How Do I Choose the Right Switching Frequency for My Design?

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2010 – Present

- MPS Senior FAE since 2010, working with industrial and automotive customers on power supply design.
- Particular specialty focus on layout and EMC topics, including frequently visiting automotive EMC lab for EVB testing / optimization and improving MPS automotive/industrial EVB’s EMC performance

1999 – 2010 FAE at Linear Technology

- Support industrial and automotive customers; Support LTC's EMC clean EV-Board DC1212 (LT3480/LT3685)

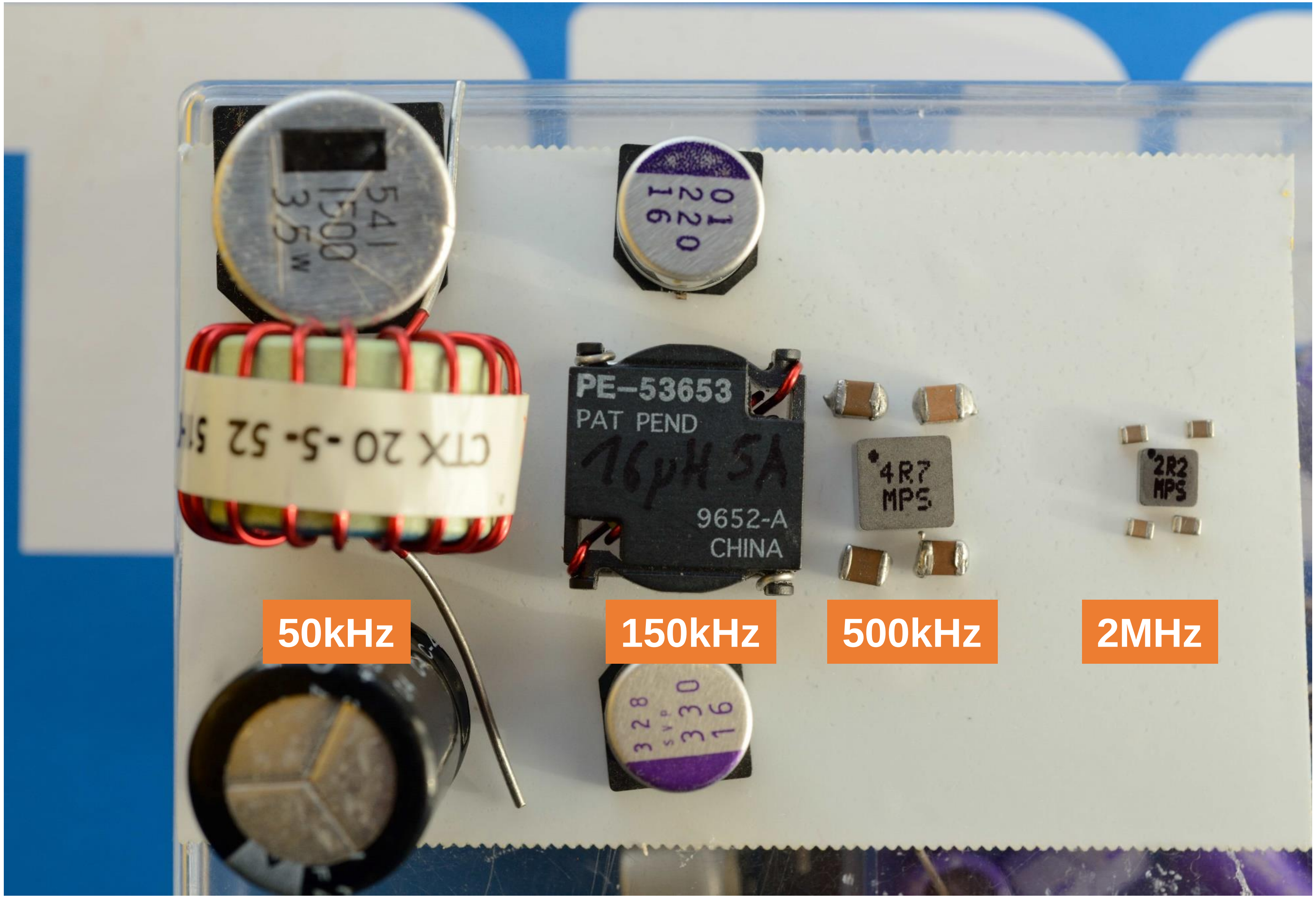
1995 – 1998

- Hardware design engineer at Nokia Mobile Phones; Worked on early automotive Telematic solution with e-call and emergency battery; EMC support

How Do I Choose the Right Switching Frequency for My Design?

- The motivation: smaller size and lower cost
- How switching frequency impacts external components - a look to key design formulas
- Duty cycle limitations from min ON time and min OFF time
- Load step response
- Efficiency and power loss
- Junction temperature
- EMC/EMI performance
- Recap/Q&A

Motivation: Achieving Smaller Size and Lower Cost Solution

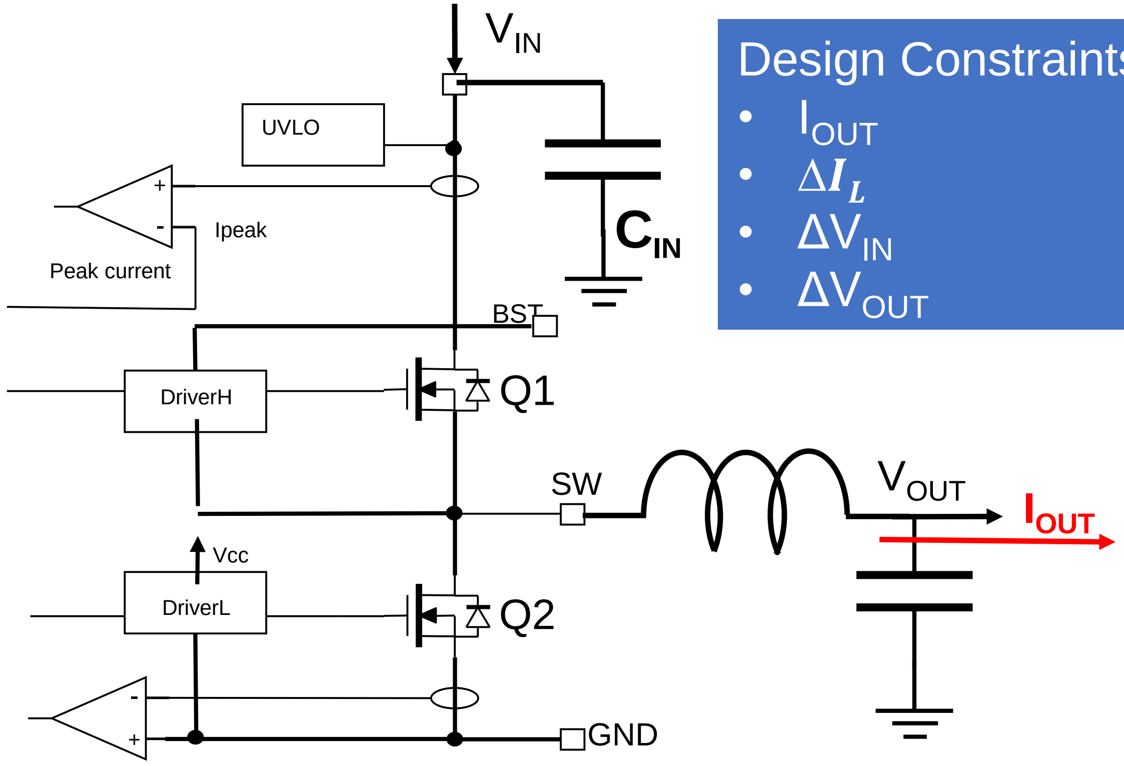


Example: 5A Buck

Switching Frequency

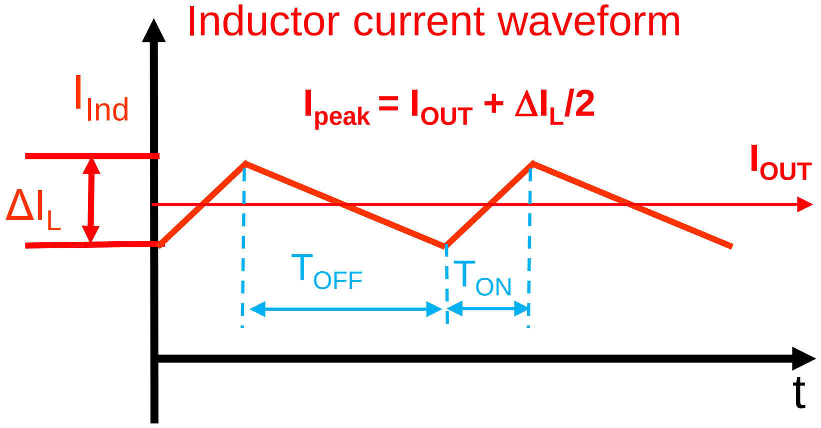
Solution Size

Formula Refresher: Buck Circuit



Design Constraints:

- I_{OUT}
- ΔI_L
- ΔV_{IN}
- ΔV_{OUT}



$$\text{Q1 Duty-Cycle} = \frac{V_{OUT}}{V_{IN}}$$

$$\text{Ton} = \frac{D.C.}{F_{SW}}$$

Example: For 40% Inductor Ripple Current

$$L = \frac{(V_{IN} - V_{OUT}) * Ton}{0.4 * I_{OUT}}$$

$$C_{IN} \geq \frac{T_{on} I_{OUT}}{\Delta V_{IN}} \qquad \Delta V_{IN} < 100\text{mV} \qquad \text{ESR} < \frac{\Delta V_{IN}}{I_{peak}}$$

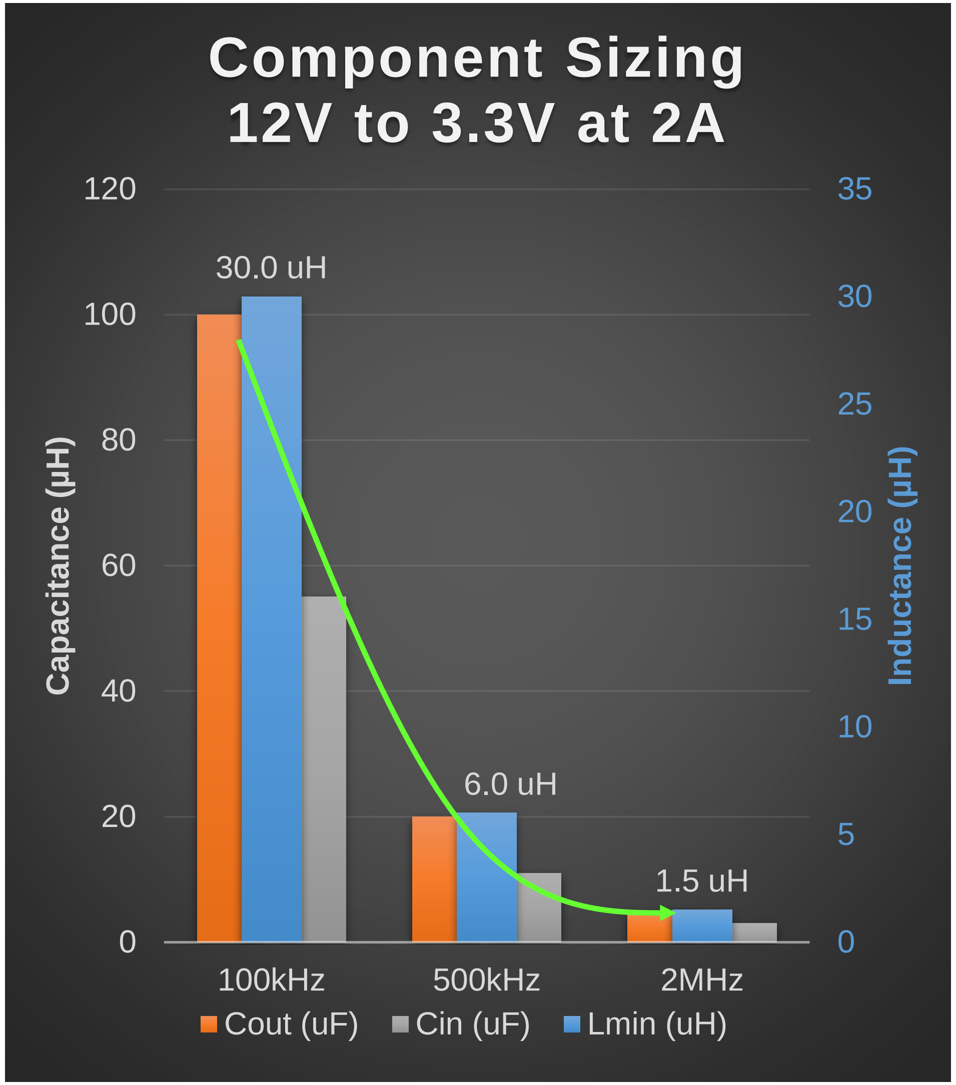
$$C_{OUT} \geq \frac{\Delta I_L}{(8 * F_{SW} * \Delta V_{OUT})} \qquad \Delta V_{OUT} < 10\text{mV}$$

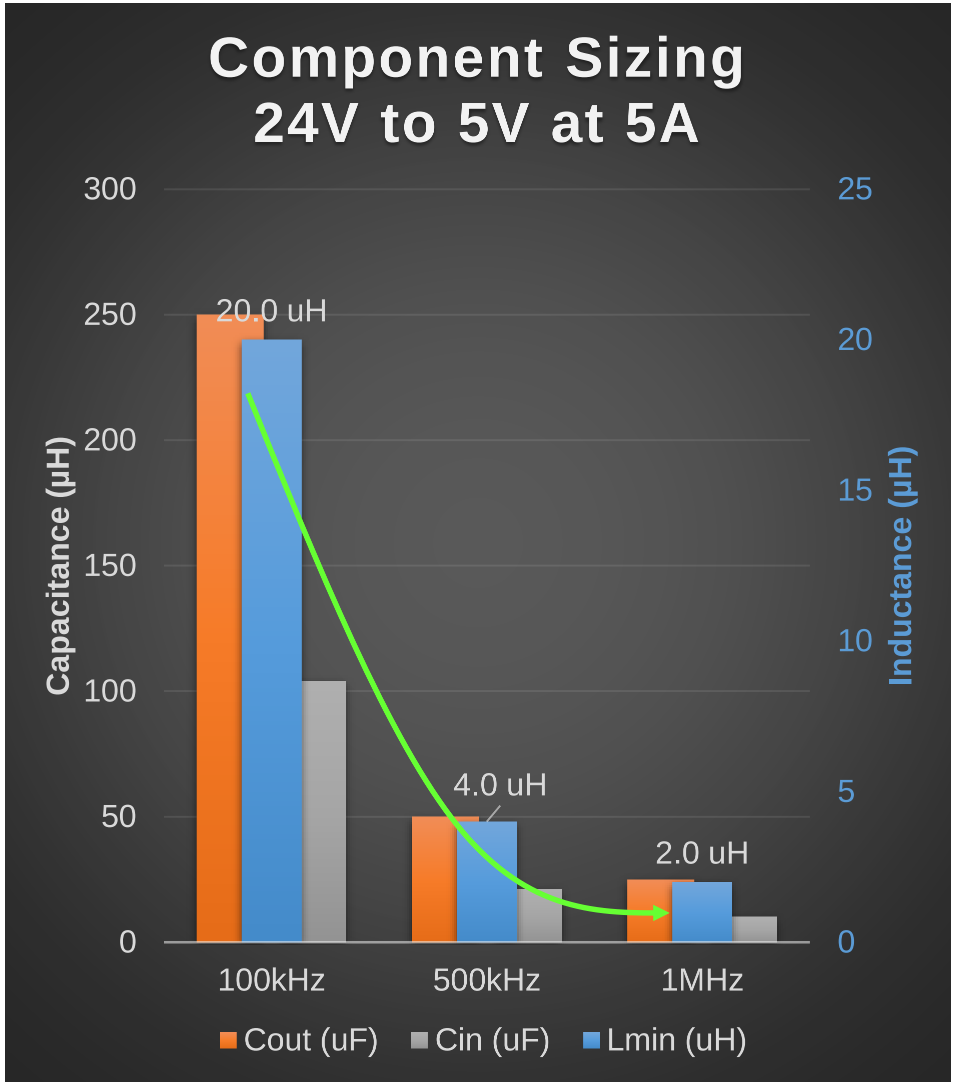
$$\text{ESR} < \frac{\Delta V_{OUT}}{\Delta I_L}$$

V_{OUT} ripple:

$$\Delta V_{OUT} \sim \Delta I_L \left(\text{ESR} + 1/(8 * F_{SW} * C_{OUT}) \right)$$

