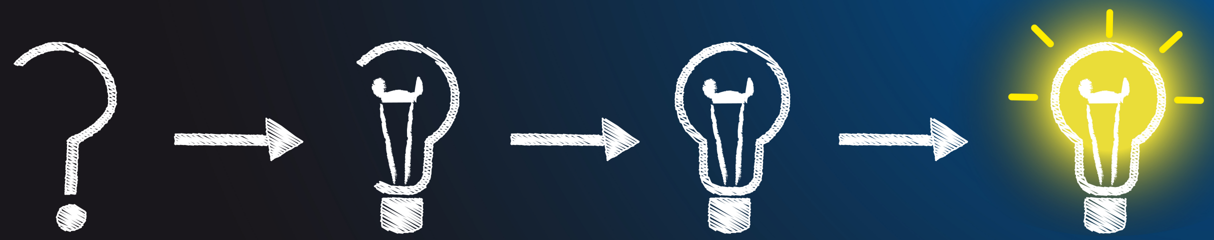


10th Power Analysis & Design Symposium

March 10th, 2021 - Worldwide (Virtual)

Single Cable and Connector Bode Diagrams and Step-Load Adapter for DC/DC Bode Measurements

by Christian Kück - Monolithic Power Systems

OMICRON LAB

Bode and Step load tests over single cable connection to DUT with Rev 2.0 Adapters

Presenter: Christian Kueck

Nov 10, 2021

MPS

Presenter Intro: Christian Kueck

- Senior FAE supporting automotive Tier-1 customers throughout Germany
- Over two decades of experience in PSU challenges
- Deeply involved in the definition and compliance testing of our leading AEC-Q100 power management solutions
- 22 years at Linear Technology
  - Strategic Marketing Manager for Europe – Product definition and product support for PSU and LED circuits
  - Field Application Engineer
- Additional:
  - Design Engineer, Quality Assurance, Materials Engineer
- Microelectronics. Dipl. Ing., Elektrotechnik University of Dortmund

Today's Agenda

- The Motivation
- Measuring bode plots. What is required
- How to reduce the hookup harness
- Examples of Bode measurement and interpretation
- Step load response with the same hookup
- Examples to Step load response and interpretation
- Open Q&A

Motivation

For switchmode PSU characterization over production parameter spread, stability analysis is essential.

For small signal stability analysis the Bode measurement of loop gain and phase gives answers.

For large signal analysis the step load analysis gives answers.

Can the results of Bode and step load be different?

For an ideal LTI (Linear Time Invariant) system large signal and small signal response behaves the same and you can calculate the expected results from Bode to step load and vice versa.

In the real world gain and slew rate of PSU stages are amplitude dependent so they are often non linear over large amplitudes/excitations. Beside slew rate limitations the gain will be device operation point dependent.

In reality you can see large signal step load responses suggesting high stability margins i.e. asymptotic step loads without any ringing, but at the same time Bode small signal analysis show low phase margins.

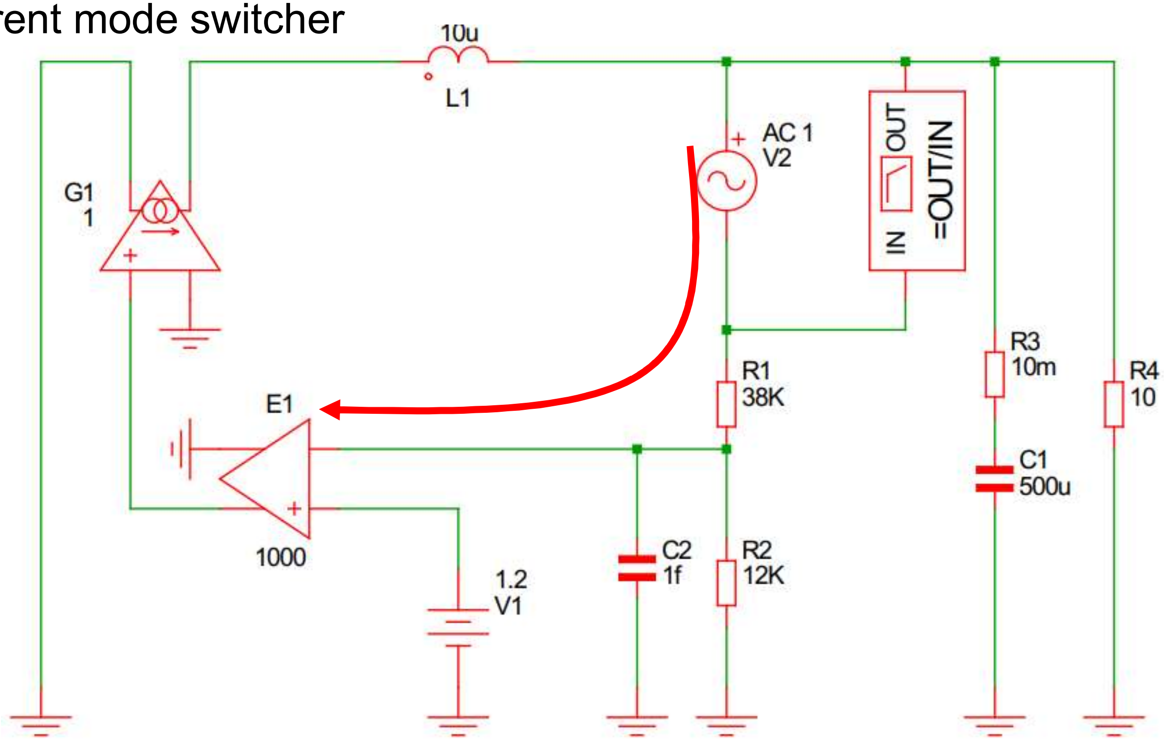
Often the regulation loop shows less gain at a step load situation because the devices operate in a different operating point compared to a small signal excitation within their linear range measured by a Bode plot.

So you should examine both: Bode and step load

How a Bode measurement is made?

You could measure the loop anywhere along this red path

Current mode switcher



You inject a small signal anywhere into the regulation loop. Then you measure the vector quotient of V(x)/V(y).

For the AC excitation source you can use an injection transformer to get a floating AC source and you have 3 wires attached to the DUT board.

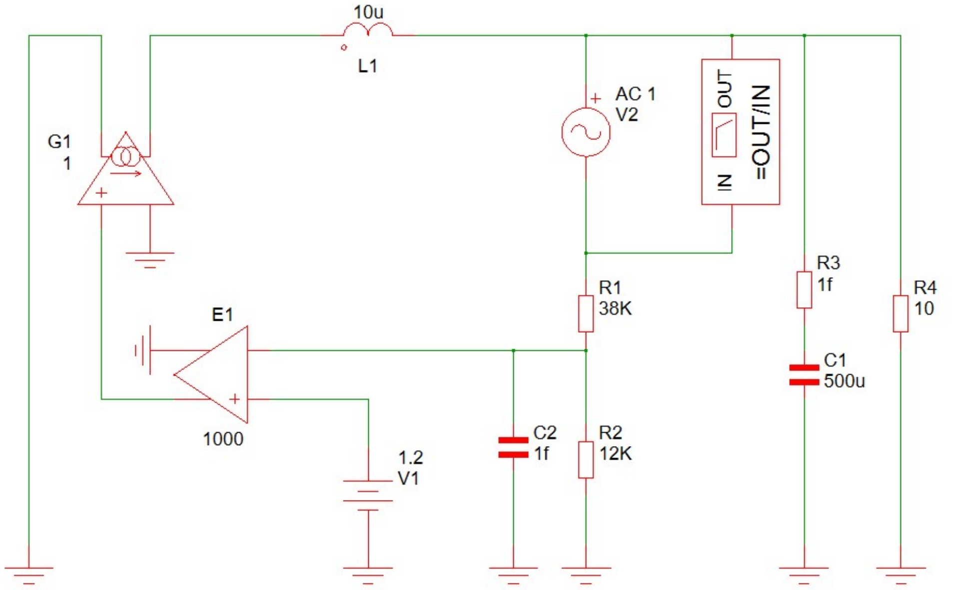
Those 3 wires can't usually be long, since they are attached to the feedback loop

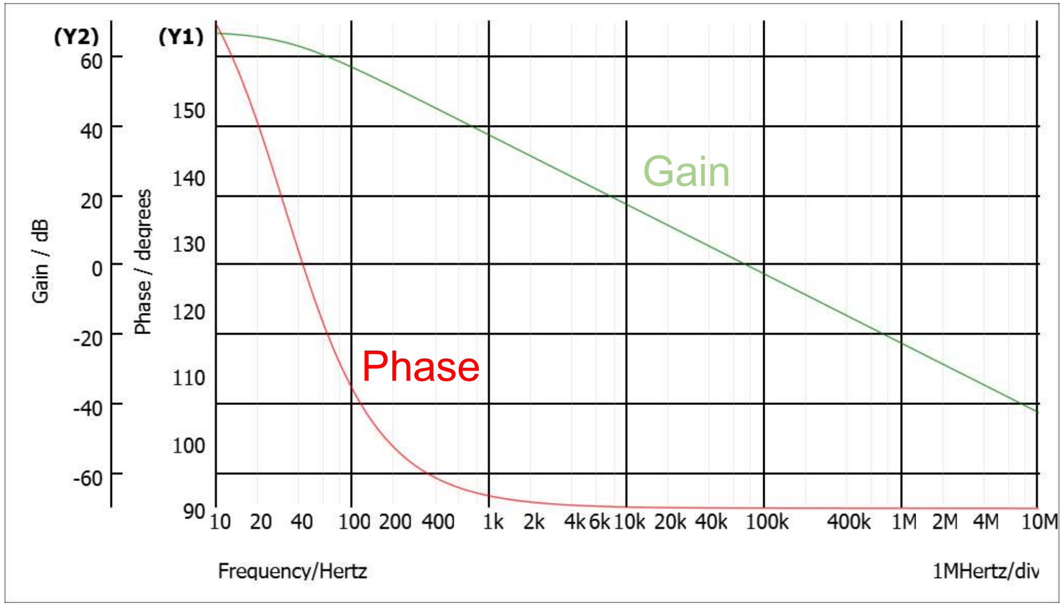
Motivation

A Bode measurement on a final production board is as much a mechanical probing problem as it is an electrical one.

Two scope probes and a banana cable or yellow wire hooked up with transformer are not a mechanical stable system to use in a climate chamber etc.

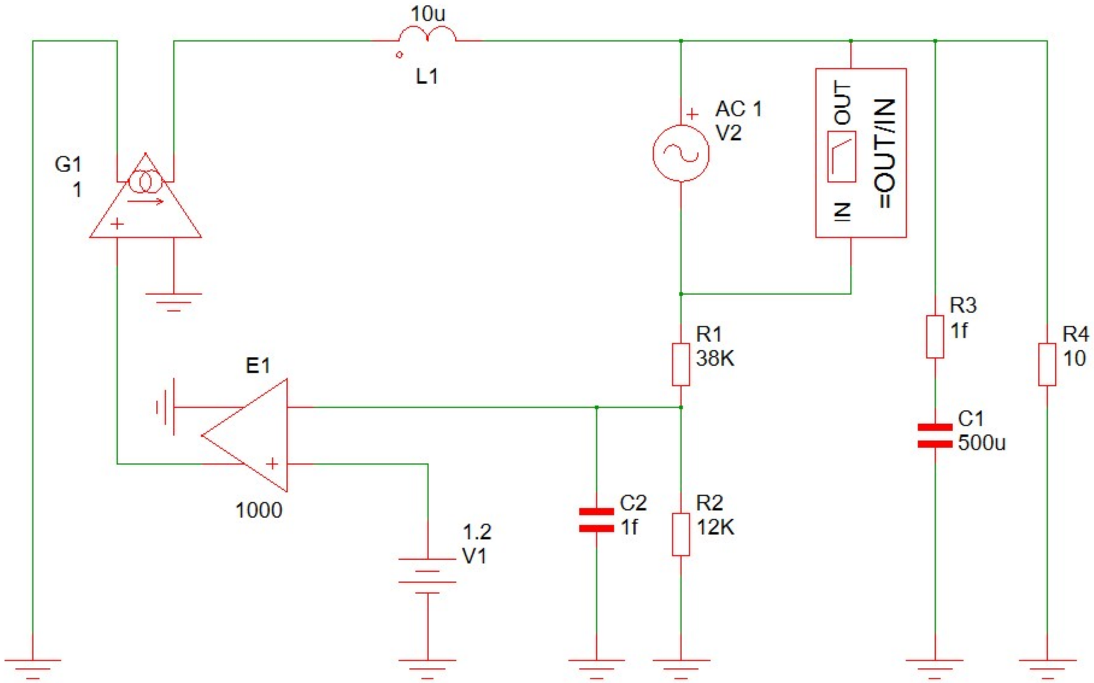
How a Bode measurement is made?





Bode plot made with MPSmart simulation of a close to ideal current mode PSU

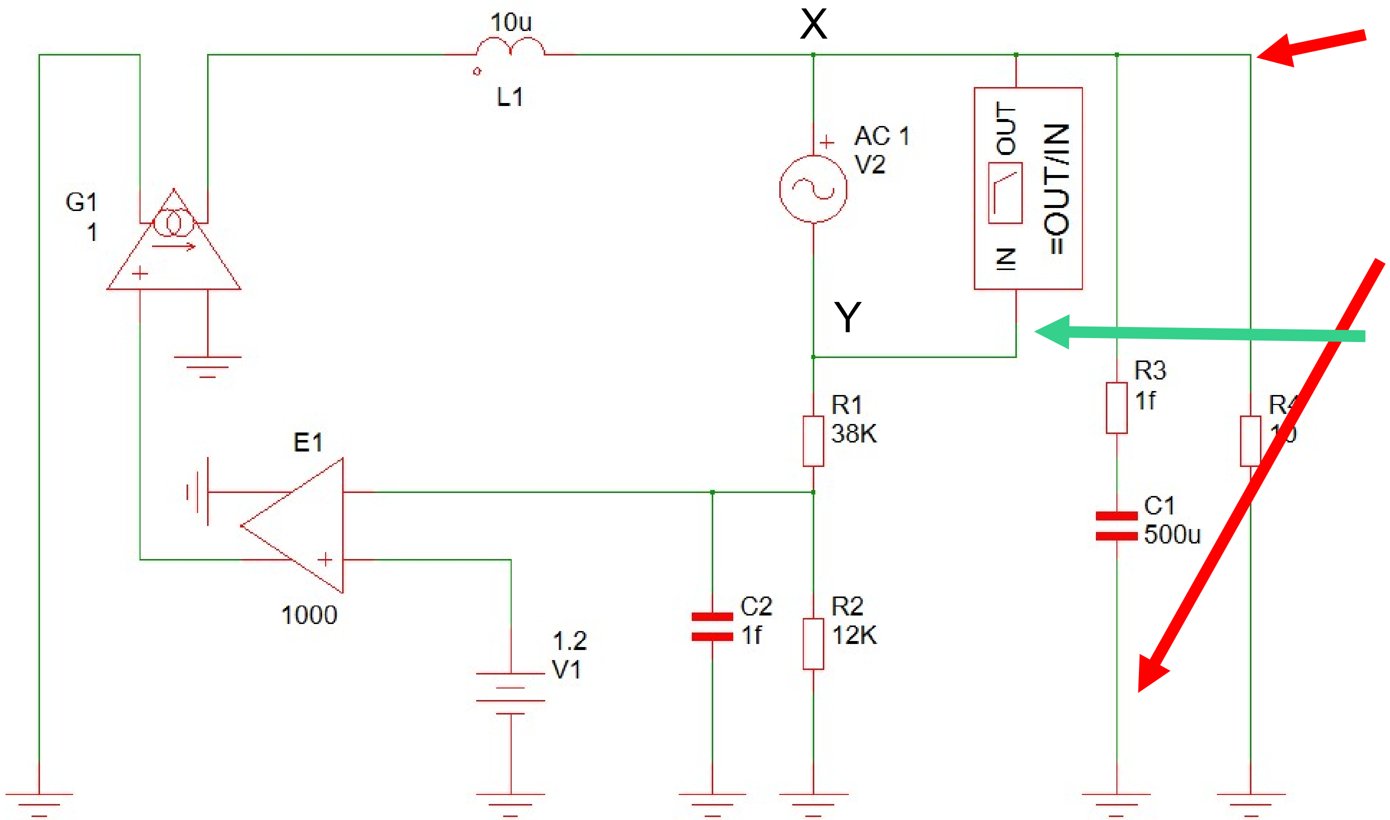
Conventional Bode measurement



For the AC source you need an injection transformer to get a floating AC source

On an auxiliary board with the injection transformer and hooks for the probes you have 3 wires attached to the DUT board.
Those 3 wires can't usually be long, since they are attached to the feedback loop

Where to hook for Bode

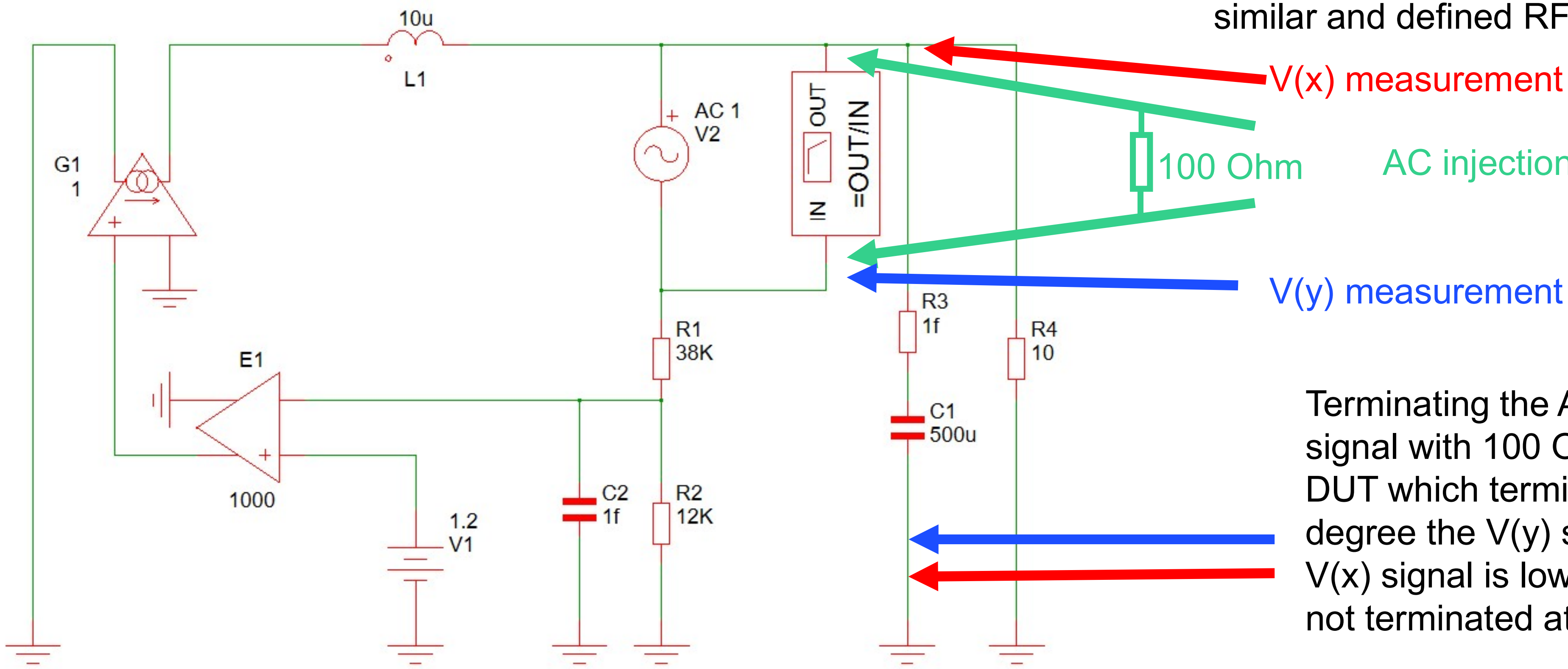


Low impedance hooks. Vout and GND found at the output capacitors. That are easy to probe low impedance points which are mechanical robust.

Y-node is higher impedance. Typical you use a 50 or 100 Ohm resistor here on the board between x and y node to keep impedance low.

Idea: Hook on the output capacitor and leave the AC source isolation at the analyzer

This will need 3 cable pairs with similar and defined RF characteristic.



Terminating the AC injection signal with 100 Ohm at the DUT which terminates to some degree the V(y) signal. The V(x) signal is low impedance not terminated at the DUT.

If you search for a single cable which does the job, LAN/Ethernet patch cables are about the ideal solution.

They combine:

- 4 pairs for 4 channels available. We need minimum 3.
- They come with specified impedance 100 Ohm +/-10%
- Good RF isolation of one pair against the other.
- Inexpensive
- Available in all length and colors with a standard RJ45 connector
- RJ45 connector inexpensive and available in surface mount packaging
- High reliability gold contacts
- Rated for 60V and small signal use (about 1A but beware of resistance).

