



GaN Power ICs at 1 MHz+: Topologies, Technologies and Performance

PSMA Industry Session, Semiconductors

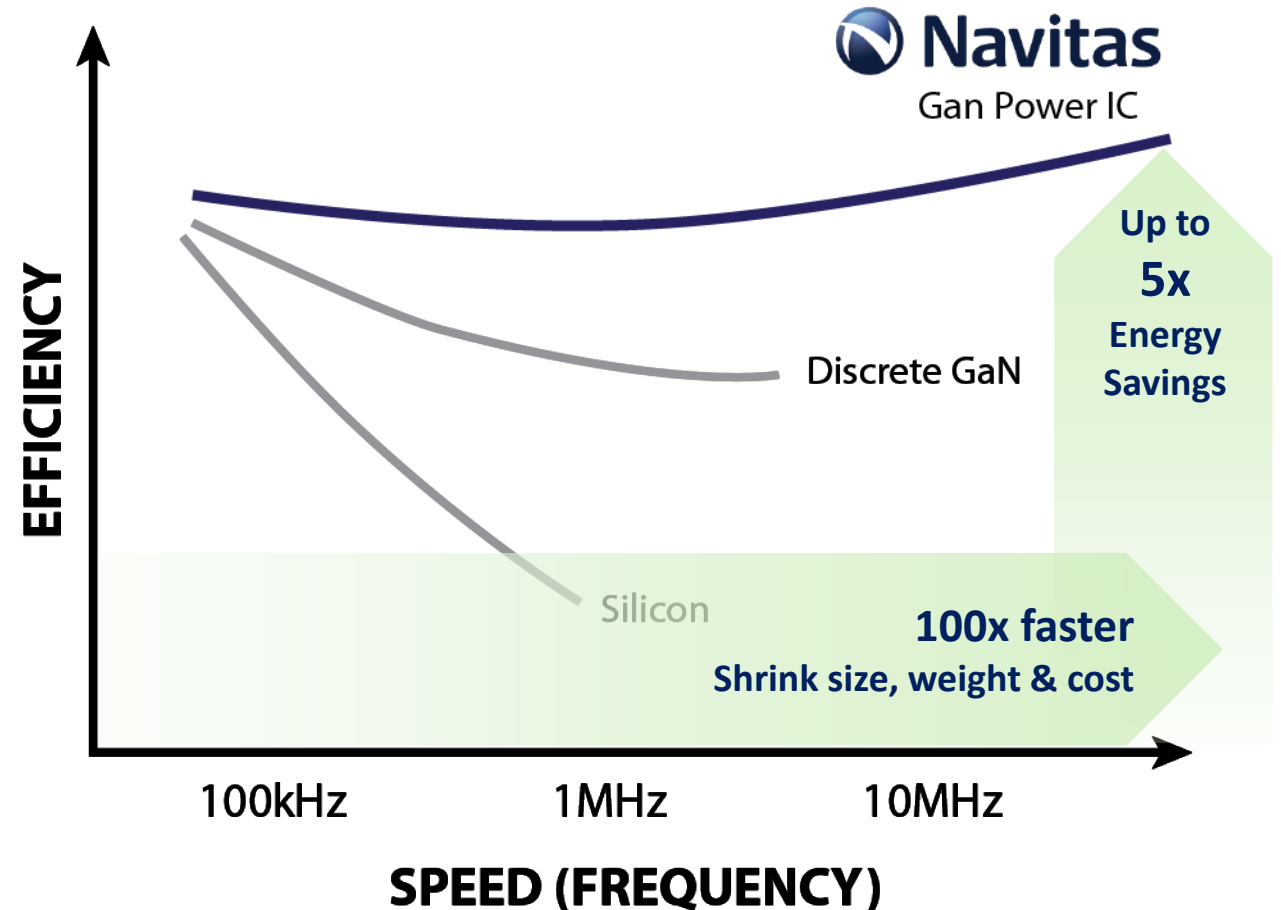
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March 29, 2017

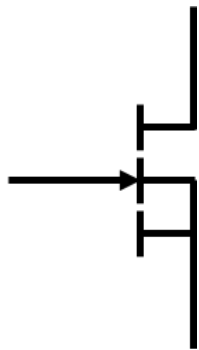
Power Electronics: *Speed & Efficiency are Key*

- **Speed** enables *small size*, *low-cost* and *faster charging*
- **Efficiency** enables *energy savings*
- With Silicon or Discrete GaN power devices, you can get one **or** the other
- With GaN power ICs, you get **both at the same time** with unequaled **Speed & Efficiency**



World's First AllGaN™ Power ICs

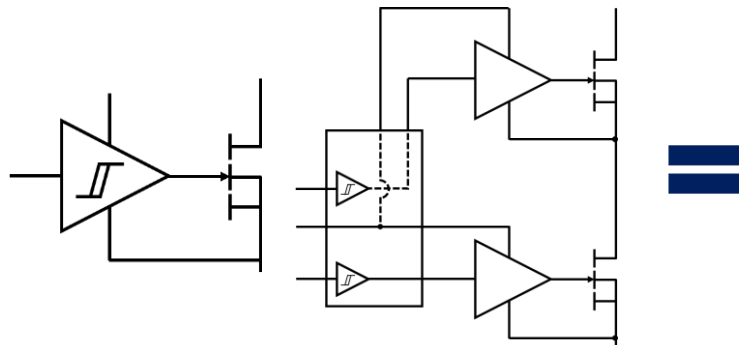
**Fastest, most efficient
GaN Power FETs**



>10x faster than silicon
>5x faster than cascoded GaN
Proprietary design
5+ pending or issued patents



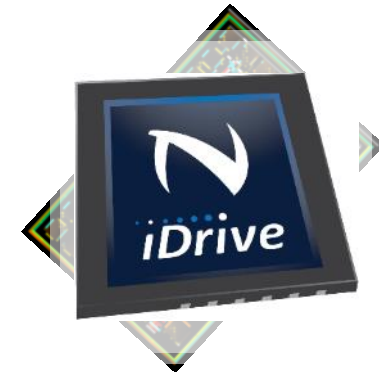
***iDrive* First & Fastest
Integrated GaN Gate Drivers**



>2x faster than any other gate driver
Proprietary design
15+ pending or issued patents



**World's First
AllGaN™ Power IC**

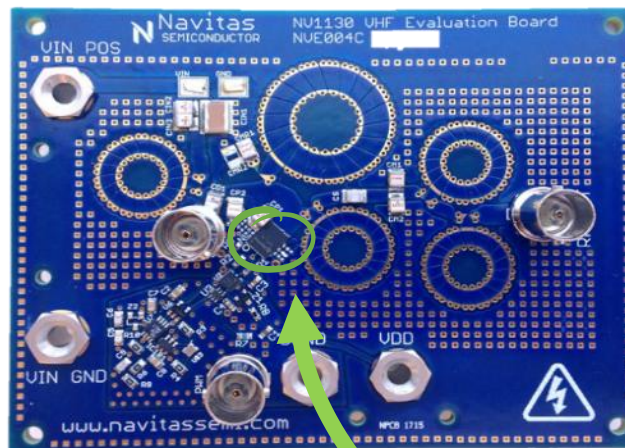
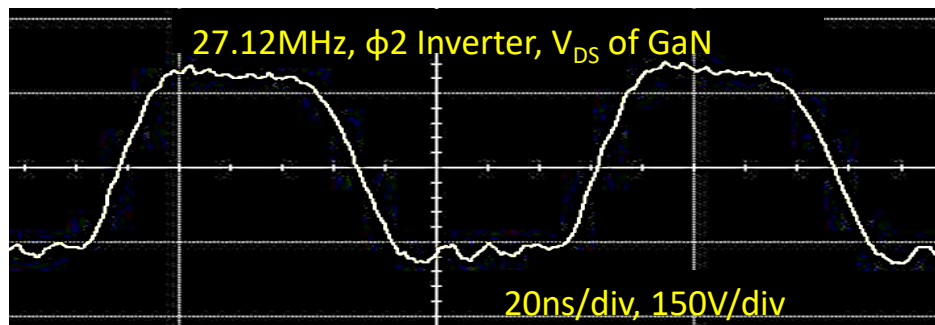
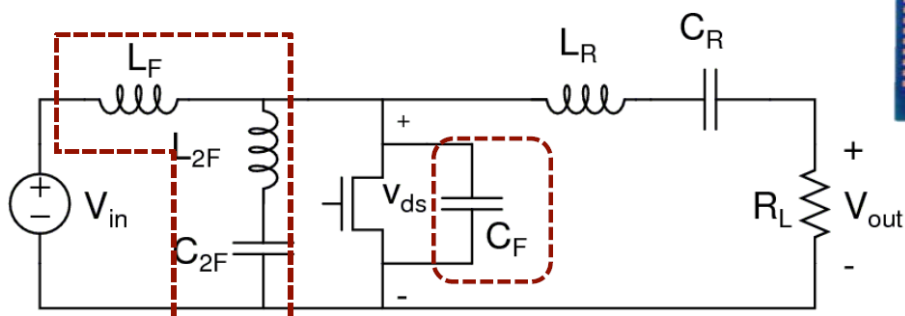


Up to 40MHz switching, 5x higher density & 20% lower system cost

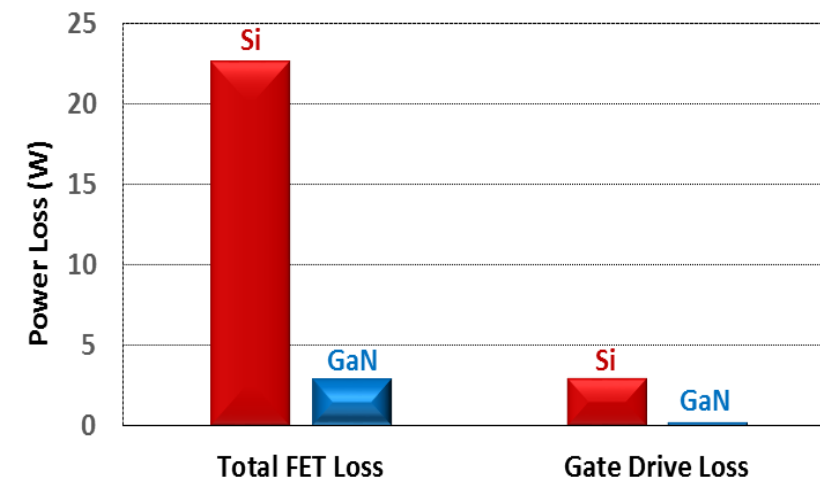
27 MHz, 40 MHz...

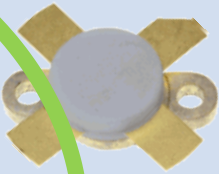
Class Phi-2 DC/AC converter

- 50% less loss than RF Si
- 16x smaller package
- Air-core inductors
- Minimal FET loss
- Negligible gate drive loss



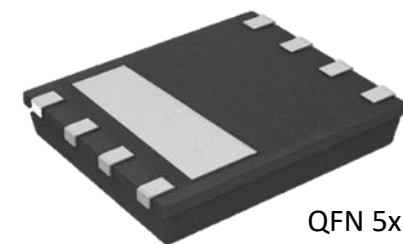
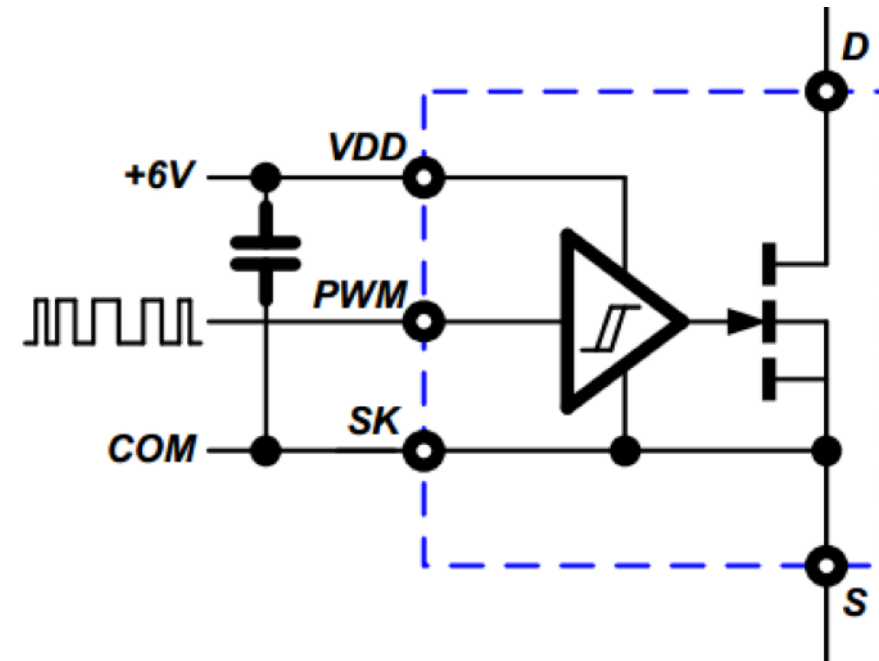
Power Loss Breakdown (Active Components)



Technology	V	Pack (mm)	F _{SW} (MHz)	Eff. (%)	Power (W)
RF Si (ARF521) 	500	M174 22x22 	27.12	91%	150
	650	QFN 5x6 	27.12	96%	150
			40.00	93%	115

Navitas GaN Power IC

- Monolithic integration
- 20X lower drive loss than silicon
- Driver impedance matched to power device
- Shorter prop delay than silicon (10ns)
- Zero inductance turn-off loop
- Digital input (hysteretic)
- Rail-rail drive output
- Layout insensitive



