Power Conversion for HEP Using Piezoelectric Elements

Coordinating Panel for Advanced Detectors Workshop
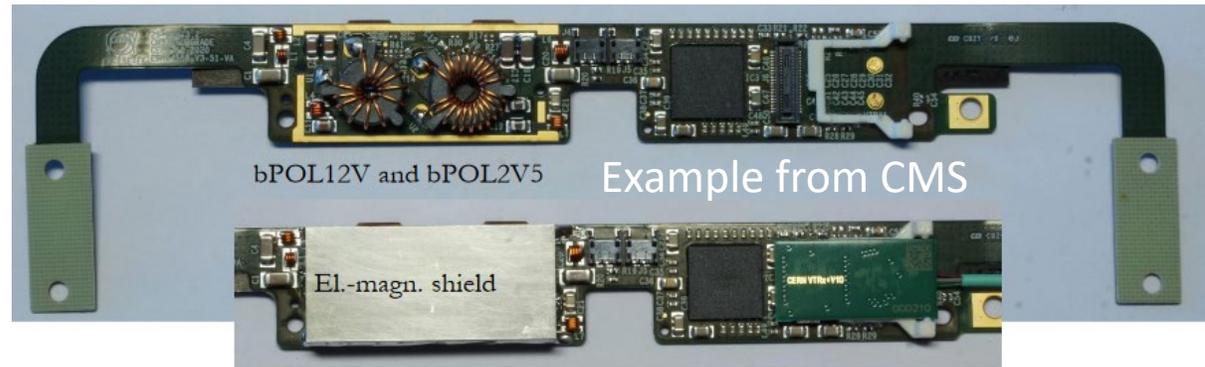
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University of Pennsylvania, 7 October 2025

1

Problem

- DC-DC converters in HEP often use inductors
  - These generate electromagnetic interference (EMI) and must be shielded if in a magnetic field
  - They are physically large

- Converter may need to be radiation tolerant

- May not be desirable to have a large number of discrete components

- Other powering schemes:
  - Serial powering* for low cable mass – constant current low dropout regulator, chip fault handling
  - Linear regulators where a specific use case exists

- Future detectors may need highly miniaturized on-chip or on-module converters

Example from CMS
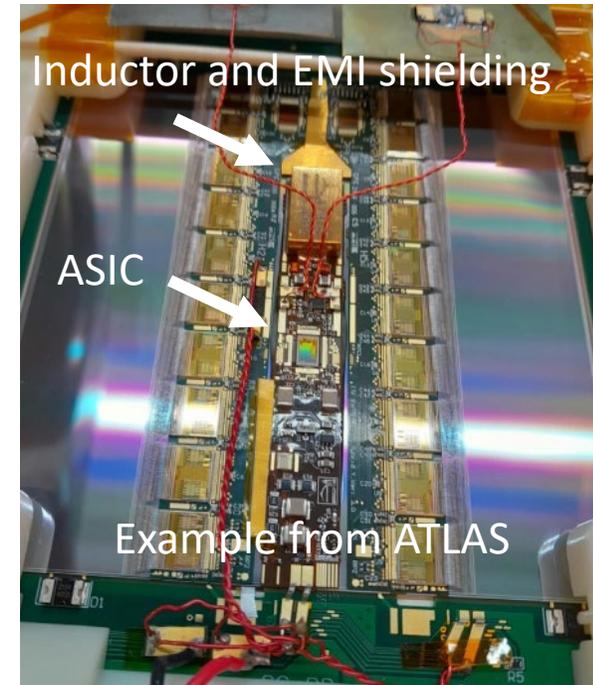
bPOL12V and bPOL2V5

El.-magn. shield

Michelis, S., "Powering Next Generation Detector Systems",
Implementing DRD7: an R&D Collaboration on Electronics and On-detector Processing, 2nd Workshop,
https://indico.cern.ch/event/1318635/contributions/5551795/attachments/2720651/4726975/WP7.1b_2023_09_25.pdf