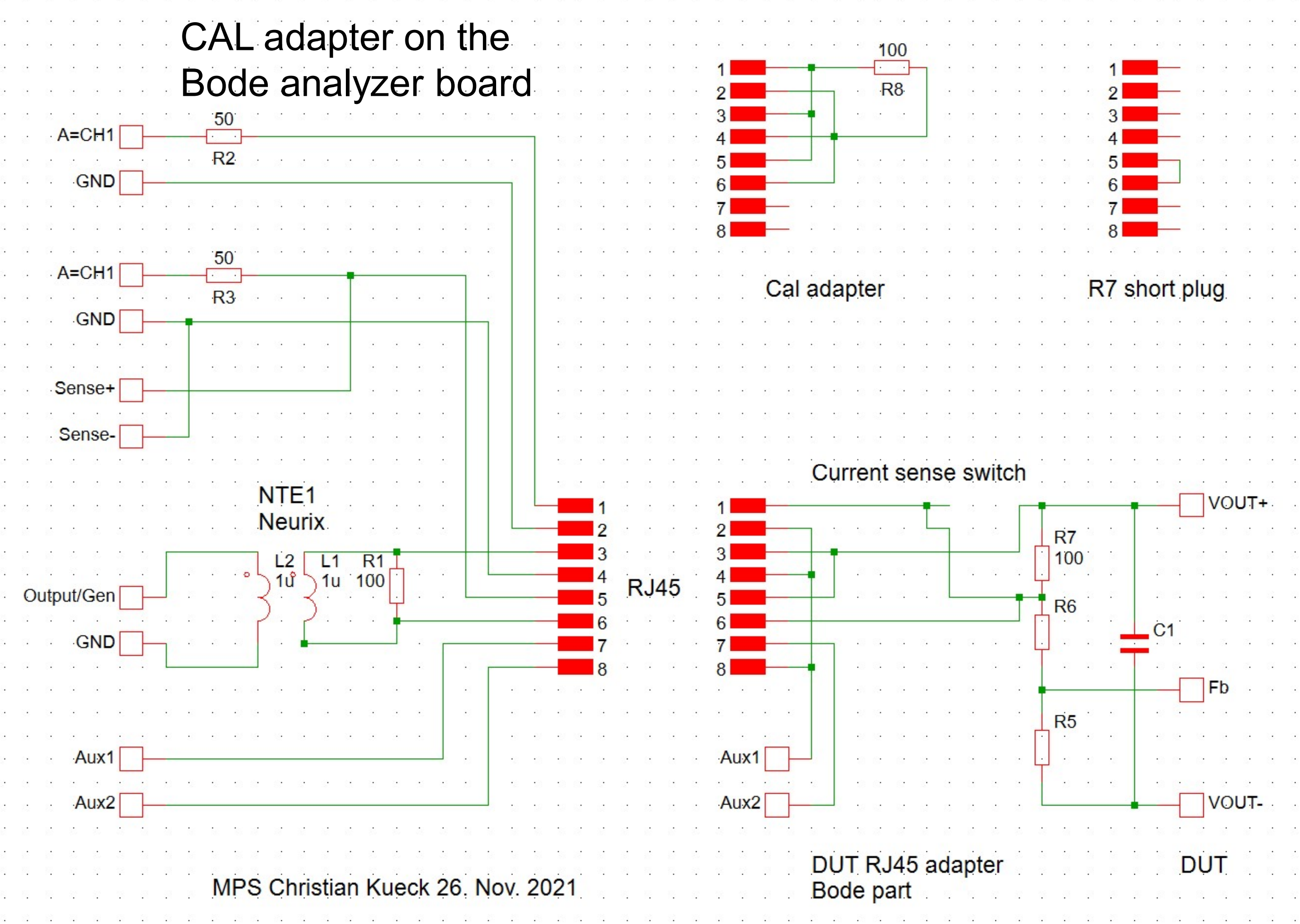
Attention:

Pair 2 is on pin 3 and 6

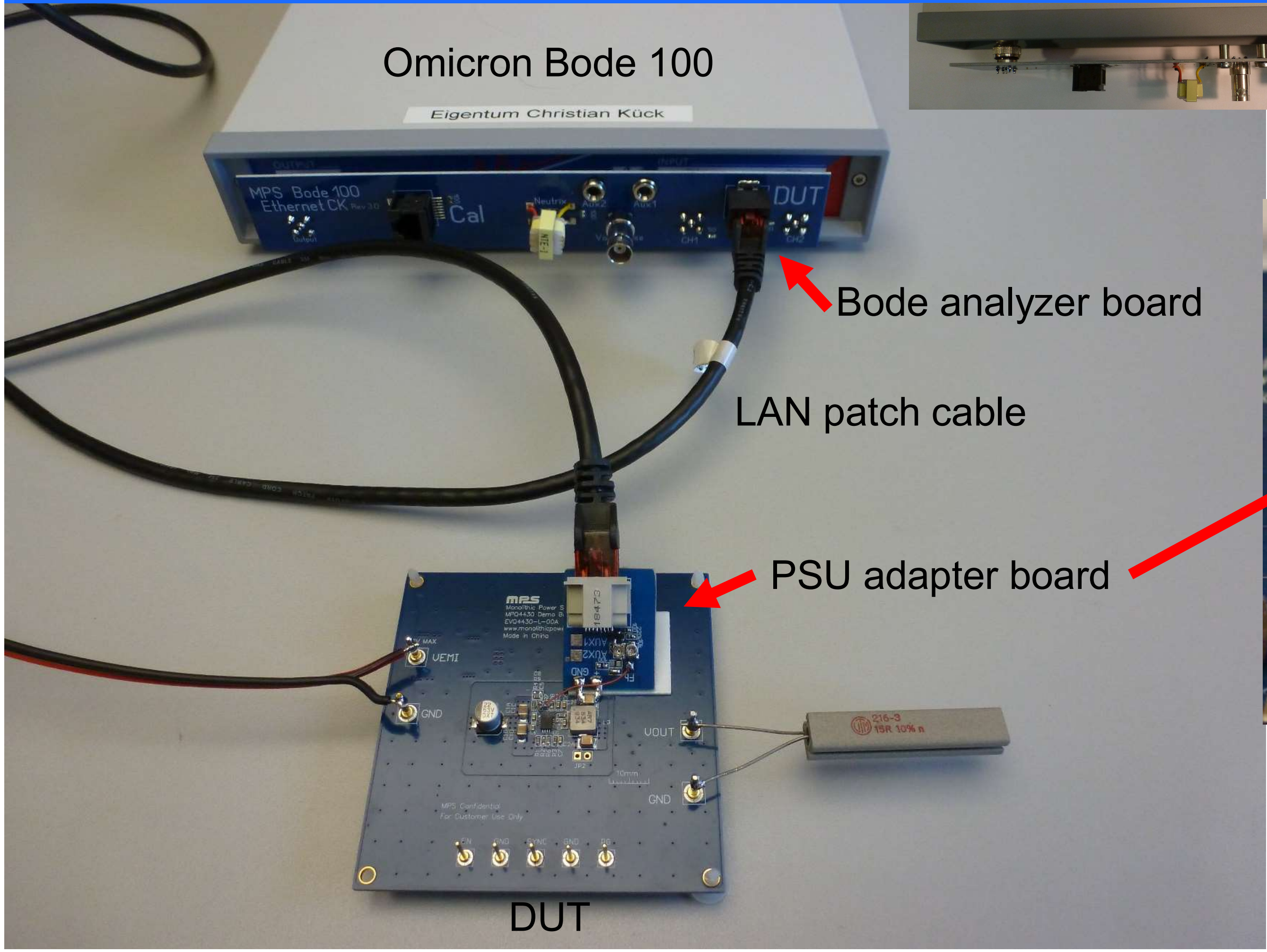
Through hole RJ45 connectors often have non standard non sequencing pin out. Keep to SMT RJ45 connectors if you can.

Why do I know….

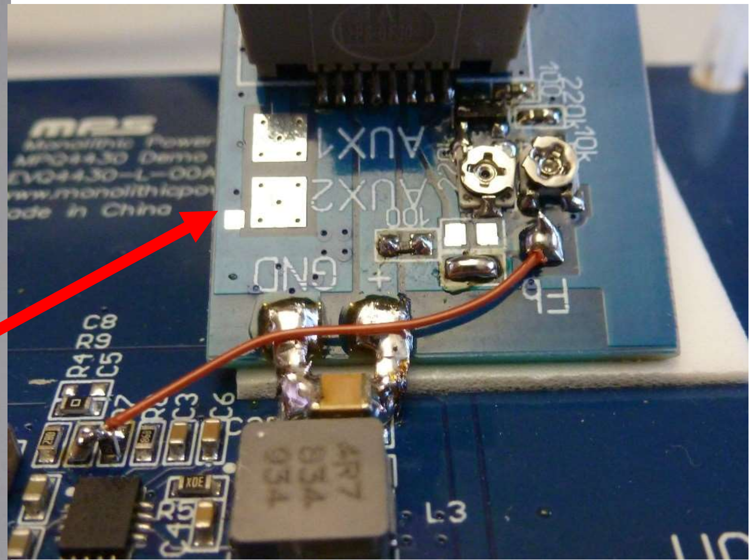
Bode Connector schematic



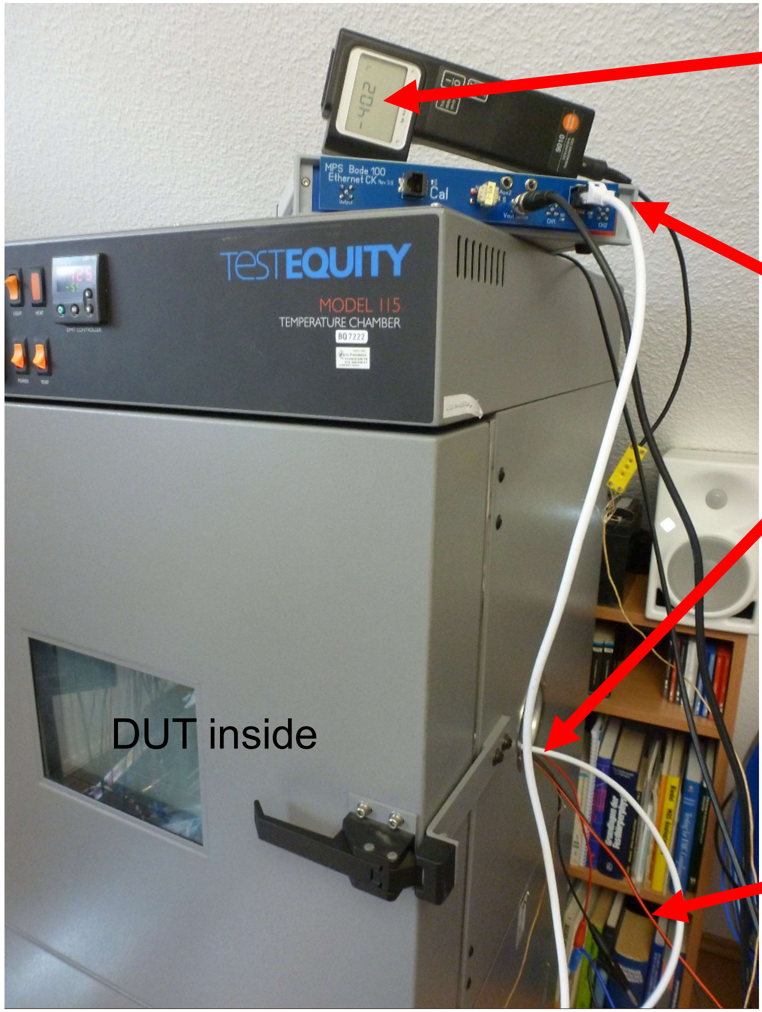
Bode Setup



PSU adapter board with Fb connection



Bode Setup in Thermal Chamber



Onboard temp measurement

1 LAN Patch cable makes the complete connection to the Bode 100

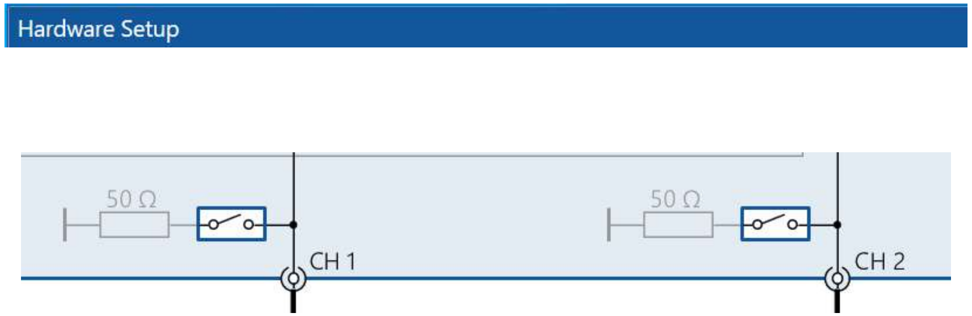
Power and DC Load connections

Caveat:

Run the Omicron Bode 100 in high impedance mode. Otherwise its max. CH1 / CH2 BNC voltage is limited to 7V due to 50 Ohm termination thermal limitation. R2 and R3 will double that to 14V but the 0402 resistors will burn easily.

Set at no termination to my knowledge the Bode 100 CH1/CH2 voltage limit is about 35V DC.

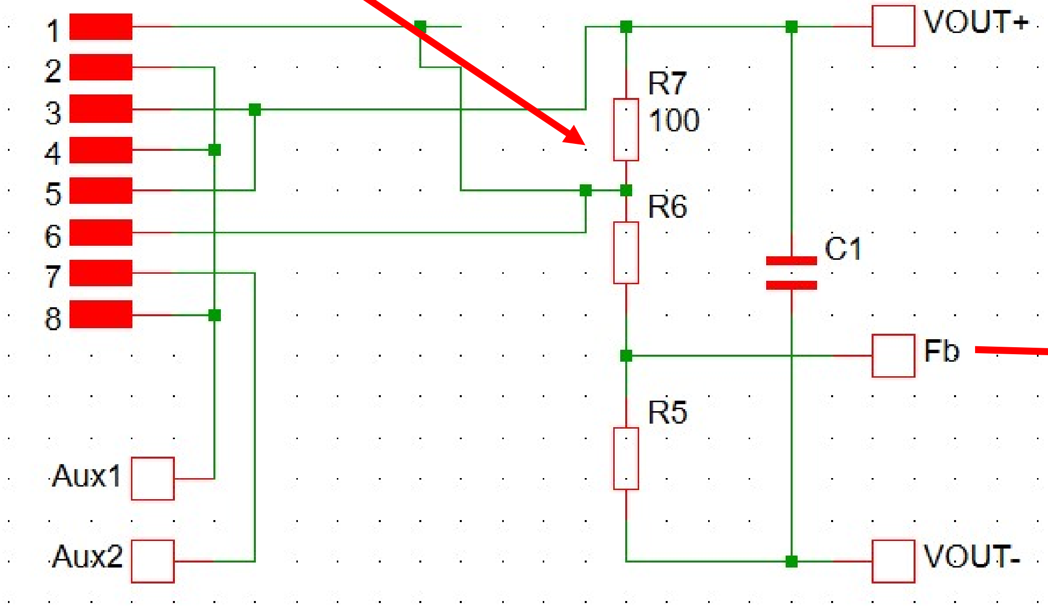
Do not exceed that.

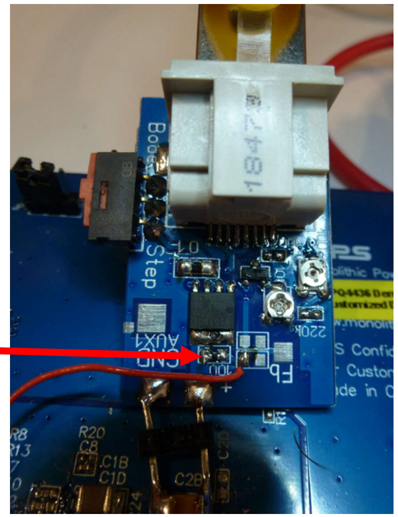


Caveat:

The FB loop is with the PSU board only closed over a small yellow wire.
If that connection breaks on buck regulators typical a VIN=Vout situation occurs. A boost will destroy itself immediate with producing over voltage.

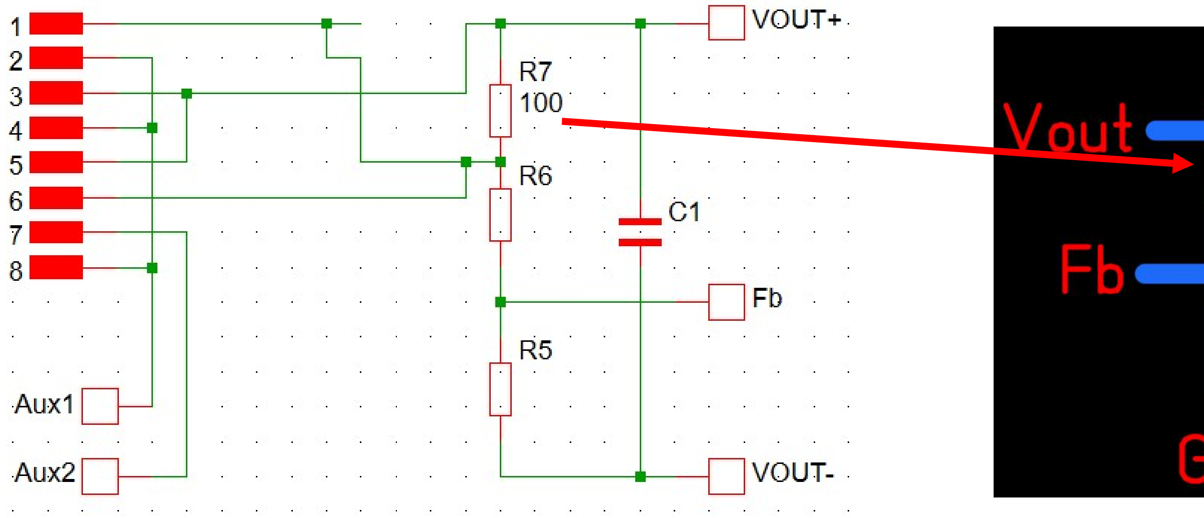
Best would be if the 100 Ohm R7 is optional placed on the final PCB right away.
Check if that is feasible.

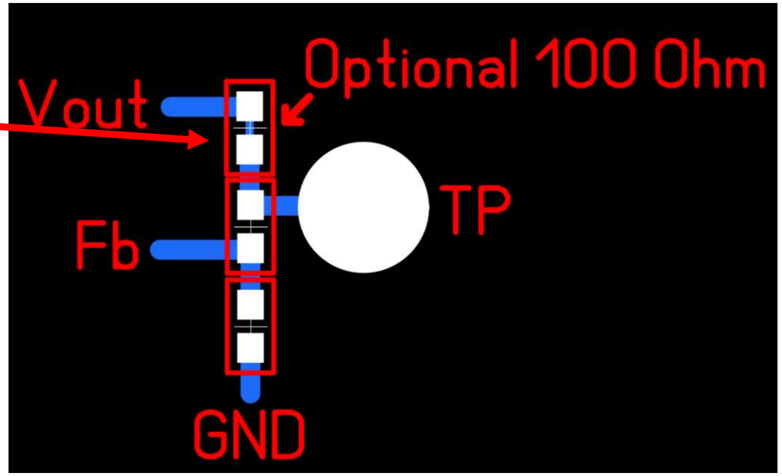




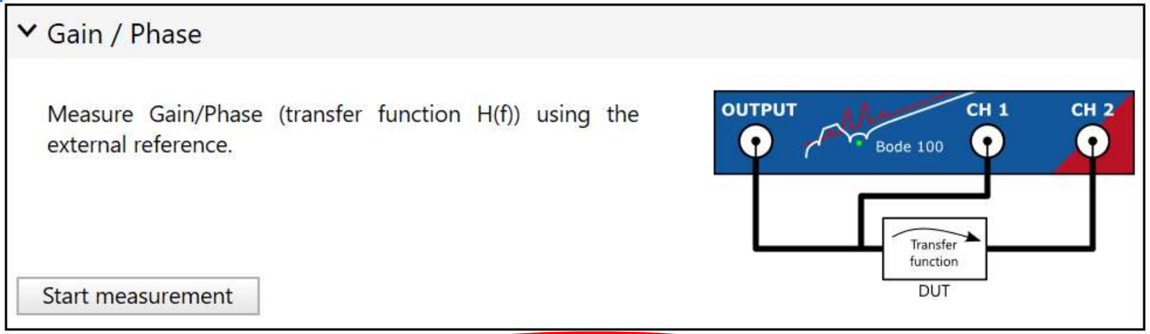
Hint:

If the PCB size allows you can place a shorted 0402 placeholder for R7 on the PCB. For Bode test you dremel the short open and place a 100 Ohm termination resistor. A test point at this location will come in handy. This way you prevent the Fb loop from opening up when you play around with heat guns, mechanical loads etc.
That is the biggest danger when using yellow wire only closing the FB loop.

