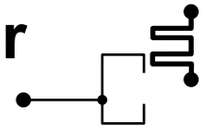
CPEEC & CPSSC 2022
Nov 5-7, 2022

Power Supplies: Heterogeneous Integration - Benefits & Limitations

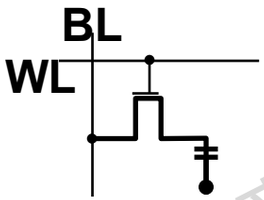
by
Fred C Lee
Center for Power Electronics Systems
Virginia Tech

Micro-electronics vs Power Electronics

Inverter



Signal Processing

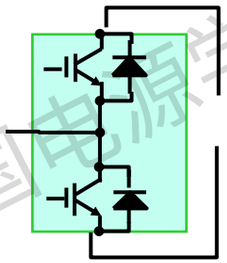


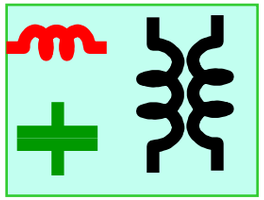
DRAM

Audio/Video → A-to-D Conv. → Number Crunching → D-to-A Conv. → Audio/Video

Monolithic Integration

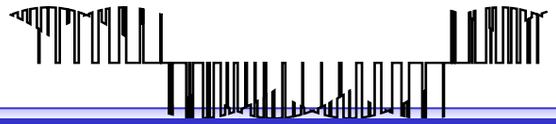
Power Processing





A-to-D → Modulation → D-to-A

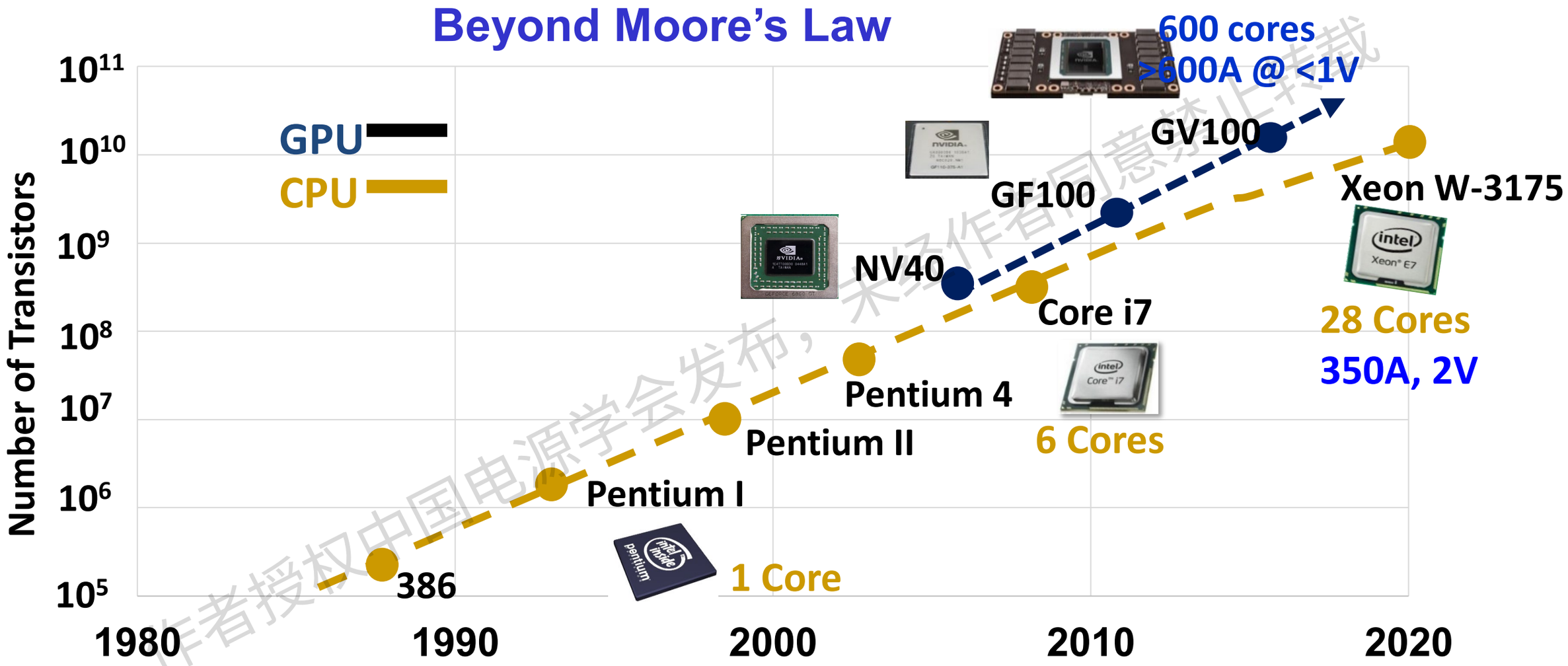
PV



60 Hz

Heterogeneous Integration

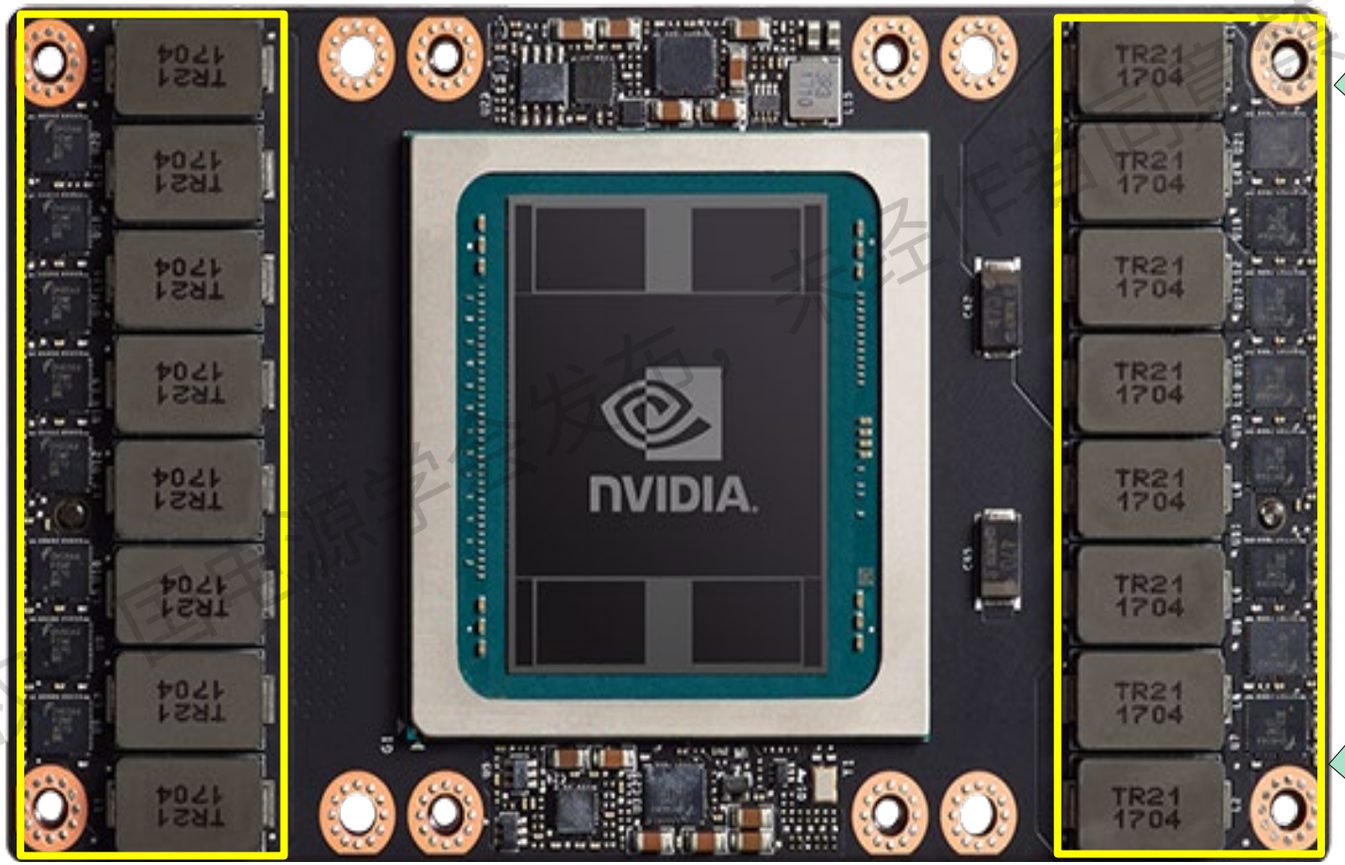
Microprocessor Trends



CPU/GPU with “Embedded Power”

