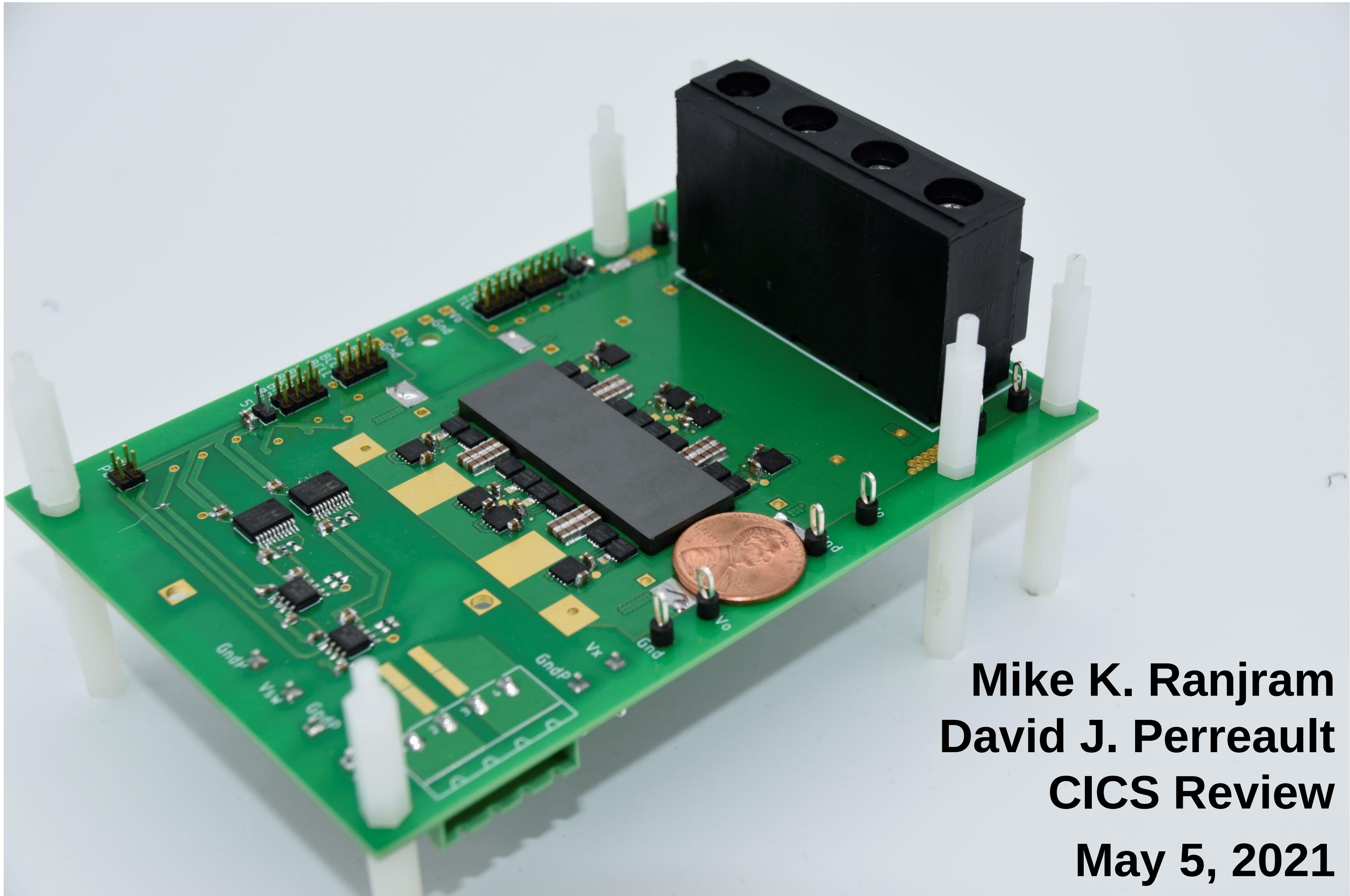
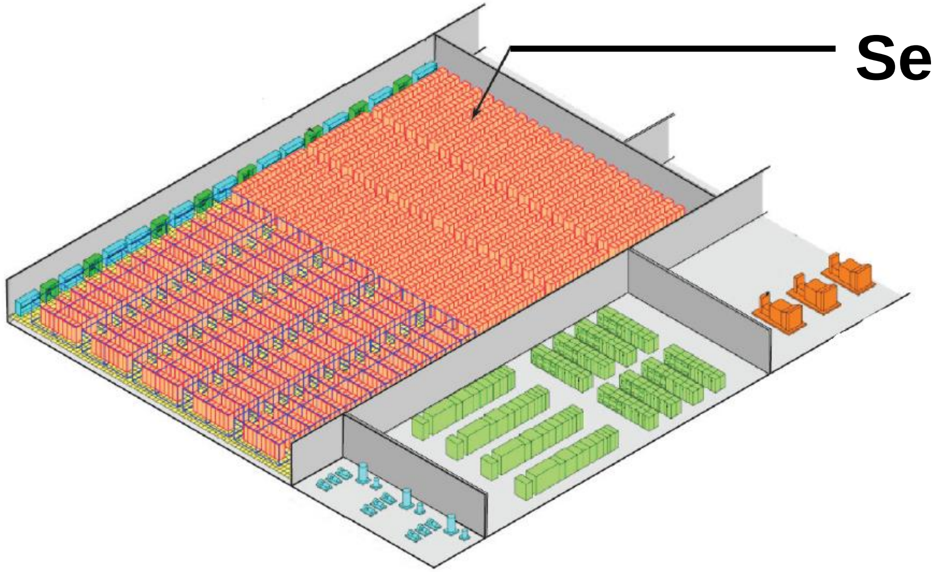
A Miniaturized Data Center Power Supply Using a Split-Phase, Fractional Turn Transformer



Mike K. Ranjram
David J. Perreault
CICS Review

May 5, 2021

Data Centers Are An Important and Growing Load

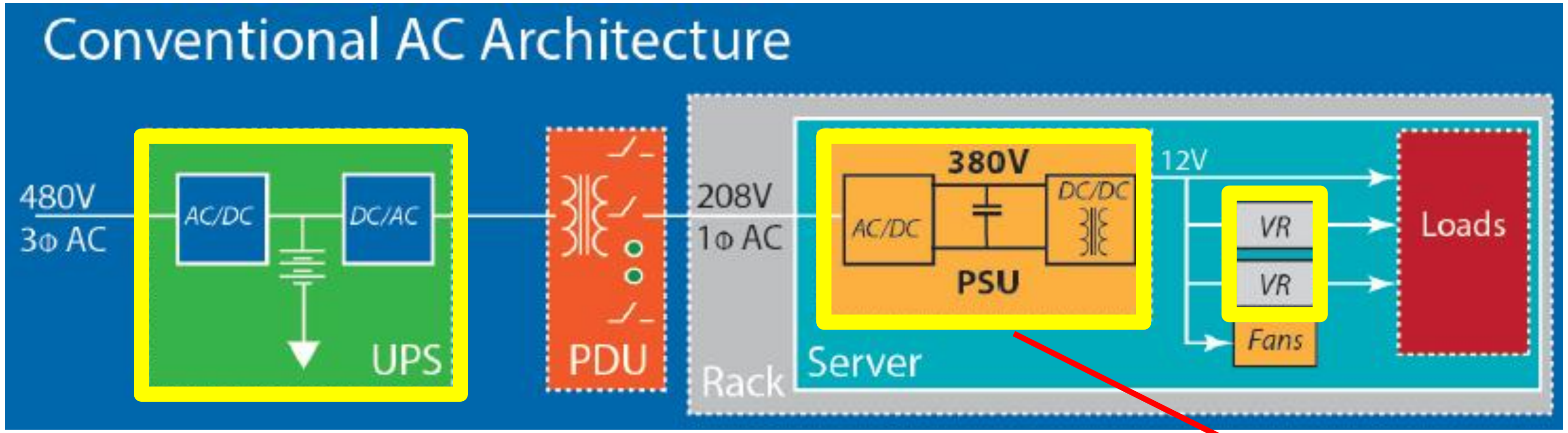


- Much of our virtual world “lives” in data centers

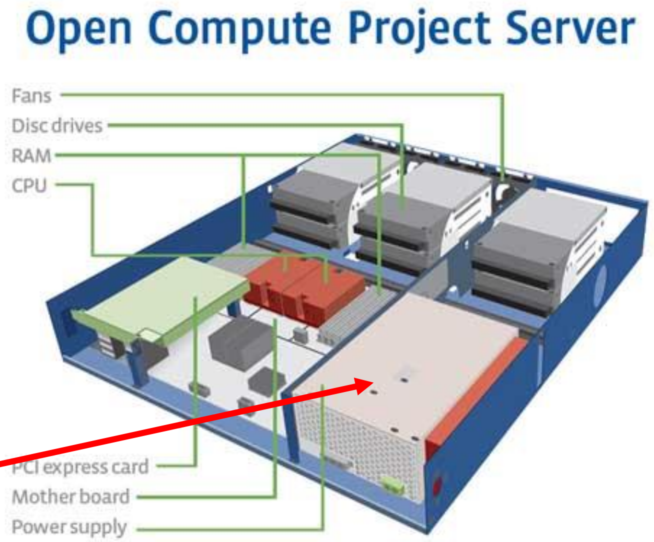
- Represent ~2% of total US electrical energy consumption
  - ~ Total solar PV energy produced in 2019

L. Barroso, J. Clidaras, U. Holzle, *The Datacenter as a Computer.* 2nd ed. Morgan & Claypool, 2013. p. 49, Fig. 4.1

Data Centers Rely on Many Power Electronic Converters



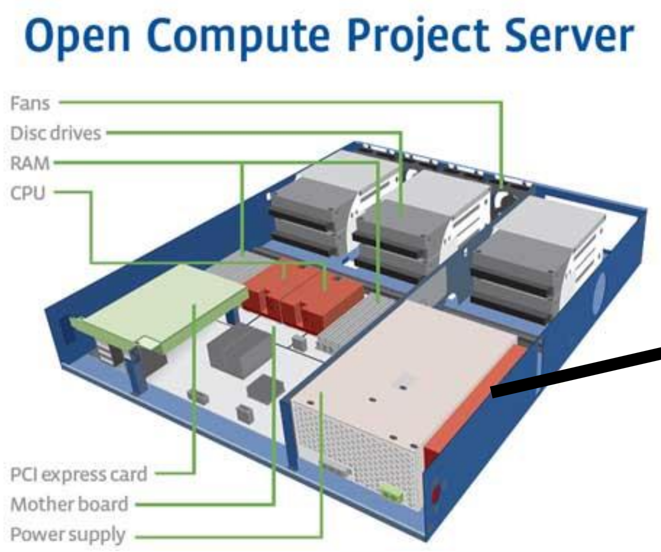
- 75% eff. typical (converters *only*)
- Much lower if cooling power included

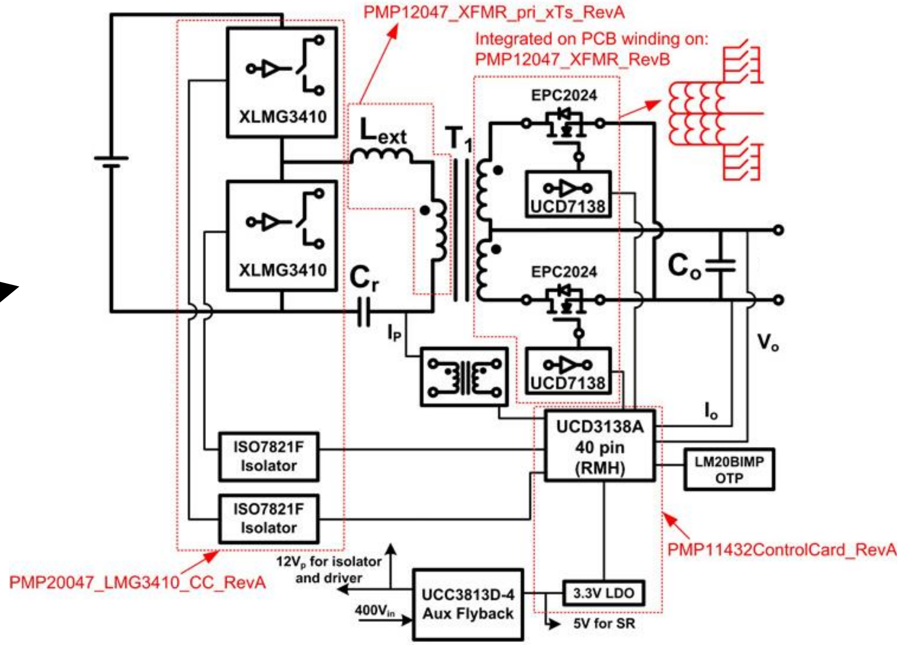


- On server level, power supply <u>miniaturization</u> especially important

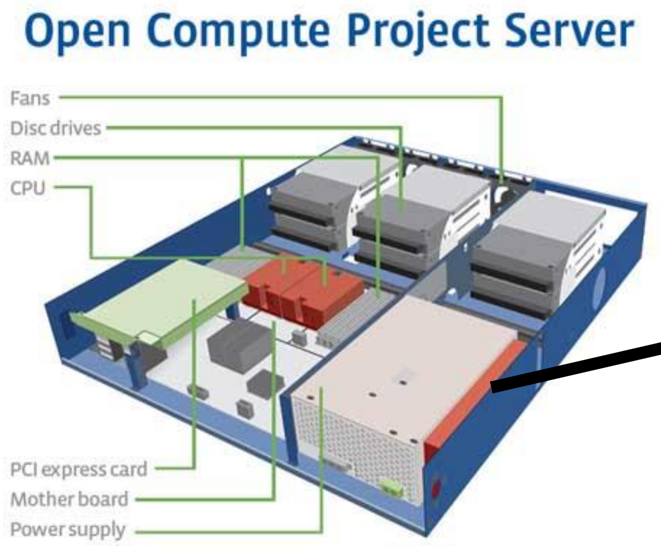
L. Barroso, J. Clidaras, U. Holzle, *The Datacenter as a Computer.* 2nd ed. Morgan & Claypool, 2013. p. 52, Fig. 4.2
R. Miller, "Facebook Opens its Server, Data Center Designs."
https://www.datacenterknowledge.com/archives/2011/04/07/facebook-opens-its-server-data-center-designs

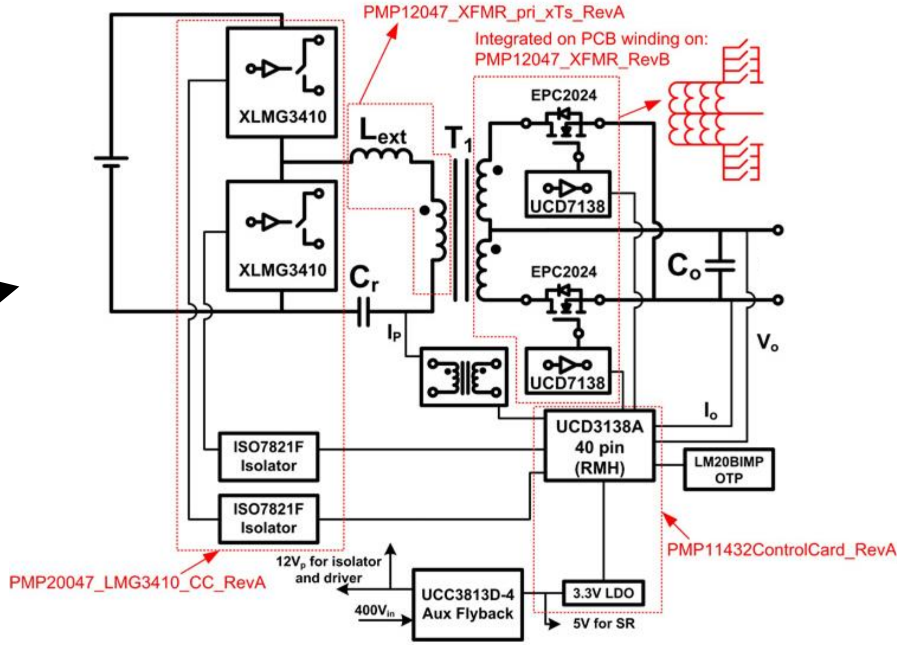
What Does This Supply Look Like Schematically?