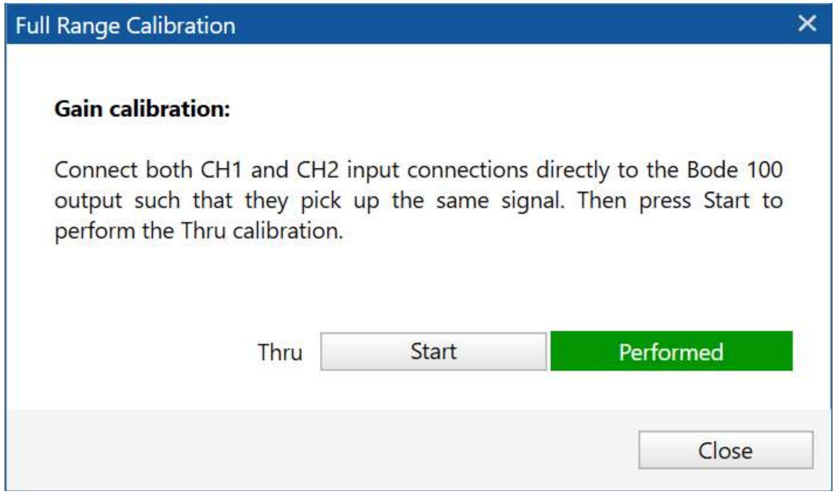




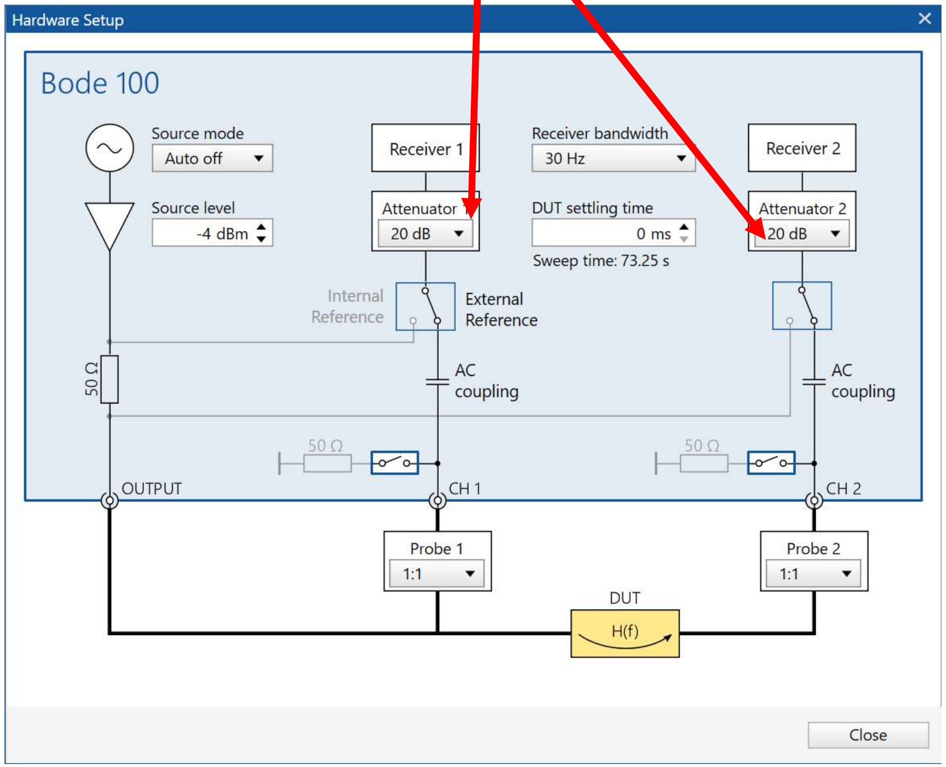
Bode 100 Setup



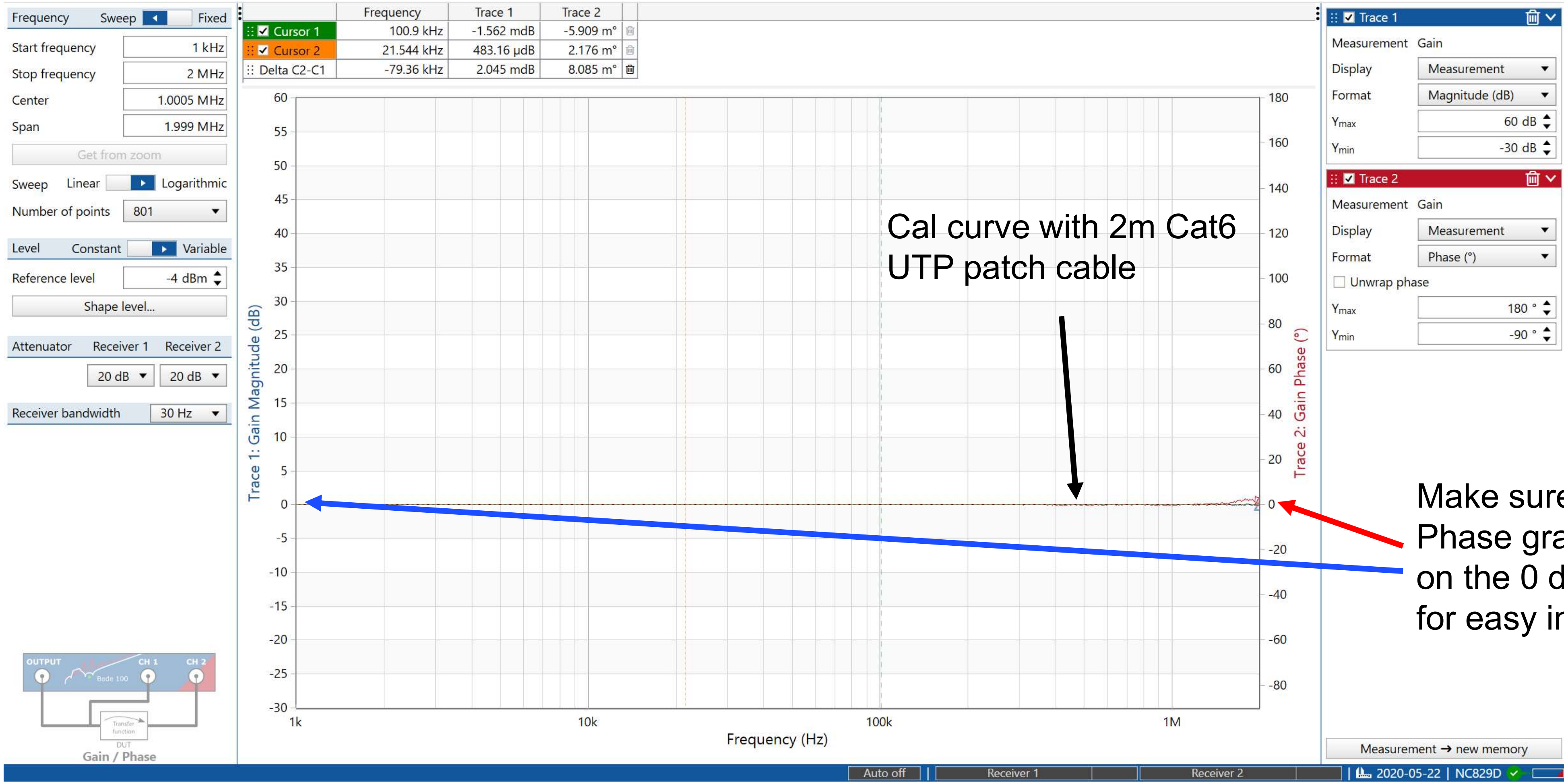
Connect patch cable into cal plug



Optimize for best S/N 0dB or 10dB might work too



Bode 100 Setup for easy interpretation for PSU

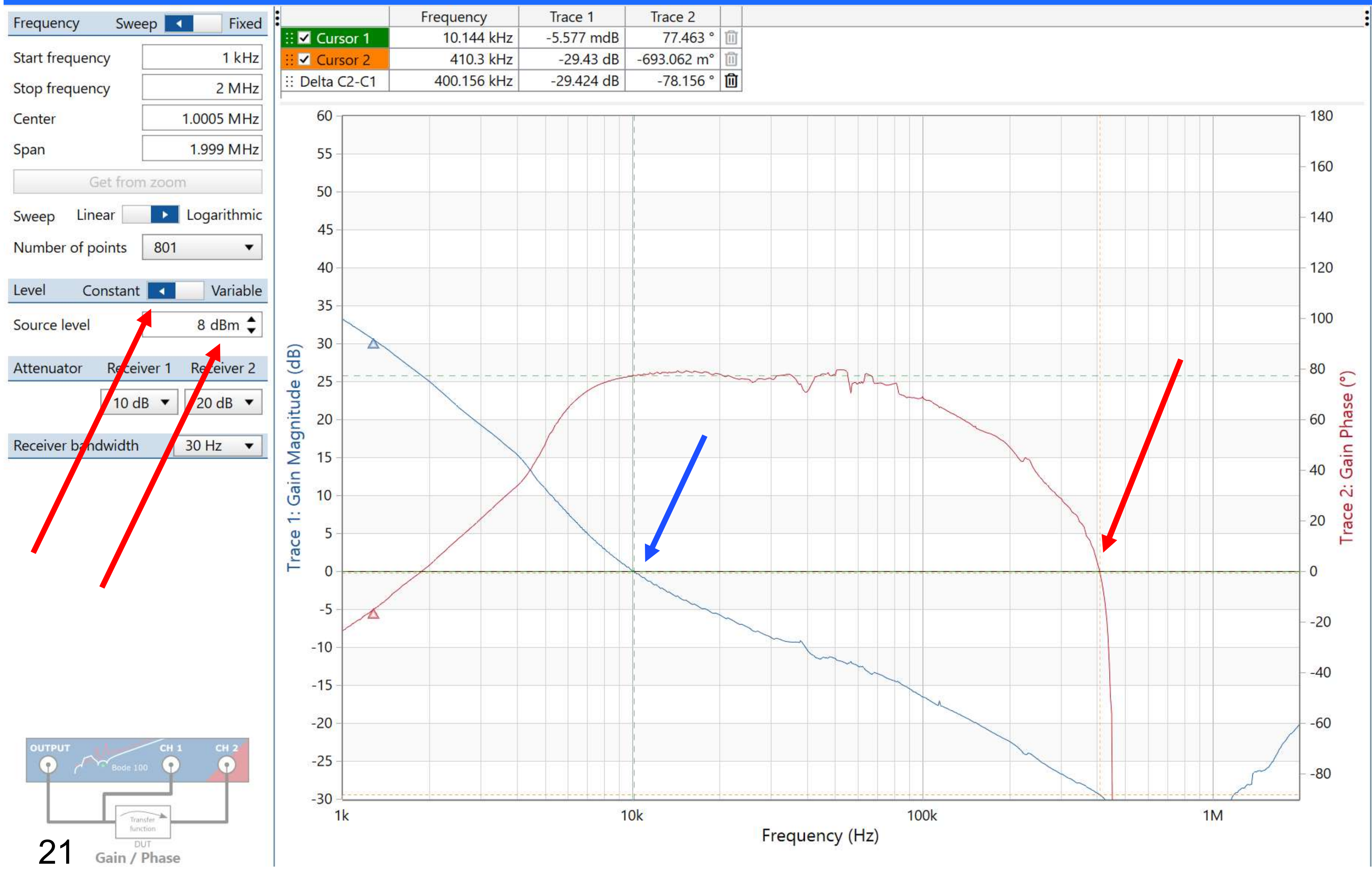


I like to have gain blue and phase red

Make sure Gain and Phase graphs align on the 0 dB 0 degree for easy interpretation

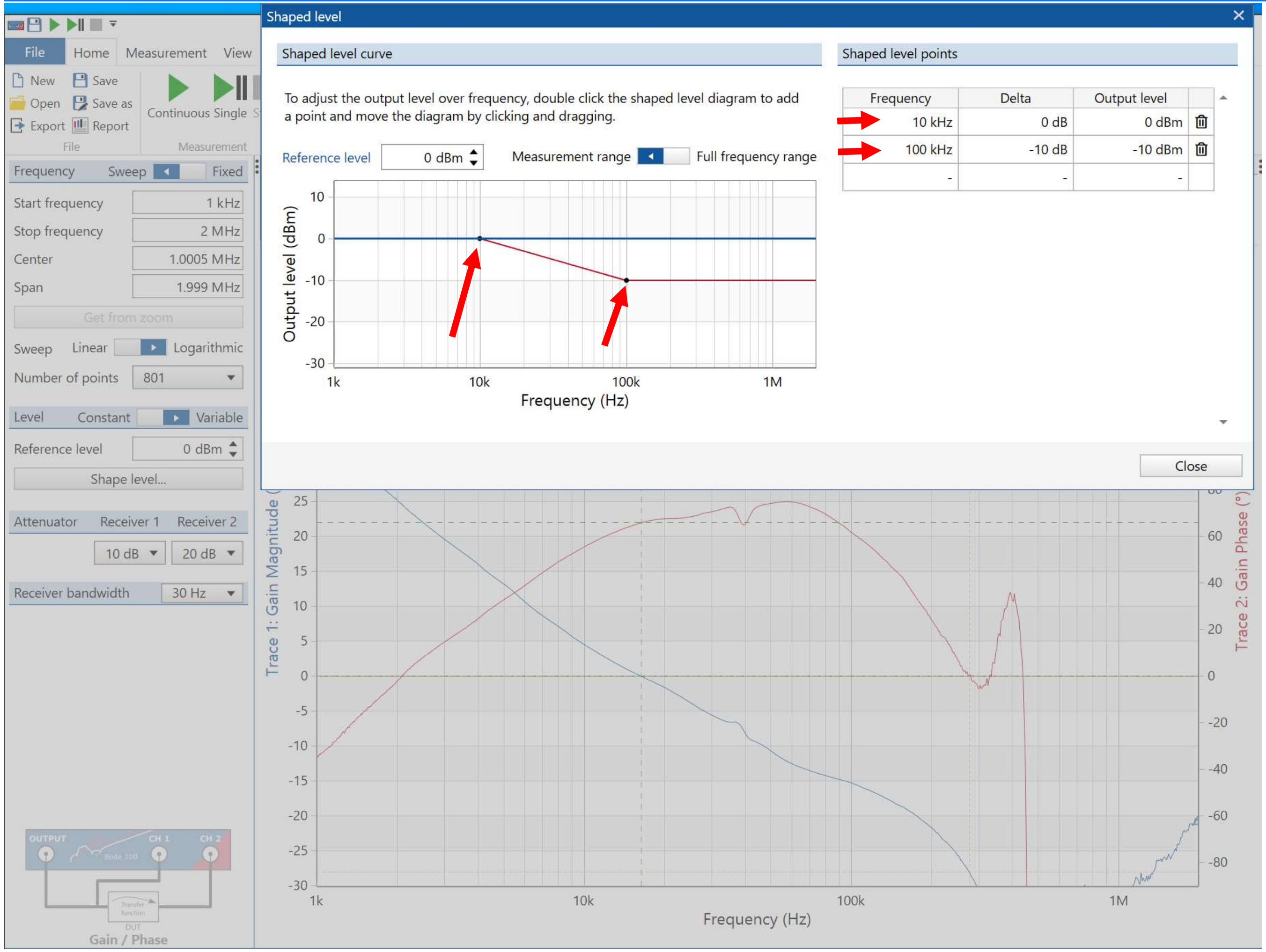
MPS

Measuring a Buck MPQ4430 with too high Source Level



With overdriven DUT you create bogus bode plots

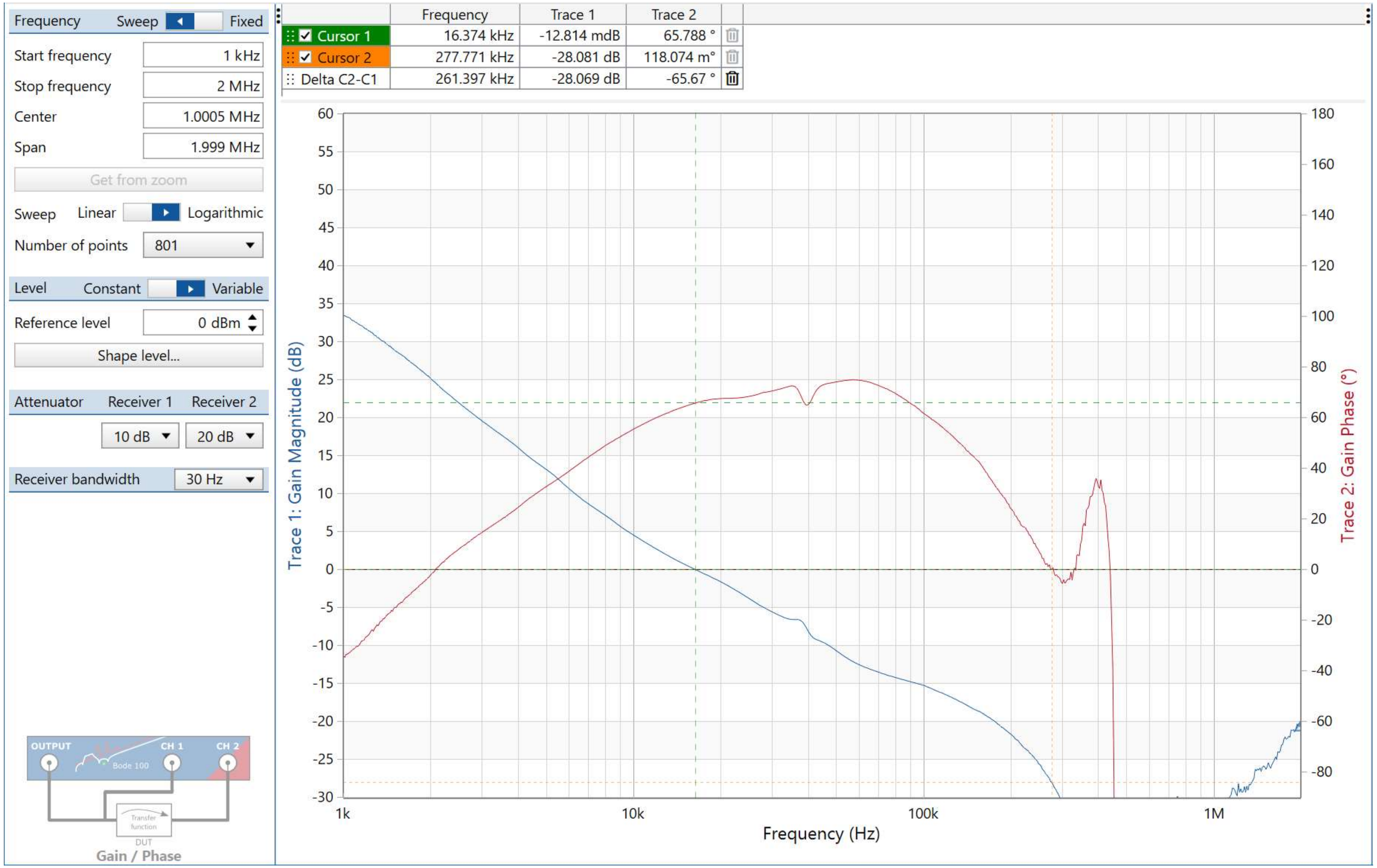
Adjust source level until plots are invariant of reduced level



You can run the measurement continuous with 1kHz RBW and adjust the shaped level curve until artefacts due to DUT overdrive disappear. Test at least -3dB to your final setting that the plot shape stays the same.

Then you can reduce the RBW to 100 or 30Hz to shoot the nicer plot for the management.

Adjust source level until plots are invariant of reduced level



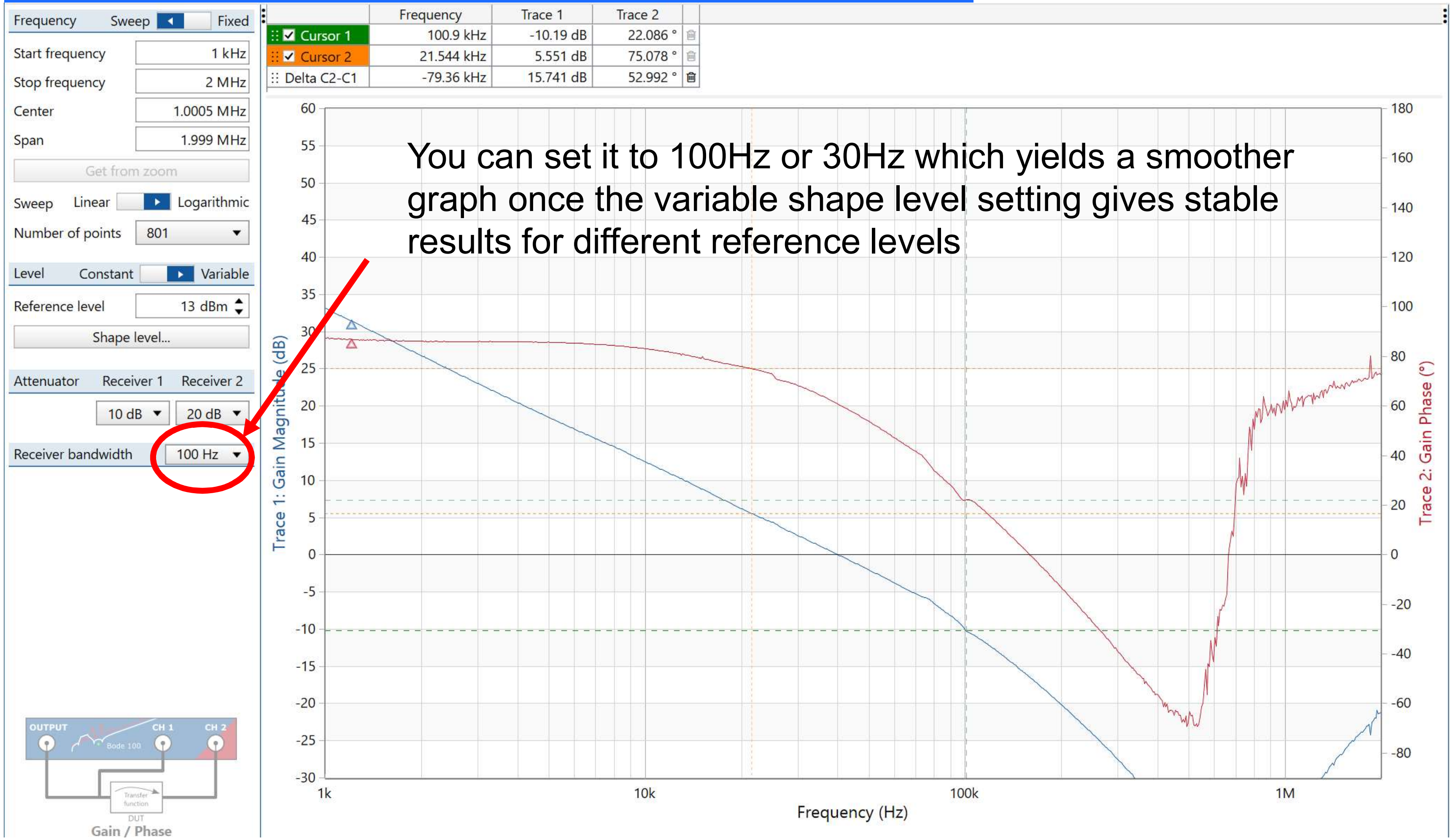
Hints:

For test of sanity always reduce the excitation amplitude at least 3 dB or more from your final setting to see if you Bode plot stays the same.

