Welcome!

Device Characterization with the Keithley Model 4200-SCS Characterization System

Ultra-Fast I-V
for Pulsed and Transient Characterization

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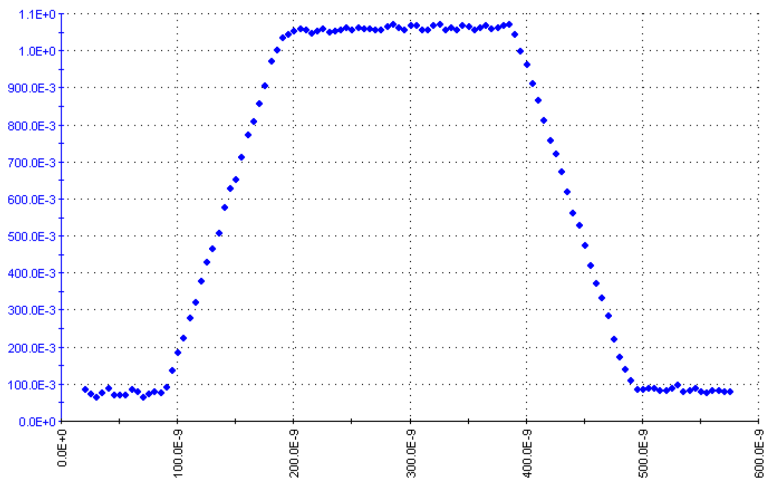
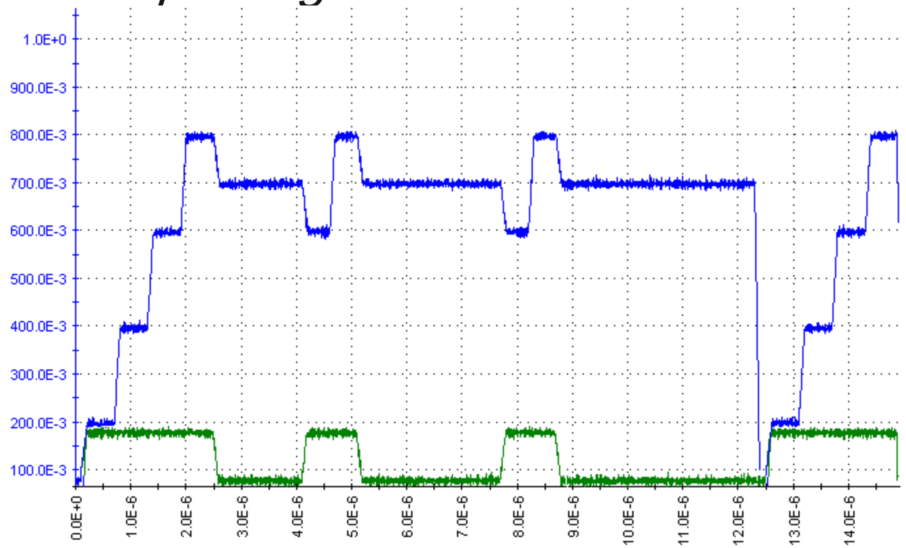
Ultra Fast I-V

- **Ultra Fast I-V means any test that requires**
  - short pulses or transitions between voltages (< 10 us)
  - Multi-level waveforms (examples: Flash testing or ultra fast BTI)
  - High-speed measurements *while pulsing*





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Ultra Fast I-V Hardware (1/2)

- **Model 4225-PMU – Ultra Fast I-V**
  - 2 channels of voltage pulsing with integrated simultaneous V and I measurement on each channel
  - Uses single slot in 4200 Chassis
  - Up to 4 cards per chassis (leaving 5 slots available for SMUs and CVU)
- **Pulse from mV to 40V (into high impedance)**
- **Pulse widths from 60 ns to 999 ms**
- **Control timing parameters**
  - Pulse Delay
  - Pulse Width
  - Rise Time and Fall Time
  - Pulse Period

Optional 4225-RPM Remote Amplifier/Switch

- Optional Remote Amplifier Switch (4225-RPM)
  - reduces cable effects, adds low current measure ranges
  - Measure signals to <5 nA
- 4225-RPM also acts as SMU/PMU/CVU switch matrix
  - Simplifies test set ups, quicker testing
  - No re-cabling when moving between test types
    - SMU
    - CV
    - Pulse IV

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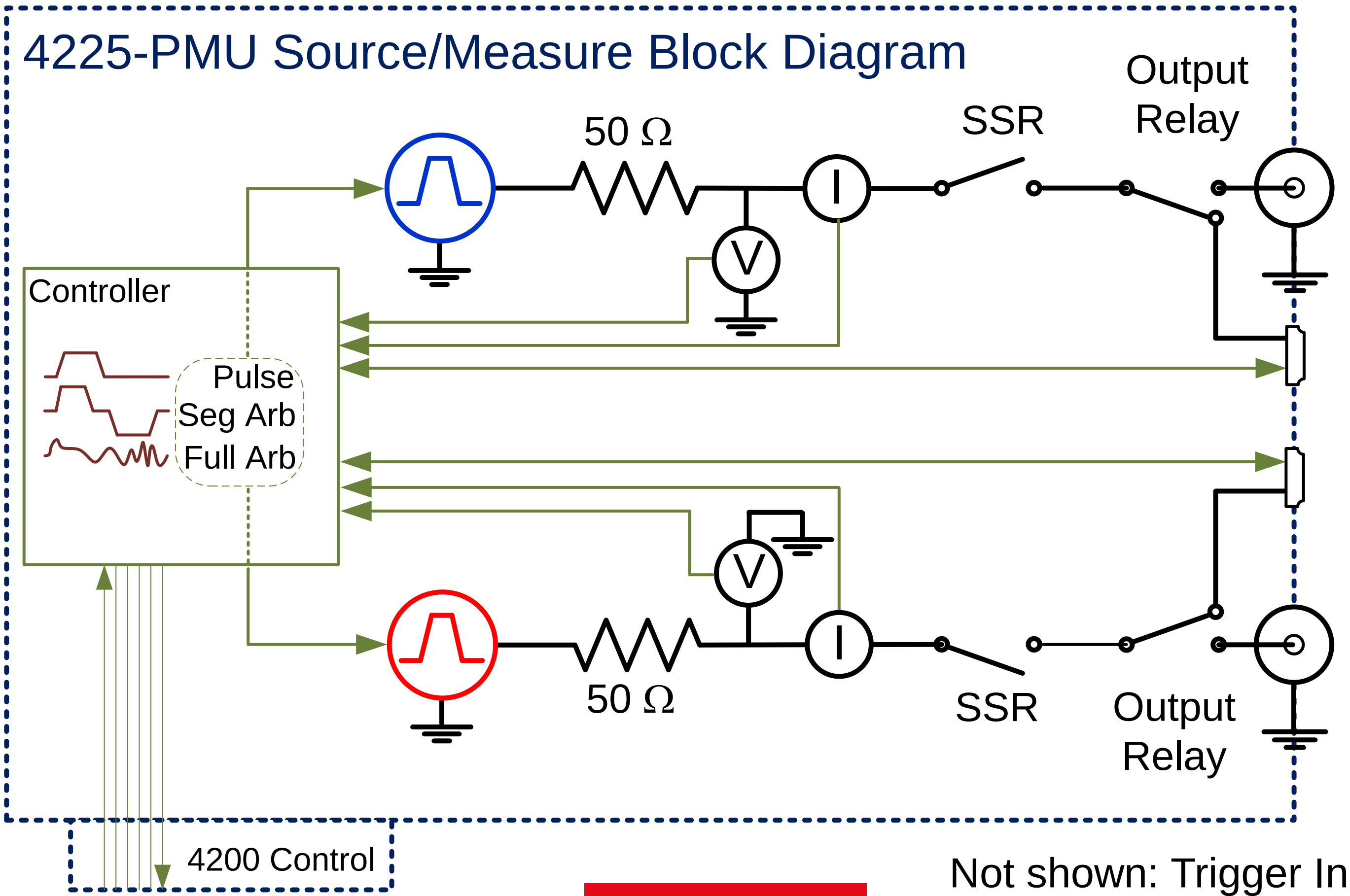
4225-PMU Block Diagram



Not shown: Trigger In and Out

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Ultra-fast IV applications require different capabilities

	Voltage	Max Current	Min Current	Rise time	Pulse Width	Duty Cycle
Single Pulse Charge Trapping / High K	+/-10v	10mA	<100nA	<100nSec	50nS-1uSec	n/a
Silicon-On-Insulator / isothermal	+/-10v	10mA	<10nA	<100nSec	100nSec	0.01%-50%
LDMOS/GaAs isothermal	+/-40v	400mA	<100nA	<100nSec	200nSec	0.01%-50%
Flash	+/-40v	10mA	<10nA	100nSec	100nS-1mSec	n/a
PC-RAM	+/-10V	10mA	<100nA	<10necS	150nSec	n/a
UF NBTI	+/-10	10mA	<2nA	50nSec	<1uSec	n/a
Thermal Impedance	+/-40V	400mA	1uA	<1uSec	1uS-1Sec	0.1%-50%
RTS	+/-40V	10mA	<10nA	n/a	100nS-1mSec	n/a
CBCM	+/-10V	10mA	100nA	1uSec	1uS-10mSec	1%-50%

