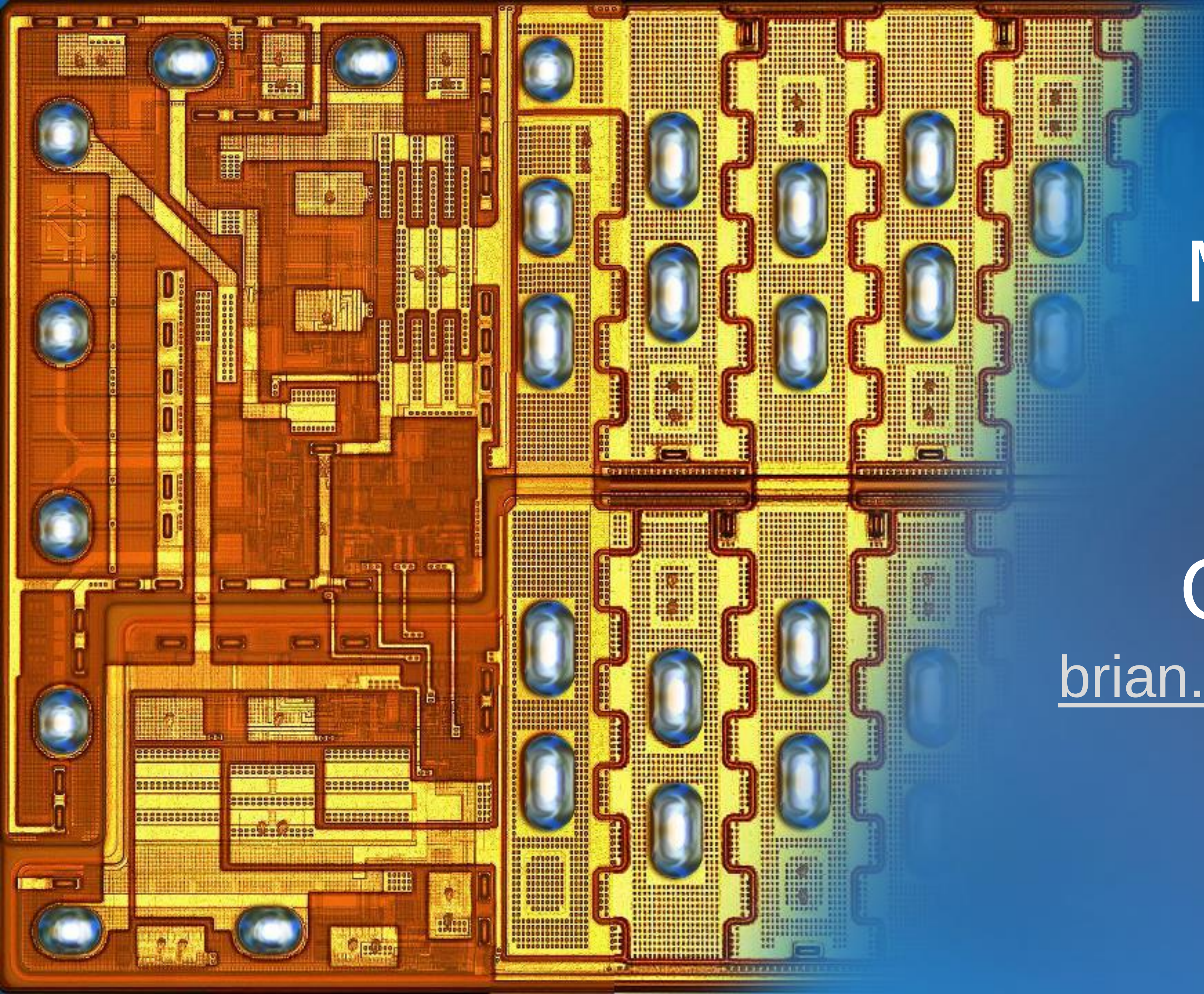


Motor Drives: GaN FETs & Magnetics

Oct. 22, 2024

brian.miller@epc-co.com

EPC
EFFICIENT POWER CONVERSION

Agenda

- GaN FETs
- Motor Drive
  - Advantages
  - Value of Wurth magnetics
- Design Examples

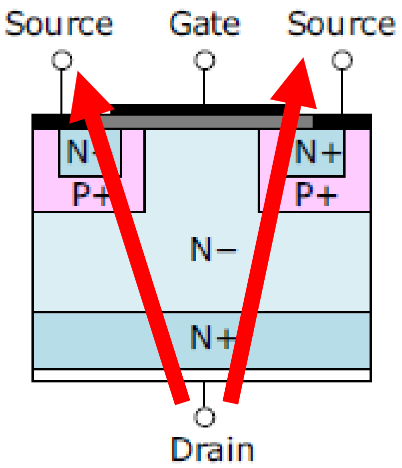
The Ideal Power Switch – Why GaN?

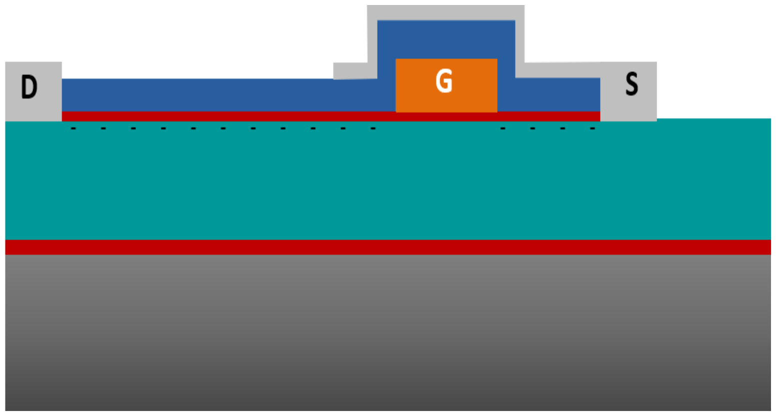
- Lower On Resistance
- Faster
- Smaller
- Lower Cost
- More Reliable

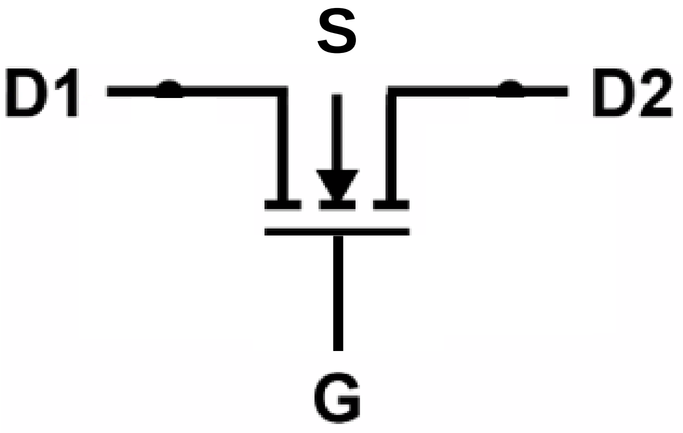
Bi-Directional Blocking GaN FET

Back-to-back 100 V FETs:

- MOSFET: not easy…
  - Vertical current flow
  - Can't combine
- GaN FET: possible!

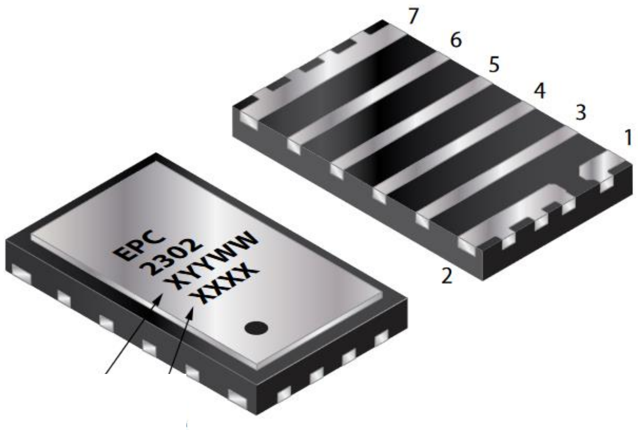






Voltage Spec – upgrade!

- Transient Voltage Spec
  - Some FETs' ratings will be upgraded… Same reliability
  - Example: EPC2302: 100 V, 1.8 mΩ, QFN package



- Previous Spec

PARAMETER		VALUE	UNIT
V_{DS}	Drain-to-Source Voltage (Continuous)	100	V
	Drain-to-Source Voltage (up to 10,000 5 ms pulses at 150 °C)	120	

- New Spec

PARAMETER		VALUE	UNIT
V_{DS}	Drain-to-Source Voltage (Continuous)	100	V
$V_{DS(tr)}$	Drain-to-Source Voltage (Repetitive Transient)(1)	120	

(1) Pulsed repetitively, duty cycle factor (DC_{Factor}) ≤ 1%;
See Figure 13 and Reliability Report Phase 16, Section 3.2.6

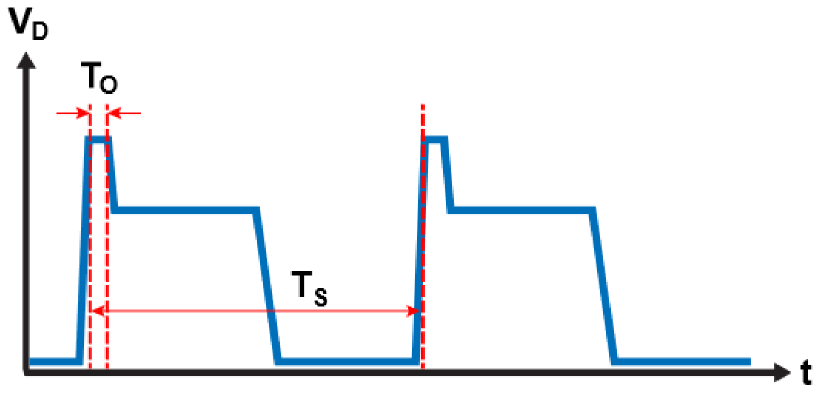
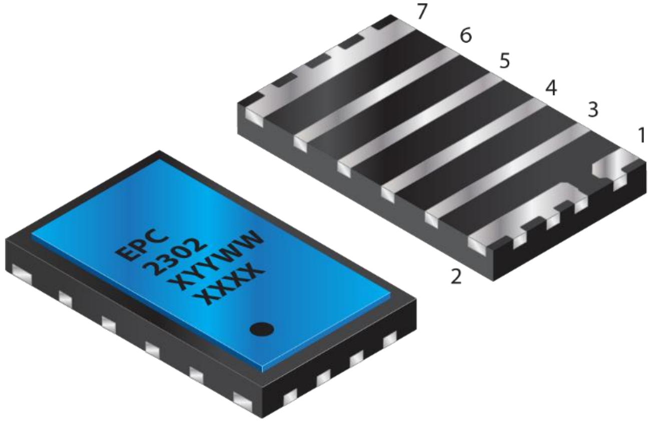
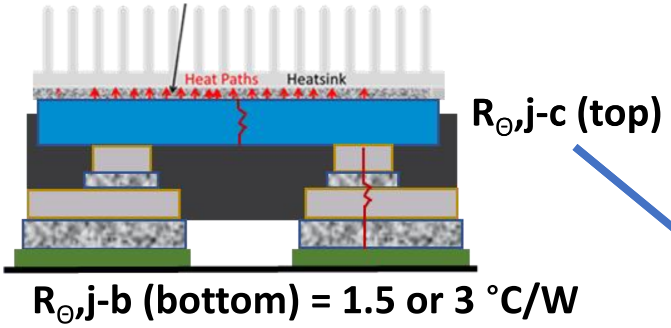


Figure 3-12: Illustration of the 1% overshoot duty cycle overvoltage specification. 1% is the ratio between T_O (overvoltage duration) and TS (one switching period).

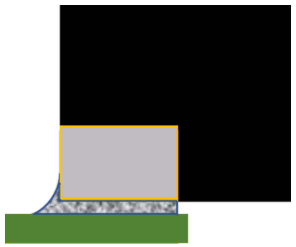
eGaN FETs in 3x5 mm QFN





	EPC2361	EPC2302	EPC2306	EPC2305	EPC2308	*EPC2304*	*EPC2307*
V_{DS}	*100 V*	100 V	100 V	150 V	150 V	*200 V*	*200 V*
$V_{DS,\ transient}$	*120 V*	120 V	120 V	170 V	180 V	*240 V*	*240 V*
$R_{DS(on)}$ max		1.8 mΩ	3.1 mΩ	3 mΩ	6 mΩ		*10 mΩ*
$R_{DS(on)}$ typ	*1.0 mΩ*	1.4 mΩ	2.5 mΩ	2.2 mΩ	4.5 mΩ	*3.1 mΩ*	*8.2 mΩ*
Q_G typ	*28 nC*	23 nC	12.3 nC	22 nC	11.7 nC	*24 nC*	*10.6 nC*
Q_{GD} typ	*2.5 nC*	2.3 nC	1.1 nC	2.1 nC	1 nC	*2.5 nC*	*1.3 nC*
Q_{OSS}typ	*86 nC*	85 nC	44 nC	103 nC	50 nC	*116 nC*	*58 nC*
Q_{RR}typ	*0 nC*	0 nC	0 nC	0 nC	0 nC	*0 nC*	*0 nC*
$R_{\Theta JC}$	*0.2 °C/W*	0.2 °C/W	0.5 °C/W	0.2 °C/W	0.5 °C/W	*0.2 °C/W*	*0.5 °C/W*
I_D	*101 A*	101 A	62 A	102 A	63 A	*102 A*	*48 A*
Production	*Q2 2025*	**Now**	**Now**	**Now**	**Now**	*Q4 2024*	*Q4 2024*

note: preliminary specs in *italics*

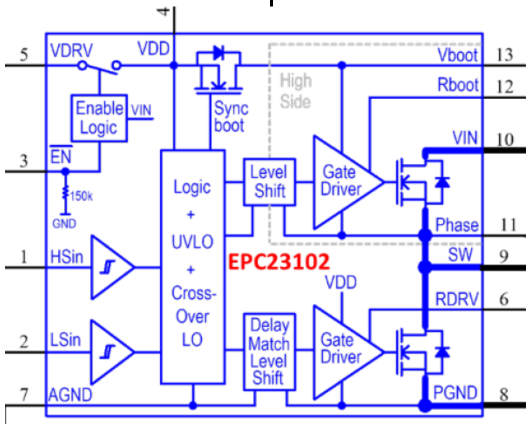


Wettable Flanks

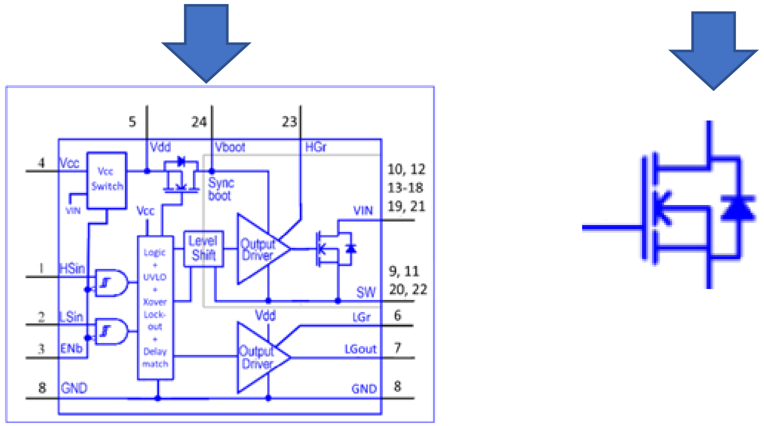
rev. 9/19/2024
BDM

Power Stages in QFN

	EPC23102	EPC23103	EPC23104	EPC23101	EPC2302
V_{DS}	100 V	100 V	100 V	100 V	100 V
$R_{DSON\ (max)}$	6 mΩ	8 mΩ	10 mΩ	3.3 mΩ	1.8 mΩ
I_{DC}	35 A	20 A	15 A	65 A	101 A
Package	QFN 3.5mm x 5mm			QFN 3.5mm x 5mm	QFN 3mm x 5mm
Samples	Now	Now	Now	Now	Now



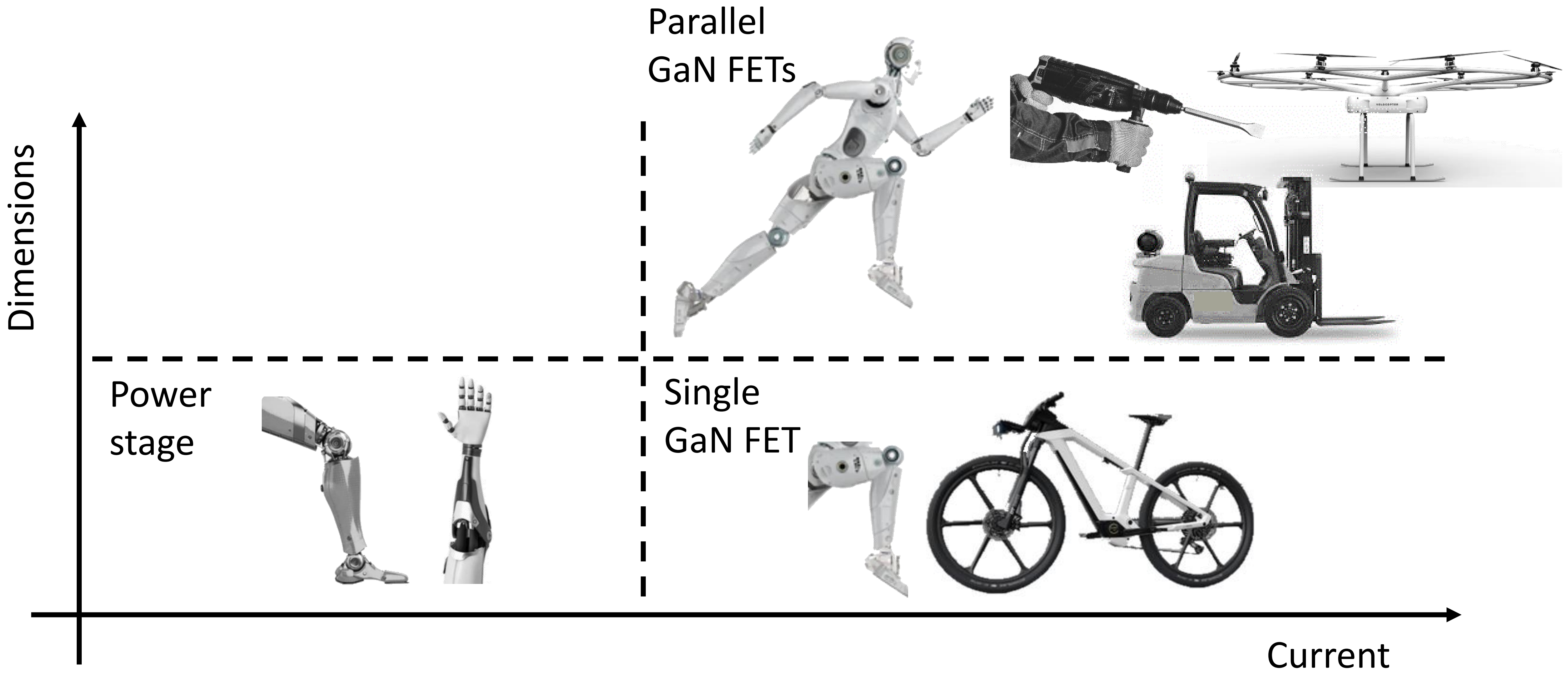
1 chip Power Stage



2 chip Power Stage

Motor Drive

Motor Applications Landscape



GaN in motor drives: common myth

"There is no benefit to using GaN devices in BLDC Motor drives"

- GaN advantages in motor drives:
  - Smoother switching
  - Effect of the increase of PWM frequency
  - Effect of very small dead time
  - Application experimental results

