The practicalities of measuring fast switching currents in power electronics using Rogowski probes

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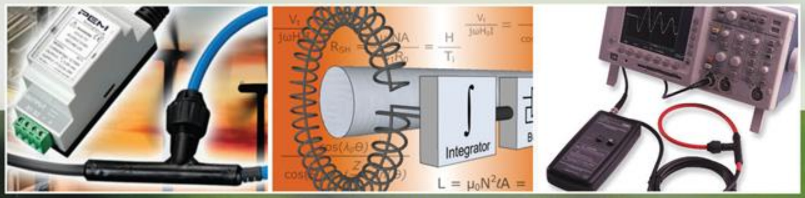
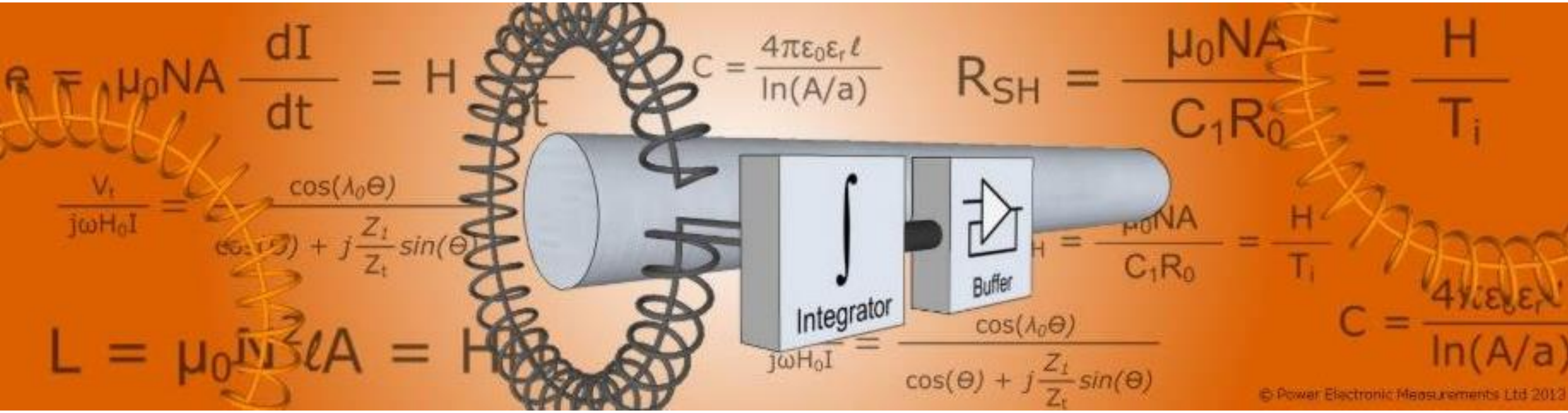
Booth No. 418



About PEM Ltd

Power Electronic Measurements



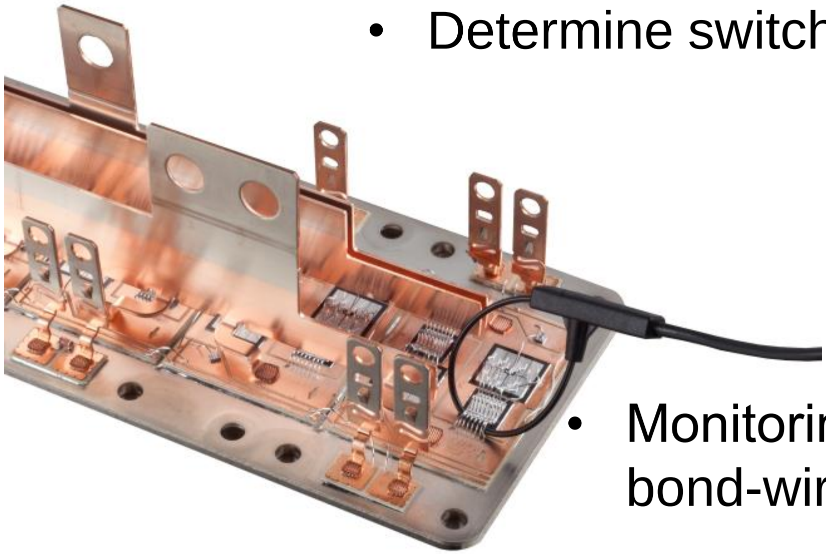
Power Electronic Measurements Ltd (PEM) are established technology leaders in the design and manufacture of wide-bandwidth current measuring devices based on Rogowski technology.

Founded in 1991 PEM can justly claim to have pioneered the general purpose wide-band Rogowski Transducer. Previously this technology was relatively unknown and only used for a few specialist applications.

PEM commitment to research and development has resulted in numerous academic publications, patents and development contracts.

Typical applications in Power Electronics

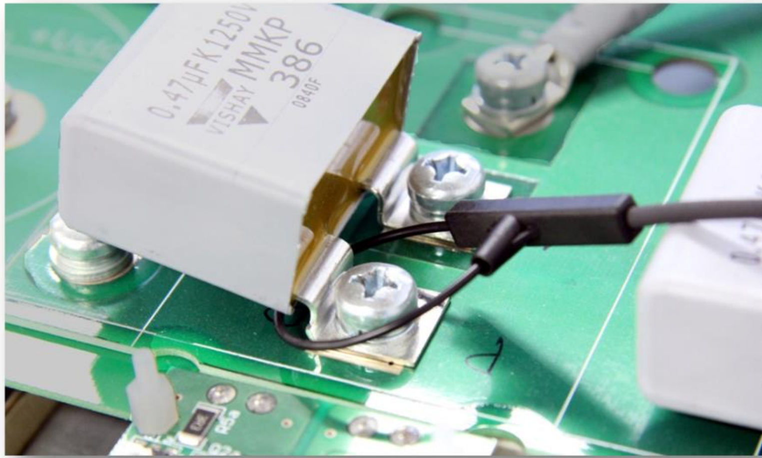
Power Electronic Measurements



- Determine switching loss in power semiconductors

- Monitoring current sharing and ‘stress’ in bond-wires in large power devices.

- Examining the effects of stray inductance on a power electronic circuit.



Content

This presentation will cover three major areas of interest when measuring fast transient currents in power electronic circuits:

Probe delay and maximum rise-time

- Measuring power loss in a device it is essential to know the intrinsic delay of both the current and voltage probes.

