Fundamentals of Low Current and Ultra-High Resistance Measurement

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Agenda for Today

- ❑ High resistance & low current measurement basics
- ❑ Sources of measurement error and how to correct for them
- ❑ Adjusting instrument settings for optimal measurement results
- ❑ Summary & final comments

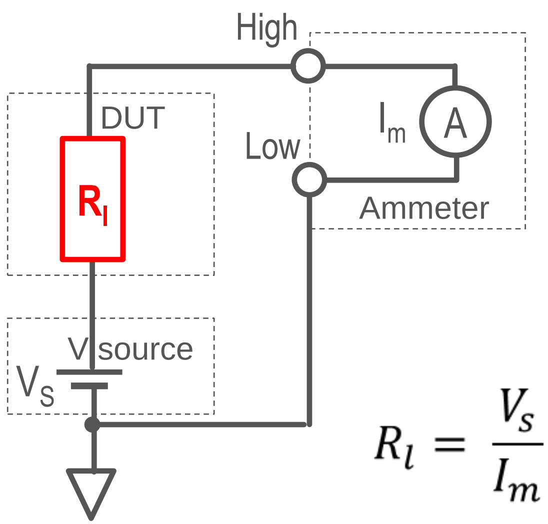
What do we mean by high resistance?

Defining High Resistance Measurement

Apply a DC voltage and measure the current flowing through a DUT (Device Under Test) to calculate resistance using Ohm's law (R=V/I).

Important terms:

- Peta (P) = 10^{15}
- Tera (T) = 10^{12}
- Giga (G) = 10^{9}
- pico (p) = 10^{-12}
- femto (f) = 10^{-15}
- atto (a) = 10^{-18}



$$R_l = \frac{V_s}{I_m}$$

- ❑ For the purposes of this presentation, we will consider high resistance measurements to be those <u>greater than 1 GΩ</u>.
- ❑ In addition, high resistance characterization generally requires current measurements of <u>less than 1 nanoamp</u>.

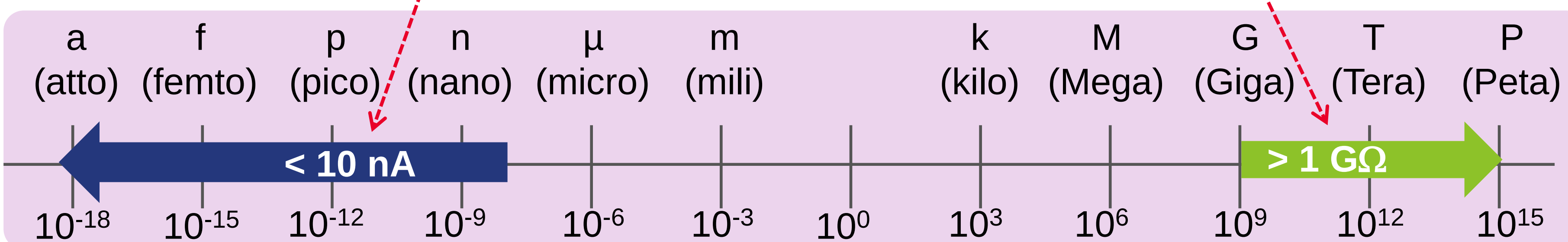
Ultra-High Resistance Measurements Need a Picoammeter (pA) or Electrometer (eM)

What is a Picoammeter ?

- Simply stated it is a Precision current meter
- Currents below 10 nA can be measured

What is an Electrometer ?

- Simply stated it is a High performance DMM
- It can measure resistances >1 GΩ



Products	Product type	Current measurement resolution	Resistance measurement	Voltage sourcing	Charge measurement resolution
B2981A/83A	Picoammeter	0.01 fA	No	No	NA
B2985A/87A	Electrometer	0.01 fA	Up to 10 PΩ	Up to 1,000 V	1 fC

Floating vs. Grounded Resistance Measurements

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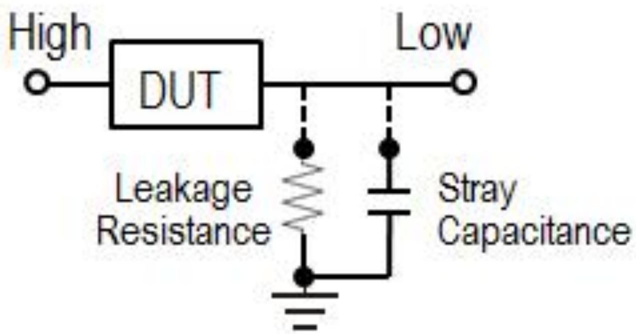
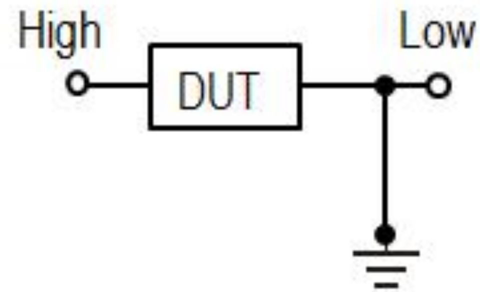
<tr><th>Floating</th><th>Grounded</th></tr>
<tr><td>
</td><td>
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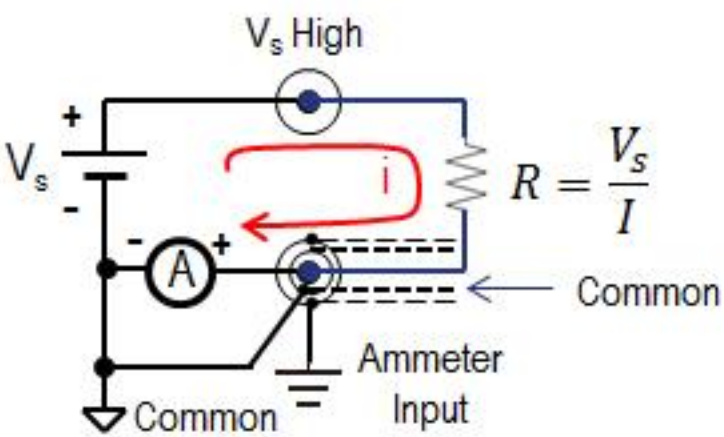
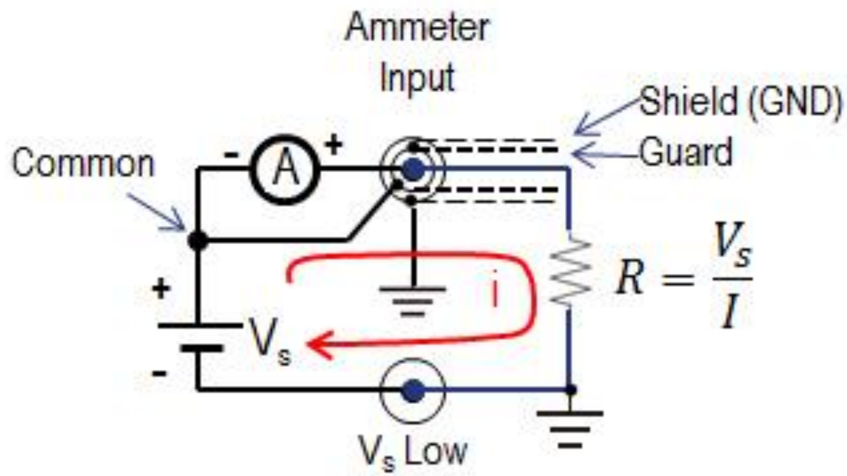
<tr><td>
</td><td>
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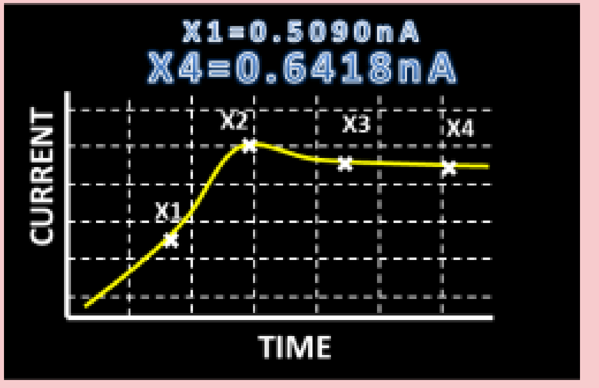
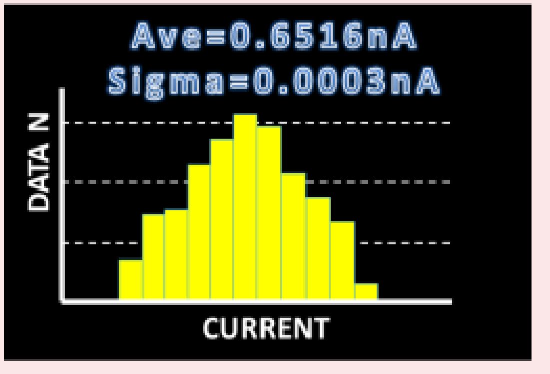
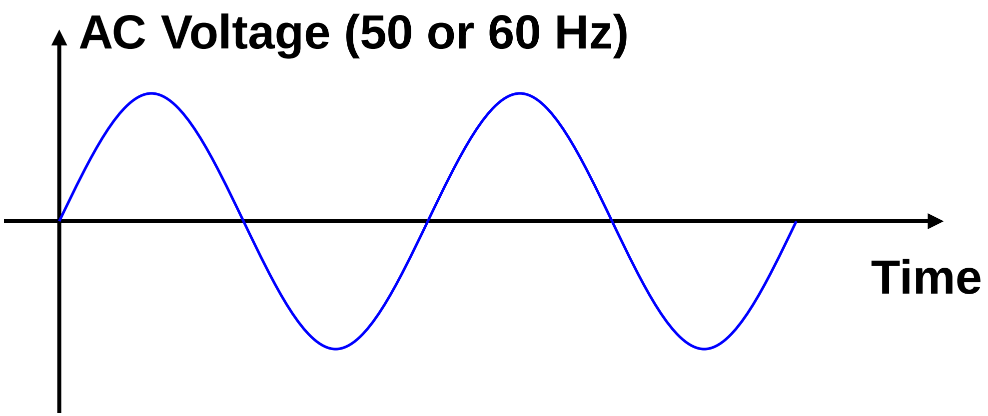
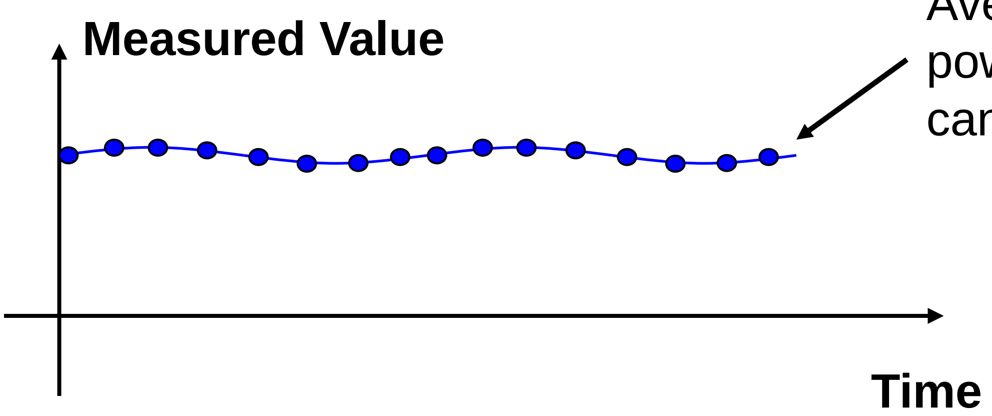
Data Measurement Issues

Understanding transient signal behavior is extremely important for low-level measurements, so it is important to be able to visually see the time-based behavior of a measurement signal and to select the appropriate measurement point(s).	
All measurements involve some amount of uncertainty, but especially in the case of low-level measurements the results need to be looked at stochastically (i.e. in terms of mean and standard deviation).	

Noise Issues - 1

The biggest lab noise source is from the AC power line



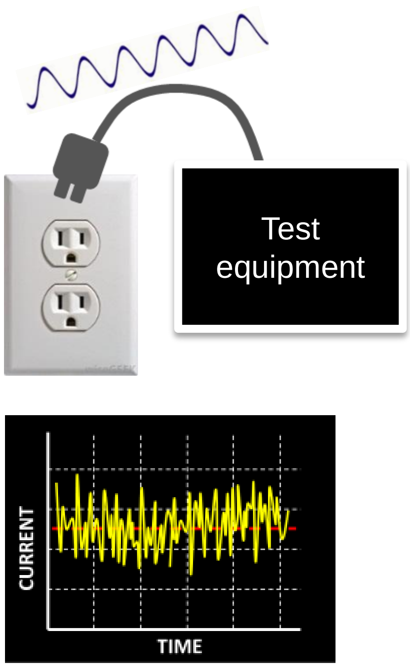


Averaging over multiple power line cycles (PLCs) can correct for this noise.

