Solve Your Toughest Low-Power Test Challenges on IoT Devices!

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KEYSIGHT TECHNOLOGIES

Agenda

Internet of Things (IoT)
- Proliferation
- Definition
- Power approaches

Challenges
- Reducing power consumption
- Battery conditioning
- Circuit and sub-circuit analysis
- Current and Power Profiling

Solutions
- Overview
- 34470 DMM
- Oscilloscope with N2820 current probe
- N6705 DC power analyzer with N6781 SMU
- B2900 Source / Measure Unit (SMU)
- CX3300 Device Current Waveform Analyzer

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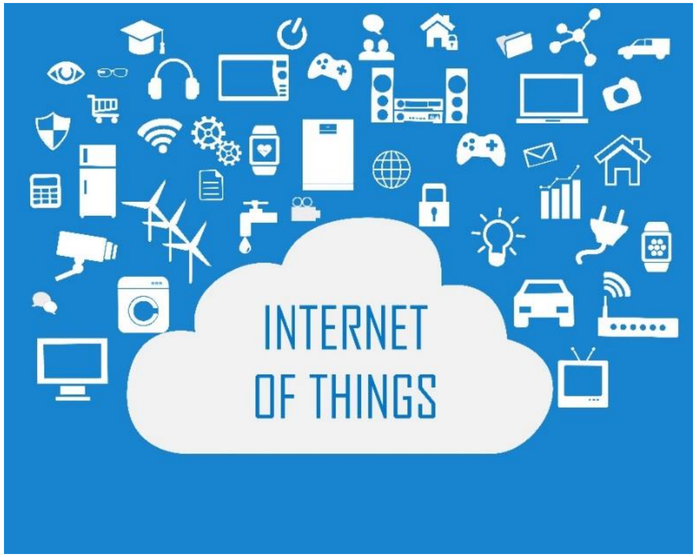
IoT Proliferation

How many IoT devices by 2020?

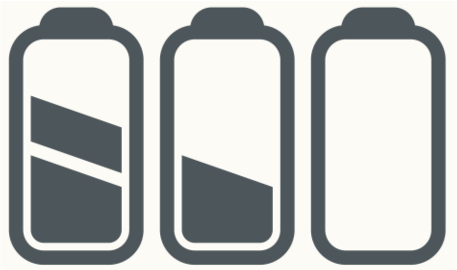


Sources	Date	Billions
Gartner	Nov 2015	21
Gartner	Dec 2013	26
Juniper	July 2015	38.5
ABI	Aug 2014	40
Cisco and DHL	Apr 2015	50
Morgan Stanley	Oct 2013	75
Intel	2016	200

What IoT devices have in common

Wireless communication

Need to be frugal with power



Wireless communication and IoT

Multiple km

- 2G Cellular $$$: (GSM, GPRS, EDGE)
- 3G Cellular $$$: (WCDMA, cdma2000)
- 4G Cellular $$$: (LTE Cat 0, Cat 1)
- LoRa $$
- Narrow Band IoT (NB-IoT) $$$
- SIGFOX $$
- Weightless $
- WiFi $

100 m and below

- 802.15.4 $
- Bluetooth $
- WirelessHART $$
- ZigBee $$
- Z-Wave $$

Power approaches in IoT mobile devices

- Harvesting from environment
  - Light
  - Mechanical/vibration
  - Fluid flow (usually air or water)
  - Radio waves
  - Thermal gradient
- Storage devices
  - Lead-acid
  - Lithium ion
  - Nickel metal hydride
  - Micro solid state (MSS)
  - Super capacitor
- Large battery from host device
  (e.g. electric car)

Harvesting from environment

Taking advantage of free energy

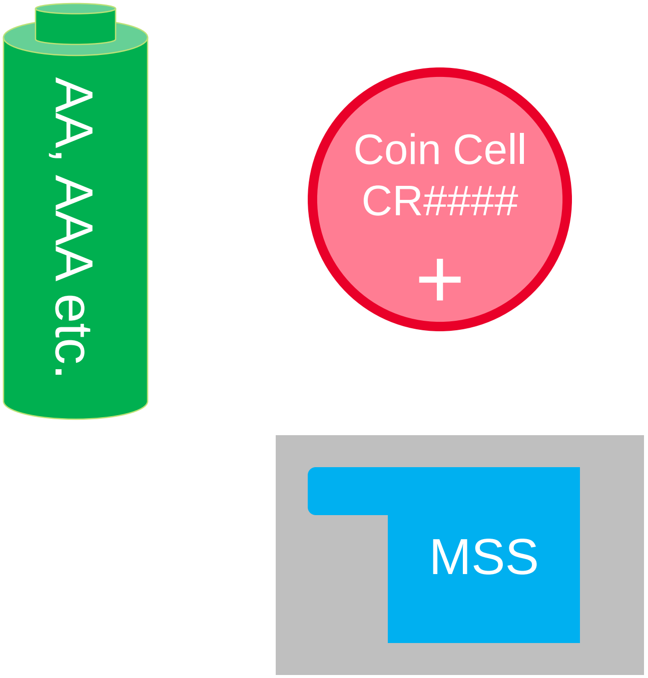
Energy Source	Harvester	Challenge
Light	Solar cell	Need for surface area, fluctuating input source
Mechanical / vibration	Piezoelectric transducer	Inconsistent frequency, fluctuating input intensity
Fluid flow	Turbine	Availability of wind or flowing water
Radio waves	Rectenna	RF coupling and rectification
Thermal gradient	Thermoelectric generator (thin-film thermoelectrics, thermoelectric energy module)	Efficiency of turning heat energy into electricity

Harvesting energy from environment
Typical reasons

- Convenience for user
- No access to large host device battery or AC power
- Difficult to change batteries because of labor cost, security, environmental danger, or human/animal implantation
- Weight of battery too heavy for application context
- Desire to reduce waste associated with batteries
- Potentially greater reliability over product lifetime

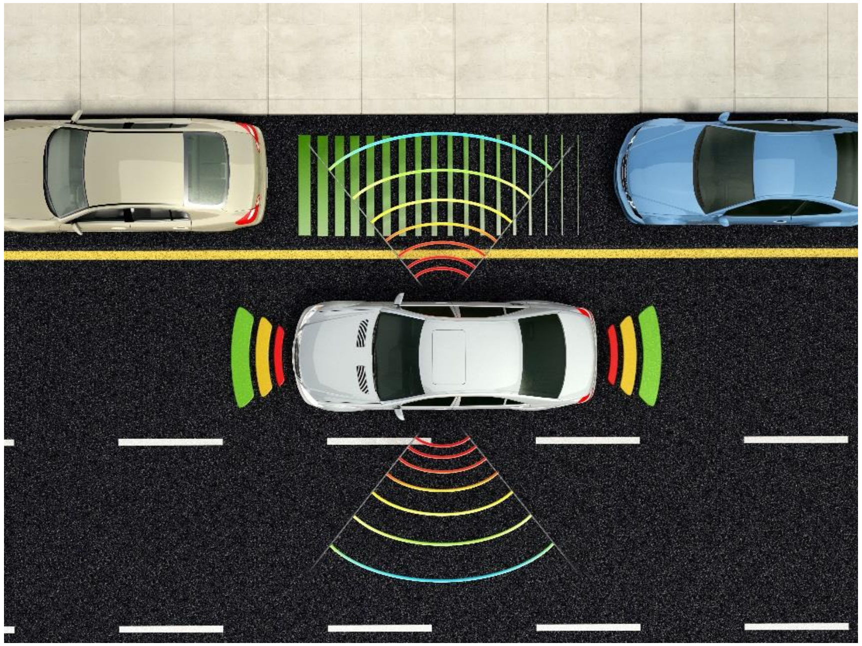
Storage devices

- Lead-acid
- Lithium ion
- Nickel metal hydride
- Micro solid state (MSS)
- Supercapacitor



Large battery from host device

- The RF communication devices and sensors in a vehicle usually use the vehicle's 12-V battery for power.
- Optimization of efficiency is less important in this case.



IoT Verification Requirements

- **Power consumption**
  - Lifetime SLA, software update drain
  - Operator settings, IoT protocol selection
  - Unhandled software and network exceptions
- **Radio frequency design**
  - Achieving deep in-building coverage
  - 3rd party enclosure/antenna effects
  - Multi-radio interference/inter-mod
- **Stability/longevity**
  - Long time between re-boot, unattended recovery
  - Authentication, security, secure boot
  - Remote software update
- **Acceptance/production**
  - Certification & regulation test e.g. GCF/PTCRB
  - Operator acceptance, interop lab and field test
  - System integrator acceptance

The Challenge: Overall

Low Current, High Dynamic Range, High Bandwidth

IoT devices vary greatly, but in general:

– Devices are low power

→ **Instrument must measure low current accurately**

– Sleep states draw a tiny fraction of operating current

→ **Instrument must measure current over a wide dynamic range**

– Devices may switch states quickly

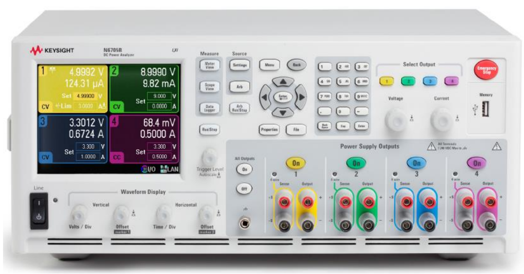
→ **Instrument must have sufficient current measurement bandwidth**

The Challenge: Overall

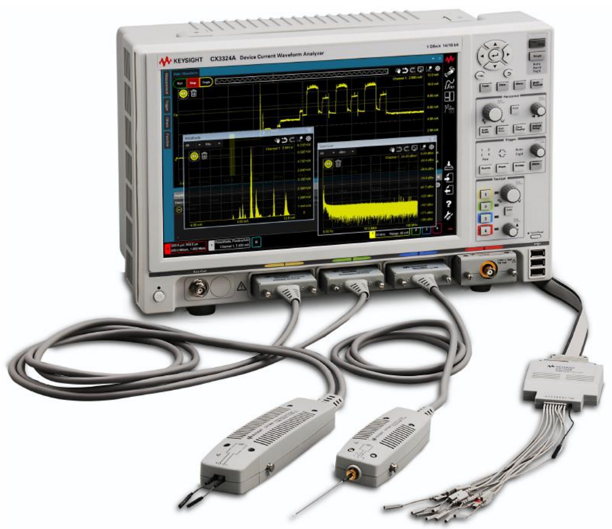
Selecting the Best Keysight Solution

34470

N6705



CX3300



Scope and
N2820 Probe

B2900

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The Challenge: Specific DUTs

Libelium WaspMote

- ON (normal operation): 15 mA
- Sleep/Deep Sleep: 55 µA
- Hibernate: 60 nA

250,000:1

18 bits

$$2^{18} = 262{,}144$$

libelium

SIGFOX READY

The Challenge: Specific DUTs

Electronic Design Article on MCUs

210,000:1

18 bits

$$2^{18} = 262{,}144$$

– Microcontroller current often averages 5 to 20 µA over a device's lifetime. Typical design:

- 20% transmit activities
- 30% receiving commands
- 20% data collection and system maintenance
- 30% idle mode (up to 99.9% of lifetime!)

– Energy Micro EFM32 Tiny Gecko:

- 12.6 mW while active at 28 MHz using 3 V power
- 60 nW in lowest-power mode

The Challenge: Specific DUTs

Microchip PIC18FXX2 Datasheet

8,000:1

13 bits

$$2^{13} = 8{,}192$$

< 1.6 mA typical @ 5V, 4 MHz

25 µA typical @ 3V, 32 kHz

< 0.2 µA typical standby current

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The Challenge: Specific DUTs

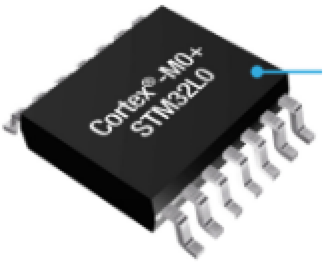
STMicroelectronics STM32L0xx

20,000:1

15 bits

$$2^{18} = 32{,}768$$

- Eleven varieties of standby, stop, low power, and sleep modes
- Range from 290 nA to 41 µA
- 5.6 mA running at 32 MHz with 1.8 V_{CORE} and up to 3.6 V_{DD}



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The Challenge: Specific DUTs

Zolertia RE-Mote platform

160,000:1

18 bits

$$2^{18} = 262{,}144$$

– Shutdown mode (150 nA)

– Active Mode (2.4 GHz RX, CPU idle) 20 mA

– Active Mode (2.4 GHz TX, 0 dBm, CPU idle) 24 mA

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The Challenge: Specific DUTs

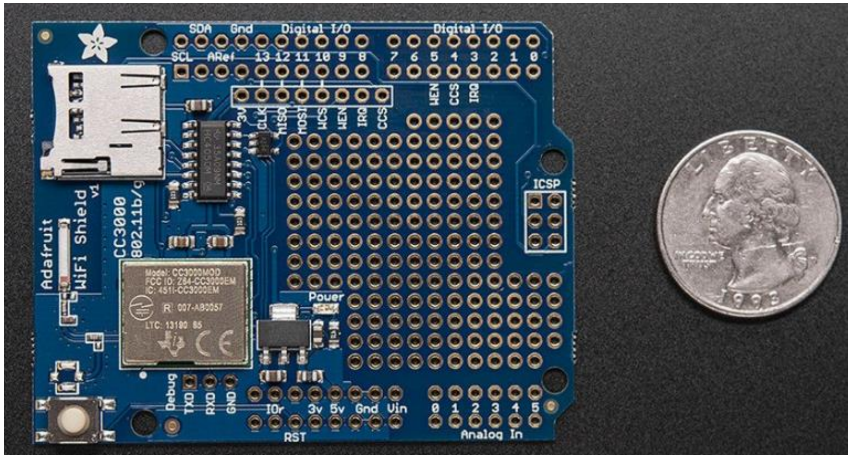
Adafruit.com: Arduino / CC3000 Project

10:1

4 bits

$$2^4 = 16$$

- Sleep mode at 19 mA
- Operation generally at 135 mA
- Spikes to 200 mA



WiFi shield with on-board antenna

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The Challenge: Specific DUTs

GreenNet (IEEE article)

4,300:1

13 bits

$2^{13} = 8,192$

The consumption of a GREENNET node is:

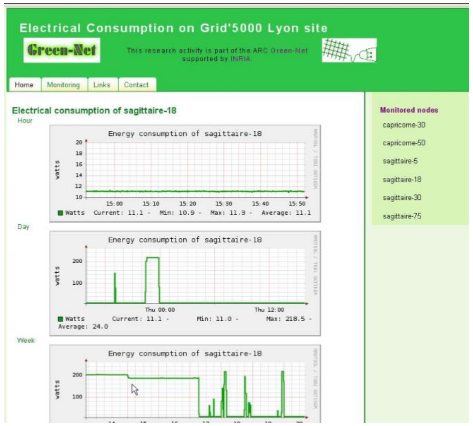
– 4.5 mA by the radio in RX mode and 4.9 mA in TX mode (0 dBm).

