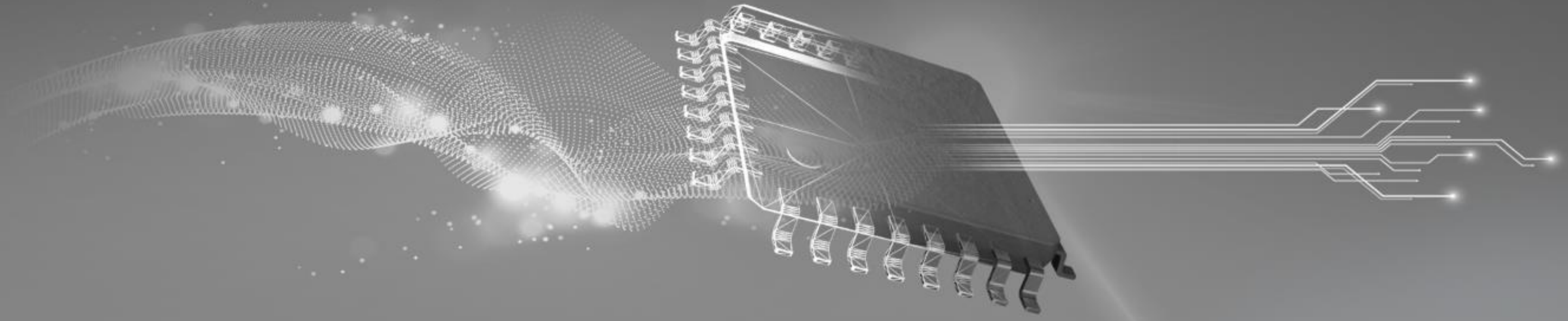
TI TECH DAYS



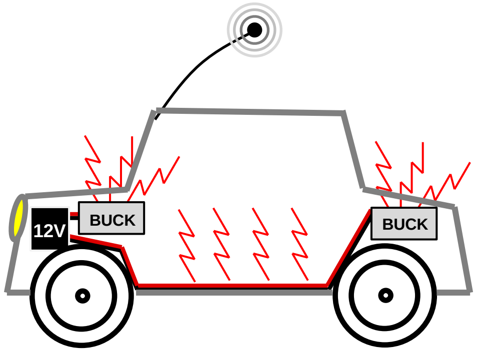
Practical Buck EMI Debugging for Automotive Applications

Sam Jaffe

Texas Instruments

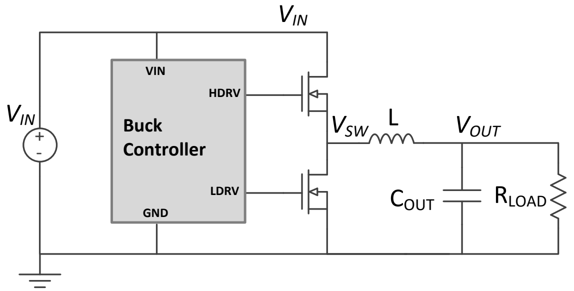
Agenda

- What is EMI?
  - Why do we need to pass EMI?
  - How do we measure EMI?
- How to achieve great EMI performance
  - Layout guidelines, part selection, part features.
- Tests and debugging
  - Quick checks.
  - Could fix the problem without changing schematic/layout!



What is EMI – a buck's perspective

- EMI = **e**lectro**m**agnetic **i**nterference
- Bucks generate noise:
  - Input ripple, coupling to nearby circuits, electromagnetic radiation.

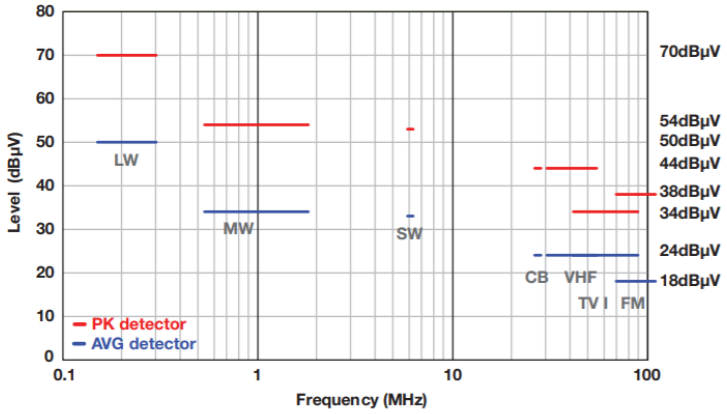


- Other components can be sensitive to noise:
  - AM broadcast 150 kHz → 30 MHz
  - AM radio 30 kHz → 1.8 MHz
  - FM radio 76 MHz → 108 MHz

and more

Too much interference degrades or prevents proper system operation.

We have standards to tell us how much we can emit without greatly affecting other systems.



Conducted EMI limits - CISPR25 class 5

Filtering

Filtering – Typical components in order of importance

5. CM Choke

Common-mode choke

Blocks common-mode current. Very effective but expensive. This is the most effective way to block common-mode noise. The inductor and ferrite bead won't help much which is why common-mode noise is such a pain.

4. FB

Ferrite bead

Blocks higher current. Acts as an inductor (<~10MHz) and resistor (>~50MHz). Rated as XΩ at 100MHz. Helps up to a couple hundred MHz

3. Inductor

Filter inductor

Blocks current. Great for low to mid frequency range (up to ~100MHz). Check datasheet for self-resonant frequency. All inductors have inter-winding capacitance which hurts HF filter performance

2. CIN

Ceramic input capacitor.

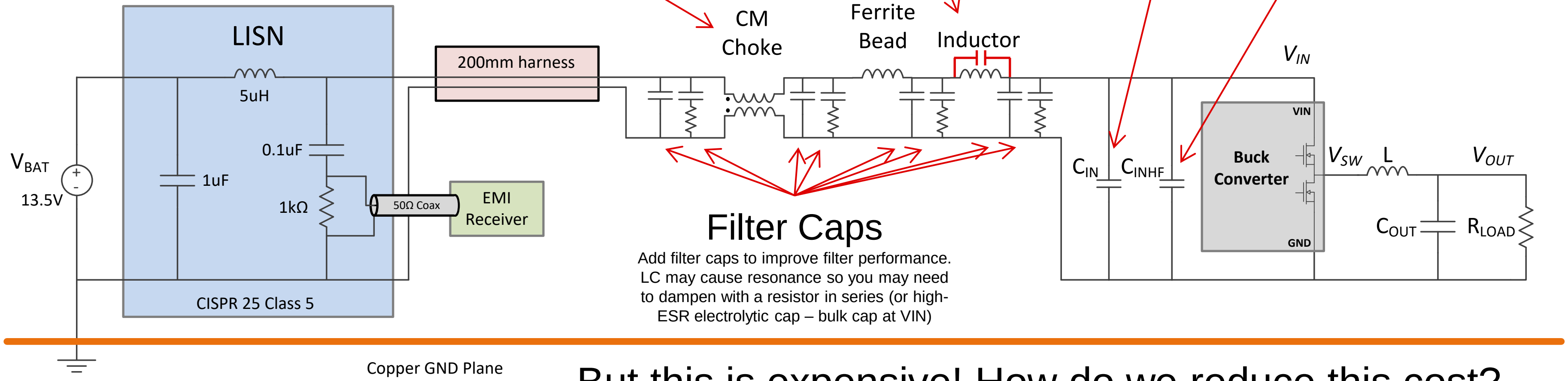
Required for proper operation (see datasheet). Extra CIN helps low frequency EMI by reducing ripple.

1. CIN_HF

Small ceramic input capacitor.

Place close to IC to minimize loop from VIN to GND. Required in datasheet for proper operation.

CISPR 25 Class 5 – Conducted EMI Test Setup



Filter Caps

Add filter caps to improve filter performance. LC may cause resonance so you may need to dampen with a resistor in series (or high-ESR electrolytic cap – bulk cap at VIN)

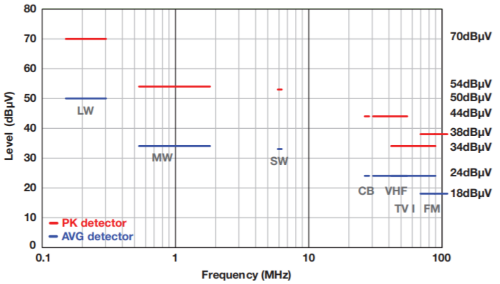
But this is expensive! How do we reduce this cost?

Where does the noise come from?

If we know where it comes from, we can optimize for it and save money on the filter!

Noise sources – low frequency (→~30MHz)

- Lots of current to fail – differential-mode EMI.
  - VIN ripple fundamental and early harmonics
    - Reduce by increasing input capacitance.
    - Filter with inductor and capacitor. Easy but expensive.



Conducted EMI limits - CISPR25 Class 5

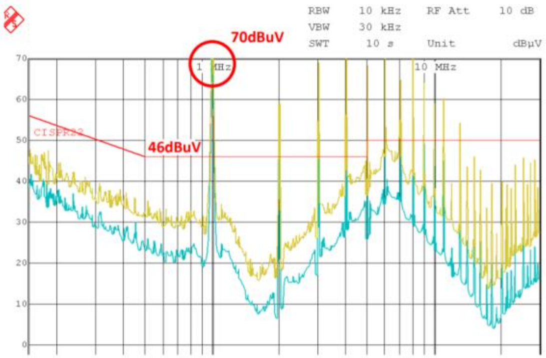


Figure 6. Initial EMI Sweep With CISPR-22 Average Limit Lines

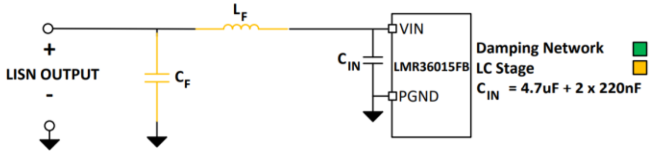


Figure 7. LC Filter Implementation

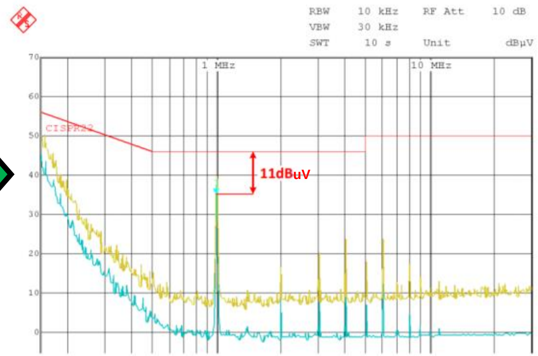


Figure 8. Passing CISPR-22 EMI Limits With a Simple LC Filter

SNVA859 shows how to size a simple LC filter to attenuate low-noise EMI for industrial CISPR22 standards.

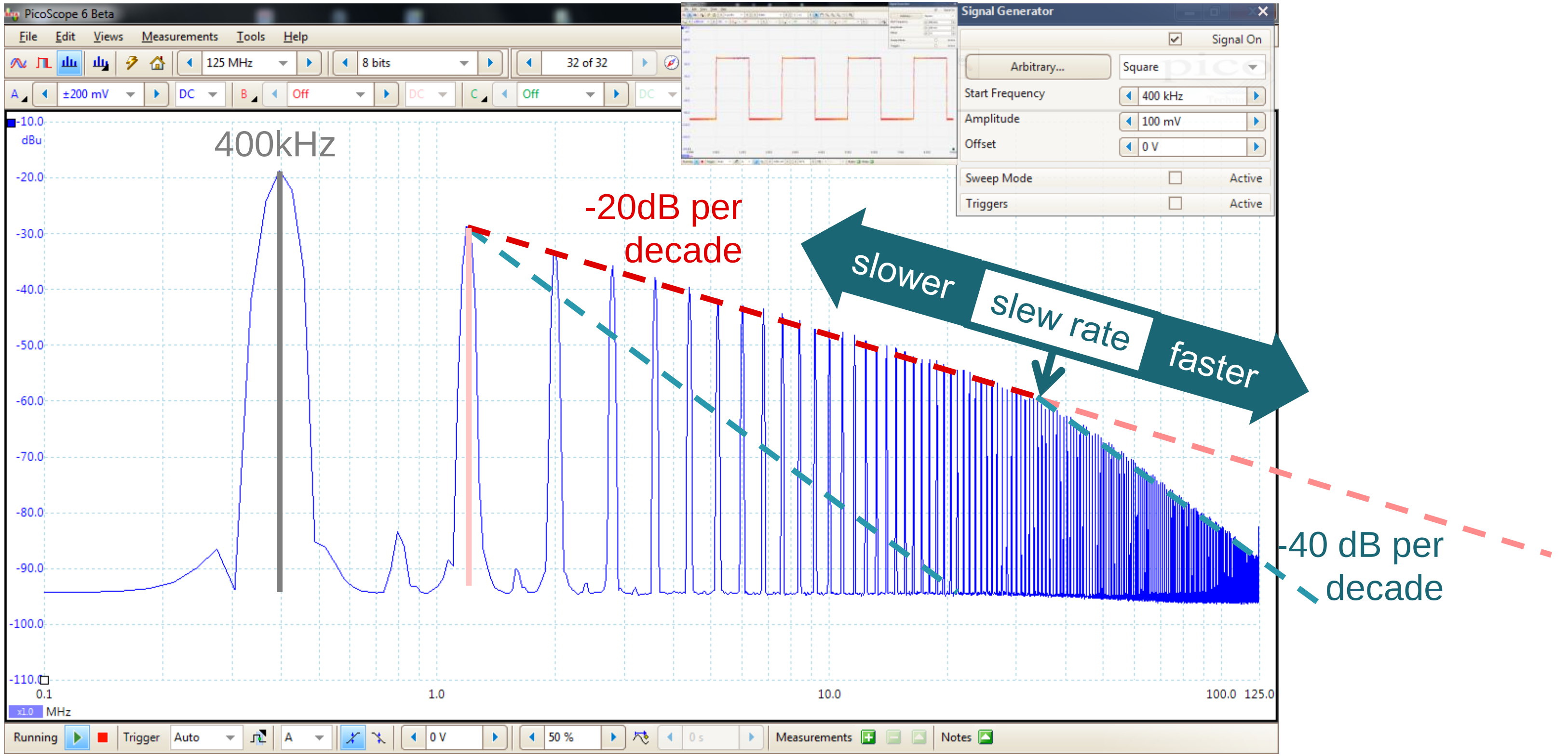
Noise sources – high frequency (>~30MHz)

- Very little current to fail – SW higher harmonics and SW ringing.
  - Differential mode:
    - Noise goes through inter-winding capacitance of filter inductor
  - Common mode:
    - SW node capacitively coupling to GND plane.
    - BOOT/BST node capacitively coupling to GND plane.
    - SW ring on V_{IN}/V_{OUT} coupling to GND plane.
- Harder to filter!
  - Is it a differential-mode or common-mode issue?
  - Adding bigger filter inductor probably increases inter-winding capacitance → more high-frequency EMI
  - Where is it coming from?

