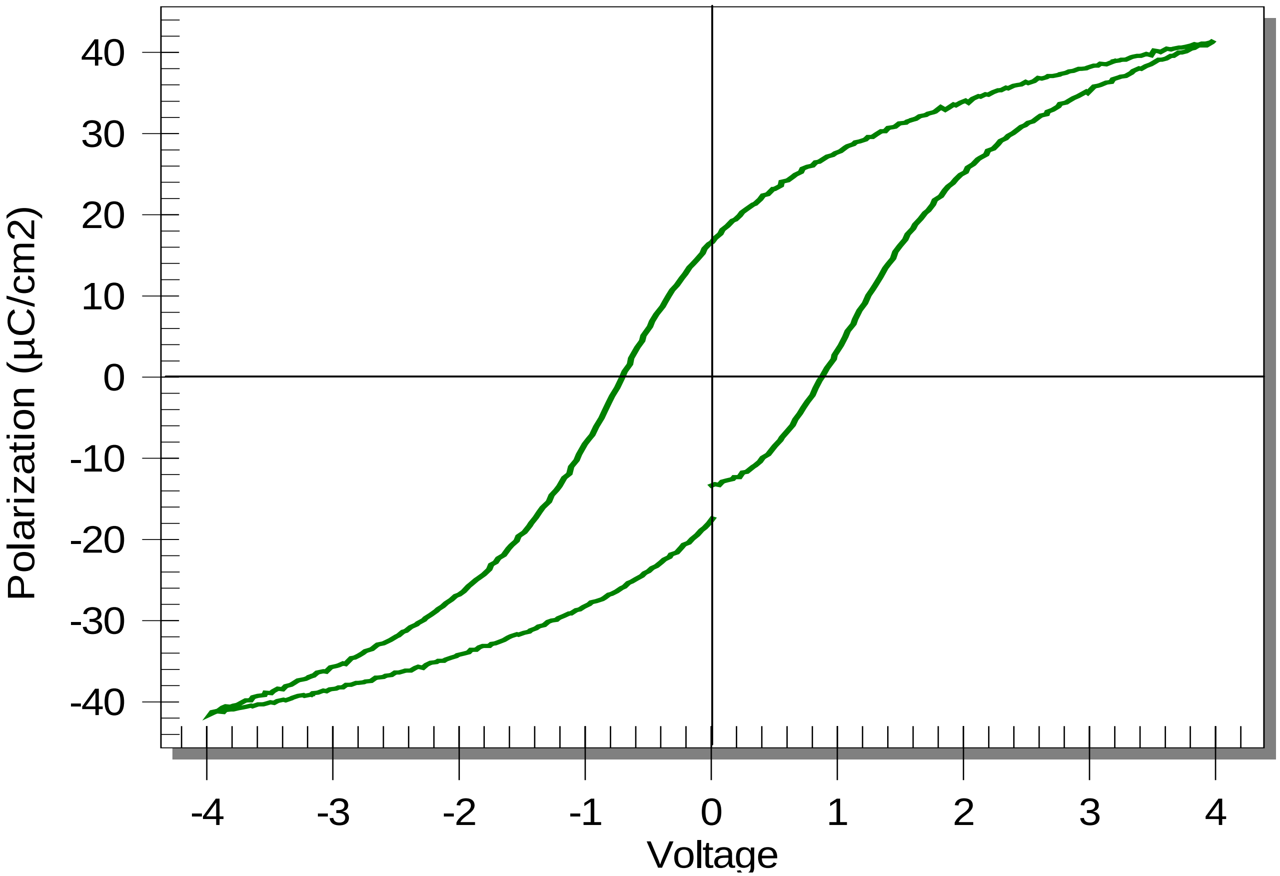
What is the Hysteresis Test?



A hysteresis test has a preset loop followed after a delay by the measurement loop.

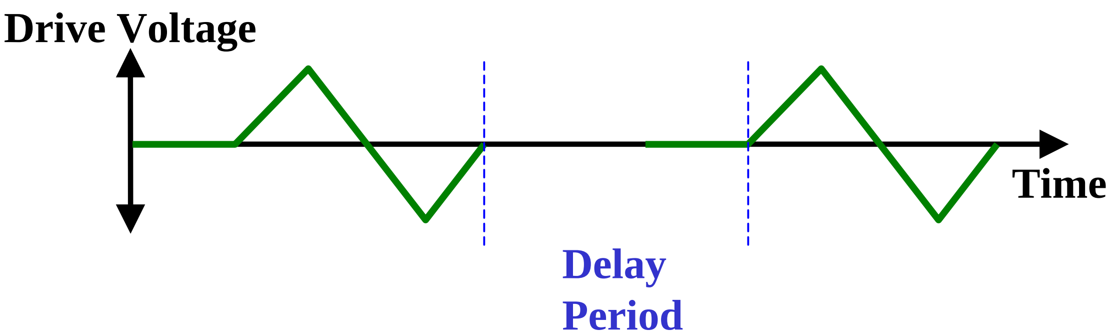
A gap in the loop develops if there is any decay of the state inside the capacitor during the delay period!

The "Gap"



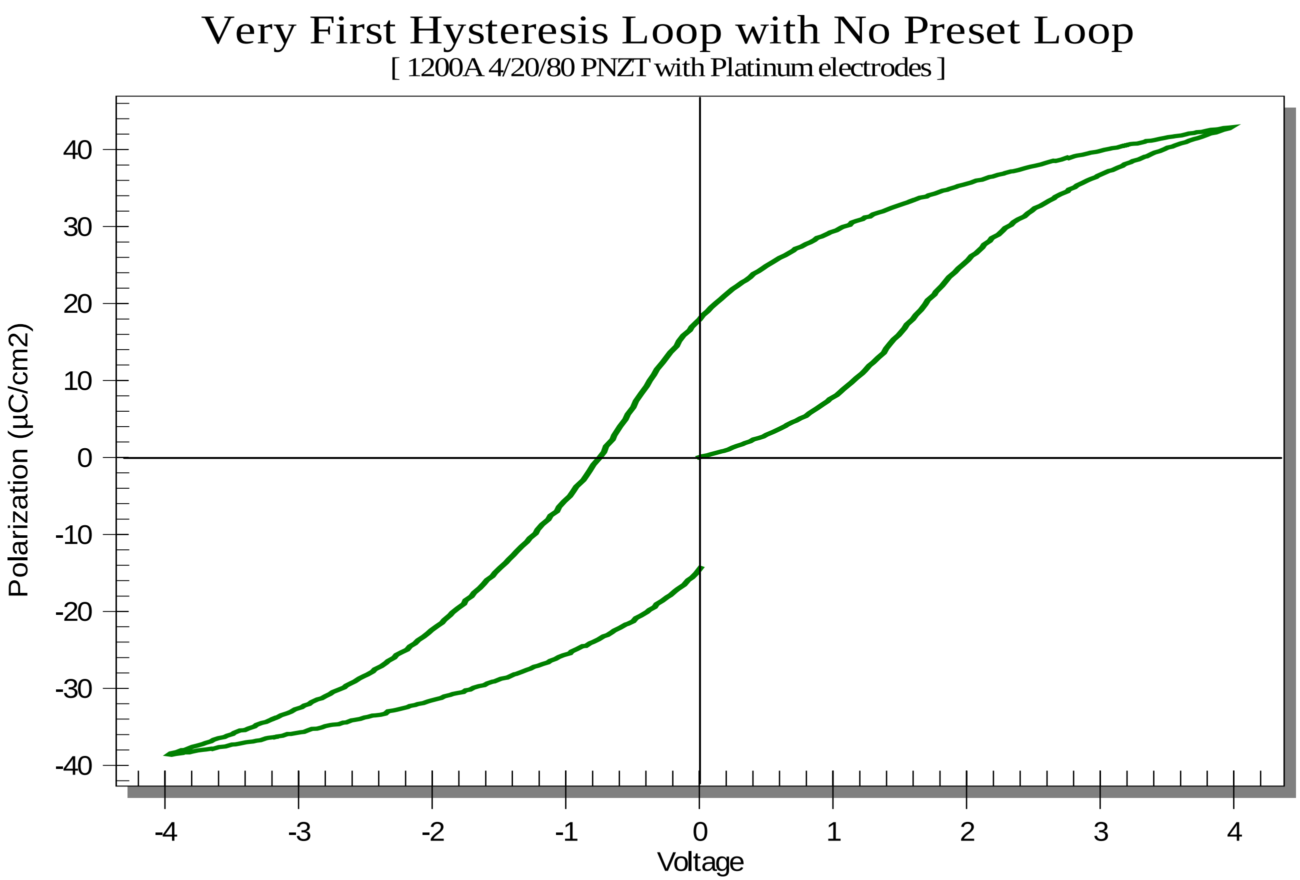
In the hysteresis loop, the end point of the first loop is usually not the same as the start point.

What if you do not do a Preset Loop?



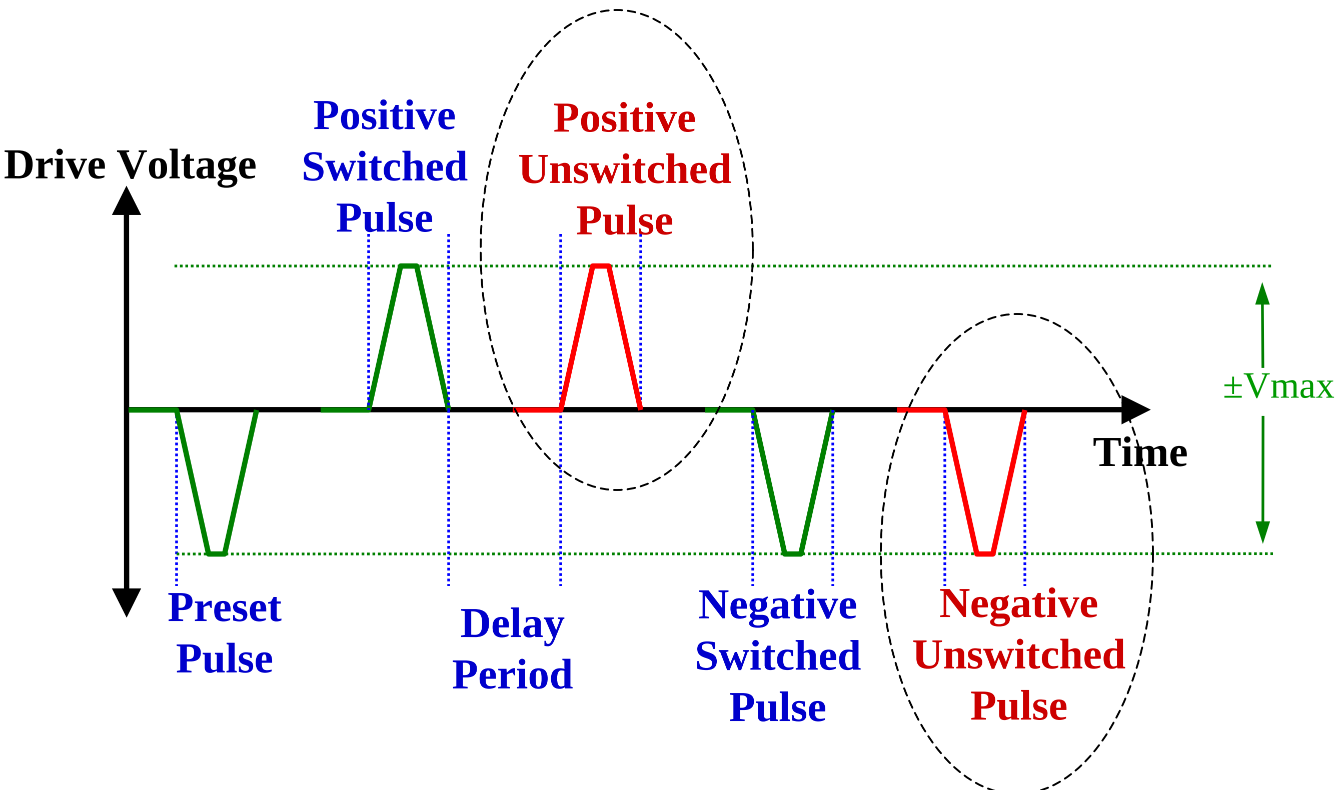
- A hysteresis test ***always*** has a preset loop even if you do not do it consciously. Ferroelectric materials by definition have memory so the *last stimulus* you applied to the sample is the Preset Loop. *The delay period might be one second or one month!*
- Only one loop does not have a preset loop: *the very first loop!*

