Stanford University

Stanford University Power Electronics Research - Laboratory

Power Electronics in the SUPER-Lab

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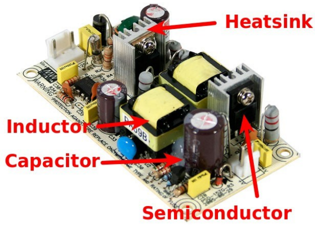
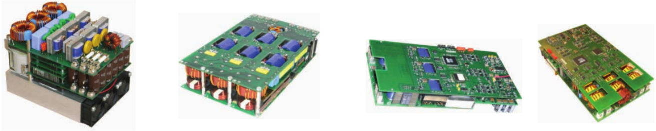
Power density in Converters



- Inductors and capacitors
  - size $\propto \frac{1}{f_s}$
  - Slow improvements in size and performance
- Semiconductors
  - Switching loss $\propto f_s$
  - Great advances in recent years
- Heatsink: Hard to extract heat from small volumes



$f_P =$	72kHz	250 kHz	500kHz	1MHz
$\rho =$	4.5 kW/dm^3	10 kW/dm^3	13 kW/dm^3	14 kW/dm^3

Fig. 18. Dependency of the power density of a unidirectional three-phase/level PFC rectifier system (Vienna Rectifier) on the switching frequency. Only for the system with f_P=72kHz the heatsink volume is considered in the given power density figure (4.5kW/dm^3 and/or 74W/in^3); accordingly the systems with f_P=250 / 500 / 1000kHz actually show a lower power density, i.e. a power density limit of $\rho \approx$ 10kW/dm^3 could be assumed for f_P= 1MHz.

Kolar, J.W.; Biela, J.; Waffler, S.; Friedli, T.; Badstuebner, U., "Performance trends and limitations of power electronic systems," CIPS, 2010 6th Int. Conf. , vol., no., pp.1,20, 16-18 March 2010

Power density trends

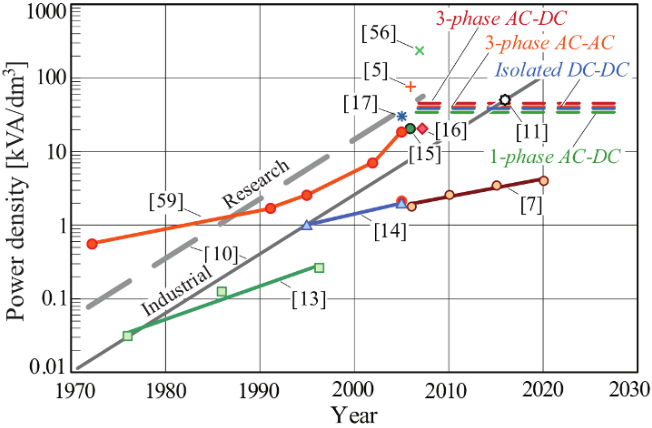


Fig. 2. Power Density trend of industrial and research systems [(10)] and the Power Density Barriers.

J.W. Kolar,U. Drofenik, J. Biela, M.L. Heldwein, H. Ertl, T. Friedli and R.D. Simon, "PWM Converter Power Density Barrier", IEEJ Transactions on Industry Applications (Section D), Volume: 128-D, Issue: 4, April 2008.

Very High Frequency Power Electronics

Switching at 10's of MHz

- High frequency operation reduces the energy storage requirements of inductors and capacitors.
- Inductors are small enough to be fabricated with an air-core

Use PCB to implement inductors

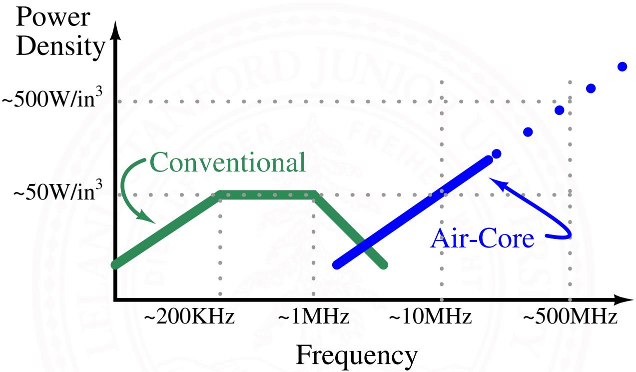
- Inductances and capacitances can be implemented within the PCB
- Filters and EMI shielding can also be implemented within the PCB.

New Circuit Topologies

Implement rectifiers that reduce switch stress allowing for higher overall gains.

- Use better switches with lower parasitics

Why switching at 10s of MHz?

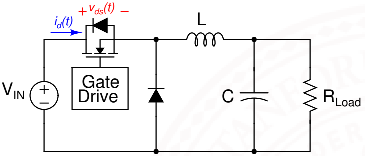


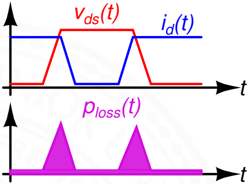
The promise of VHF power conversion

Reduced energy storage → Smaller passive components & Faster transient response

J. S. Glaser, et al, "A 900W, 300V to 50V dc-dc power converter with a 30 MHz switching frequency," In Proc. Twenty-Fourth Annual IEEE Applied Power Electronics Conf. and Exposition APEC 2009, pp. 1121-1128, 2009.

Device Switching Loss





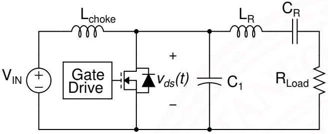
Switching loss (hard switching)

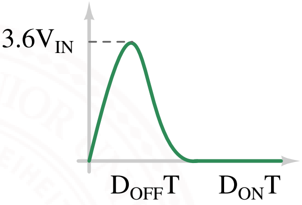
- V-I overlap during device switching
- Includes device charge removal at turn off (device recovery)
- Includes device capacitance discharge at turn on
  - Energy stored at turn off, discharged at turn on (if not ZVS)

Loss dependency

- Proportional to switching frequency
- Some components increase with load current, some independent
- Increase as device area increases

Soft Switching Operation





Resonant Zero-Voltage Switching reduces switching loss (e.g., Class E)

- V-I overlap loss greatly reduced via capacitive snubbing
- ZVS turn-on avoids capacitive energy dump