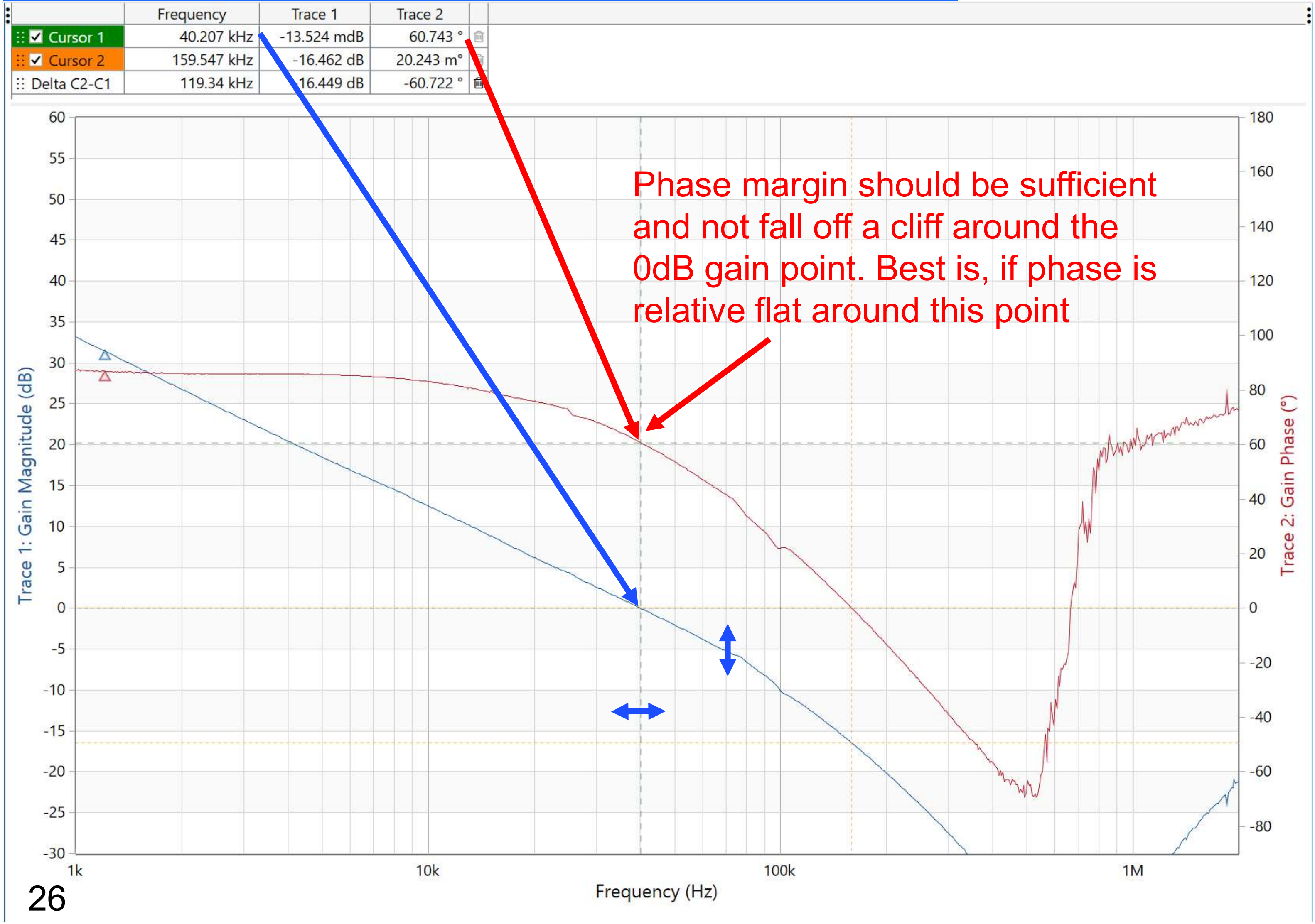
It will become more noisy but should not change in shape or remove/add steps. If you see changes it is a sign of overloading your loop linearity. You need then to adjust your shaped level to stay in the linear loop behavior.
This can be done with a 1kHz RBW setting and you get a quick live optimization.

There is in most cases no need for very low start frequencies. They do not add any useful information and slow down the measurement.

Final measurement with lower RBW



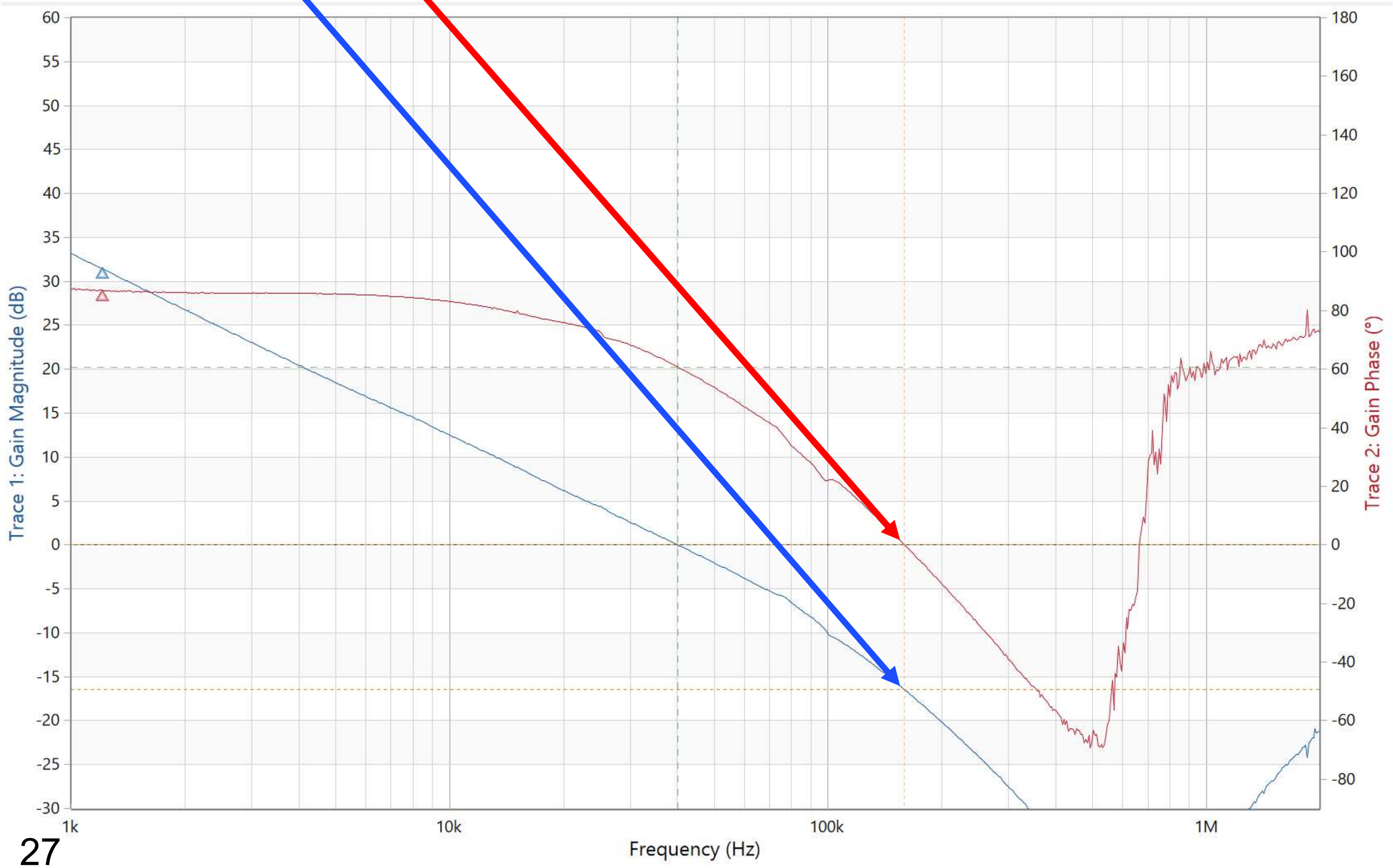
What to look for: Phase Margin



Gain curve will change a bit up and down over temperature and production variations. That will move the 0 dB point a bit with frequency. You want to have reserves for this.

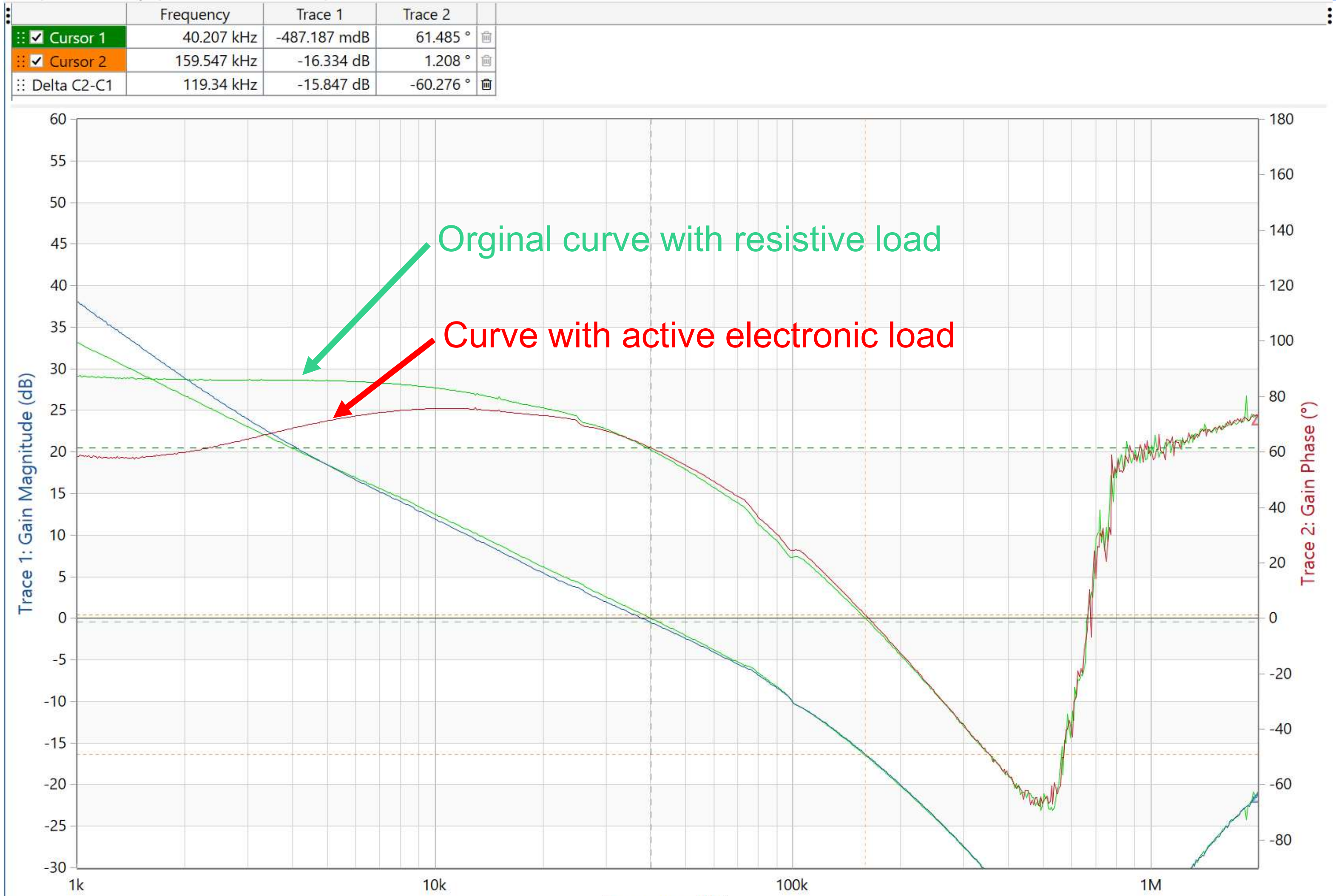
What to look for: Gain Margin

	Frequency	Trace 1	Trace 2
Cursor 1	40.207 kHz	-13.524 mdB	60.743 °
Cursor 2	159.547 kHz	-16.462 dB	20.243 m°
Delta C2-C1	119.34 kHz	-16.449 dB	-60.722 °



At the 0 degrees phase reserve point there should be enough attenuation (<-10dB) that the loop can not oscillate. There are lots of mechanisms like load resonances and current loop gain, which can easy give some additional gain at those frequencies yielding in oscillation.

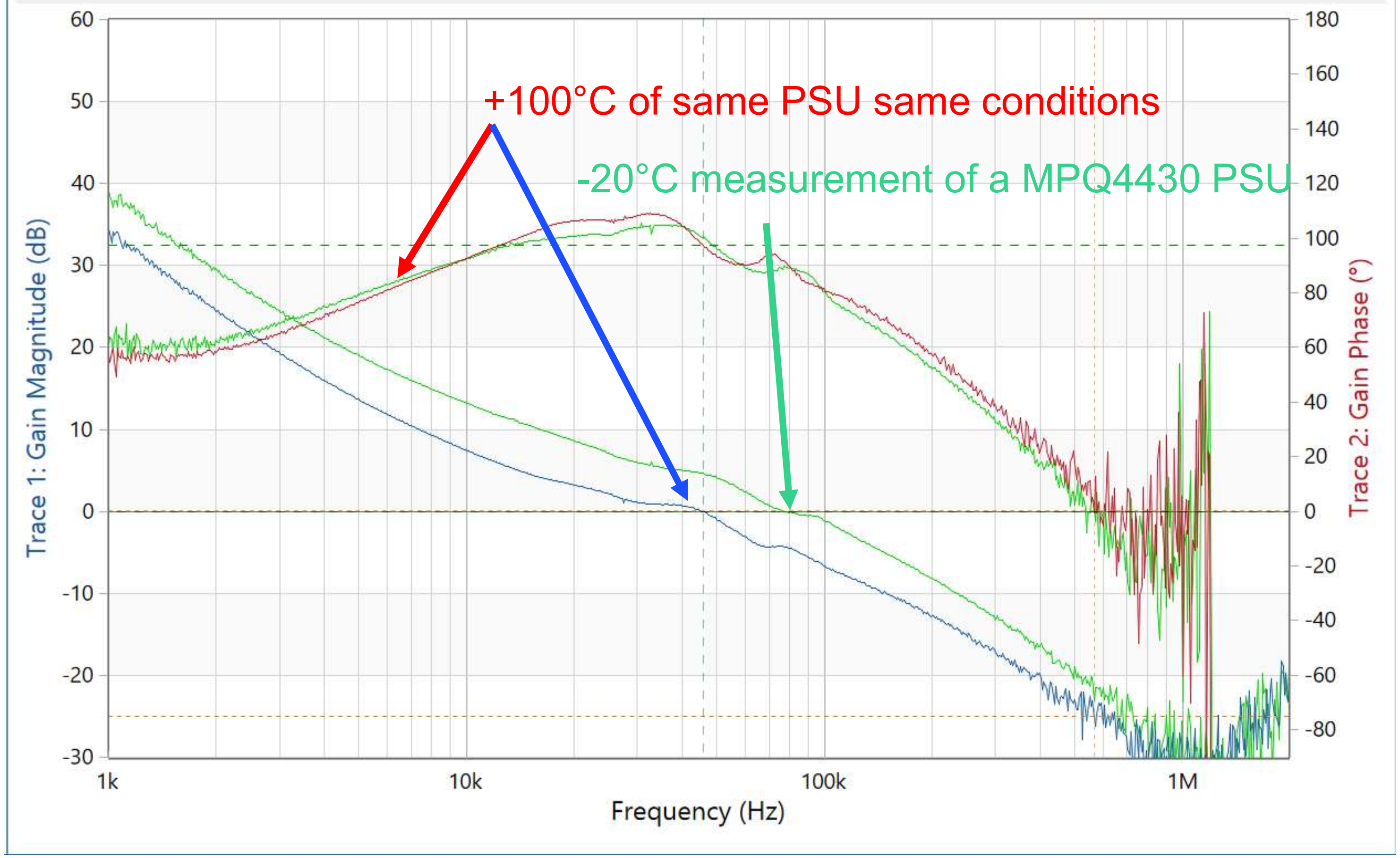
Always use a resistive load for Bode measurements



Do not include the frequency response of an active electronic load in a Bode measurement.

Typical PSU loop gain effect of temperature

	Frequency	Trace 1	Trace 2
Cursor 1	45.951 kHz	-26.6 mdB	97.413 °
Cursor 2	570.041 kHz	-25.023 dB	157.737 m°
Delta C2-C1	524.09 kHz	-24.997 dB	-97.255 °

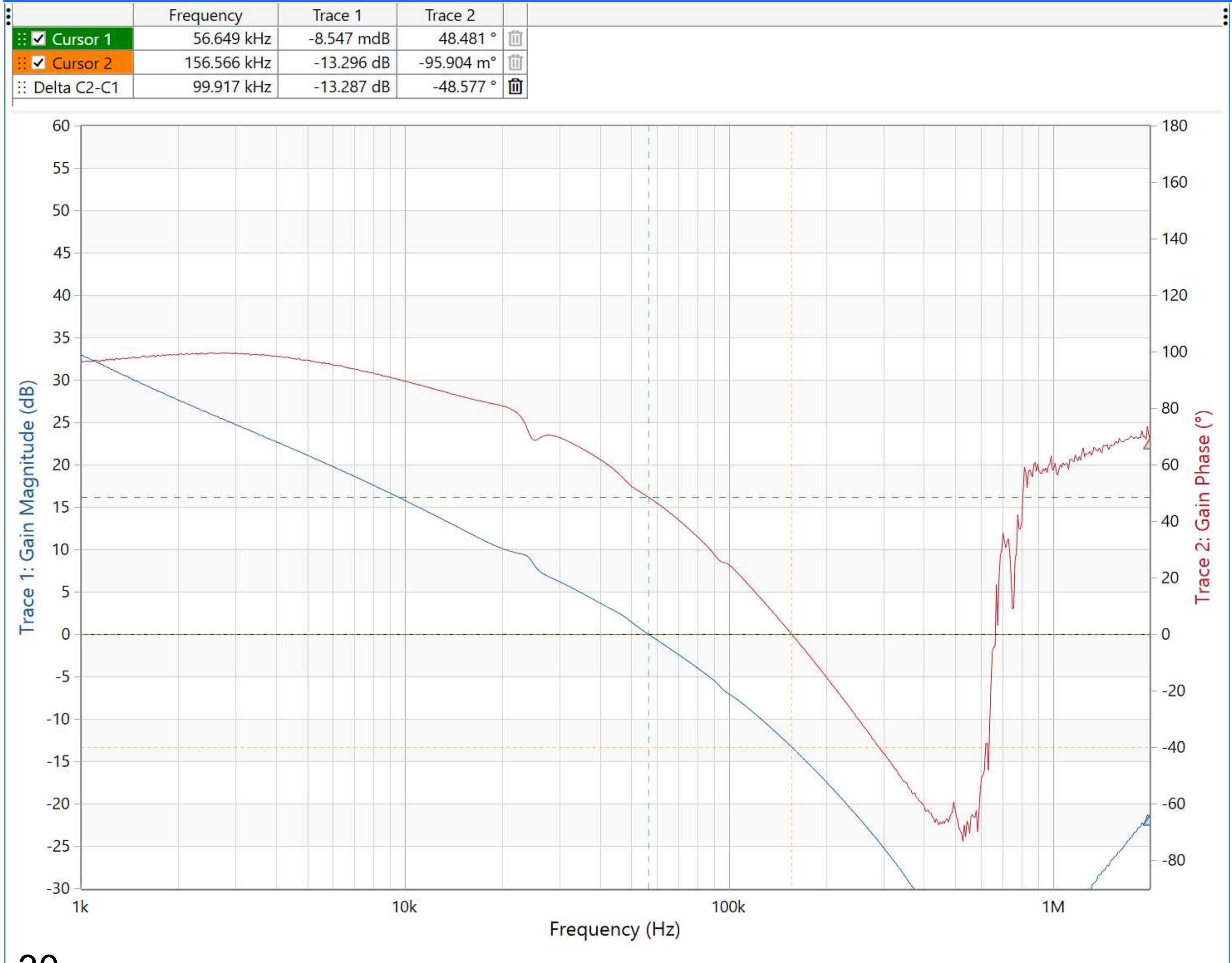


Cold is typical the most severe loop condition for MLCC Cout regulators with MOSFET error amps.

Cout of MLCC goes down resulting in a higher 0dB crossover frequency. See page 6. At the same time the error amp gain stage has higher gain. MOSFET amp. structures typ. decrease gain with rising temperatures. Bipolar amps increase with temperature.

So best practice is to keep good phase margin for the increase of crossover during low temps.

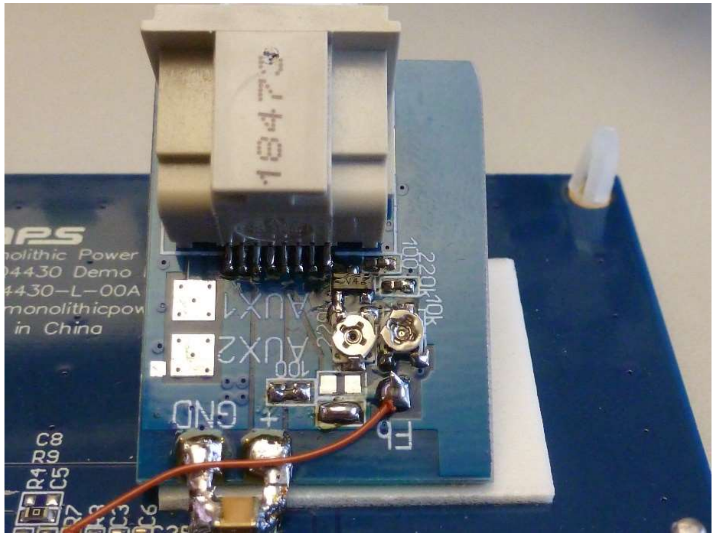
Omicron Bode 100 RBW 30Hz 801 points

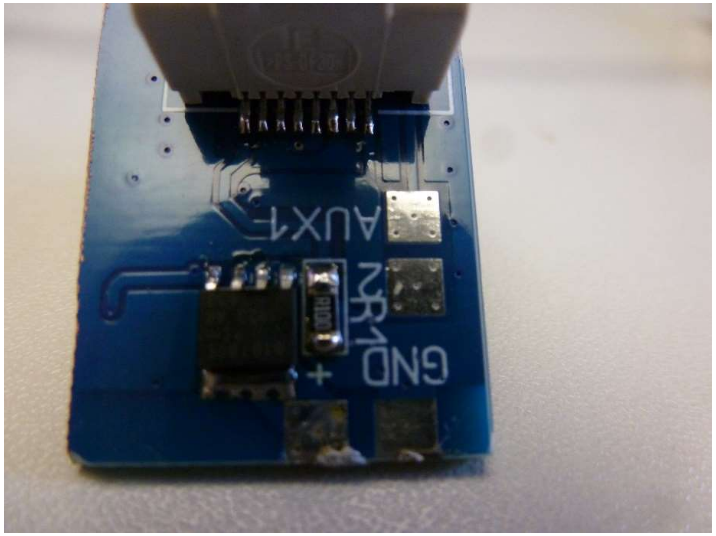


MPQ4430 12V to 5V 1.2A

Step Load

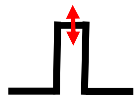
The AC (stepped) load of the step load should be done with closest lowest impedance connection to the DUT cout. So typical a step load dissipating MOSFET with a current sense resistor is placed on or near the DUT output capacitors. With the Bode hookup we have already that connection to the Cout capacitors so enhancing it to do step load too is an easy task.