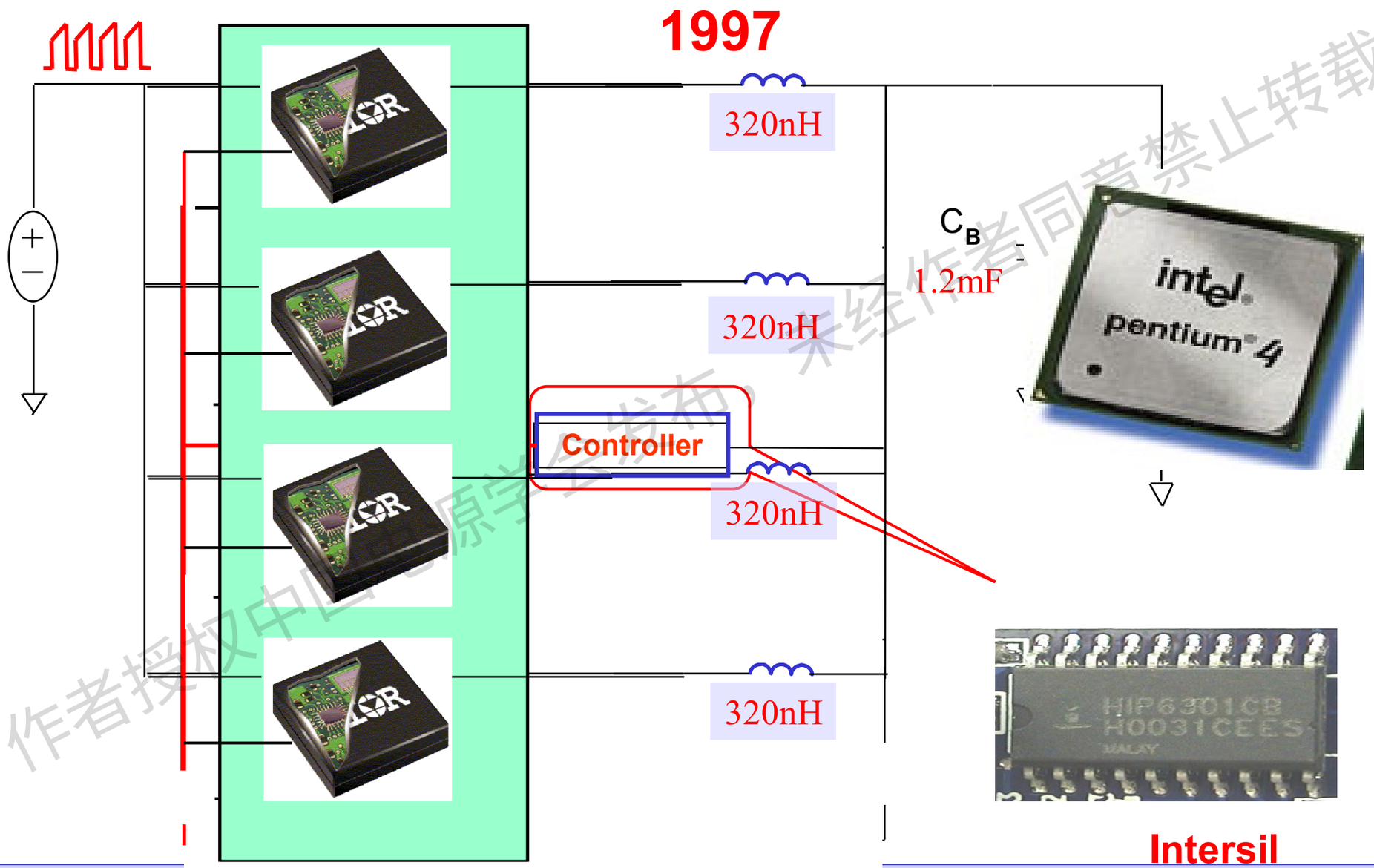
12V/1V

GV100: 16 phase > 600A. Slew rate >1000A/us



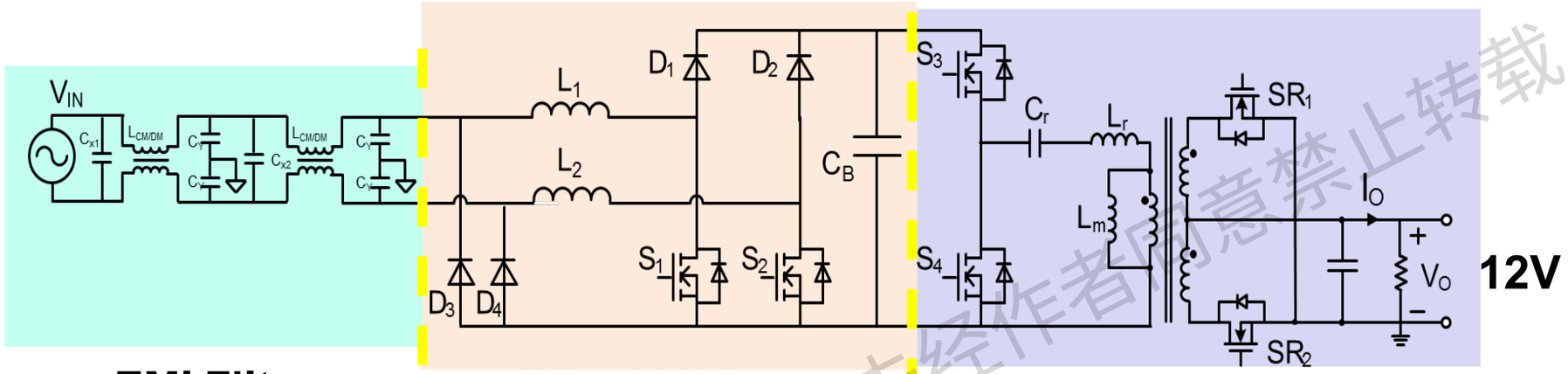
12V/1V

“Integration” of Voltage Regulation Modules



“External Power” :Server Power Supply for Data Center

208VAC

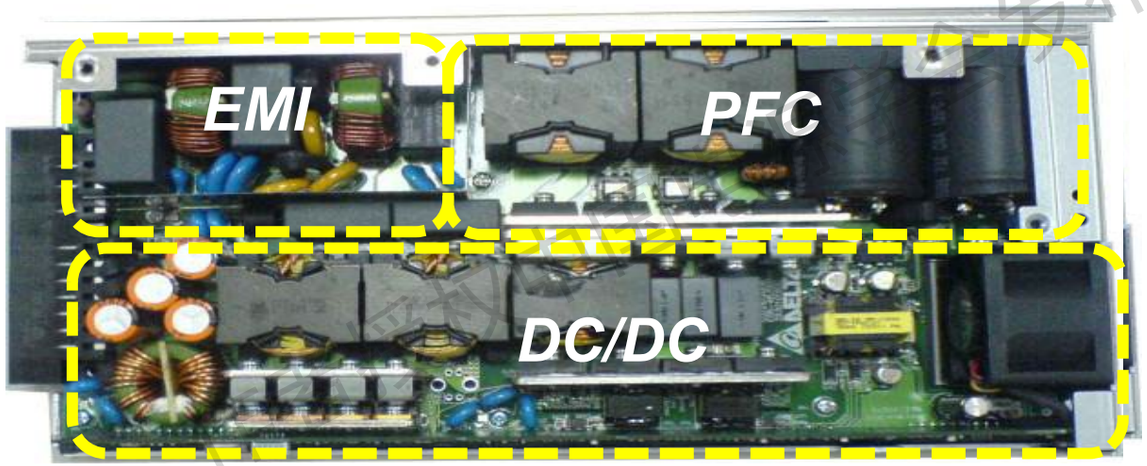


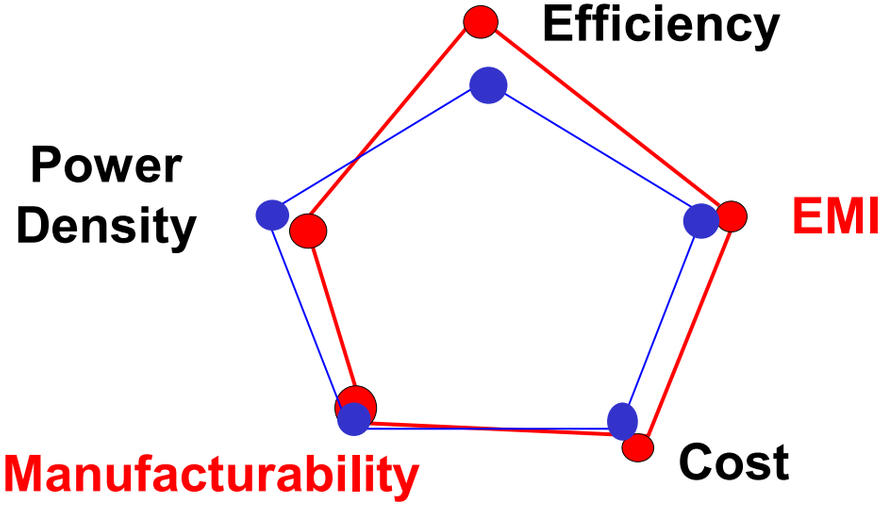
12V

EMI Filter

PFC 100KHz

LLC DC/DC 100-200 KHz



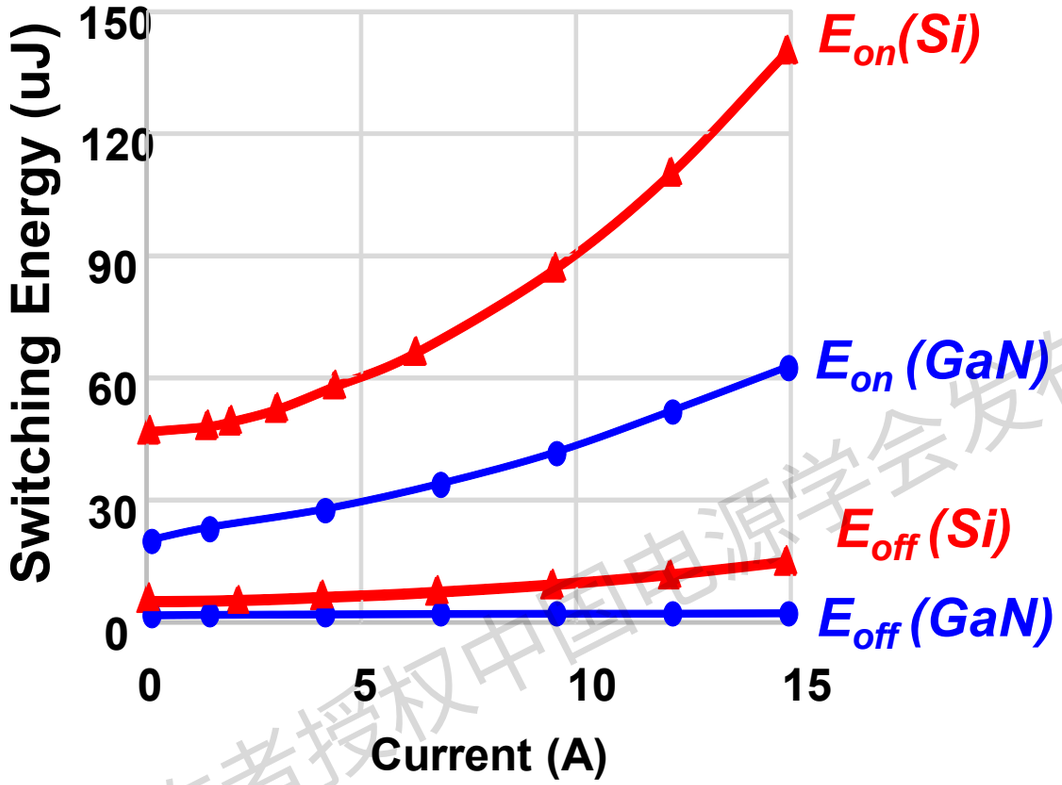


Matured Product 96-97% and 30-40 W/in^3

Labor Intensive Manufacturing

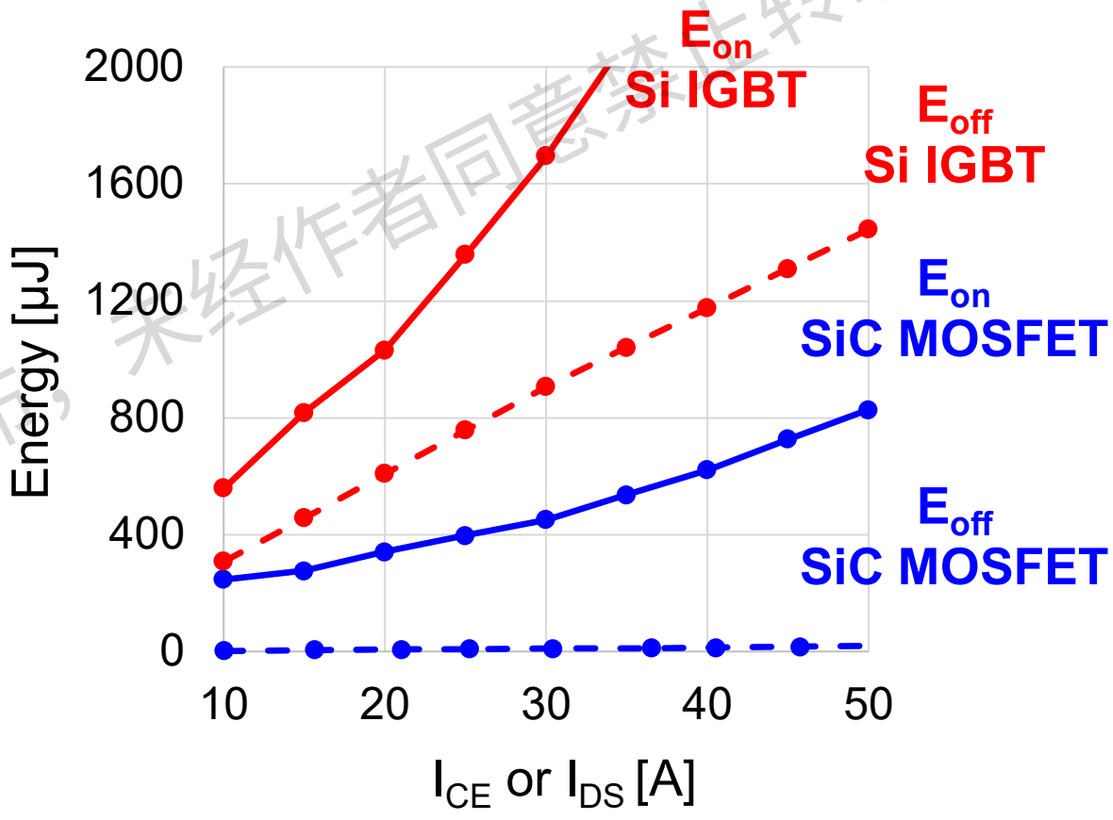
Wide-Band-Gap vs Silicon MOSFET

GaN. vs Si MOSFET



GaN: 3X better

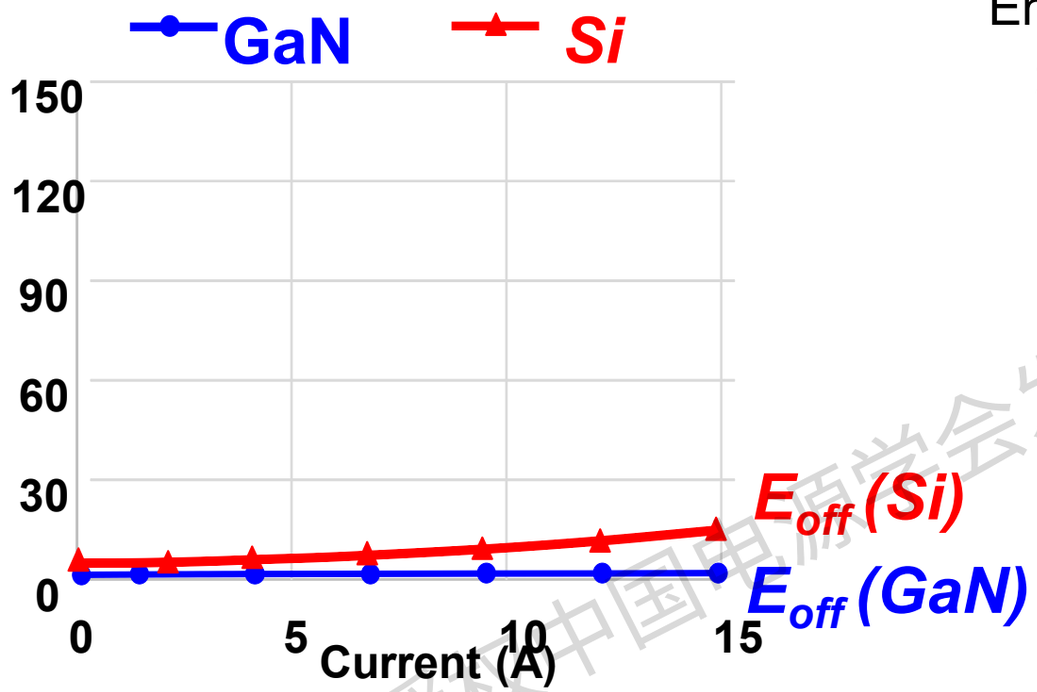
SiC vs IGBT

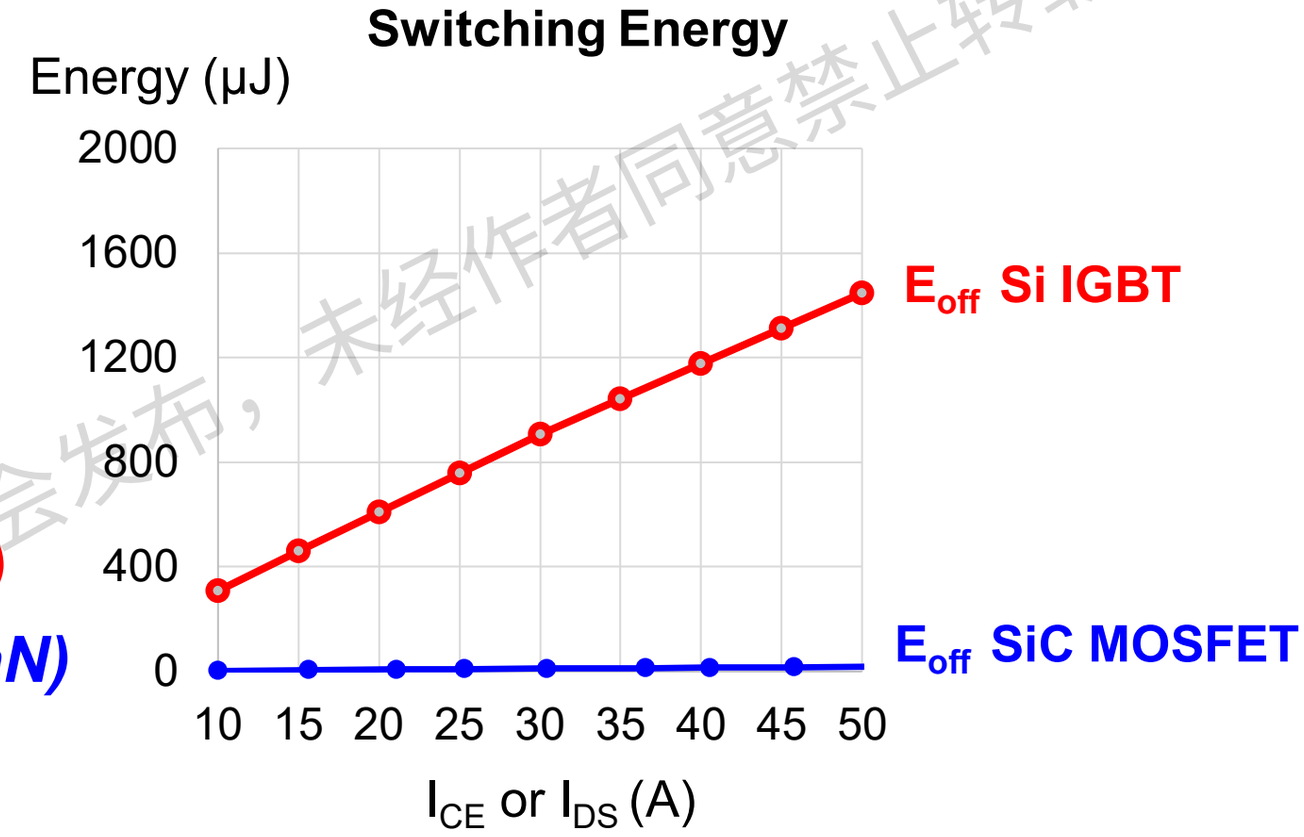


