# High Frequency Performance Delay, Rise-time and Peak di/dt


## Abstract

All measuring instruments are subject to limitations. The purpose of this technical note is to explain some of those limitations and to help the engineer maximise the many advantages of PEM's CWT current probes based on Rogowski technology. This note defines the terms used to describe the high frequency performance of the CWT probes and provides practical examples of measurements including details of rise-time capability, slew rate and measurement delay.


## Contents

## 1. High Frequency (-3dB) Bandwidth

The CWT behaviour at frequencies approaching and exceeding its specified high frequency (hf) (-3dB) bandwidth is very complicated. It is related to the distributed inductance and capacitance of both the Rogowski coil and the connecting co-axial cable (which have different characteristic impedances) and their terminations, and to the gain-frequency characteristic for the op-amps and associated parasitic impedances used to implement the integrator and buffer electronics. It also varies depending on the position of the current within the loop, although up to the (-3dB) bandwidth this variation is very small.

At frequencies >3MHz the various CWT 'HF' ranges produce the most predictable frequency response. This is because the Rogowski coil is fitted with an electrostatic shield (screen), thus the coil capacitance is closely controlled and unaffected by the measurement environment. For measuring high frequency sinusoids in the MHz range the various CWT 'HF' ranges are recommended if space allows.

An example of the frequency response of the CWT MiniHF range is shown below for both the 100mm and 200mm coil length versions.

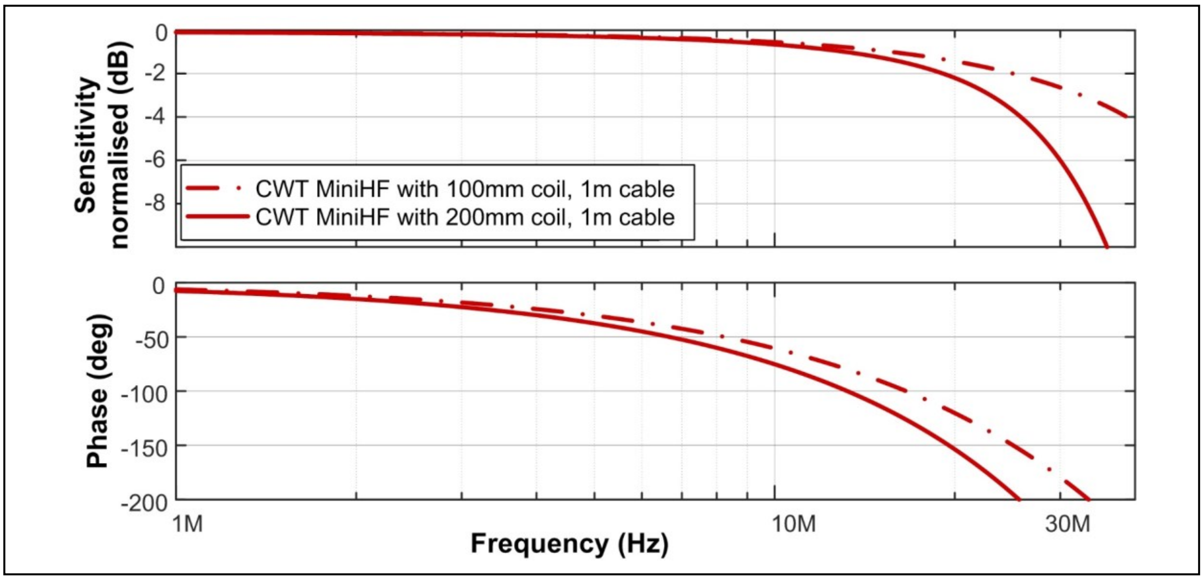



***Figure 1. High frequency performance CWT MiniHF, 1m cable, 100 and 200mm coil***

If you have a specific requirement and need to know the gain / phase of a certain model over a particular frequency range please contact PEM. Simulated and some measured frequency responses are included in the Appendix for the various products at the end of this document.

PEM has produced several publications regarding the high frequency behaviour of Rogowski current transducers and these can be requested.

