

Track D: RIDING THE WAVE OF POWER EVOLUTION

THE UNTOLD CHARACTERISTICS OF HIGH VOLTAGE PROBES

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ROHDE & SCHWARZ

Make ideas real



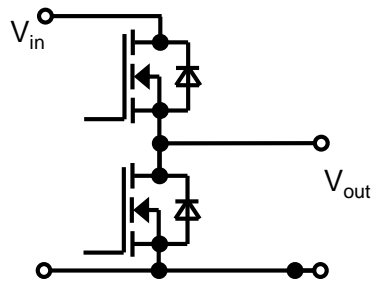
AGENDA

- ▶ Typical measurements on power electronics
- ▶ Overview of voltage Probes
- ▶ Characteristics of high voltage probes
- ▶ Untold characteristics in specifications
- ▶ Untold characteristics in setup
- ▶ Optimizing the best results with probes

TYPICAL MEASUREMENTS ON POWER ELECTRONICS

TYPICAL MEASUREMENTS ON POWER ELECTRONICS

- ▶ Basic circuit for inverter/unfolder, sync buck converter/resonant (LLC) converter, sync boost converter consists of a so called **high-side** and **low-side switch**



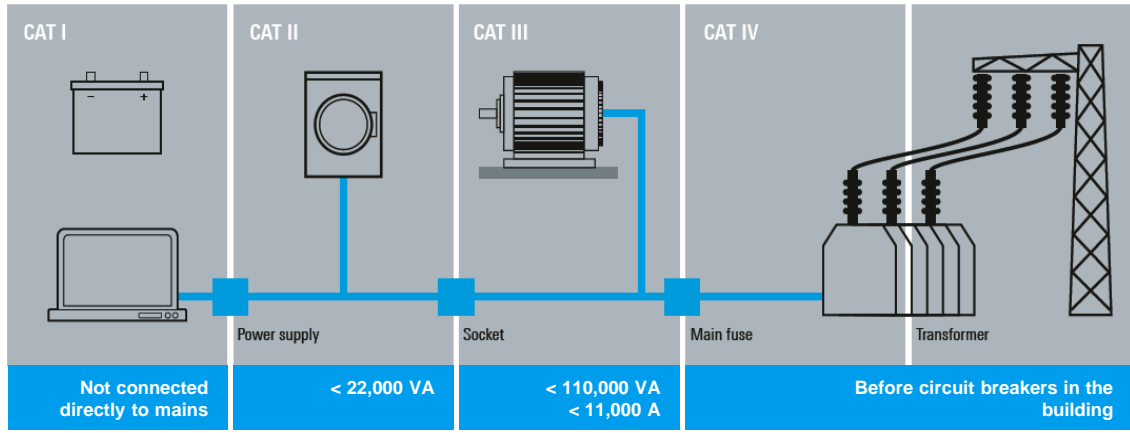
High-side switch: referenced to output voltage

Low-side switch: ground referenced

- ▶ DC-Offset of high-side switch has to be considered by design of measurement setup
- ▶ Floating measurement on high-side switch is necessary

ELECTRICAL MEASUREMENT SAFETY

POWER RATING CATEGORY



Rated Voltage	UL 61010B – 1 (Transient)			IEC 61010-1 (Transient)		
	I	II	III	II	III	IV
150V	800V	1500V	2500V	1500V	2500V	4000V
300V	1500V	2500V	4000V	2500V	4000V	6000V
600V	2500V	4000V	6000V	4000V	6000V	8000V
1000V	4000V	6000V	8000V	6000V	8000V	12000V
Resistance	30 ohm	12 ohm	2 ohm	12 ohm	2 ohm	2 ohm



Lugo SWR: Electrical arc from power lines, by Neil Brady, 2013. Retrieved from www.youtube.com

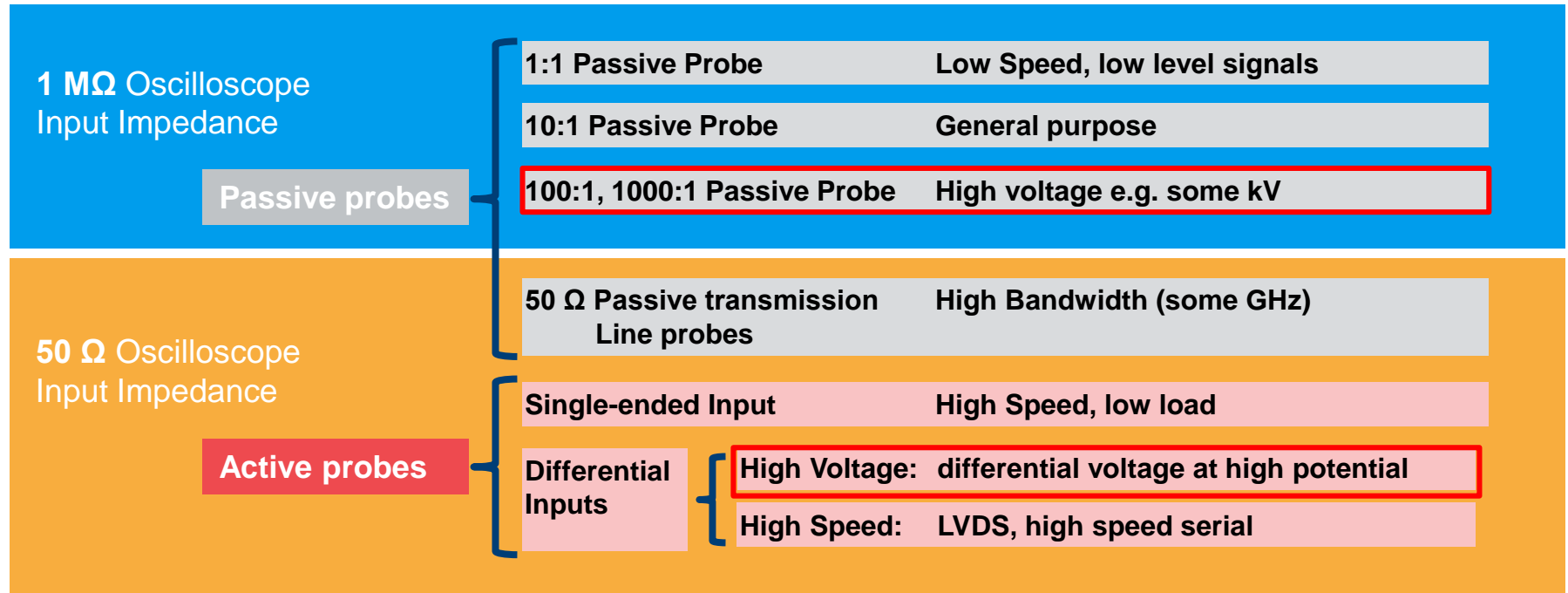


Nuclear Power Plant. Retrieved from www.gifphy.com

Power category is relative!