SiC: 3X better

GaN vs Silicon MOSFET

With ZVS



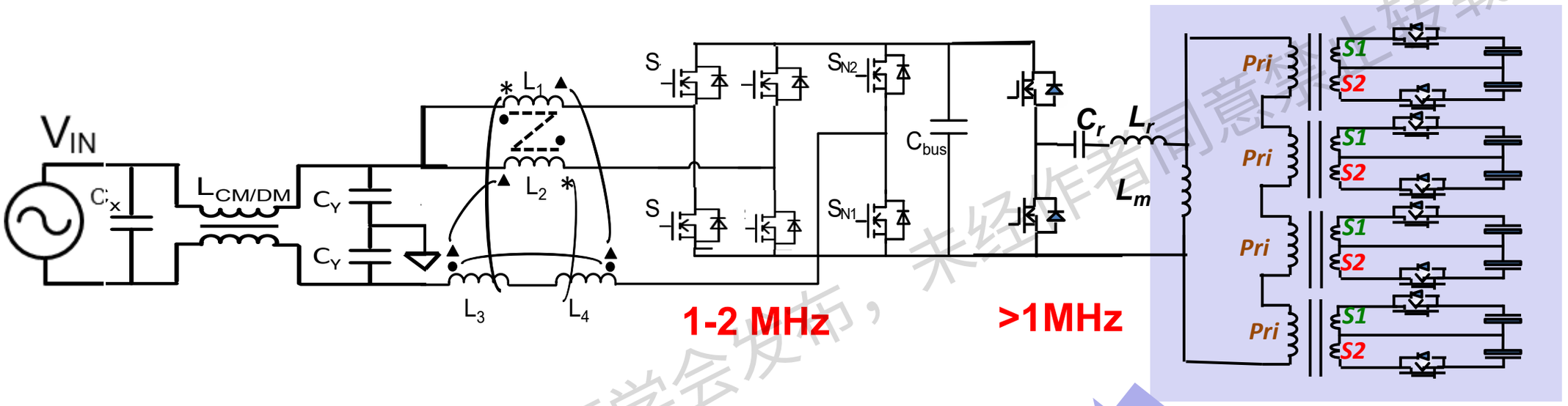


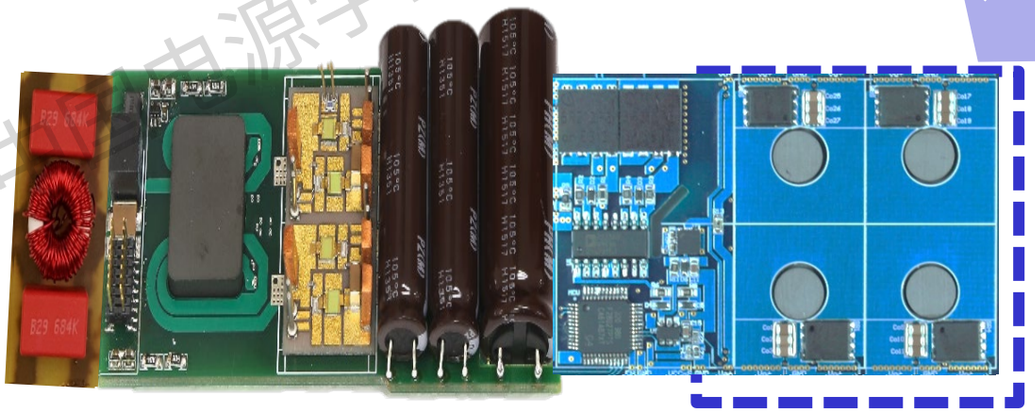
GaN: 10 - 20X better than silicon

SiC: 10 - 20X better than IGBT

GaN Based Integrated Power Supplies

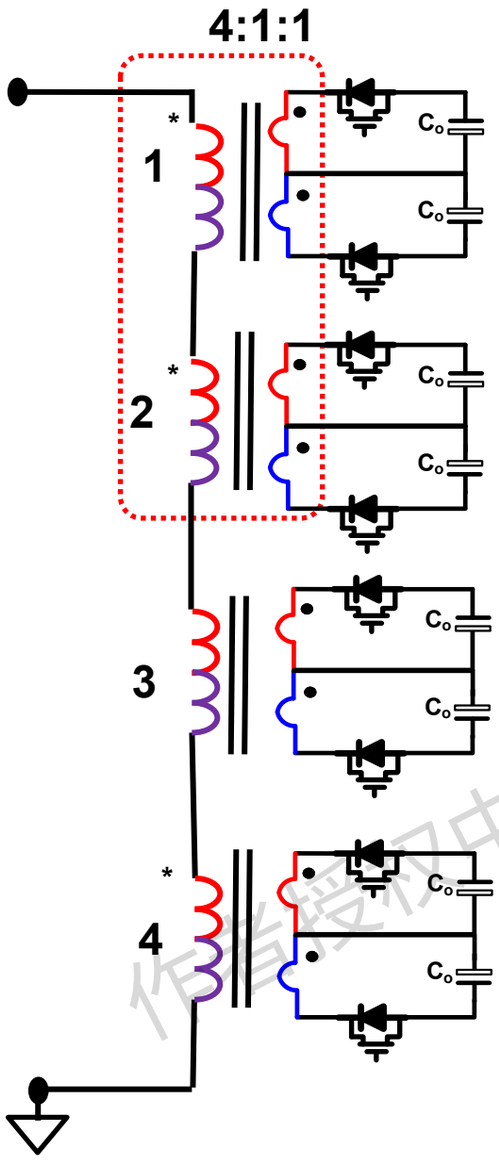
1KW @ 1MHz

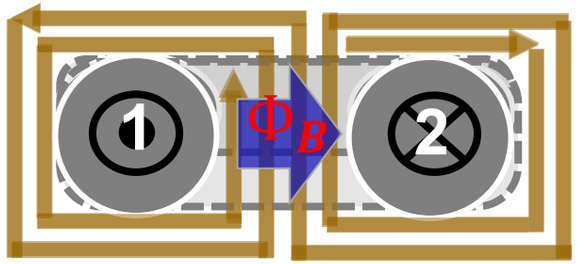


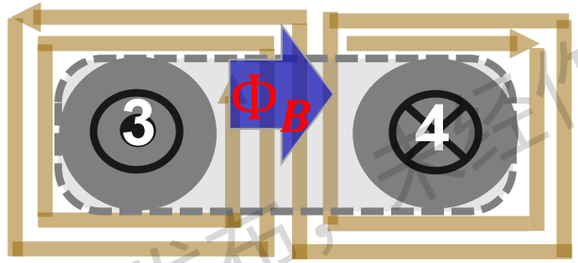


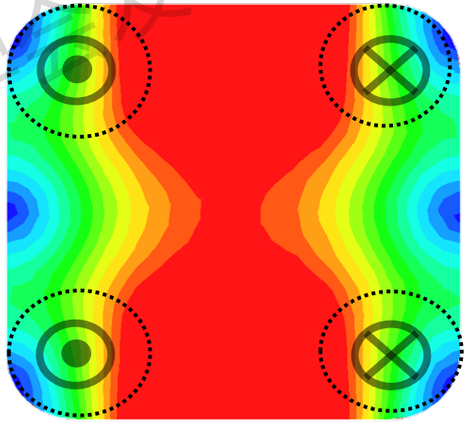
Heterogeneous Integration via PCB

Integration of 4 Transformers in 4 Layer PCB

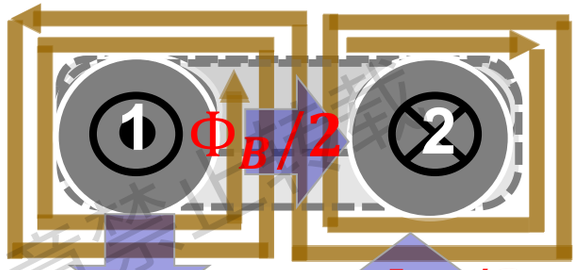


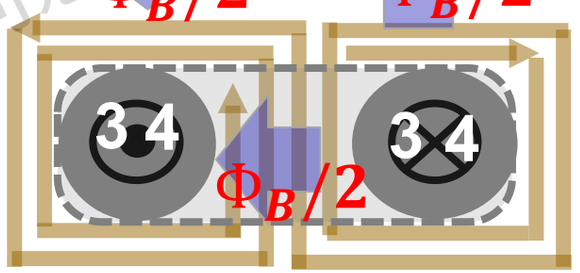


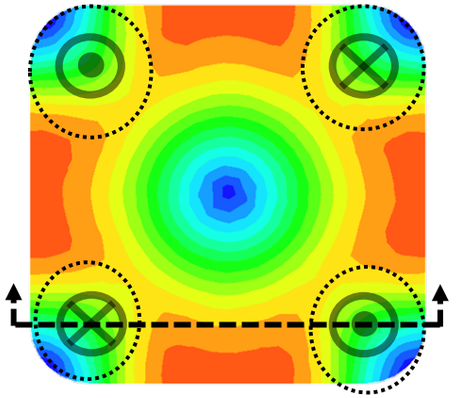




60% volume reduction



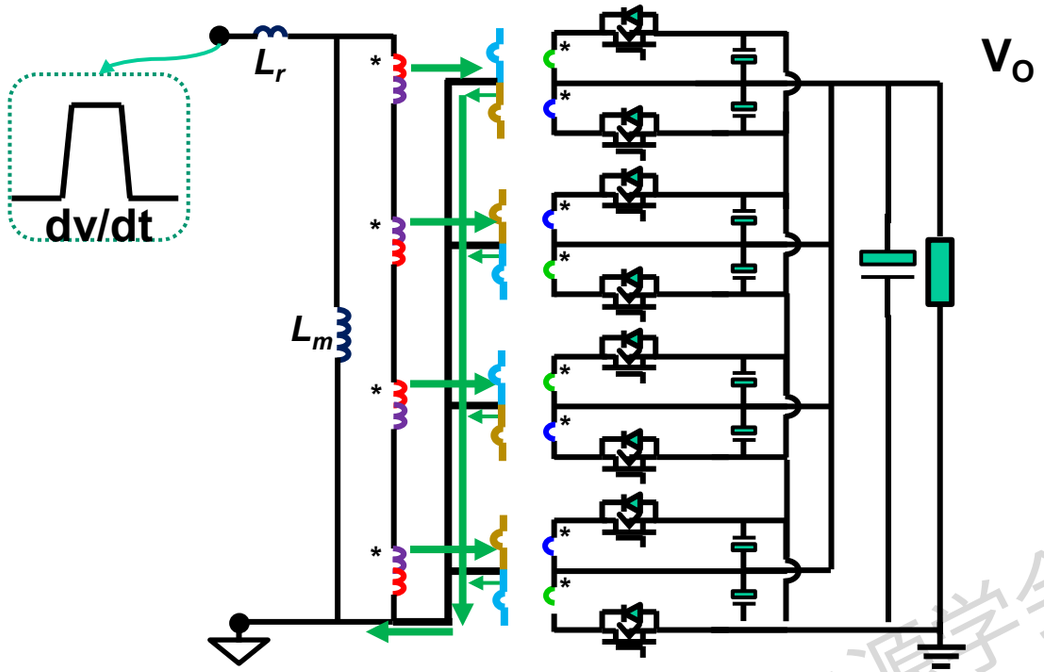


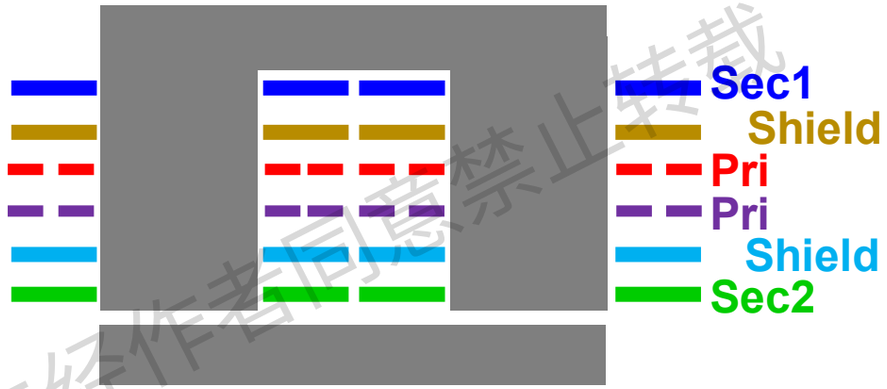


