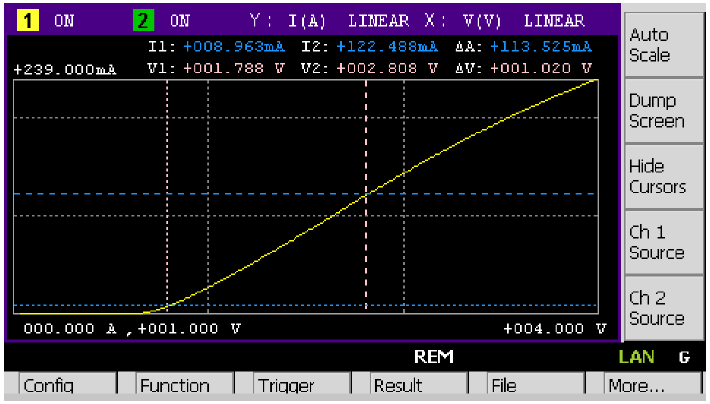
The Fundamentals of IV (Current/Voltage) Measurement



April 10, 2012

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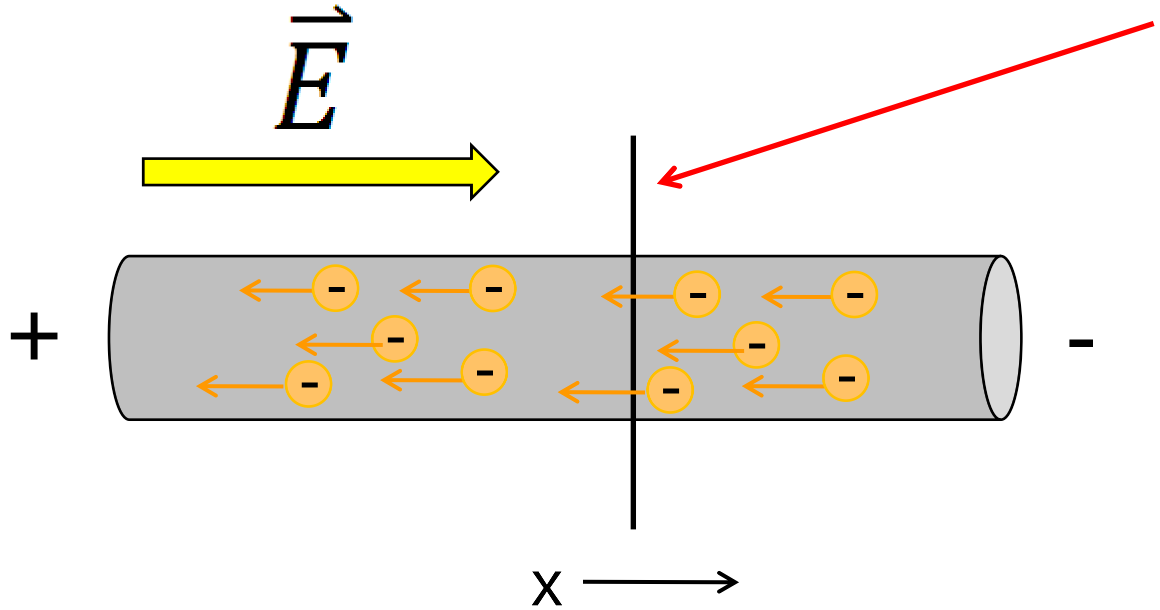
Webcast Agenda

- IV Measurement Basics
- Source/Measure Units (SMU) Introduction
- Low Current Measurement Techniques
- Making Accurate Resistance Measurements
- B2900A SMU Series Features & Benefits
- Final Remarks

IV MEASUREMENT BASICS

What is Current?

$$Current = \frac{Total\,(+)\,Charge}{Unit\ Time}$$



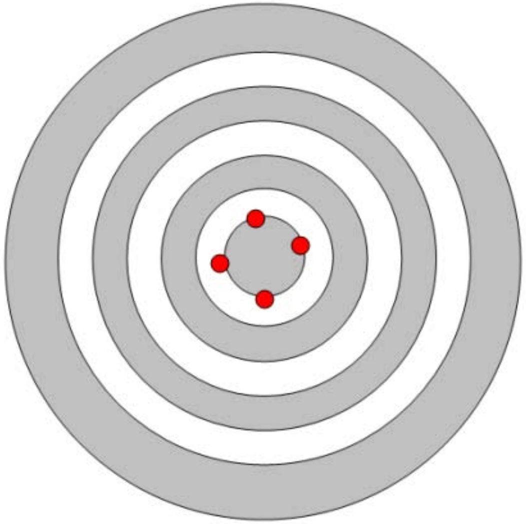
Negative charge (electrons) flowing in the negative x direction is equivalent to positive charge flowing in the positive x direction.

Note: In semiconductors it is possible to measure the flow of positively charged electron holes.

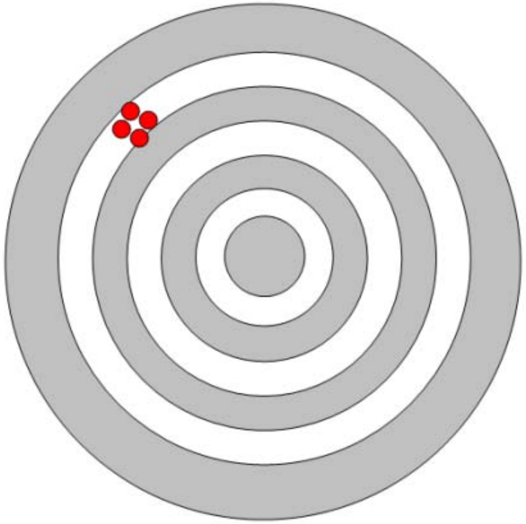
Understanding Accuracy & Repeatability

Accuracy – The degree of conformity of a measured or calculated quantity to its actual (true) value.

Repeatability (aka precision) – The degree to which repeated measurements or calculations show the same or similar results.



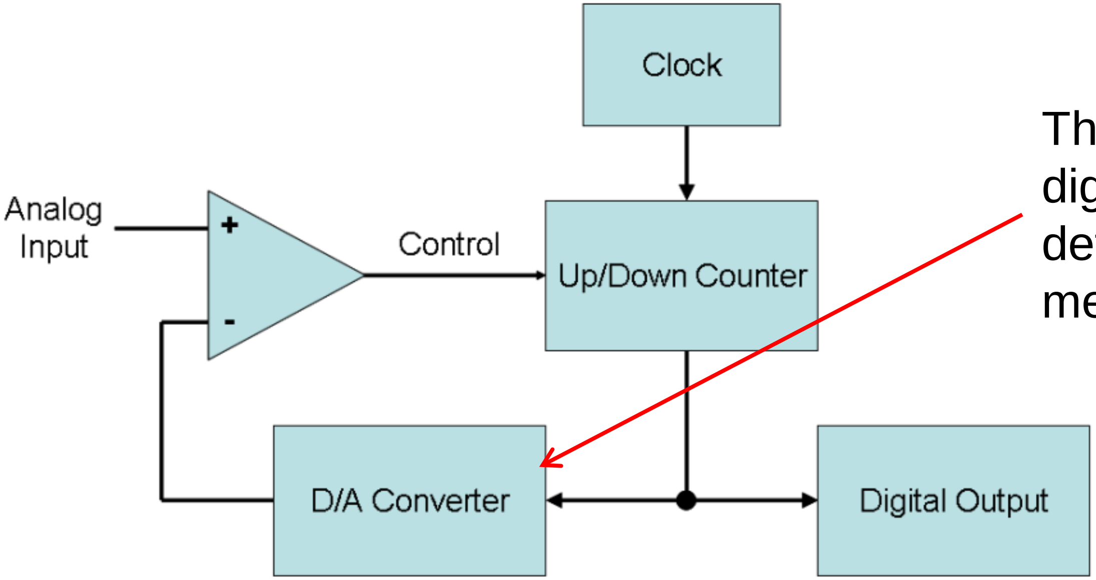
High accuracy, low repeatability



Low accuracy, high repeatability

Understanding Measurement Resolution

Resolution – The smallest change in data that an instrument can display.



The number of bits available to the digital-to-analog converter (DAC) determines the fineness of the measurement detail.

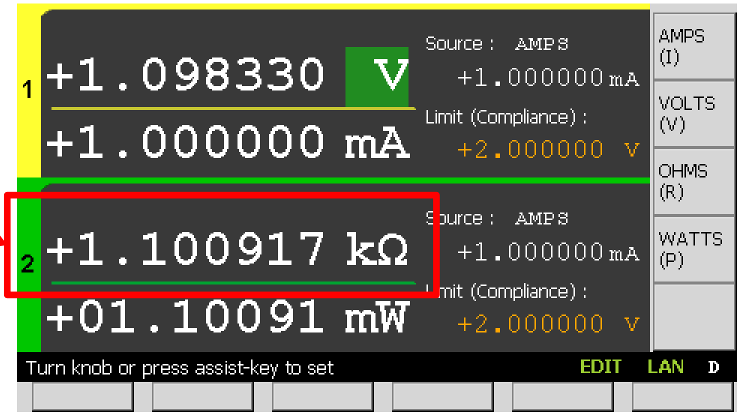
Example: 20 bits of resolution represents the ability to distinguish one part in 2^{20} or 1,048,576.

Simplified analog-to-digital converter (ADC) circuit.

What is a Half Digit of Resolution?

→ Be careful! This can mean different things for different instruments

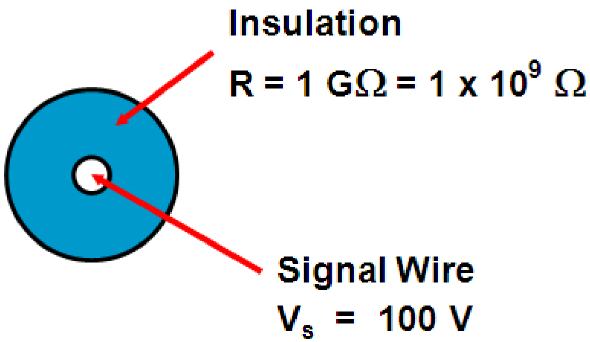
Question: What is the ½ digit here?



Answer: It is the 7. In this case the least significant digit only has ½ the resolution of the other digits.

Why Are Triaxial Cables Needed for Low-Current?

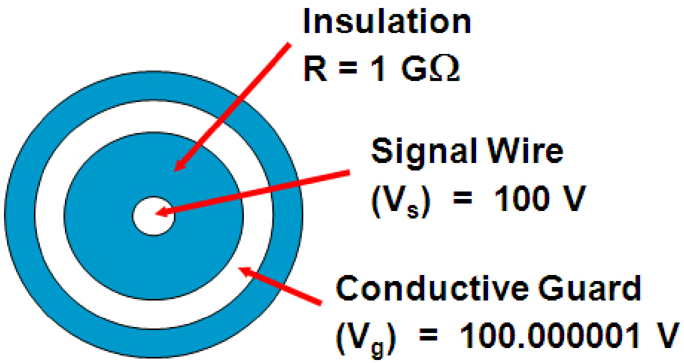
BNC (Coaxial) Cable:



Leakage Current:

$$\frac{100\ V}{1 \times 10^{9}\Omega} = 100\ nA$$

Triaxial Cable:

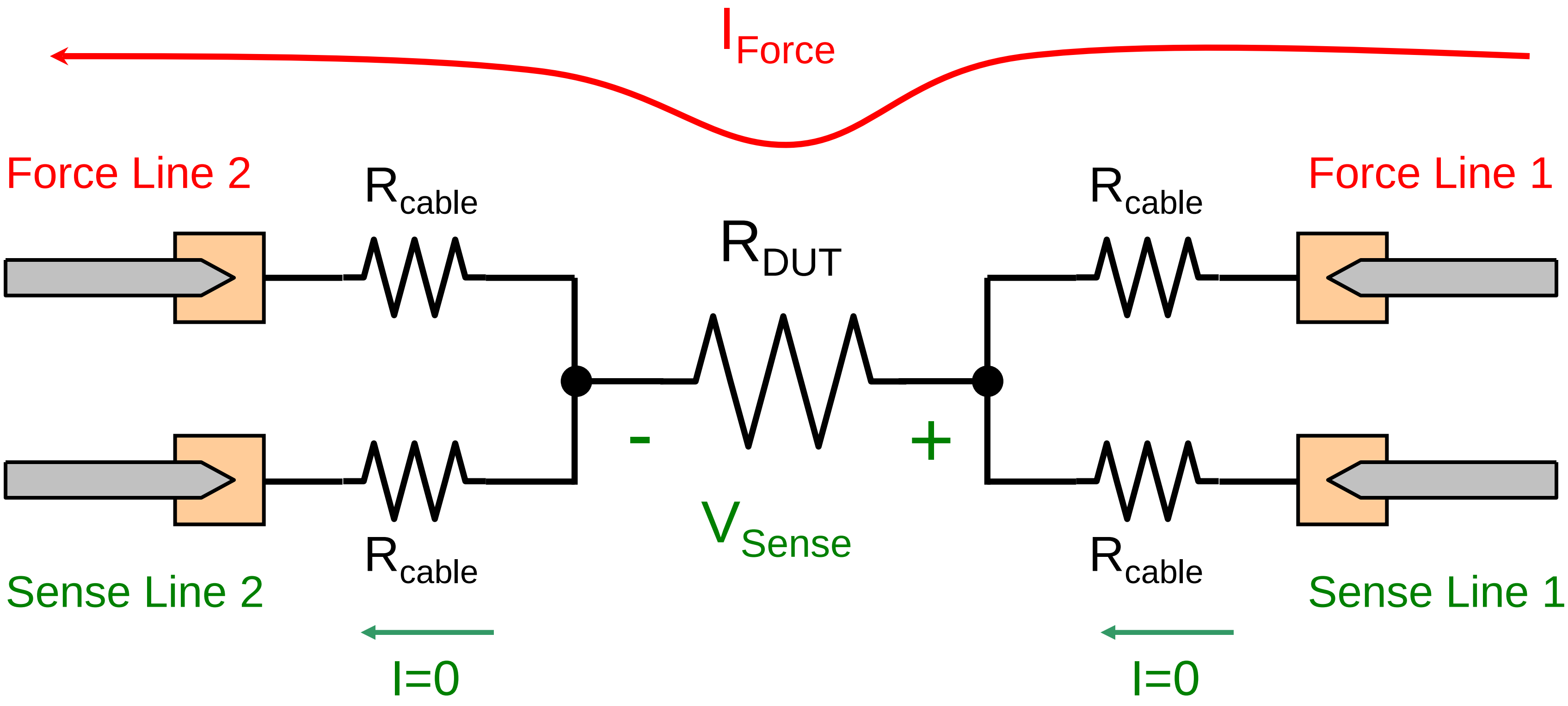


Leakage Current:

$$\frac{(100.000001\ V - 100\ V)}{1 \times 10^{9}\Omega} = 1\ fA$$

Triaxial cable reduces leakage current by a factor of 100,000,000.