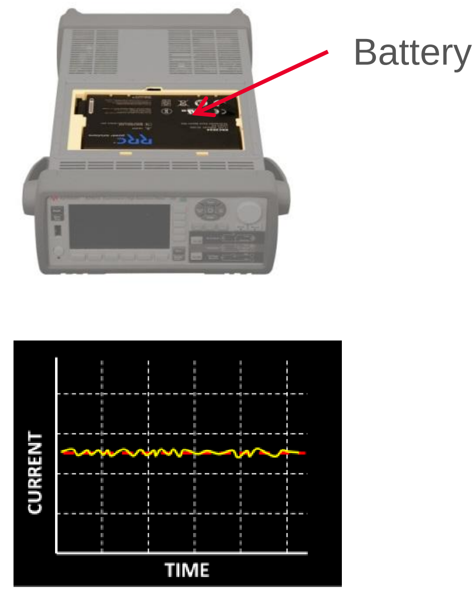
Noise Issues - 2

Complete isolation is the best way to remove AC noise

Measurement made while connected to AC power

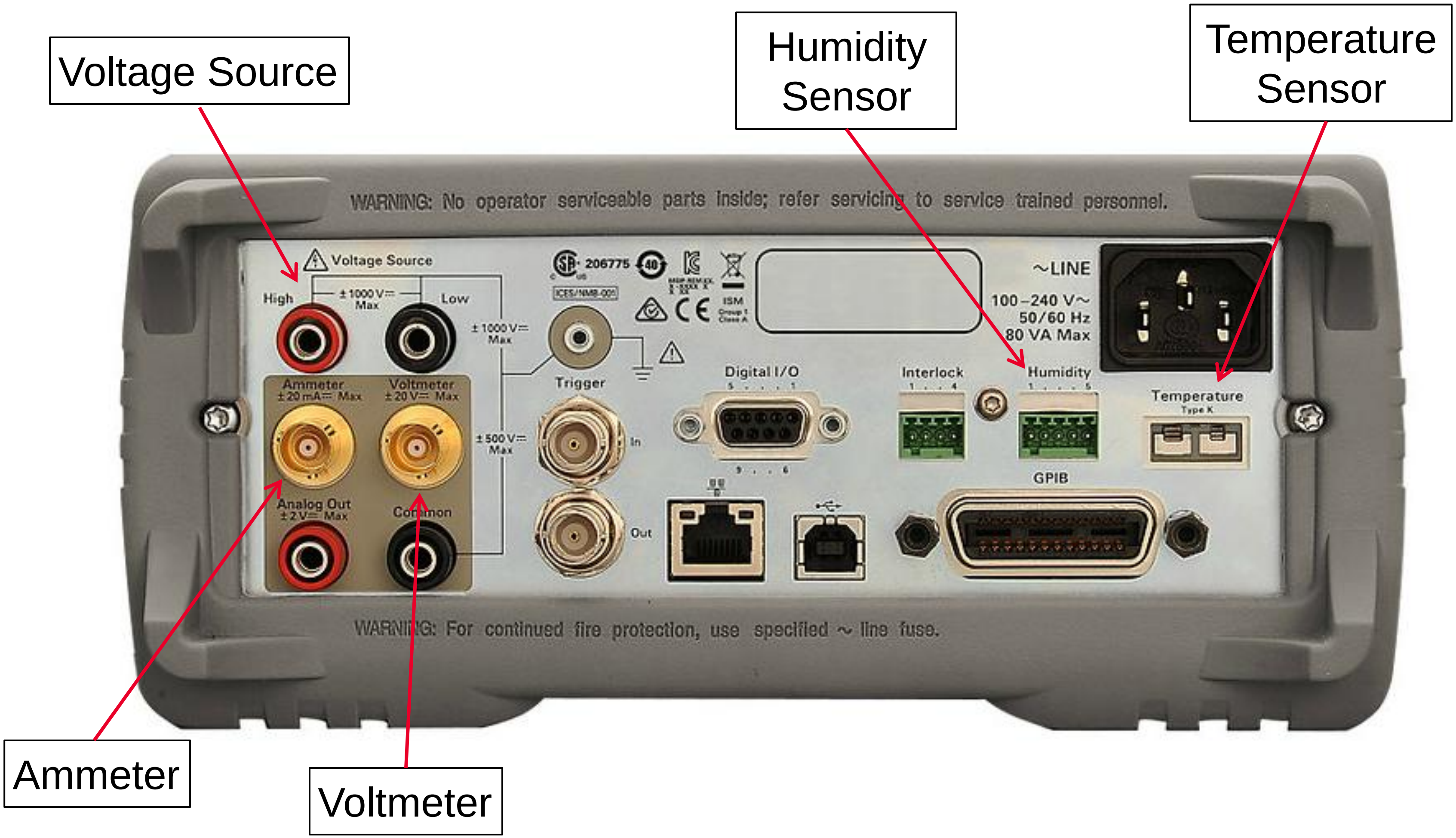


Measurement made using a battery powered instrument



Low Current/High Resistance Measurements Typically Use an Electrometer

What are the key features of an electrometer?



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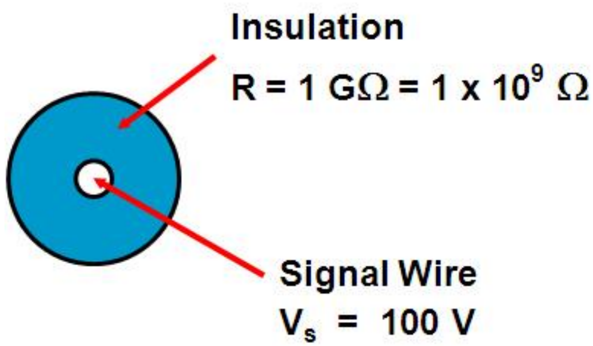
Low Current Measurements Must be Triaxial

Why are triaxial cables & fixtures needed for low current?

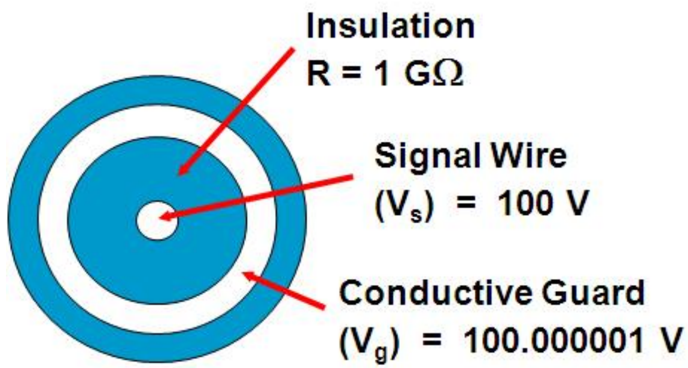
BNC (Coaxial) Cable:



Leakage Current:

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

Triaxial Cable:



Leakage Current:

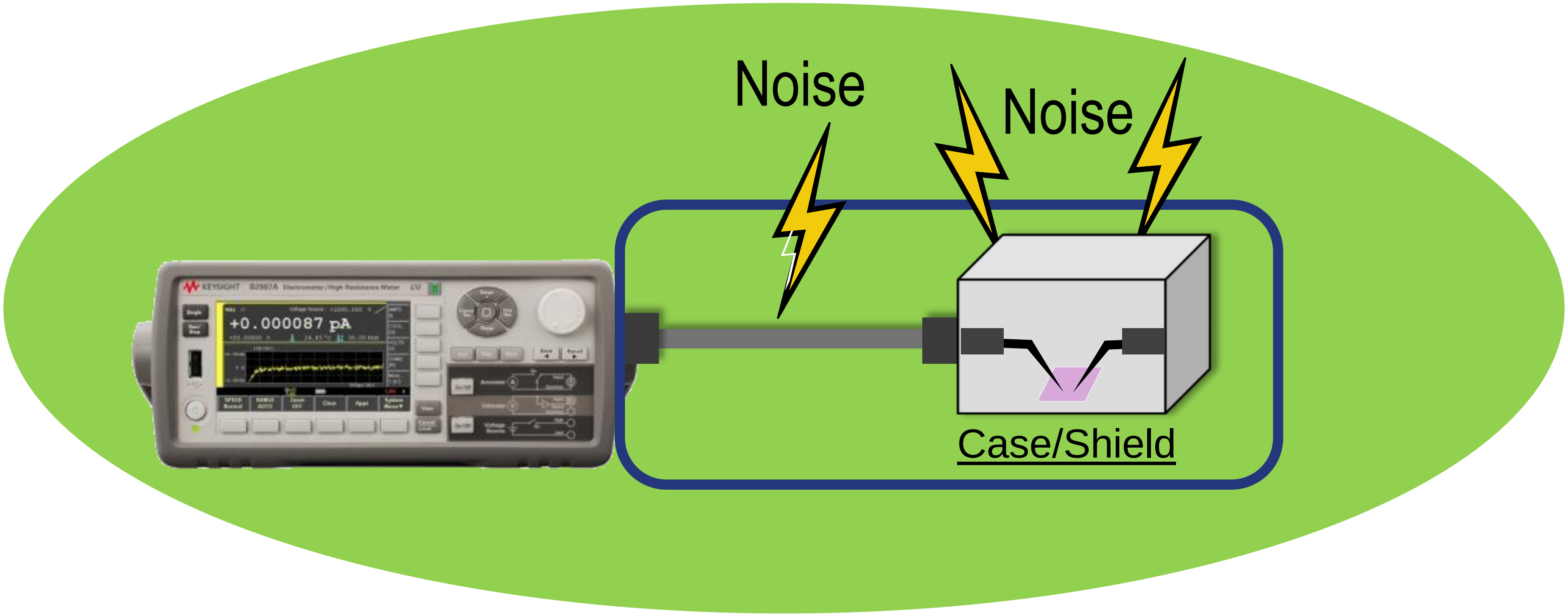
$$\frac{(100.000001\ V - 100\ V)}{1 \times 10^9 \Omega} = 1\ fA$$

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

External Cabling & Fixturing Issues

How do you know if your cables & fixturing are OK?

It is important to verify the performance of your cables and test fixturing when making low-level measurements, as these are often the “weak link” in the entire measurement system.



Electrometer Referenced in This Presentation

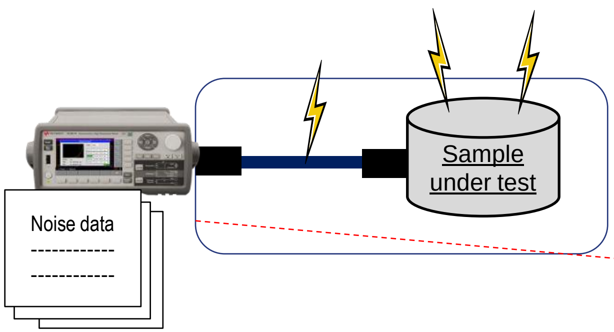
Keysight B2985A/B2987A

– Current measurement down to 0.01 femtoamps

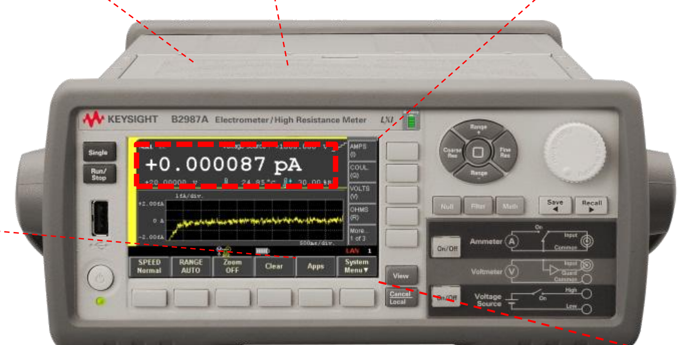
– Resistance measurement up to 10 PΩ

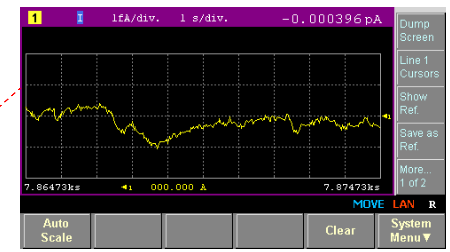
0.01 fA (0.00001 pA) effective resolution and 0.001 fA display resolution

Available battery operation (B2987A)

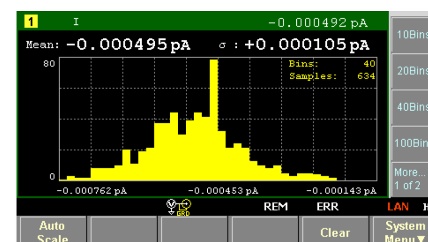


Optional setup integrity checker function measures and records measurement setup noise level





Time domain view



Histogram view

Agenda for Today

- ❑ High resistance & low current measurement basics
- ❑ **Sources of measurement error and how to correct for them**
- ❑ Adjusting instrument settings for optimal measurement results
- ❑ Summary & final comments