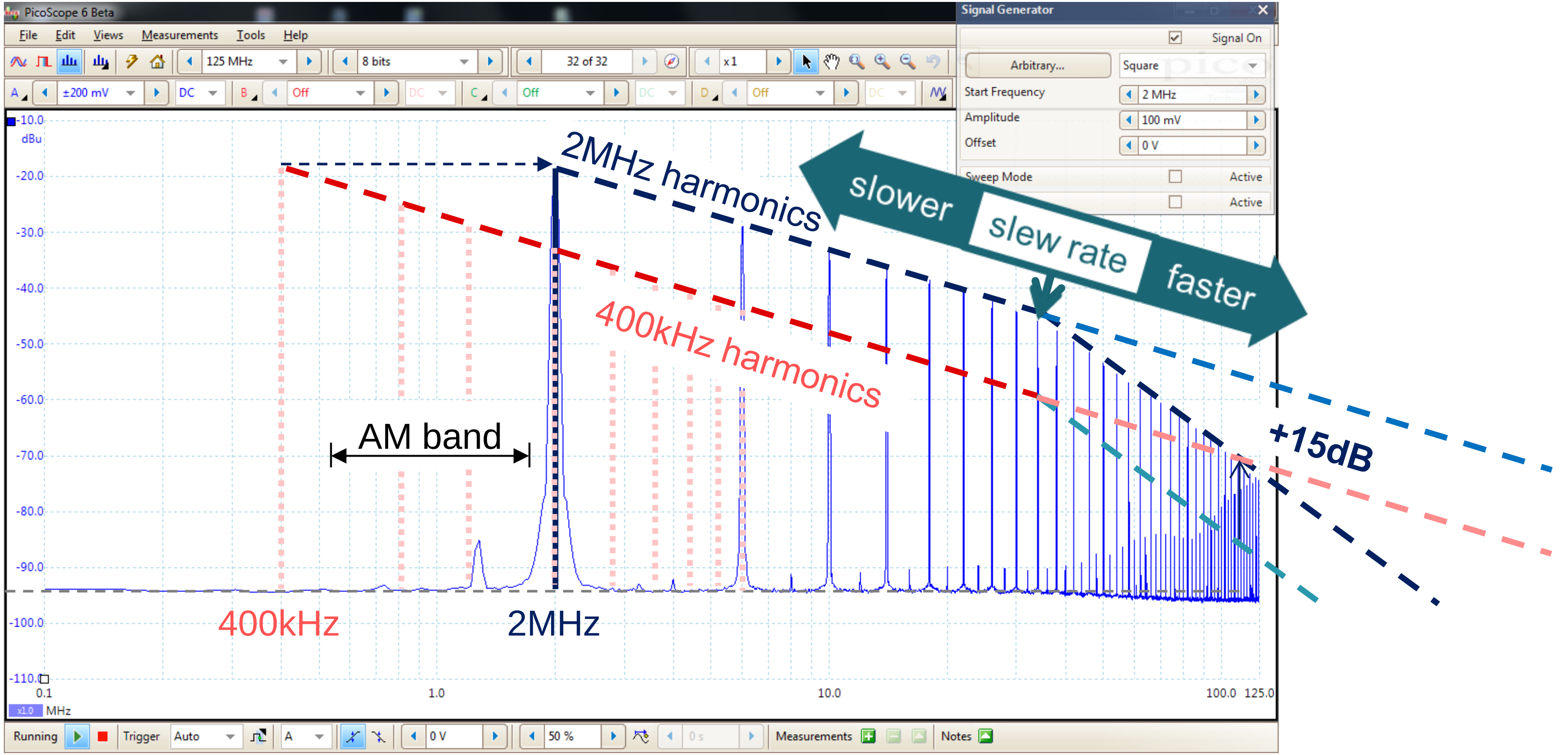
And to make it harder:

400kHz → 2.2MHz

400 kHz square wave spectral density



400 kHz switch to 2 MHz



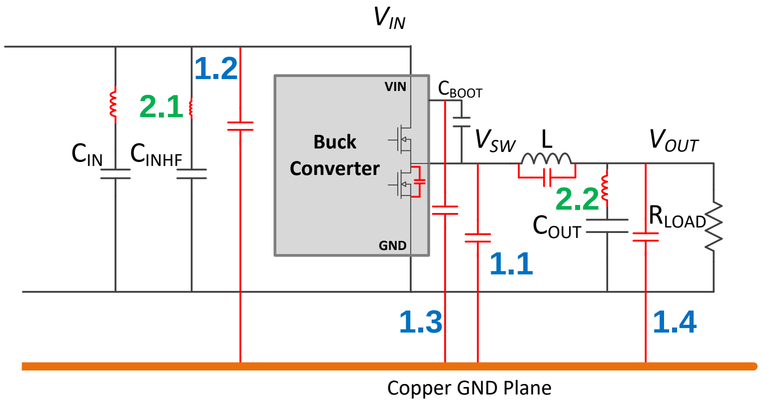
Layout guidelines

How to achieve optimal EMI performance

EMI-optimized layout – two simple rules to reduce noise generation

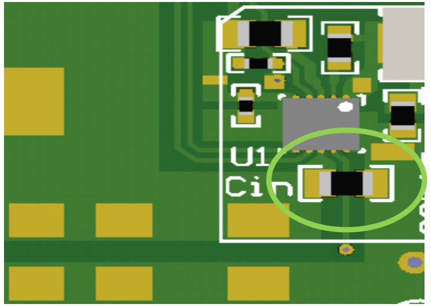
1. Keep high dv/dt nodes shielded or small.
2. Keep high di/dt loops small.

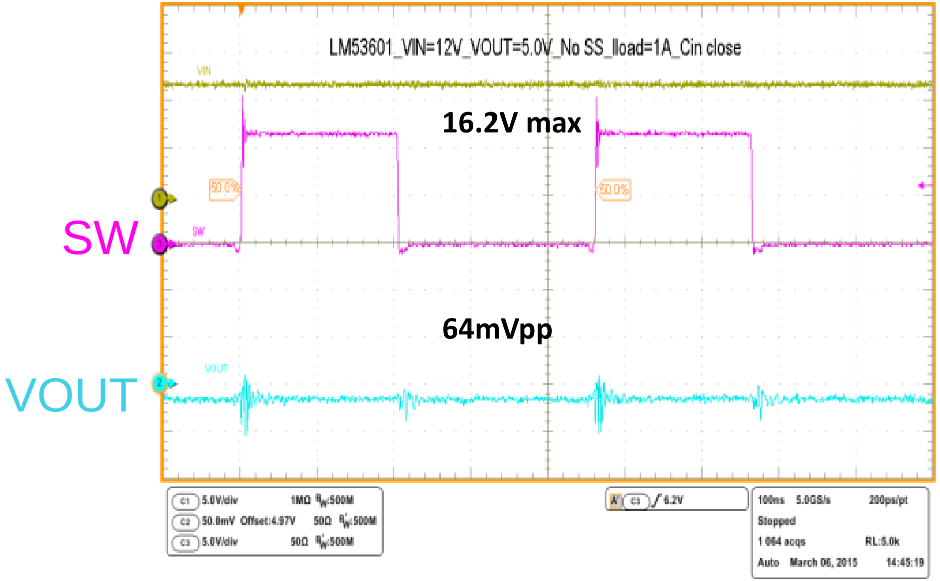
1.1) SW node size, proximity, lack of shielding
→ coupling from SW harmonics/ringing
1.2) VIN ringing coupling proportional to VIN size, proximity, lack of shielding
1.3) BOOT/BST pin also noisy
1.4) VOUT noise coupling proportional to VOUT size and noise on VOUT
2.1) CIN loop inductance → ringing
2.2) Output capacitance loop through inter-winding cap of L

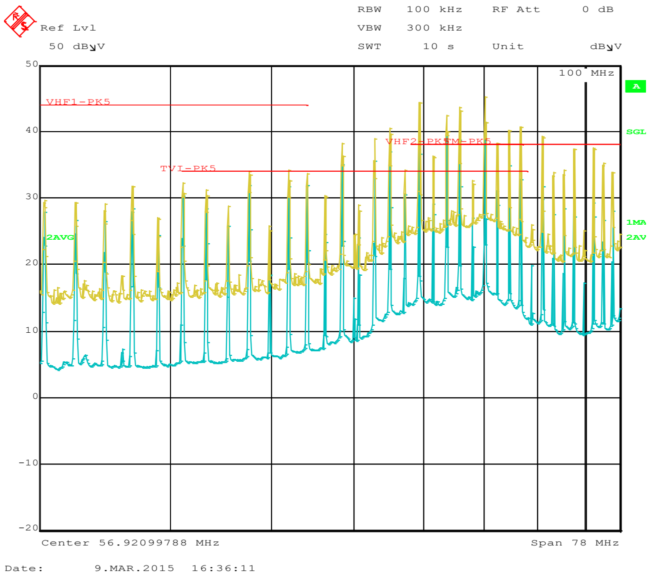


Critical path area comparison

- Input cap close to IC
- Small input loop, small parasitic inductance



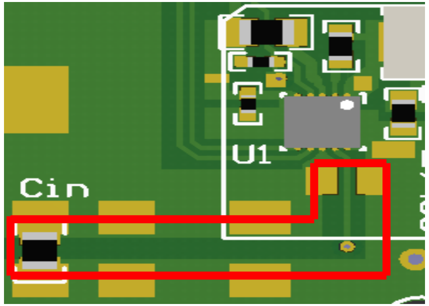


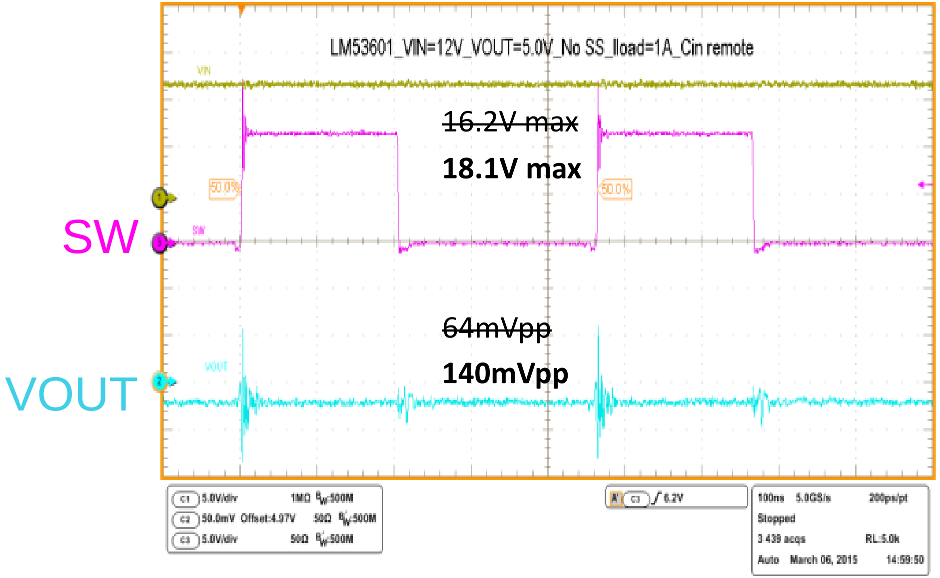


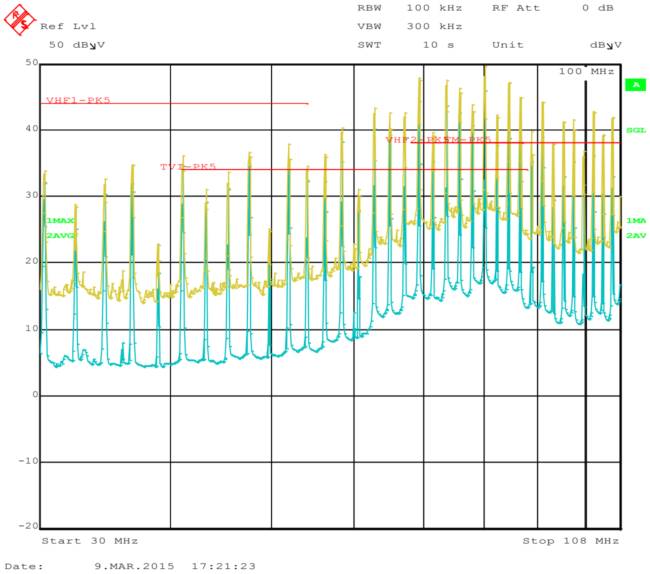
TEXAS INSTRUMENTS

Critical path area comparison

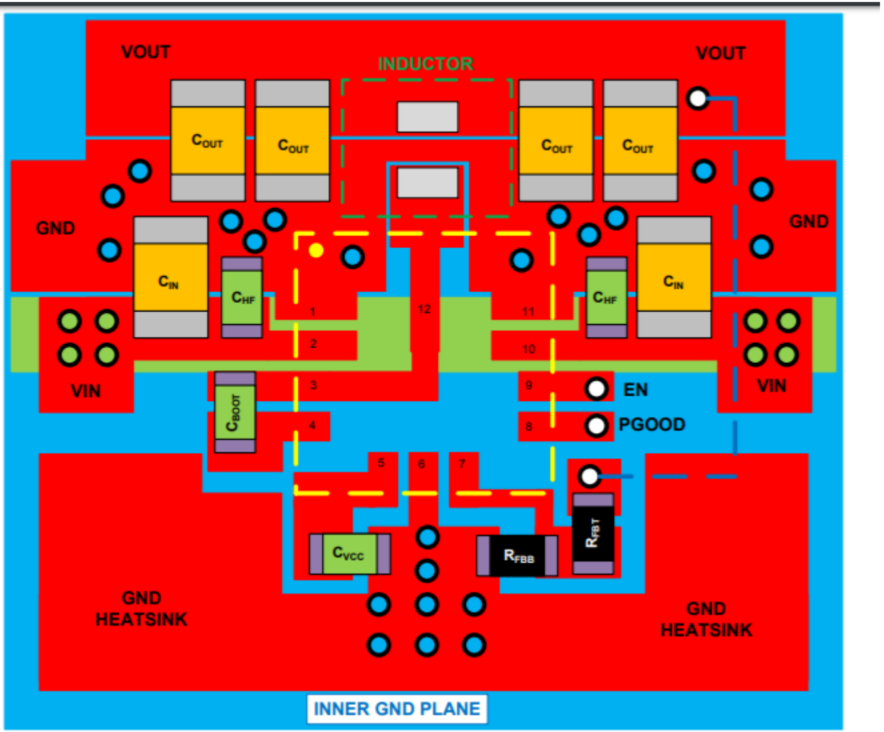
- Input cap close to IC
- Small input loop, small parasitic inductance



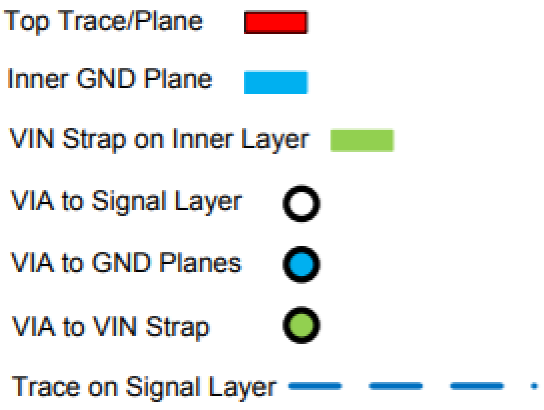


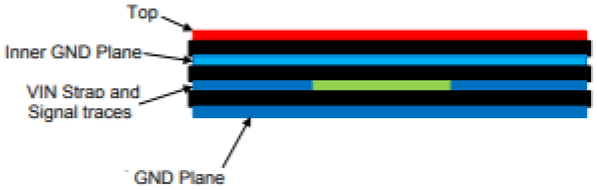


EMI-optimized layout



GND plane under IC





But what if we don't have an EMI-optimized layout?