Component Shrink Often Drives Higher Switching Frequency

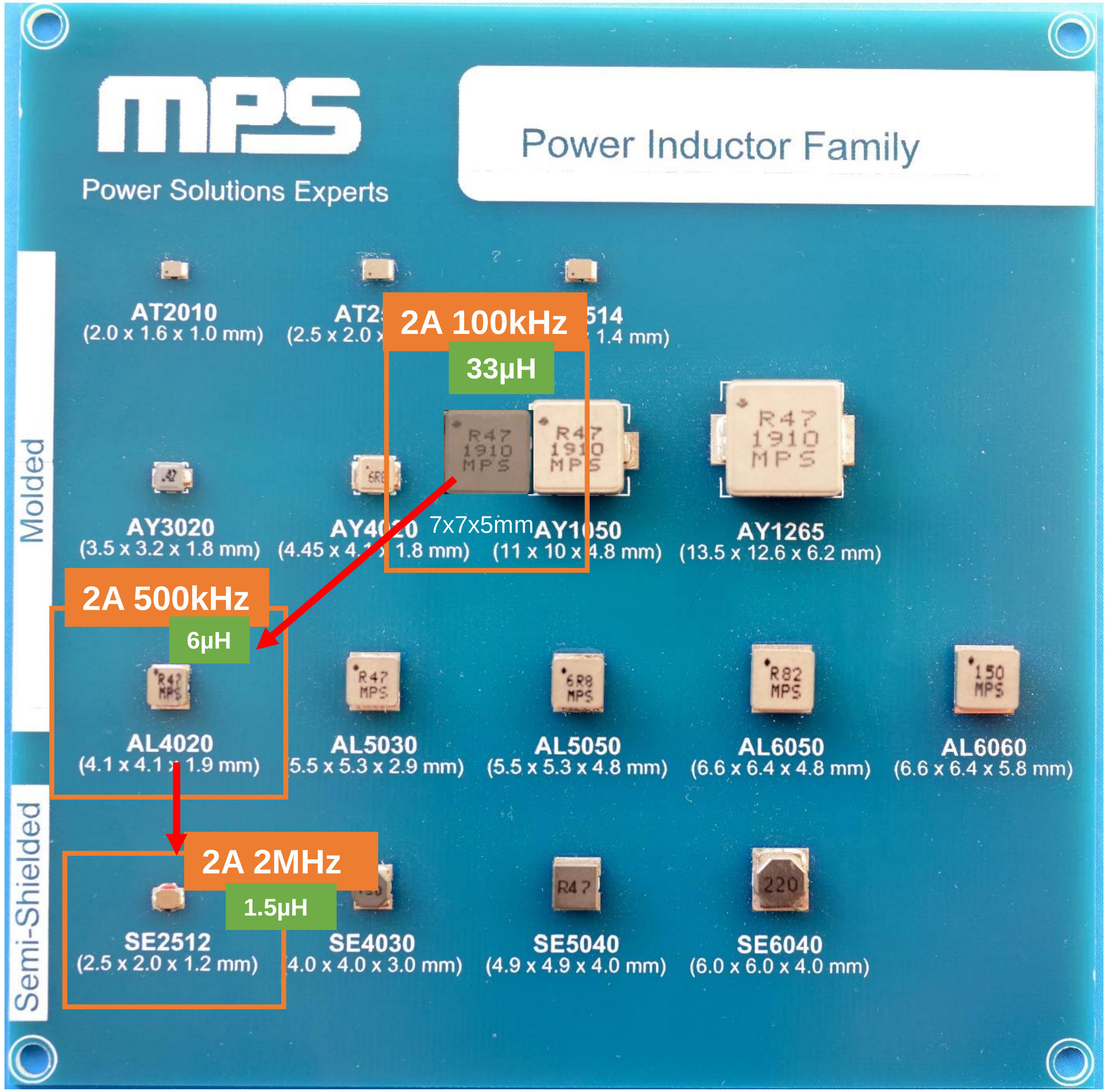




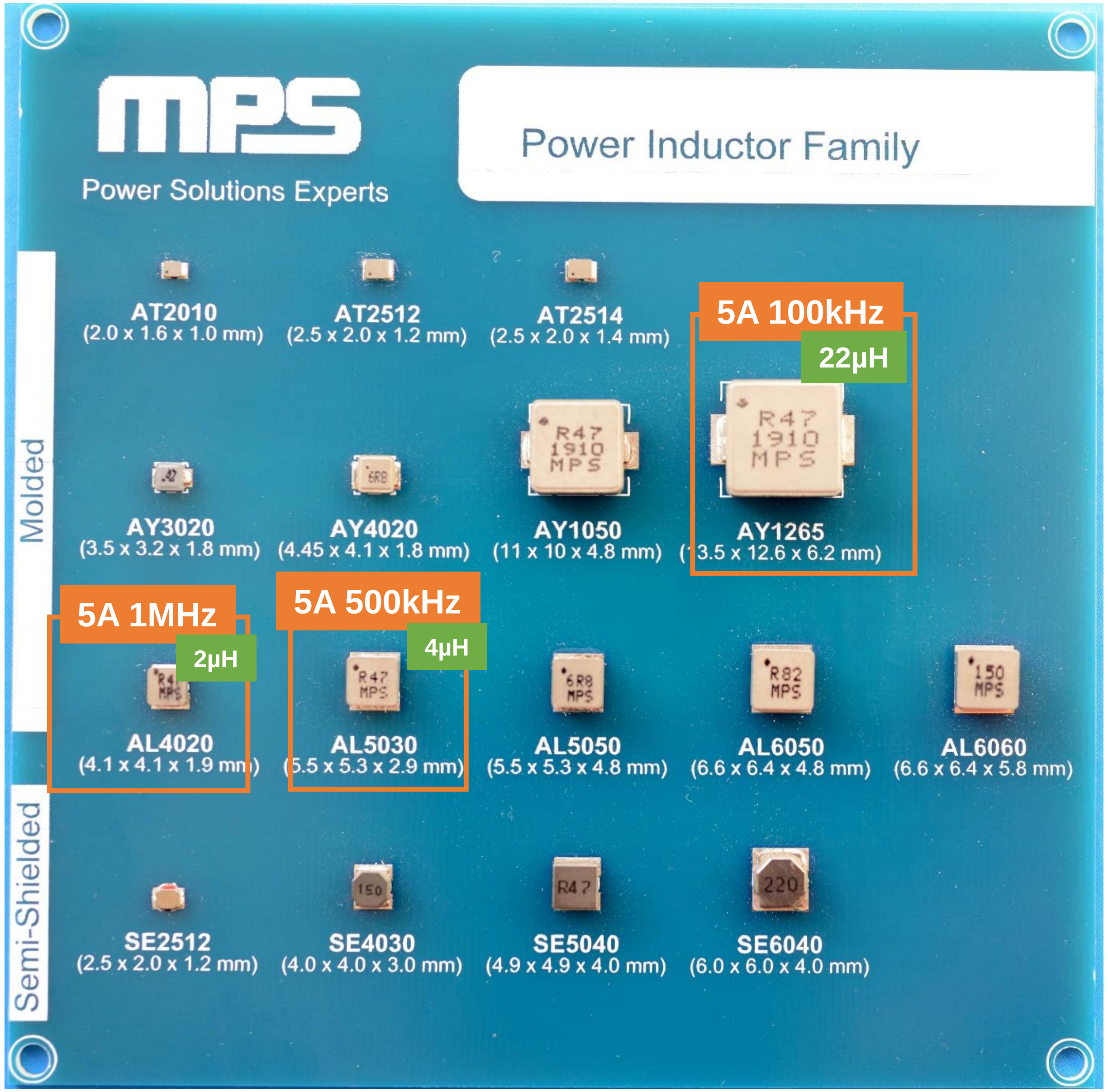
Design Example:

- 40% Inductor Ripple Current
- 10mVpp Output Ripple
- 100mV Input Ripple

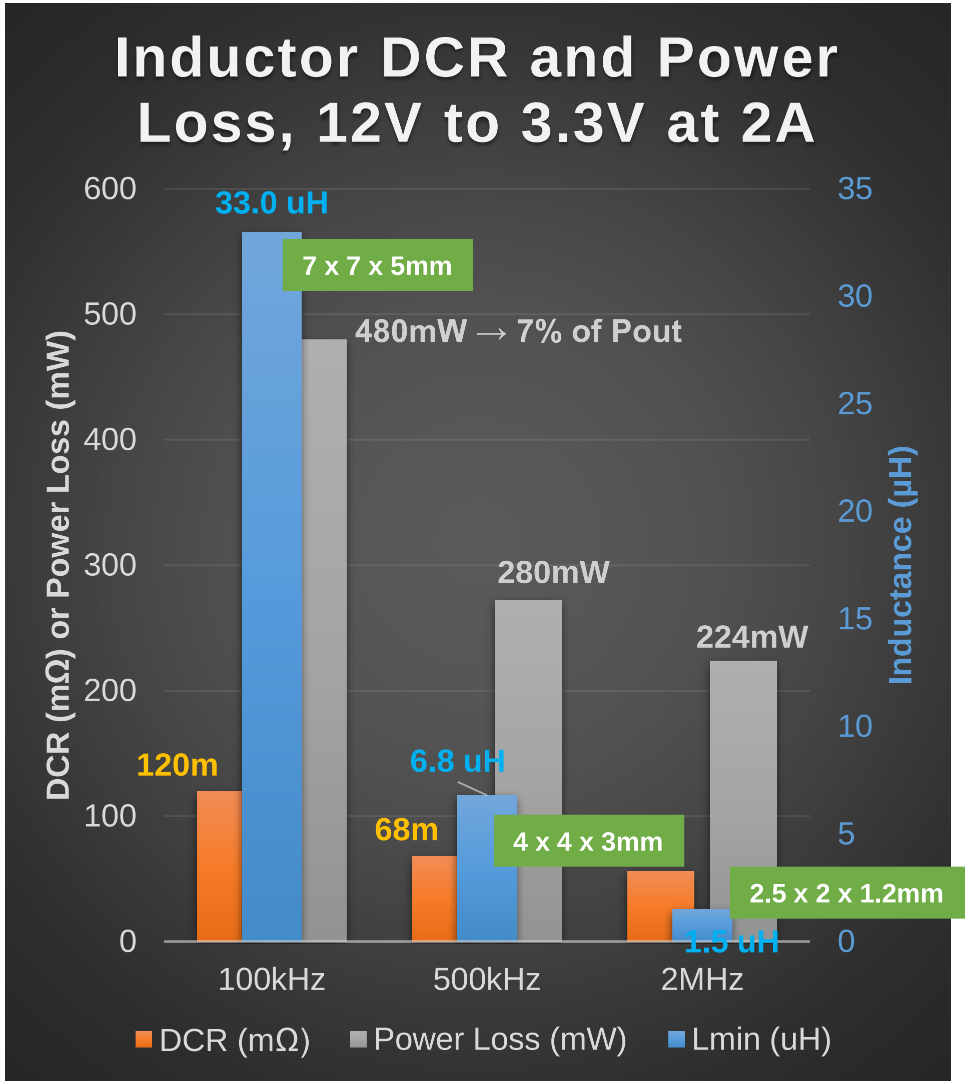
Coil Size vs. Fsw and Current: 12V to 3.3V 2A

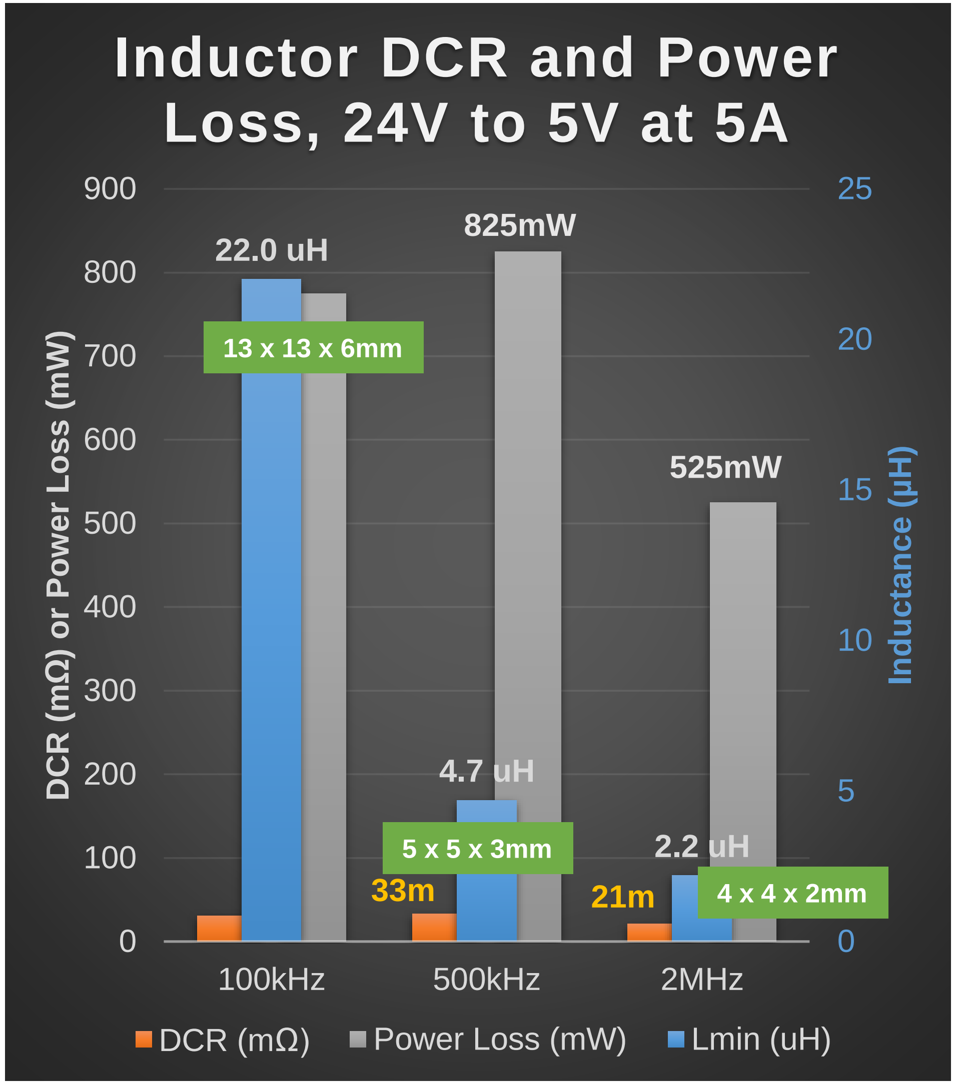


Coil Size vs. Fsw and Current: 24V to 5V 5A

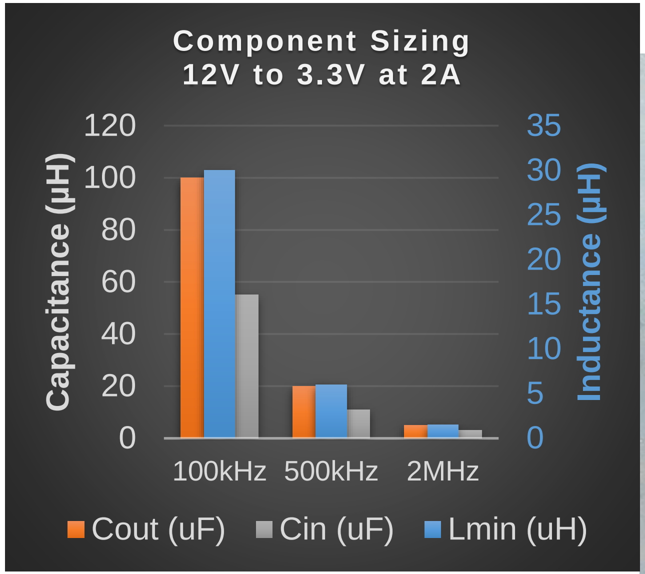


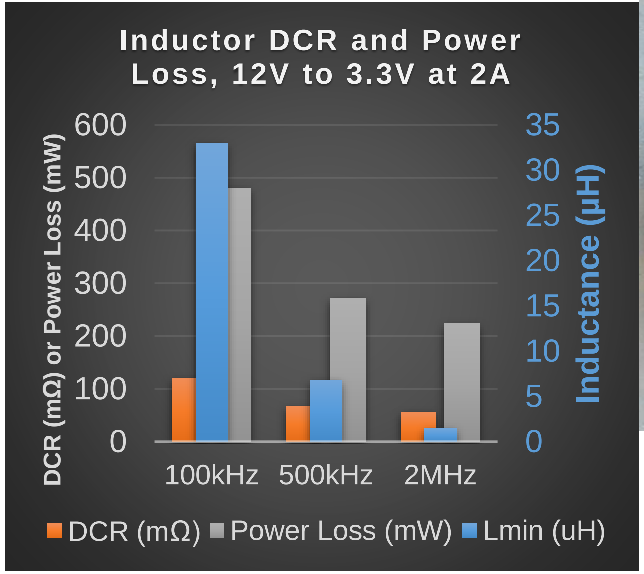
Motivation for High Switching Frequency: Inductor Size & Losses





Solution Size Example: 12V to 3.3V at 2A



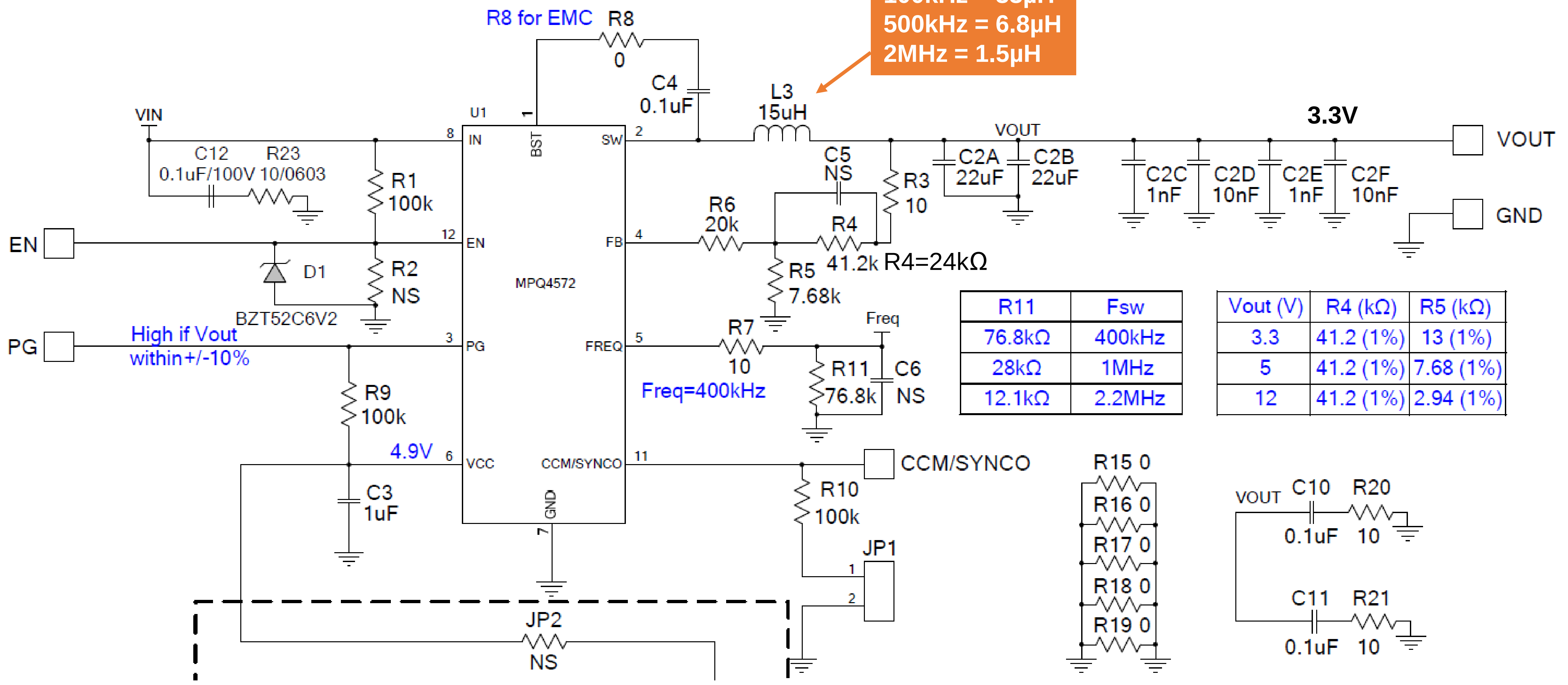


Notes:

- **Cout ESR** must be below 12mΩ!
- Assume effective MLCC capacity ~50% at used voltage
- IC Example is MPQ4572 – 60V, 2A Sync. Buck 250/45mΩ (2.5mm x 3mm FC-QFN)

EV-Board Schematic MPQ4572

L3 sizing:
100kHz = 33µH
500kHz = 6.8µH
2MHz = 1.5µH



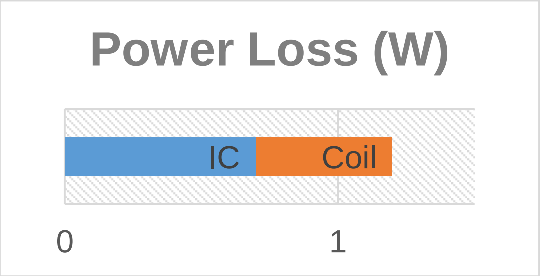
R11	Fsw
76.8kΩ	400kHz
28kΩ	1MHz
12.1kΩ	2.2MHz

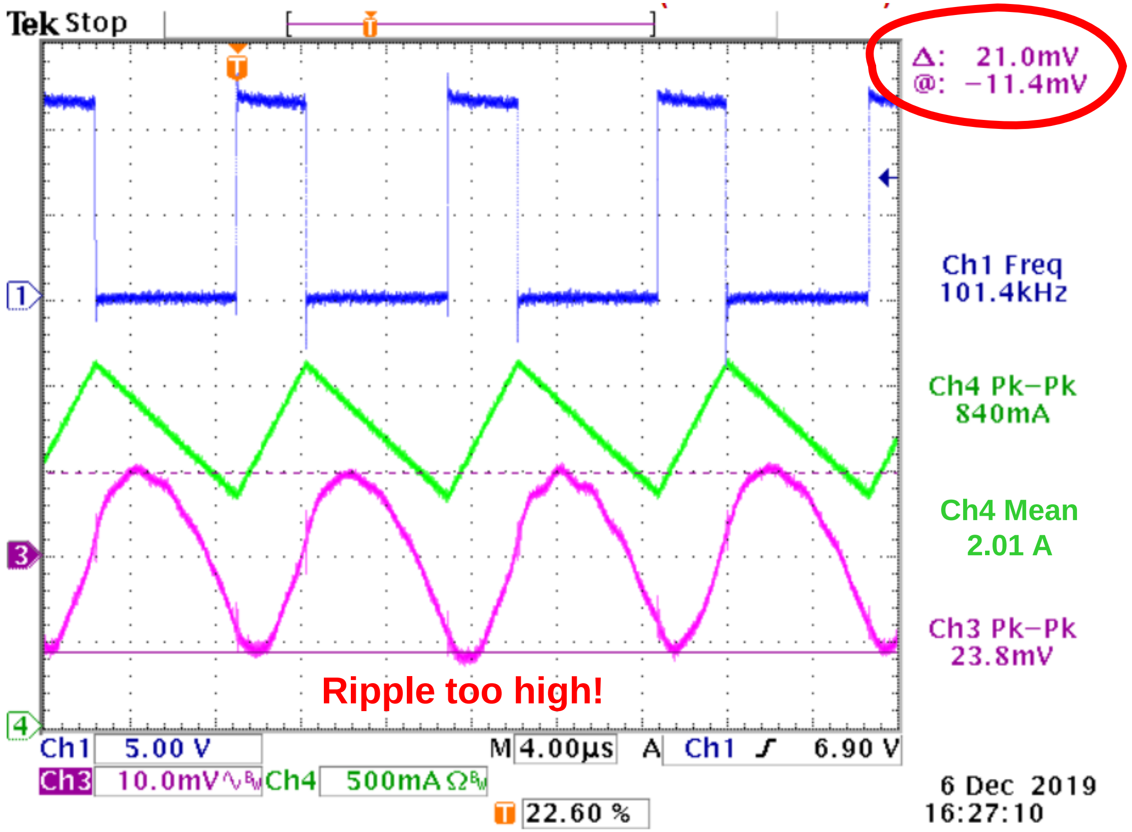
Vout (V)	R4 (kΩ)	R5 (kΩ)
3.3	41.2 (1%)	13 (1%)
5	41.2 (1%)	7.68 (1%)
12	41.2 (1%)	2.94 (1%)