Strategy is effective, but

- Only efficient over a narrow load range
- Control becomes challenging at very high frequencies
- Device stresses are high for many topologies
  - increased conduction loss

Magnetic Losses

Conventional cored magnetics

- Core loss increases rapidly with frequency ($\propto f^k$)
- Good core materials become scarce above 10 MHz
- An optimum frequency range exists for cored inductors

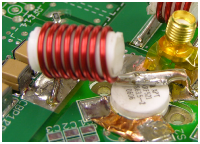
At high enough frequencies, the inductor values needed are small

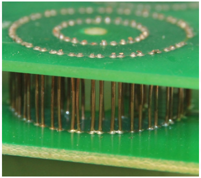
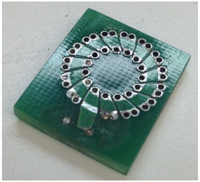
- Build entirely coreless designs
- Air-core components not subject to Curie temperature limitations

Core-less magnetics

- Get better as frequency increases
- Easier to integrate
- Can be made self shielding in some cases

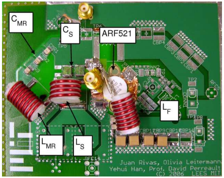
Air-core inductors for VHF converters

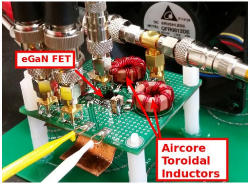


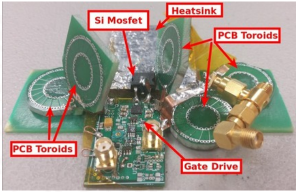



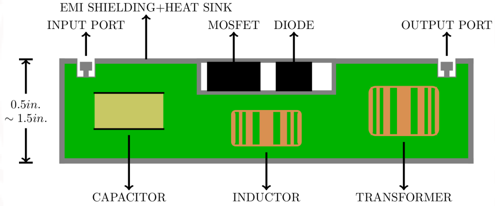
- Air-core components not subject to saturation or Curie temperature limitations
- Toroidal are an improvements over solenoids as the magnetic field is constrained to the torus
  - Lower stray fields → Lower EMI issues
- PCB toroids have better copper coverage and lower loss and very repeatable
- Better air-core passives are possible with new fabrication techniques: 3D-printing

Path forward





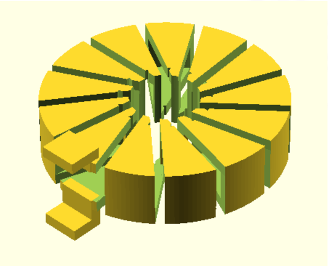


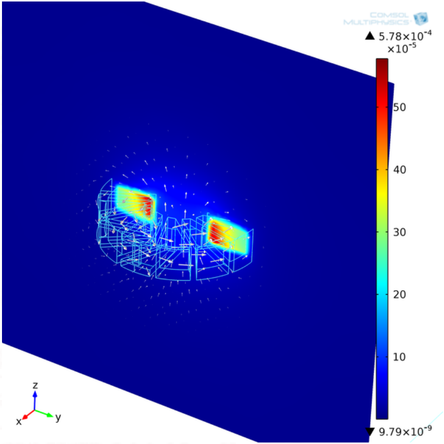


Replacing solenoids with toroids → Printing passives within inner layers of PCB.

- Top and bottom layers function as EMI shield and heatsink
- Planar-stackable structure

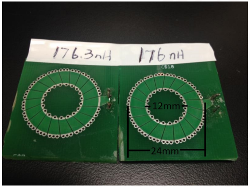
“one turn” inductance

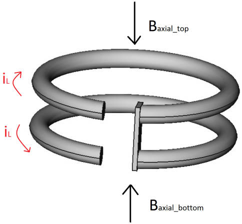


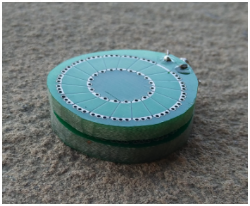


- one turn axial direction inductance that can lead to EMI, extra losses on the ground plane
- Also results in current crowding on the inner ring of the toroid
- For air core inductors, the “one turn” inductance is comparable in value to the toroidal value

“one turn” inductance cancellation







- We can place two inductors with same dimensions but opposite winding direction vertically stacked to cancel the axial fields.

Capacitor Implementation: dielectric loss

- Capacitors in the converter experiences high frequency (27.12 MHz) and high voltage swing(e.g. greater than 500 V)
- Low "loss tangent" is the key to select dielectric material

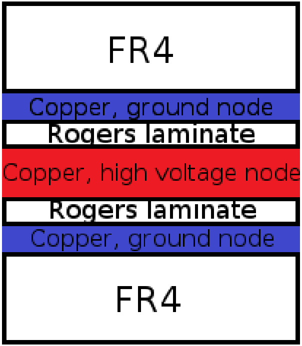
	FR4	Rogers 4360G2
ϵ_r	4.5	6.15
$\tan\delta$	0.018	0.0038

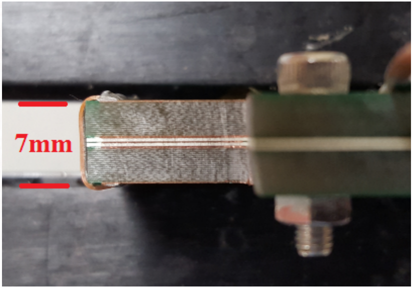
- For example, for a capacitor with 20mm × 20mm, 0.3mm thickness, and 300 V_{RMS},

$$P_{loss,FR4} = V_{RMS}^2 \times \frac{\omega\epsilon_0\epsilon_r tan\delta A}{d} = 6.4W$$

$$P_{loss,Rogers4360} = V_{RMS}^2 \times \frac{\omega\epsilon_0\epsilon_r tan\delta A}{d} = 1.8W$$