- Reasons we might not have an EMI-optimized layout:
  - Space constraints:
    - Must place circuit into small area or particular shape.
    - Component placement may be less than optimal, far away, bottom-side of board.
  - Thermal considerations:
    - More copper on hot nodes (GND, VIN, SW) will spread heat but more copper on noisy nodes (SW, VIN) will hurt EMI performance.
  - Time constraints:
    - Not enough design time to optimize layout for EMI.
  - Inexperience or lack of attention:
    - It's hard to know and consider everything.
    - Layout issues can happen to anyone.
- What else can we do to improve EMI?

How do we make this easier?

Package, features, external add-ons

How to achieve good EMI – part selection and features

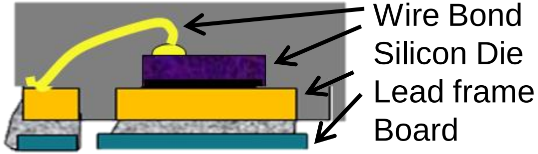
- Package:
  - HotRod™/flip-chip technology.
  - Symmetrical VIN / PGND pins.
  - EMI-friendly pinout.
  - Integrated capacitors.
- Features:
  - Spread spectrum.
  - Advanced frequency modulation.
  - SpSp ripple cancellation.
  - Slew rate control.
  - Active EMI filter.
- Other options:
  - Optimize layout.
  - Flip inductor around 180 degrees.
  - Use small, short, shielded inductor.
  - Snubber.
  - Add more front-end filtering.
  - Add a shield over noisy node.

HotRod/flip-chip package

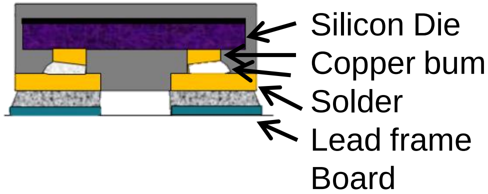
HotRod/flip-chip package technology

- Bond wire = inductance.
- Inductance → switch node ringing → poor EMI.
- Flip-chip eliminates bond wires → great EMI!

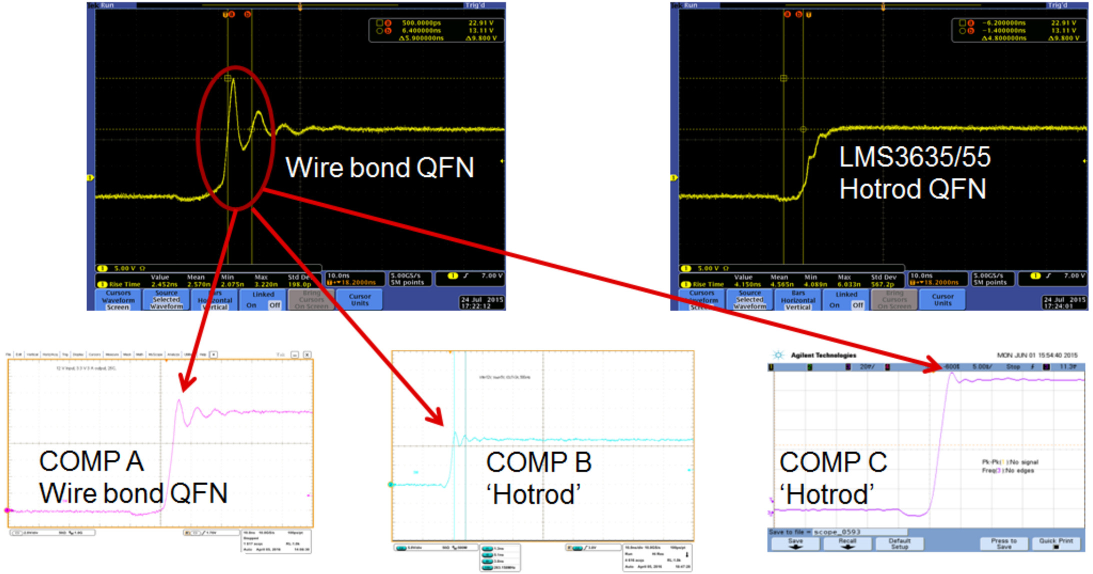
Standard wire bond QFN package



‘Hotrod’ flip chip on lead frame QFN

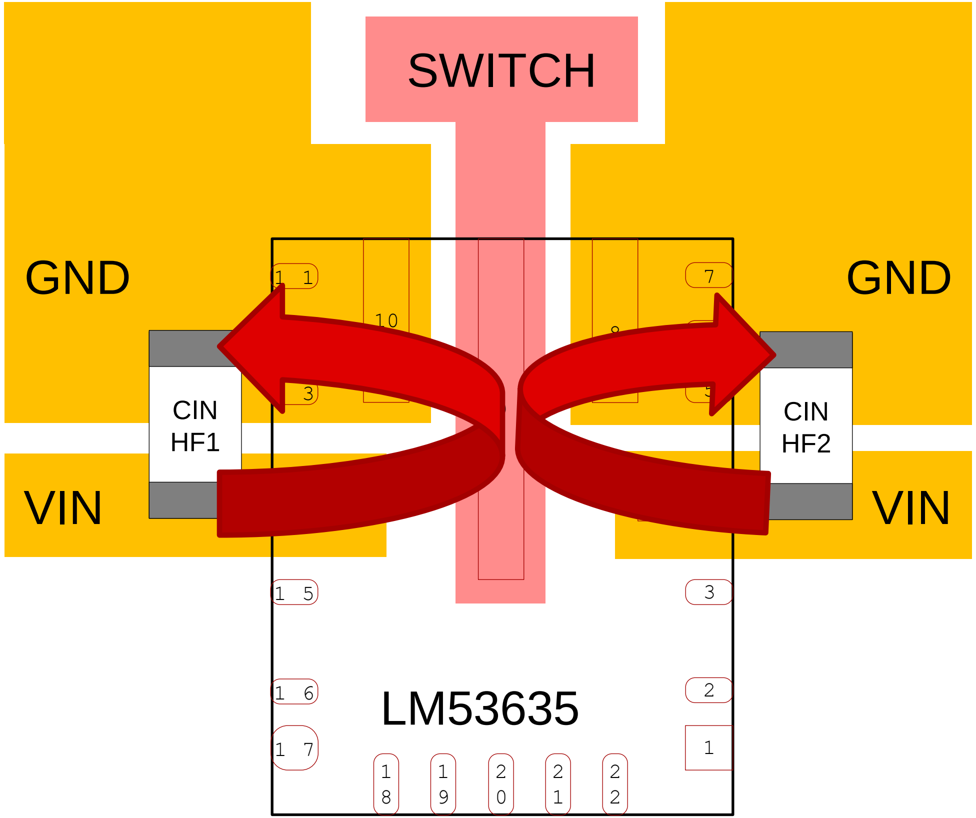


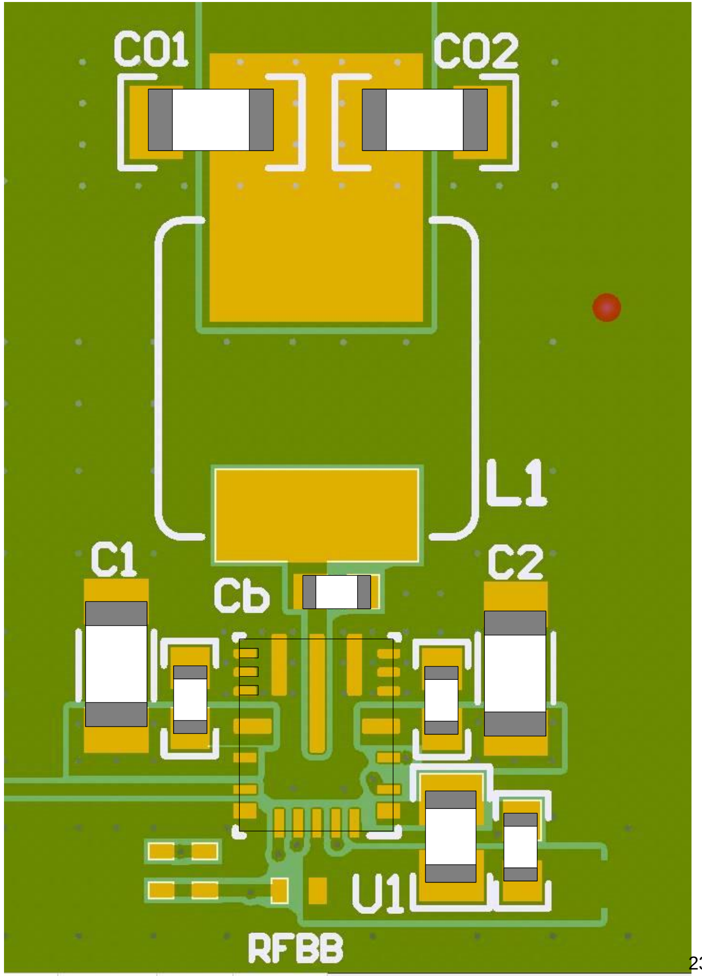
Die is flipped and placed directly onto the lead frame



Parallel input path

Parallel input cap placement





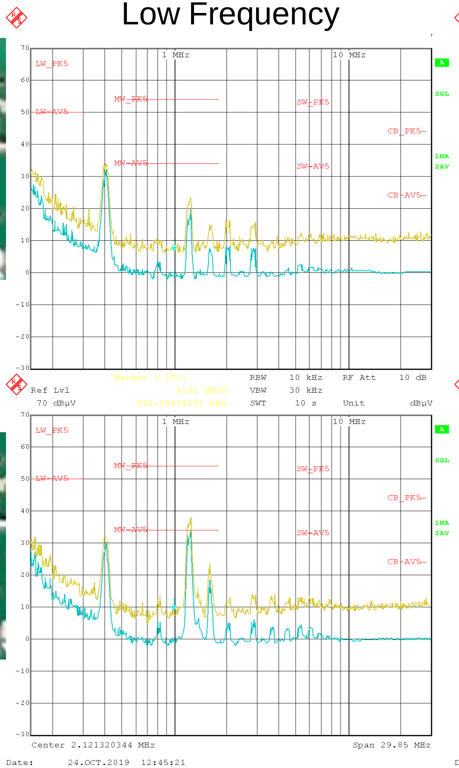
EMI: CIN placement

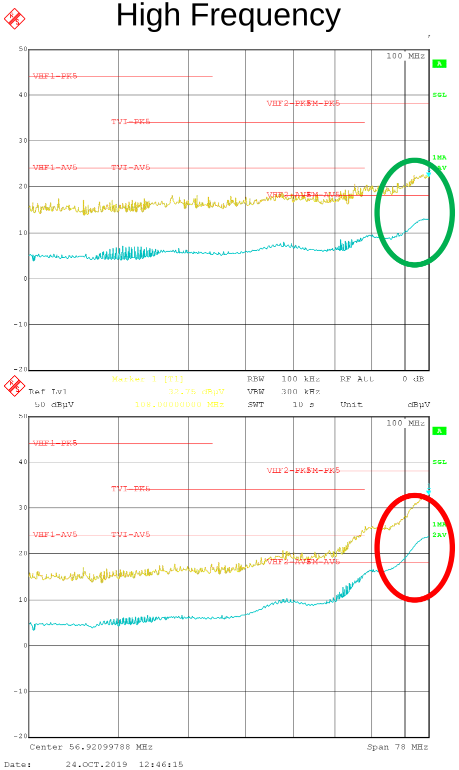
Left: 1x150nF, 2x10uF
Right: 1x150nF, 2x10uF