The First Loop



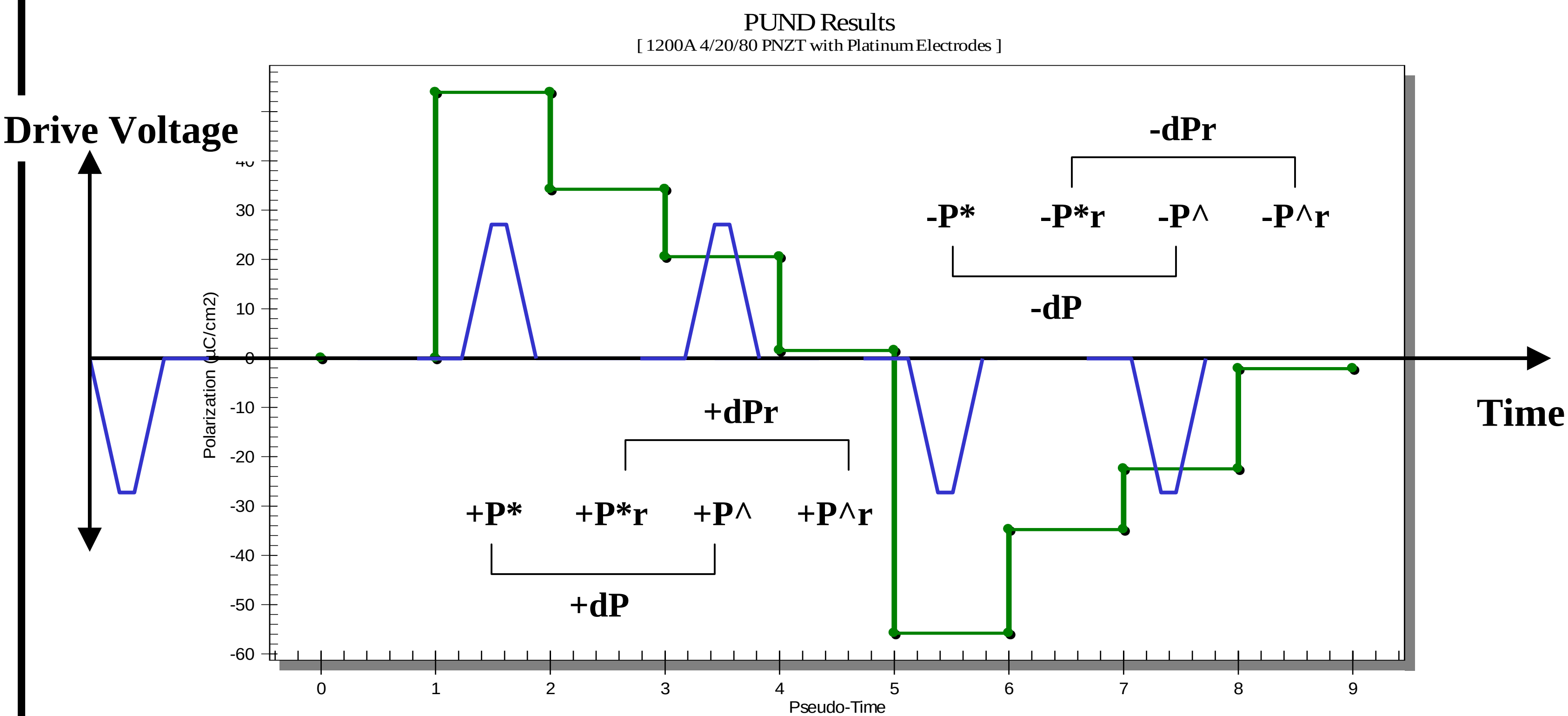
- Ferroelectric films with symmetrical metal electrodes come down from the Curie Temperature with zero remanent polarization.

"PUND"



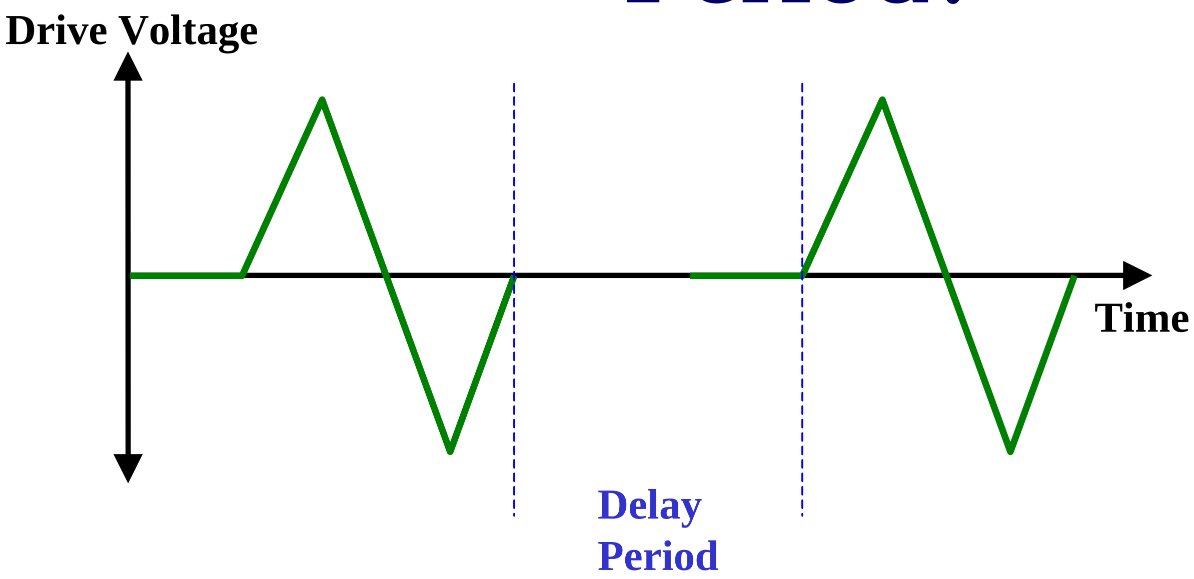
In a PUND test, polarization produced by the non-switching pulses does not go back to zero! These values are labeled ±**P^r** on Radiant Technologies' testers.

"PUND" Results



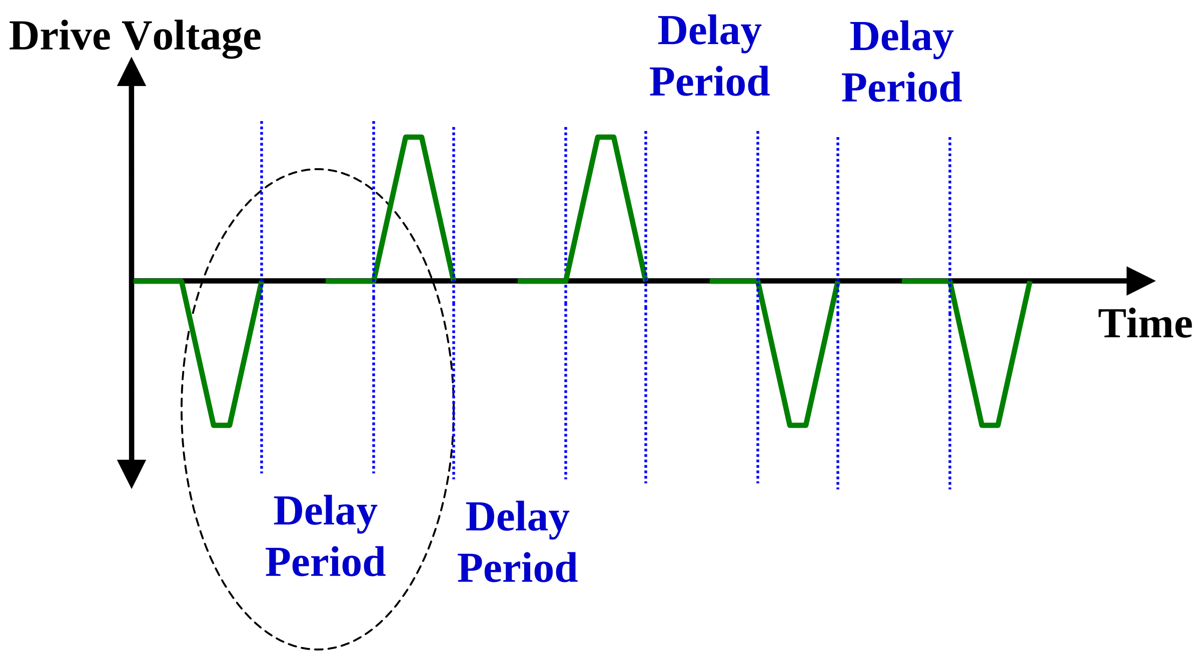
***This data taken from a separate 4/20/80 PNZT capacitor than the remainder of the data.**

What is the Hysteresis Delay Period?



The Delay Period is the waiting time between the end of the preset loop and the start of the measurement loop.