Sources of Measurement Error and How to Correct for Them

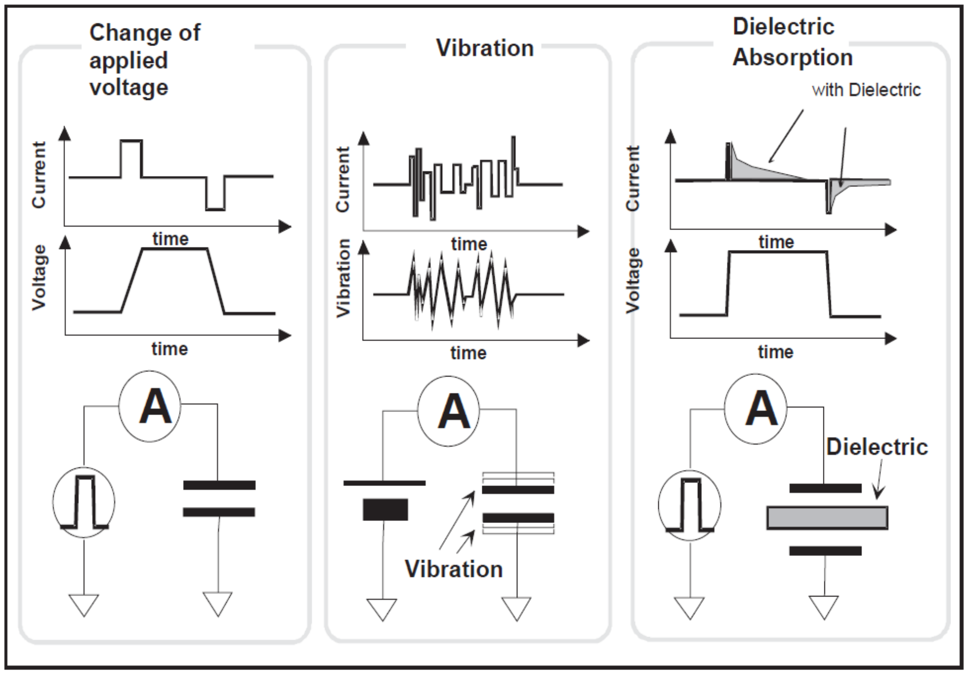
- ❑ Capacitive coupling
- ❑ Insulator effects
- ❑ Leakage currents
- ❑ Electro-mechanical noise from the cable
- ❑ External environment noise

Capacitive Coupling - 1

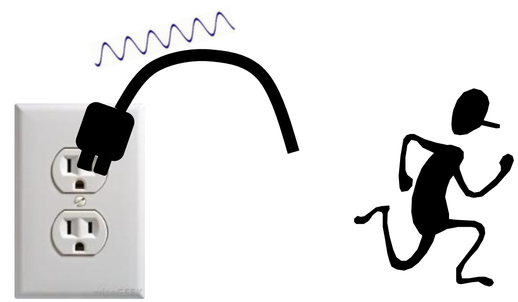
What causes capacitive coupling noise?

- The noise currents caused by capacitive coupling arise in two distinct ways: through changes in applied voltage and through vibration

$$I = C\frac{dV}{dt} + V\frac{dC}{dt}$$



Major sources of capacitive coupling noise



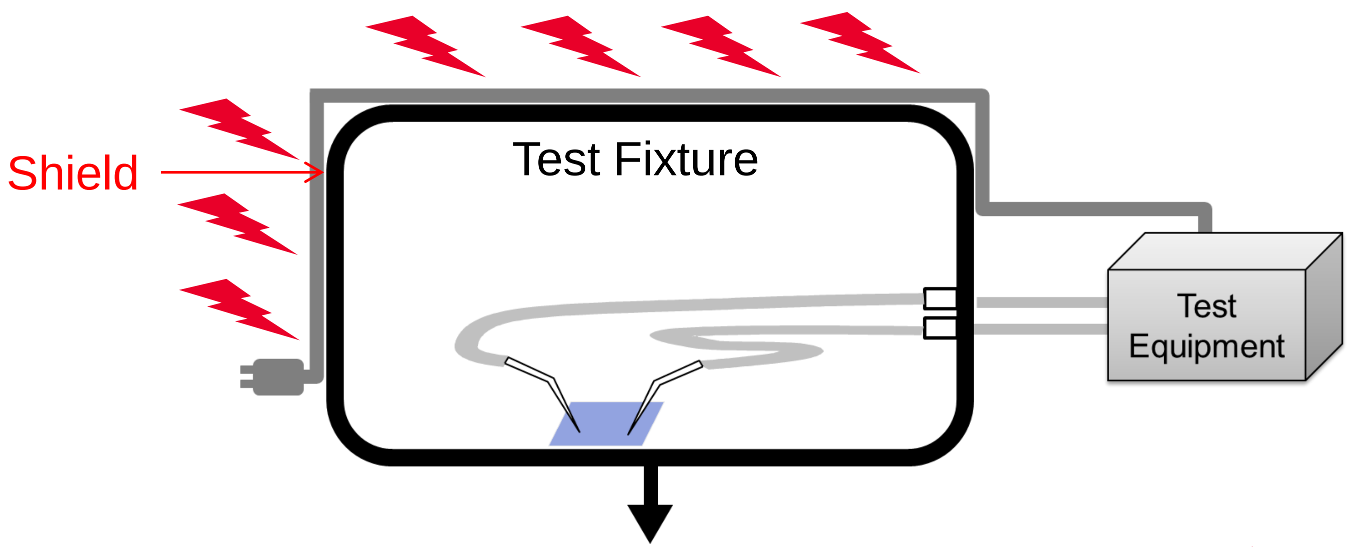
Random voltage fluctuations:
- ✓ AC power line
- ✓ Signal line

Human body movement
The human body holds charge and can apply significant voltage

Capacitive Coupling - 2

How to Minimize Capacitive Coupling Effects

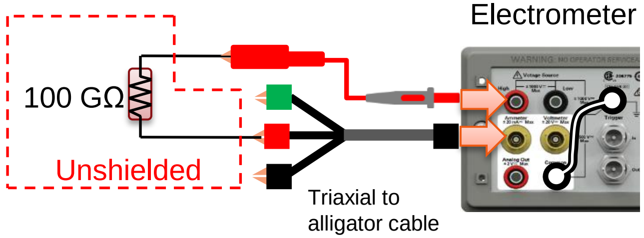
- ❑ Shielding
  - ✓ Since high resistance & low current measurements are very sensitive to external noise, proper shielding is critical.
  - ✓ The ideal test fixture completely encloses the DUT in conductive material that is at ground potential and keeps all unnecessary wires outside of the internal test environment.

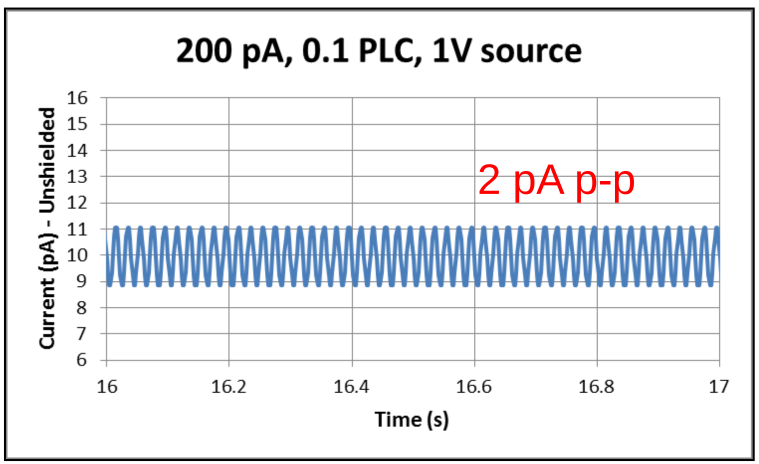


Capacitive Coupling - 3

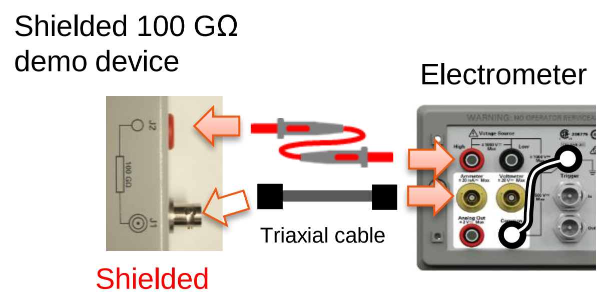
Measurement Example: Unshielded vs. Shielded

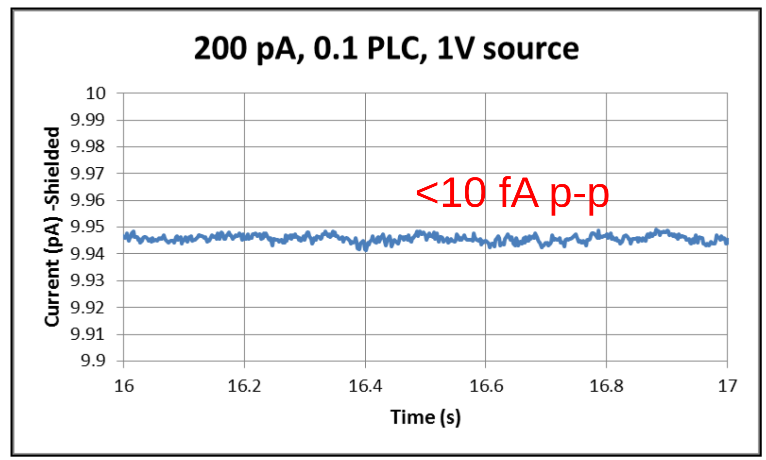
Unshielded Measurement





Shielded Measurement





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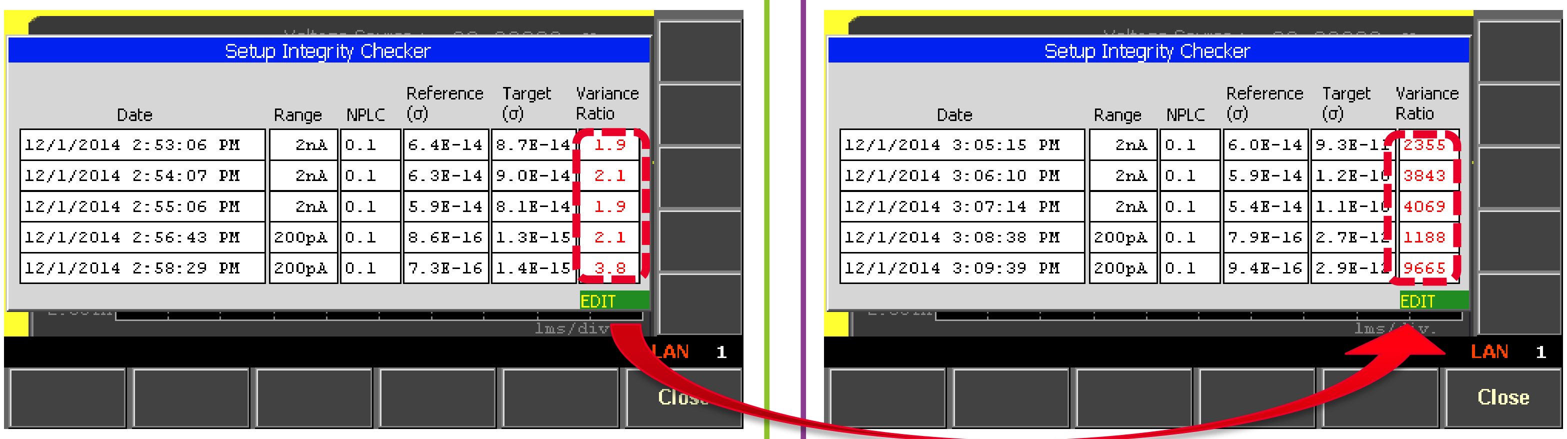
Capacitive Coupling - 4

Verifying test setup integrity

Having a **test setup integrity checking function** enables you to compare the noise level of your test setups **statistically.**

Shielded Measurement

Unshielded Measurement



Much more noise

Reference (σ): Reference noise level with the test setup disconnected
Target (σ): Target noise level with the test setup connected
Variance ratio: Variance ratio of the reference and target values

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Sources of Measurement Error and How to Correct for Them

- ❑ Capacitive coupling
- ❑ Insulator effects
- ❑ Leakage currents
- ❑ Electro-mechanical noise from the cable
- ❑ External environment noise

