정확한 다이나믹 전류 및 노이즈 측정

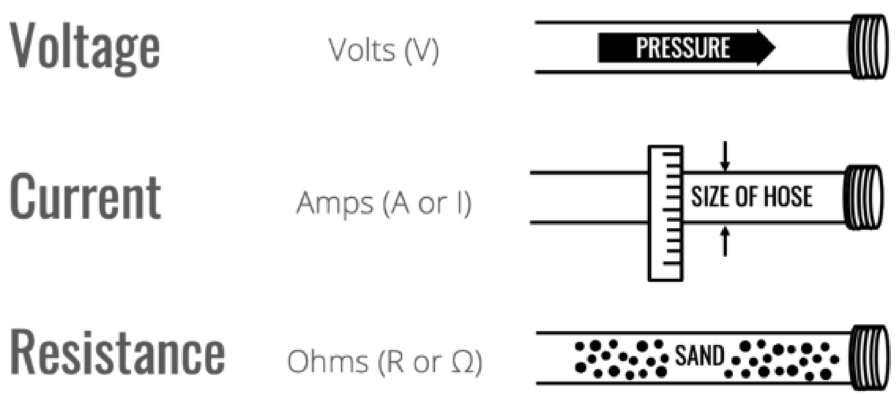
전류 측정 원리부터 IsoVu™ 절연 전류프로브 실제 활용 사례까지

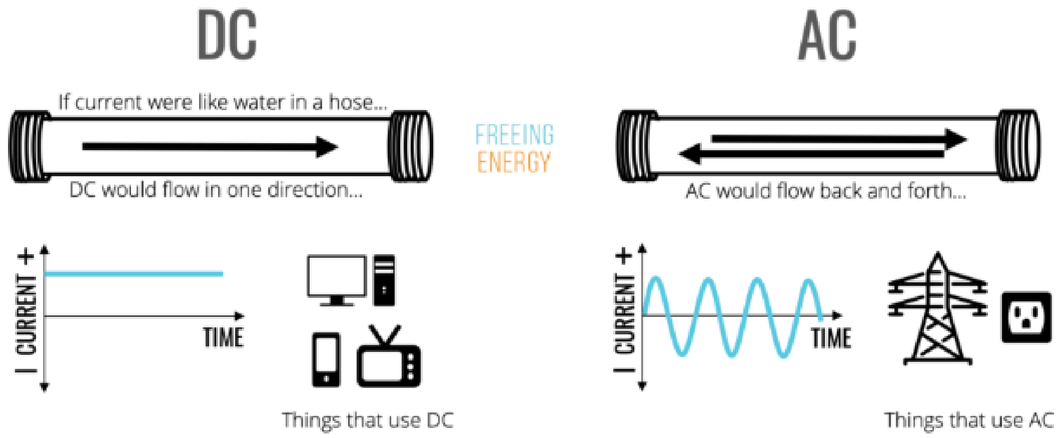
Agenda

- Basics of Current Measurement
- Current measurement on an oscilloscope
  - Base on a sensor
  - Base on Ohm’s Law
- Bandwidth of Current Probes and Limitations
- Introducing: TICP Series IsoVu Isolated Current Probe
- Shunt Resistance and Measurement Range
- Uses Cases
  - High Power
  - Low Power

What is current?

DEFINITION AND COMMOMANALOGIES





Source: freeingenergy.com

Why do we measure current?

P = V X I

Power Electronics **characterization**,

Electric energy **consumption**, converters efficiency determination

Monitor load **absorbtion**,

Implement current based feedback control

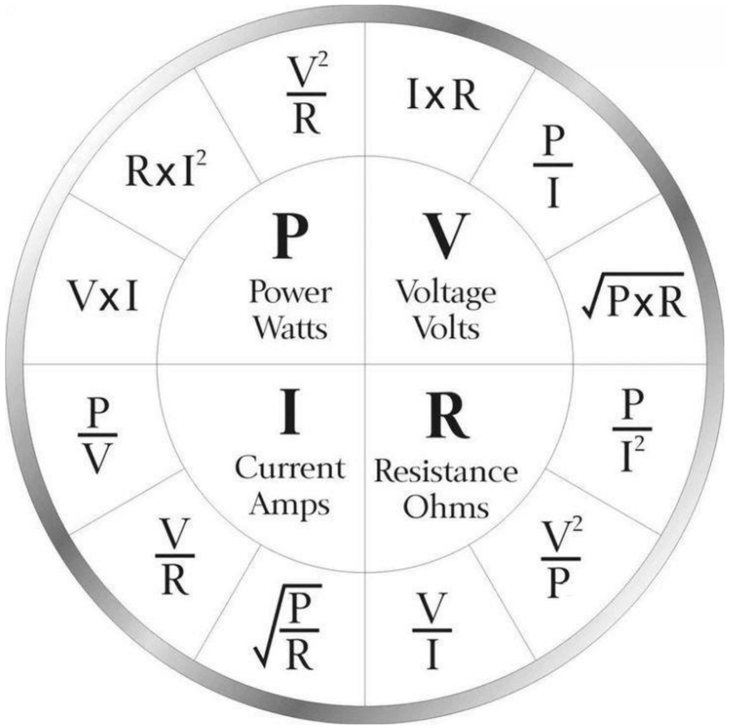
Calculate **battery duration**,

storage discharge time...

Insulator resistance measurements

Detection of **shorts**, over currents, diagnose malfunctioning...

Other...



How do we measure current?

NOMENCLATURE AND SEMANTIC

How= using **what** equipment+ using **which** technique

It depends on the Application Context

nA DC not the same as kA AC

Measure vs Sense

Examples:

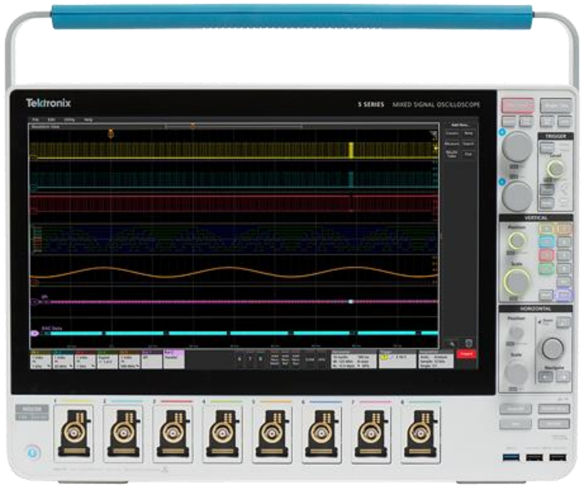
SMU

DMM

Oscilloscope

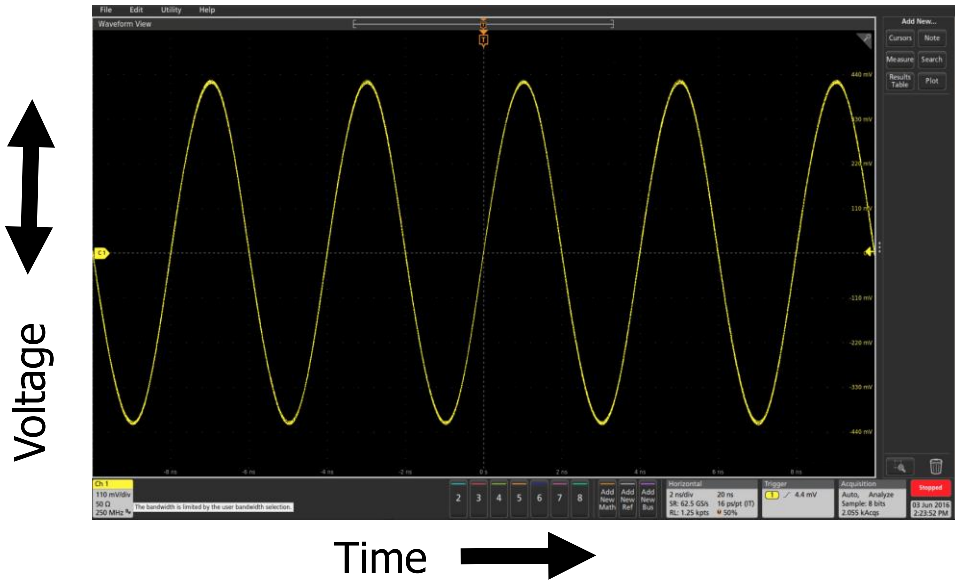
SMU

DMM



Oscilloscope

Can Oscilloscopes measure current?

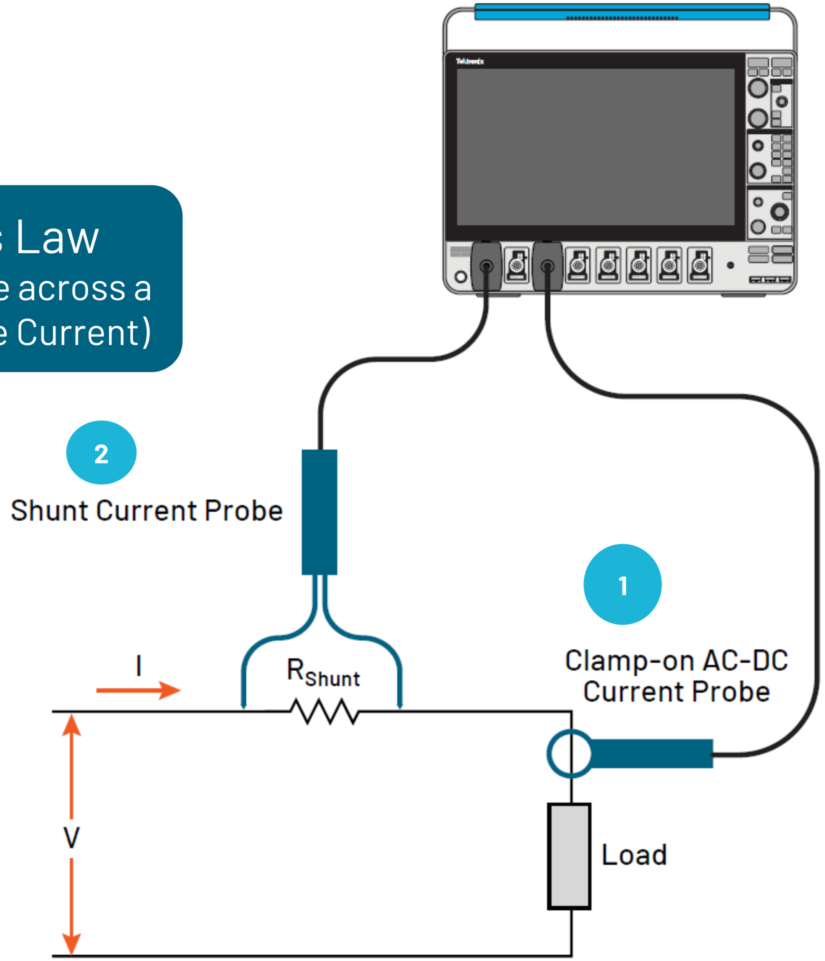


Yes, But need to get it converted into Voltage

Two Main Current Probing Techniques

2 Based on Ohm's Law
(V = IR; Measure Voltage across a known shunt and derive Current)

New!