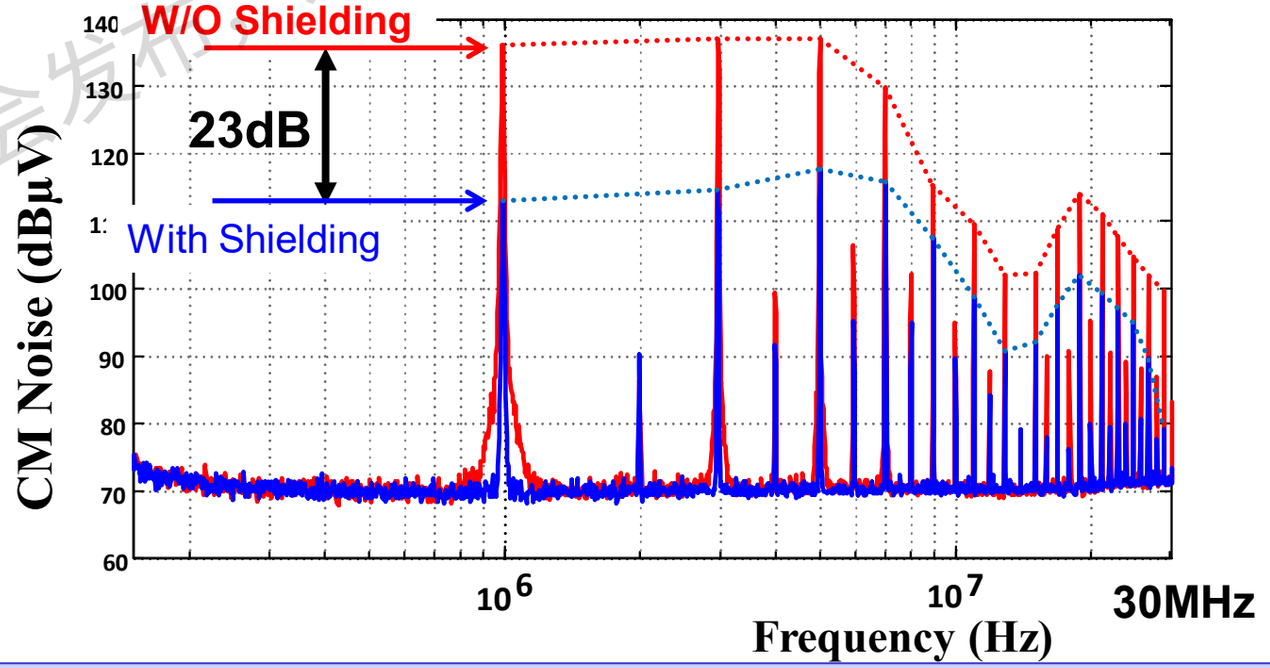
75% volume reduction

25% core loss reduction

CM Noise Reduction by Shielding



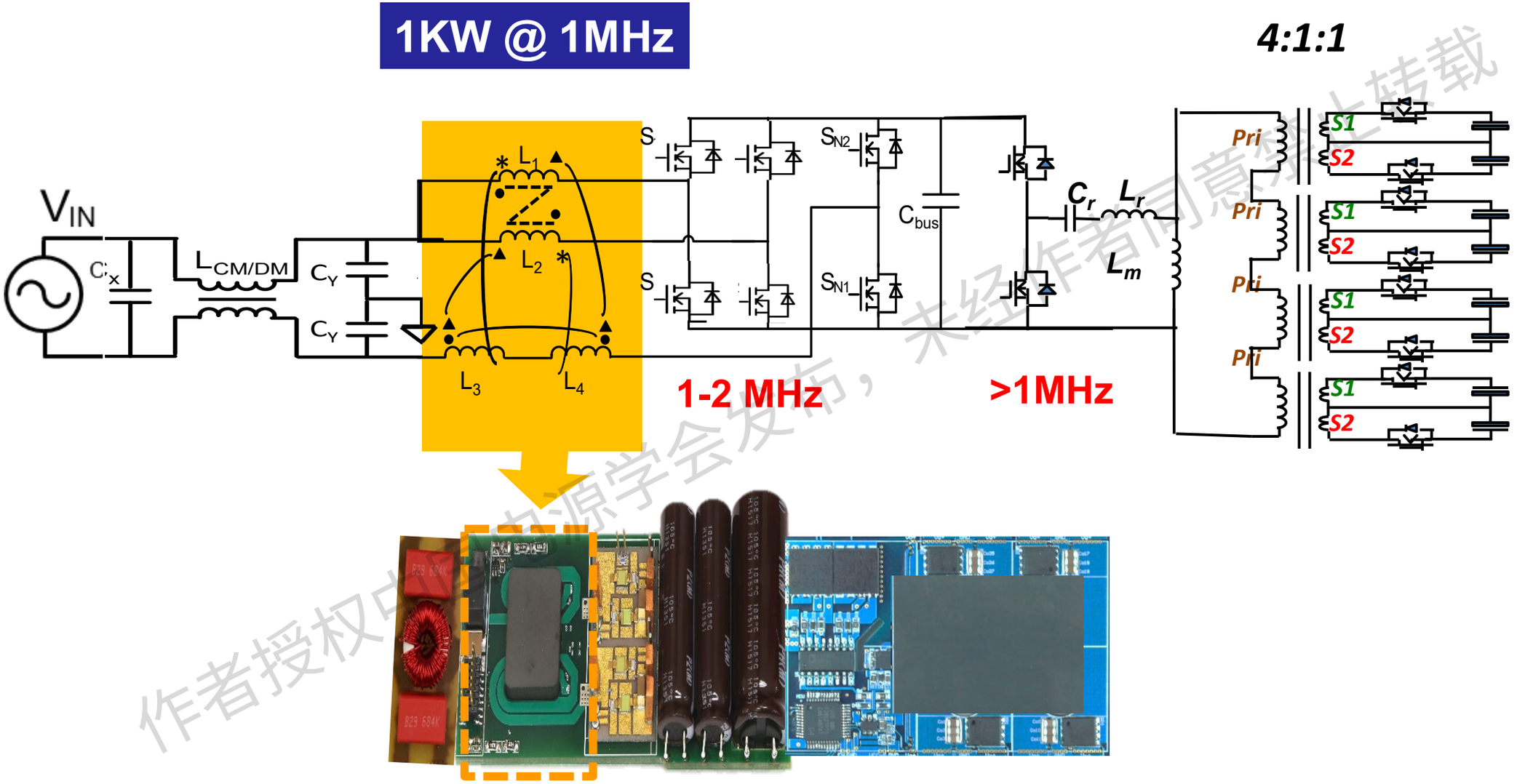




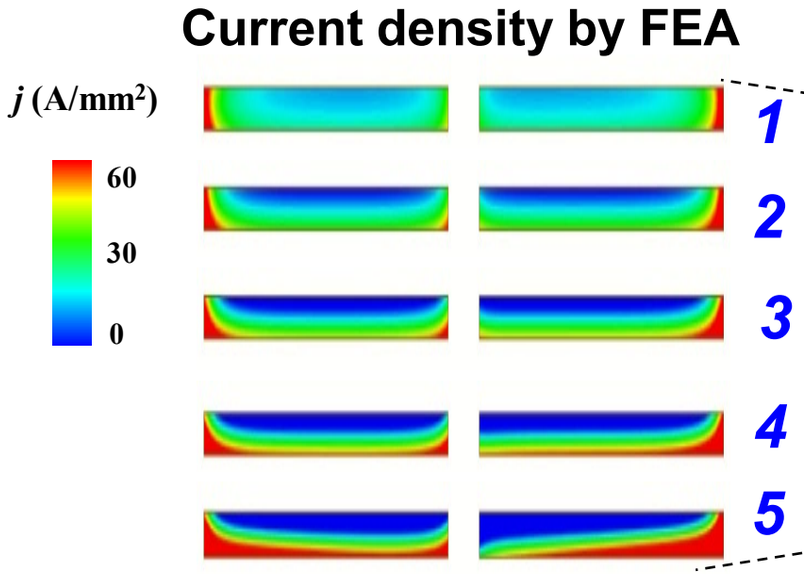
Yuchen, Yang, D. Huang, F. C. Lee, and Q. Li. "Analysis and reduction of common mode EMI noise for resonant converters" *APEC 2014*, pp. 566-571

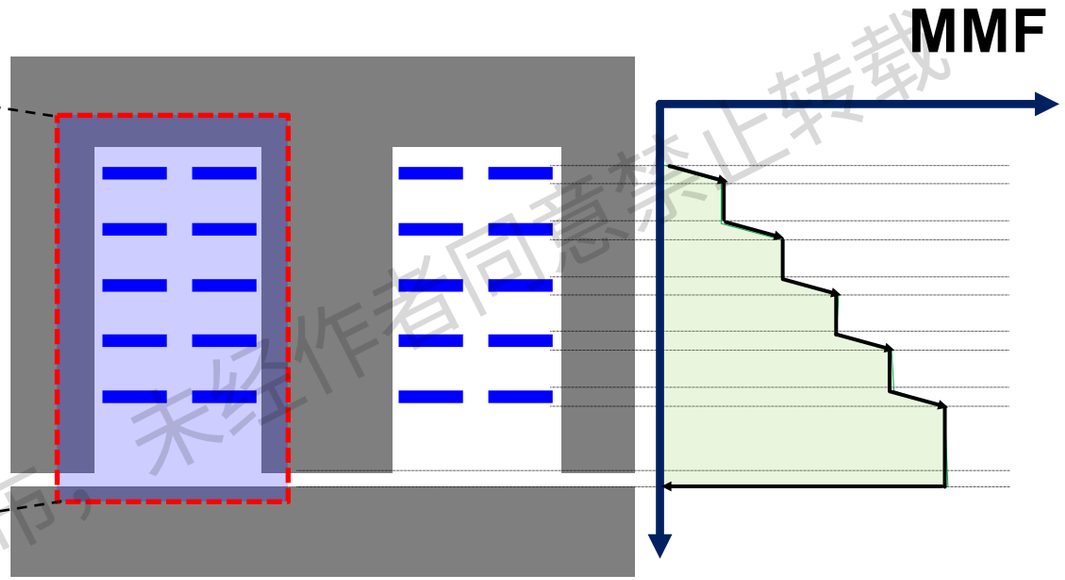
GaN Based Integrated Power Supplies

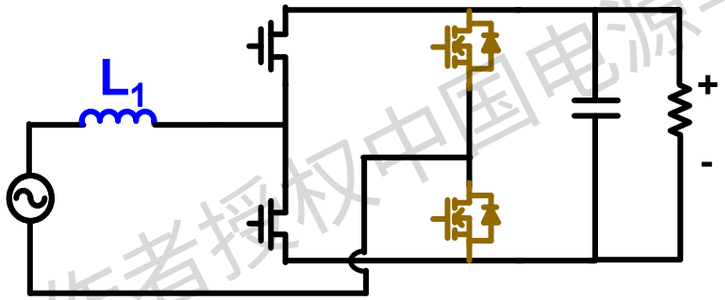
1KW @ 1MHz



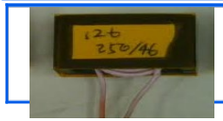
Issue with PCB Based Inductor







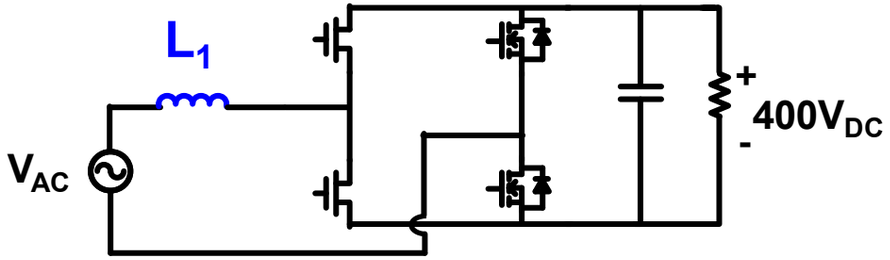
F_s >1MHz

	Winding Loss (W)	Core Loss (W)	Total Loss (W)
PCB w/o interleaving	4.5	2.3	6.8
	2.3	2.3	4.6