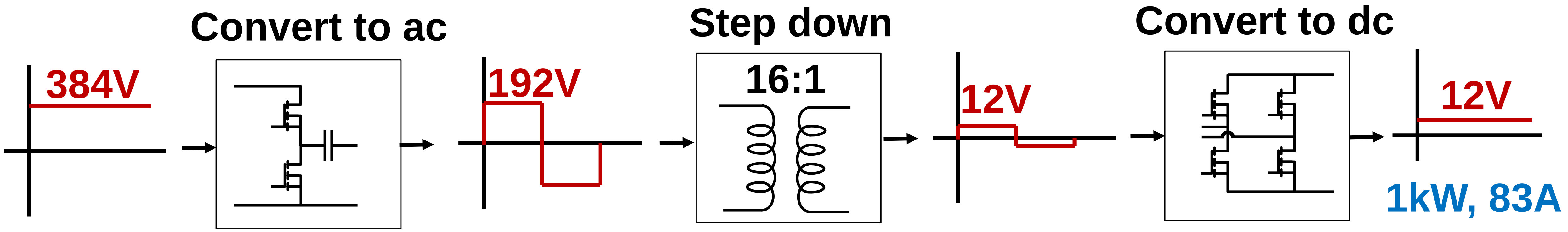




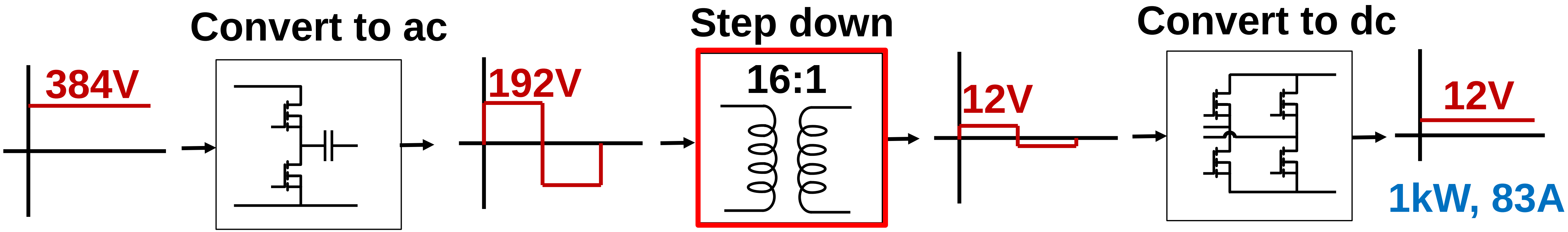
Three Conversion Steps, but the Transformer Does the Most



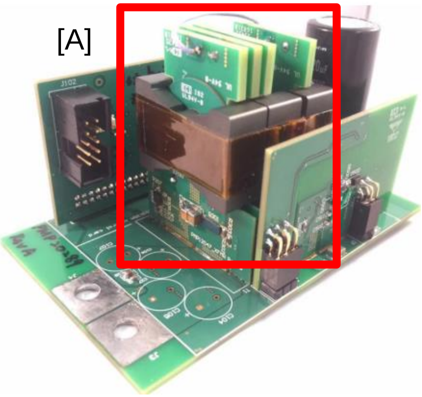




High Step-Down, High Current Transformer is a Critical Bottleneck

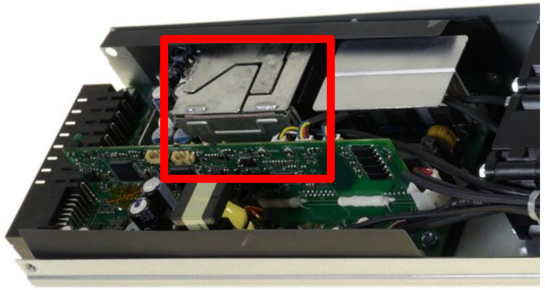


[A]



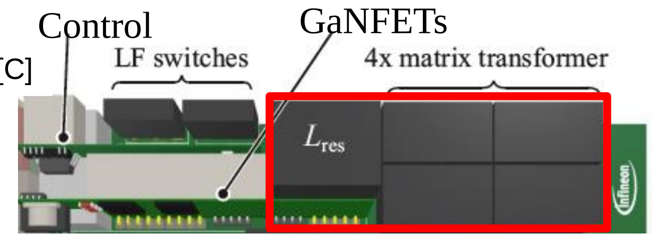
12V/500W

[B]



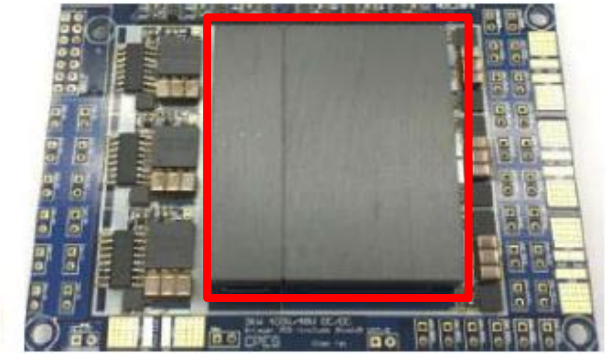
12V/1kW

[C]



12V/3kW

[D]

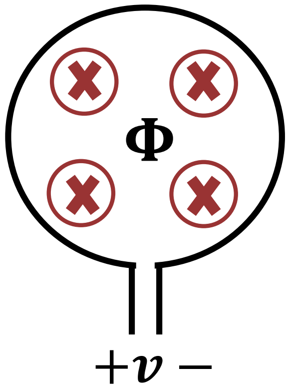


48V/3kW

[A] https://www.ti.com/tool/PMP20289
[B] https://benchmarking.ihsmarkit.com/550162/teardown-delta-dps-1600ab-4-a-psu
[C] M. Kasper, D. Bortis, J. W. Kolar and G. Deboy, "Hyper-efficient (98%) and super-compact (3.3kW/dm3) isolated AC/DC telecom power supply module based on multi-cell converter approach," *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, 2014, pp. 150-157
[D] C. Fei, R. Gadelrab, Q. Li and F. C. Lee, "High-Frequency Three-Phase Interleaved LLC Resonant Converter With GaN Devices and Integrated Planar Magnetics," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 2, pp. 653-663, June 2019.

Review: Transformer Operating Principle

- $\frac{\mathrm{d}\Phi}{dt} = \frac{v}{N}$ (sign by Lenz's Law)



Review: Transformer Operating Principle

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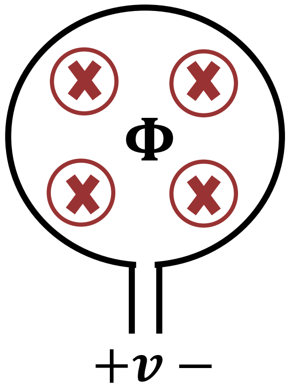
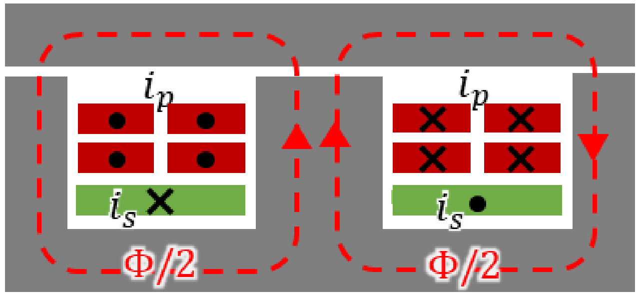
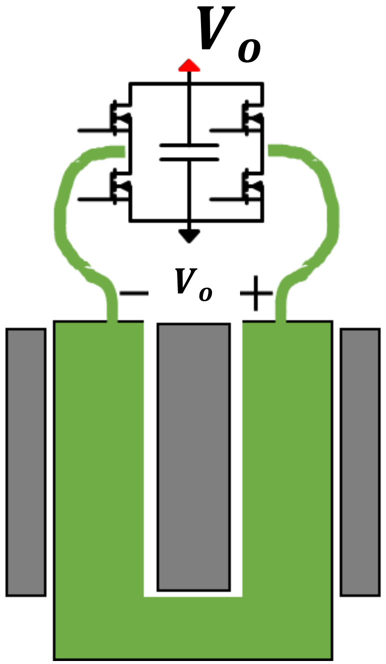


- $\frac{v_p}{N_p} = \frac{v_s}{N_s} \Rightarrow v_p : v_s = N_p : N_s$

e.g. $N_p : N_s = 4:1$





Planar Transformers Use PCB Windings

- **Windings of inductors/transformers implemented as copper traces on printed circuit boards (PCBs)**

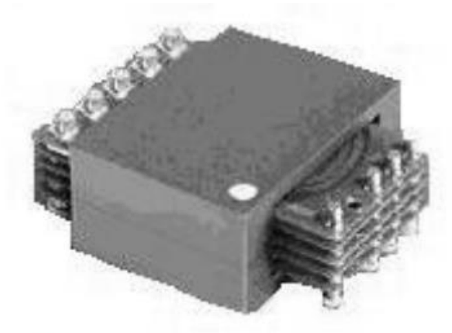
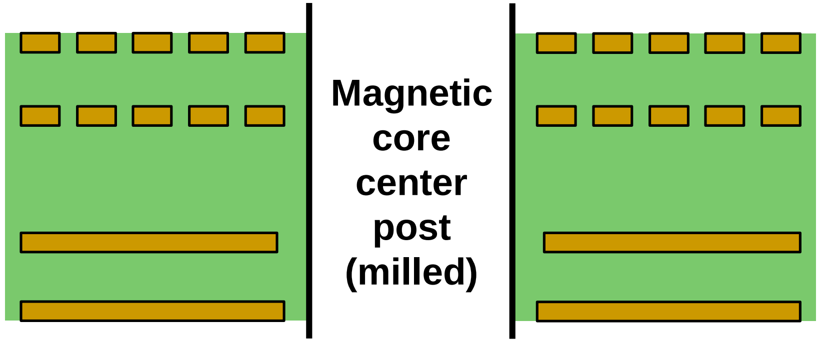


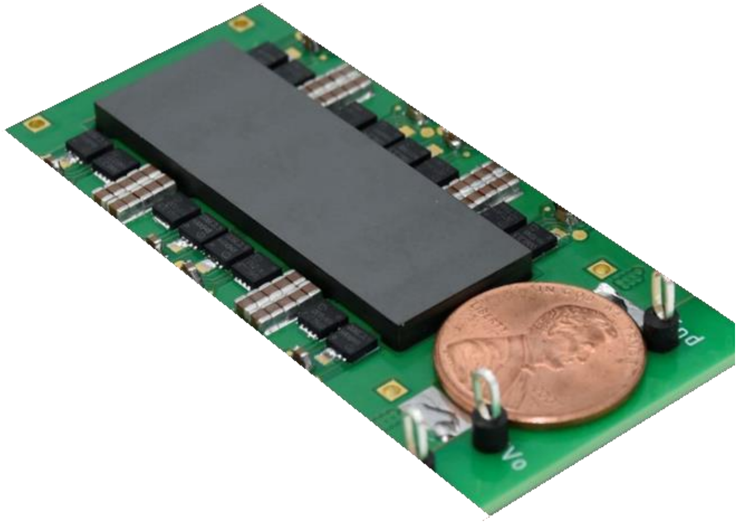
Fig. 1. Planar transformer.



L. H. Dixon, "Designing planar magnetics," Texas Instruments Application Note. [Online]. Available: http://www.ti.com/download/trng/docs/seminar/Topic4LD.pdf

Planar Magnetics are Cheap, Easy to Build, with Great Thermals

- Low profile (minimize box volume)
- Good thermal characteristics (high surface area to volume)
- Ease of manufacturability
- Highly repeatable
- Lower cost than wire-wound alternatives



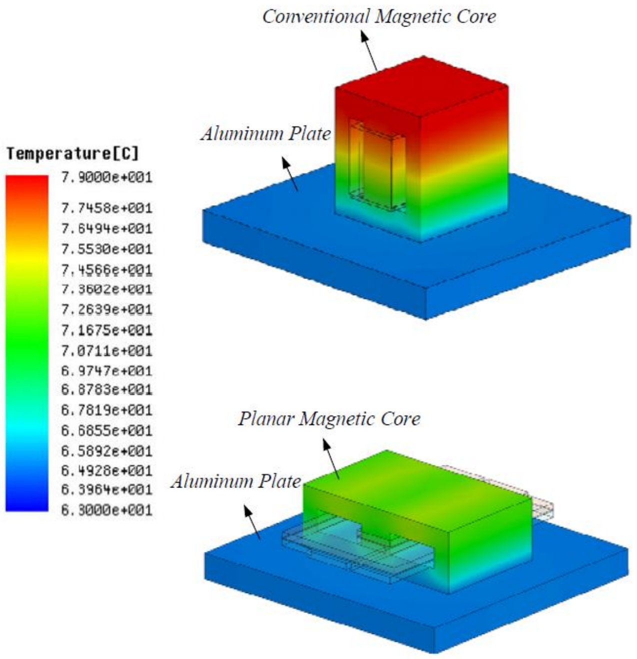
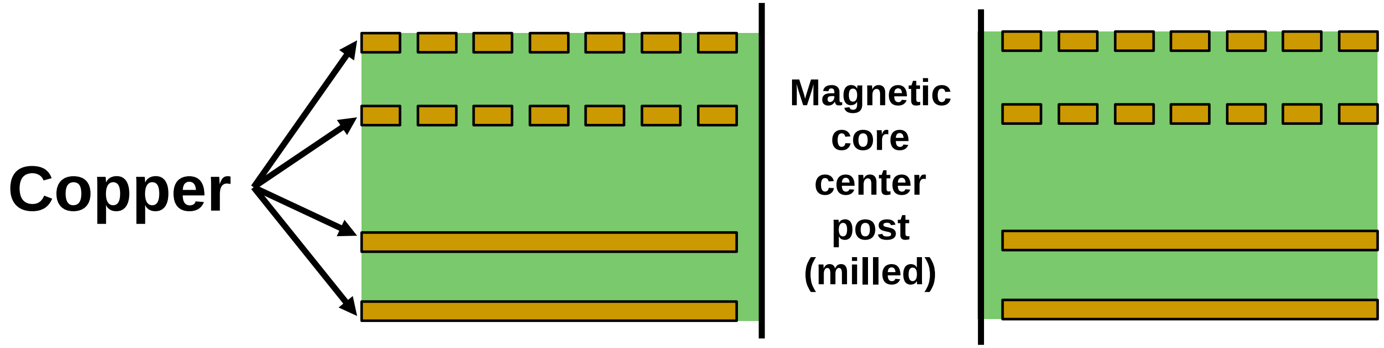


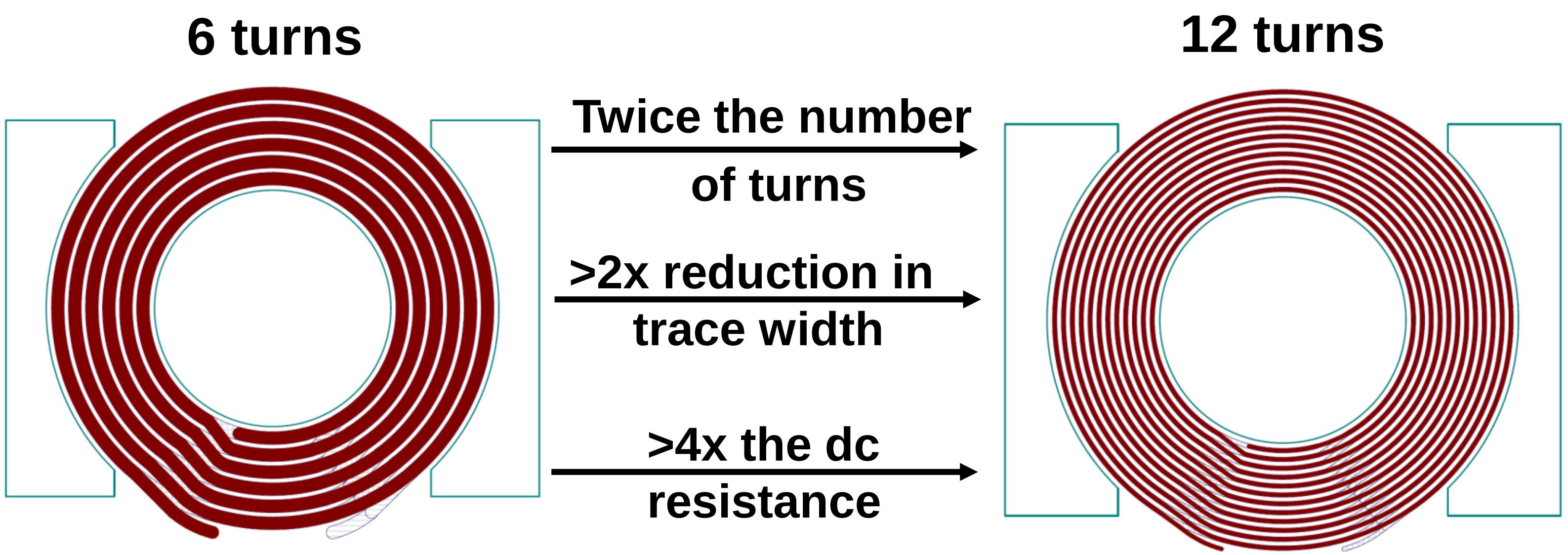
Fig. 1. Comparison of thermal behavior between conventional core and planar core.