What is a 4-Wire (Kelvin) Measurement?

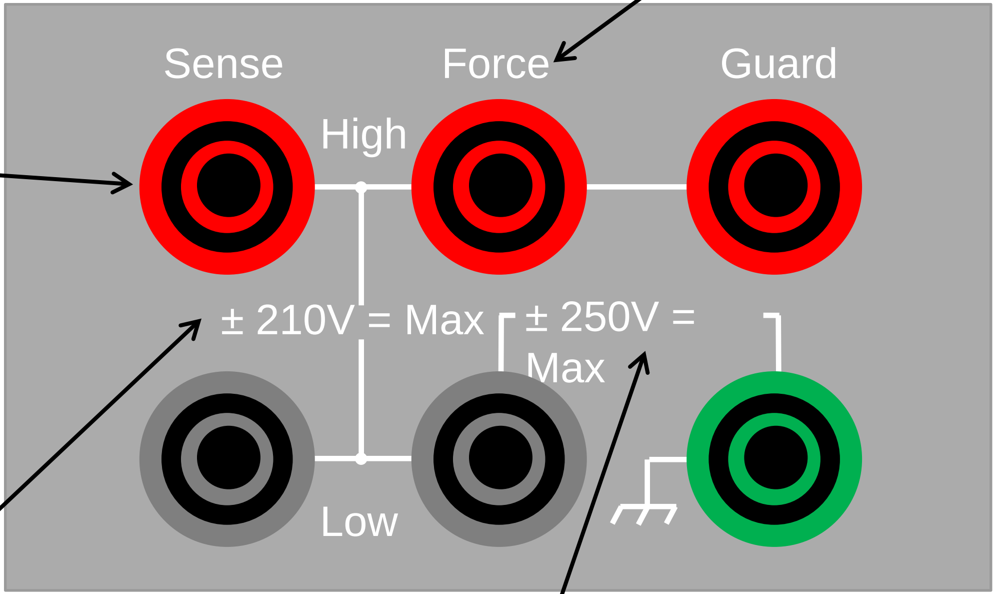


→ Eliminate cable resistance from the measurement

Example Instrument Outputs (Banana Jack)

When making a basic 2-wire measurement you should use the **Force** outputs.

4-wire measurements require the use of the Sense lines in addition to the Force lines.



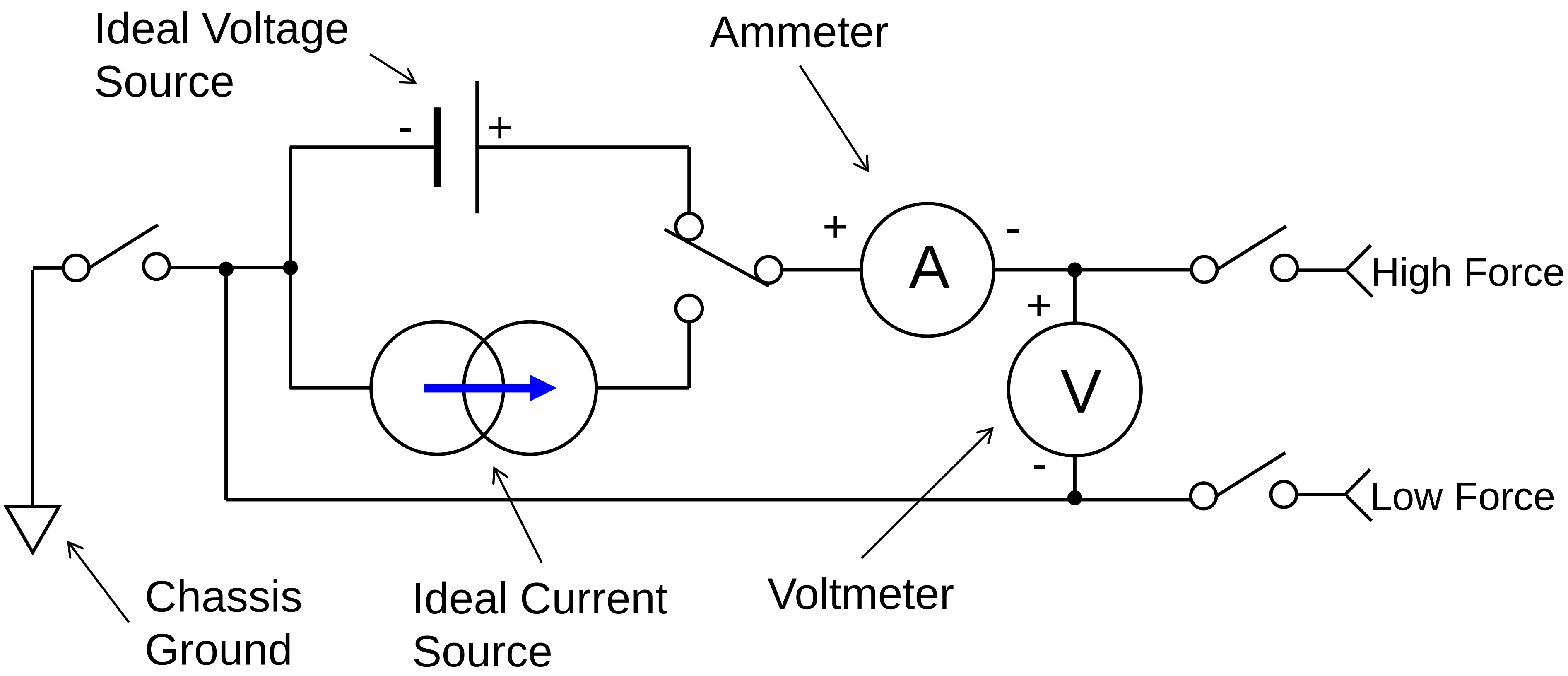
This tells you the maximum allowable voltage (210 V in this case) between the high and low inputs.

By default the low outputs are tied to chassis ground, but in this case they can be floated up to 250 V above or below chassis ground if desired.

SOURCE/MEASURE UNIT (SMU) INTRODUCTION

What is a Source/Measure Unit (SMU)?

Simplified equivalent circuit (2-wire measurements):



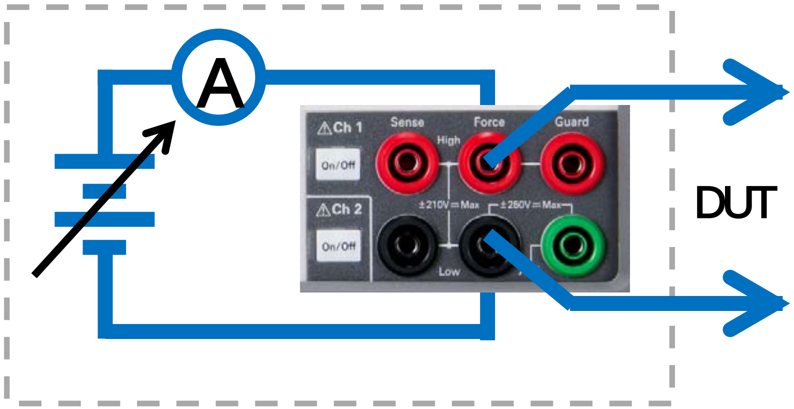
Note: The tight integration of these measurement resources yields better accuracy and faster measurement than would an equivalent collection of separate instruments.

Why Would You Use an SMU for IV Measurements?

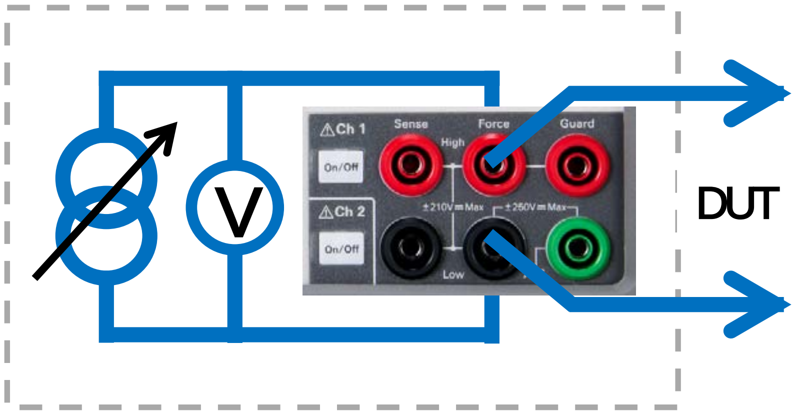
An SMU integrates the following capabilities into <u>each</u> <u>channel</u>:

- Four-quadrant voltage source
- Four-quadrant current source
- Voltage meter
- Current meter

Here are the two most common modes of operation:



VFIM (Force voltage & measure current)



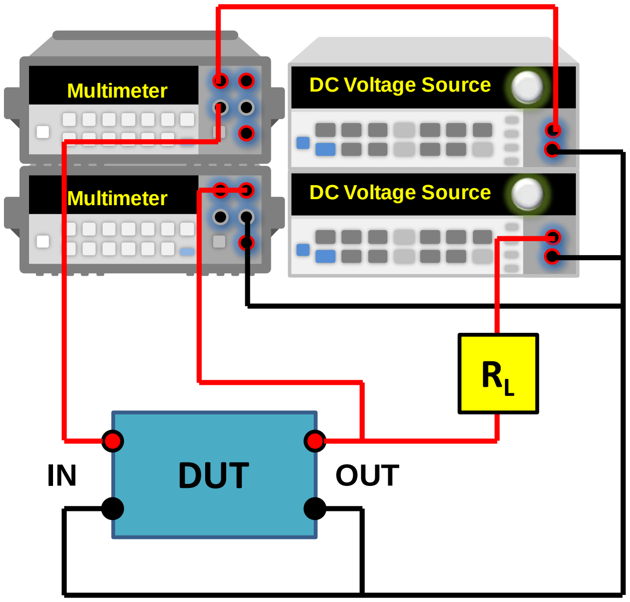
IFVM (Force current & measure voltage)

Why Use a Benchtop SMU for IV Measurements?

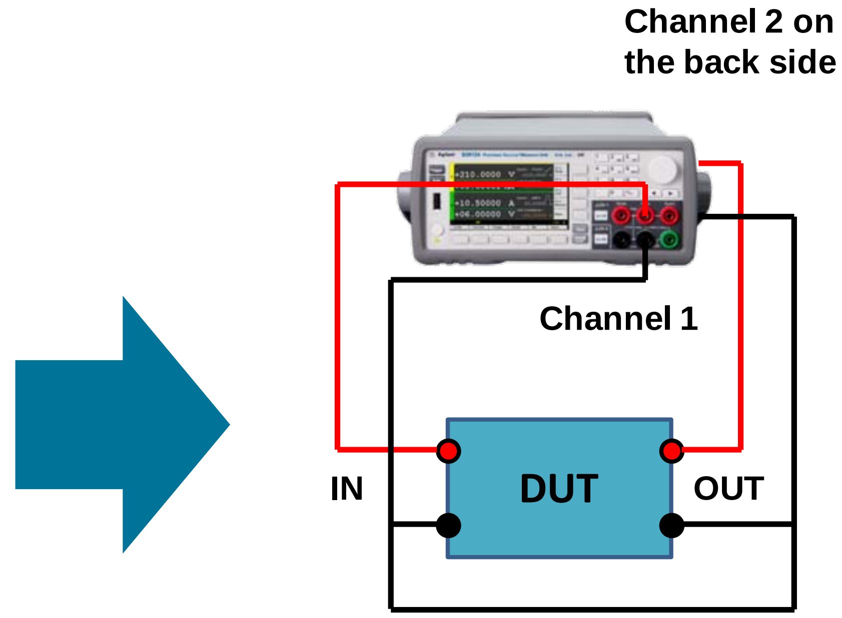
Reason #1: Improved Measurement Efficiency

Problem: Limited bench-top space for single-function instruments.