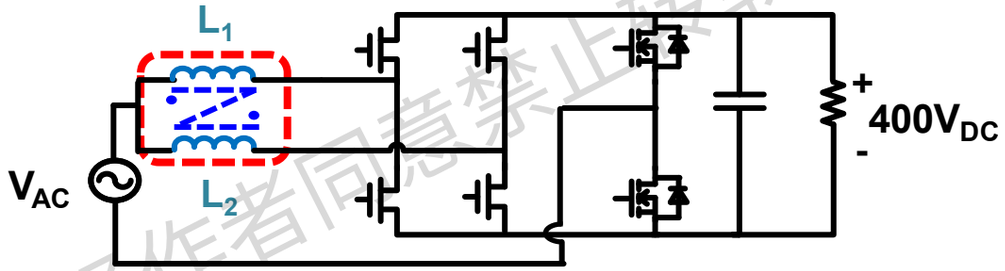
Large winding loss for PCB-based inductor

Solution: Reducing Winding Loss by Interleaving

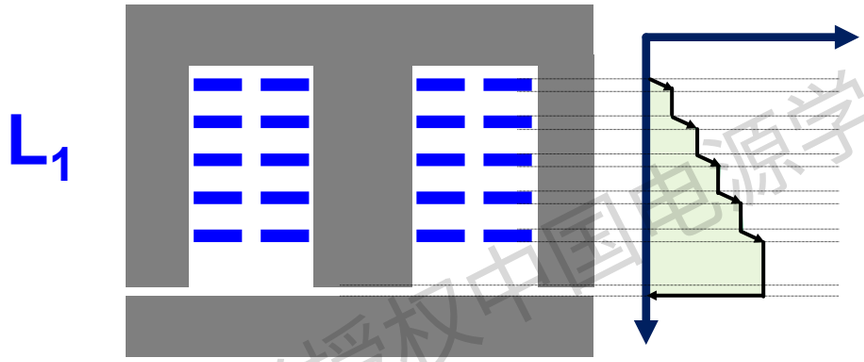
1kW, 1-2MHz



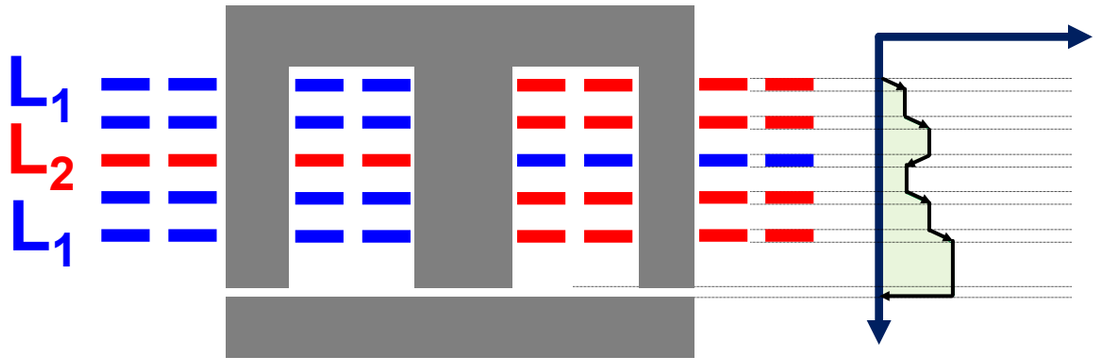
Inversely coupled inductors



MMF



MMF

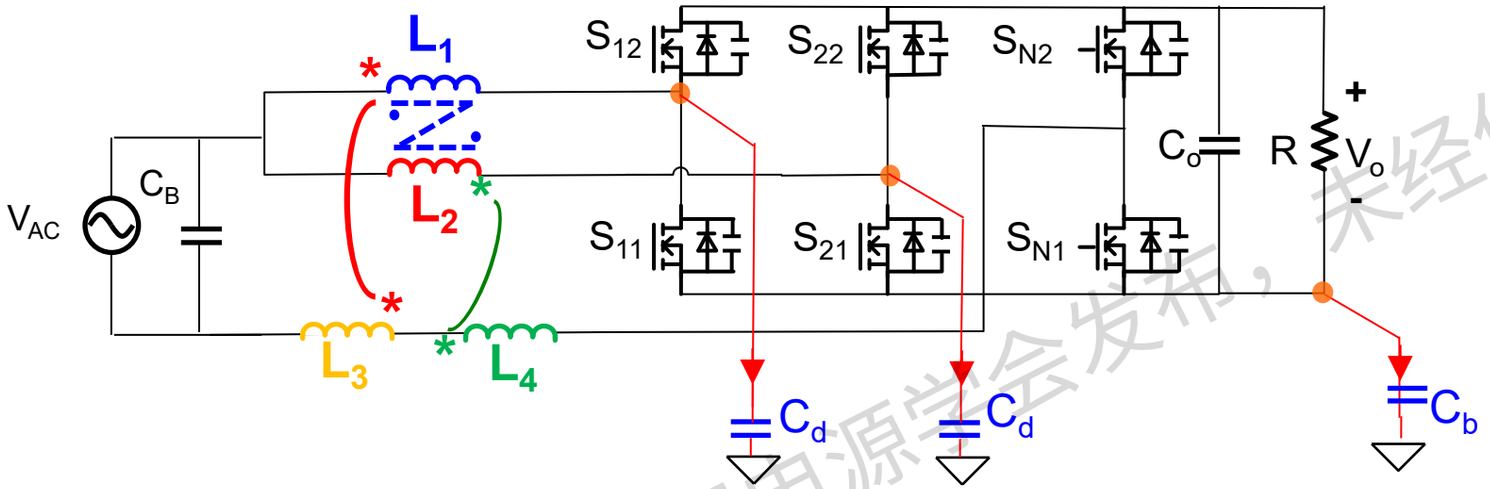


Winding Loss: 4.5W

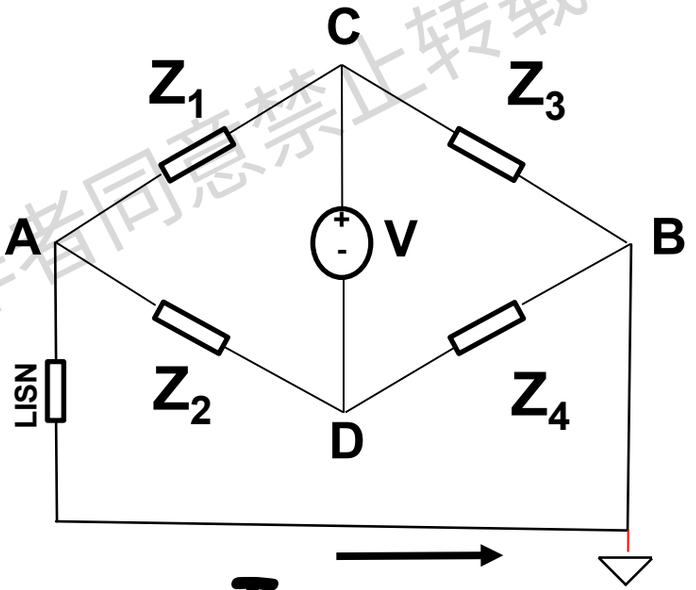
Winding Loss: 2.6W

Interleaving reduces winding loss by 40%

CM Noises Reduction Using Balance Principle



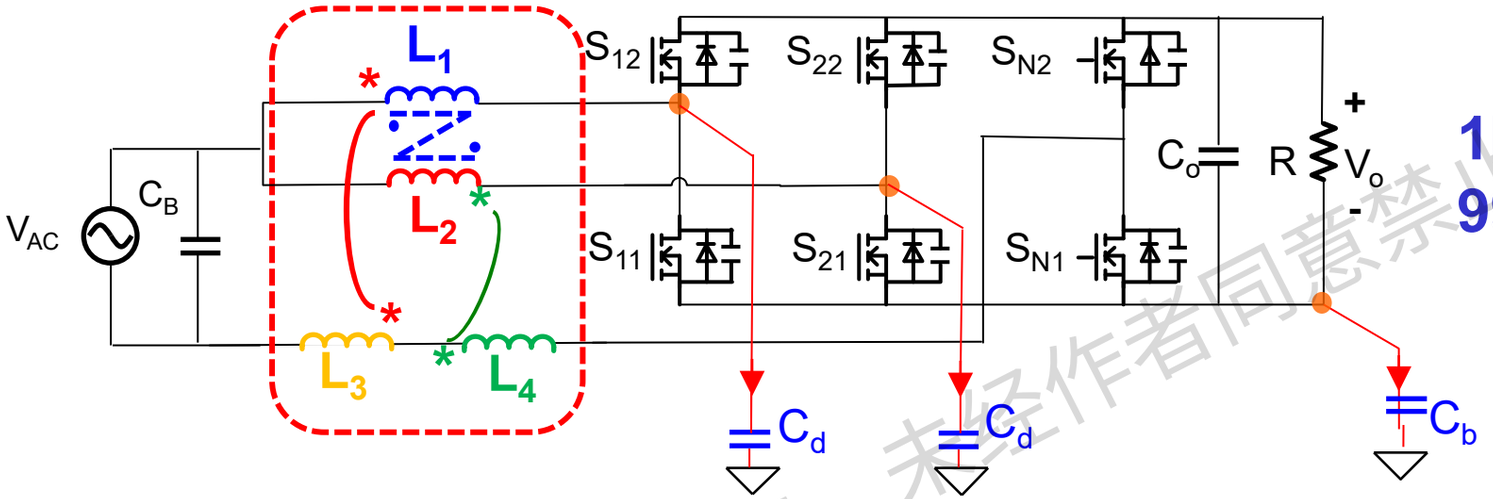
Wheatstone Bridge



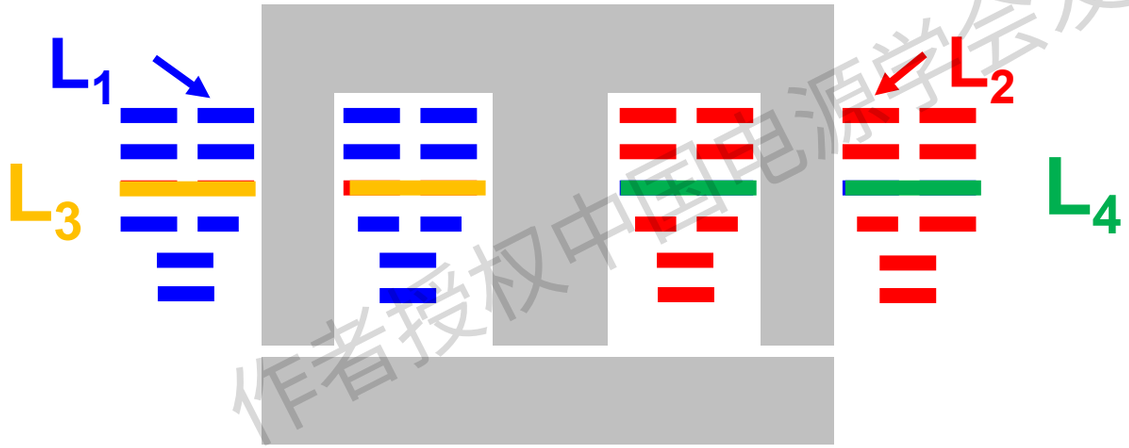
$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

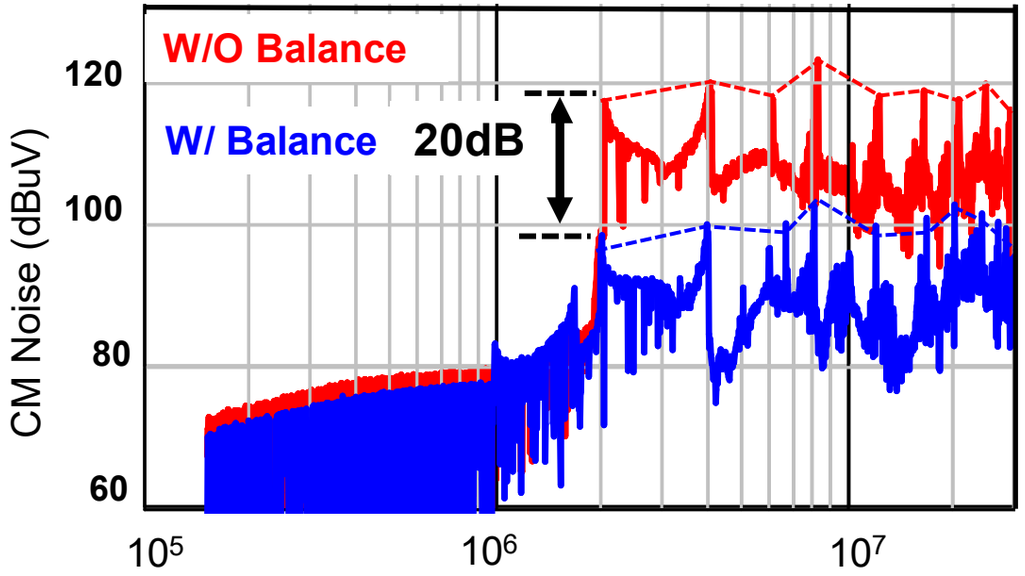
$$i_{CM} = 0$$

Reduce CM Noises via "Balance Principle"