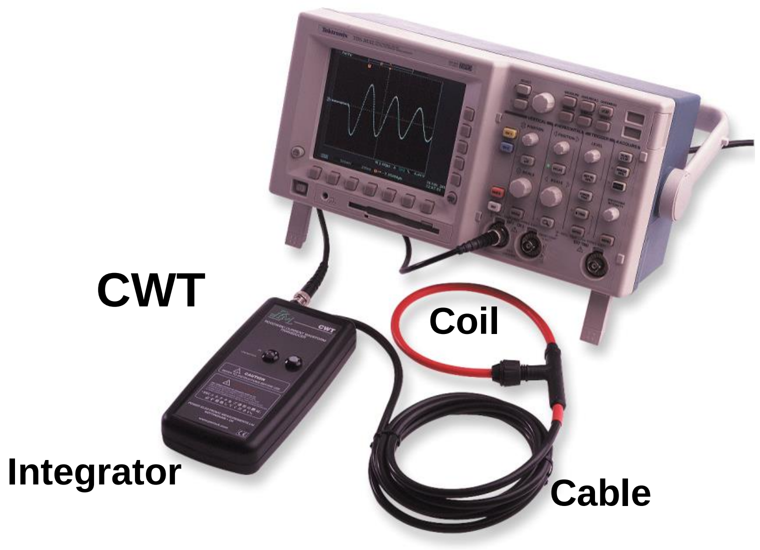
How much does the probe load the circuit under test

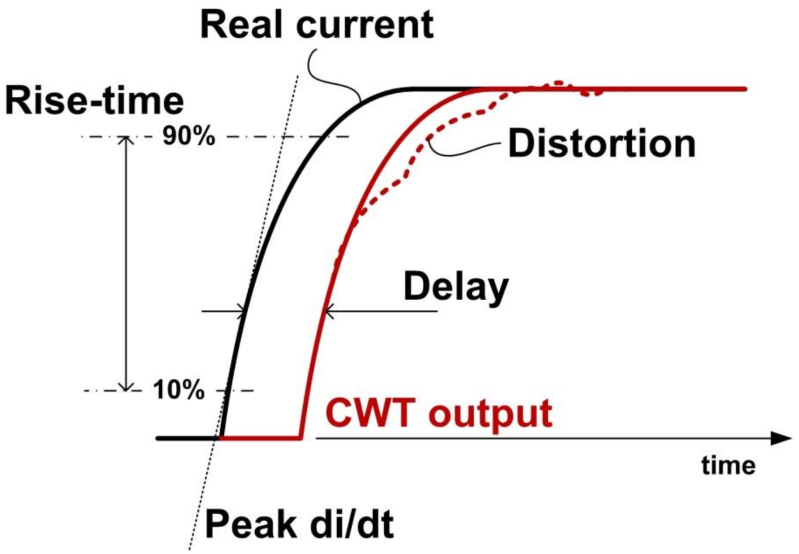
- Engineers strive to remove as much stray inductance from a circuit as possible for more efficient switching and prevent undue device stress.

Rejecting external interference EMI

- Often a requirement to measure a small current in the presence of large dV/dt – power electronics is a very hostile environment.

Delay and maximum rise-time: Definitions



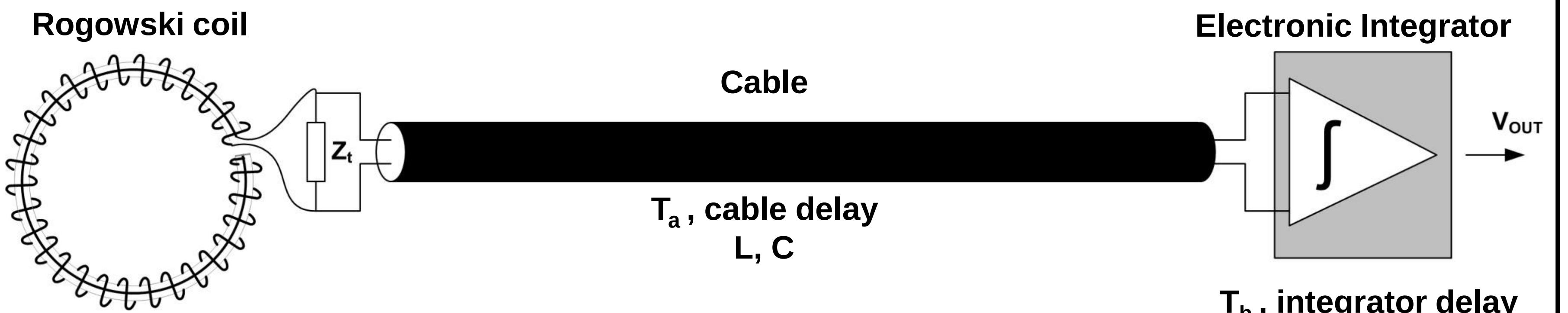


The CWT has an inherent measurement **delay**. Provided the rise-time of the current is within the limits of the high frequency bandwidth (termed **Max. rise-time**) of the CWT the delay is predictable.

If the pulse is outside the Max. rise-time the probe the measurement will become increasingly distorted.

There is also a slew rate limitation on Rogowski current sensors, this is termed the **Peak di-dt** of the probe. This is typically very large for the CWT range.

Delay and maximum rise-time: Explanations



Delay = $T_{coil} + T_a + T_b$

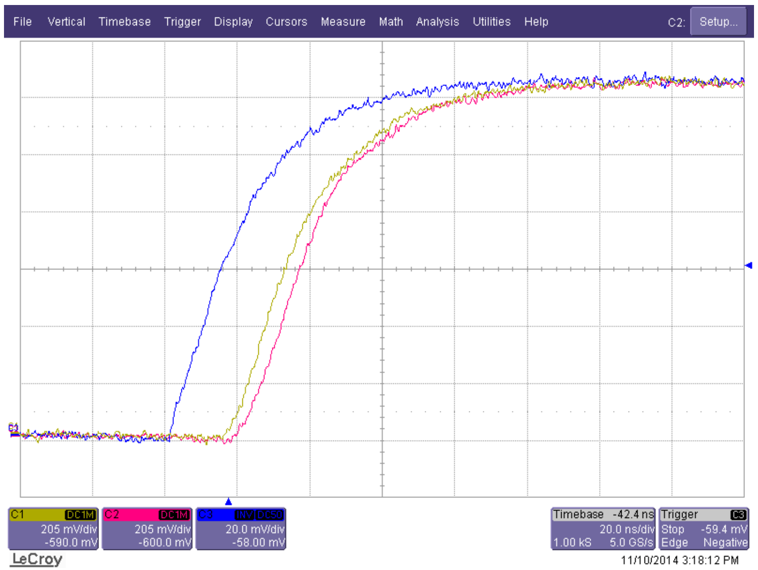
Max. rise time = $5 * T_{coil}$ or if > $5 * T_b$