– The MCU and an activated sensor consume < 5 mA.

– The PMU consumes < 5% of the harvested energy.

– In low-power mode (sleep state), the entire board

Radio + MCU + PMU consumes < 2.3 µA.



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The Challenge: Specific DUTs

Silicon Labs Si1060 Transceiver

- 10/13 mA Receiving
- 18 mA Transmitting at +10 dBm
- 30 nA shutdown, 50 nA standby

600,000:1

20 bits

$2^{20} = 1{,}048{,}576$

The Challenge: Specific DUTs

Silicon Labs Ultra-low power 8051µC

- 25 MHz CPU
- Extremely low active and sleep currents
- 160 µA/MHz: active mode
- 10 nA sleep w/ brownout detectors disabled
- 50 nA sleep w/ brownout detectors enabled
- 600 nA sleep with internal RTC

400,000:1

18 bits

$$2^{18} = 262{,}144$$

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When Enough Isn't Enough
Dynamic Range

The dynamic range on my DUT is this big.

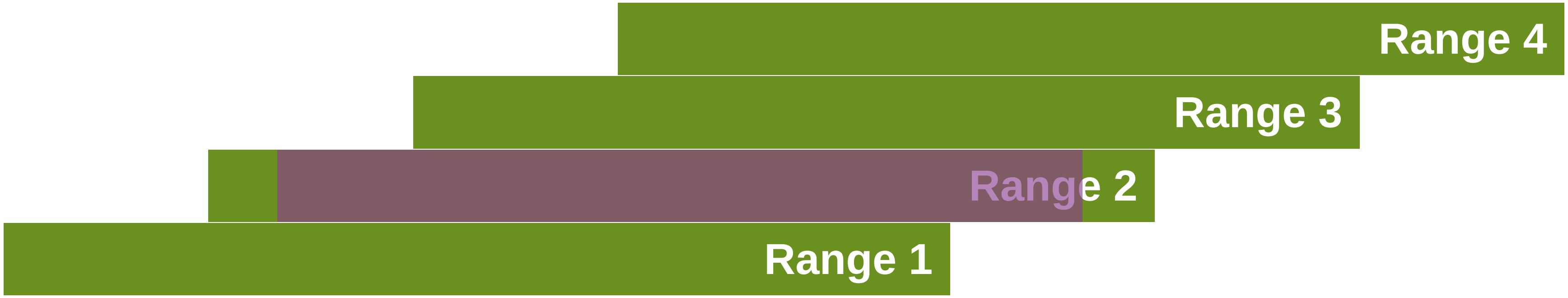
My instrument has dynamic range this big.

I should be good, right?

When Enough Isn’t Enough

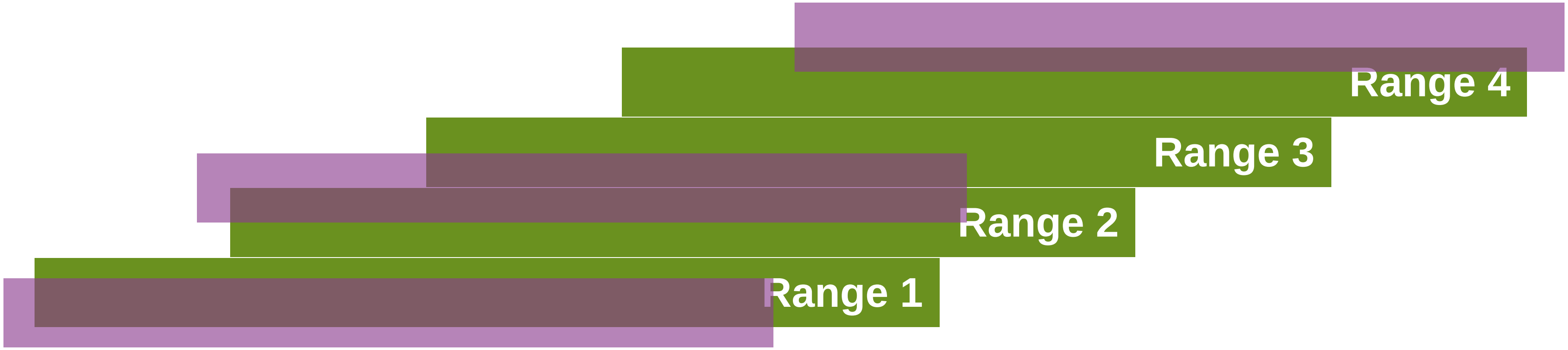
Dynamic Range

Maybe . . . .



When Enough Isn't Enough
Dynamic Range

Maybe Not!



When Enough Isn't Enough

Resolution

The lowest current I need to measure is this.

My instrument has this resolution

I should be good, right?

When Enough Isn't Enough

Resolution

Maybe . . . .

When Enough Isn't Enough

Resolution/Accuracy Rule of Thumb

For 1% accuracy, the ADC must have at least 7 bits more than the number of bits required to cover the dynamic range ($2^7 = 128$).

	Example 1		Example 2	
Lowest current	100 nA		50 µA	
Highest current	60 mA		200 mA	
Dynamic range	600,000:1	20 bits	4,000:1	12 bits
Accuracy	1%	7 bits	5%	5 bits
Total		27 bits		17 bits

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When Enough Isn't Enough
Effective Bandwidth

The BW on my scope (or similar) is 200 MHz.

The BW on my current probe is also 200 MHz.

What is the effective bandwidth of the system?

When Enough Isn't Enough
Effective Bandwidth

Keypsight Infiniium/InfiniiVision scopes:

200 MHz Scope
+200 MHz Probe
200 MHz Combined

"Brick Wall" Response

When Enough Isn't Enough

Effective Bandwidth

Keysight CX3300 Device Current Waveform Analyzer

200 MHz Scope
+200 MHz Probe
140 MHz Combined (actually $100\sqrt{2}$ MHz)

$$\frac{1}{BW_{eff}} = \sqrt{\left(\frac{1}{BW_{scope}}\right)^2 + \left(\frac{1}{BW_{probe}}\right)^2}$$

"Gaussian" Response

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When Enough Isn't Enough

Effective Bandwidth – Caveat for CX3300 Series

- Optimal BW when source impedance < 1 Ω
- BW degrades for large source impedances
  (approx. 3 MHz at 50 Ω)

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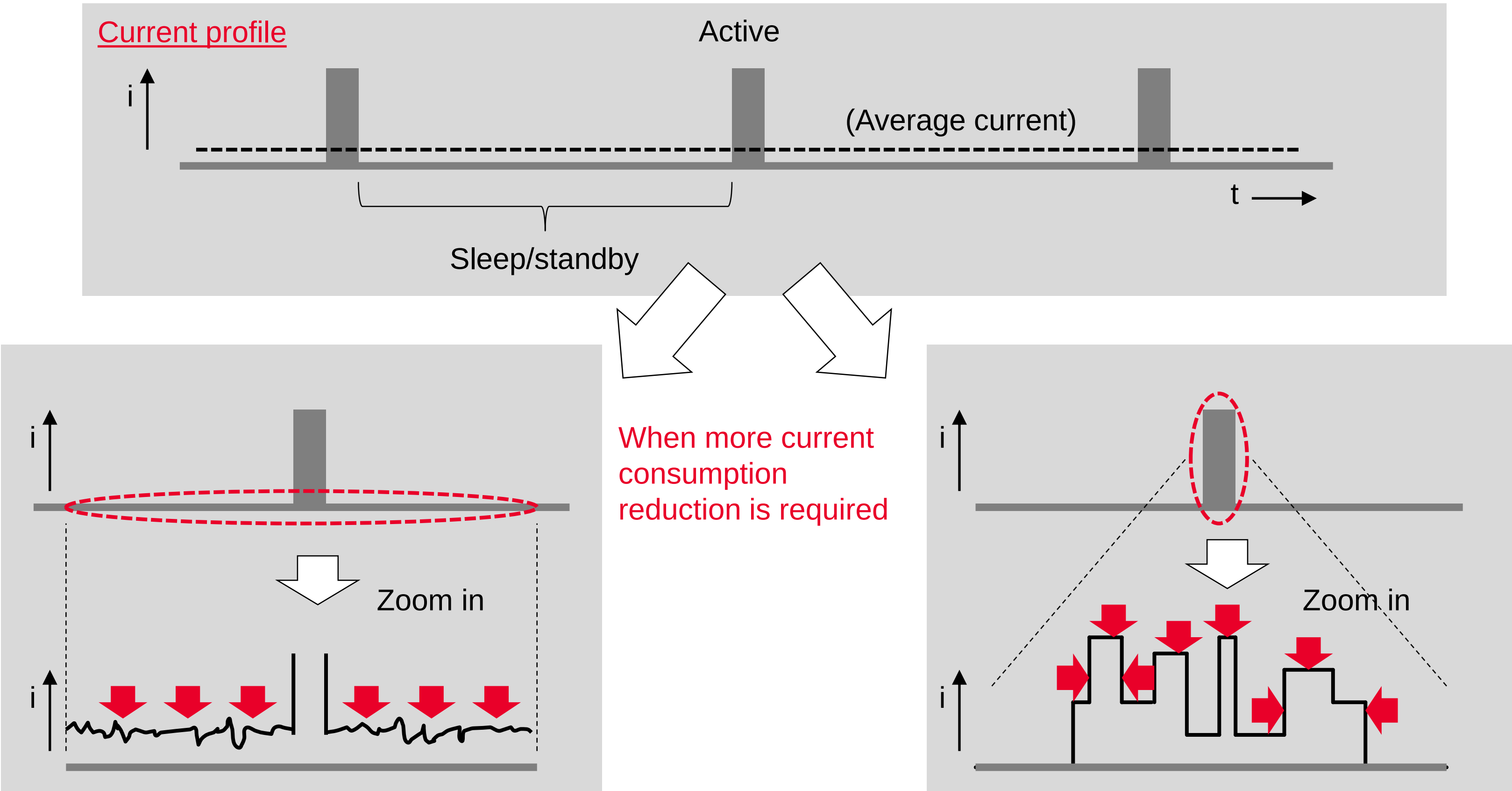
Reducing power consumption in IoT devices

Further reduction of low power devices operating intermittently



Reduce sleep/standby current
(< 1 µA level)

Reduce active current and duration
(>10 mA level)

1 - IoT | 2 - Challenges | 3 - Solutions

Low-power device tests

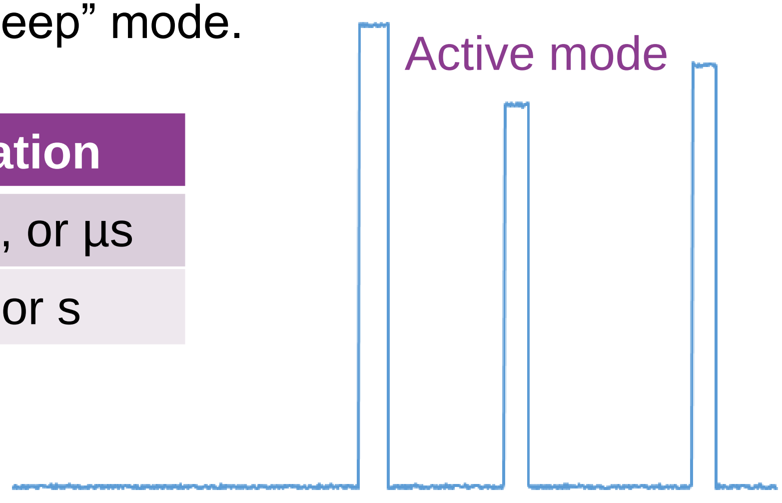
- **Charging behavior:** Factory charging, first use (when not done at factory), trickle, instantaneous piezoelectric (examples: harvesting energy from flipping switch or pushing a button)
- **Battery conditioning:** Preparing battery charge/discharge levels and sequences to test operational performance, especially under various environmental circumstances (temperature, humidity, etc)
- **Circuit-level and sub-circuit analysis:** Measuring WHERE the current consumption takes place under different operating circumstances
- **Current and power profiling:** Measuring WHEN the current consumption takes place under different operating circumstances

The #1 current measurement challenge

– Regardless of the protocol, mobile IoT devices are not always communicating via RF (which is what requires relatively high power).