## 2. Rise-time and Delay

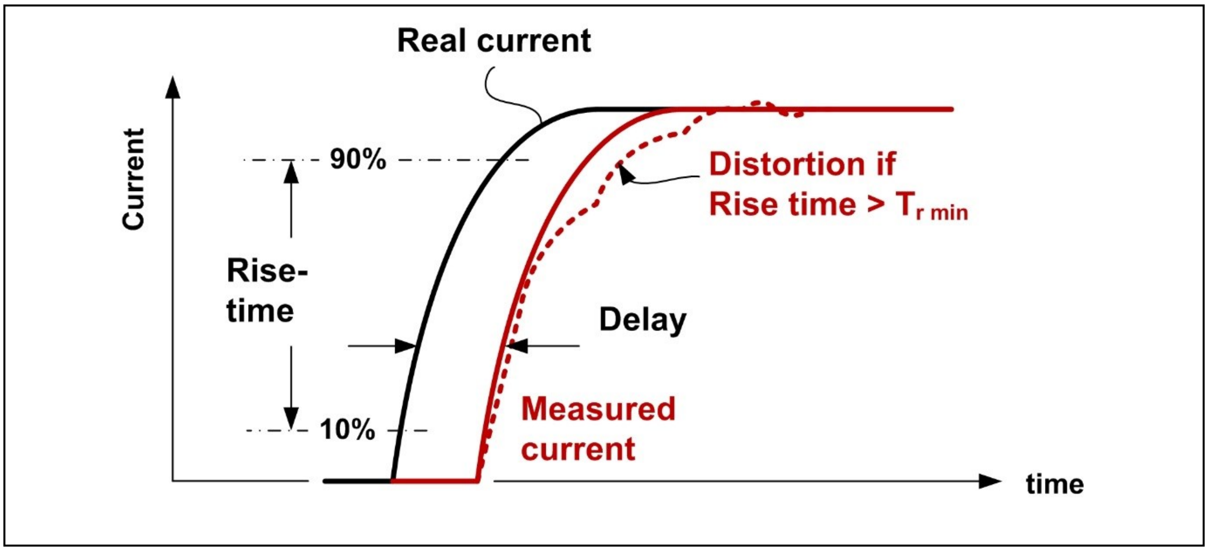



*Figure 2. Rise time and Delay definitions*

The CWT has an inherent measurement delay. Provided the current rise-time is within the limits of the high frequency bandwidth of the CWT the delay is predictable. The delay is a combination of:

- $T_a$ – the transit delay for the cable connecting the coil to the integrator.
- $T_b$ – the delay of the electronic integrator. This is a function of the GBW product of the integrating op-amp, the buffer electronics and the various parasitic impedances on the electronic PCB.
- $T_c$ – the delay for the Rogowski coil. This is dependent on the distributed inductance and capacitance of the Rogowski coil and the terminating impedance.

$T_b$ and $T_c$ cause an attenuation of the measurement, $T_a$ does not.

The fastest 10 to 90% rise-time for which PEM would recommend the CWT is used is dependent on $T_b$ and $T_c$ and is different for the various CWT models. The inherent delay and recommended minimum rise-time, $T_r$, for each model is listed in Table 1.

The Appendix contains example waveforms of each of the various CWT probes including a

- High frequency sinusoid
- Fast transient pulse

The waveforms are shown first with the inherent delay, and then using the 'deskew' function on an oscilloscope to remove the probe delay quoted in Table 1. In all cases the comparative (reference) device, having a high frequency bandwidth >> the CWT, is also connected to the oscilloscope with a 0.5m 50Ω BNC:BNC cable.

| Model (Cable length , Coil length) | | Typical Delay (ns) | $T_r$ - Minimum Rise Time (ns) |
|---|---|---|---|
| CWTUM | (1m, 80mm) | **17.0** | **19.0** |
| | | | |
| CWTMiniHF | (1m, 100mm) | **17.3** | **20.0** |
| | (1m, 200mm) | **20.7** | **36.0** |
| | | | |
| CWTMini50HF | (1m, 100mm) | **12.6** | **12.5** |
| | | | |
| CWTMini | (1m, 100mm) | **21.5** | **40.0** |
| | (1m, 200mm) | **24.5** | **50.0** |
| | | | |
| CWTHF < 600A | (1m, 300mm) | **21.4** | **44.0** |
| | (1m, 500mm) | **26.5** | **69.0** |
| | (1m, 700mm) | **31.7 \| 33.0** | **90.0 \| 95.5 (015HF, 03HF)** |
| | | | |
| CWTHF ≥ 600A | (1m, 300mm) | **18.2** | **27.5** |
| | (1m, 500mm) | **21.3** | **43.5** |
| | (1m, 700mm) | **24.5** | **59.4** |
| | | | |
| CWT | (1m, 300mm) | **25.6** | **50.0** |
| | (1m, 500mm) | **30.3** | **70.0** |
| | (1m, 700mm) | **35.0** | **90.0** |

***Table 1. Typical Delay and Rise-time values***

Additional cable length between the Rogowski coil and integrator will add

+4.8ns/m up to 2.5m (for the CWT Ultra mini | CWT Mini/HF | CWTMini50HF)
+4.1ns/m up to 4.0m (for the CWT | CWTHF)

but not change the maximum rise time or high frequency bandwidth.

The delay values do not include the output cable from the CWT, for the standard 0.5m 50Ω BNC:BNC output cable supplied with the unit, terminated into the recommended DC 1MΩ input on an oscilloscope, the cable adds an additional +2.5ns to the values quoted in Table 1.