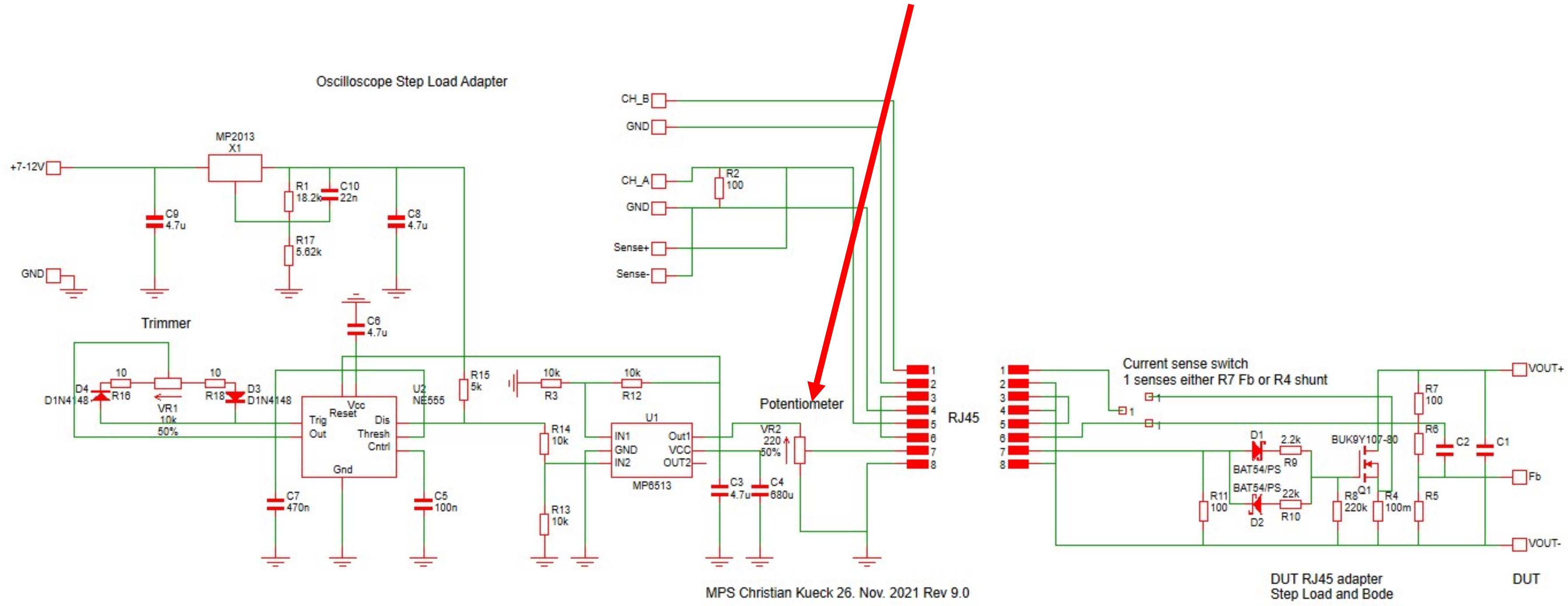




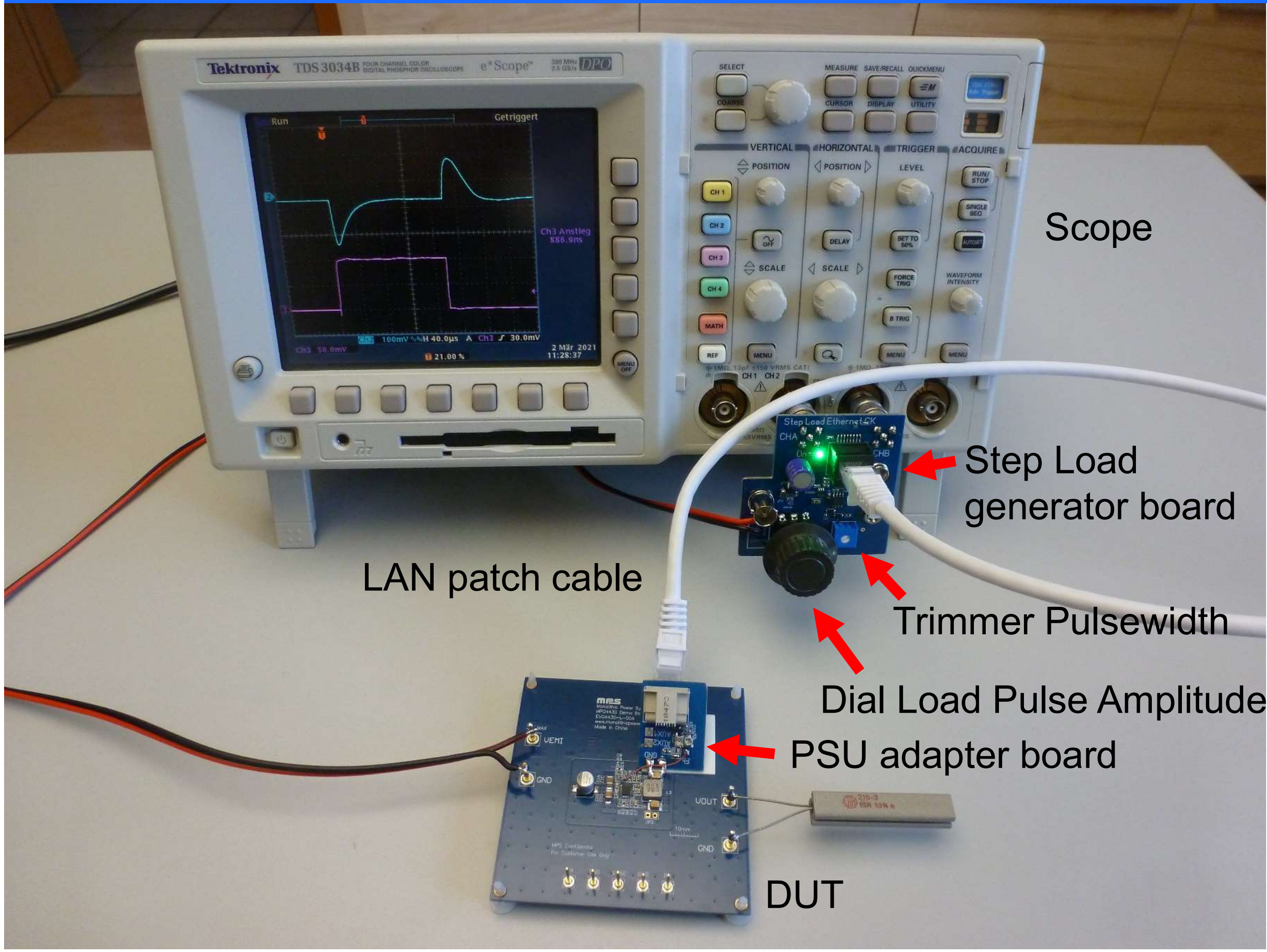
Step Load

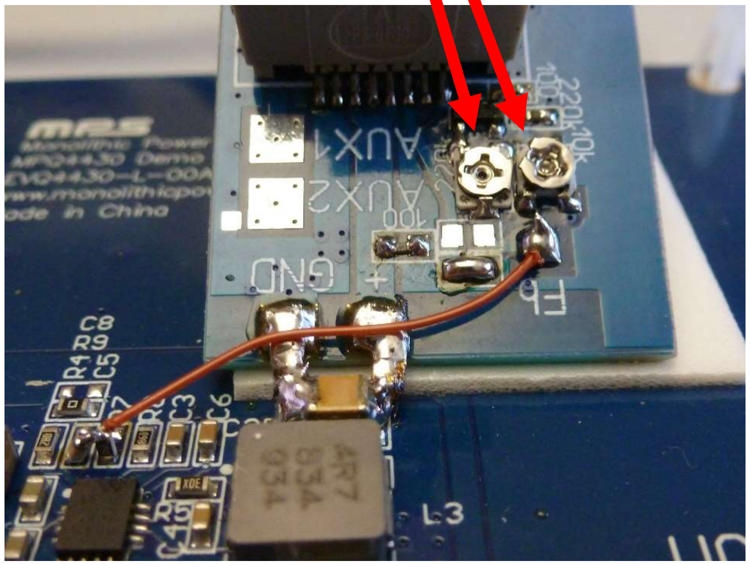
A voltage variable pulse is generated



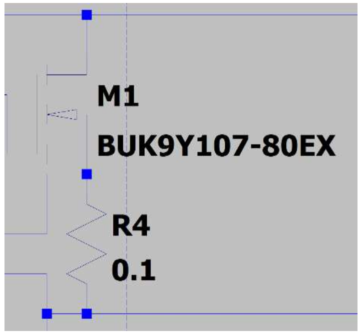


Step Load Setup





Step Load MOSFET selection is not trivial



Important is the SOAR (Safe operating area). Load MOSFETs see voltage and current = power at the same time. Most MOSFETs are not designed for that. Gate threshold VGS has a strong negative temperature coefficient which makes the MOSFET unstable in a high power dissipation area with analog drive. In addition the Qg drive capability is limited over our 100 Ohm cable system. Beware at higher Vout (>5V) with larger currents and load on times/duty cycle. Check the SOAR graph carefully before you make a load MOSFET selection.

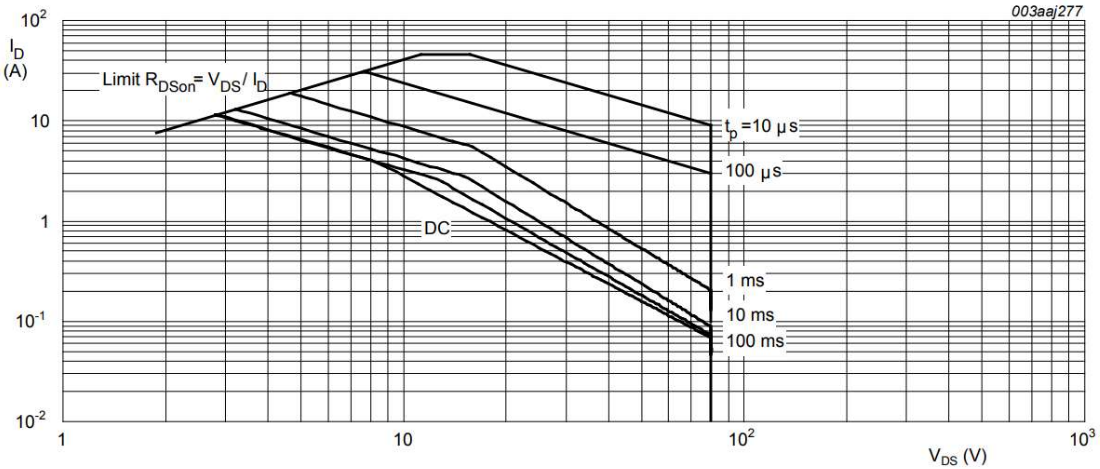


Fig. 4. Safe operating area; continuous and peak drain currents as a function of drain-source voltage

$T_{mb} = 25°C$; I_{DM} *is a single pulse*

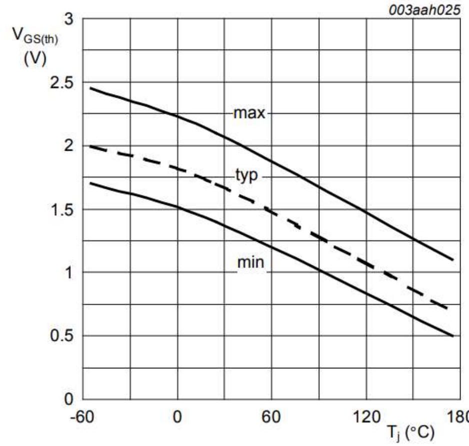


Fig. 9. Gate-source threshold voltage as a function of junction temperature

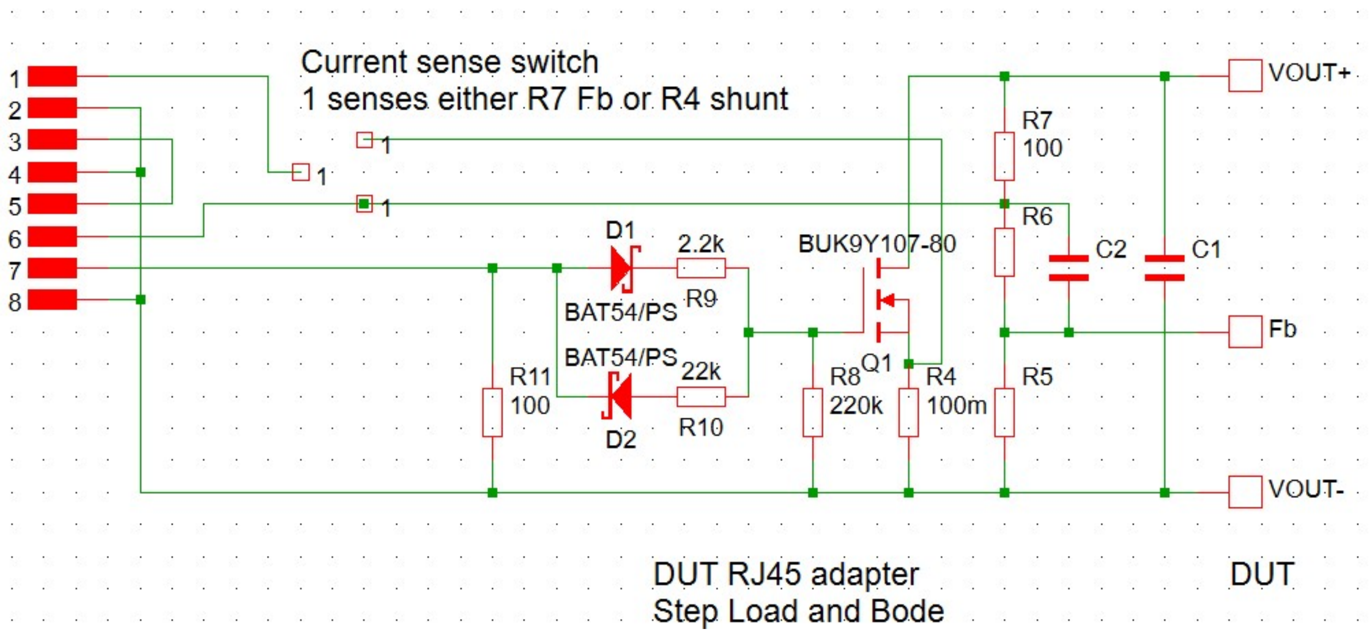
$I_D = 1$ mA; $V_{DS} = V_{GS}$

N-channel 80 V, 107 mΩ logic level MOSFET in LFPAK56

2.5	-	nC

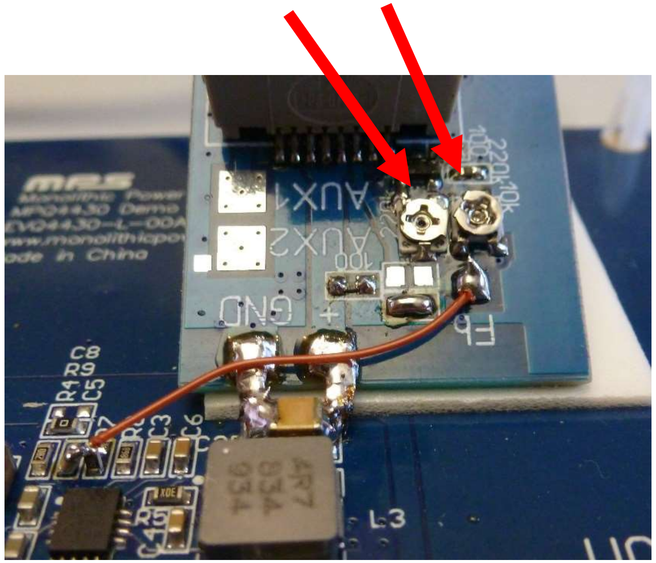
Combined Bode and Step Load Adapter with Switch

Bode and Step load adapter are on the same PCB and share the connections GND and Vout on the DUT output capacitor. The step load switch is direct attached to the PSU Cout so round trip loop inductance is low. It does not interfere during Bode measurements.



Trimmer R9 R10

falling rising edge slope

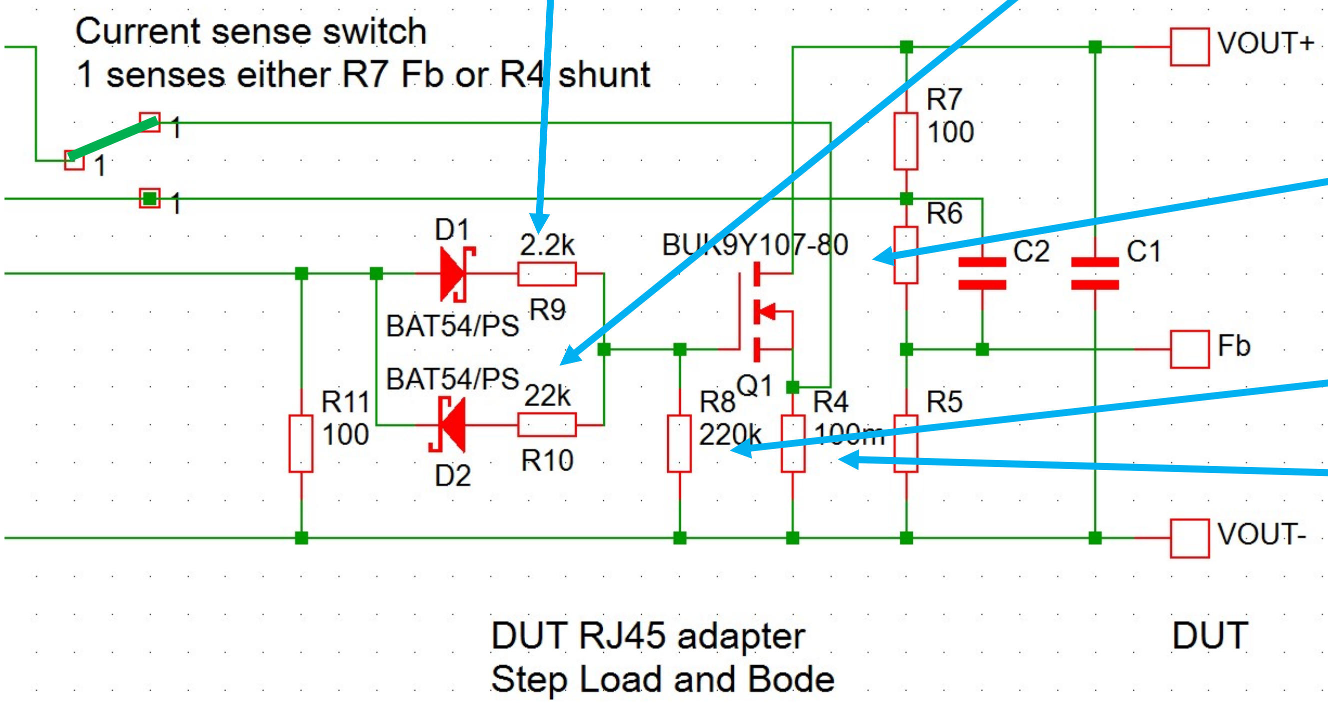


Step Load Adapter Details

R9 selects rising edge. You can use a 10k trimmer for R9 if adjustment is desired.

R10 selects the falling edge. You can use a 220k trimmer for R10 if adjustment is desired.

D1 D2 is a single SOT23 BAT54S



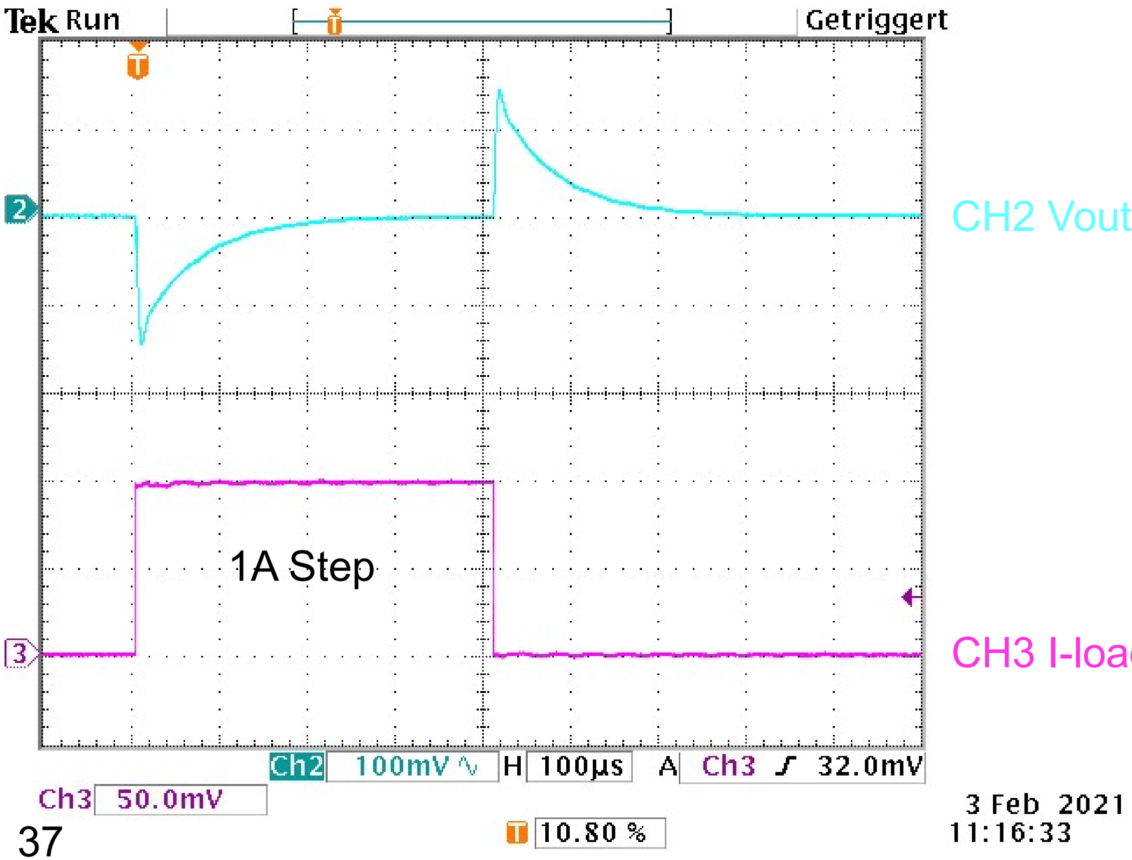
Select MOSFET M1 for SOAR and not to high Qg (here 6.2nC)

R8 prevents current from creeping up during on time due to D3 leakage.