FEAST/bPOL,
0.35μm rad hard

F. Faccio *et al.*, "FEAST2: A Radiation and Magnetic Field Tolerant Point-of-Load Buck DC/DC Converter," *2014 IEEE Radiation Effects Data Workshop (REDW)*, Paris, France, 2014, pp. 1-7, doi: 10.1109/REDW.2014.7004569
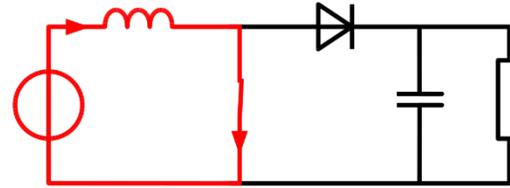

Inductor and EMI shielding

ASIC

Example from ATLAS

*Chan, Jay, "Serial Powering for ATLAS ITk Pixel Modules",
10th International Workshop on Semiconductor Pixel Detectors for Tracking and Imaging (PIXEL 2022), Santa Fe, USA, 11 - 16 Dec 2022, https://cds.cern.ch/record/2845615

Cold Noise Studies, ITk Strips Barrel Modules PRR,
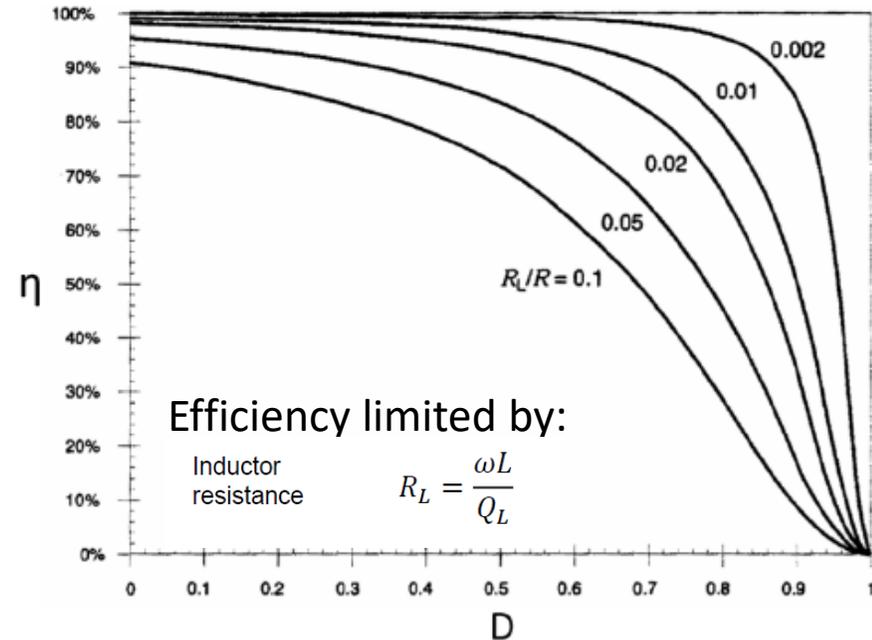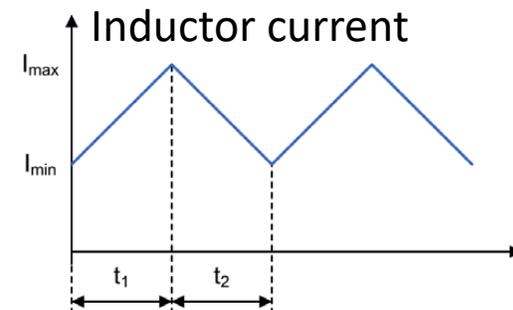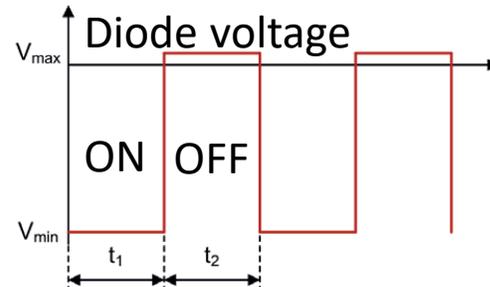https://indico.cern.ch/event/1269138/contributions/5350778/attachments/2642336/4577685/affolder-CN-modulePRR-v4.pdf
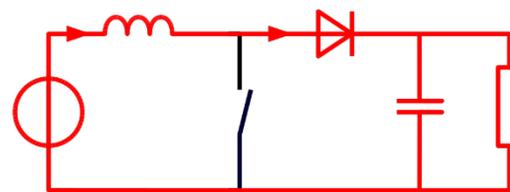
Inductive DC-DC Converter