# 3. di/dt (slew rate) Ratings

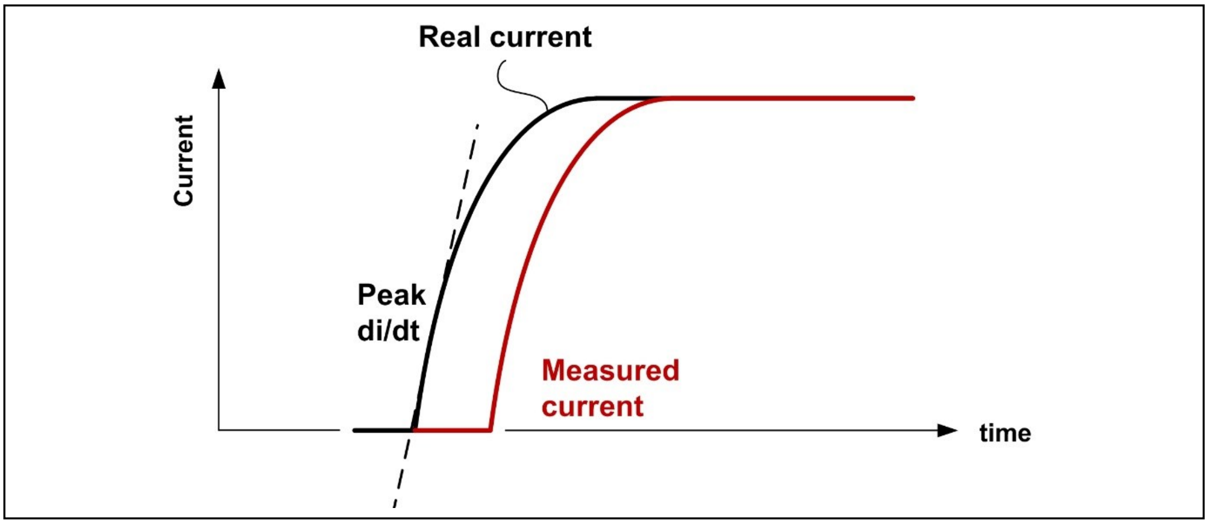



*Figure 3.1 Peak di/dt definitions*

There is a slew rate limitation on Rogowski current sensors, this is termed the **Peak di-dt** of the probe. This is the maximum rate of change of current, di/dt, above which the transducer will fail to correctly measure the current. The values are specified on each datasheet.

The peak di/dt is typically very large for the whole CWT range. For the CWTMiniHF and CWT Ultra-mini ranges it is very difficult to exceed the peak di/dt values if the current is within the minimum specified rise time (see Table 2.1)

## 3.1 Absolute Maximum Peak di/dt

An excessive di/dt transient will create a large voltage within the Rogowski coil which will damage the transducer. The individual datasheet gives an absolute maximum rating for Peak di/dt for each transducer that must not be exceeded.

## 3.2 Absolute Maximum RMS di/dt

The Rogowski coil can also be damaged by sufficiently high repetitive di/dt even though the peak di/dt rating is not exceeded. The damage can result from two different effects:

A damping resistor is used to provide correct termination of the Rogowski coil and cable to prevent reflections (seen as high frequency damped oscillations) appearing on the measured waveform. A high repetitive di/dt can cause excessive power to be dissipated in this resistor.

The Rogowski coil itself can overheat due to the resultant magnetic field created by the primary current inducing eddy currents either in the coil winding, or coil screen.

The absolute maximum rms di/dt rating is very rarely a problem. Typically it is only a limitation for very high power induction heating, or high power rf plasma applications, where continuous sinusoidal currents greater than 1kA, at frequencies of several 100kHz and into the MHz range, can occur.

For **sinusoidal waveforms** the calculation of rms di/dt is straight-forward,
**rms di/dt = $2\pi f\, I_{rms}$** (where **f** is the frequency and $I_{rms}$ is the rms value of the measured current)

For example for a continuous sinusoidal current of 300A, at 200kHz
rms di/dt = $2\pi$ * 0.2 (MHz) * 0.3 (kA) = 0.38 kA/µs

For **pulsed waveforms** the absolute maximum rms di/dt is very rarely a problem as can be seen in the example of Fig 3.2.