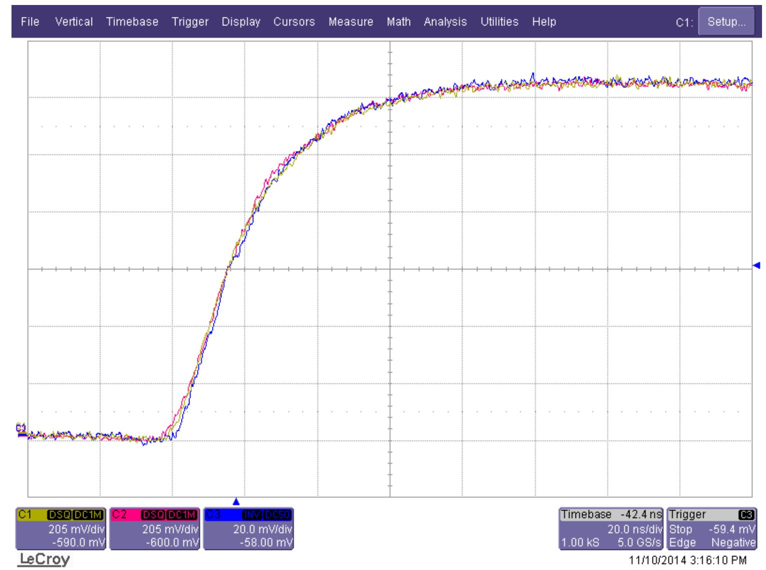
- T_b and T_{coil} cause an attenuation of the measurement, T_a does not. Thus rise-time is dependent on T_b and T_{coil} and is different for the various CWT models.
- Calculating the maximum rise-time not as straight-forward as other probes such as shunts or CT's but it can be approximated to 5 times the dominant time constant T_b or T_{coil}.

Delay and maximum rise-time: CWTMiniHF

Model (Cable length, Coil length)		Delay (ns)	Maximum Rise Time (ns)
CWTMiniHF	(1m, 100mm)	17.5	20.0
	(1m, 200mm)	20.9	36.0

10 to 90% rise time 40ns





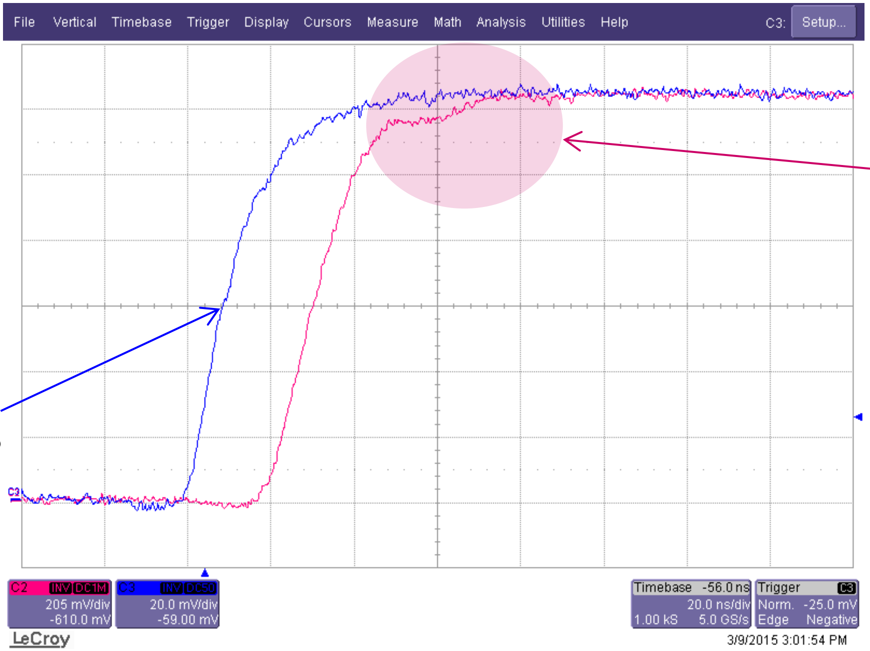
Ch 1: Co-ax shunt, DC-800MHz – 20mV/div
Ch 2: CWTMiniHF 03 (200mm) – 205mV/div (2A/div)
Ch 3: CWT MiniHF03 (100mm) – 205mV/div (2A/div)
Time 20ns / div

Delay and maximum rise-time: Exceeding rise-time

Power Electronic Measurements

CWTMiniHF 03
1m cable, 200mm coil
Max. rise time = 36ns

Actual rise time = 19ns



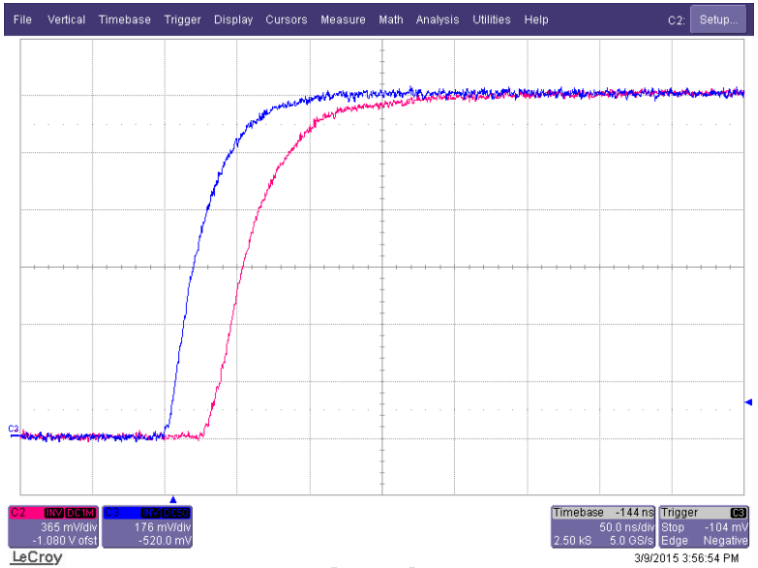
Distortion

Ch 1: Co-ax shunt, DC-800MHz – 20mV/div
Ch 2: CWTMiniHF 03 (200mm) – 205mV/div (2A/div)
Time 20ns / div

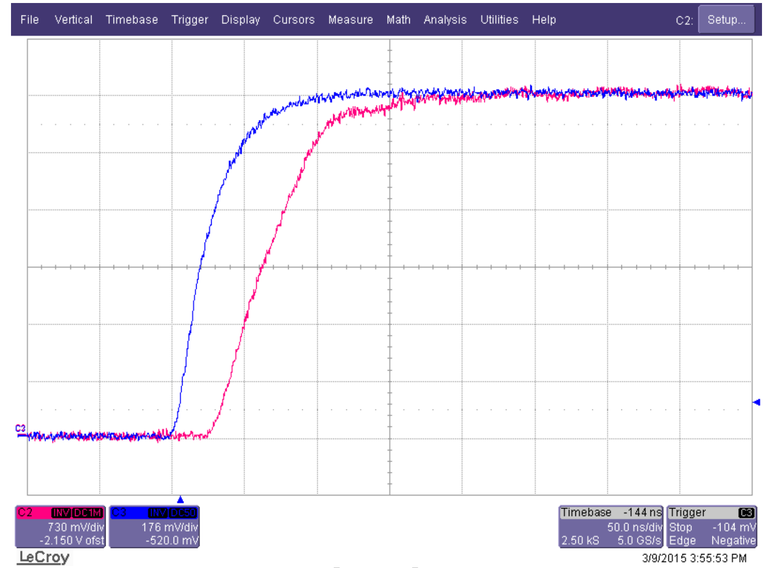
- Oscillations increase as the rise time increases beyond maximum.
- CWT output becomes more susceptible to variation of conductor position within the Rogowski coil