Left: 2x150nF, 4x10uF
Right: Depopulated

CISPR 25 Class 5
Low Frequency

CISPR 25 Class 5
High Frequency





Passing

Failing

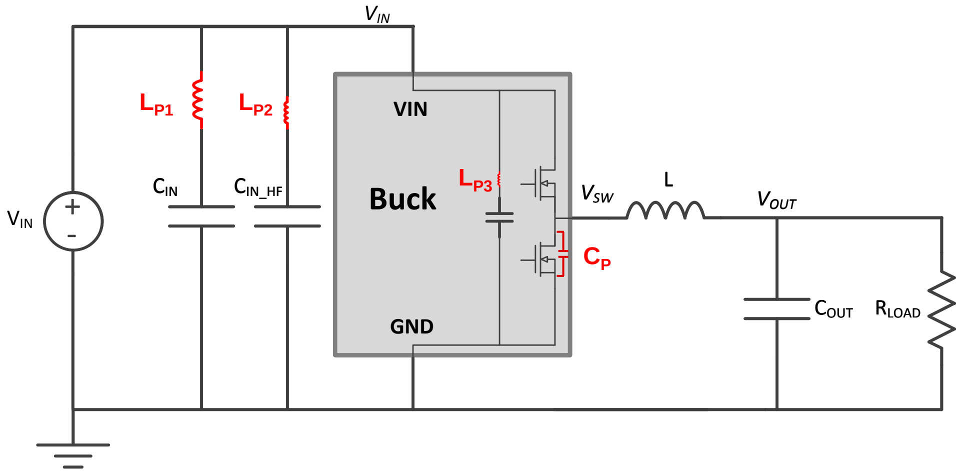
Integrated capacitors

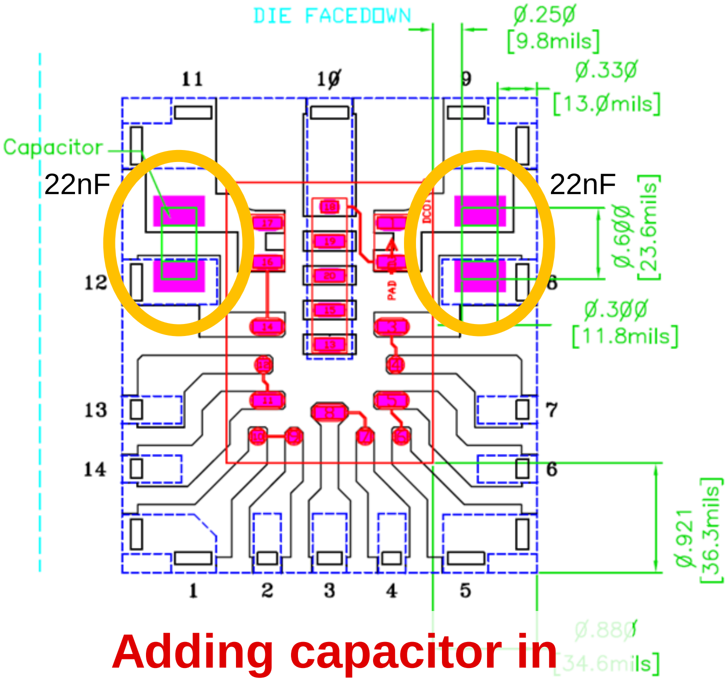
Integrated V_{IN} capacitors

Reduce parasitic inductance.

Reduce ringing.

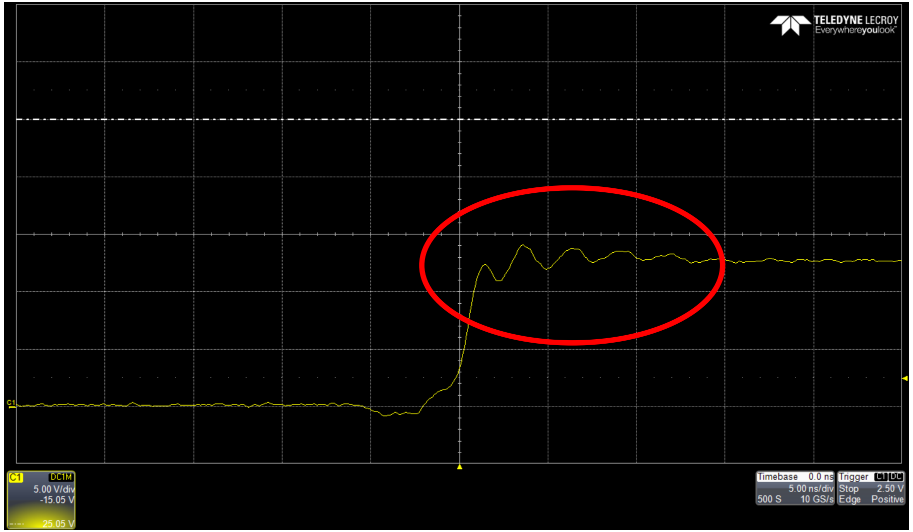
Reduce high-frequency EMI.



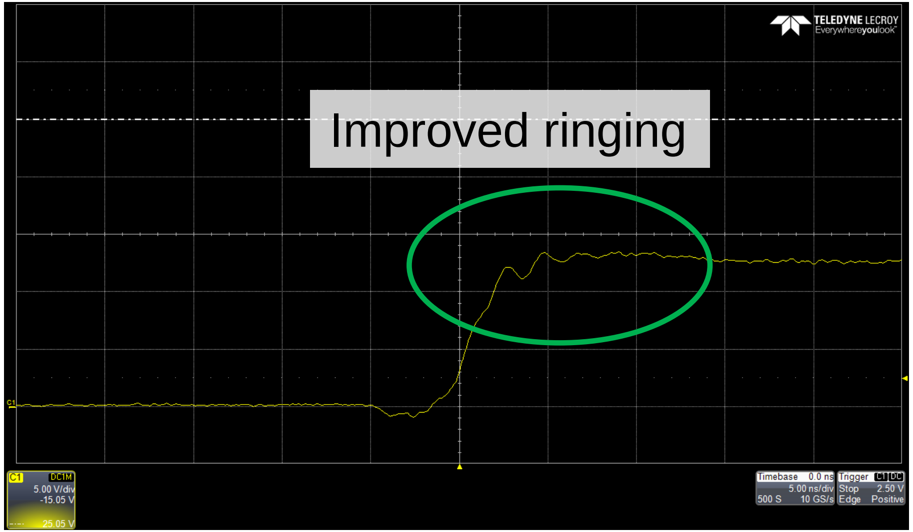


Adding capacitor in package on leadframe.

SW ringing

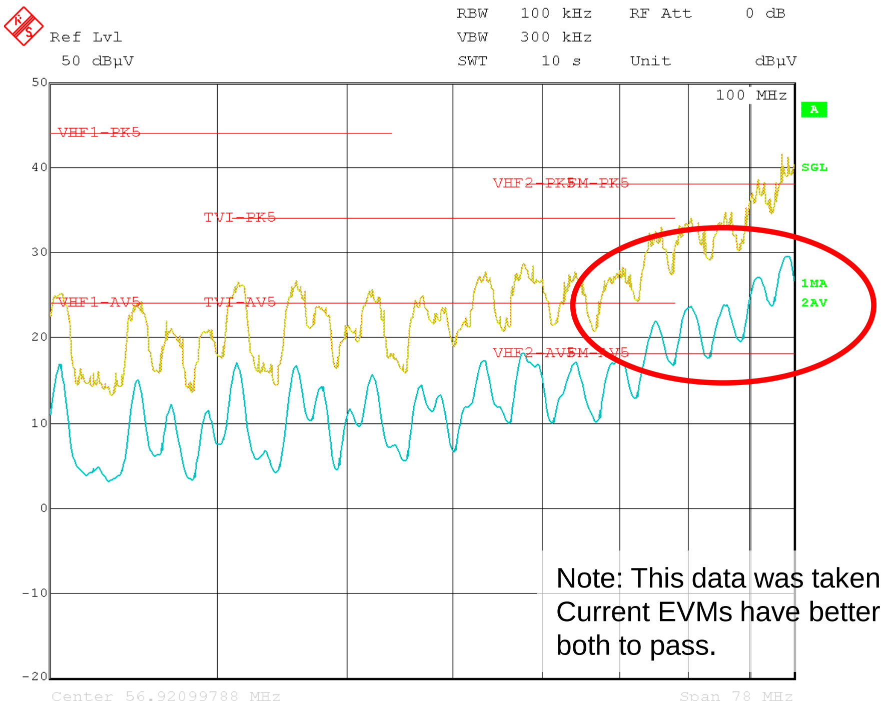


LM62440-Q1 SW ringing

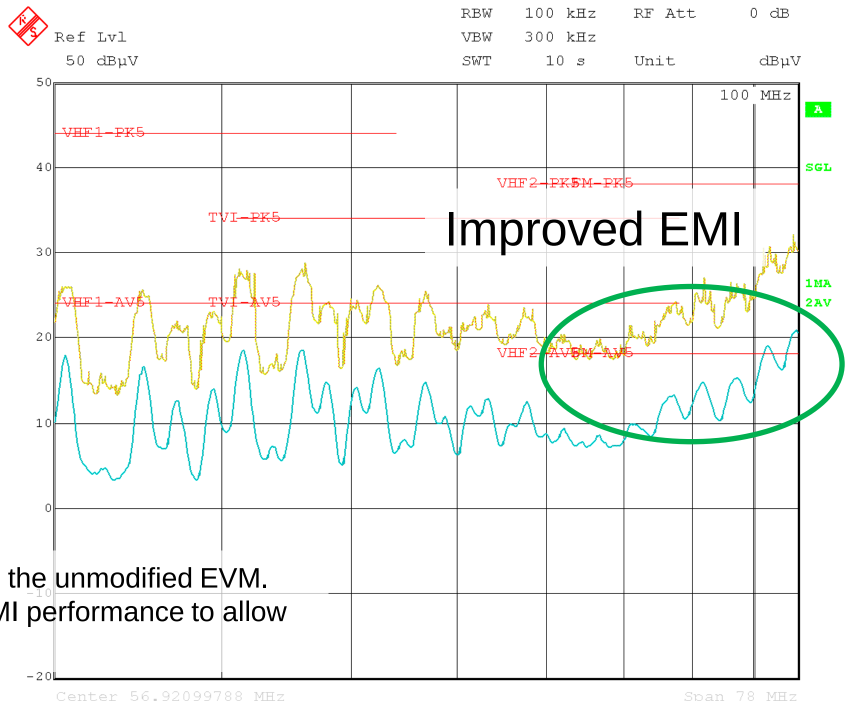


LMQ62440-Q1 SW ringing

EMI results – identical board and BOM



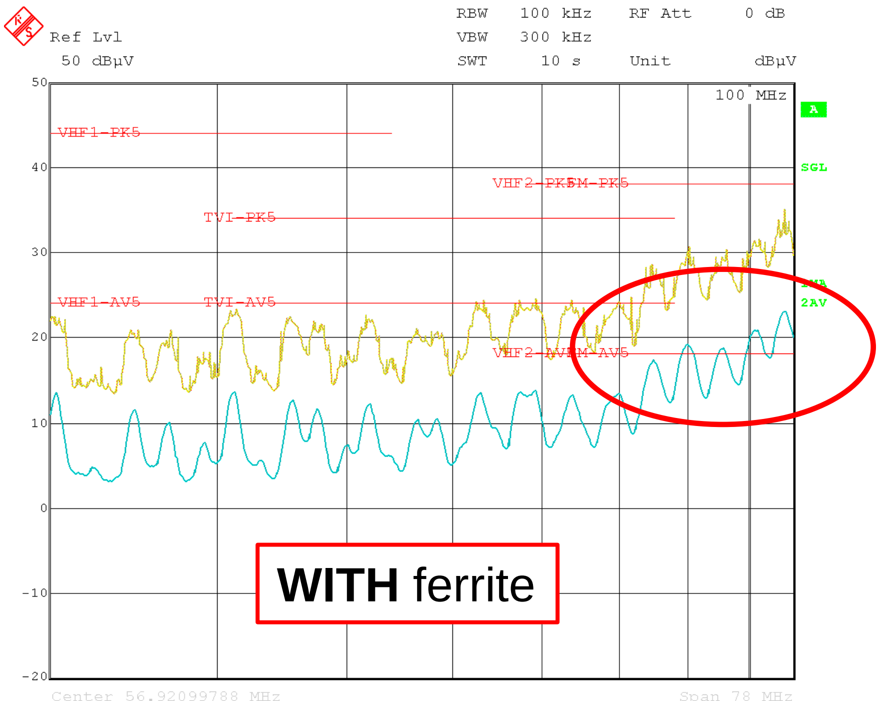
LM62440-Q1 EMI
CISPR 25 class 5 conducted high frequency



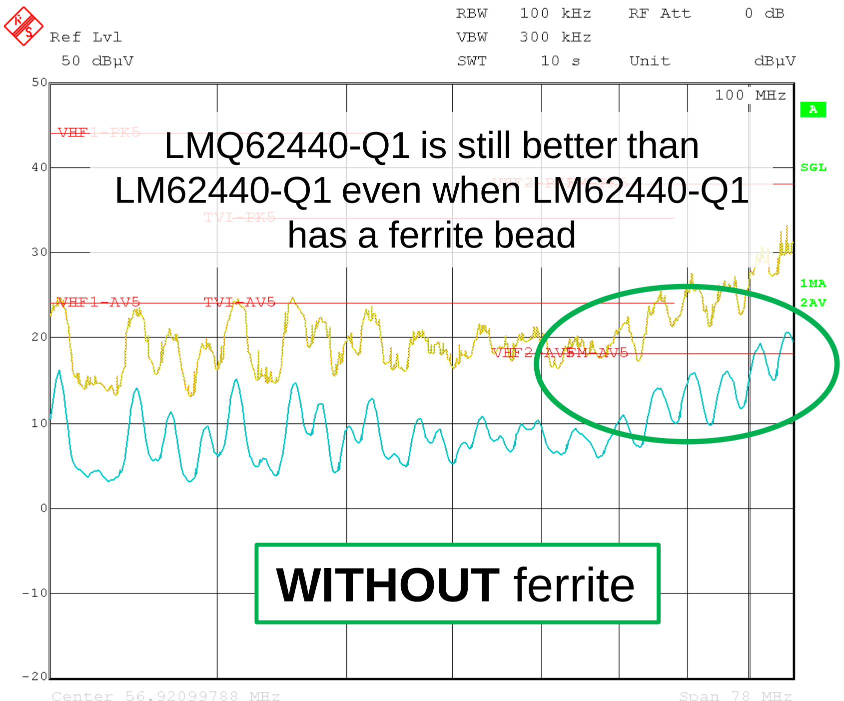
LMQ62440-Q1 EMI
CISPR 25 class 5 conducted high frequency

Note: This data was taken on the unmodified EVM. Current EVMs have better EMI performance to allow both to pass.