- Energy stored in **magnetic field**

- MANY topologies! (boost, buck, buck-boost …)

- Advantages:
  - simplest and lowest cost (usually)

- Disadvantages:
  - Inductors are lossy
    - Resistance dissipates some energy as heat
    - Magnetic hysteresis
  - Quality inductors are **difficult to miniaturize**
    - L, Q (and R_L) decrease with volume
  - Hard switched -> electromagnetic Interference (EMI)
  - Discontinuous conduction mode and synchronous rectification can be used, but are more complex
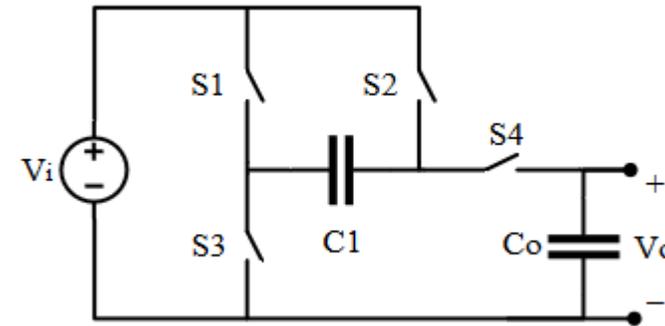
On-State   (boost example)

Off-State

Diode voltage

V_{max}

ON OFF

V_{min}

t_1 t_2

Inductor current

I_{max}

I_{min}

t_1 t_2

η

Efficiency limited by:

Inductor resistance

$$R_L = \frac{\omega L}{Q_L}$$

R. W Erickson, "DC-DC Power Converters," *J. Webster (ed.), Wiley Encyclopedia of Electrical and Electronics Engineering*, pp. 1-18, 2007.
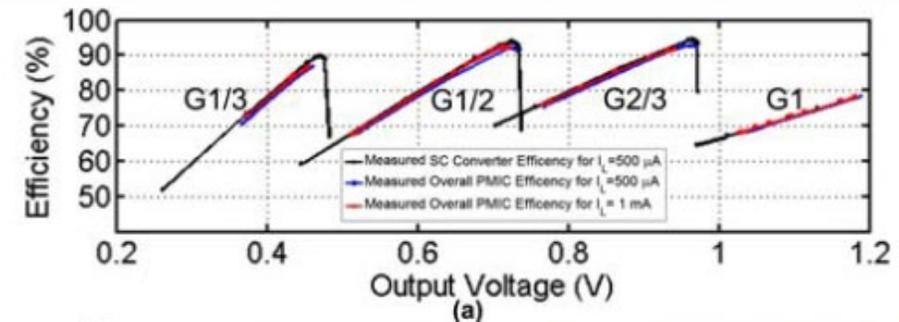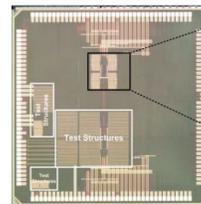
inductor

Image: https://en.wikipedia.org/wiki/Boost_converter

3

Switched Capacitor (SC) Converter

- Charge pump principle, descended from voltage doubler
  - Energy stored in **electric field** instead of magnetic
  - Also MANY topologies

- Advantages:
  - Higher **energy density** than inductors
  - **Monolithic integration into ASICs** (compatible with common process nodes)
  - **Lower EMI** than inductors

- Disadvantages:
  - Voltage **regulation is more difficult** than inductor based converters
    - Discrete gain ratios (unless dynamic topology change)
    - Duty cycle does not linearly relate to output voltage
    - Difficult to control charge balance with multiple capacitors
  - FET switching losses (resistive, gate drive)
  - Bottom plate parasitic capacitance to substrate limits efficiency

de Souza, A.F., Tolofi, F.L., Ribeiro, E.R., "Switched Capacitor DC-DC Converters: A Survey on the Main Topologies, Design Characteristics, and Applications", MDPI Energies 2021, 14(8), 2231; https://doi.org/10.3390/en14082231

El-Damak, D., S. Bandyopadhyay, and A. P. Chandrakasan. "A 93% Efficiency Reconfigurable Switched-Capacitor DC-DC Converter Using on-Chip Ferroelectric Capacitors." 2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers (February 17-21, 2013), San Francisco, CA.