OVERVIEW OF VOLTAGE PROBES

TYPES OF VOLTAGE PROBES



GENERAL PURPOSE HIGH-VOLTAGE DIFFERENTIAL PROBES

- ▶ 25 MHz and **100 MHz** Bandwidth
- ▶ 750 V_{peak} and 1400 V_{peak} input voltage
- ▶ BNC Interface
- ▶ BNC interface fits to all scopes / applications
- ▶ Cost-effective differential solution



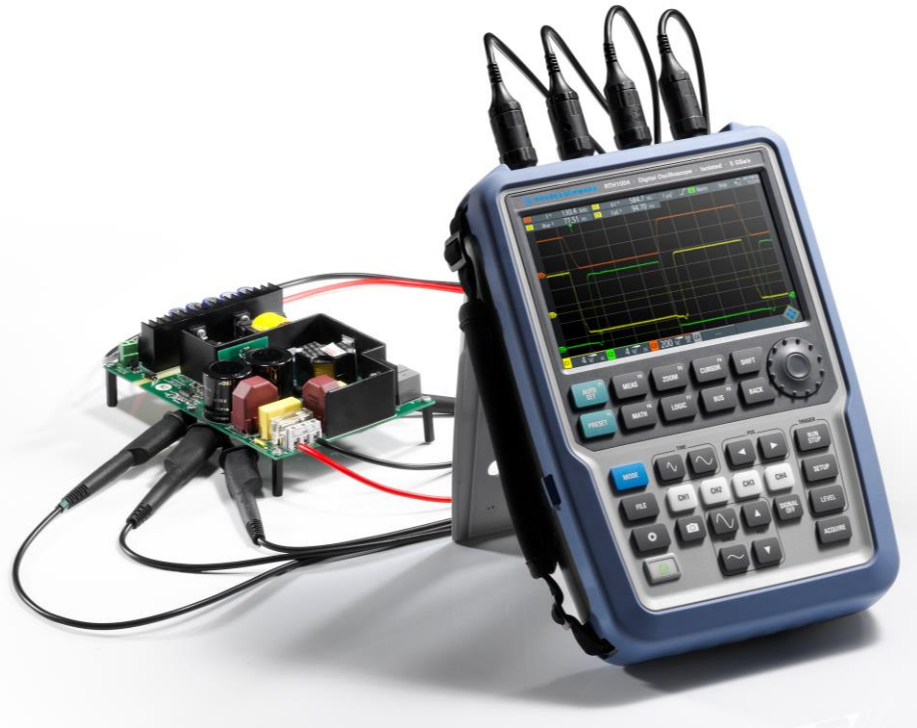
HIGH-VOLTAGE DIFFERENTIAL PROBES – RT-ZHD FAMILY

- ▶ **100 MHz and 200 MHz models**
- ▶ **750 V, 1500 V and 6000 V Input Voltage Range**
- ▶ **Up to 2000 V Offset Compensation**
 - Independent of probe attenuation factor or vertical scale on oscilloscope
- ▶ **Excellent DC Accuracy: 0.5%**
 - Integrated DC Voltmeter with 0.1% Accuracy
 - Very low drift
- ▶ **Very low noise**
- ▶ **High CMRR**
 - 80 dB @ DC – 60 Hz
 - 60 dB @ 1 MHz
 - 30 dB @ 100 MHz
- ▶ **Overrange Indicator,**
integrated 5 MHz low pass filter, R&S probe interface

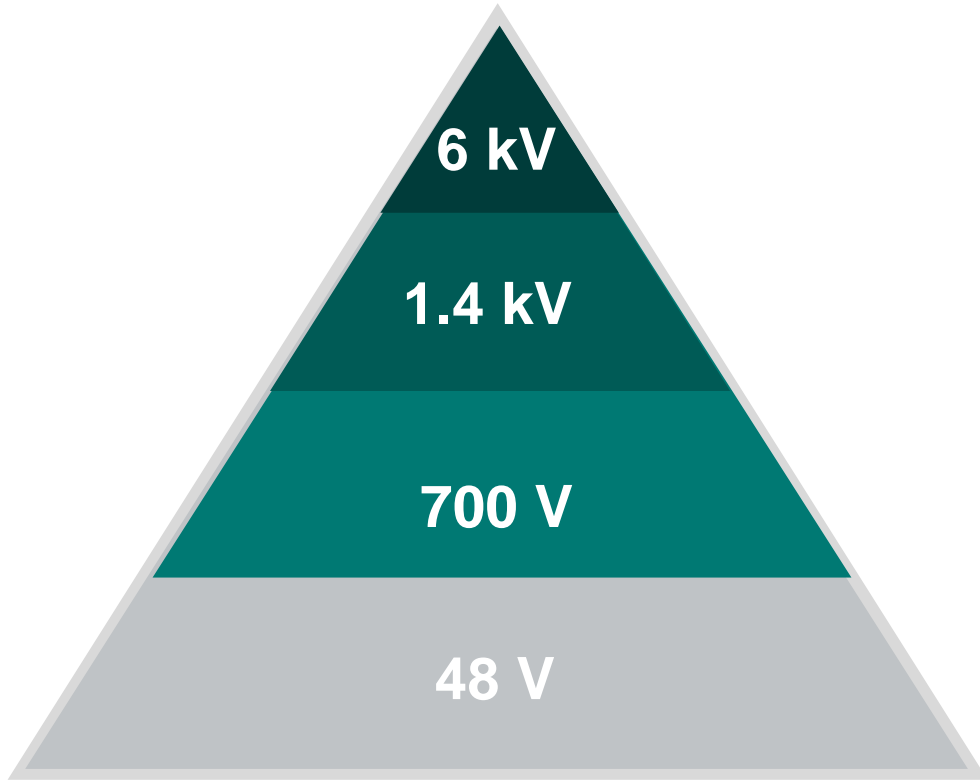


ISOLATED CHANNEL OSCILLOSCOPE – RTH FAMILY

- ▶ 60 MHz, 100 MHz, 200 MHz, **350 MHz** and **500 MHz** models
- ▶ Unique combination of channel isolation for up to 1000 Vrms and 500 MHz bandwidth
- ▶ Isolated channels → no need for differential probes
- ▶ CAT IV 600 V, CAT III 1000 V with R&S®RT-ZI10 or R&S®RT-ZI11 probe
- ▶ **High CMRR** > 100 dB @ DC – 100 kHz
- ▶ Up to **16 bit vertical resolution** with High resolution mode