– Other than these communication bursts, IoT devices spend a lot of time in low-current modes, sometimes referred to as “rest” or “sleep” mode.

Mode	Current	Duration
Active	A or mA	ps, ns, or µs
Sleep	µA, nA, or pA	ms or s



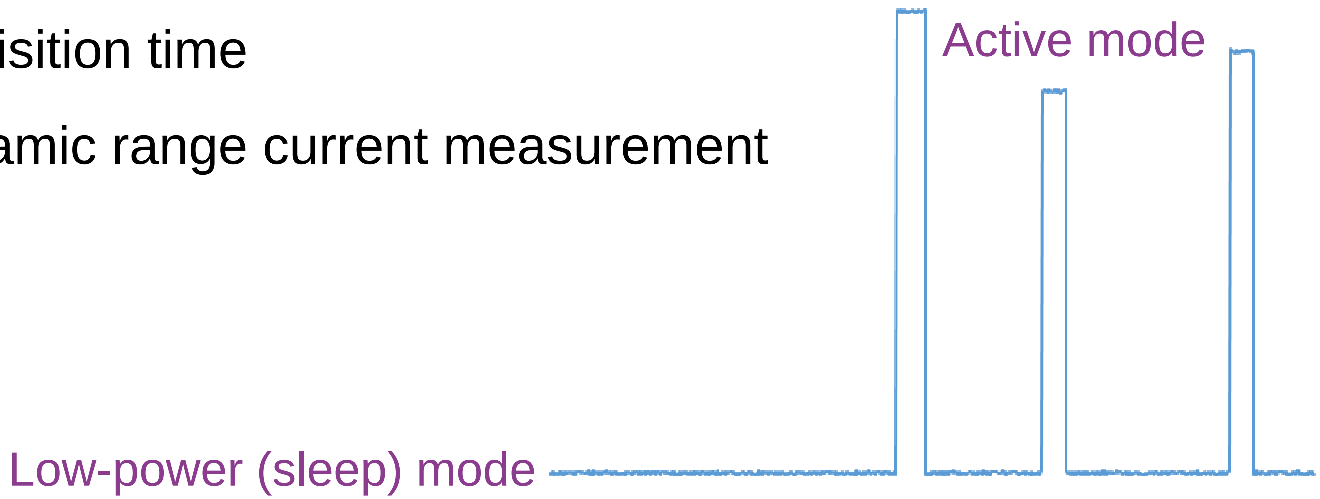
The #1 current measurement challenge

Implications of rapidly switching modes

Mode	Current	Duration
Active	A or mA	ps, ns, or µs
Sleep	µA, nA, or pA	ms or s

– Fast acquisition time

– Wide dynamic range current measurement



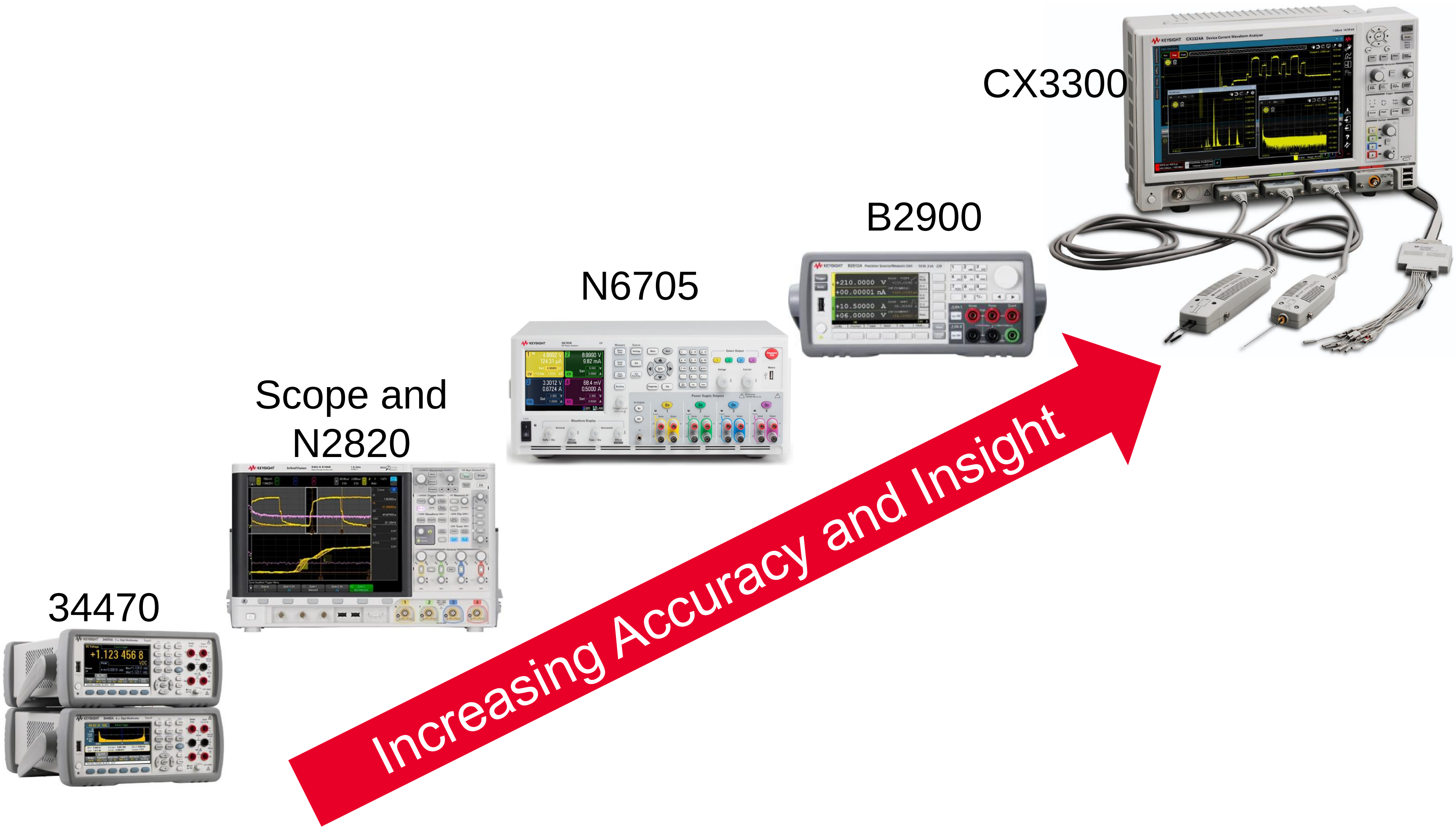
Key Test Needs

- **Fast data acquisition:** Need to make sure that acquisition is fast enough to catch short transients associated with RF data transmission
- **Wide dynamic range current measurement:** Need to measure wide variations between high and low currents with precision and accuracy

Specifications and Characteristics to Consider

- Speed to insight
  - Connection to DUT
  - Ease of setup and use
  - Visualization
  - Automated profile analysis
- Measurement capabilities
  - Types of Measurement
  - Ranges
  - Accuracy/resolution
  - Bandwidth
- Table stakes
  - Connectivity
  - Programmability
  - Cost of unit and accessories
  - Multi-purpose usability
  - Support

The full spectrum of solutions



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Overview of Solutions

Answers to the key questions

	34470 DMM	34470 Digitized	N2820	N6705/N6781[1]	B2900[2]	CX3300[3] Normal	CX3300[3] Hi Res
Bandwidth, Sample Rate	10 kHz, 6 Sa/s	10 kHz, 50 kSa/s	3 MHz, 5 GSa/s	30 kHz, 200 kSa/s	10 kHz, 100 kSa/s	200 MHz, 1 GSa/s	15 MHz, 75 MSa/s
Meas. Resolution	23 bits	14 bits	8 bits	18 bits	20 bits	14 bits	16 bits
Min Measurable Current[4]	10 pA		40 µA	10 nA	1 pA	150 pA	
Burden Voltage[5]	27 mV		1 mV	0 mV	0 mV	4 mV	
Price	+		++	++	++	++++	
Typical Use	R&D / Mfg		R&D	R&D / Mfg	R&D	R&D	

[1] Using N6700 frame with N6781 SMU in mfg and N6705 frame with N6781 SMU in R&D

[2] 1 pA is RMS noise (NBW = 0.1 Hz to 10 Hz).

[3] 150 pA is RMS noise (NBW = 10 Hz to 20 MHz)

[4] Accounts for typical noise

[5] When measuring 10 mA on appropriate range; the N6781 and B2900 both source current, so always 0 mV burden voltage.

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Truevolt 34470A Digital Multimeter (DMM)

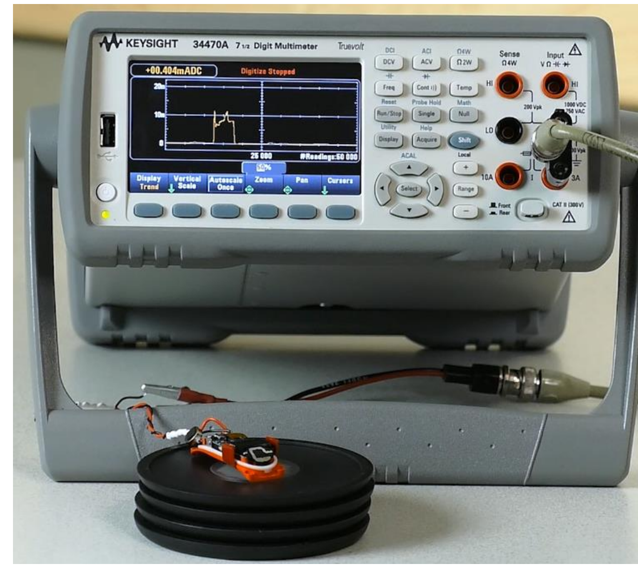
- General purpose instrument beyond BDA
- Up to 7.5 digits
- Accuracy to 30 picoAmperes
- Digitizing up to 50,000 rdgs/sec (20 µs/rdg).
- Capable of precise current consumption measurement over various time spans.
- With DUT in a steady state, user can measure V or I with high resolution using normal modes and selectable integration times. This yields seven orders of magnitude resolution from ranges down to 1 µA full scale.

Truevolt 34470A Digital Multimeter (DMM)

- Digitizing mode can sample current at very high rates and generate numerical or graphical results for examination of transient circuit behavior.

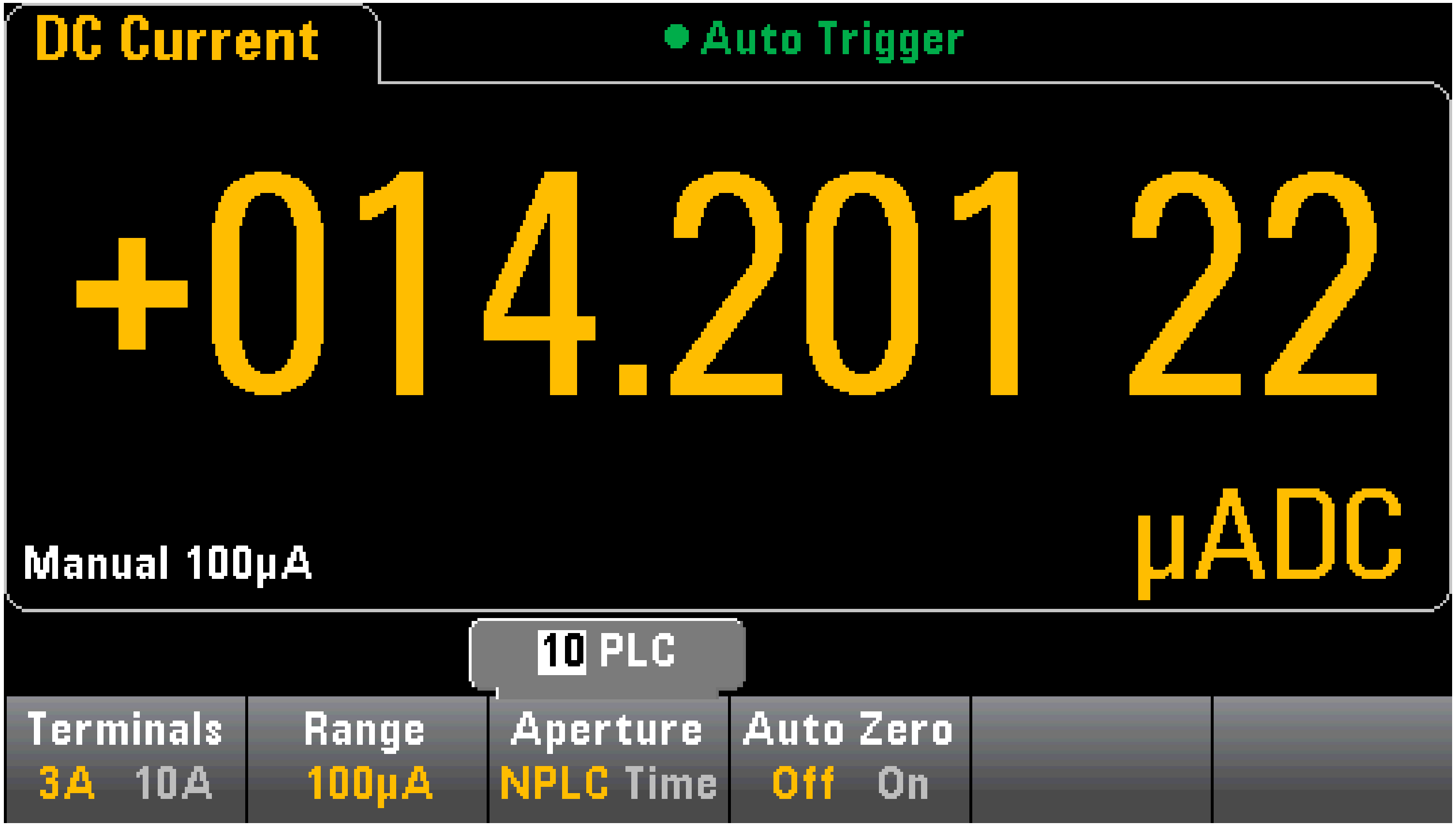
- DMM can manage high common mode voltages and has fast recovery from brief high current transients, allowing the operator to measure circuits without ground reference.