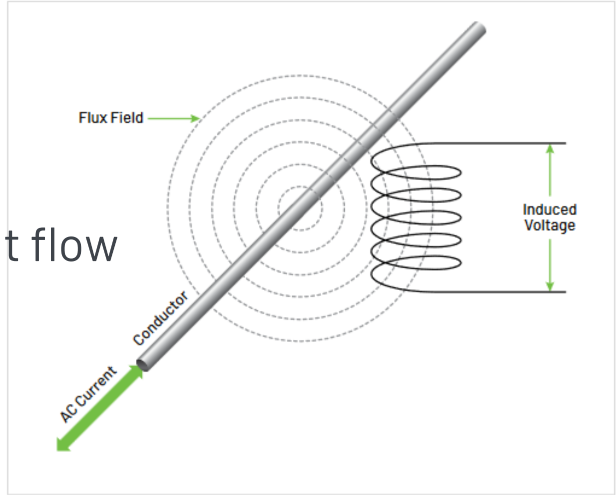


1 Based on a sensor
(Hall sensor, Rogowski coils)
Simple. and most popular

Based on a sensor

AC CURRENT PROBE

Measures the electromagnetic flux field around conductor to determine the current flow

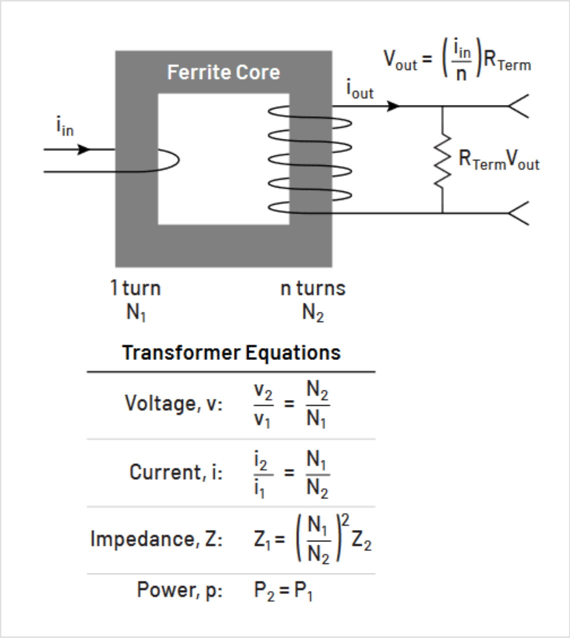


Types:

- AC current probes (passive)

Features to Consider:

- High current measurement
- Small footprint
- Low Bandwidth
- Manual scaling and units



Tektronix TRCP3000
AC Current Probe
3000 A, 1Hz to 16 MHz

Based on a sensor

AC/DC CURRENT PROBE

Measures the electromagnetic flux field around conductor to determine the current flow

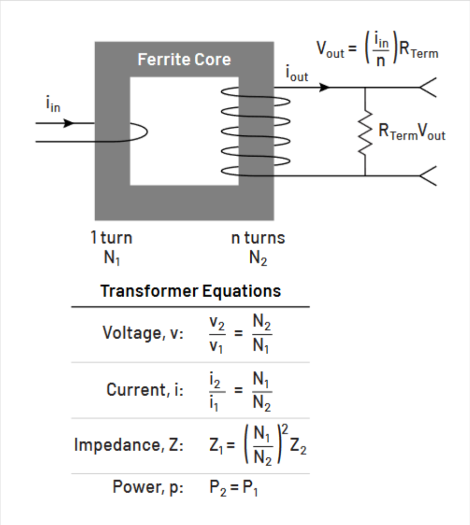
Added Hall sensor for DC current measurement

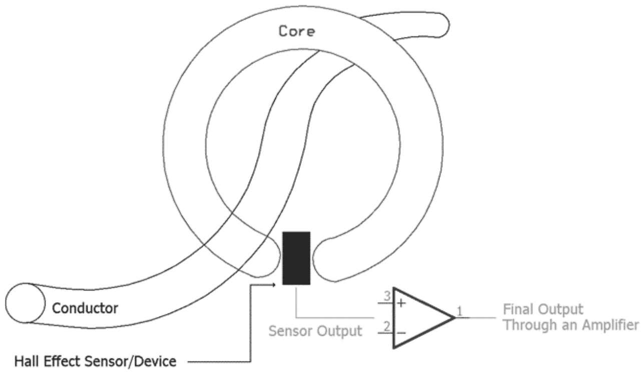
Types:

- AC/DC current probes (active)

Features to Consider:

- Operating power supply
- Automatic scaling and units





Tektronix TCP0150
AC/DC Current Probe
150 A, DC to 20 MHz

Based on Ohm's Law

Using Ohm's Law:

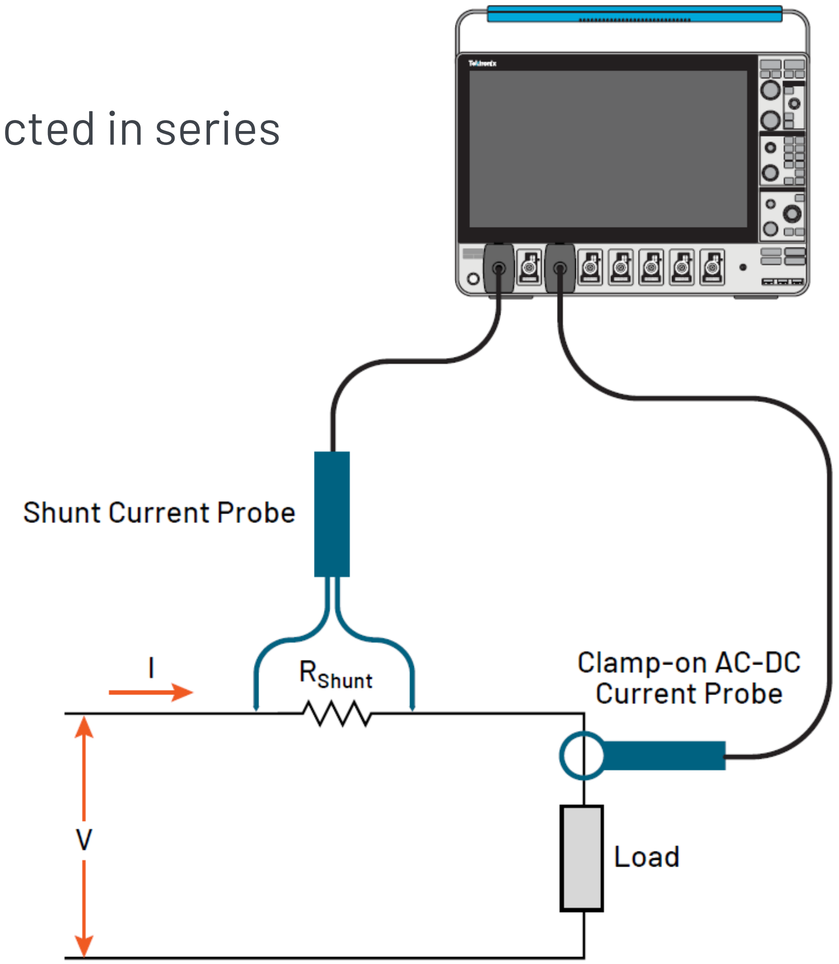
- measuring the voltage across a known resistance connected in series

Ohm's Law:

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

Features to Consider:

- Resistance values
- Tolerance
- Temperature coefficient
- Power rating



New Segments Emerging

Clamp-on Probe Operating Range

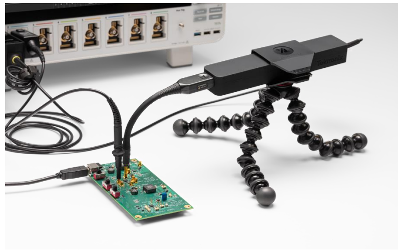
1 GHz

High Bandwidth, Low Current

High Bandwidth High Current

Magnetics can saturate at high currents limiting the usage

Requirements:
1. High Bandwidth to measure fast switching transients
2. Measure high currents driven by Automotive and Industrial applications
3. Isolation for rejecting the impact of common mode transitions (CMRR)
4. Measure High Currents with Safety



100 MHz

μA

1kA

Sensors in the probes cannot detect the magnetic fields accurately, impacting the accuracy

Requirements:
1. Measure uA to mA low-currents with high accuracy and high sensitivity
2. Low noise – as presence of noise impacts results at low levels
3. Wide dynamic range to make sleep and active current measurements with a single probe tip
4. Connectivity – flexible tips to connect to tight spaces

Low Bandwidth, Low Current

Low Bandwidth, High Current

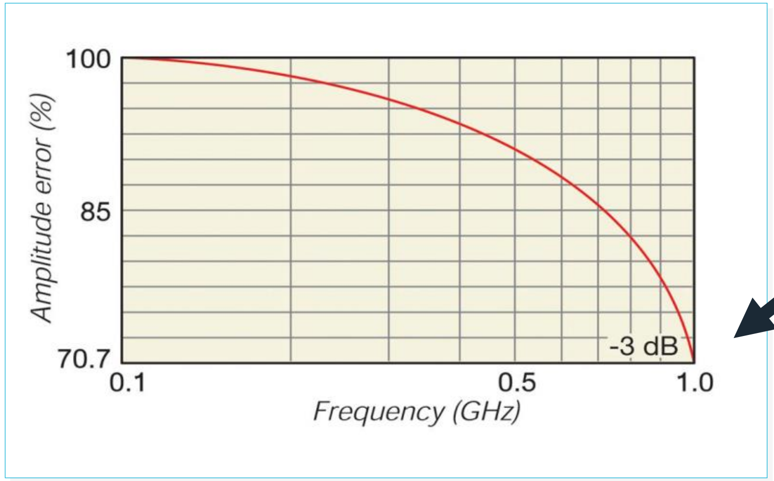
< 1 MHz

Bandwidth

Must have sufficient bandwidth to capture high frequency components

Bandwidth specified at -3 dB point

$$BW = \frac{0.35}{t_{rise}} \qquad t_{rise} = \frac{0.35}{BW}$$

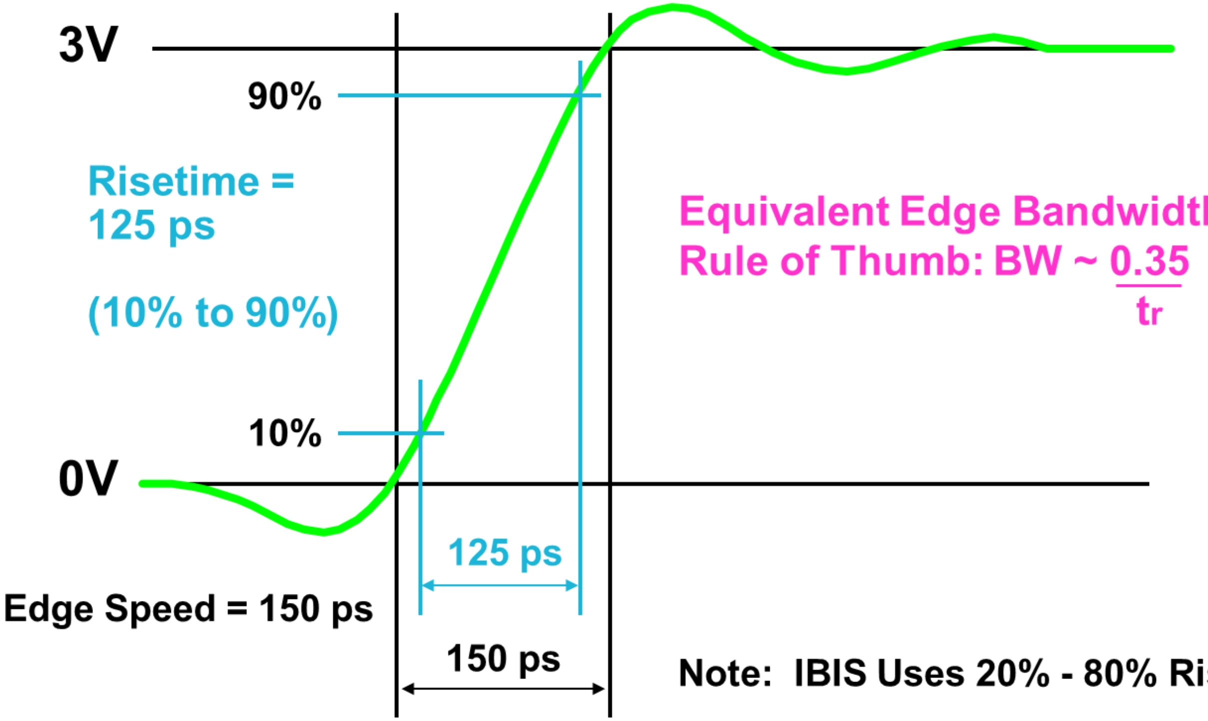


30% amplitude degradation!