Solution: A benchtop SMU reduces the number of instruments and reduces messy wiring.



Non-SMU setup example for 4-terminal device



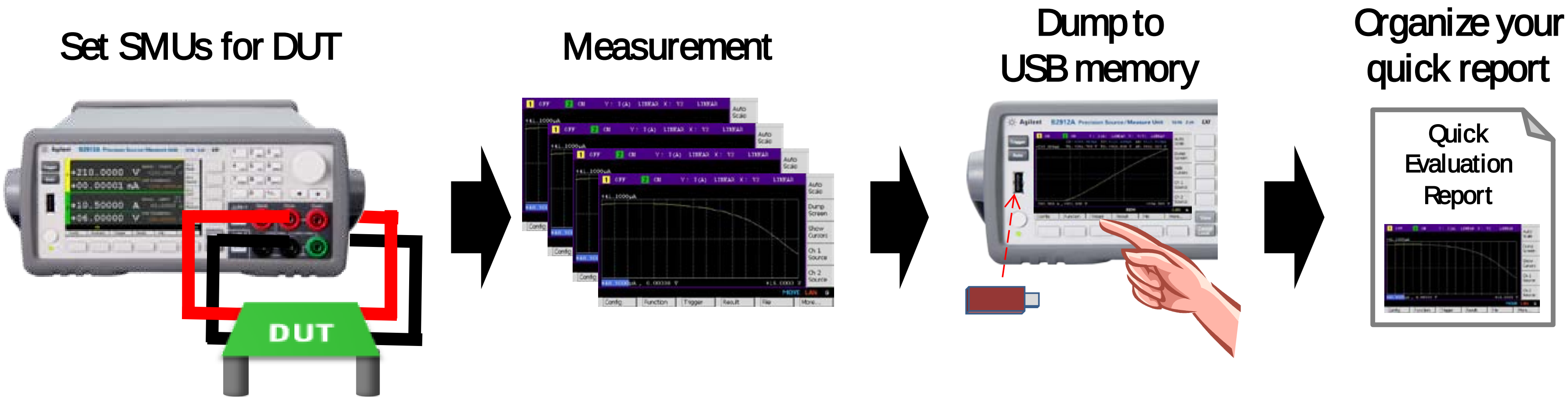
SMU setup example for 4-terminal device

Why Use a Benchtop SMU for IV Measurements?

Reason #2: Eliminate the Need for a PC

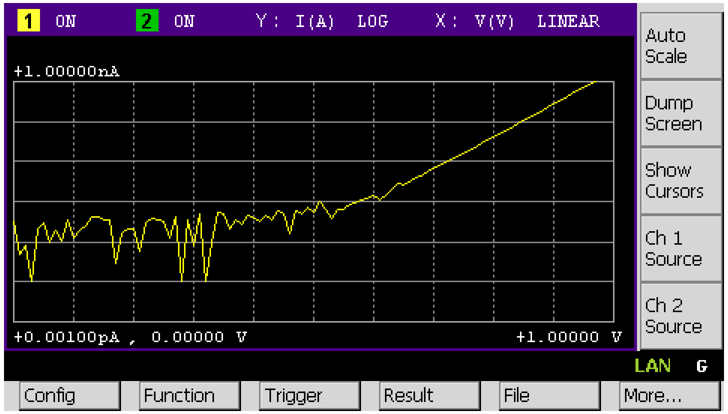
Problem: Many bench-top instruments require a PC to graphically display data and to make measurements.

Solution: A GUI-based benchtop SMU supports real-time IV curve monitoring directly on the instrument. You can also save graphs and data to a flash drive for report generation.



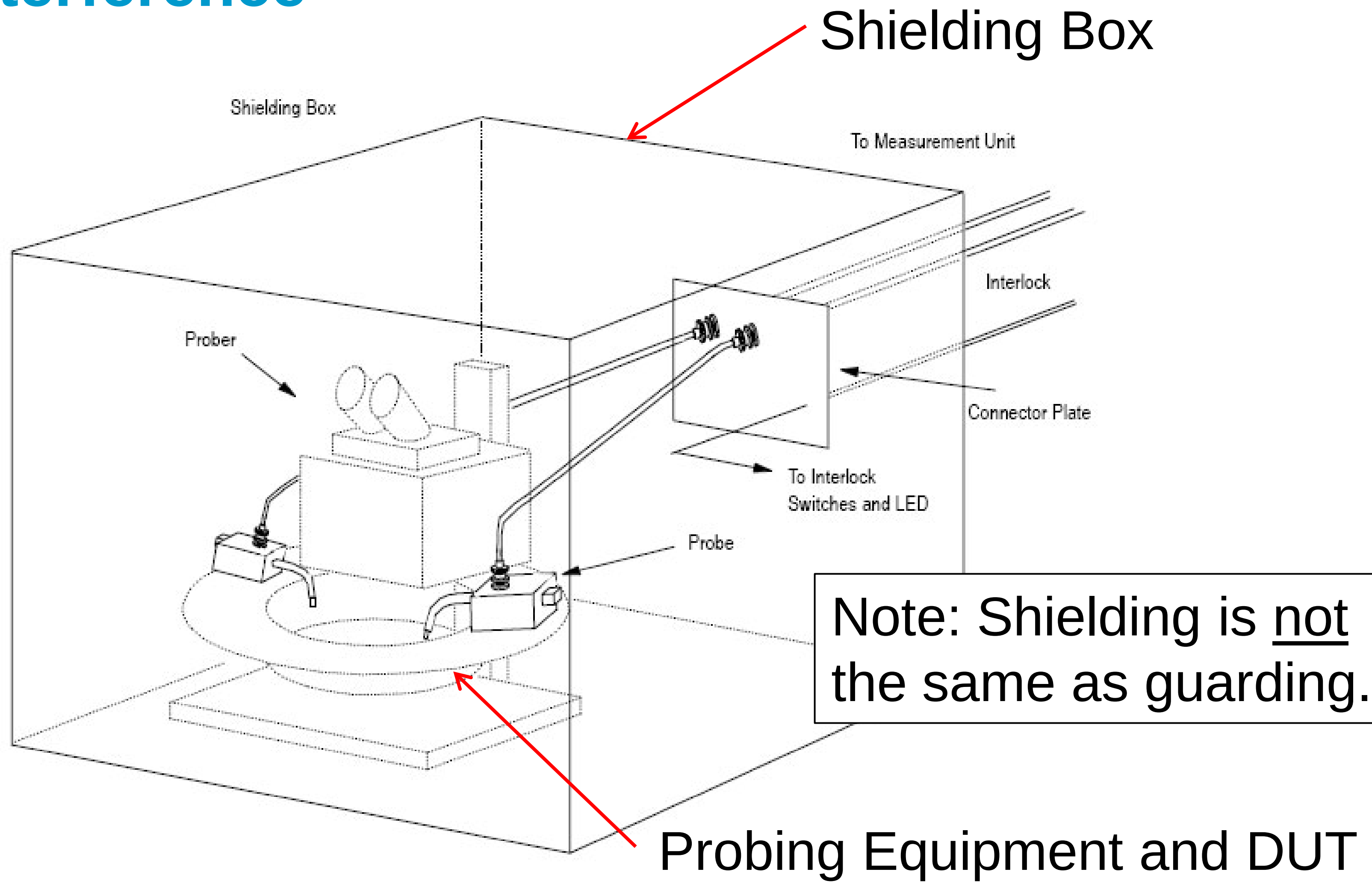
LOW CURRENT MEASUREMENT TECHNIQUES

Low-Current Measurement Challenges



- How do I eliminate electromagnetic interference?
- How do I avoid creating ground loops?
- What is measurement ranging and how do I optimize it?
- Why is integration time important in eliminating noise?
- How do I eliminate voltage and current transients?

Use Shielding to Avoid Electromagnetic Interference



Note: Shielding is not the same as guarding.

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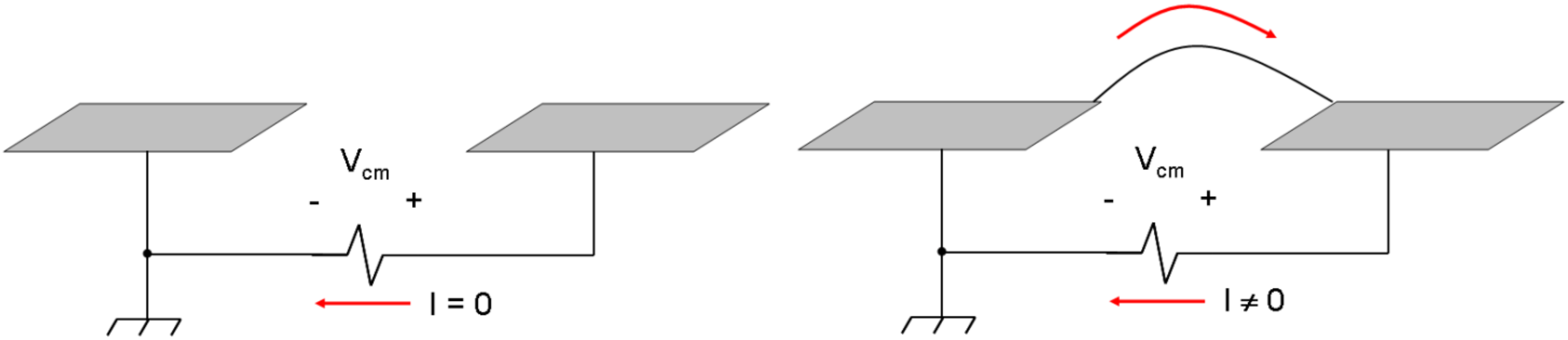
Avoiding Ground Loops

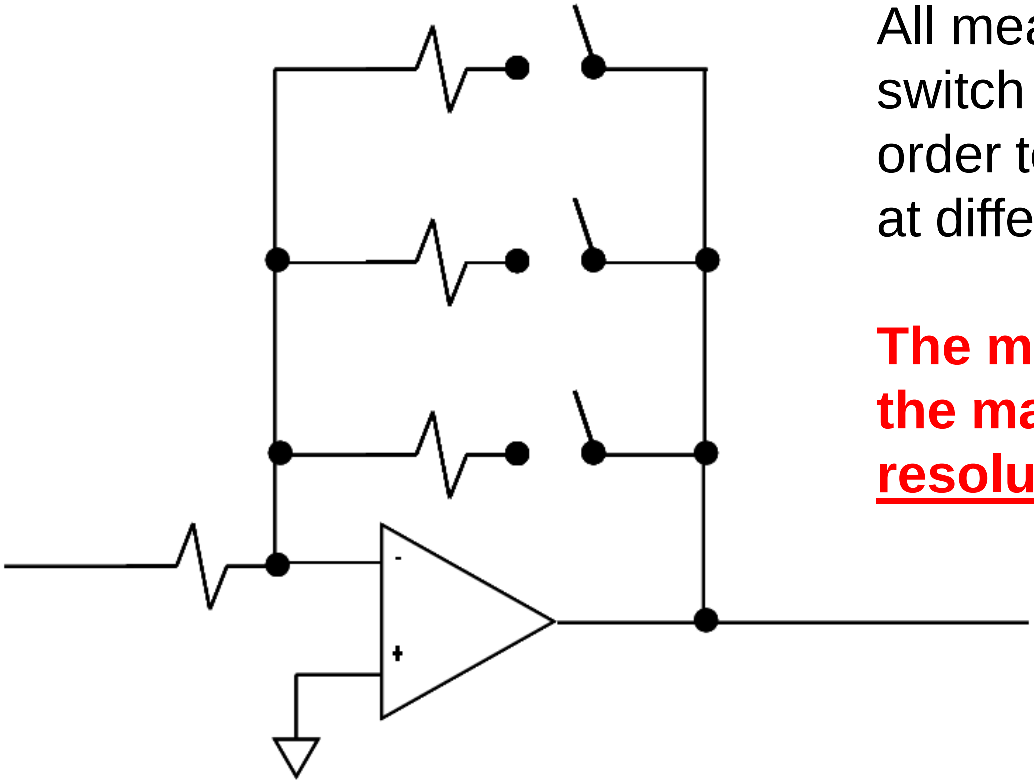


Conductive planes tied together at only one point cannot have any current flowing between them.

Conductive planes tied together at multiple points creates a loop for current (a condition to be avoided).

→ Do not connect up equipment to ground at more than one point!