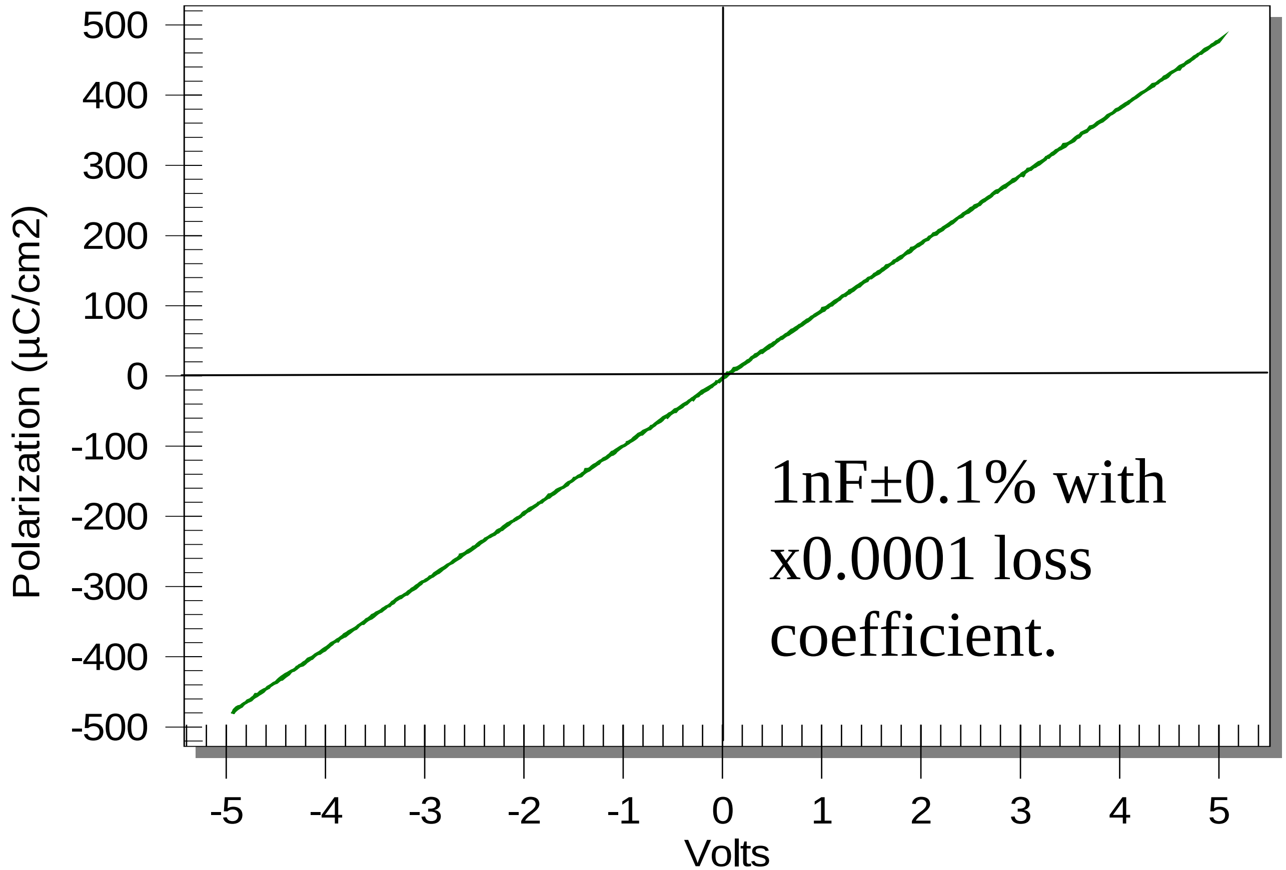
What is the PUND Delay Period?



For the standard PUND, the delay period is a constant 1 second between all pulses. But, the delay period can be varied to create sub-second retention tests.

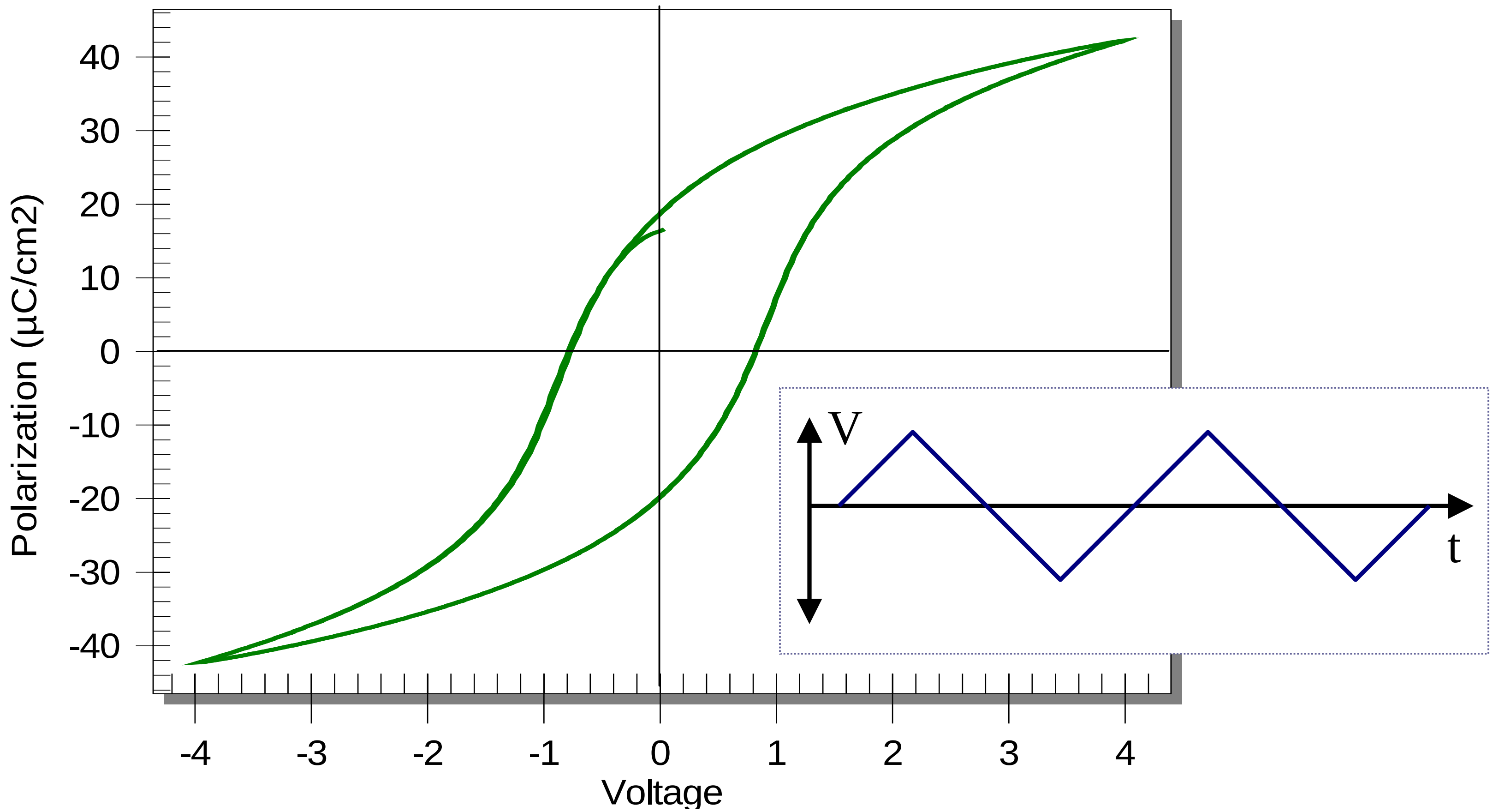
Is the "Gap" Real?

A high quality linear capacitor has no "Gap":



The "Gap" is not caused by the tester.

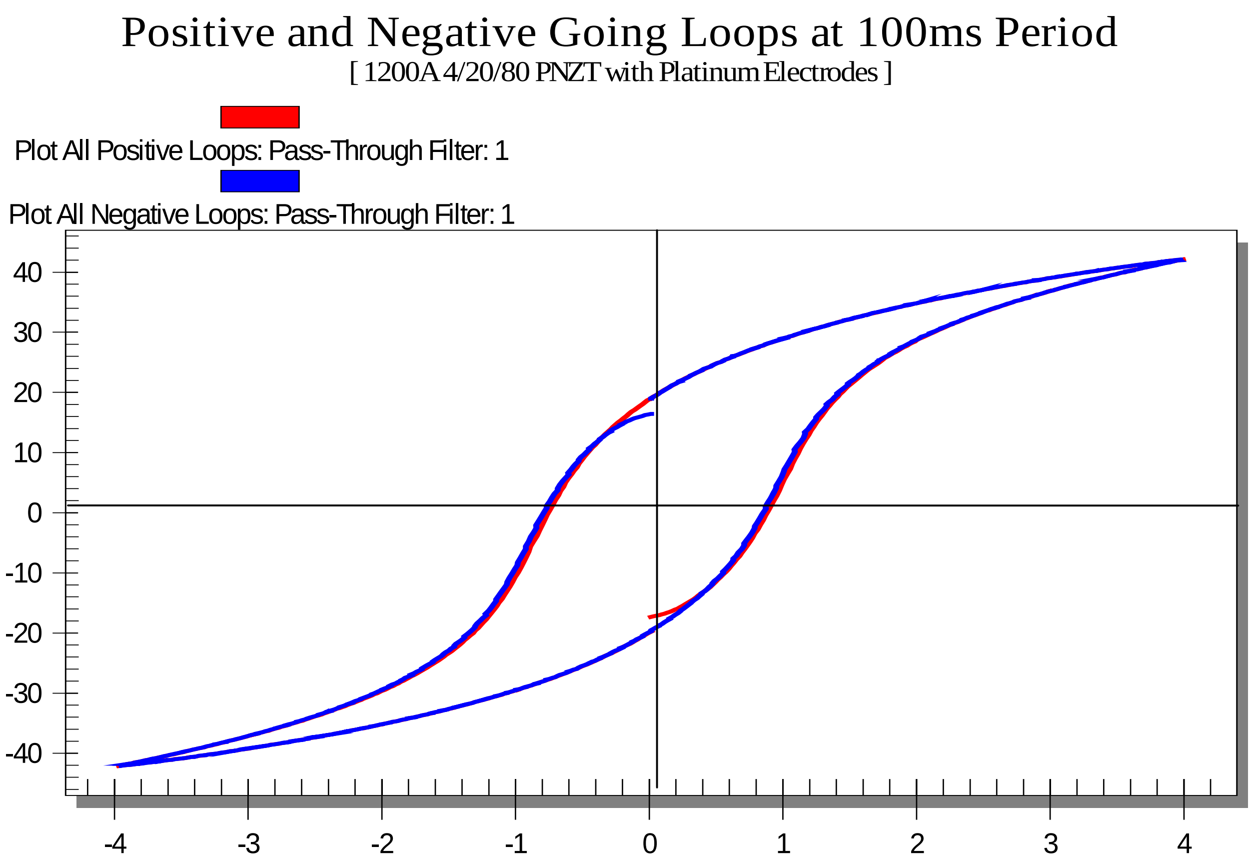
Is the “Gap” Real?



The loop closes smoothly if you continue into the second loop.