At the 3dB bandwidth frequency, the vertical amplitude error will be approximately 30%.

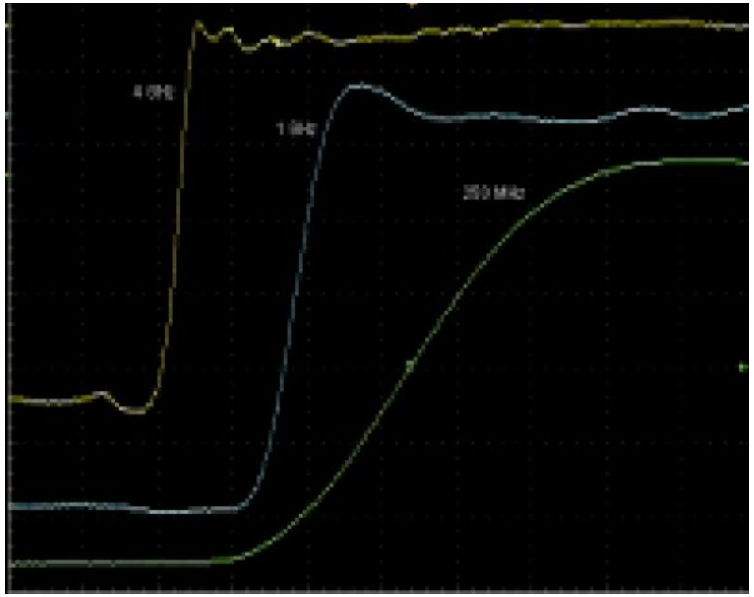
When you depend on the specified maximum vertical amplitude error, divide the specified bandwidth by 3 to 5 as a rule of thumb, unless otherwise stated.

Rise Time

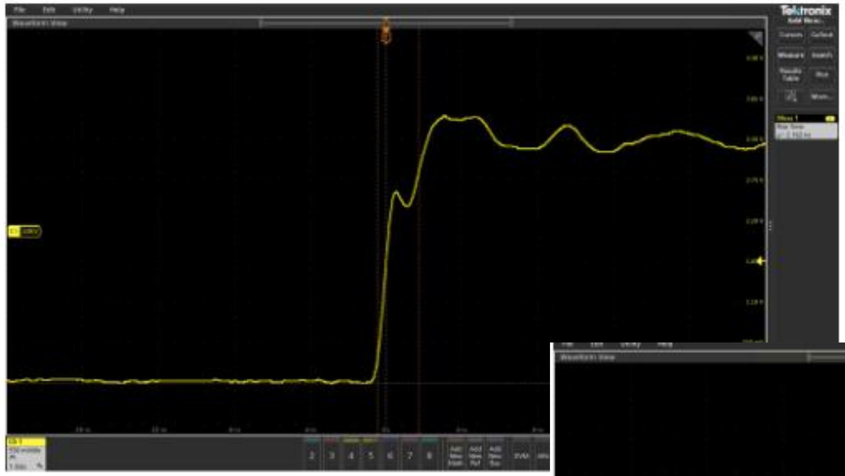


Equivalent Edge Bandwidth:
Rule of Thumb: $BW \sim \frac{0.35}{t_r}$

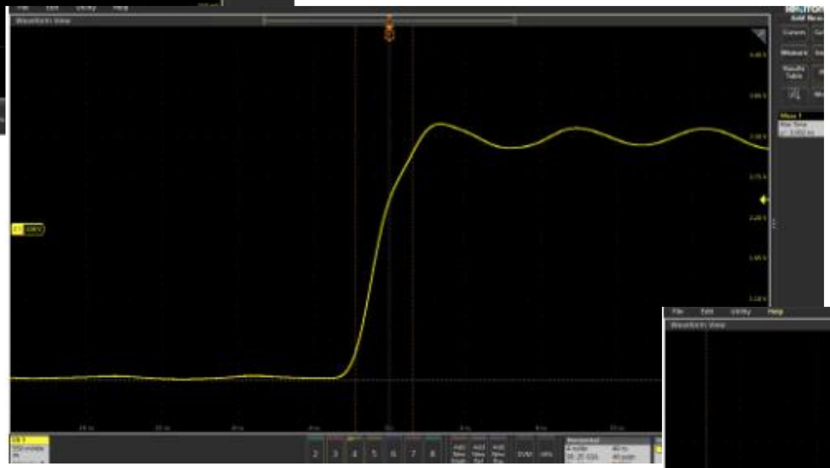
Note: IBIS Uses 20% - 80% Risetime



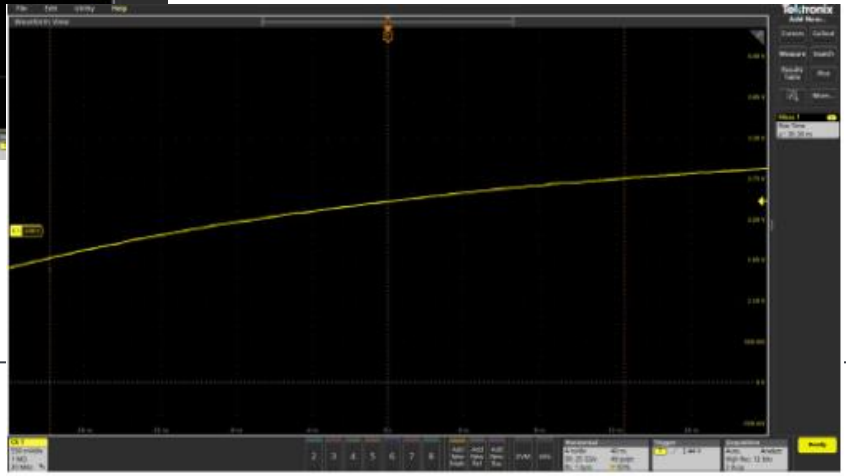
Relationship Between Bandwidth & Rise Time



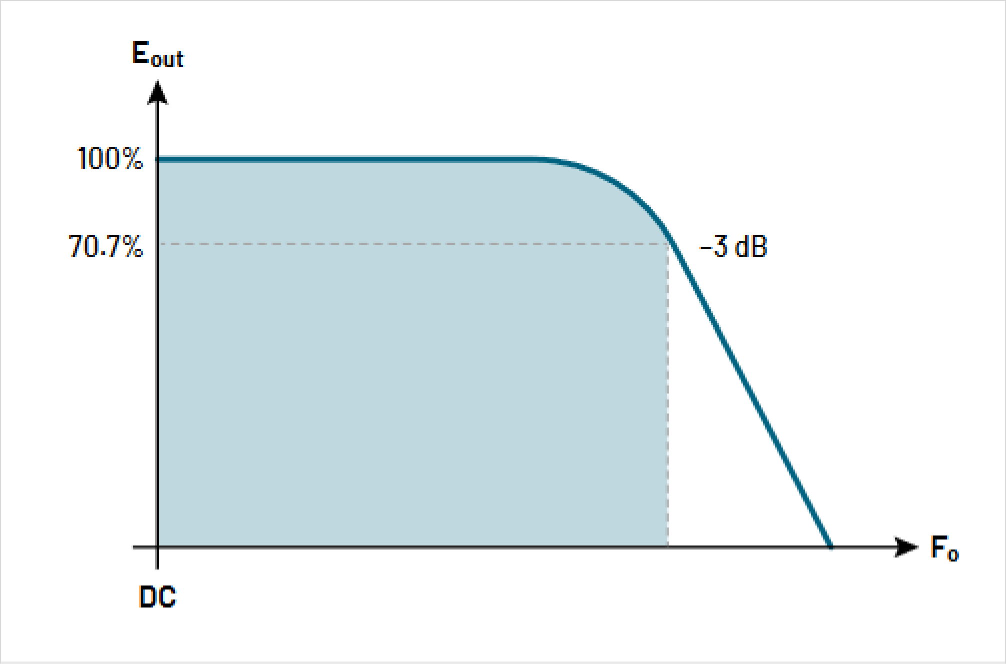
1GHz Probe



200MHz Probe



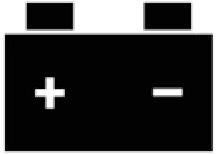
20MHz Probe



What's pushing the High Bandwidth and Current needs?

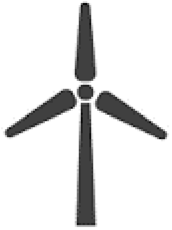
Automotive:

- Battery Technology Advancements
    - Smaller batteries with higher efficiency
- Demand for Performance, Faster Charging and Range Improvements
    - More power - Higher voltage/current levels = More distance traveled, faster recharge cycles
- Emergence of New Market Segments
    - Heavy duty vehicles – Trucks, Buses, Off-roading vehicles



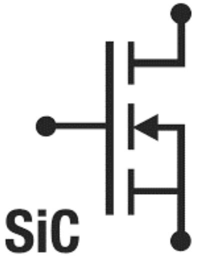
Industrial:

- Efficient Turbines and Advancements in Solar Power
    - Generate significantly higher power outputs



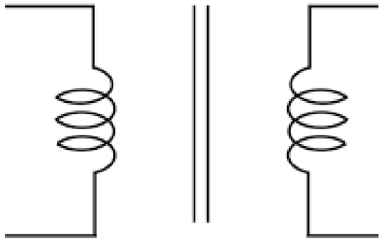
Power Semi:

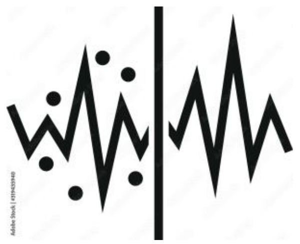
- Adoption of WBG Technology
    - Switching frequency rising due to WBG device validation

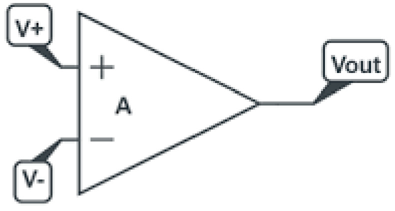


Summarizing the Requirements...

A Current probe that meets...