GaN Benefits in BLDC Motor Drives

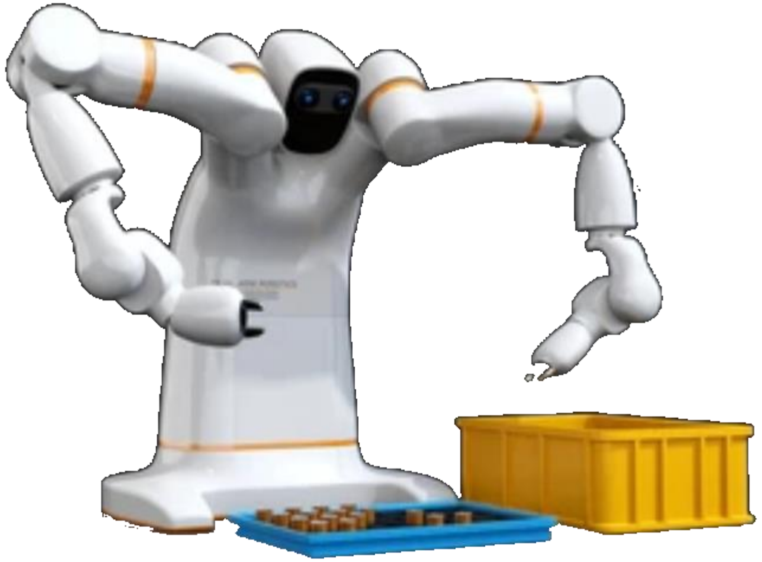
GaN FET/ICs switch fast with $Q_{RR} = 0$

Higher switching frequency

Electrolytic capacitor elimination Reduced motor losses

Lower dead time

Higher torque per Ampere



Improves **inverter & motor** system **efficiency**

Reduces size & weight by integrating the inverter inside the motor

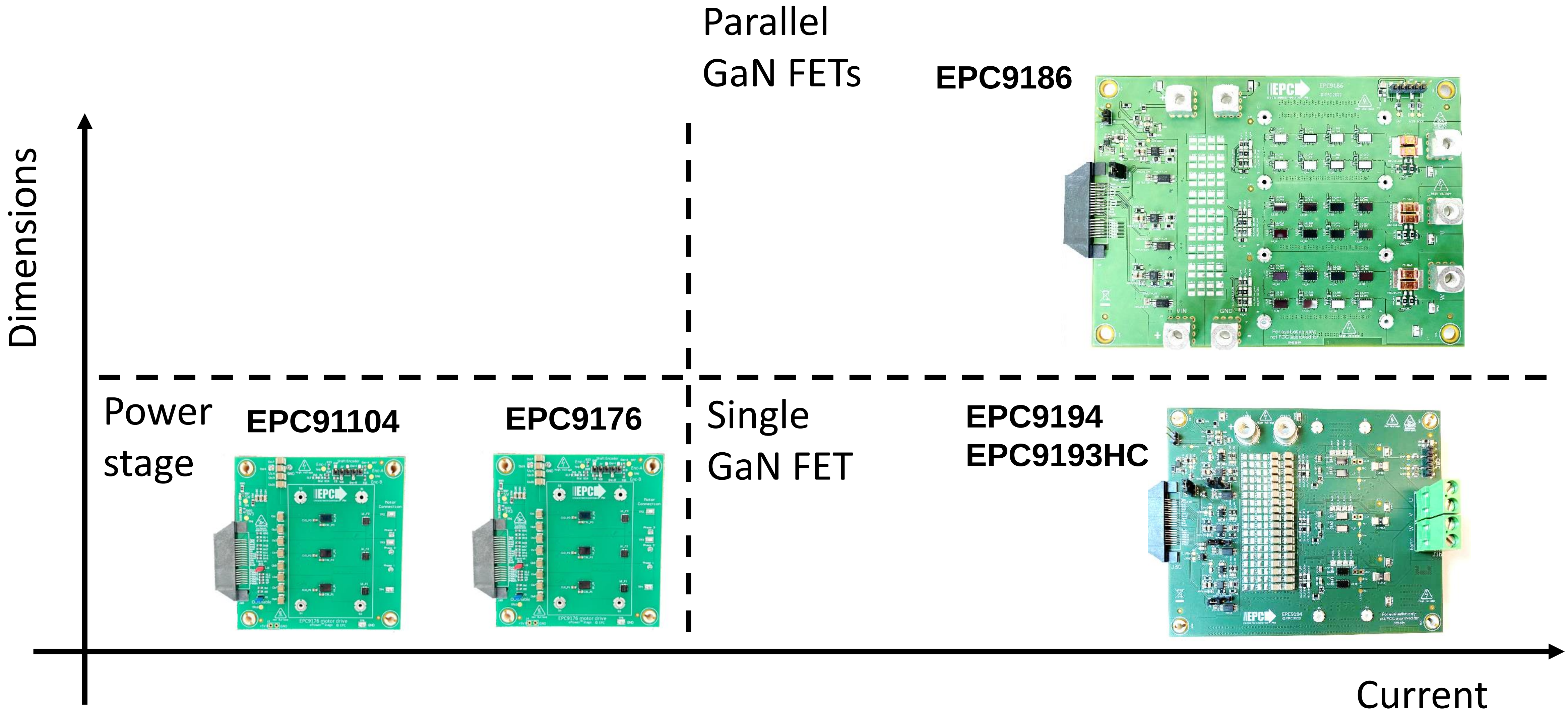
Evaluation boards

Part Number	Description	V_{IN} (V)	I_{Phase} (A_{RMS})	f_{SW} (kHz)	gate driver	current sense	controller board	GaN Product
EPC9167	20 A_{RMS} 3-Phase BLDC Motor Drive	14 - 60	20	20 - 250			ST STM32 Nucleo	EPC2065
EPC9176	20 A_{RMS} 3-Phase BLDC Motor Drive	14 - 65	20	20 - 250	(integrated)		Microchip dsPIC	EPC23102
EPC9167 HC	30 A_{RMS} 3-Phase BLDC Motor Drive, 2x Parallel FETs	14 - 60	30	20 - 250			ST STM32 Nucleo	EPC2065
EPC9173	35 A_{RMS} 3-Phase BLDC Motor Drive	20 - 85	35	20 - 250	(integrated)		Microchip dsPIC	EPC23101
EPC9194	40 A_{RMS} 3-Phase BLDC Motor Drive	14 - 65	40	20 - 250			ST STM32 Nucleo	EPC2302
EPC9186	150 A_{RMS} 3-Phase BLDC Motor Drive, 4x Parallel FETs	14 - 60	150	20 - 120			(none included)	EPC2302

e-bike light load

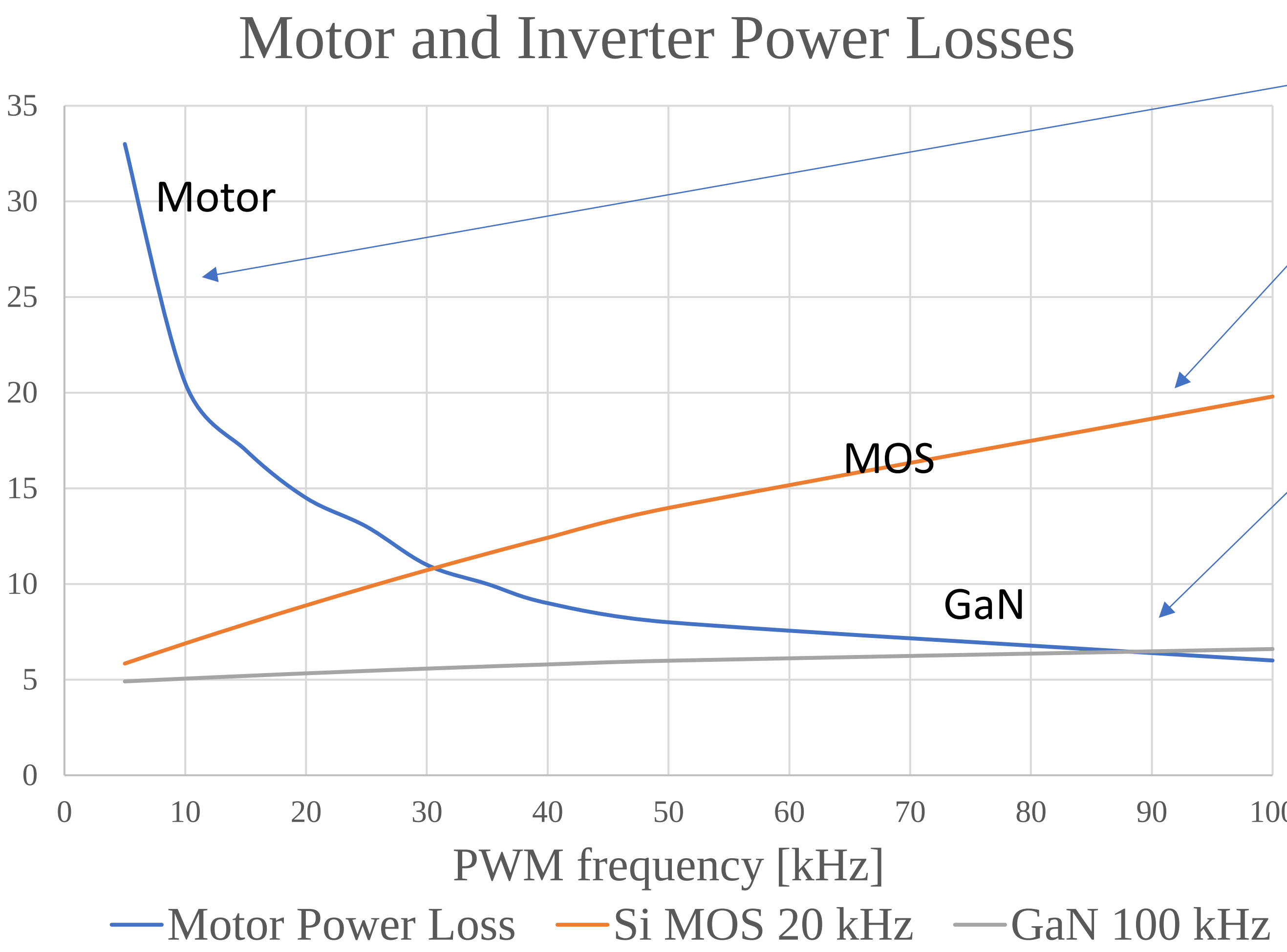
Setup	MOSFET Inverter 20 kHz, 500 ns dead time 400 RPM, 5 A_{RMS}	GaN Inverter 100 kHz,21 ns dead time 400 RPM, 5 A_{RMS}
Input Inductance	2.7 µH	None
Input capacitor	660 µF electrolytic	44 µF ceramic
P_{IN}	121.3 W	113.3 W
P_{OUT}	119.6 W	111.3 W
$\eta_{inverter}$	98.5 %	98.2%
Speed	42.25 rad/s	41.94 rad/s
Torque	1.876 N·m	1.940 N·m
Pmech	79.3 W	**81.36 W**
η_{motor}	66.3 %	73.1 %
η total efficiency	65.3 %	71.8 %

EPC Reference Designs



1- PWM frequency increase

Frequency Effect on Motor + inverter



Estimated motor power losses decrease with frequency

Si MOS inverter power losses increase with frequency 5 times faster than GaN inverter

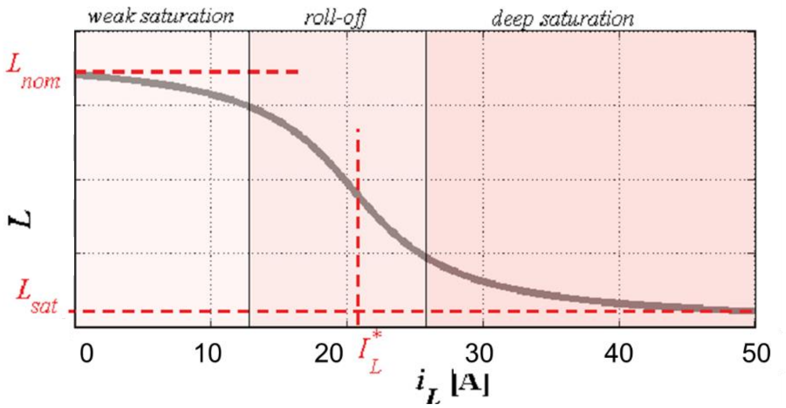
Total system power losses are minimized with GaN inverter

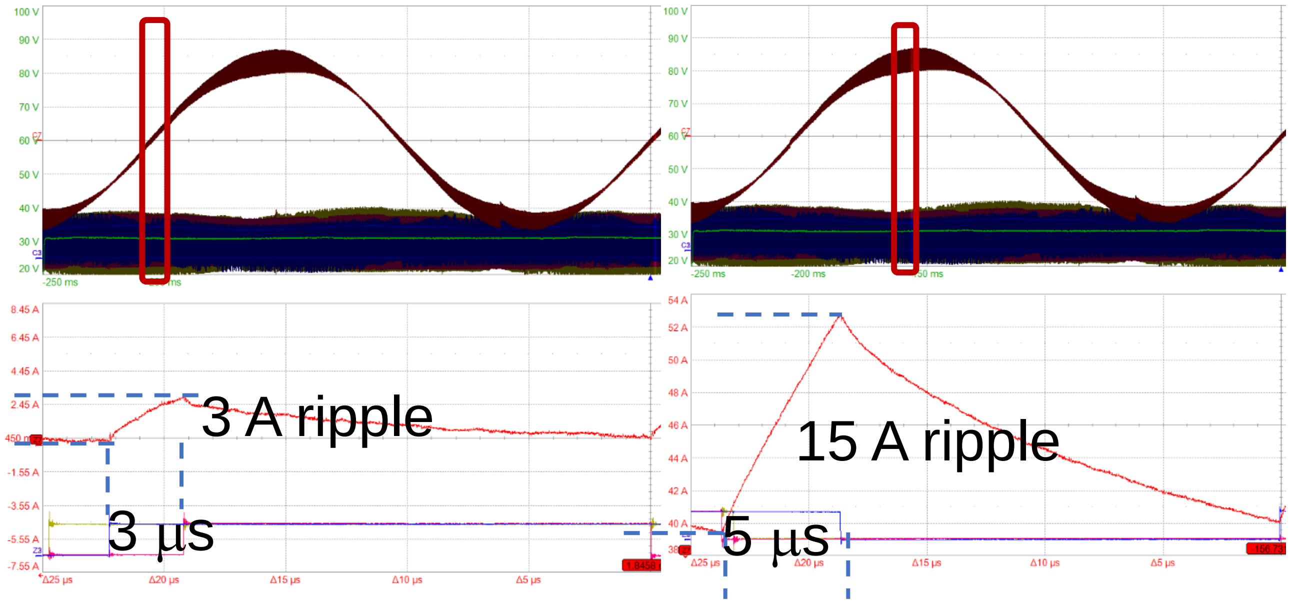
Example of a permanent Magnet motor for power tool

Poles	R [mΩ]	L [µH]	Ke [mV/s]
10	75	90	14

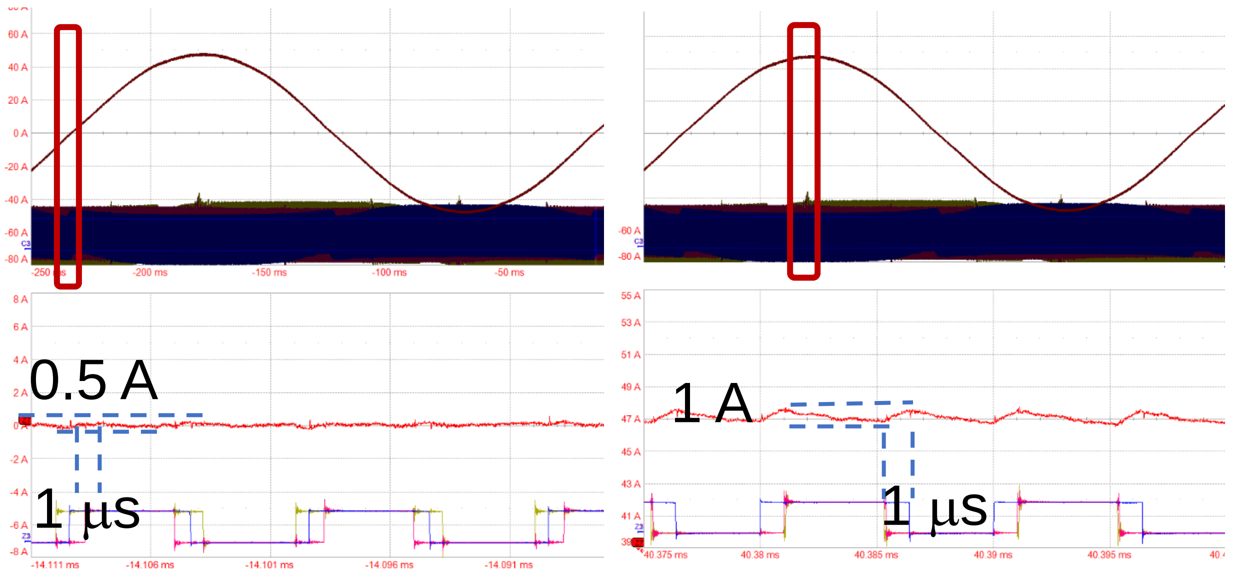
Frequency effect – operation near saturation

In all cases: sinusoidal current - 46 A peak





500 ns deadtime, f_{SW} = 20 kHz



50 ns deadtime, f_{SW} = 100 kHz

Frequency effect – Input filter reduction

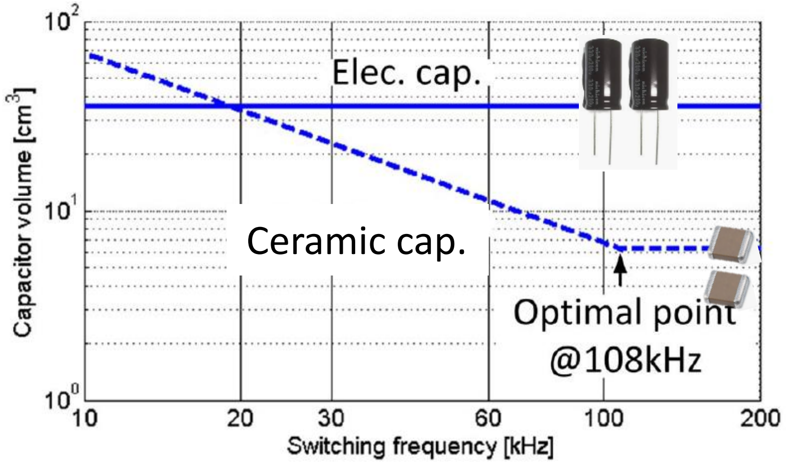
- In a motor inverter the RMS current flowing in the input capacitor does not depends on PWM frequency
- Input voltage ripple is inversely proportional to PWM and capacitance
- **Ceramic capacitors can substitute electrolytic capacitors**

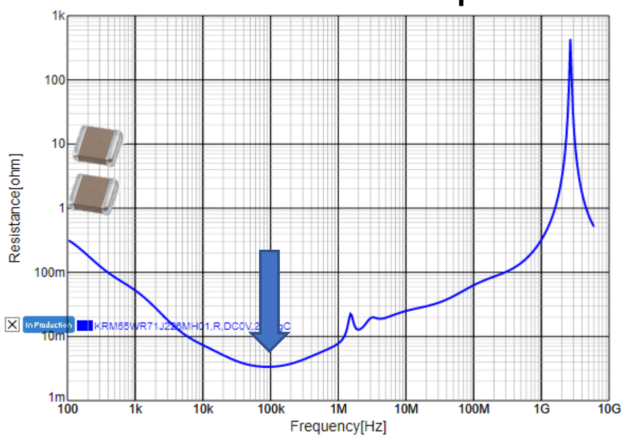
$I_{Cap\_RMS} \approx 0.65 \times I_{line\_RMS}$

$$\Delta v_{pp} \propto \frac{1}{4 f_{sw}} \frac{I_0}{C_f}$$

- Electrolytic capacitors are sized with **RMS current** -> they are over-sized and their value does not change with PWM frequency