- Users can "zoom in" on low current states and still make accurate measurements of those sleep modes.



Truevolt 34470 Digital Multimeter (DMM)

High-resolution 7½-digit measurements



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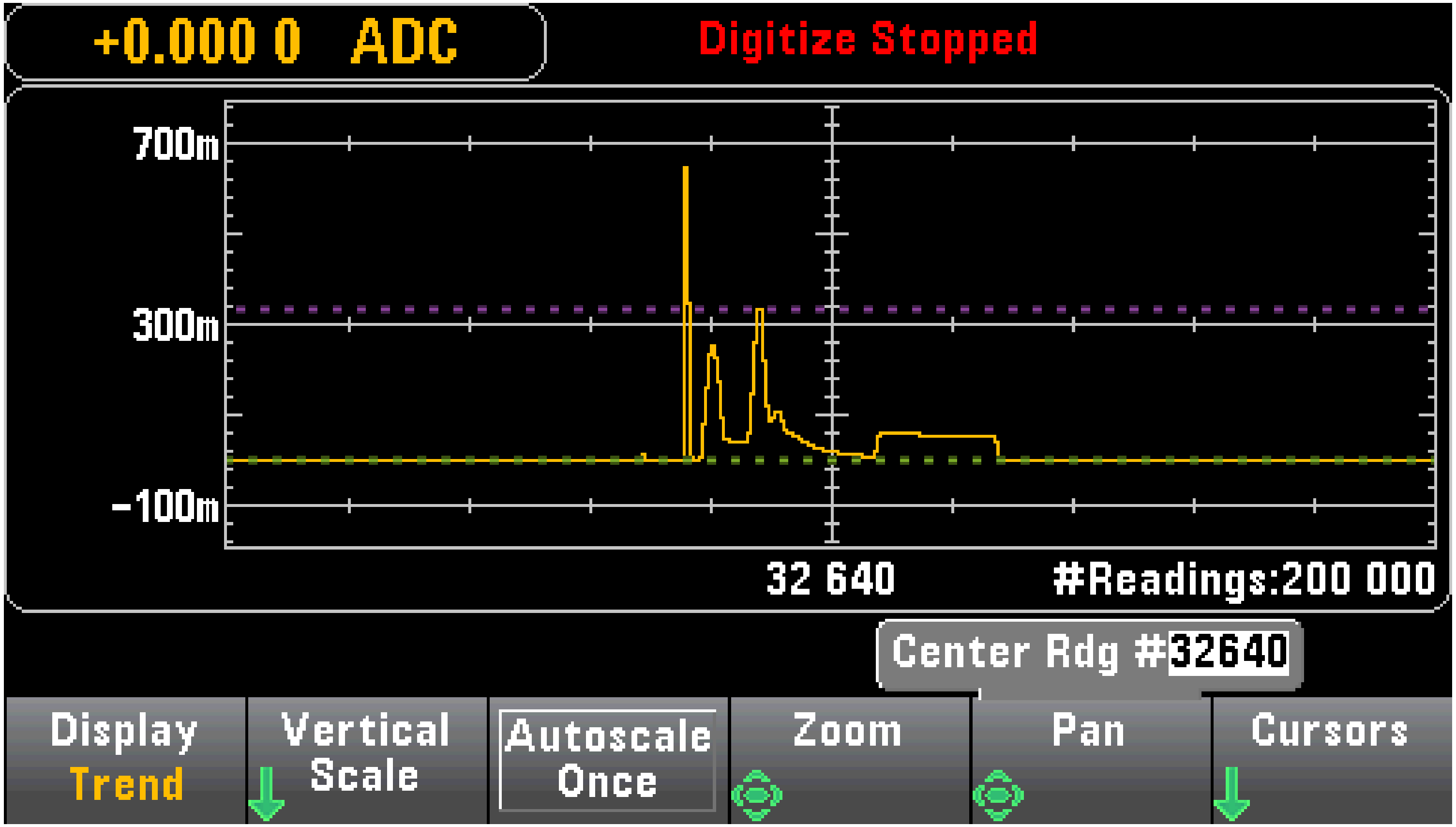
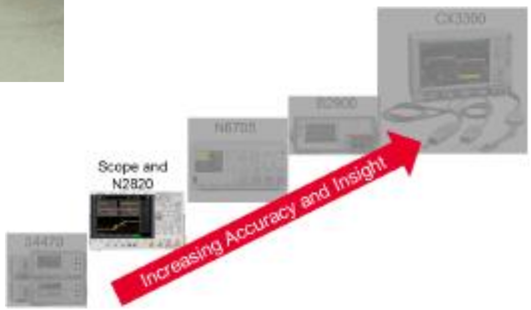
Truevolt 34470 Digital Multimeter (DMM)

Image of digitized data



KEYSIGHT TECHNOLOGIES

Oscilloscope with N2820 Current Probe



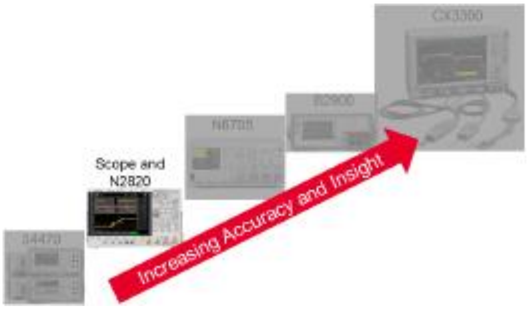
Oscilloscope with N2820 Current Probe

Application Guidelines

– Higher measurement bandwidth than SMU or power supply

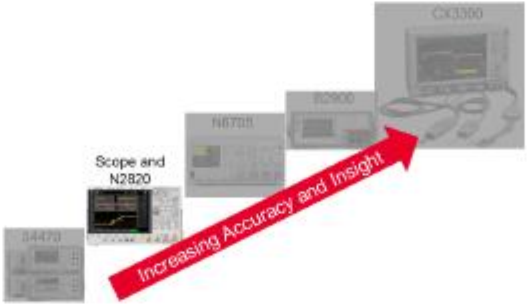
– Use when you already have or need a scope on your bench and you can accept the tradeoff accuracy for bandwidth

- Accuracy may be in the 2-6% range, and is a combination of scope and shunt or probe accuracies
- Okay for high to mid-level current measurements, noise floor limits applicability for low current measurements
- Varying shunt and probe technologies to choose from, each with their own + & -’s



Oscilloscope with N2820 Current Probe

Image of IoT device measured with N2820



1 - IoT | 2 - Challenges | 3 - Solutions

N6705 DC Power Analyzer w/ N6781 SMU

- Simulate dynamic conditions including power sequencing, battery droop and other supply variations.
- Measure accurately (0.025% up to 18 bits) and quickly (100 KHz).
- Use familiar scope-like operating model to rapidly explore circuit behavior.
- Use data logging device to record long-term power consumption.

N6705 DC Power Analyzer w/ N6781 SMU

– Gain insights into your DUT's power consumption in minutes, without programming.

– A scalable, integrated solution to meet a wide variety of power sourcing, characterization, disturbance and vulnerability test requirements.

– Four module slots for maximum combined DC output power of 600 W

– 36 modules available: up to 500 W, 60 V, and 50 A

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N6705 DC Power Analyzer w/ N6781 SMU

– Built-in arbitrary waveform generator, DVM, ammeter, data-logger and scope-like display

– Digitizing V and I measurement up to 200 kSa/s verifies shape, power, energy

– Can re-use same module and code with N6700 mainframe in manufacturing

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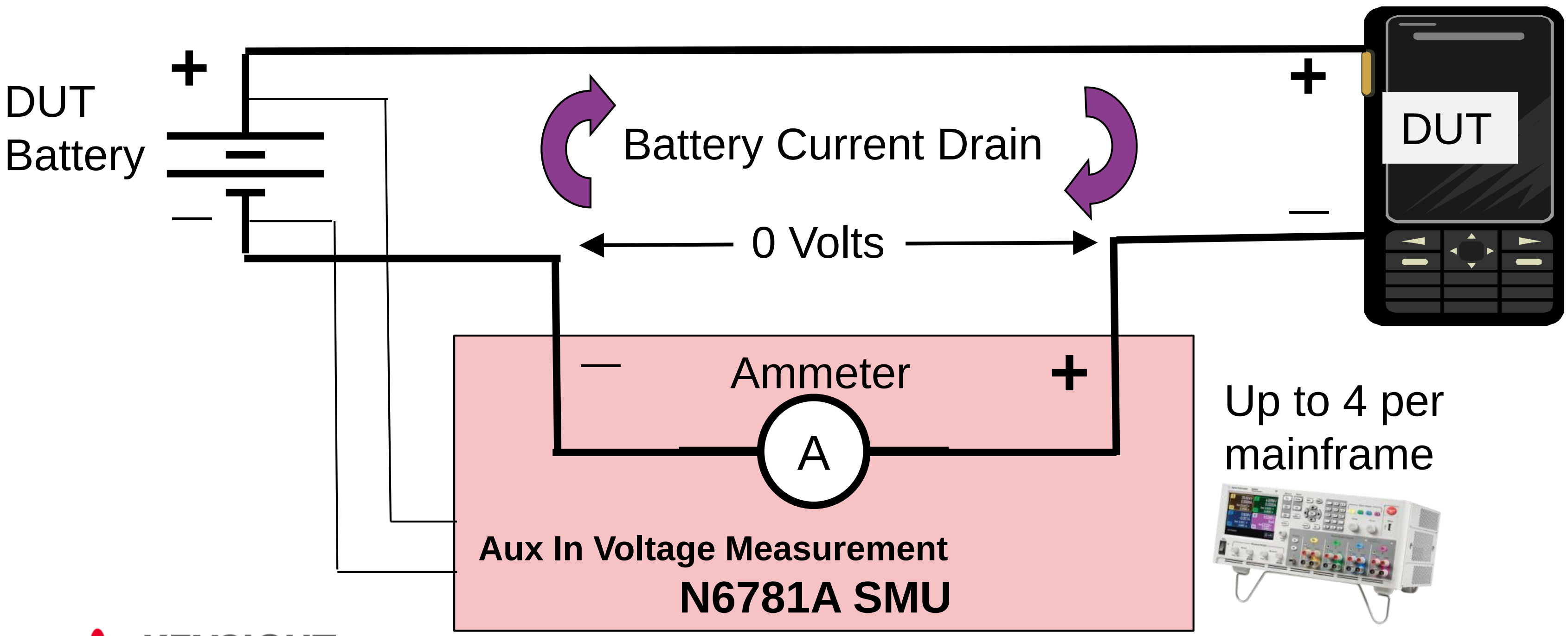
1 - IoT | 2 - Challenges | 3 - Solutions

Zero Shunt

Realistic assessment of a DUT's performance is with its battery

- Logging battery run-down voltage and current yields insights about the device and its battery in combination as a system
- N6781A features a Measure-only operating mode for battery run-down testing:
  - N6781A's output regulates zero volts while measuring current, becoming a zero-burden ammeter. Eliminates voltage drop problems that current shunt resistors have
  - N6781A's Auxiliary DVM input simultaneously logs battery voltage