QFN 5x6mm

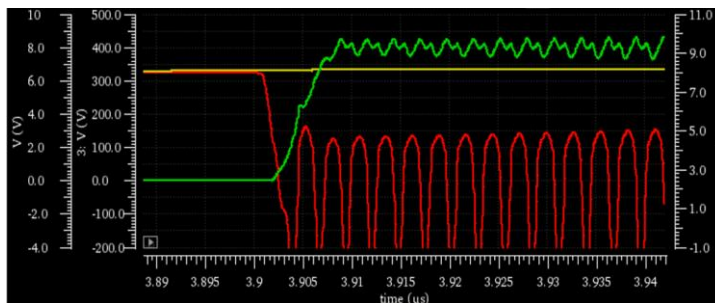
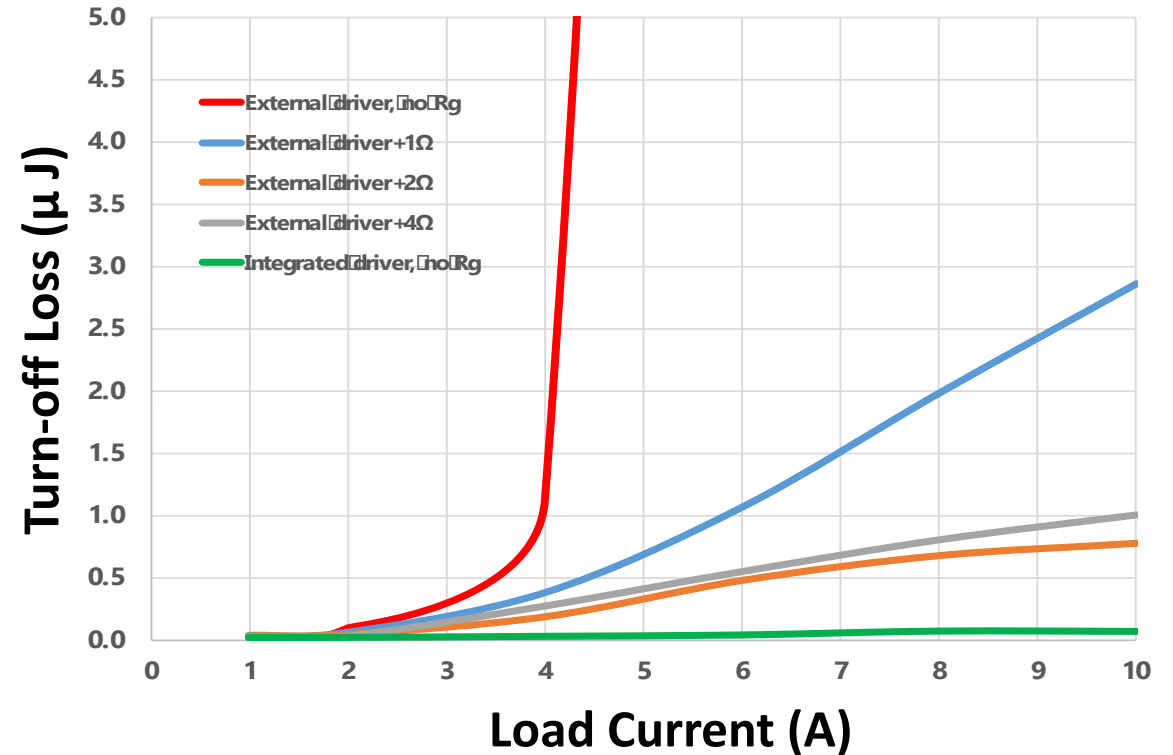
Speed & Integration → Eliminate Turn-off Losses

External drivers

- Just 1-2 nH of gate loop inductance can cause unintended turn-on
- Gate resistors reduce spikes but create additional losses

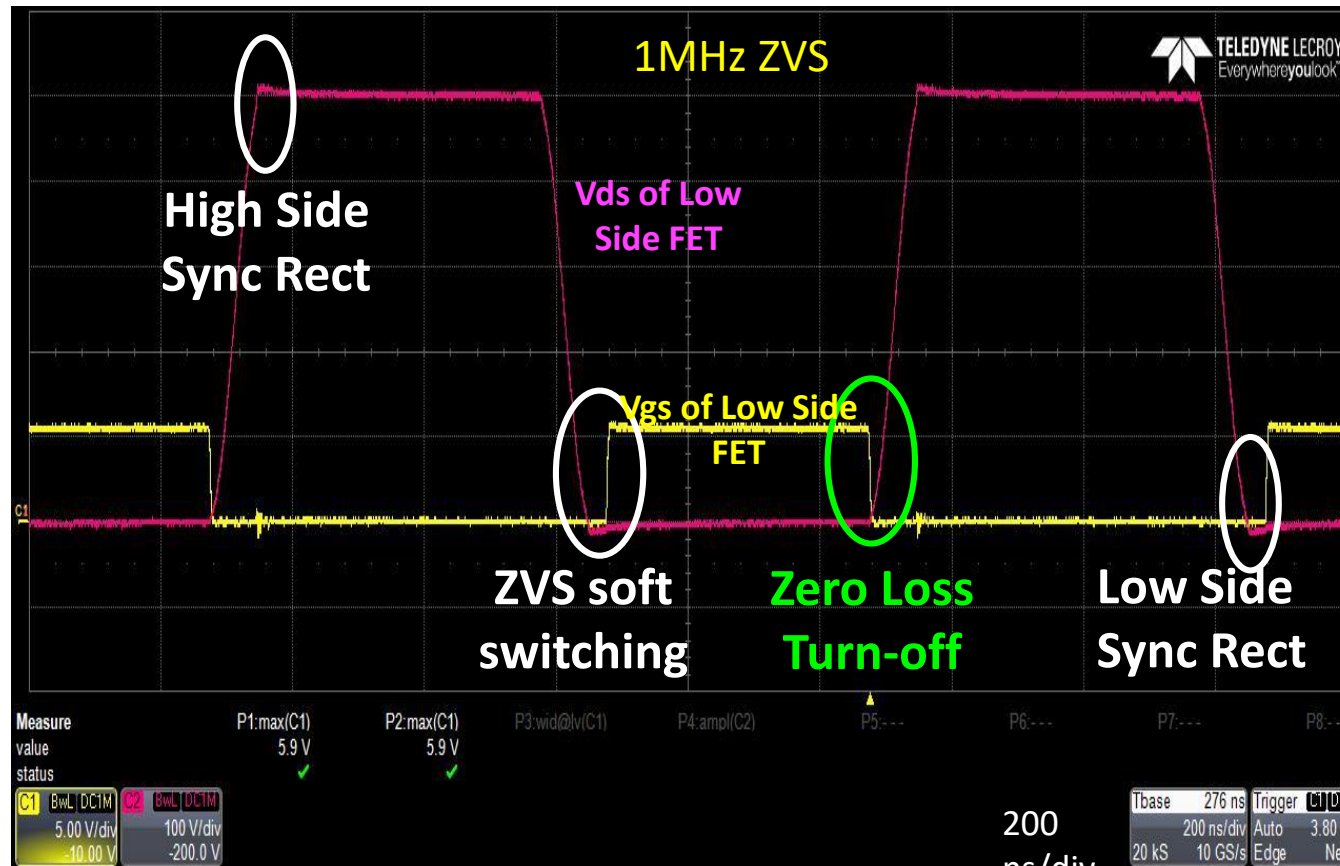
Integrated GaN drivers (iDrive™)

- Eliminate the problem
- Negligible turn-off losses



GaN Power IC – *Fast & Efficient*

- No overshoots, No spikes, No oscillations , S-curve' transitions,
- Zero Loss Turn-on (Soft switching) Zero Loss Turn-off (Integrated Gate Drive)



Wireless Power ... Accelerated

Existing Silicon-based multi-stage wireless power



AC-DC Adapter
88% Efficiency



DC-DC
94% Efficiency

Power Amplifier
93% Efficiency



Wireless Transfer
90% Efficiency



Single-Stage Amplifier
90% Efficiency

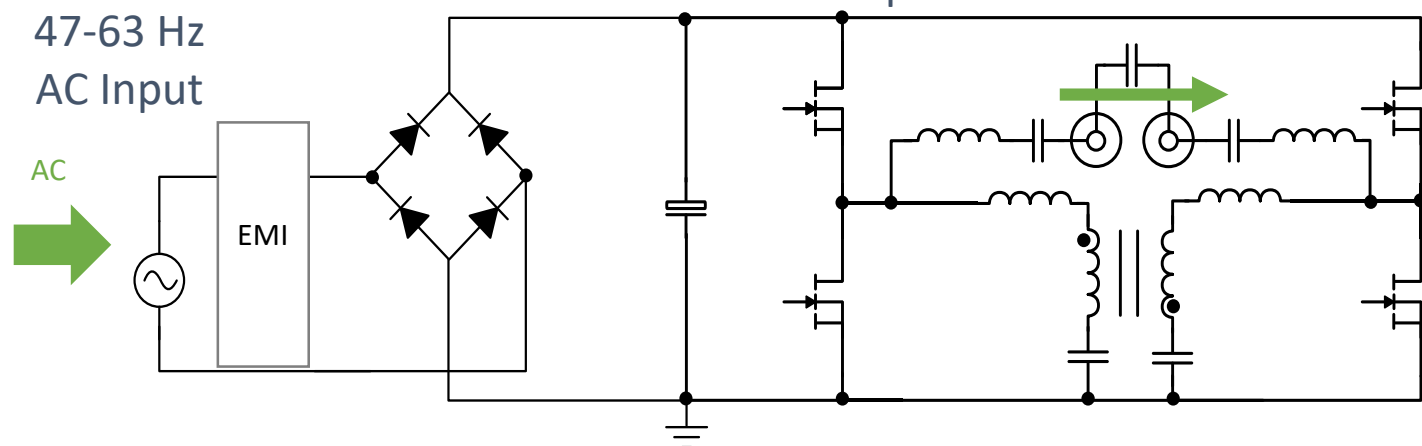
- 650V GaN Power ICs
- 3-stages integrated in 1-stage
- 6.78MHz Operation
- High-Efficiency

- Multi-stage Efficiency: **77%**
- GaN-enabled single stage: **90%**
- 20% lower system cost
- 3x faster charging

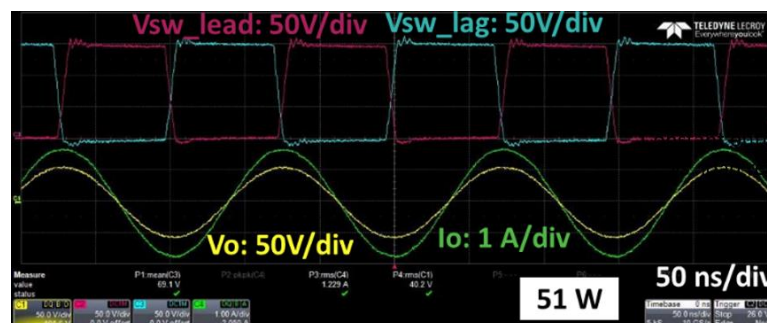
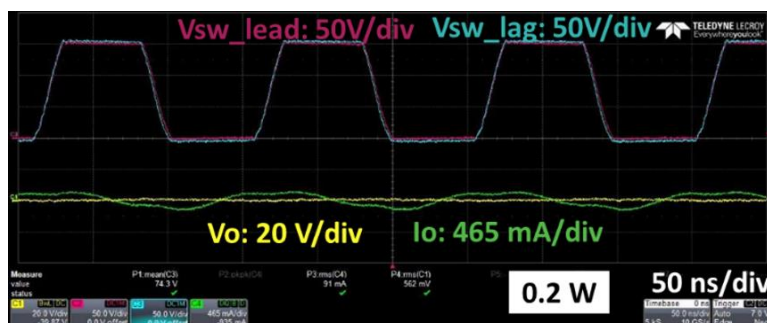
AC-RF Single Stage, Efficient & Cost-effective

400V Phase-shifted Full Bridge with ZVS Coupled Inductors

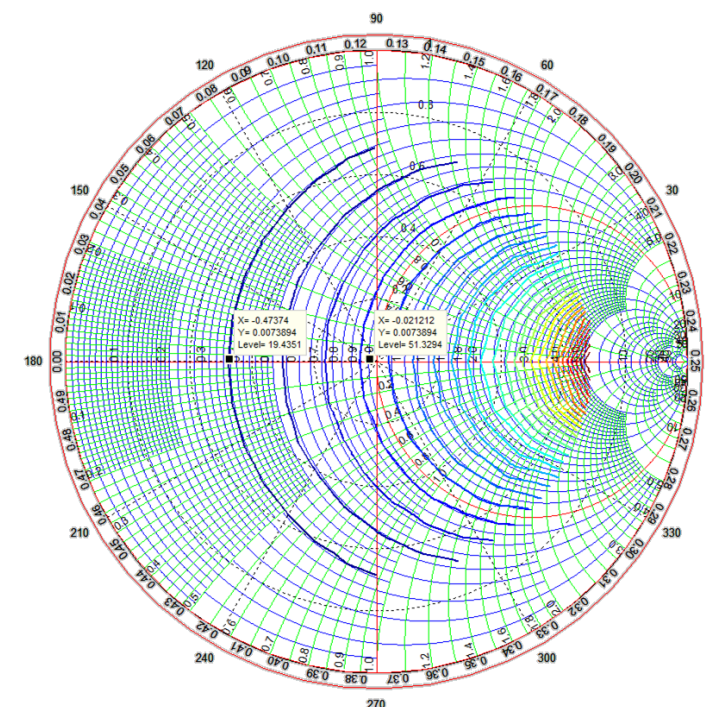
6.78 MHz Output Direct to Transmitter Antenna



GaN Phase-Shift vs. Load

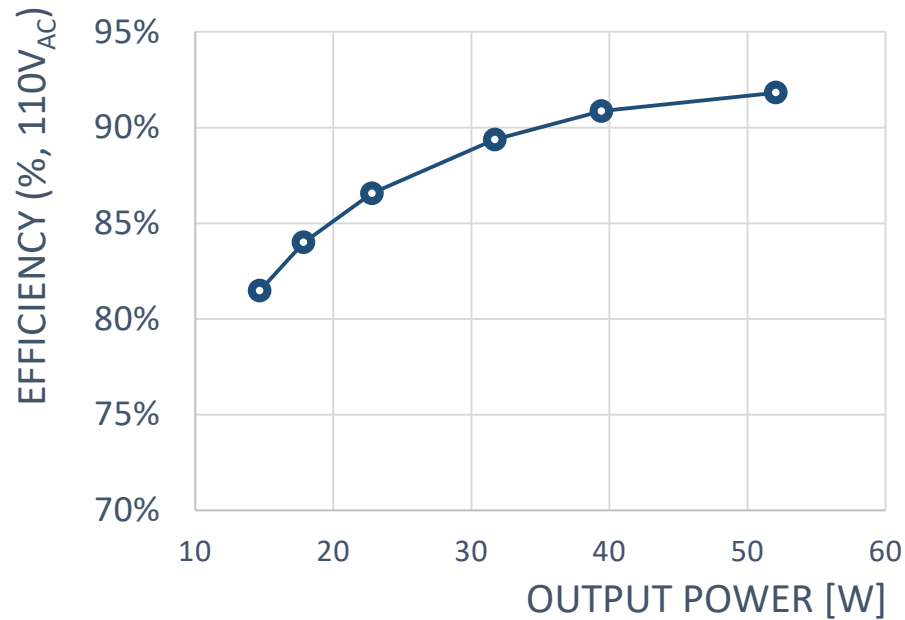


Meets Key System Requirements:
Constant output current vs. load reactance

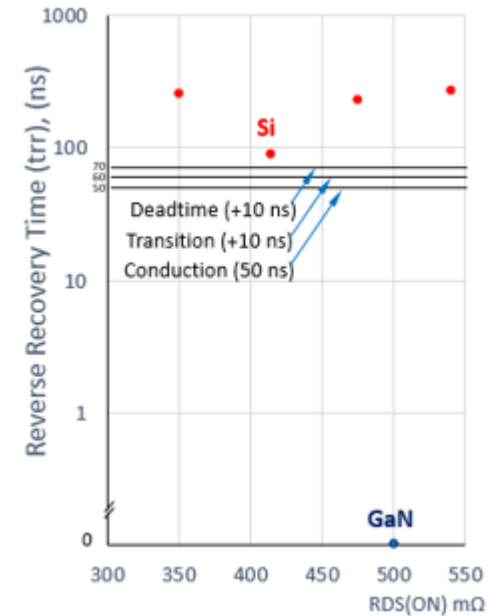


Cool AllGaN, No Chance for Silicon

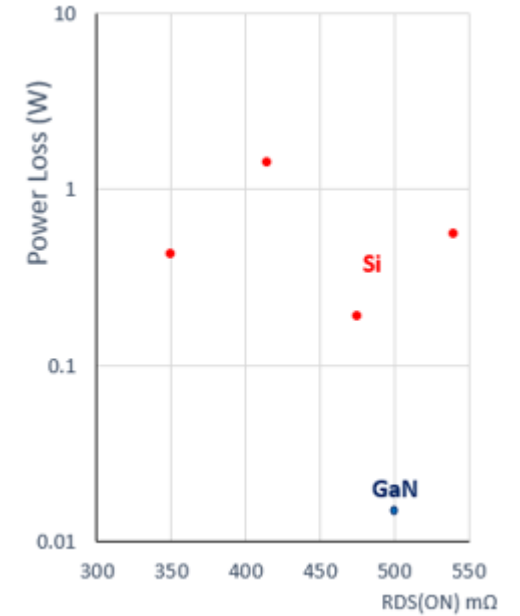
Efficiency from AC line to Transmitter Coil