Is there a “Gap” on both Ends?

Yes!



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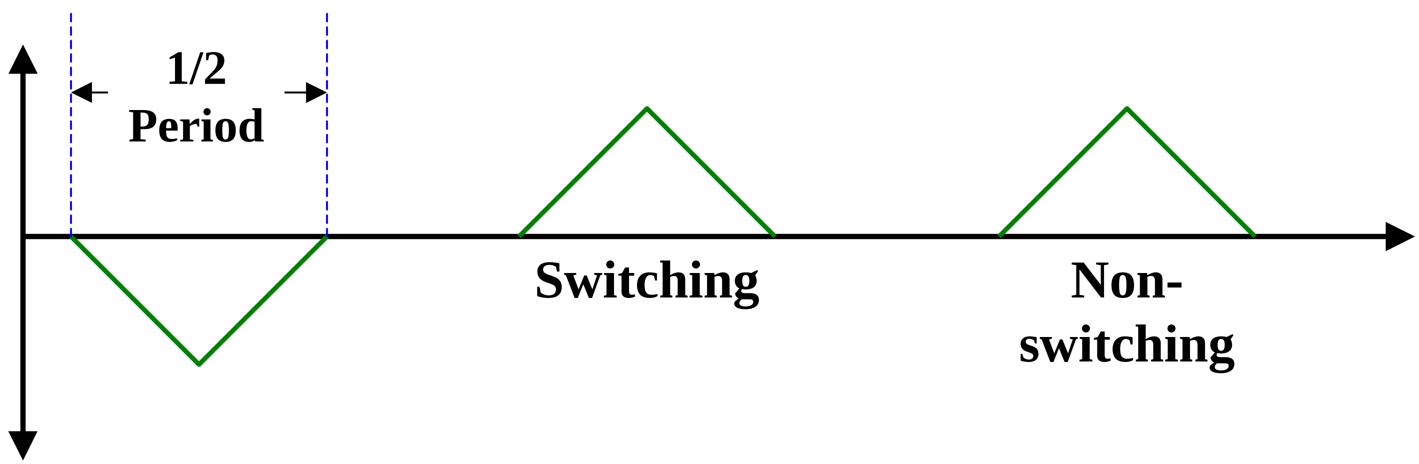
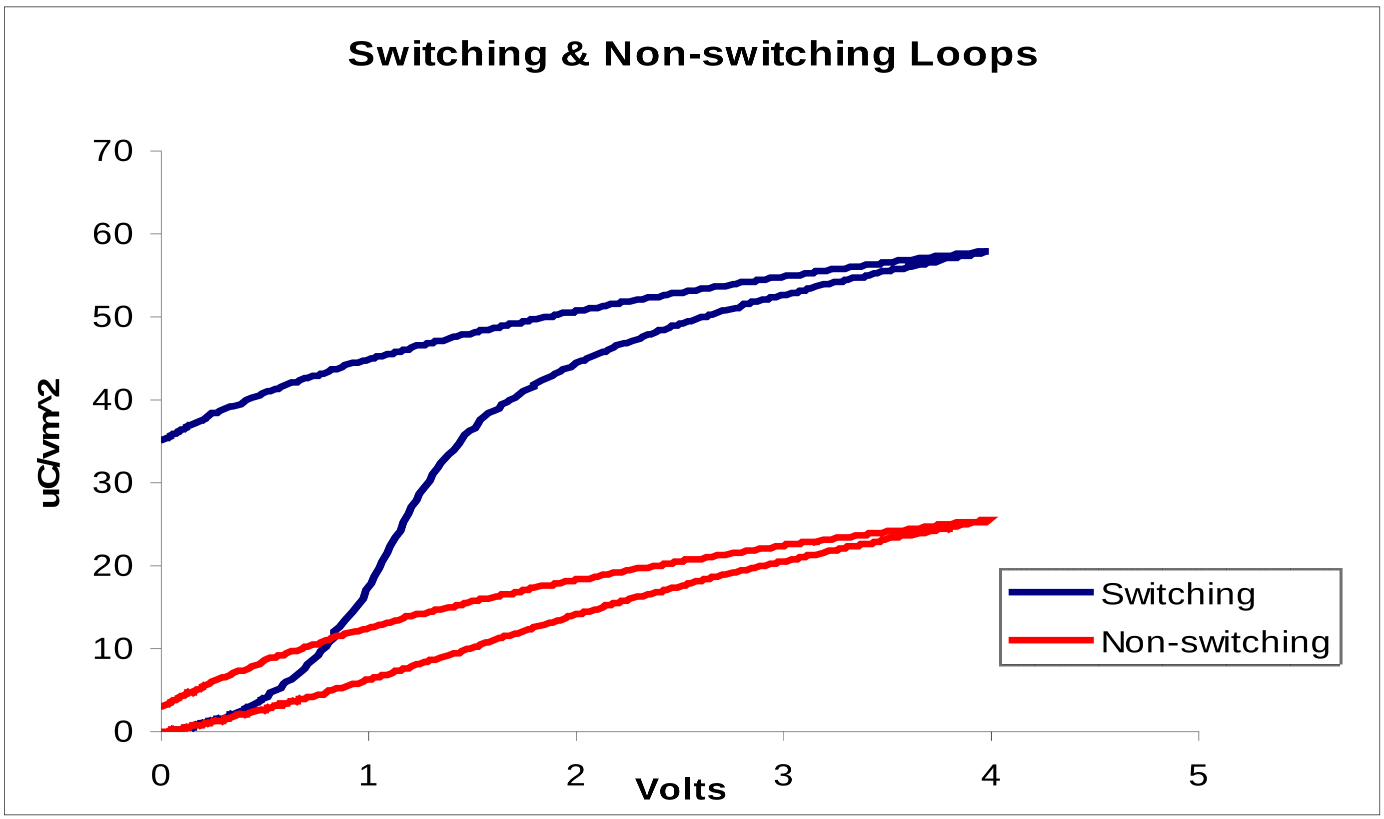
Can We do the PUND test with Hysteresis Loops?

Use half loops:



The Parts of the Hysteresis

Switching and Non-switching half loops:



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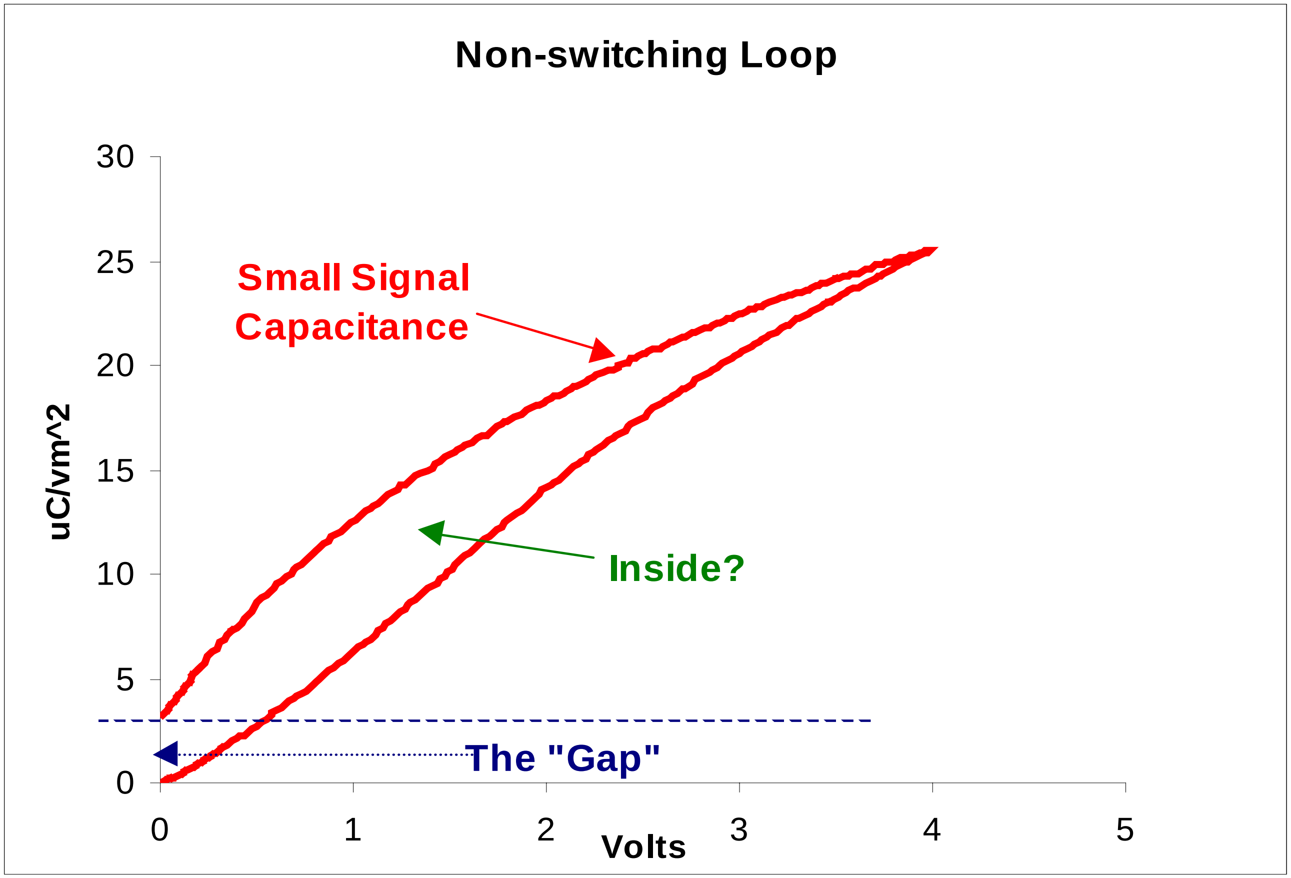
"Gap" in the Half Loop