Z. Ouyang and M. A. E. Andersen, “Overview of planar magnetic technology - fundamental properties," IEEE Trans. Power Electron., vol. 29, no. 9, pp. 4888-4900, Sep. 2014

Many Turns and High Currents are Difficult in Planar Transformers

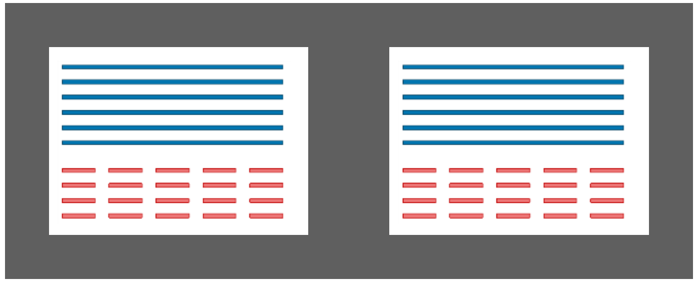


- Poor “fill factor”
- Little area for copper

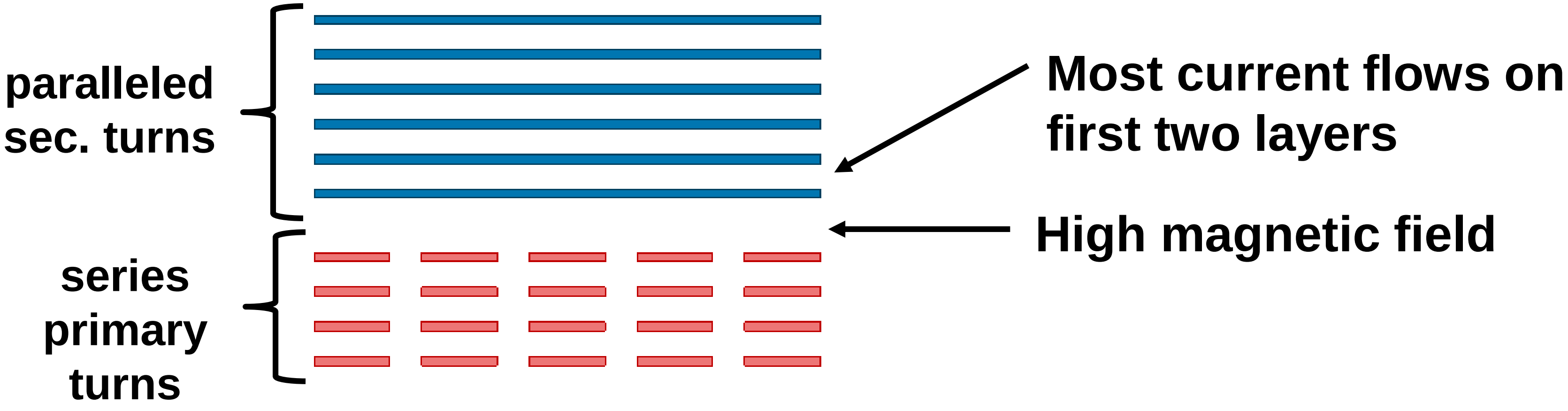


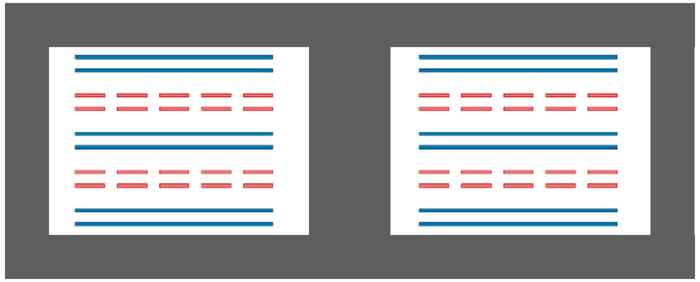
- Large penalty for many turns on a layer

It Can Also Be Difficult to Use Additional Layers

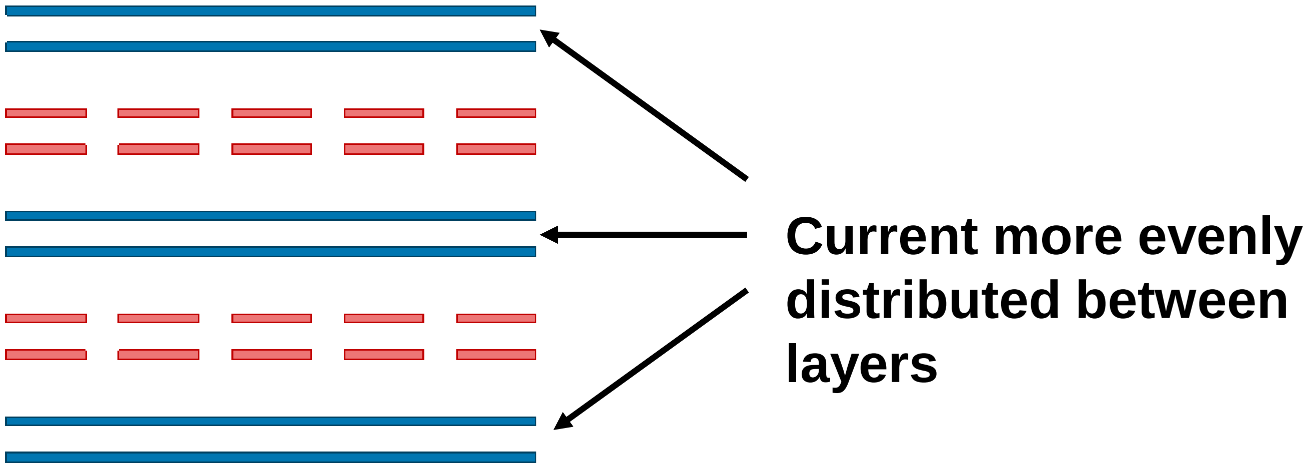


Non-interleaved

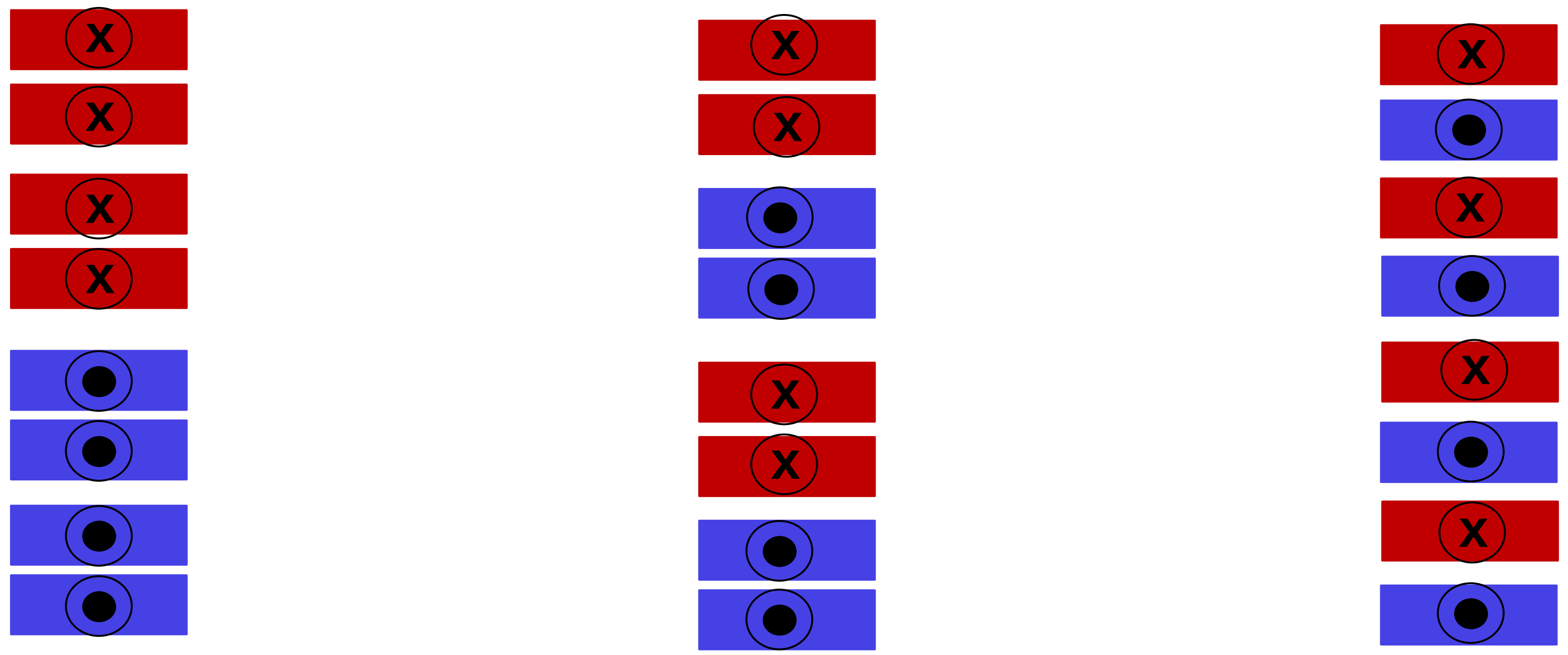




Interleaved



Resistance vs. Capacitance Trade-off of Interleaving

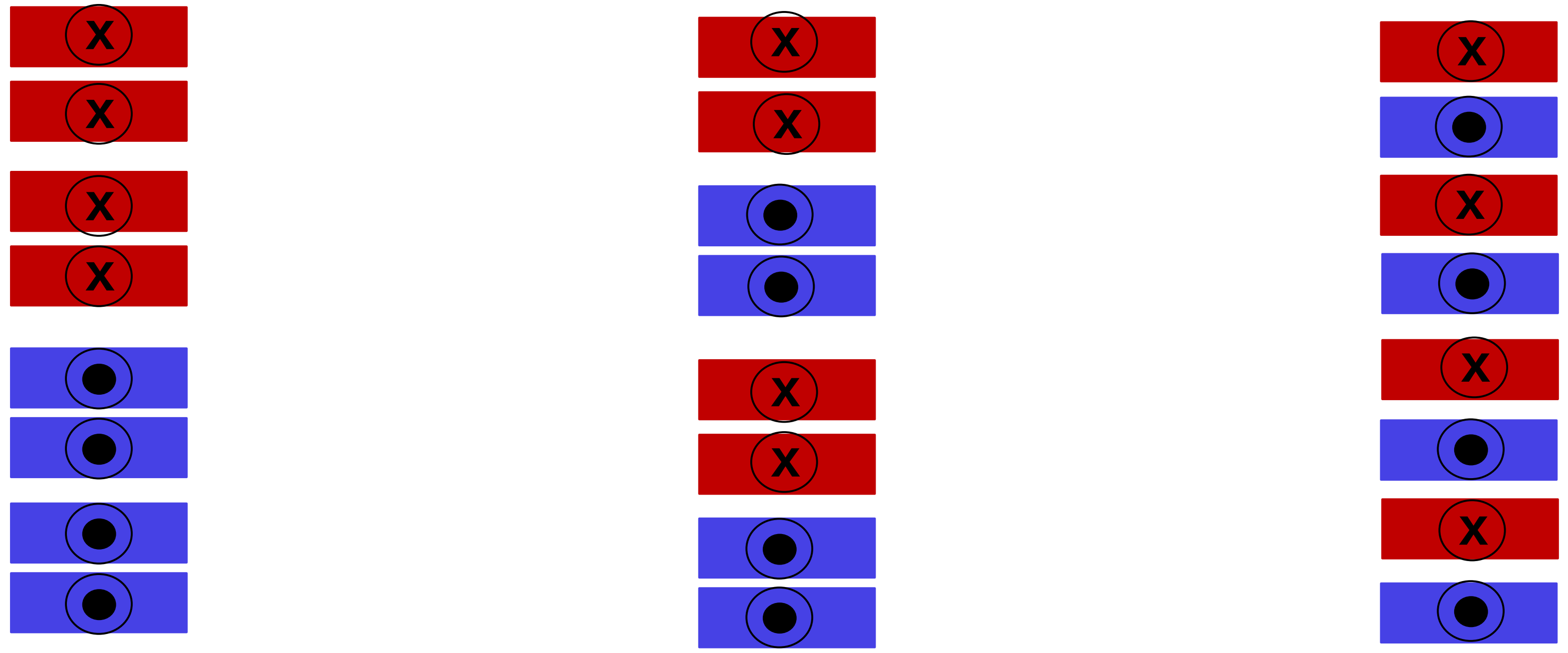


Not interleaved | Interleaved | Ideally interleaved

ac resistance → lower

capacitance → higher

Resistance vs. Capacitance Trade-off of Interleaving



ac resistance → lower

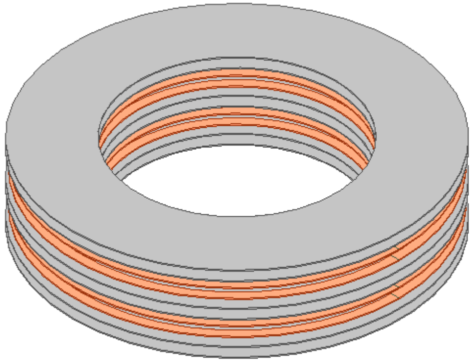
capacitance → higher

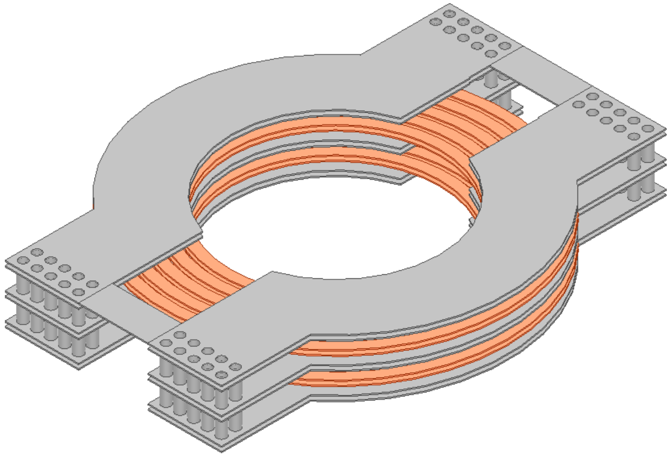
termination loss → Much higher

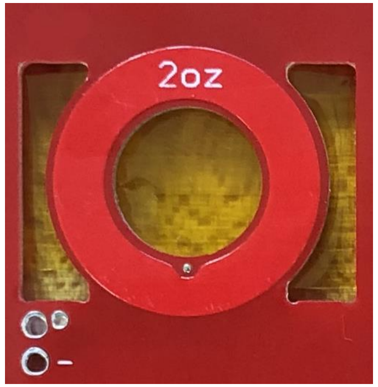
With Realistic Terminations, Loss Can Be Much Higher Than Expected