4

Inductors and capacitors are the only energy storage elements

Is this the best we can do?

Only if we think strictly in the electrical domain…

Modeling Piezoelectric Elements

- The mechanical mass, spring, damper model can be transformed to an electrical RLC model
  - Damping -> resistance
  - Spring (stiffness) -> capacitance
  - Mass -> inductance

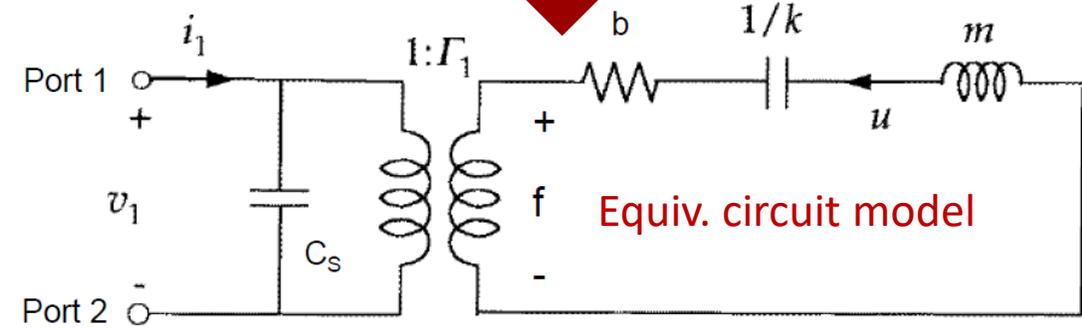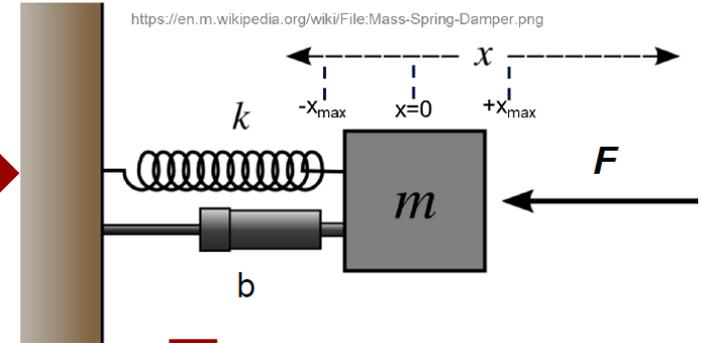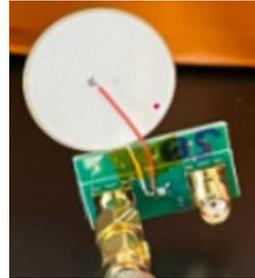- Transform is proportional to Young's modulus, and the strain coefficient of the material

$$R_x = \frac{b}{\Gamma^2}$$

$$\Gamma = d_{31} E \pi r^2$$

Strain coeff. (pm/V)

Young's modulus (GPa)

$$L_X = \frac{m}{\Gamma^2}$$

$$C_X = \frac{\Gamma^2}{k}$$

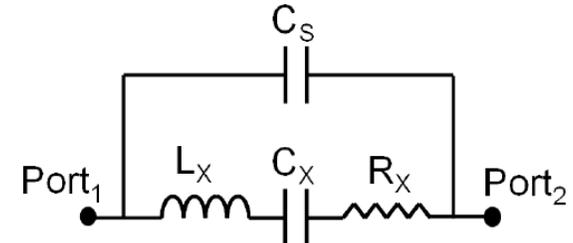- Origin of larger Q and L (per volume) in piezoelectric element is the effective stiffness and mass of the material