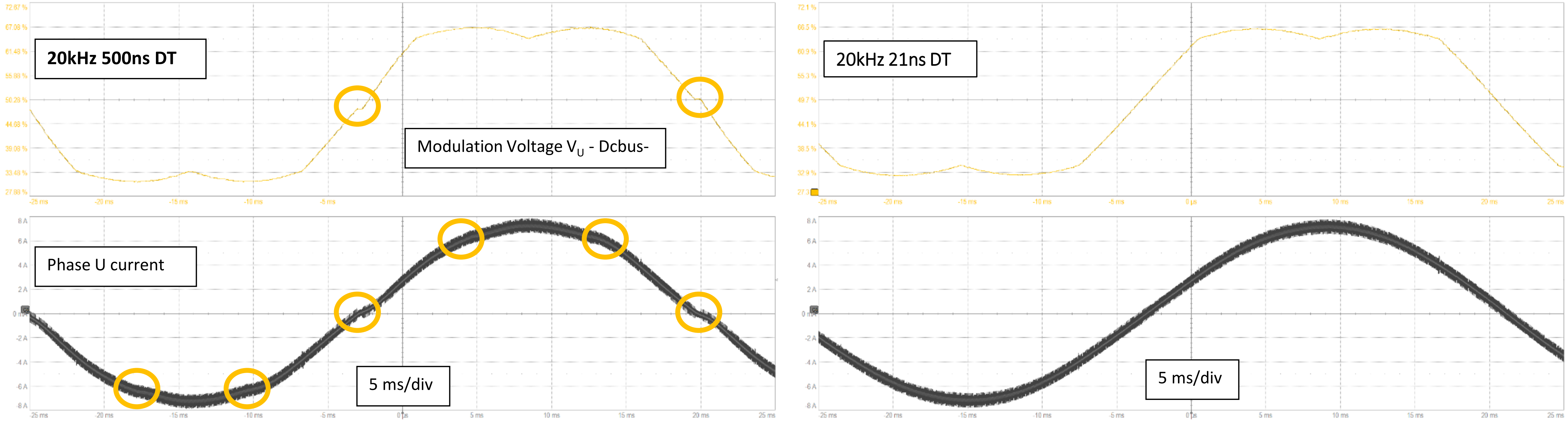
- Ceramic capacitors are sized with **voltage ripple** -> they are sized as per minimum required capacitance and their value and size decreases with increasing PWM frequency
- The optimum ESR of ceramic caps is at 100kHz





2- dead time reduction

Dead time effect – torque and current ripple

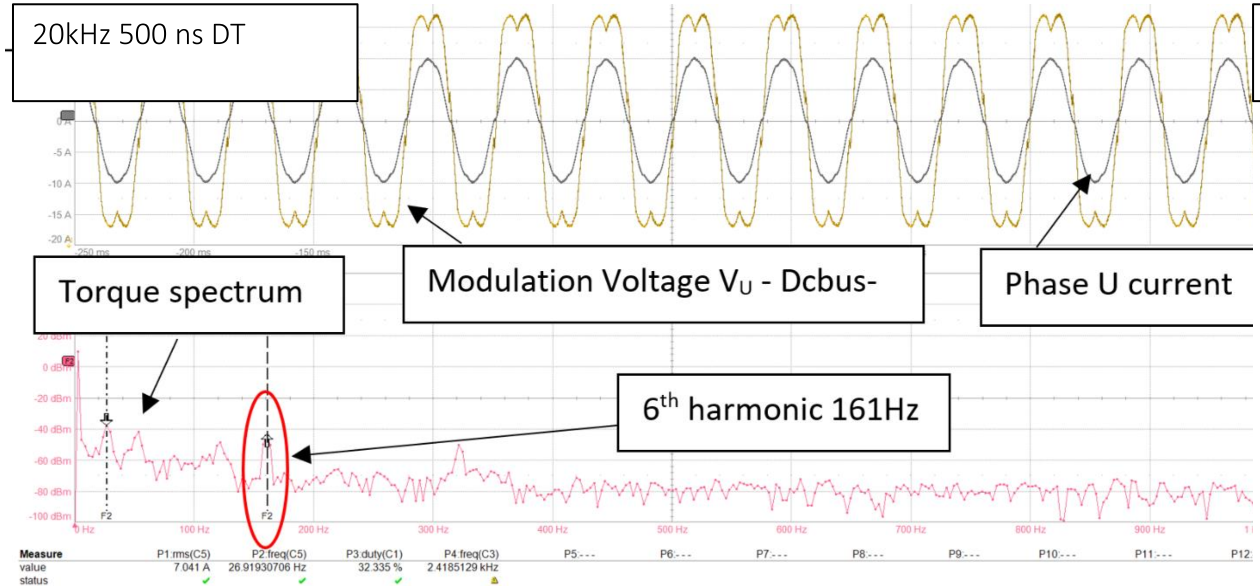


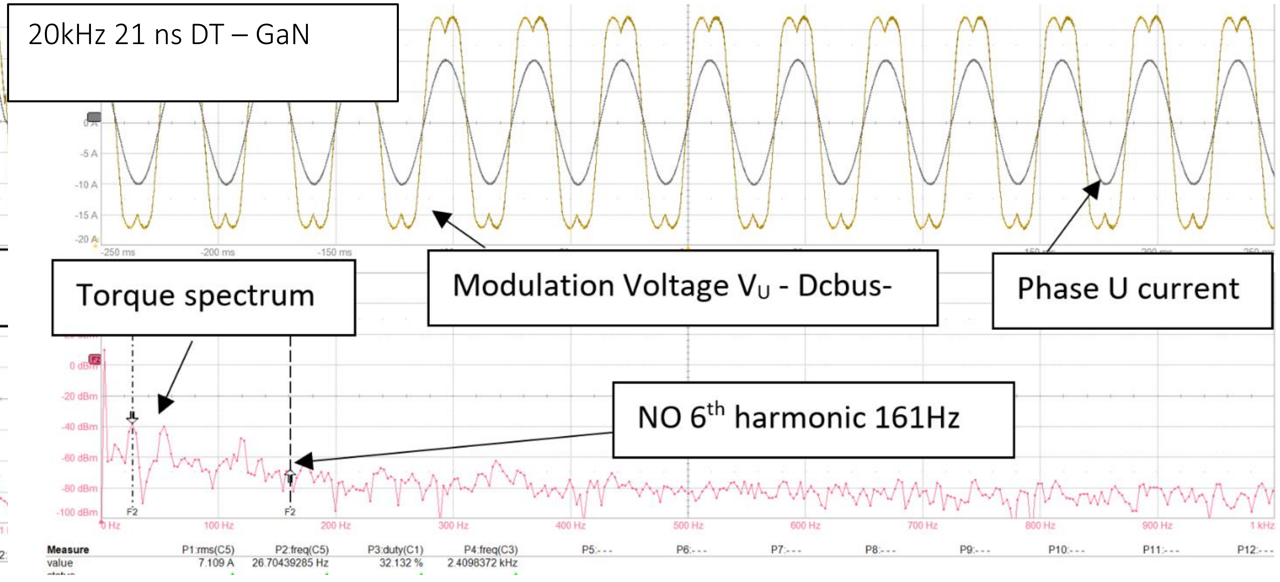
500ns dead time **21ns dead time**

Vin 36 V_{DC} , 5 A_{RMS} Motor phase current

Dead time effect – Mechanical loss

Reduction in 6th harmonic = lower mechanical loss



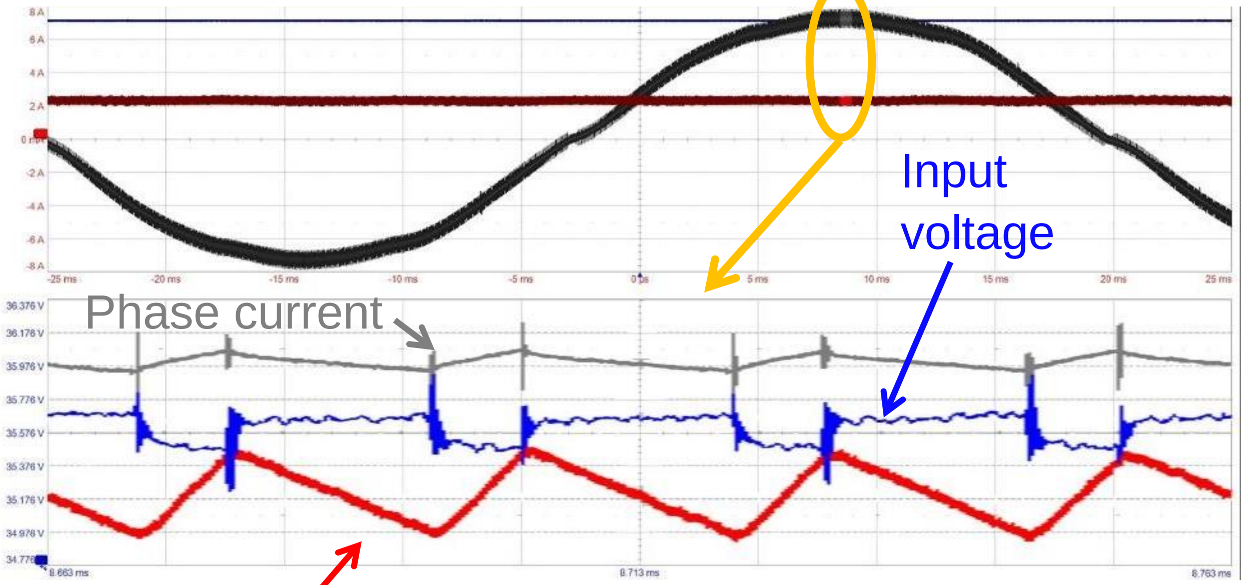


- The 6th harmonic of the torque signal is removed when dead time is reduced to 21ns -> phase current is converted in higher torque
- Torque signal is obtained with a torque/speed transducer

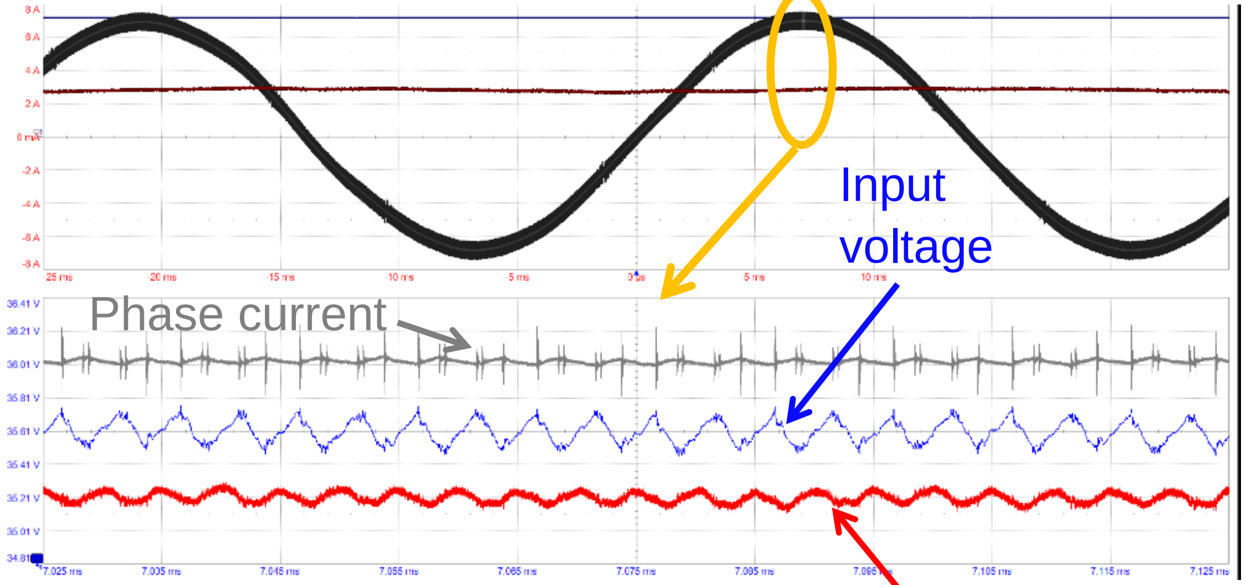
Vin 36 V_{DC} , 5 A_{RMS} Motor phase current 400RPM