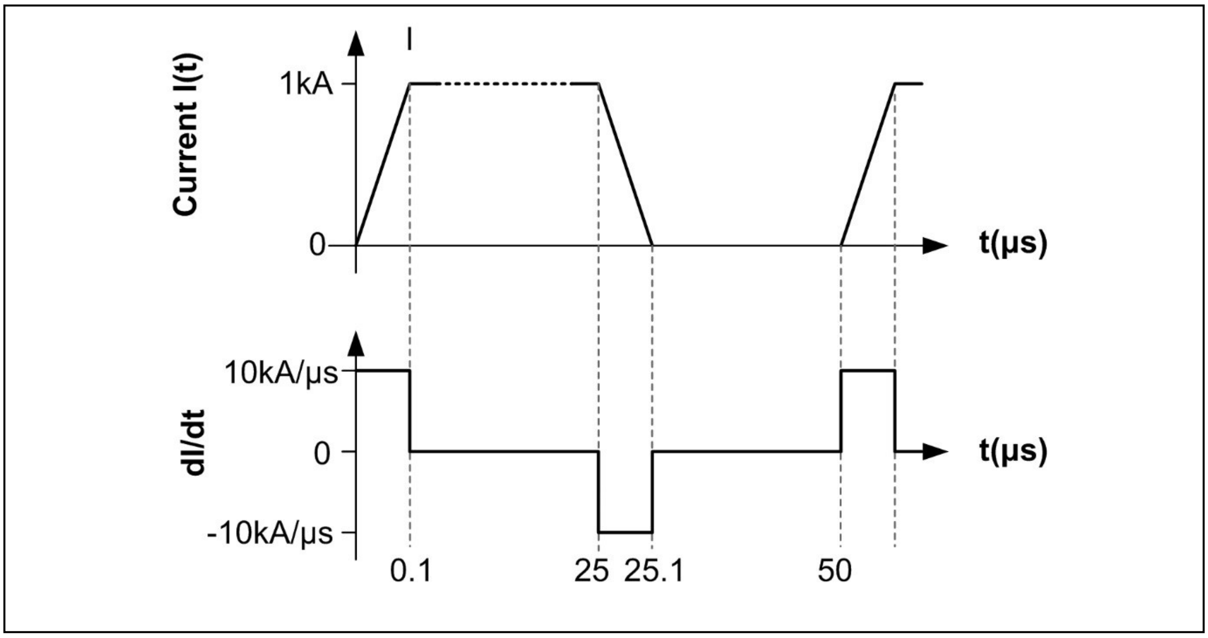



***Figure 3.2. The rms di/dt of a repetitive pulsed waveform***

Consider the current waveform shown in Figure 3.2. with a repetition frequency of 20kHz and also the corresponding di/dt waveform.
rms di/dt = 10kA/µs x $(0.1µs/25µs)^{0.5}$ = 0.63 kA/µs

The di/dt ratings of the various CWT models are listed on the product datasheet.

## 4. Output Cable and Terminating Impedance

The minimum input impedance for any recording device (e.g. oscilloscope, DVM or power analyser) connected to the CWT must be 100kΩ or greater for rated accuracy. PEM recommend using the DC 1MΩ termination on an oscilloscope.

The output impedance of all the CWT models is 50Ω. Any cables used to connect the output of the transducer to the recording device should be 50Ω co-axial cable.

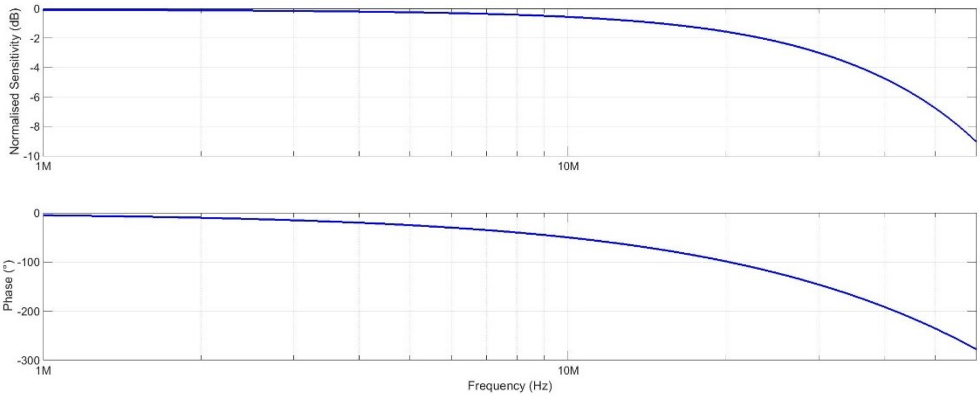
PEM has conducted tests using a 0.5m, 2m and a 30m 50Ω co-axial cable on the output of the CWT UM, CWT Mini HF and CWT Mini, the cable is terminated into DC 1MΩ on a 500MHz analog bandwidth oscilloscope having an input capacitance of 11.5pF. There is no discernible attenuation of the measured current signal although, as is to be expected, there is an increased measurement delay of 5ns/m.

Most CWT models can be terminated into a 50Ω impedance, though this is not recommended. It is only necessary to terminate into 50Ω if either the input impedance of the terminating device is >> 25pF, and/or >>1MΩ. A load of 50Ω will reduce the sensitivity to half its nominal value and reduce the peak output to ±2V. Terminating into 50Ω will also reduce battery life.

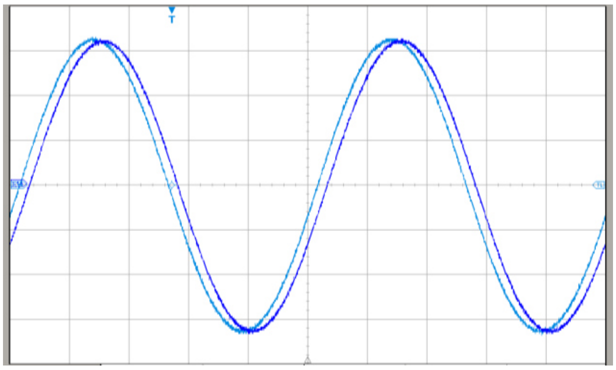
If the device under test is a long way from the recording equipment it is worth contacting PEM to discuss your application. In some circumstances, particularly electrically noisy environments, it is better to increase the cable length between the Rogowski coil and the integrator electronics rather than use a long cable on the output of the electronic integrator.

## Appendix 1 – CWT Ultra-mini

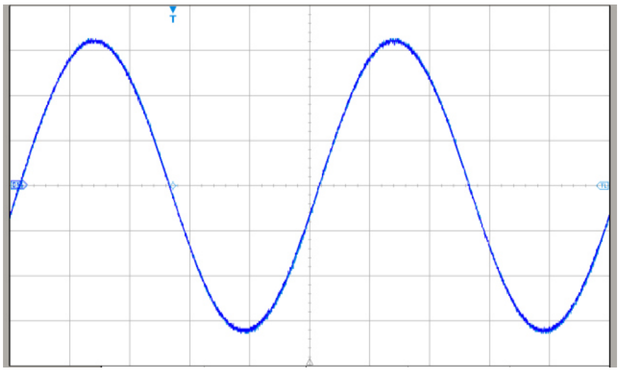
**Features:**- Very thin 1.7mm thick Rogowski coil, 1.2kV peak insulated, hf (-3dB) 30MHz.