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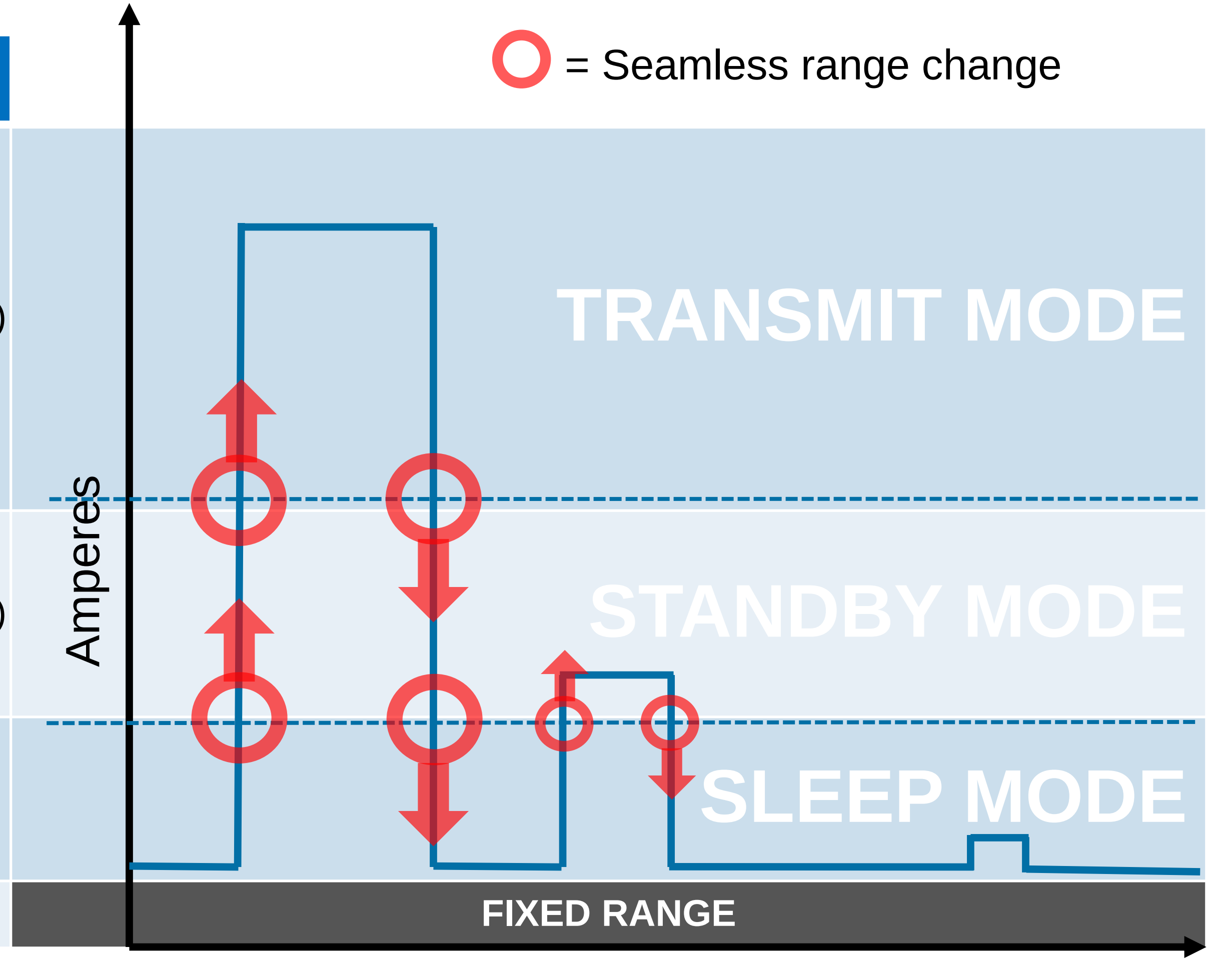
Seamless Current Measurement

Think: Vertical Mega-Zoom

Seamless Range Changes

Range	Measurement Accuracy
3 A	±(0.03% + 250 µA)
100 mA	±(0.025% + 10 µA)
1 mA	±(0.025% + 100 nA)
10 µA	±(0.025% + 8 nA)



See the complete current waveform you've never seen before
– from nA to A –
in one pass and one picture

N6781A Seamless Ranging Innovation Performance

Voltage				
Range	**20 V**	**6 V**	**1 V**	**100 mV**
Programming Accuracy	±(0.025% + 1.8 mV)	±(0.025% + 600 µV)		
Measurement Accuracy	±(0.025% + 1.2 mV)		±(0.025% + 75 µV)	±(0.025% + 50 µV)

Seamless measurement between these 3 ranges

Current						
Range	**3 A**	**1 A**	**300 mA**	**100 mA**	**1 mA**	**10 µA**
Programming Accuracy	±(0.04%+ 300µA)	±(0.04%+300µA)	±(0.03%+150µA)			
Measurement Accuracy	±(0.03% + 250 µA)			±(0.025% + 10µA)	±(0.025% + 100 nA)	±(0.025% + 8 nA)

Seamless measurement between these 3 ranges

- Seamless ranging continually changes ranges without glitch nor lose readings
- 200 kHz, 18-bit digitizer, with seamless ranging, acts likes single range of ~28-bits
- 3 A range with an effective offset error as low as 100 nA (0.03 PPM) Accurate measurements from Amps to µA during a single scope sweep or data-log

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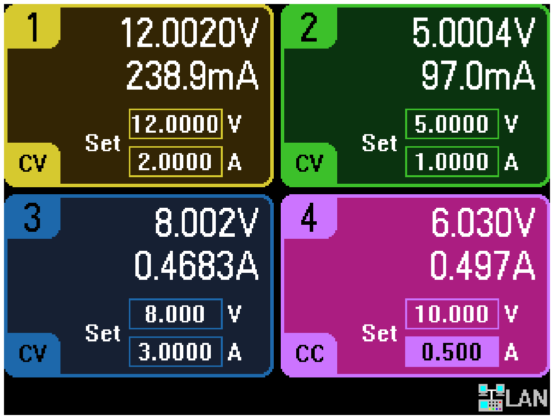
N6705 DC Power Analyzer w/ N6781 SMU

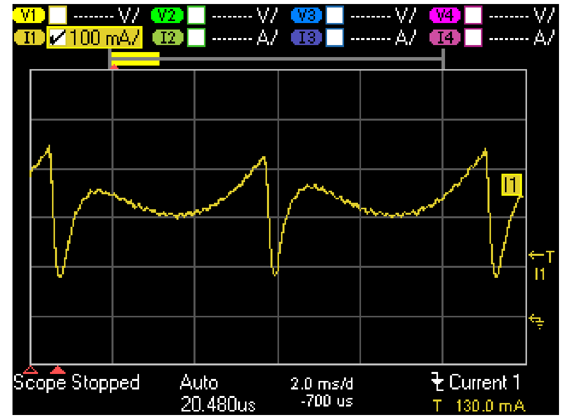
Flexible user interface

Meter View



V and I meas. for all 4 channels

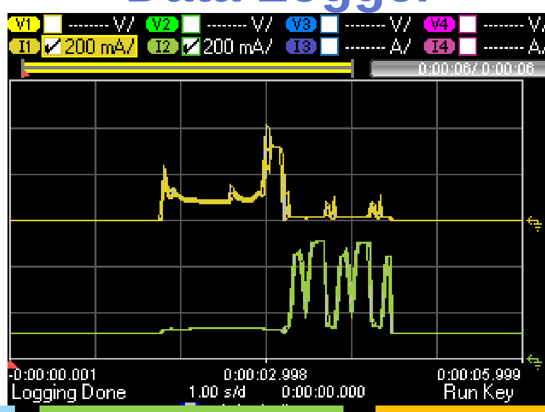
Scope View



V and/or I waveform capture

Data Logger

Log data for seconds, hours, or days



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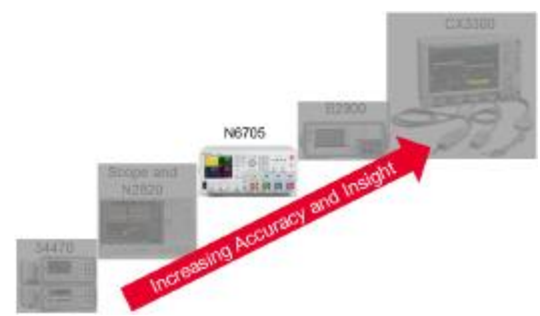


KEYSIGHT TECHNOLOGIES

14585 Control and Analysis Software

– Control any N6700 DC power module in up to four N6705 instruments (16 modules) simultaneously, without programming.

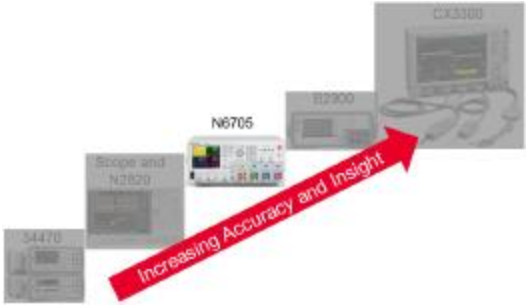
– Four operation modes:
  - scope (waveform capture)
  - data log
  - CCDF statistical analysis (N6781A only)
  - ARB (waveform creation)

– Accurately capture current drain measurements from seconds to days at up to 200,000 measurements per second (in scope mode) directly to a PC

– Easily create complex waveforms to stimulate or load down a DUT by inputting a formula, choosing from built-in, or importing waveform data

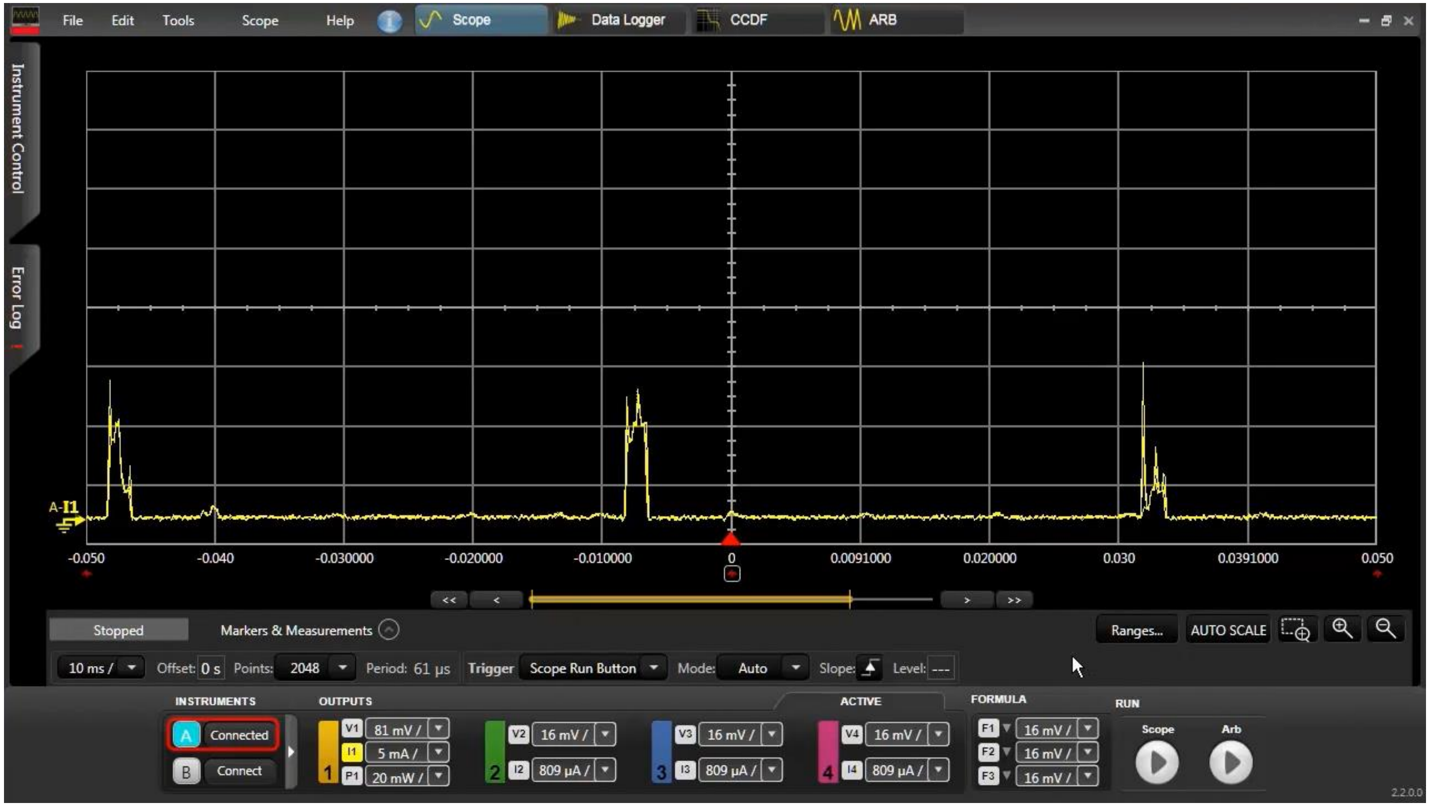
– Capture a waveform, then “play” it back