1KW @1-2MHz
99% efficiency

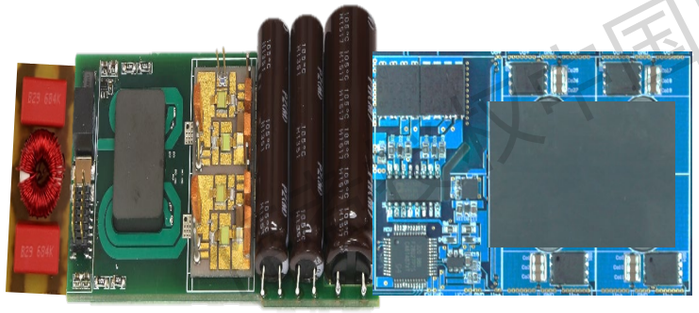


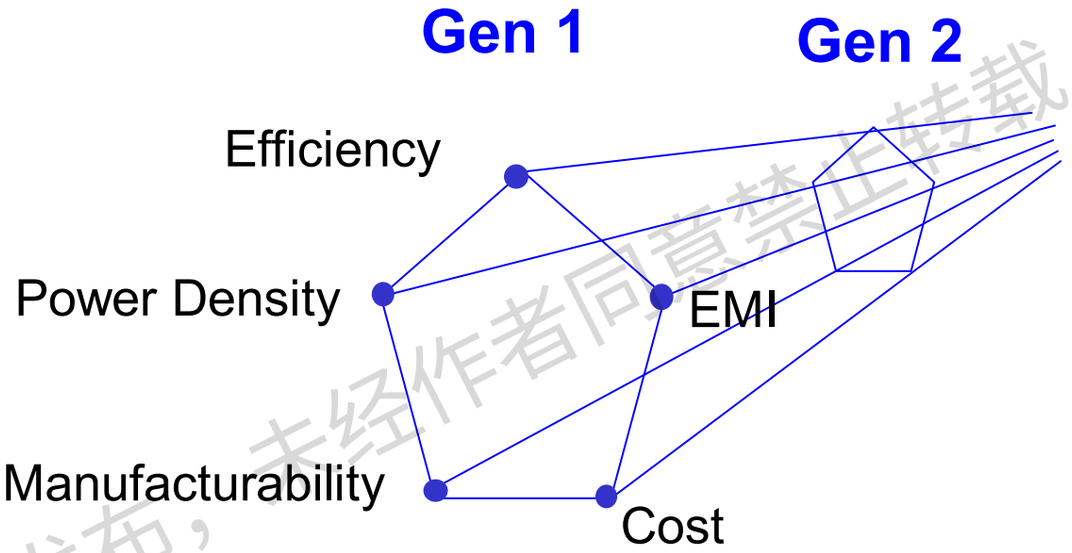


Design Trade Off & Optimization

Gen 1 **100KHz, 1KW**

Gen 2 **1 MHz, 1KW**





Eff ≈ 98%

Power density $> 3 - 5X$

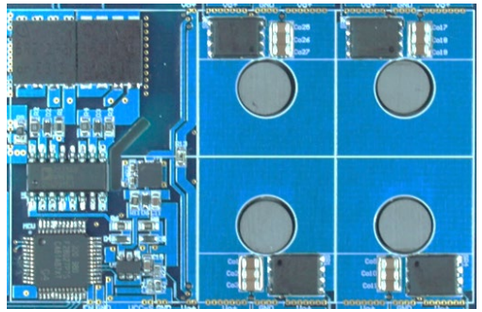
Improved EMI ≈ 20dB

Manufacturability

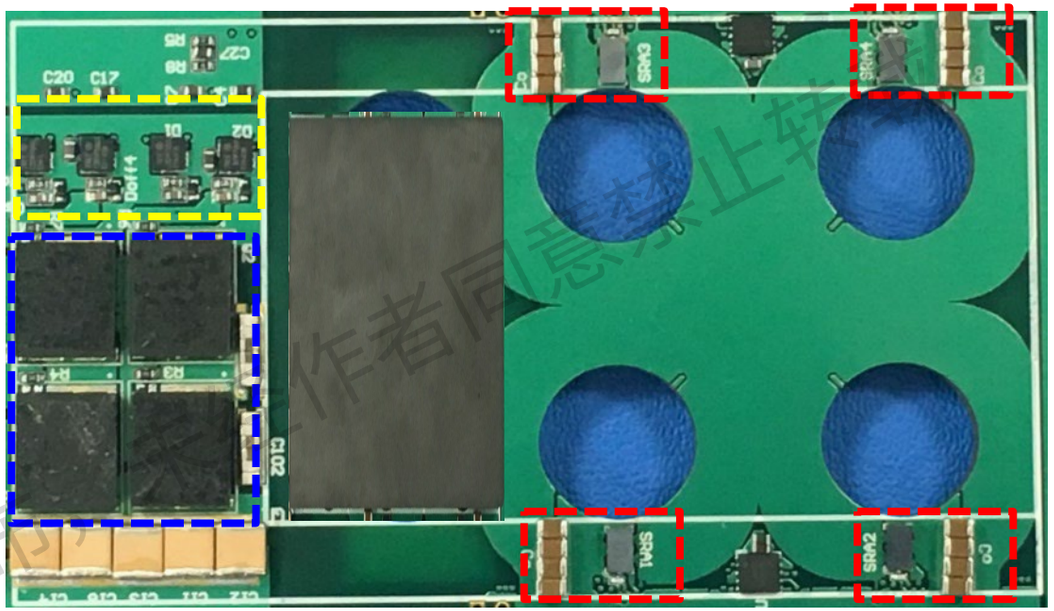
Low Cost

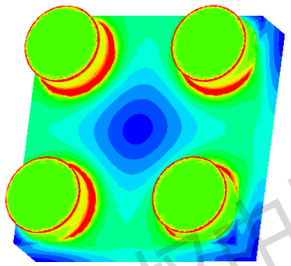
Extended to 3KW for Gen 2 Data Center Server

1KW



3KW

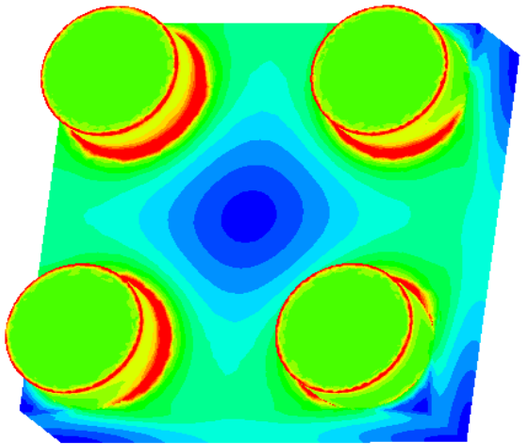




1.1 W

14 W

8.5 W Eddy Loss



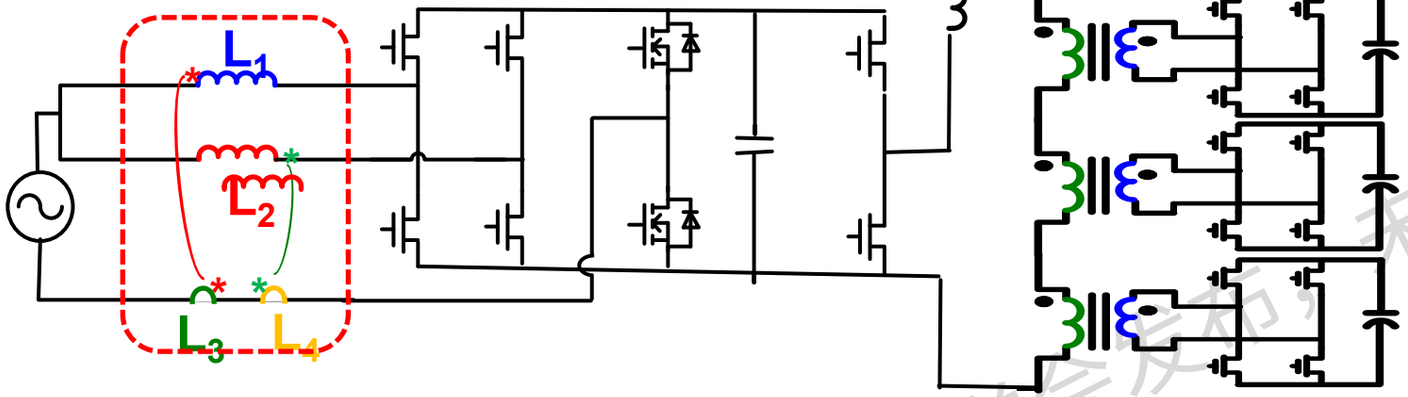
PCB based transformer with significant increase in core loss

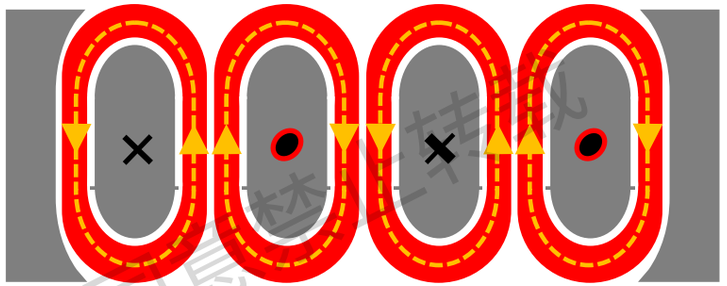
Gen 2: Data Center Server Power Supplies