Device Speed

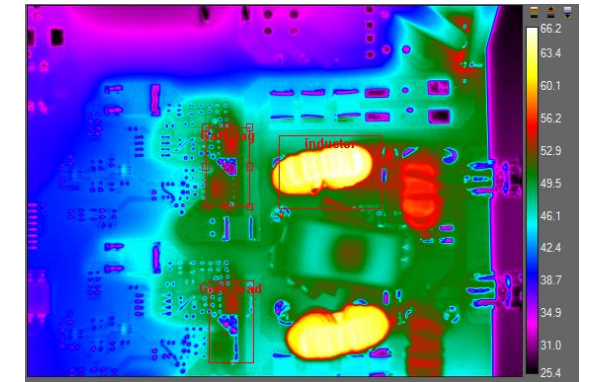
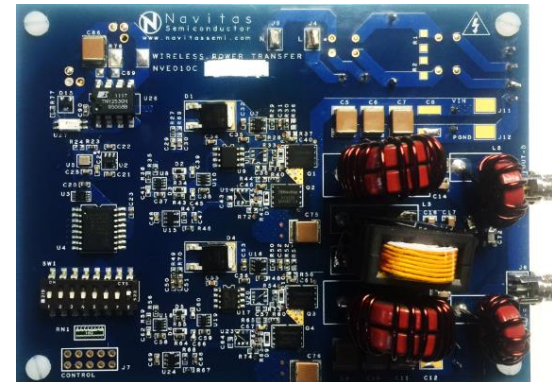


ZVS Current-Induced Loss



50W Prototype Board:

- a) Significant potential for further integration (control & GaN Power IC)
- b) Thermal performance (50W):
Max GaN Power IC $T_{CASE} = 53^{\circ}\text{C}$

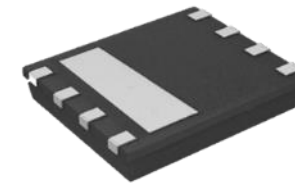
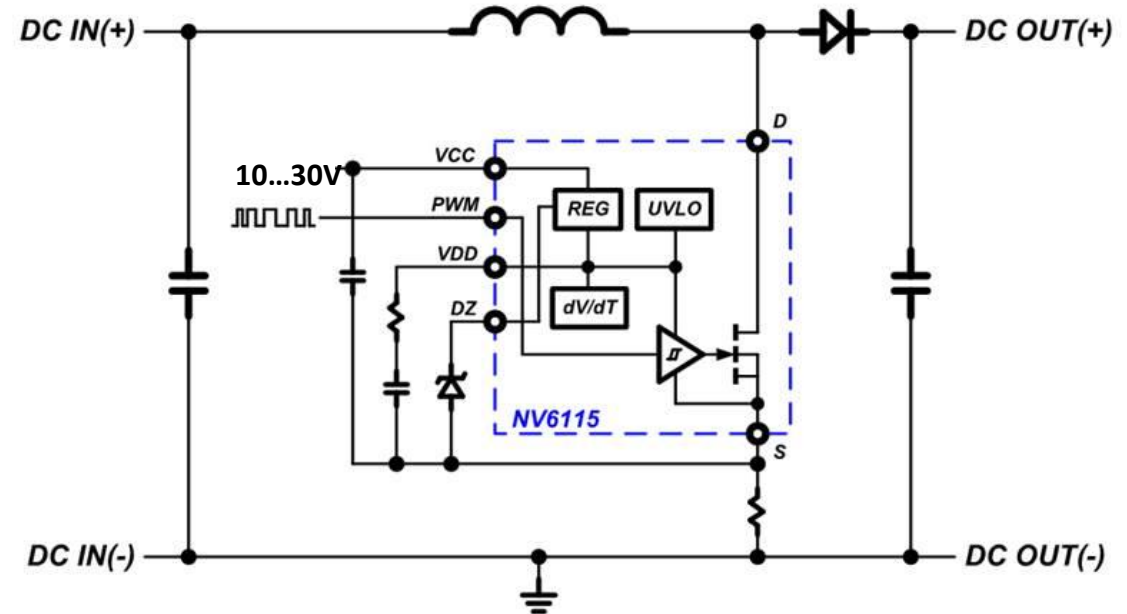


The Road Ahead (as per APEC 2016...)



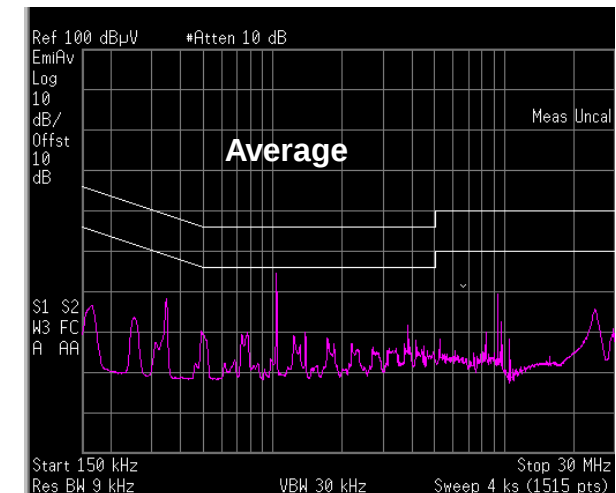
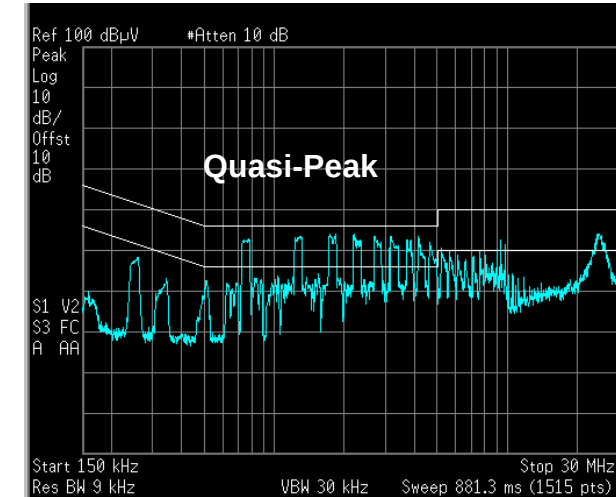
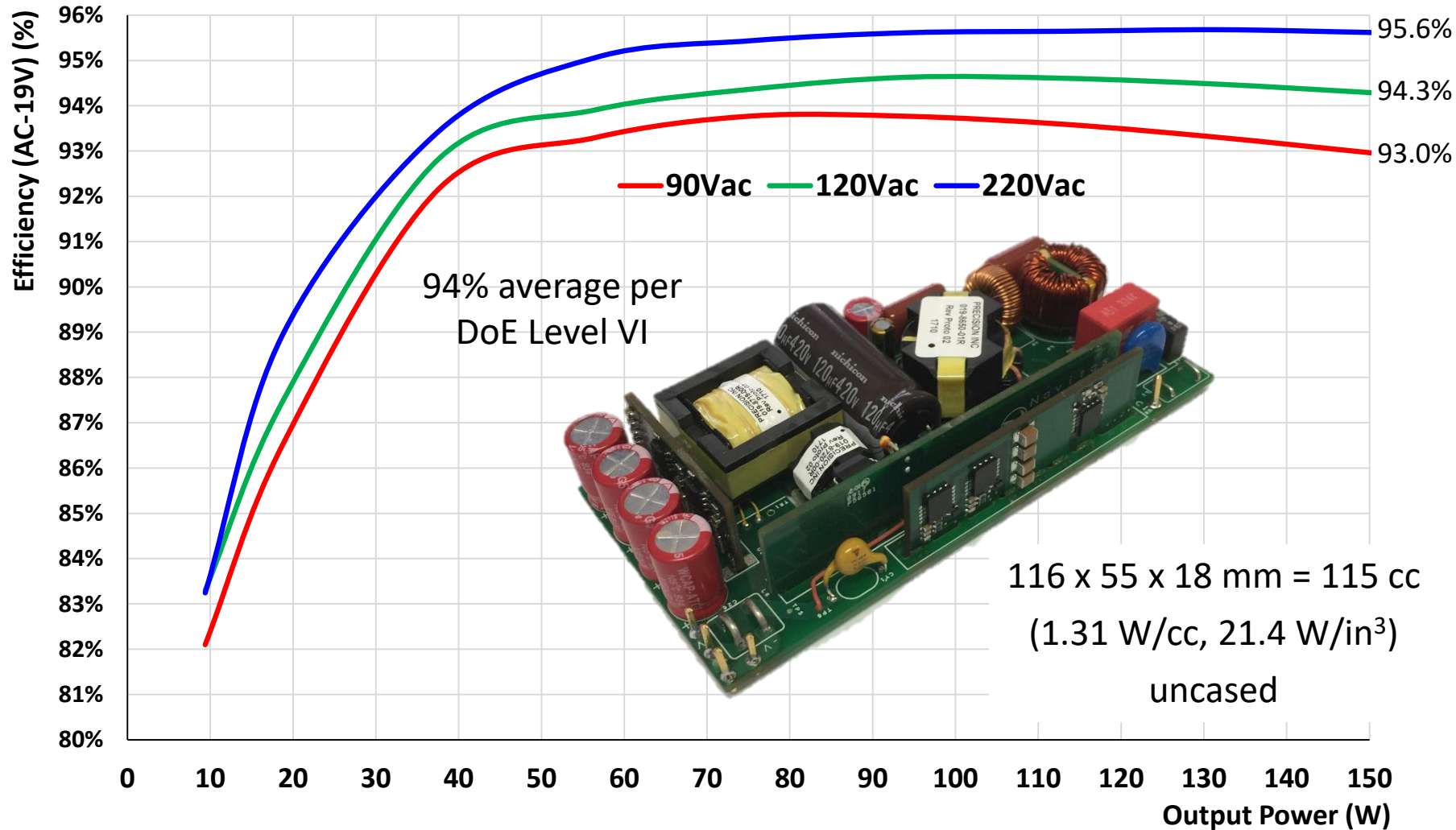
GaN Power IC: Hi-Speed FET, Drivers & More

- Proprietary AllGaN™ technology
- **Monolithic** integration of GaN FET, GaN Driver, GaN Logic
- 650 V eMode
- 20x lower drive loss than silicon (<35 mW at 1 MHz)
- Driver impedance matched to power device
- Very fast (prop delay and turn-on/off of 10-20 ns)
- Zero inductance turn-off loop
- High dV/dt immunity (200 V/ns) with control
- Digital input
- Complete layout flexibility

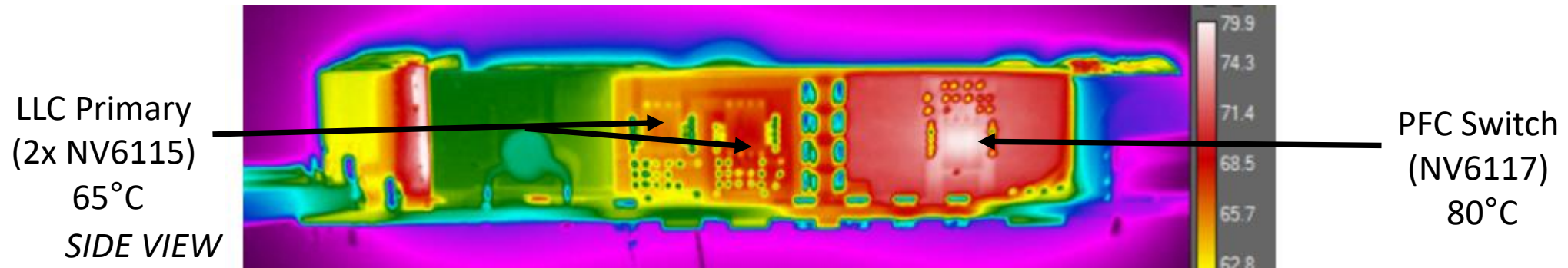
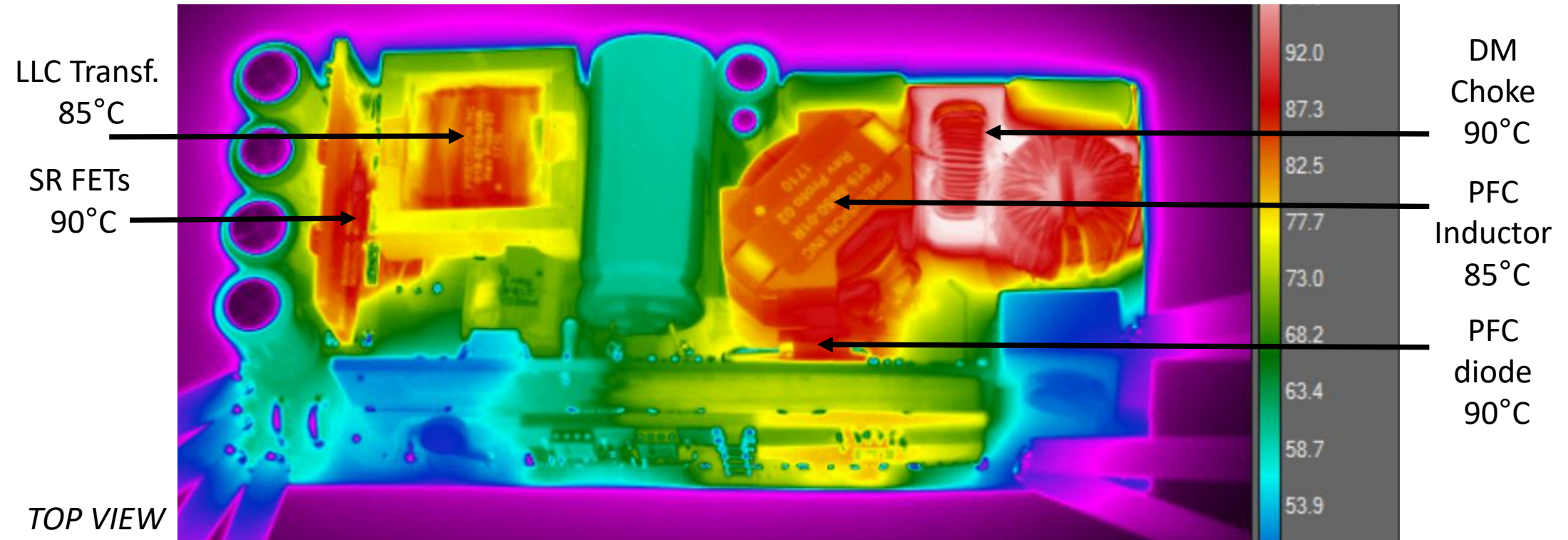