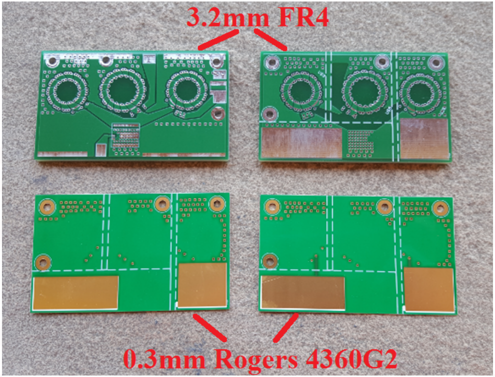
Capacitor Implementation





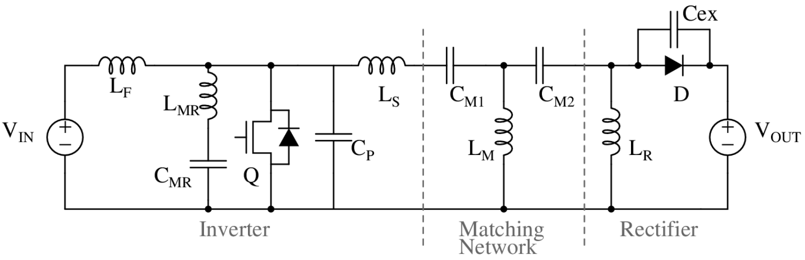
- To minimize dielectric loss, we avoid having high voltage node and ground node through FR4

PCB implementation



- FR4 and Rogers laminates used for inductors and capacitors respectively. They are mechanically holed together to form a stack
  - Rogers laminates was limited to capacitor implementation due to cost considerations
  - Rogers has much better electrical and thermal characteristics

Dc-dc Converter



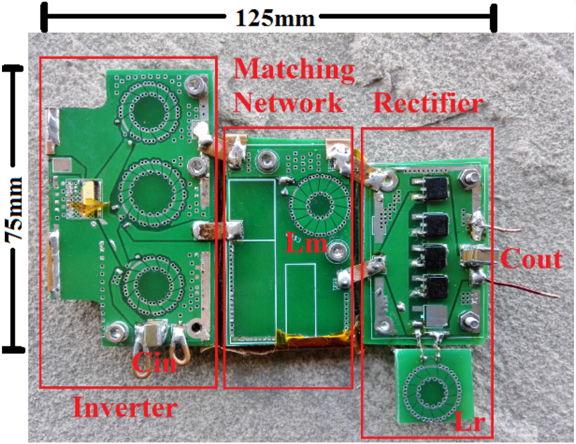
- Inverter, matching network, rectifier stage
- The matching network is chosen such that no dc block is necessary in the inverter stage
- All inductors and capacitors are resonant and feasible to implement in PCB

Bill of Material

Part	Value	Description
L_F	105 nH	2 $\times$ 52.5 nH PCB inductor (Q=85@27.12MHz)
L_{MR}	105 nH	2 $\times$ 52.5 nH PCB inductor (Q=85@27.12MHz)
L_S	180 nH	2$\times$ 90 nH PCB inductor (Q=90@27.12MHz)
L_M	67 nH	2$\times$ 134 nH PCB inductor (Q=94@27.12MHz)
L_R	81 nH	1$\times$ 81 nH PCB inductor (Q=100@27.12MHz)
C_{MR}	82 pF	0.3 mm Rogers 4360G2
C_P	160 pF	0.3 mm Rogers 4360G2
C_{M1}	235 pF	0.254 mm Rogers 6010.2LM
C_{M1}	436 pF	0.254 mm Rogers 6010.2LM
C_{IN}	3 μF	X7R capacitor
C_{OUT}	6 μF	X7R capacitor
MOSFET	GS66508T	650 V GaN FET
Diode	STPSC4H065B-TR	650 V SiC shottky diodes

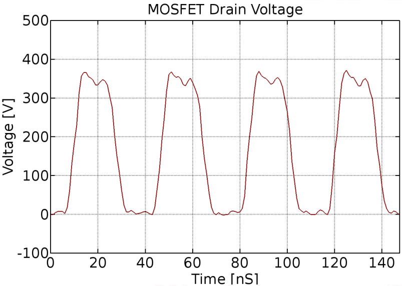
- PCB implementation greatly simplifies the tuning and improves repeatability
- Input and output filter capacitors implemented with SMD device.
  - Multi-resonant structure are currently under investigation to reduce capacitor size to some extent

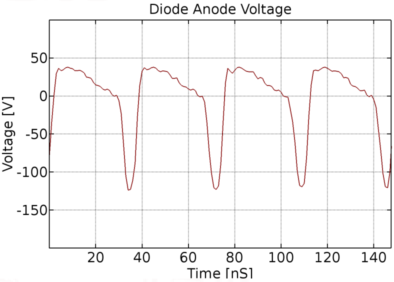
Prototype Implementation

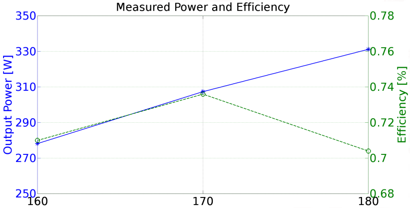


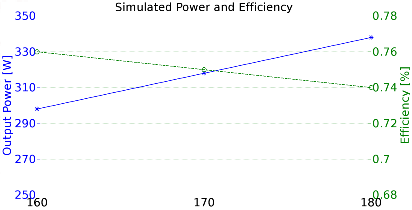
Specs	
V_{IN}	170V
V_{OUT}	28V
P_{OUT}	320W
η	73.6 %

Prototype waveforms









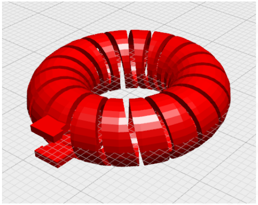
3D printed passive components

(a) 3D CAD model (b) 3D printed plastic mold (c) cast silver model

Fig.: Steps in the fabrication of a 3D inductor. (a) shows the OpenJSCAD model, (b) shows a translucent plastic model and (c) shows a sterling silver inductor. The 3D inductor has 10nH inductance and its dimensions are OD=18mm, ID=6mm, N=4. Also notice the rounded cross section.