High Bandwidth	High Sensitivity	Isolation	Low Noise	High CMRR
View transient signals	Reduce noise amplification	Reduce ground loop and bounce	Measure signals in uA	Reject common signals for better resolution

And purpose built for making current shunt measurements

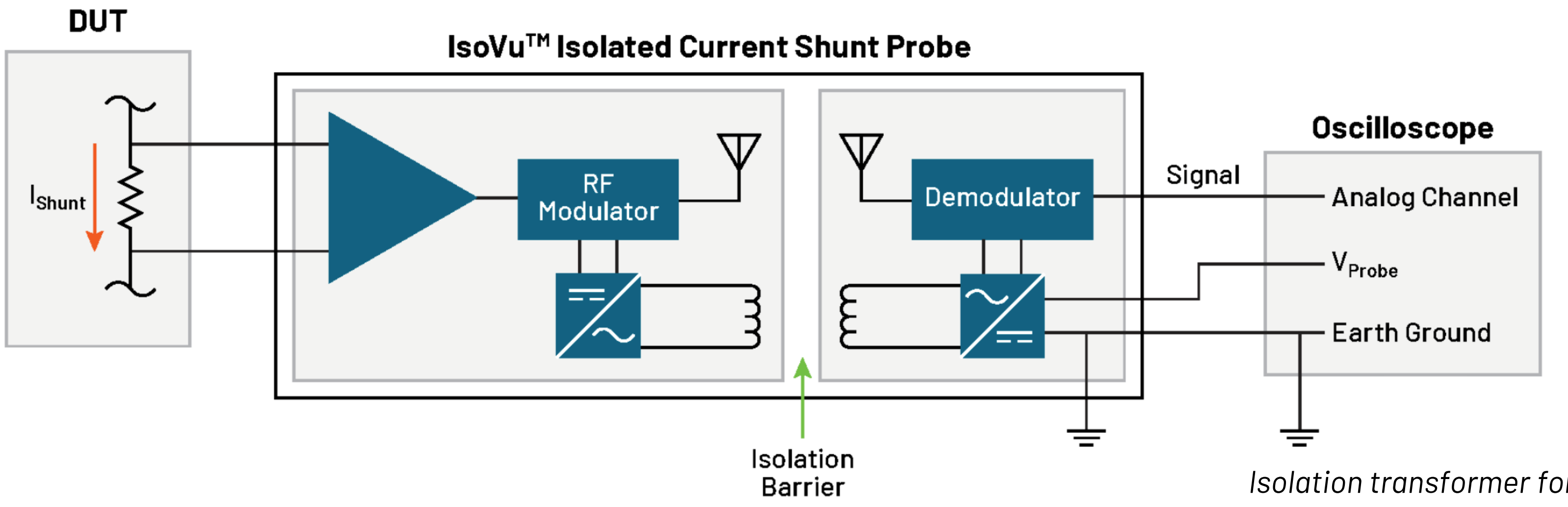
Introducing: TICP Series IsoVu™ Isolated Current Probes

INDUSTRY FIRST RF ISOLATED CURRENT PROBES

Bandwidth	250 MHz, 500 MHz, 1 GHz
DC Gain Accuracy	± 1.5%
Isolation	RF Isolation scheme
Common Mode Rejection Ratio (CMRR)	140 dB at DC Up to 90 dB at 1 MHz
Common Mode Voltage	1800 V; For use in a Pollution degree 1 environment 1300 V; Pollution degree 2 1000 V CAT II; 600V CAT III
RMS Input Referred Noise	4.7 nV/RT Hz (<150 µV at 1 GHz, <21 µV at 20 MHz)
Current Measurements	AC + DC
Compatible Oscilloscopes	4 Series MSO, 5 Series MSO, 6 Series MSO, 4 Series B MSO, 5 Series B MSO, 6 Series B MSO, 5 Series MSO LP

Active Isolated Current Shunt Probe

INDUSTRY FIRST RF ISOLATED CURRENT PROBES



Isolation transformer for powering the isolated side.
The signal path uses a 4 GHz up-mixer and a local oscillator

Advantages of Electrical Isolation in Current Measurements:

- Enables safety and accuracy (due to improved common mode rejection)
- Low-noise architecture offers greater sensitivity than a standard differential probe
- Lower Burden Voltage: Decreases loading on DUT
- Increases usable bandwidth
- Increased common mode range (90dB at 1 MHz)

What's in the standard package?

1X MMCX Tip

The Probe

10X MMCX Tip

Bipod Holder

1X SMA Tip

Tripod Adapter

MMCX to Square Pin adapter

Common mode choke (pre-installed)

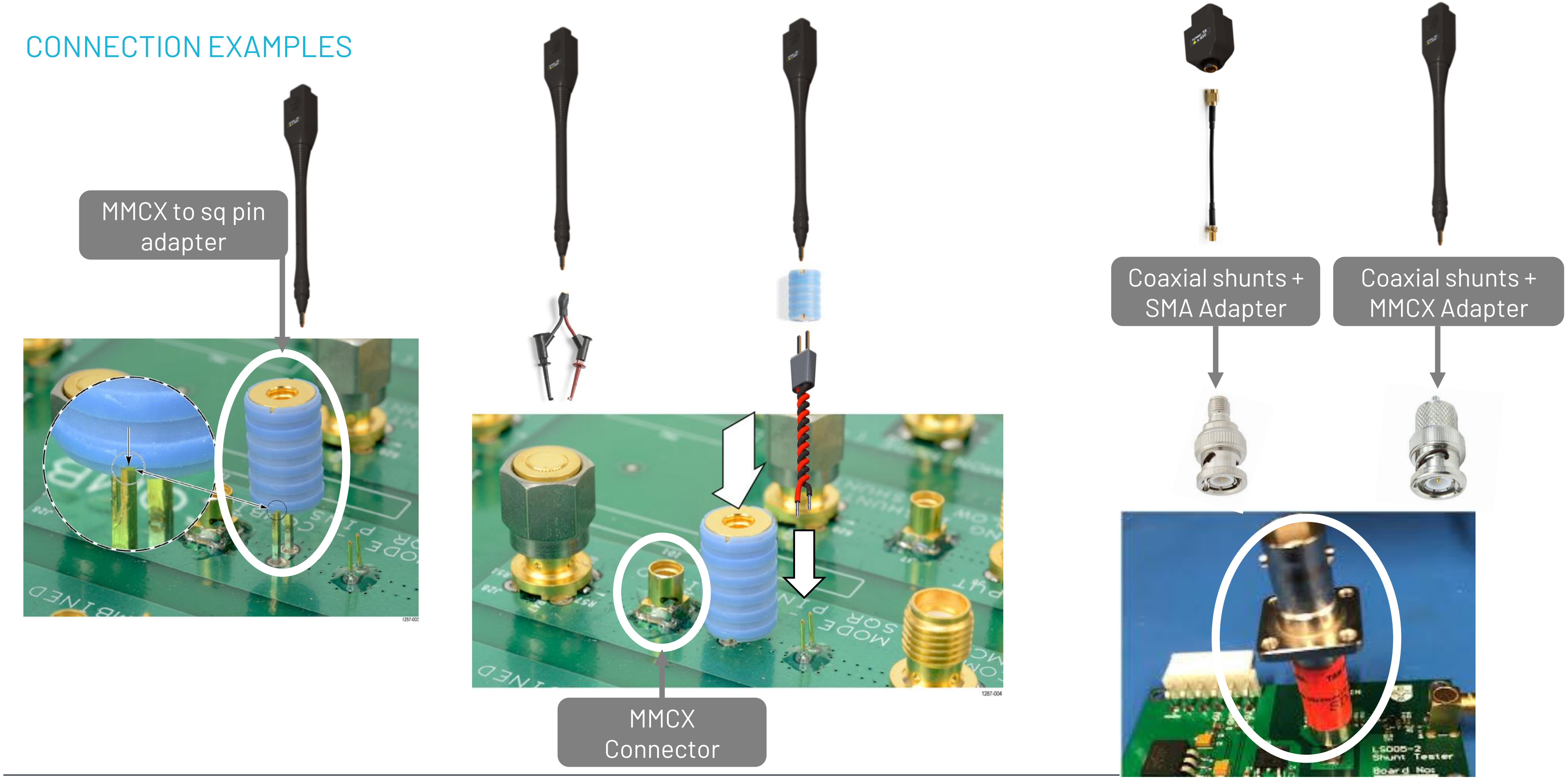
100X MMCX Tip (optional)

Probe Tip Specifications

Probe Tips	1X SMA Input	1X MMCX Tip	10X MMCX Tip	100X MMCX Tip
Main Purpose	Lowest-noise	Lowest-noise	Debug	High-side Vgs
Dynamic Range and Max Voltage	±0.5V	±0.5V	±5V	±50V
Maximum Non-Destructive Differential Voltage	1V RMS	1V RMS	5V pk	50V pk
Input Resistance	50 Ω	50 Ω	500Ω	5000Ω
Capacitance	-	-	<3pF	<3pF
Length	0.025M (1")	0.15M (6")	0.15M (6")	0.15M (6")
Noise Floor	<21 μV_{RMS} at 20 MHz	<21 μV_{RMS} at 20 MHz	<210 μV_{RMS} at 20 MHz	<2.1 mV_{RMS} at 20 MHz

How to connect to off the shelf shunts?

CONNECTION EXAMPLES



TICP Accessory Options

MMCX to IC Grabber

Square pin to IC Grabber

Square Pin Y-Lead

MicroCKT Grabber

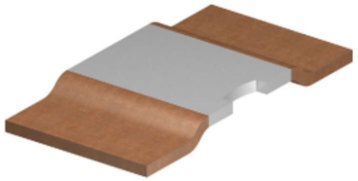
Popular Types of Shunts

EXAMPLES

The TICP works with any off the shelf shunts as long as we have access, and the voltage drop <0.5V with 1X tip

Vishay

Power Metal Strip® Resistors, Very High Power (to 15 W), Low Value (Down to 0.0001 Ω), Surface-Mount



FEATURES

- All welded construction of the Power Metal Strip® resistors are ideal for all types of current sensing, voltage division and pulse applications
- Proprietary processing technique produces extremely low resistance values, down to 0.0001 Ω
- Sulfur resistance by construction that is unaffected by high sulfur environments
- Specially selected and stabilized materials allow for high power rating (to 15 W)
- Very low inductance 0.5 nH to 5 nH
- Low thermal EMF (< 3 μV/°C)
- AEC-Q200 qualified (1)
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

AUTOMOTIVE GRADE · Pb-free · RoHS COMPLIANT · HALOGEN FREE · GREEN (5-2008)

Note

(1) Flame retardance test may not be applicable to some resistor technologies

LINKS TO ADDITIONAL RESOURCES

3D Models · Design Tools · Upgrade Performance · Calculators · Reference Designs

T&M Research (CVR)

Ohmite

SHA Series

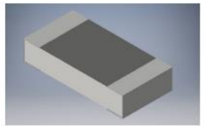
Precision manganin copper alloy shunt

The Ohmite SHA series shunts can support up to 1KA of rated current. Due to its special alloy material, the SHA series has good long-term stability and can withstand pulse current several times higher than the rated current. The special heat treatment process of the SHA series enables a low current coefficient providing stability in high current applications. The SHA series has thermal potential of less than 0.5pV/°C to copper, and has little effect on the voltage output of the millivolt level. The flat structure of the SHA series makes the inductance less than 3nH creating a shunt compatible with high frequency applications.