Understanding Measurement Ranging - 1

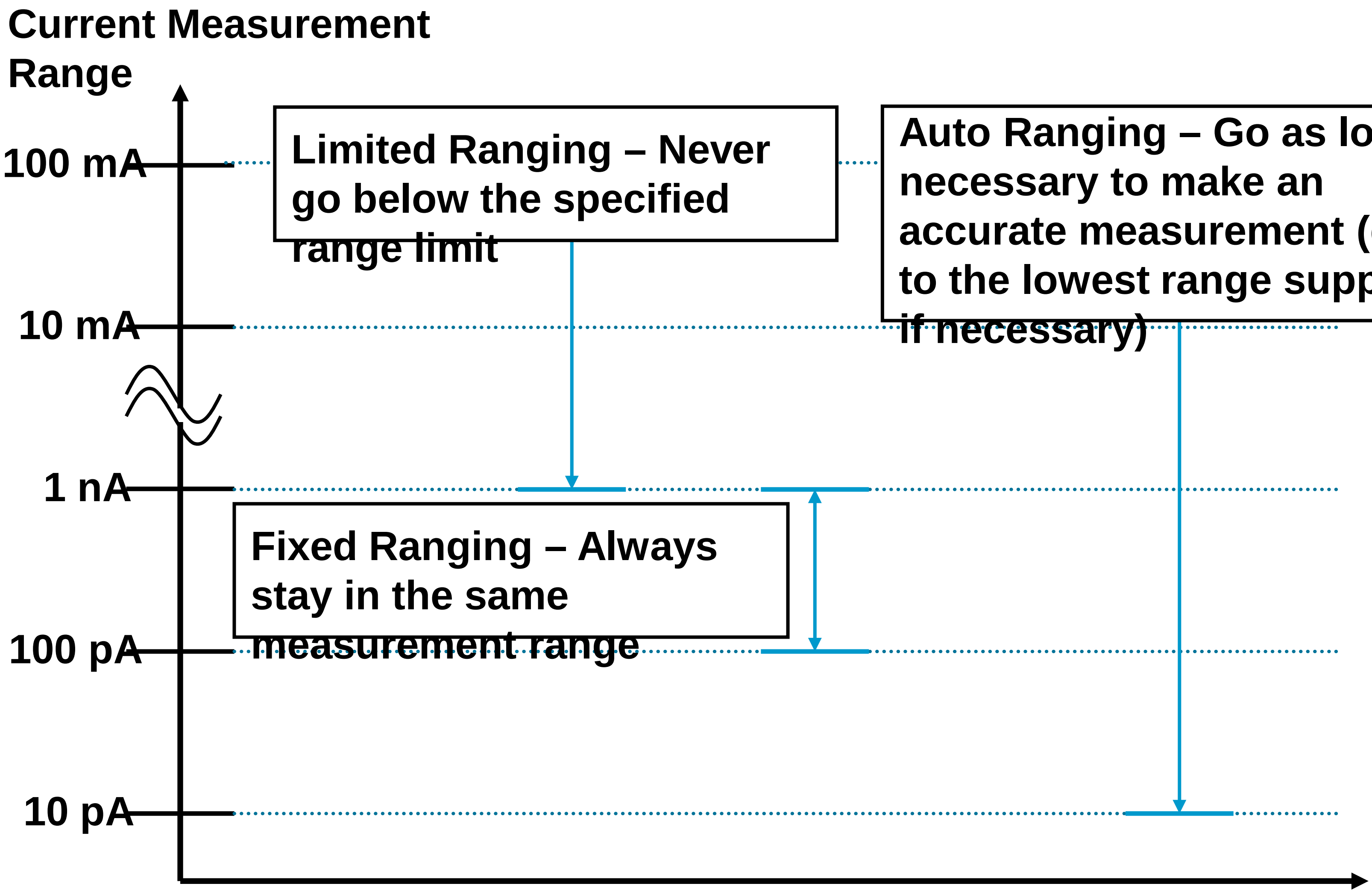


All measurement circuitry needs to switch in and out various resistors in order to measure currents and voltages at different levels.

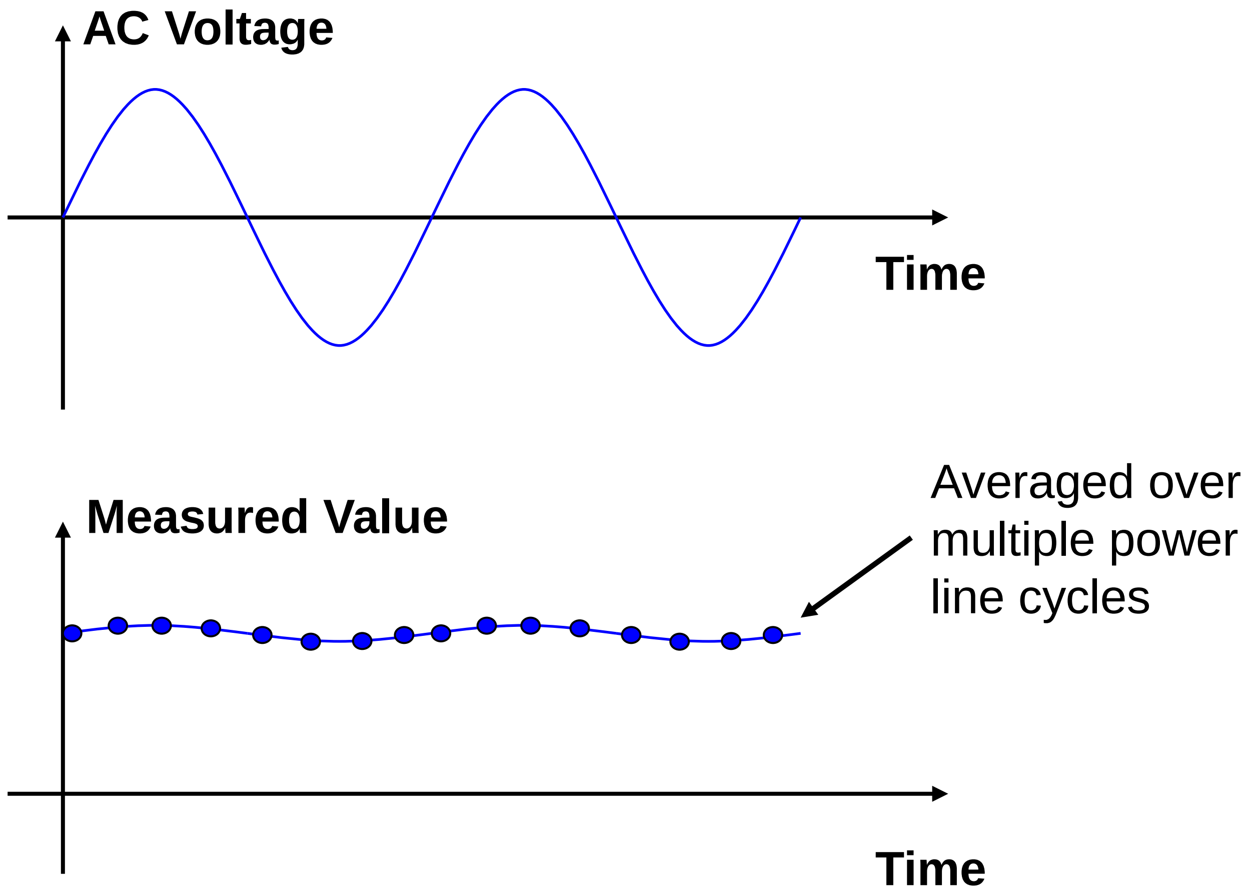
The measurement range determines the maximum measurement resolution that you can obtain*.

*Typically 5 decades below the measurement range.

Understanding Measurement Ranging - 2

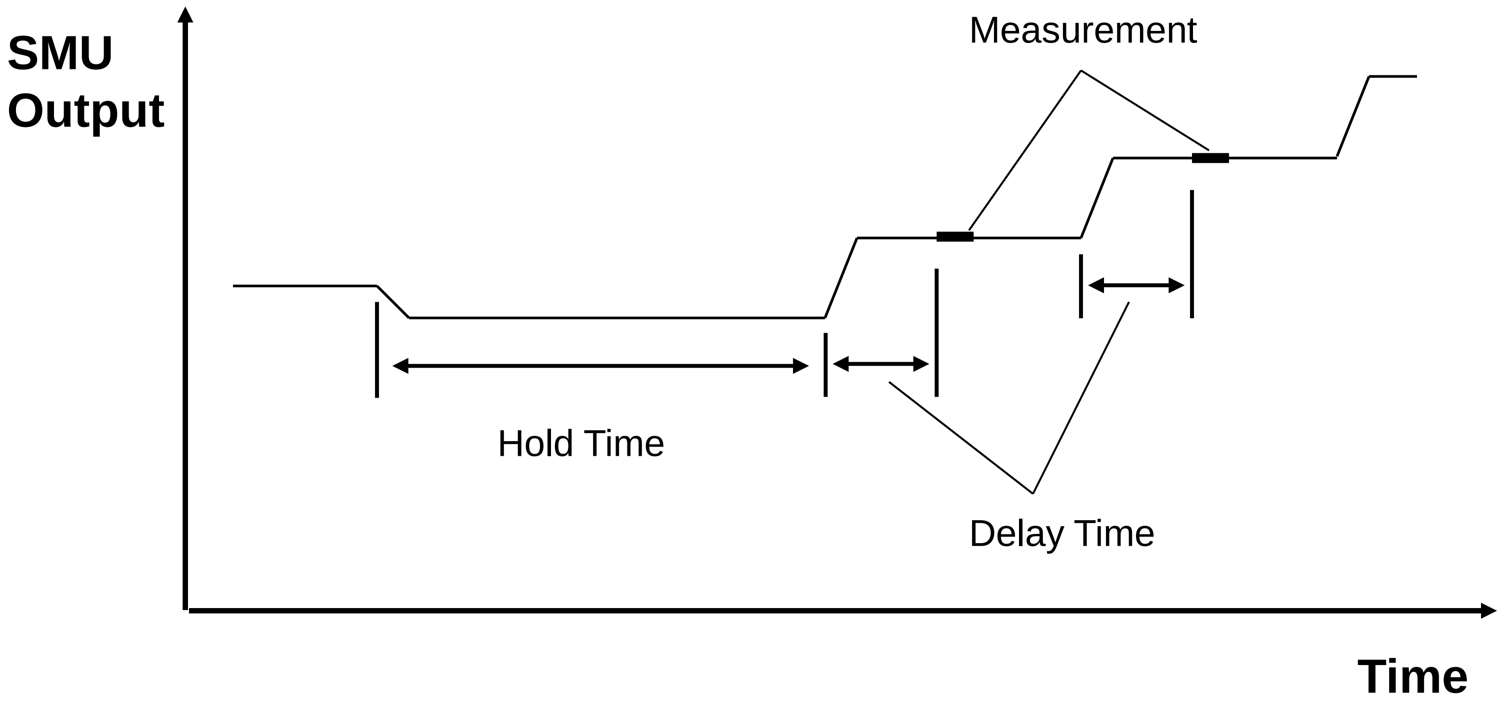


Integration Time Eliminates Measurement Noise



Integration **DOES NOT** have any effect on the measurement resolution.

Eliminating Transient Effects

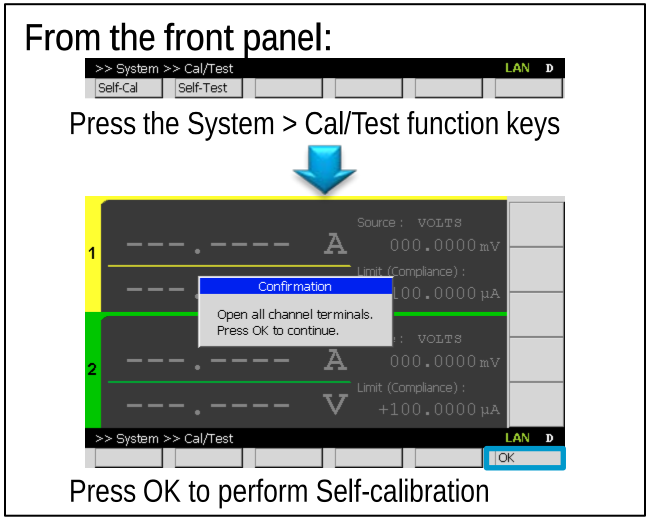


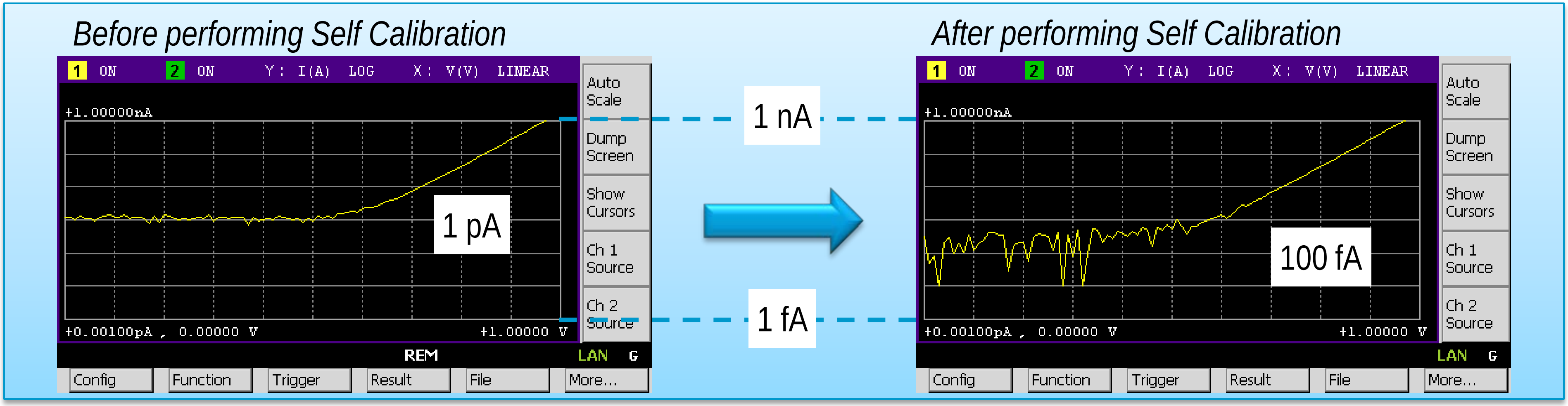
The hold time and delay time settings allow you to specify how long to wait before starting a measurement after the SMU applies voltage or current.