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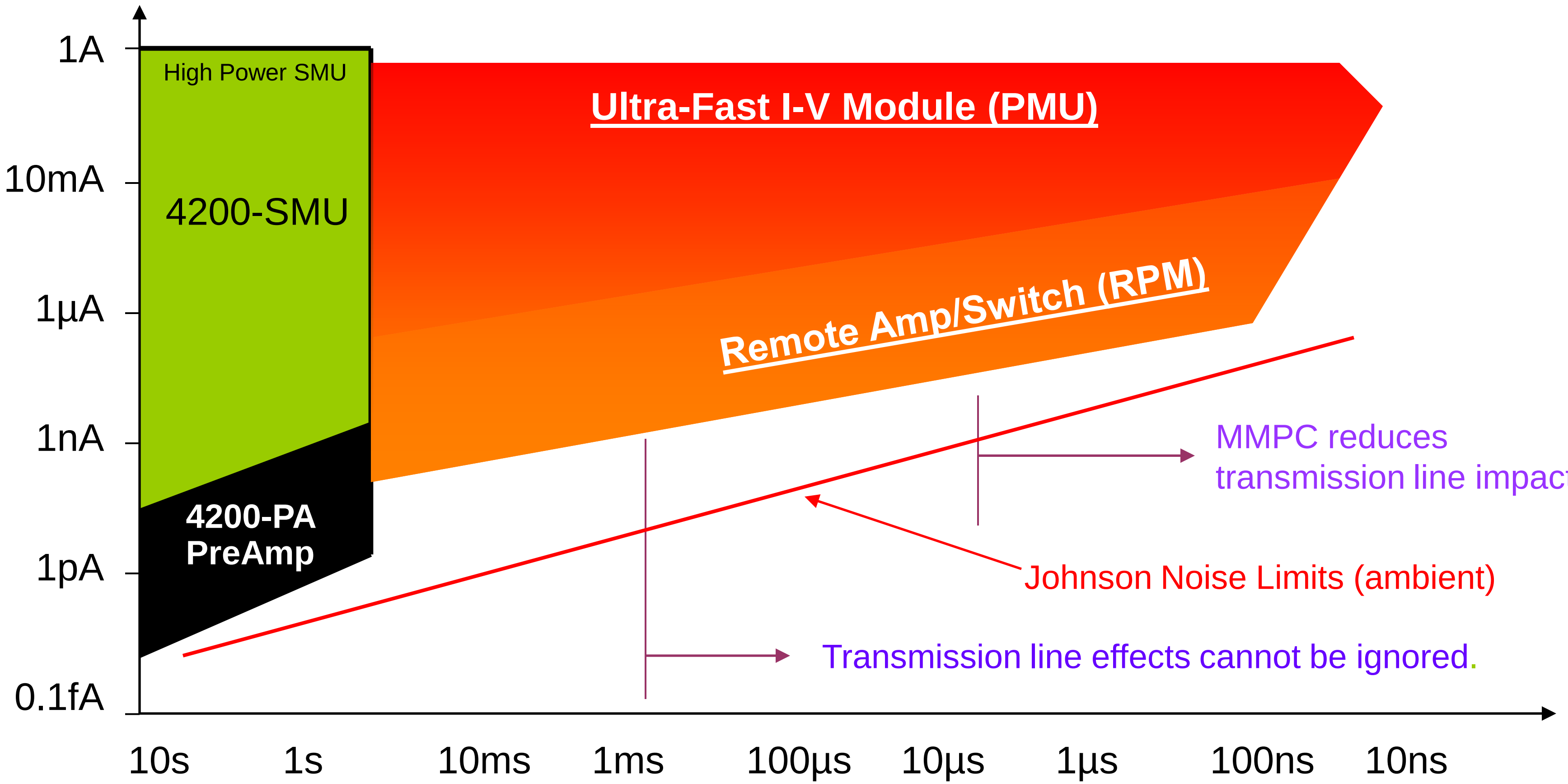
Difference between DC and Ultra Fast I-V?

- **What are the main differences between a 4200 SMU and the 4225-PMU?**
- **DC I/V – Accuracy/Precision Priority**
  - Force voltage and/or current conditions on device
  - Delay until the system reaches equilibrium
  - Measure with long integration time to maximize accuracy and precision
- **Ultra-Fast I/V – Deterministic Timing Priority**
  - Force sequence is precision timed
  - Delays are limited to "time available" in sequences
  - Measurement sequence runs in "lock step" with force sequence

Current vs. Time Measurement Comparison



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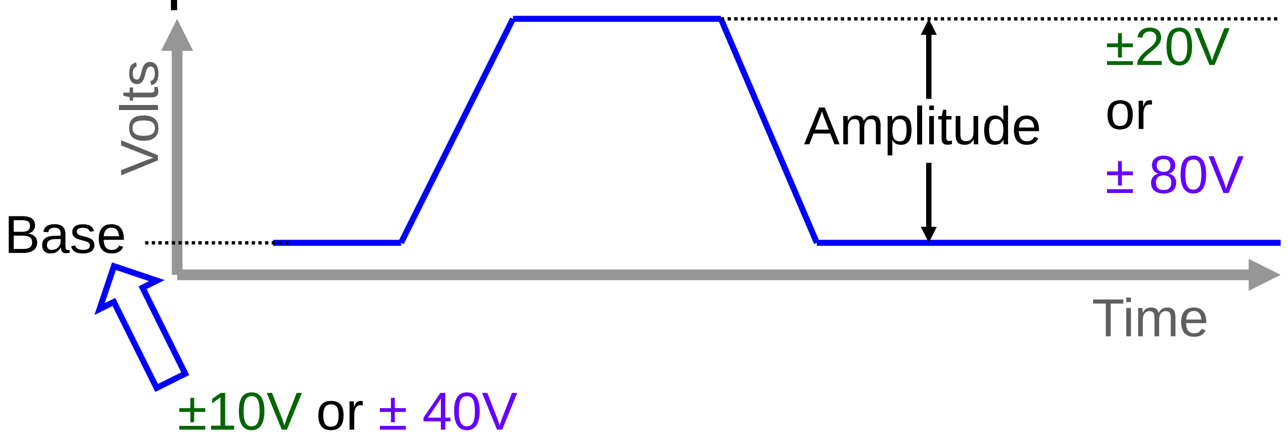
Pulse Voltage

- 2 voltages to define standard (2-level) pulse
- Two PMU source ranges
  - 10V (into high impedance)
  - 40V (into high impedance)
- Base: 10V or 40V
- Amplitude: 20V or 80V



Key:
±10V range
± 40V range

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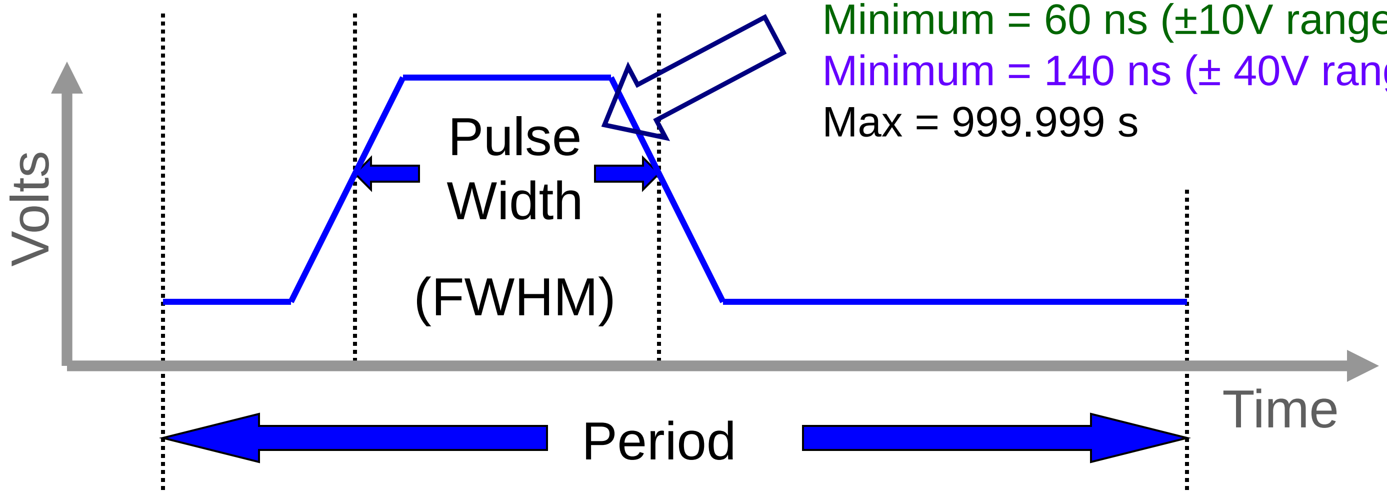
Pulse Timing (1/2)

- **Pulse Width is calculated at 50% amplitude**
  - Full Width at Half Maximum (FWHM)

Pulse Width
Minimum = 60 ns (±10V range)
Minimum = 140 ns (± 40V range)
Max = 999.999 s



Minimum of 120 ns for   10V range
Minimum of 280 ns for ± 40V range
Max = 1 s

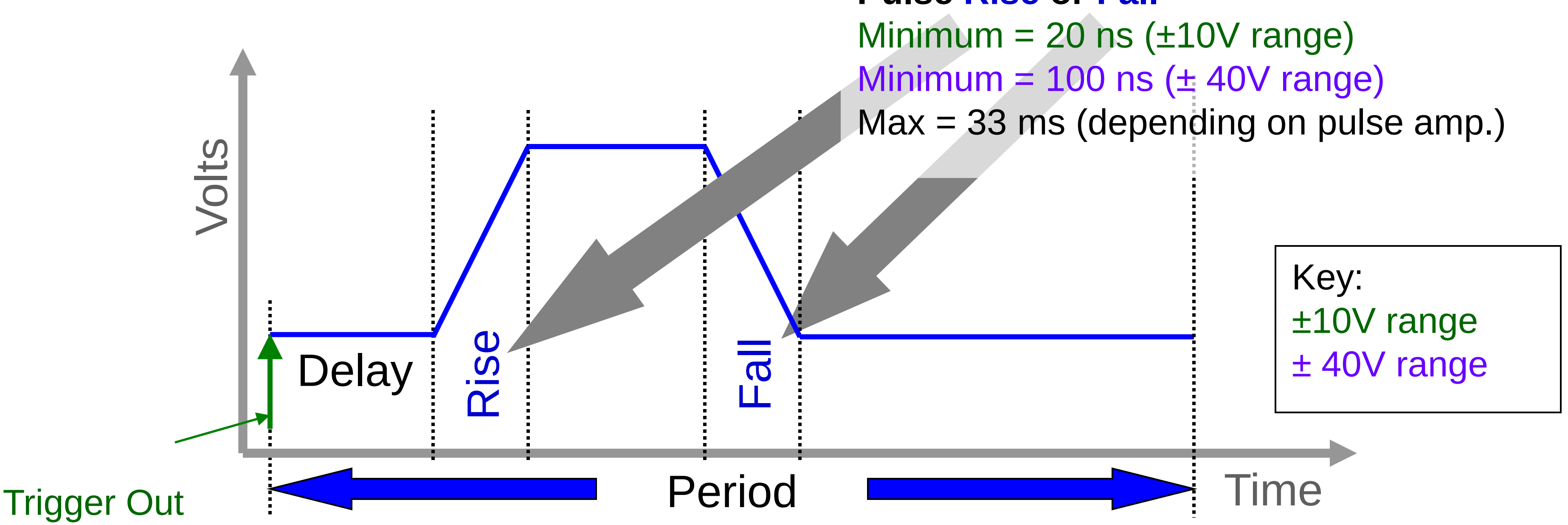
Key:
±10V range
± 40V range

Timing values shown for measurement enabled.
Shorter minimums available for source only.