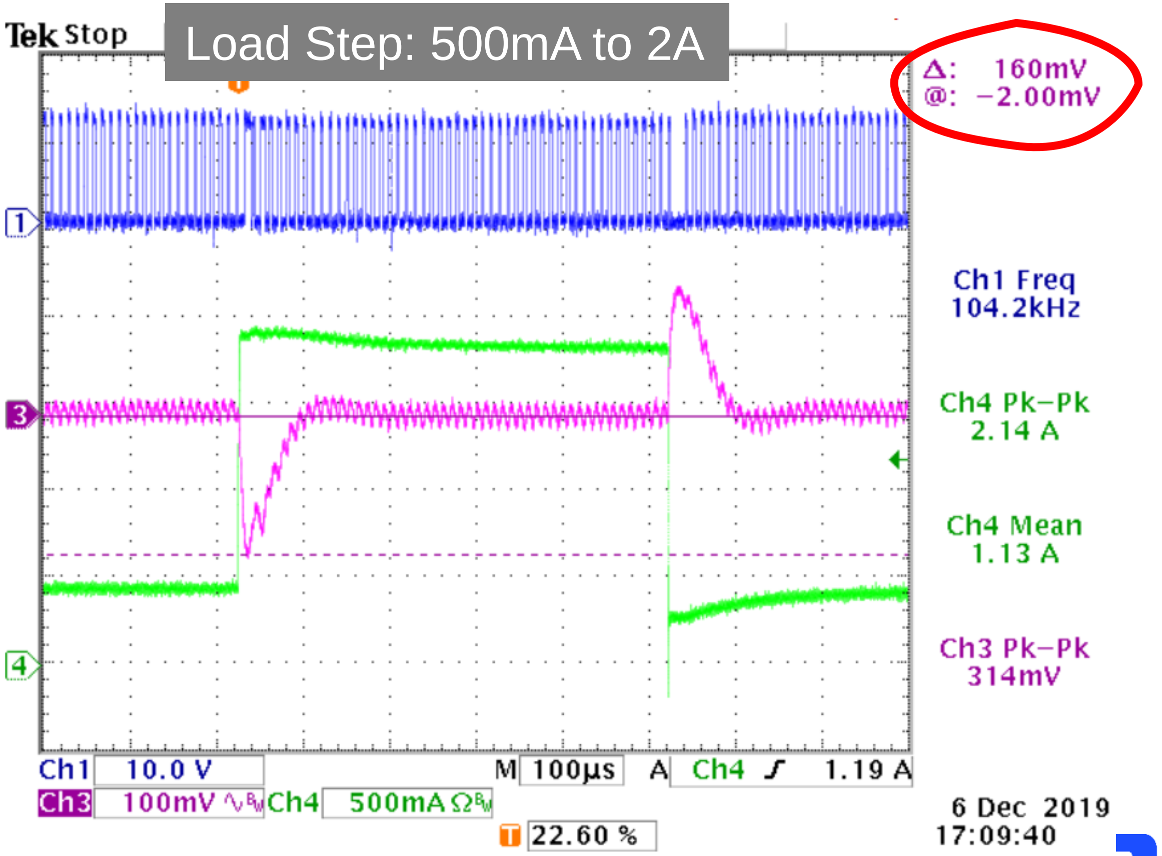
Cout(100kHz) = 2x 1210 22µF + 100µF 4V 100µF 4TPB100M **70mΩ**

Real World Picture: Switch, Vout Ripple, Inductor Current at 100kHz

Conditions:
12V to 3.374V at 2A
L = 33µH (120mOhm)
Cout = 2x 22uF 1210 + 1x 100uF (70mOhm)
85% Efficiency
1.2W Power Loss



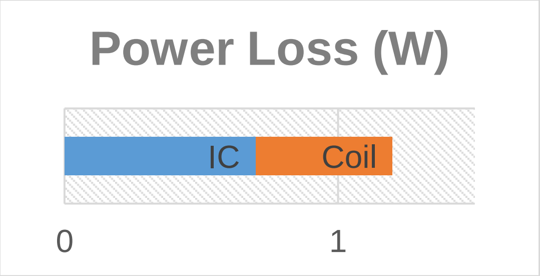


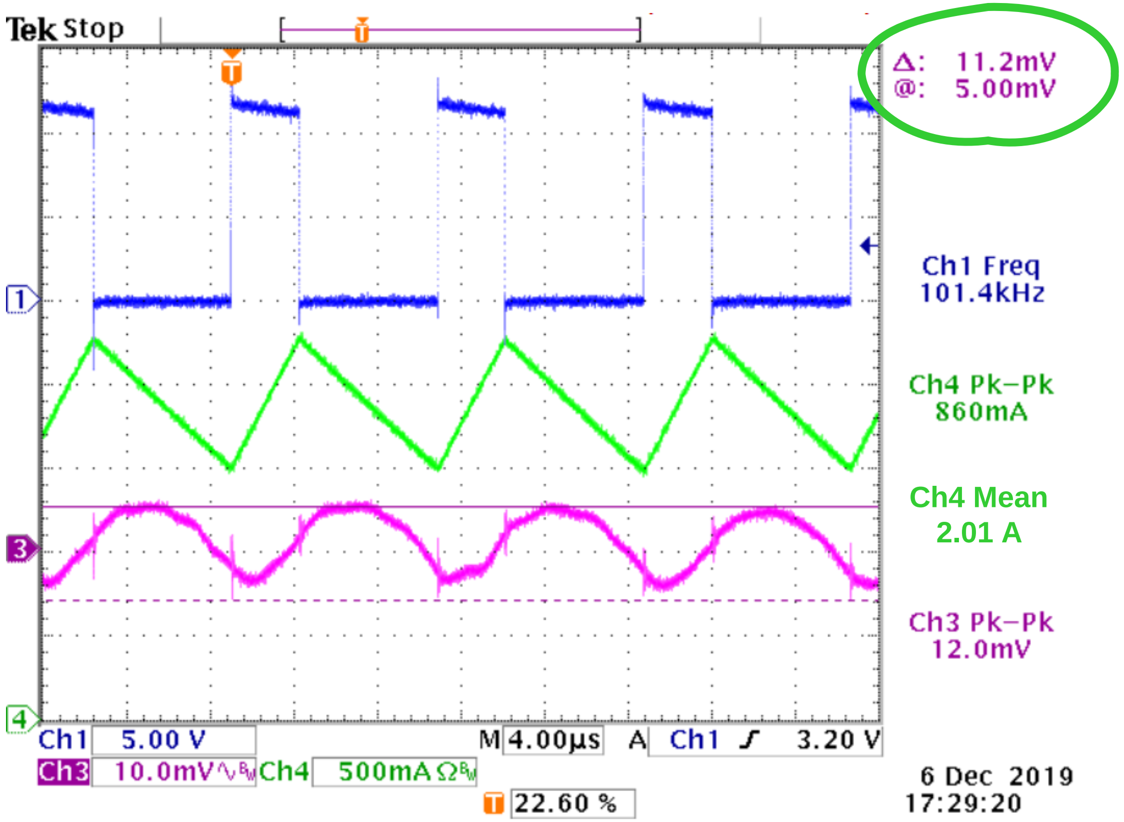


L = ETQP5N330YFM

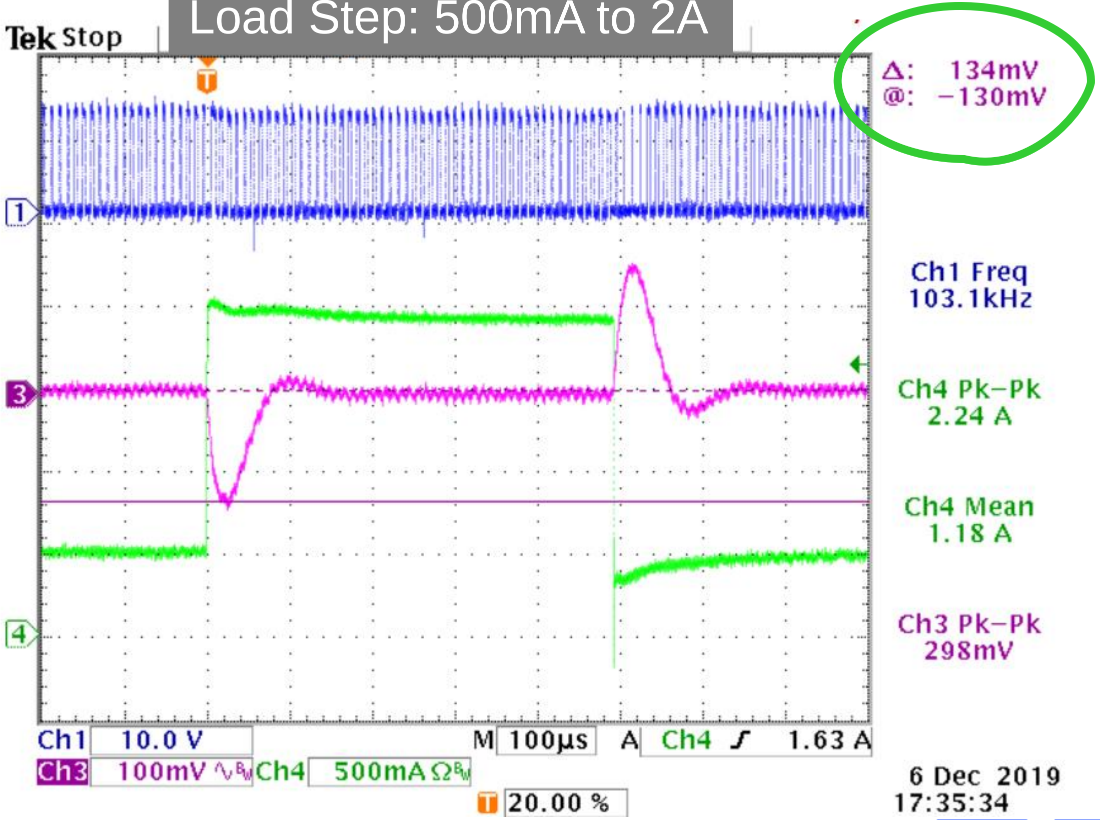
Same 100kHz Design with 100µF 15mΩ Output Capacitor

Conditions:
12V to 3.374V at 2A
L = 33µH (120mOhm)
Cout = 2x 22uF 1210 + 1x 100uF (15mOhm)
85% Efficiency
1.2W Power Loss





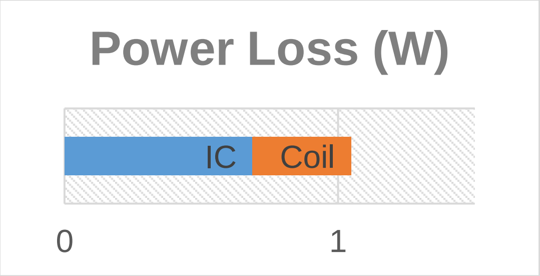
Load Step: 500mA to 2A

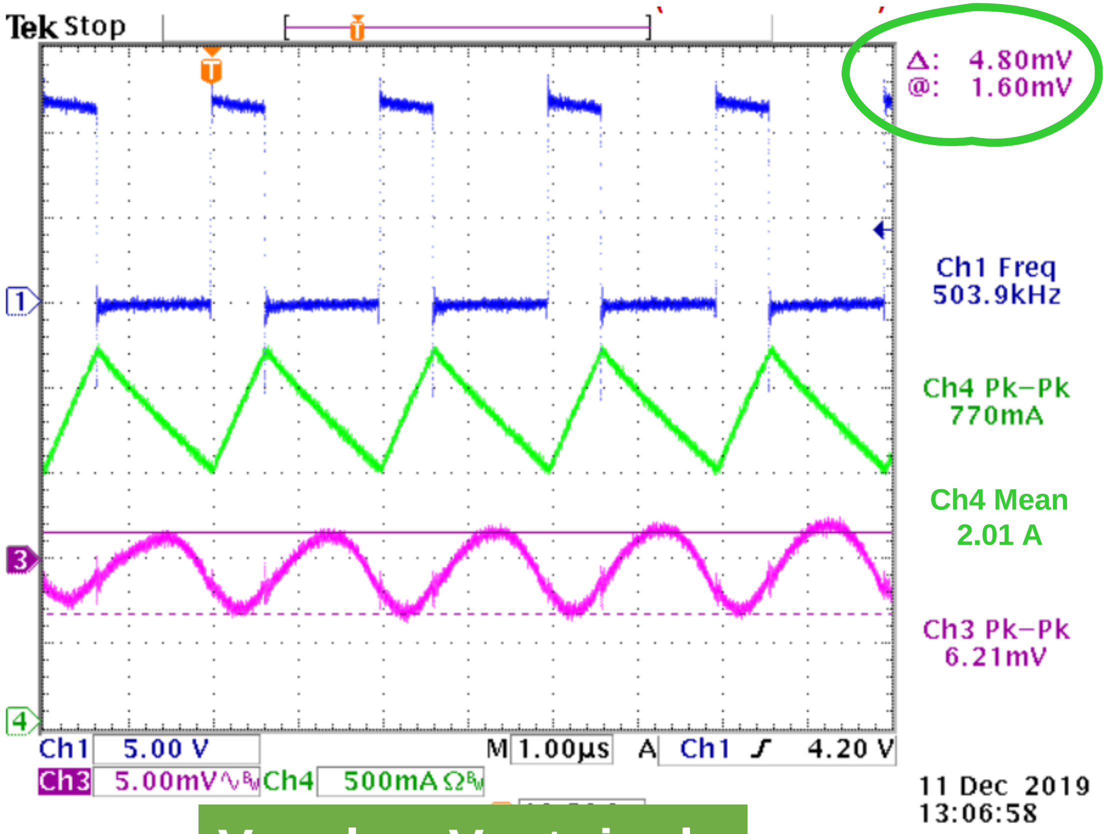


L = ETQP5N330YFM
Cout = EEFCX0J101R 7.3 x 4.3 x 1.9 mm

Real World Picture: Design at 500kHz

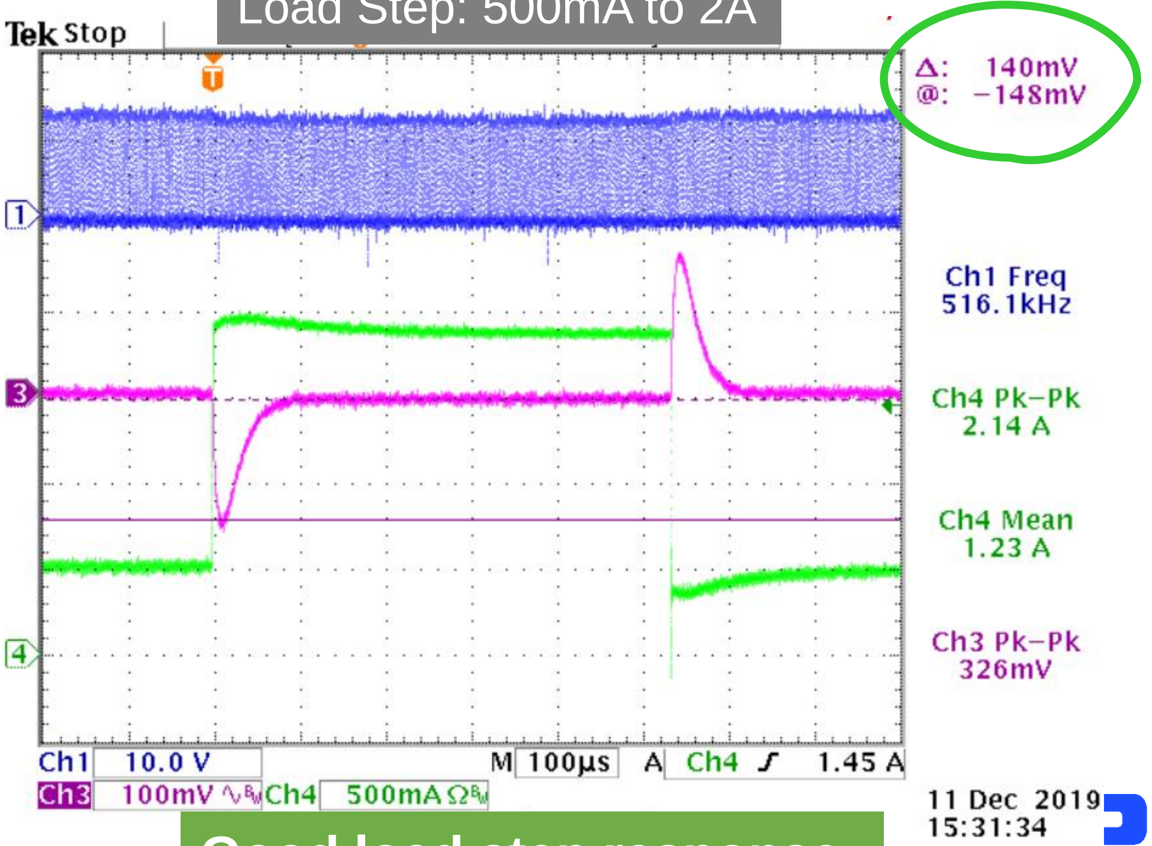
Conditions:
12V to 3.374V at 2A
L = 6.8µH (68mOhm)
Cout = 2x 22uF 1210
86.6% Efficiency
1.05W Power Loss