Insulators Effects - 1

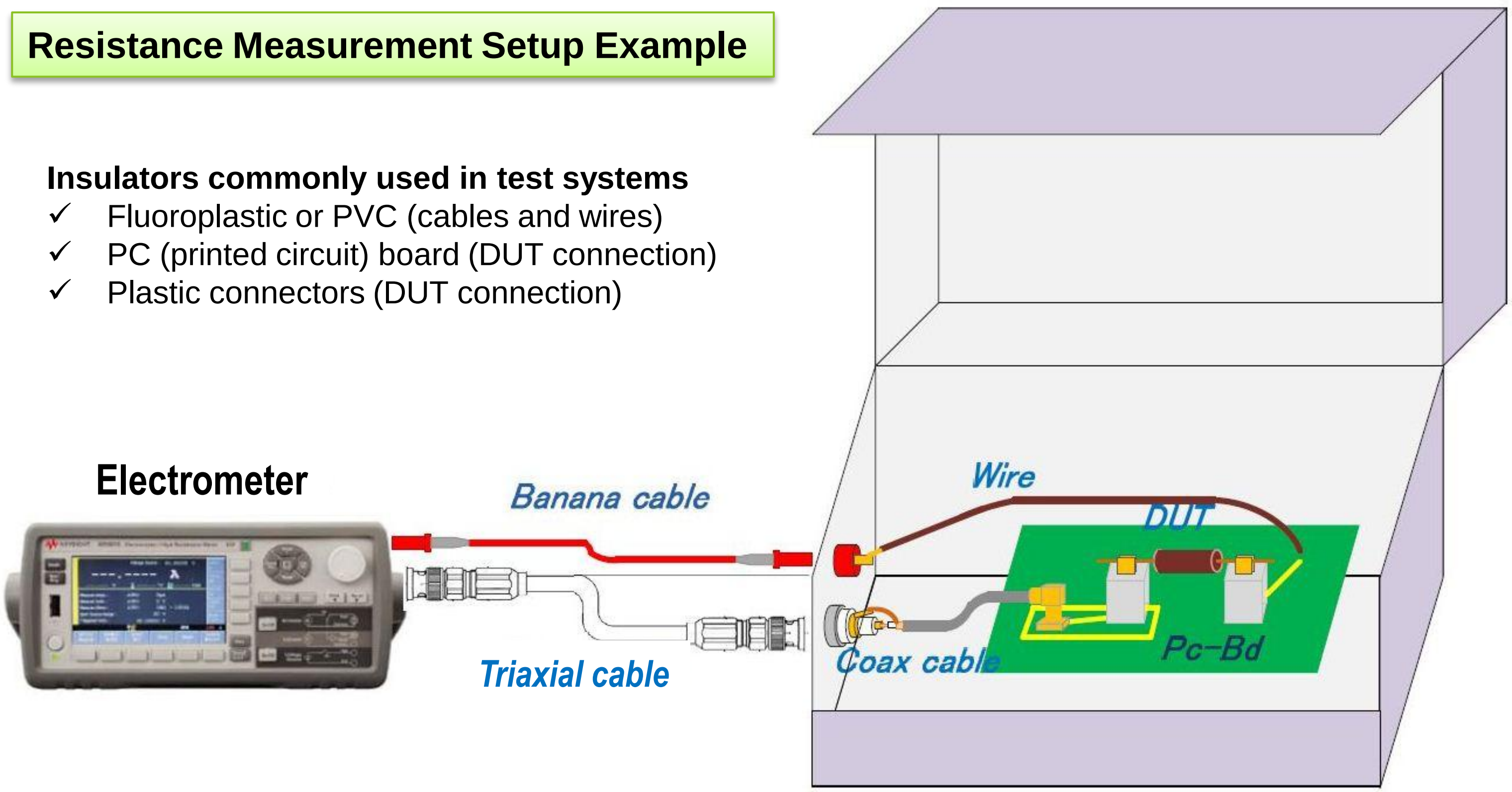
Insulators can have a significant impact on measurements

Know the **properties of the insulators** used in your test system

Resistance Measurement Setup Example

Insulators commonly used in test systems

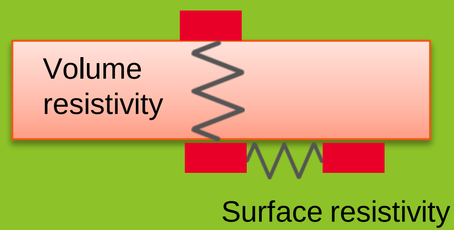
- ✓ Fluoroplastic or PVC (cables and wires)
- ✓ PC (printed circuit) board (DUT connection)
- ✓ Plastic connectors (DUT connection)



Insulators Effects - 2

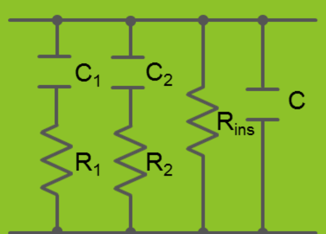
Leakage Current & Dielectric Absorption

Leakage Current



- ❑ Leakage current is determined by the applied voltage and the insulator's resistance
- ❑ Key points to remember:
  - ✓ You must take into account the insulator's resistance when applying large voltages (hundreds of volts)
  - ✓ Keep the insulator surfaces clean since the surface resistivity is influenced by surface contamination

Dielectric Absorption



Equivalent circuit

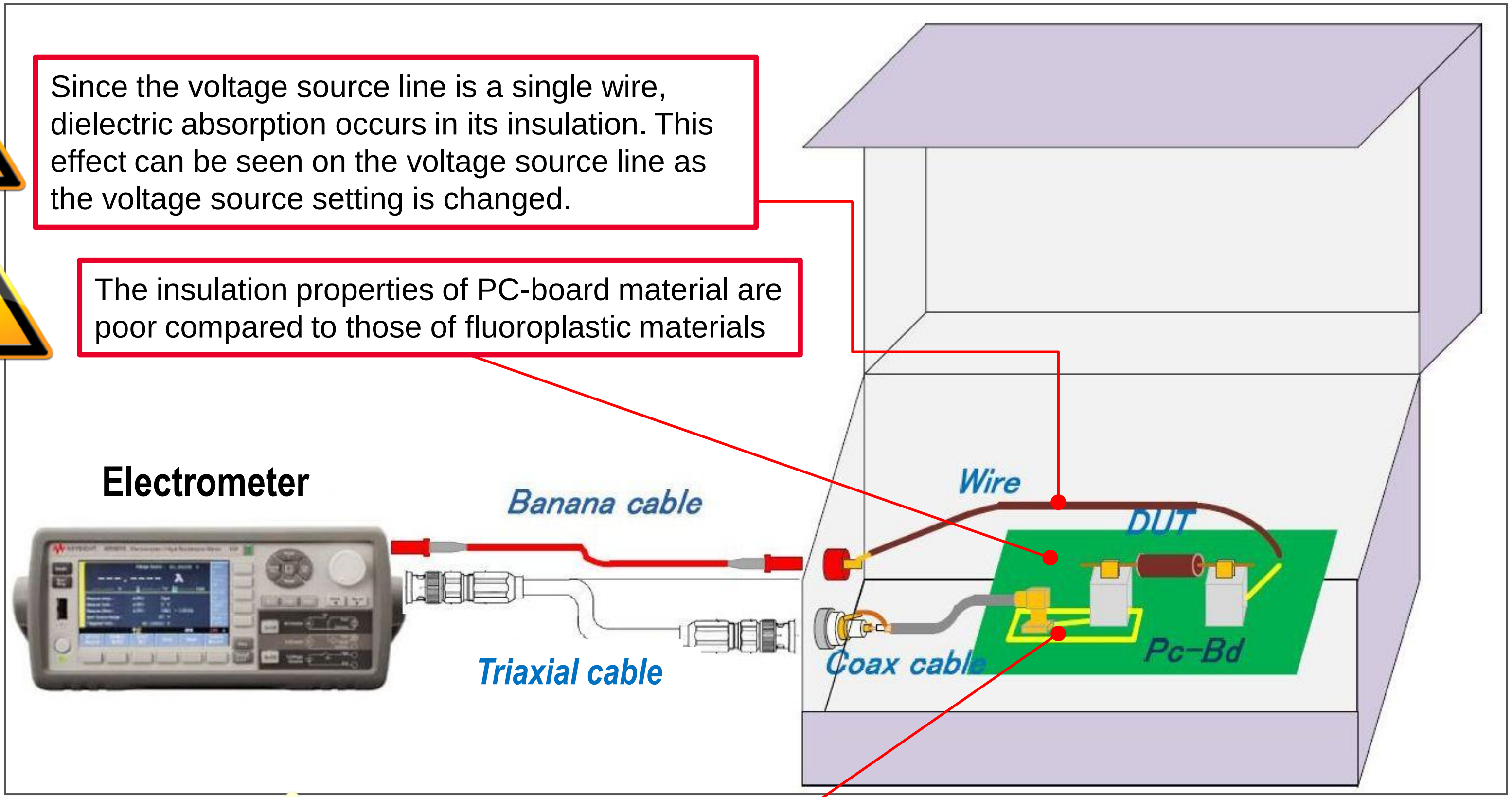
- ❑ Applying voltage to an insulator causes charge to polarize which in-turn generates decay currents.
- ❑ Key points to remember:
  - ✓ Minimize insulators surrounding wires with fluctuating voltages as much as possible and isolate the insulators from the signal line with conductors biased at a constant voltage.

Insulators Effects - 3

Issues with previously shown test setup

Since the voltage source line is a single wire, dielectric absorption occurs in its insulation. This effect can be seen on the voltage source line as the voltage source setting is changed.

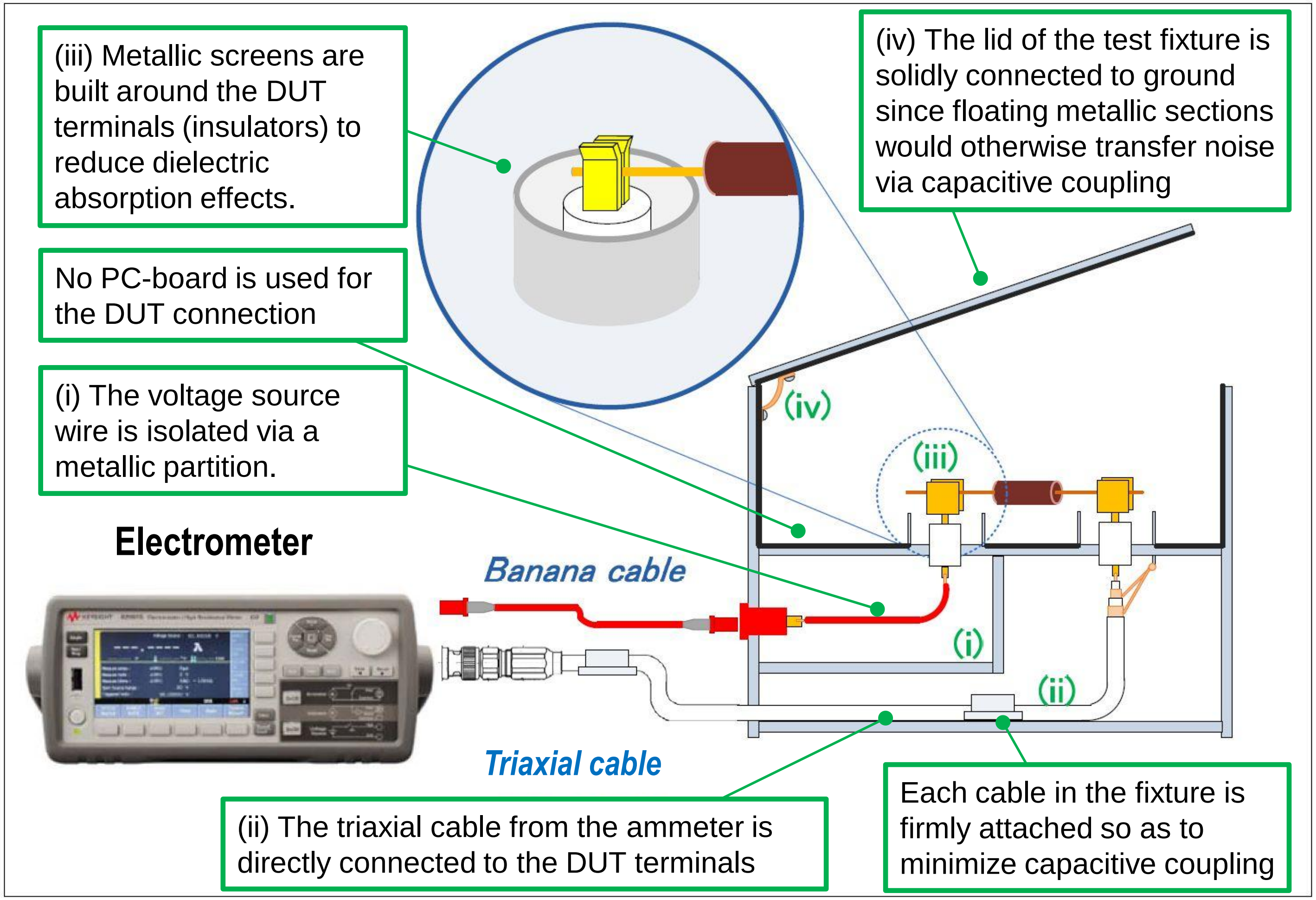
The insulation properties of PC-board material are poor compared to those of fluoroplastic materials



A short wiring pattern can minimize the surface leakage currents. However, leakage currents into the board cannot be eliminated.