– Perform statistical analysis of power consumption



14585 Control and Analysis Software

Scope mode



KEYSIGHT TECHNOLOGIES

1 - IoT

2 - Challenges

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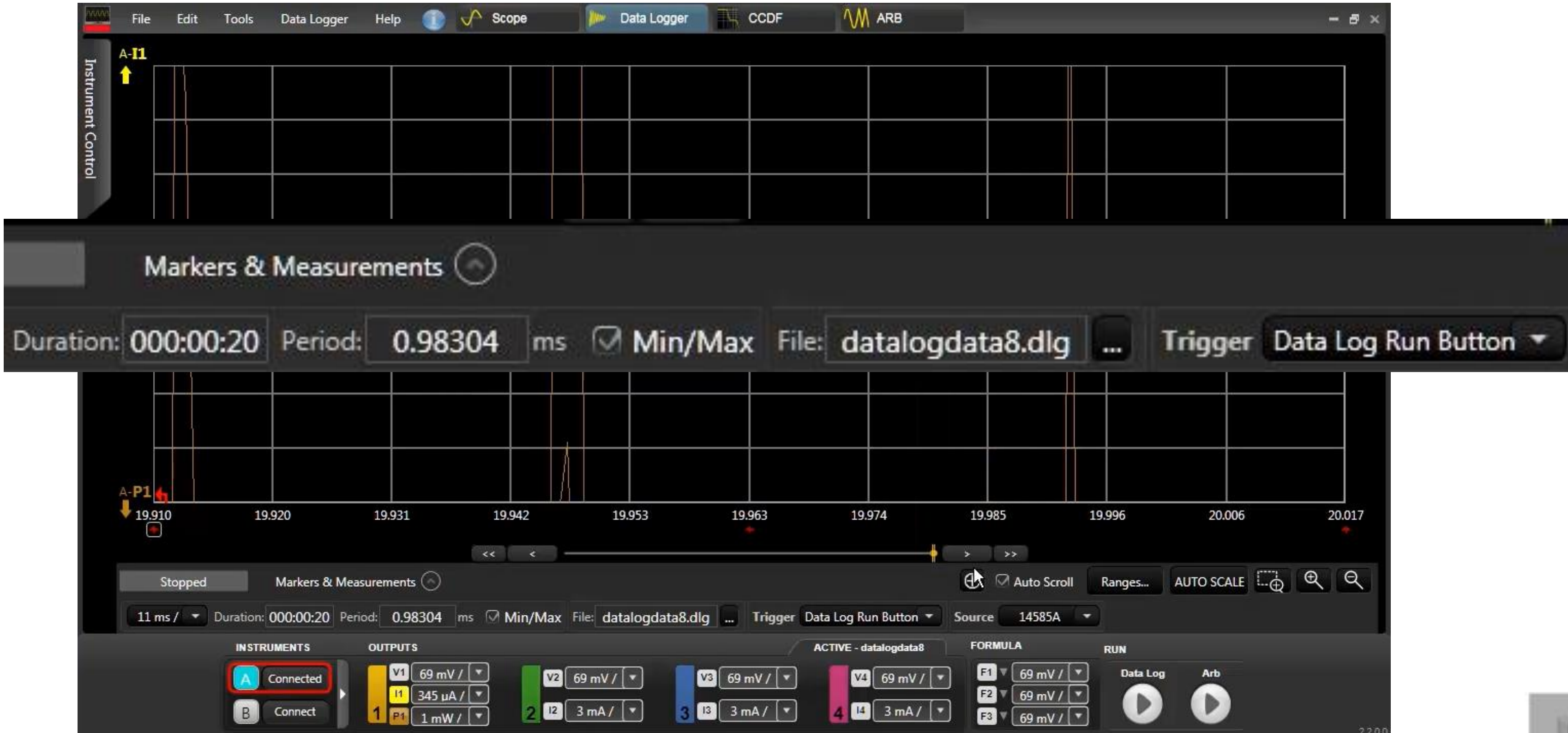
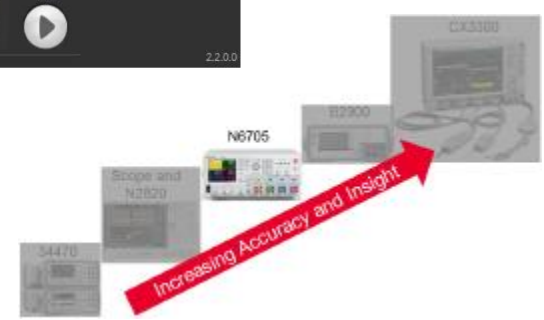
14585 Control and Analysis Software

Data Logger mode





KEYSIGHT TECHNOLOGIES

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14585 Control and Analysis Software

CCDF mode

1 - IoT

2 - Challenges

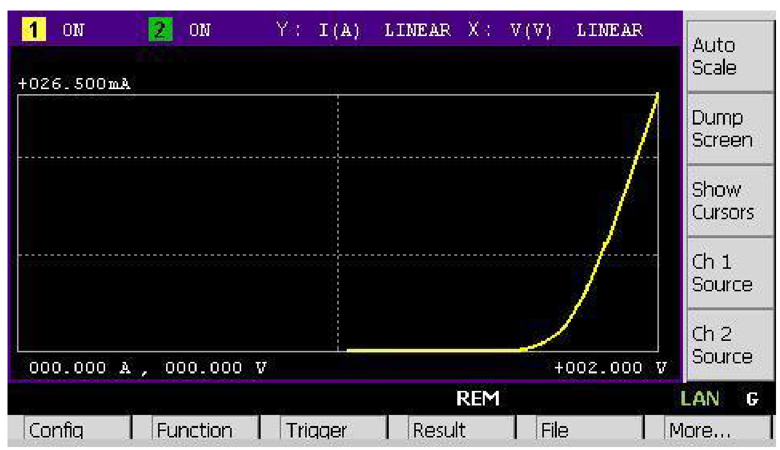
3 - Solutions

B2900 Series Precision Source/Measure Unit

– Up to ±210 V and ±3 A (DC) / ±10.5 A (pulsed) provides wider coverage for testing a variety of devices

– Resolution: 10 fA and 100 nV

– GUI for quick bench-top testing, debug and characterization



KEYSIGHT TECHNOLOGIES

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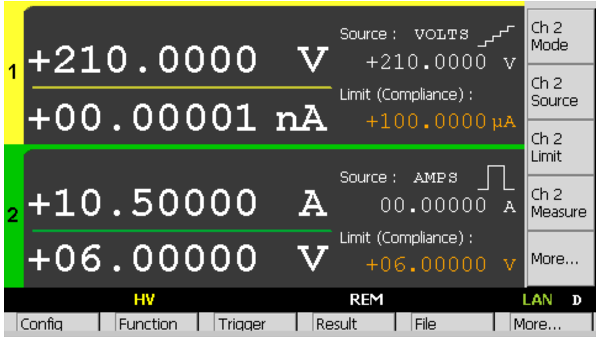
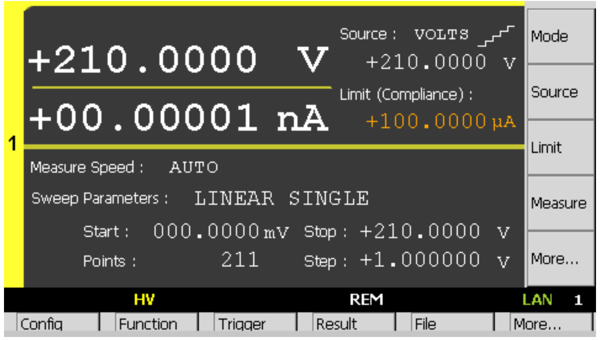
B2900 Series Precision Source/Measure Unit

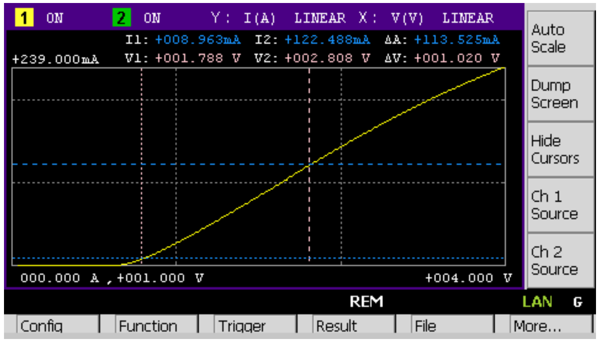
Perform interactive device evaluation with four viewing modes



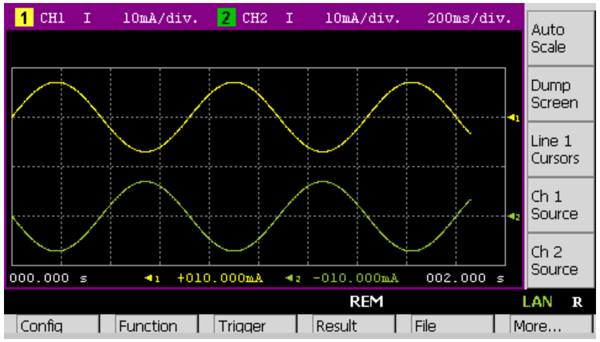
Dual Channel (2-ch Units Only)



Single Channel



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



Roll View (strip chart)

KEYSIGHT TECHNOLOGIES

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B2900 Series Precision Source/Measure Unit

Maximum voltage and current output

	Max. Voltage (V)	Max. Current (A)
DC or Pulsed	210	0.105
	21	1.515*
	6	3.03*
Pulsed only, max duty cycle 2.5%	200	1.515
	6	10.5

* See data sheet for additional restrictions on the combined current output of both channels.

B2900 Series Precision Source/Measure Unit

Model Details

Model	# Ch	Setting Resolution: Digits	Setting Resolution: Min. Resolution I	Setting Resolution: Min. Resolution V	Measurement Resolution: Digits	Measurement Resolution: Min. Resolution I	Measurement Resolution: Min. Resolution V	Dig. Rate kSa/s
B2901	1	5½	1 pA	1µV	6½	100 fA	100 nV	50
B2902	2							
B2911	1	6½	10 fA	100 nV	6½	10 fA	100 nV	100
B2912	2							

All four models include XY View and AWG/List Sweep.
The B2911A and B2912A also include Roll View.

KEYSIGHT TECHNOLOGIES

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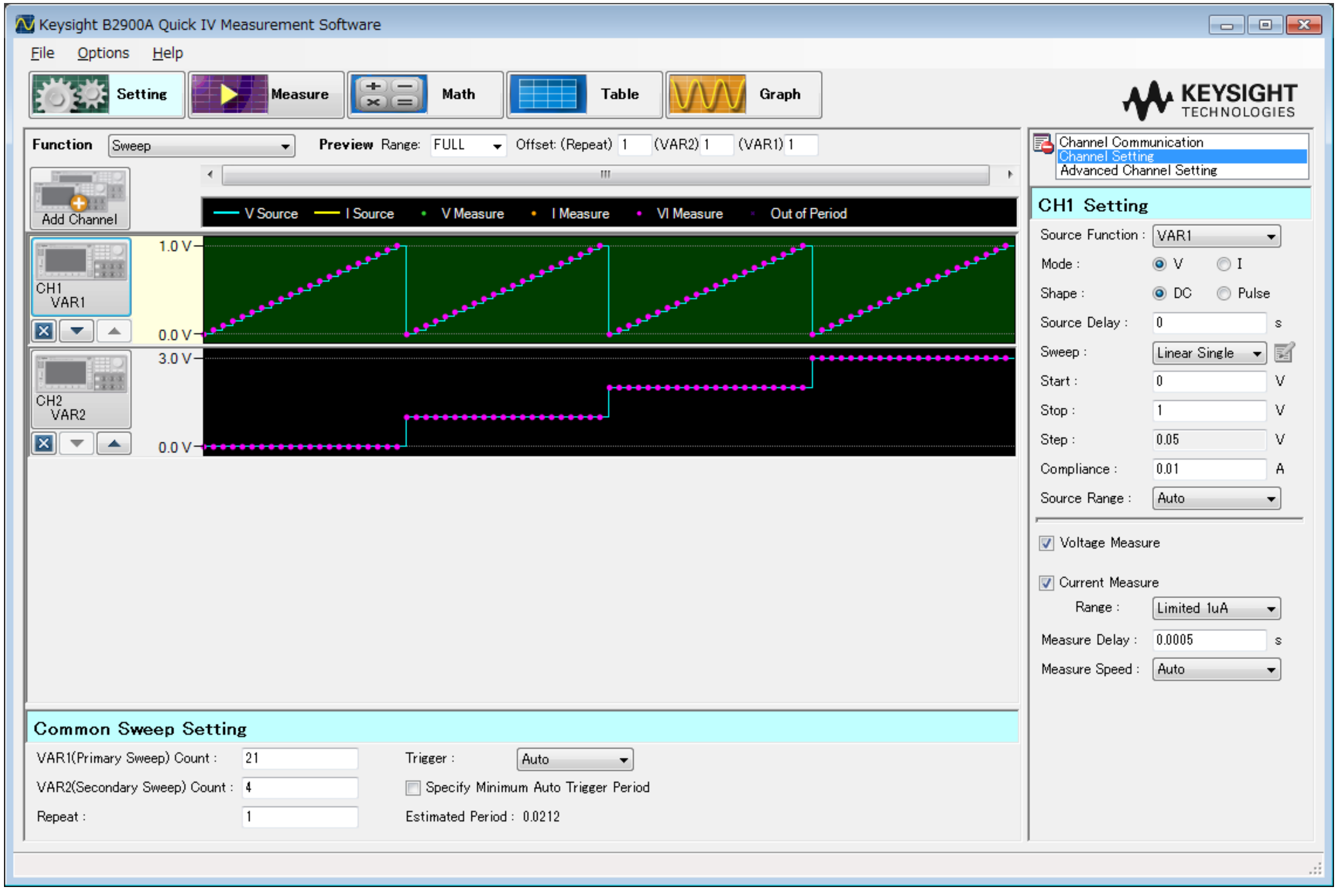
B2900 Quick IV Measurement Software