PROBING OPTIONS FOR DIFFERENT VOLTAGE LEVELS



100:1, 1000:1 High Voltage Passive Probe

1:1, 10:1 Passive Probes

Differential High Voltage probes

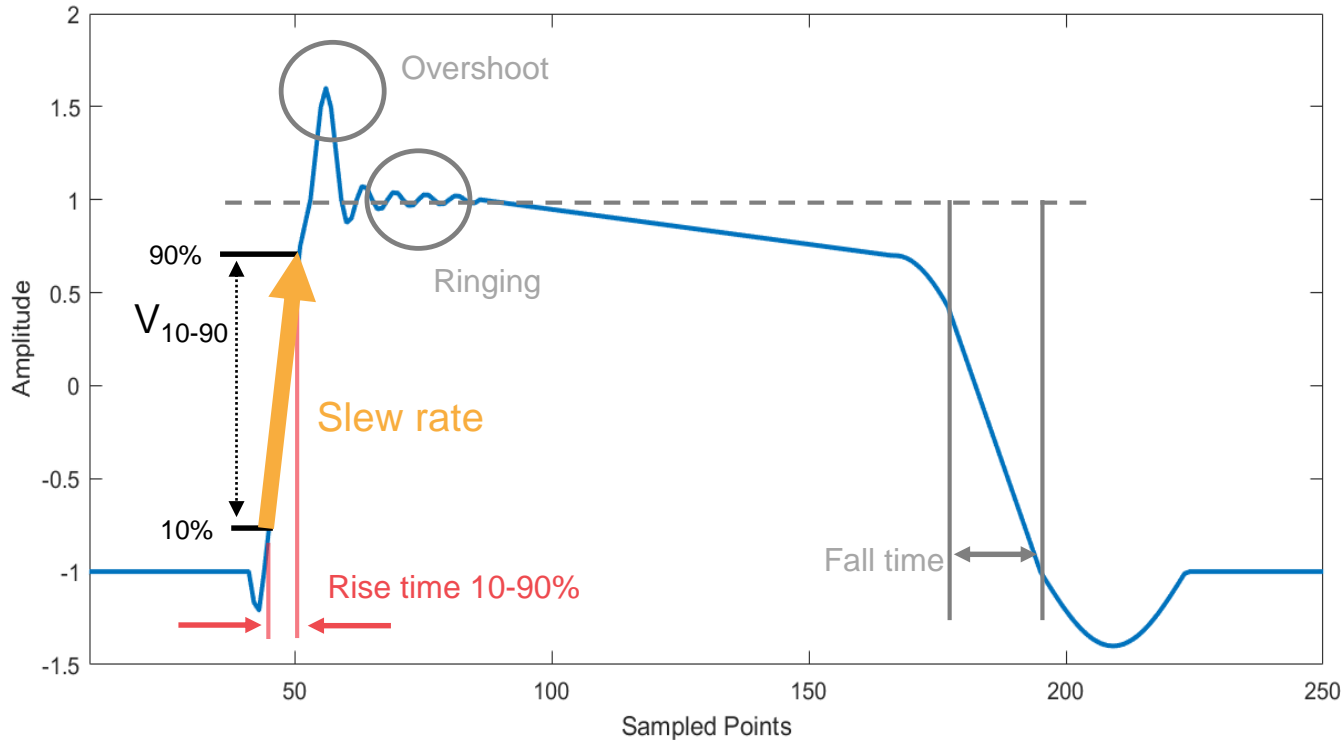
RT-ZHD07/15/16/60

General Purpose HVD Probes

Active single & differential probes

CHARACTERISTICS OF HIGH VOLTAGE PROBES

BANDWIDTH & RISE TIME



Rise time & Slew rate

Very important parameters to characterize power electronics

Measurement equipment (oscilloscopes & probes) usually specify the bandwidth.

→ How are bandwidth, rise time and slew rate related?

BANDWIDTH & RISE TIME & SLEW RATE

Bandwidth

Frequency range over which the frequency response of a signal degrades by 3 dB

$$f_{BW} = \frac{0.35}{t_r}$$

It is derived by considering a first-order passive filter and calculating its step-response in frequency and time domain.

Rise time

Transition time for a signal to go from the 10% to the 90% level of the steady maximum value

Slew Rate

the maximum input frequency and amplitude applicable to an amplifier, or large-scale signals

$$SR = \frac{V_{10-90}}{t_r}$$

It helps to identify peak current:

$$I_{peak} = SR * Capacitance$$

MEASUREMENT EXAMPLE: RISE TIME / SLEW RATE

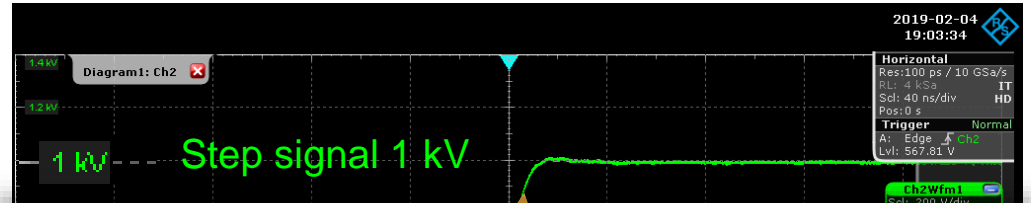
▶ Step signal: 1 kV

▶ Measured using R&S®RT-ZHD
(high-voltage differential probe)



▶ Sufficient bandwidth to measure rise time & slew rate:

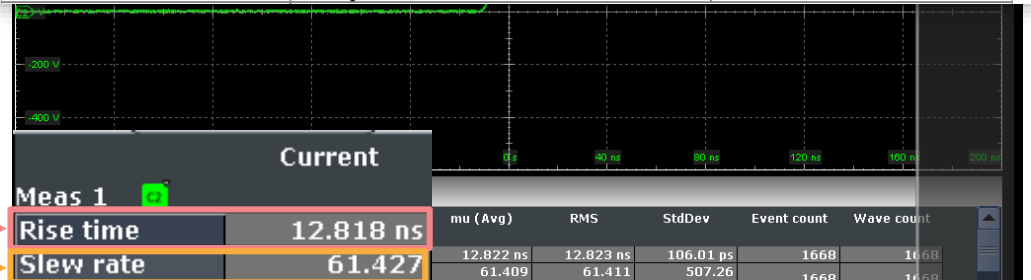
- Rise time: 12 ns
- Slew rate: 61 V/ns



R&S®RT-ZHD07 high voltage differential probe

All parameters are valid when the probe is connected to an appropriate Rohde & Schwarz oscilloscope with an input impedance of 1 M Ω . See table on page 4 and Rohde & Schwarz oscilloscope operating manual for more details.

Attenuation setting		25:1	250:1
Step response			
Rise time	10 % to 90 %, both attenuations	< 2 ns	
Frequency response			
Bandwidth	starting at DC, calculated from 0.4/rise time	200 MHz	



UNTOLD CHARACTERISTICS IN SPECIFICATIONS

LOOK INTO DATASHEET

Model overview

Probes with the

Attenuation	25X / 250X	50X / 500X
Differential Voltage	250X: ±750 V 25X: ±75 V	500X: ±1500 V 50X: ±150 V
Common Mode Voltage	±750 V	±1500 V
Maximum Input Voltage-to-Earth	550 V CAT I 300 V CAT III	1000 V CAT II 600 V CAT III
Bandwidth	200 MHz	200 MHz
Rise Time	<1.8 ns	<1.8 ns
Slew Rate	<275 V/ns at 1/250 gain	<650 V/ns at 1/500 gain
Input Impedance at the Probe Tip	5 MΩ <2 pF	10 MΩ <2 pF
Typical CMRR	DC: > -80 dB 100 kHz: > -60 dB 3.2 MHz: > -30 dB 100 MHz: > -26 dB	DC: > -80 dB 100 kHz: > -60 dB 3.2 MHz: > -30 dB 100 MHz: > -26 dB
Cable Length	1.5 m	1.5 m

R&S®RT-ZHD07 high voltage differential probe

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Attenuation setting		25:1	250:1
Step response			
Rise time	10 % to 90 %, both attenuations		< 2 ns
Frequency response			
Bandwidth	starting at DC, calculated from 0.4/rise time		200 MHz
Common mode rejection	DC to 60 Hz +15 °C to +35 °C 0 °C to +50 °C 60 Hz to 1 kHz 1 kHz to 1 MHz 1 MHz to 50 MHz	> 80 dB > 75 dB 70 dB (meas.) 55 dB (meas.) 35 dB (meas.)	65 dB (meas.) 55 dB (meas.) 20 dB (meas.)
Input impedance			
DC input resistance	differential (between signal sockets) single-ended (each signal socket to ground)	5 MΩ 2.5 MΩ	
Input capacitance	differential (between signal sockets) single-ended (each signal socket to ground)	2.5 pF (meas.) 5 pF (meas.)	
Dynamic range			
Differential input	between signal sockets	±75 V	±750 V
Offset compensation range	in both attenuations	±1000 V	
Offset compensation error	offset compensation setting = 0 V offset compensation setting ≠ 0 V	no additional error ±0.2 % of setting ±40 mV (meas.)	
Operating voltage window	each signal socket to ground	±750 V	
Noise voltage	referenced to probe input	12 mV (RMS) (meas.)	40 mV (RMS) (meas.)
Maximum rated input voltage			
Continuous voltage	derated, see figure, each signal socket to ground	300 V (RMS), CAT III 600 V (RMS), CAT II 600 V (RMS)	
Transient voltage	each signal socket to ground	±4500 V (peak)	
Base unit			
Input coupling	AC/DC		1 MΩ