EMI – Optimized EMI Filter



LM62440-Q1 **WITH** ferrite bead
CISPR 25 class 5 conducted high frequency



LMQ62440-Q1 **WITHOUT** ferrite bead
CISPR 25 class 5 conducted high frequency

AEC-Q100 Grade 1

LMQ61460-Q1 / LMQ62440-Q1

Ultra-low-EMI and highest power density 36-V 2.1-MHz 4-A/6-A

Features

- **Ultra-low EMI**:
  - **Dual co-packaged internal bypass capacitors.**
  - Spread spectrum & adjustable SW node rise time (Rboot).
  - Tolerant to non-ideal layout.
- **<7 µA standby I_Q** with BIAS to V_{OUT} 2.1 MHz 13.5 V to 3.3 V no load
- **3.5 mm x 4 mm HotRod™ package; -40C to 150°C T_J operation**
- **Pin to pin compatible** with LM614x0-Q1, LM62440-Q1 family
- **Synchronize** to external clock: 200 kHz to 2.2 MHz
- LMQ62440-Q1: pin 6 = MODE/SYNC (4-A DC current max)
  - **Pin-select auto mode or FPWM operation;** Fixed 2.1 MHz frequency
- LMQ61460-Q1: pin 6 = RT (6-A DC current max)
  - **Frequency set by resistor;** factory auto mode or FPWM versions
- 3V – 36 V (Abs. Max = 42V) wide input voltage range
- Factory fixed-3.3V, fixed-5 V and adjustable V_{OUT} versions available

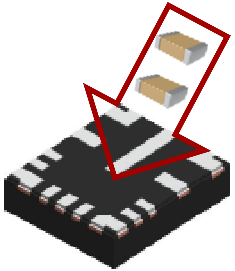
Benefits

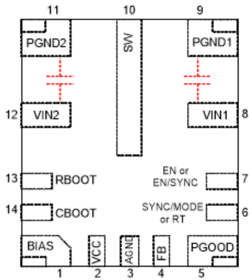
- **High efficiency** at heavy load and light load; long standby time with **no load Iq as low as 7 µA** and auto mode
- **Low EMI** with co-packaged bypass capacitors; Wettable Flank HotRod™ package; spread spectrum; and adjustable SW node rise time
- **Small solution size** with **3.5 mm x 4 mm** Wettable Flank HotRod™ package, **2.2-MHz** max frequency and **internal HF capacitors**
- **Flexible design options** with Auto Mode (high efficiency at light load and low Iq) or FPWM (fixed frequency for noise reduction)
- **High ambient temp pperation** with high efficiency at heavy load and **150°C T_{JMAX}**

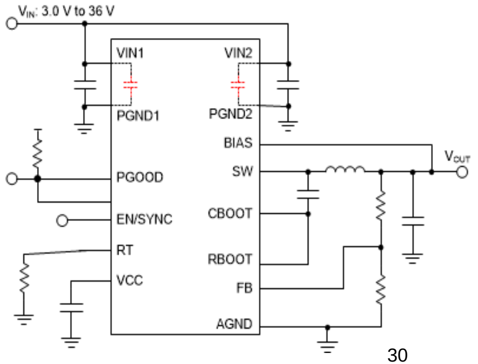
Applications

- Surround view camera ECU.
- Infotainment head unit.
- Digital cockpit.

High Frequency Cap Integration







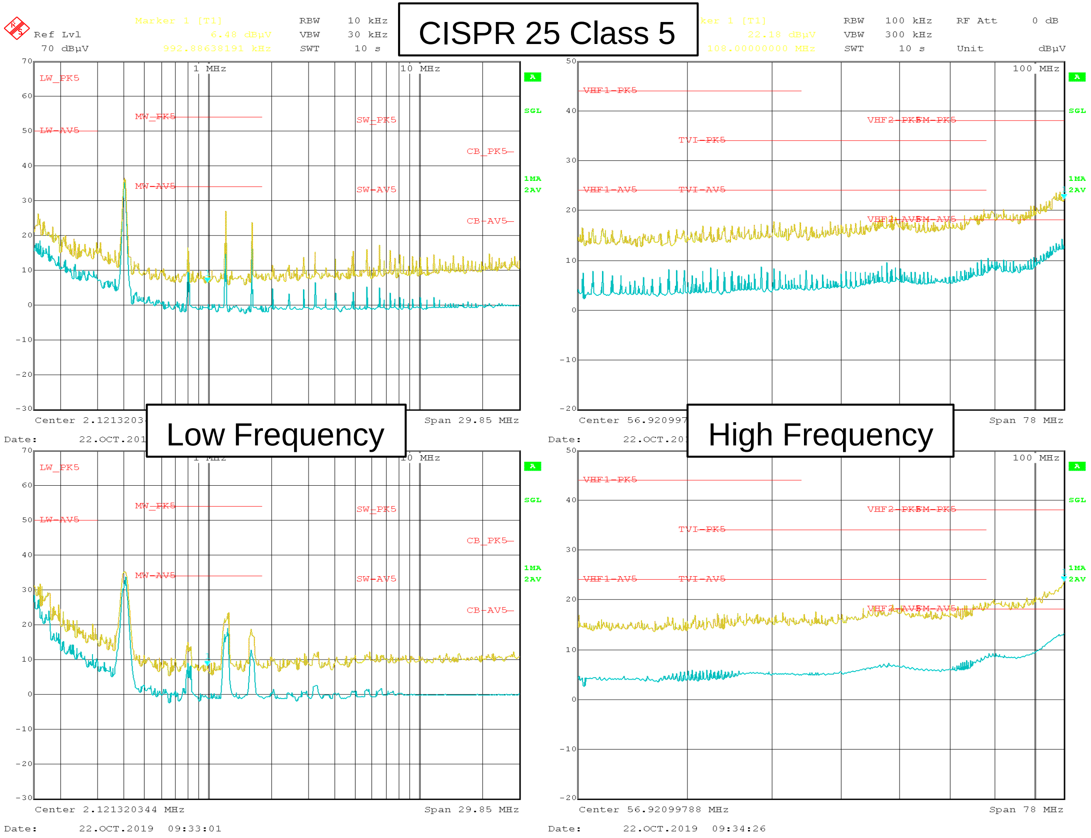
Spread spectrum

EMI: spread spectrum effect

V_{IN} = 12V
V_{OUT} = 5V
I_{OUT} = 10A
F_{SW} = 400kHz

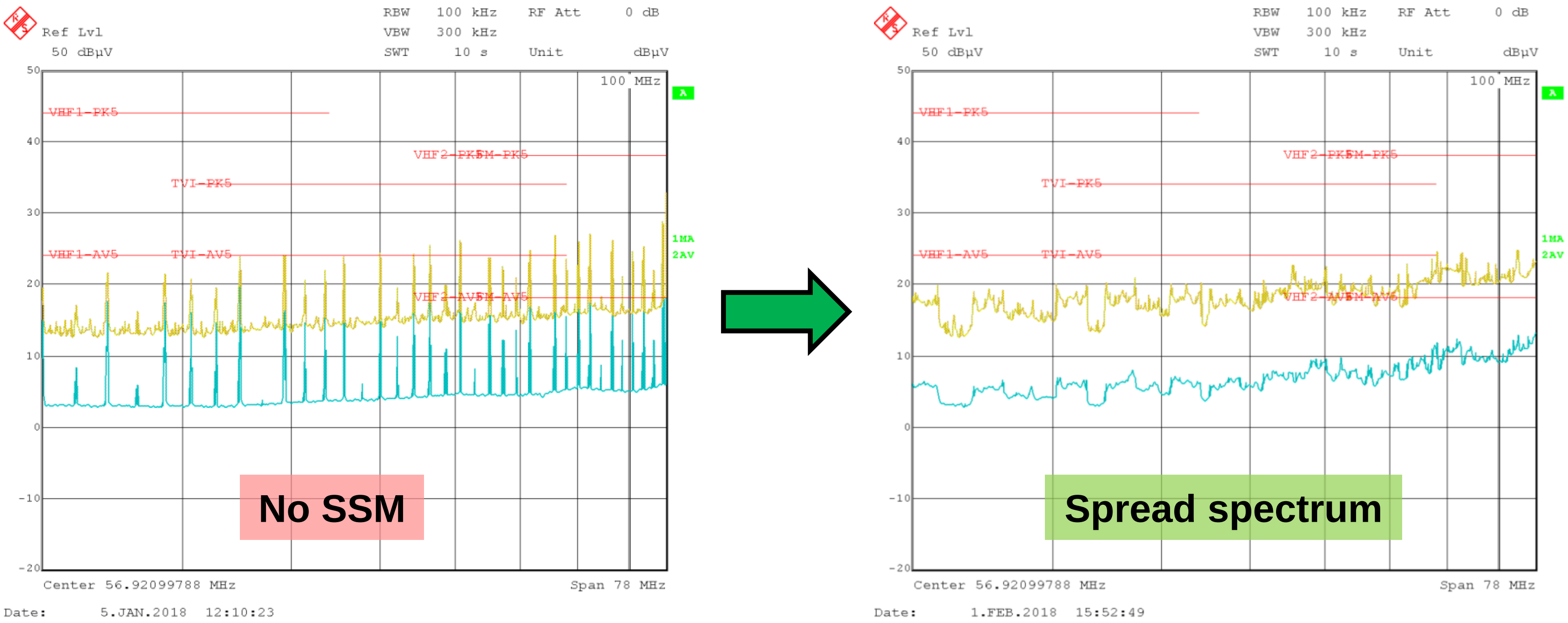
Spread spectrum OFF

Spread spectrum ON



Spread spectrum - concept

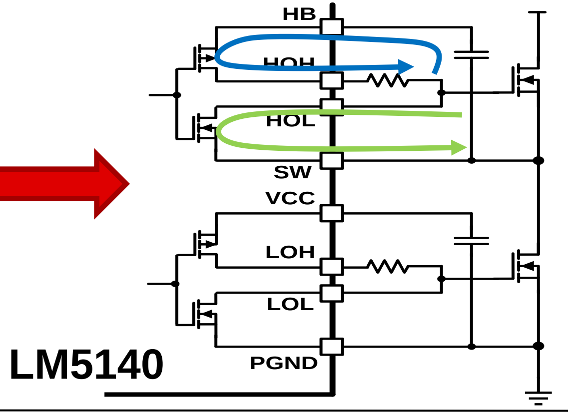
- Dither switching frequency to smooth out the EMI peaks.



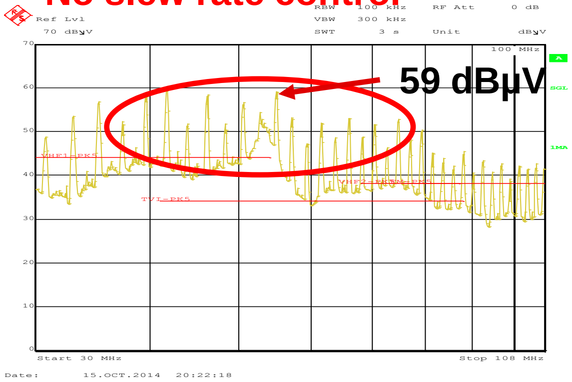
Slew rate control

Slew rate control: controller with gate resistors

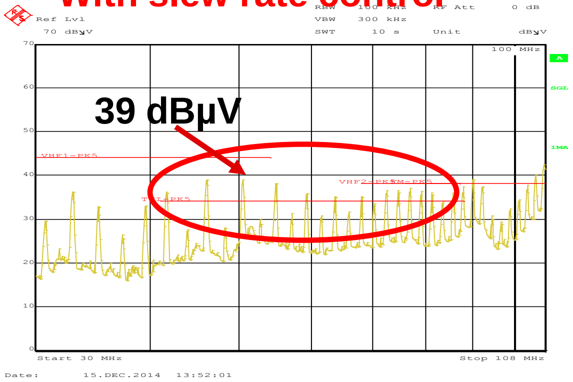
- High and low side FET drivers have separate source and sink pins allowing the turn-on and turn-off times to be independently controlled via series resistors.
- Optimizing gate drive slew rate reduces EMI with ~1% reduction in efficiency (as measured on LM5140 EVM).



No slew rate control



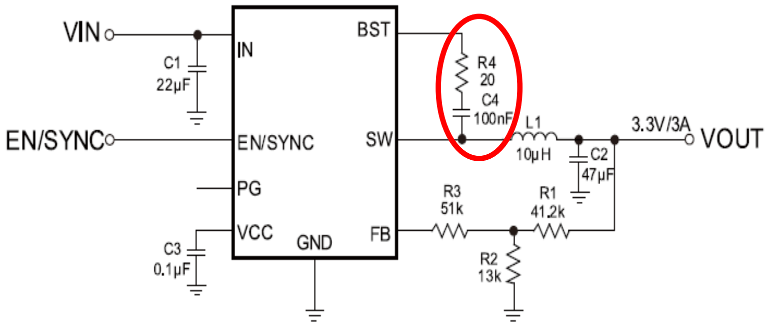
With slew rate control



Measured on LM5140 standard EVM: 2.2 MHz, 3.3 V/5.0 Vout

Converter: series RBOOT vs true slew rate control

TYPICAL APPLICATION



1. **Power loss.**
2. **Not easy to layout.**
3. **Boot UVLO.**
4. **Limitations on how much slew.**

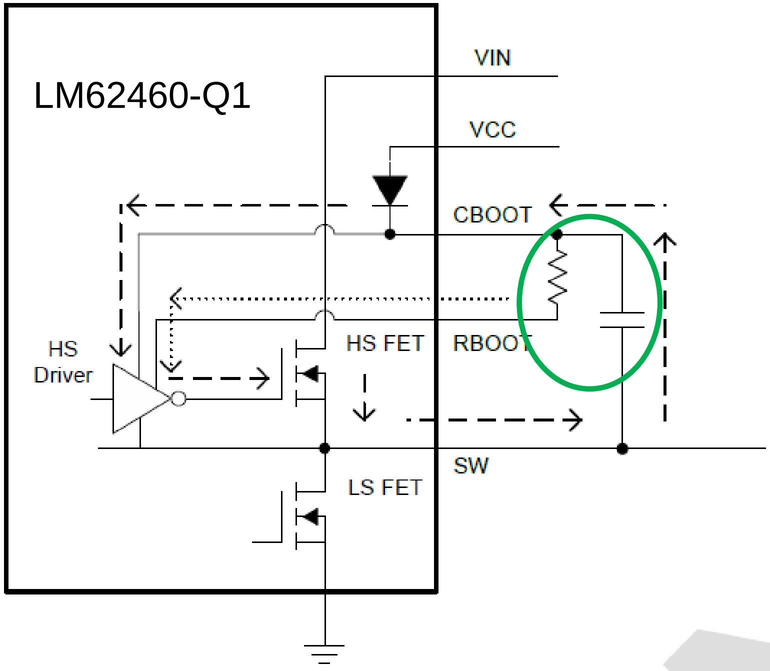


Figure 30. Simplified circuit showing how RBOOT functions.