KEYSIGHT TECHNOLOGIES

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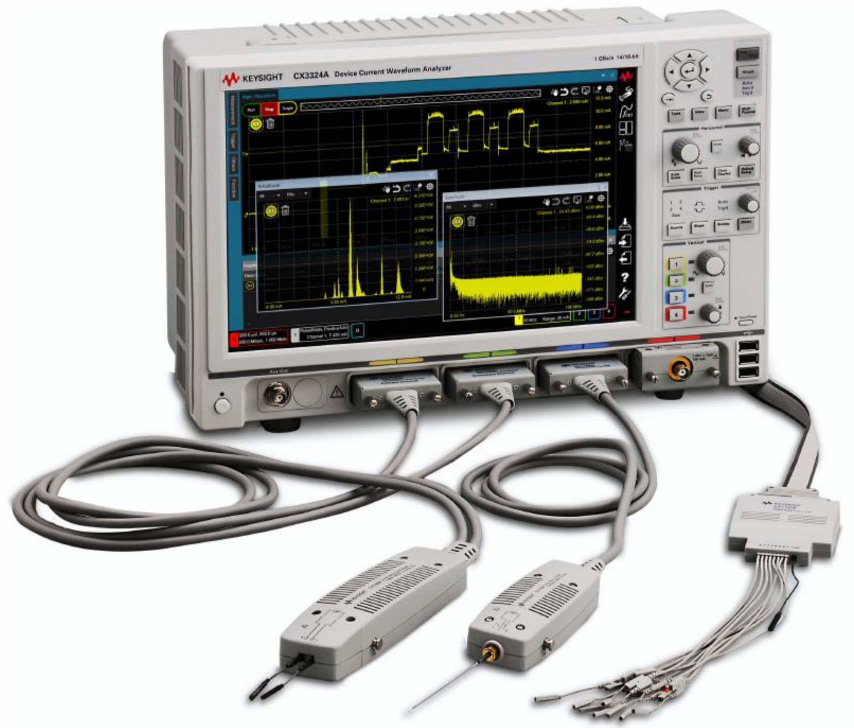
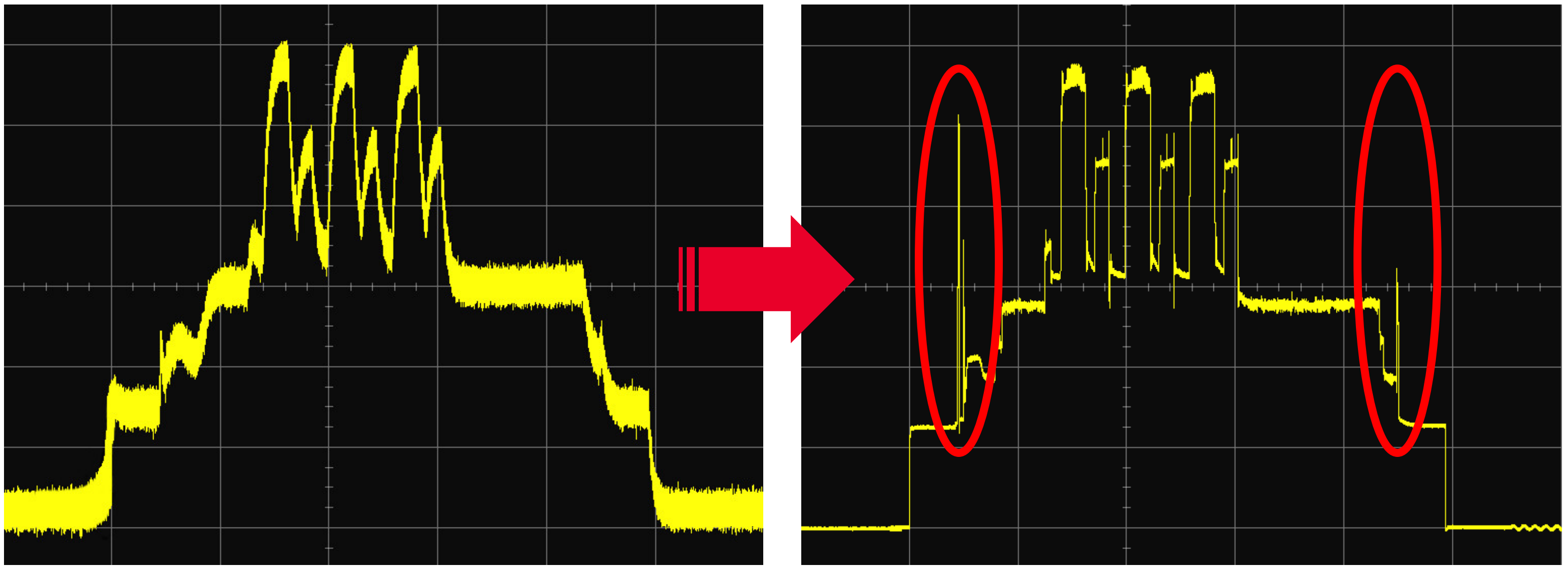
CX3300 Series Device Current Waveform Analyzer



Precisely view low-level current waveform features that were previously undetectable.

CX3300 Series Device Current Waveform Analyzer



Previous Technology

CX3300

KEYSIGHT TECHNOLOGIES

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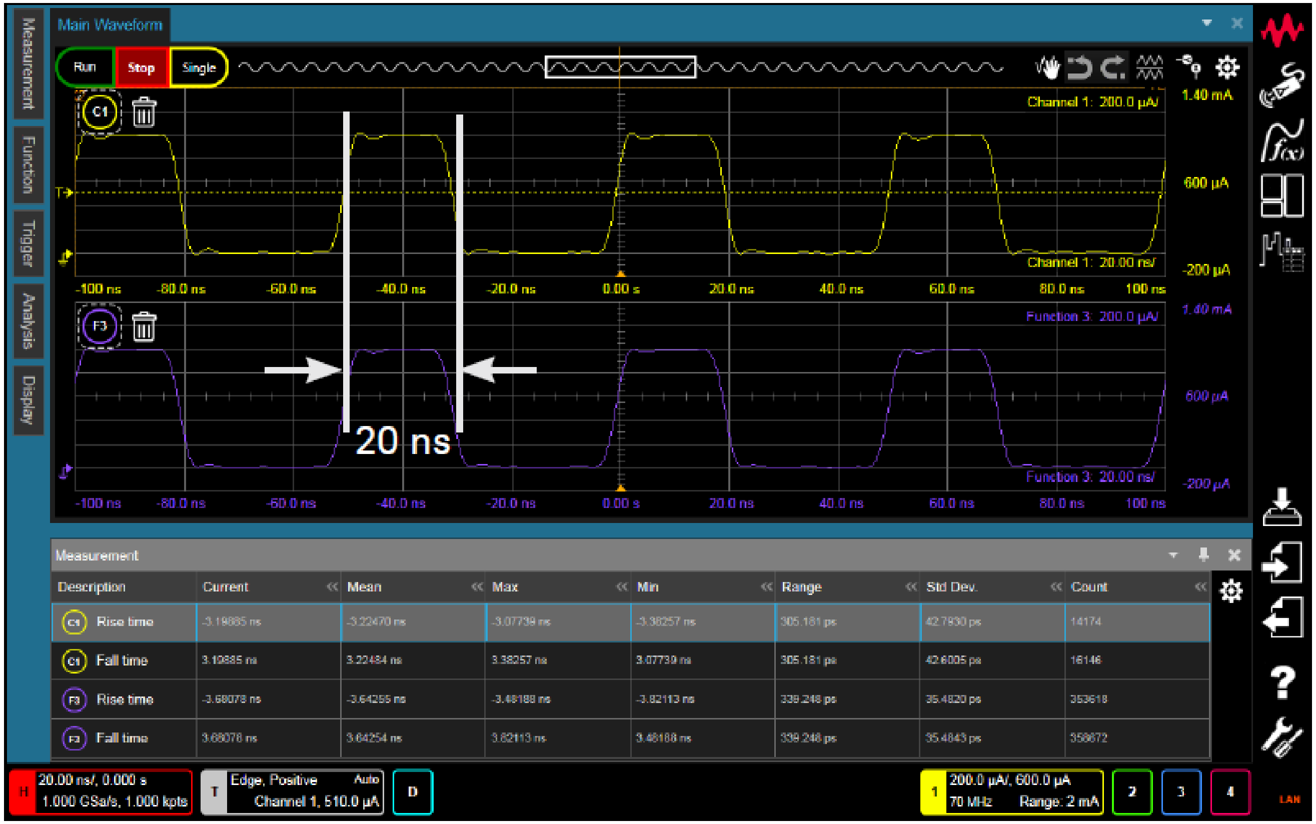
CX3300 Series Device Current Waveform Analyzer



Easily measure transient current with less than 100 ns pulse width to evaluate and analyze two-terminal devices such as PRAM, ReRAM, MRAM, etc.

KEYSIGHT TECHNOLOGIES

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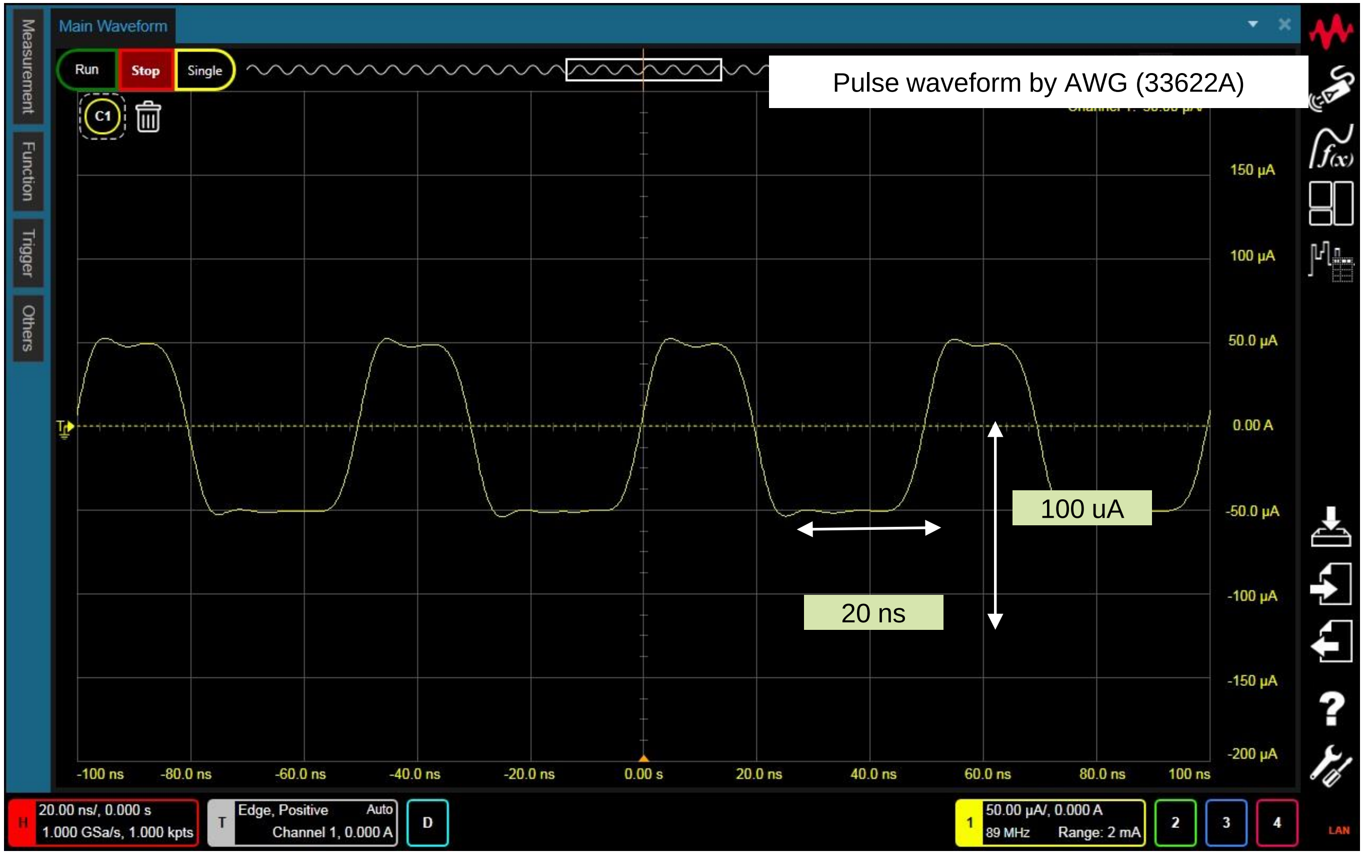
CX3300 Series Device Current Waveform Analyzer



KEYSIGHT TECHNOLOGIES

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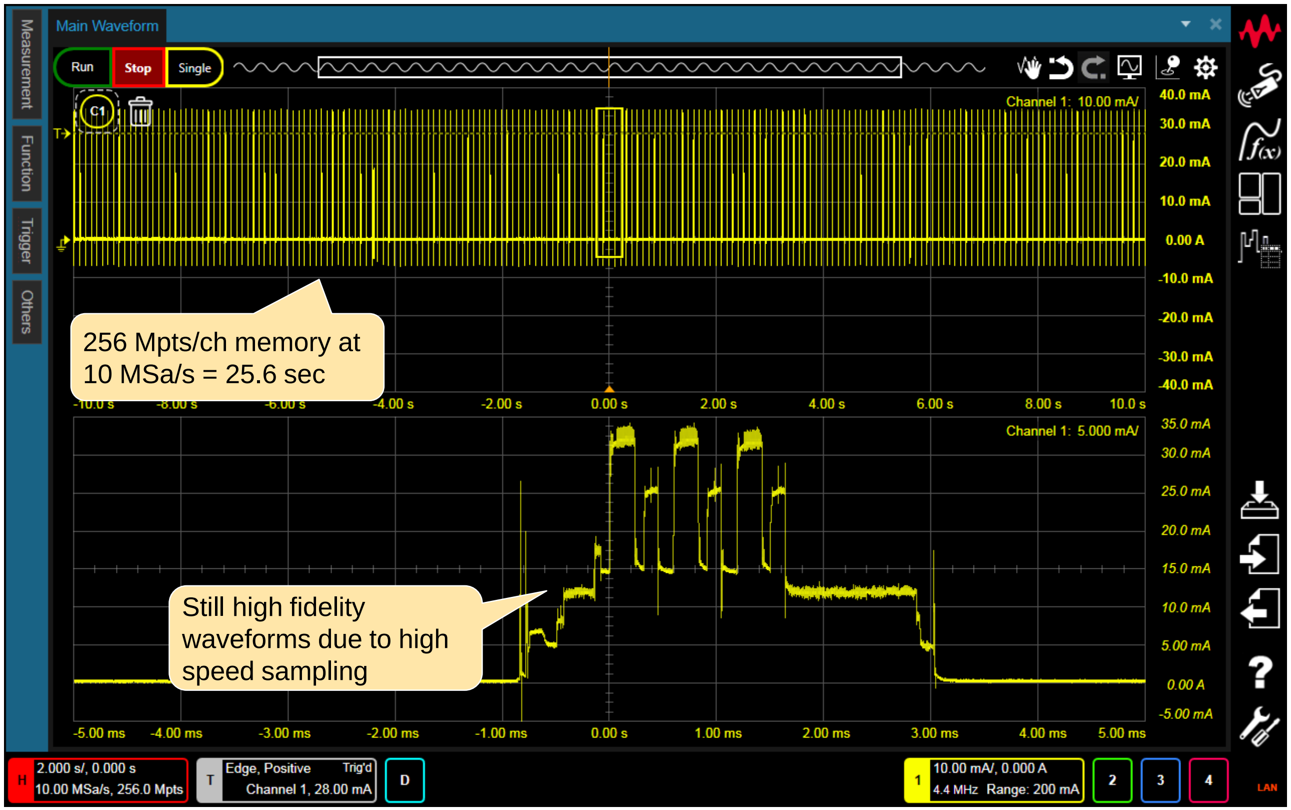
CX3300 Series Device Current Waveform Analyzer

Example of long duration measurement



KEYSIGHT TECHNOLOGIES

1 - IoT

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CX3300 Series Device Current Waveform Analyzer

Key features and benefits

– 14/16-bit wide dynamic measurement ranges display clearly even very low-level current waveforms.