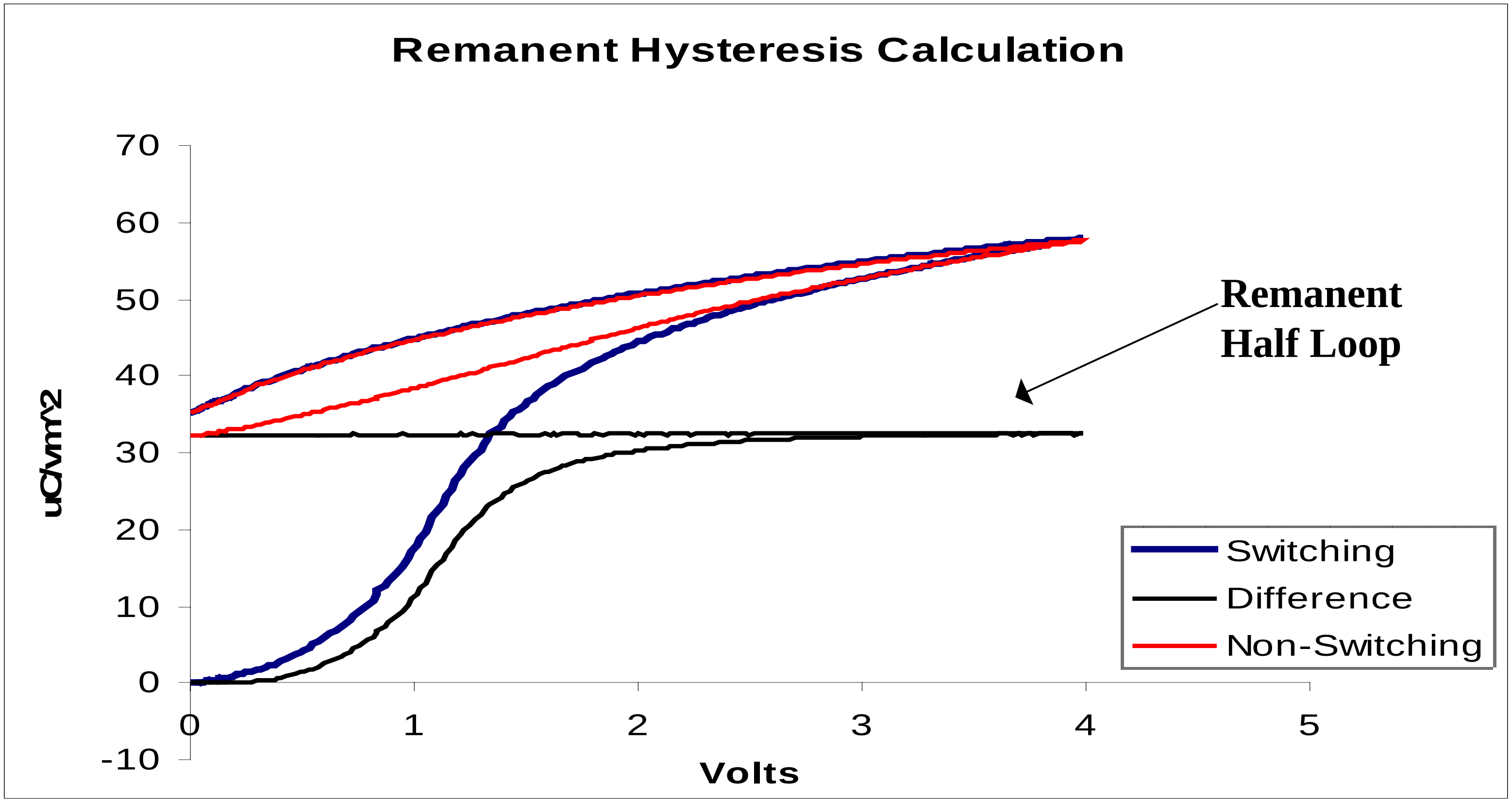
The Non-switching half loop does not go back to zero!



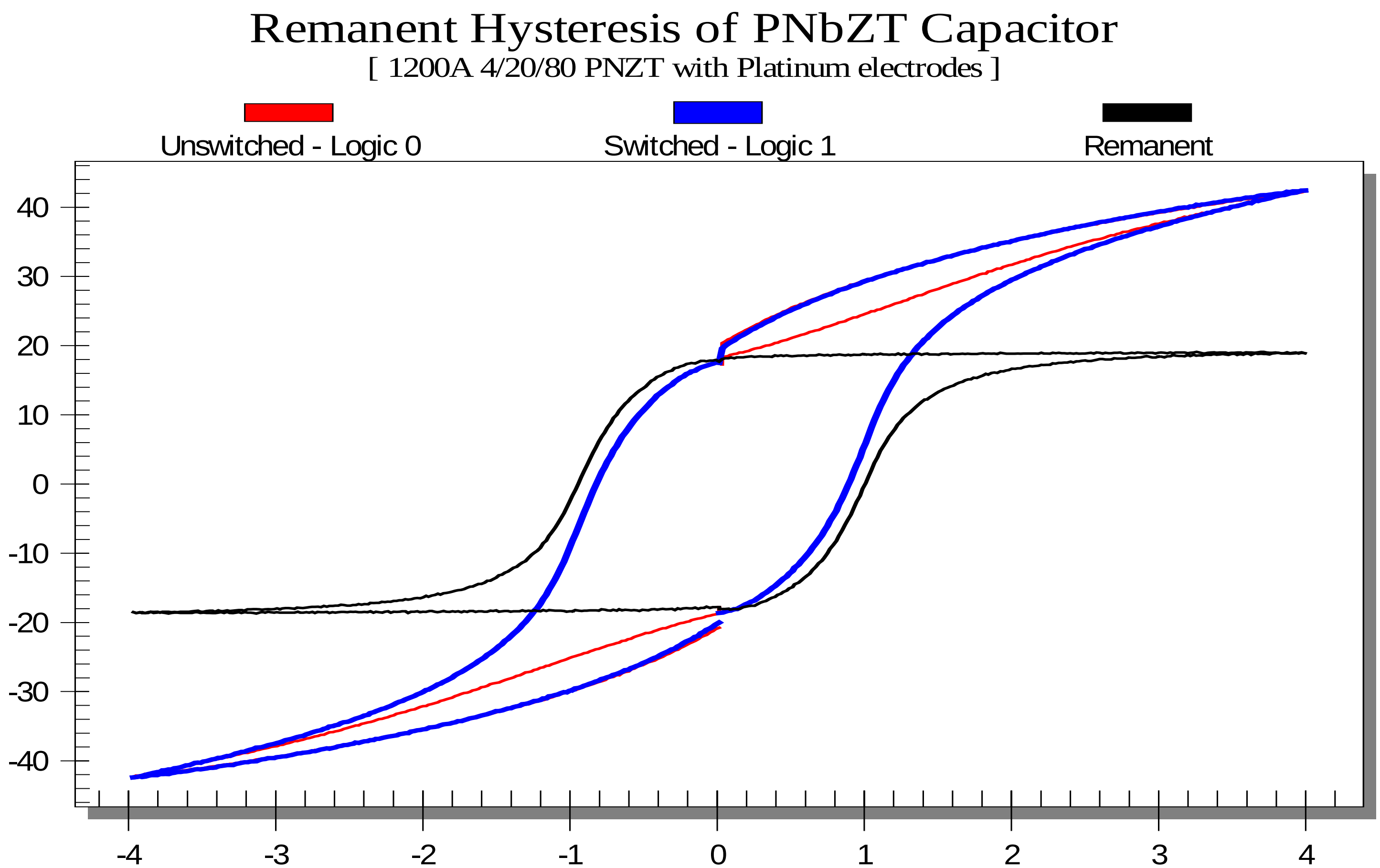
Remanent Hysteresis

PUND: P*r - P^r = dP = Qswitched

Hysteresis: Switching - Non-switching = Remanence:



The Full Remanent Loop



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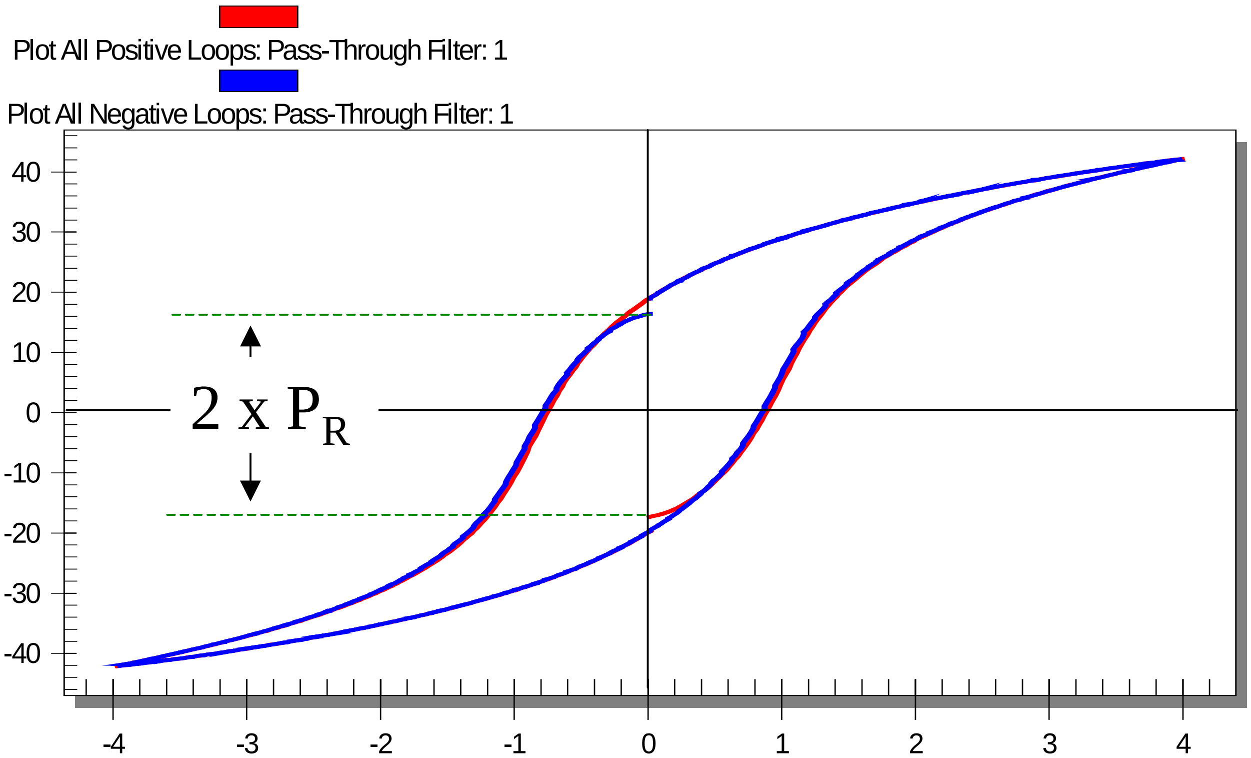
Remanent Polarization in the Hysteresis Loop