Delay and maximum rise-time: Exceeding di/dt

CWT Mini 1 /4/200 -- 300A peak, Peak di/dt = 2.5kA/µs, 200mm coil, Max. rise time = 50ns



105A peak, Rise = 50ns



210A peak, Rise = 50ns

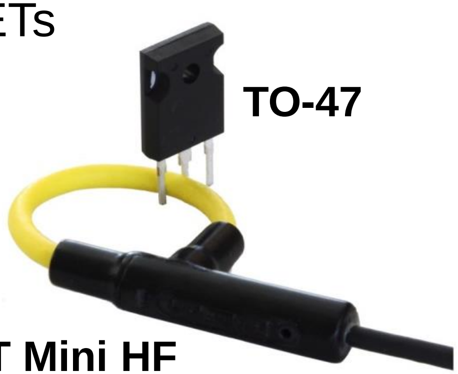
Ch 1: Co-ax shunt, DC-800MHz – 20mV/div
Ch 2: CWTMini1 (200mm) – 205mV/div (2A/div)
Time 20ns / div

- Very difficult to exceed the peak di/dt values for CWTUM and CWTMiniHF (up to 100kA/µs) ranges if current is within the max. rise time
- CWTMini range with the optimised LF performance it is possible to exceed Peak di/dt whilst staying within the maximum rise time criteria

Insertion impedance

- Insertion impedance from a current sensor can impair the performance of power converters,

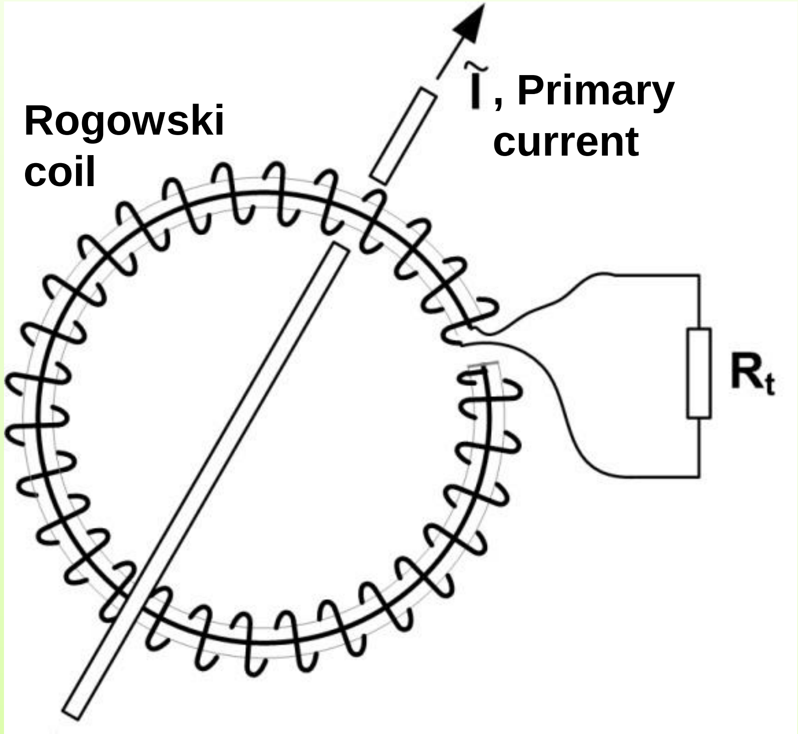
  - **Physical size,** if circuit has to be altered to fit a current sensor this adds unnecessary additional track resistance and inductance
  - **Reflected impedance,** for some magnetic-core based sensors inserted impedance of a few 100nH is common >> package inductance of modern devices.
  - **Direct impedance,** although low inductance, even with careful placement SMD and co-axial shunts can add resistance > $R_{D\ ON}$ of many modern MOSFETs



CWT Mini and CWT Mini HF
3.5mm (2kV) and
4.5mm (5kV) insulation

CWT Ultra-mini
1.7mm (1.2kV) insulation

Insertion impedance



Let:

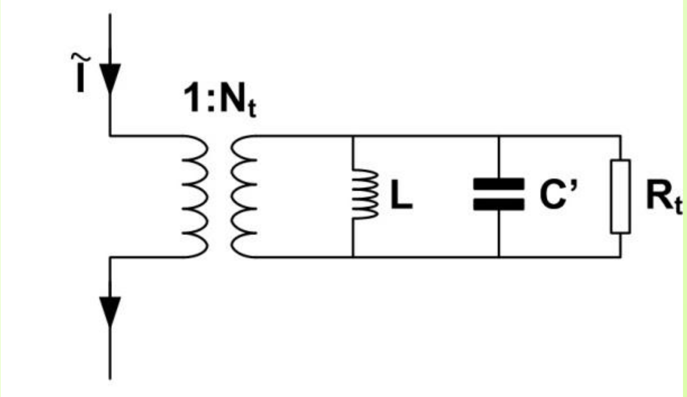
L = coil inductance (H)
C' = equivalent coil capacitance (F)
H = coil sensitivity (Vs/A)
N_t = equivalent coil turns = L / H

And:

R_t = coil characteristic impedance $\sqrt{(L/C')}$
ω_n = $1 / \sqrt{(LC')}$ coil natural frequency

By considering the power dissipated in the termination resistance and the distributed coil impedance the injected impedance into the primary circuit can be ascertained.