Step #1: Perform Self-calibration

Almost all instruments designed for low-current measurement have some sort of self-calibration mechanism. It is important that you DO THIS before attempting a low-current measurement.

Note: B2900A example shown





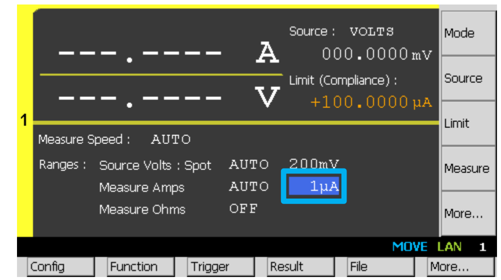
Step #2: Select the Correct Current Measurement Range

Most instruments DO NOT boot up in their lowest measurement range. In this example notice the improvement in measurement performance obtained by changing from the 1 μA current measurement range to the 10 nA current measurement range.

Note: B2900A example shown

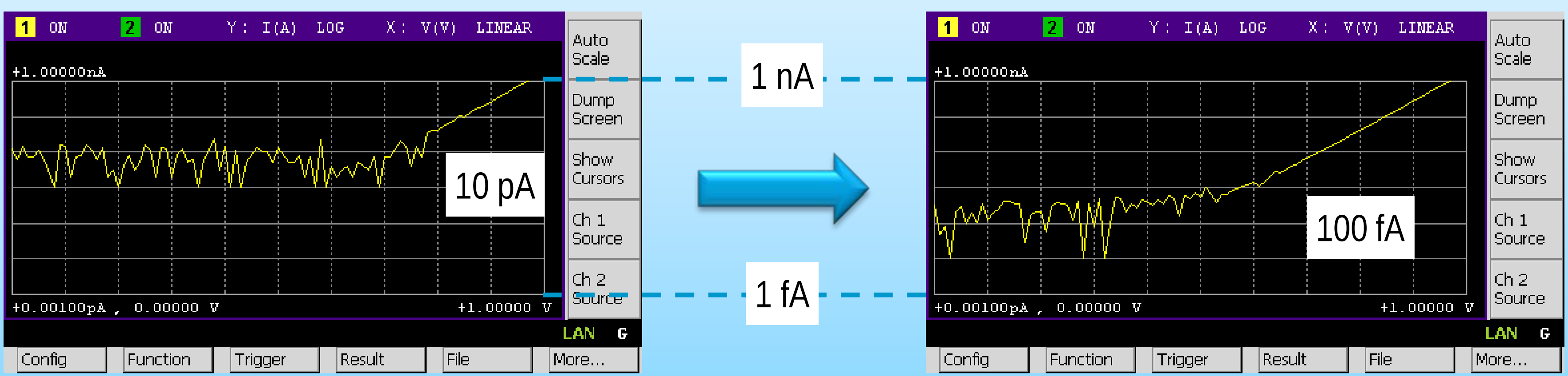
From the front panel:

In Single View mode you can specify the current measurement range.



Using 1 μA Current Measurement Range:

Using 10 nA Current Measurement Range:



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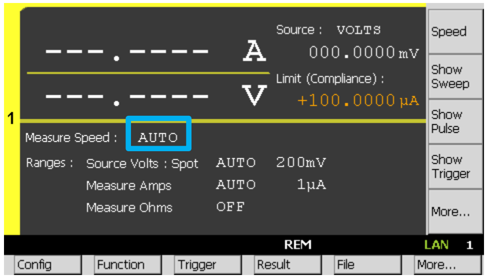
Step #3: Increase the Integration Time to Eliminate Measurement Noise

In general, low-current measurements need at least 1 power line cycle (PLC) of integration to obtain decent results (in this example NORMAL integration). Extremely low currents and/or noisy environments may require LONG integration (16 PLCs). You can use MANUAL integration to select PLC values between these two extremes.

From the front panel:

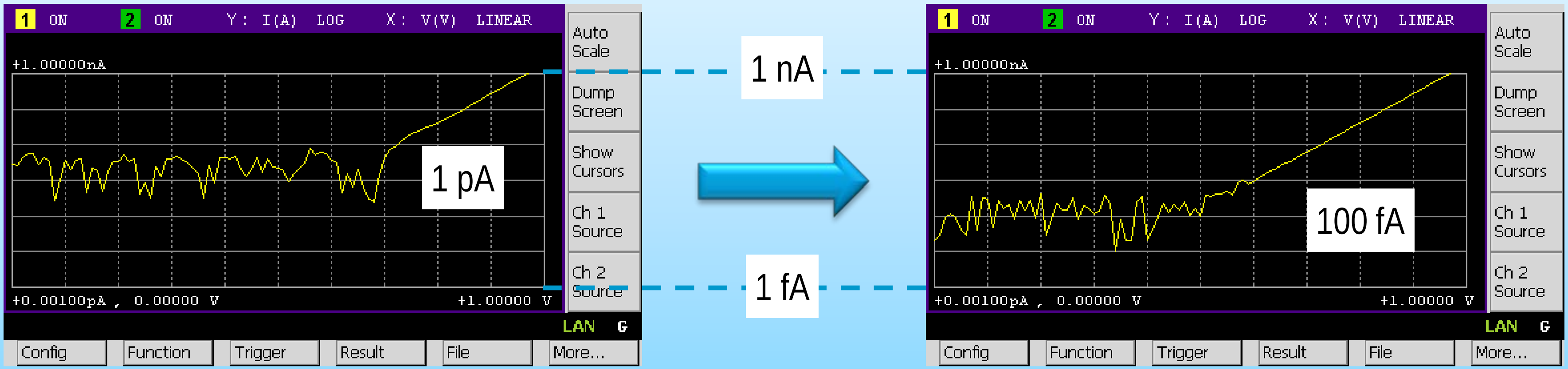
In Single View mode you can select the measurement speed (integration time)



Note: B2900A example shown

Using SHORT(0.01 PLC) integration time:

Using NORMAL (1 PLC) integration time:



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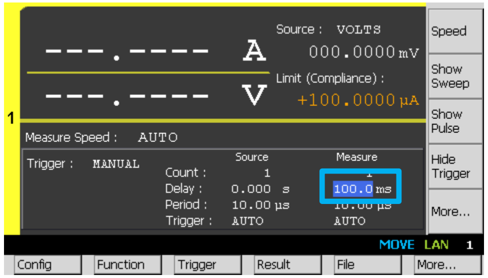
Step #4: Select an Appropriate Measurement Trigger Delay Time

The length of the wait time depends primarily on the size of the voltage step; larger voltage steps require longer wait times. However, the magnitude of the capacitance being driven also impacts the wait time (larger C → longer wait times).

Note: B2900A example shown

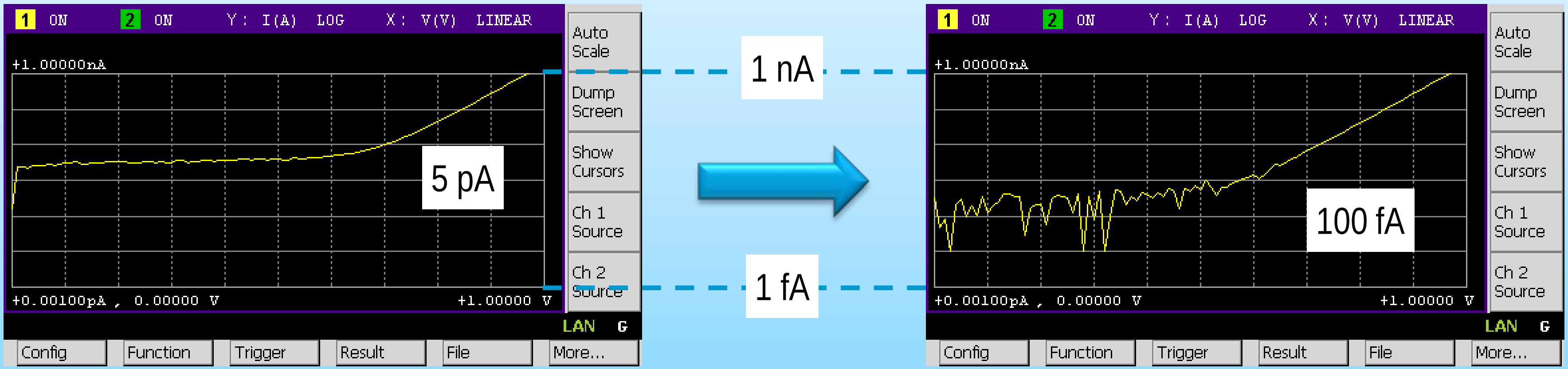
From the front panel:

In Single View mode you can select the measurement delay time



Using a Trigger Delay Time of 0 ms

Using a Trigger Delay Time of 200 ms



Important! Current Measurements <1 nA Require Triaxial Cabling & Fixturing

Kelvin Adapter

Non-Kelvin Adapter

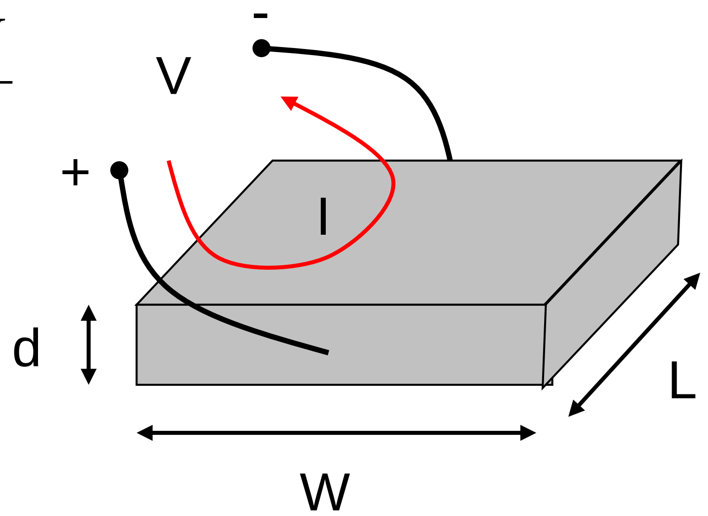
N1294A-001 Banana–Triaxial Adapter for 2-wire connection (non-Kelvin)

N1294A-002 Banana–Triaxial Adapter for 4-wire connection (Kelvin)

MAKING ACCURATE RESISTANCE MEASUREMENTS

Understanding Resistivity and Resistance

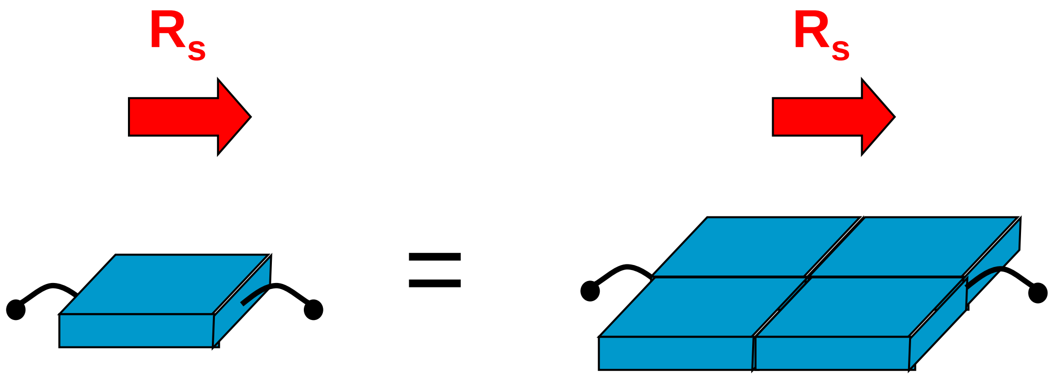
$$R = \frac{V}{I}$$



$$\rho = R\frac{A}{L} = R\frac{Wd}{L}$$

When characterizing materials we typically want to know the resistivity, which is a material property that is independent of the dimensions of the device being measured.

Understanding "Ohms per Square"



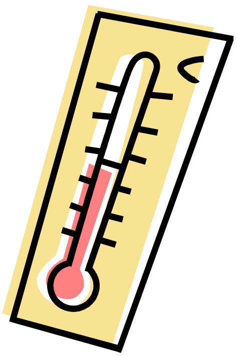
$$R_S = (R_S \parallel R_S) + (R_S \parallel R_S)$$

You may sometimes see the term "Ohms per Square". This is simply another way of specifying resistivity. As long as the thickness of a material is constant, it has the same measured resistance for any sized square of the material.