Input Voltage and Current Ripple Comparison

500 ns deadtime, f_{SW} = 20 kHz

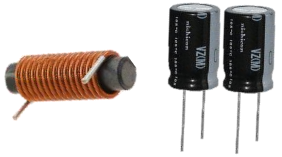


21 ns deadtime, f_{SW} = 100 kHz



V_{DC} = 36 V , I_{phase} = 5 A_{RMS}

Input filter
2.7 µH + 660 µF

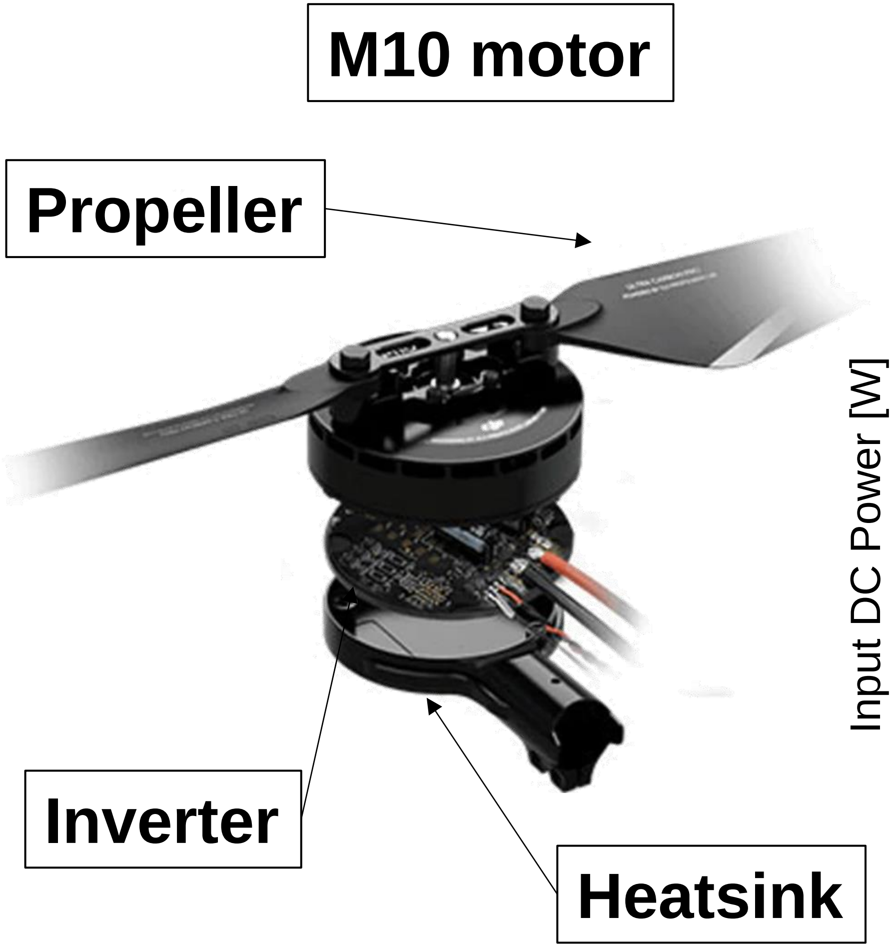


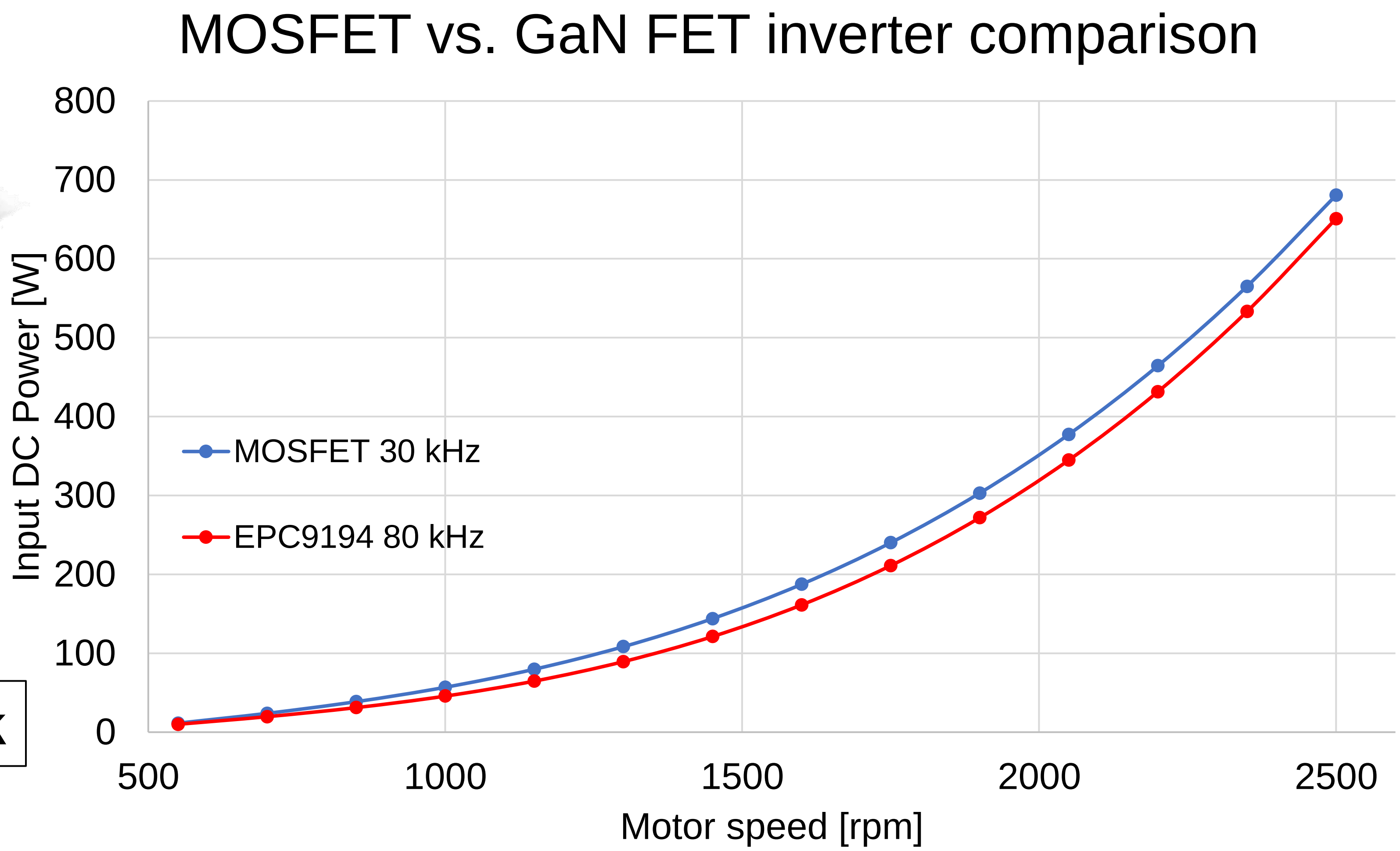
Input filter
44µF

3- application examples

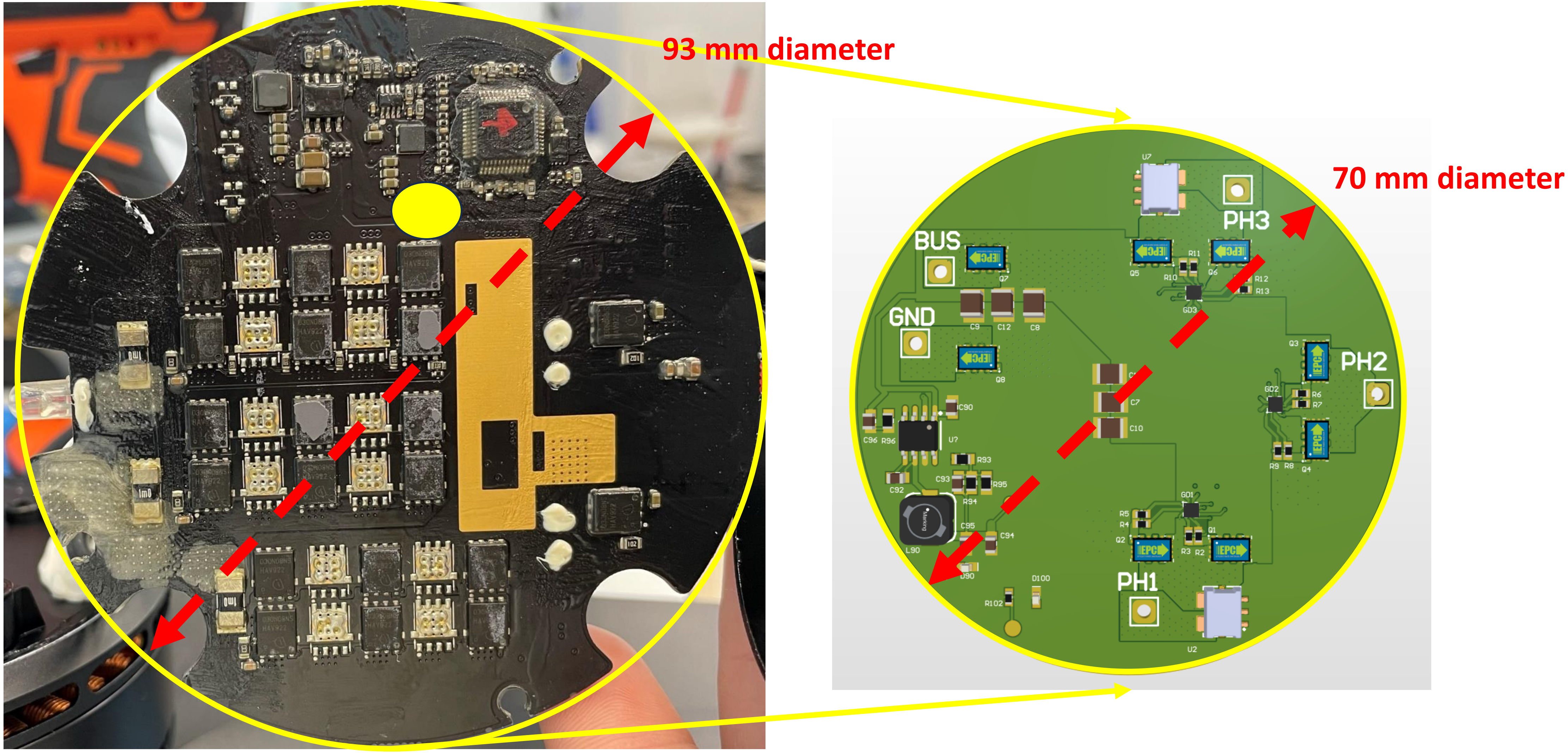
Drones - sinusoidal commutation

Motor 3

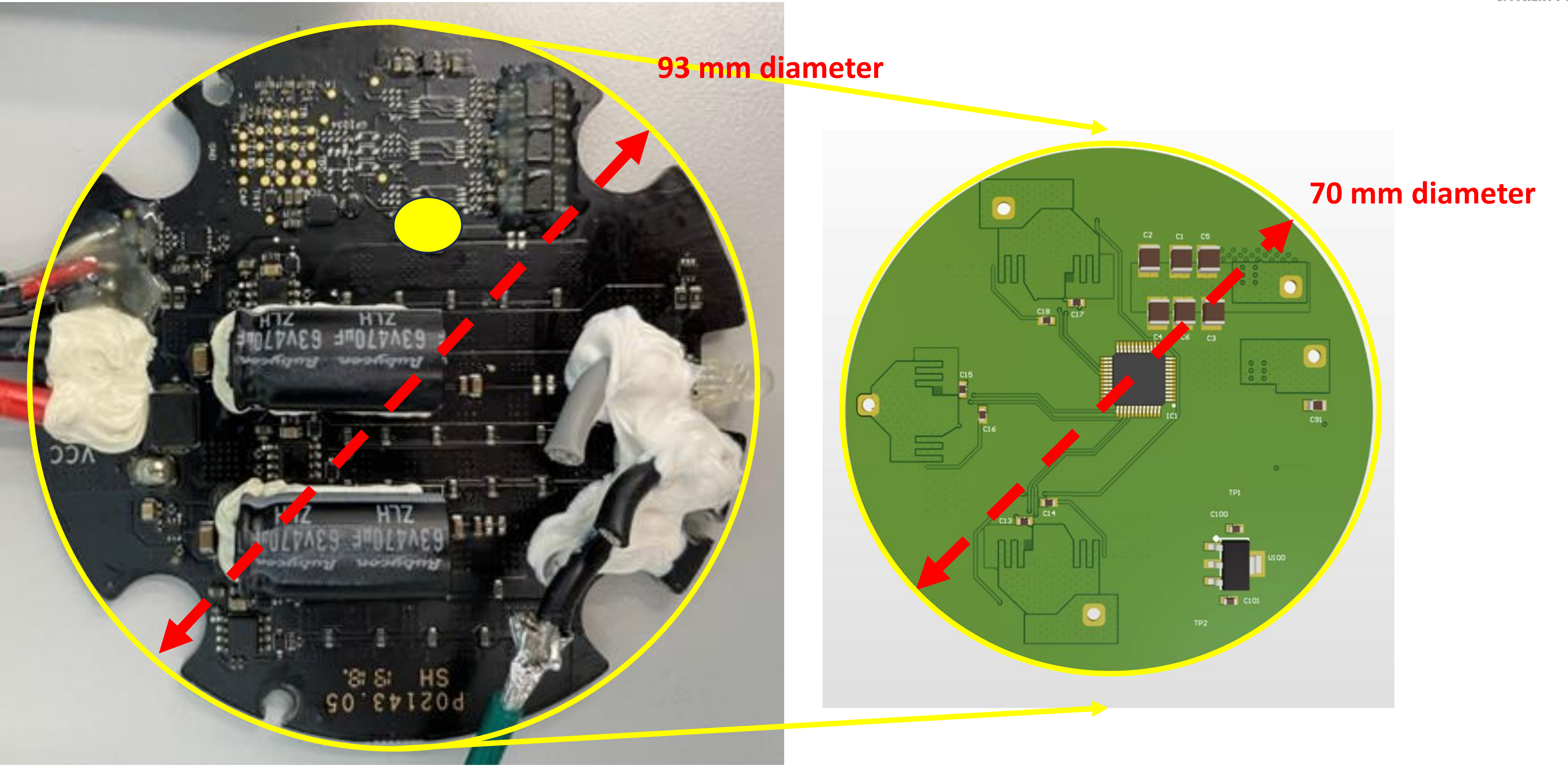




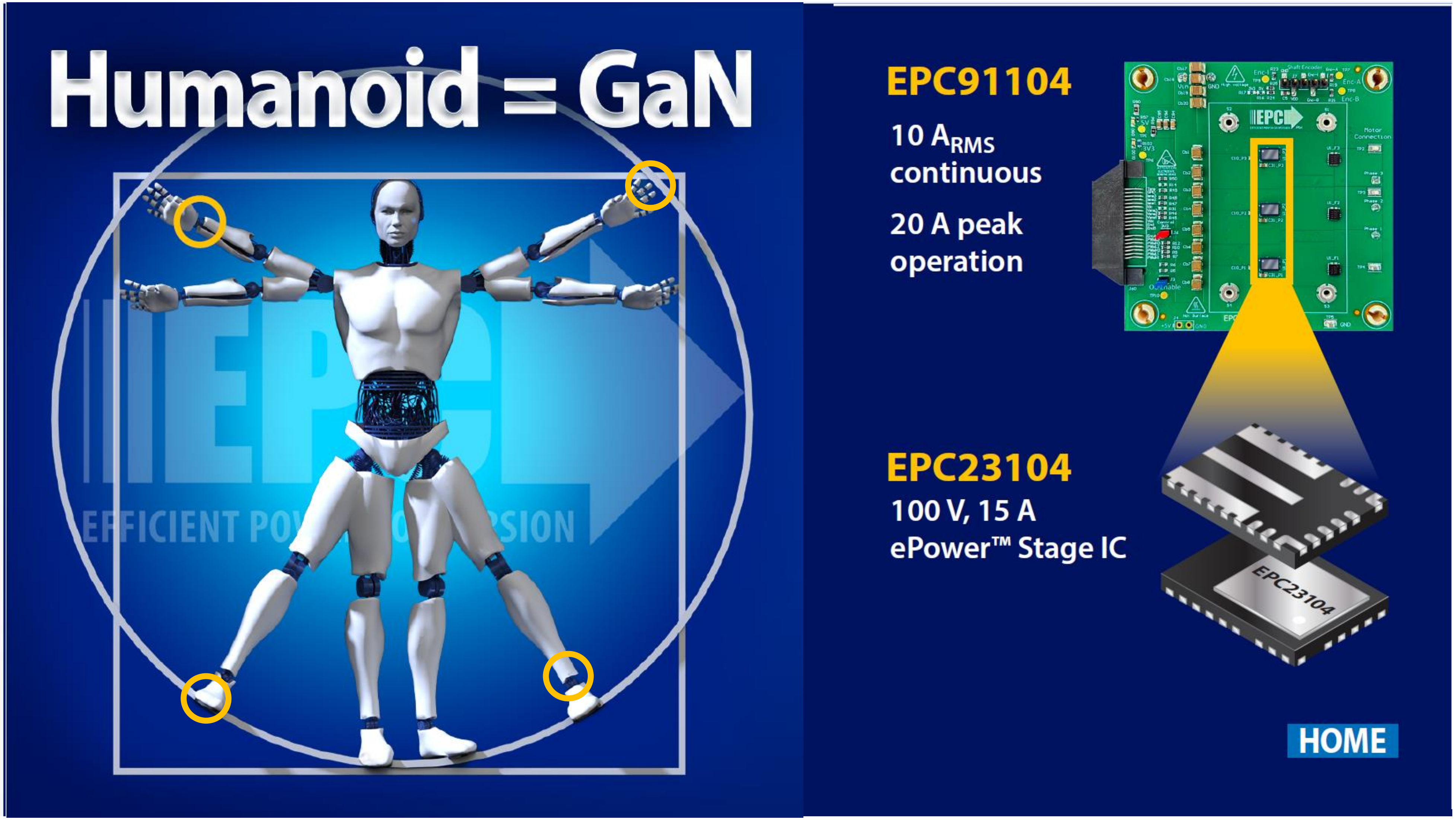
Motor 3 size reduction - top



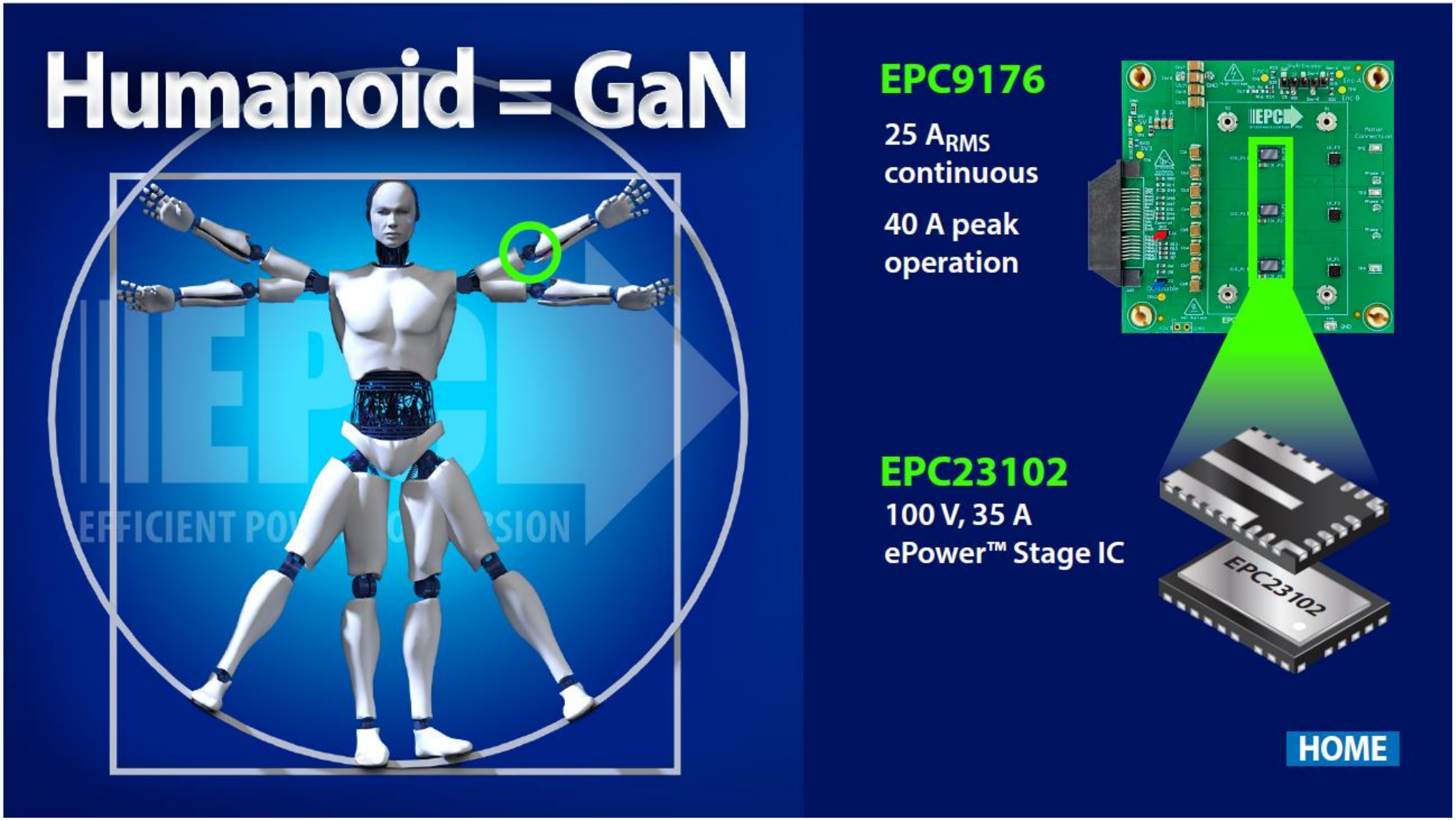
Motor 3 size reduction - bottom



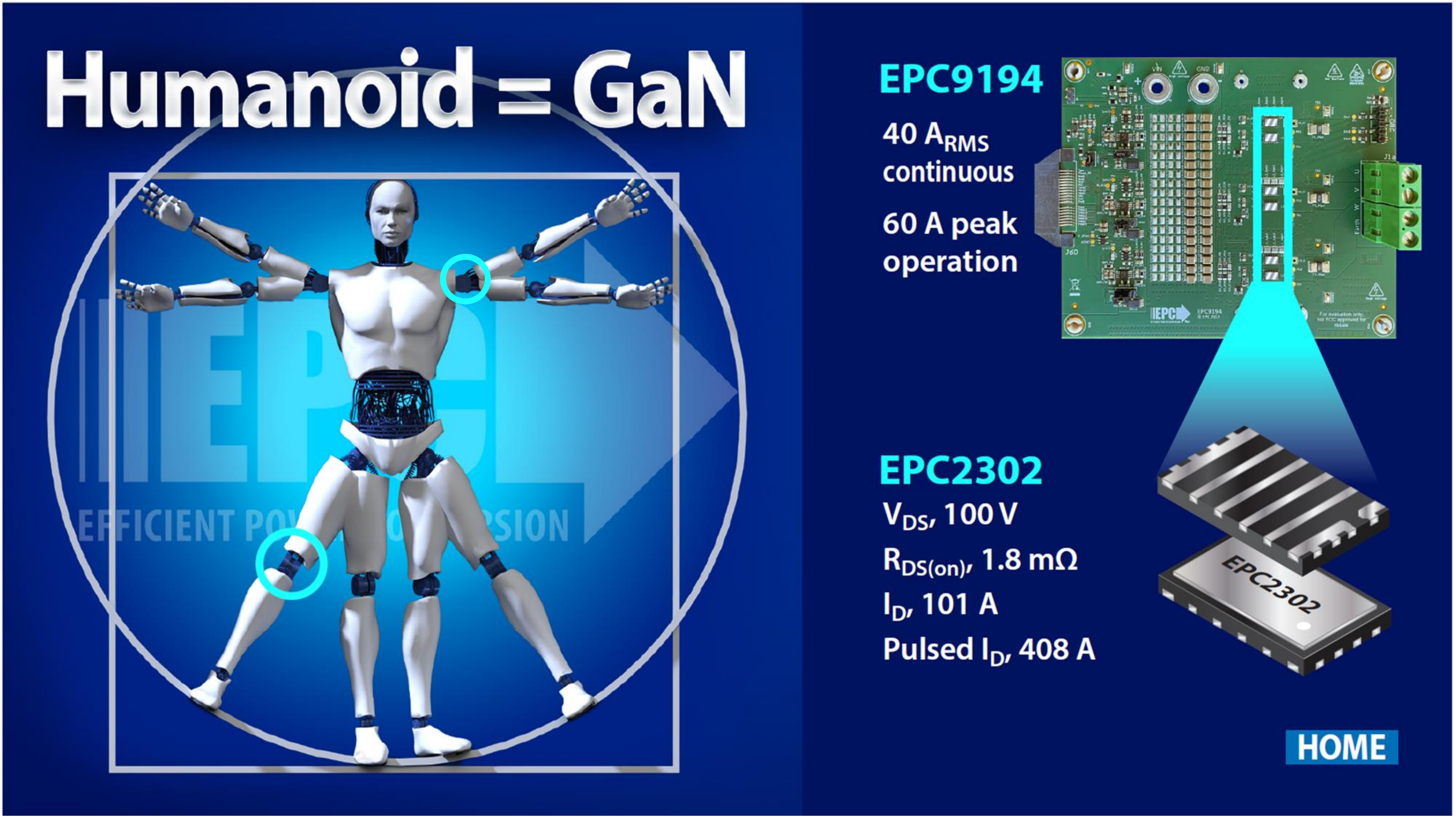
Humanoid Robots



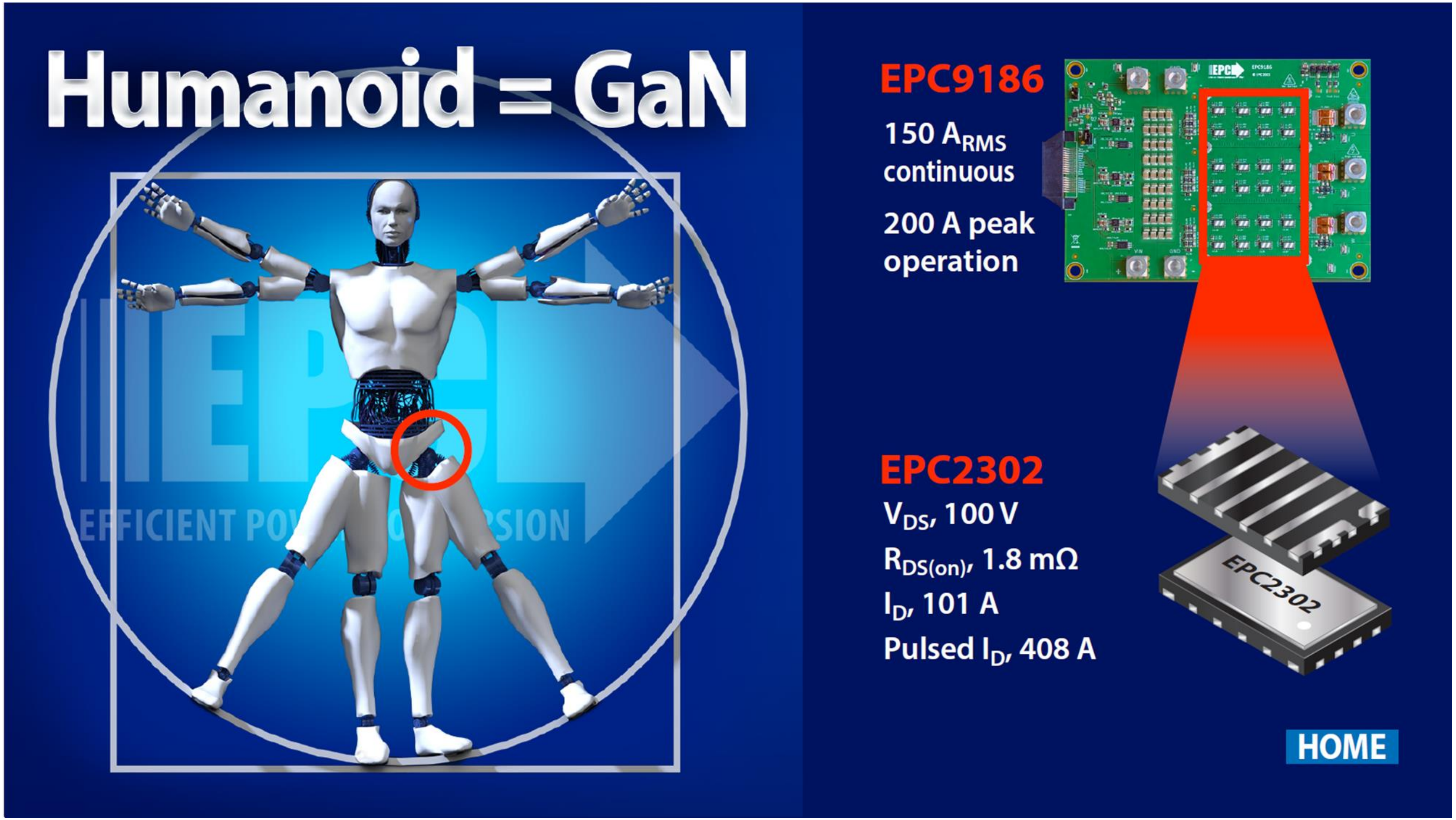
Humanoid Robots



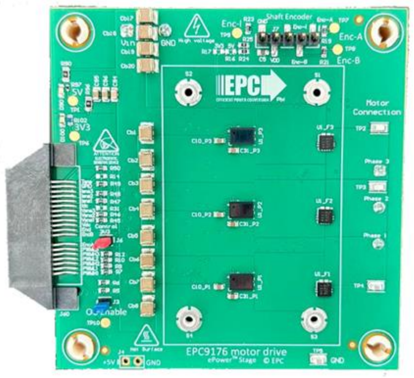
Humanoid Robots



Humanoid Robots

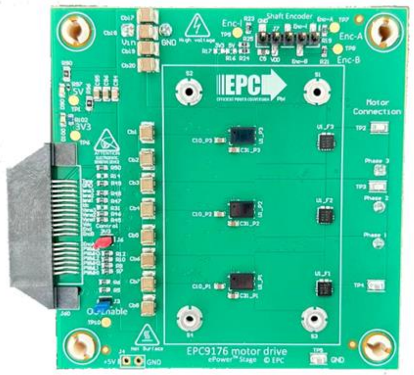


EPC Reference Motor Drive Boards

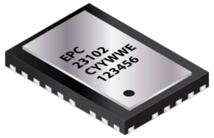


EPC91104 ->
EPC23104 GaN IC

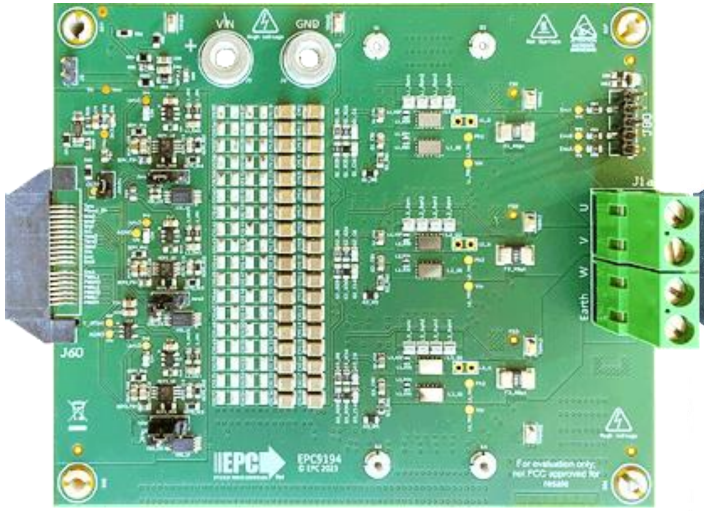
10 A_{RMS}
20 A peak



EPC9176 ->