R4 sets the current measurement sensitivity here 100mV=1A

1A Load Step measured over 0.5m UTP patch cable

The measurement is noisy and can be perfect filtered with averaging and/or BW reduction (20MHz is plenty) since the trigger points (CH3) are well defined.



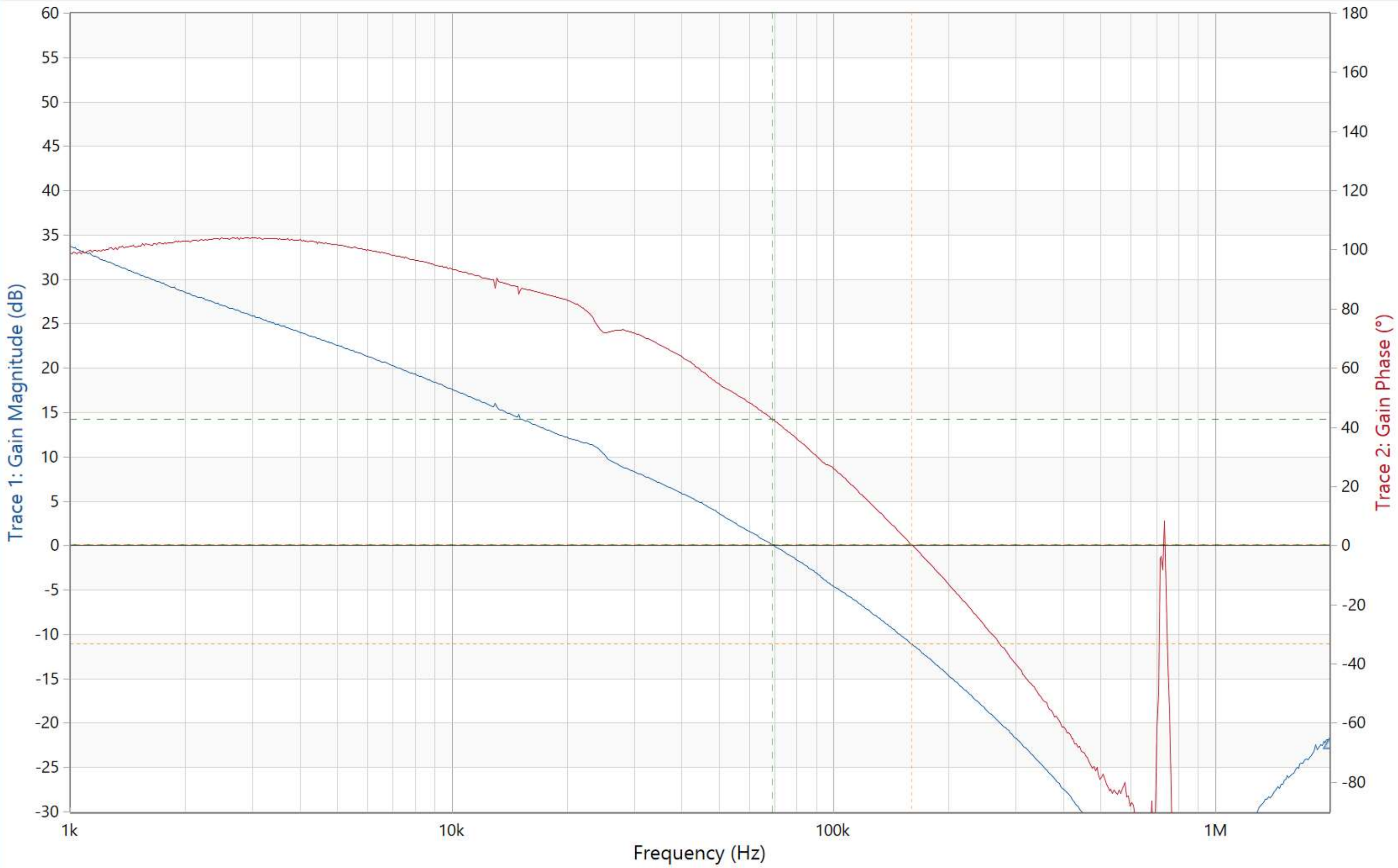
You see asymptotic behavior as to expect with 60 degrees phase margin

CH2 Vout AC coupled

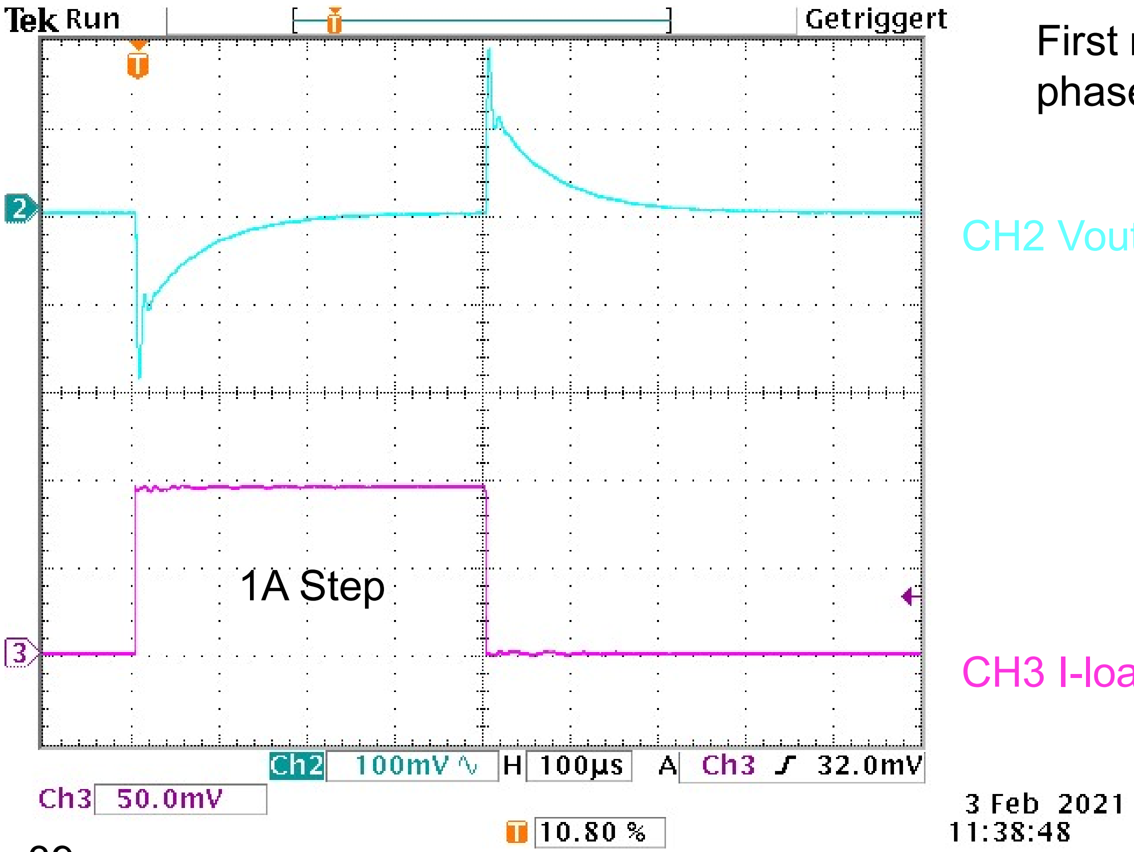
CH3 I-load-step 100mOhm shunt 100mV=1A

Now we reduce Cout to ½

	Frequency	Trace 1	Trace 2
Cursor 1	69.147 kHz	111.942 mdB	42.768 °
Cursor 2	160.357 kHz	-11.078 dB	295.9 m°
Delta C2-C1	91.21 kHz	-11.19 dB	-42.472 °



1A Load Step with ½ Cout



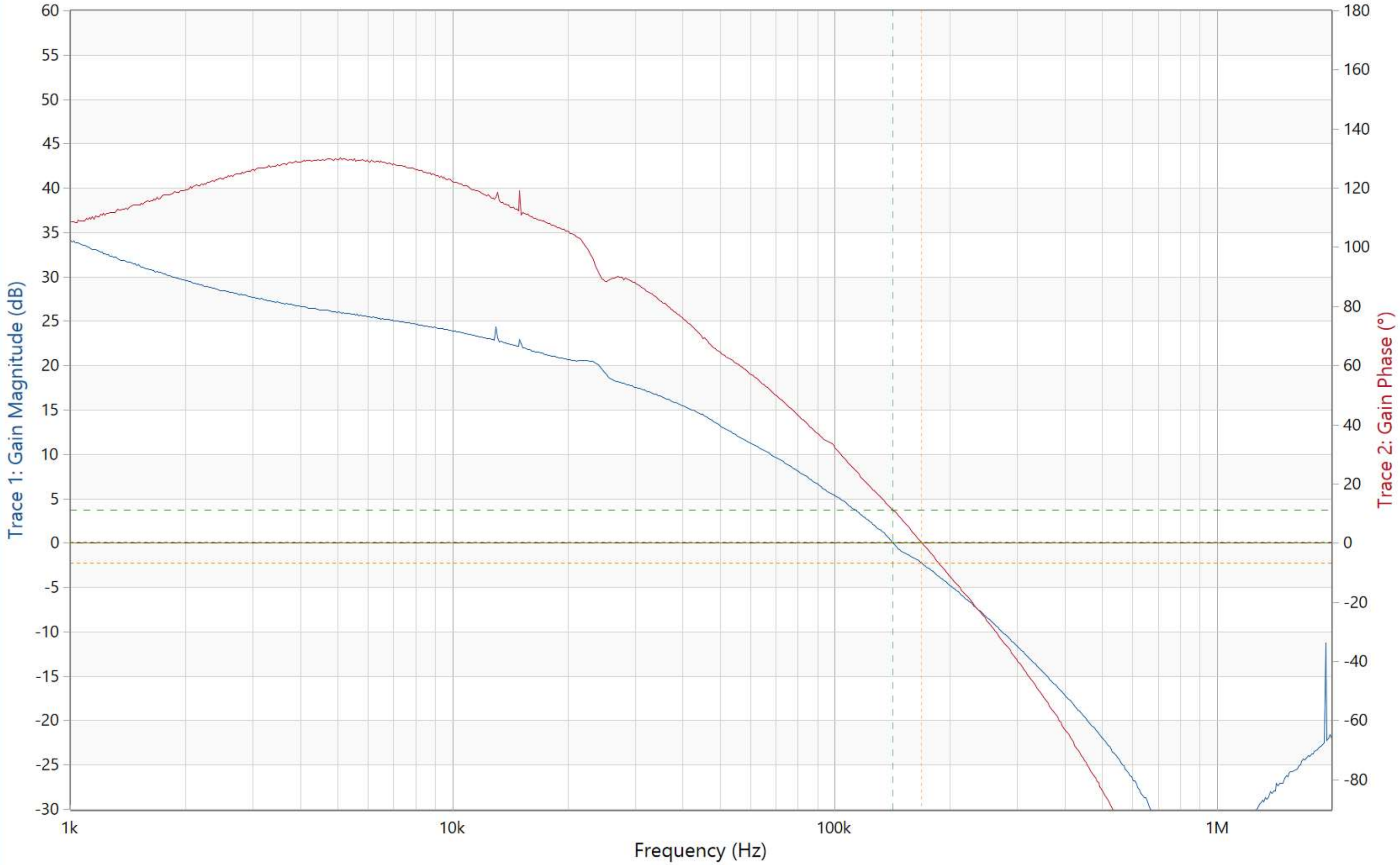
First ringing occurs with the 42 degrees phase margin

CH2 Vout AC coupled

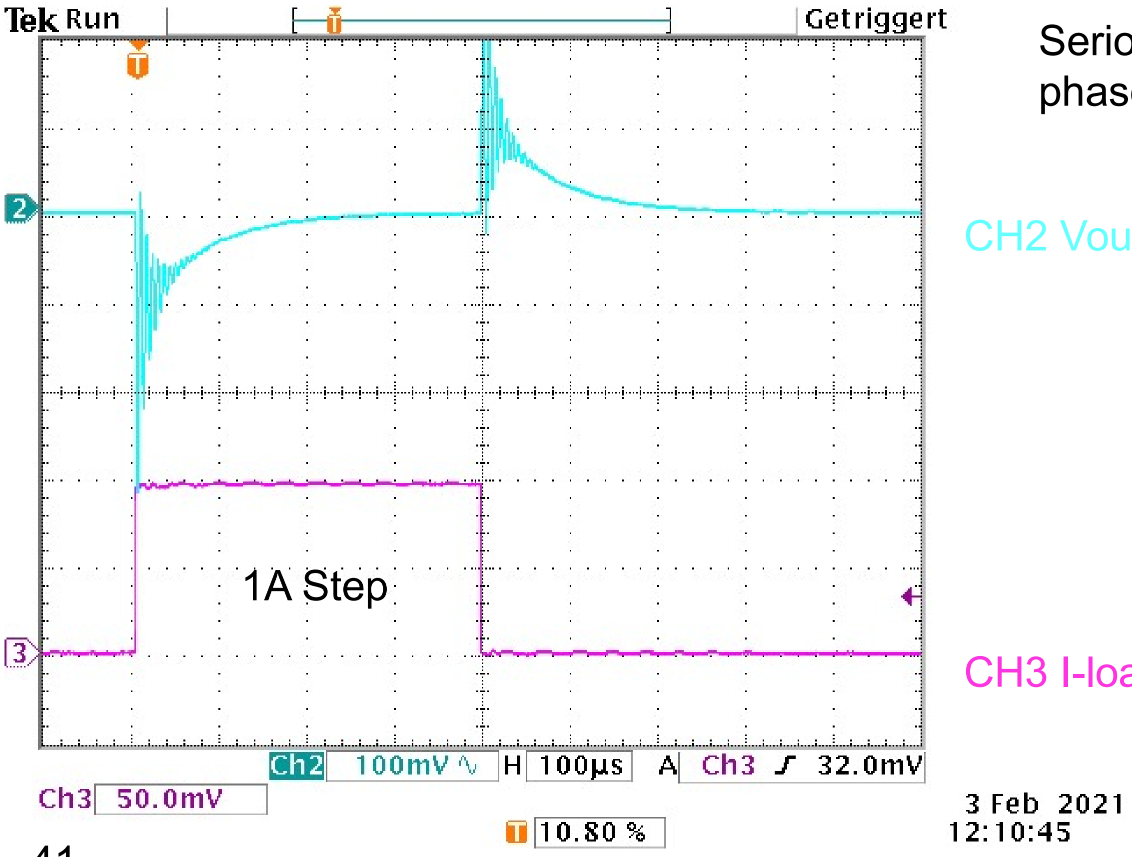
CH3 I-load-step 100mOhm shunt 100mV=1A

Now we reduce Cout to ¼

	Frequency	Trace 1	Trace 2
Cursor 1	141.995 kHz	3.963 mdB	11.235 °
Cursor 2	168.692 kHz	-2.25 dB	362.859 m°
Delta C2-C1	26.698 kHz	-2.254 dB	-10.872 °



1A Load Step with ¼ Cout



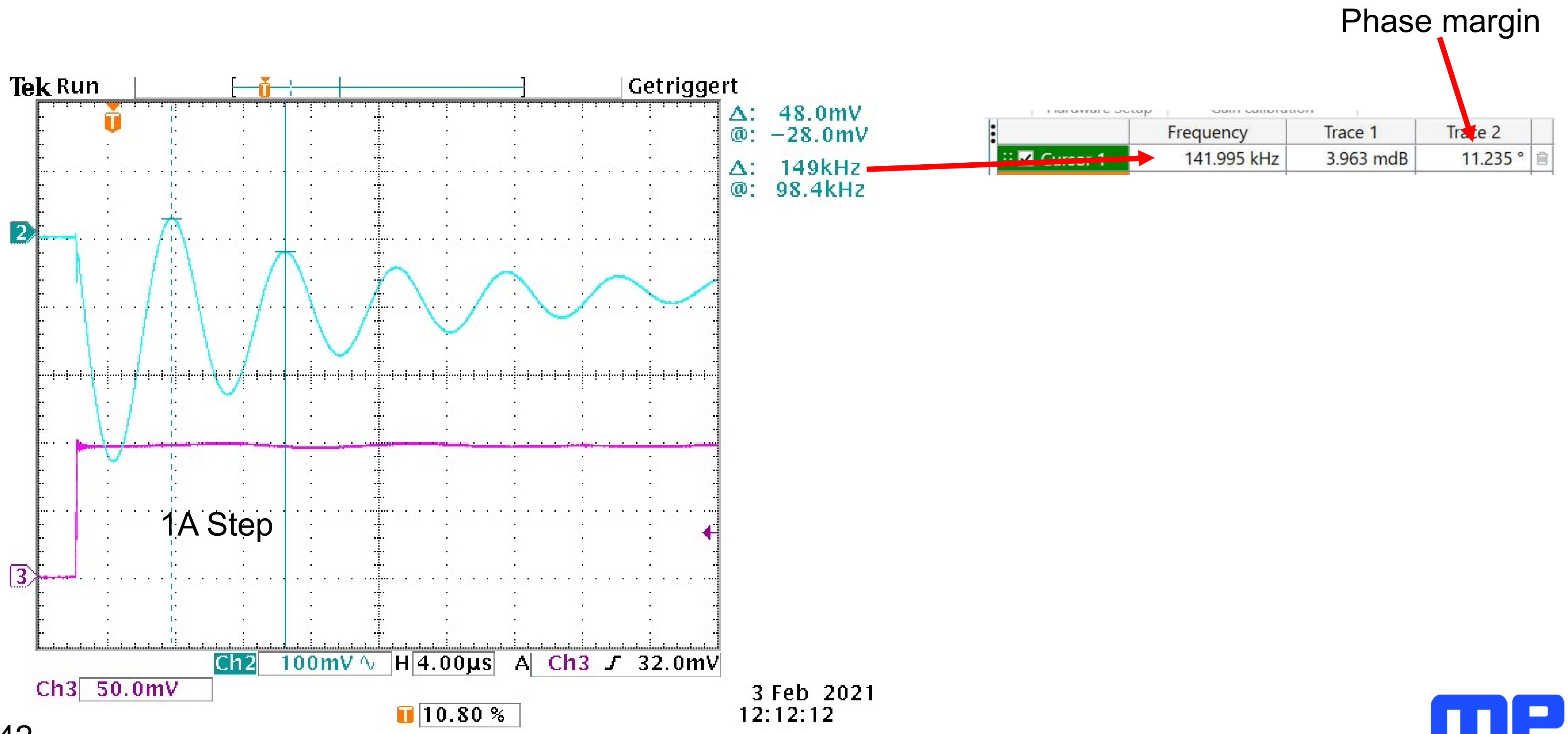
Serious ringing occurs with only 11 degrees phase margin