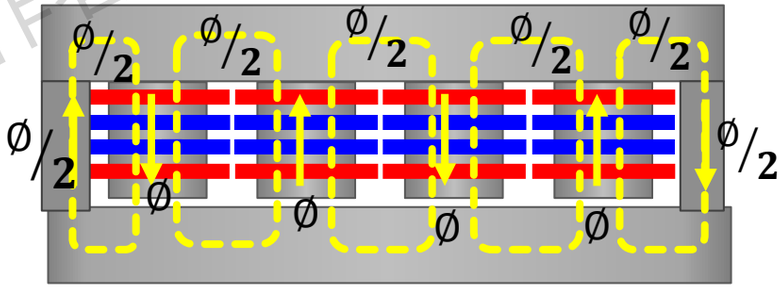
3KW, 300KHz

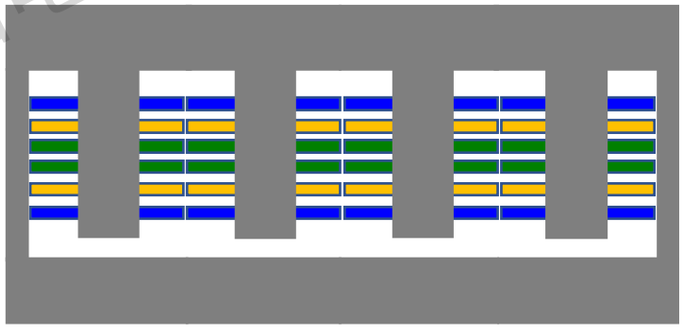
2:2

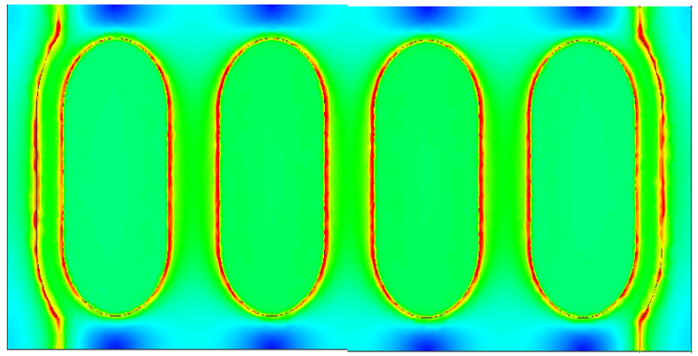
48V



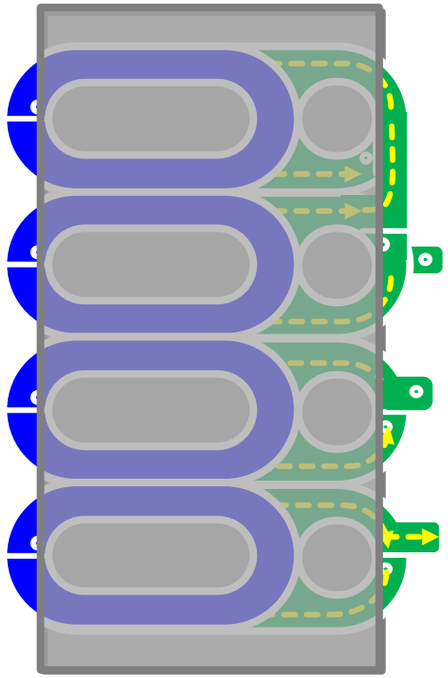


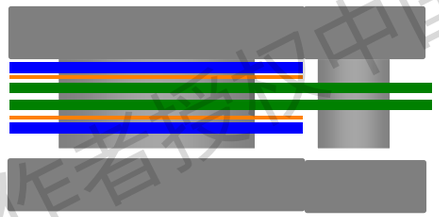


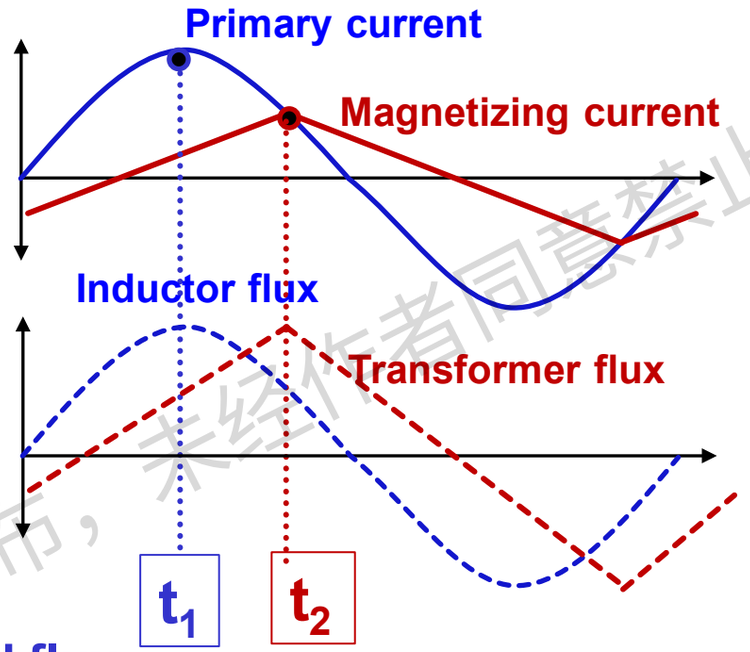




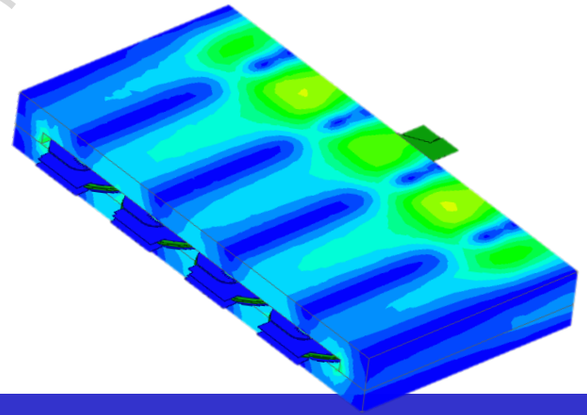
Inductor & Transformer Integration



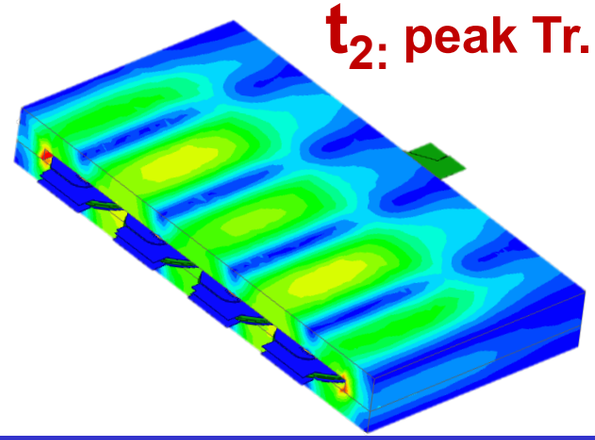


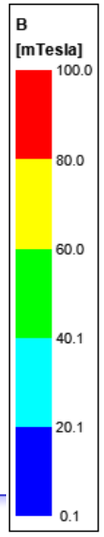


t_1: peak ind flux



t_2: peak Tr. flux

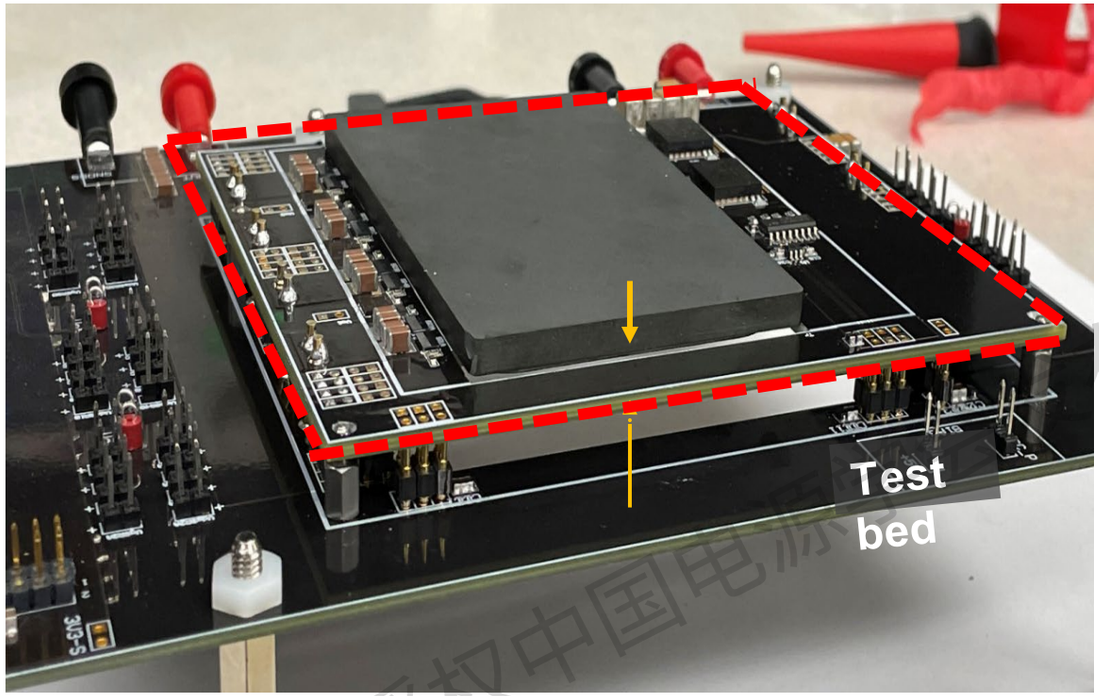


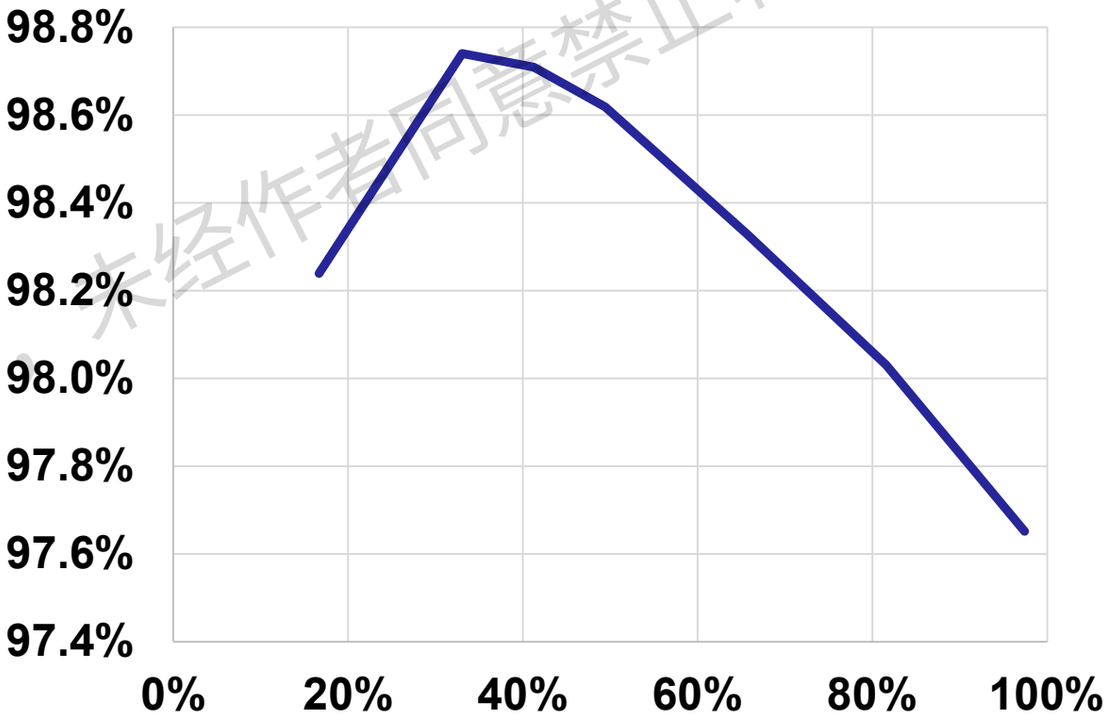


Reduction in flux density in plates (~20% reduction in core loss)

Hardware Prototype

400V- 48V 300kHz LLC





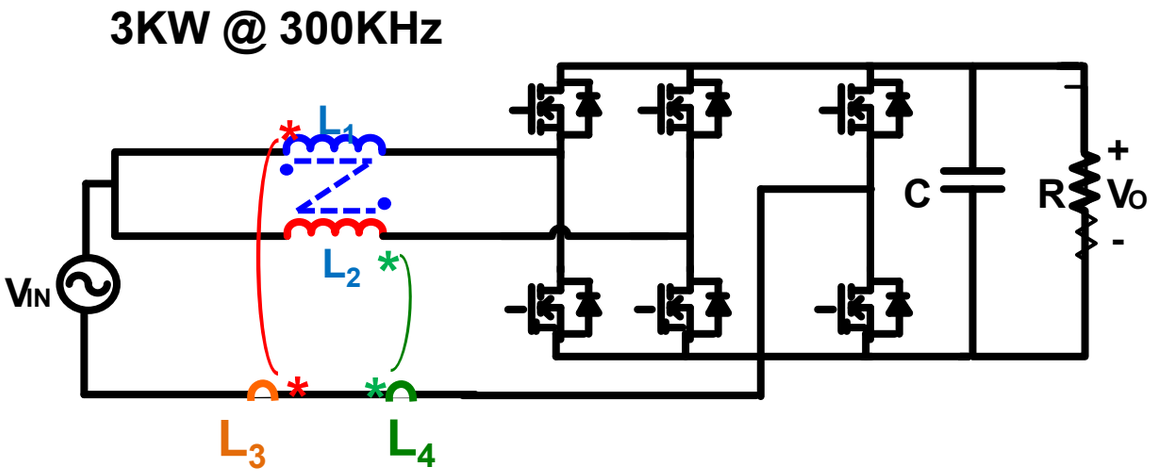
Profile: 11mm

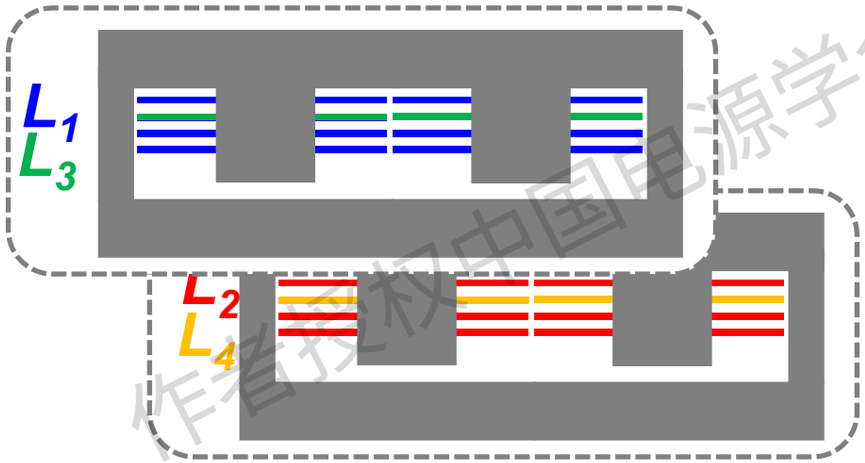
Power Density: 600W/in3

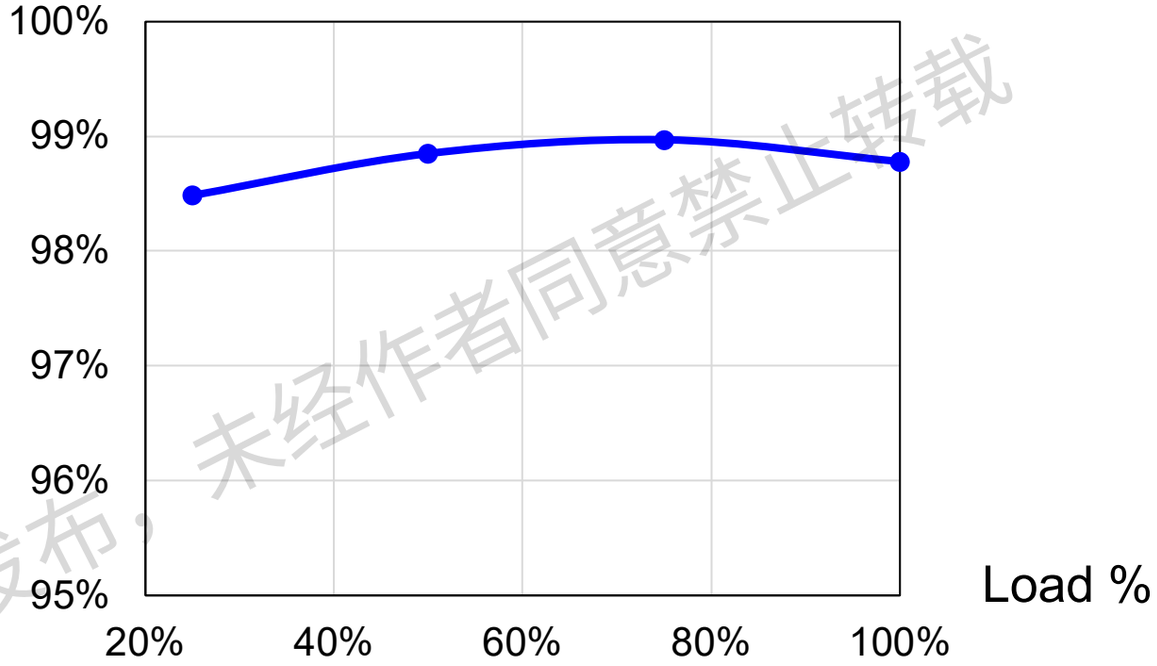
Low profile transformer at 300kHz with the help of Integrated Magnetics