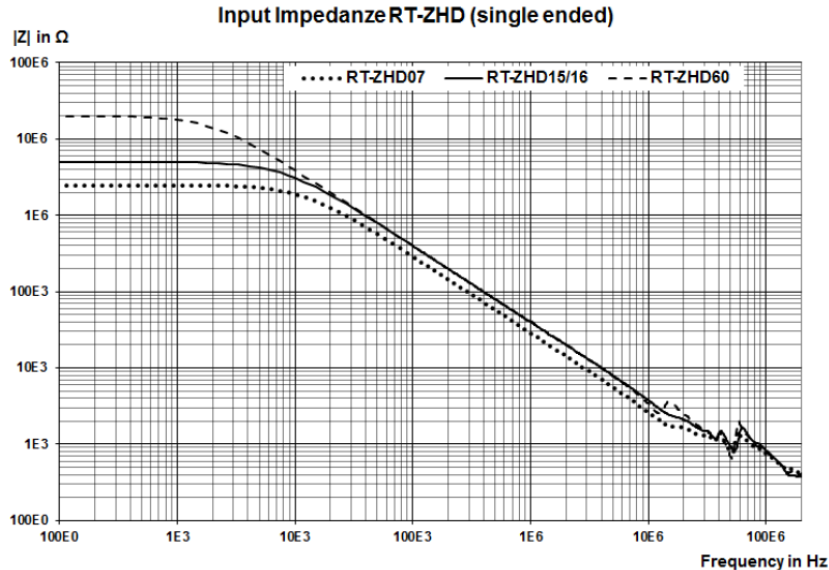
Specifications may look very close and most vendors will have similar information included



DERATING

- Some characteristics are specified in DC, which changes in higher frequencies

Input impedance		
DC input resistance	differential (between signal sockets)	5 M Ω

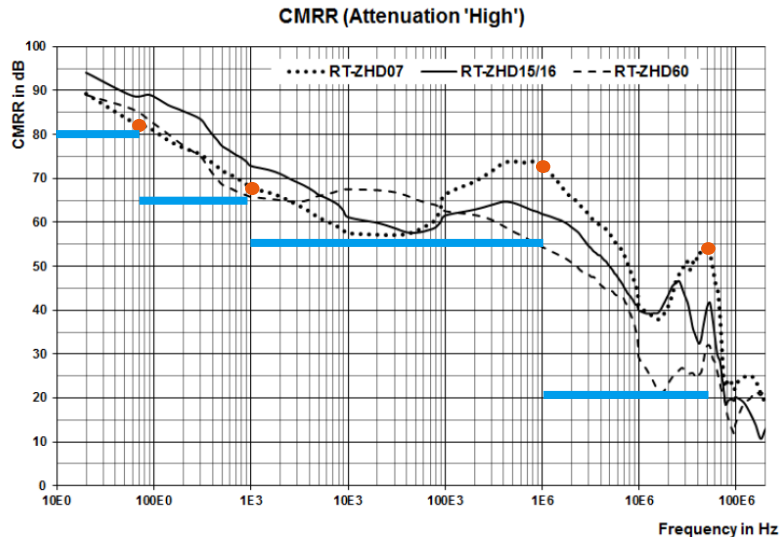


ZHD07 can maintain a relative high impedance of 5 M Ω up to 5 kHz and drop down to 400 Ω at 200 MHz

NOT ALL SPECS ARE LINER PLOT

- ▶ While the datasheets only include a few key frequencies characteristics, reality is different

Common mode rejection	DC to 60 Hz		
	+15 °C to +35 °C	> 80 dB	
	0 °C to +50 °C	> 75 dB	
	60 Hz to 1 kHz	70 dB (meas.)	65 dB (meas.)
	1 kHz to 1 MHz	55 dB (meas.)	55 dB (meas.)
	1 MHz to 50 MHz	35 dB (meas.)	20 dB (meas.)

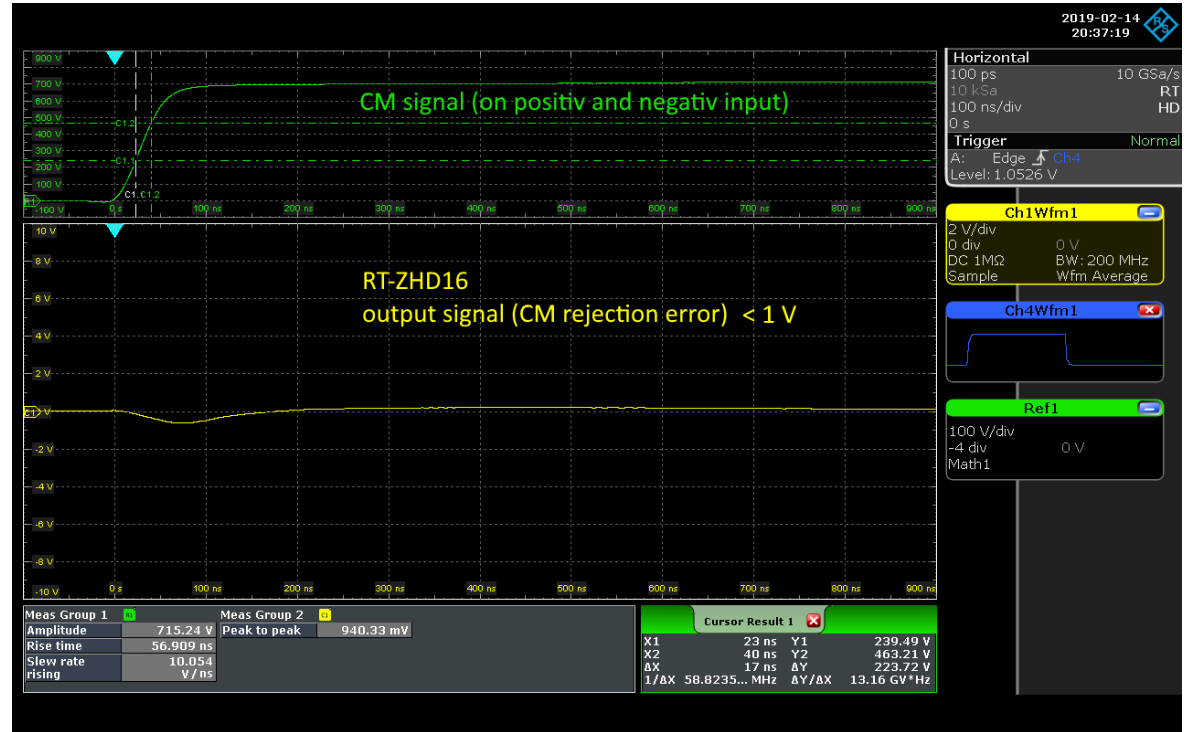


There can be a certain frequency that the probe may perform better or worse.