QFN 5x6mm

150W AC-19V, ~300 kHz

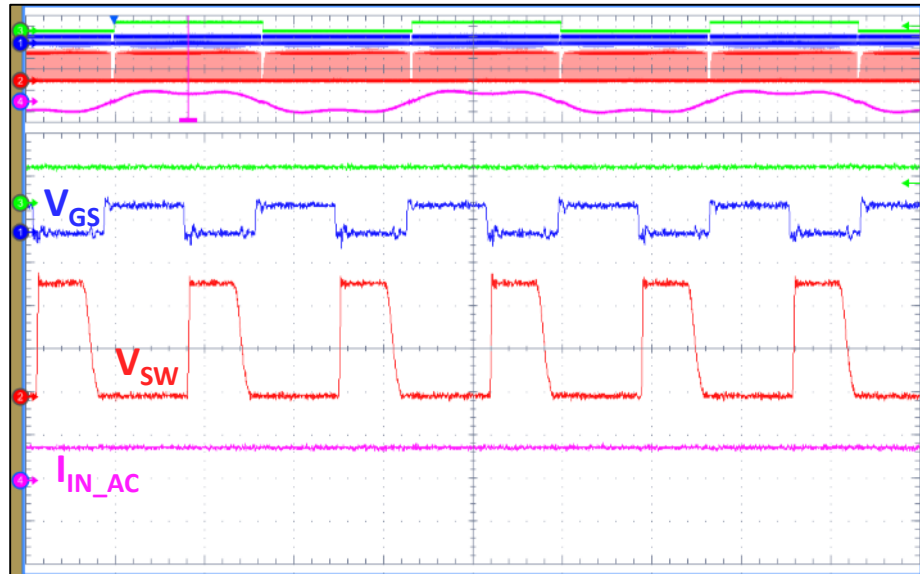


150W: Running Cool

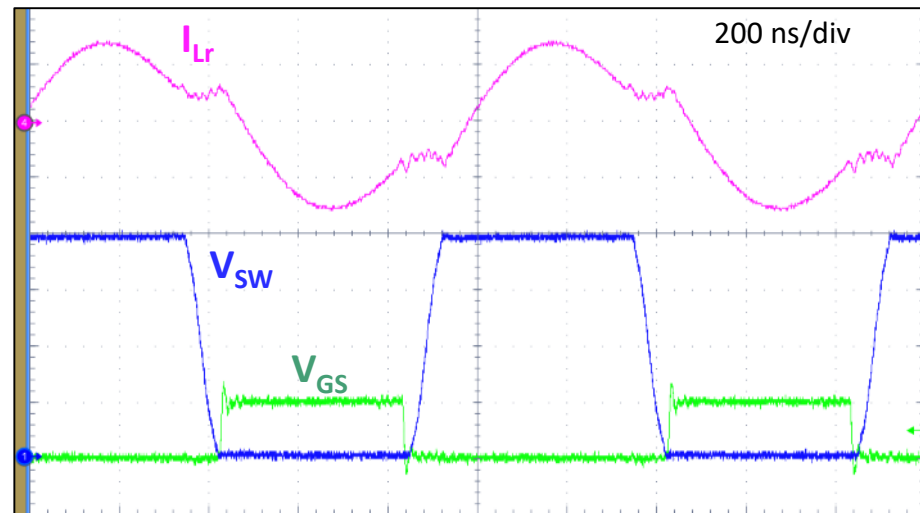


AllGaN 2017: MHz 150W Totem-pole + LLC

PFC

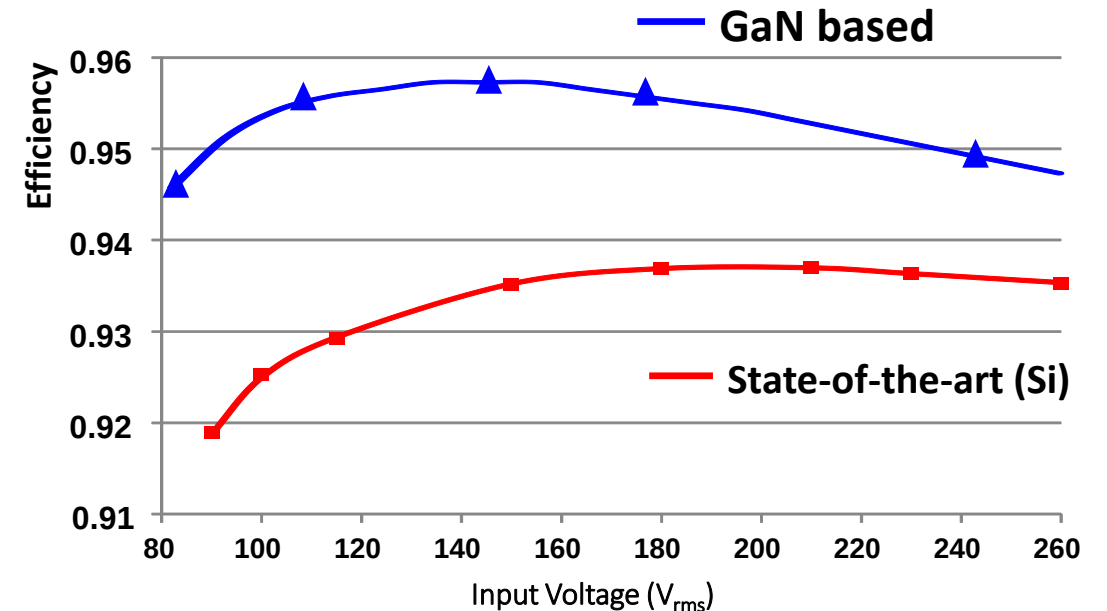
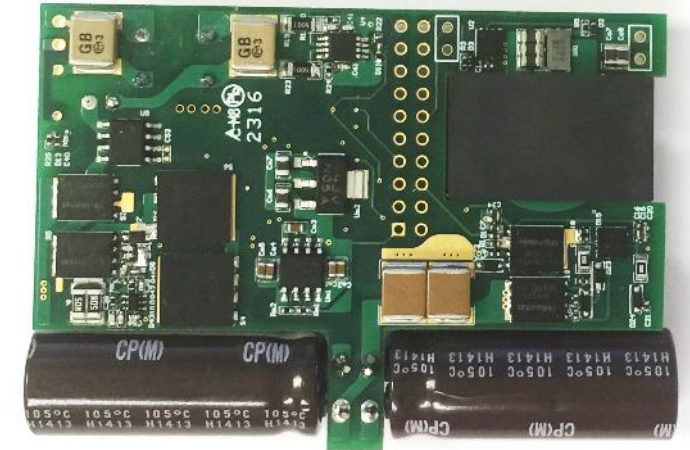


LLC

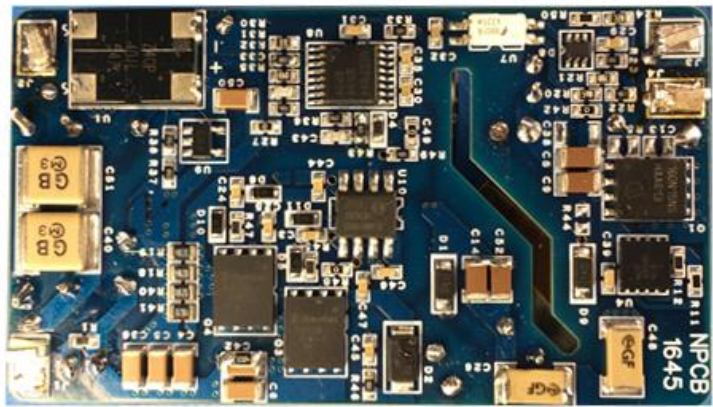
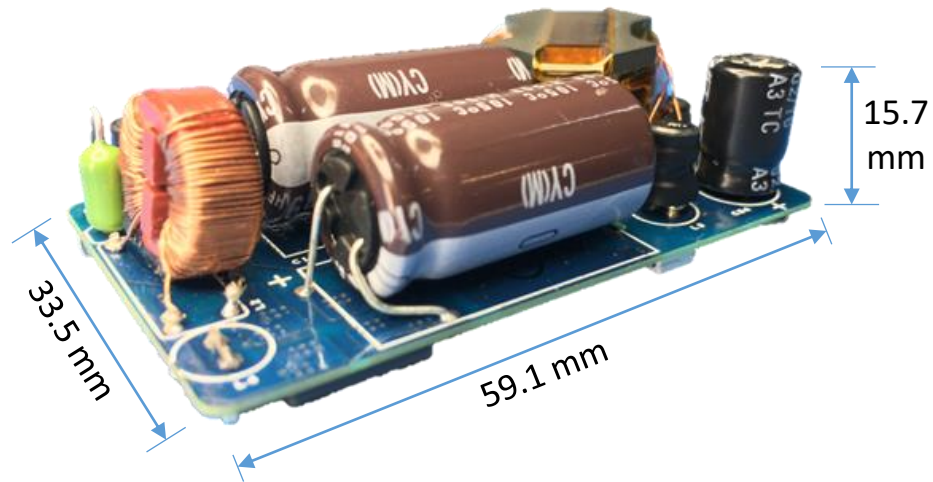


GaN-based
Power Density
 $= 35 \text{ W/in}^3$

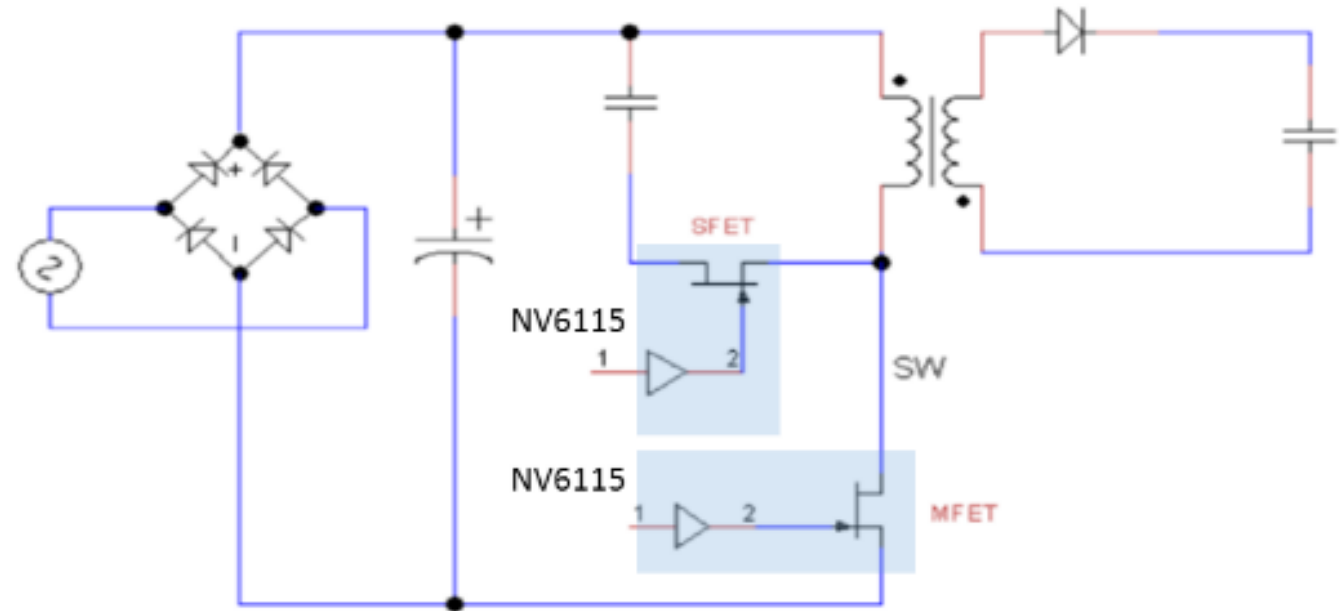
(Best commercial benchmark
 $= 12 \text{ W/in}^3$)