EPC23102 GaN IC

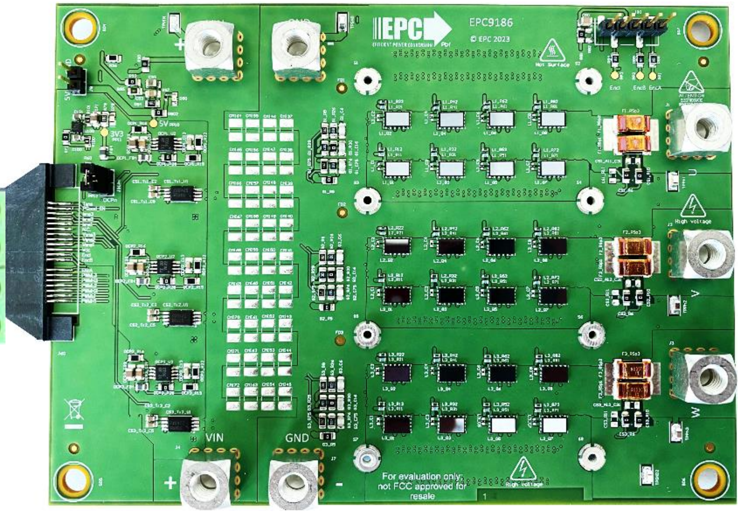


25 A_{RMS}
40 A peak



EPC9194 -> EPC2302

40 A_{RMS}
60 A peak



EPC9186 -> 4x EPC2302

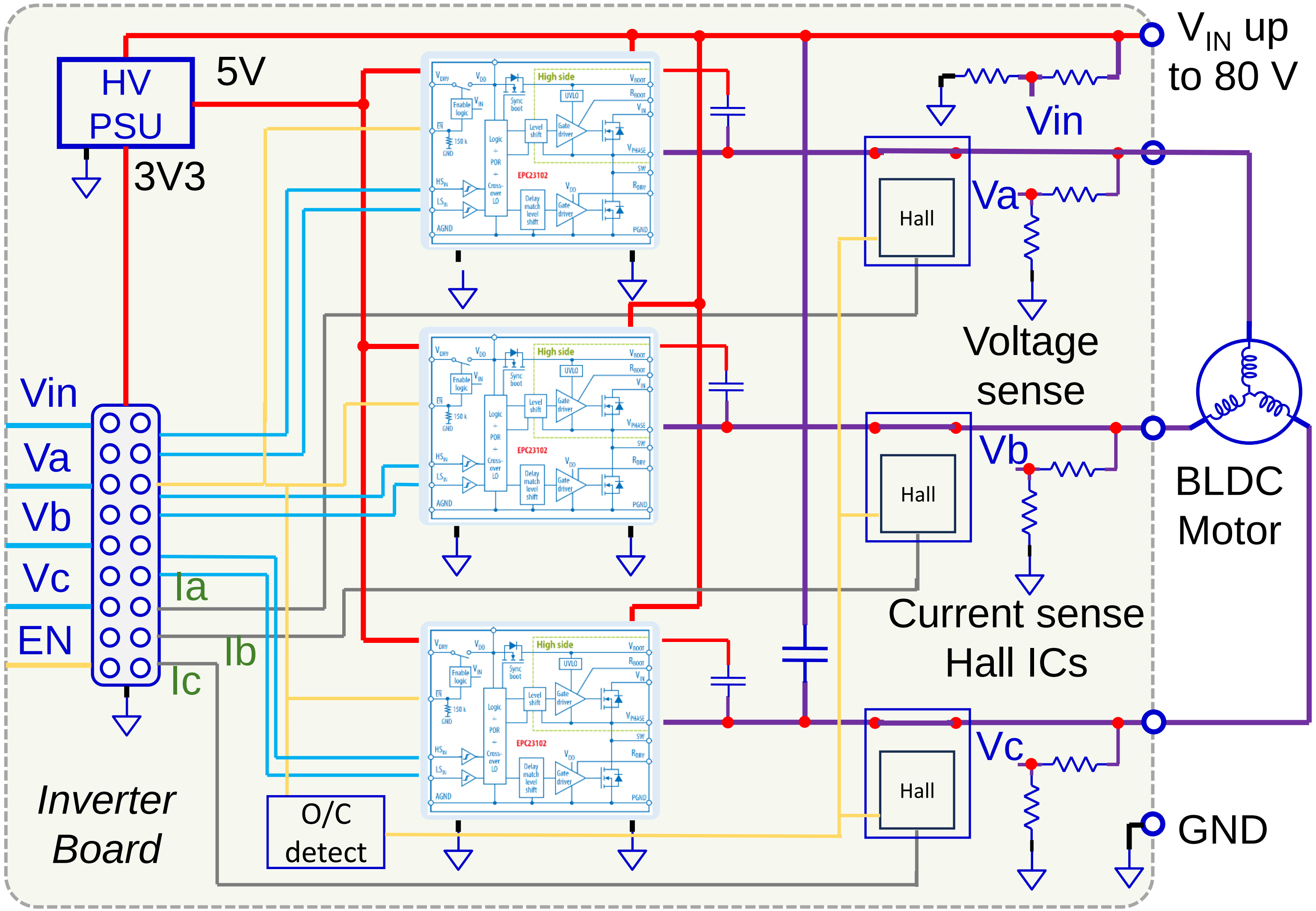
150 A_{RMS}
200 A peak

Phase current (Peak for 100 ms)

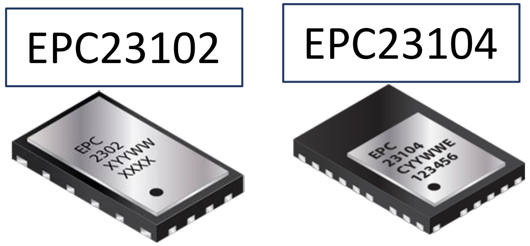
Reference design block diagram

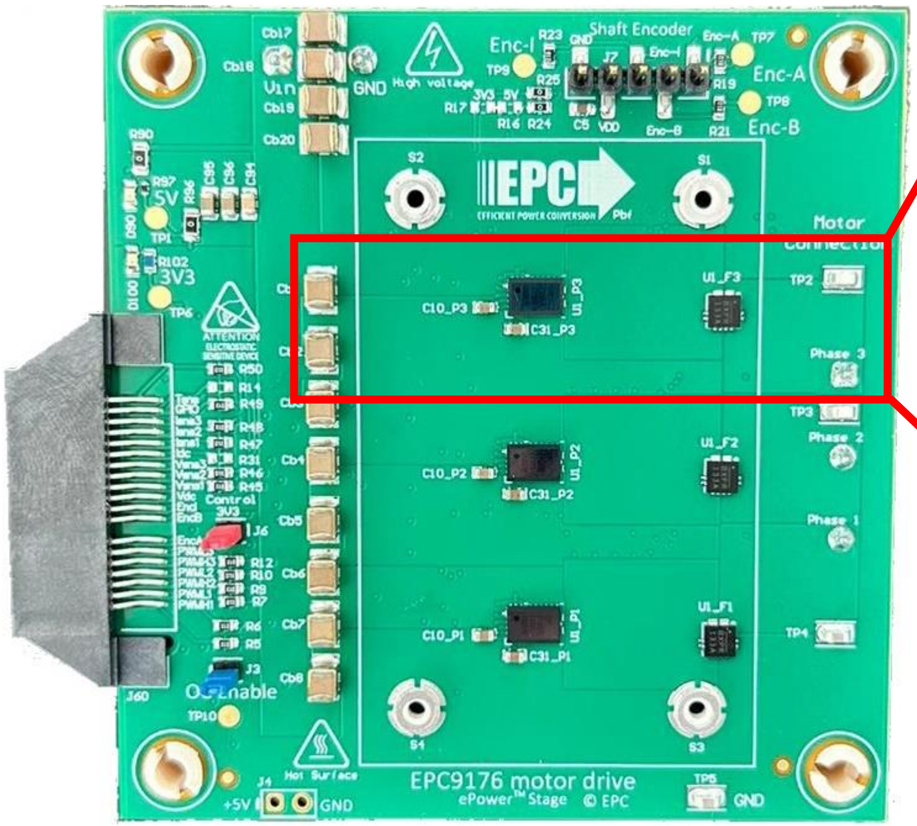
- All reference design have a block diagram as the one in the picture (EPC9176)
- Offline power supply to feed gate drivers and microcontroller
- Three phase inverter
- Phase current sensing
- Phase voltage sensing
- DcBus voltage sensing
- PCB Temperature sensing
- Over current detect
- Common interface to the controller boards

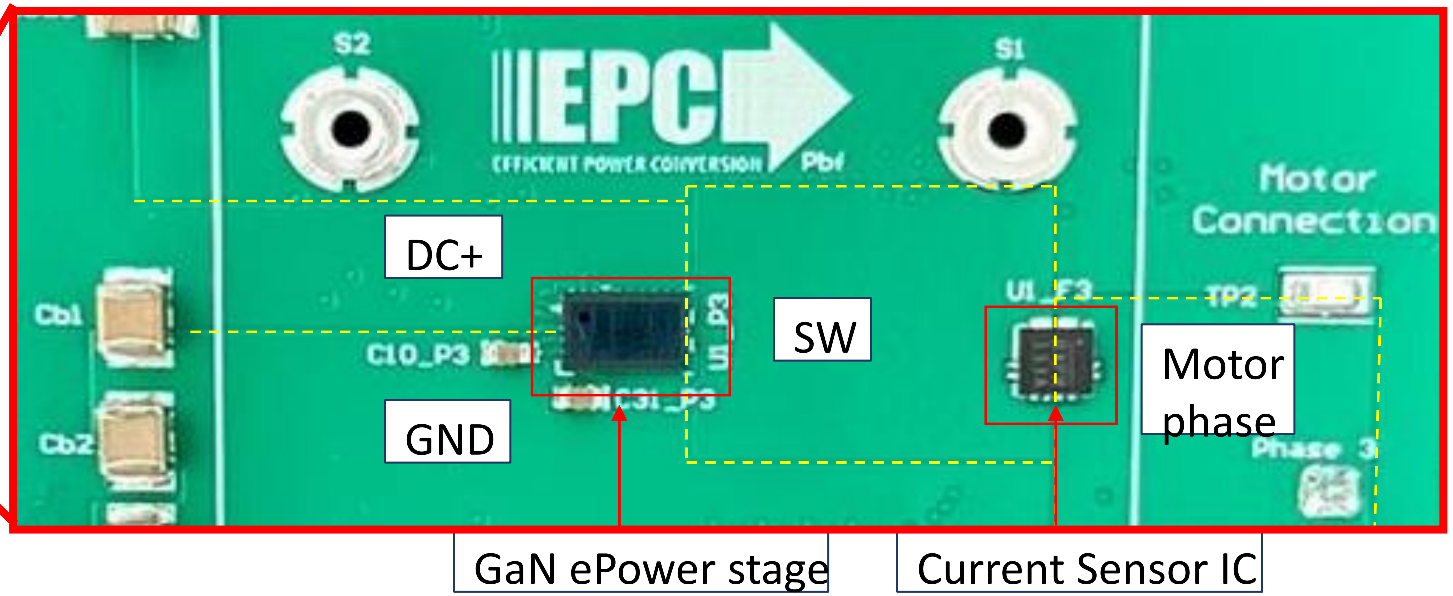
To/From Controller Interface board



EPC9176 – EPC91104

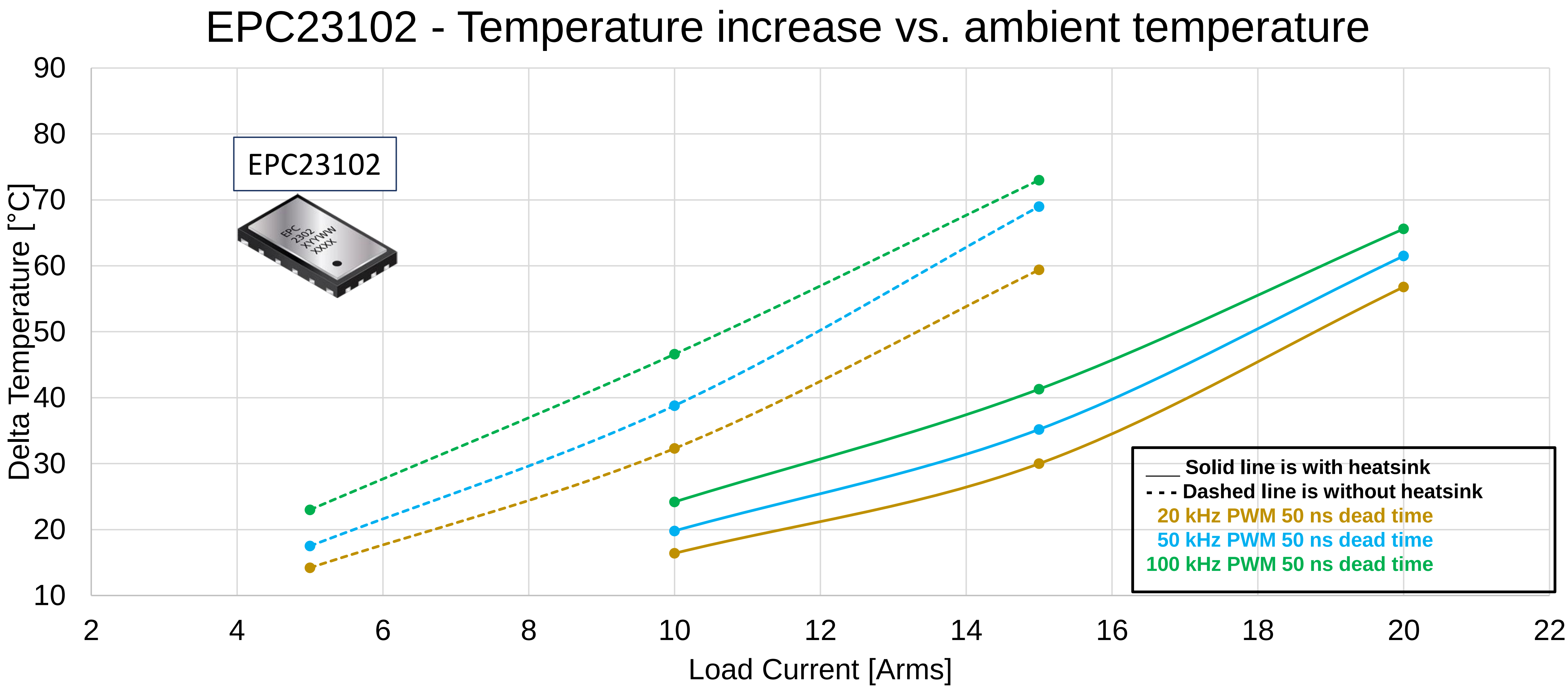






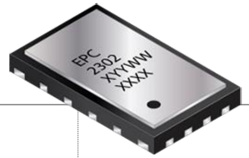
- Compact layout, optimized for current and thermal
- Thick copper to reduce resistance and increase heat transfer. 2 oz on the top and 4 oz in the inner layers