Take note of those and make full use of the probe performance

MEASUREMENT EXAMPLE: COMMON MODE REJECTION RATE

- ▶ 700 V step
- ▶ Measured with RT-ZHD
- ▶ High CMRR
- ▶ Suitable for high side gate measurements



NOISE VS ATTENUATION RATIO VS BANDWIDTH

- Higher attenuation ratio means higher noise

Attenuation setting		25:1	250:1
Noise voltage	referenced to probe input	12 mV (RMS) (meas.)	40 mV (RMS) (meas.)

Bandwidth

- General rule: Less bandwidth → Less (white) noise
- Reducing the bandwidth to the needed minimum helps to improve the noise behavior
- Mostly used connectors (4 mm plug & cable) has resonant frequency ~200 MHz (or less)

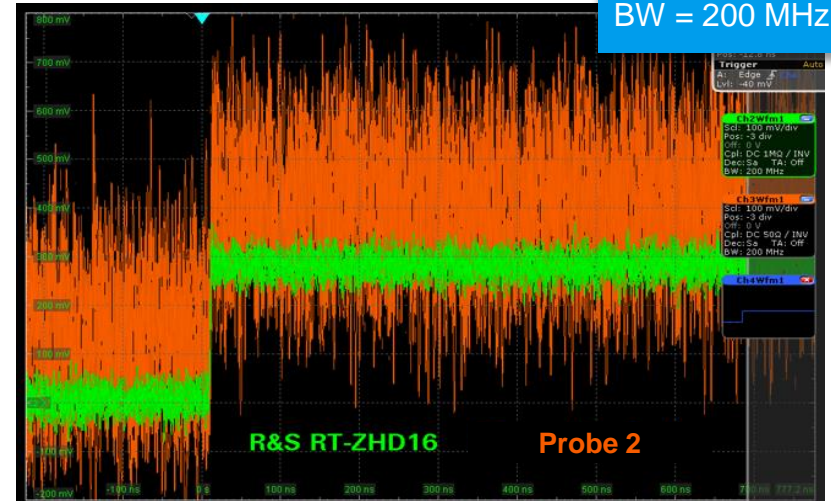
Is a coaxial cable a good alternative?

Trade-offs:

It has low withstand voltage

Additional connector must be added to DUT design

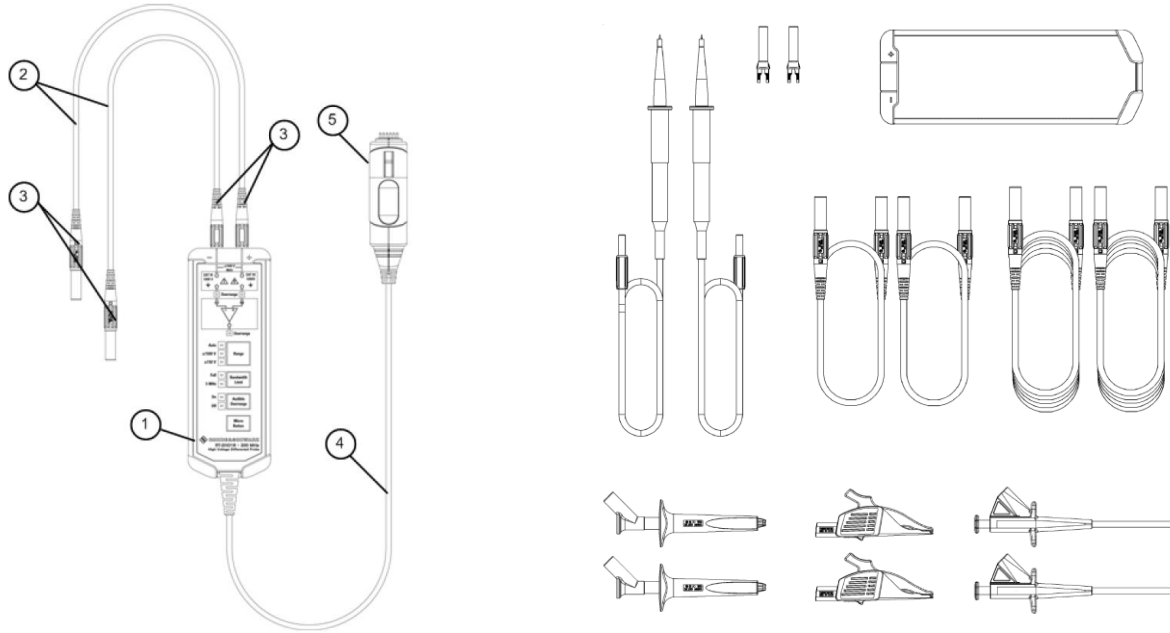
Impedance mismatch DUT to coaxial cable



Choose a good probe

PROBES ARE SPECIFIED WITH BEST SETUP

- ▶ Changing to longer leads and clips will change the behavior

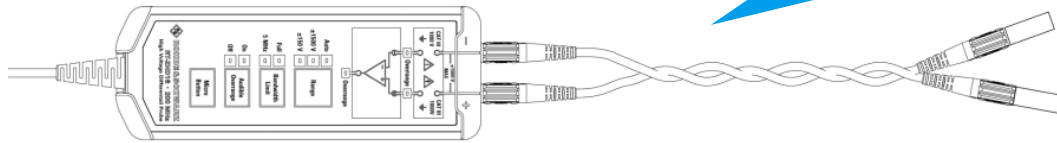


UNTOLD CHARACTERISTICS IN SETUP

TWISTED OR UNTWISTED CABLES

Overview: Pros & Cons

Leads twisted

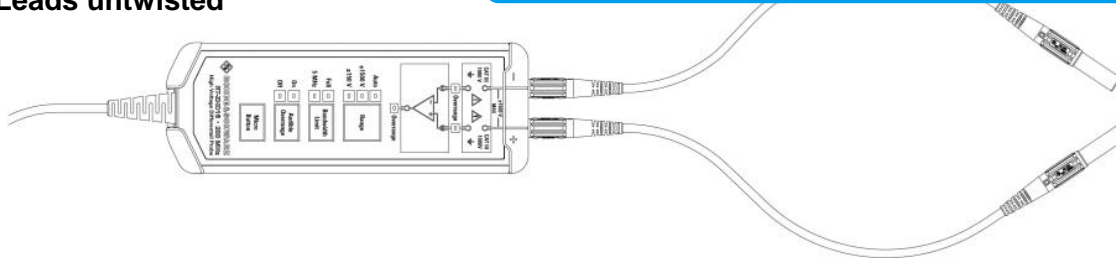


Usually the best option

pro interferers are minimized

con greater load on the measuring point

Leads untwisted



Only recommended if the loading of probe is the biggest problem

pro minimizes the capacitive load on the measuring point

con interferers are looped in

TWISTED OR UNTWISTED CABLES

Input Capacitance

Single ended input capacitance: **RT-ZHD16**

(P input to GND)

without meas. lead: **3.5 pF**

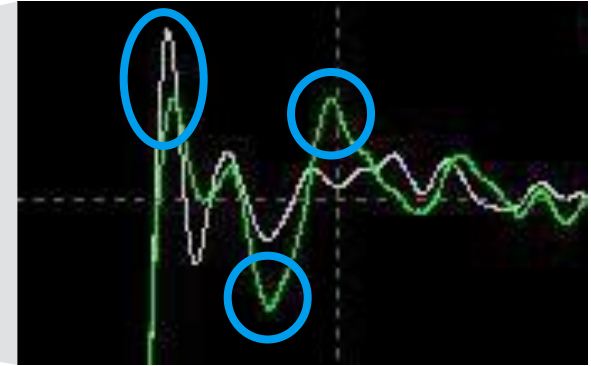
	RT-ZHD16 + meas. leads	RT-ZHD16 + meas. leads + alligator clips
untwisted	9 pF	10 pF
twisted	12 pF	15 pF