Measuring Resistance: A Trivial Measurement?

V = I x R, correct? NO!

V = I x R(T) → Resistance depends on temperature!

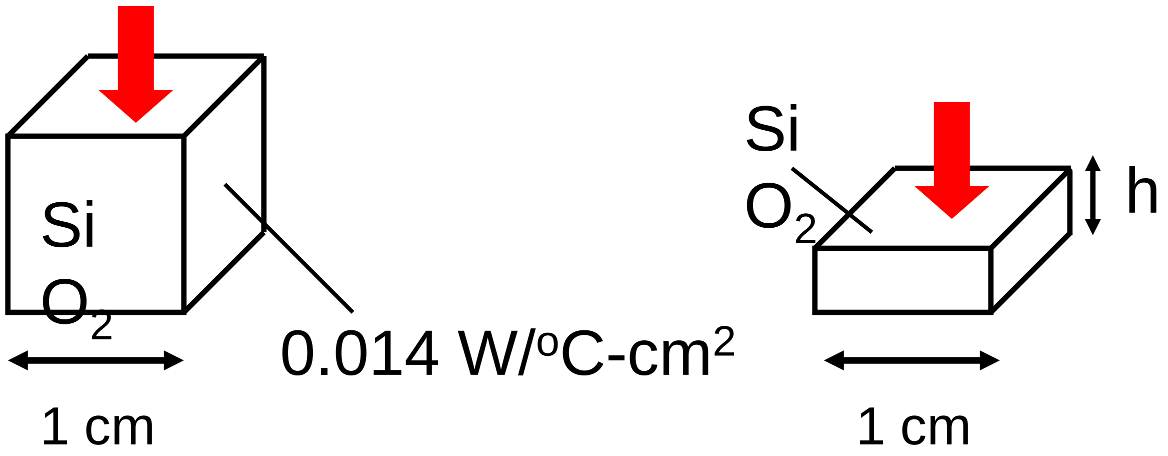


This is referred to as the Joule self-heating effect.

Resistance measurement is a tricky balance between two factors:

1. To keep the resistor from heating up and the resistance value from changing, we need to keep the current (= power) low.
2. Small currents imply that we need to measure smaller voltages, which in-turn requires more voltage measurement resolution capability.

The Importance of Thermal Resistance



$(h \times 71)$ °C-cm²/W, or

0.007 °C-cm²/W for h = 1 μm

- For a 1 cm² block of SiO_2 1 μm thick, if you apply 1 W the temperature will rise by 0.007 °C
- For a 10 μm² block of SiO_2 1 μm thick, if you apply 1 W the temperature will rise by 7,000 °C!

How Much Power Can I Apply to a Structure?

$$P = V \times I = V \times \frac{V}{R} = \frac{V^2}{R} \quad \rightarrow \quad V_{\max} = \sqrt{P_{\max} \times R(T)}$$

At or near room temperature the resistance of a Cu or Al metal line changes by about 0.35%/°C. This allows us to compute the maximum amount of power that can be dissipated to produce a 0.1% change in resistance for a Cu or Al metal square 10 mm by 10 mm.

$$0.1\% = P_{\max} \times 0.007\ {}^{o}C - cm^2 / W \times 0.35\% / {}^{o}\ C \times 1/(10\ mm)^2 \times (10\ mm / 1\ cm)^2$$

$$\therefore P_{\max} = 0.04\ mW$$

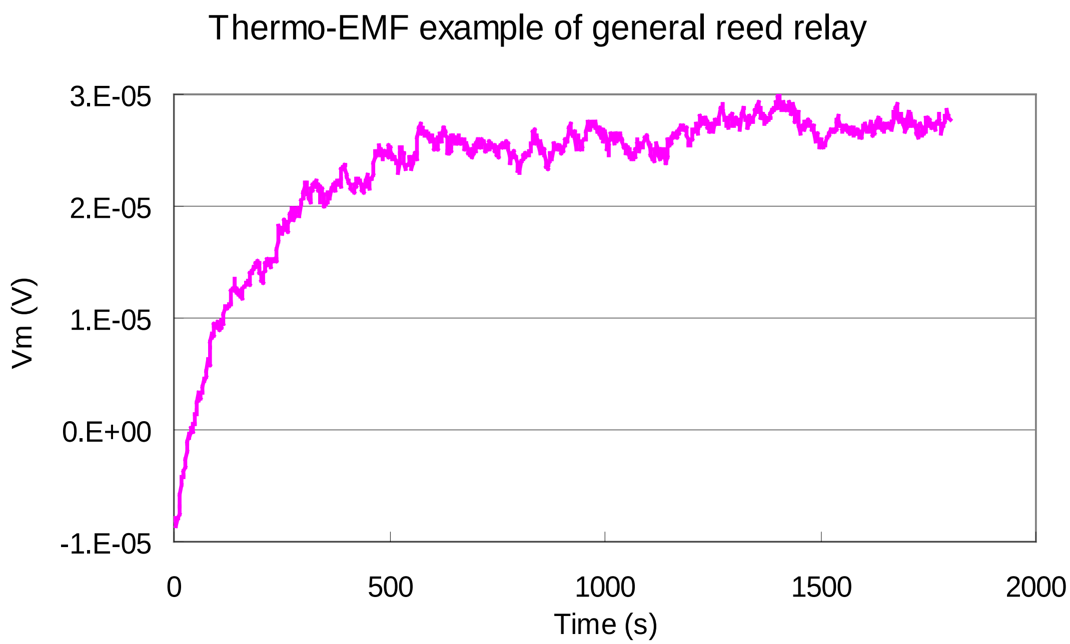
To achieve 0.1% accuracy in a copper structure with an equivalent resistance of 10 mΩ per square (1 mm thick film) we have the following:

$$V_{\max} = \sqrt{(0.04\ mW) \times (10\ m\Omega)} \approx 0.000632\ V$$

→ Need 1 μV of voltage measurement resolution!

Thermo Electro-Motive Force (EMF): What is It?

EMF: A transient voltage pulse that is associated with reed relay switches.



Note: This is NOT an example of the relays used in our instrumentation.

EMF can have a significant impact on low-level resistance measurements.

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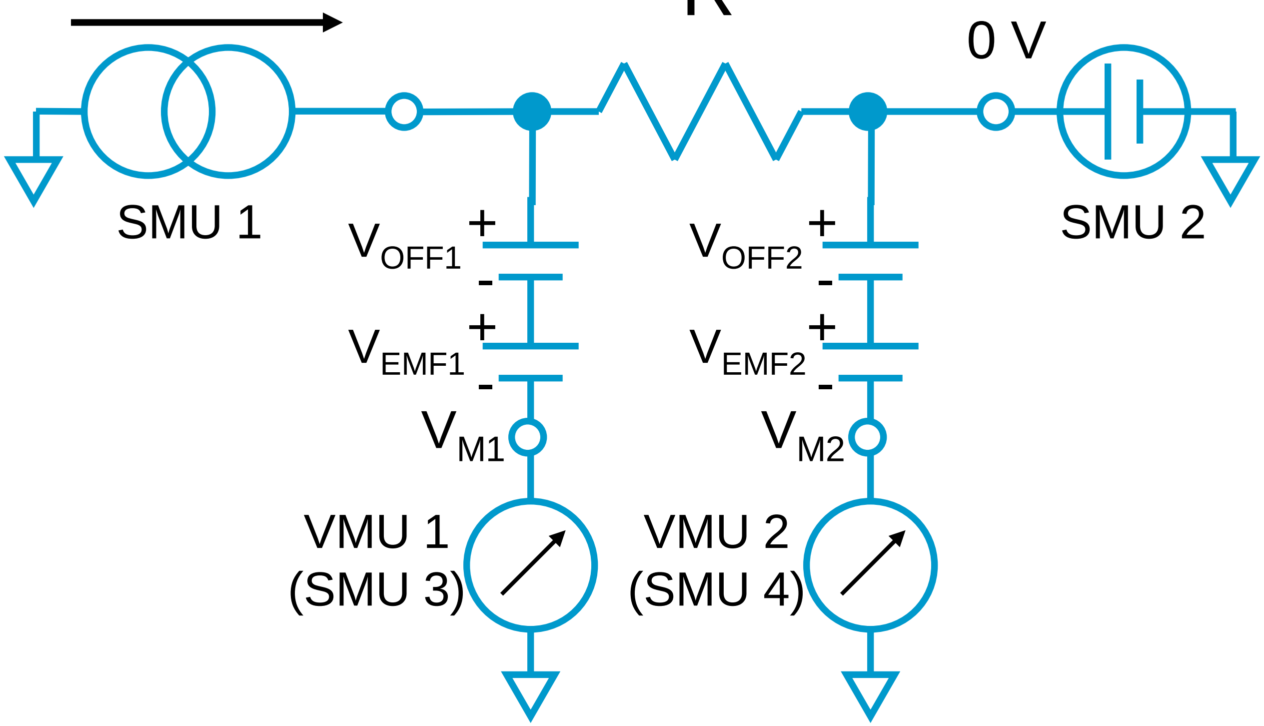
Modified Kelvin Resistance Measurement

$$R = \frac{(V_{M1} - V_{M2})}{I_F}$$

Key Points:

1) Make sure that you eliminate Joule self-heating effects
2) Measure twice and average the two resistances

Force Current Twice (both ways), i.e. +/- I_F



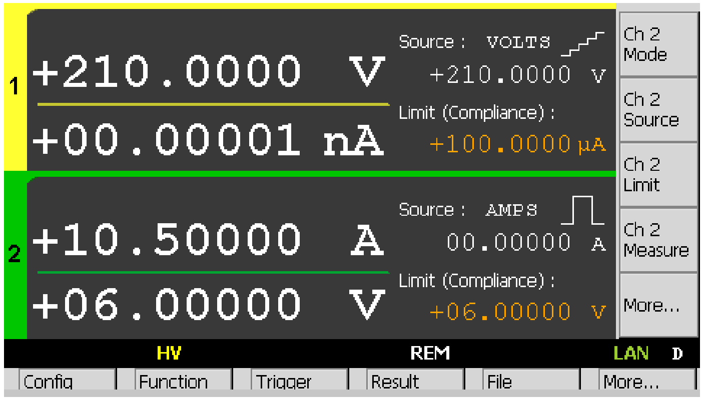
B2900A SMU SERIES FEATURES & BENEFITS

B2900A Series of Precision Source/Measure Units

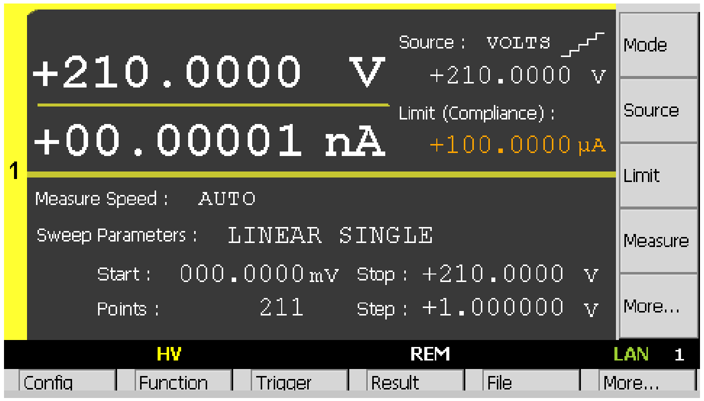
B2900A Key Features:

1. Range of up to ±210 V and ±3 A (DC) / ±10.5 A (pulsed) provides wider coverage for testing a variety of devices
2. Measurement resolution of 10 fA and 100 nV offers better source and measurement performance
3. GUI for quick bench-top testing, debug and characterization

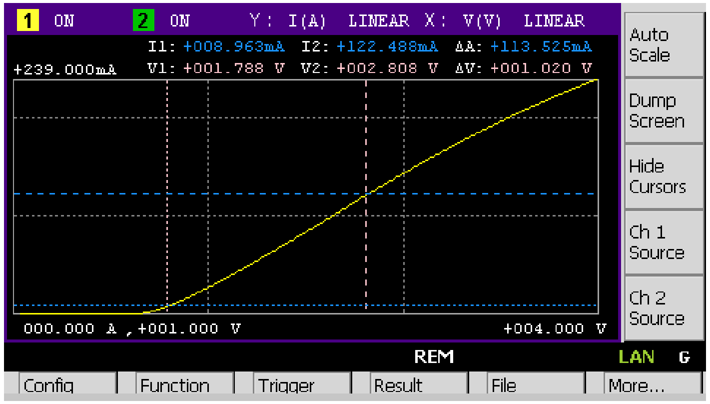
Interactive Device Evaluation Can be Performed Entirely from the Front Panel (4 Viewing Modes):



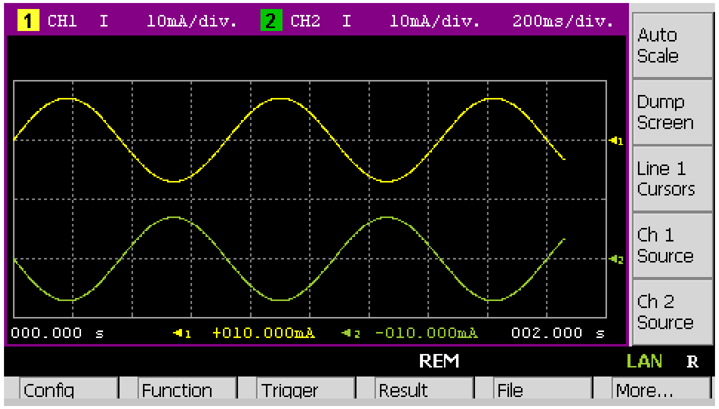
Dual Channel View (2-ch Units Only)