Final design with Transformer FP = 3400mm^{2,} Inductor FP = 1400mm2 (after integration)

Magnetic Integration for 3KW PFC[7]



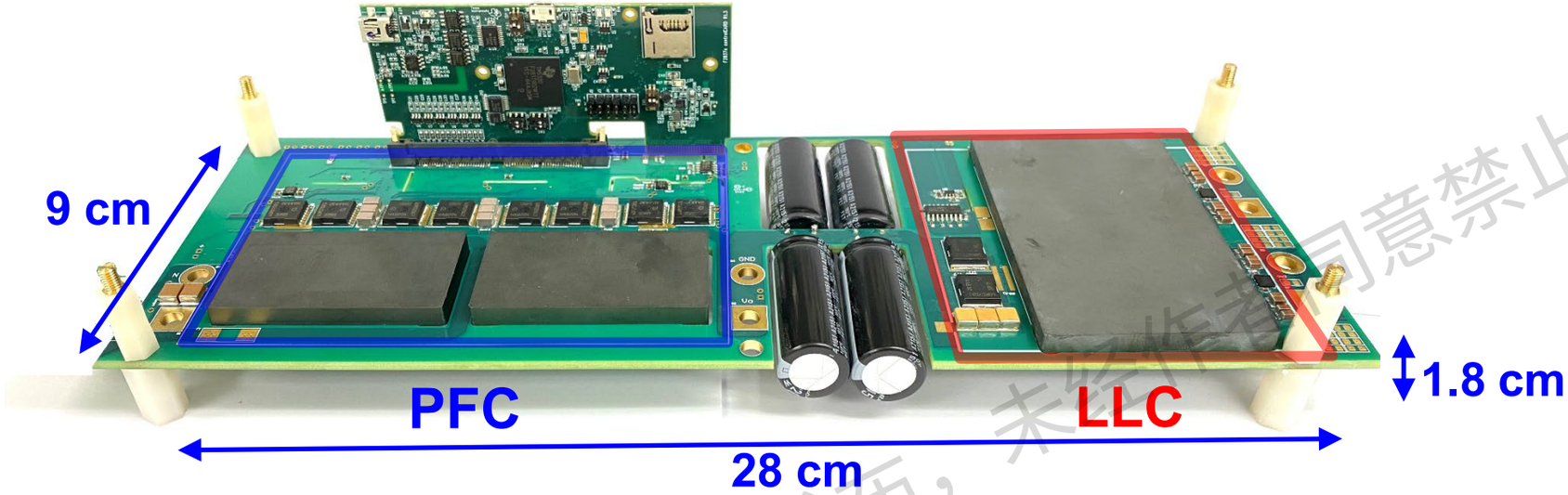




	Wind Loss	Core Loss	Total Loss
PCB	6.2	6.0	12.2
	5.8	6.2	12.0

[7] Shuo Wang, High Frequency PCB Based Coupled Inductor for 3kW Power Supplies, PMC review, May 2021

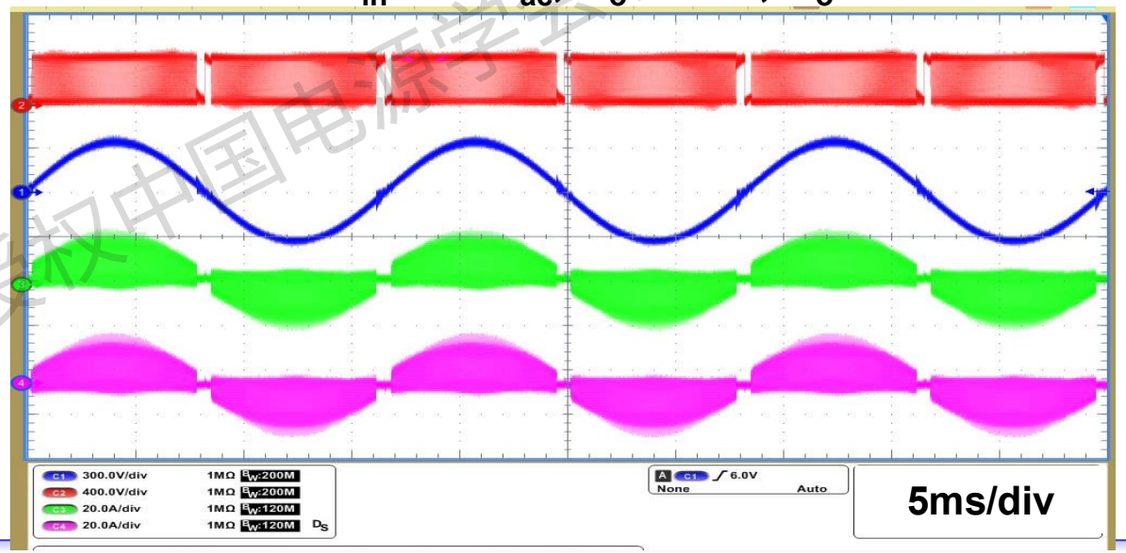
Experiment Results



Power Density (w/o controller):

110 W/in^3

PFC: V_{in}=230V_{ac}, V_o=400V, P_o=3.0kW



V_{DS} (400V/)

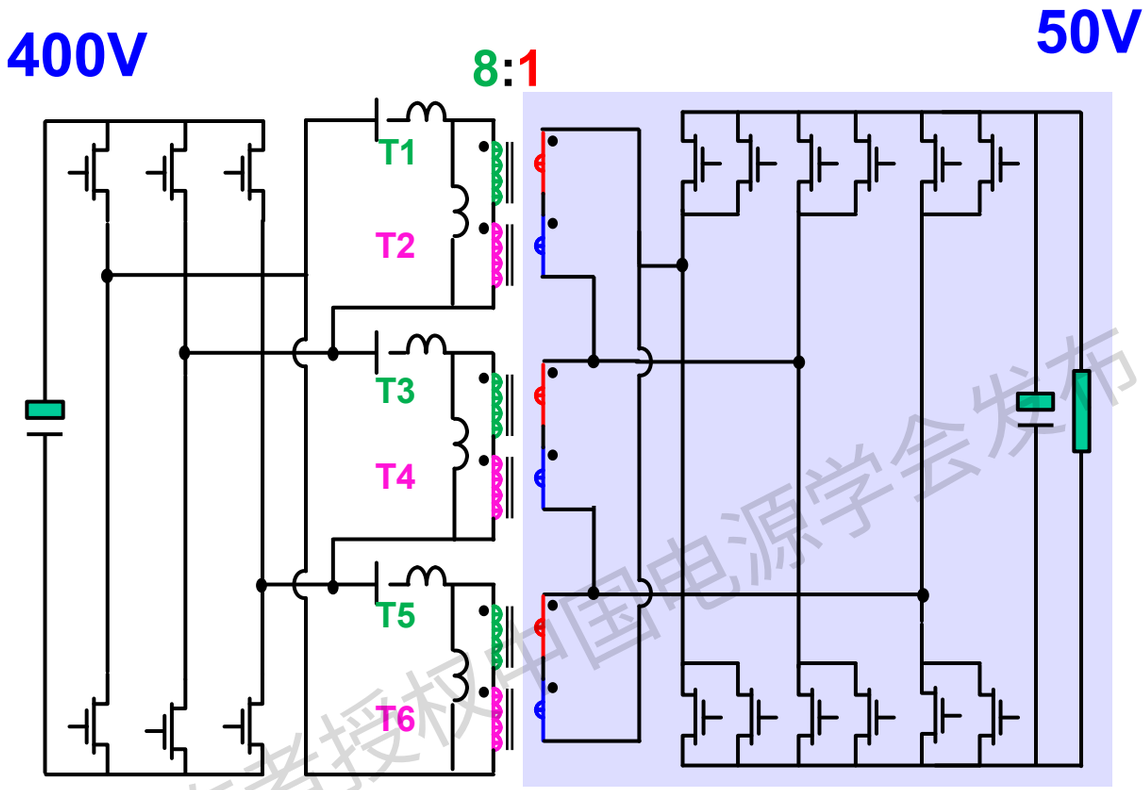
V_{in} (300V/)

I_{L1} (20A/)

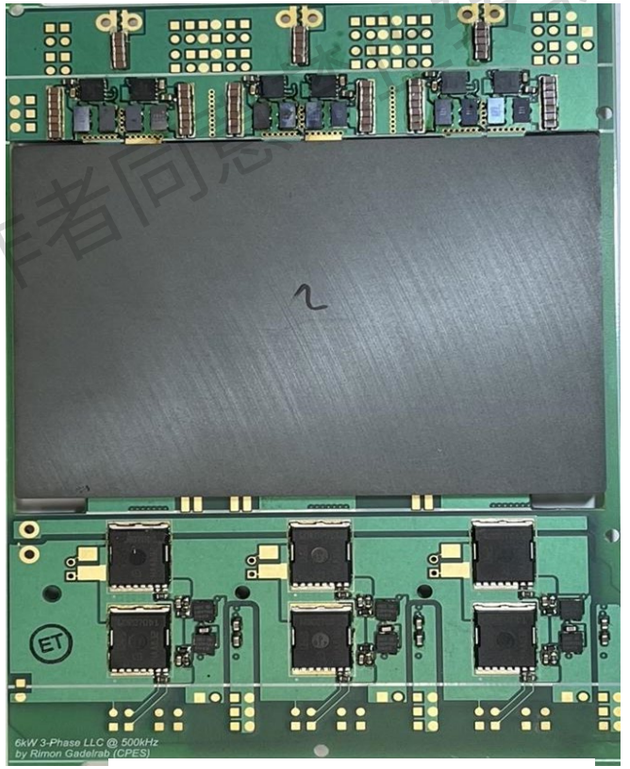
I_{L2} (20A/)

Extended to Higher Power 6-9kW

3-Phase LLC



113 x 101 x 9 (mm)



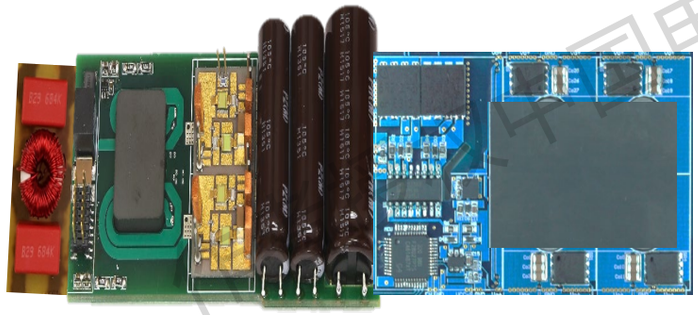
6-layer PCBDC-

~ 99%

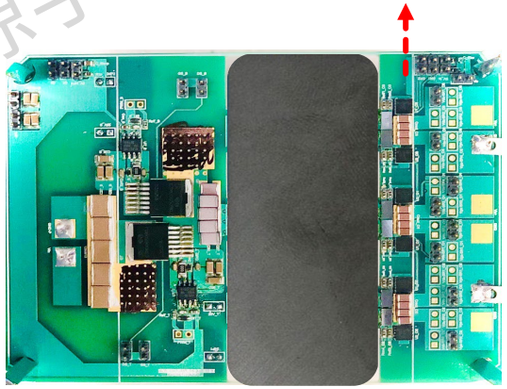
~ 300-400 W/in^3

A Paradigm Shift

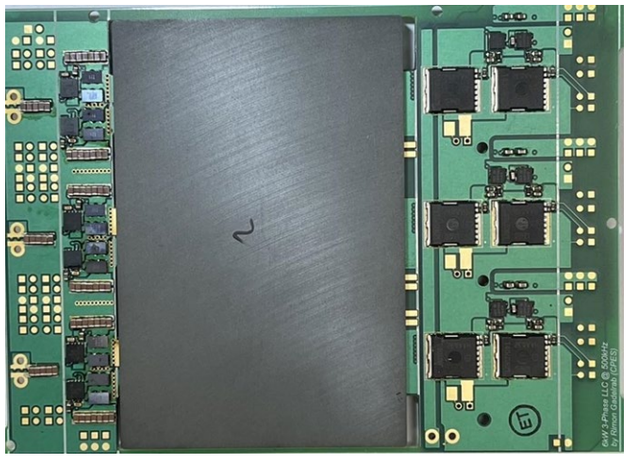
Product Specifications



1KW Sever Power



3KW Sever Power



6-9 KW Server Power

Thank You