EPC9176 – Steady state operation

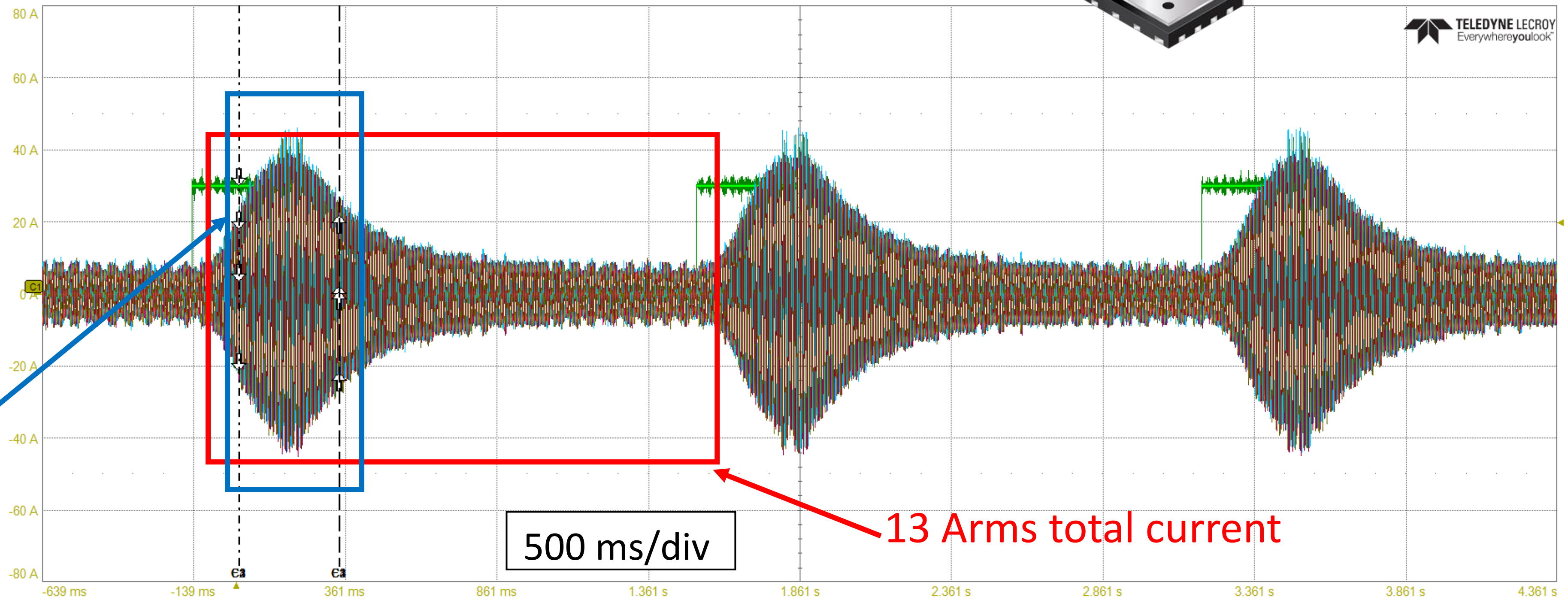


EPC9176 - 38 A peak operation

EPC23102



C1: Phase 1 Current
C2: Phase 2 Current
F3: Phase 3 Current
C4: Brake signal



38 A peak operation 20% duty cycle

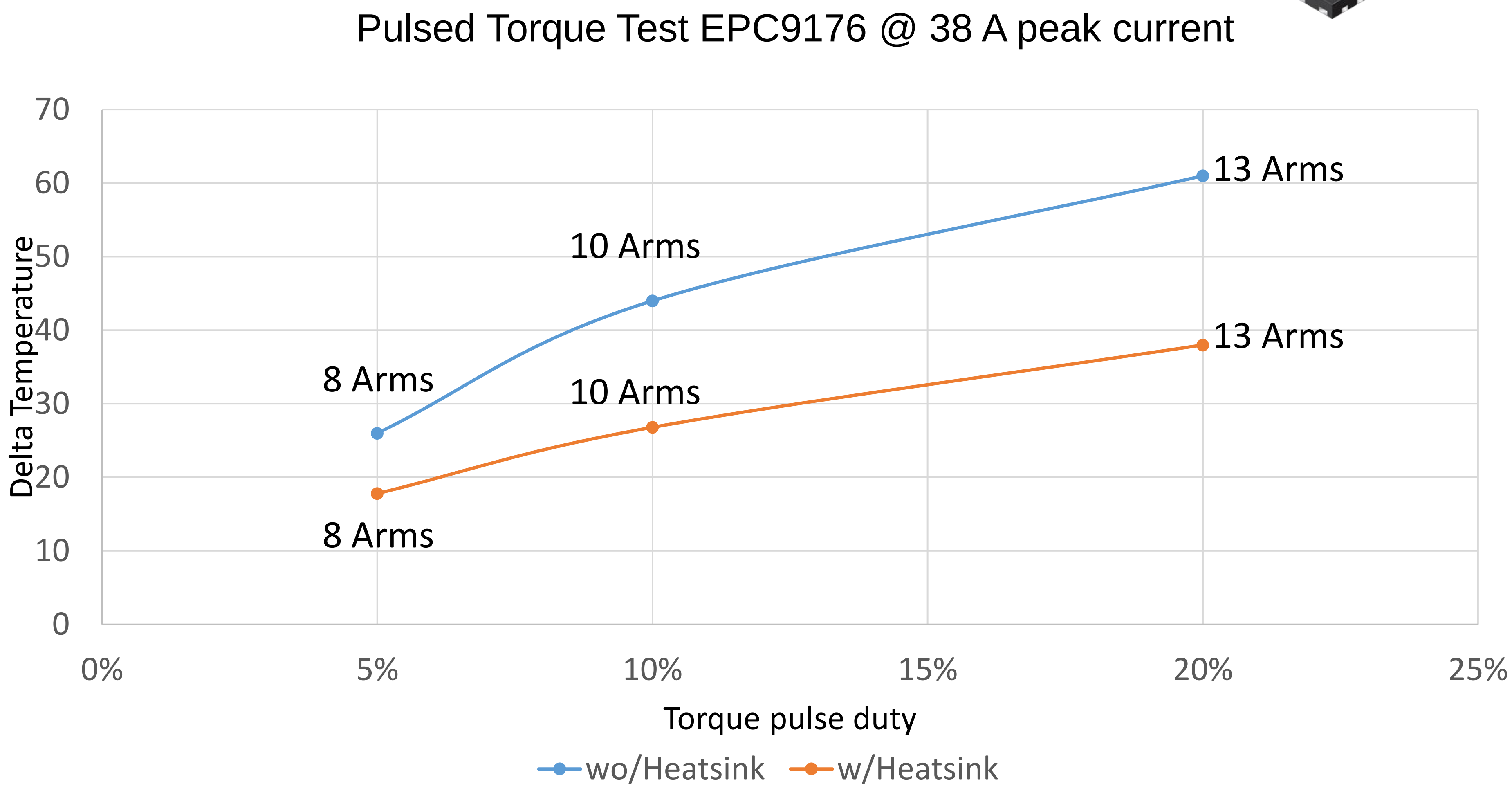
60° C increase without heat sink

38° C increase with heat sink

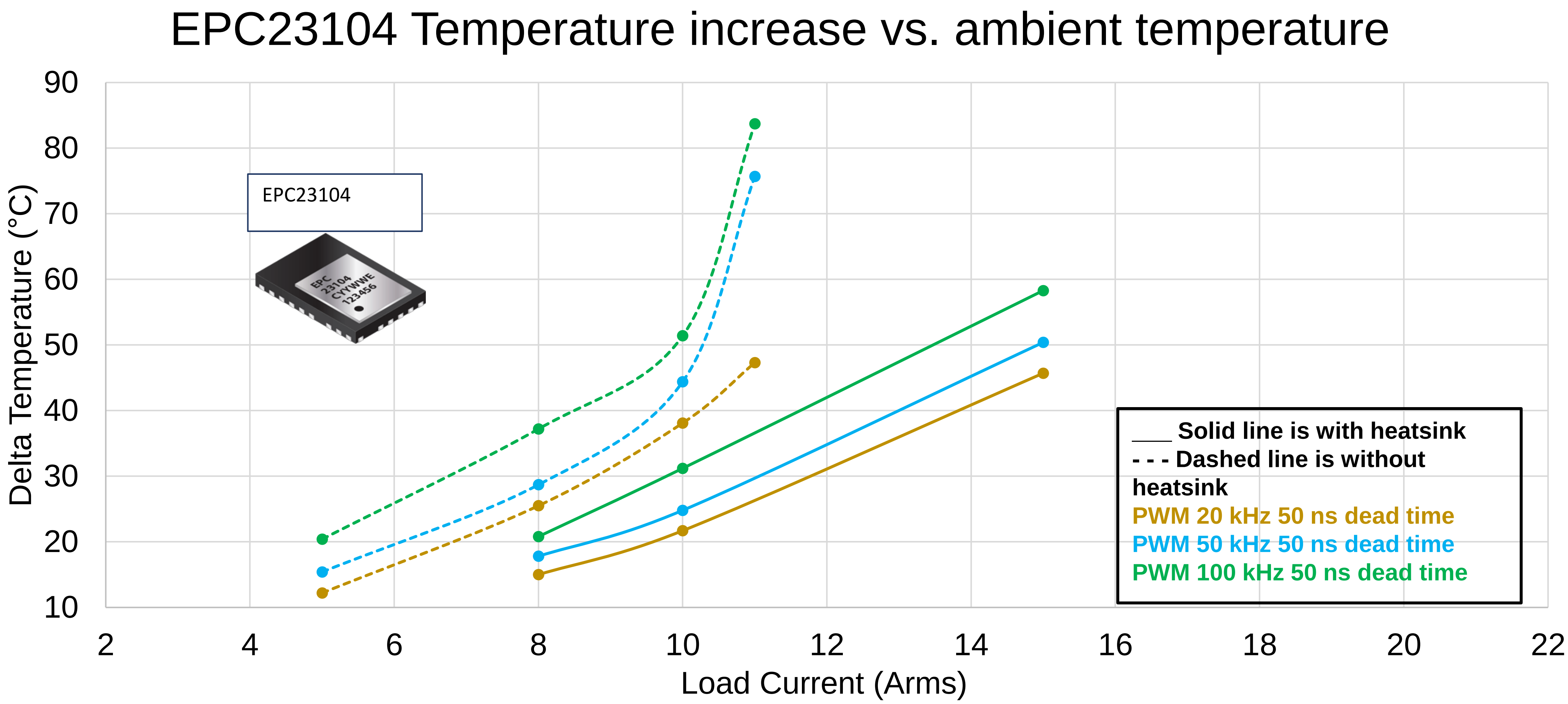
- The EPC9176 has been tested in a dynamometer bench
- 38 A peak operation followed by 8 Arms with duty 20%
- The average temperature follows the steady state curves

EPC9176 pulsed torque tests

EPC23102

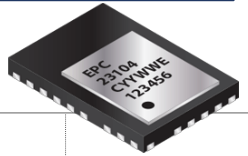


EPC91104 – Steady state operation

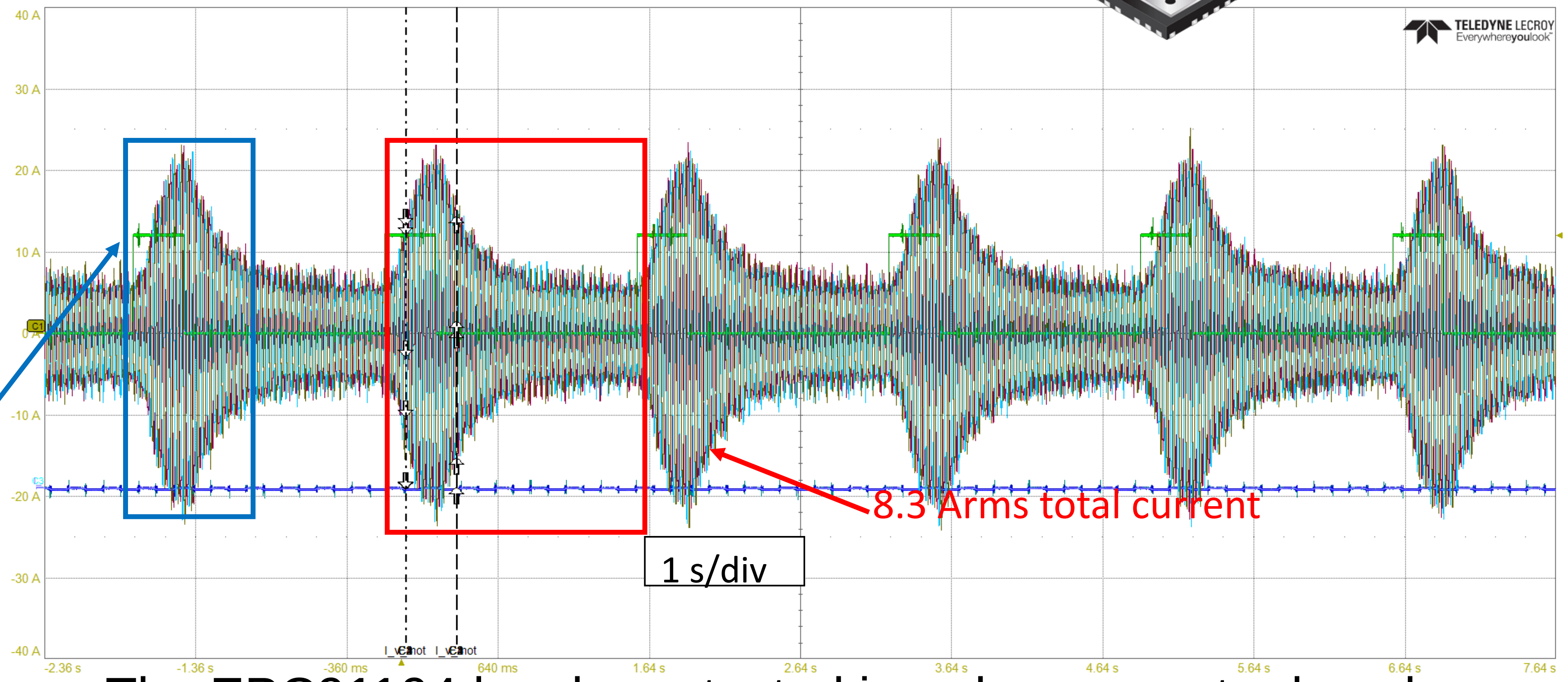


EPC91104 - 20 A peak operation

EPC23104



C1: Phase 1 Current
C2: Phase 2 Current
F3: Phase 3 Current
C4: Brake signal



20 A peak operation 20% duty cycle

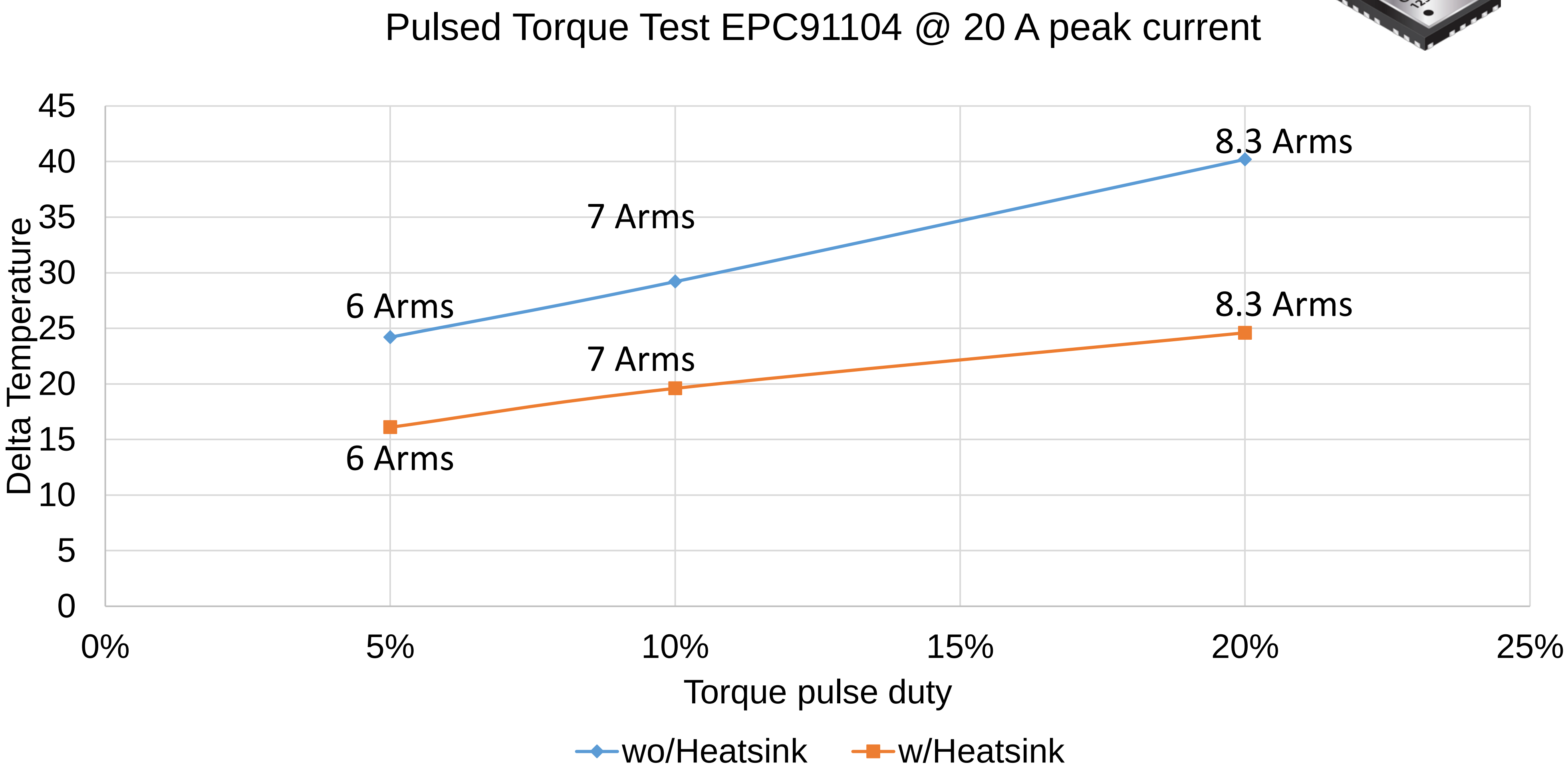
40° C increase without heat sink

25° C increase with heat sink

- The EPC91104 has been tested in a dynamometer bench
- 20 A peak operation followed by 4 Arms with duty 20%
- The average temperature follows the steady state curves