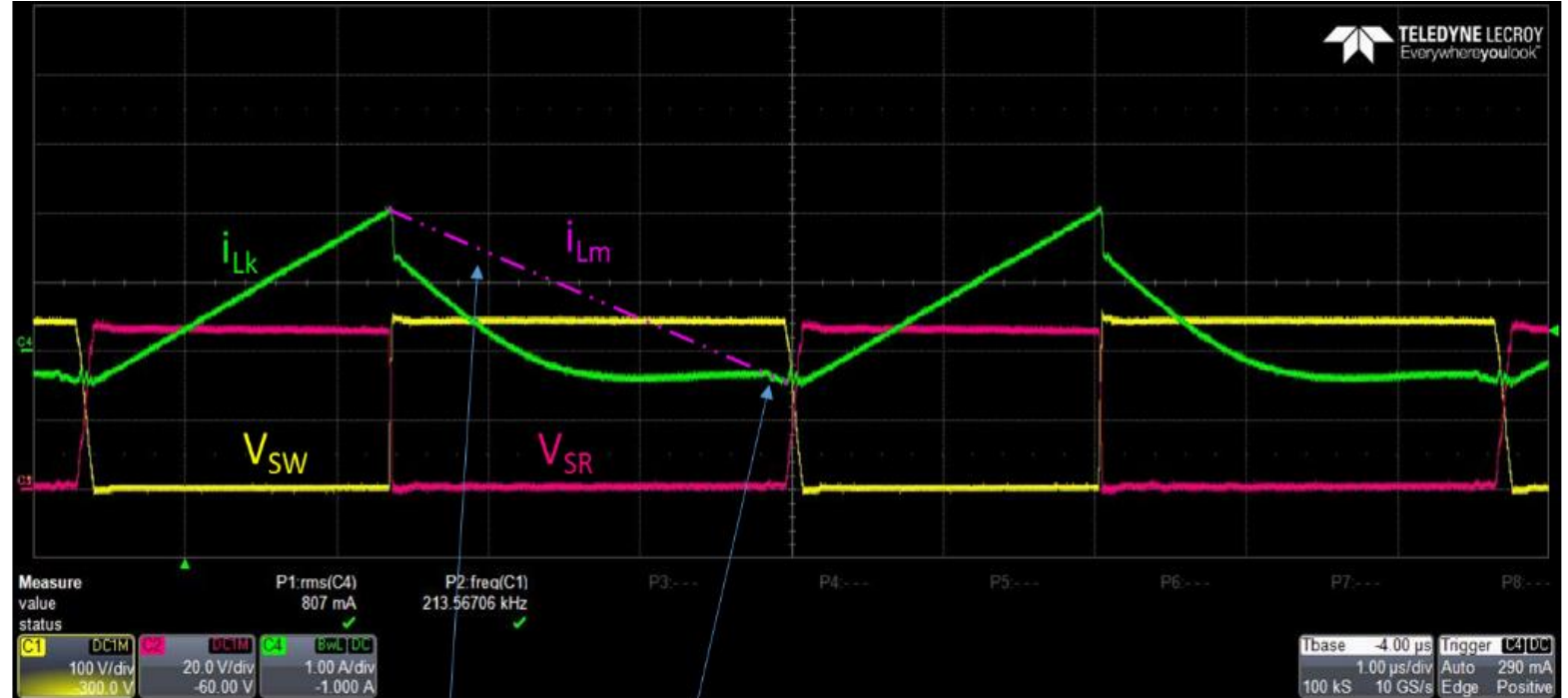
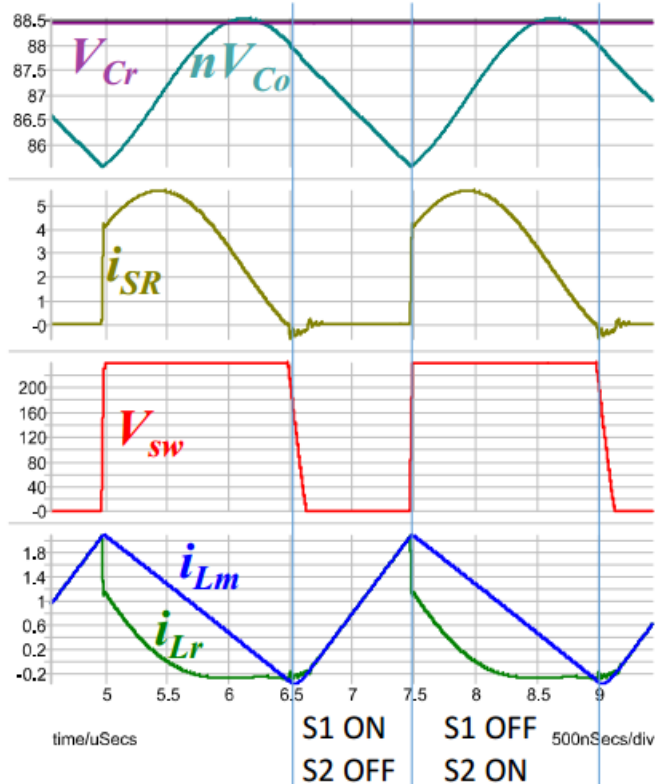
45W Active Clamp Flyback & AlGaN Power ICs



- 94.5% efficient at 220 V (94.2% at 120 V_{AC}, 93.1% at 90 V_{AC})
- 23.7 W/in³ density (uncased)
- 15.7 mm profile



45W CrCM ACF Operation

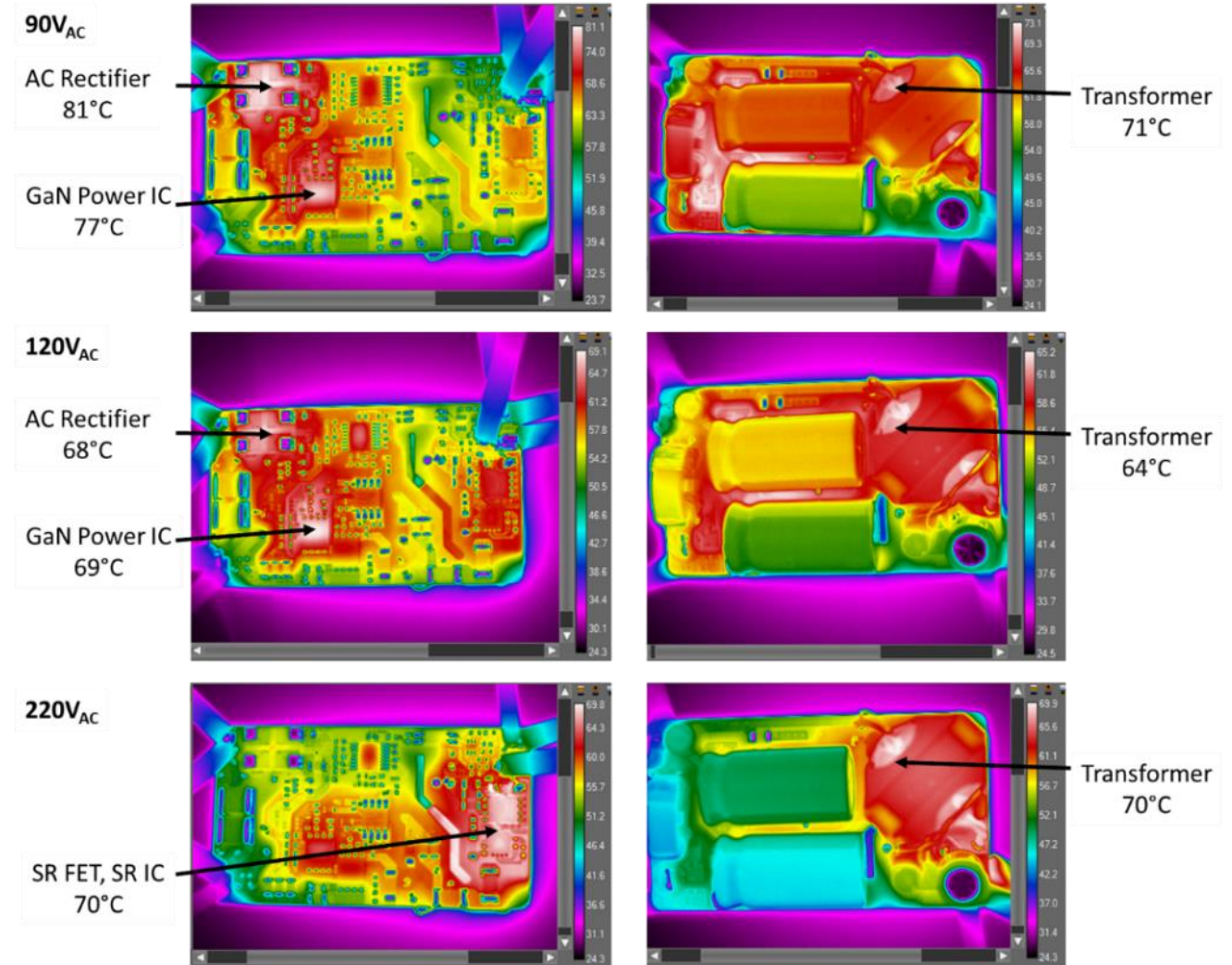
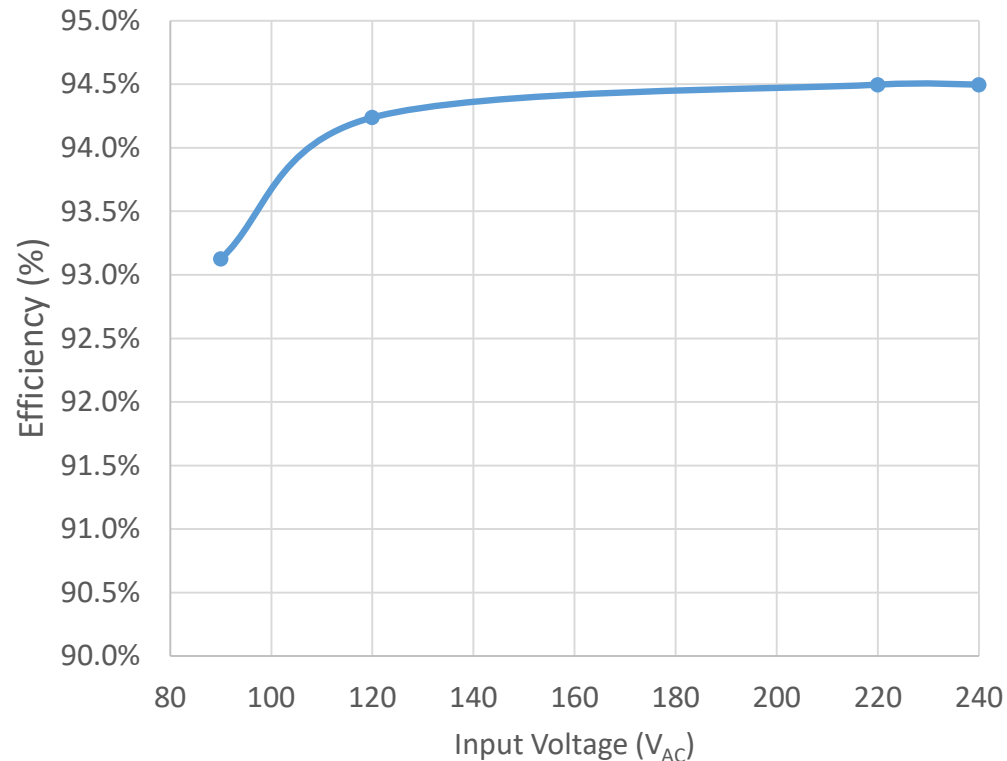


Magnetizing current (drawing)

Inductor current merges with magnetizing current, achieves SR ZCS turn-off

- Switch-node voltage (V_{sw}), SR FET voltage (V_{sr}), leakage current (i_{Lk}) and magnetizing current (i_{Lm})
- 120V_{AC}, 0.2A load, $F_{sw} = 210\text{kHz}$, Circulating Current minimized using Secondary Resonance

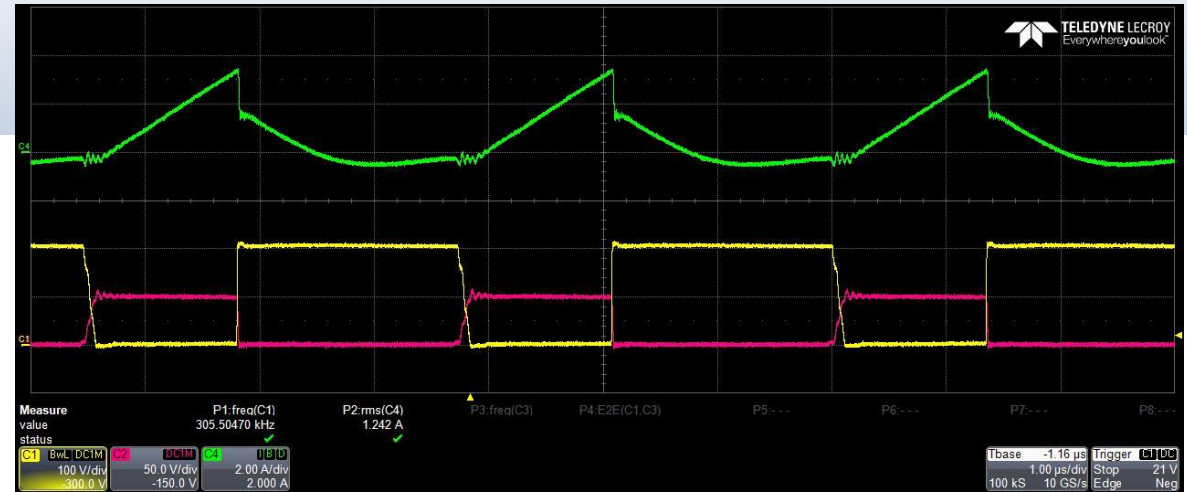
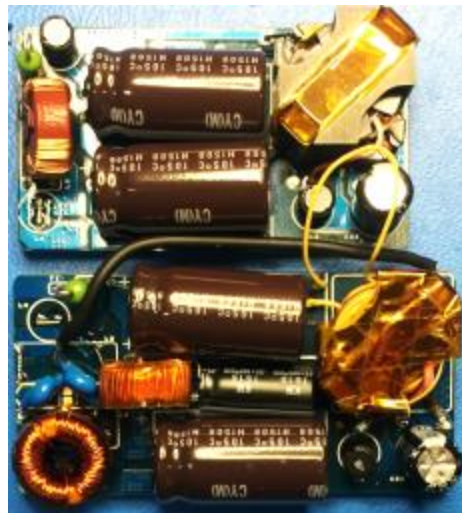
45 W ACF: High Efficiency, Cool Temperatures