Other options:

Snubber

Snubber

- SW ringing comes from:
  - Parasitic L of input loop (CIN+ to VIN to GND to CIN-) resonating with...
  - Parasitic C from low-side FET
- Snubber absorbs this energy.

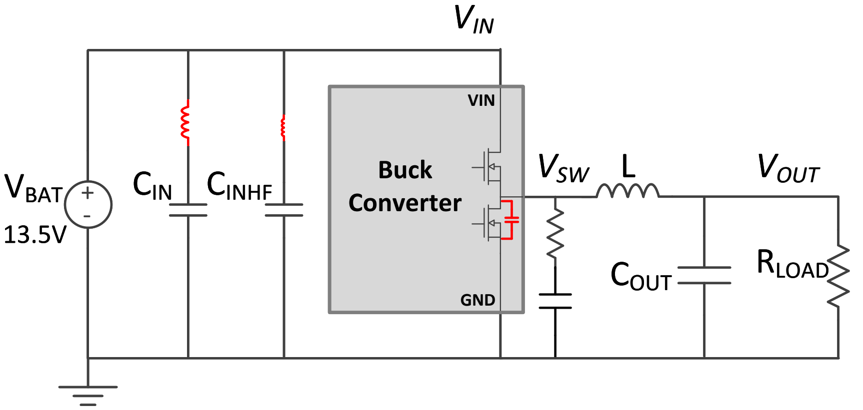
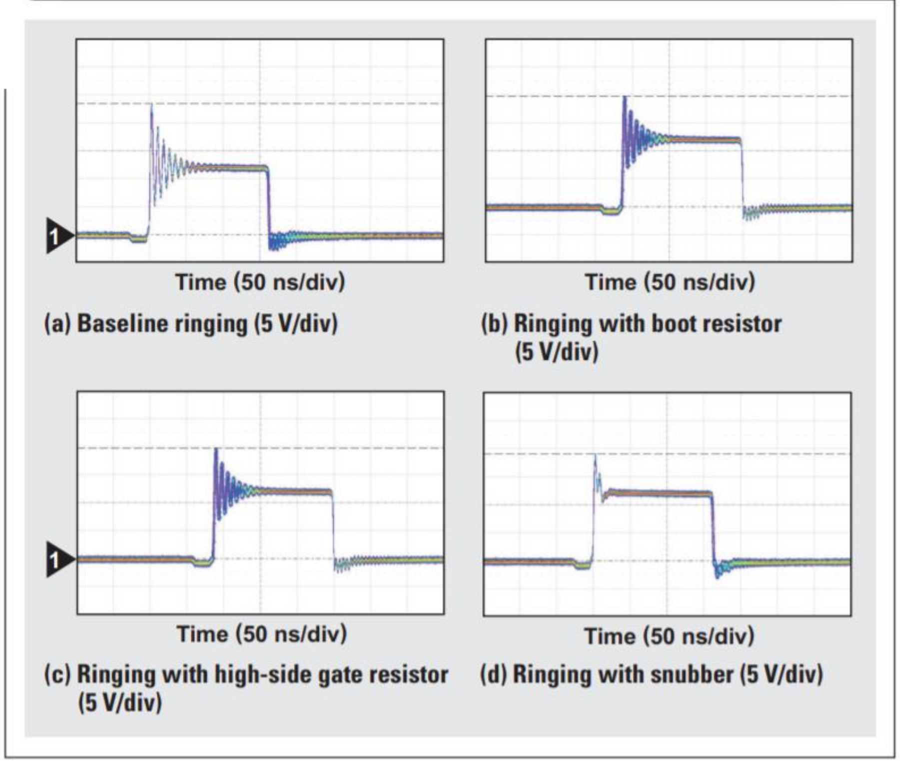


Figure 2. Waveforms of switch-node ringing with 12-V input



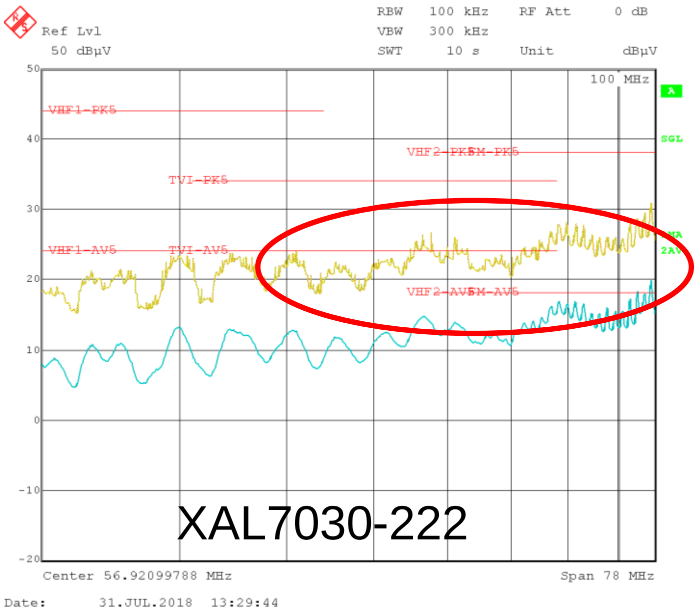
Trade EMI performance for efficiency

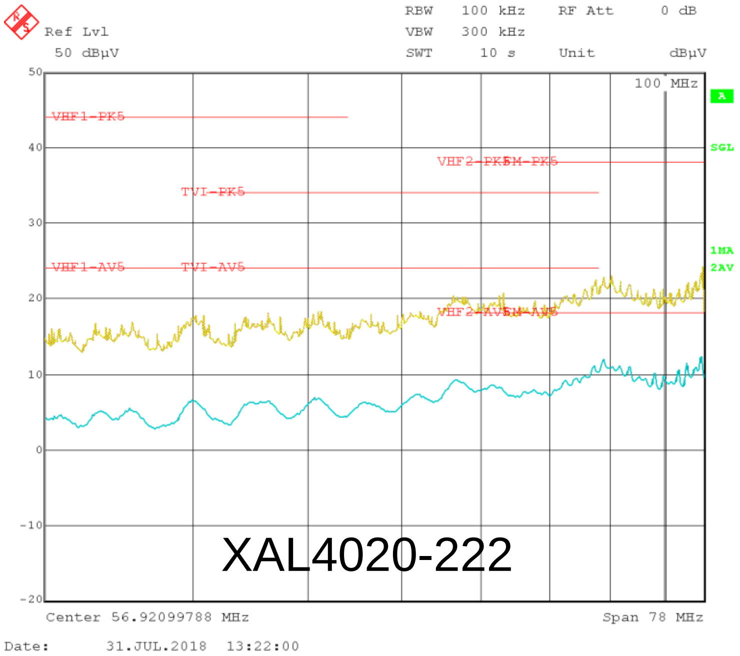
SLYT465

Inductor selection

Effect of well shielded small output Inductor

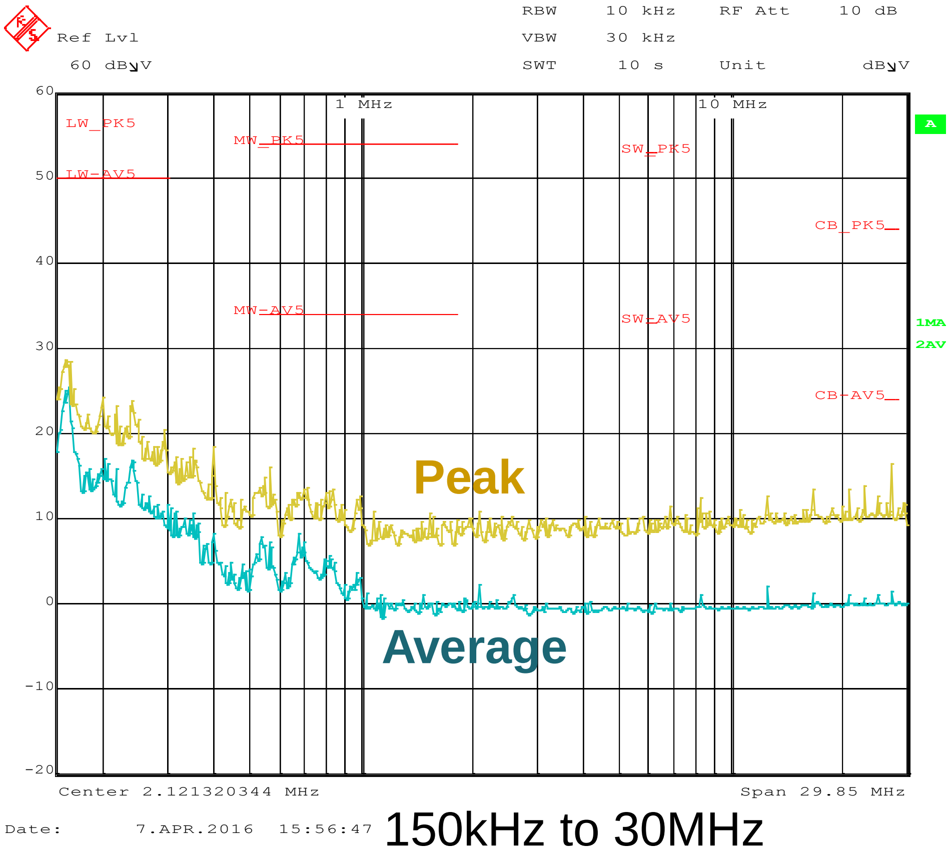
30 MHz-108MHz EMI performance comparison