https://en.m.wikipedia.org/wiki/File:Mass-Spring-Damper.png

Equiv. circuit model

H.A.C. Tilmans, "Equivalent Circuit Representation of Electromechanical Transducers:
I. Lumped-parameter Systems", J. Micromech. Microeng. 6 157, 1996, doi: 10.1088/0960-1317/6/1/036
Illustration adapted by Troy Olsson
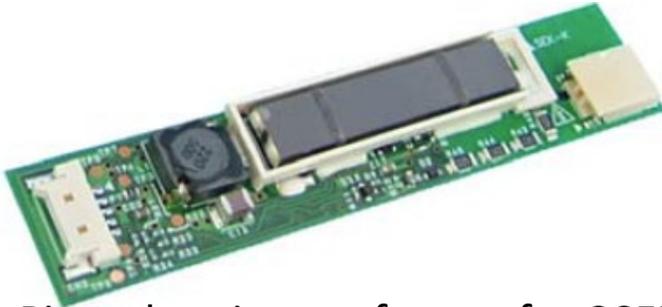
Electrodes

Energy storage

Microresonator Butterworth Van Dyke
(BVD) equivalent circuit model
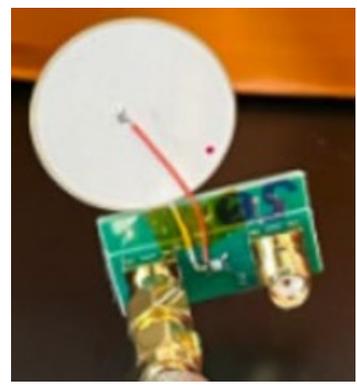
(Image: Troy Olsson)

6

Piezoelectric (PR) DC-DC Converter

- Energy storage is **mechanical**, not magnetic/electric field
  - **Low EMI**
  - Potentially radiation tolerant

- Long history of piezoelectrics in power conversion*

- But recent advances in resonant PR converters are promising**
  - "Soft-switched" (sinusoidal current)
  - **Wide conversion ratios**

- For equivalent inductor volume:
  - **High quality factor (Q)**
  - **Large inductance**
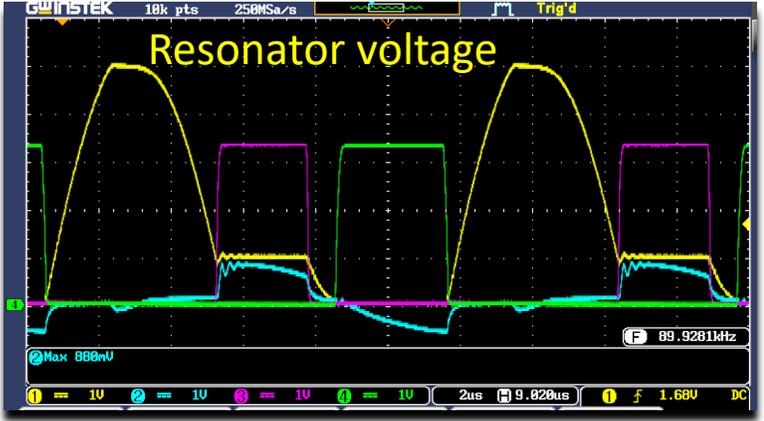 - Low series resistance

- Potentially integrated into ASICs

Piezoelectric transformer for CCFL

"Piezoelectric Transformers: An Historical Review"
https://www.mdpi.com/2076-0825/5/2/12