***Appendix 1a. CWTUM 1/B/1/80 Simulated frequency response for indication only***

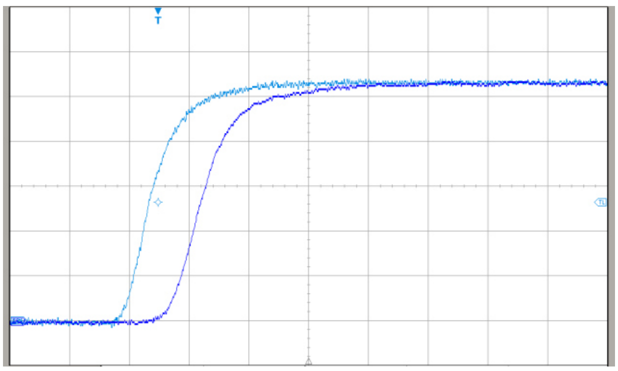


**Ch 1: Co-axial shunt** - DC-800MHz – 60mV/div (3A/div)
**Ch 2: CWTUM/1** - 60mV/div (3A/div)
Time base: 100ns/div

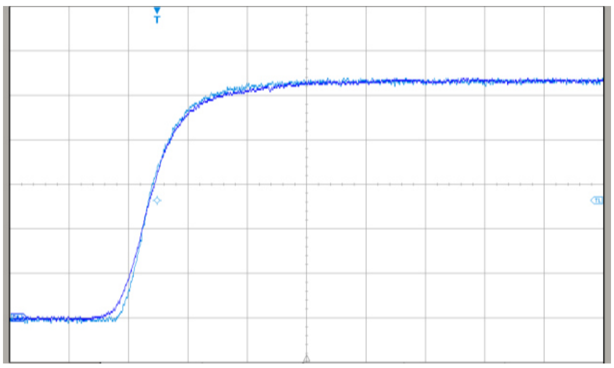


**Ch 1: Co-axial shunt** - DC-800MHz – 60mV/div (3A/div)
**Ch 2: CWTUM/1 – 16.8ns DE-SKEW** - 60mV/div (3A/div)
Time: 100ns/div

***Appendix 1b. CWTUM 1/B/1/80 measuring a 2MHz sinusoidal current***



**Ch 1: Co-axial shunt** - DC-2GHz – 200mV/div
**Ch 2: CWTUM/1** - 400mV/div (20A/div)
Time: 20ns/div

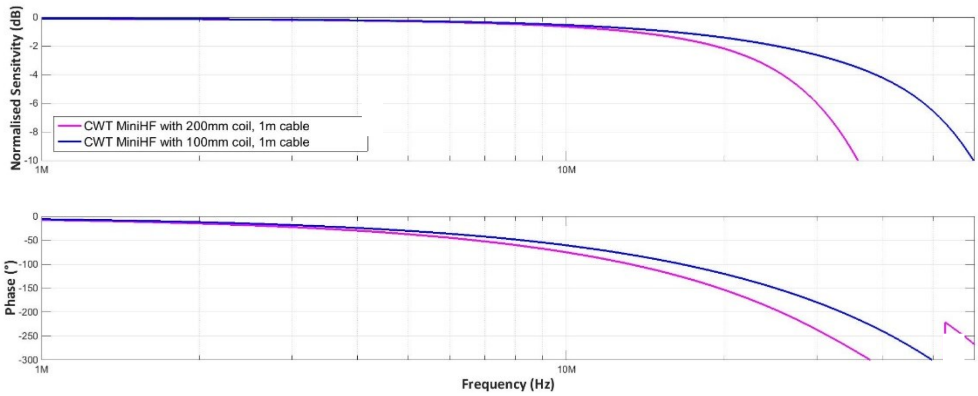


**Ch 1: Co-axial shunt** - DC-2GHz – 200mV/div
**Ch 2: CWTUM/1 – 16.8ns DE-SKEW** - 400mV/div (20A/div)
Time: 20ns/div

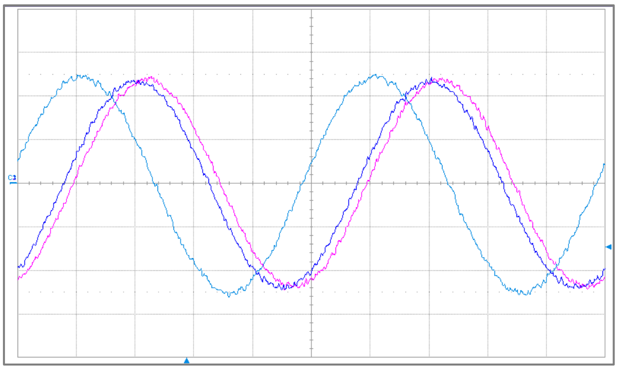
***Appendix 1c. CWTUM 1/B/1/80 measuring Rise-time - $T_r$ = 23ns, Peak current = 110A***