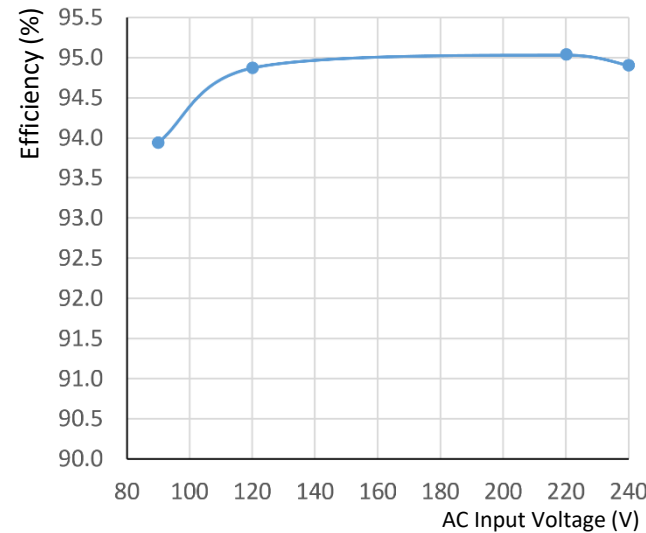
45W→65W ACF

Just 13% longer for 44% more power

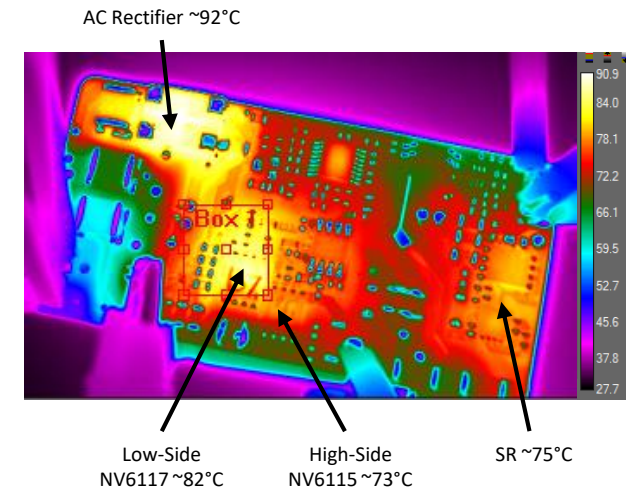
45W = 59.1 x 33.5 x 15.7 mm = 24 W/in³ (uncased)
2x NV6115 (160mΩ)



ACF switching waveforms, 300 kHz

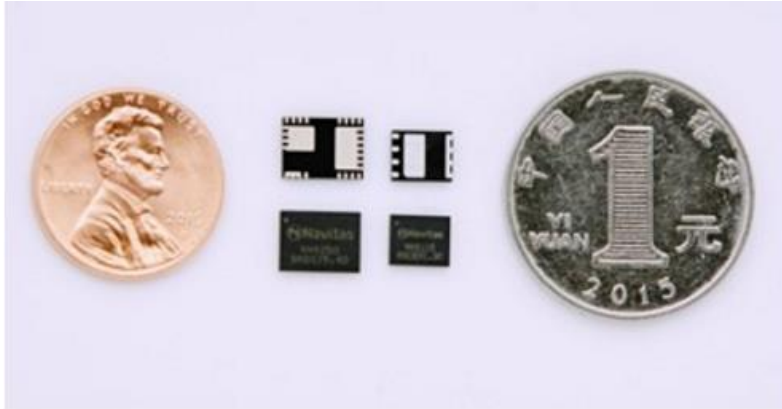


65W Efficiency (excluding EMI) vs. AC line
(25°C ambient, no airflow, full load)

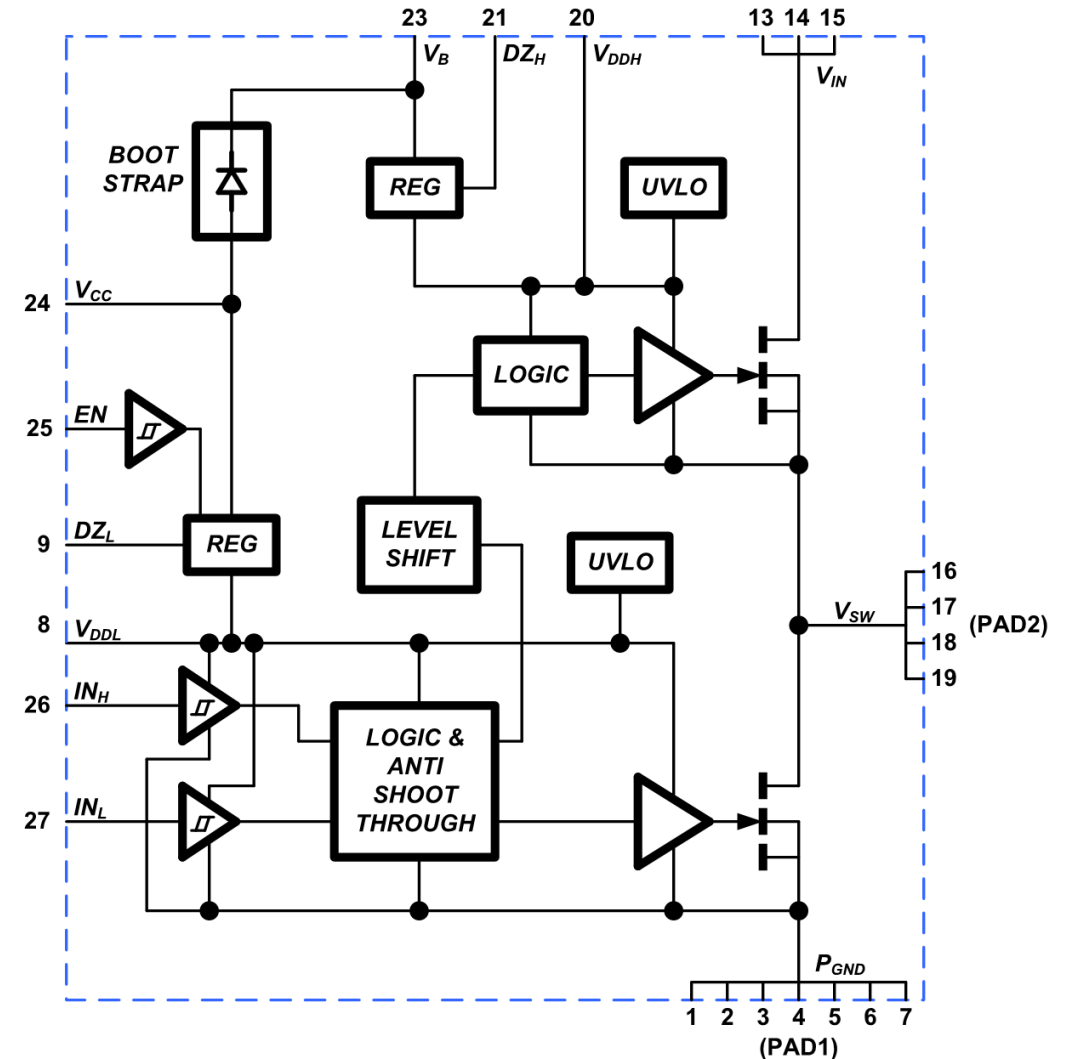


65W Thermal Performance
(90VAC, 25°C ambient, no airflow, full load)

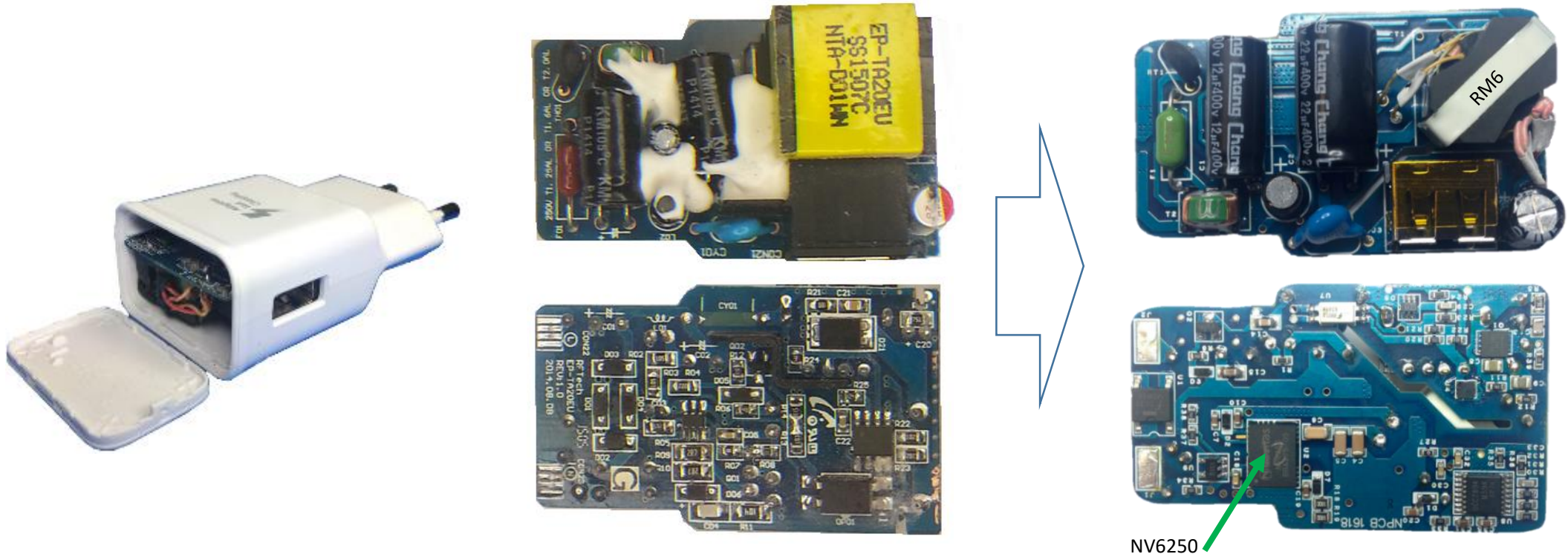
650V Half-Bridge AllGaN™ Power IC



- Proprietary AllGaN™ technology
- Monolithic integration of 650V eMode GaN FET, driver, logic
- Internal level-shift, bootstrap
- Ground-referenced, digital input
- High dV/dt immunity (200 V/ns)
- Zero inductance turn-off loops
- ESD, UVLO, shoot-through protection
- Flexible topologies: Active Clamp Flyback, Half-Bridge, LLC, etc.