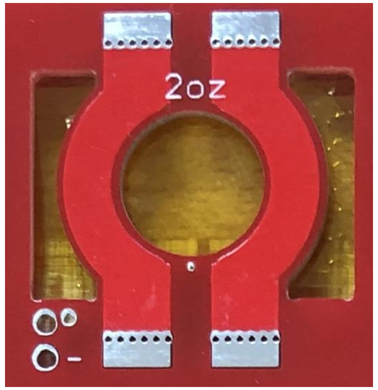
Ideal, perfectly terminated

Practically terminated







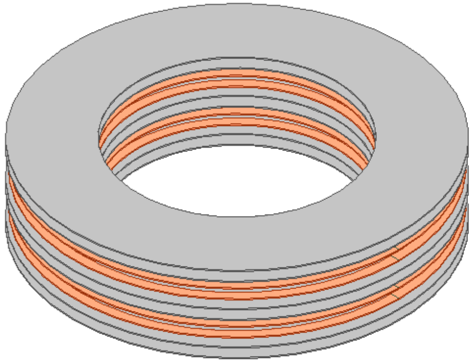


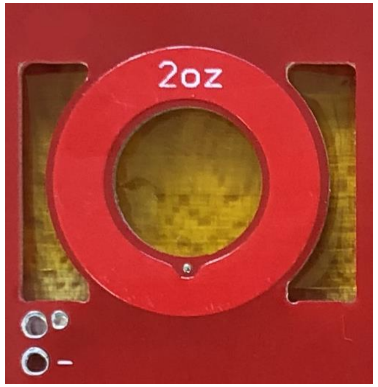
0.29Ω → **0.73Ω**

Key: Avoid complex vertical stack-ups in this application space

With Realistic Terminations, Loss Can Be Much Higher Than Expected

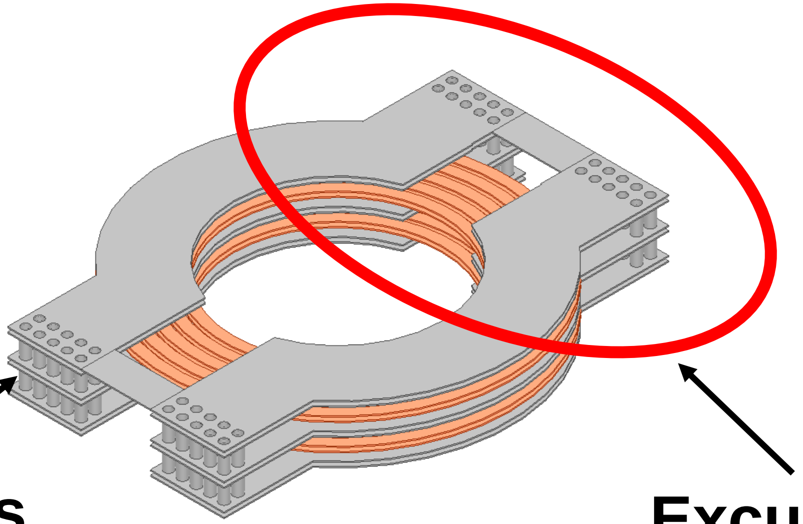
Ideal, perfectly terminated





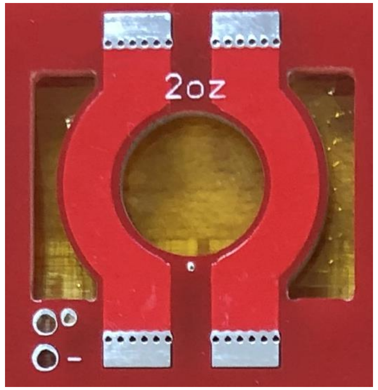
0.29Ω →

Practically terminated



Via losses

Excursion penalties

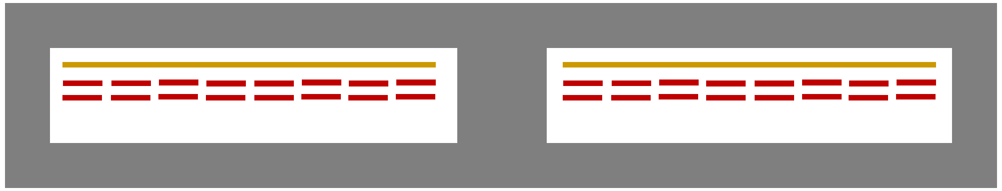


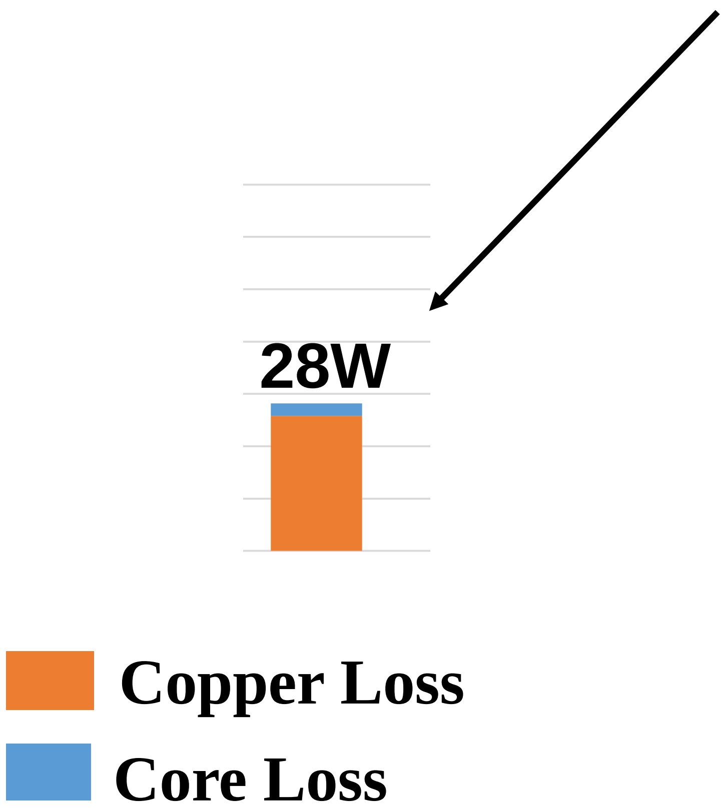
0.73Ω

Key: **Avoid complex vertical stack-ups** **in this application space**

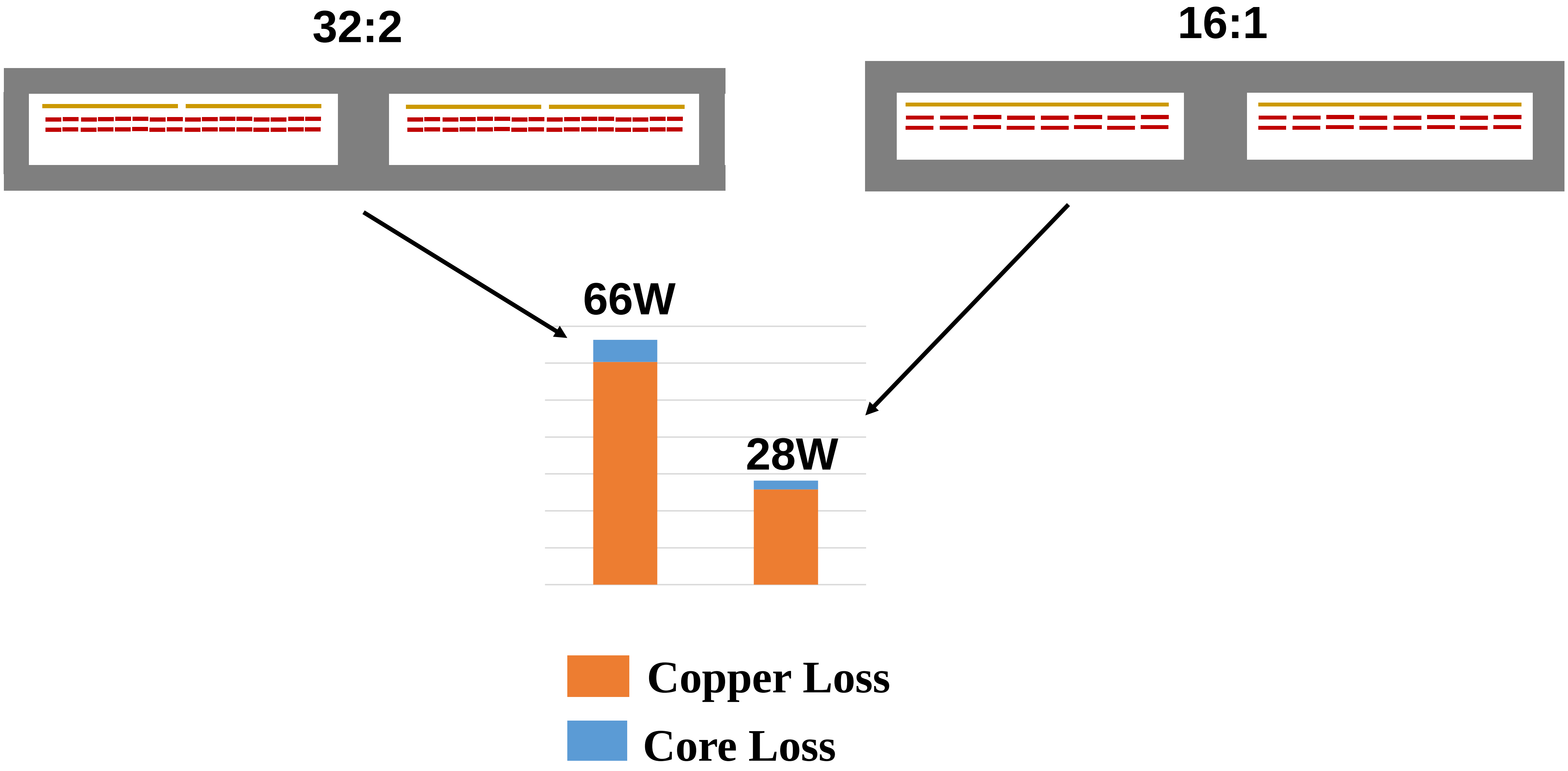
Minimizing Turns Count is Greatly Advantageous

16:1

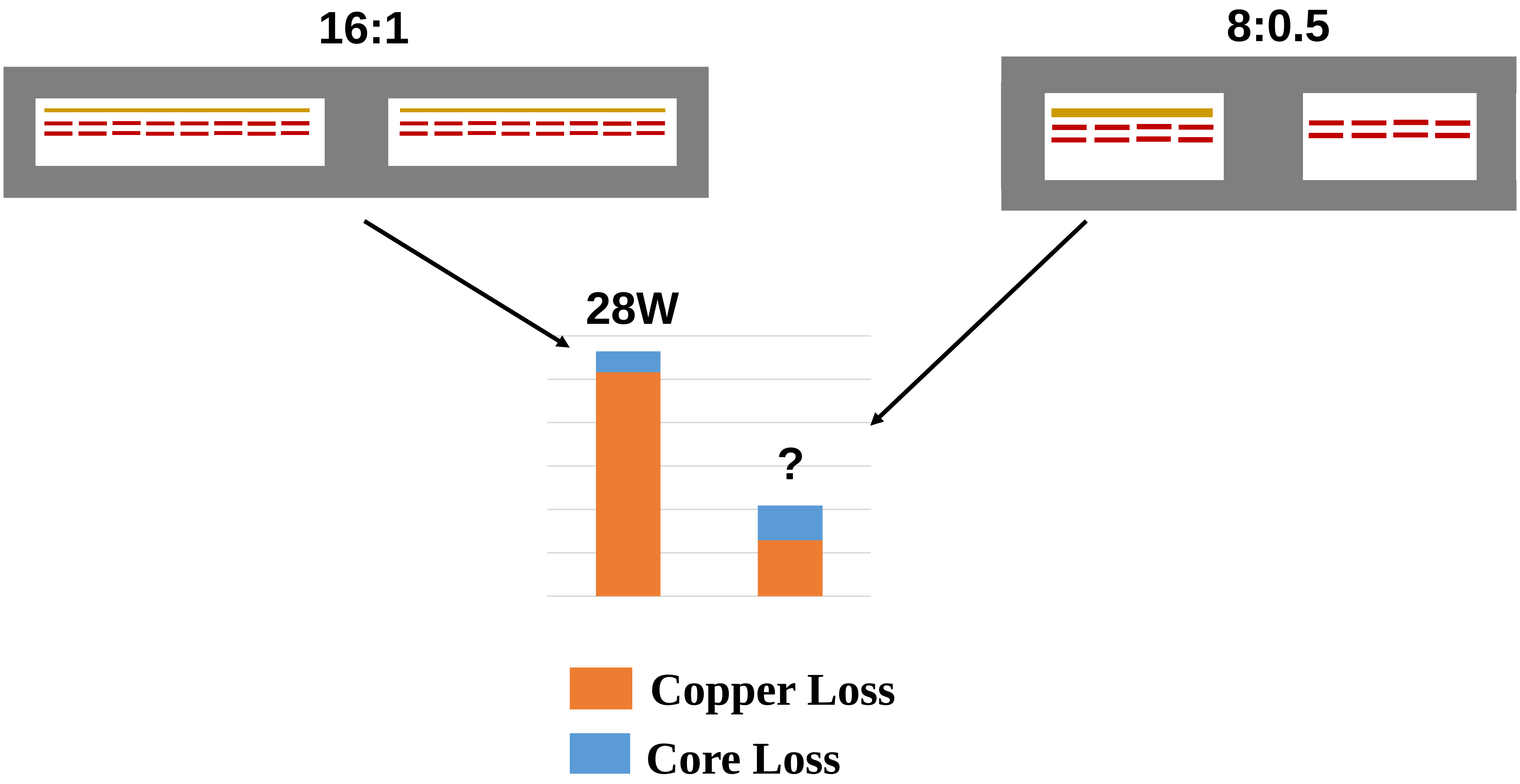




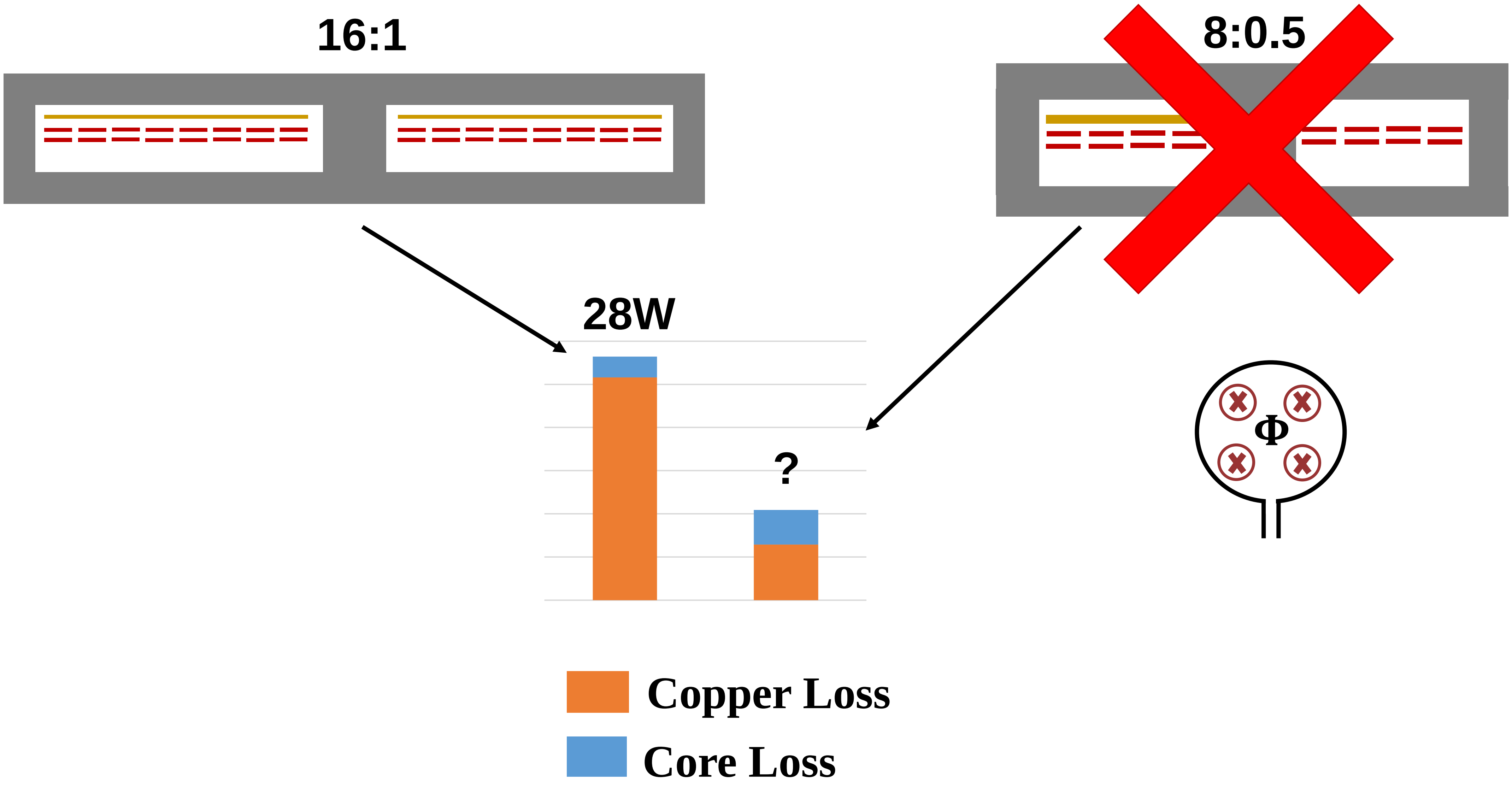
Minimizing Turns Count is Greatly Advantageous