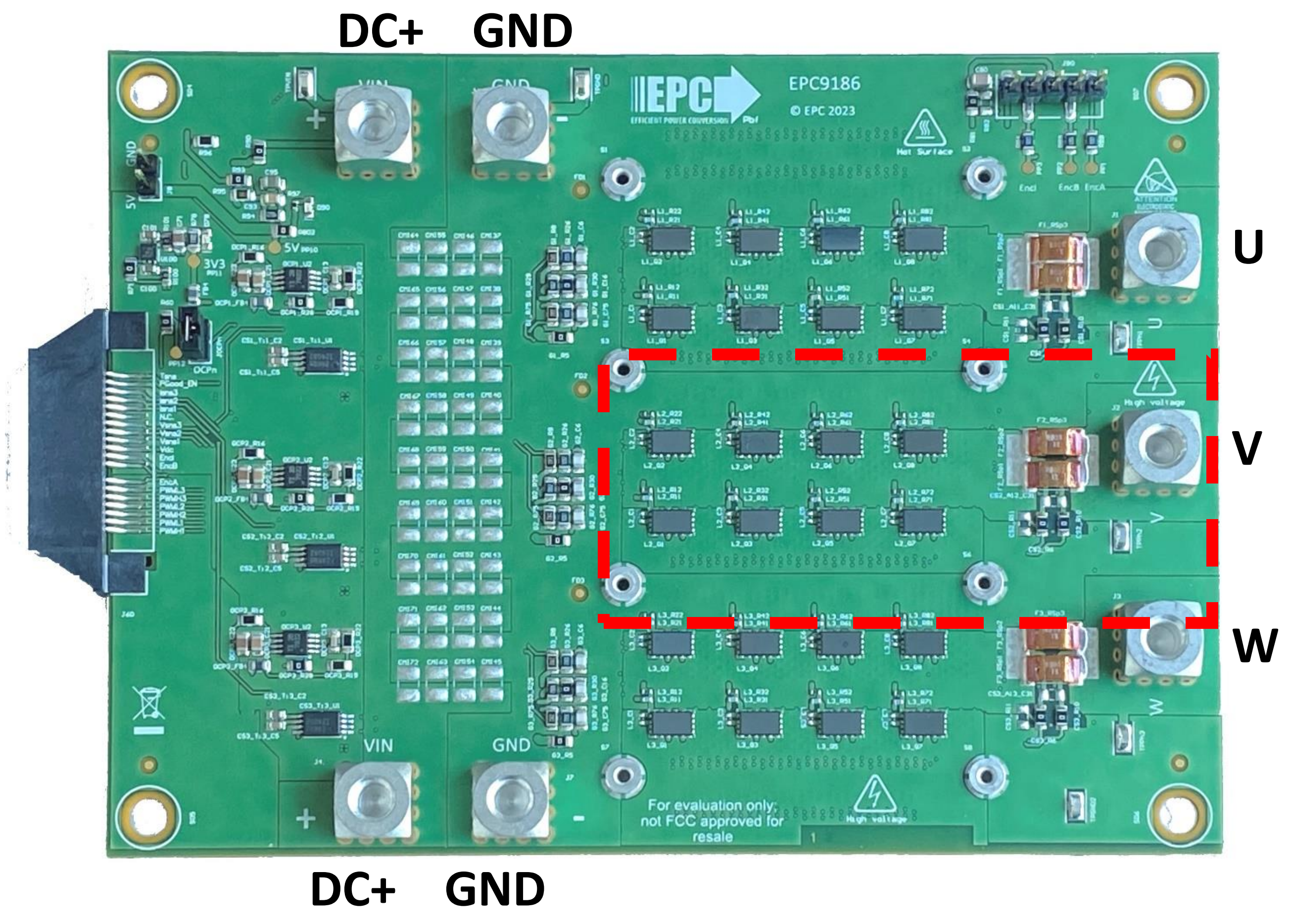
EPC91104 pulsed torque tests

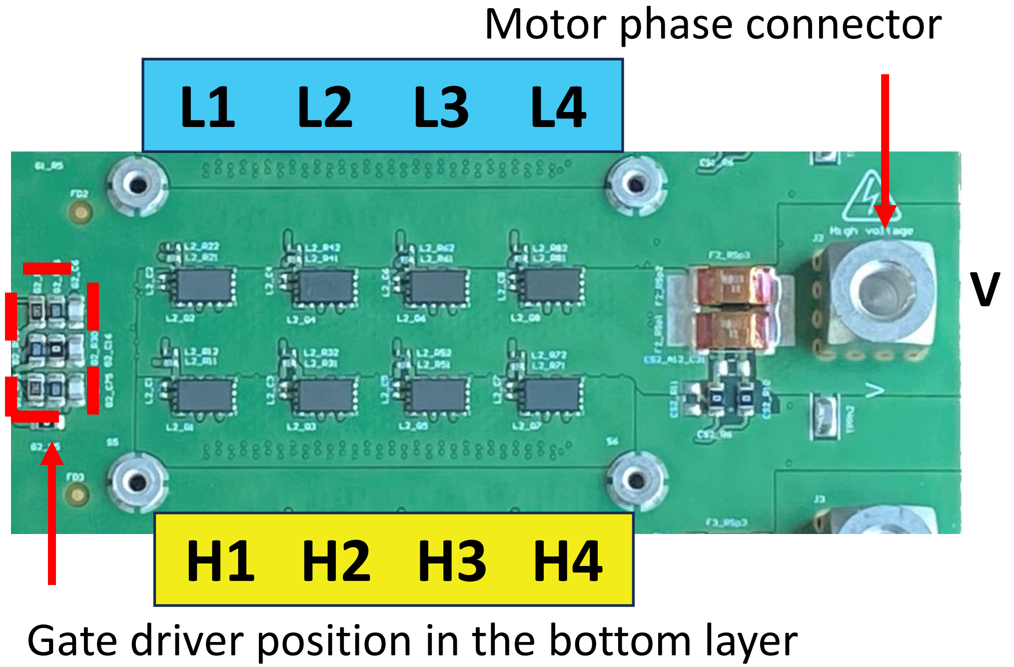
EPC23104



EPC9186

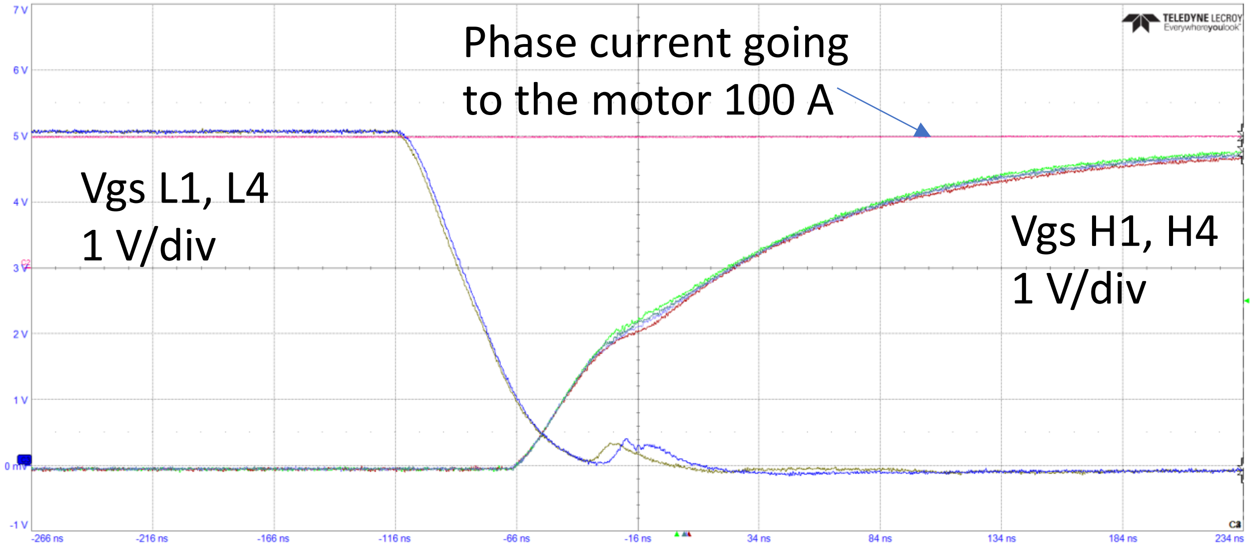
New Slide



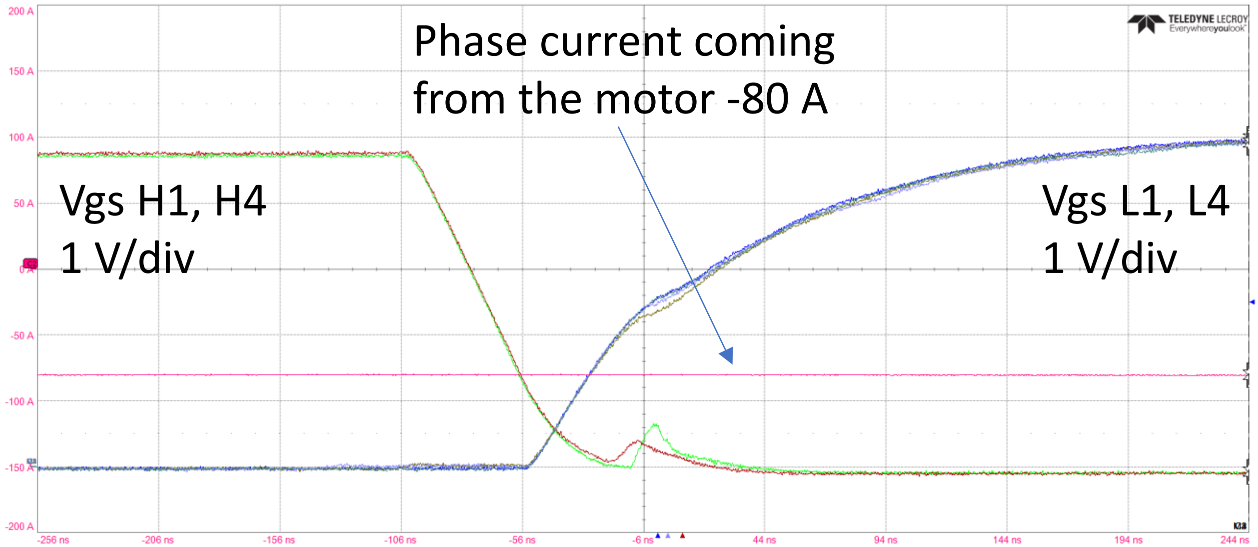


EPC9186 Vgs

New Slide

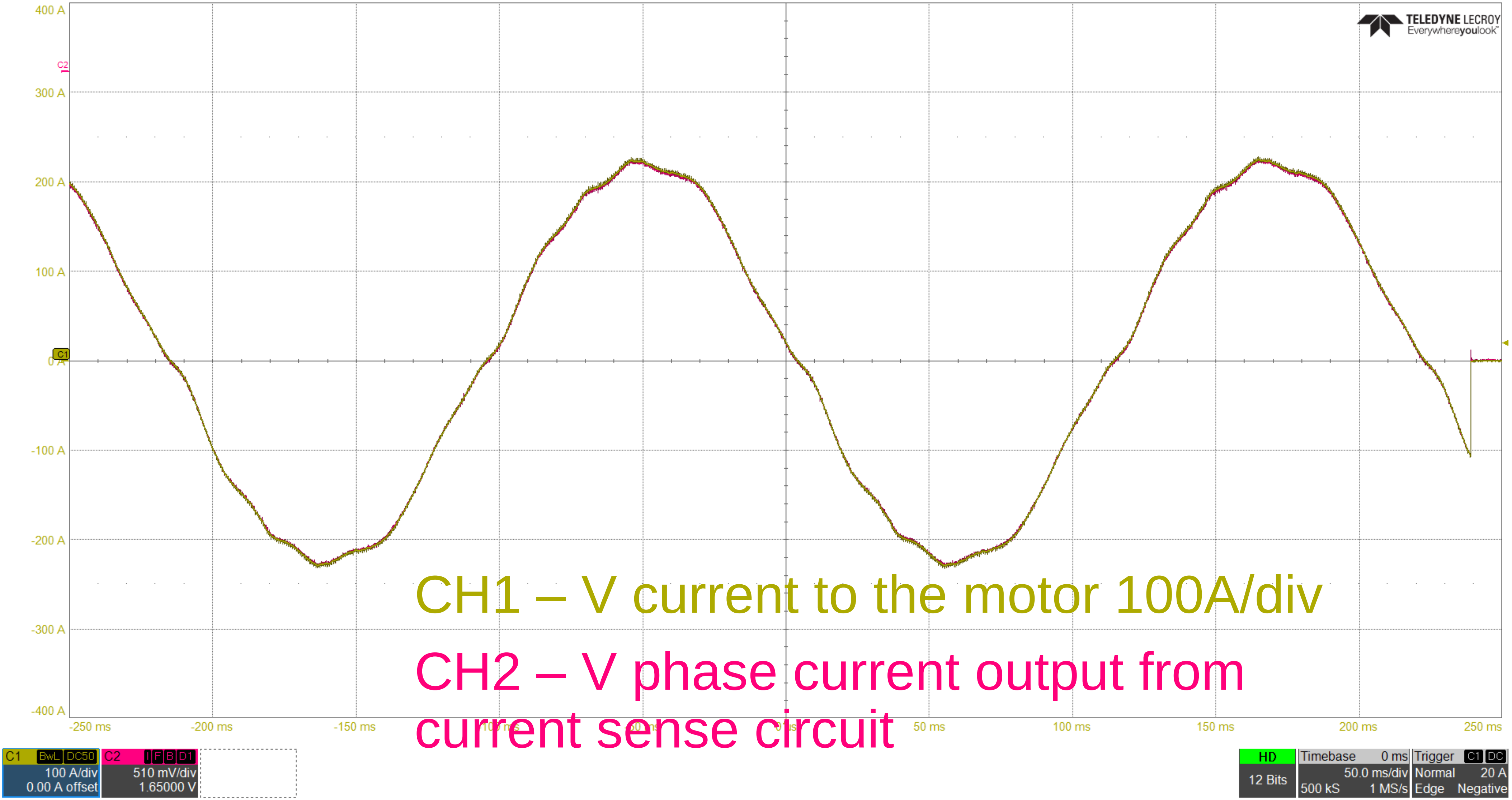


a) 50 ns/div



b) 50 ns/div

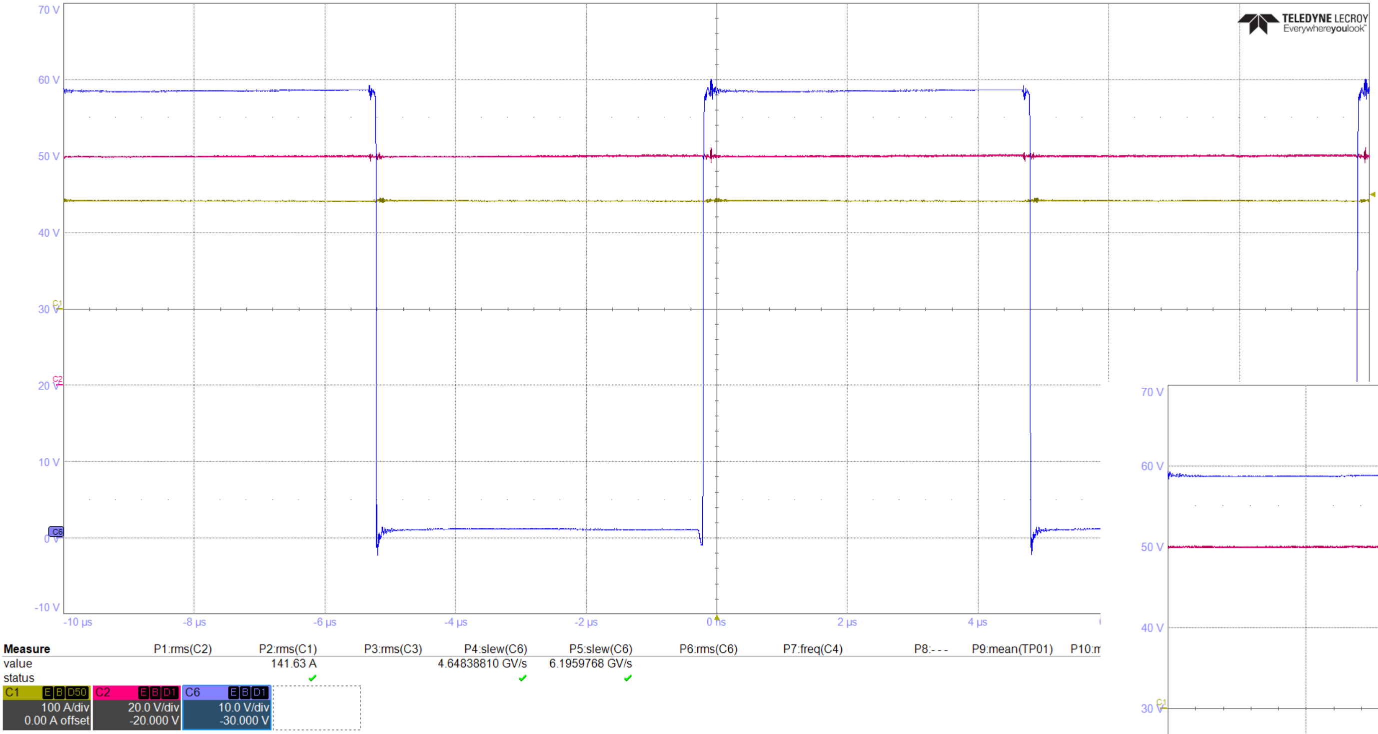
+/- 200 A peak current



CH1 – V current to the motor 100A/div

CH2 – V phase current output from current sense circuit

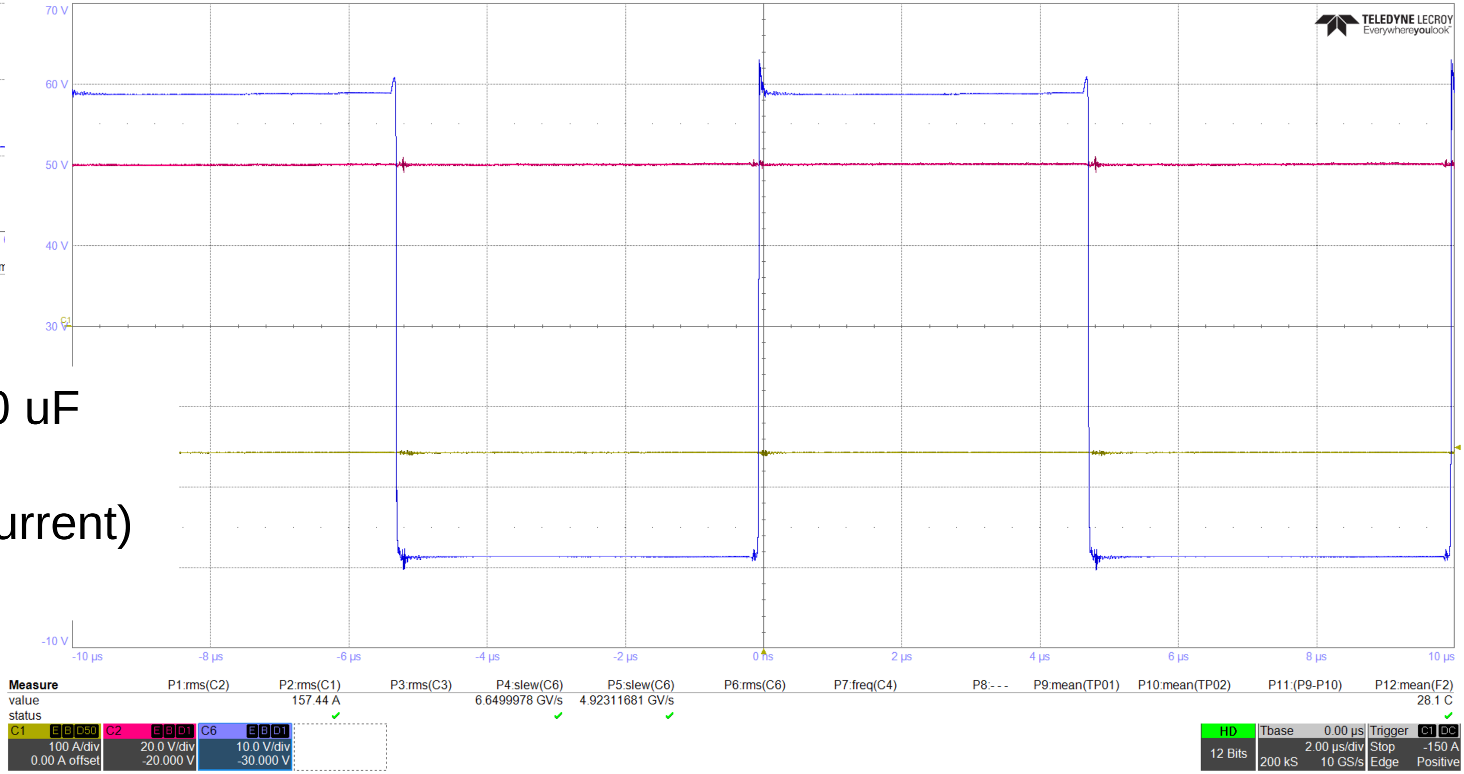
100 kHz – 60Vdc - +/-150A – dv/dt and ringing