# Appendix 2 – CWT MiniHF

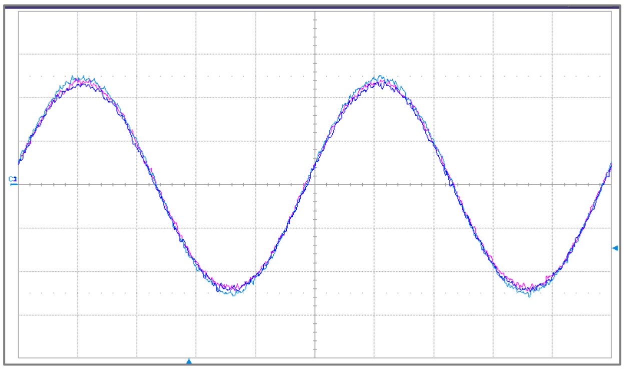
**Features:** Voltage shielded/screened Rogowski coil, 4.5mm thick, 5kV peak insulated, hf (-3dB) 30MHz, two coil lengths 100mm or 200mm




*Appendix 2a. CWTMiniHF 1 / B / 1 / 100 / 5 (and 200mm) - Simulated frequency response for indication only*

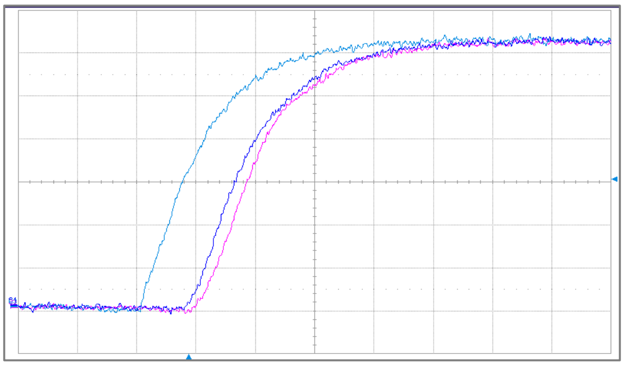


**Ch 1: Co-axial shunt** - DC-800MHz – 40mV/div
**Ch 2: CWTMiniHF 03 (100mm)** - 200mV/div (2A/div)
**Ch 3: CWTMiniHF 03 (200mm)** - 200mV/div (2A/div)
Time base: 20ns/div

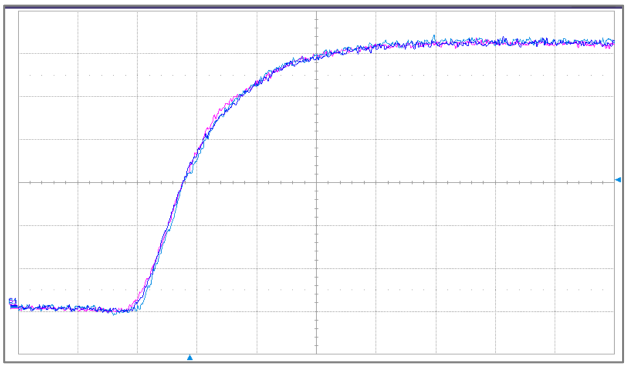


**Ch 1: Co-axial shunt** - DC-800MHz – 40mV/div
**Ch 2: CWTMiniHF 03 (100mm)** - **17.5ns DE-SKEW**
**Ch 3: CWTMiniHF 03 (200mm)** - **20.9ns DE-SKEW**
Time base: 20ns/div

*Appendix 2b. CWTMiniHF 03 / B / 1 / 100 / 5 (and 200mm) measuring a 10MHz sinusoidal current*



**Ch 1: Co-axial shunt** - DC-2GHz – 20mV/div
**Ch 2: CWTMiniHF 03 (100mm)** - 205mV/div (2A/div)
**Ch 3: CWTMiniHF 03 (200mm)** - 205mV/div (2A/div)
Time base: 20ns/div

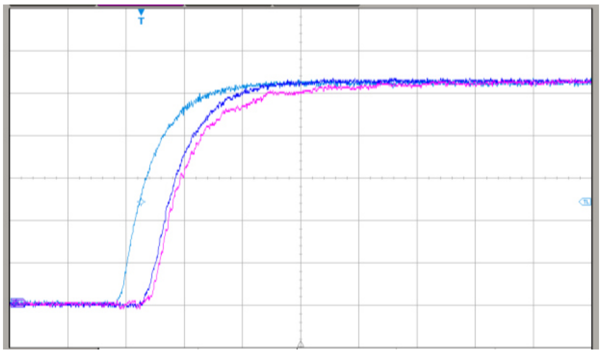


**Ch 1: Co-axial shunt** - DC-2GHz – 40mV/div
**Ch 2: CWTMiniHF 03 (100mm)** - **17.5ns DE-SKEW**
**Ch 3: CWTMiniHF 03 (200mm)** - **20.9ns DE-SKEW**
Time base: 20ns/div