– Ultra-low noise and low voltage drop current sensors precisely capture current waveforms from 100 pA to 10 A.

– Up to 200 MHz bandwidth and a 1 GHz max sampling rate enable you to see transient currents never visible before.

– A single instrument that provides a wide variety of current/power waveform measurement and analyses capabilities that were previously impossible.

CX3300 Series Device Current Waveform Analyzer

Key features and benefits

– Intuitive touch screen based GUI and familiar scope-like functions reduce the learning curve.

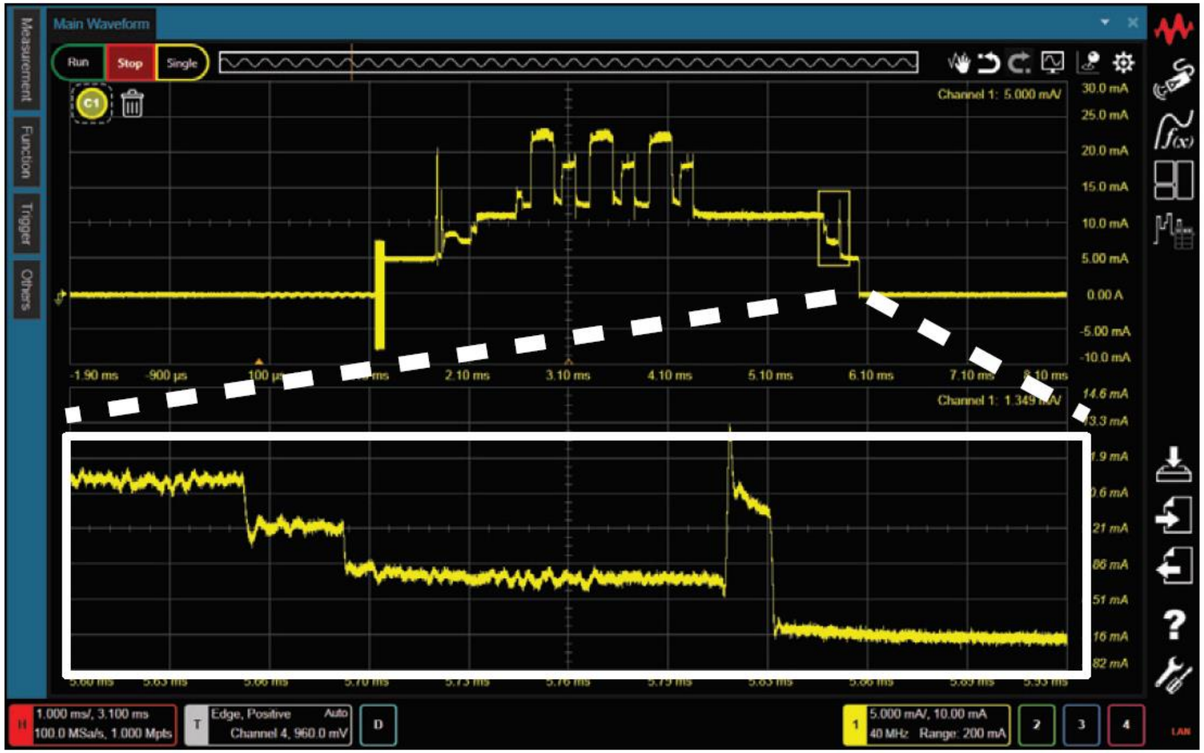
– Innovative “Anywhere” Zoom and ”Automatic Power and Current Profiler” functions make anyone a current measurement expert

– Dual Channel Current Sensor achieves a 100 dB dynamic range to visualize low-power device operations

CX3300 Series Device Current Waveform Analyzer

"Anywhere" zoom function

Quickly expand any current waveform segment in X and Y to see detail.



KEYSIGHT TECHNOLOGIES

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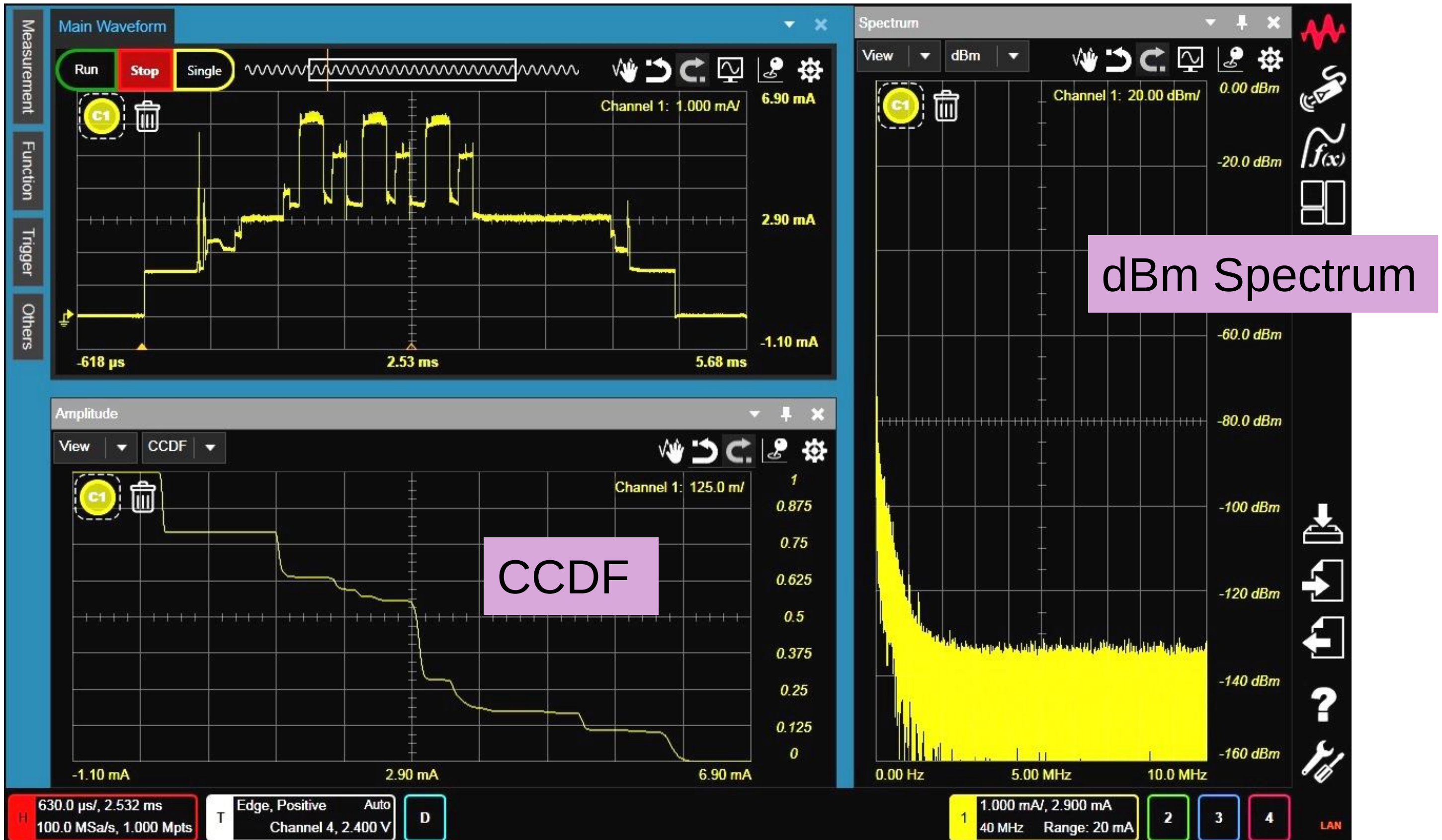
CX3300 Series Device Current Waveform Analyzer

Powerful analysis functions

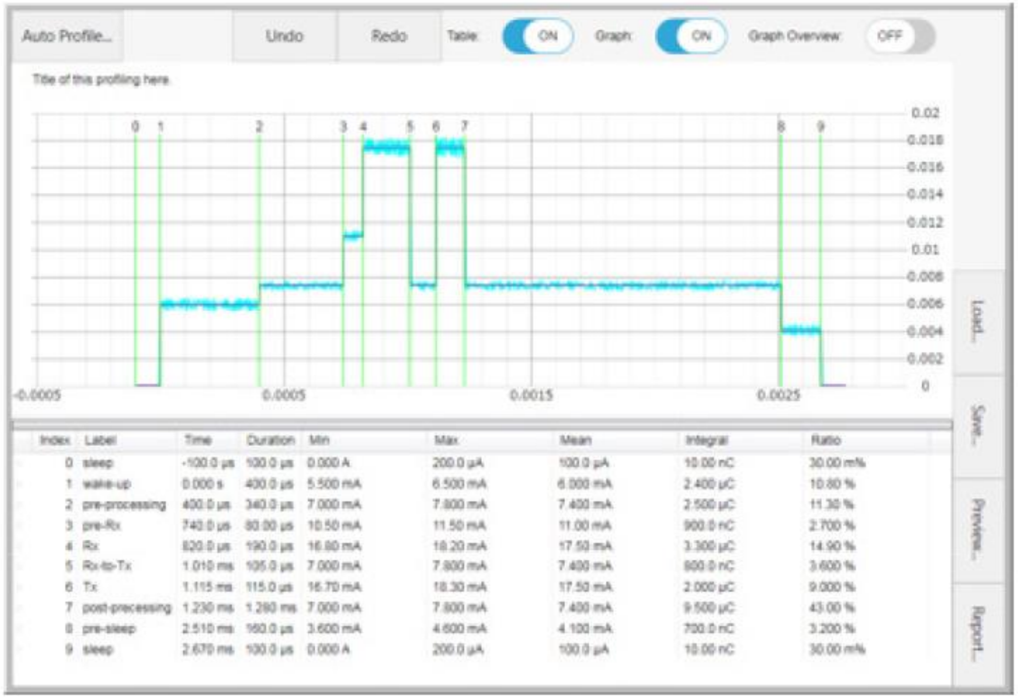


CX3300 Series Device Current Waveform Analyzer

Automatic Current and Power Profiler

– Power or current profile analysis is essential for knowing how much current is consumed at a certain event or status, but it can be time-consuming.

– The Automatic Power and Current Profiler automatically graphs and instantly calculates key parameters and statistics for each segment in the table. You can also manually adjust profile segments



1 - IoT

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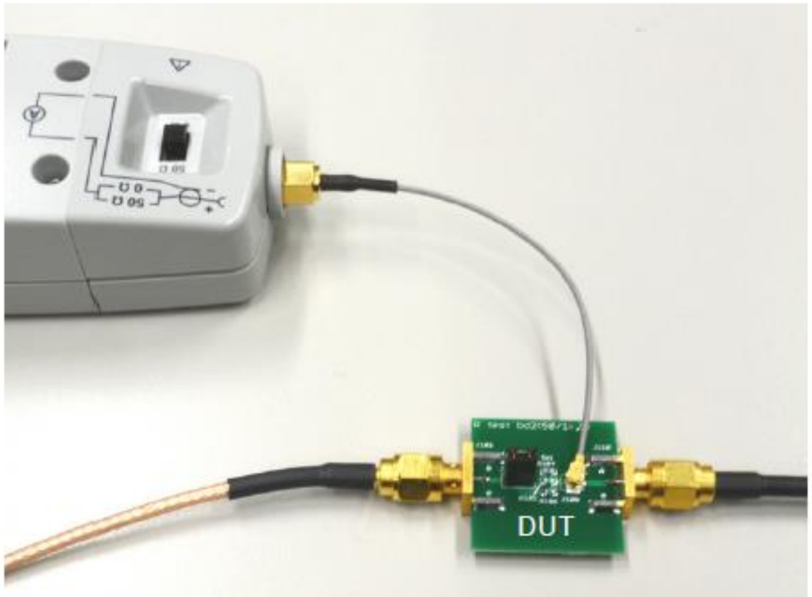
CX3300 Series Device Current Waveform Analyzer

Connecting to DUT



SMA Cable

Test Lead

Conclusion

– The IoT is a huge source of both opportunity and challenge in terms of battery drain.

– The key to BDA is the ability to make fast current measurements across a wide dynamic range.

– Keysight has a wide variety of tools that meet the BDA challenge in different prices ranges and with different capabilities and use models.

Questions