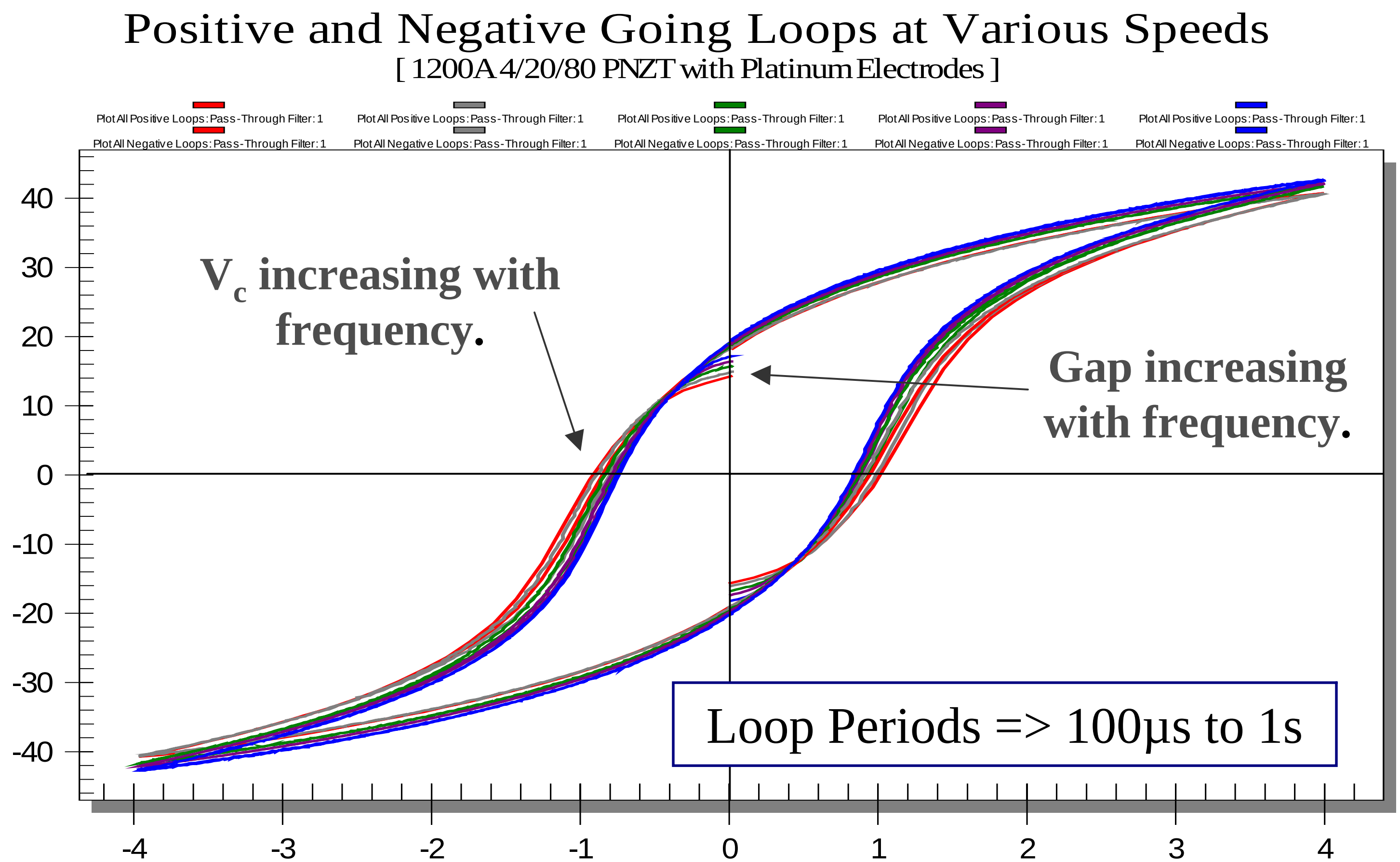
Positive and Negative Going Loops at 100ms Period

[1200A 4/20/80 PNZT with Platinum Electrodes]



The distance between the gaps is the remanent polarization.

The “Gap” vs Speed

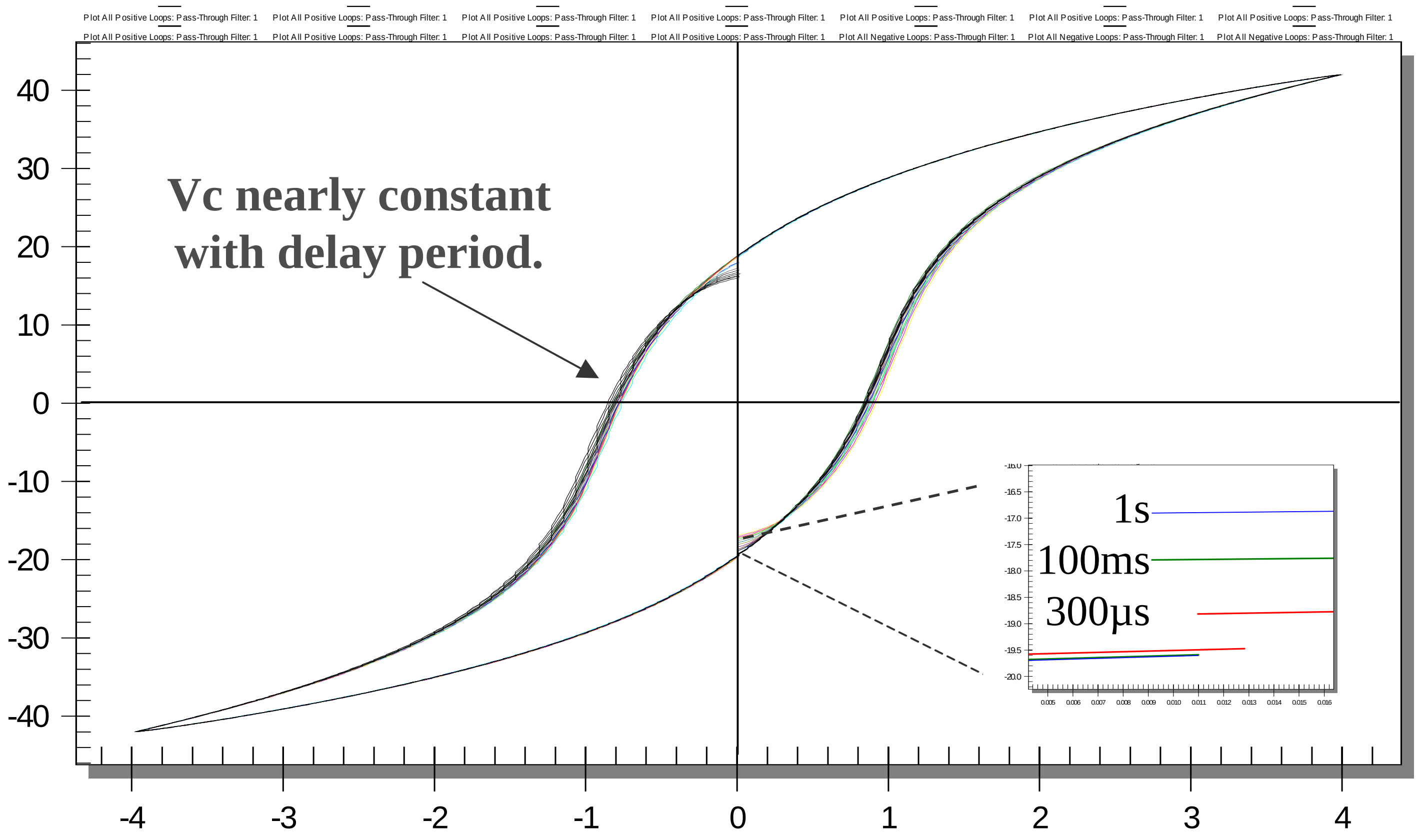


The “Gap” in hysteresis as a function of frequency with a fixed delay period of 1 second.

The “Gap” vs Delay between Loops

Positive and Negative Loops at 100ms with Increasing Delay

[1200A 4/20/80 PNZT with Platinum Electrodes]

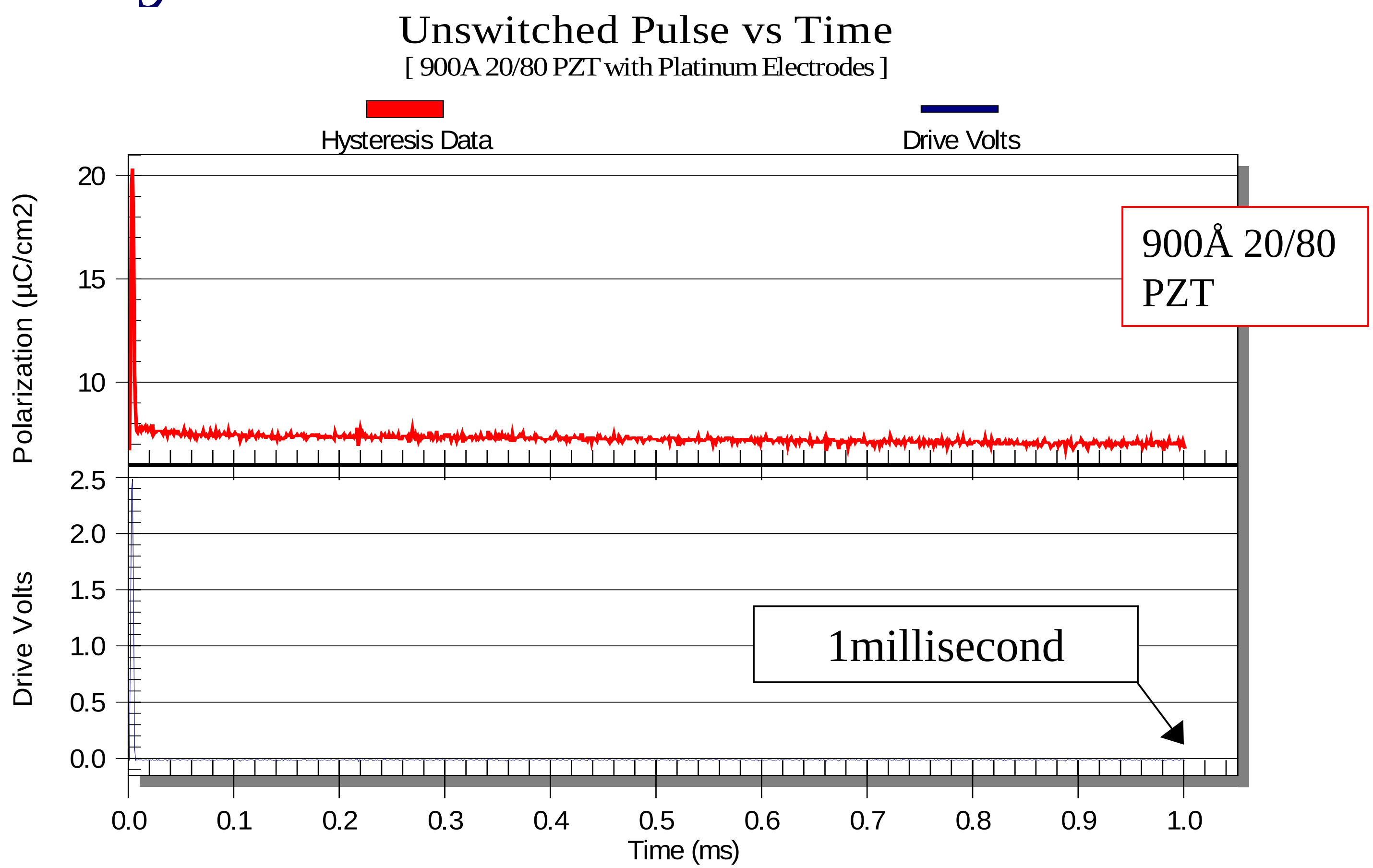


The “Gap” in hysteresis as a function of delay (retention) between loops. There seems to be an effect though not as large as with frequency.