A Fractional Turn is What We Want…

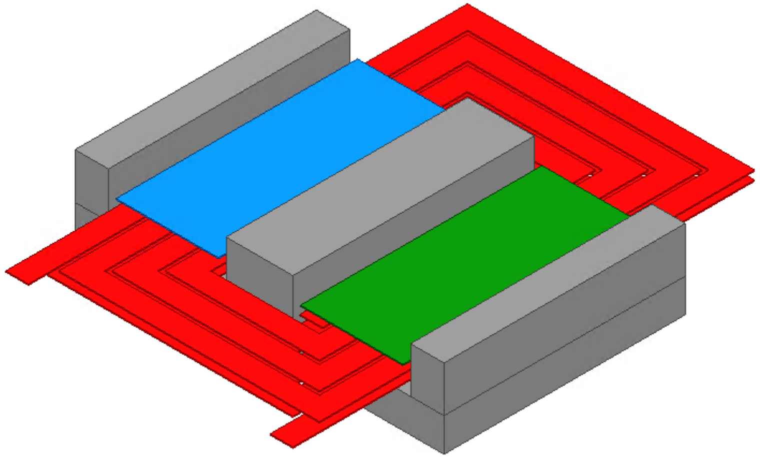


A Fractional Turn is What We Want… But Not Practical

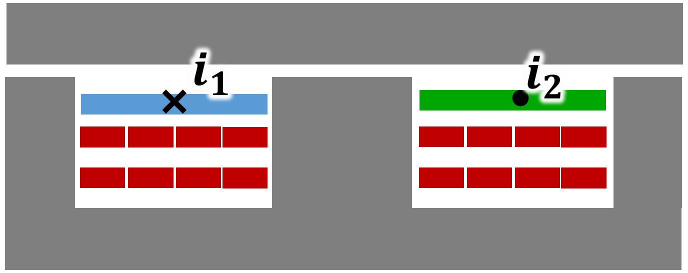


A Fractional-Turn Transformer Using a New Kind of Structure

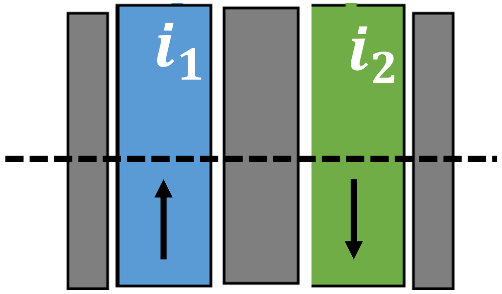
Orthographic View



Side View



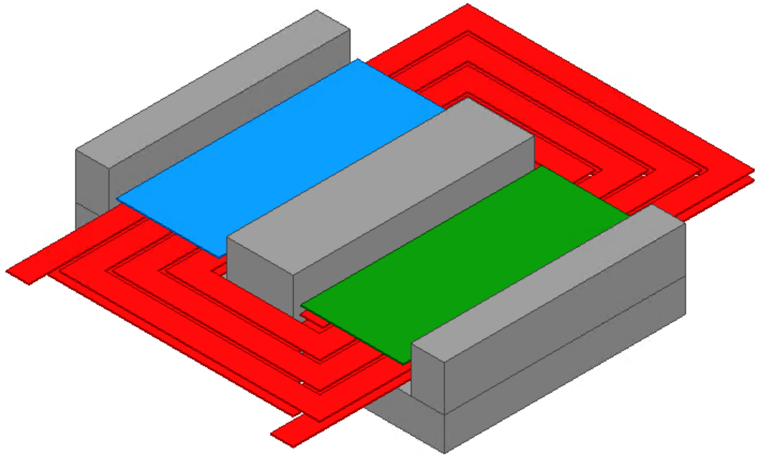
Top View



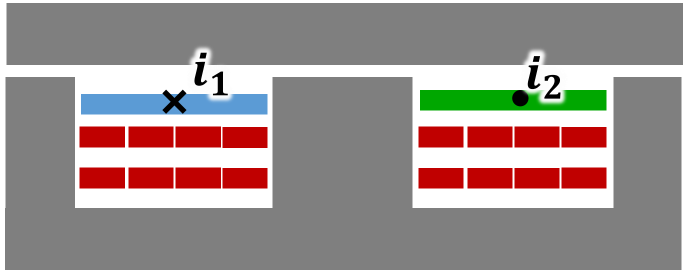
Assume Physical Symmetry About Center of the Core

Assume symmetry

Orthographic View



Side View



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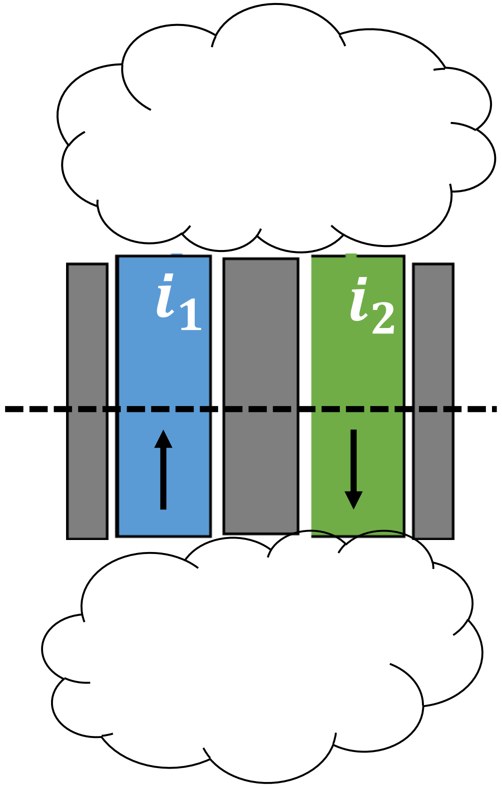
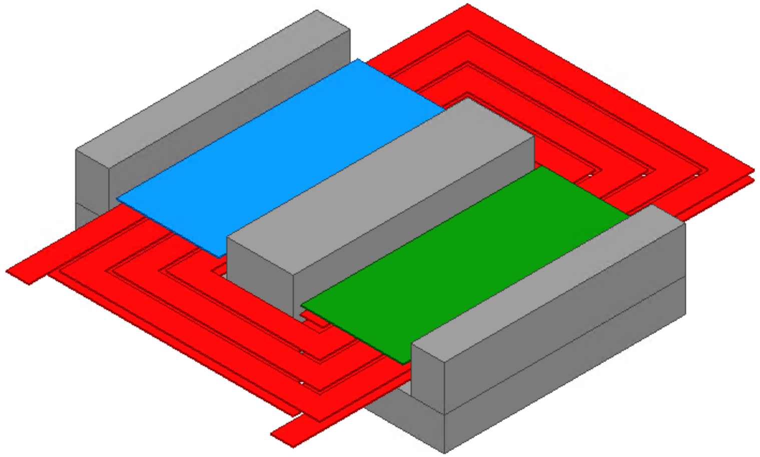


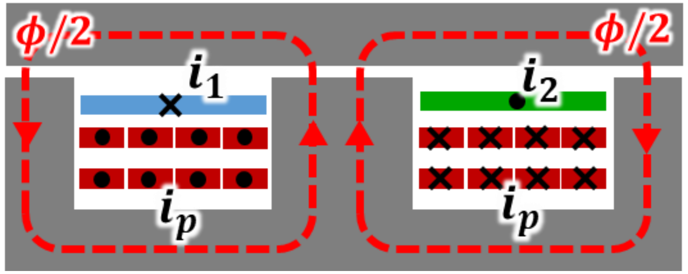
Excite the Primary Winding, Flux Flows Symmetrically

Assume symmetry

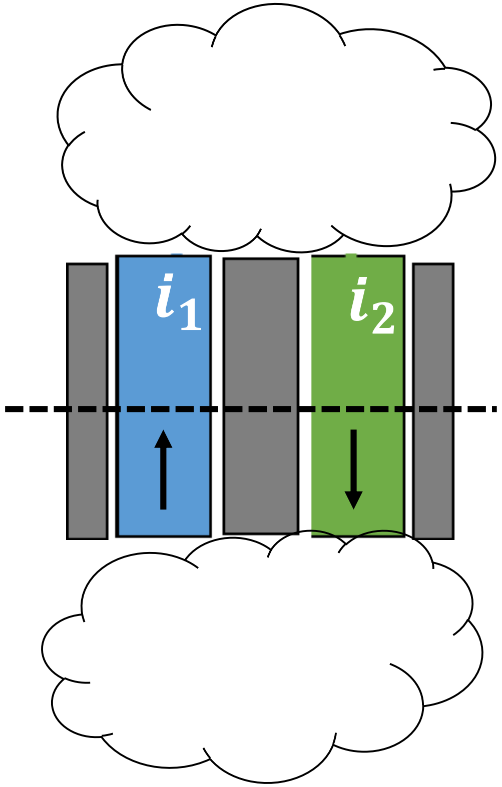
Orthographic View



Side View



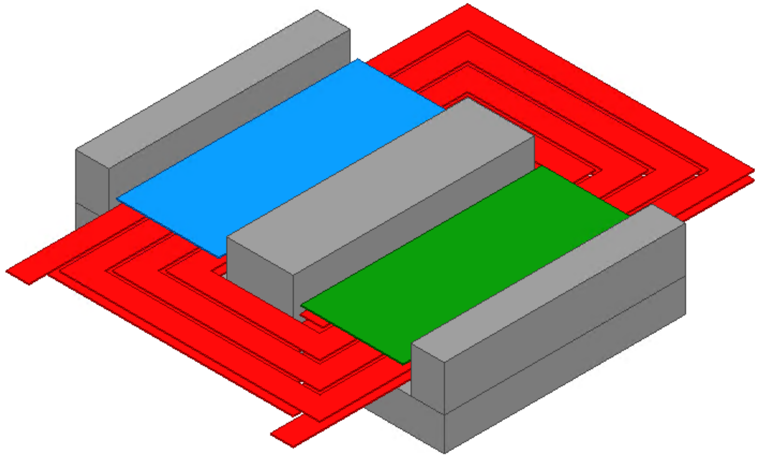
Top View



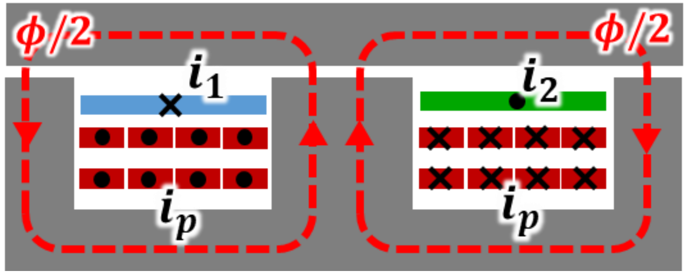
Symmetry and Magnetic Core Enforce Equal Currents

Assume symmetry

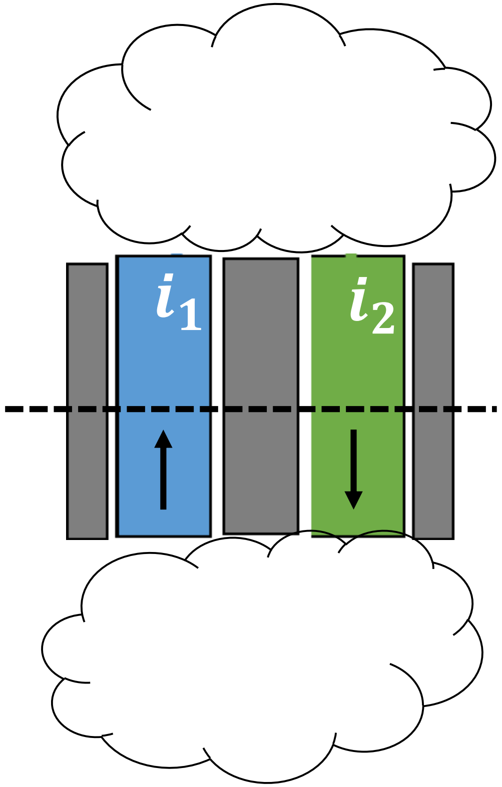
Orthographic View



Side View



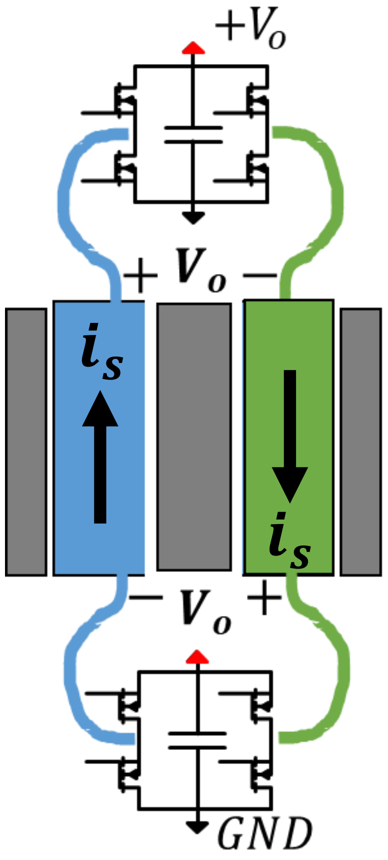
Top View

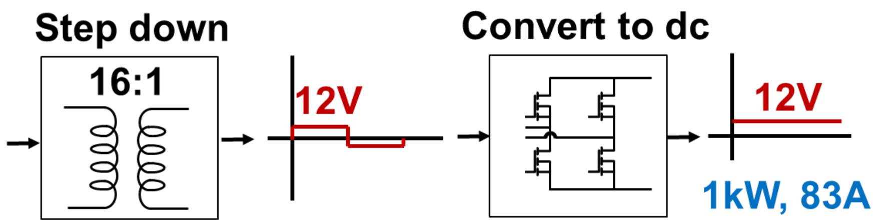


$\oint H.dl = 8i_p - i_1 = 8i_p - i_2 \quad \Rightarrow \quad i_1 = i_2$ by **symmetry**

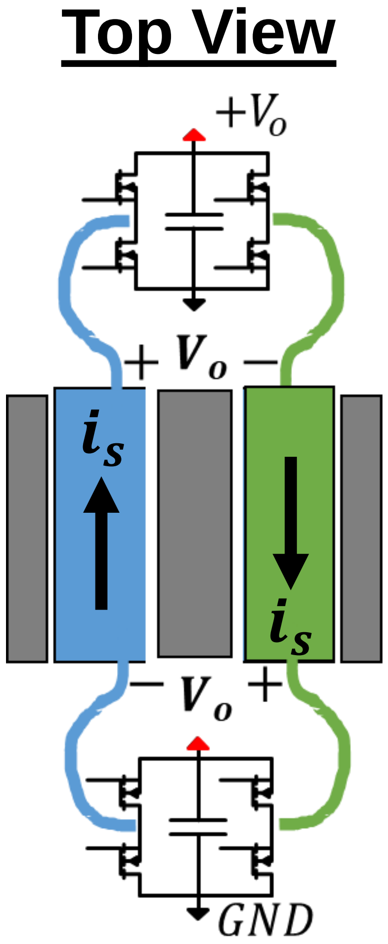
Symmetrically Distribute Two Full Bridge Rectifiers Around the Core

Top View





The Structure Behaves Like a Fractional Turn Transformer

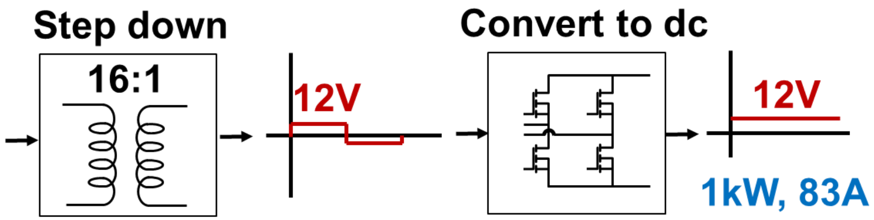


- Free to treat conductors as independent elements
- Connections yield:

$$2V_o = \frac{V_p}{N_p}$$

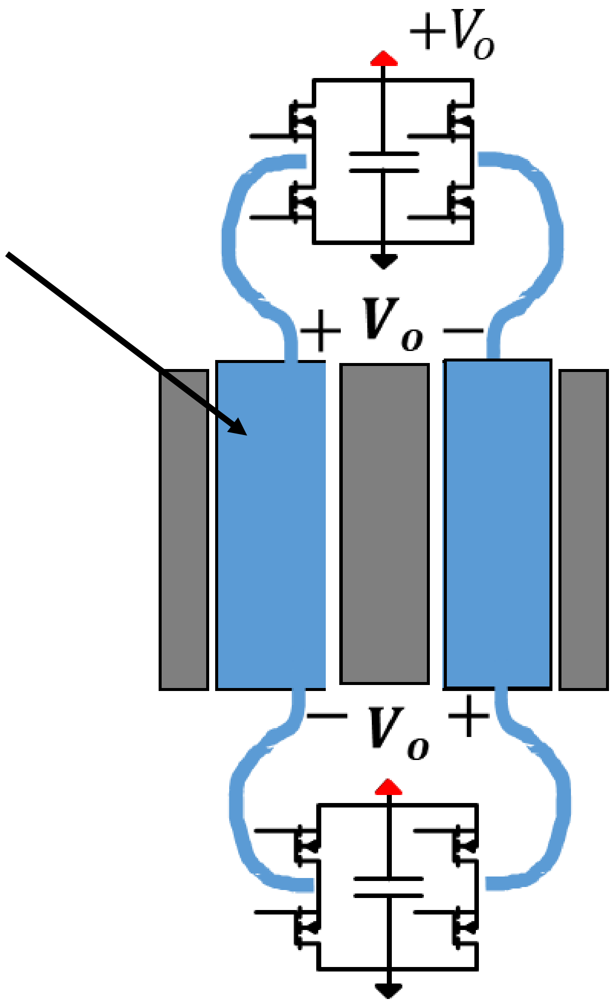
$$\frac{V_o}{V_p} = \frac{1/2}{N_p}$$

A **fractional turn** transformer



VIRT: An Example of a Coupled Electronic and Magnetic System

Equivalence of induced currents is ensured by symmetry

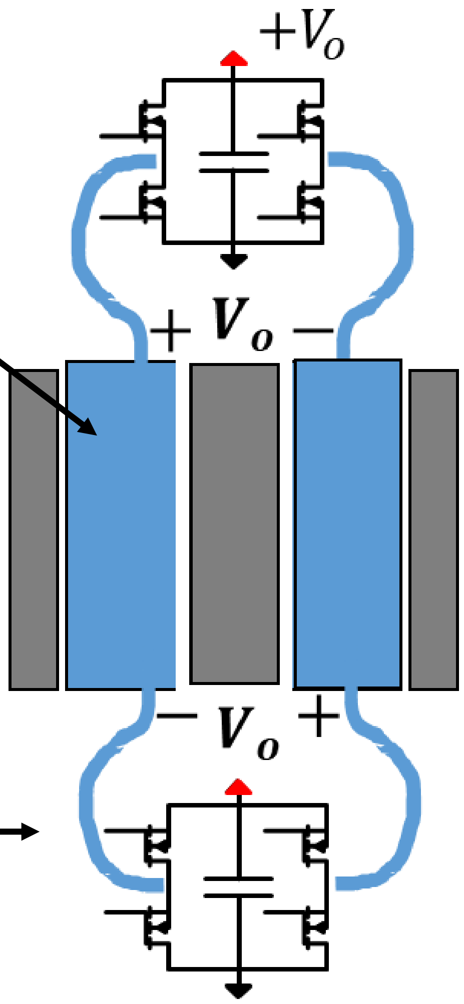


M. K. Ranjram, I. Moon and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," in *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509-6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