Rule of thumb:

The differential input capacitance is approx. half the single ended capacitance

TWISTED OR UNTWISTED CABLES

200 MHZ BANDWIDTH



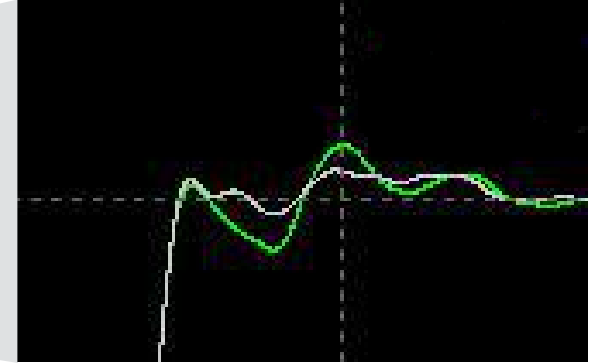
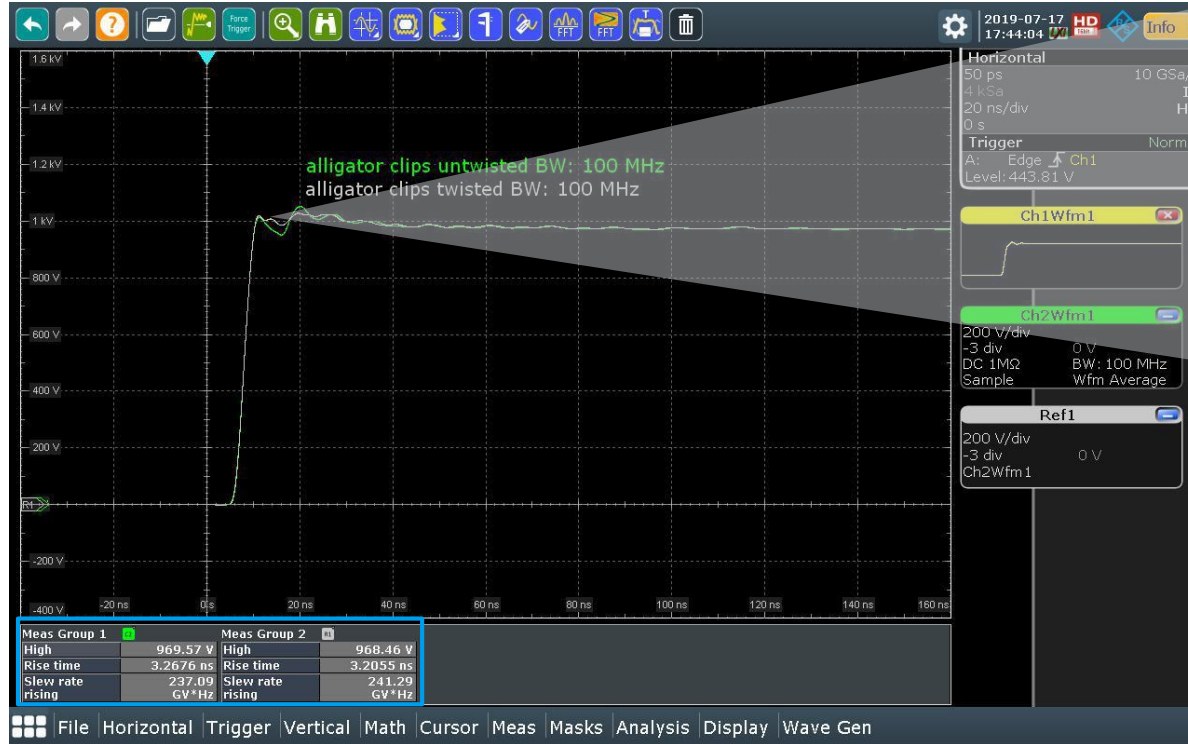
The impulse response of the probe is optimized with twisted test leads

Higher overshoot due to twisting

For non twisting:
relatively high ringing later

TWISTED OR UNTWISTED CABLES

100 MHz BANDWIDTH

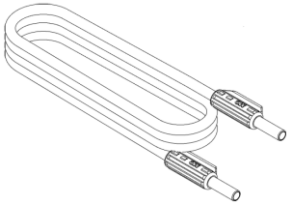


Deviation at BW: < 100 MHz
relatively small

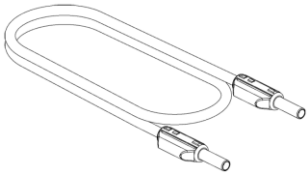
Signals with slower rise times are
less influenced by the type of
probing

INFLUENCE OF MEASUREMENT LEADS

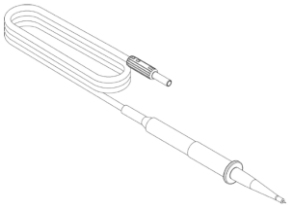
- ▶ **Long Leads (100 cm):** Max. rating 1000 V (RMS) CAT III



- ▶ **Short Leads (17 cm):** Max rating 1000 V (RMS) CAT III



- ▶ **Test Leads :** Max rating 1000 V (RMS) CAT III



LENGTH OF MEASUREMENT LEADS

200 MHz BANDWIDTH



RT-ZHD w/o leads



Negative properties of the standard measurement lines (eg.17cm) are compensated in the probe head!

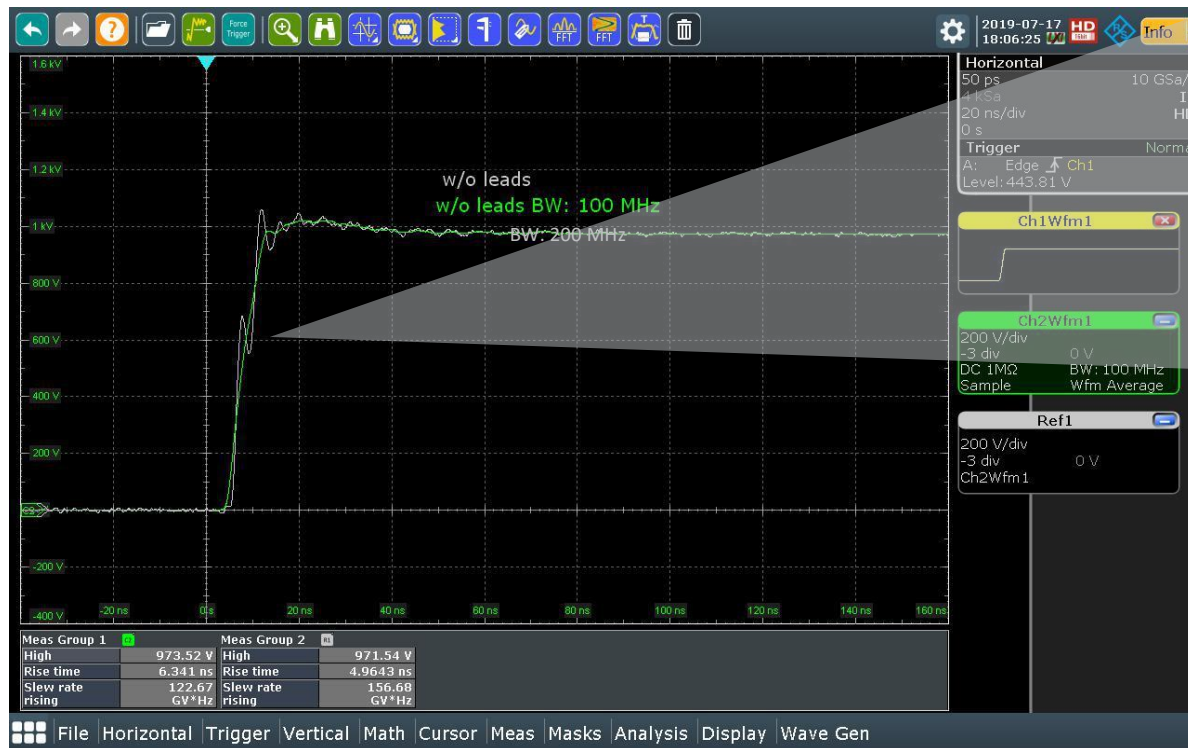
Shorter or longer meas. leads cause measurement errors.