Insertion impedance



The insertion impedance is a parallel combination of L_l, C_l, R_l, where

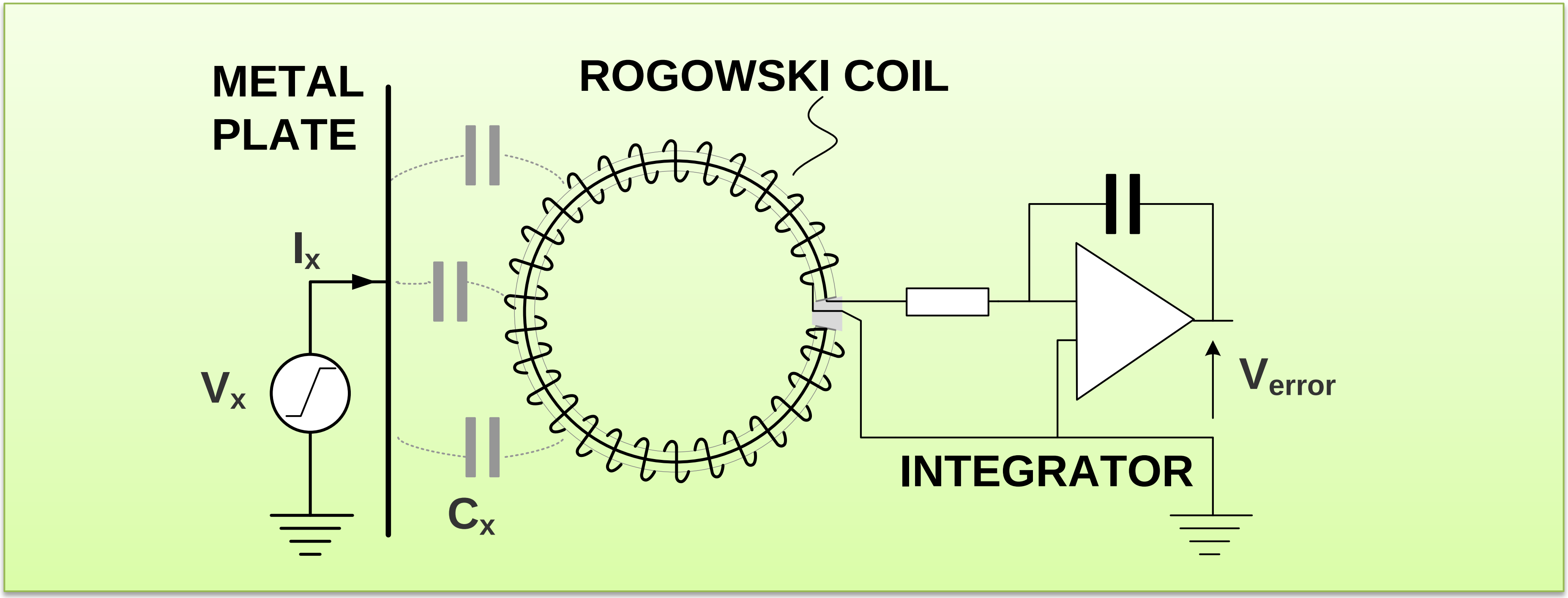
$L_l = L / N_t^2$
$C_l = C'. N_t^2$
$R_l = R_T / N_t^2$

Where:
- **$\omega \ll \omega_n$** the inserted impedance is $j\omega L_l$ ($\ll R_l$).
- **ω approaches ω_n** the impedance increases up to R_l.
- **$\omega > \omega_n$** the model is no longer valid due to the transmission line effects of the coil but this is outside the bandwidth of the coil.

CWT type	Coil Length	L_l	R_l	f_n
	mm	pH	mΩ	MHz
CWT Standard	300	45.4	5.21	30.8
CWT Mini HF	200	5.0	0.50	26.4
CWT Mini	200	20.1	3.24	32.0
CWT Ultra mini	90	13.1	3.22	64.5

Rejecting external interference voltage

The problem is well rehearsed – PEM have produced several papers on the effect of voltage disturbance on Rogowski coils. Problem described as follows:



A disturbance dV_x/dt causes an unwanted displacement current to flow onto the coil winding ultimately giving rise to interference V_{error}

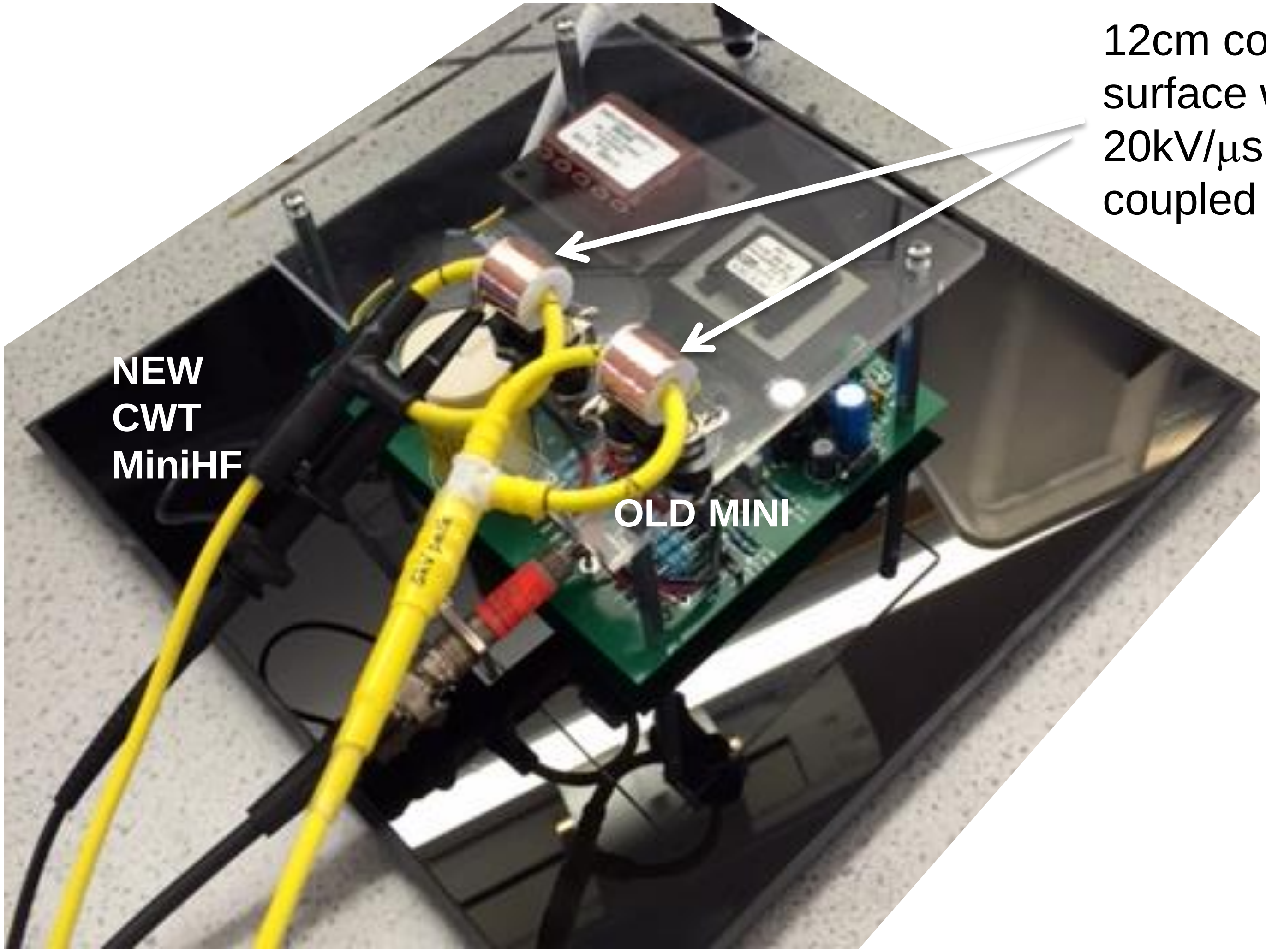
Rejecting external interference voltage

Only concerned with PEM's small CWT coils, usually the 'worst case' i.e. small currents, very little space to insert the current sensor and fast devices with high dV/dt.

The obvious solution to the problem is to screen the Rogowski coil, and PEM produce screened coils of just 4.5mm thickness. Even then sometimes even smaller coils are necessary!