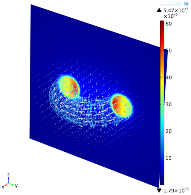
- 3D printing can overcome limitations of PCB and wire-wound inductors
- Overhangs, curved surfaces, texture possible

Preliminary designs (Circular Cross Section)



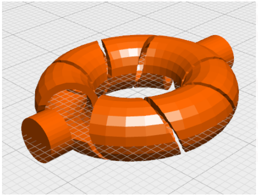
(a) CAD

(b) Cast



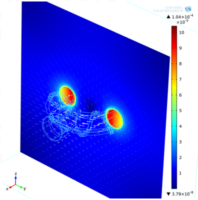
(c) FEM

Fig.: toroid inductor with a round cross section. OD=29mm, ID=11mm, N=20.



(a) CAD

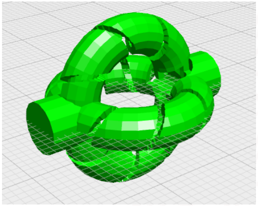
(b) Cast



(c) FEM

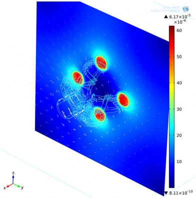
Fig.: Toroid inductor with a round cross section and two parallel windings. OD=28mm, ID=13mm, N=4.

Preliminary designs



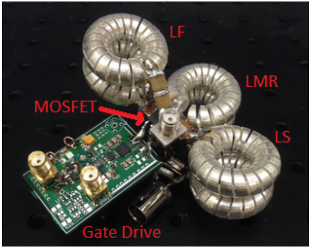
(a) CAD

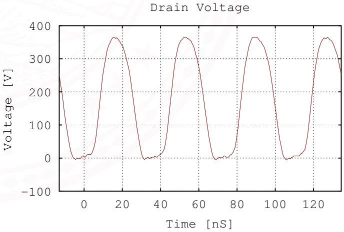
(b) Cast



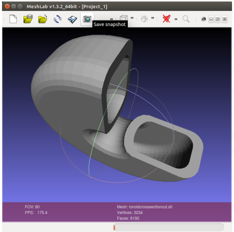
(c) FEM

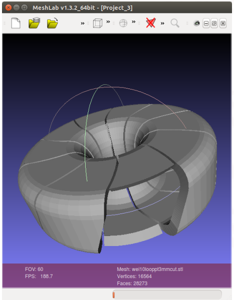
Fig.: Toroid inductor with a round cross section and four parallel windings. OD=21mm, ID=10mm, N=4.

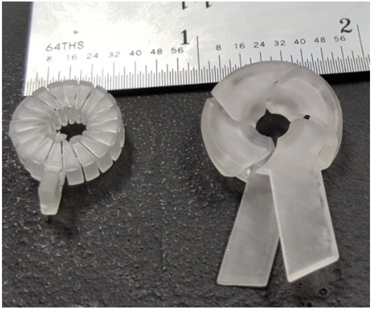


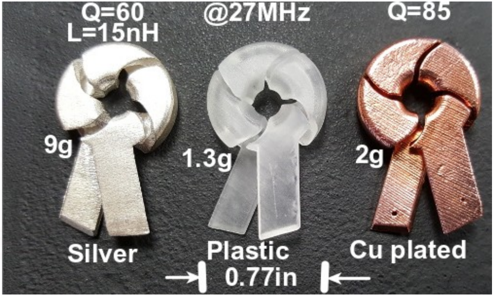


3D printed inductor with optimal cross-sections

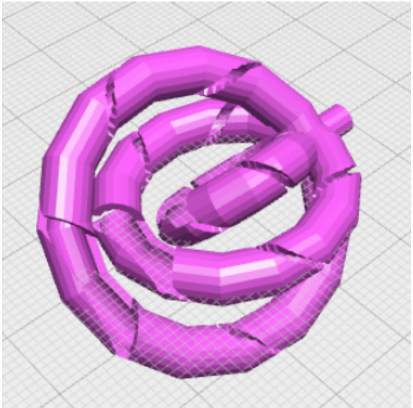


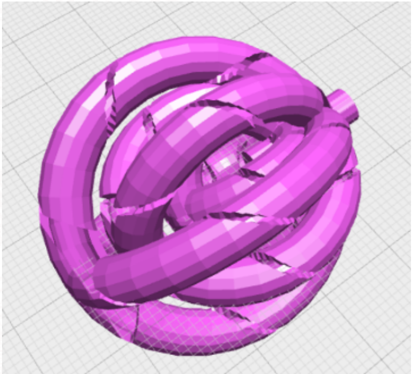






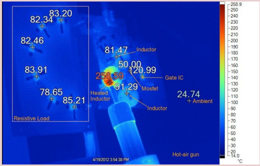
3D printed converters





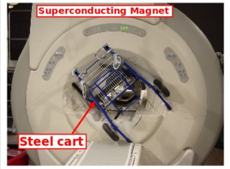
Harsh environment operation

Operation at high temperature



- Air-core inductors don't saturate or have Curie temperature limitation
- WBG high-temp semiconductors will enable new applications
  - Power converters in engines, catalytic converter

Operation an large magnetic fields



- Conventional converters not MRI friendly
- Ferromagnetic components saturate
- Air-cored converters can operate inside magnet
  - Harmonics miss imaging bands

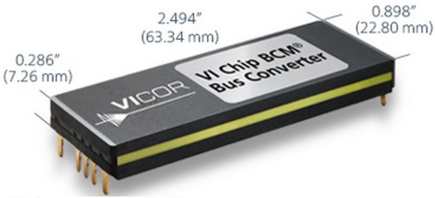
Good progress made in low voltage power electronics

Low Voltage Power Conversion

- Focus on moderate gain ratio step down
- Efficient, power dense converters commercially available
- Efficiencies in the upper 90%s
- Power densities approaching 3 kW/in^3

VICOR 400 V to 50 V dc-dc

- 2750 W/in^3
- ≈98% efficient
- 1750 W



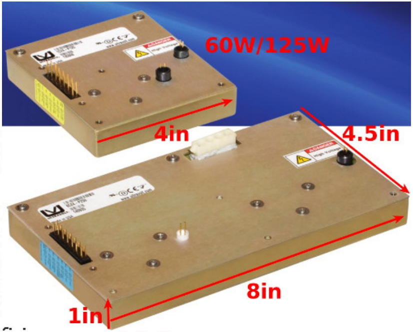
www.vicor.com

High voltage supply development has Lagged

- High voltage power supplies remain expensive and relatively inefficient
- If fast pulses are needed a high voltage switch is generally used in conjuction with a capacitor
- Efficiencies in the 60%s are common
- Typical power densities <10 W/in^3