Very low Vout ripple

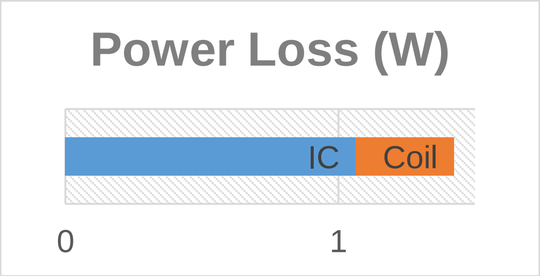
Load Step: 500mA to 2A



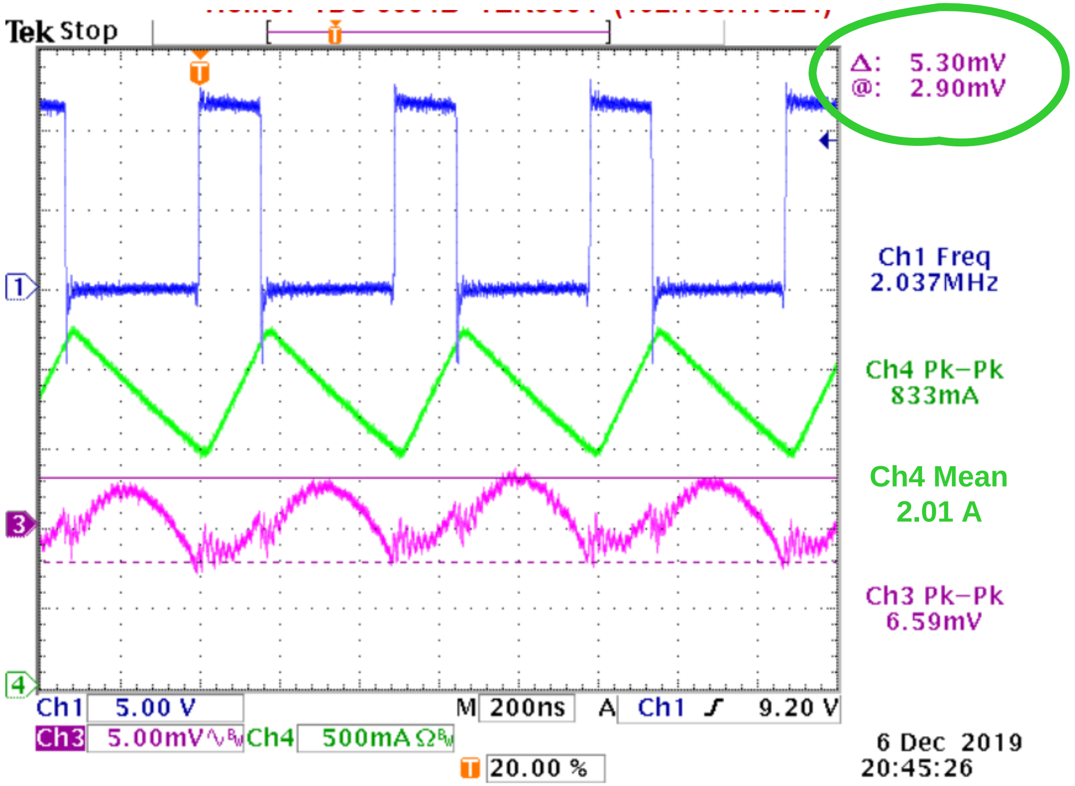
Good load step response

Real World Picture: Design at 2MHz

Conditions:
12V to 3.374V at 2A
L = 1.5µH (56mOhm)
Cout = 2x 10uF 0805
82.5% Efficiency
1.42W Power Loss

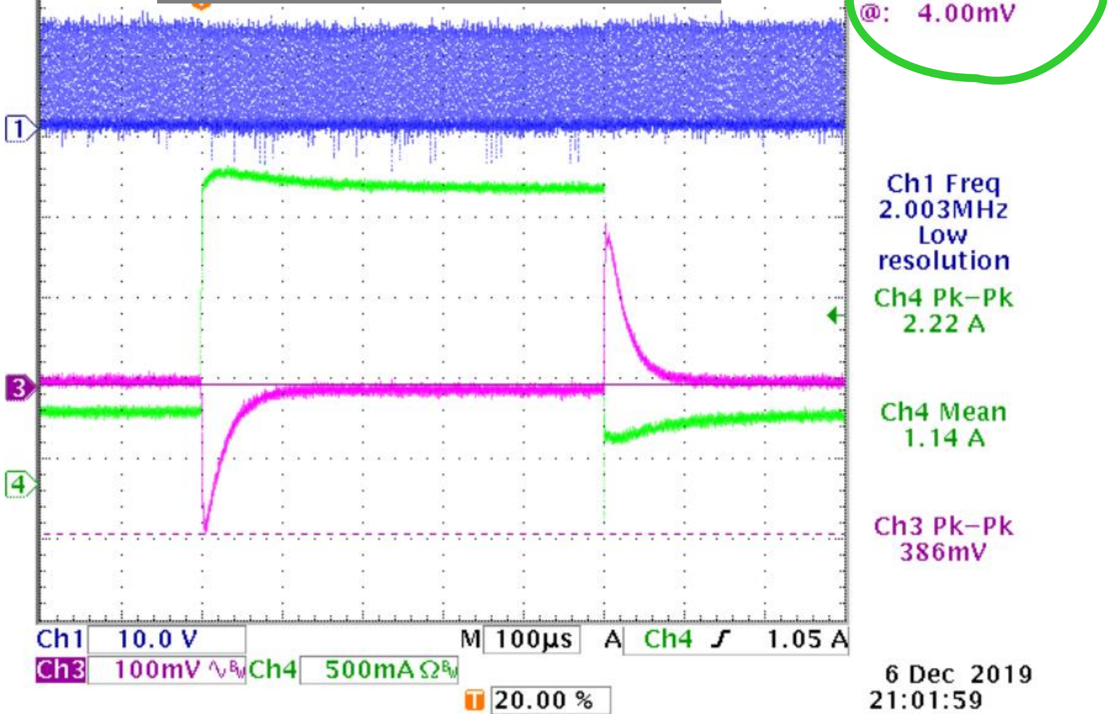


L = MPL-AT2512
Cout = JMK212AB7106KG



Very low Vout Ripple!

Load Step: 500mA to 2A



Excessive deviation - Cout not enough

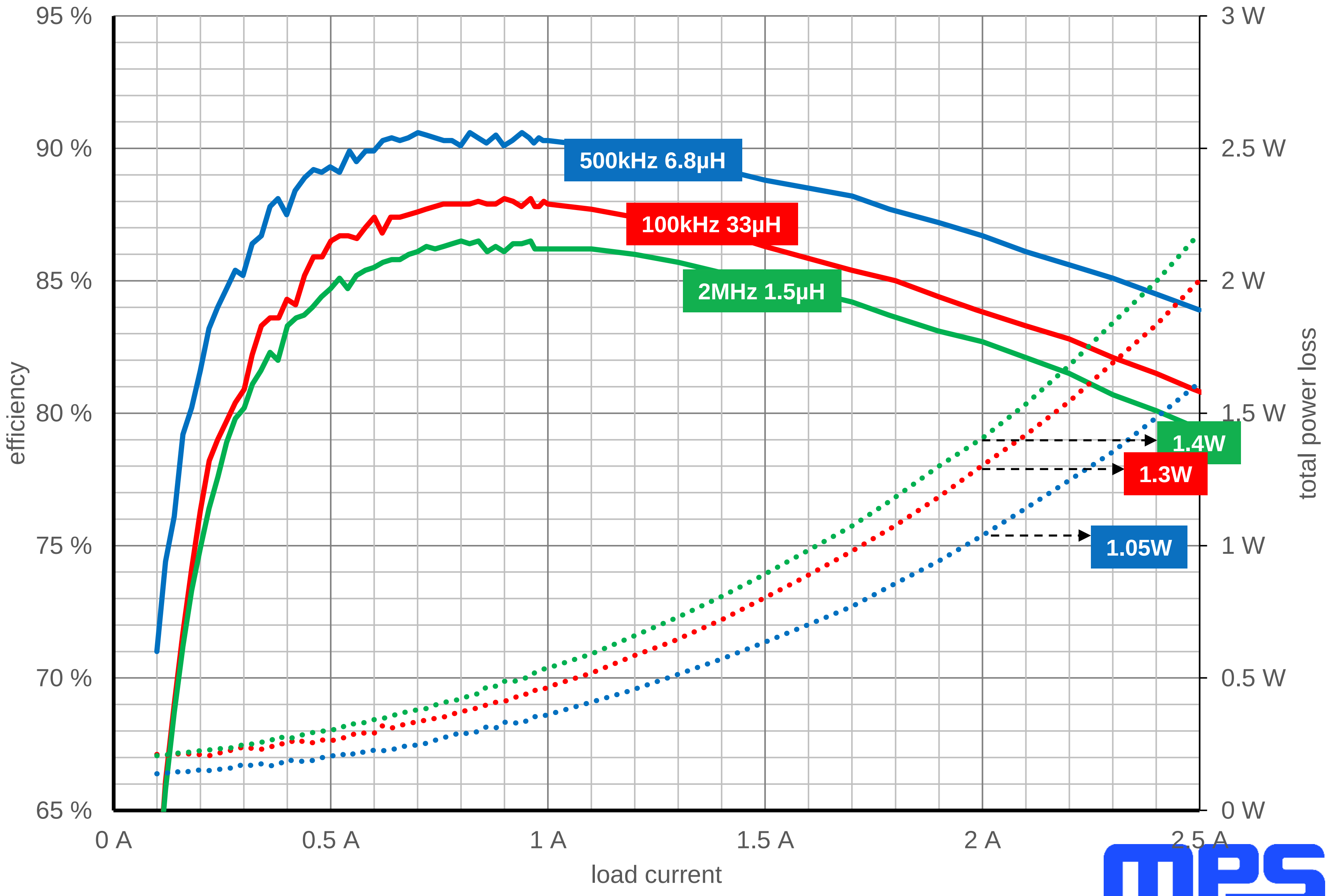
Efficiency Curves for 12V to 3.3V

Results for MPQ4572 65V, 2A Sync. Buck (250mΩ/45mΩ)

Real world 2MHz efficiency is lowest due to switch transition losses

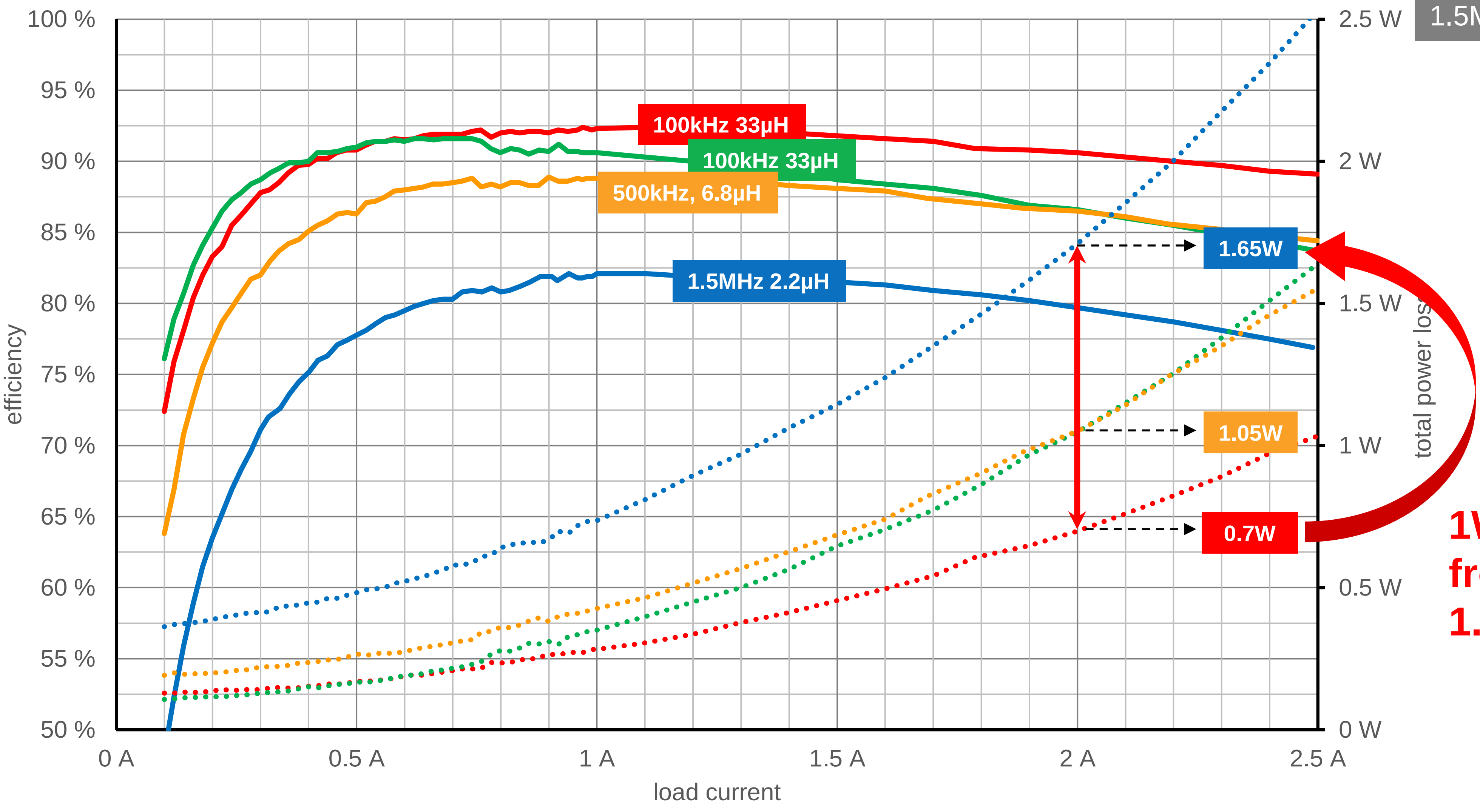
Calculation shows lowest DCR loss in coil for 2MHz setup

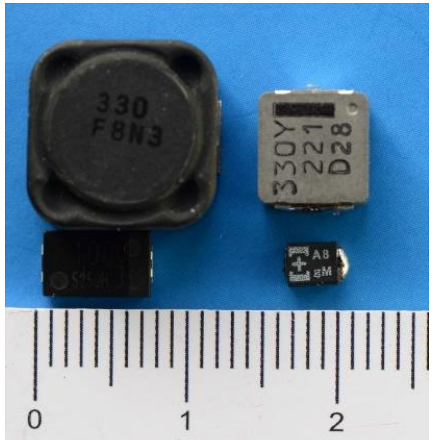
How do losses split up?
1.4W:
IC-FET Ron: 520mW
Coil DCR: 230mW
Coil AC: ~150mW
Remaining 500mW are transition losses and IC supply losses.



Efficiency Curves for 24V to 3.3V

Conditions:
100kHz: 33µH 64mΩ 12 x 12mm
100kHz: 33µH 120mΩ 7 x 7mm
500kHz: 6.8µH 68mΩ 4 x 4mm
1.5MHz:L 2.2µH 70mΩ 2.5 x 2mm





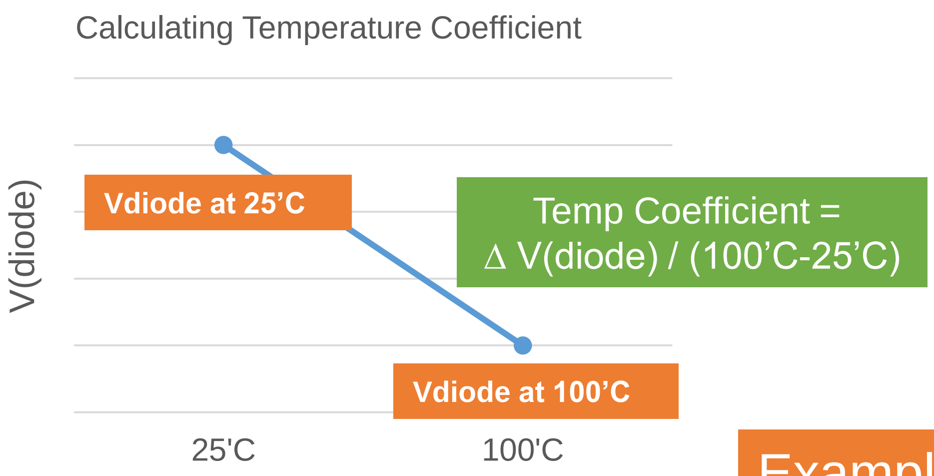
1W Higher Loss from 100kHz to 1.5MHz

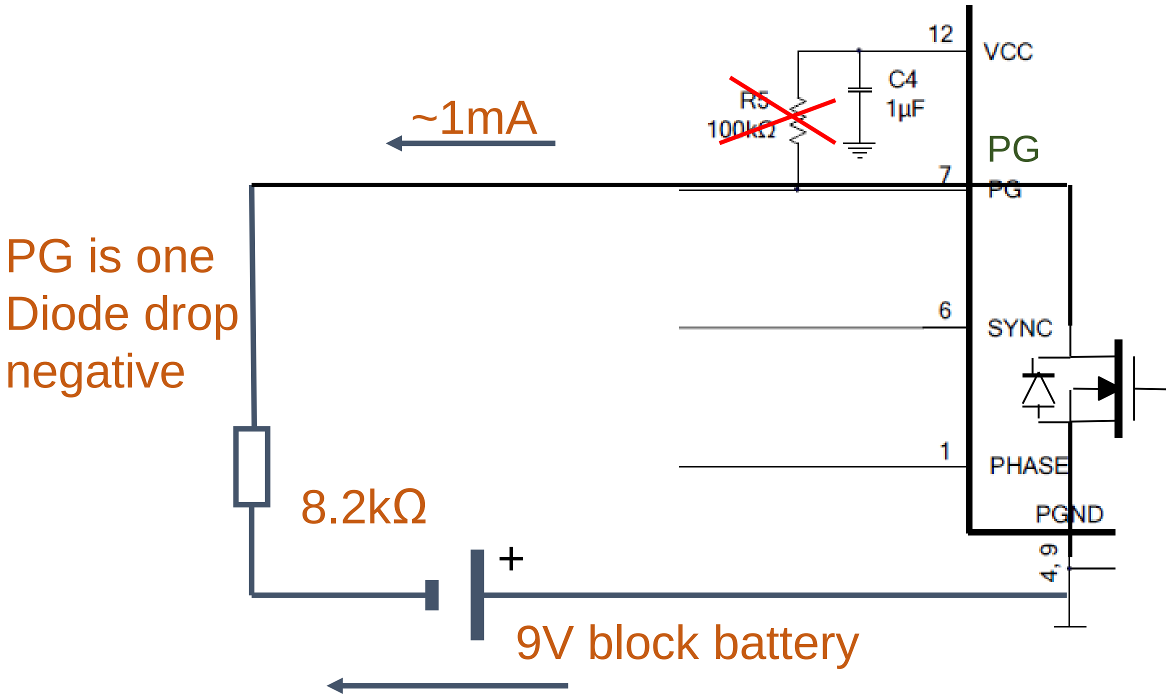
Calculating Die Temperature

Method: Characterize PG-Pin Body Diode

1. Measure V_diode at two temperature points, 25°C and 100°C
   - Use same Vin as in application
2. Calculate temperature coefficient
   - **MPQ4430 has Tc=-1.55mV/K at 1mA current**
3. Measure V_diode at No Load
4. Measure V_diode at specified load condition
5. Die Temperature is ∆Vdiode / Tc °C above ambient.