Summary of the Introduction

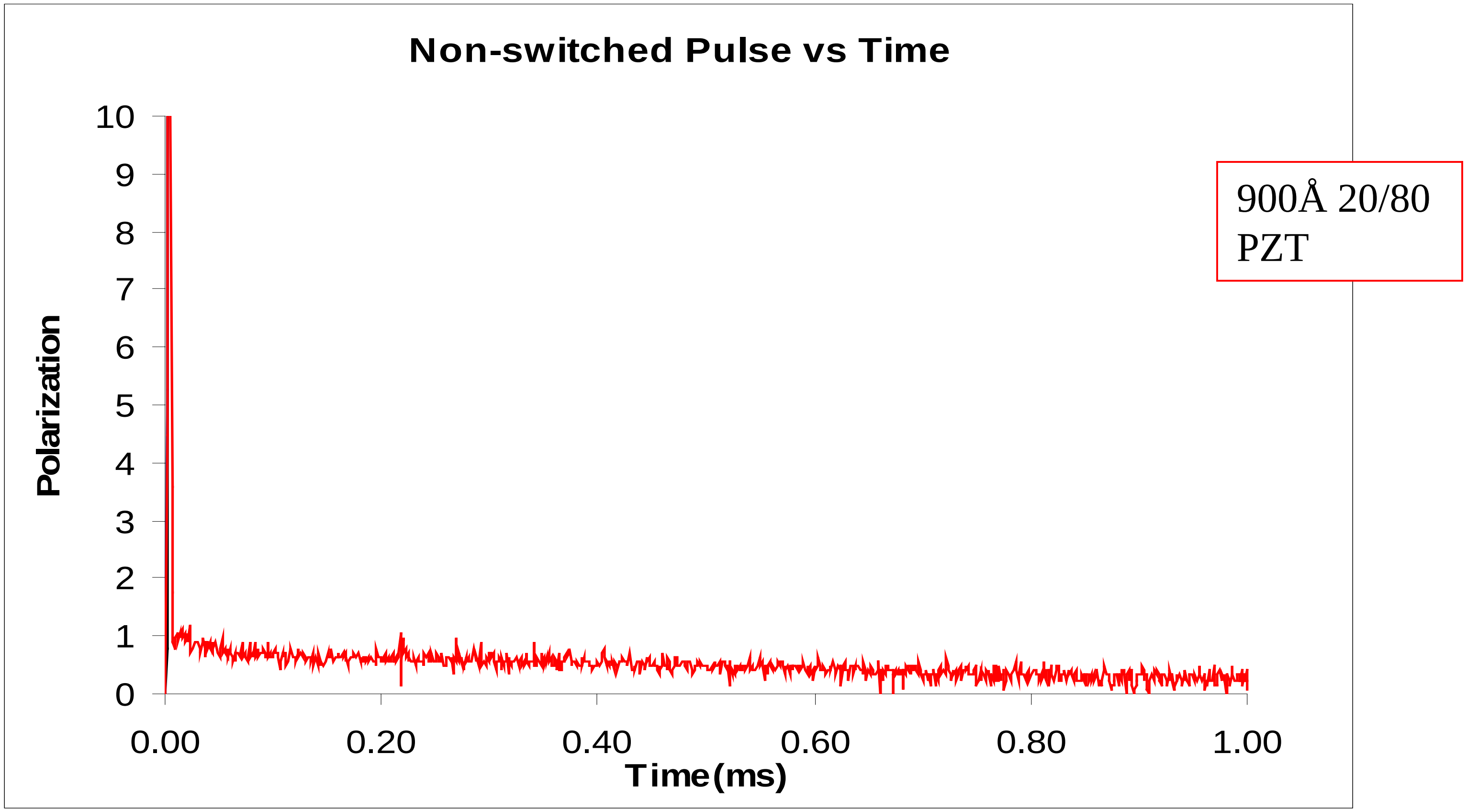
- The definitions have been given.
- The relationship has been established between:
  - the “gap”,
  - P^r,
  - the full hysteresis loop
  - the remanent hysteresis loop
- *What is the time evolution of the gap and does it <u>steal</u> from remanent depolarization?*

Decay on the Microsecond Scale



A single non-switching pulse shows the Non-Return-to-Zero (NRZ) and the immediate onset of the decay.

Decay on the Microsecond Scale



For this 20/80 PZT capacitor, the pulse response stops at $1\mu C/cm^2$ and then begins to decay.

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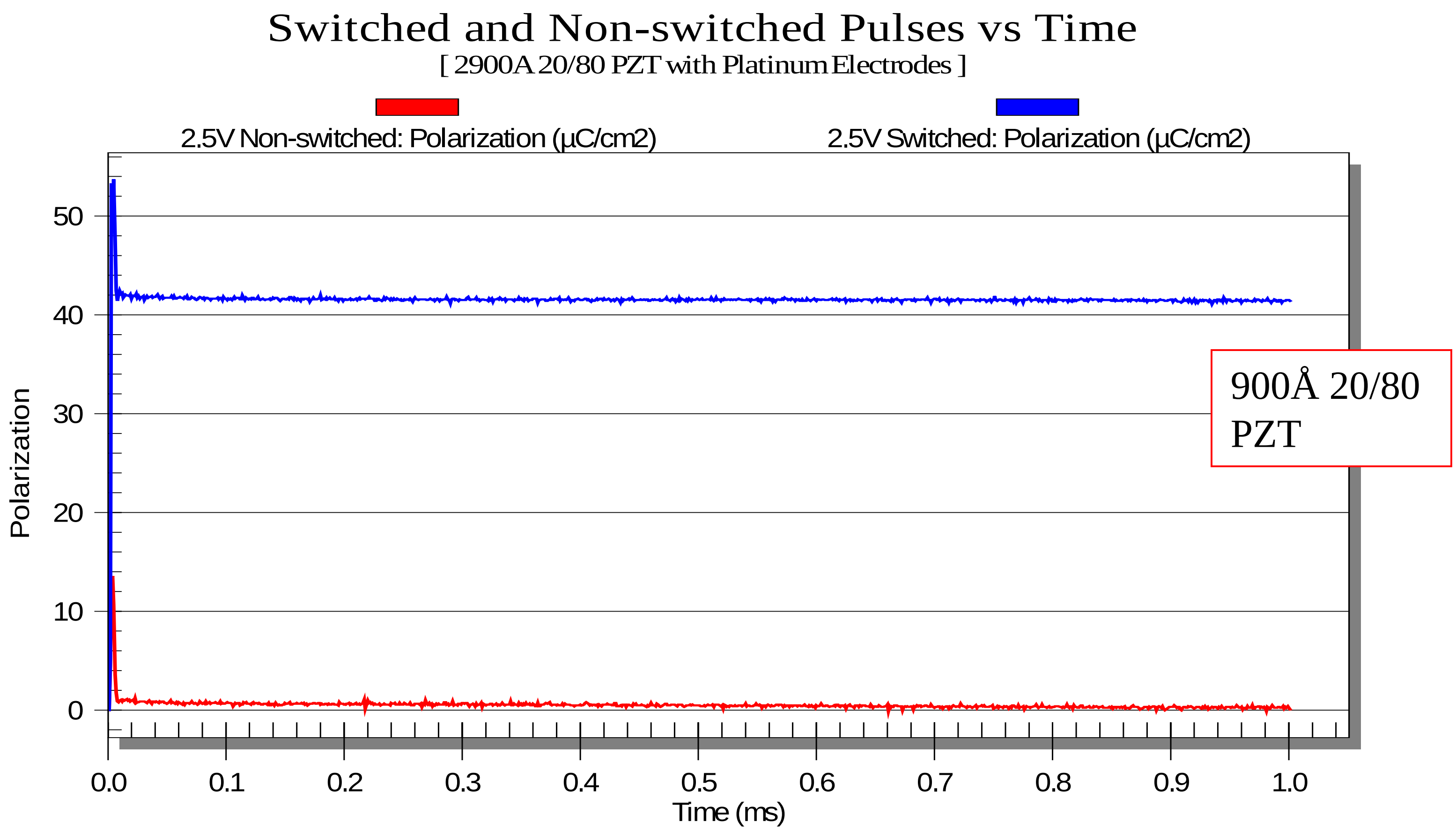
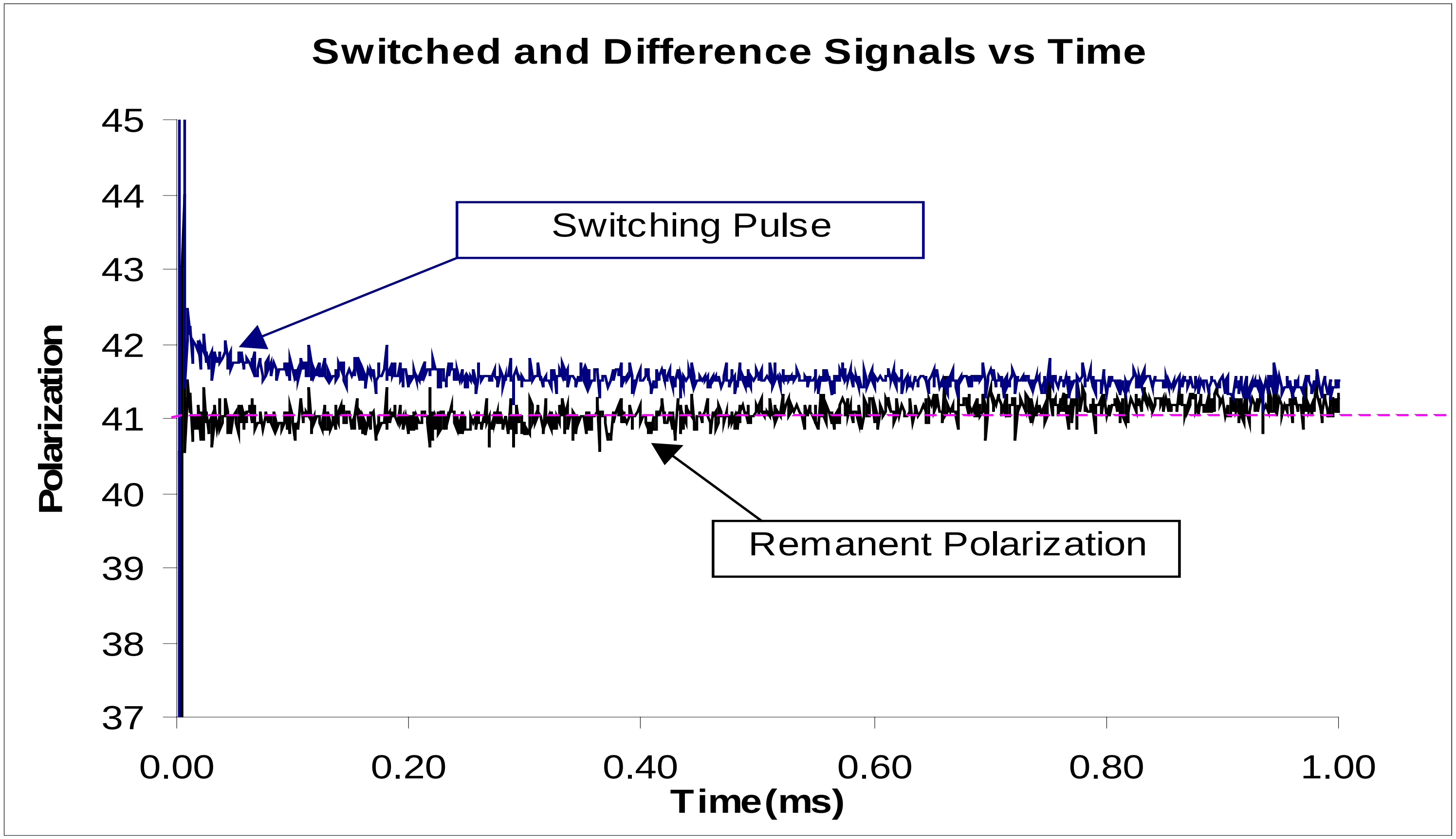
Decay on the Microsecond Scale



The switching and non-switching pulses both generate a decay. *Is it the same rate or different for both?*

Decay on the Microsecond Scale



The difference of the two pulse responses is the time evolution of the remanent polarization.