Ultravolt High Power C Series

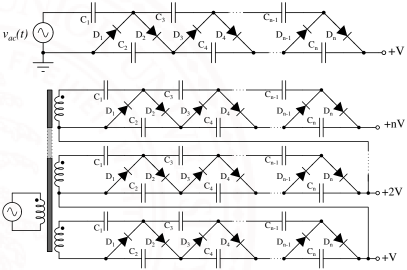
- 9 W/in^3
- 30 V to 2000 V dc-dc



www.ultravolt.com

high voltage circuits

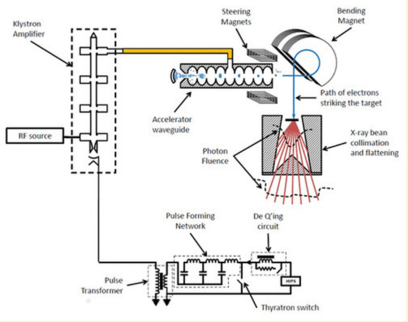
- Various circuits can be used to generate high voltages:
  - Fly-back converters
  - Marx generators
  - Cockcroft–Walton multiplier
  - Quasi–resonant, resonant converters
  - and cascaded versions of these



- Parasitics, output impedance, device stress, etc, impose practical limits to the number of stages that can be cascaded to produce large voltage gains
  - CockcroftWalton multiplier limited to 10-12 stages due to loading effects

High tech applications demand innovation

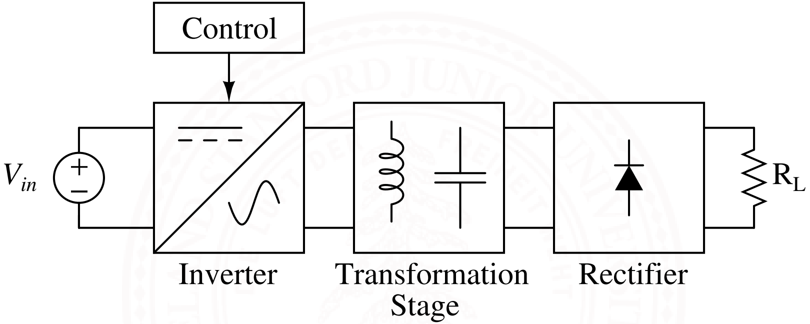
- Applications in medical, space, military, etc. require short pulses of high voltage
- Transient response of conventional supplies is typically slow



Anderson R., et. al “Simulation of a medical linear accelerator for teaching purposes” Journal of Applied Clinical Medical Physics, 2015

- Fast pulses generally require a fast high voltage switch discharging a large storage capacitor
- Charging time limits pulse duty cycle
- Energy stored within the circuit is high

Resonant converter structure



Inverter

Takes dc input power, deliver ac power

Transformation stage

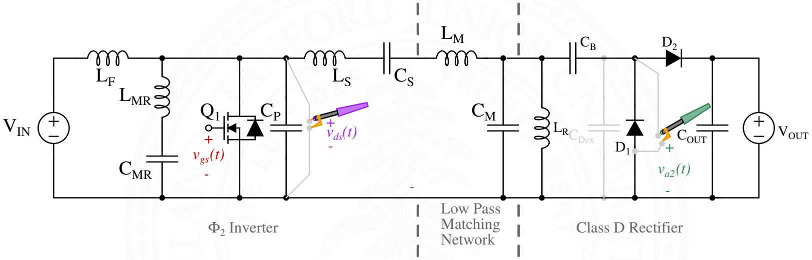
Provides impedance matching

Rectifier

Takes ac power, delivers dc power to R_L

[2] J.M. Rivas, O. Leitermann, Y. Han, et al, "A very high frequency dc-dc converter based on a class Φ_2 resonant inverter," in Proc. Power Electronics Specialists Conference, 2008. pp. 1657-1666
[4] W. Liang, J. Glaser, and J. Rivas, 13.56 MHz high density dc-dc converter with PCB inductors, in Proc. 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2013, pp. 633640.

Previous work involving a single stage resonant design

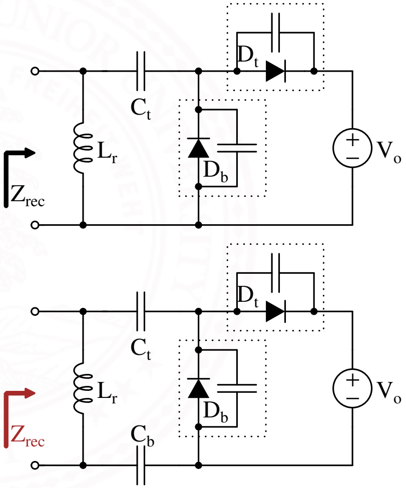


- 40 V to 500 V 27.12 MHz step up design was tested
- Output voltage limited by rectifier diode ratings
- Matching network quality factor (Q) increases with increasing gain ratio

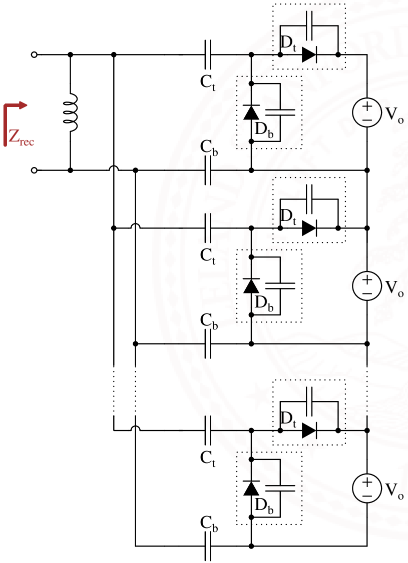
[5] Raymond, L.; Wei Liang; Jungwon Choi; Rivas, J., “27.12 MHz large voltage gain resonant converter with low voltage stress,” Energy Conversion Congress and Exposition (ECCE), 2013 IEEE , vol., no., pp.1814,1821, 15-19 Sept. 2013

Class-D rectifier modification

- $v_{\text{diode,max}} = V_{OUT}$
- Relatively low equivalent input resistance compared to related resonant rectifier topologies
- DC blocking capacitor can be split to achieve isolation