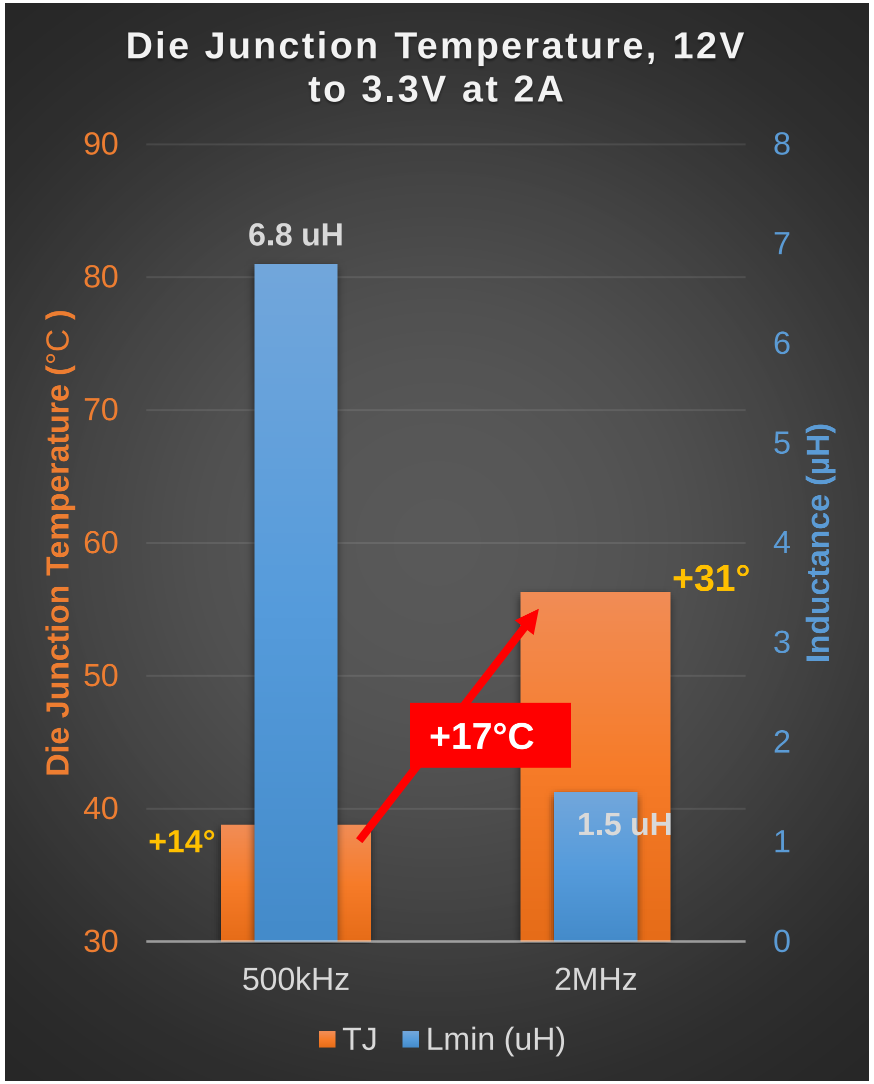
Conditions:
12V to 3.3V at 2A
Using MPQ4430 – 40V, 3.5A Low Iq Sync Buck

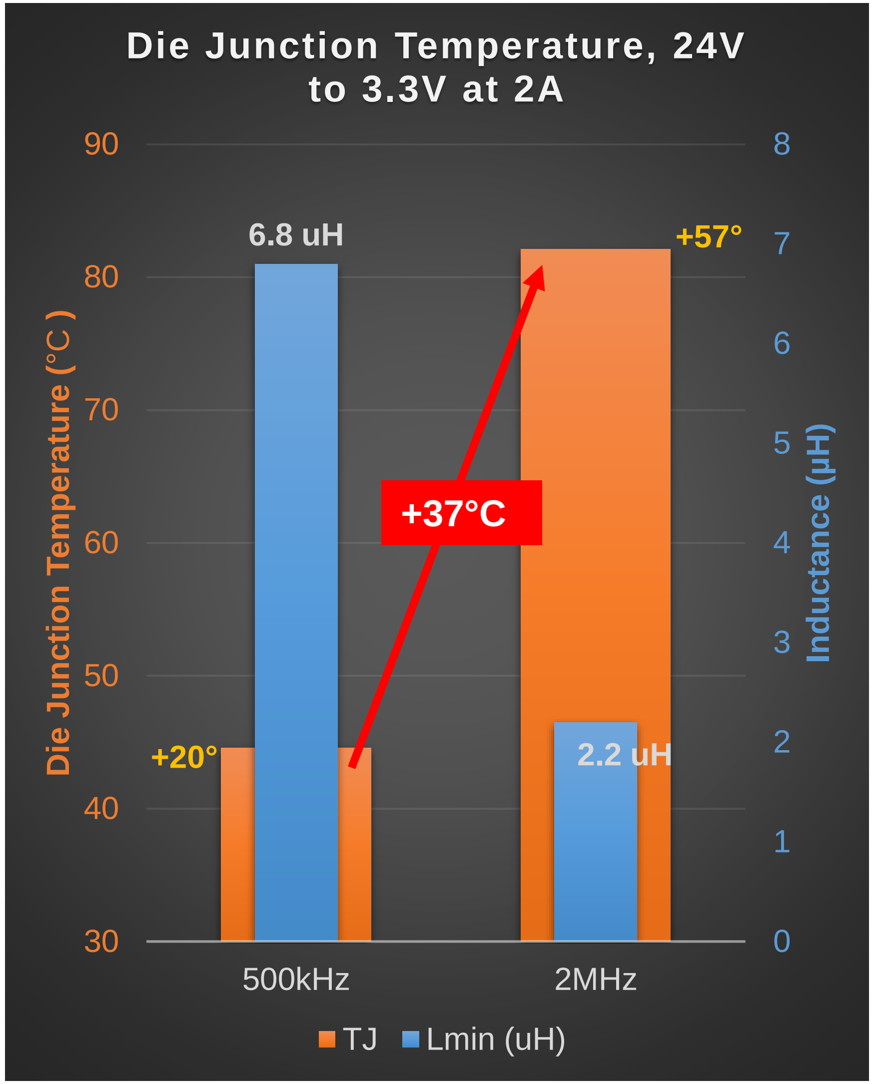




Example: MPQ4430 PG-Pin body diode has
-1.55mV/K at 1mA current.

Switching Frequency Effect on Thermals





Measured using method described in previous slide

Duty-Cycle Limitations: $T_{ON,min}$

$T_{ON,min}$ is the shortest OFF-ON-OFF sequence for high side FET.
(Charge FET Gate → Sense Current → Discharge Gate)

For given V_{OUT} and $T_{ON,min}$: $V_{IN,max} = \frac{V_{OUT}}{T_{ON,min} * F_{SW}}$

The higher the F_{SW}, the lower the max. Vin for fixed frequency operation

$$F_{SW,max} = \frac{V_{OUT,min}}{T_{ON,min} * V_{IN,max}}$$

Example:
$T_{ON,min}$ of 100ns
Vout = 3.3V
Vin,max = 36V
Max. Fsw ≤ 0.92 MHz

In real world effective duty-cycle is

D.C.real = $V_{OUT}/(V_{IN} * \eta)$

Example:
$T_{ON,min}$ of 100ns
Vout = 3.3V
Vin,max = 36V
and η = 80%
Max. Fsw ≤ 1.15MHz

Duty-Cycle Limitations: $T_{OFF,min}$

$T_{OFF,min}$ is the shortest OFF-ON-OFF sequence for Low side FET.
(Charge FET Gate → Sense Current → **Charge BST-Cap** → Discharge Gate)

For given V_{OUT} and $T_{OFF,min}$: $$V_{IN,min} = \frac{V_{OUT}}{(1 - T_{OFF,min} * F_{SW})}$$

The higher the F_{SW}, the lower the max. Vin for fixed frequency operation.

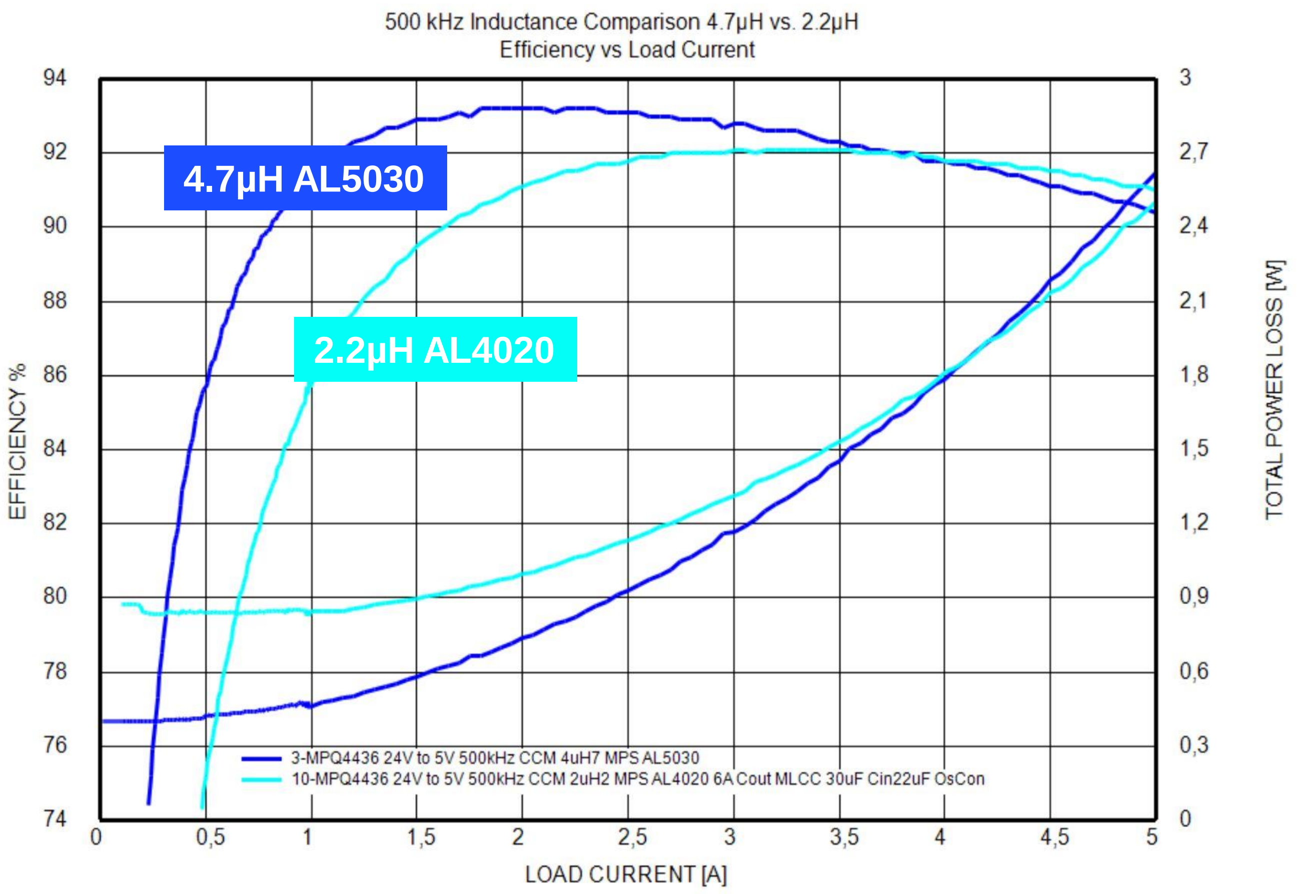
$$F_{SW,max} = \left(1 - \frac{V_{OUT}}{V_{IN,min}}\right) * \frac{1}{T_{OFF,min}}$$

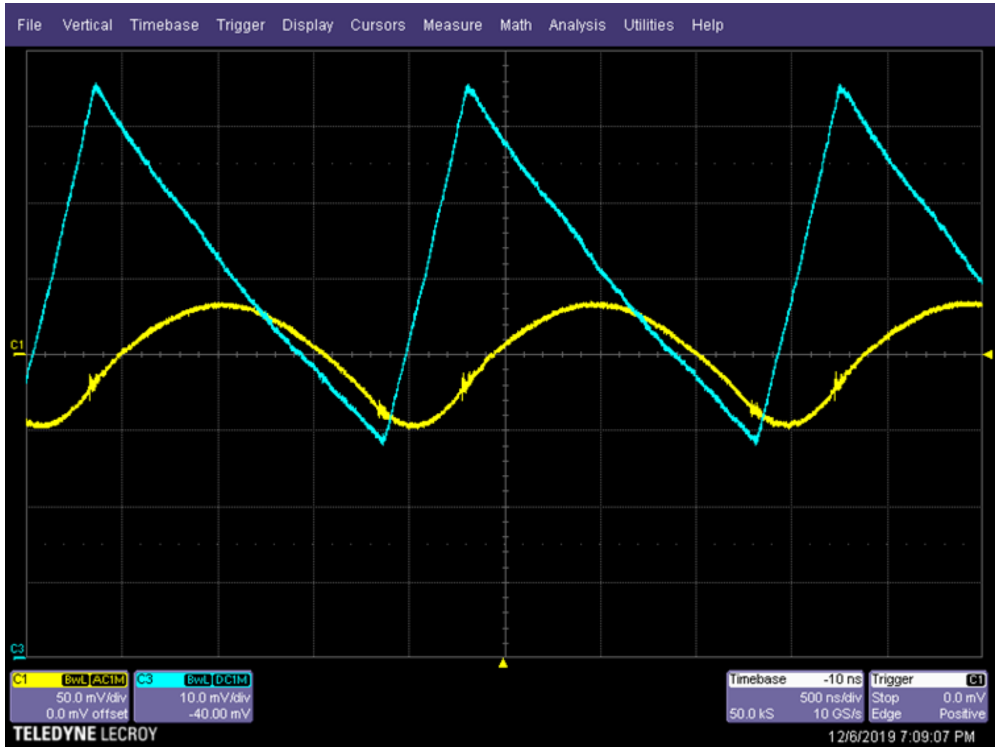
Example:
$T_{OFF,min}$ of 100ns
Vout = 3.3V
$V_{IN,min}$ = 3.8V
Max. Fsw ≤ 1.3MHz
In real world drop across FETs, Coil and PCB trace will require lower Fsw.

Modern ICs fold back Fsw at low input voltage down to Drop-Out Mode.

Alternative Solution

Operate the circuit with higher ΔI_L, increase from 40% to 50% or 60%





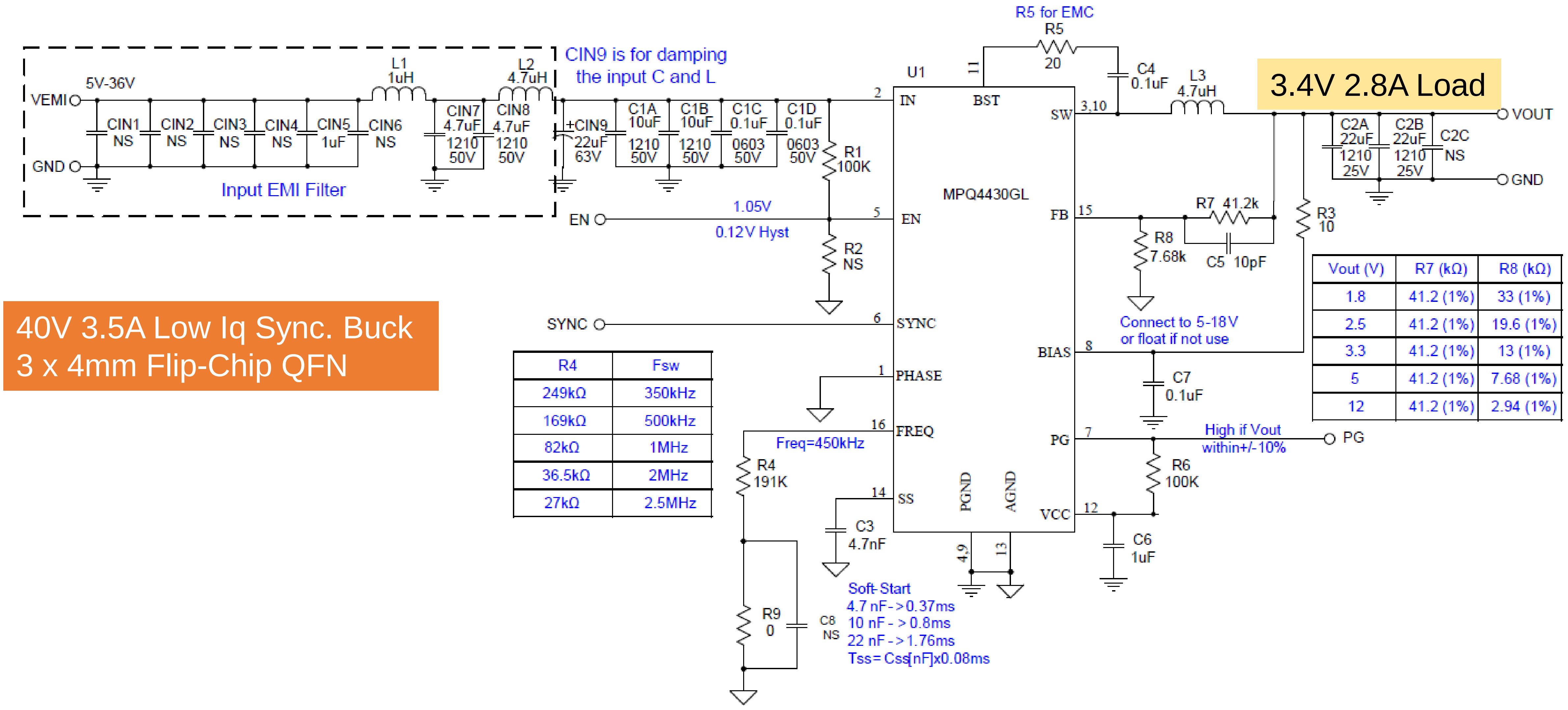
Example with 500kHz using *2.2µH: ΔI_L=2.44A; Ipk=6.22A instead of 2A and 6A respectively*.
Cout of 3x 10uF (25V, 1206)

Impact on EMI/EMC

Pre-Compliance measurements for Conducted Emission (voltage-method acc. to CISPR25) tested with MPQ4430 EVB

Example: MPQ4430

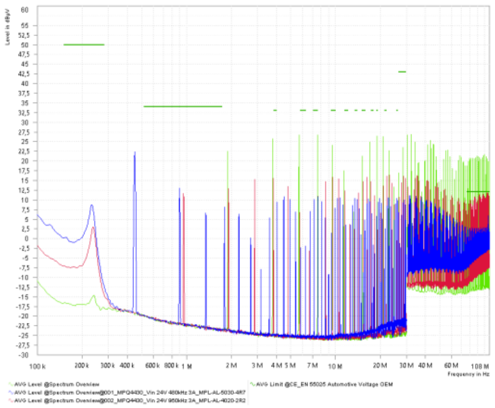
40V 3.5A Low Iq Sync. Buck
3 x 4mm Flip-Chip QFN



R4	Fsw
249kΩ	350kHz
169kΩ	500kHz
82kΩ	1MHz
36.5kΩ	2MHz
27kΩ	2.5MHz

Vout (V)	R7 (kΩ)	R8 (kΩ)
1.8	41.2 (1%)	33 (1%)
2.5	41.2 (1%)	19.6 (1%)
3.3	41.2 (1%)	13 (1%)
5	41.2 (1%)	7.68 (1%)
12	41.2 (1%)	2.94 (1%)

Conducted Emissions (CE) From 100kHz – 108MHz



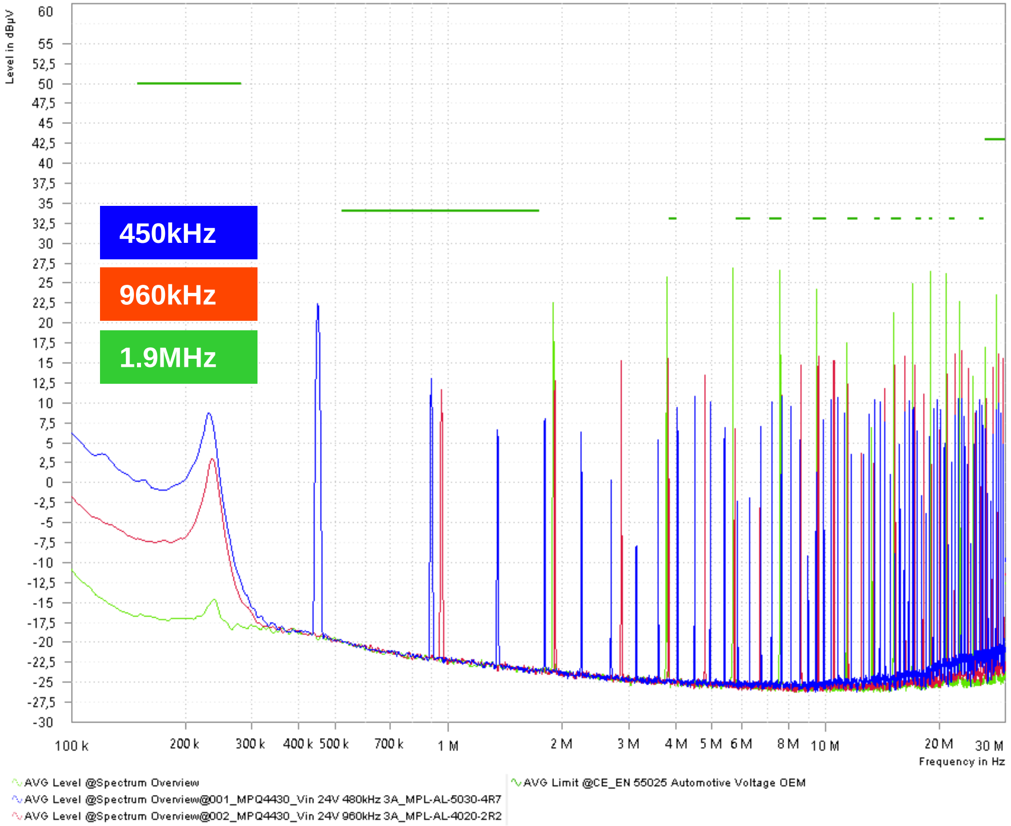
Configuration
Vout of 3.4 V 2.8A
R8 = 7.68 kohm
C5= 33 pF