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Summary of Microsecond Scale Test Results

- The capacitor response to the non-switching pulse does not return to zero at the bottom of the pulse.
- The remanent “pseudo-remanent” polarization begins to decay immediately.
- The switching pulse appears to have the same property.
- The difference between the switching and non-switching pulse responses gives the time response of the remanent polarization.
- The remanent polarization goes immediately to its value and does not decay or increase.

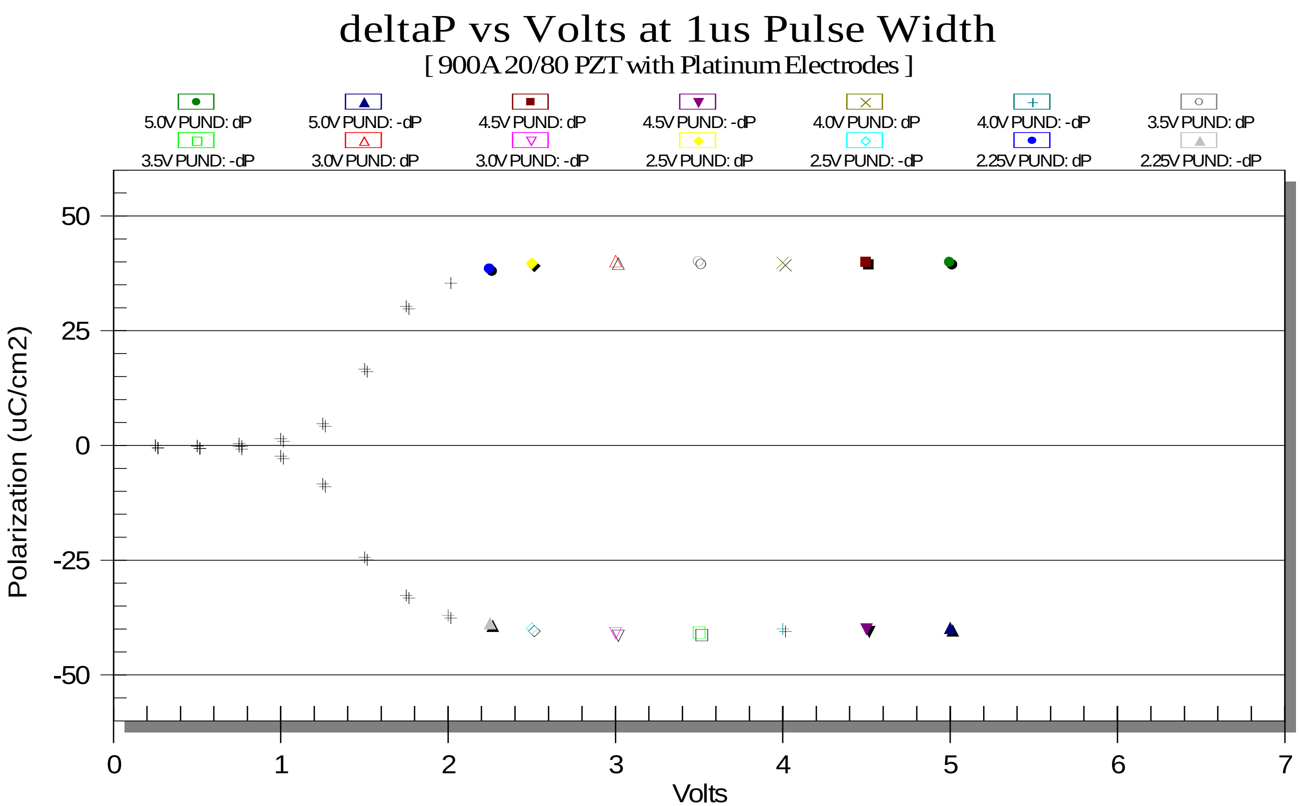
Summary of Microsecond Scale Test Results

- The signal that decays seems to be *exactly* common mode to both the switching and non-switching pulses so it is not affected by the remanent polarization state.
- The remanent polarization of the domains is not decaying.
  - *The signal that decays originates from another source in the material.*

Polarization vs Voltage

- One final test will strengthen the case.
- By executing the PUND test at a series of increasing voltages and plotting Qswitched vs voltage, the saturation voltage and saturation polarization for the remanent polarization can be determined.
  - Qswitched = P* - P^

Remanent Polarization vs Voltage



1µ pulse width on 20/80 PZT capacitor. Delay between pulses is 1 second.

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Remanent Polarization vs Voltage vs the Delay Period.

Experiment: Conduct Remanent Polarization vs Voltage tests with a fixed 1μs pulse width but vary the delay between the pulses:

Test 1:	100μs delay
Test 2:	1ms delay
Test 3:	10ms delay
Test 4:	100ms delay
Test 5:	1 second delay

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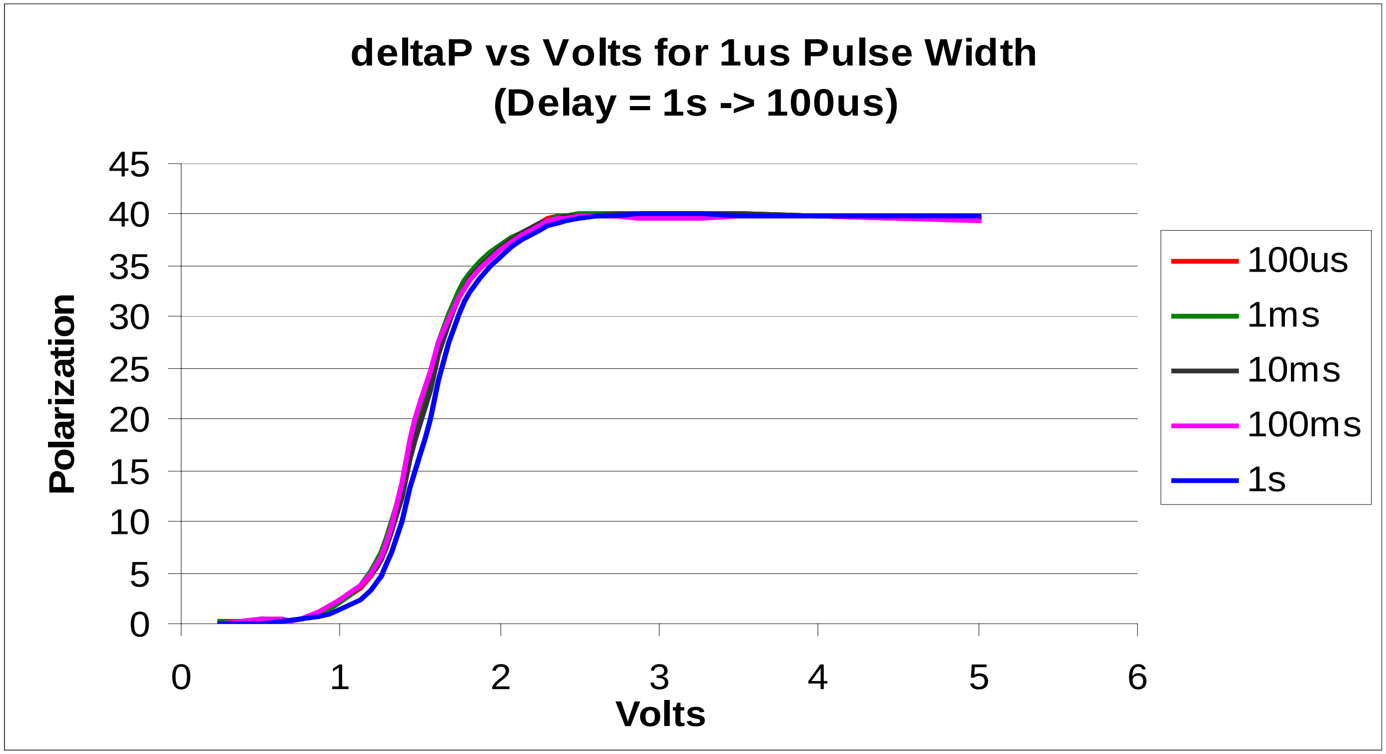
Remanent Polarization vs Voltage vs the Delay Period.



It all goes to the same remanent polarization independent of the delay between the pulses.

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Summary

1. In our tests, remanent polarization developed immediately during a pulse measurement and remained constant from 1µs onward.

2. Despite the constancy of the remanent polarization, both the switching and non-switching polarizations showed a decay.

Summary

3. Since remanent polarization is constant during the decay, *domain polarization is not depolarizing nor is it being shielded by moving charge.*

4. There must be an extra charge source in the ferroelectric capacitor besides the domain polarization, one that is stimulated by the applied voltage and decays when the hysteresis stops.

Why is this important?

- Ferroelectric materials are being tested, commercialized, probed, and modeled.

- The parasitic “charge” or “polarization” of the “gap” might be
  - mobile free charge
  - space charge from carriers
  - space charge formed from lattice distortion
  - piezoelectric energy storage
  - heat dissipation
  - energy storage in resonant mechanical oscillation
  - charge traps at the electrode interfaces
  - depletion region modulation

Why is this important?

– Band gap trap emission and recapture

– bulk trap emission and recapture

– some other mechanism

– some combination of some or all of the possibilities listed above with non-linear coupling relationships!

–>(My bet is on this one! Why not!)

- Any probe (optical, physical, force, or electrical) will be affected by one or more of the mechanisms listed above.
  - I spotted this effect in several papers given at the conference so far: SHG and piezoelectric displacement.
- *We need to understand and model this mechanism*!