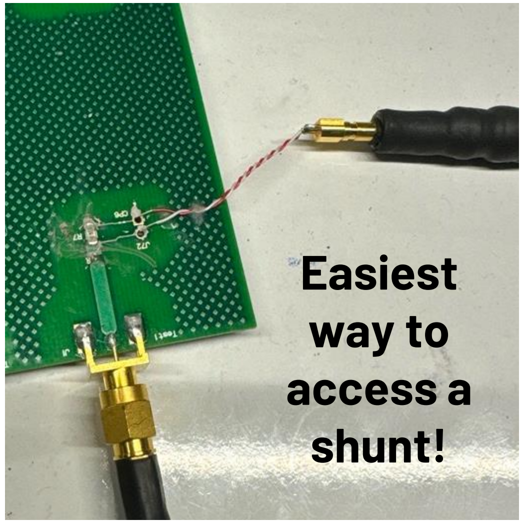
PMK, Uni of Cambridge

Stackpole

Stackpole Electronics, Inc.
Resistive Product Solutions



Bourns



Min and Max Currents

- Min currents are dependent on the noise floor
  - $I_{min(rms)} = V_{min} / R_{shunt} = [4.7\ nV/\sqrt{Hz} \times \sqrt{(Bandwidth)}] / (R_{shunt})$
- Max current depends on shunt power rating
  - $I_{max(rms)} = (\text{Max input } V_{pk})/R_{shunt}$

1. Min currents table

Shunt selection	20 MHz	250 MHz	1 GHz
50 Ω TICP as shunt	420 nA	1.5 µA	3.0 µA
5 Ω shunt	4.2 µA	14.9 µA	29.7 µA
1 Ω shunt	21 µA	74.3 µA	149 µA
500 mΩ shunt	42 µA	149 µA	297 µA
50 mΩ shunt	420 µA	1.5 mA	3.0 mA
5 mΩ shunt	4.2 mA	14.9 mA	29.7 mA
500 µΩ shunt	42 mA	149 mA	297 mA
50 µΩ shunt	420 mA	1.5 A	3.0 A
15 µΩ shunt	1.4 A	5.0 A	9.9 A

2. Max currents table

Shunt selection	TICPMM1	TICPSMA	TICPMM10	TICPMM100
50 Ω TICP as shunt	13 mA		-	-
5 Ω shunt	130 mA		1.3 A	10 A
1 Ω shunt	650 mA		6.5 A	50 A
500 mΩ shunt	1.3 A		13 A	100 A
50 mΩ shunt	13 A		130 A	1.0 kA
5 mΩ shunt	130 A		1.3 kA	10 kA
500 µΩ shunt	1.3 kA		13 kA	100 kA
50 µΩ shunt	13 kA		130 kA	1000 kA
15 µΩ shunt	43.3 kA		433.3 kA	3300 kA

3. Input Voltage Range

Ensure the tip voltages do not exceed max value

Probe tips	Differential input voltage range	Offset range	Maximum measurable input voltage (Vpk)	Maximum non-destructive differential voltage	Input impedance
TICPSMA	±0.5 V	±0.5 V	0.65 V	±3 V; 3 V_{RMS}	50 Ω || N.A.
TICPMM1	±0.5 V	±0.5 V	0.65 V	±3 V; 3 V_{RMS}	50 Ω || N.A.
TICPMM10	±5 V	±5 V	6.5 V	±15 V; 15 V_{RMS}	500 Ω || <3 pF
TICPMM100	±50 V	±50 V	50 V	±60 V; 50 V_{RMS}	5000 Ω || <3 pF

4. Gain Settings

Gain settings help understand the tradeoffs between noise, sensitivity and dynamic range

Probe Ranges

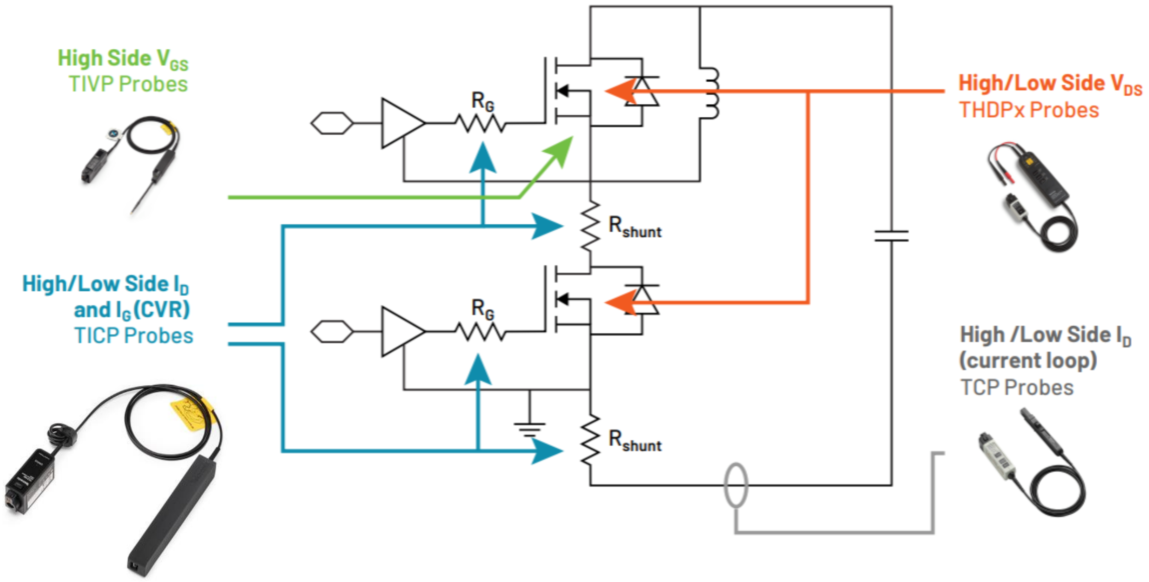
Numbers are published for TICPSMA and TICPMM1 tips. For 10X or 100X tips, multiply by 10 or 100 respectively.

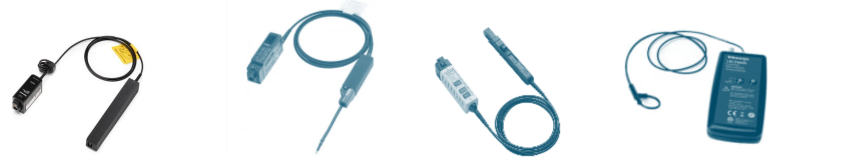
Input range	Offset range	RMS noise spectral density (V_{RMS})	Noise floor at 20 MHz (V_{RMS})
±0.5 V	±0.15 V	22.9 nV / √Hz	102.5 µV_{RMS}
±0.35 V	±0.30 V	17.4 nV / √Hz	77.8 µV_{RMS}
±0.25 V	±0.40 V	15.0 nV / √Hz	67.2 µV_{RMS}
±0.175 V	±0.475 V	9.5 nV / √Hz	42.4 µV_{RMS}
±0.125 V	±0.5 V	8.7 nV / √Hz	38.9 µV_{RMS}
±0.09 V	±0.5 V	6.3 nV / √Hz	28.3 µV_{RMS}
±0.065 V	±0.5 V	5.5 nV / √Hz	24.7 µV_{RMS}
±0.045 V	±0.5 V	4.7 nV / √Hz	21.2 µV_{RMS}
±0.03 V	±0.5 V	4.7 nV / √Hz	21.2 µV_{RMS}
±0.02 V	±0.5 V	4.7 nV / √Hz	21.2 µV_{RMS}

High Power Example Uses Cases

How does TICP compare to other probes?

HIGH-POWER



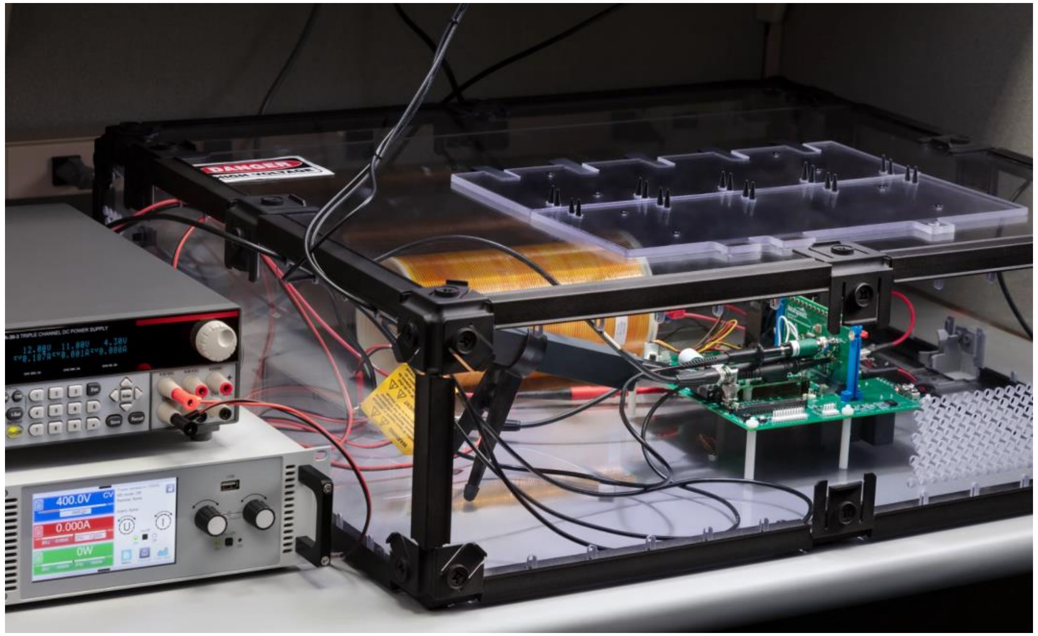


Market Solutions	TICP with Shunt	IsoVu / TIVP with Shunt	TCPx Current Probes	Rogowski Current Probes
Bandwidth	High	High	Medium	Low
DC Coupling	Yes	Yes	Yes	None
Isolation	Yes	Yes	Yes	Yes
Intrusive	Yes	Yes	No	No
Common Mode Voltage	1.8kV	60kV	N/A	N/A
Position	Doesn't matter	Doesn't matter	Important	Important
Saturation	No	No	Yes	No
Probe Tip size	Small	Small	Large	Large
CMRR	Medium	High	N/A	N/A

Ideal for SiC and GaN Power Converters

HIGH BANDWIDTH / HIGH CURRENT

1. Bandwidth up to 1 GHz for measuring fast rise-times on SiC and GaN FETs
2. Complete RF Isolation - Measure tiny changes while rejecting noise from high common mode voltages
3. Safety rating to 1000V CAT II