Pulse Timing (2/2)

- **Transitions**
  - Rise and Fall are for 0-100% (Industry uses 10-90%)
- **Pulse Top & Pulse Base Time**

Pulse Rise or Fall
Minimum = 20 ns (±10V range)
Minimum = 100 ns (± 40V range)
Max = 33 ms (depending on pulse amp.)



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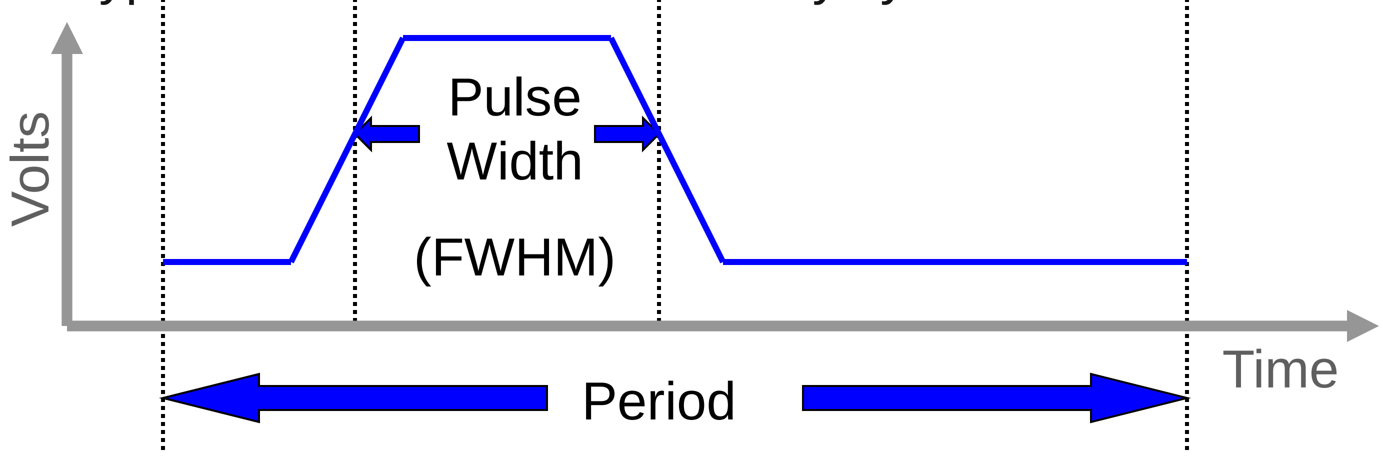
Duty Cycle

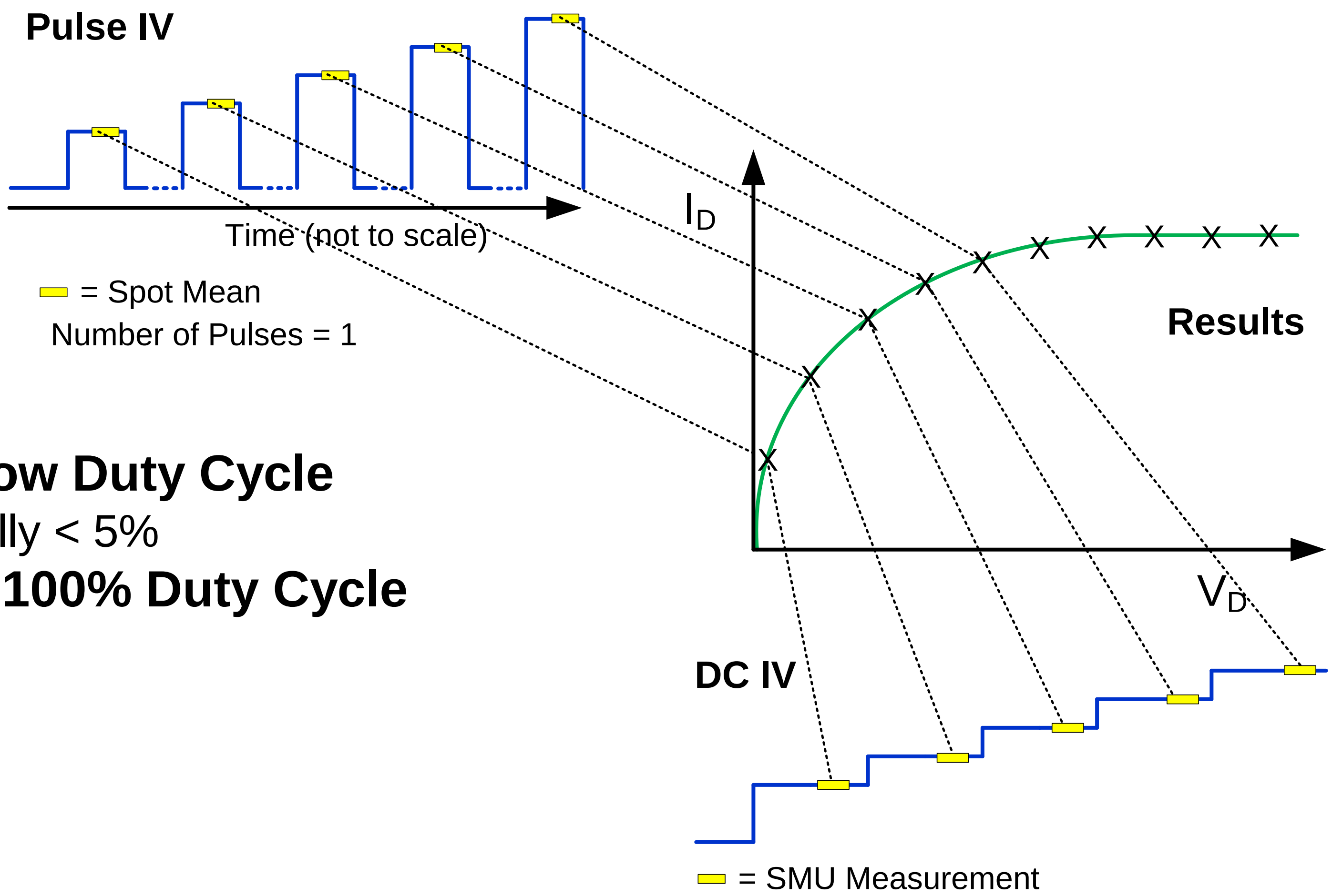
- **Duty Cycle = Pulse Width / Period**
  - Amount of time that the pulse is “on”
  - Typical isothermal tests use duty cycle < 5%



Example: 100 ns PW, 1 us Period:

Duty Cycle = PW / Period = 100e-9 / 1e-6 = 0.1 = 10%

Pulse IV vs DC Testing Diagram



Pulse IV: Low Duty Cycle

- Typically < 5%

DC testing: 100% Duty Cycle

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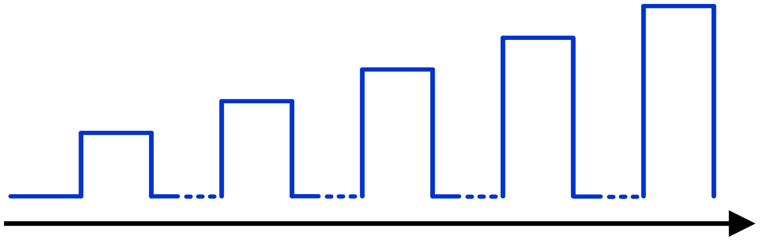
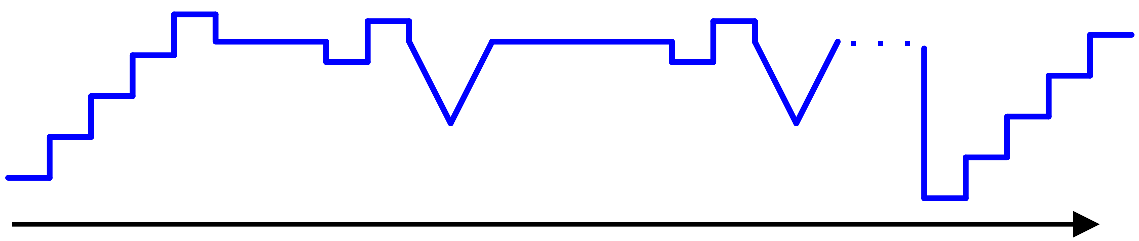
PMU Source modes

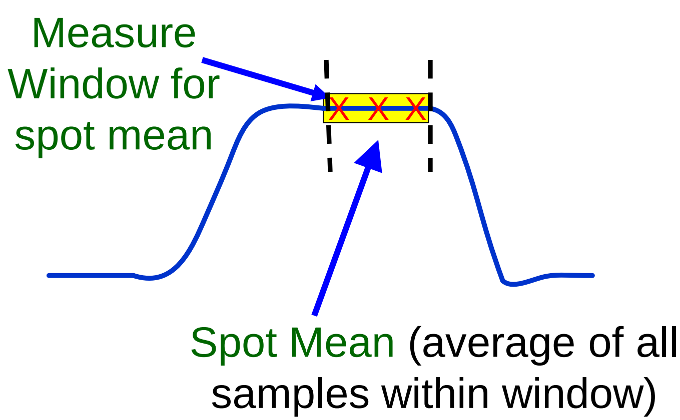
- **PMU provides Ultra-fast IV through 2 types of Source Modes**
  - Standard (2-level) Pulse
  - Segment ARB™