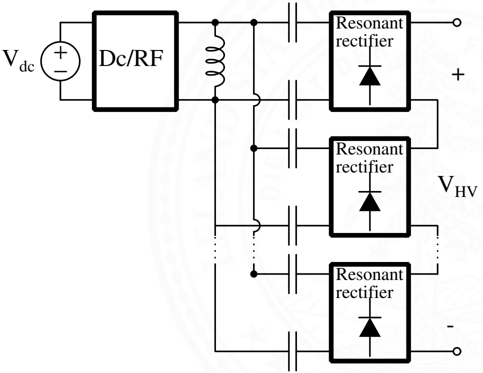


Isolation allows for multiple rectifiers



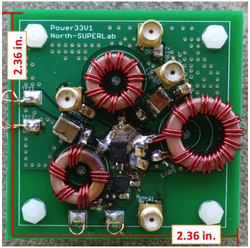
- Isolated rectifiers can be driven in parallel from a single input source
- Equivalent resistance seen by the ac source is R_{rect}/n
- Outputs can be added in series to achieve voltage gain
- Elimination or reduction of matching network
- L_R of each rectifier can be combined into a single inductor of value L_R/n
- Overall efficiency is equal to efficiency of each individual stage

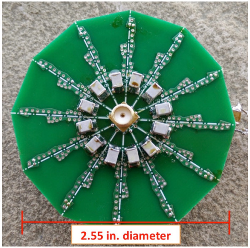
High voltages at 10’s of MHz



- Capacitive isolation feasible at 10’s of MHz
- Cascading multiple converters for high voltage gain
- Also effective for impedance matching
- Fast pulse capability

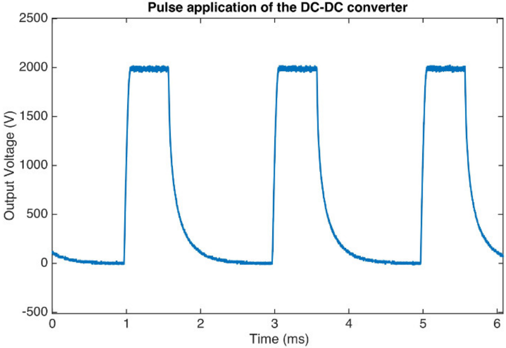
12 Stage Design with Silicon

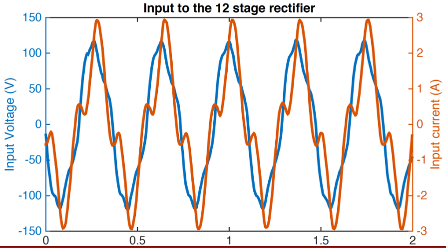




- 100 W 40 V to 2000 V dc-dc 27.12 MHz converter
- Silicon devices exhibit more ideal behavior allowing for 27.12 MHz operation
- 12 class-D stages for a voltage gain of 50 using a matching network with a quality factor of 2
- A single stage design would require a $Q > 20$

Power Supply Performance

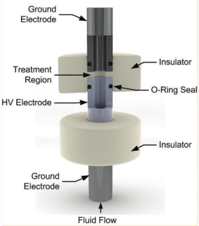




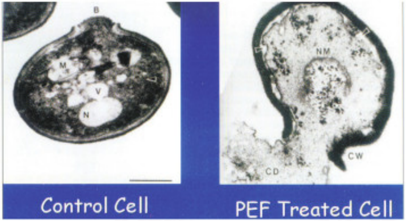
DC-DC Performance

- 90% conversion efficiency
- Silicon diodes yield 95 % rectification efficiency as expected
- Ability to produce very square pulses

Pulsed electric field pasteurization



Diversified Technologies Inc.

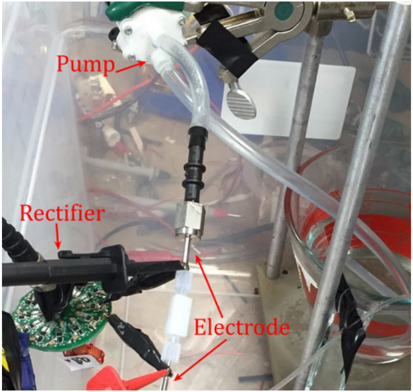


Diversified Technologies Inc.

Diversified Technologies Inc.

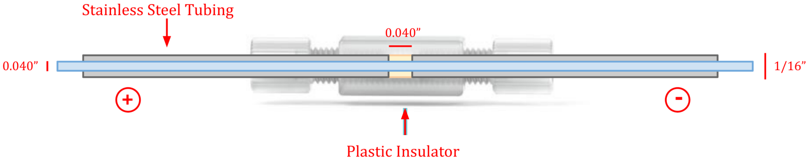
- High electric field $\approx 20 - 50$ kV/cm pulses causes rupture bacterial membranes
  - Render bacteria un-viable
  - Non-thermal means to pasteurize foodstuffs
  - Less energy intensive than thermal pasteurization
  - Effective for pasteurization, algai oil extraction, dehydration, wastewater treatment
- Current PEF systems are costly and limited to industrial settings

Experimental Setup



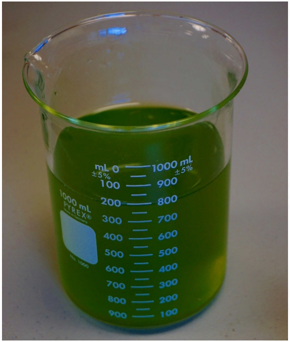
Electrode Design for Milk and Water

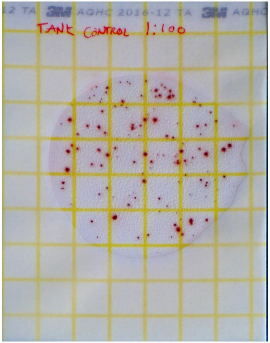
- 2 kV/mm field strength
- Variable speed pump
- 50Ohm rectifier allows for remote inverter location for test purposes