Insulators Effects - 4

A better test setup



Insulators Effects - 5

Keysight off-the-shelf test fixtures & cabling

16339A Component Test Fixture

16008B Resistivity Cell

16117B/C Test Lead

N1413A high resistance meter fixture adapter

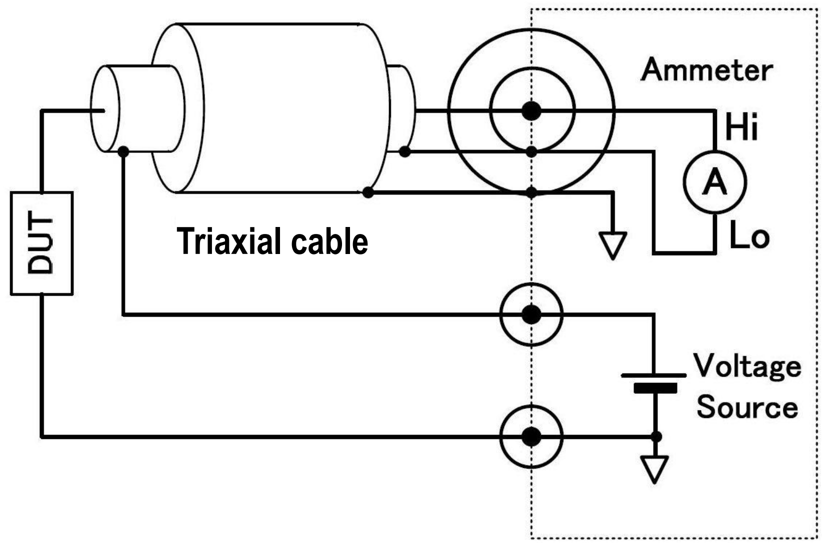
Sources of Measurement Error and How to Correct for Them

- ❑ Capacitive coupling
- ❑ Insulator effects
- ❑ **Leakage currents**
- ❑ Electro-mechanical noise from the cable
- ❑ External environment noise

Leakage Currents - 1

What is the guarding technique?

Guarded configurations require the use of a **triaxial environment**.



Benefit of using a guarded configuration (B2985A/87A example):

Leakage current without Guarding: $I_{leak} = \dfrac{V_S}{R_{leak}}$

Leakage current with Guarding: $I_{lk1} = \dfrac{V_d}{R_{lk1}}$

V_d is less than 100 µV (20 µV according to the B2985A/87A's voltage burden specification). When V_s = 100 V and $R_{leak} = R_{lk1}$,

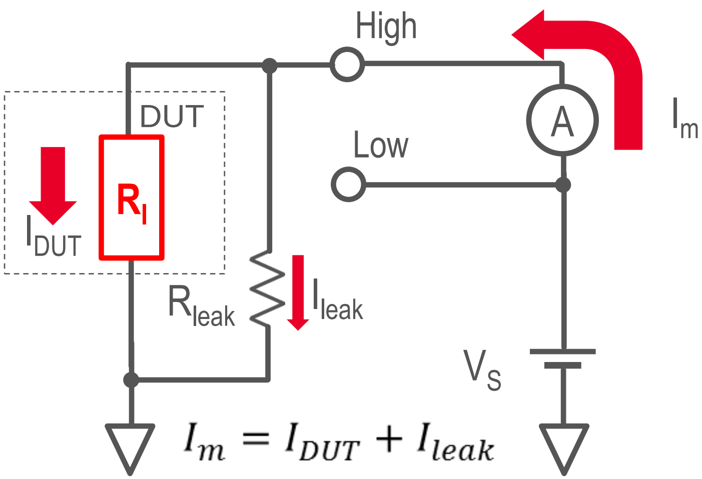
$$I_{lk1} = \frac{1}{10^6} \times I_{leak}$$

Leakage Currents - 2

How does the guarding technique work?

The guarding technique reduces leakage current through the parasitic shunt resistance path.

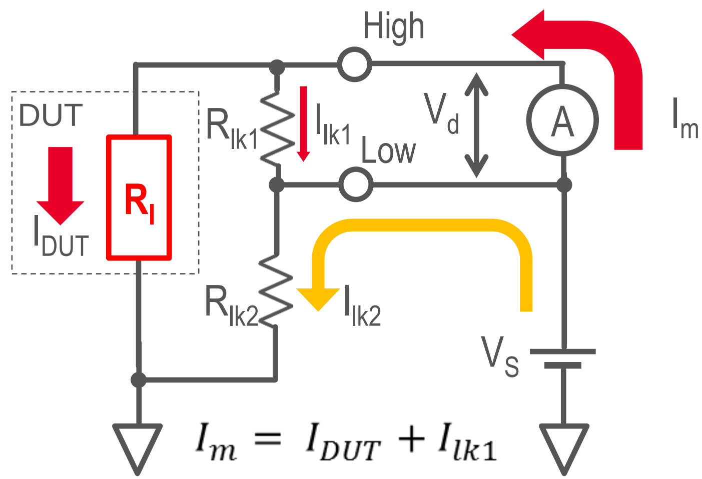
Without Guard



$$I_m = I_{DUT} + I_{leak}$$

$$I_{leak} = \frac{V_S}{R_{leak}}$$

With Guard



$$I_m = I_{DUT} + I_{lk1}$$

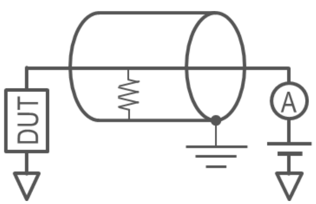
$$I_{lk1} = \frac{V_d}{R_{lk1}}$$

$$V_d \ll V_S \;\therefore\; I_{lk1} \ll I_{leak}$$

Leakage Currents - 3

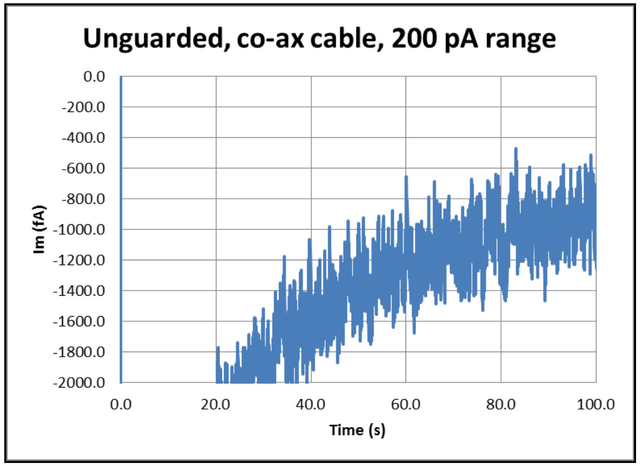
Measurement Example: Guarded vs. Unguarded

Unguarded measurement with coaxial cable

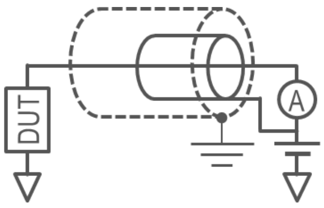


Electrometer

Cable: 16493B Coaxial cable
(with N1254A-106 Triaxial to BNC adapter)
DUT: Open

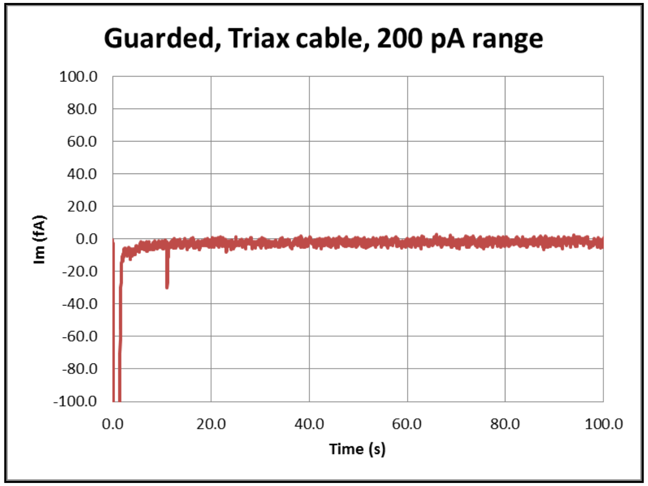


Guarded measurement with triaxial cable



Electrometer

Cable: 16494A Triaxial cable
DUT: Open



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- ❑ Capacitive coupling
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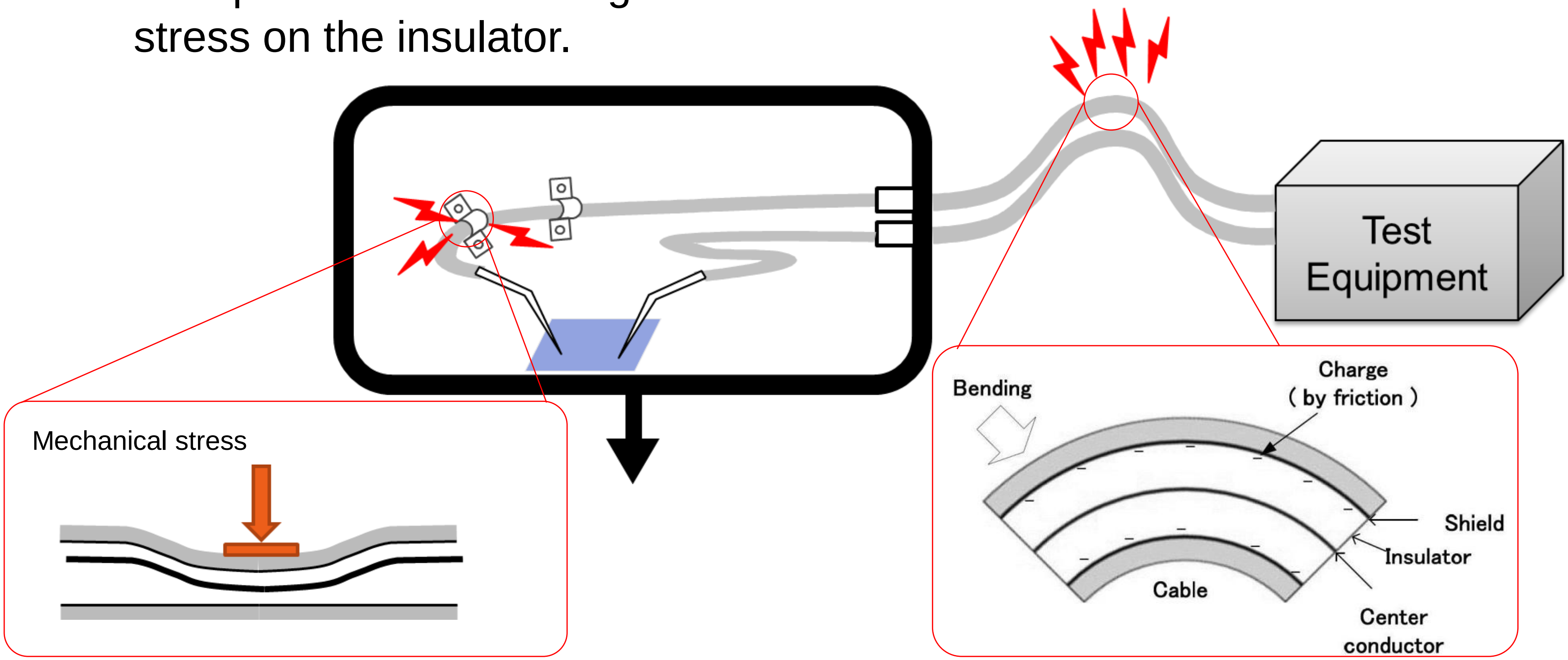
- ❑ External environment noise

Electro-Mechanical Noise from Cable - 1

The triboelectric & piezoelectric effects

- The triboelectric effect generates noise current flow due to friction between a conductor and an insulator.
- The piezoelectric effect generates noise current flow due to mechanical stress on the insulator.



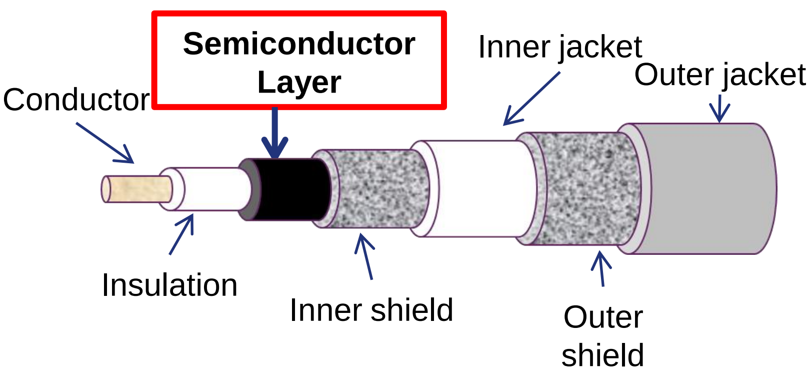
Electro-Mechanical Noise from Cable - 2

Keysight low noise cable

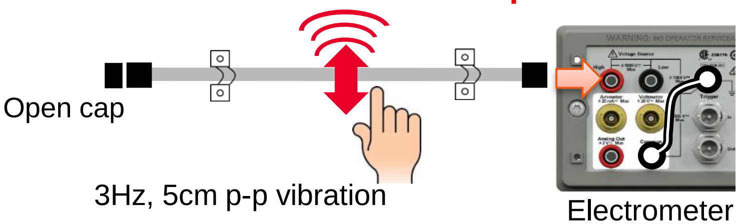
Use a low noise cable and isolate measurements from vibrations.