LENGTH OF MEASUREMENT LEADS

100 MHz BANDWIDTH



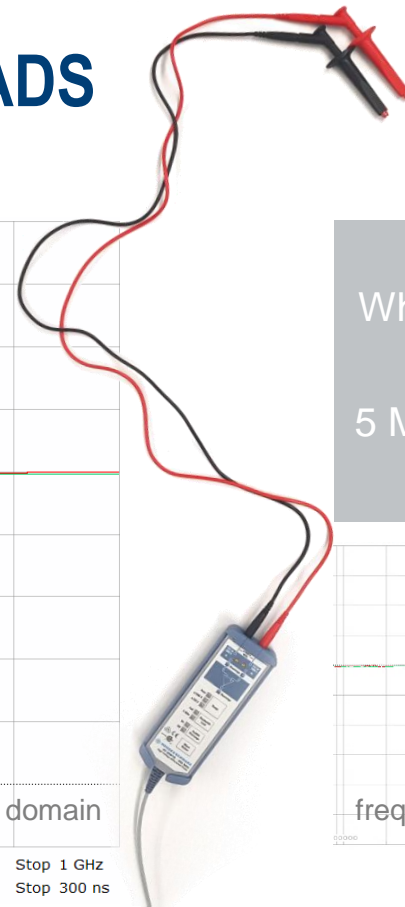
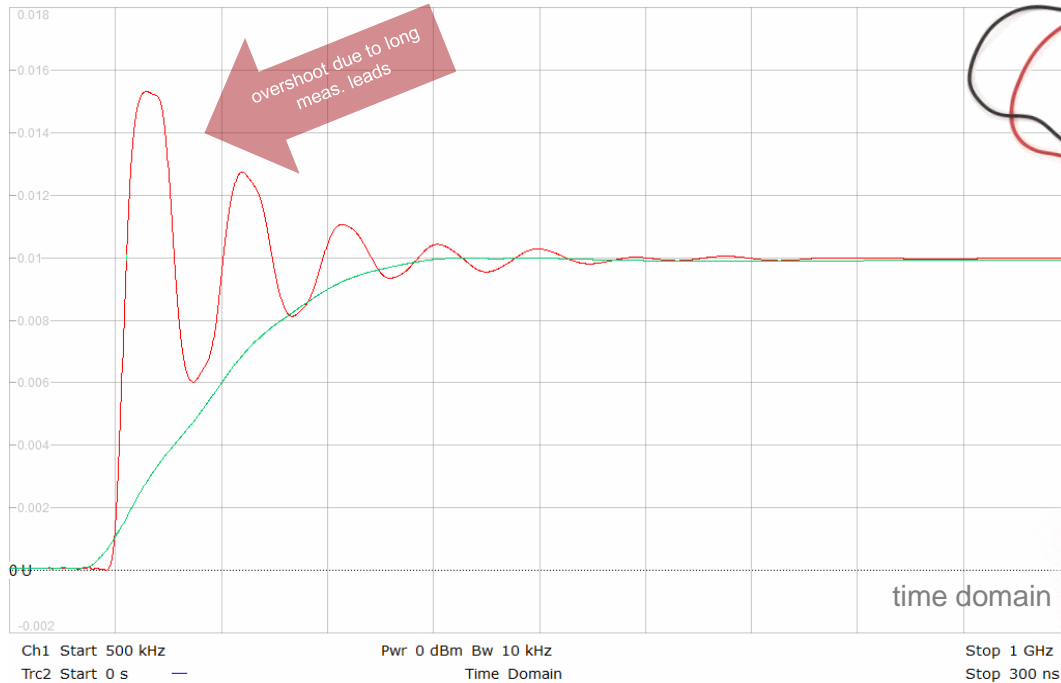
RT-ZHD w/o leads



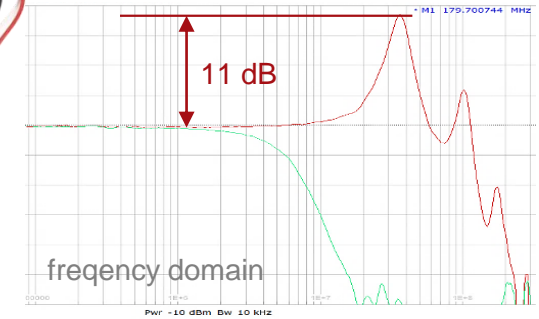
For input signals with a rise time slower than 6 ns you can also use longer or shorter test leads

LENGTH OF MEASUREMENT LEADS

Length of measurement leads 1 m

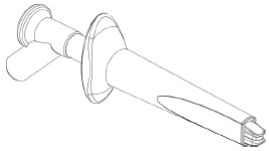


In general:
When using very long test leads (1 m), the 5 MHz low pass should be switched on

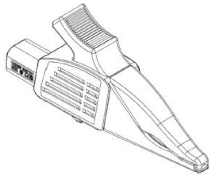


INFLUENCE OF CLIPS

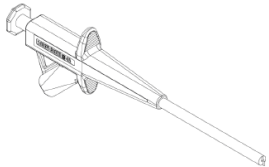
- ▶ **Test Clip:** Max. rating 1000 V (RMS) CAT IV



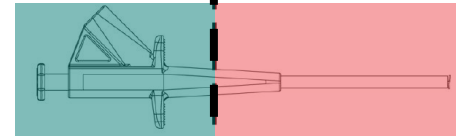
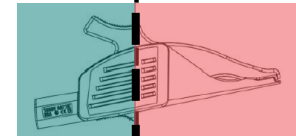
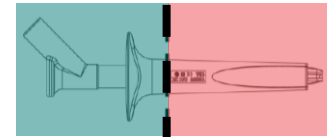
- ▶ **Safety Alligator Clip:** Max. rating 1000 V (RMS) CAT III