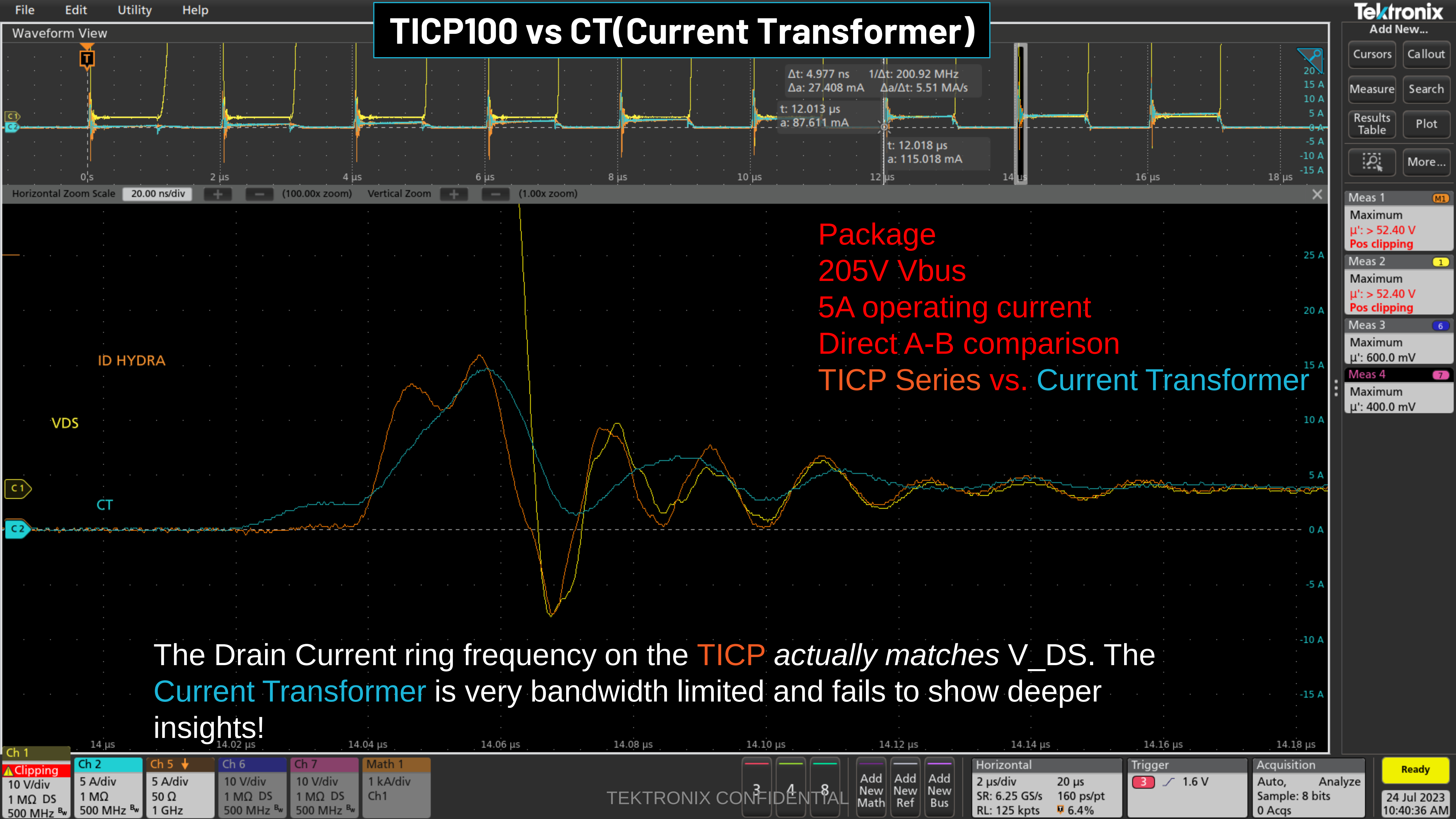
Summary: TICP offers higher bandwidth and lower noise than Clamp-on style and Rogowski probes or differential voltage probes with shunts

High Power Example Uses Cases

TICP100 VS CURRENT TRANSFORMER

Current Transformer

Tektronix TICP100
IsoVu Isolated Current Probe
DC to 1GHz



TICP100 vs CT(Current Transformer)
File
Edit
Utility
Help
Waveform View
Δt: 4.977 ns 1/Δt: 200.92 MHz
Δa: 27.408 mA Δa/Δt: 5.51 MA/s
t: 12.013 µs
a: 87.611 mA
t: 12.018 µs
a: 115.018 mA
Horizontal Zoom Scale 20.00 ns/div (100.00x zoom) Vertical Zoom (1.00x zoom)
Package
205V Vbus
5A operating current
Direct A-B comparison
TICP Series vs. Current Transformer
ID HYDRA
VDS
CT
The Drain Current ring frequency on the TICP *actually matches* V_DS. The Current Transformer is very bandwidth limited and fails to show deeper insights!
Tektronix
Add New...
Cursors
Callout
Measure
Search
Results Table
Plot
More...
Meas 1 Maximum µ': > 52.40 V Pos clipping
Meas 2 Maximum µ': > 52.40 V Pos clipping
Meas 3 Maximum µ': 600.0 mV
Meas 4 Maximum µ': 400.0 mV
Ch 1 Clipping 10 V/div 1 MΩ DS 500 MHz
Ch 2 5 A/div 1 MΩ 500 MHz
Ch 5 5 A/div 50 Ω 1 GHz
Ch 6 10 V/div 1 MΩ DS 500 MHz
Ch 7 10 V/div 1 MΩ DS 500 MHz
Math 1 1 kA/div Ch1
TEKTRONIX CONFIDENTIAL
Add New Math
Add New Ref
Add New Bus
Horizontal 2 µs/div 20 µs SR: 6.25 GS/s 160 ps/pt RL: 125 kpts 6.4%
Trigger 1.6 V
Acquisition Auto, Analyze Sample: 8 bits 0 Acqs
Ready
24 Jul 2023 10:40:36 AM

High Power Example Uses Cases

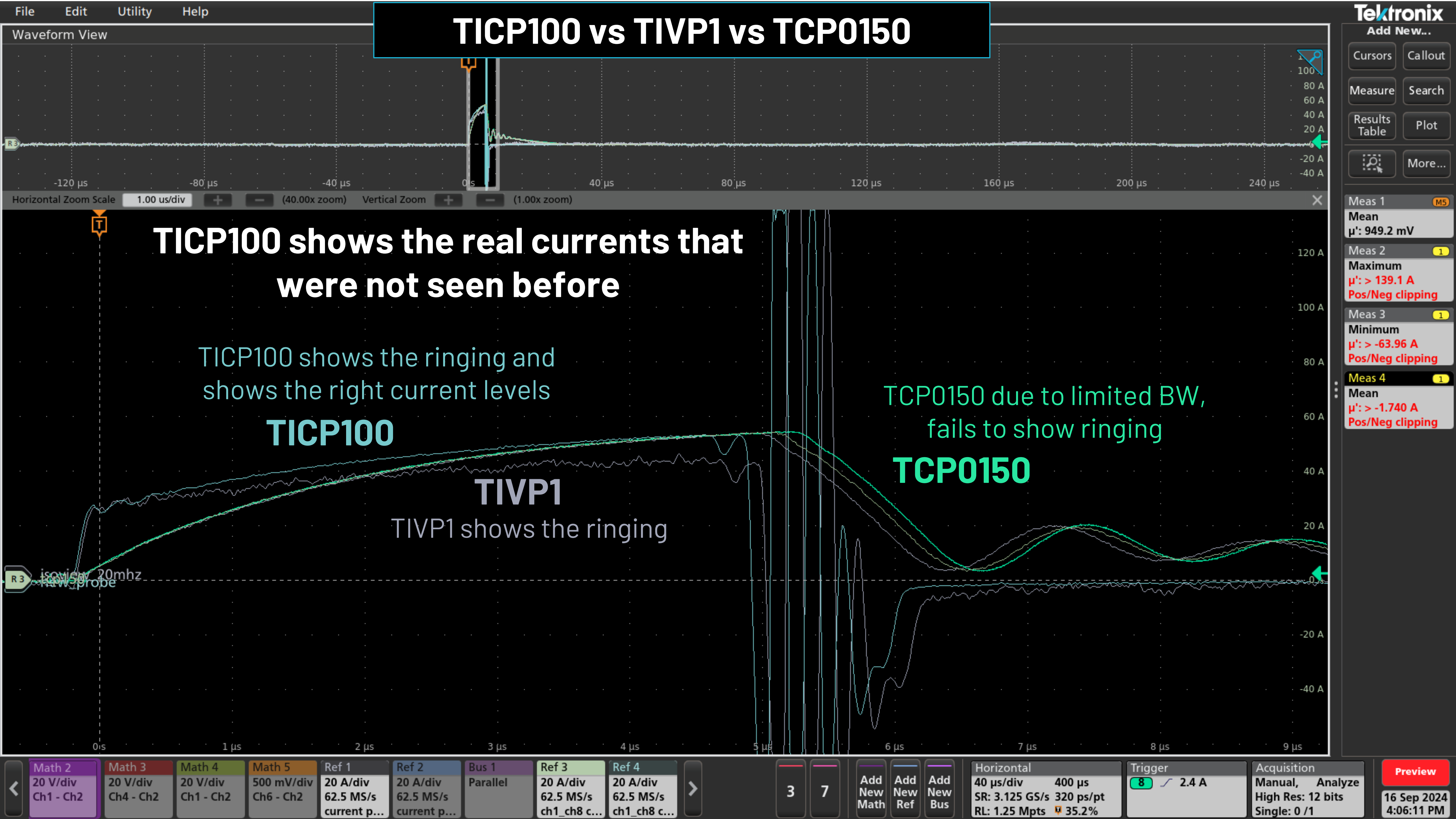
TICP100 VS TIVP1 VS TCP0150

Tektronix TICP
IsoVu Isolated Current Probe
DC to 1GHz

Tektronix TIVP
IsoVu Isolated Voltage Probe
DC to 1GHz

Tektronix TCP0150
AC/DC Current Probe
150 A, DC to 20 MHz

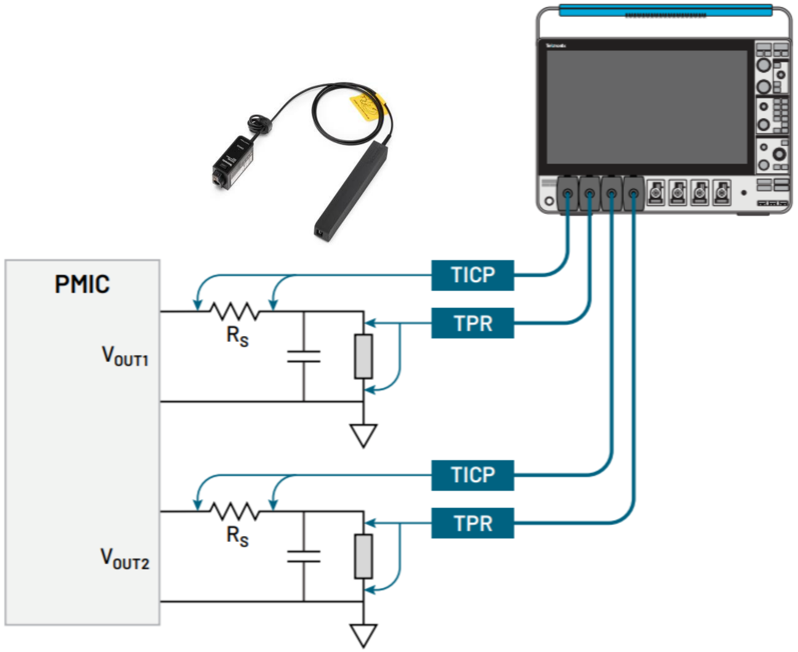
TICP100 vs TIVP1 vs TCP0150



Low Power Example Uses Cases

How does TICP compare to other probes?