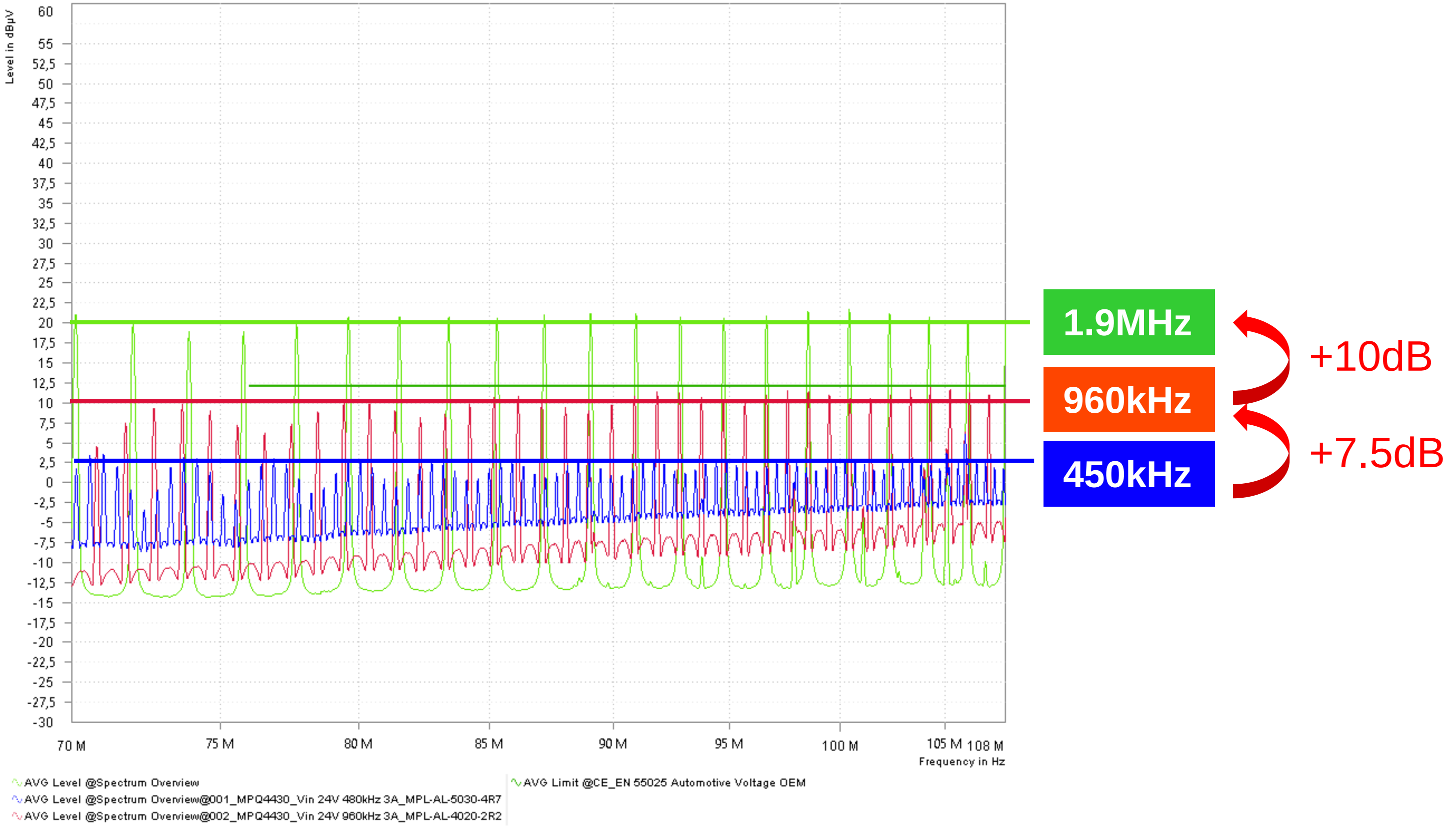
450 kHz
R4 = 191 kohm
Main Coil: MPL-AL-5030 4R7
5.5 x 5.3 x 2.9 mm

960 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 2R2
4.1 x 4.1 x 1.9 mm

1900 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 1R0
4.1 x 4.1 x 1.9 mm

All Test are Average





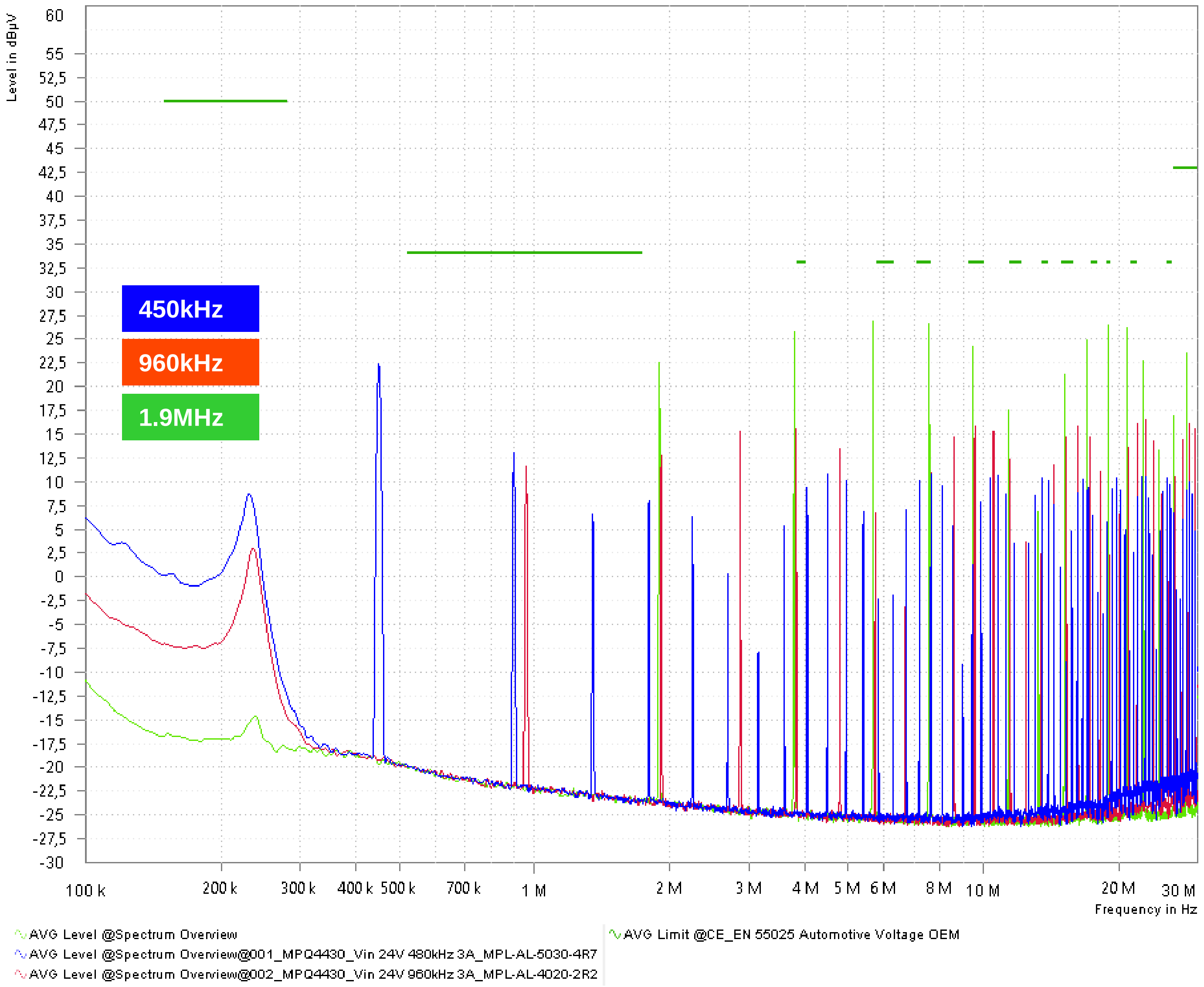
CE From 100kHz – 30MHz

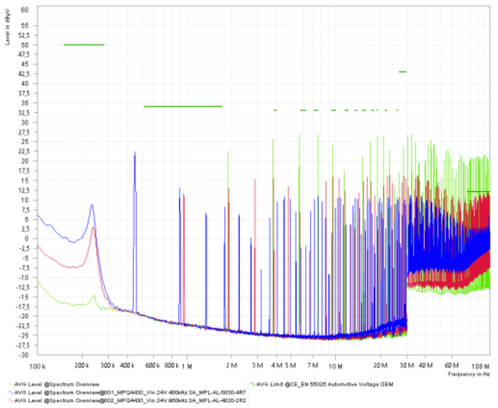
Configuration
Vout of 3.4 V 2.8A
R8 = 7.68 kohm
C5= 33 pF

450 kHz
R4 = 191 kohm
Main Coil: MPL-AL-5030 4R7
5.5 x 5.3 x 2.9 mm

960 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 2R2
4.1 x 4.1 x 1.9 mm

1900 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 1R0
4.1 x 4.1 x 1.9 mm





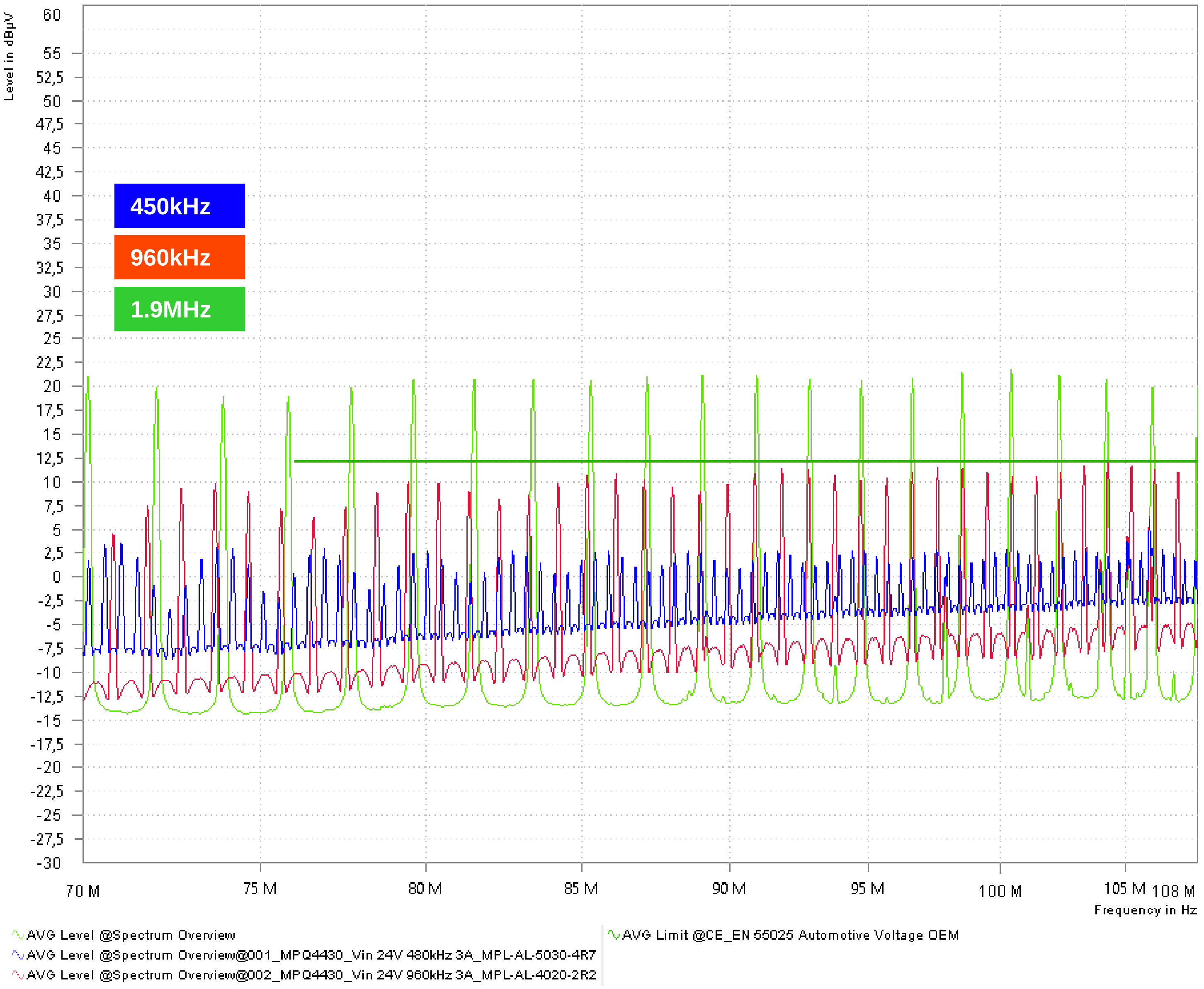
CE From 70MHz – 108MHz

Configuration
Vout of 3.4 V 2.8A
R8 = 7.68 kohm
C5= 33 pF

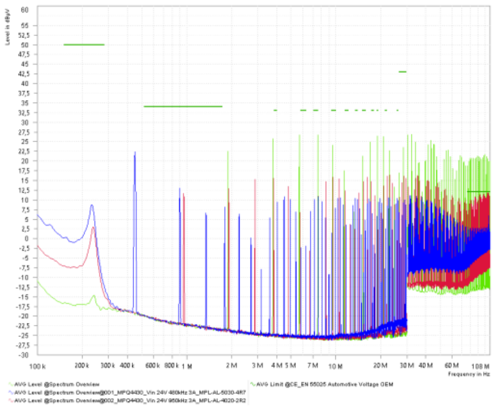
450 kHz
R4 = 191 kohm
Main Coil: MPL-AL-5030 4R7
5.5 x 5.3 x 2.9 mm

960 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 2R2
4.1 x 4.1 x 1.9 mm

1900 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 1R0
4.1 x 4.1 x 1.9 mm



Automotive OEM Limit



For Customer Use Only

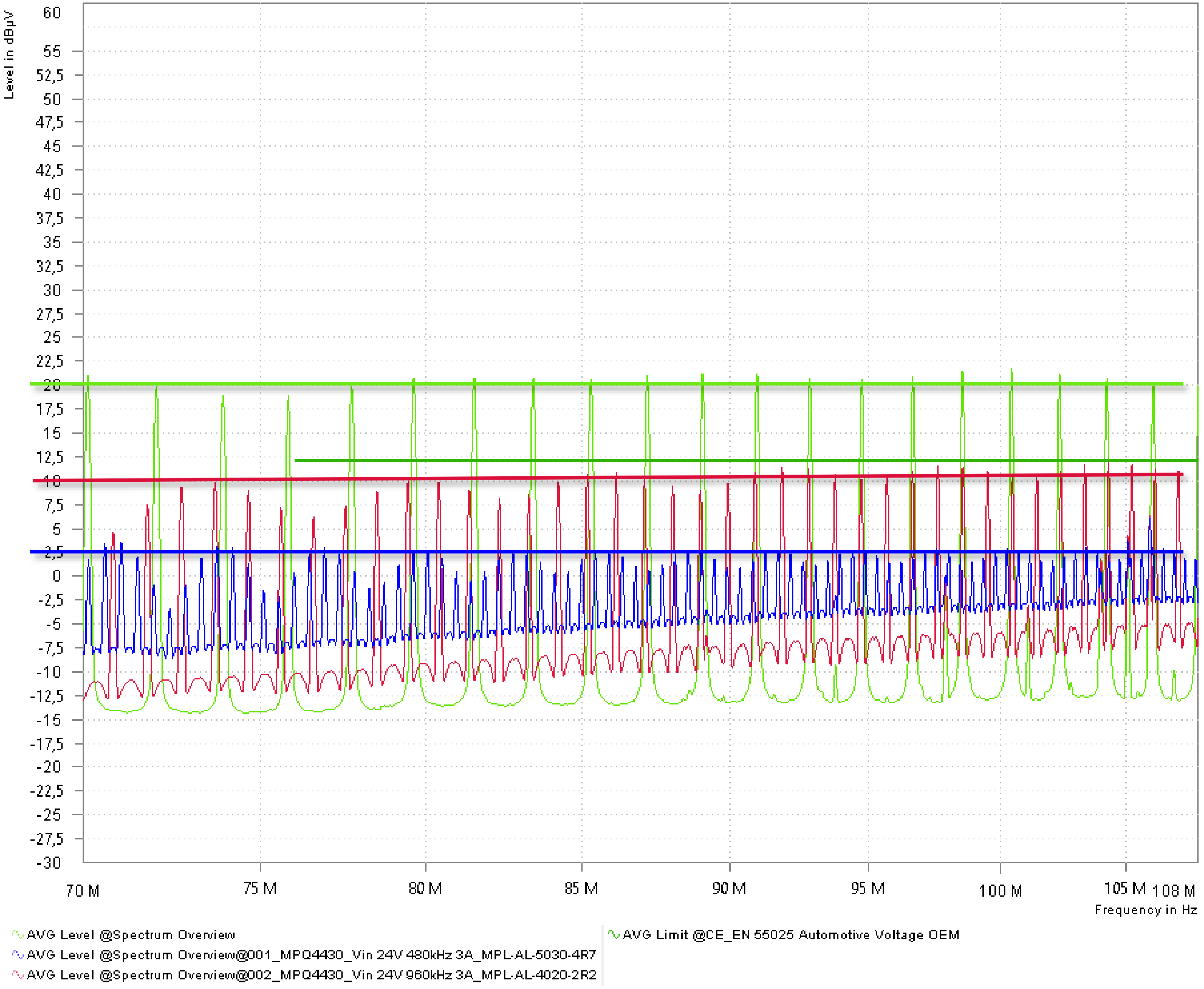
CE From 70MHz – 108MHz

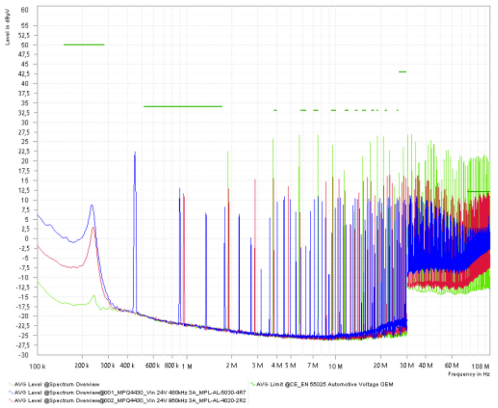
Configuration
Vout of 3.4 V 2.8A
R8 = 7.68 kohm
C5= 33 pF