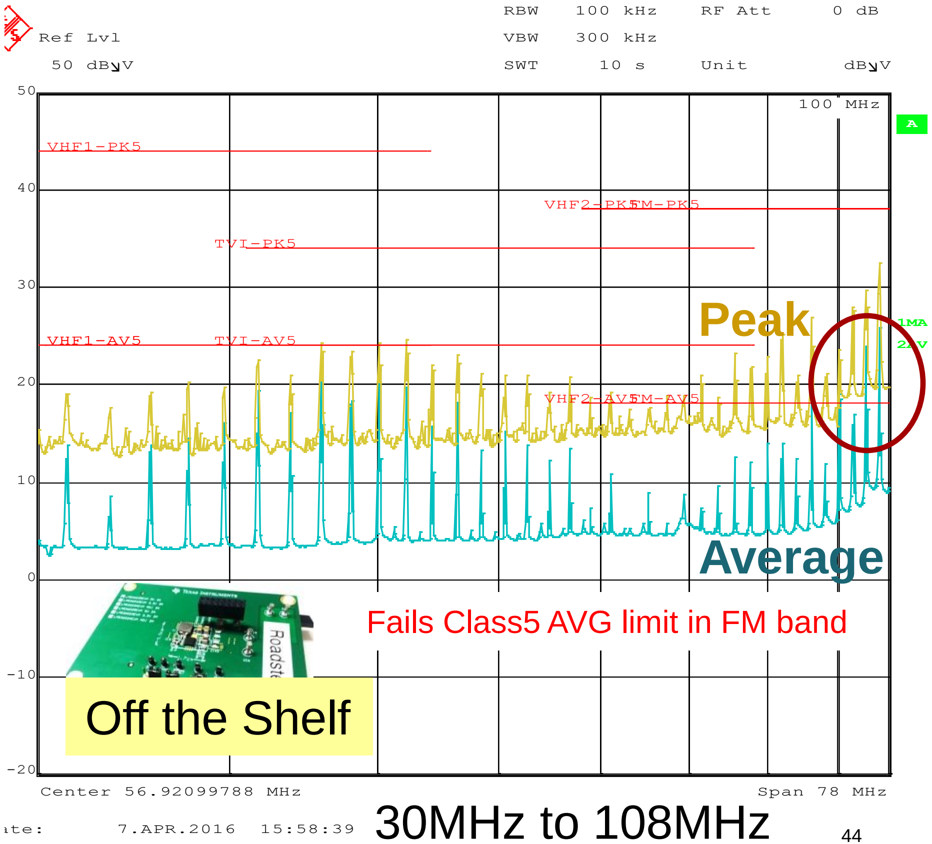


Shield

EMI performance – 13.5Vin / 5Vout @ 3A

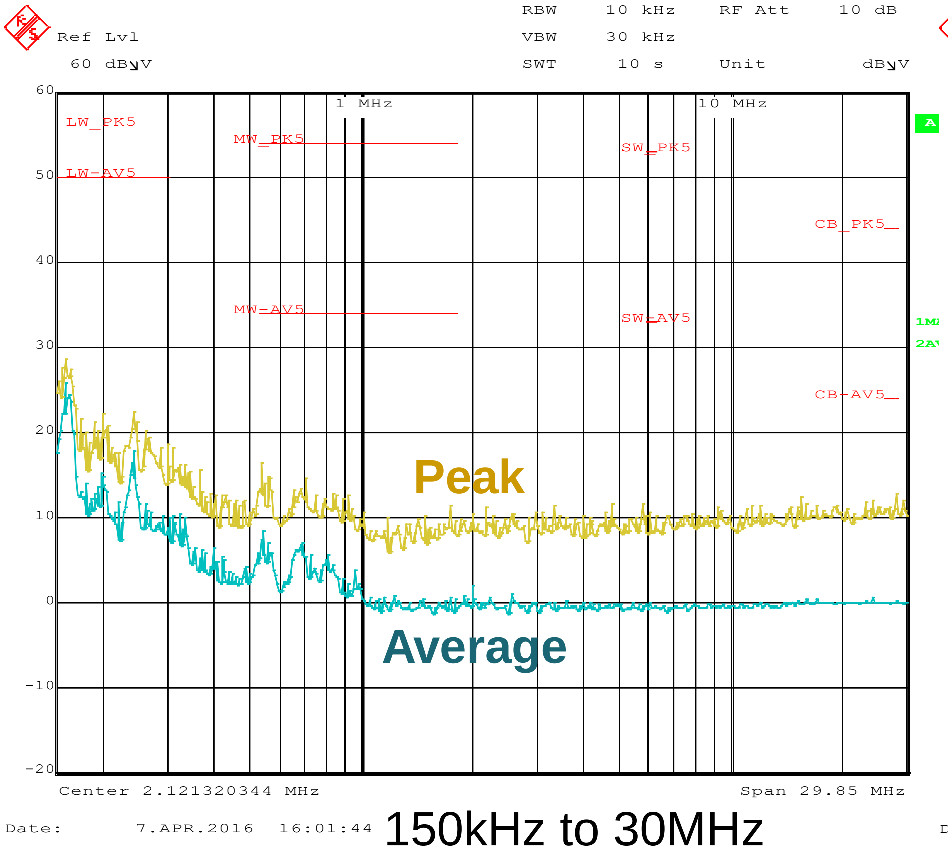


150kHz to 30MHz

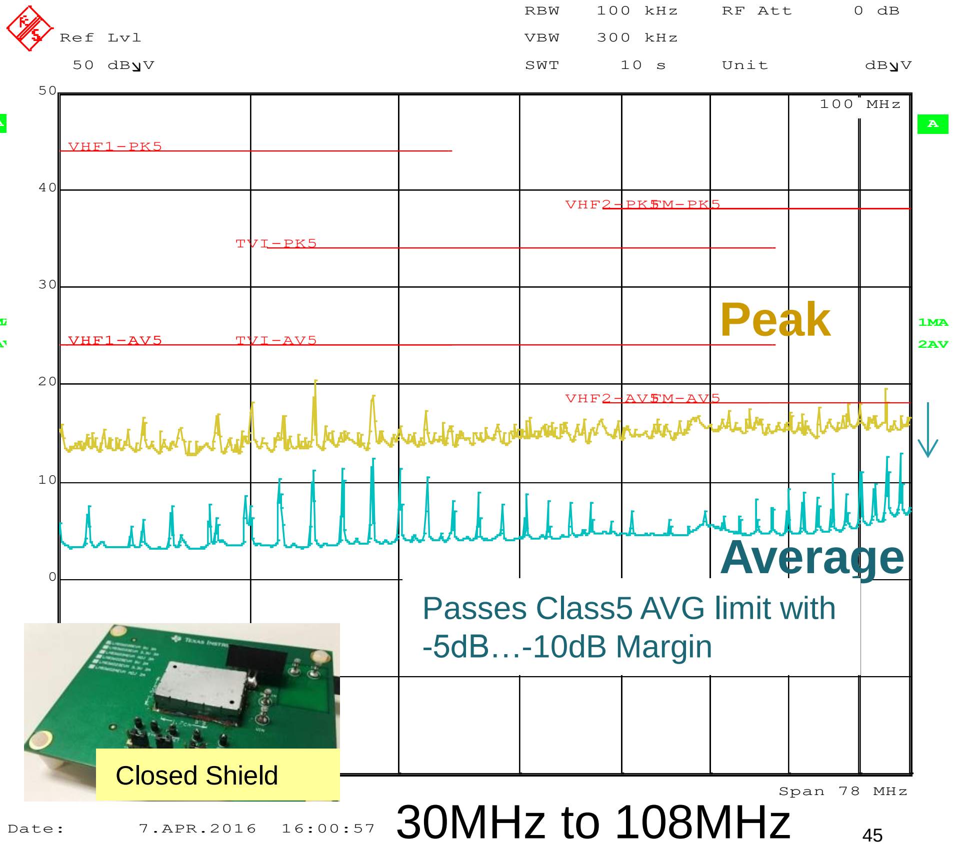


30MHz to 108MHz

LM53603 EVM - closed shield with metal lid



150kHz to 30MHz



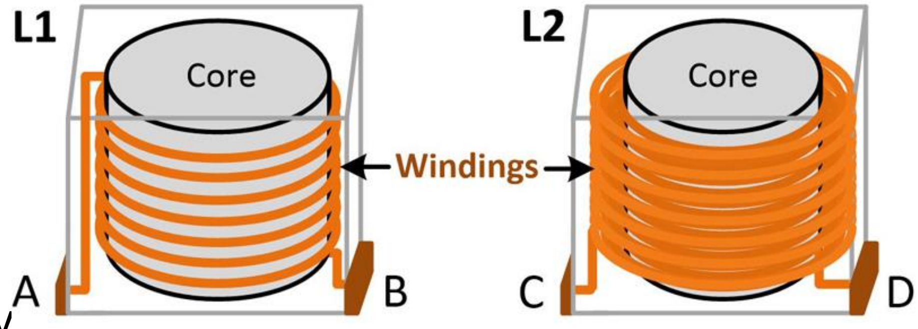
Passes Class5 AVG limit with -5dB…-10dB Margin

30MHz to 108MHz

Quick tests and debugging

Rotate the inductor

- Inductors are not symmetrical.
- One pad connects to SW (noisy).
- Other pad connects to VOUT (quiet).
- Connect the lower winding to the noisy node:
  - Shielded better by the GND plane of the board.
- Connect the inner winding to the noisy node:
  - Shielded by the outer winding.



Article: Three Quick Buck EMI Checks

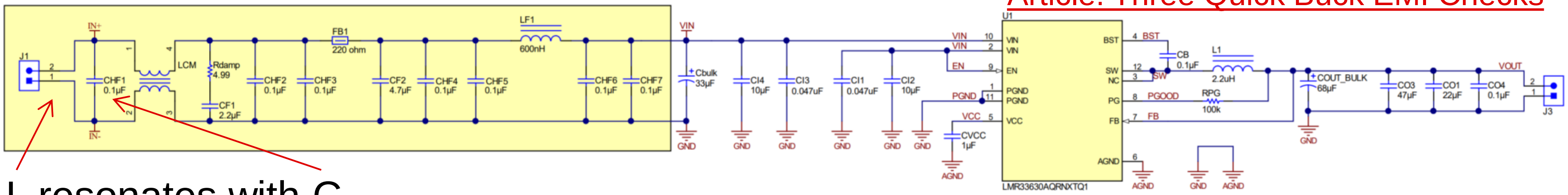
- But how do you know without cracking open the inductor?
- **Test it, flip it, test it again. Take the better result**

Real result: LMR33630-Q1 13.5-V_{IN}, 5-V_{OUT}, 3-A_{OUT}, 400-kHz two-layers
CISPR 25 Class 5: 15 dBµV → 7 dBµV (3 dBµV margin → 11 dBµV margin)

Remove first CIN cap. resonates with harness

- Test board schematic for LMR33630 showing EMI filter → buck

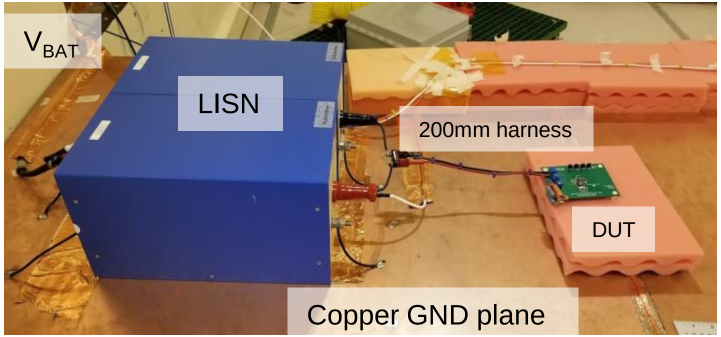
Article: Three Quick Buck EMI Checks



L resonates with C

- Parasitic inductance of harness (200mm or 1.5m) resonates with undamped C.
- May cause worse results or may need to be damped with series R (or electrolytic cap).

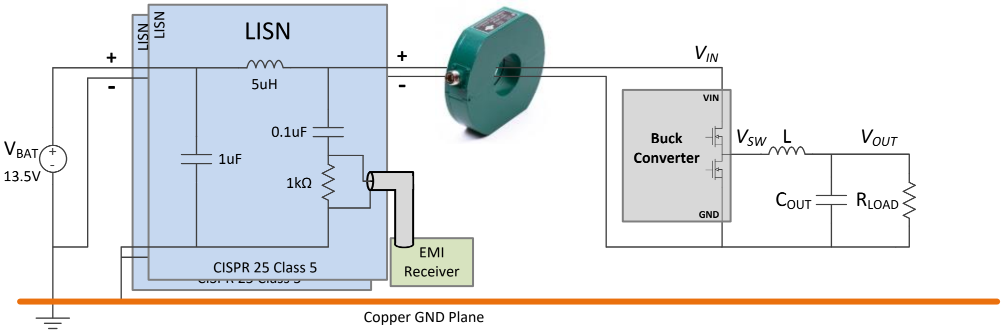
Real result: removing CHF1 resulted in a 3-5 dBµV improvement in the FM band.



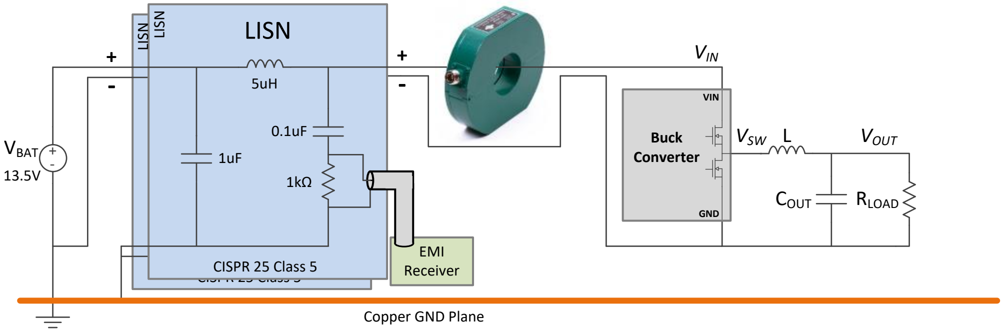
Current probe around harness

- Place high-frequency current probe around harness to measure noise current.

Place around both wires to measure common-mode current.

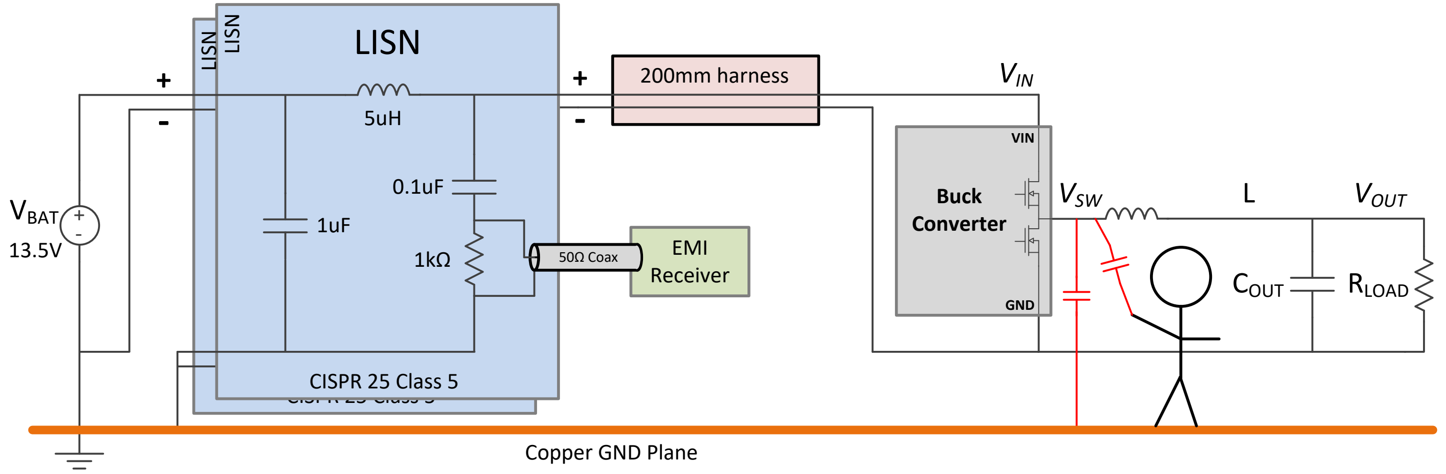


Place around one wire to measure differential-mode current (plus common-mode current).



Wave hand over the board

- You're adding more capacitance to GND → more capacitively coupled current to GND → more common-mode EMI.
- If there's a large source of common-mode capacitively-coupled EMI, the results will get worse when you place your body close to the board

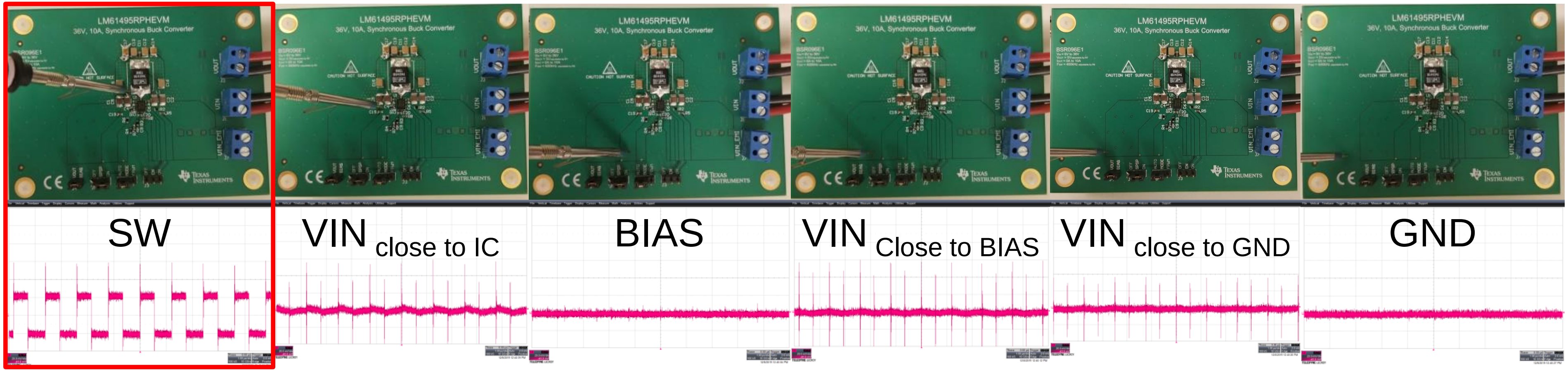


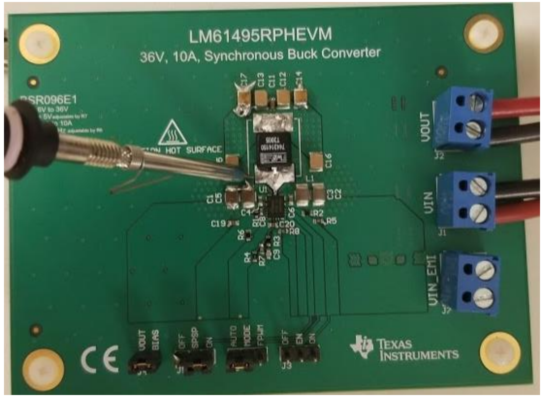
Texas Instruments

E-field probe – scope probe over board

- Place a scope probe tip on the board (not electrically connected).
- Scope will show capacitively coupled noise.