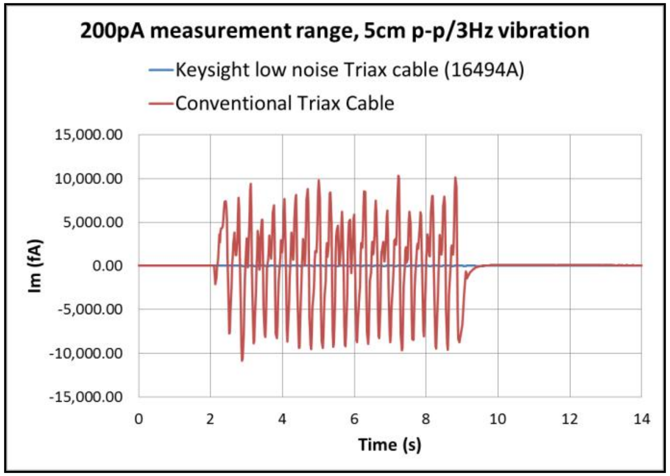
Keysight triaxial cable (16494A)

A semiconductor layer positioned between the insulator and the inner shield minimizes the triboelectric charge generated at this boundary by friction.



Noise current comparison





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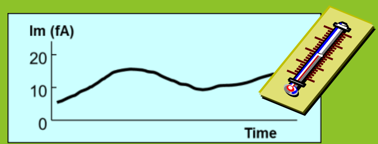
External Environment Noise - 1

Temperature, Humidity and Light

Temperature



- ❑ Temperature fluctuation affects low current measurements
- ❑ Key points to remember:
  - ✓ Keep the temperature constant
  - ✓ Keep the test environment away from heating elements
  - ✓ Wait a sufficient time for the test environment to achieve thermal equilibrium before starting to make measurements

Humidity

- ❑ High humidity in combination with contaminants will affect the surface insulation resistance and may cause leakage currents due to electrochemical migration.
- ❑ Key points to remember:
  - ✓ Maintain constant low humidity in the test environment
  - ✓ Keep the surface of insulator clean and free of contamination.

Light

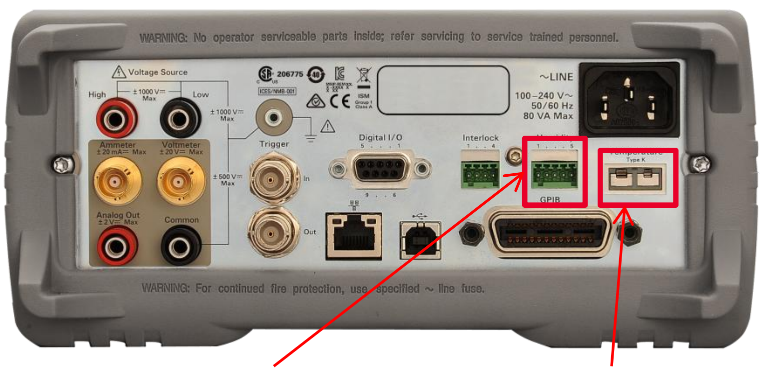
- ❑ If the DUT is a semiconductor then electron-hole pairs generated by light can create currents, which will impact low level measurements.
- ❑ Key points to remember:
  - ✓ *Use a light shield to isolate the measurement environment*

External Environment Noise - 2

Use an electrometer that can monitor temperature & humidity

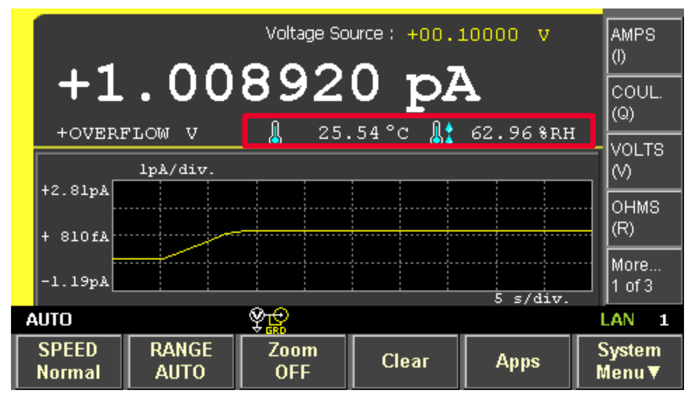
- ❑ The B2985A/87A has K-type thermocouple inputs to monitor external temperature and a humidity sensor input to monitor relative humidity.

- ❑ The temperature and humidity data can be time stamped with each measurement data point to enable accurate comparisons of measurements made under different conditions.



Humidity Sensor I/F

Thermocouple I/F



B2985A/87A Electrometer

Test Setup Best Practices Summary

For accurate high resistance & low current measurements

- ❑ Use shielding and minimize movement (especially people) around the test setup
- ❑ Use the guarded measurement technique and good quality insulating materials to construct the test system
- ❑ Use low noise triaxial cables and isolate the measurements from vibration
- ❑ Maintain stable humidity and temperature
- ❑ Keep insulator surfaces clean

Agenda for Today

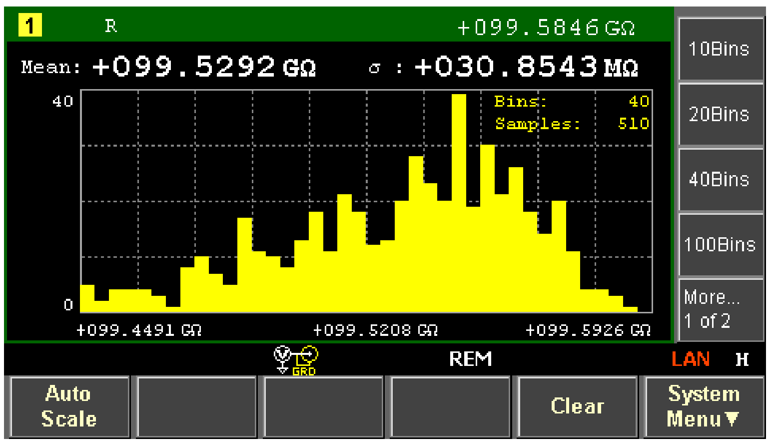
- ❑ High resistance & low current measurement basics
- ❑ Sources of measurement error and how to correct for them
- ❑ **Adjusting instrument settings for optimal measurement results**
- ❑ Summary & final comments

Adjusting instrument settings for optimal measurement results

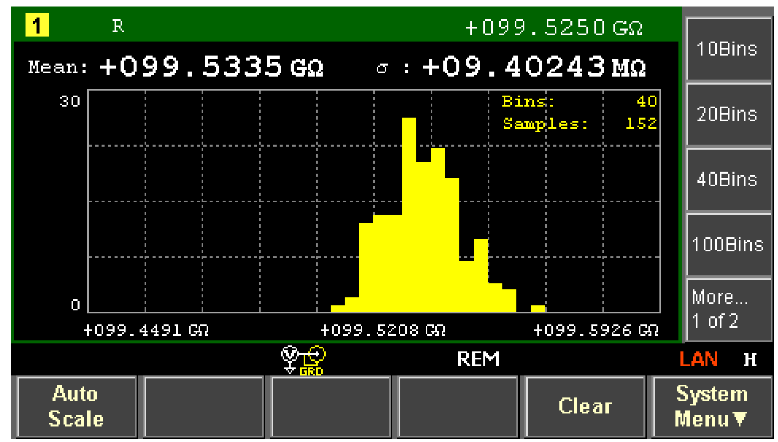
- ❑ Instrument self-calibration & warm-up
- ❑ Wait (delay) time
- ❑ Aperture (integration) time
- ❑ Offset cancelation

Instrument self-calibration & warm-up

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. Also, most instrument data sheets require ~30 minutes of warm-up for specifications to be valid.



100 GΩ resistance measurement performed without auto-calibration & warm-up



100 GΩ resistance measurement performed after auto-calibration & warm-up

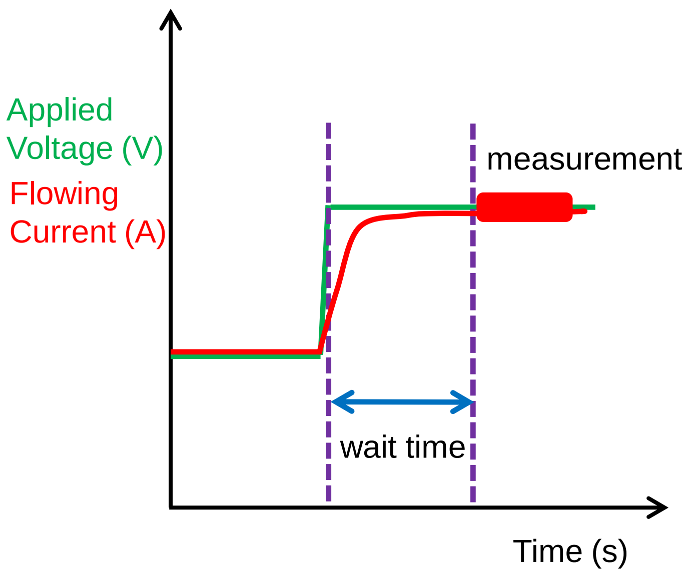
Adjusting instrument settings for optimal measurement results

- ❑ Instrument self-calibration & warm-up
- ❑ Wait (delay) time
- ❑ Aperture (integration) time
- ❑ Offset cancelation

Wait (Delay) Time - 1

Instrument Settling Time and Dielectric Absorption

Ensure **sufficient wait time** before taking measurement data



- ❑ The main factors affecting settling time of measurement system are:
  - ✓ Ammeter settling time
  - ✓ Dielectric absorption time constants when the applied voltage is changed

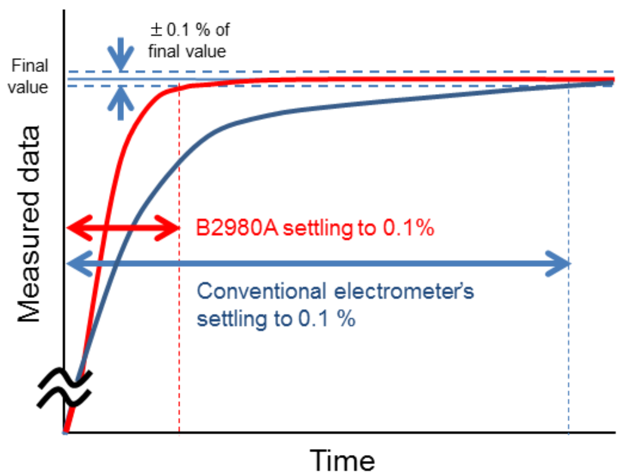
- ❑ You have to factor in sufficient settling time after considering all of the factors impacting your measurement system.

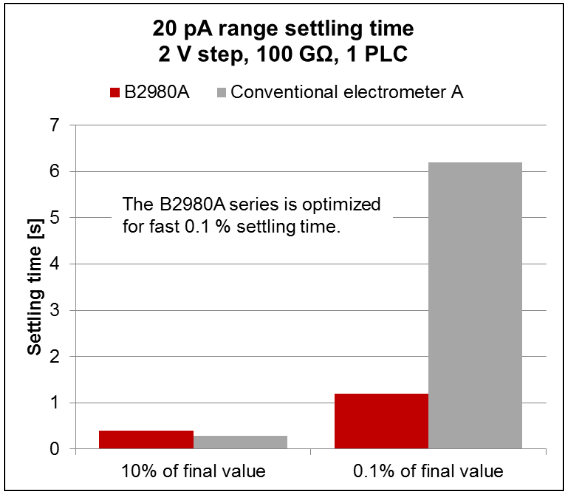
Wait (Delay) Time - 2

Make sure you know how settling time is defined

Important! How measurement settling time is defined varies from instrument to instrument.

- ❑ Most instruments define settling time as the time to reach 10% of the final value. However, the B2985A/87A use a **value of 0.1%.**
- ❑ By reducing dielectric absorption, the B2985/87A achieves a faster settling time even in its lower measurement ranges.





Wait (Delay) Time - 3

The benefit of having a time domain view

You can check required wait time for accurate measurement by using the B2985/87A's **time domain view**.