CH2 Vout AC coupled

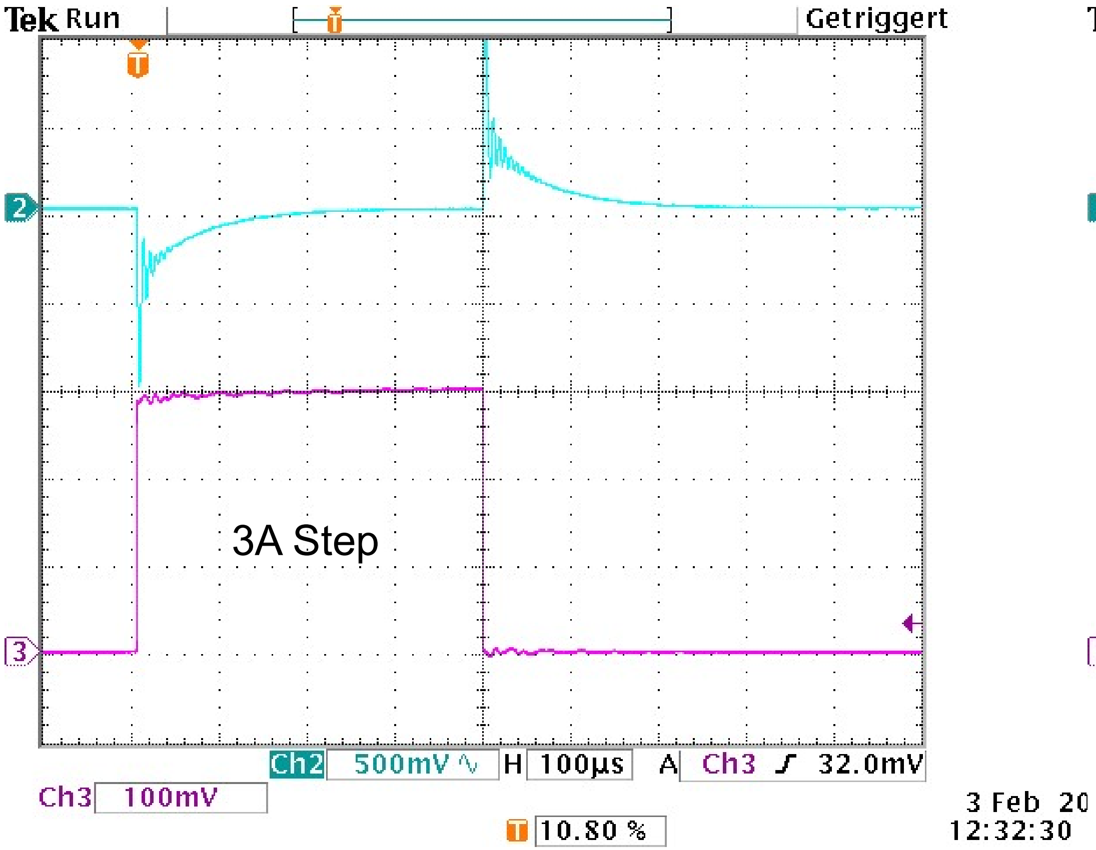
CH3 I-load-step 100mOhm shunt 100mV=1A

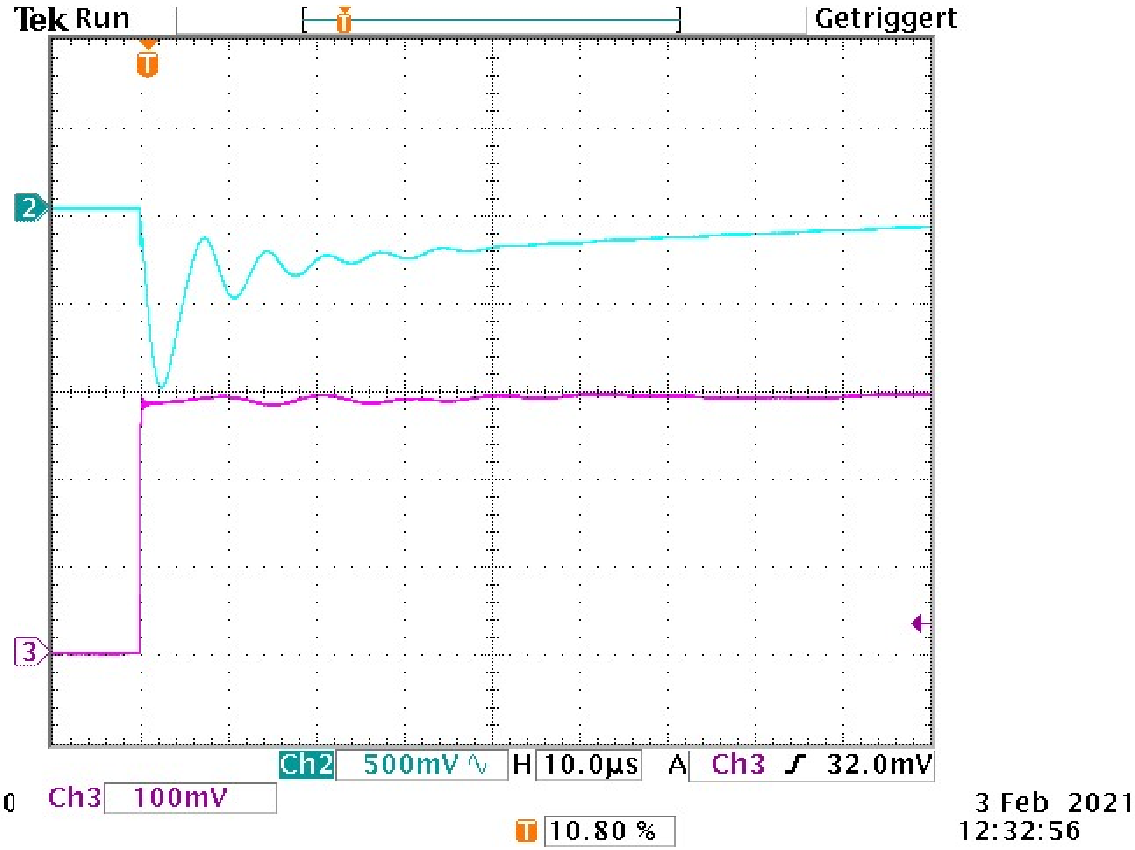
1A Load Step with ¼ Cout

Ringing frequency matches well with 0dB crossover



3A Load Step with ¼ Cout might look nicely damped having only 11 degrees phase margin

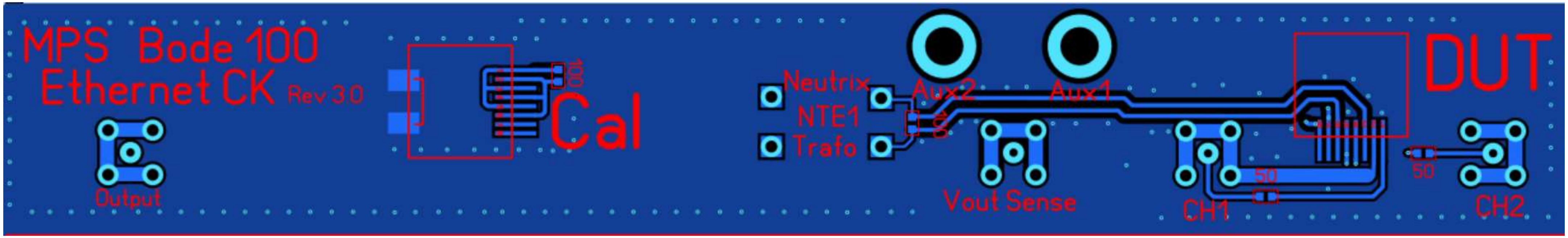


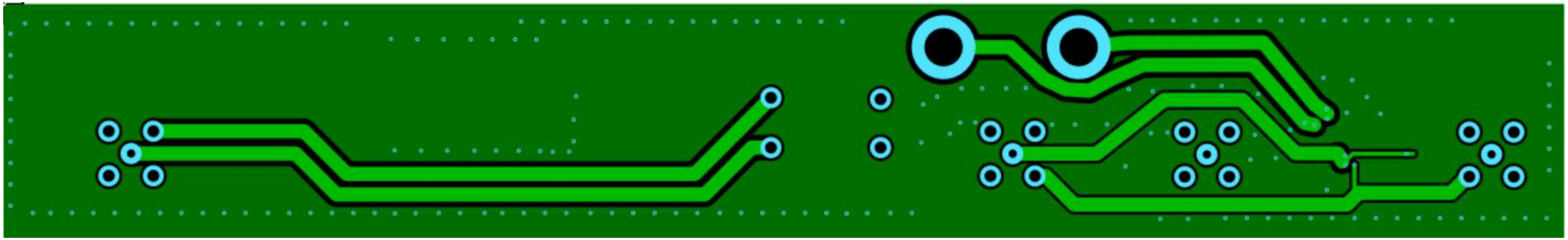


Conclusion

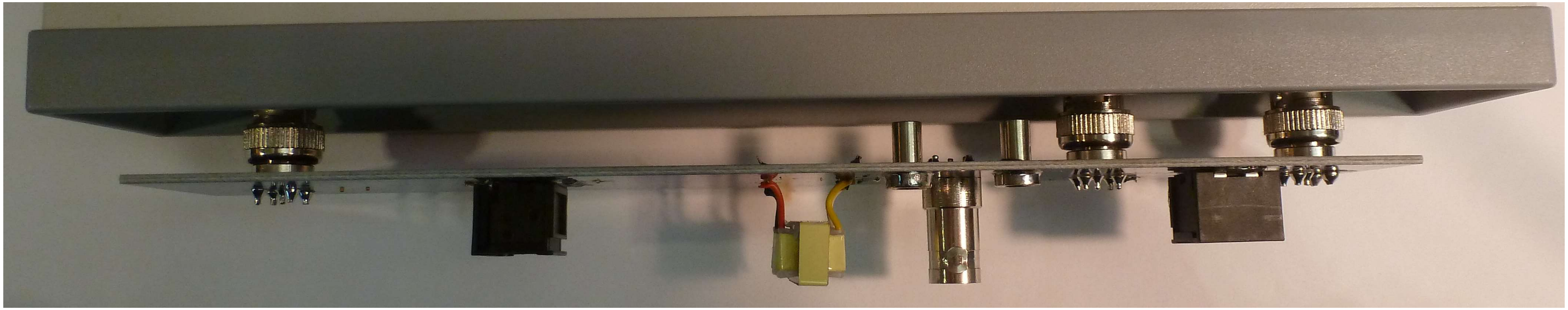
- Ethernet patch cable is well suited as versatile connection for bode and step load measurements
- The PSU adapter is small and connects with low parasitic inductance to the DUT Cout
- The load MOSFET on the DUT adapter enables low parasitic artefacts for fast step load tests
- Bode measurements are lower noise than with conventional scope probe hook ups
- Bode measurements can run faster with higher RBW settings.
- Simple single point connections can be used for easy hook ups in temperature chambers
- Low cost DUT adapters can be left with soldered on the DUT and enable quick setup times
- The patch cables up to 3m can be changed to in most cases without a need for new calibration.