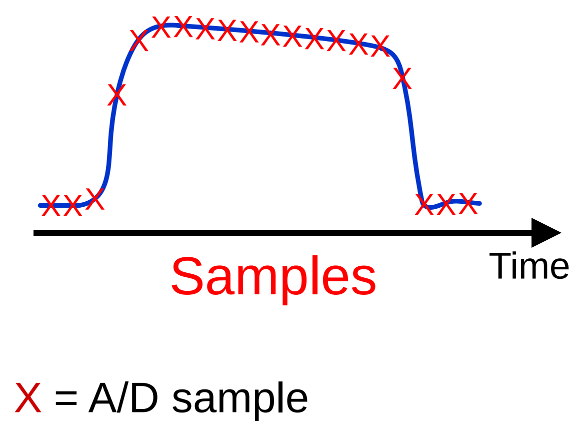




PMU Measure types

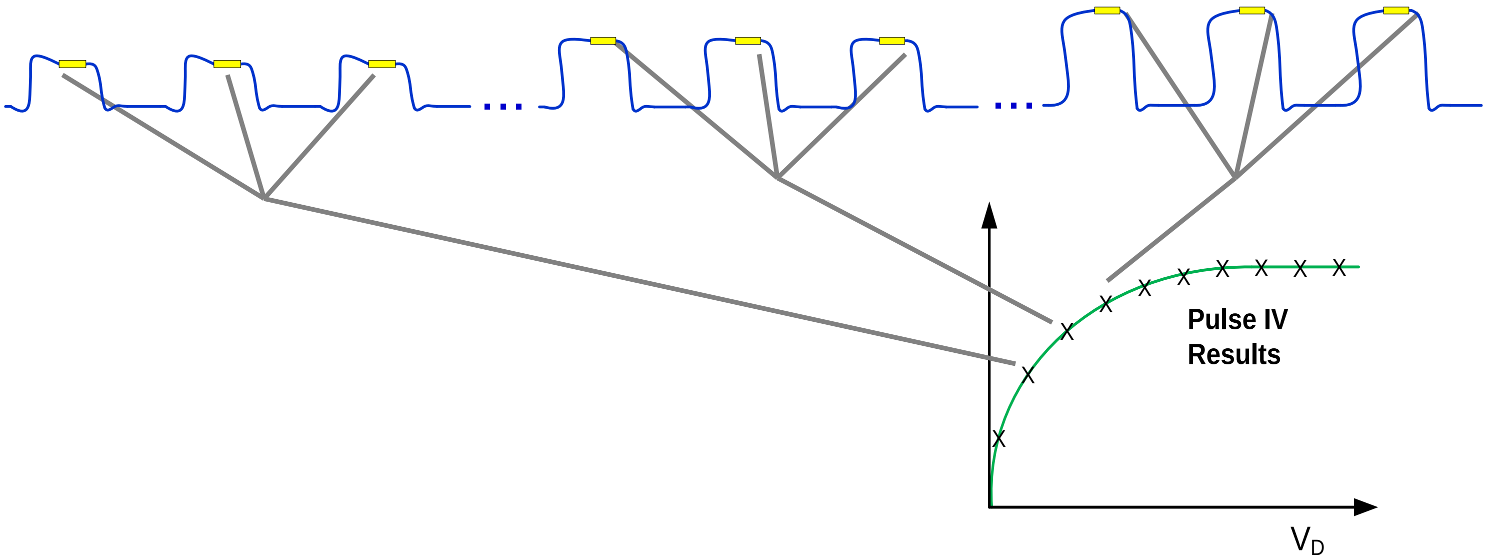
- **PMU provides Ultra-fast IV through 2 types of Measure Types**
  - Spot Mean – used for Pulse IV
    - **Just a mean of all samples within the measure window**
  - Sample – used for Waveform Capture
    - **Individual A/D samples across the measure window**
- **Averaging and Discrete**
  - When sourcing multiple pulses, can choose to average them, or keep them as individual readings





Tests using Spot Mean

- **Spot Mean**
  - Used for
    - **IV Sweeps using standard (2-level) source mode**
  - Provides the mean of samples within measure window



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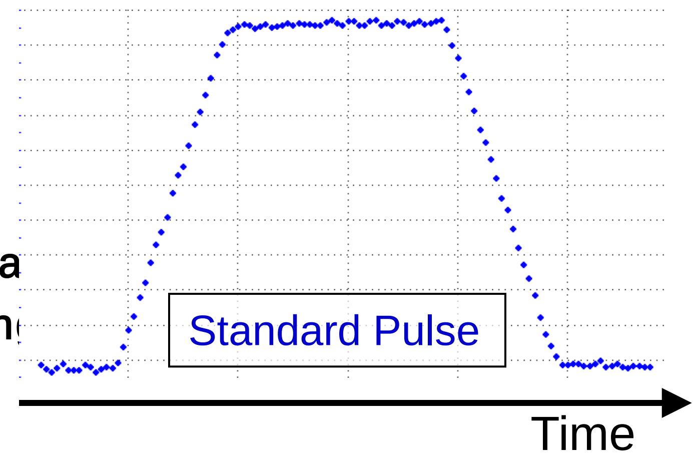
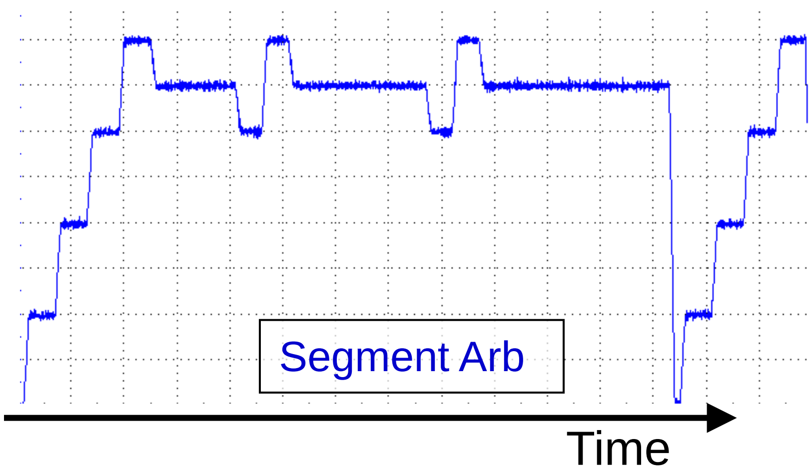
Tests using Sample Measurement

- **Sample**
  - Used for
    - **Waveform Capture**
    - **Instrument setup verification and valida**
    - **Pulse shape validation prior to IV testin**
    - **Transient IV**
    - **Time-resolved reliability**
  - Provides signal versus time data
  - Maximum sample rate = 200 MSa/s
    - **Sample every 5 ns**
    - **Minimum sample rate = 1kSa/s**





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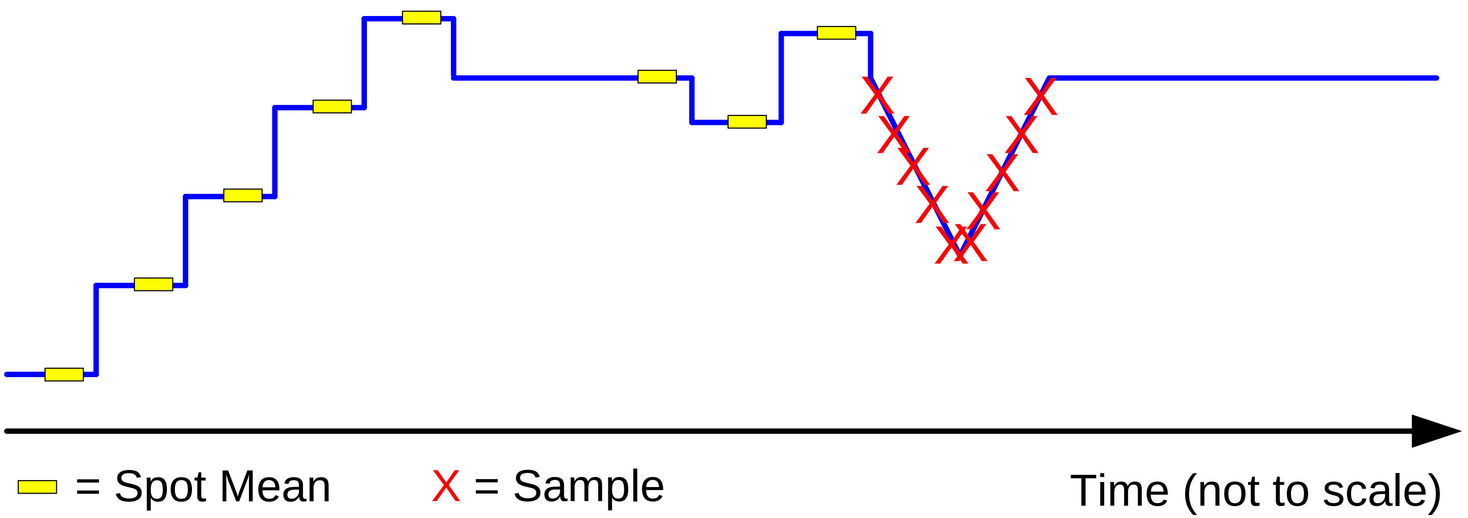
Segment Arb supports Spot Mean and Sample

- Segment Arb allows both Spot Mean and Samples within a single waveform



Segment Arb with multiple levels, Spot Means and Sample measurements

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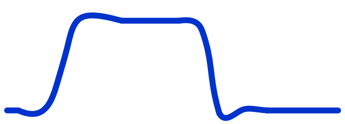
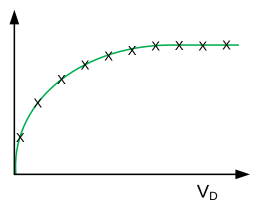
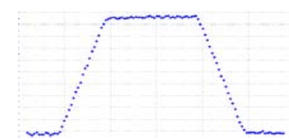
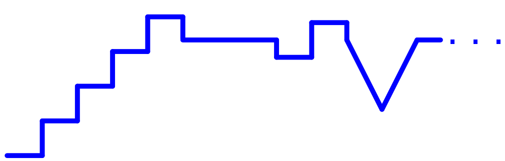
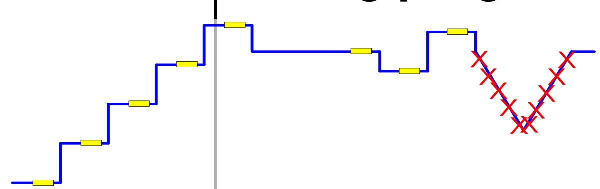
PMU source and measure modes for UF IV