66% Higher Power with Half-Bridge GaN Power IC

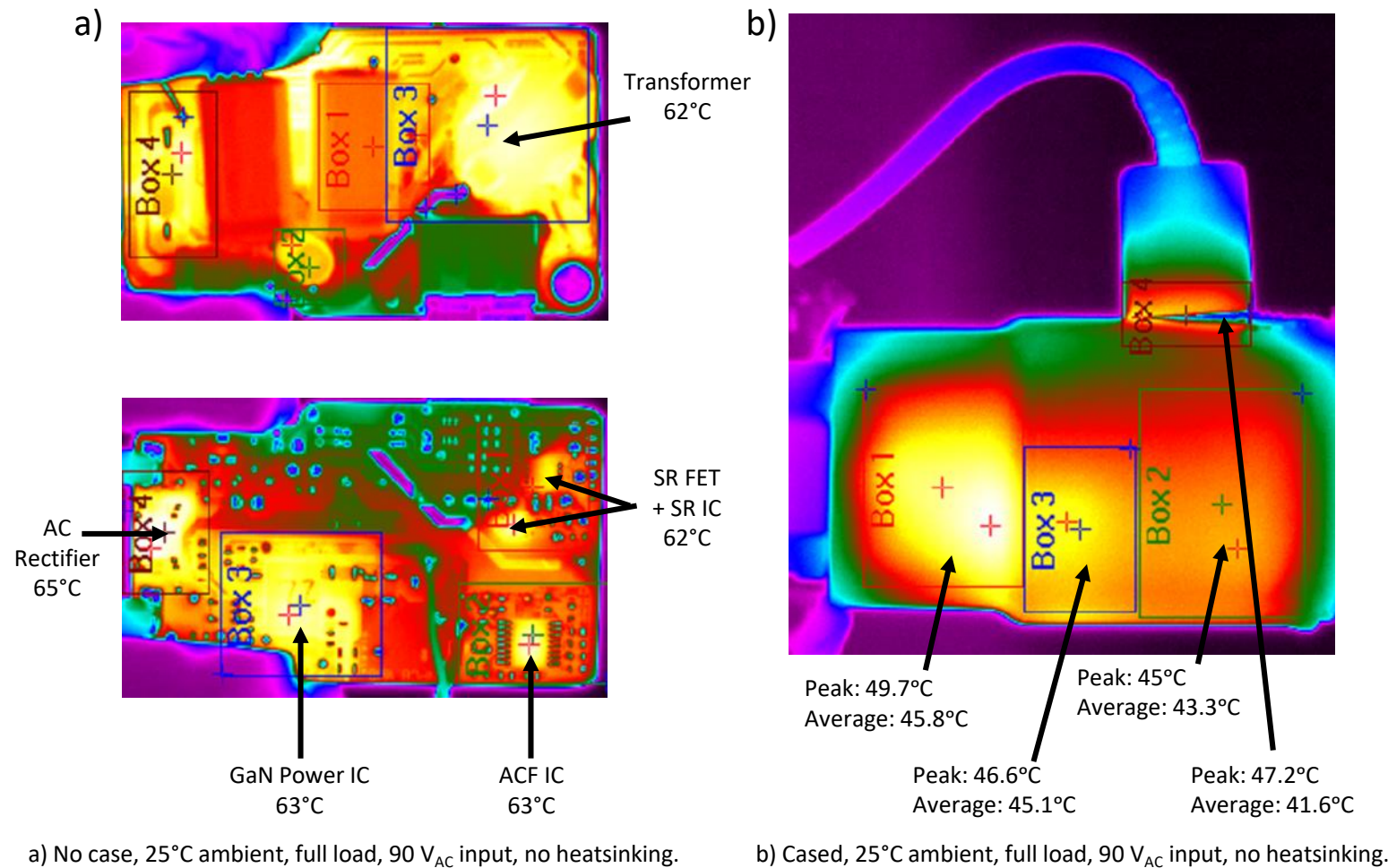


a) Original 15 W AC charger case

b) Original 15 W, Si-based QR Flyback, ~100 kHz

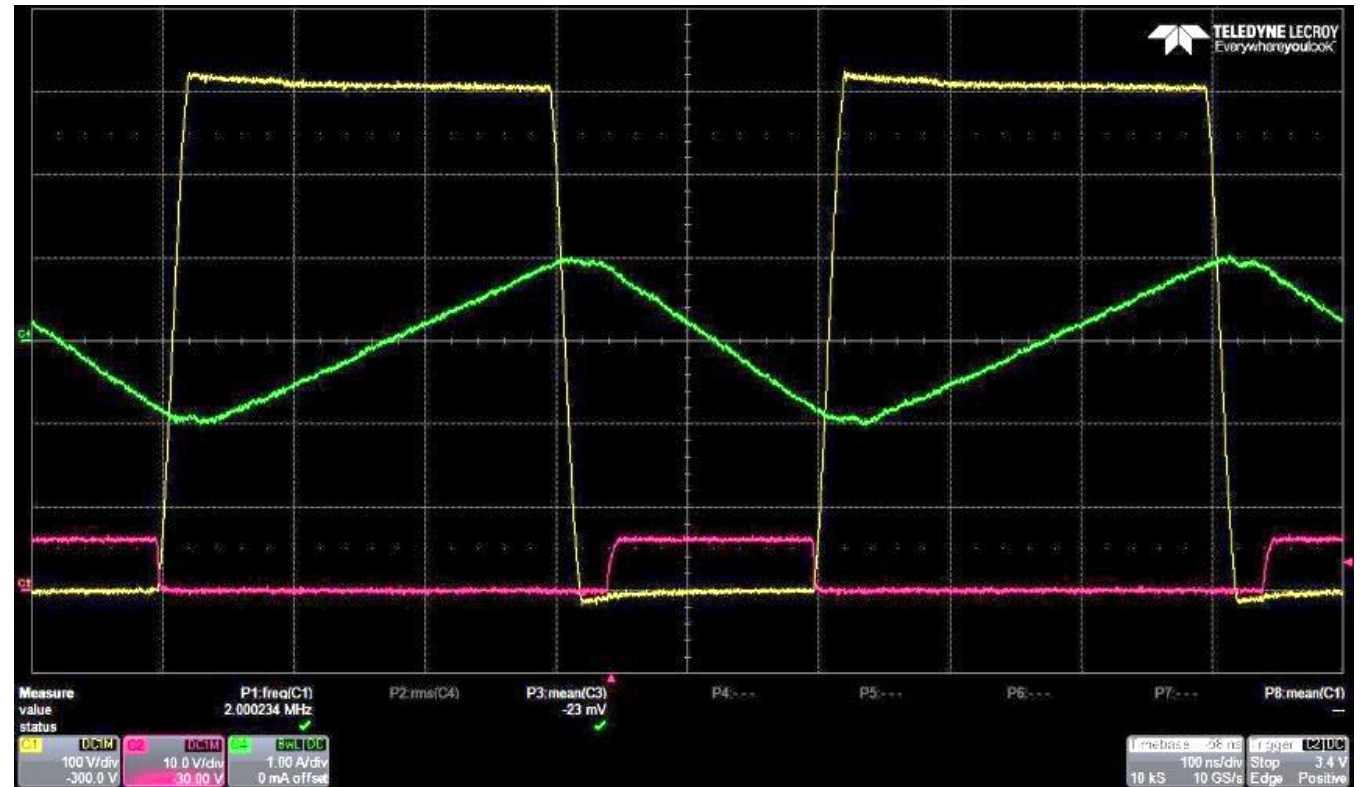
c) Upgraded 25 W, Half-Bridge GaN Power IC ACF, ~400 kHz

25W Cool Thermals (12.5V, 2A)

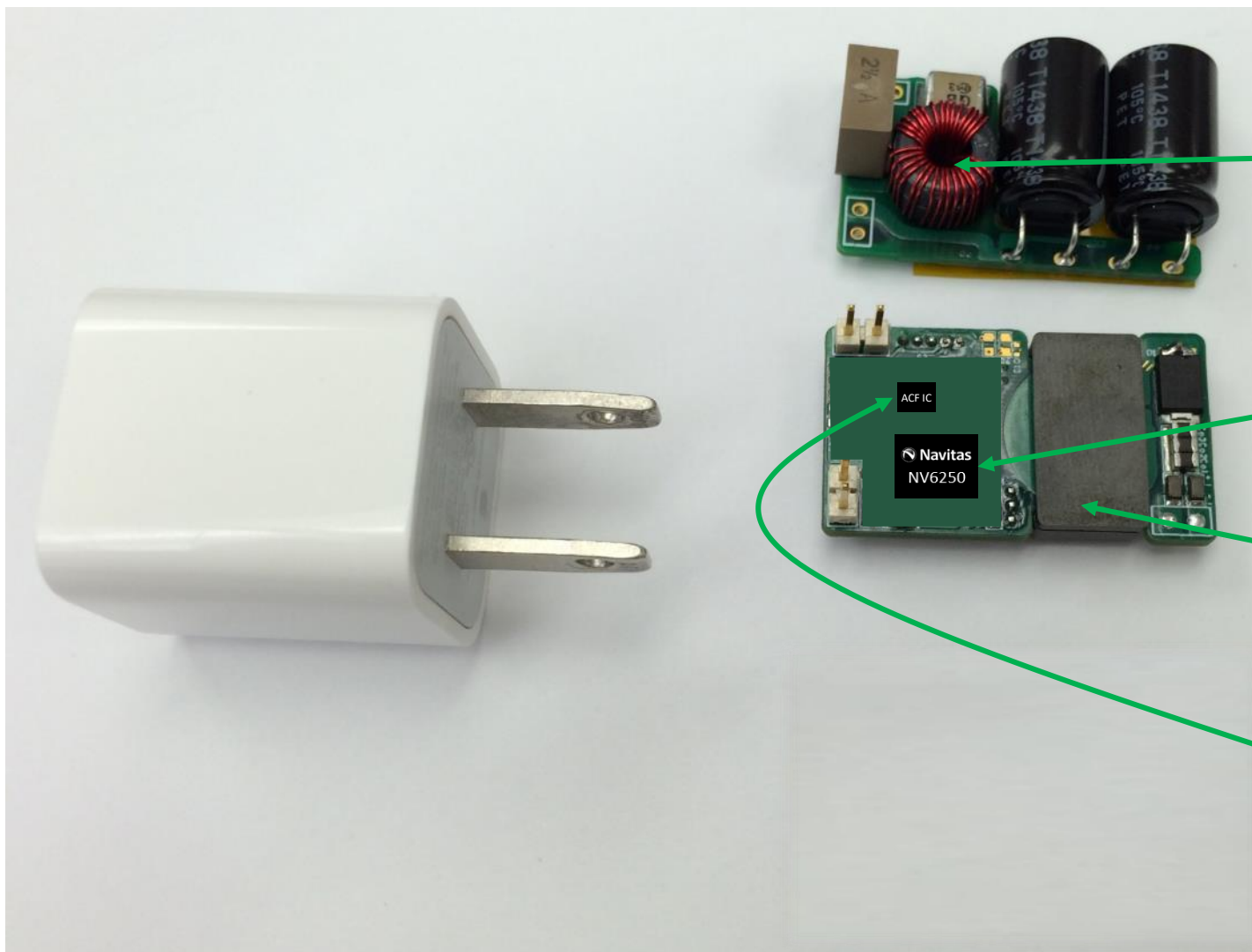


Clean 600V ZVS switching at 2 MHz

- Demonstration board with half bridge AllGaN™ Power IC driving an LC resonant load
- Nearly perfect, loss-free half bridge switching up to 650V with a single part
- Only 5V PWM logic signals are needed
- No diode recovery losses
- No turn-on losses
- Nearly zero turn-off losses



1 MHz, 25 W ACF – Next Step



- Single-stage EMI

- 1x Navitas Half-Bridge GaN Power IC

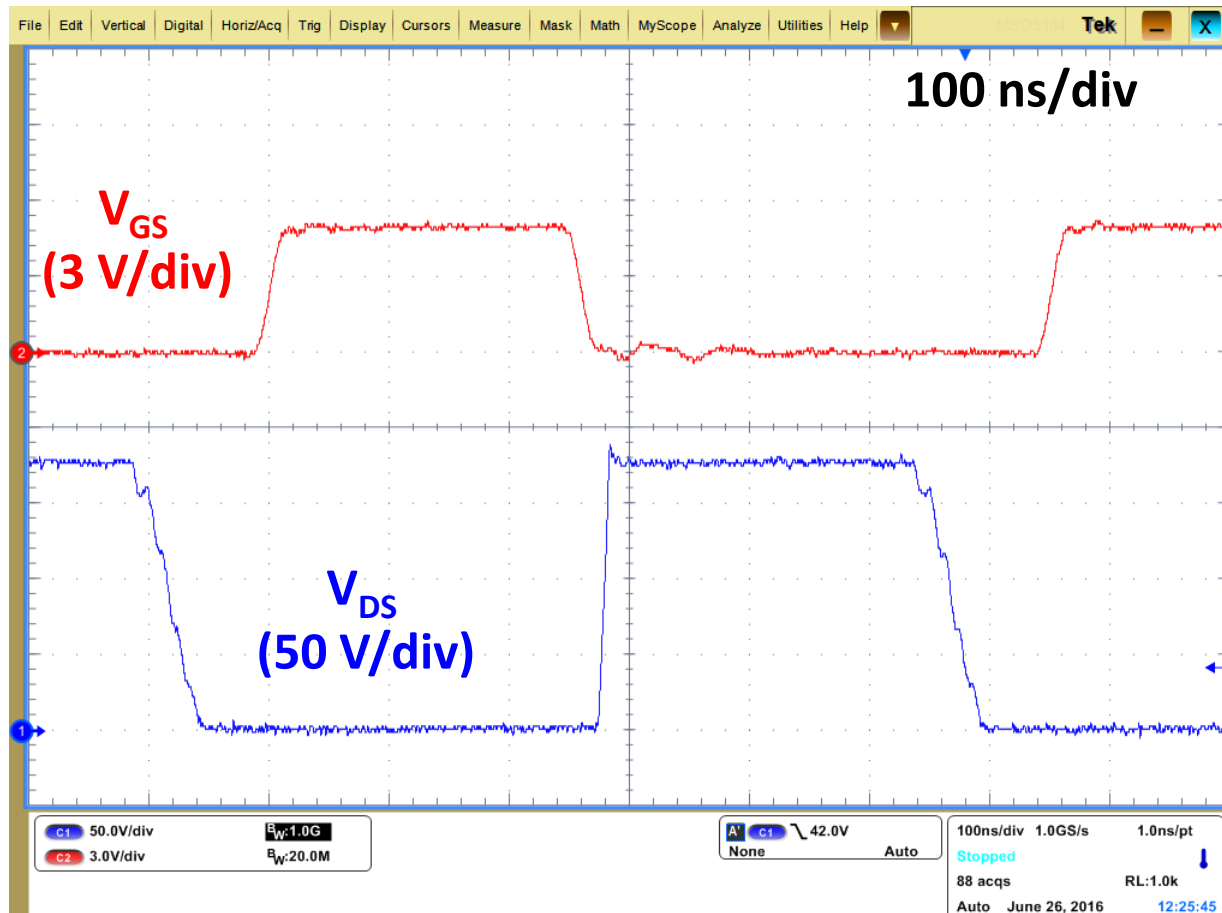
- Planar transformer

- ACF IC

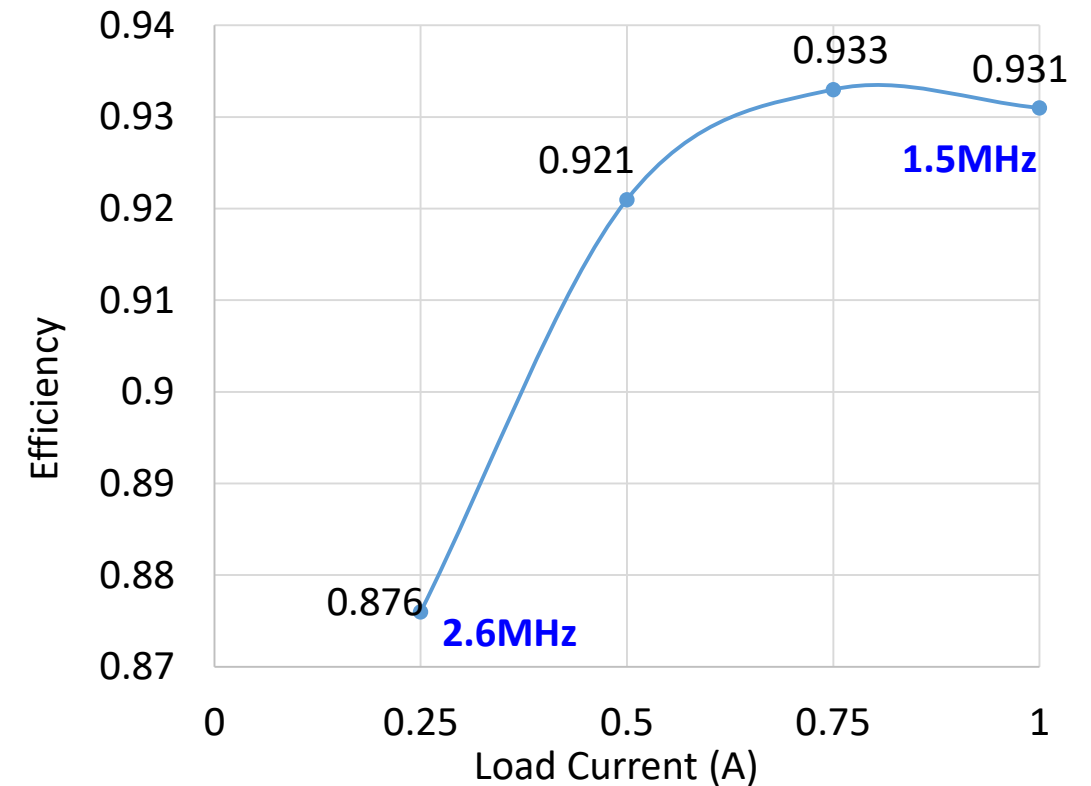


MHz+ 25 W ACF Prototype Performance

$F_{sw}=1.5\text{MHz}$



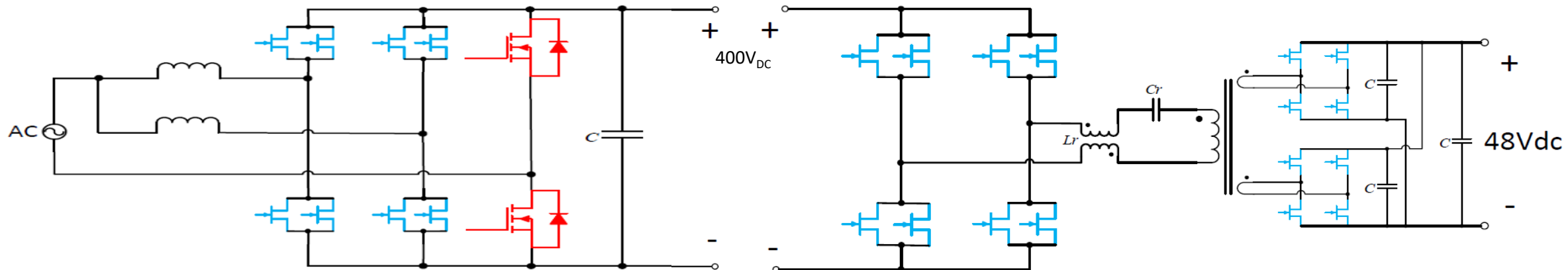
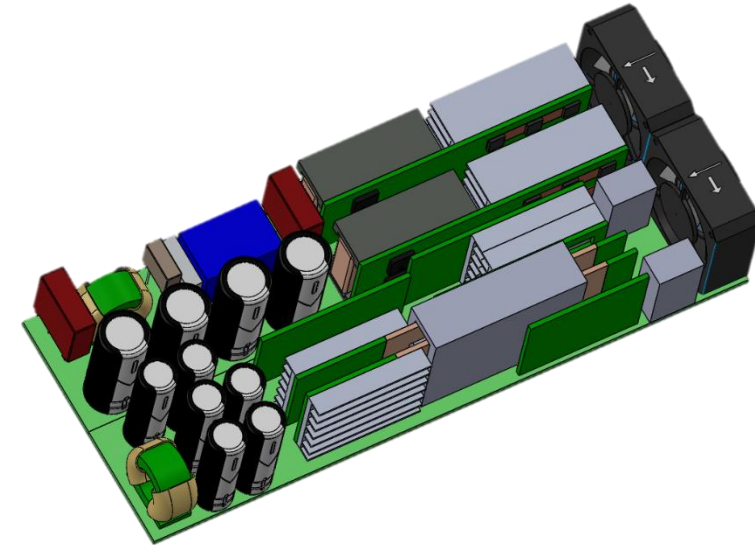
Efficiency vs. Load