VIRT: An Example of a Coupled Electronic and Magnetic System

Equivalence of induced currents is ensured by symmetry

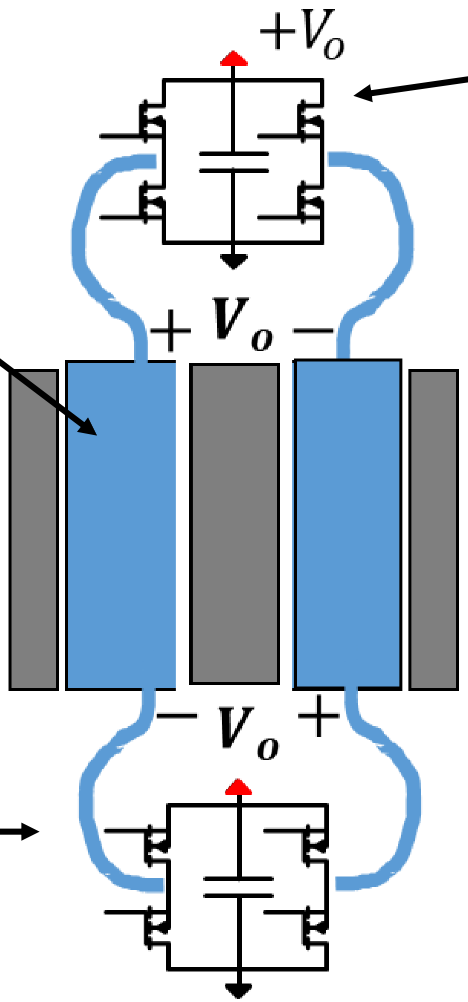
Connecting electronics are physically distributed around the core



M. K. Ranjram, I. Moon and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," in *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509-6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

VIRT: An Example of a Coupled Electronic and Magnetic System

Equivalence of induced currents is ensured by symmetry



Electronics can be controlled to modify magnetic properties

FB/FB:	$N_p : \frac{1}{2}$
FB/HB:	$N_p : \frac{2}{3}$
HB/HB:	$N_p : 1$
HB/0:	$N_p : 2$

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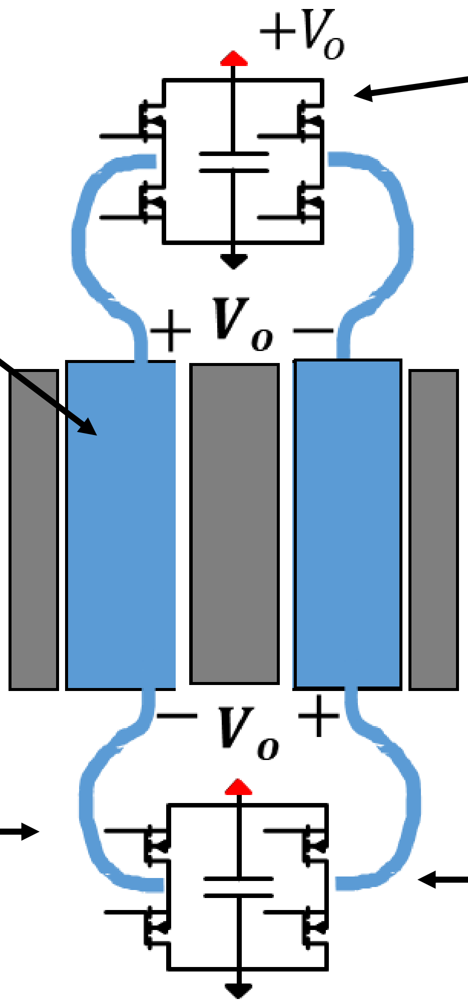

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HB/0: $N_p : 2$

Higher switch count, but each carries less current (effectively paralleled)

M. K. Ranjram, I. Moon and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," in *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509-6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

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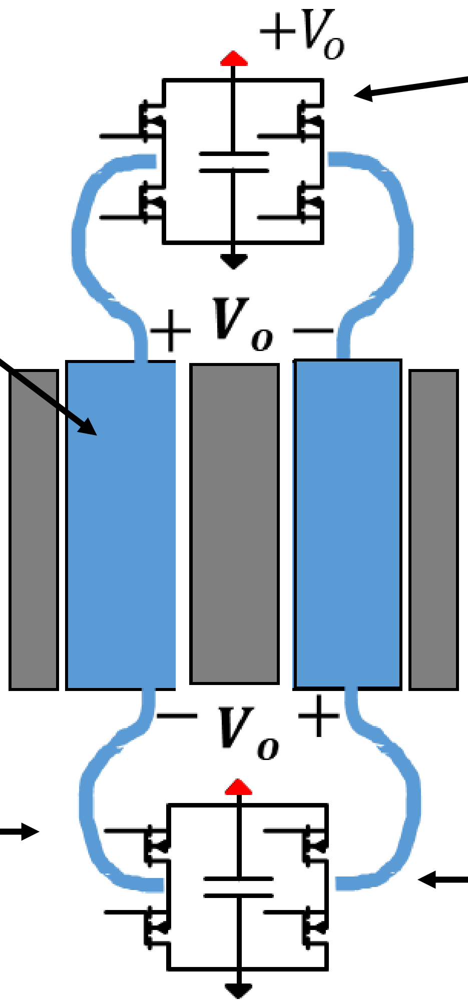

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Higher switch count, but each carries less current (effectively paralleled)

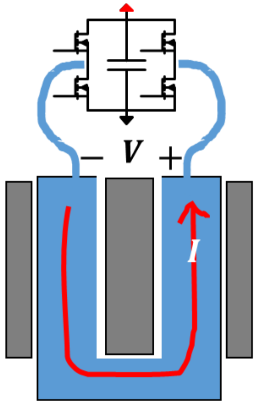
Requires a different modeling framework

M. K. Ranjram, I. Moon and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," in *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509-6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

VIRT Exponentially Reduces Copper Loss

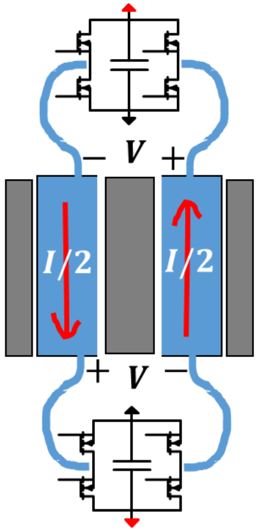
Increase Degree of Fractional Turn

Exponential Rebalancing



Single-phase
P_{cu}, P_{core}

16:1



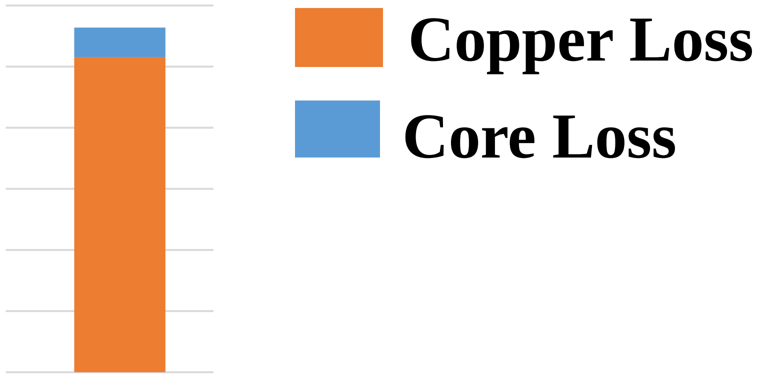
Single-phase Half-turn
$\sim P_{cu}/4$, $\sim 2^{\beta} P_{core}$

8:0.5

$$P_{cu} \propto i^2 R$$

$$P_{cu}$$

$$\sim \frac{P_{cu}}{4}$$

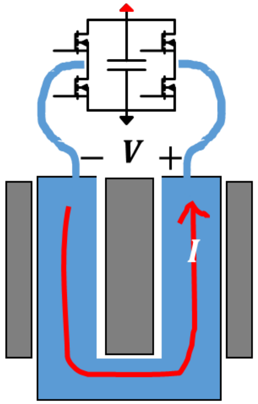


VIRT Exponentially Reduces Copper Loss and Increases Core Loss

Increase Degree of Fractional Turn

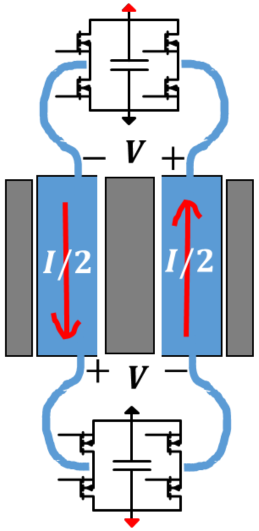
↓

Exponential Rebalancing



Single-phase
P_{cu}, P_{core}

16:1



Single-phase Half-turn
$\sim P_{cu}/4$, $\sim 2^{\beta} P_{core}$

8:0.5

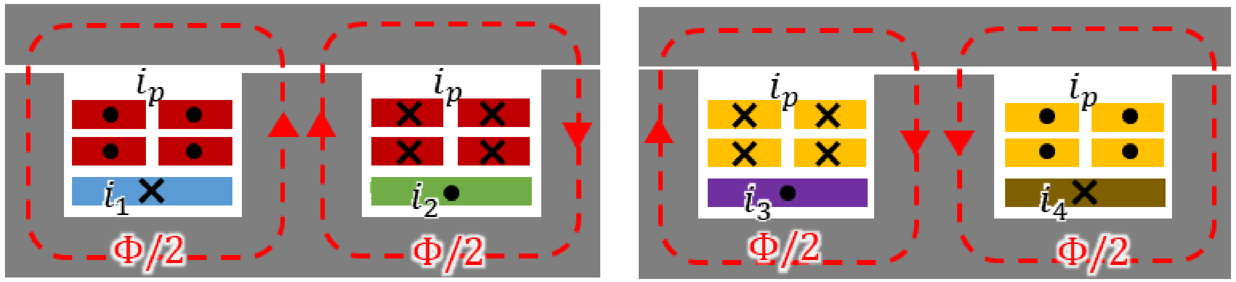
$$P_{cu} \propto i^2 R$$

$$P_{core} \propto \left(\frac{V}{N}\right)^{\beta} \quad \beta \leftarrow 2-3$$

$$P_{cu} \longrightarrow \sim \frac{P_{cu}}{4}$$

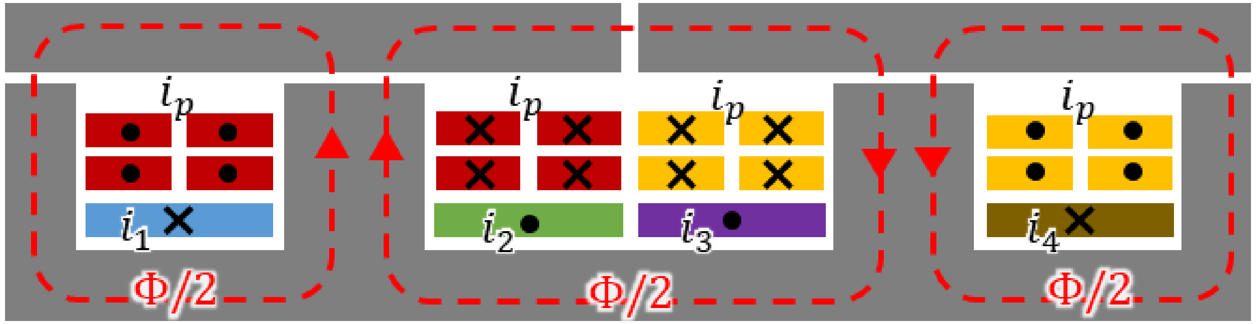
$$P_{core} \longrightarrow P_{core} \times 2^{\beta}$$