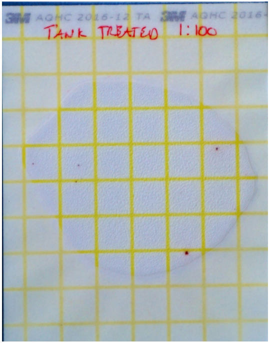


Idex Health & Sciences

Bacteria Test Results







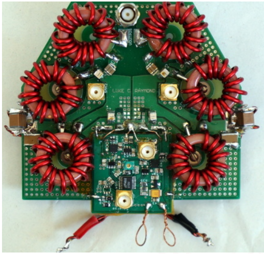
- Tested Effectivness on E. Coli and Coliform
- 2-3 log reduction in measured bacteria levels
- Energy requirement of 0.5wh/L

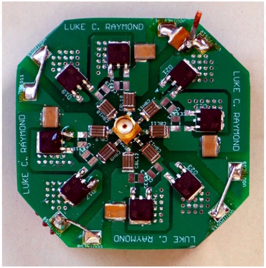
40% of milk in some emerging markets spoils

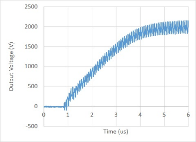
- Small farmers can't afford current pastuerizing equipment
- Communities rely on a network of aggregators and milk collectors to process and distribute milk
- Weather, road conditions etc., can risk milk delivery

Photo credit: Nestle, Sri Lanka & Varick Schwartz, Kiva Fellow serving in Nairobi, Kenya

2 kW 13.56 MHz 275 V to 2 kV output isolated dc-dc

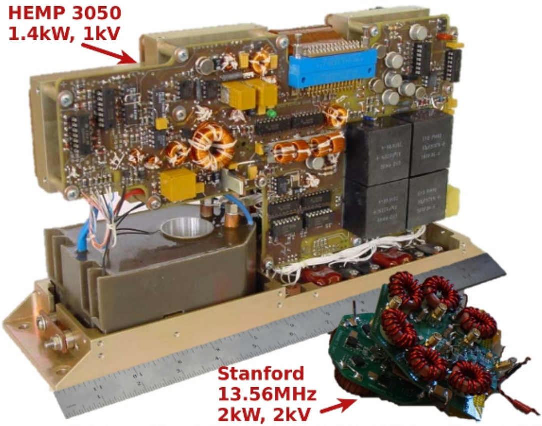






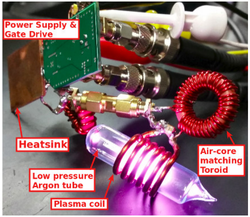
- 2 $\times$ Φ_2 inverters using GaN Systems 650 V MOSFETs
- 4x500 W rectifiers with 500 V outputs in series
- 94% inverter efficiency
- 4 μs transient response
- 250 W/in^3 including gate drive and cold plate
- 90% rectifier efficiency vs. 97% predicted by simulation model

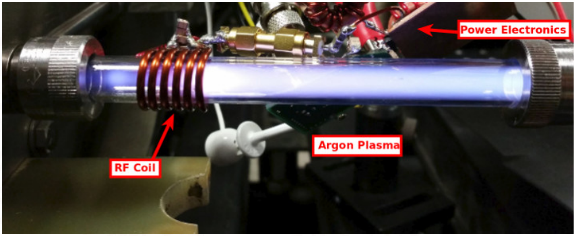
HV supplies for satellite applications



- Stanford's 2 kW, 2 kV 13,56 MHz converter
  - $\approx$ 200 W/in^3
  - 5 kW/kg

Applications: Satellite propulsion



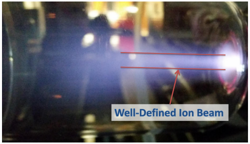


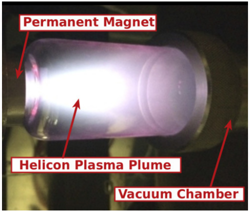
Plasma Discharge Modes

Capacitive → Inductive → Helicon

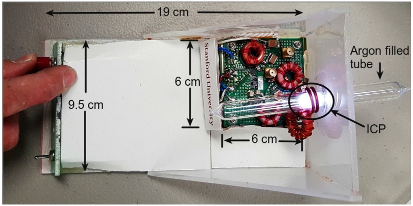
- Miniaturized plasma sources have enormous potential for satellite propulsion
- Ion drives (RFIT, Hall Thrusters) use large PPUs
- We are collaborating with Prof. Mark Capelli to make a miniature helicon thruster for cubesats

Miniature Helicon Thruster





Parameter	Value
Ion mean velocity:	52 km/s
Ionization fraction:	27%
Mass flow rate:	13.4 μg/s



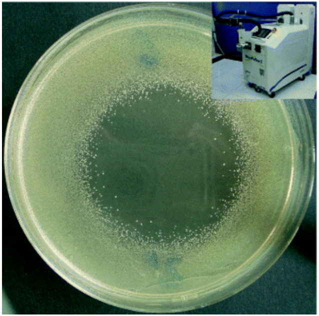
- Preliminary measurements are very promising
- It fits in a cubesat!

David Biggs, Sam Avery, Luke Raymond, Wei Liang, Nicolas Gascon, Juan Rivas-Davila, Mark Cappelli, "A Compact Helicon Thruster for Small Satellites" 2015 Interplanetary Small Satellite Conference, Santa Clara CA.

Plasma Medicine

Max Planck Institute

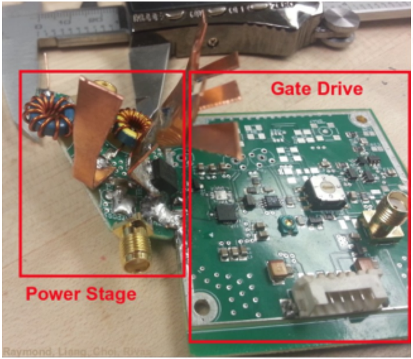
Max Planck Institute

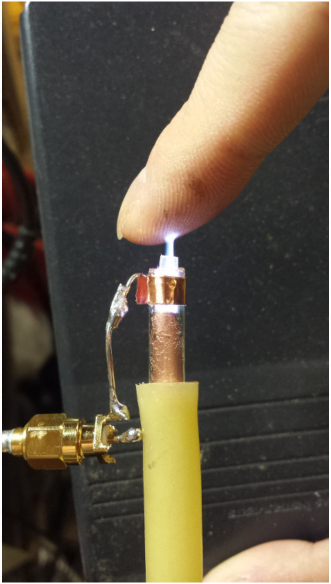


Max Planck Institute

- Plasma is effective for wound treatment and biofilm control
- Effective against MRSA and other anti-biotic resistant pathogens
- Current plasma systems are large and costly