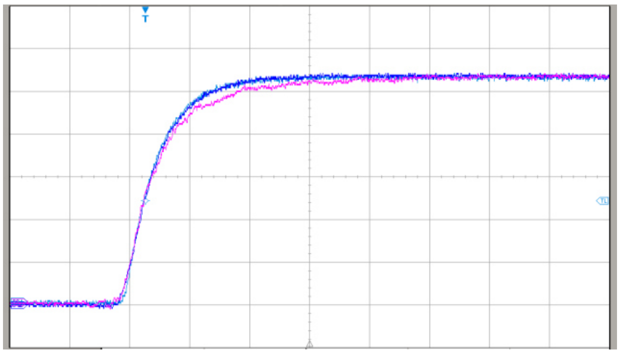
*Appendix 2c. CWTMiniHF 03 / B / 1 / 100 / 5 (and 200mm) measuring Rise-time - $T_r$ = 40ns, Peak current = 12.7A*

## Appendix 3 – CWT MiniHF vs. CWTMini

**Features:** The CWTMini has the same coil size as the CWTMiniHF but it is optimised for low frequency performance

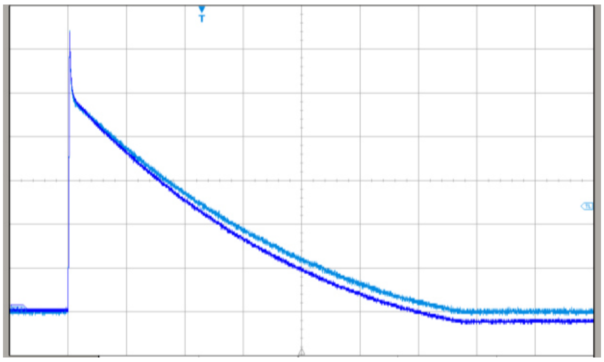


**Ch 1: Co-axial shunt** - DC-2GHz – 200mV/div
**Ch 2: CWTMiniHF 6 (100mm)** - 100mV/div (20A/div)
**Ch 3: CWTMini 6 (100mm)** - 100mV/div (20A/div)
Time base: 50ns/div

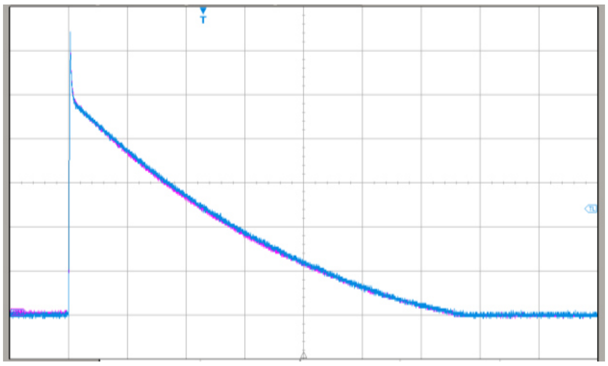


**Ch 1: Co-axial shunt** - DC-2GHz – 200mV/div
**Ch 2: CWTMiniHF 6 (100mm) – 24.7ns DE-SKEW**
**Ch 3: CWTMini 6 (100mm) – 28.8ns DE-SKEW**
Time base: 50ns/div

***Appendix 3a. HIGH FREQUENCY COMPARISON***
***CWTMini 6 / B / 2.5 / 100 / 5 vs. CWTMiniHF 6 equivalent***
***Rise-time - $T_r$ = 55ns***
***Peak current = 107A***



**Ch 1: Co-axial shunt** - DC-800MHz – 16.2mV/div
**Ch 2: CWTMiniHF 3** - 250mV/div (25A/div) – LF(-3dB) 11Hz
Time base: 200µs/div

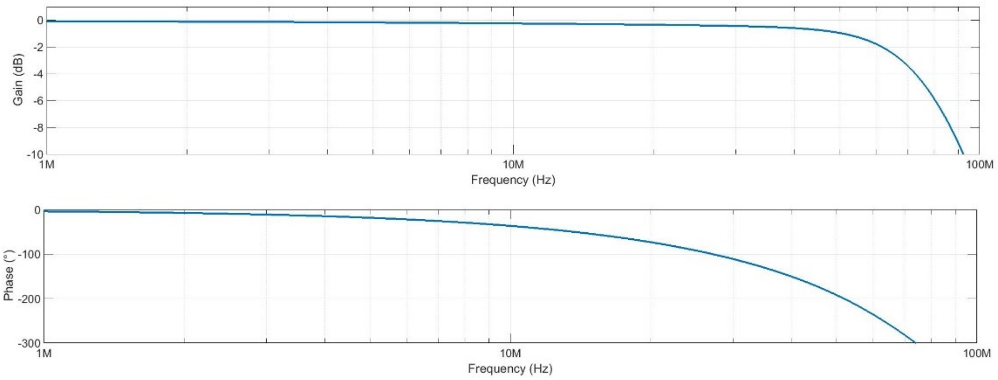


**Ch 1: Co-axial shunt** - DC-800MHz – 40mV/div
**Ch 3: CWTMiniHF 3** - 250mV/div (25A/div) – LF(-3dB) 2.3Hz
Time base: 200µs/div