LOW-POWER





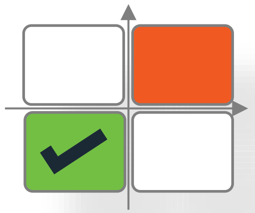


Market Solutions	TICP + Shunt	Diff probe + shunt	Coaxial Cable + Shunt	SMUs	DMMs	TCPx Current Probes
Bandwidth	High	High	High	Low	Ultra Low	Medium
Isolation	Yes	No	No	No	No	Yes
Intrusive	Yes	Yes	Yes	Yes	Yes	No
Position	Doesn't matter	Doesn't matter	Doesn't matter	Doesn't matter	Doesn't matter	Important
Saturation	No	No	No	No	No	Yes
Probe Tip size	Small	Small	Large	Large	Large	Large
Attenuation	Low	High	Low	Low	Low	N/A

Measuring Microamps in Microseconds

LOW BANDWIDTH / LOW CURRENT

1. Capture transient and fast changing currents in embedded systems, as they change state
2. 1X attenuation and 50Ω input impedance are designed for a low-noise architecture
3. Flexible tips help connect to the DUT in tight spaces under challenging test environments



Summary: TICP offers higher accuracy and sensitivity for low-power measurements compared to Clamp-on style probes or using DMMs

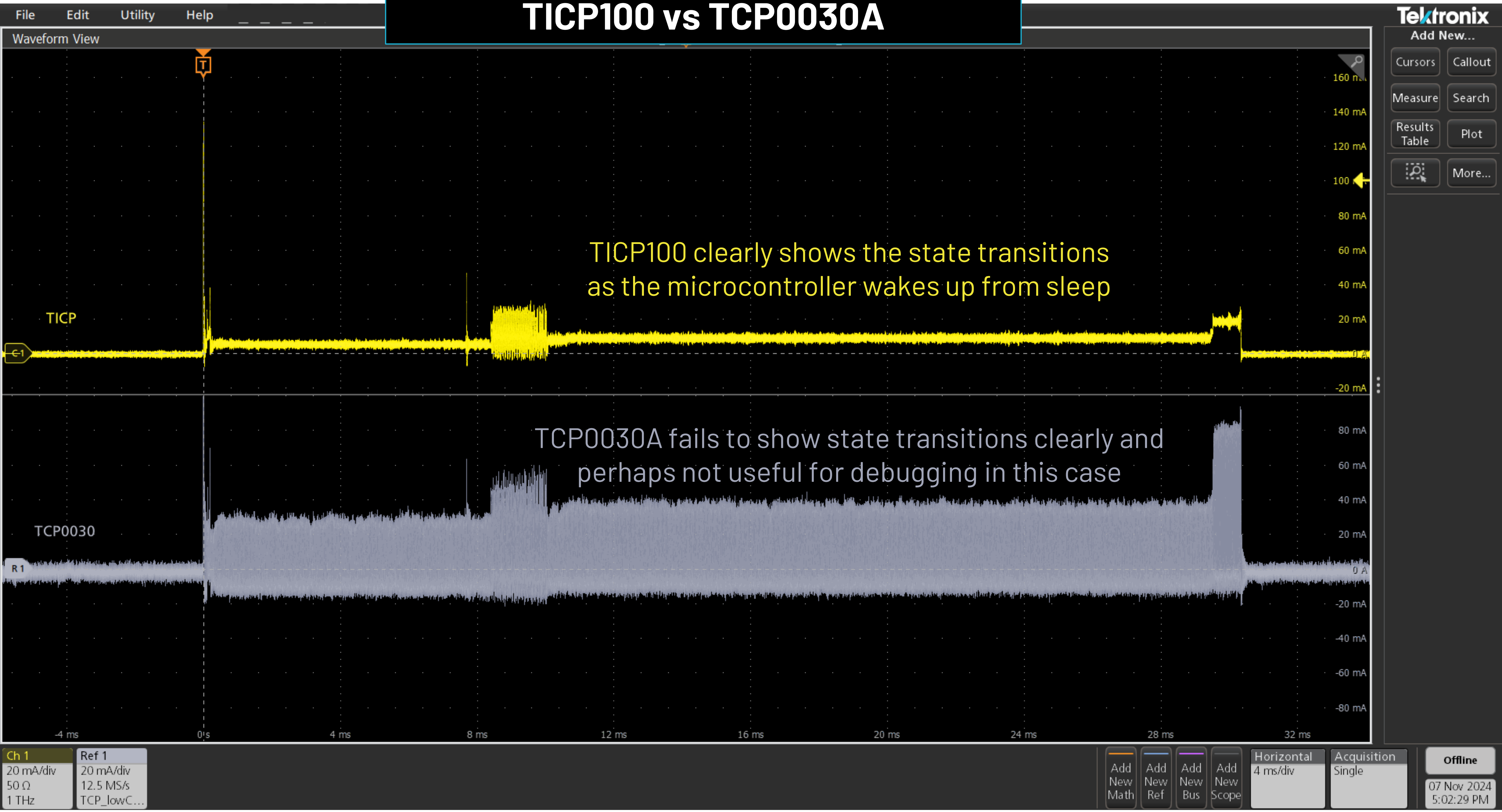
Low Power Example Uses Cases

TICP100 VS TCP0030A

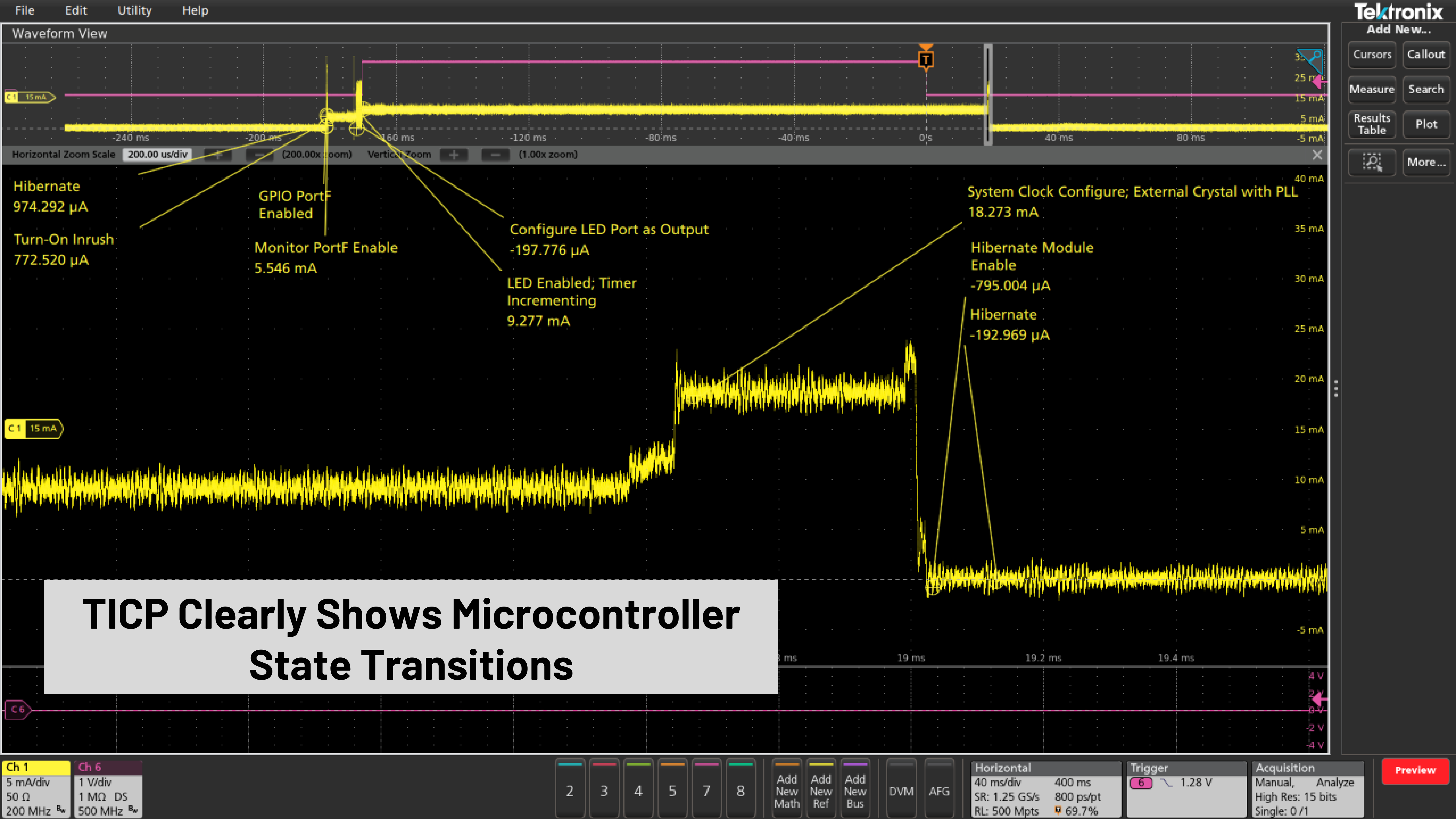
Tektronix TICP
IsoVu Isolated Current Probe
DC to 1GHz