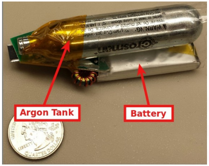
VHF Power enables miniature plasma sources

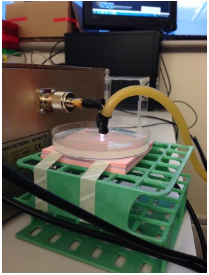


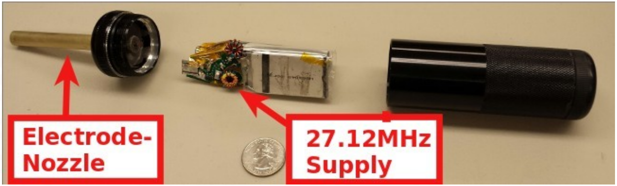


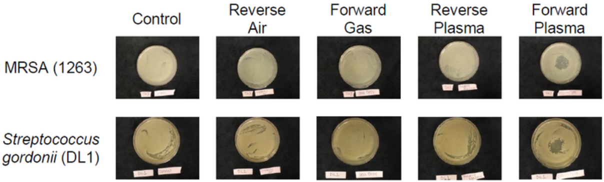
- Miniaturized plasma generator for bio-film control
- Prototype battery operated & switching at 13.56 MHz

Portable plasma source





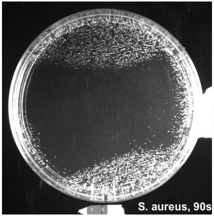


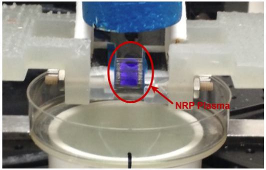


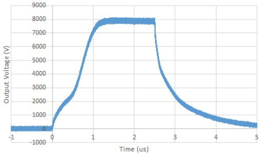
In Collaboration with Prof. Alex Rickard (UofM)

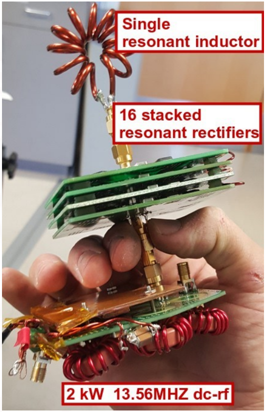
- Preliminary testing shows substantial bacterial reduction even with short pulses

Nanosecond Repetitively Pulsed (NRP) Plasma



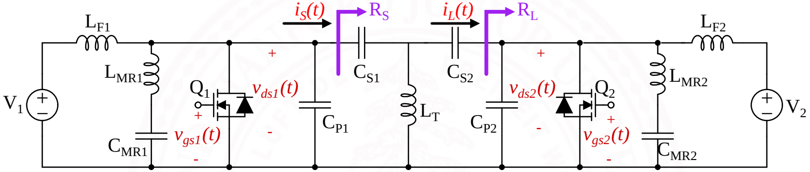


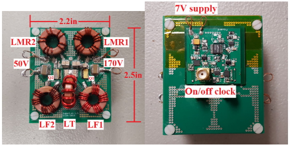


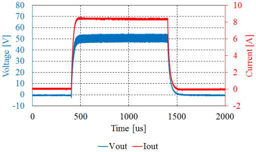


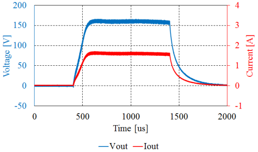
- NRP plasmas can kill biofilm and wound treatment
  - Validated in vitro and in vivo
  - Significant reduction in healing time
  - Effective on S. aureus, MRSA
- HF converters can reduce the size of the supply coupled to PFN

27.12 MHz GaN Bi-directional Resonant Power Converter



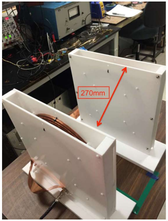


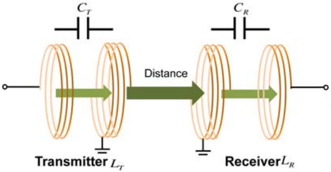


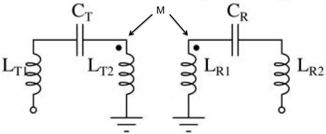


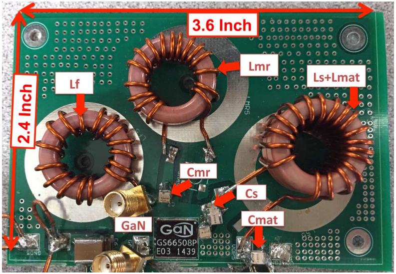
- 27.12 MHz 420 W Bidirectional dc-dc converter
- $V_{in} = 170$ V, $V_{out} = 50$ V, $\eta \approx 81\%$, power density ≈ 120 W/in^3

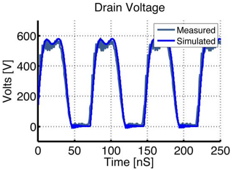
Wireless power transfer at 13.56 MHz

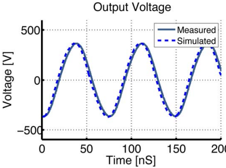












- η=86.6 %, P_{IN}=950 W, P_{OUT}=823 W at V_{IN}=200 V and distance=270 mm

Acknowledgments

Students and Collaborators

- Superlab
  - Wei Liang, Luke Raymond, Jungwon Choi, Lei Gu, (North) Kawin Surakitbovorn, Brian Holman, Gabriel Vega, Molly Dicke
- Stanford Plasma Physics Laboratory
  - Prof. Capelli, David Biggs, Sam Avery, Nicolas Gascon
- Stanford Medical school
  - Peter Lorenz, Michael Longaker, Johan Andreasson, Michael Hu, Julie Saiki, Claire Jacobson, Erwan Pannier
- UofM Center for Molecular and Clinical Epidemiology of Infectious Diseases
  - Prof. Alexander Rickard, Ella Dolan

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