The Conventional Approach: Increasing Phase Count



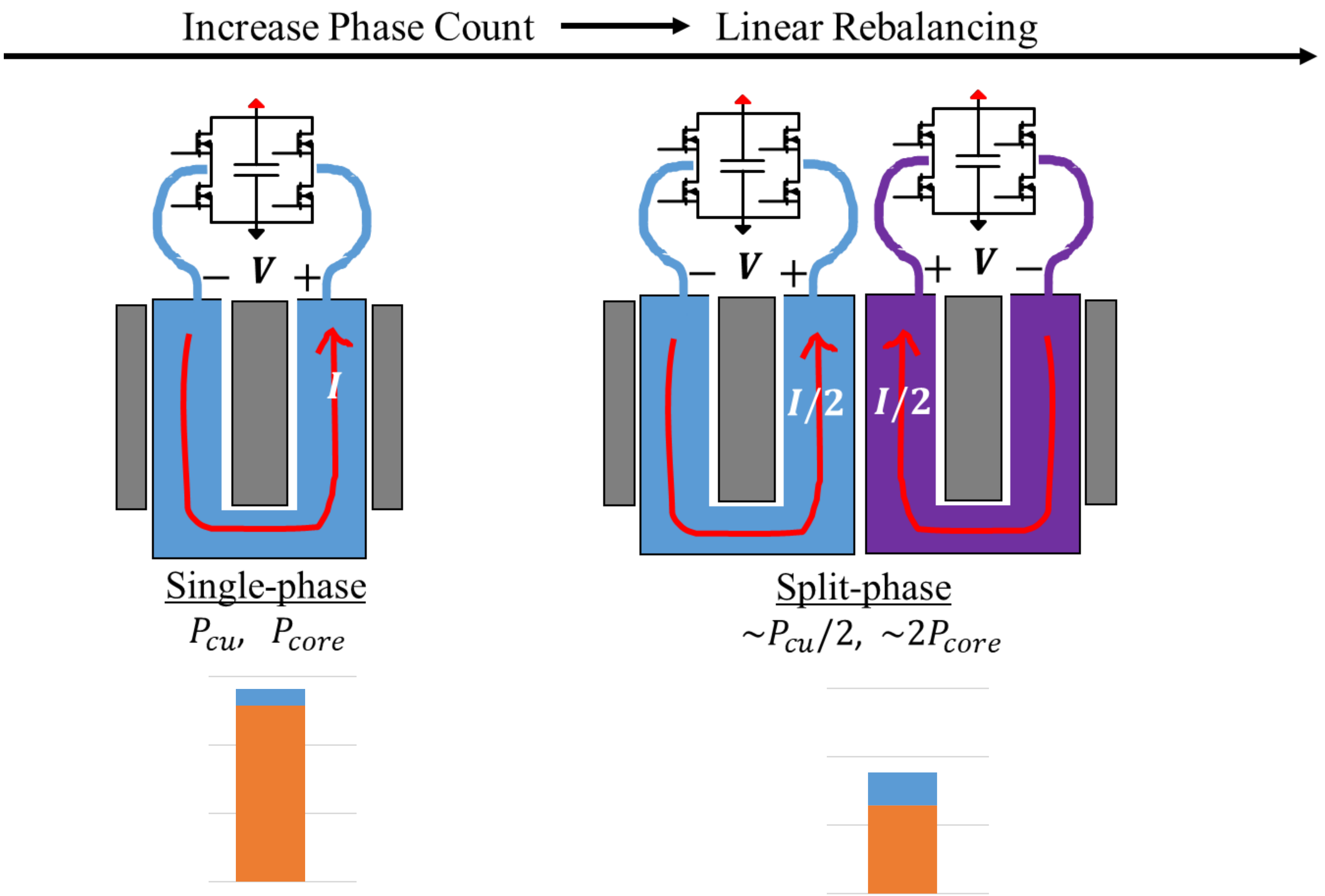
Combine

Wound such that equal and opposite flux flows on outer legs

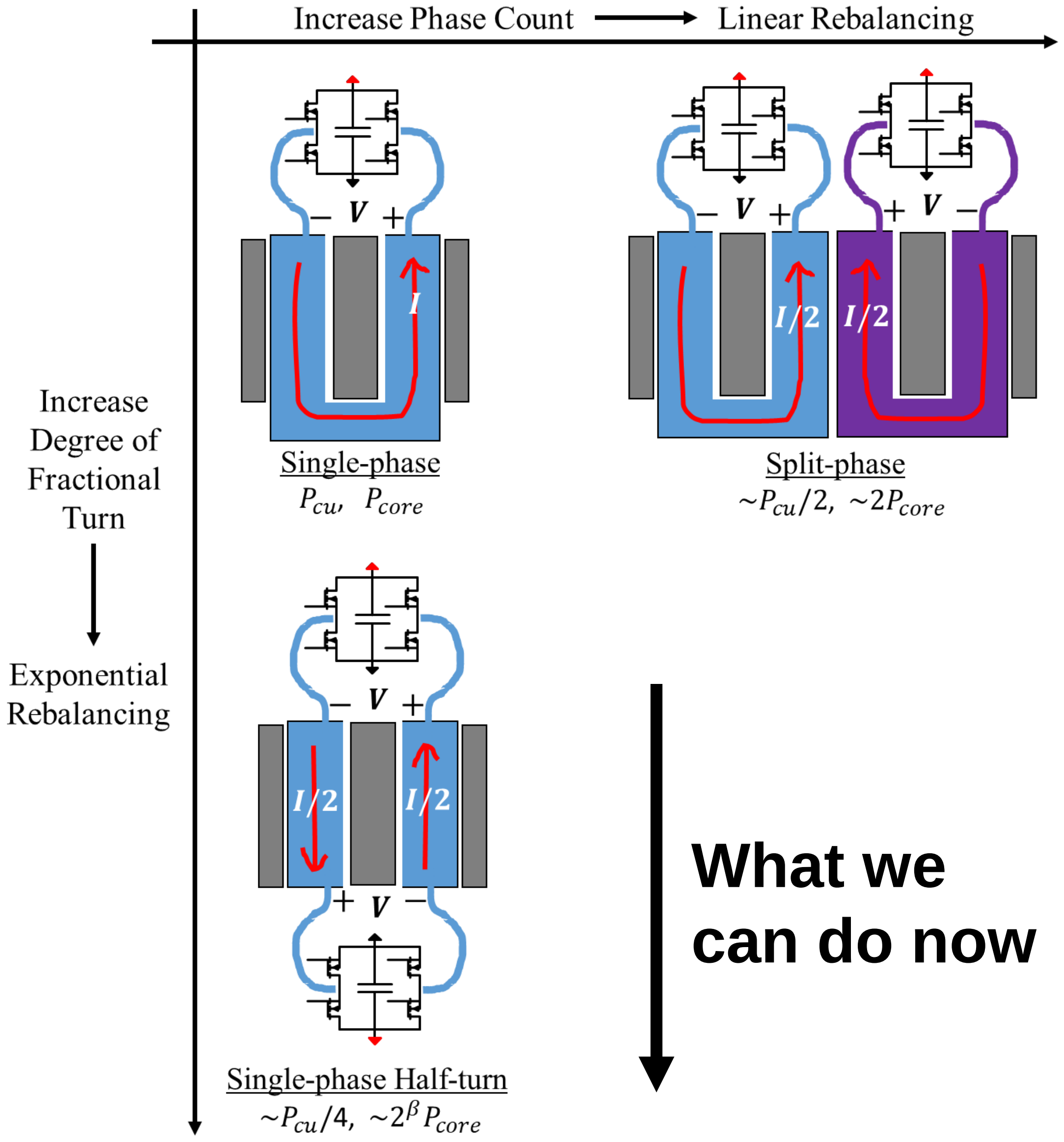


Combine cores for volume reduction

Increasing Phase Count Yields Linear Rebalancing



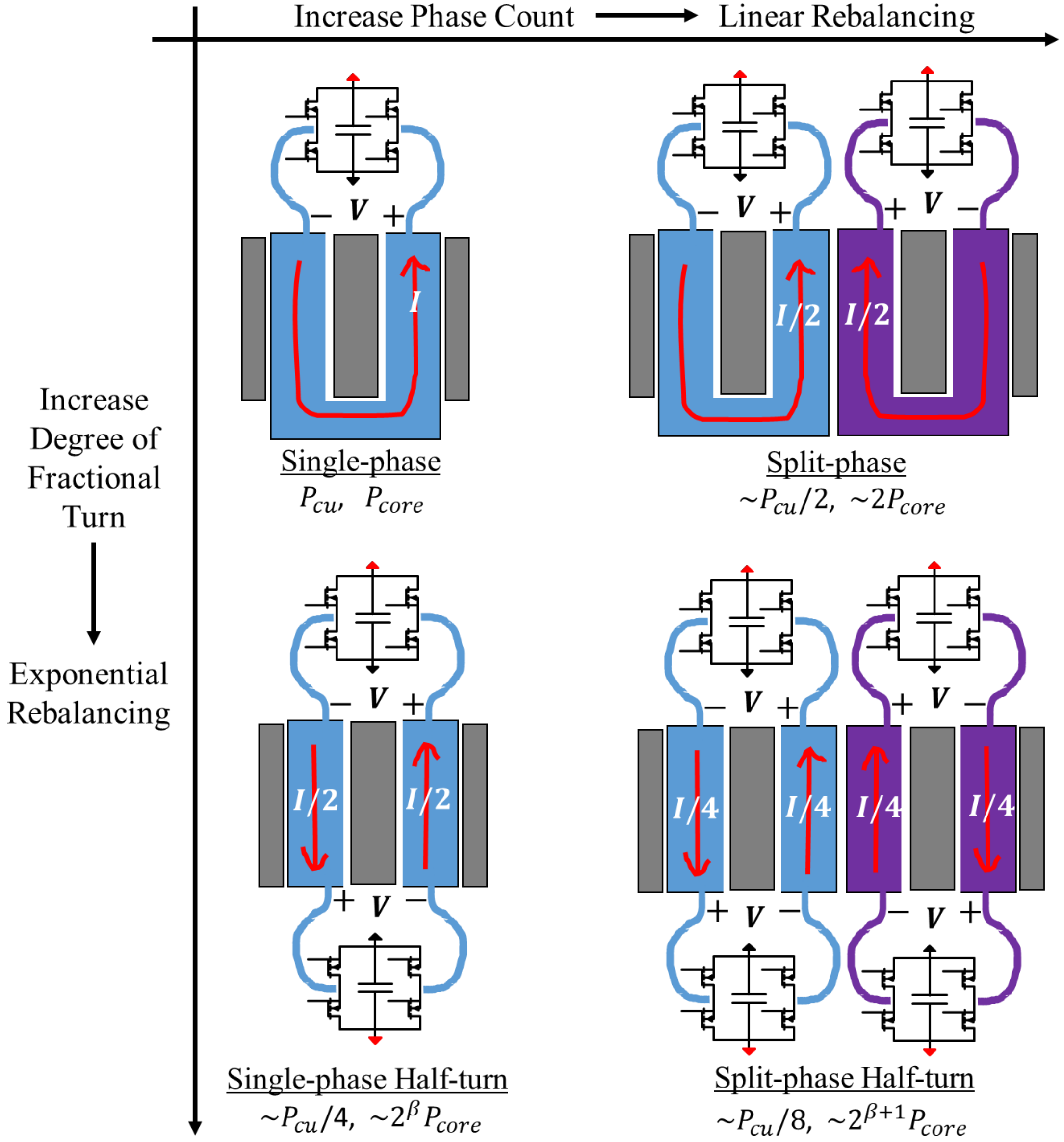
These Techniques Offer Distinct Loss Trade-offs



What we've been doing

What we can do now

“Gear Shifting” Transformer Core and Copper Loss

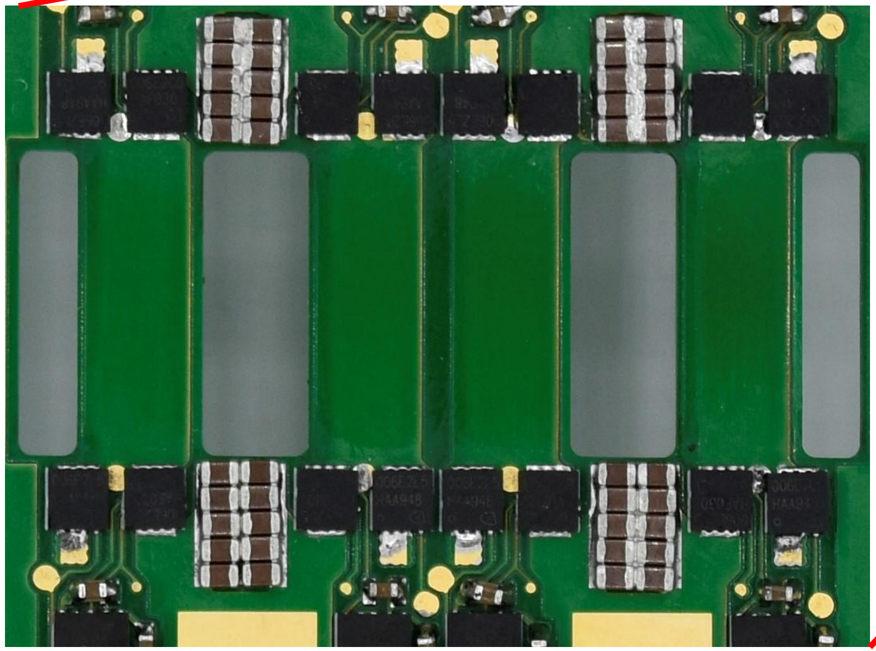


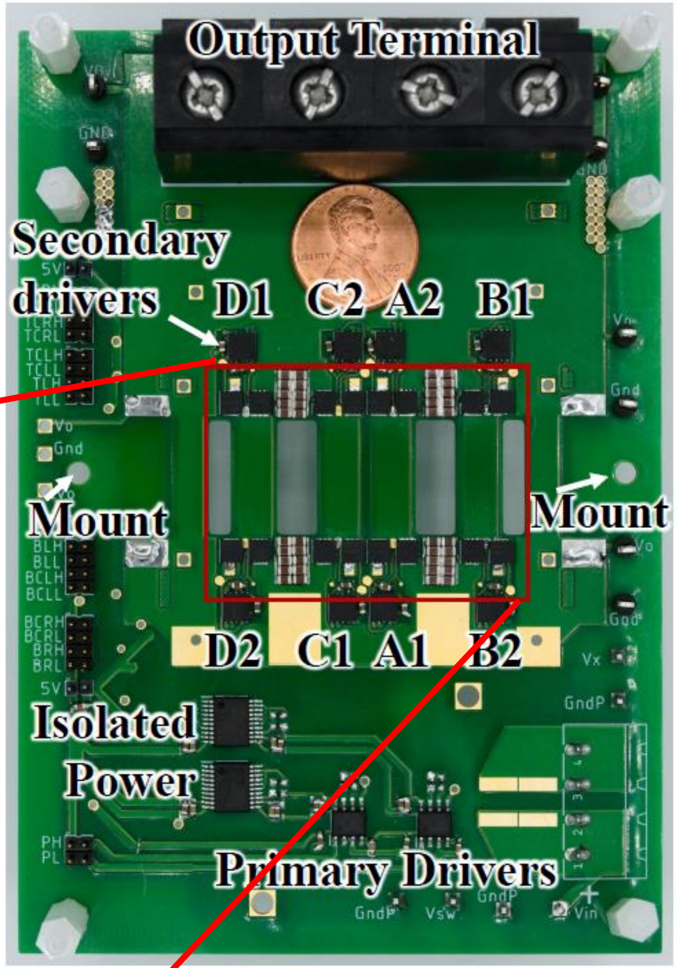
SPHTV

M. K. Ranjram and D. J. Perreault, "Leveraging Multi-Phase and Fractional-Turn Integrated Planar Transformers for Miniaturization in Data Center Applications," *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020, pp. 1-8, doi: 10.1109/COMPEL49091.2020.9265752.

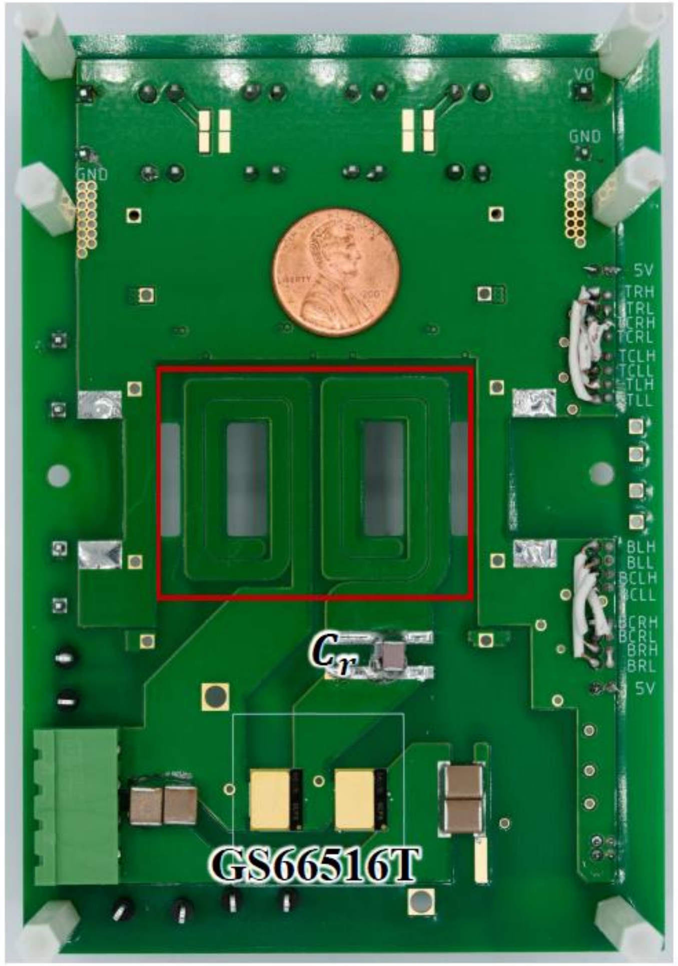
SPHTV Prototype

(a)





(c)

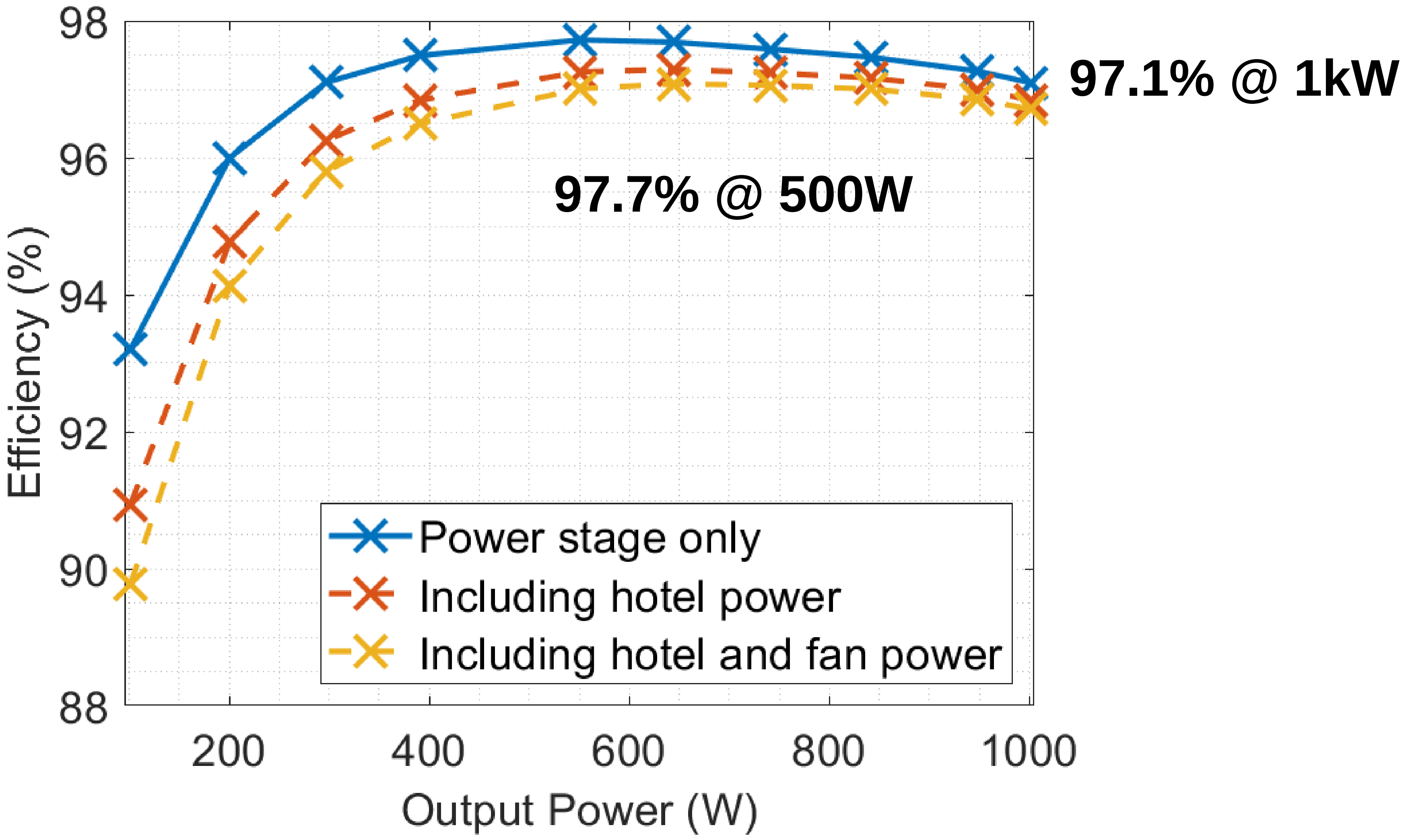


(d)