Source\Measure	Spot Mean	Sample (waveform capture)
2-level 	**Pulse IV Sweeps** 	**Transient Characterization** •Thermal effects •Charging effects (hysteresis) 
Segment ARB 	**UF BTI** **NVM**	**UF BTI dynamic recovery** **NVM Transient Characterization during program and erase**



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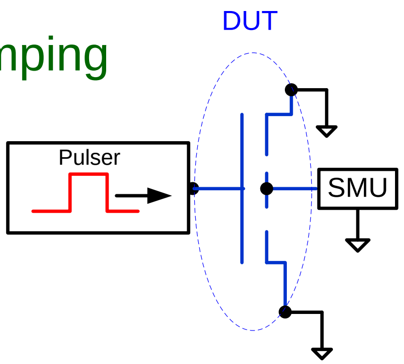
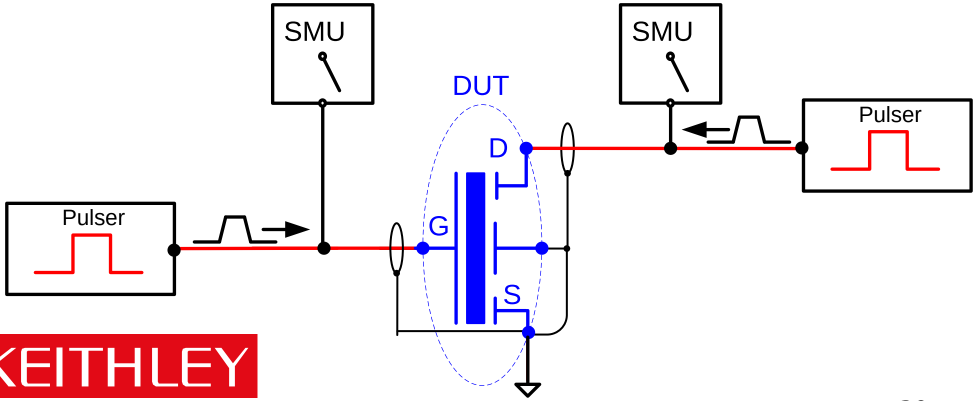
Other Common Pulse Tests: Charge Pumping, Flash Testing

- **Why are Charge Pumping and Flash testing missing from previous slide?**
- **Both Charge Pumping and traditional Flash testing do not require Pulse IV (no fast measuring during the pulse)**
  - Charge Pumping
    - Pulse on gate (ground drain and source)
    - SMU measures DC current on bulk
  - Flash
    - Pulser to Program and Erase device
    - SMU to characterize (usually V_T sweep)

Charge Pumping



Flash



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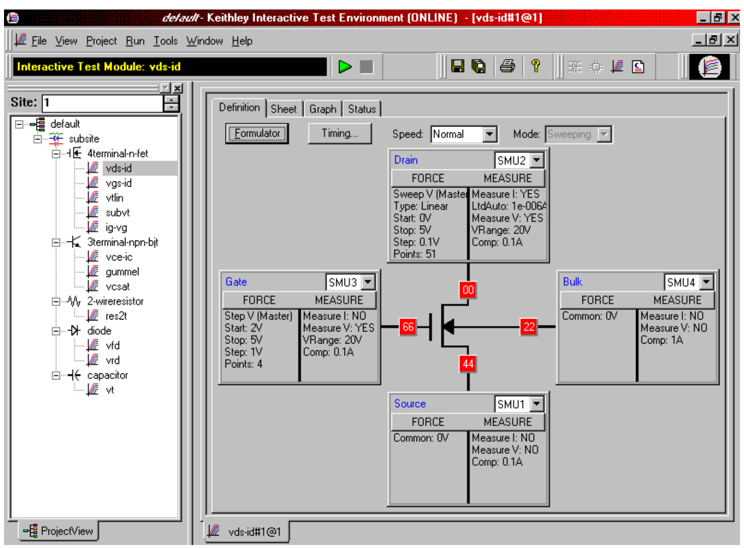
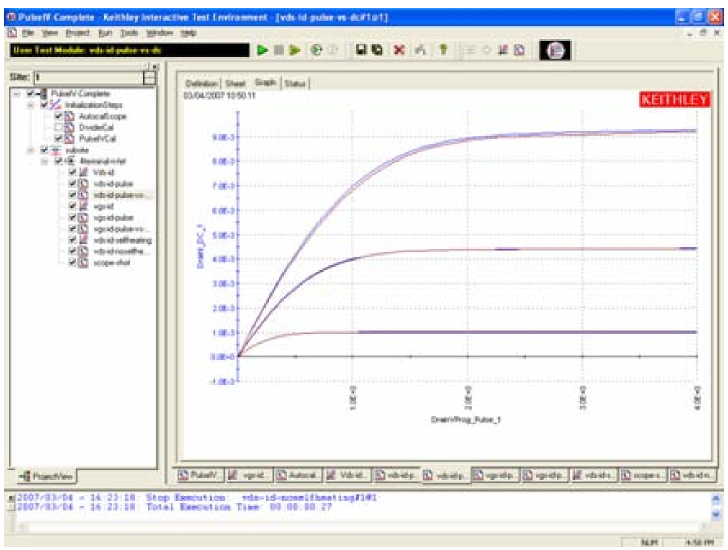
Pulsed (or Ultra-Fast) I-V
As easy as DC

1. Connect your DUT
2. Set up the PMUs using KITE graphical user interface
3. Click on the green arrow
4. See the Curve and data





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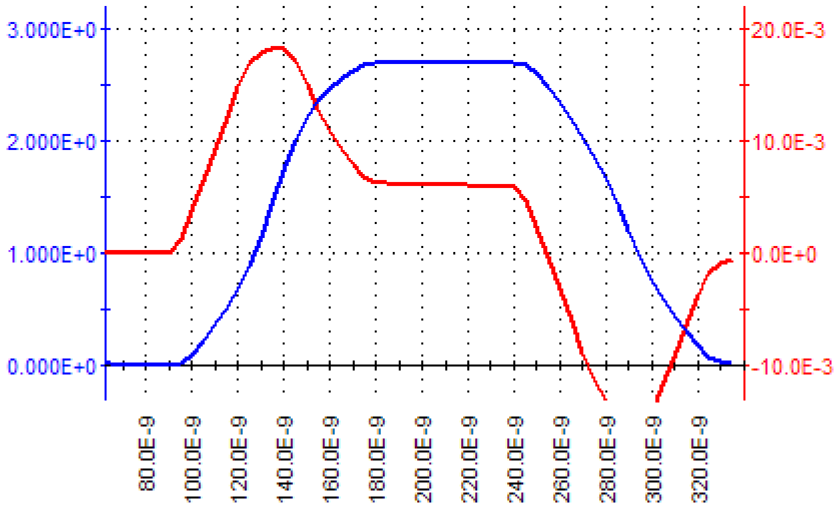
Introduction to Transient Pulse Analysis

- Pulse shape determines Spot Mean value for Pulse IV Curves
- Pulse top must be settled for Pulse IV result to correlate to SMU result
- Brief introduction to current charging effects during pulse transitions



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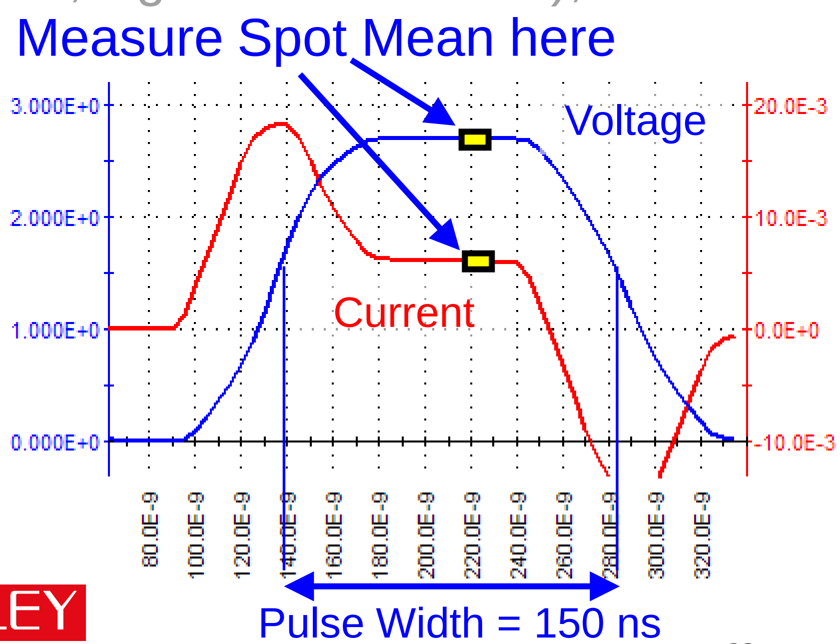
Why pulse shapes are important for Pulse IV

- **Pulse IV sweep use measurement from settled part of pulse**
  - PMU does not have any way to tell if signal is settled
  - Spot mean measure window is at the latter part of the pulse
  - If the pulse width is too short (that is, signal is not settled), a spot mean is still provided