Single Channel View



Graph View (I-V, I-t, and V-t plots)



Roll View (similar to strip chart)

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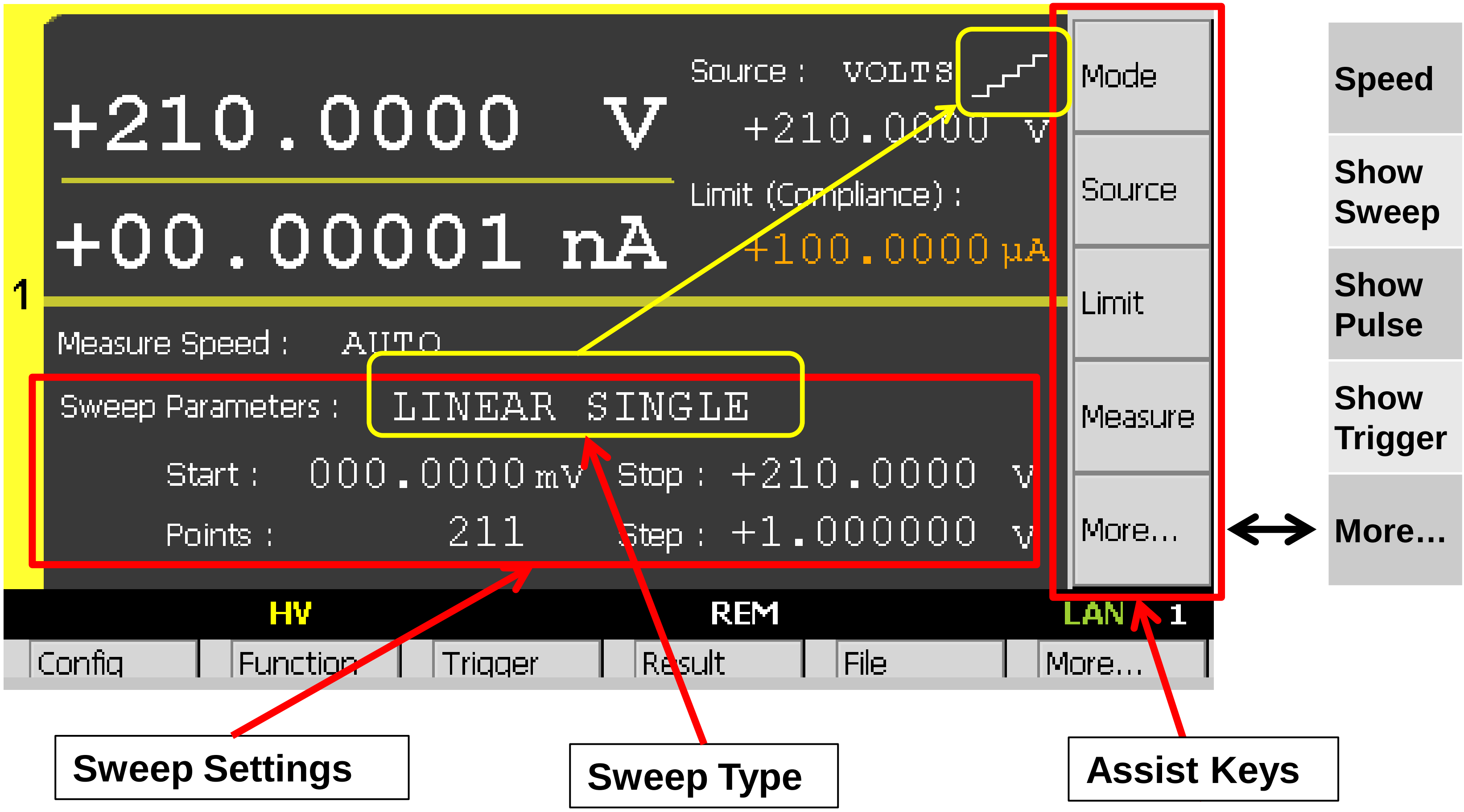
Setting Up a Sweep Measurement from the Front Panel is Easy!



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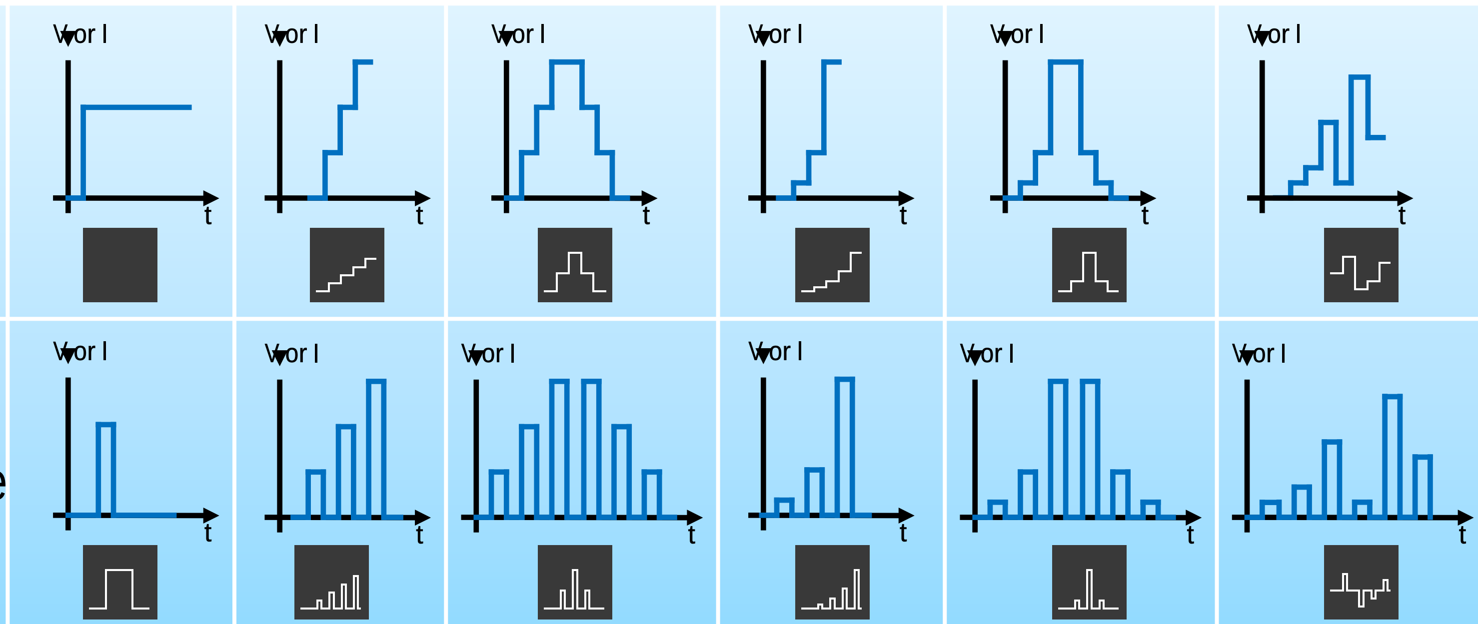
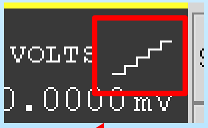
B2900A Series Sourcing Capabilities

		Constant	Linear Sweep		Log Sweep		List Sweep
			Single	Double	Single	Double	
Source Function	DC						
	Pulse						

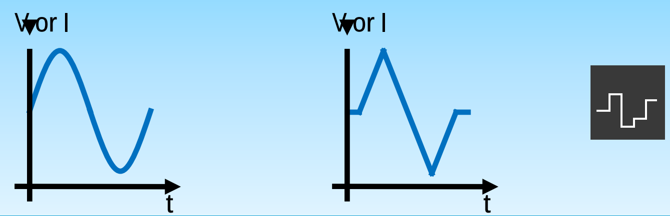




An icon appears in the GUI to indicate the type of sweep function selected.

Arbitrary Waveform Generation

The List Sweep function allows you to create arbitrary waveforms with up to 2500 steps. The timing resolution varies by B2900A model (20µs for B2901/02A, 10µs for B2911/12A).



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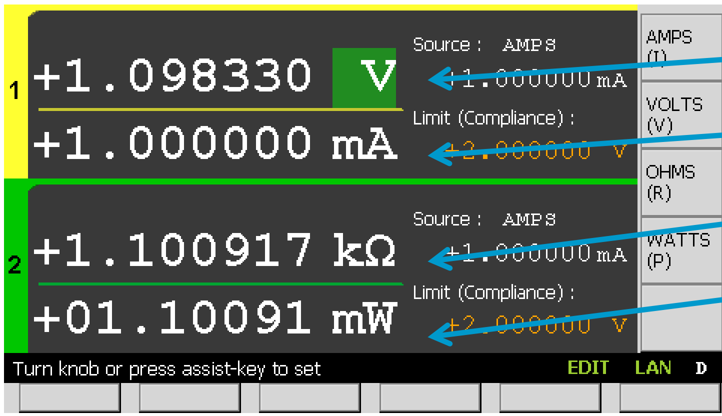
B2900A Series Measurement Capabilities

The B2900A Series has four measurement functions that can be selected for either channel using its front-panel GUI or SCPI commands.



Voltage Measurement

Current Measurement

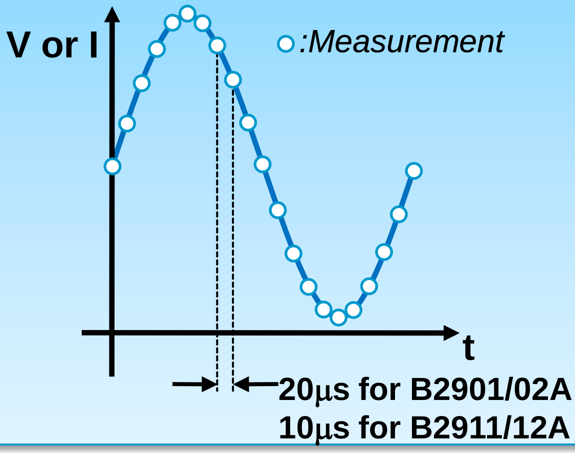
Resistance Measurement

Power Measurement

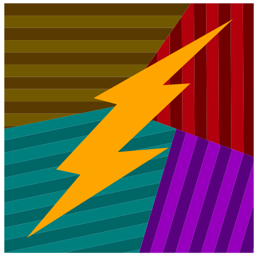
Note: The Power Measurement function cannot be specified when using remote control

High Speed Digitizing Capability

In addition to its intrinsic measurement functions, the B2900A Series has an advanced trigger design that enables high speed digitizing measurements (20µs for B2901/02A, 10µs for B2911/12A).



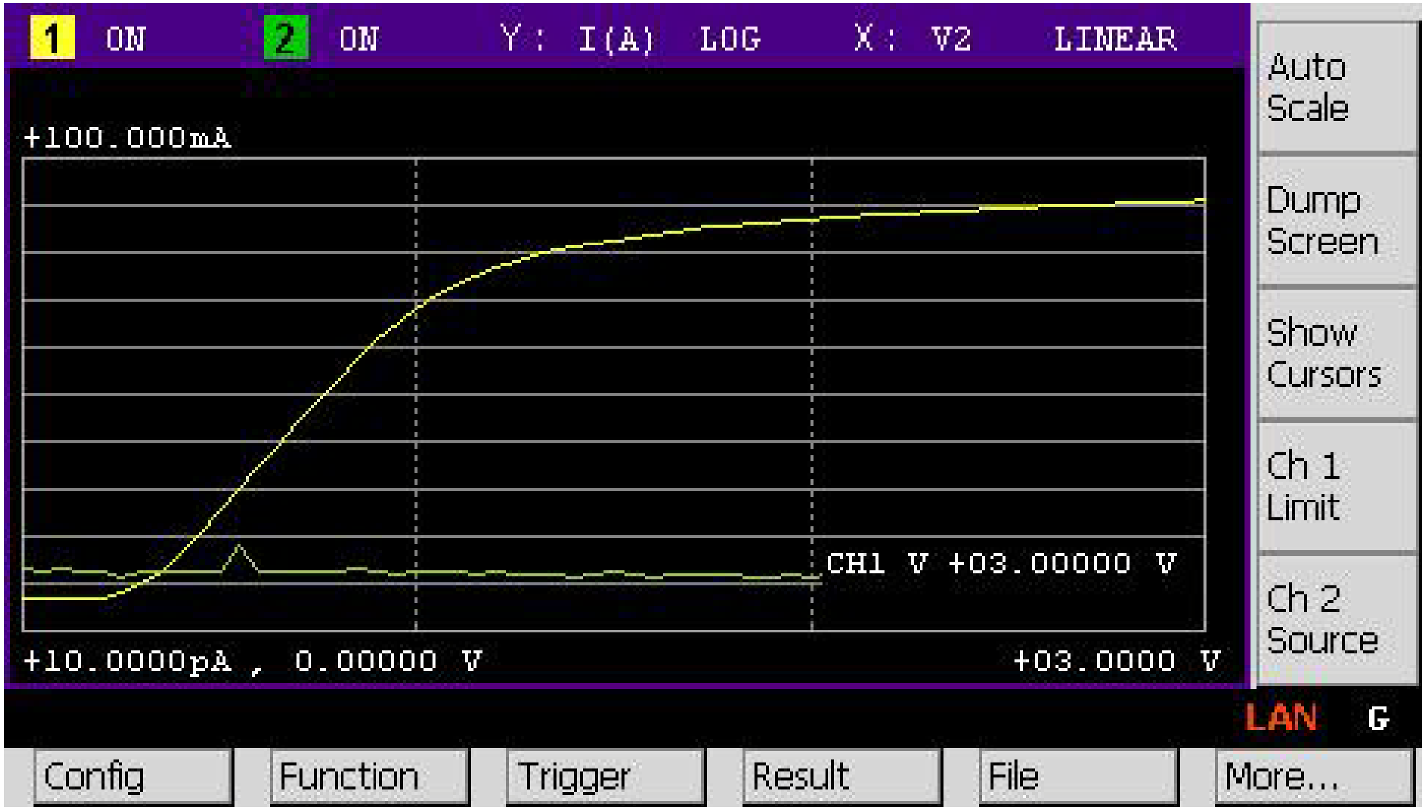
B2900A Maximum Voltage and Current Output