B2985A/87A Electrometer

Roll view (time domain view) mode

Adjusting instrument settings for optimal measurement results

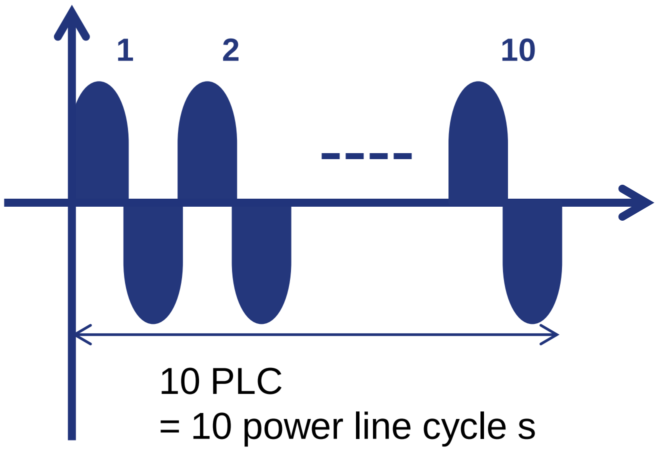
- ❑ Instrument self-calibration & warm-up
- ❑ Wait (delay) time
- ❑ Aperture (integration) time
- ❑ Offset cancelation

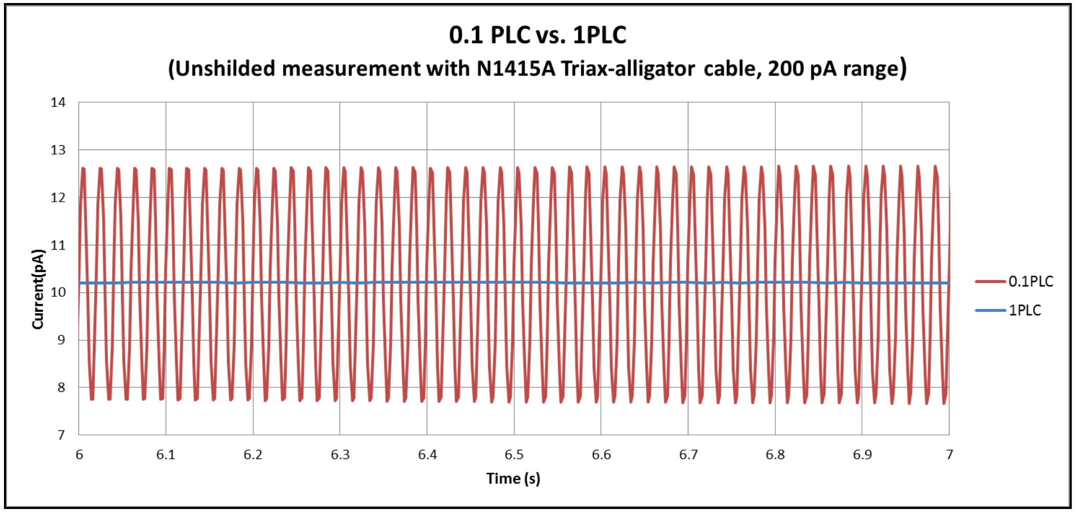
Aperture (Integration) Time - 1

Reduce the Effect of Power Line Noise

The effect of power line noise can be minimized by setting the integration time to average measurements over multiple AC power line cycles.

AC power is usually the **biggest noise** source.



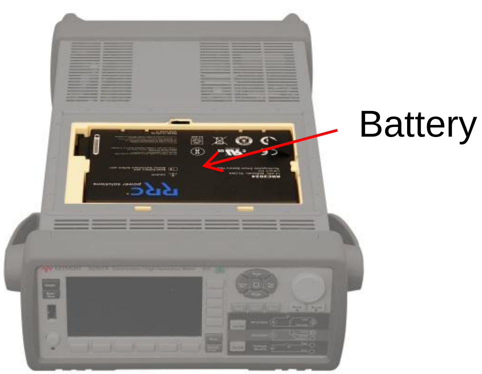


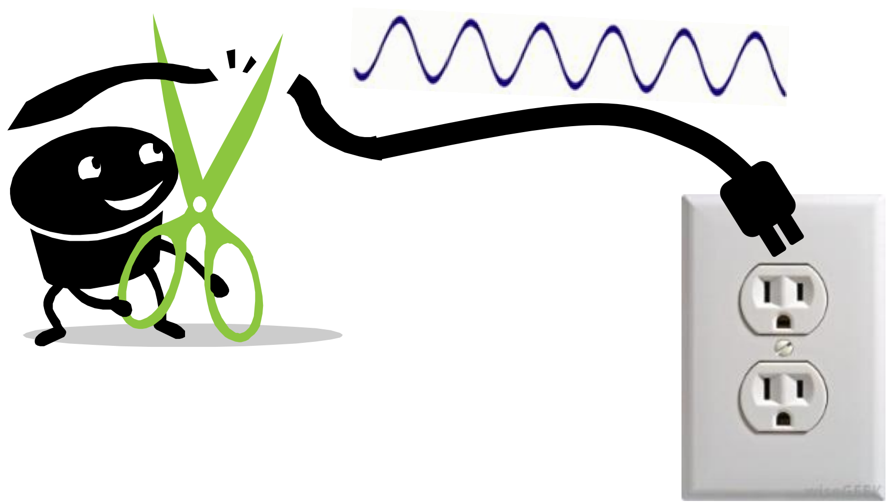
Aperture (Integration) Time - 2

Battery operation is the best way to eliminate power line noise

- If your measurement is still affected by AC power line noise even after integrating over one or more PLCs or you need to make a measurement quickly (in less than one PLC), then you should consider using a battery powered electrometer (such as the B2987A).

- In addition, battery operation gives the unit portability in case you need to use it in a location without easy access to AC power.





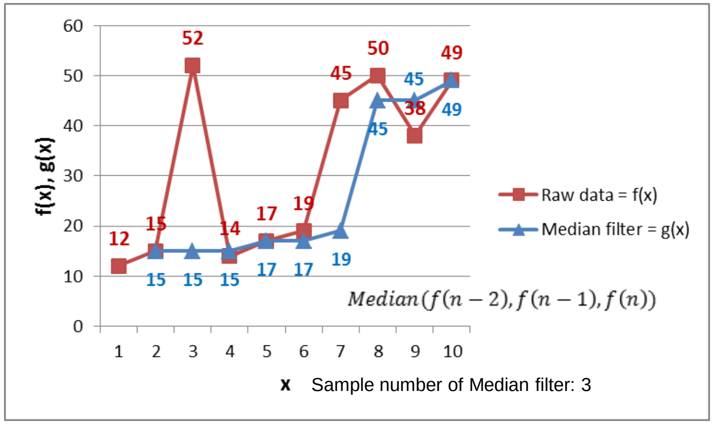
Aperture (Integration) Time - 3

Reduce unexpected noise spikes

The **median filtering technique** can reduce unexpected noise spikes using shorter aperture times than can pure PLC averaging.

What is Median Filtering?

It is a signal processing technique, often used to remove noise. Median filtering replaces each entry with the median value of the neighboring entries.



Noise Reduction Effect

- *Median Filter*
  If the median filter sample number is R, then exp(-R/2) noise reduction can be expected.
- *Averaging*
  N times samples is required to reduce the effect of noise to one-Nth.
- *Example: Required integration time to reduce unexpected spike noise to 1/100*
  - ✓ *Median Filter*
    10 x ammeter time constant
  - ✓ *Averaging*
    100 x ammeter time constant

10x shorter

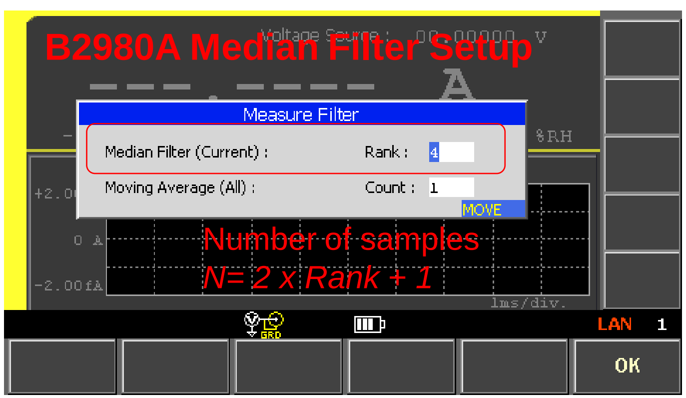
KEYSIGHT TECHNOLOGIES

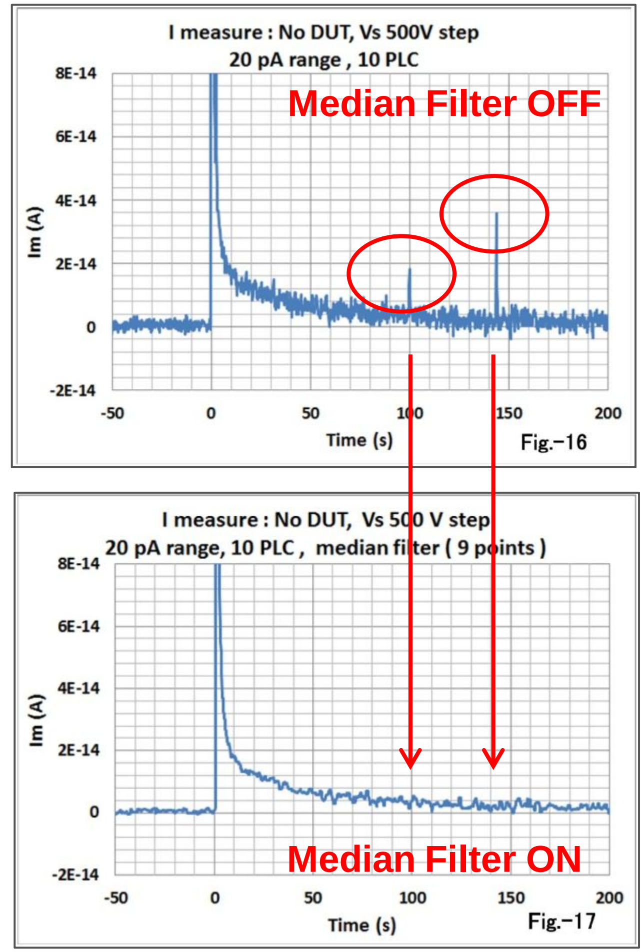
Aperture (Integration) Time - 4

Measurement Example: Median Filter

16008A
Resistivity Cell

B2985A/87A
Electrometer





Adjusting instrument settings for optimal measurement results

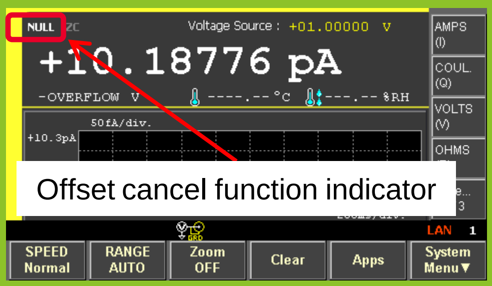
- ❑ Instrument self-calibration & warm-up
- ❑ Wait (delay) time
- ❑ Aperture (integration) time
- ❑ Offset cancelation

Offset Cancelation

Null Function and Offset Compensated Resistance

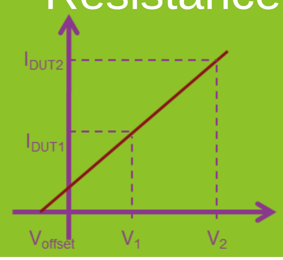
The **ammeter offset null function** and **offset compensated resistance** calculation (if available) can be used to cancel offset errors.

Offset Cancel Function



- ❑ Every measurement system contains a certain amount of offset current.
- ❑ The offset cancel (null) function of the ammeter can subtract out the offset value from the actual measurement value.

Offset Compensation Resistance



- ❑ Both voltage and current offset can be canceled out by using the following offset compensated resistance calculation.

$$R_{DUT} = \frac{V_2 - V_1}{I_{DUT2} - I_{DUT1}}$$

- ❑ The B2985A/87A have built-in math function capabilities to automatically calculate the offset compensated resistance.

Instrument Setup Best Practices Summary

For accurate high resistance & low current measurements

- ❑ Perform a self-calibration and wait 30 minutes before performing any sensitive measurements.
- ❑ Ensure sufficient wait time before taking measurement data
- ❑ Increase the PLC setting of the ammeter to minimize AC power line noise effects. If AC power line noise still affects your measurement even after integrating over multiple PLCs, you might want to consider a battery operated electrometer.
- ❑ Use the offset cancelation function if available on your electrometer.