450 kHz
R4 = 191 kohm
Main Coil: MPL-AL-5030 4R7
5.5 x 5.3 x 2.9 mm

960 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 2R2
4.1 x 4.1 x 1.9 mm

1900 kHz
R4 = 191 kohm
Main Coil: MPL-AL-4020 1R0
4.1 x 4.1 x 1.9 mm

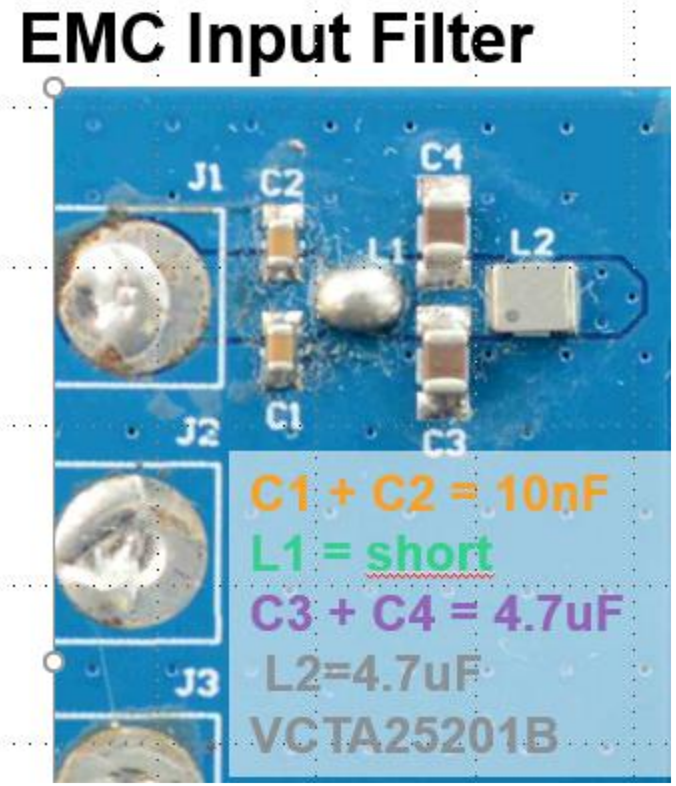




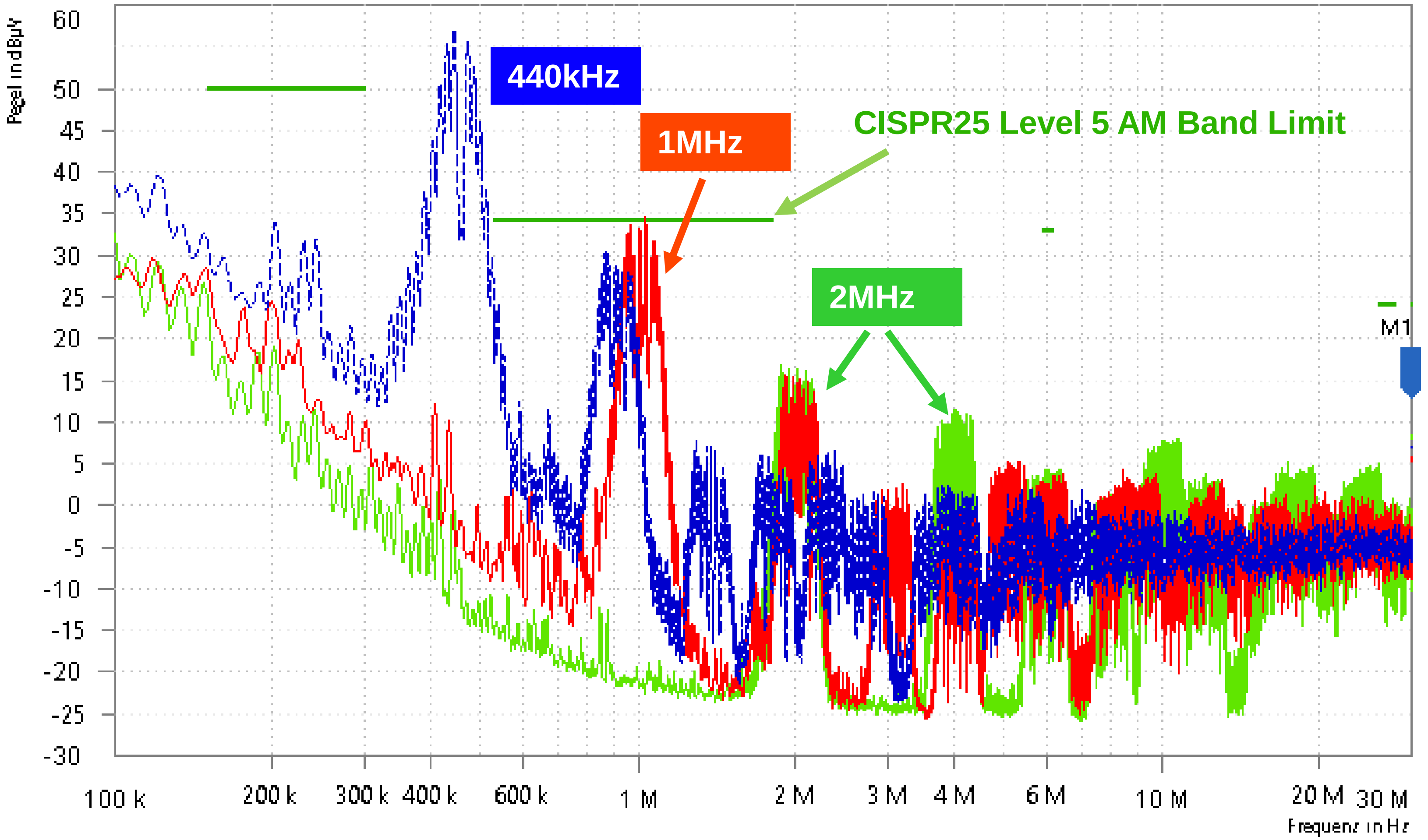
1.9MHz
960kHz
450kHz
+10dB
+7.5dB

How About Spread Spectrum Frequency Modulation?

Example with MPQ4313:
45V 3A Synch. Buck with SSFM + Reduced EMC Filtering



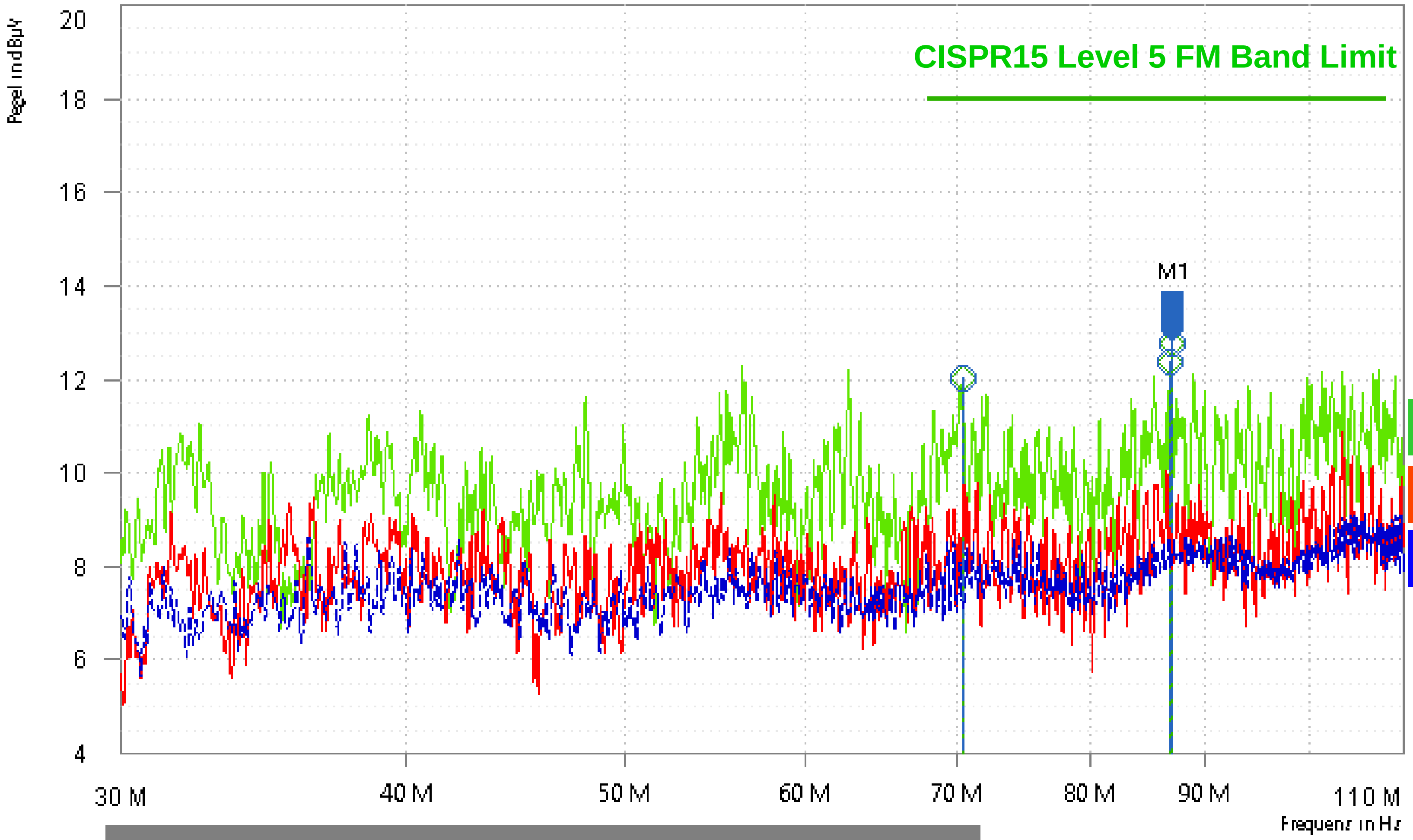
440kHz vs 1MHz vs 2MHz – Low Frequency Radiated Emissions



Note 1MHz config needs a bit more input filter

Conditions:
440kHz: IHLP2525 6.5 x 6.5 x 3mm 6.8µH 54mΩ
1MHz: AY5030 5 x 5 x 3mm 3.3µH 32mΩ
2MHz: AY4020 4 x 4 x 2mm 1.5µH 35mΩ

440kHz vs 1MHz vs 2MHz High Frequency Radiated Emissions



In theory, the noise level should increase by 3dB for double Fsw with Spread Spectrum.

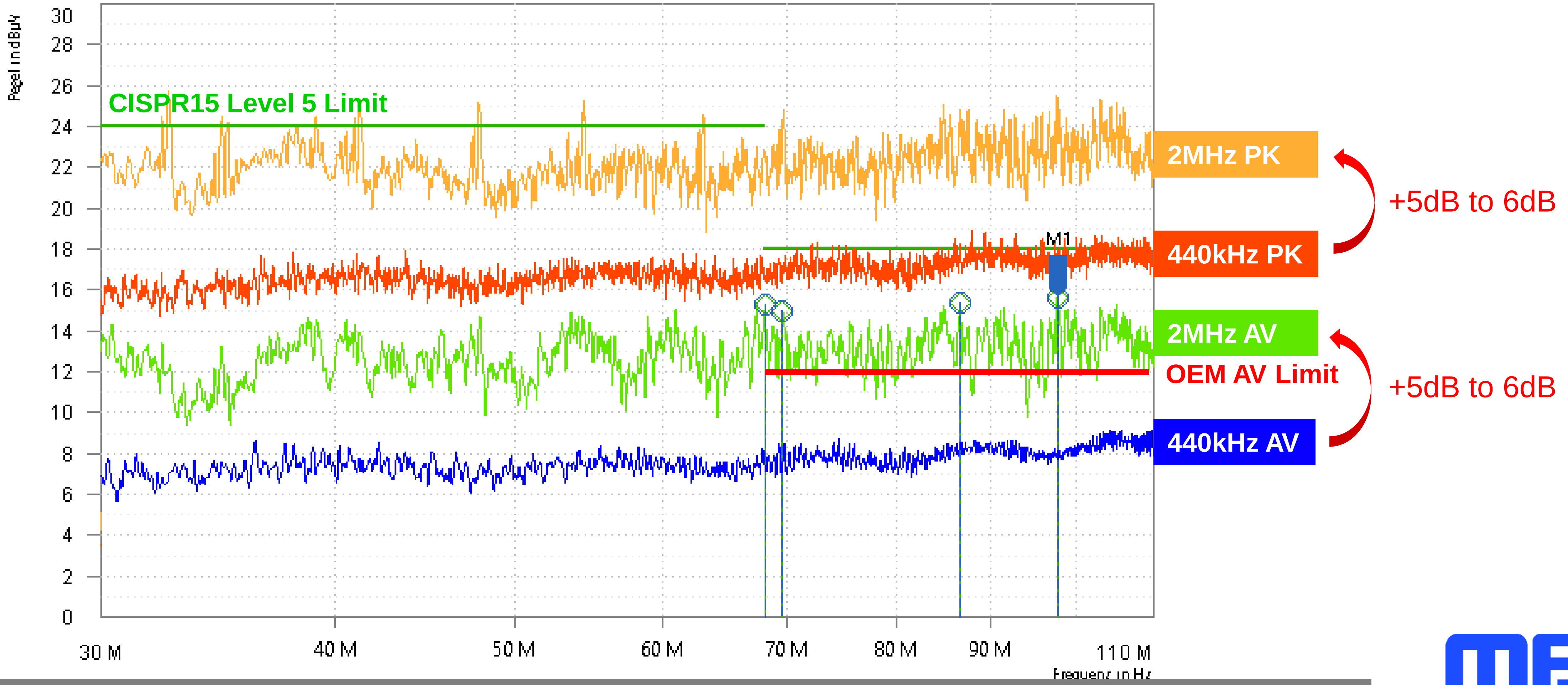
With fixed frequency it would be an increase of 6dB.

The increase in noise level is offset slightly as the inductor (antenna) size and height reduced also with switching frequency

Conditions:
440kHz: IHLP2525 6.5 x 6.5 x 3mm 6.8µH 54mΩ
1MHz: AY5030 5 x 5 x 3mm 3.3µH 32mΩ
2MHz: AY4020 4 x 4 x 2mm 1.5µH 35mΩ

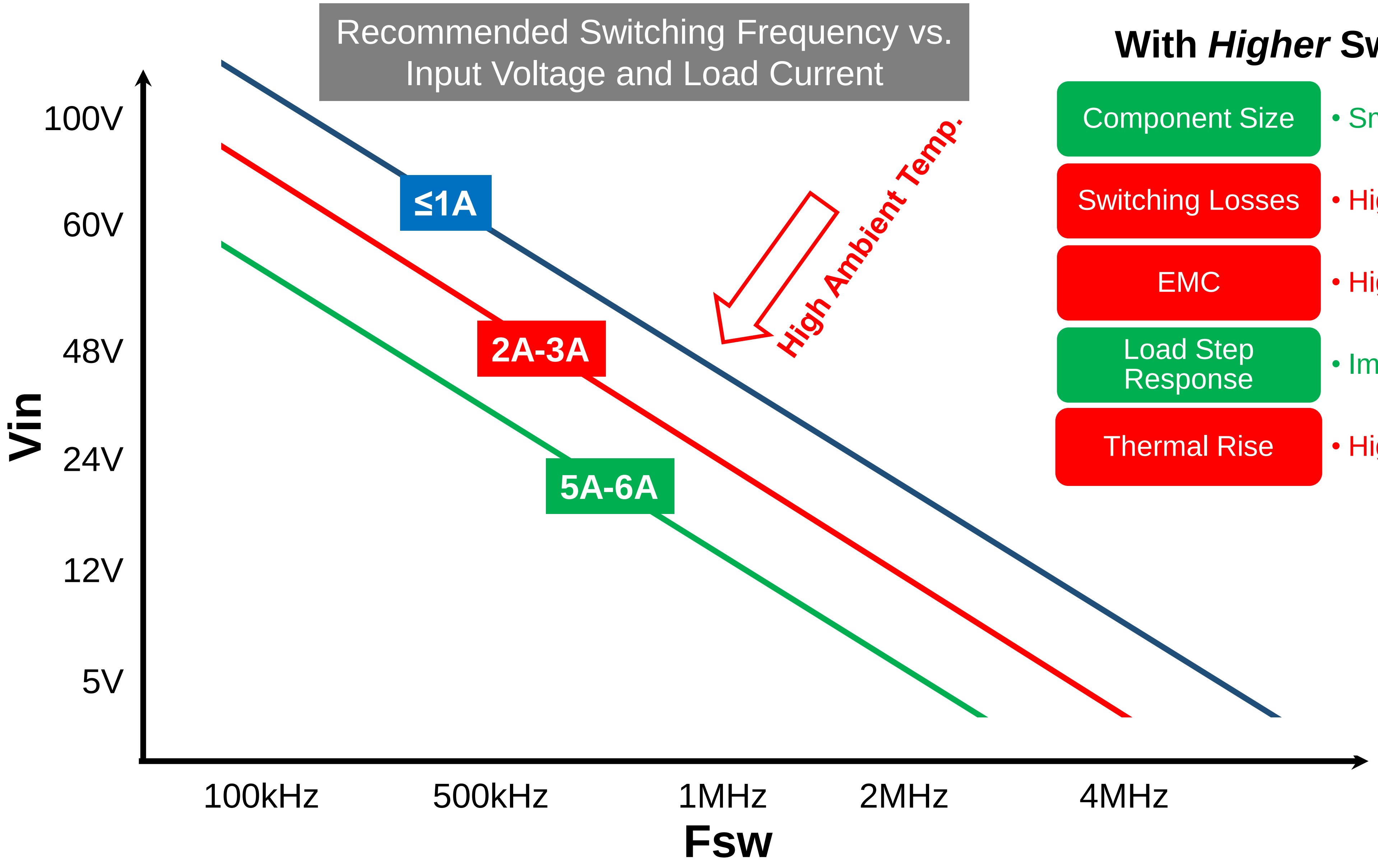
440kHz vs 2MHz High Frequency Radiated Emissions

Conditions:
L: IHLP2525-6.8µH
Frequency Spread Spectrum



Note: for a deeper dive into EMC/EMI, check out our webinar, "Automotive EMI Benefits of Spread Spectrum" at monolithicpower.com/webinars

Recap



With *Higher* Switching Frequency:

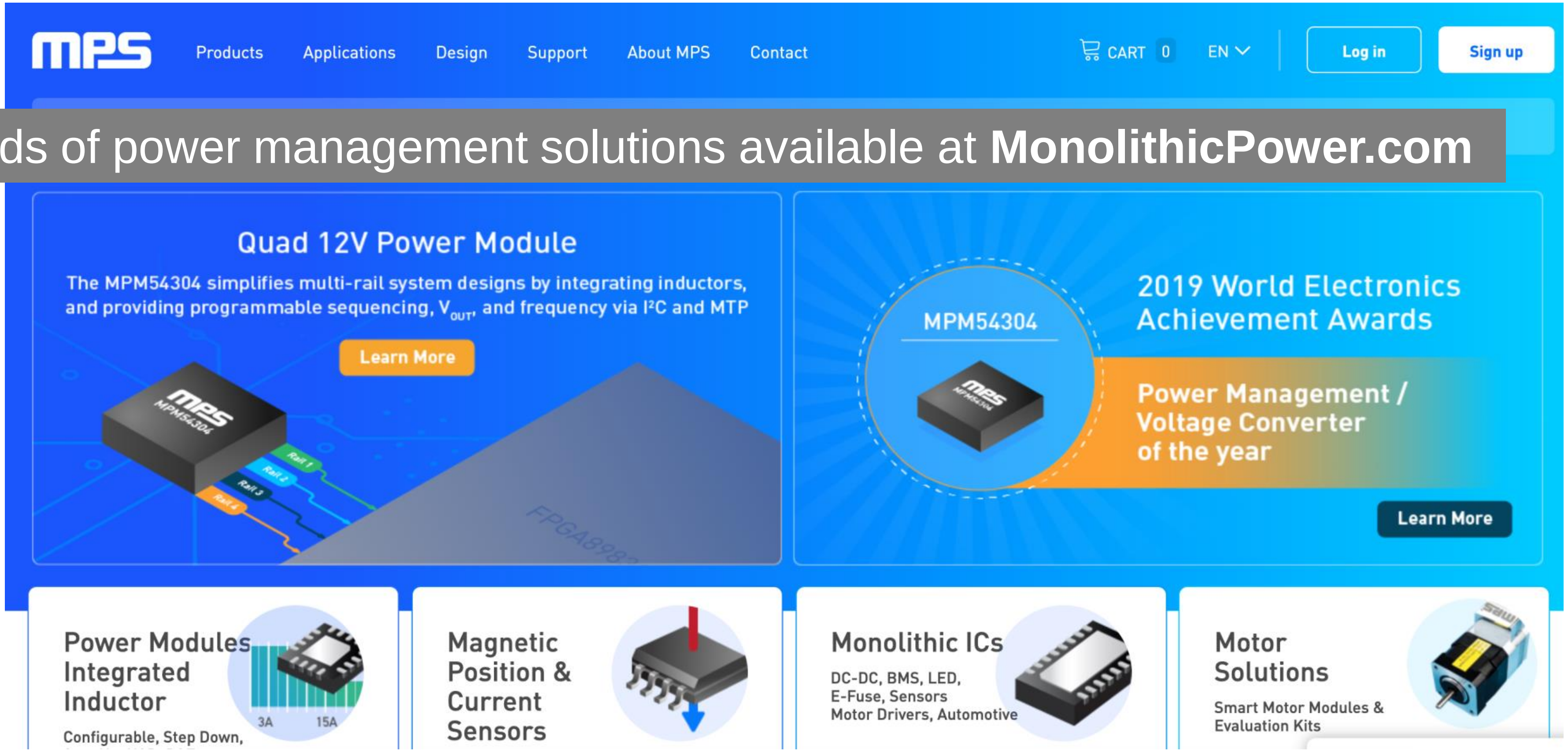
Component Size	• Smaller, Lower Cost
Switching Losses	• Higher at higher input voltage
EMC	• Higher in higher frequency bands
Load Step Response	• Improved
Thermal Rise	• Higher