	Maximum Voltage	Maximum Current
DC or Pulsed	210 V	0.105 A
	21 V	1.515 A[2]
	6 V	3.03 A[2]
Pulsed only[1]	200 V	1.515 A
	6 V	10.5 A

1. Maximum duty cycle is 2.5%
2. On 2-channel units some additional restrictions apply on the combined current output of both channels (please refer to data sheet)

The B2900A Allows You to View Graphical Measurement Results



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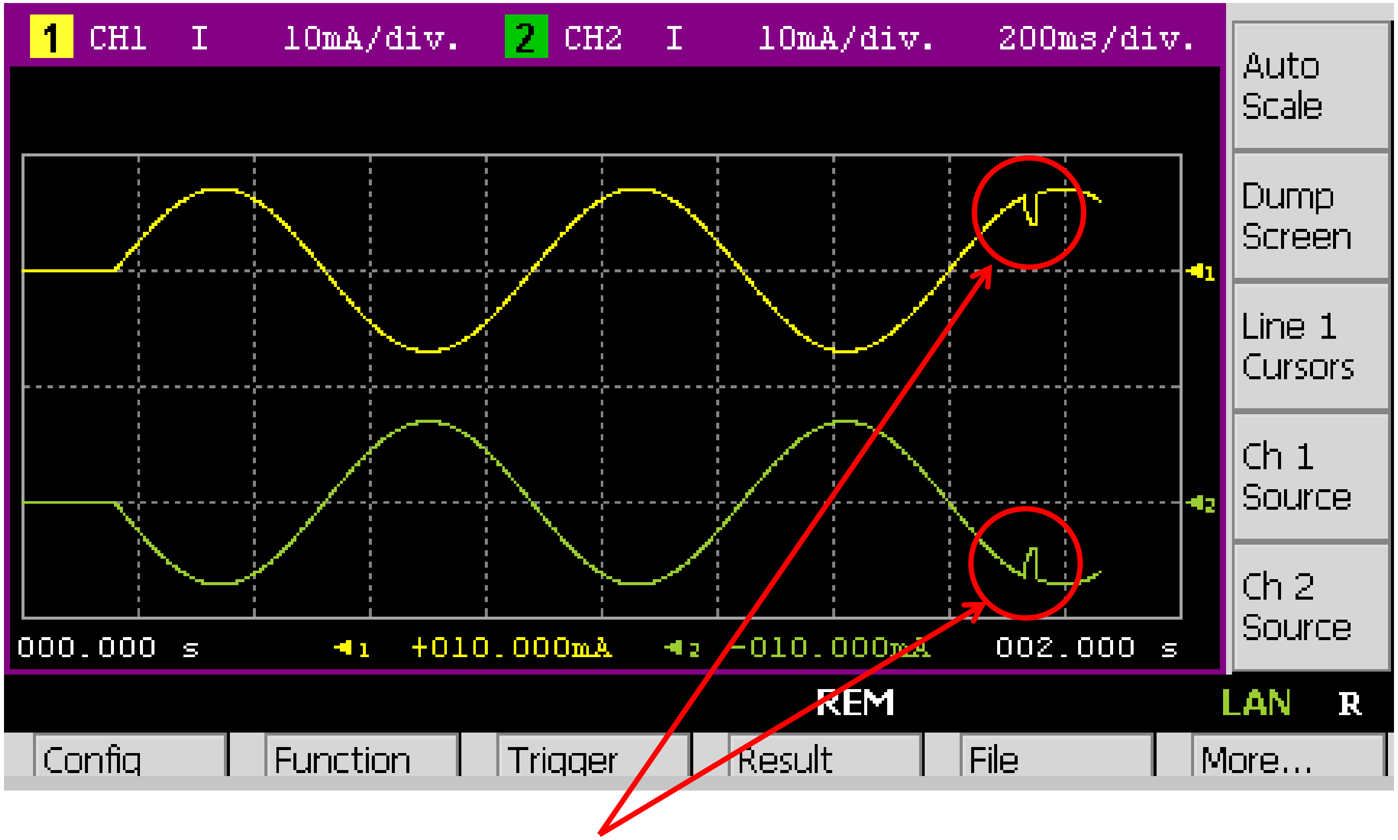
Roll View Provides a Convenient Way to View Slow-Moving Voltages/Currents Over Time



Can capture low-frequency “glitches”.

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Agilent Has Free "Quick I/V" Software for Customers Wanting PC-Based Instrument Control

B2900A Series Model Comparison

Model	# of SMU Ch's	Set/Measure Range		Setting Resolution			Measurement Resolution			Digitizing Rate (sample/s)	Other Features	Approximate Pricing (US)
				Digits	Min. Resolution		Digits	Min. Resolution				
		V	I		I	V		I	V			
B2901A	1	±210V	±3A/ch (DC) ±10.5A/ch (Pulsed)	5½	1pA	1μV	6½	100fA	100nV	50 k/sec (20μs/pt)	• XY View • AWG/List Sweep	$5.8K
B2902A	2											$8.5K
B2911A	1			6½	10fA	100nV	6½	10fA	100nV	100 k/sec (10μs/pt)	• XY View • AWG/List Sweep • Roll View	$8.3K
B2912A	2											$12.8K

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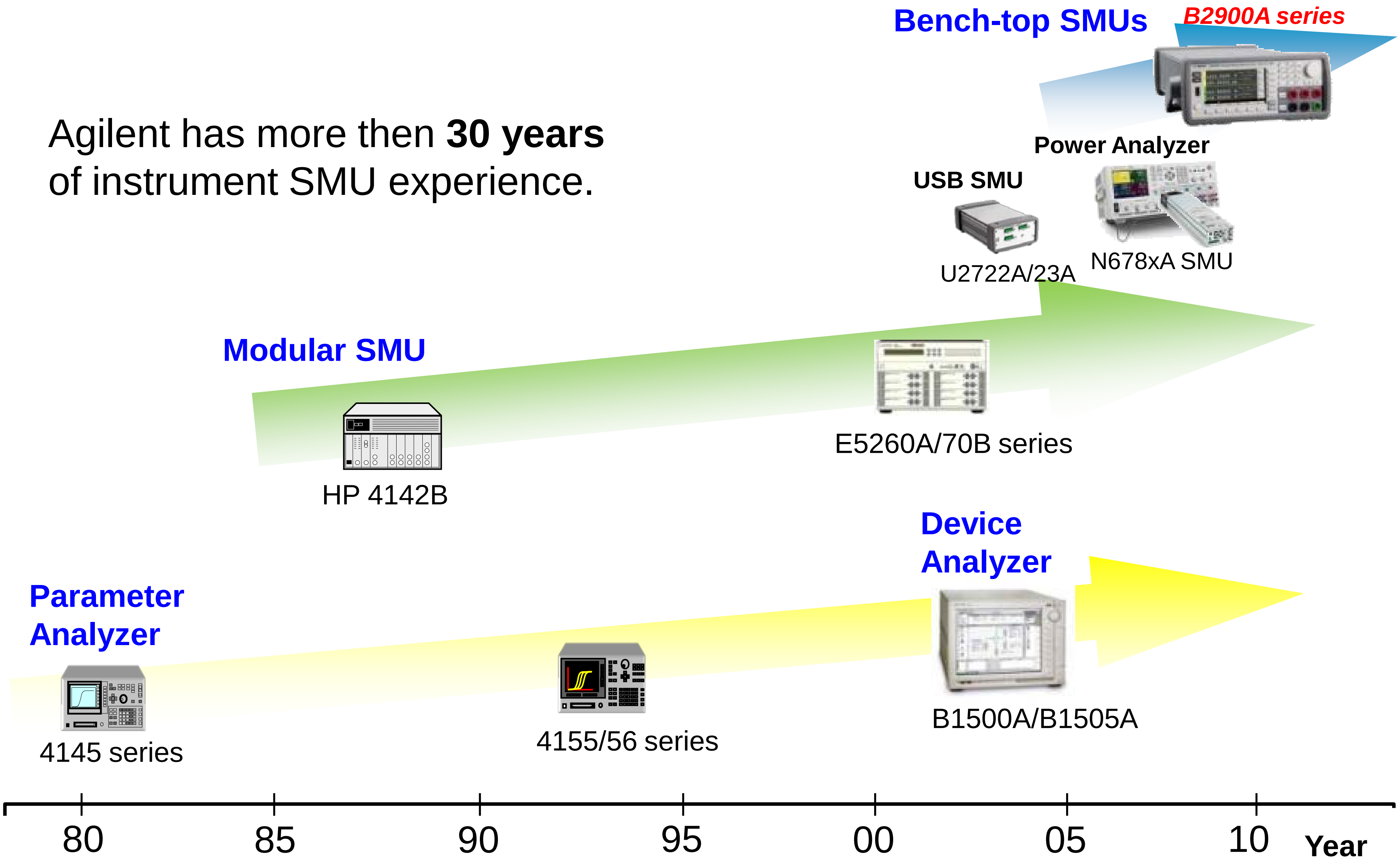
FINAL REMARKS

Additional Agilent SMU Instrument Products

Agilent has more then **30 years** of instrument SMU experience.



Comparison of the B1500A & B1505A

B1500A

Modules
- MPSMU
- HRSMU
- ASU
- HV-SPGU
- WGFMU

Accessories
- SCUU
- GSWU

Max I/V - 1 A, 200 V

Meas. Res. - 0.1 fA, 0.5 µV

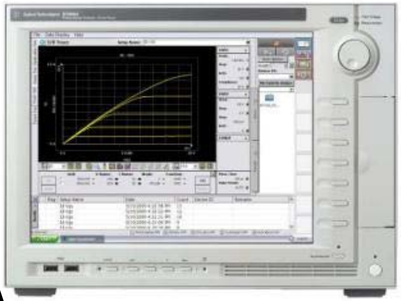
B1500A & B1505A (common)

Software

EasyEXPERT
- Tracer Test
- Classic Test
- Application Test
- Quick Test

Modules
- HPSMU
- MFCMU

B1505A



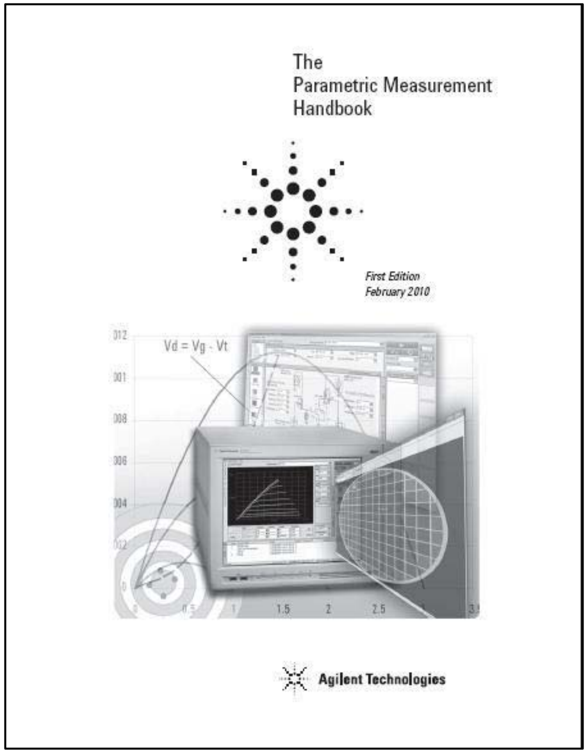
Modules
- HCSMU
- HVSMU

Accessories
- HV Bias-T
- Module Selector Unit

Max I/V - 40 A, 3000 V

Meas. Res. - 10 fA, 2 µV

Parametric Measurement Handbook Available



>200 pages of invaluable information on parametric test

You can download the PDF file (Rev 3) from the web:
http://www.agilent.com/find/parametrichandbook

You can also request it after completing the evaluation form.

Question & Answer Session

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