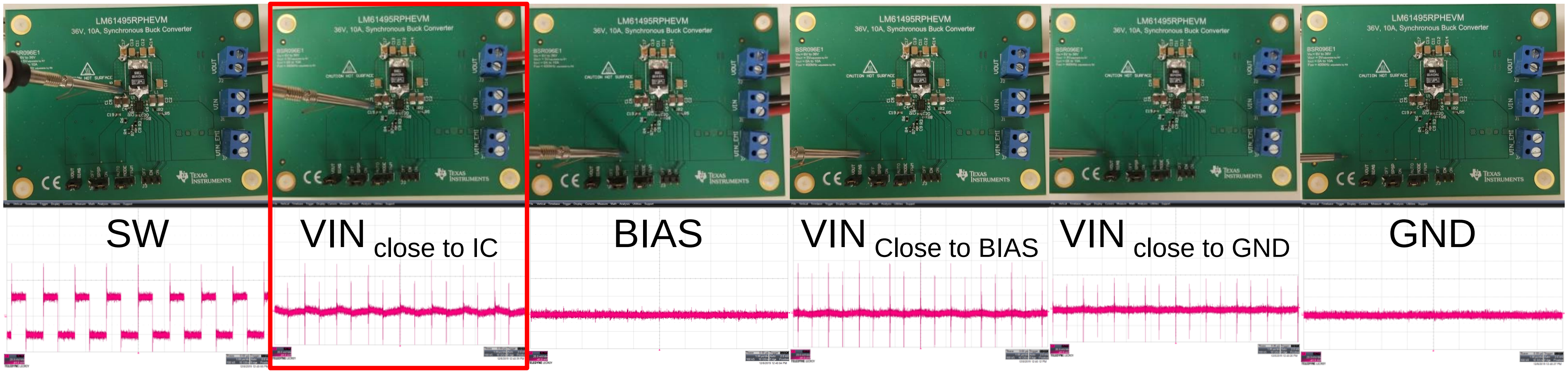
E-field probe – scope probe over board

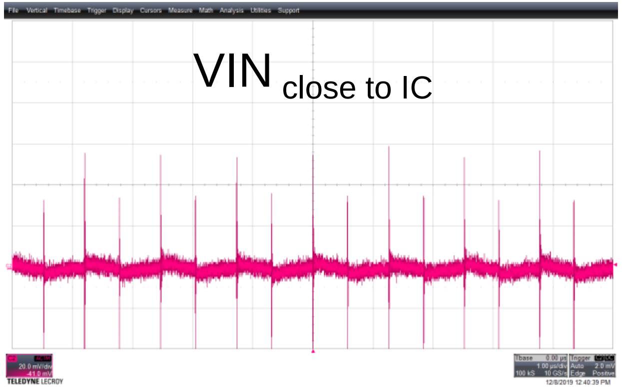




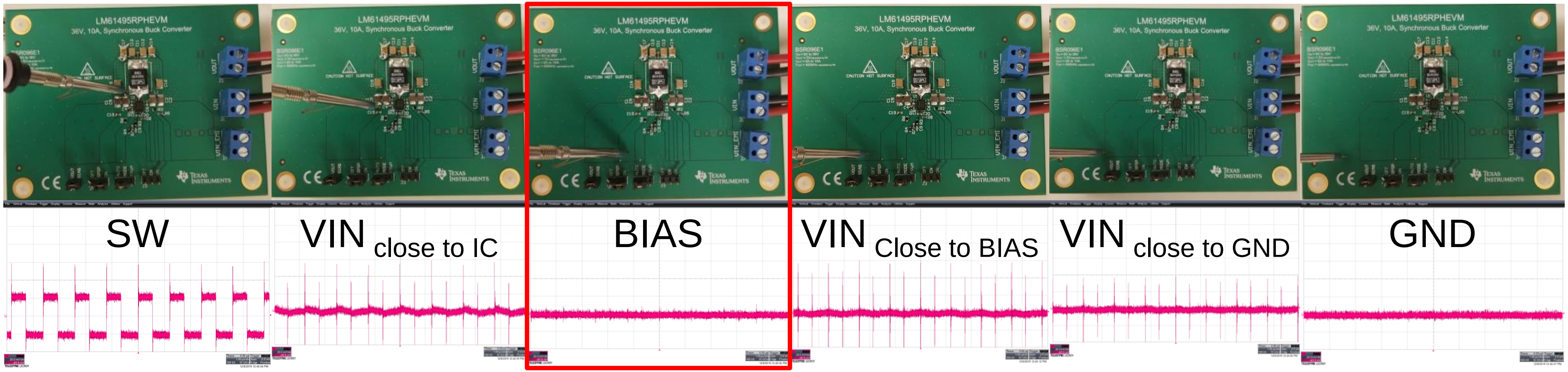
*Not electrically connected. This is capacitively coupled noise

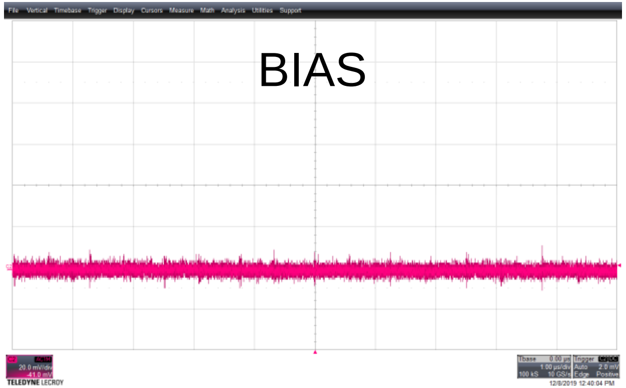
E-field probe – scope probe over board



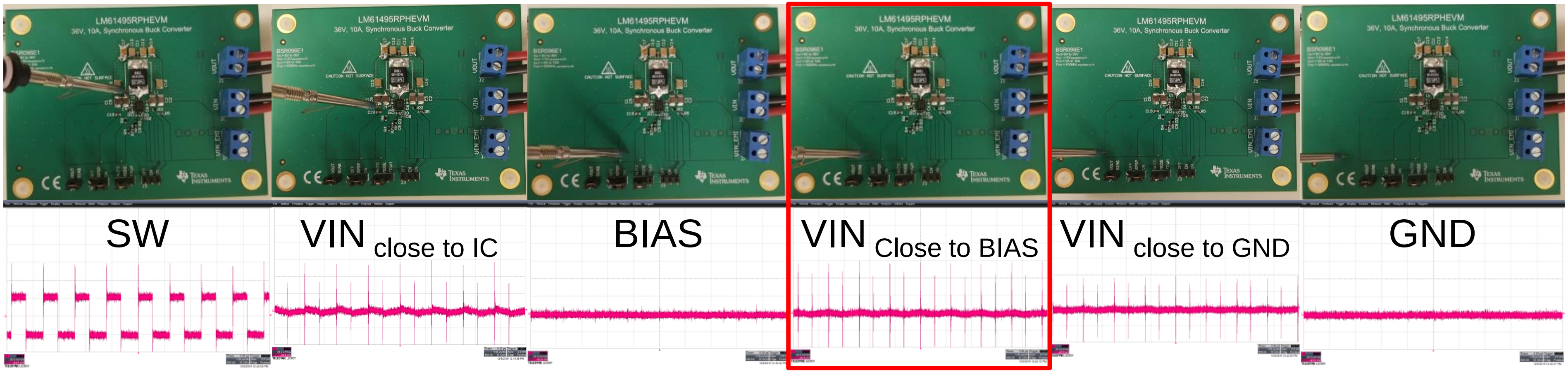


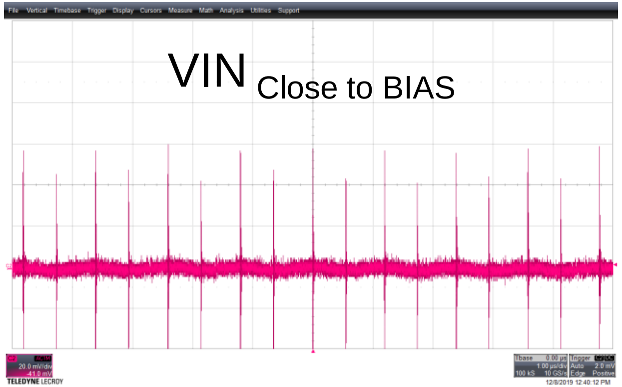
E-field probe – scope probe over board



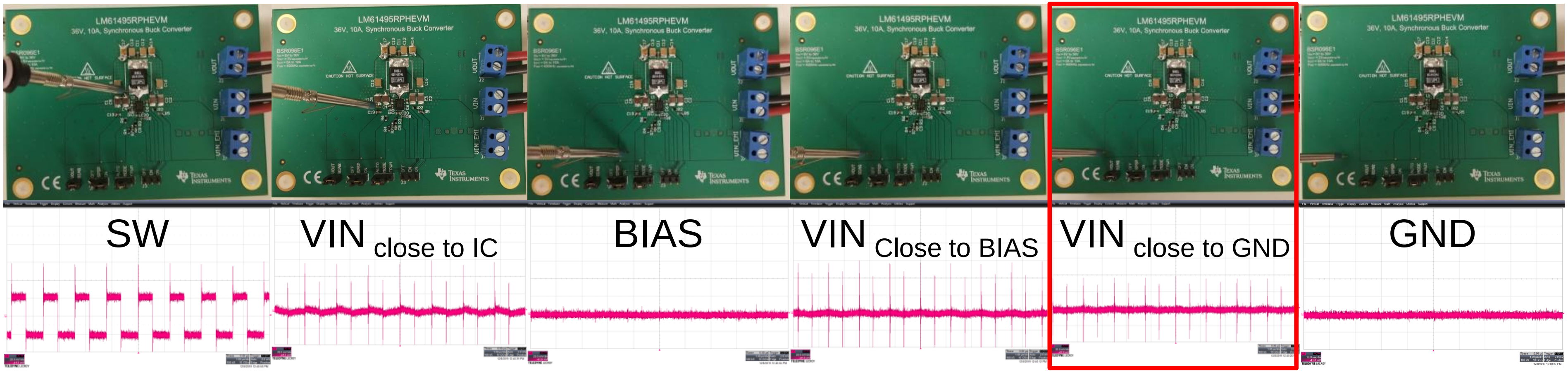


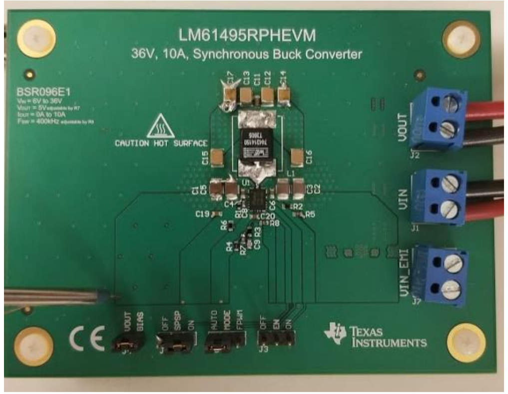
E-field probe – scope probe over board



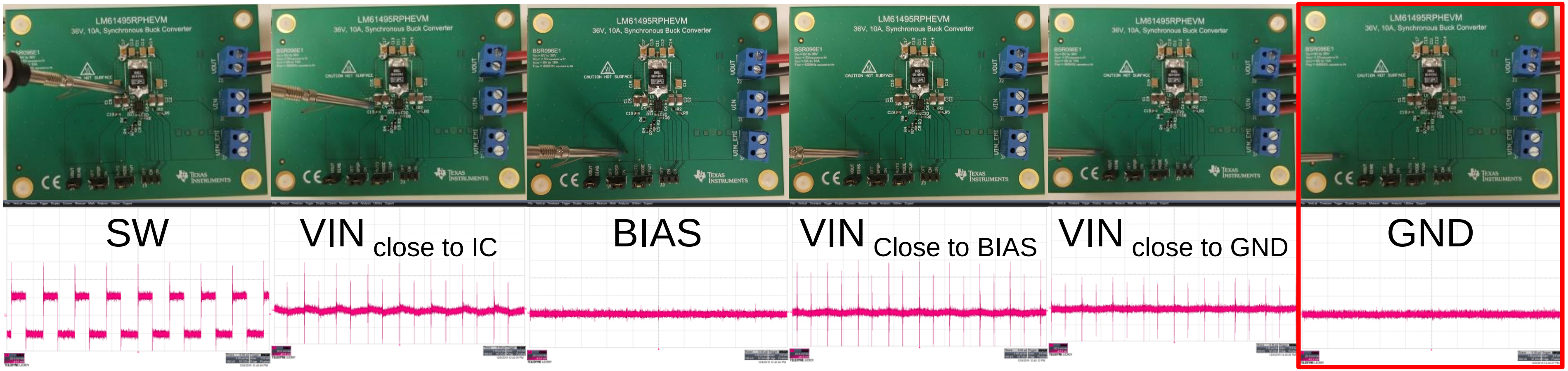


E-field probe – scope probe over board





E-field probe – scope probe over board



That's all! Any questions? Topics:

- EMI:
  - What is it?
  - CISPR25
  - Buck EMI
- Package:
  - Hotrod/flip-chip technology
  - Symmetrical VIN/PGND pins
  - EMI-friendly pinout
  - Integrated capacitors
- Features:
  - Spread spectrum
  - Slew rate control
- Other options:
  - Optimize layout
  - Flip inductor around 180 degrees
  - Use small, short, shielded inductor
  - Snubber
  - Use more EMI filter
  - Add a shield over noisy node
- Debugging:
  - Current probe
  - Literal hand waving
  - E-field probe (scope probe)

Important notice and disclaimer