Agenda for Today

- ❑ High resistance & low current measurement basics
- ❑ Sources of measurement error and how to correct for them
- ❑ Adjusting instrument settings for optimal measurement results
- ❑ Summary & final comments

Summary

Accurate low-current and high resistance measurements require:

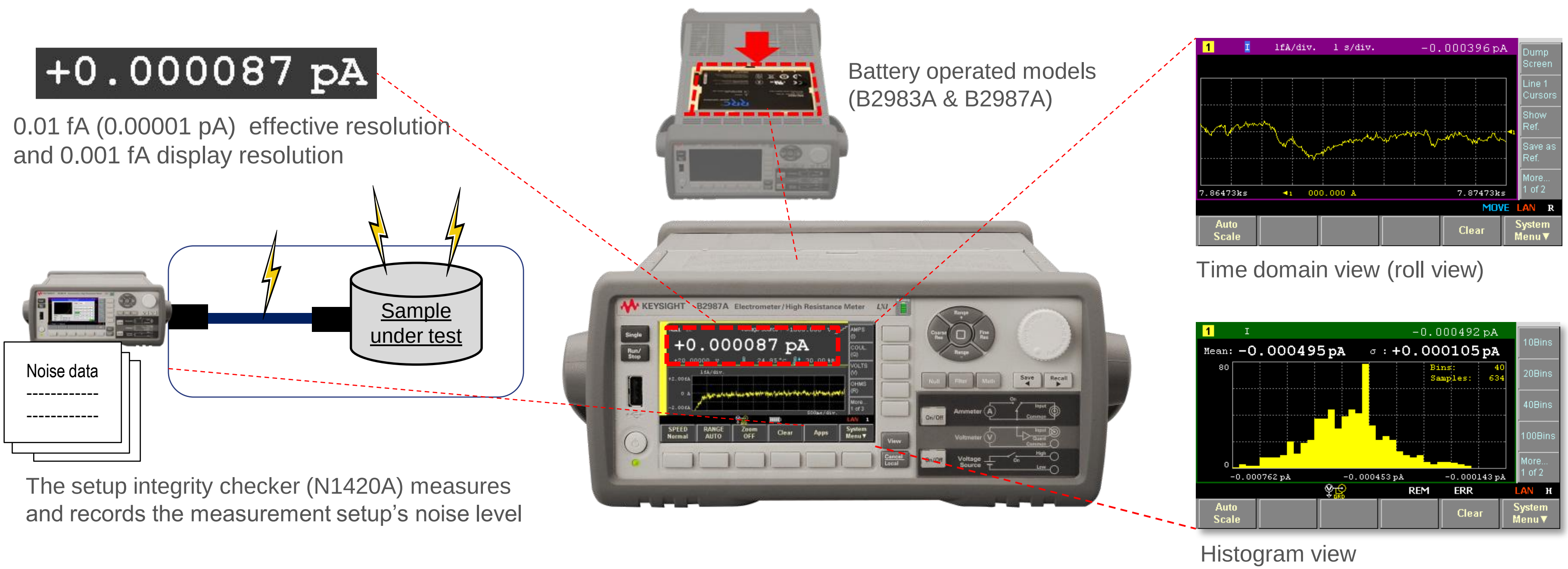
- ❑ An electrometer with sufficient specifications to measure femtoamp currents and Tera-Ohm resistances.
- ❑ Knowledge of the appropriate measurement techniques to avoid measurement errors.
- ❑ Optimized instrument settings based on the type of measurement fixturing being used.

It his highly desirable to have an electrometer with:

- ❑ Time domain & histogram viewing capabilities
- ❑ Battery operation for total AC power line isolation
- ❑ Some means to verify the integrity of external cables & fixturing

Keysight Picoammeters & Electrometers

The world's only graphical picoammeters & electrometers that can confidently measure down to 0.01 fA and up to 10 PΩ

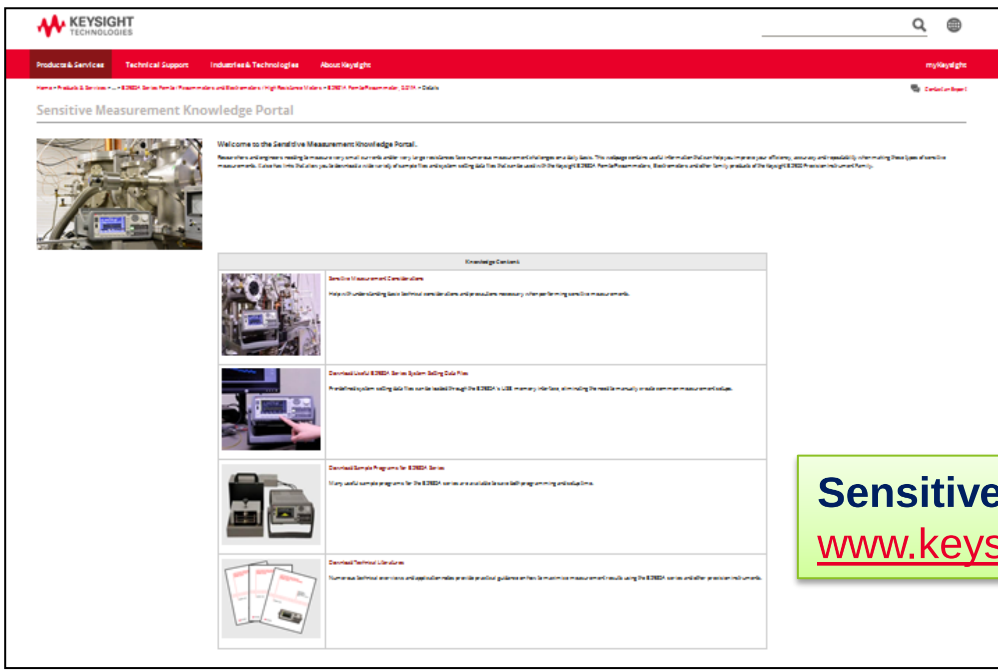


For more information, www.keysight.com/find/b2980a

Need Application Help?

Visit our Sensitive Measurement Knowledge Portal

You can find great resources that give guidance on how to make sensitive measurements, and you will have access to numerous free technical overviews, sample programs, etc.



Sensitive Measurement Knowledge Portal:
www.keysight.com/find/sensitivemeasurement

Keysight B2900 Precision Instrument Family

The B2980A series is a member of the B2900A Precision Instrument Family, which includes several different source and measurement solutions.

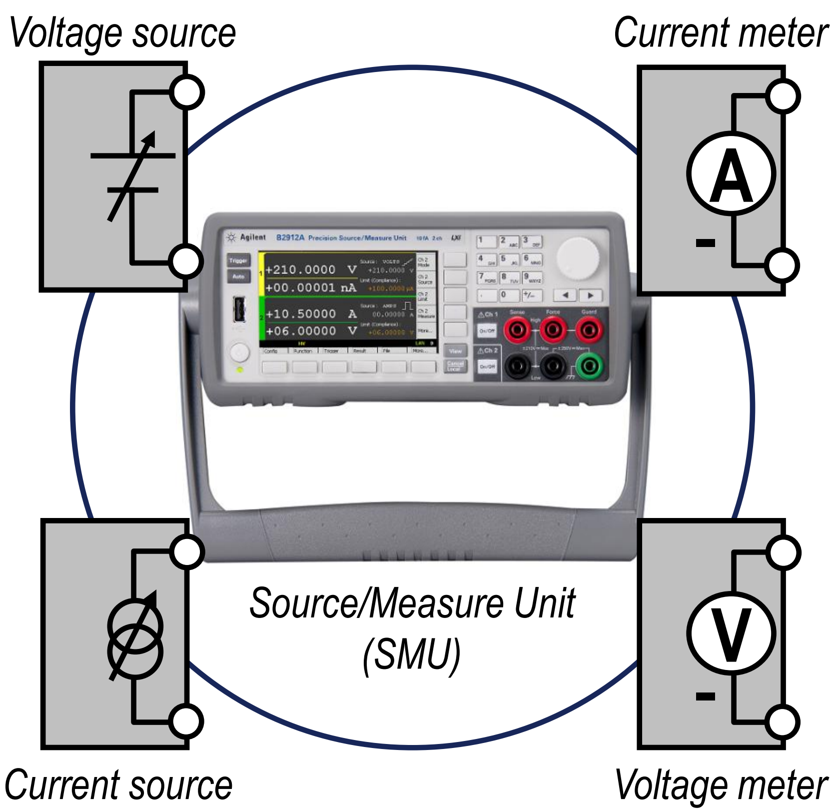
B2900A Series of Source Measure Units (SMUs)
for cost-effective source/measurement capabilities

B2960A Series of Low Noise Power Source
for ultra low noise and more sourcing capabilities

KEYSIGHT TECHNOLOGIES

What is a Source/Monitor Unit (SMU)?

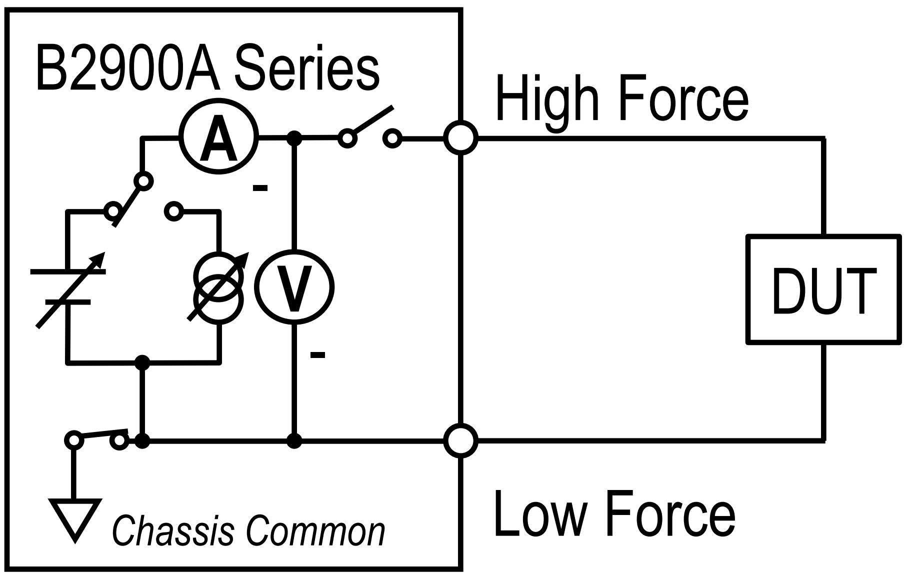
Source/Measure Unit (SMU)



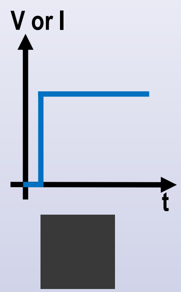
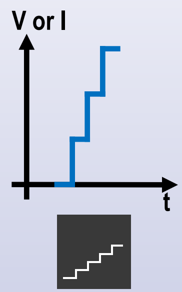
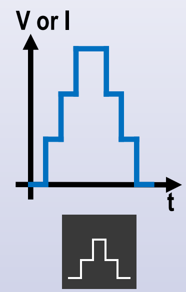
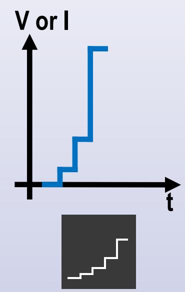
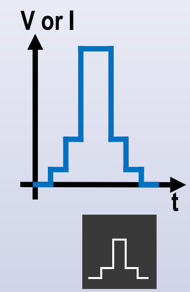
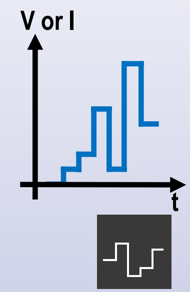
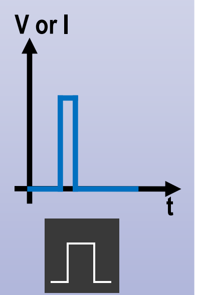
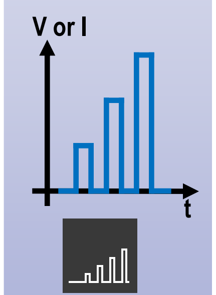
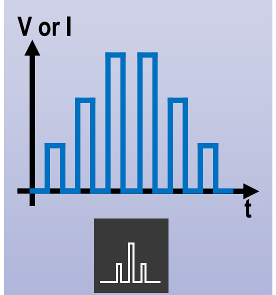
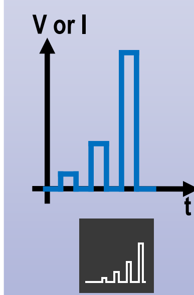
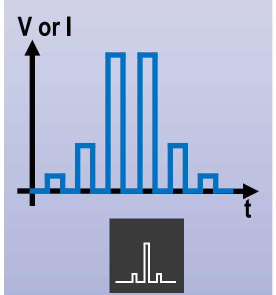
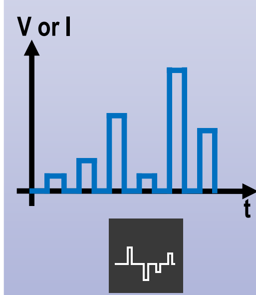
It combines the capability of

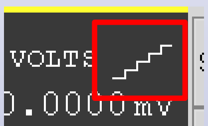
- •Current source
- •Voltage source
- •Current meter
- •Voltage meter

along with the capability to switch easily among them into a single instrument.



B2900A Series' Source Capability

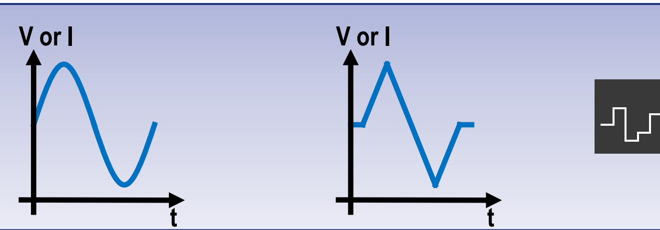
		Constant	Linear Sweep		Log Sweep		List Sweep
			Single	Double	Single	Double	
Source Function	DC						
	Pulse						



You can see the Source Shape in GUI, which shows the recent function.

Arbitrary Waveform Generation

List Sweep capability allows you to create arbitrary waveform with up to 2500 steps for maximum flexibility with arbitrary timing resolution (20us for B2901/02A, 10us for B2911/12A at minimum).



Thank you for your kind attention