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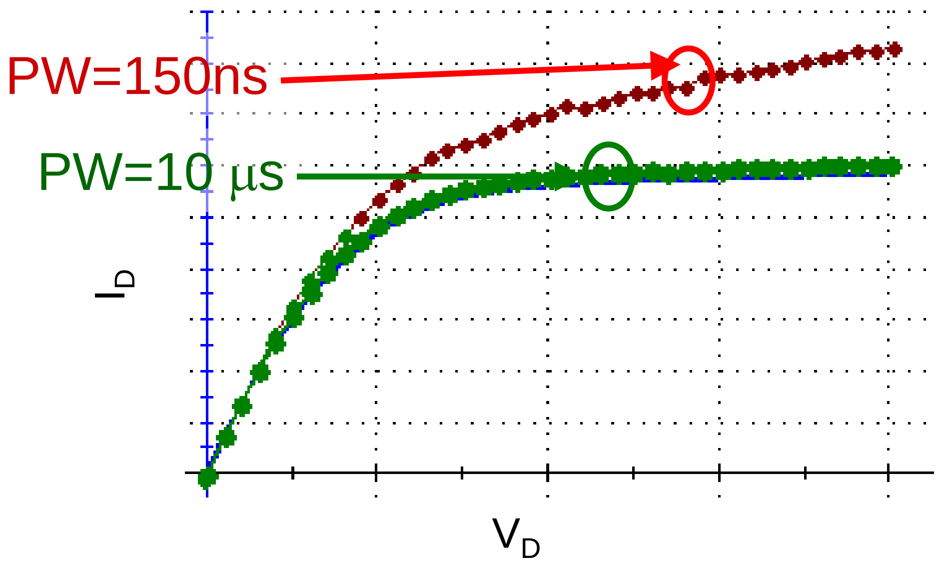
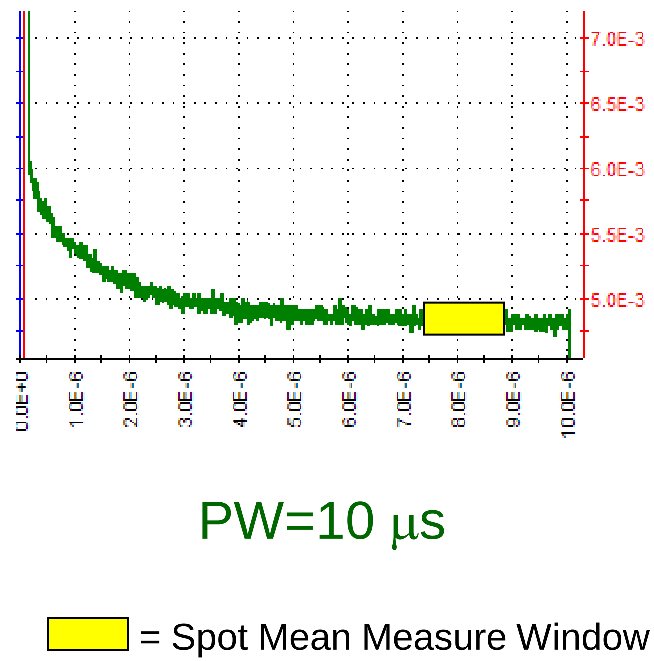
Pulse IV curve versus Pulse Width

- Pulse width directly effects the resulting Pulse IV Curve
- PW = 150 ns (not settled)
- PW = 10 µs (settled)





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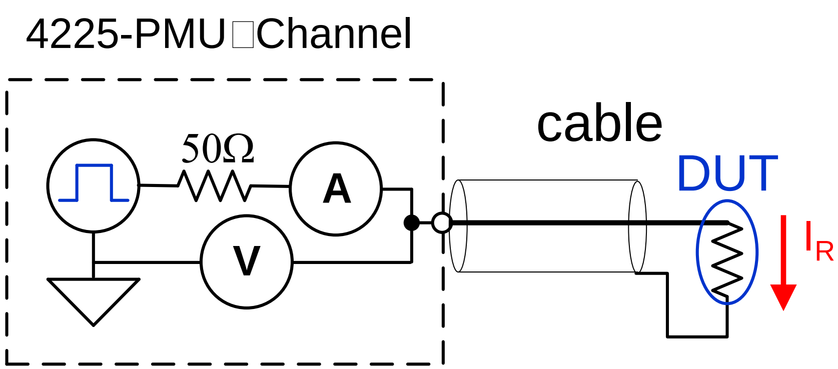
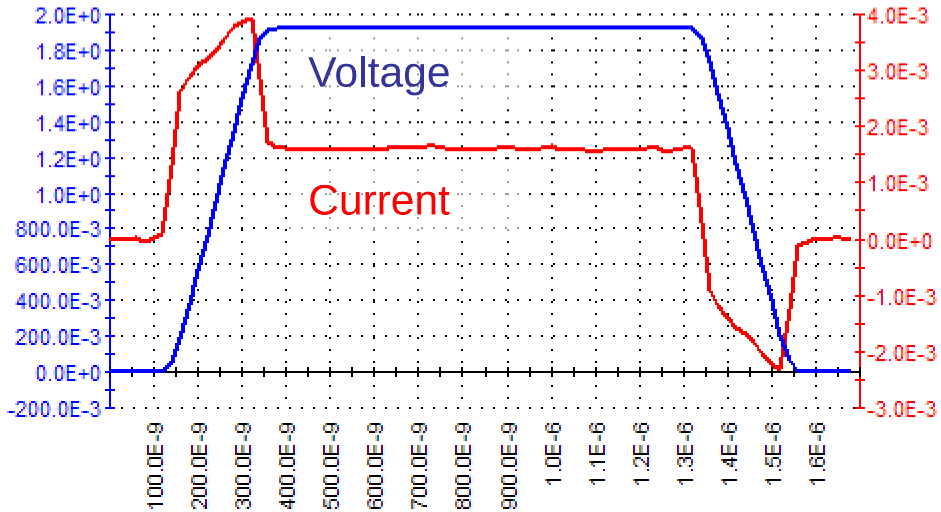
Current Waveform

- **Pulse voltage across resistor**
- **Measure voltage and current versus time**





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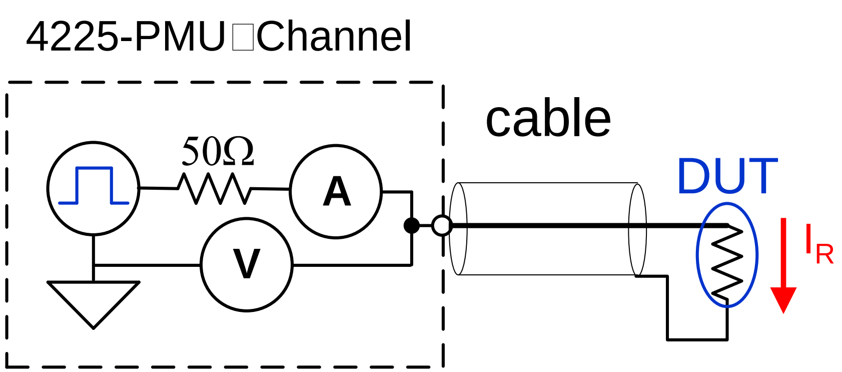

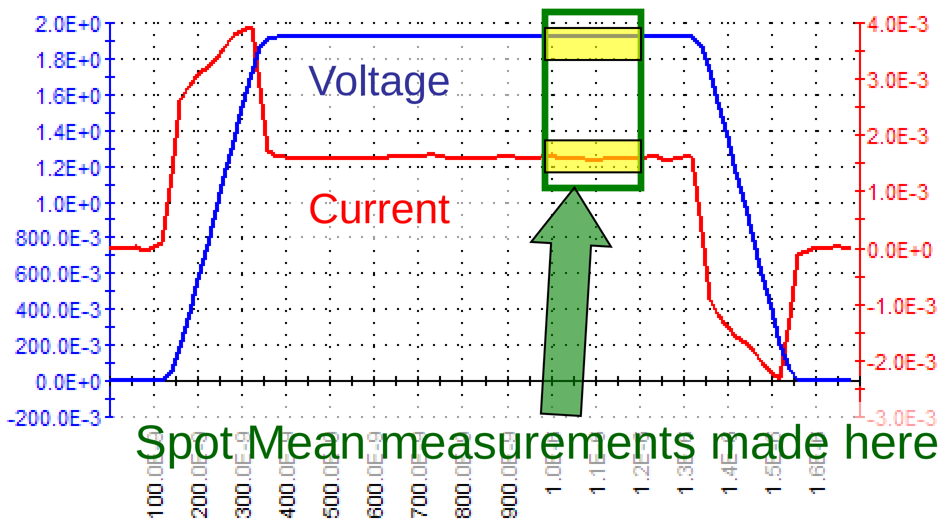

= Spot Mean Measure Window

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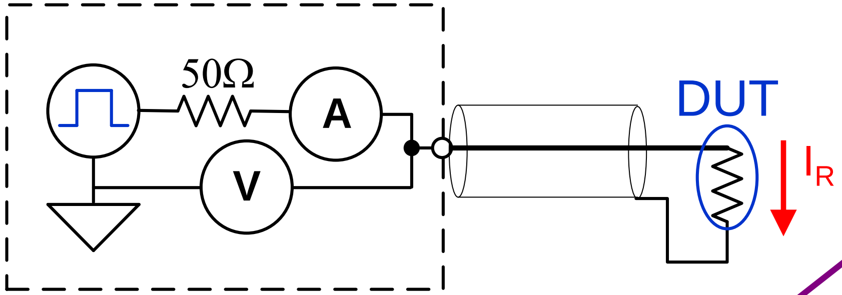
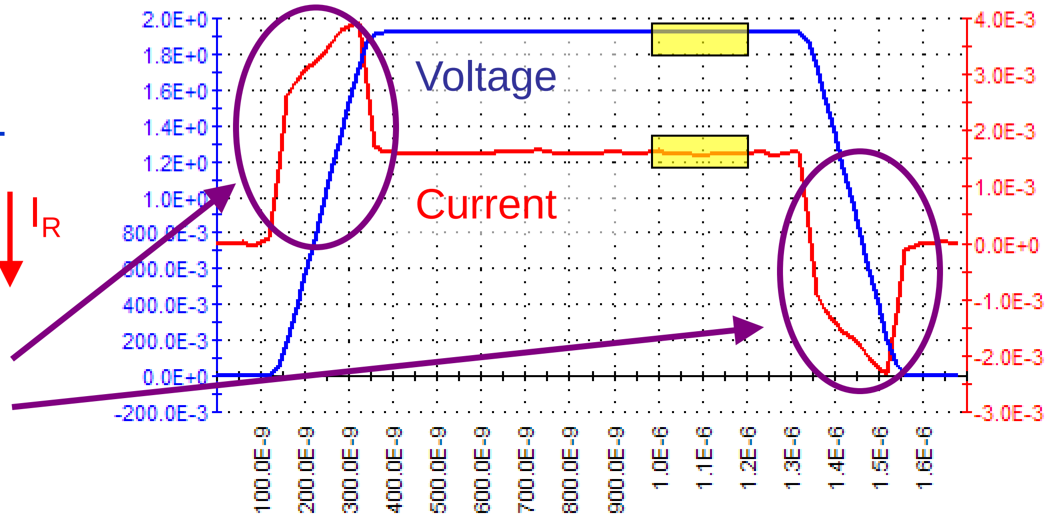
Current Waveform

- Pulse voltage across resistor
- Measure voltage and current versus time

4225-PMU Channel



What are these features?