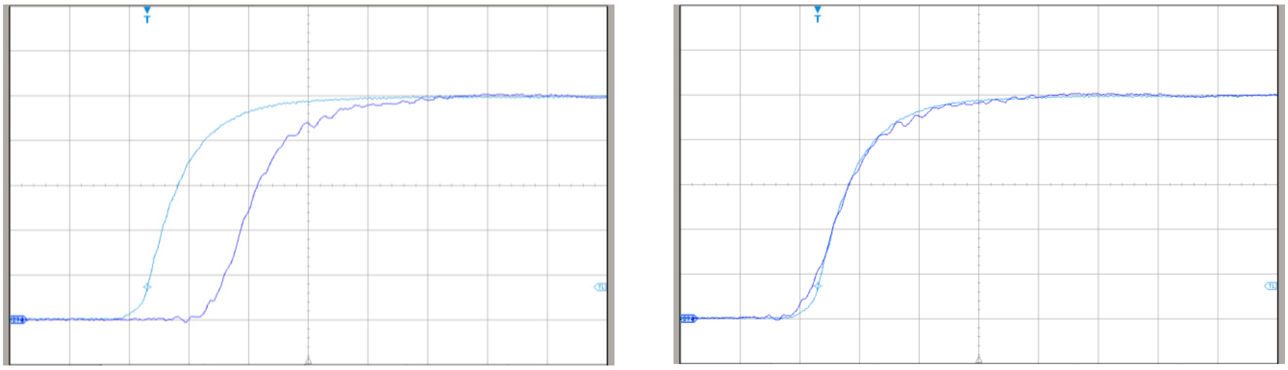
***Appendix 3b. LOW FREQUENCY COMPARISON***
***CWTMini 3 / B / 2.5 / 100 / 5 vs. CWTMiniHF 3 equivalent***
***Rise-time $T_r$ = 4µs,***
***Pulse length $T_p$ = 1.3ms,***
***Peak current = 162A***

## Appendix 4 – CWT Mini50HF

**Features:** The CWTMini50HF is an extension of the CWTMiniHF range, available as a 600A and 1200A version with a 50MHz (-3dB) for a 100mm coil



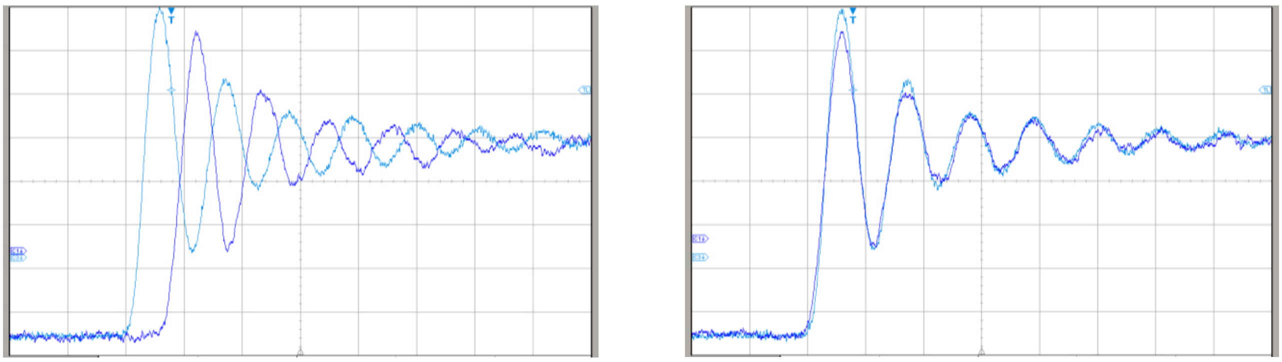

***Appendix 4a. CWTMini50HF 3 / B / 1 / 100 / 2 - Simulated frequency response for indication only***



**Ch 1: Co-axial shunt** - DC-2GHz – 1V/div
**Ch 2: CWTMini50HF 3 (100mm)** - 101mV/div (10A/div)
Time base: 10ns/div

**Ch 1: Co-axial shunt** - DC-2GHz – 1V/div
**Ch 2: CWTMini50HF 3 (100mm)** - **12.8ns DE-SKEW**
Time base: 10ns/div

***Appendix 4b. CWTMini50HF 3 / B / 1 / 100 / 2 measuring Rise-time - $T_r$ = 14.0ns, Peak current = 50A***



**Ch 1: Co-axial shunt** - DC-800MHz – 10mV/div
**Ch 2: CWTMini50HF 3 (100mm)** - 5mV/div (0.5A/div)
Time base: 20ns/div

**Ch 1: Co-axial shunt** - DC-800MHz – 10mV/div
**Ch 2: CWTMini50HF 3 (100mm)** - **12.8ns DE-SKEW**
Time base: 20ns/div

***Appendix 4c. On the limits of the bandwidth***
***CWTMini50HF 3 / B / 1 / 100 / 2 measuring Rise-time $T_r$=10ns with 42MHz ripple, Peak current = 3.8A***

**COSINUS Messtechnik – Ihr Partner für Messlösungen in allen elektrischen und physikalischen Anwendungen.**


**COSINUS Messtechnik GmbH**
Rotwandweg 4
82024 Taufkirchen
Tel.: 089 / 66 55 94 - 0
Fax: 089 / 66 55 94 - 30

office@cosinus.de
www.cosinus.de