- ▶ **Pincer Clip:** Max. rating 1000 V (RMS) CAT III

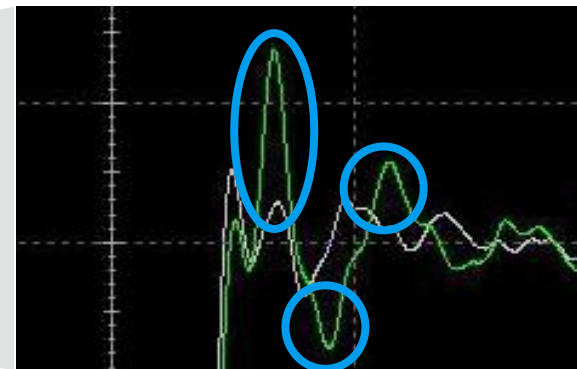
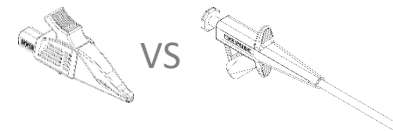


handheld area | unsafe area



ALLIGATOR VS Pincer CLIPS

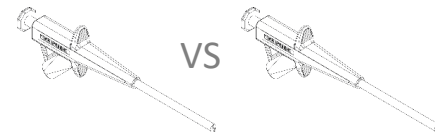
200 MHz BANDWIDTH



Clips have an influence on measuring accuracy especially at full bandwidth (e.g. 200 MHz)

PINCER VS PINCER CLIPS

DIFFERENCE 50 MHZ VS 200 MHZ BANDWIDTH



For an input signal with a rise time of 6 ns the influence of the pincer clips are negligible

Influence highly depends on the input signals rise time

OPTIMIZING THE BEST RESULTS WITH PROBES

COMPENSATION OF PROBE ERRORS BY BASIC DEVICE

All R&S oscilloscopes with R&S Probe Interface can compensate for probe measurement errors:

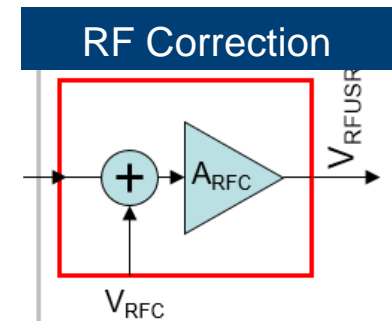
- Zero point error
- Gain error
- Cable Runtimes

The oscilloscope takes correction data from the probe and calculates them with the internal settings

Result:

Better measurement accuracy and less adjustment.

Zero point drift, offset drift and errors due to range switching are eliminated with RT-ZHD probes by DC stabilization circuit very strongly

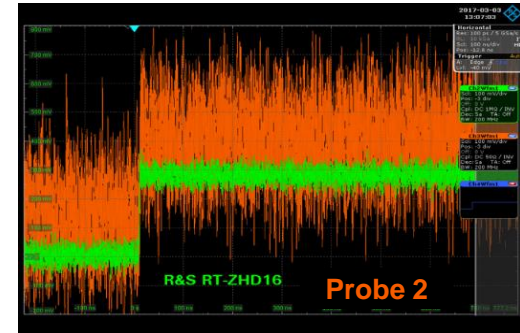


NOISE AND ZERO POINT DRIFT

► Noise

- Small vertical scaling:
 - total noise dominated by the active probe (e.g. 100 mV/ Div for RT-ZHD16)
- High vertical scaling:
 - total noise dominated by the oscilloscope (e.g. 10 V/ Div for RT-ZHD16)
- Generally, noise level depends on attenuation ratio

50:1	500:1
20 mV (meas.)	70 mV (meas.)
25 mV (meas.)	80 mV (meas.)



► Zero point drift

- Zero point drift of the active probe with no scaling dominant
 - For large scales, the base unit is dominant
- Due to the high temperature response, the zero point is too low with active probes difficult to stabilize (no active cooling)
- Range switching with active probes can be done by easily lead to zero point errors

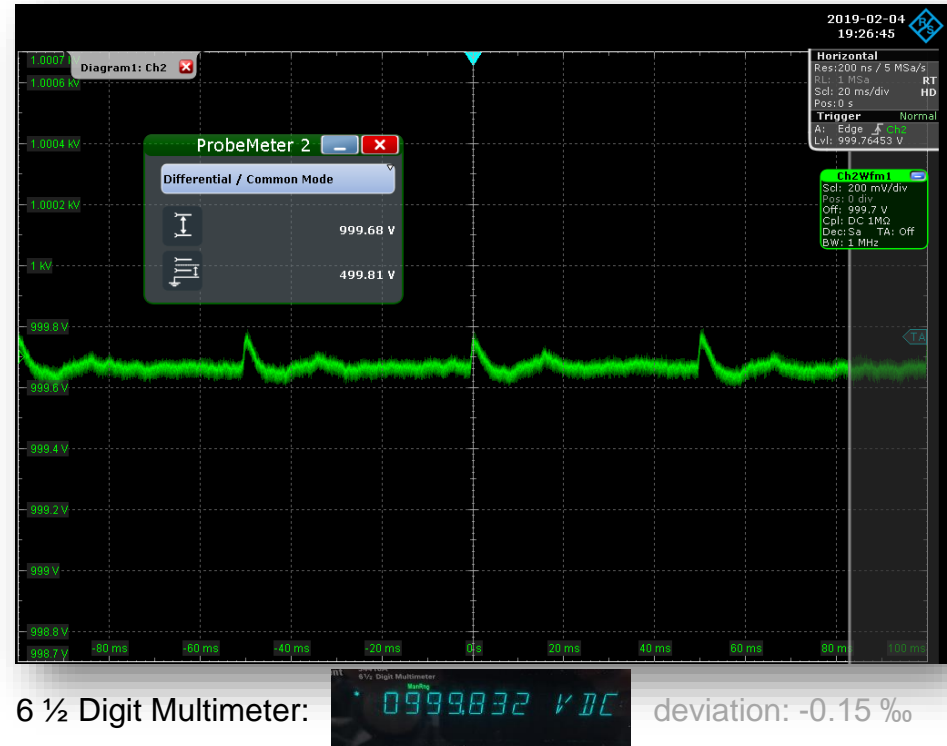


OFFSET COMPENSATION

CHARACTERIZE SMALL VARIATIONS IN HIGH DC VOLTAGES

- ▶ **Application e.g.:**
Ripple voltage detection on DC link
- ▶ **Signal characteristics**
 - ▶ 1000 V DC
 - ▶ ± 100 mV variations

→ High vertical measurement resolution required, e.g. 200 mV/div
- ▶ RT-ZHD: Differential offset **up to 2000 V**
- ▶ **Most differential probes cannot compensate a DC offset**



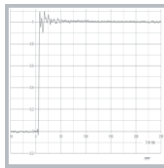
CONCLUSION

Summary: Key parameters and characteristics for selecting high voltage probes

High measurement accuracy



Low noise

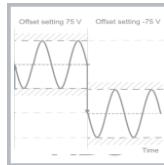


High linearity and
small zero error



High temperature
stability

Versatile range of applications



High DC-Offset range
(e.g. +/-2000 V with 25 mV/div)

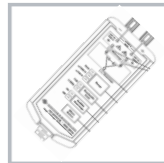


Precise voltage
measurements
(0.1% via R&S®ProbeMeter)

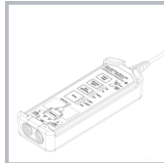


Measurements
in CAT III
conditions

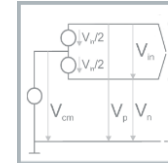
Easy operation



Control the oscilloscope
via probe



DC common mode
voltage always readable
(R&S®ProbeMeter)



Automatic divider
setting and over-
voltage display

Rohde & Schwarz Technology Symposium 2021

THANK YOU

For more information:

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