= Spot Mean Measure Window

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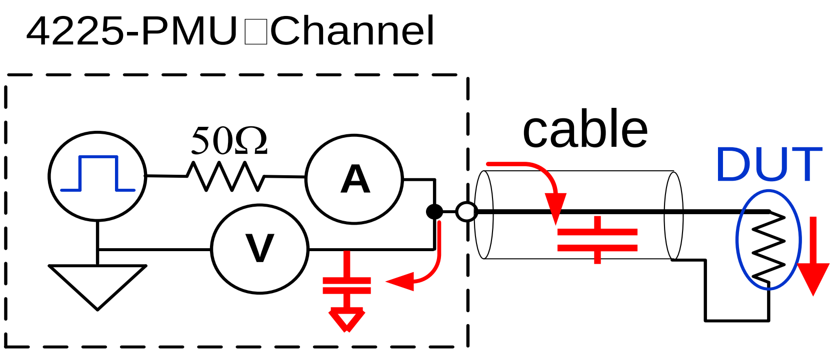
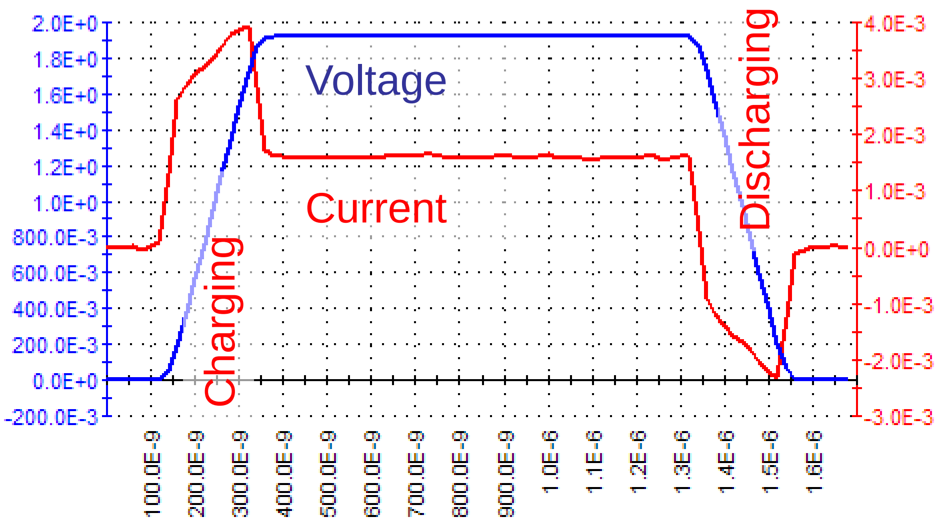
Current Charging Effects During Pulse Transistions

- During pulse rise and fall times, current charges the interconnect and instrument capacitance





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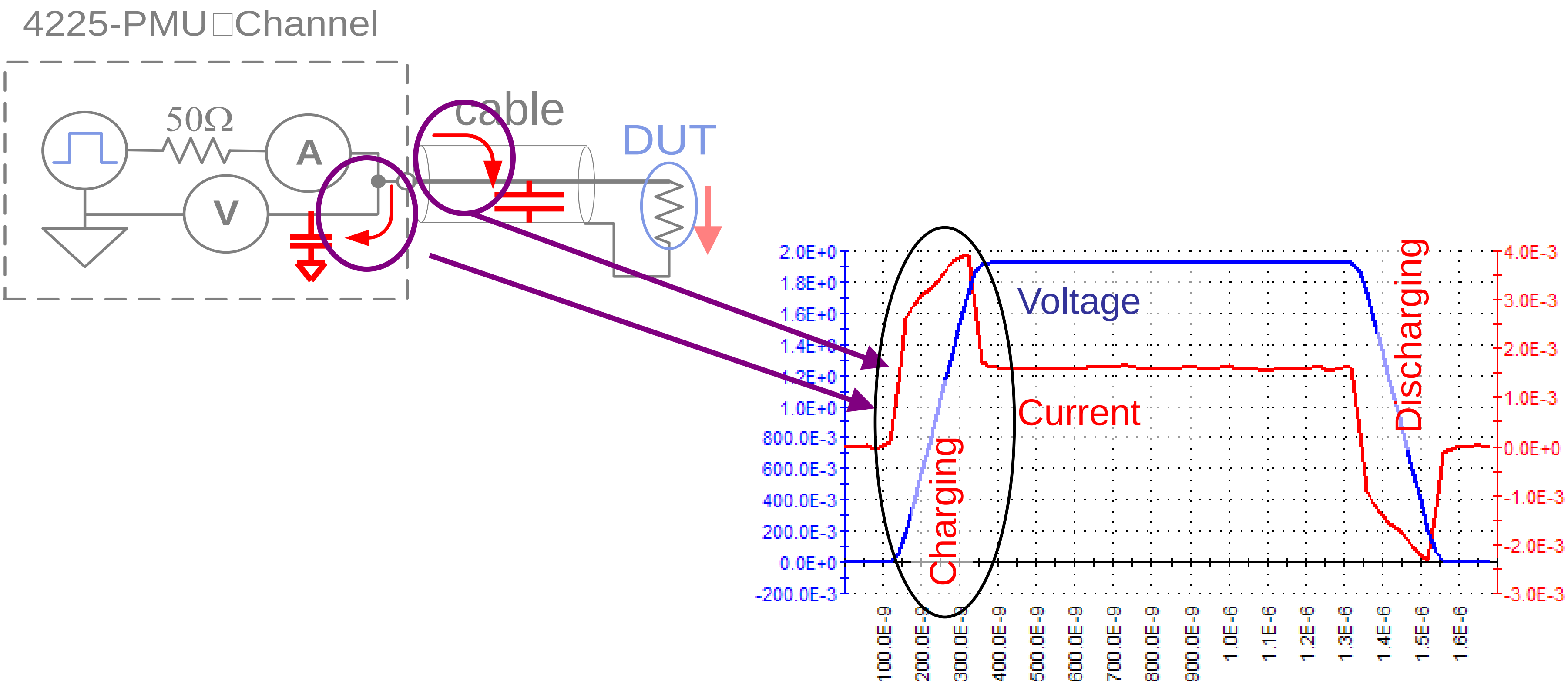

Current Charging Effects During Pulse Transistions

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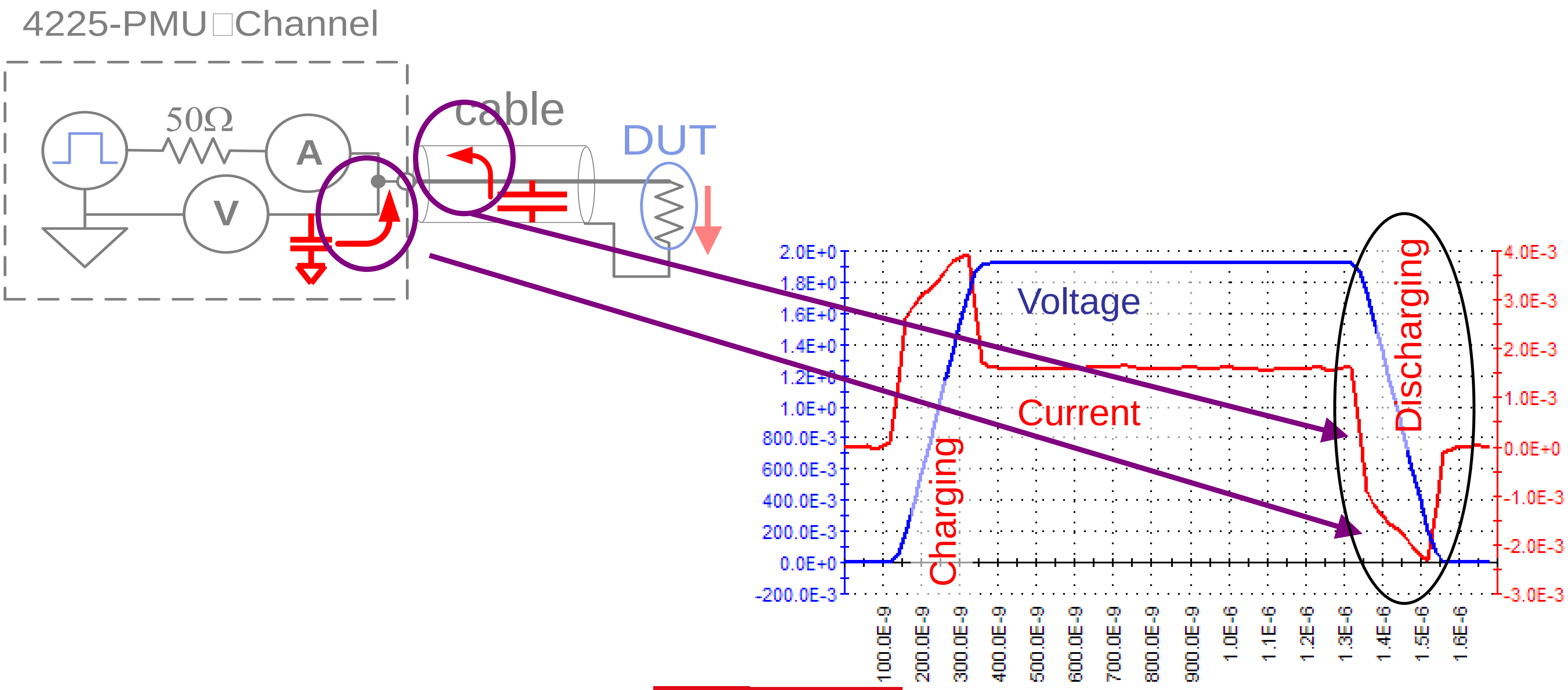

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Why haven't I seen this current charging effect before?