- 4 layer, non-interleaved SPP, 3/2/3oz

Prototype is Extremely Efficient

High efficiency



Losses and Thermal Performance Well Predicted

Losses fit expectation

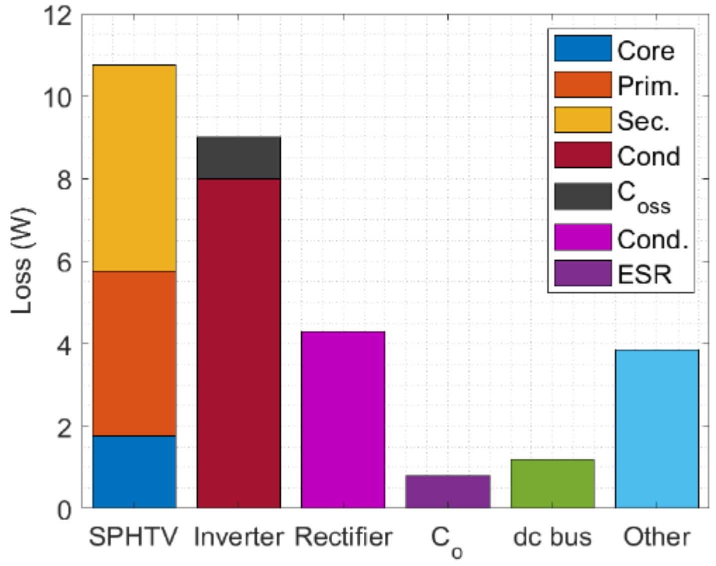


Fig. 12: Estimated loss breakdown at full load, not including hotel power (2.7W) and fan power (1.44W).

Thermal performance

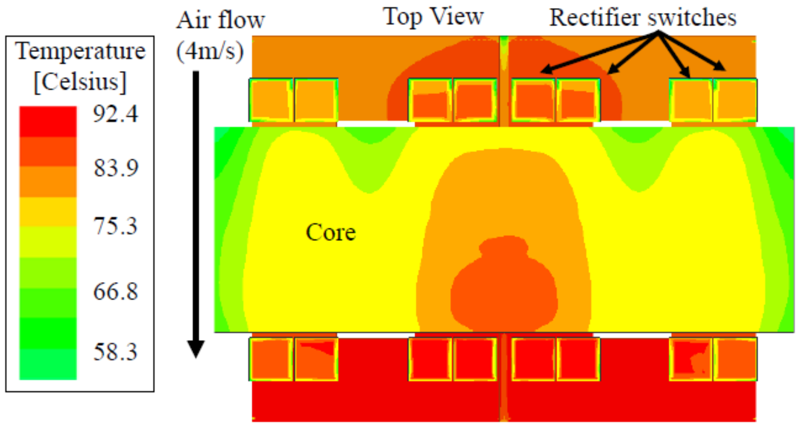


Fig. 7: ANSYS Icepak thermal simulation of the transformer.

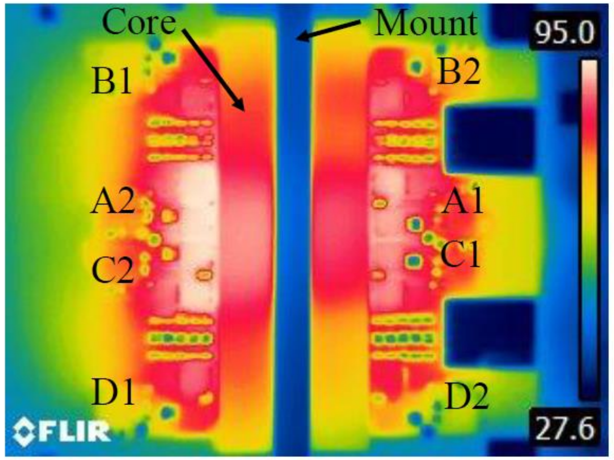
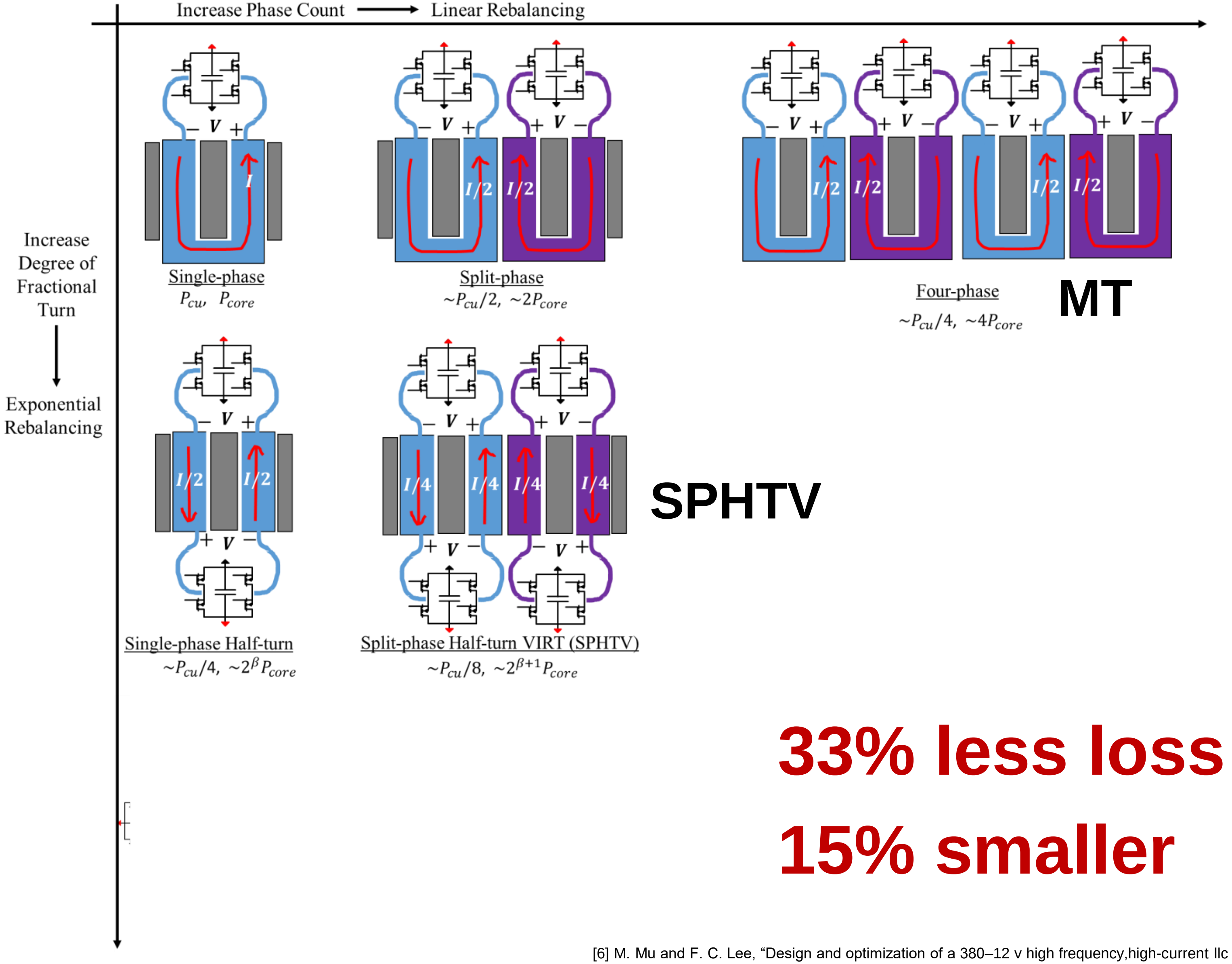


Fig. 11: Thermal image of secondary-side under full-load (obtained after 15 minutes of continuous operation, 22°C room temperature). The fan is located to the right of the PCB.

SPHTV: Much Lower Loss and Much Smaller than Best Alternatives



380-12V, 1kW

	This work	MT [6]
Stack-up	S/_/P/P	S/P/P/S
Peak power stage efficiency	97.7%	-
Peak efficiency including hotel power	97.3%	97.1%
Full load loss (power stage only) [W]	29.9	34.4
Transformer loss at full load [W]	10.8	16.3
Transformer footprint [mm^2]	1536	2200
Height [mm]	9.23	7.3
Transformer box volume [cm^3]	14.2	16.1

[a] 'G' is a secondary layer tied directly to secondary ground

33% less loss

15% smaller

[6] M. Mu and F. C. Lee, "Design and optimization of a 380–12 v high frequency,high-current llc converter with gan devices and planar matrix transformers," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 854–862, 2016.

[11] Y. Liu, K. Chen, C. Chen, Y. Syu, G. Lin, K. A. Kim, and H. Chiu,"Quarter-turn transformer design and optimization for high power density 1-mhz llc resonant converter," IEEE Transactions on Industrial Electronics, vol. 67, no. 2, pp. 1580–1591, 2020.

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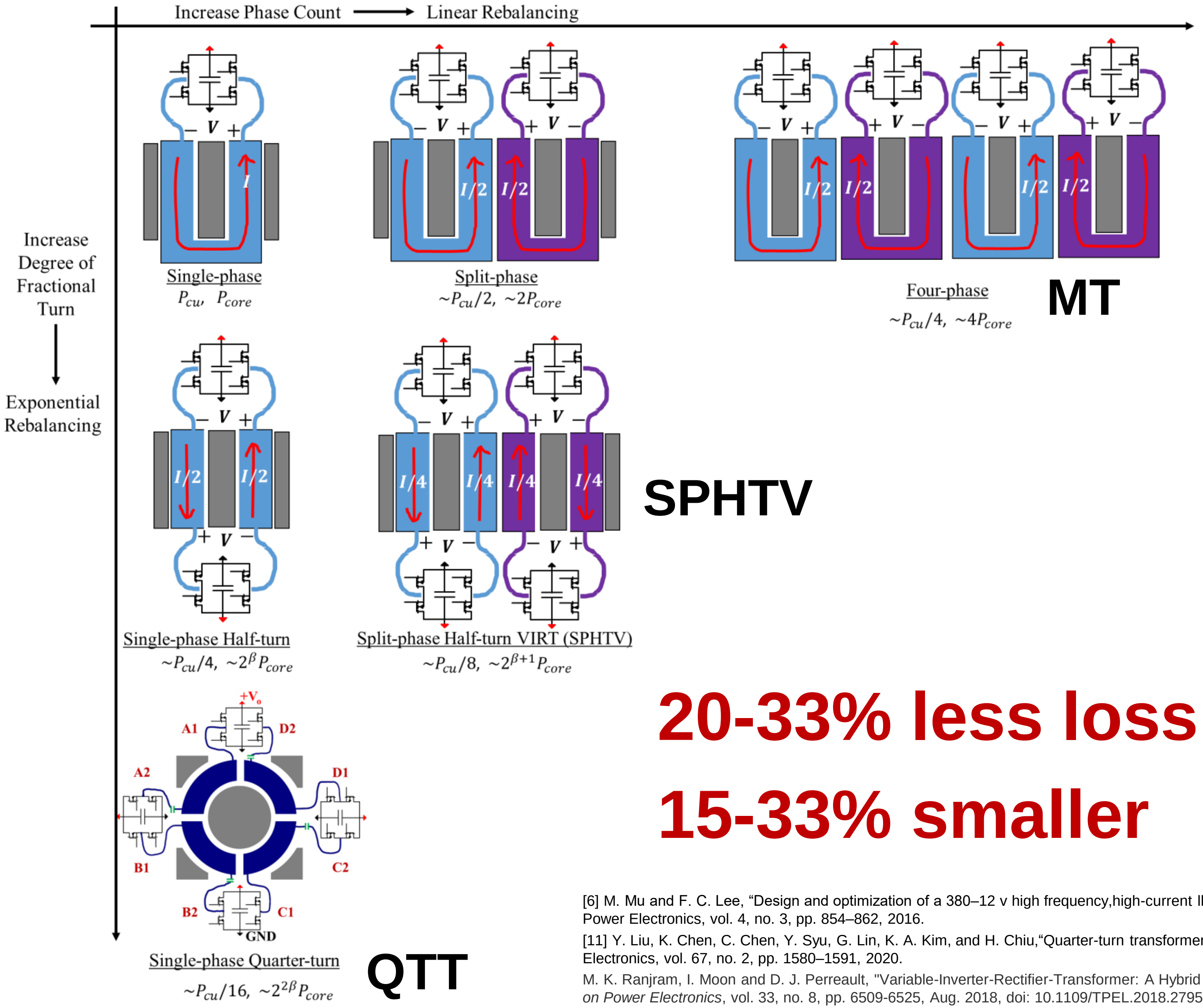

380-12V, 1kW

	This work	MT [6]	QTT [11]
Stack-up	S/_/P/P	S/P/P/S	S/G/P/P/G/S[a]
Peak power stage efficiency	97.7%	-	97.0%
Peak efficiency including hotel power	97.3%	97.1%	-
Full load loss (power stage only) [W]	29.9	34.4	41
Transformer loss at full load [W]	10.8	16.3	13.2
Transformer footprint [mm^2]	1536	2200	2500
Height [mm]	9.23	7.3	8.9
Transformer box volume [cm^3]	14.2	16.1	22.3

[a] 'G' is a secondary layer tied directly to secondary ground

20-33% less loss

15-33% smaller

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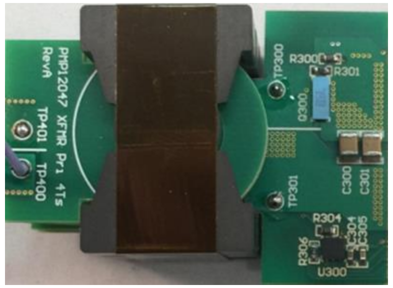
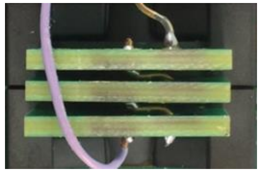
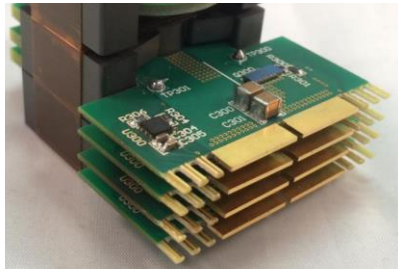
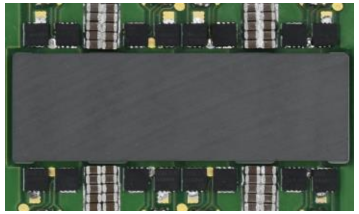
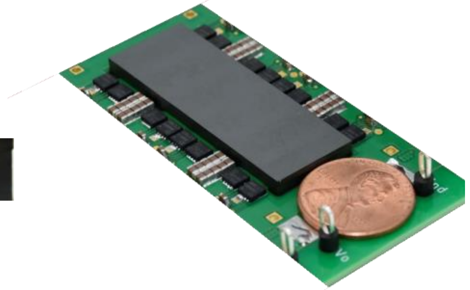
Much More Efficient, Capable, Smaller than Industry Reference Design

Top	Front	Orthographic
		
		

Volume	P_{max}	Efficiency
33cm3	500W	96.8% @500W
14.5cm3	1000W	97.7% @500W 97.1% @1000W

2.3x smaller | **2x more capable** | **25% less loss**

Conclusion

- Coupled Electronic and Magnetic System (CEMS) paradigm enables the VIRT concept
- Fractional and variable turns ratios unachievable in conventional design
- Used to build much smaller and much more efficient datacenter supply