Tektronix TCP0030A
AC/DC Current Probe
30 A, DC to 120 MHz

TICP100 vs TCP0030A



TICP Clearly Shows Microcontroller State Transitions



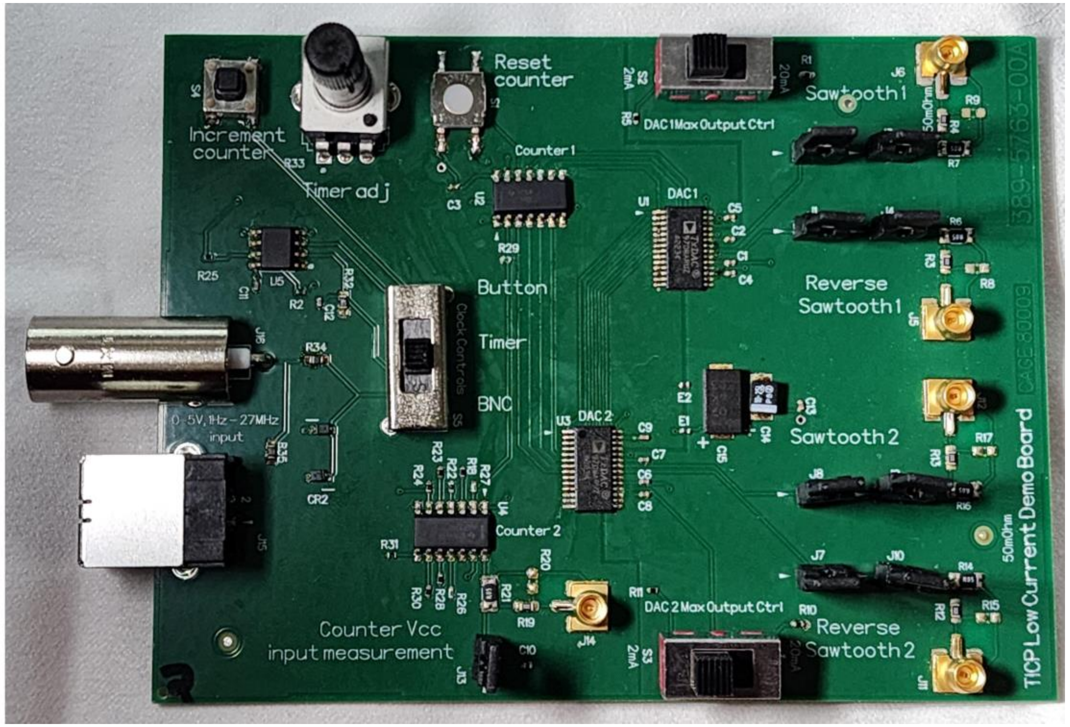
DAC output current

TICP100 vs TCP0030A

DAC Steps = 255

Current Range 0-20 mA

Current per step change = 20/255 = **78 uA**



Low Power Example Uses Cases

TICP100 VS TCP0030A

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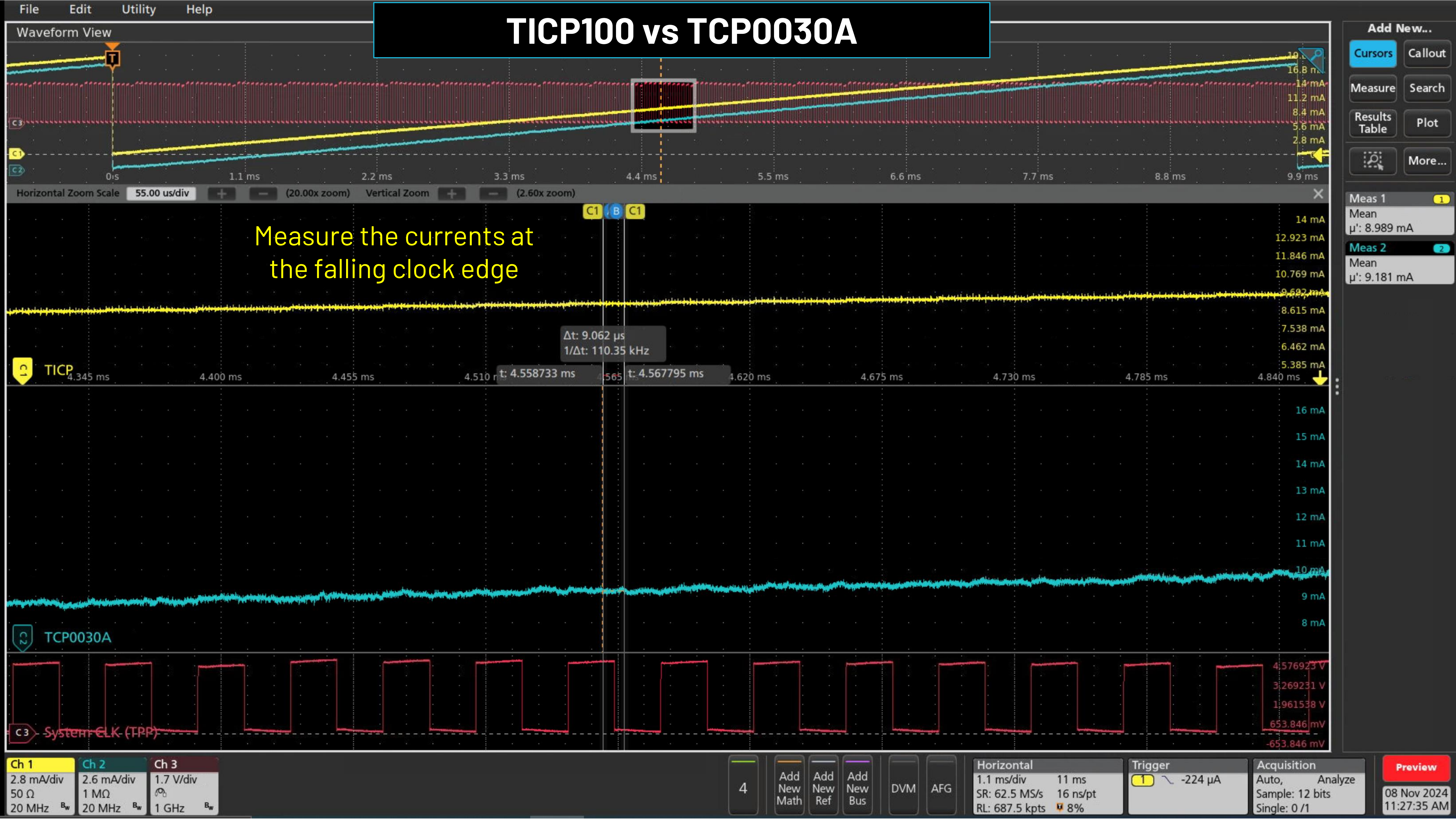
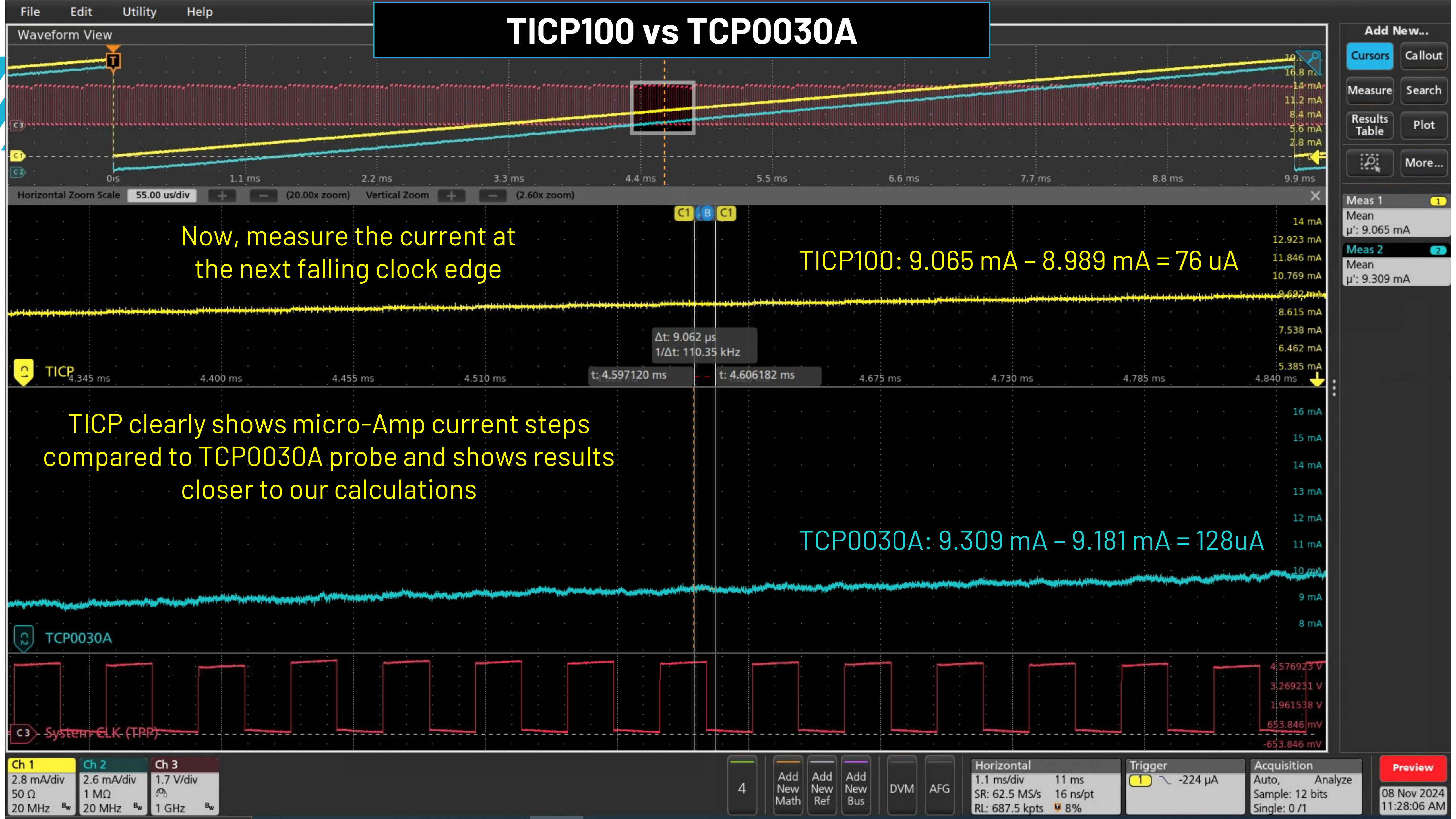
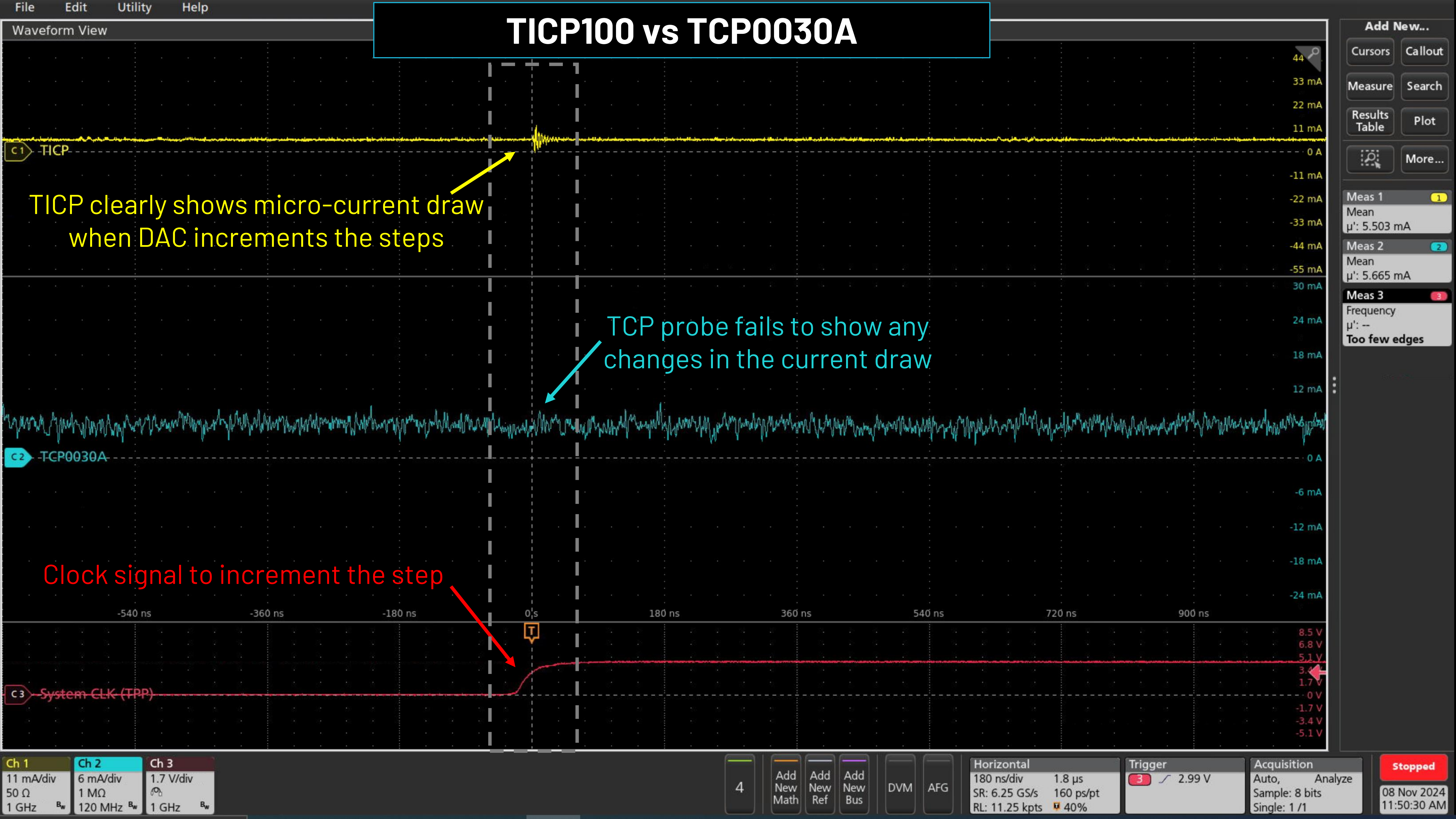
TICP100 vs TCP0030A



TICP100 vs TCP0030A



TICP100 vs TCP0030A



TICP Series IsoVu™ Isolated Current Probes

INDUSTRY FIRST RF ISOLATED CURRENT PROBES

Bandwidth	250 MHz, 500 MHz, 1 GHz
DC Gain Accuracy	± 1.5%
Isolation	RF Isolation scheme
Common Mode Rejection Ratio (CMRR)	140 dB at DC Up to 90 dB at 1 MHz
Common Mode Voltage	1800 V; For use in a Pollution degree 1 environment 1300 V; Pollution degree 2 1000 V CAT II; 600V CAT III
RMS Input Referred Noise	4.7 nV/RT Hz (<150 µV at 1 GHz, <21 µV at 20 MHz)
Current Measurements	AC + DC
Compatible Oscilloscopes	4 Series MSO, 5 Series MSO, 6 Series MSO, 4 Series B MSO, 5 Series B MSO, 6 Series B MSO, 5 Series MSO LP

THANK YOU