CH1 – V current to the motor 100A/div

CH2 – DcBus voltage 20 V/div

CH6 – V Phase voltage 10 V/div

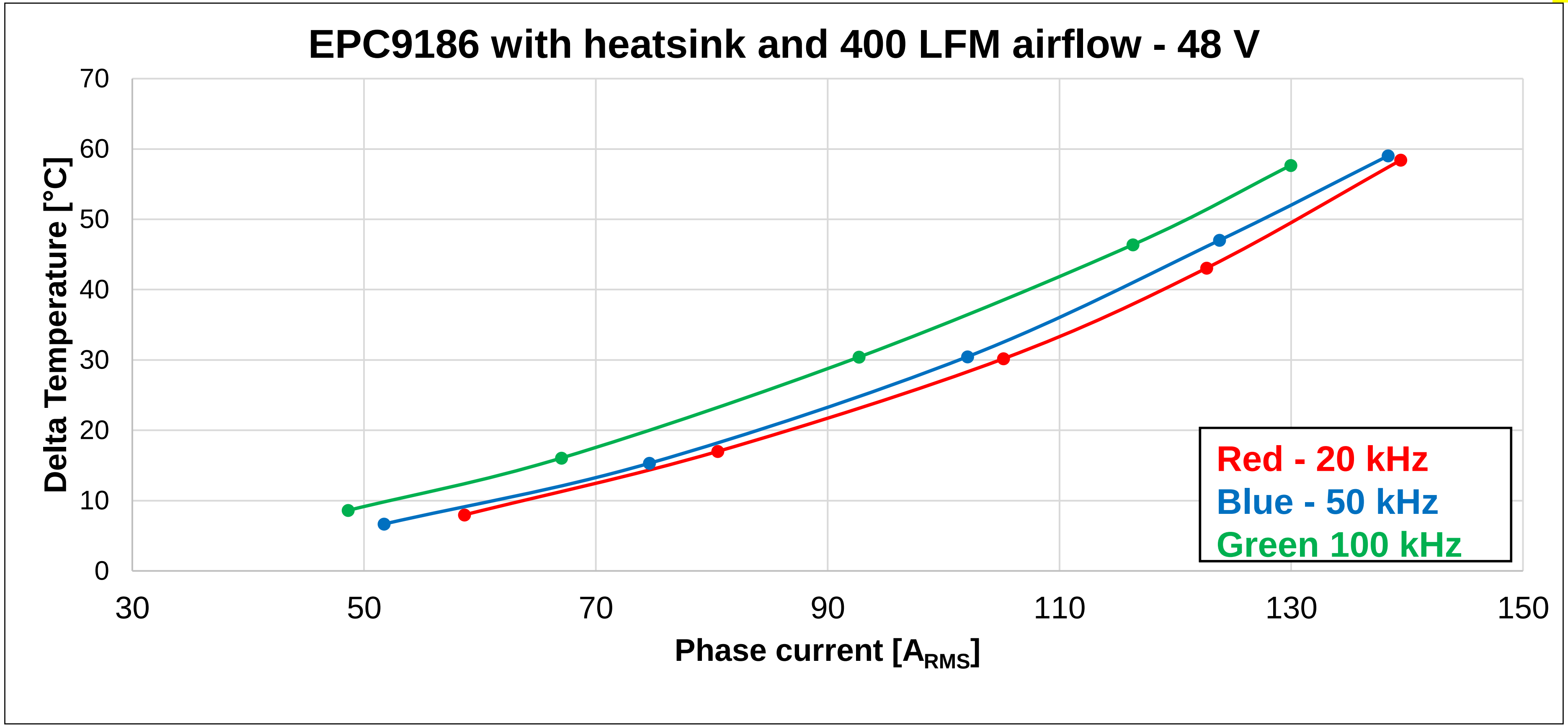


Inverter switching 150 Apk at 60 V DcBus with 720 uF DcBus capacitors.

The ringing in both cases (positive and negative current) is limited. No over voltage spikes are observed

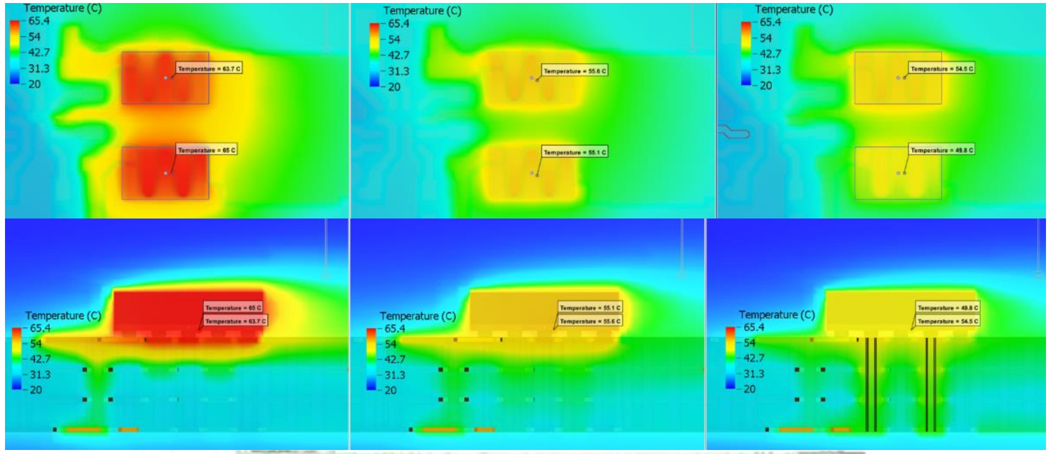
EPC9186 steady state

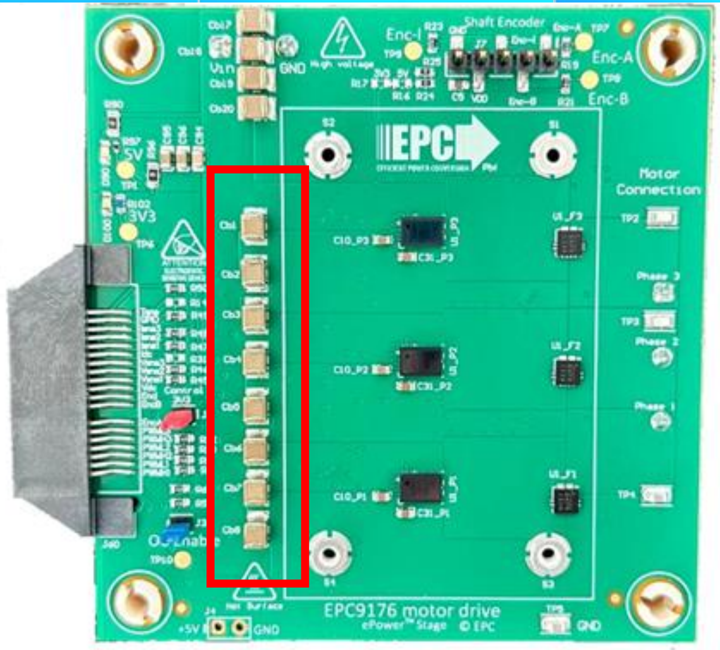
New Slide



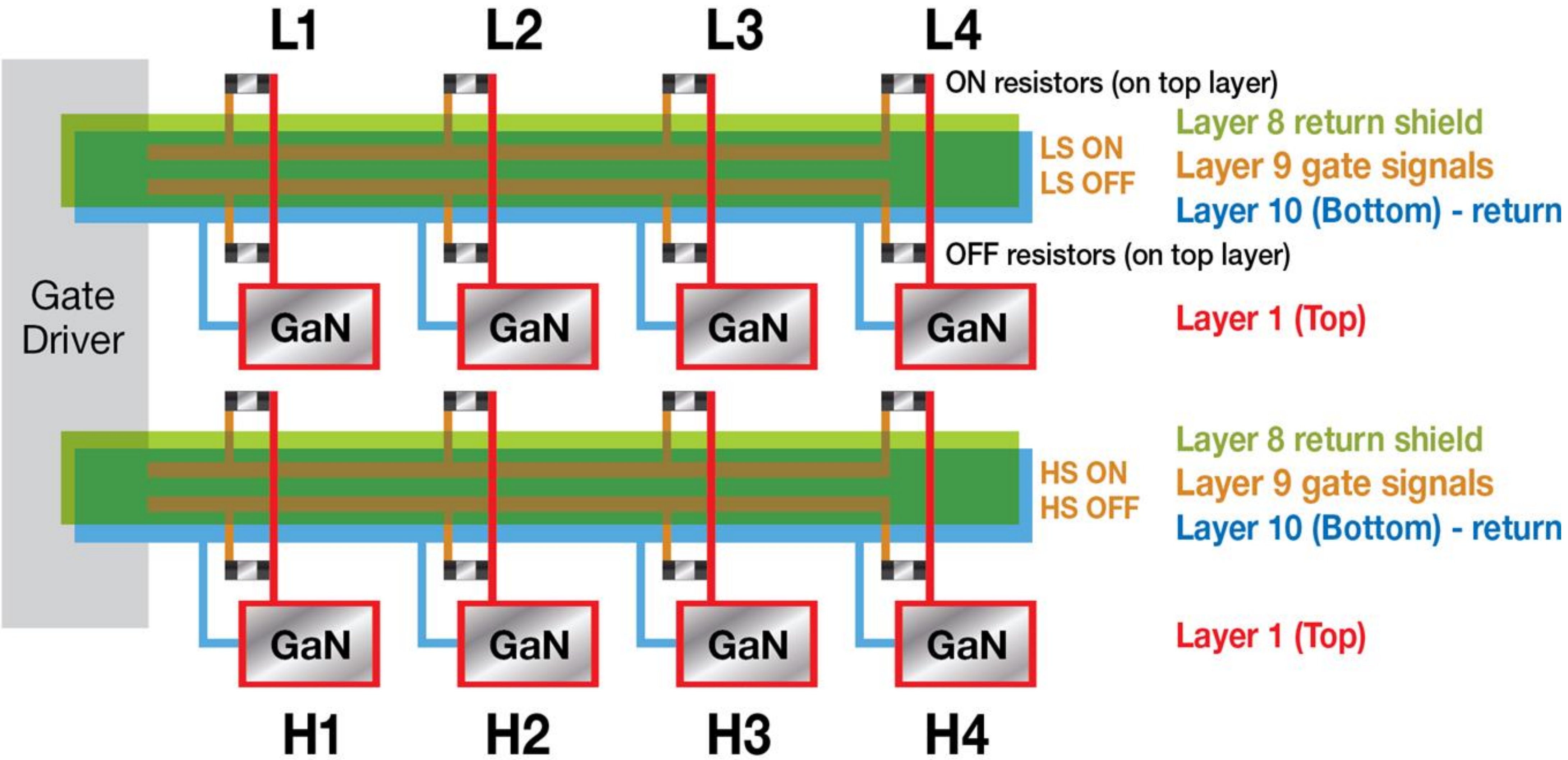
GaN Layout Rules for Motor Drives

- Minimize common source inductance
- Use thick copper in the first layers to reduce resistance and increase heat transfer. 2 oz on the top and 4 oz in the inner layers
- Use vias-in-pad to increase heat transfer
- Distribute the DcBus capacitors to have the same impedance to DcBus+ and DcBus- at each switching cell
- When switching less than 5 V/ns, high-frequency capacitors on the top layer are not needed -> The first inner layer does not have to be ground return; use all layers for the current
- Minimize the DC resistance of the copper; use a PCB tool to predict the DC resistance
- Minimize the device interconnection resistance to the PCB by analyzing the current density with a PCB tool





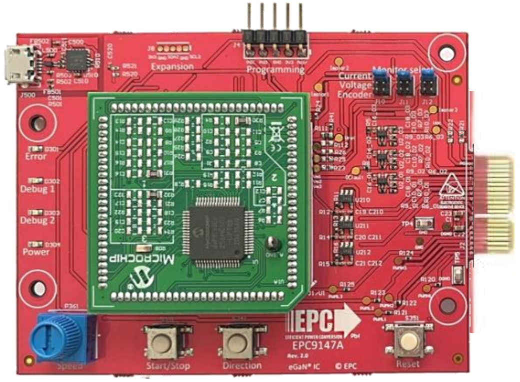
EPC9186 layout – gate signal distribution

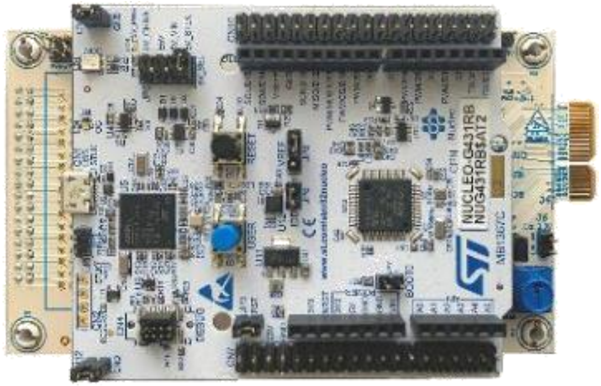


EPC adapters for Motor Drive Controllers

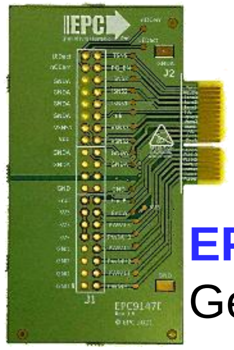
Sensorless Sinusoidal Field Oriented Control

EPC9147A
dsPIC33



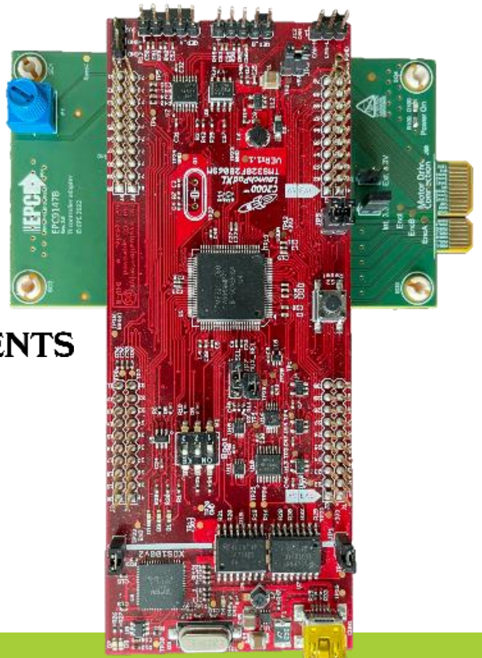


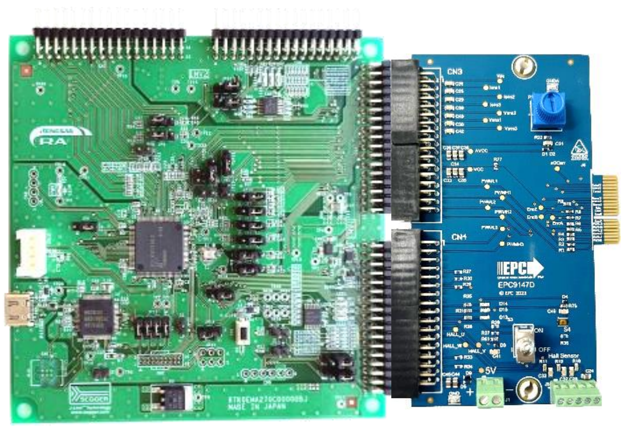
EPC9147C
Nucleo



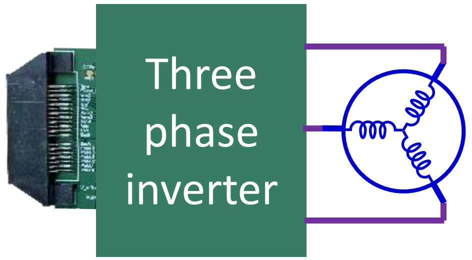
EPC9147E
Generic Interface

EPC9147B
Piccolo





EPC9147D
RA6T2
RA4T1

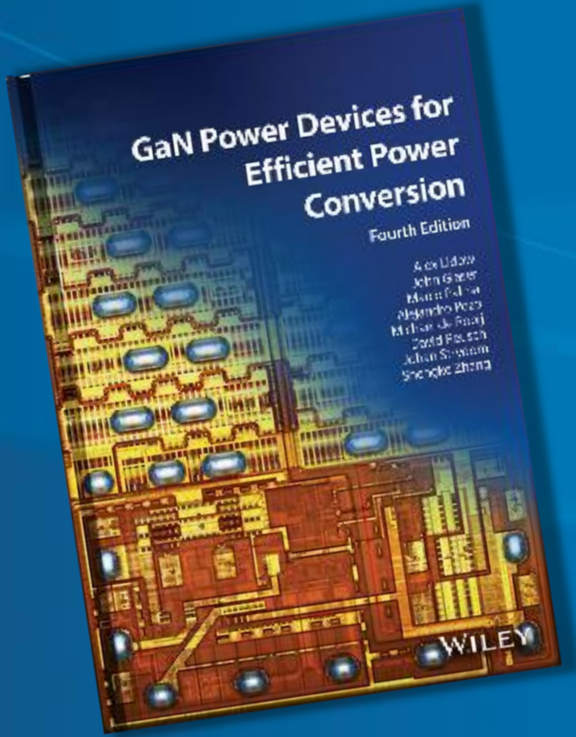


Summary

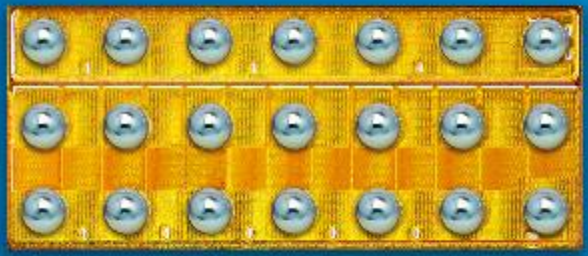
- EPC devices allows smaller, lighter, quieter and more accurate motor drives
- Given same $R_{DS(on)}$, EPC eGaN devices
  - Are smaller
  - Have lower switching dissipation
  - Have no reverse recovery
- GaN inverters make BLDC Motors more efficient

Click on images to learn more

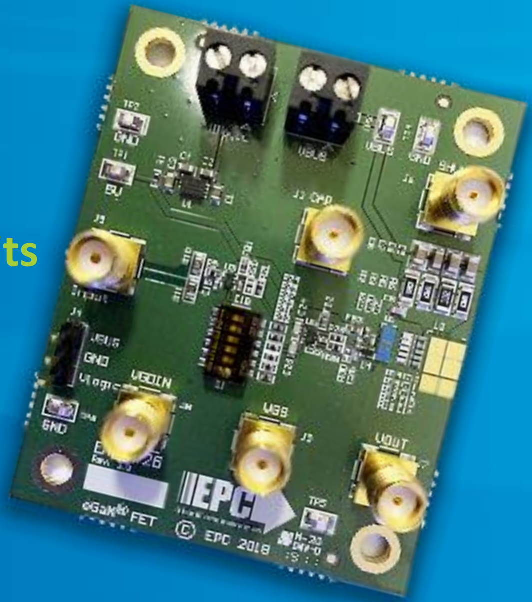
How To GaN Video Series



4th Edition Textbook



eGaN® FETs and ICs



Evaluation Kits

epc-co.com