* Exclude bridge and EMI filter loss

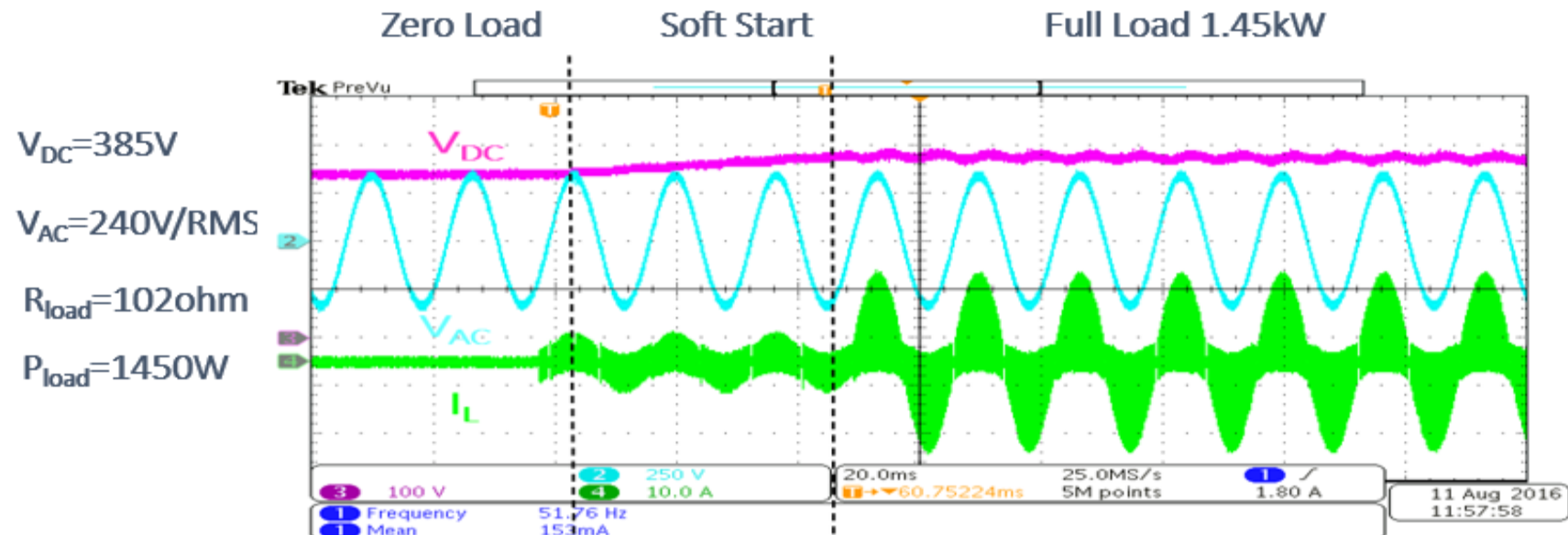
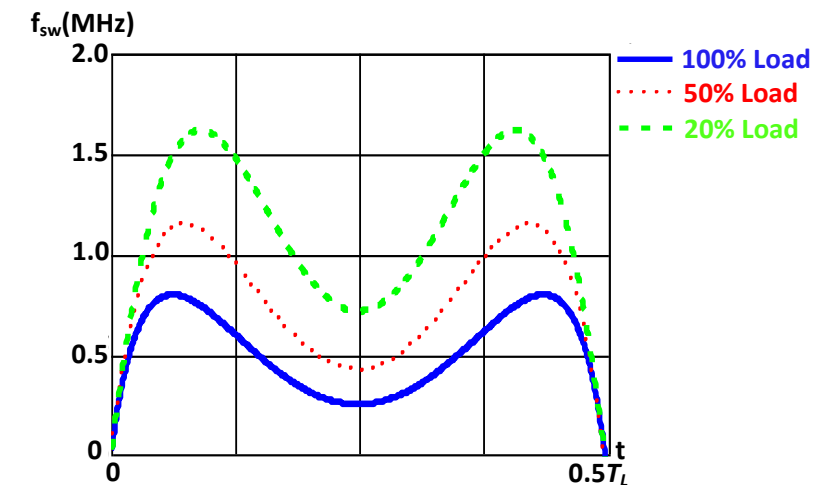
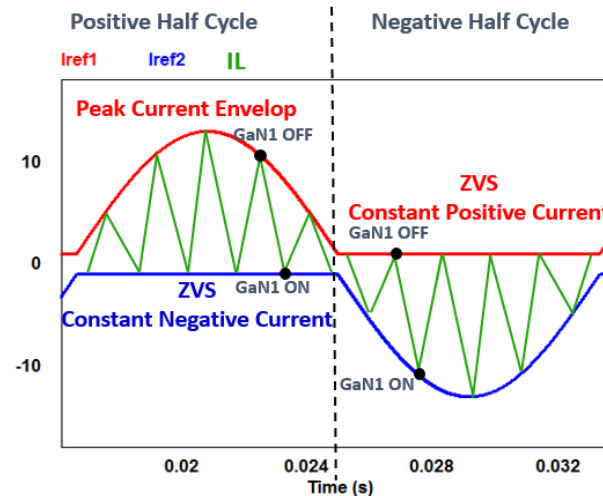
1 MHz, 3.2 kW Server Supply – 65 W/in³

- 220 V_{AC} (47-63 Hz) to 48 V, 3.2 kW
 - Target > 97.5% efficiency (<80W loss)
 - >99% efficiency demonstrated on PFC alpha version
- Multi-phase Totem-Pole CrCM
 - Variable frequency interleaving (500 kHz – 1.5 MHz)
- 2-phase full-bridge LLC with full-bridge SR
 - Fixed-frequency interleaved 1 MHz

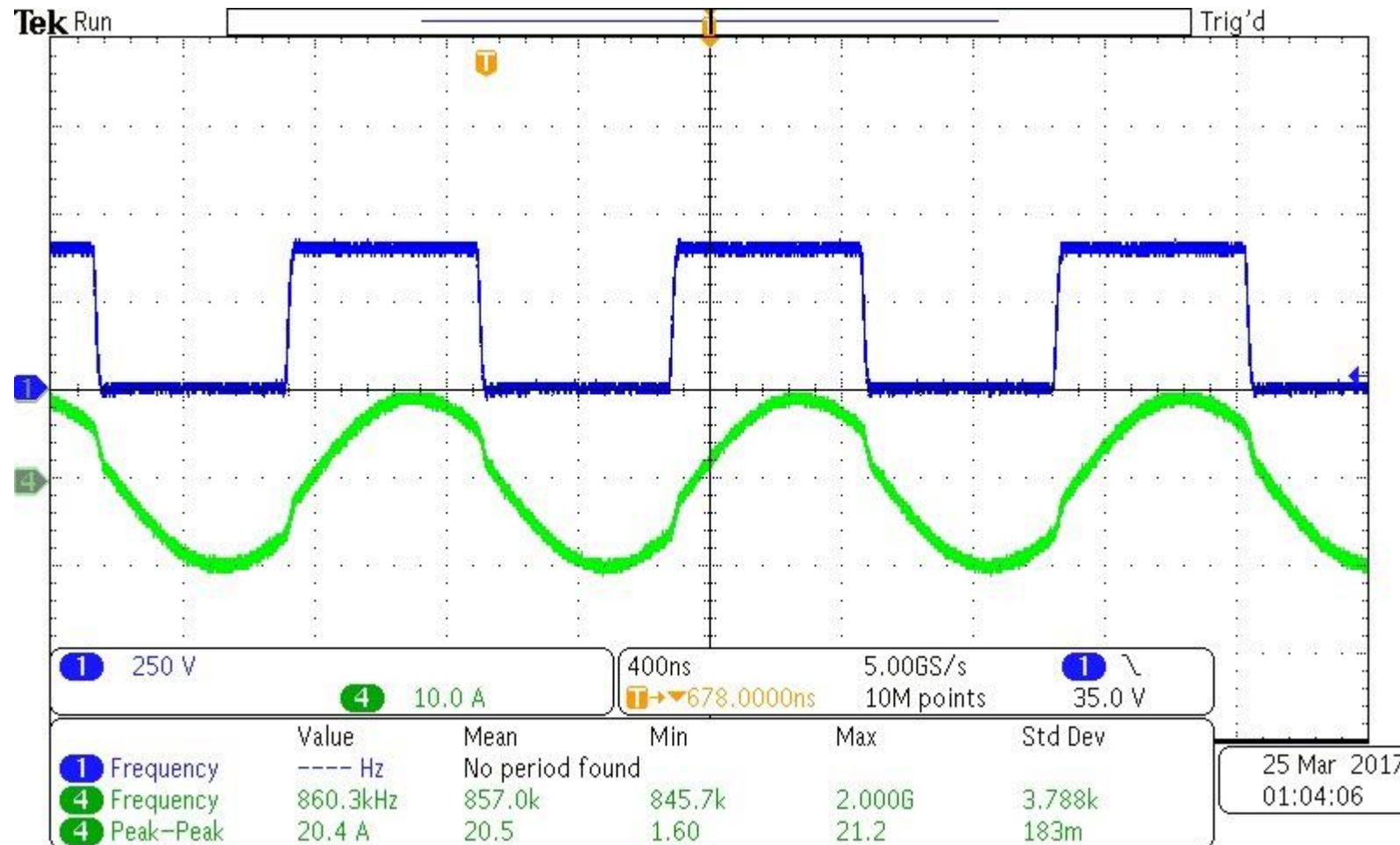


Quasi-Square Wave PFC Full-range ZVS Operation

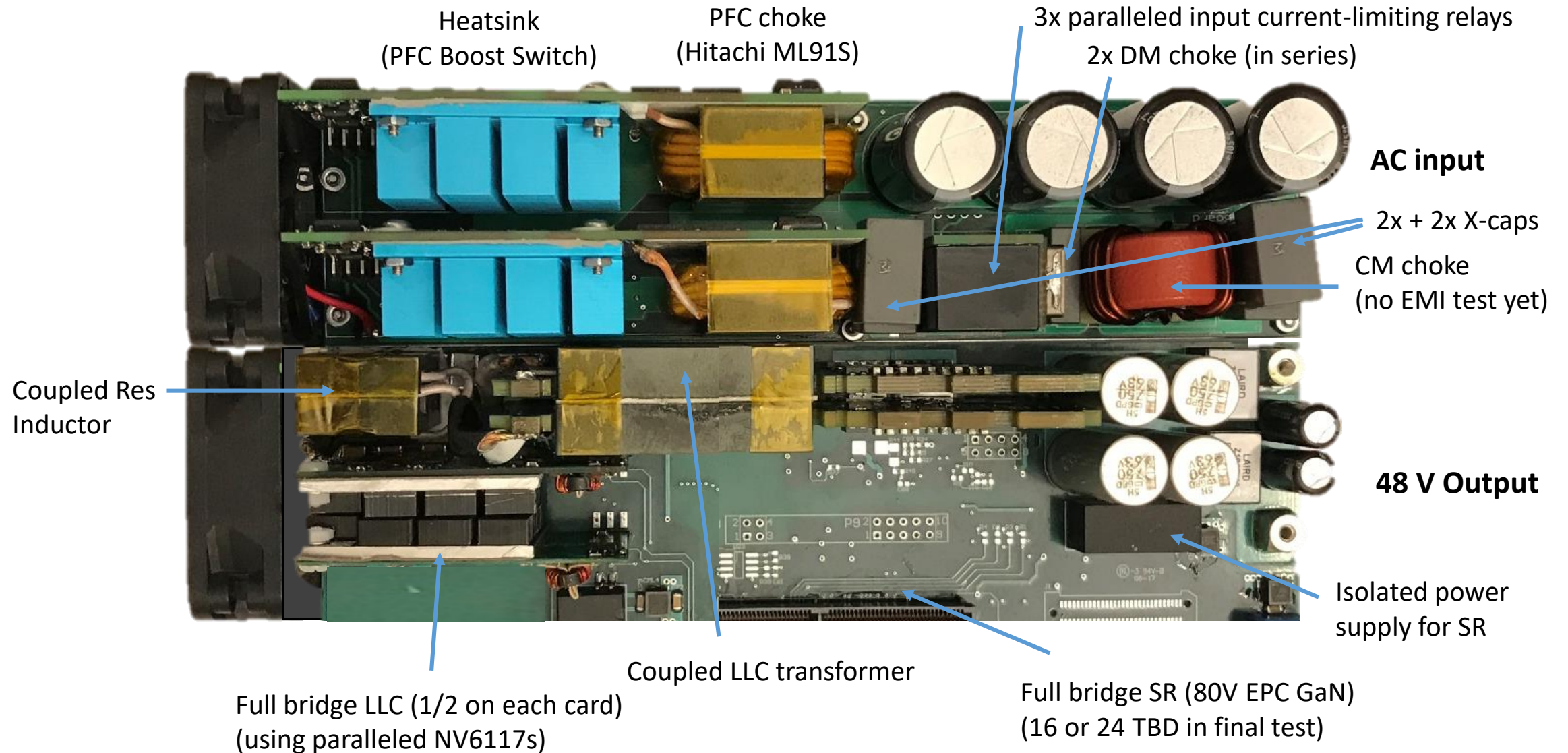
- Totem Pole Configuration
- Current Mode Control
- Constant ZVS current point
- Alpha version waveforms



Preliminary LLC Waveforms at 400V, 2.4kW



1 MHz, 3.2 kW – 100% GaN



We Have Arrived!

- GaN Power ICs are now delivering these desired features and more
- System designers are taking a major step forward to deliver more power with less loss in smaller form factors than ever before
- It's time to go “GaN Fast”



PSMA Industry Session, Semiconductors

March 2017