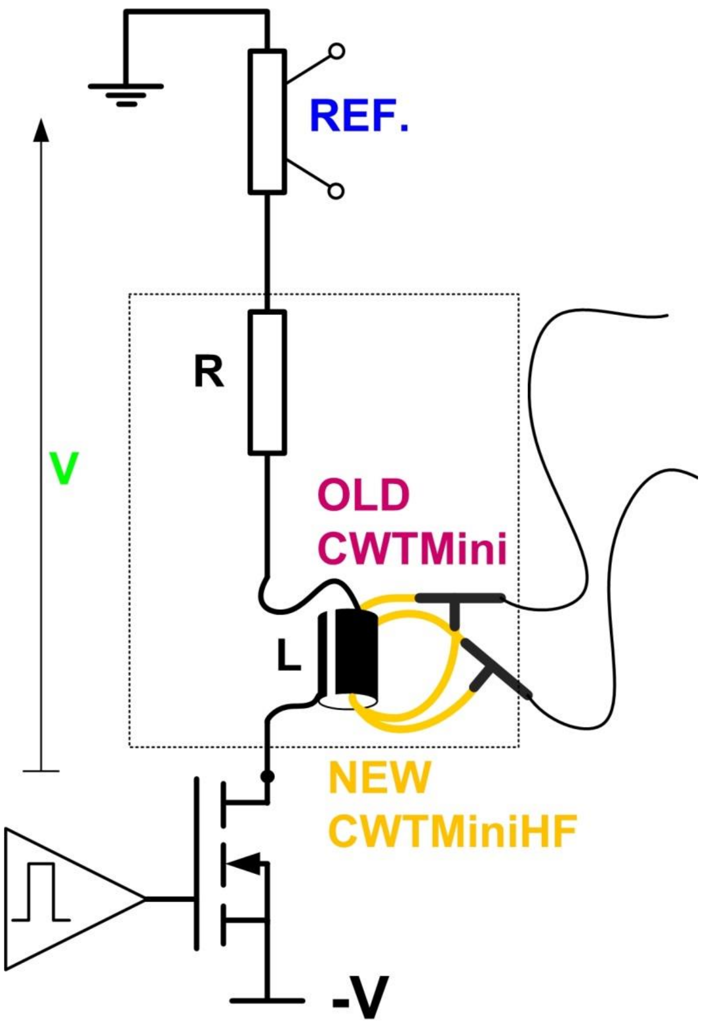
	OLD CWT Mini	NEW Jan 2015-- CWTMiniHF	CWT Ultra mini
Screened coil	NO	YES	NO
Max. Coil thickness / (Minimum length)	4.5mm / (100mm)	4.5mm / (100mm)	1.7mm / (80mm)
Improved peak di/dt	40kA/μs	YES (up to 100kA/μs)	YES (up to 70kA/μs)
Improved hf (-3dB)	17MHz	YES (30MHz)	YES (30MHz)