Addendum Bode 100 adapter PCB 2Layer 33x220mm





Addendum Bode 100 adapter PCB 2Layer 33x220mm

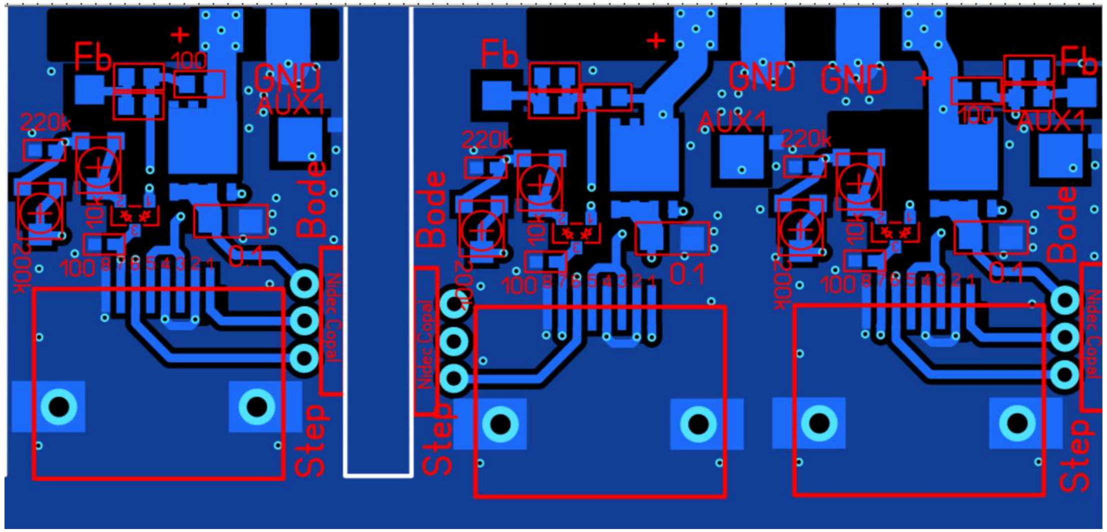


Addendum Simple DUT single + dual adapter PCB 2Layer 60x35mm

Top Bode

Single adapter

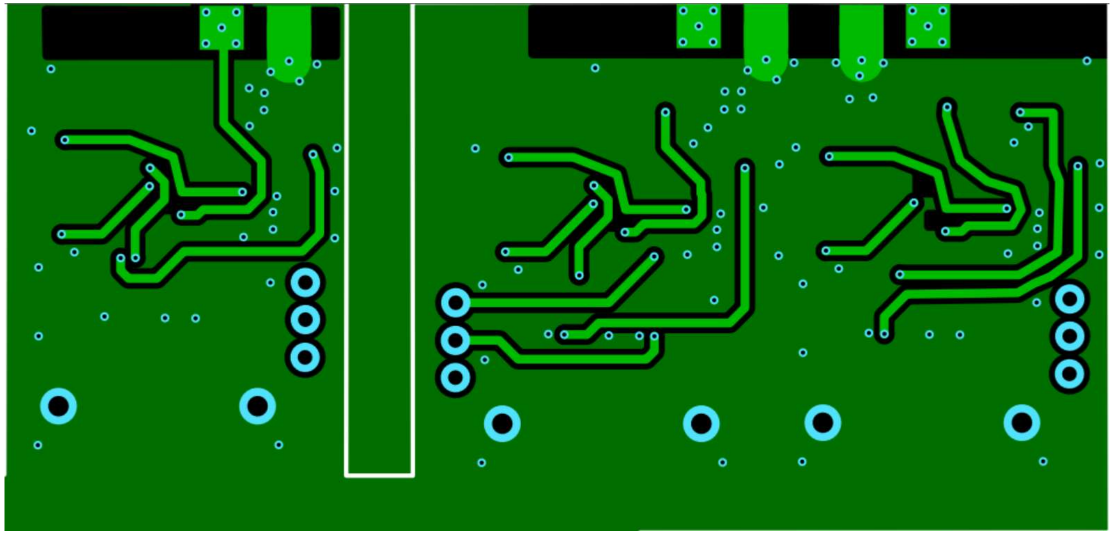
Dual adapter



Bottom Step Load

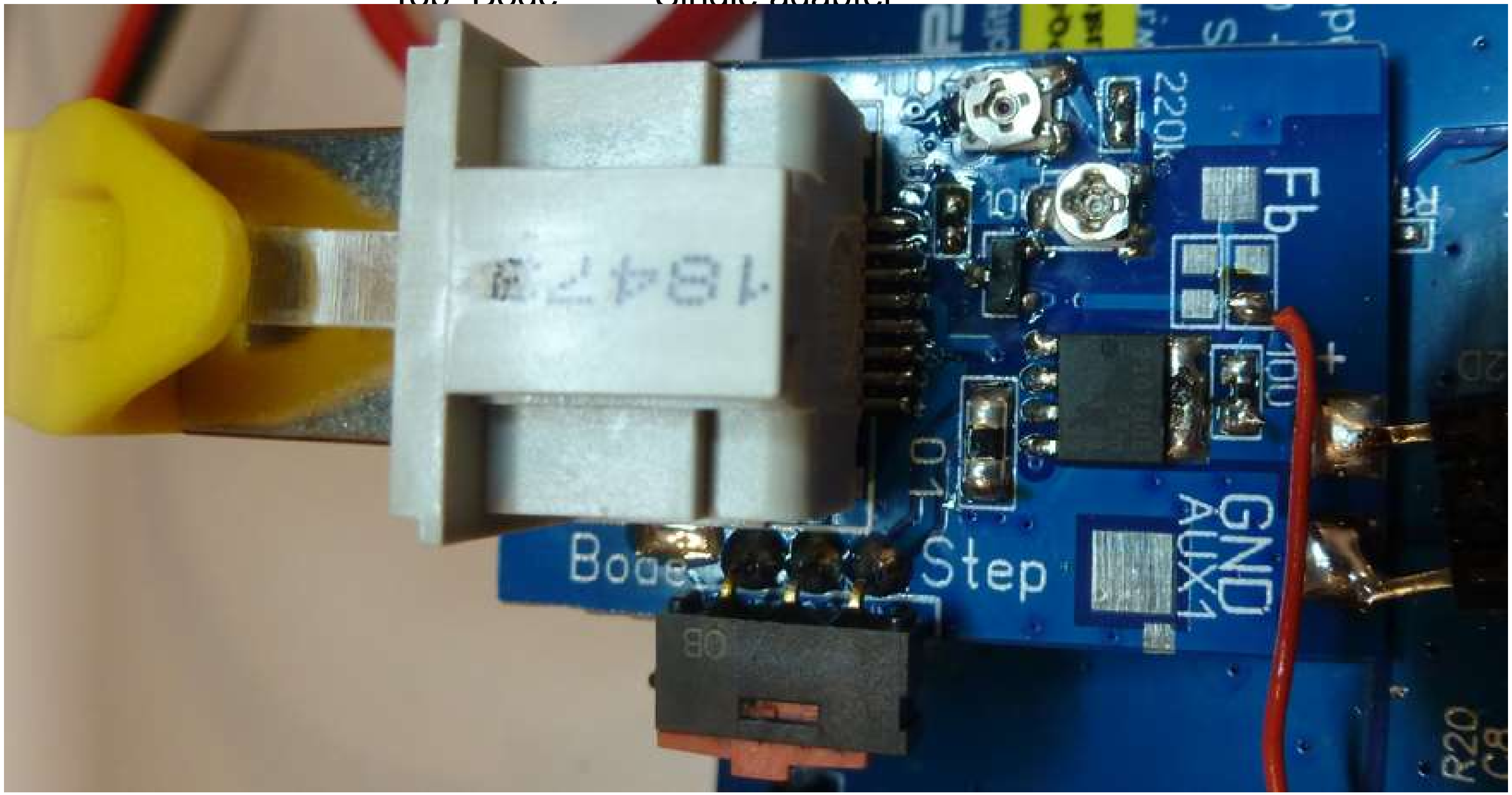
Single adapter

Dual adapter

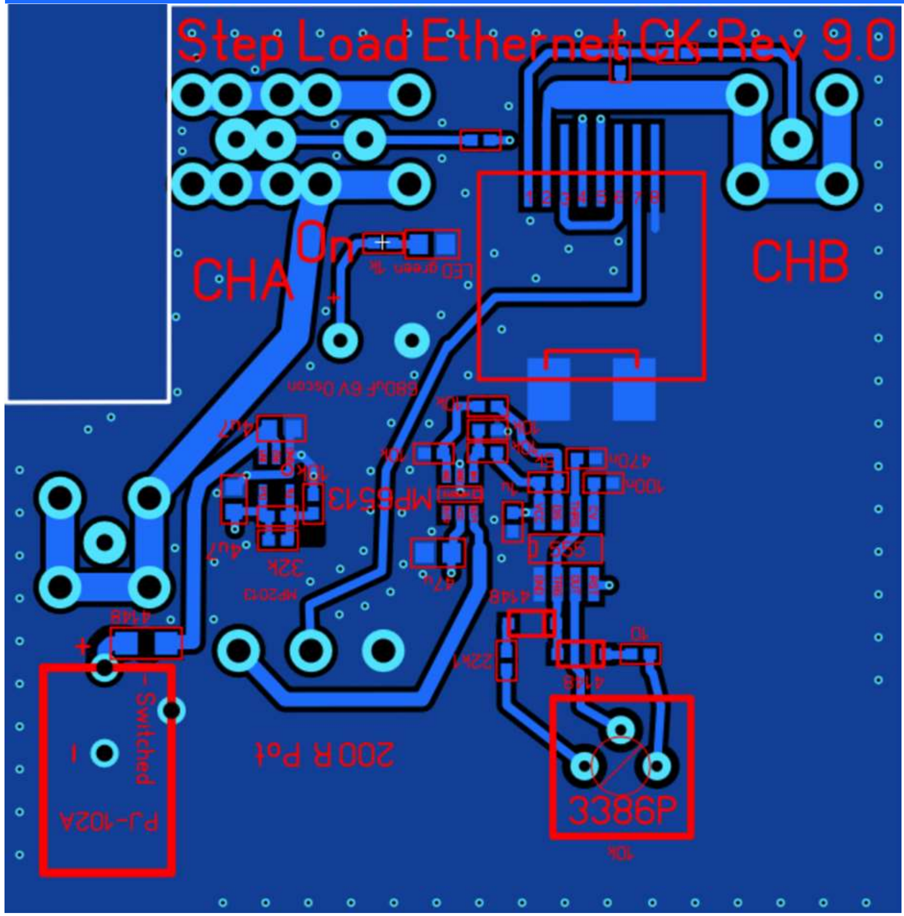


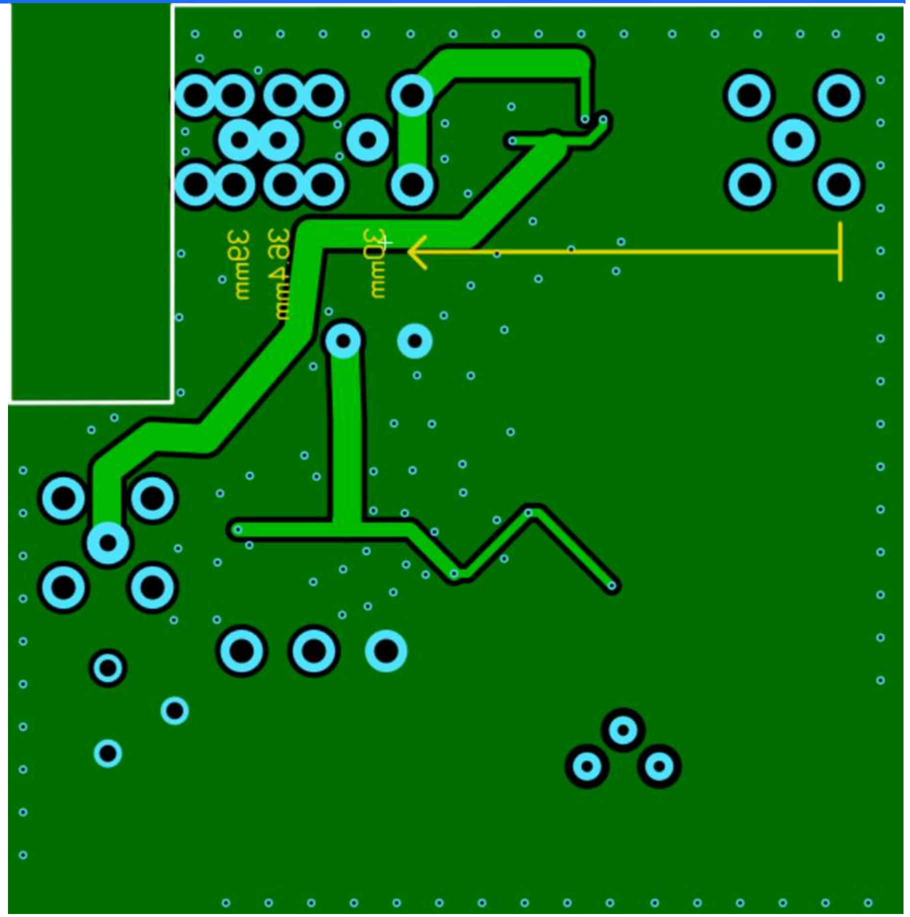
Addendum DUT single PCB 2Layer 35x27mm

Top Bode Single adapter

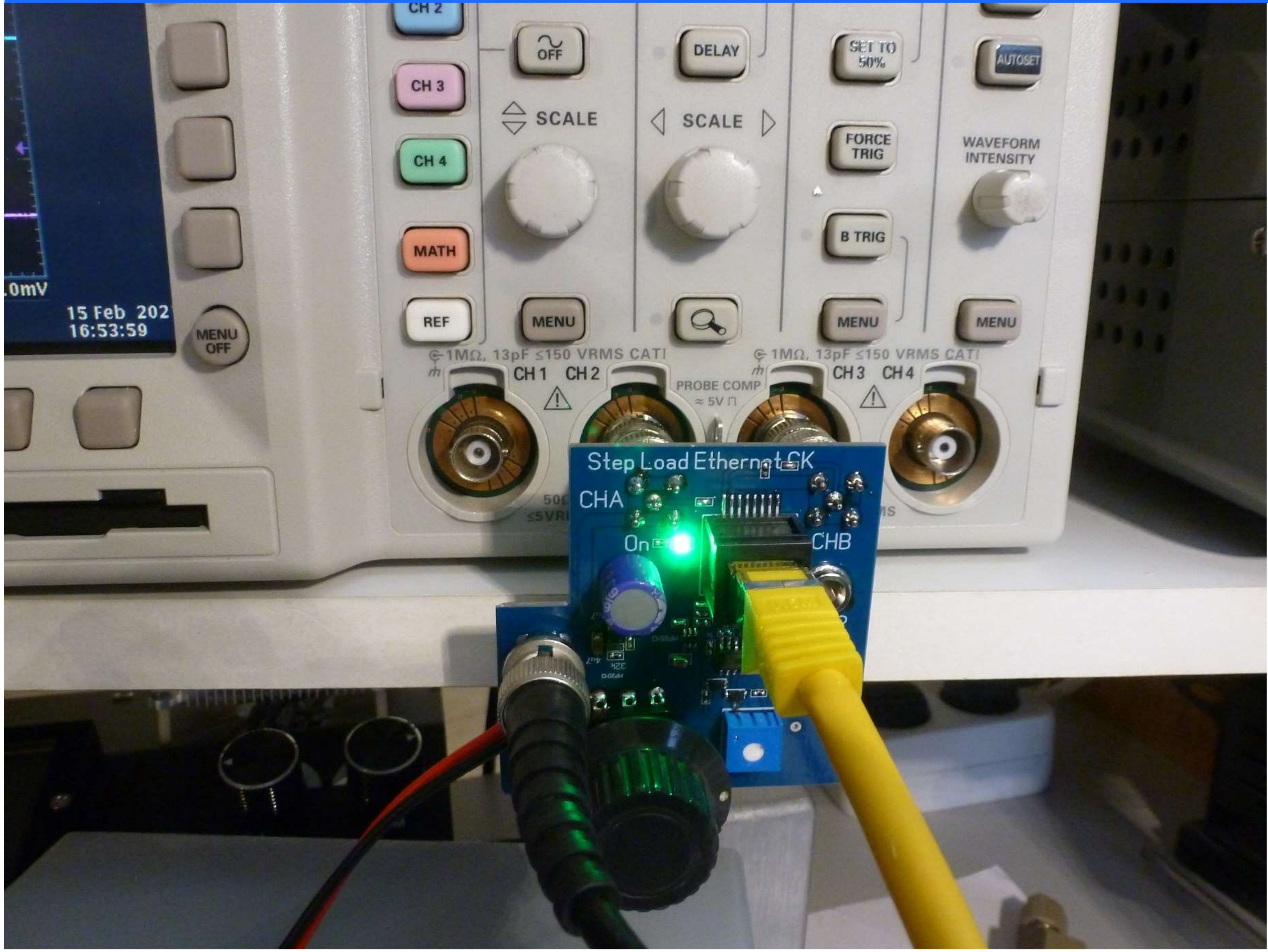


Addendum Step load adapter Scope 2 layer 44x63mm

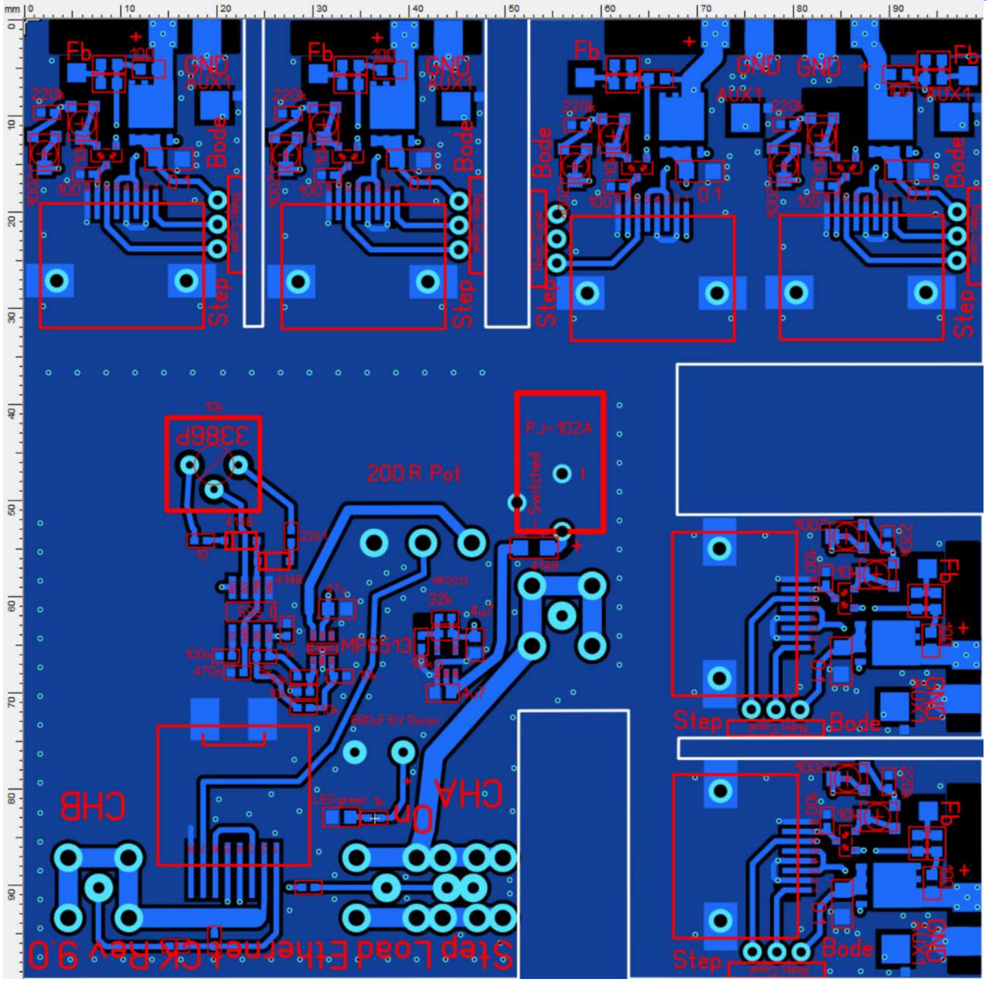


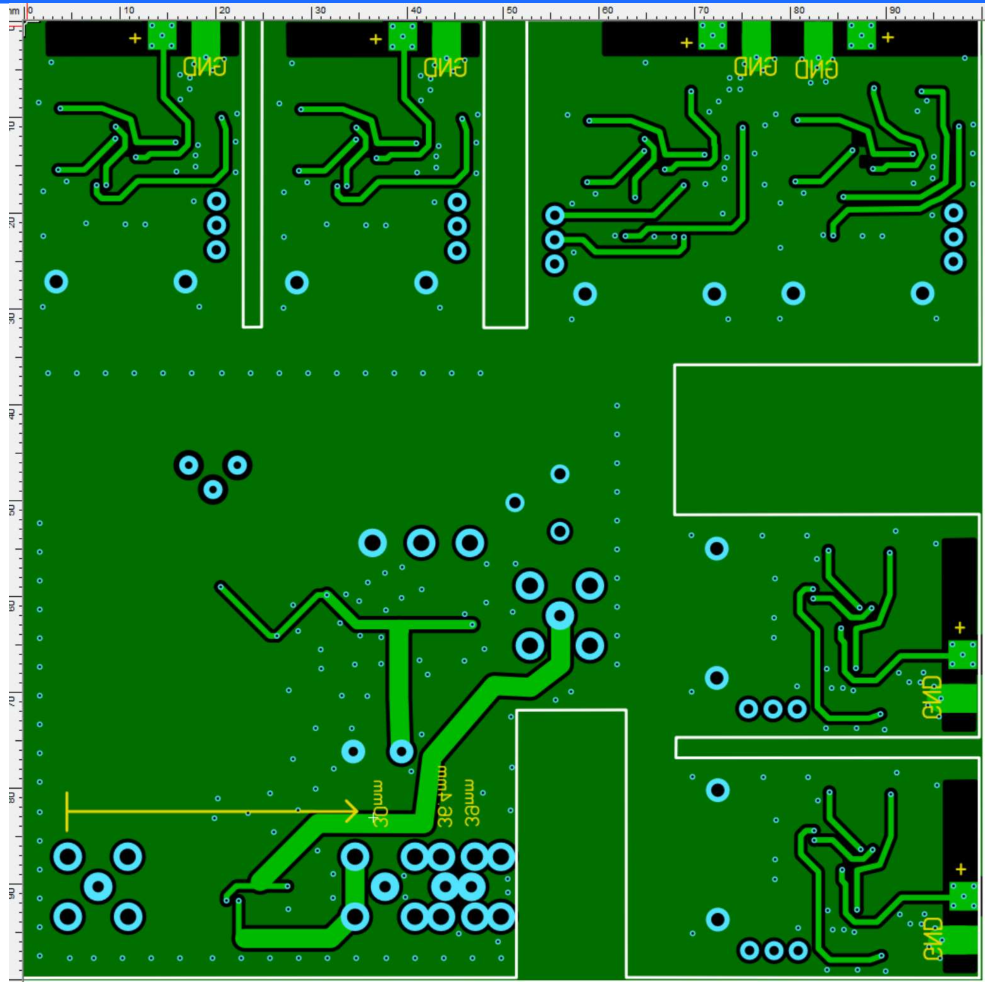


Addendum Step load adapter Scope

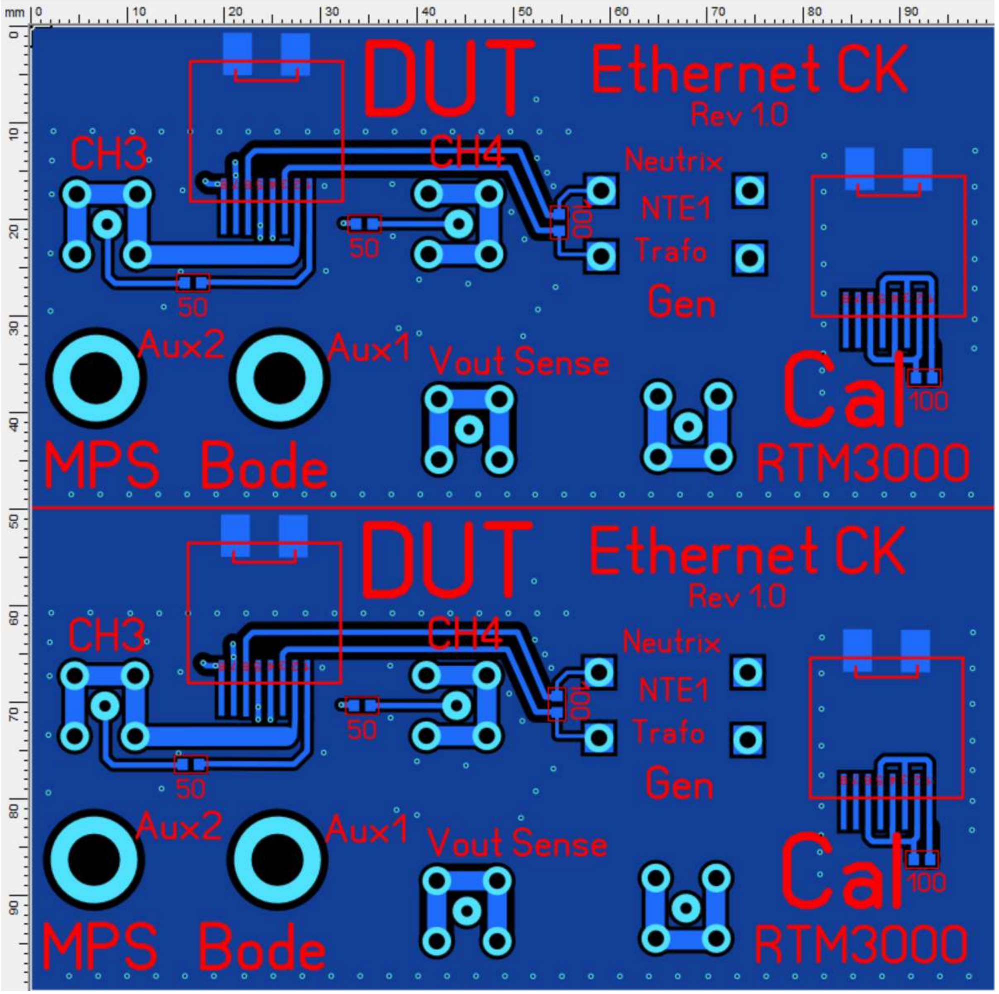


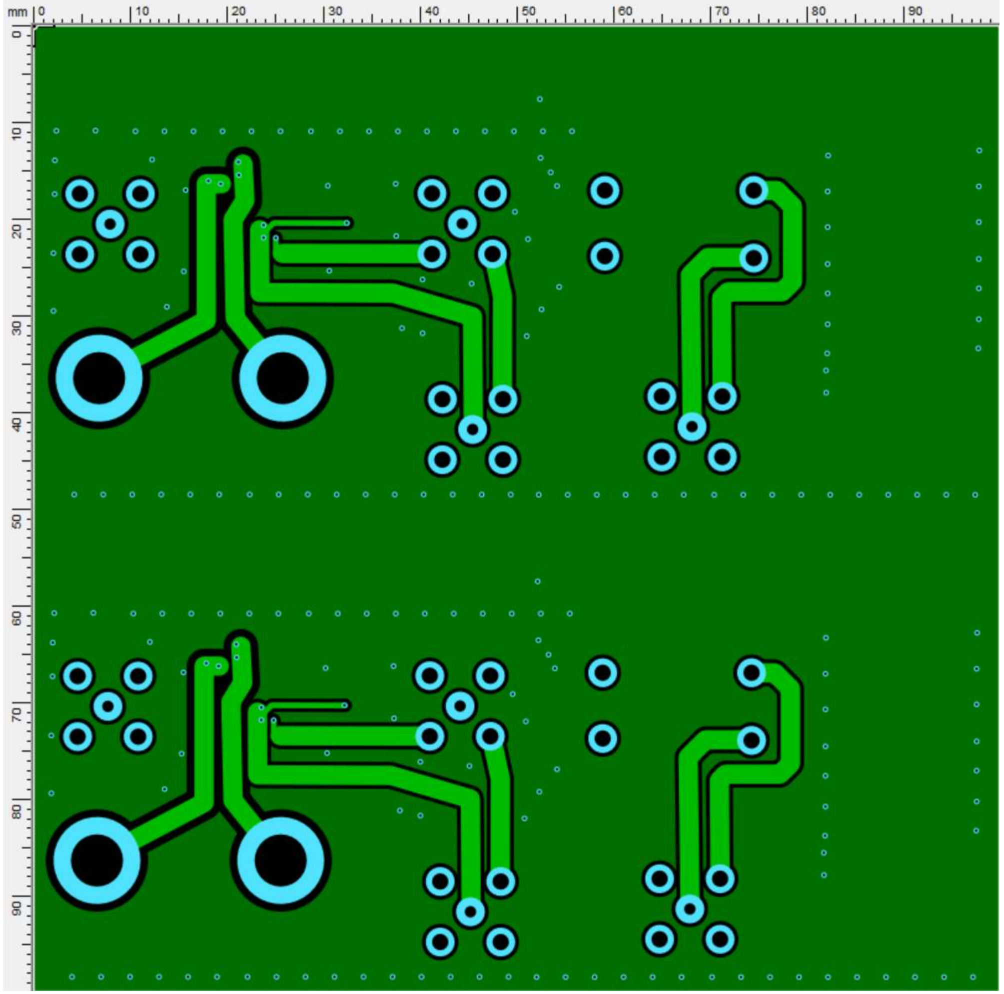
Addendum real multi PCB 100x100mmm



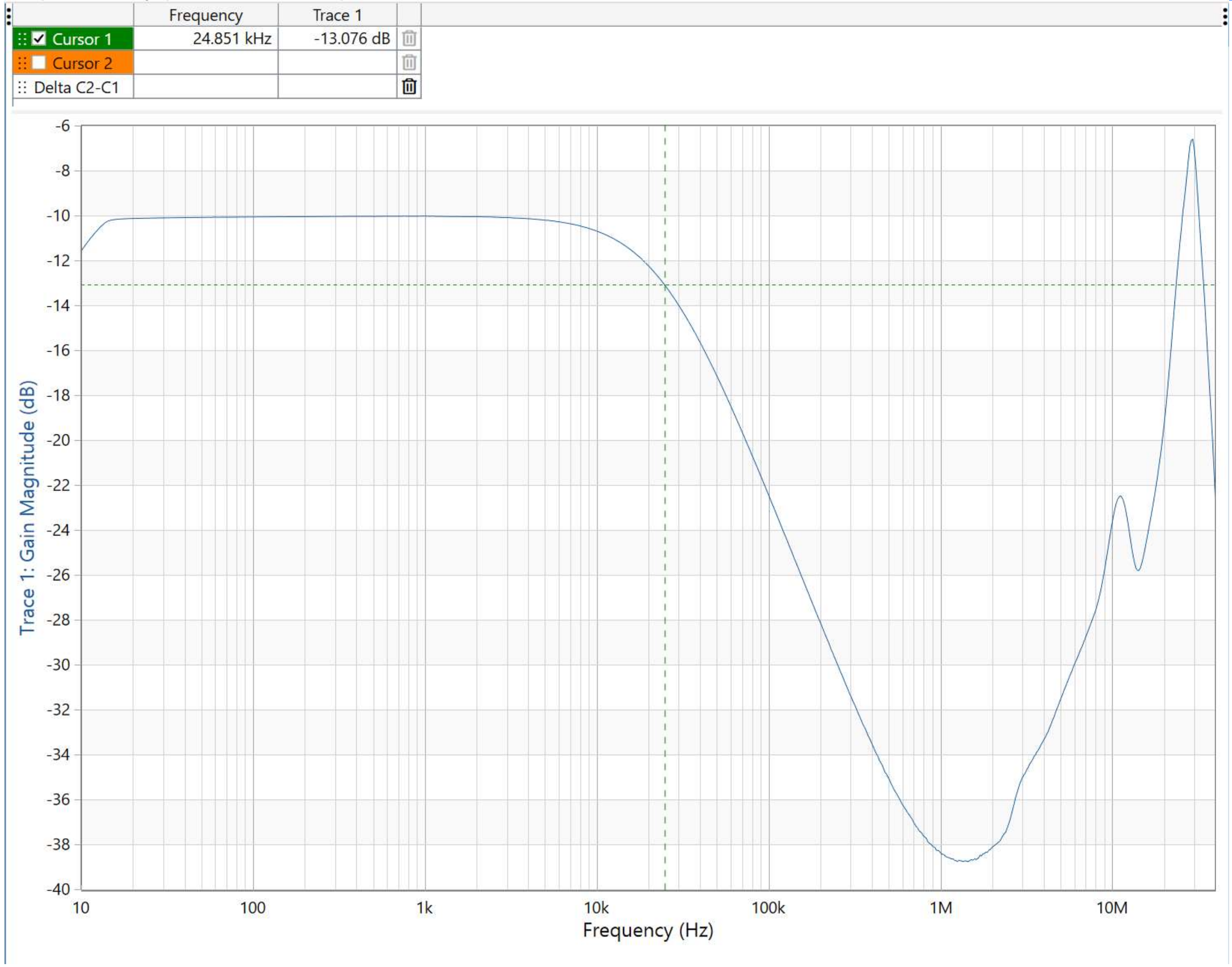


RTM3000 Series Bode adapter





NTE1 Transformer damping with 50 Ohm load



With the used 2x100Ohm parallel = 50 Ohm load the transformer shows flat (-3dB) response from 10Hz to 24kHz and has about a 3rd order low pass damping down to 1MHz.
This frequency dependent damping comes in handy and needs in most PSU cases only minor additional correction with the shape level feature.

The general frequency and phase response of the transformer does not affect the measured phase plot other than with the frequency dependent amplitude. Its only purpose is to isolate the generator voltage from the V(x)=Ch1 and V(y)=Ch2 measurement nodes.

Some special BOM Articles

Christians Bode Step Load Adapter

<table>
<tr><th>o.k.</th><th>QTY.</th><th>Ref.</th><th>Description</th><th>Package</th><th>Manufacturer</th><th>Manuf._PN</th><th>Source</th><th>Order #</th><th>Price ea. €</th><th>Price Total.</th><th>Website</th></tr>
<tr><td></td><td>2</td><td>NA</td><td>Vertical RJ45</td><td>RJ45</td><td>Amphenol</td><td>98435-311LF</td><td>Digikey</td><td>609-6038-1-ND</td><td>0.99</td><td>1.98</td><td>98435-311LF Amphenol ICC (FCI) | Steckverbinder, Verbindungen | DigiKey</td></tr>
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<tr><td></td><td>2</td><td>P1,P1</td><td>4mm jacket solder</td><td>THC</td><td>Keystone</td><td></td><td>Digikey</td><td>36-575-8-ND</td><td>0.682</td><td>1.364</td><td>https://www.digikey.de/product-detail/de/keystone-electronics/575-8/36-575-8-ND/318495</td></tr>
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