Q&A

Please submit questions through the ”Q&A” menu option in the Zoom app

This webinar and others will be available for on-demand streaming at:

MonolithicPower.com/webinars



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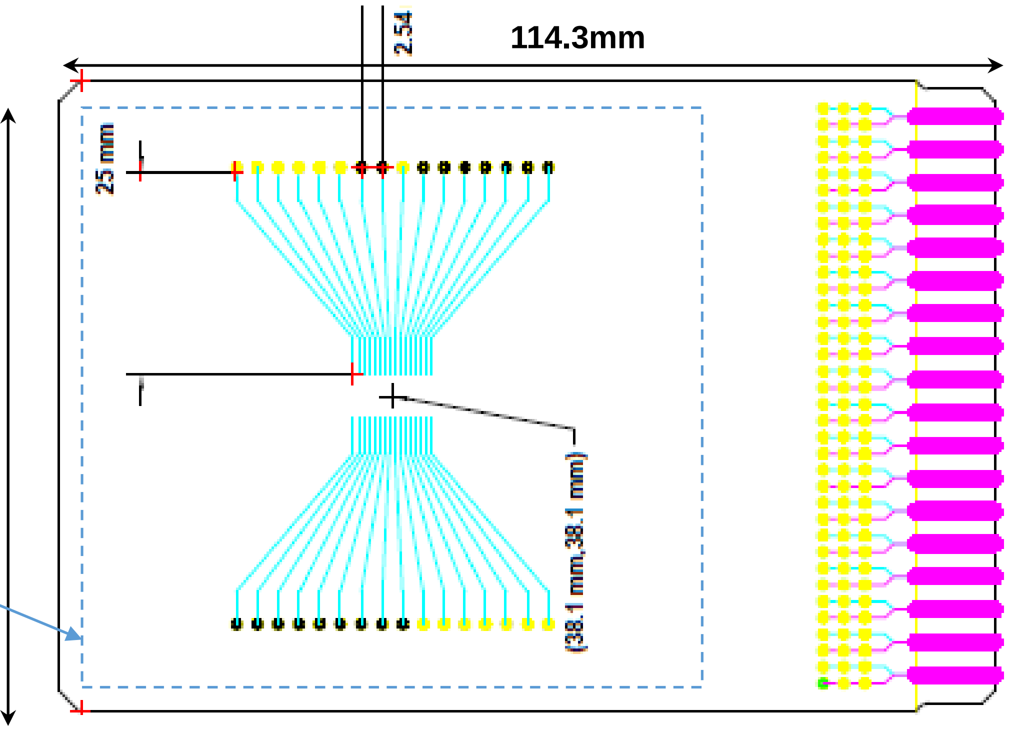
Thermal Resistance

Thermal Resistance (4)	θ_{JA}	θ_{JC}	
QFN-16 (3mmx4mm)			
JESD51-7	48	11 ...	°C/W

Thermal Characterization Parameter (5)	
QFN-16 (3mmx4mm)	Ψ_{JT}
EV4430-L-00A ……..……....5.................	°C/W

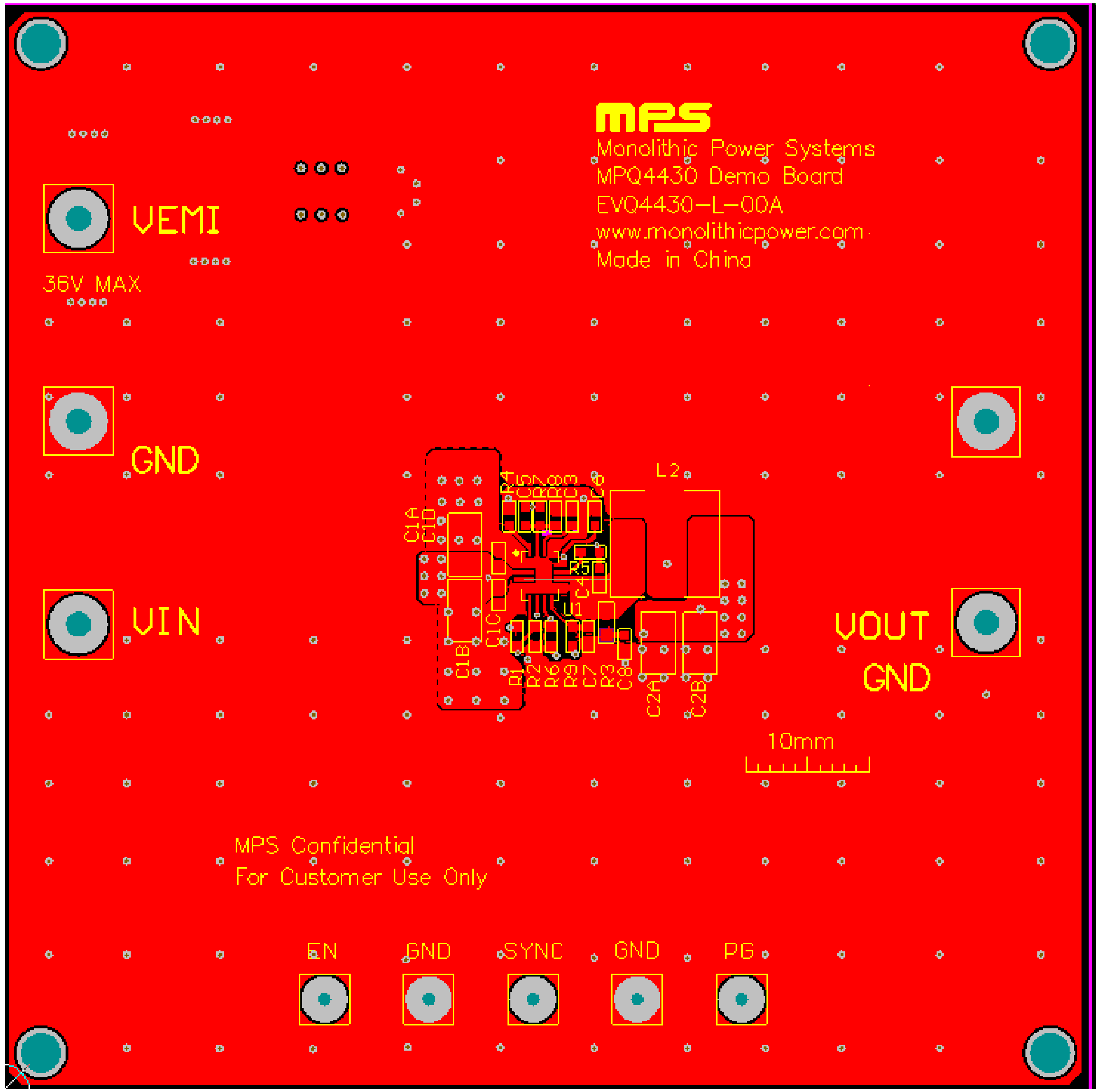
θ_{JA} = 41°C/W
θ_{JC} = 5°C/W

4) Measured on JESD51-7, 4-layer PCB.
5) Measured on EV4430-L-00A, 6.35cm * 6.35cm size, 2oz, 4-layer PCB.

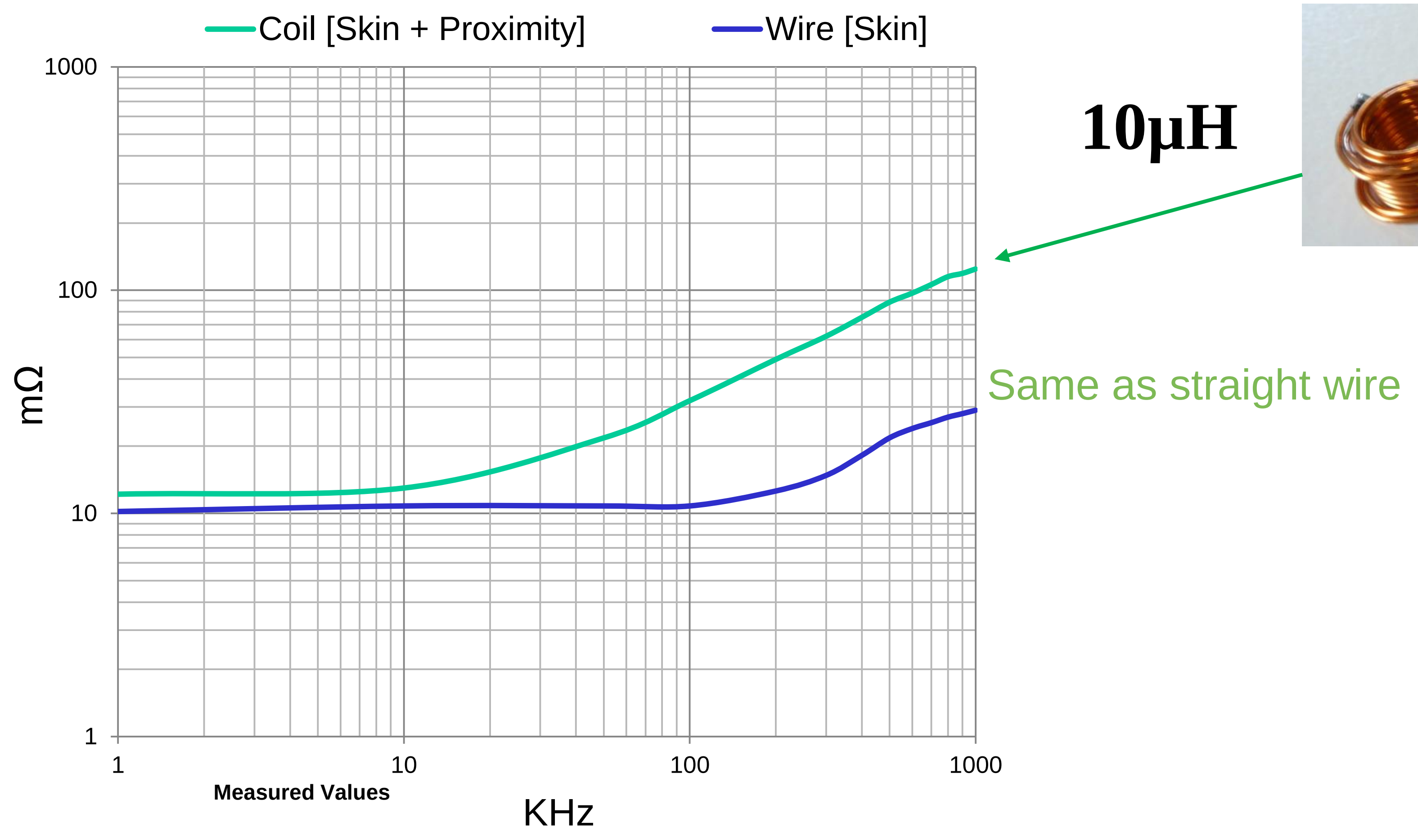


JESD51-7 PCB TOP

Copper area in inner Layer

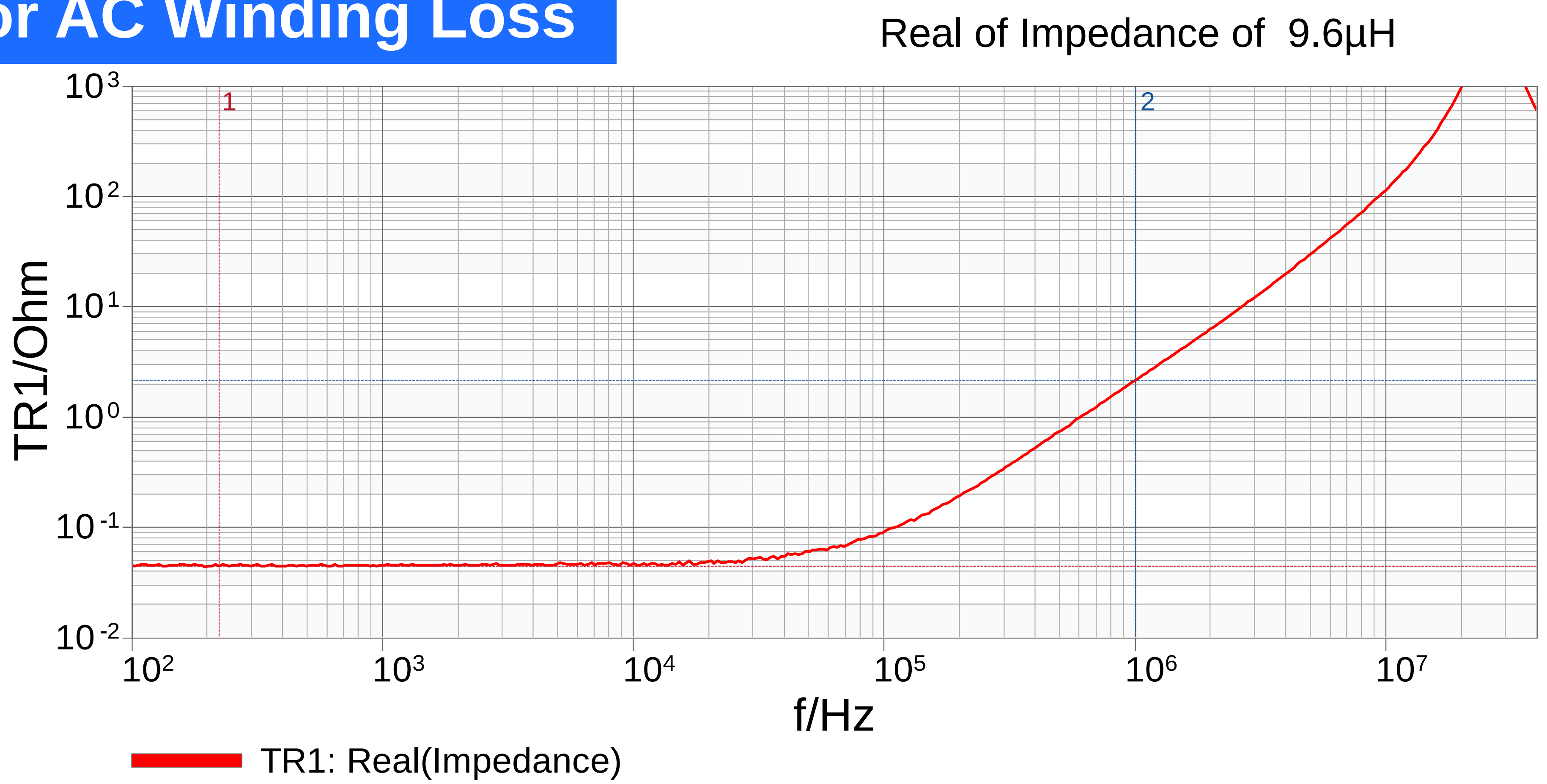


Copper Losses AC (Skin & Proximity Effect)



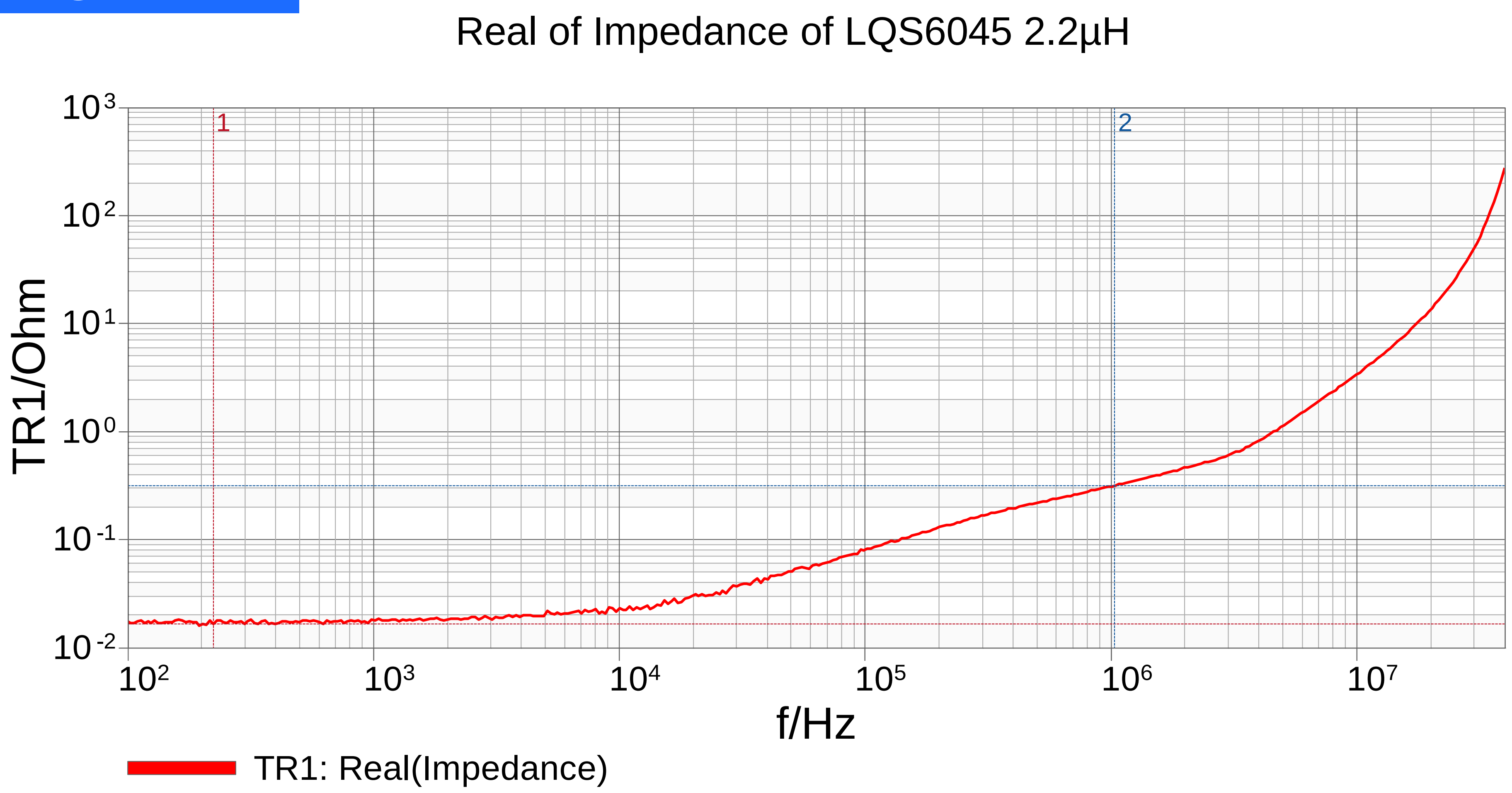
10µH

Inductor AC Winding Loss



	Frequency	Trace1	Trace2
Cursor 1	**223.938 Hz**	**44.360 mOhm**	
Cursor 2	**1.012682 MHz**	**2.139 Ohm**	
Delta C2-C1	**1.012458 MHz**	**2.095 Ohm**	

Inductor AC Winding Loss



	Frequency	Trace1	Trace2
Cursor 1	**223.938 Hz**	**16.259 mOhm**	
Cursor 2	**1.035029 MHz**	**312.641 mOhm**	
Delta C2-C1	**1.034805 MHz**	**296.381 mOhm**	