Rejecting external interference voltage

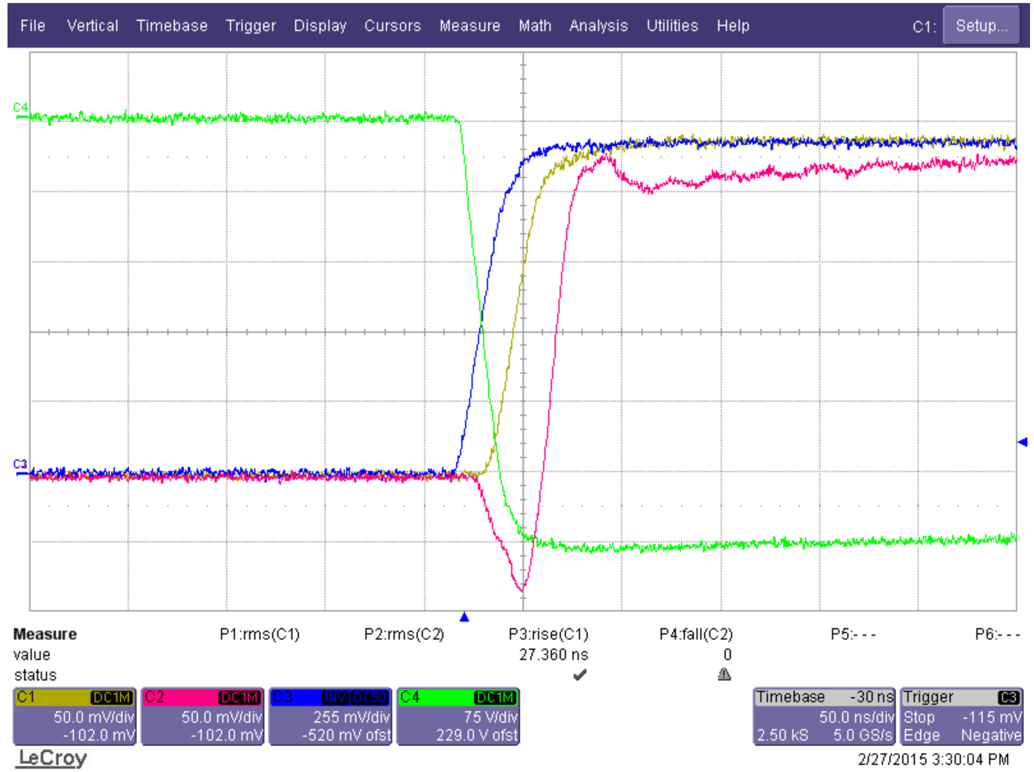


12cm copper surface with 20kV/μs close coupled to the coil

Rejecting external interference voltage

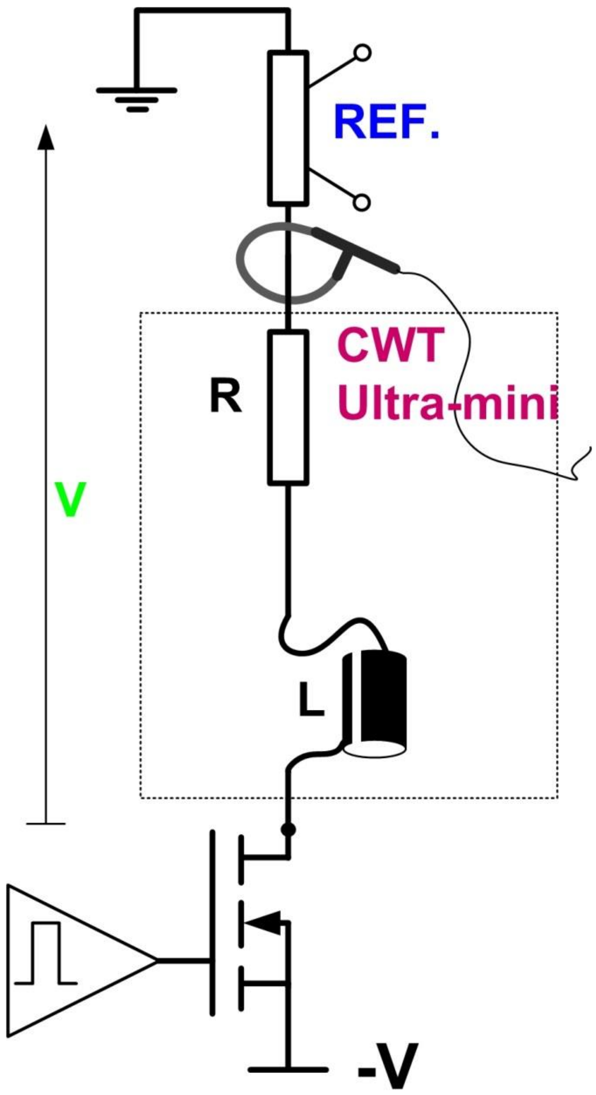


12A peak (300A peak probes),
Rise-time 20ns, dV/dt = 20kV/µs

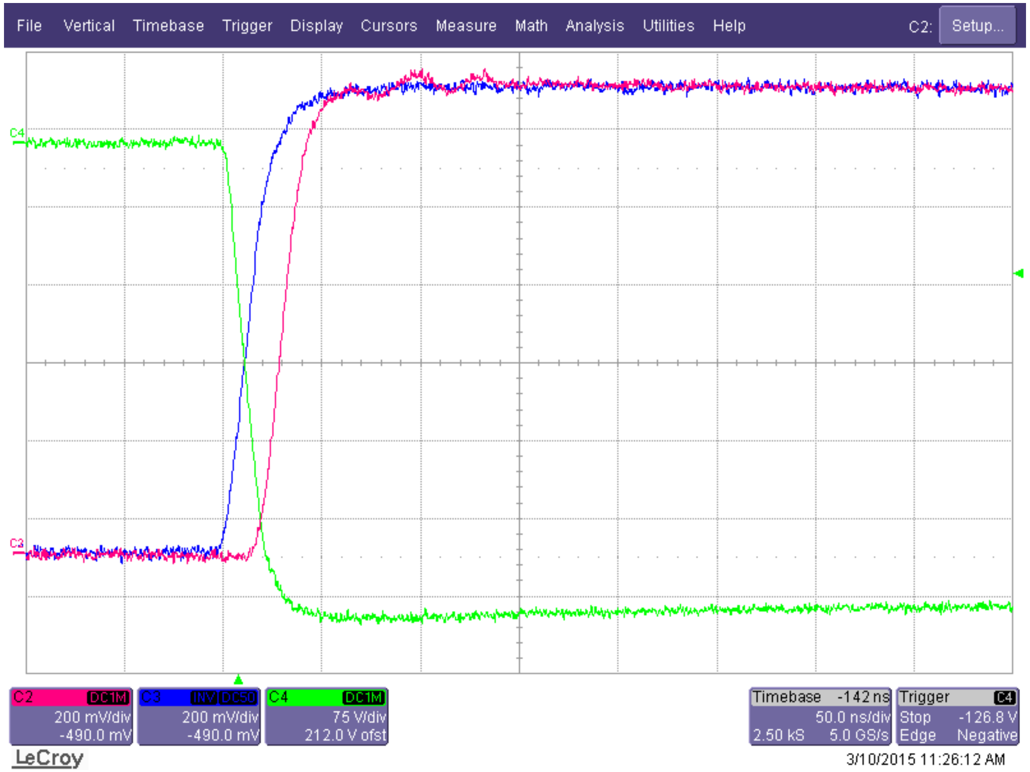


Ch 1: Co-ax shunt, DC-800MHz – 255mV/div (2.5A/div)
Ch 2: OLD CWT1B/1/100M/5 – 50mV/div (2.5A/div)
Ch 3: NEW CWT MiniHF1/B/1/100/5– 50mV/div (2.5A/div)
Ch 4: Voltage – 75V /div
Time 50ns / div

Rejecting external interference voltage

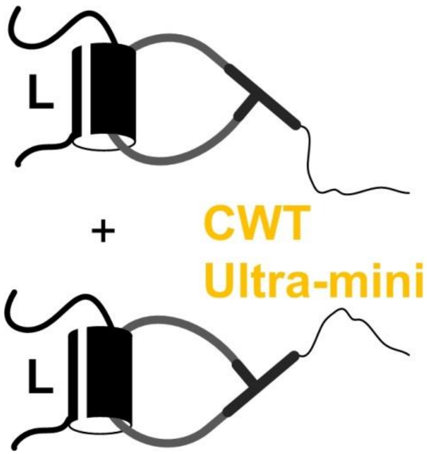


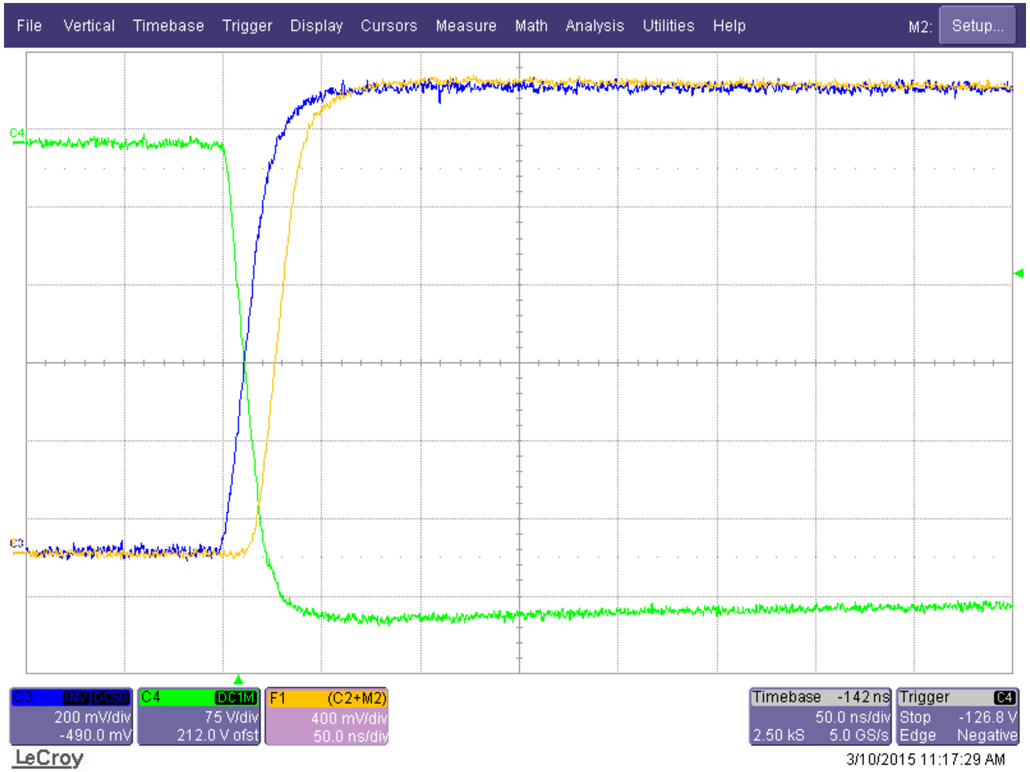
12A peak, Rise-time 20ns,
dV/dt approx 1kV/μs as R>>R_{REF}