- **Possible reasons**
  1. Oscilloscopes measure voltage not current
  2. SMU measurements are made on a settled signal
  3. Minimal experience with pulse waveform measurement (especially current measure waveforms)
  4. Must look at pulse waveforms where current is relatively low, or DUT impedance relatively high (> ~100 Ω)
  5. Must use pulse transition times that are relatively fast (< ~1 us)

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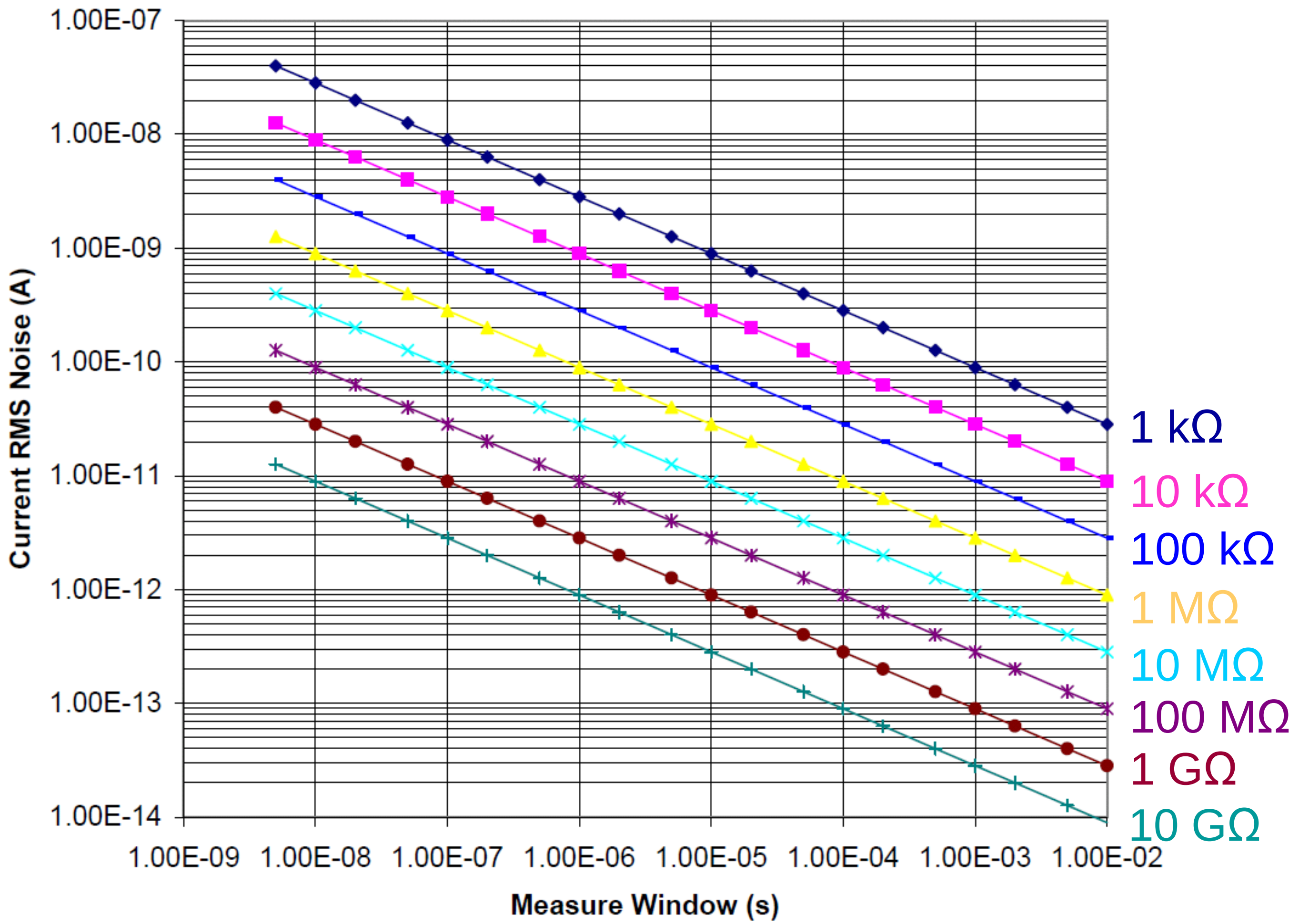
Measuring Small Currents Quickly

- **It is impossible to measure low current (~nA) quickly (< 10us)**
- **Why?**
  - Signal Level (number of electrons)
  - Noise
- **Signal Level Example: Measure 5 nA in 1 ns**
- **Calculate the number of electrons for 5 nA during 1 ns window**
  - 1 A = 1 C/s = 6.24×10^{18} electrons/s
  - 5 nA = (6.24×10^{18} e/s) * (5×10^{-9}) = 31.2×10^{9} e/s
  - In 1 ns: (31.2×10^{9} e/s) * (1×10^{-9}) = 6.24×10^{2} e = **31.2 electrons**

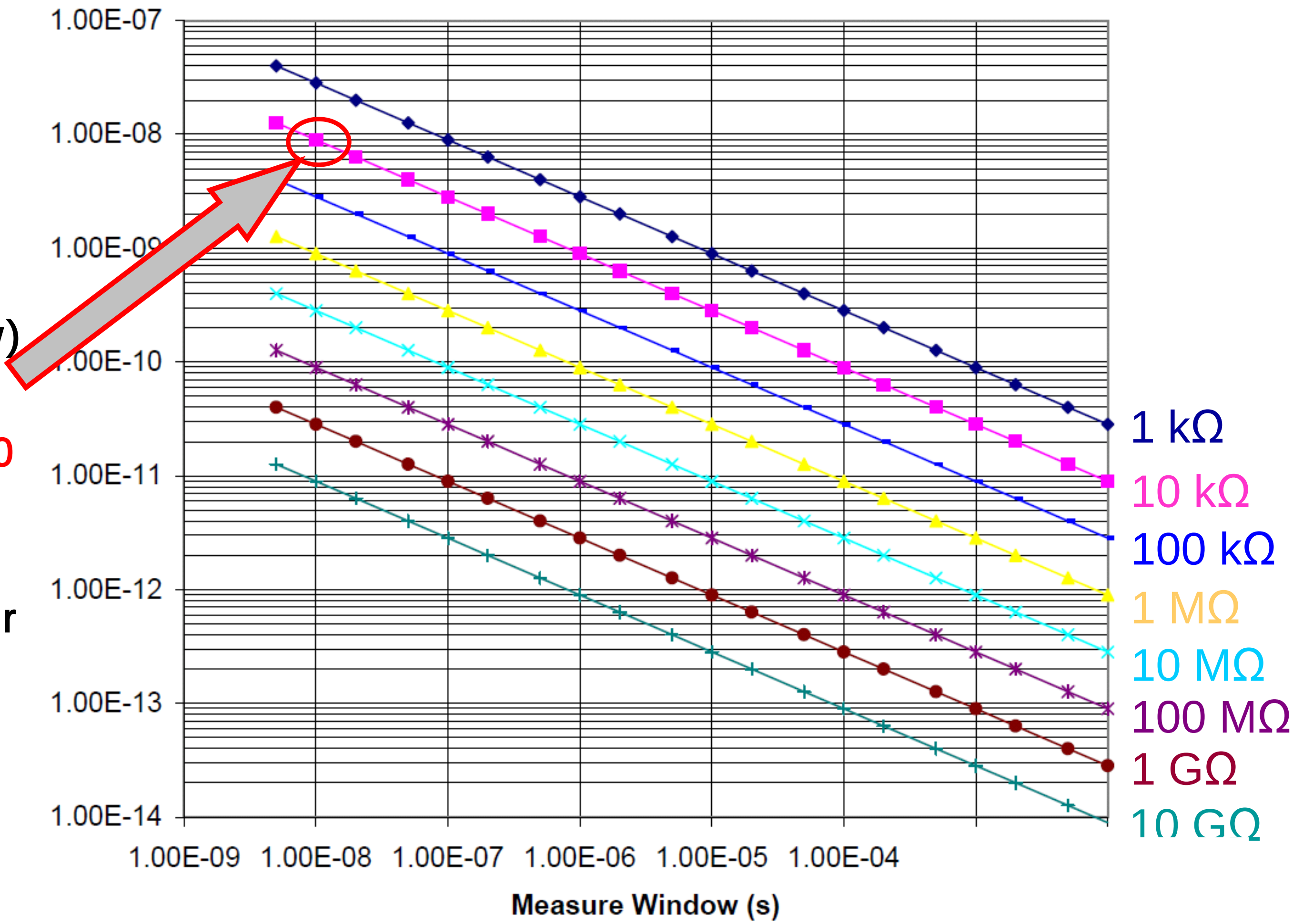
Johnson-Nyquist Noise vs Measure Window

- **Johnson Noise**
  - Caused by electrons flowing through a resistance
  - V=sqrt(4kTBR)
  - I=sqrt(4kTBR)/R
  - k = 1.38E-23 J/K, Boltzmann's constant
  - T = 290 K
  - B = Bandwidth = 1/(2 x Measure Window)
  - R = Resistance



Example: Johnson-Nyquist Noise vs Measure Window

- CMOS Transistor
- 10 kΩ drain-source channel
- Goal: Measure lowest possible current in 10 ns (spot mean window)
- Current Noise due to device alone = 10 nA RMS
- 10 nA does not include any cable or instrument effects (each element in test system contributes Johnson noise)



Conclusion

Further information about using the Model 4200, applications information, and measurement techniques is available:

1) Model 4200 Reference Manual – on CD, HELP menu, desktop
2) Model 4200 Applications Manual – on CD, HELP menu, desktop
3) Applications Notes – on CD, HELP menu, Keithley website, desktop
4) Low Level Measurement Handbook – can be requested from Keithley website
5) Labview Drivers – can be downloaded from Keithley website.
6) Example Projects – available from Keithley applications and in the projects folder – C:\S4200\kiuser\Projects
7) External Instrument Libraries – many already installed in KULT and others are available from Keithley applications