Ch 1: Co-ax shunt, DC-800MHz – 200mV/div (2A/div)
Ch 2: OLD CWTUM/03/B/1/80 – 200mV/div (2A/div)
Ch 4: Voltage – 75V /div
Time 50ns / div

Rejecting external interference voltage





Ch 1: Co-ax shunt, DC-800MHz – 20mV/div
F1: CWT Ultra mini without the voltage interference
Ch 4: Voltage – 75V /div
Time 50ns / div

Rejecting external interference current

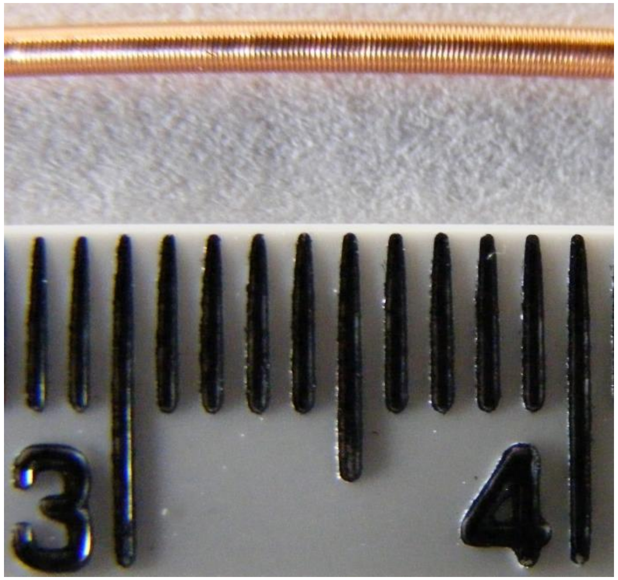
Theoretically a perfectly wound Rogowski coil with

- no discontinuity (clip-together),
- uniform turns density,
- and a return conductor or winding with perfect concentricity

will reject any current external to the Rogowski coil loop.

Due to small variations in the winding density and in the cross-section area of the former, the coil does not perfectly reject external currents.

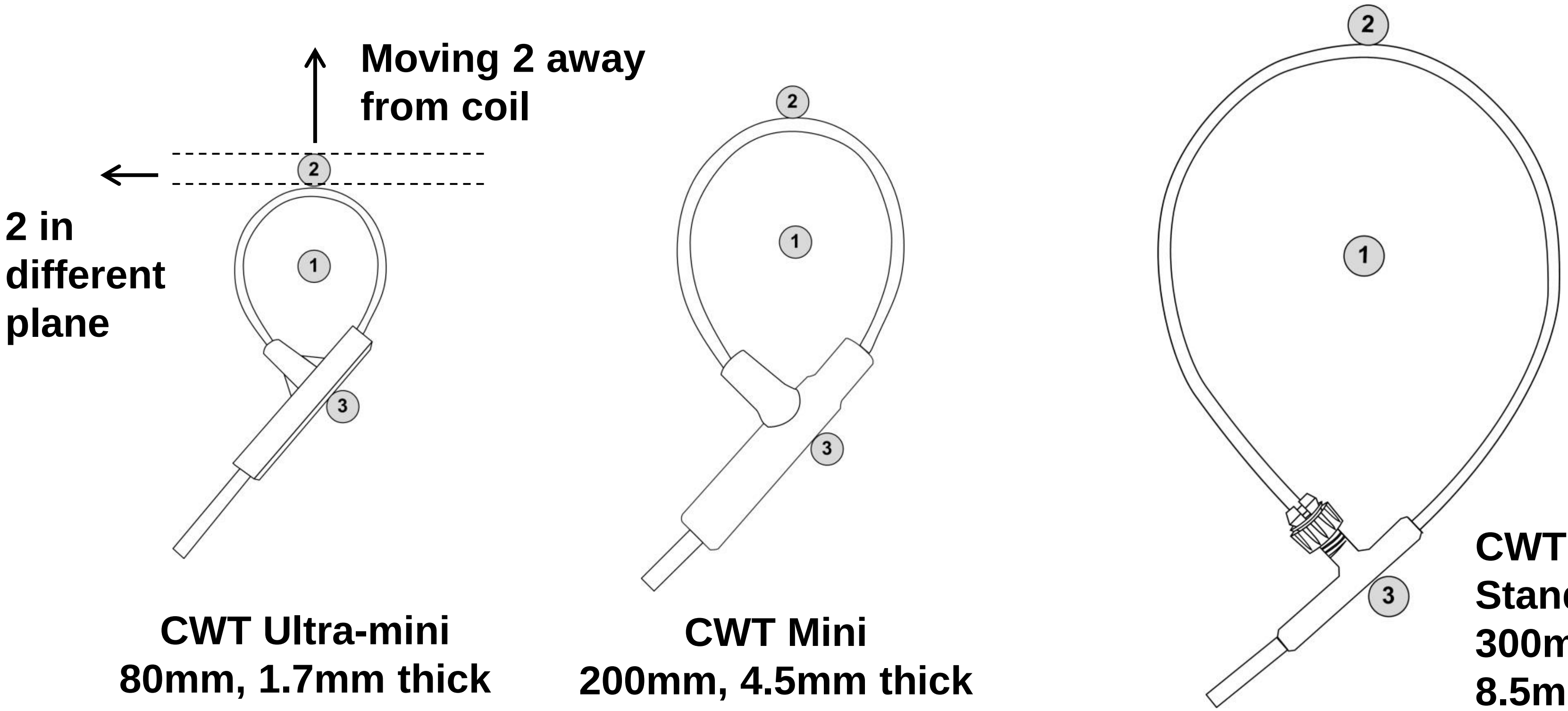
More significantly, particularly for the very small CWT Mini and CWT Ultra mini coils minimising the effect of the clip-together discontinuity and the coil cable connection is critical to ensuring good rejection of external currents.



Old CWTUM

Rejecting external interference current

The conductor is 1mm radius



CWT Ultra-mini
80mm, 1.7mm thick

CWT Mini
200mm, 4.5mm thick

CWT Standard
300mm,
8.5mm thick

Position	CWT Ultra Mini	CWT Mini	CWT
2	±3%	±2%	±1.5%
2 + 1 coil radius	< ±2%	<±1%	<±0.5%
3	-8.0%	-6.0%	-3.5%

Summary

Probe delay and maximum rise-time

- Improvements to bandwidths and slew rate of the CWT Ultra-mini and CWT MiniHF enable rise-time of up to 20ns to be measured.

Virtually zero insertion impedance

- Small clip-around probes add negligible inductance and resistance to the primary circuit

Rejecting external interference EMI

- The new CWTMiniHF has an electrostatic screen to attenuate voltage interference
- Even very thin small coils can be used in high dV/dt environments with a careful placement or some simple post processing
- Accurate manufacture enables good rejection of external magnetic fields whilst retaining a simple to use coil