Commercial lead zirconate titanate (PZT) resonator

Resonator voltage

A piezoelectric conversion cycle using PZT resonator

*Carazo, A., Piezoelectric Transformers: An Historical Review ", MDPI *Actuators* 2016, *5*(2), 12; https://doi.org/10.3390/act5020012
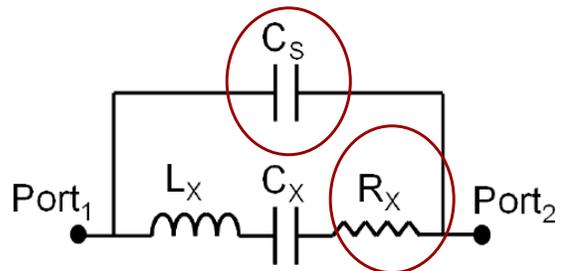**B. Pollet, G. Despesse and F. Costa, "A New Non-Isolated Low-Power Inductorless Piezoelectric DC–DC Converter," in *IEEE Transactions on Power Electronics*, vol. 34, no. 11, pp. 11002-11013, Nov. 2019, doi: 10.1109/TPEL.2019.2900526.
**J. D. Boles, J. J. Piel and D. J. Perreault, "Enumeration and Analysis of DC–DC Converter Implementations Based on Piezoelectric Resonators," in *IEEE Transactions on Power Electronics*, vol. 36, no. 1, pp. 129-145, Jan. 2021, doi: 10.1109/TPEL.2020.3004147.
**J. D. Boles, J. E. Bonavia, J. H. Lang and D. J. Perreault, "A Piezoelectric-Resonator-Based DC–DC Converter Demonstrating 1 kW/cm Resonator Power Density," in *IEEE Transactions on Power Electronics*, vol. 38, no. 3, pp. 2811-2815, March 2023, doi: 10.1109/TPEL.2022.3217773.
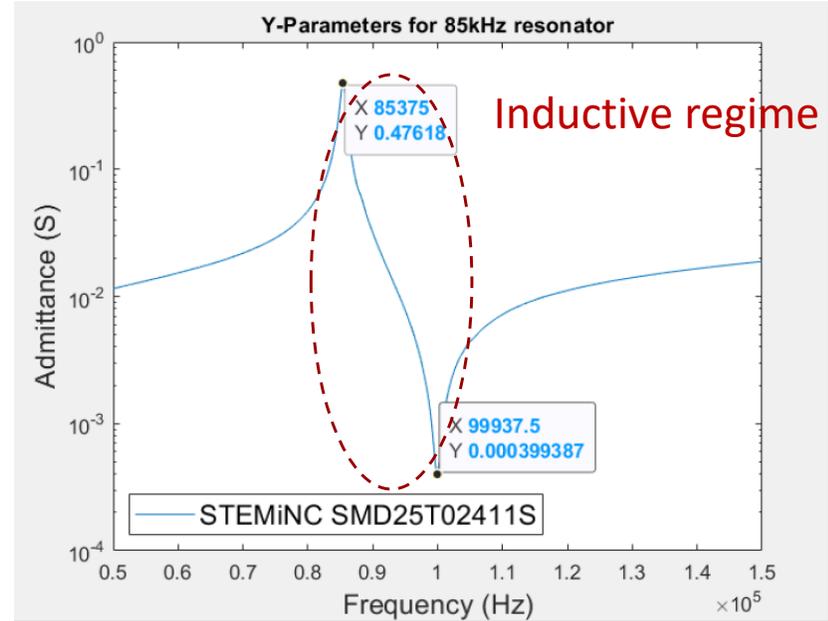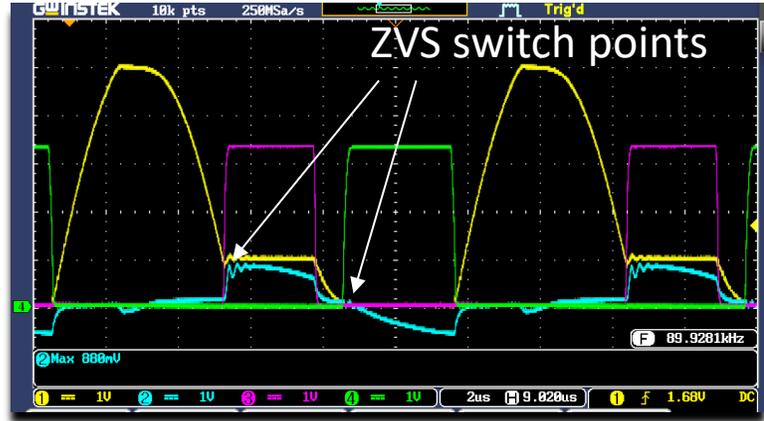
PR Limitations

- Shunt C_s

- Need low series resistance R_x to maximize voltage gain efficiency

- Operates near resonance
  - Load change → frequency change

- Control depends on **zero volt switching (ZVS)**
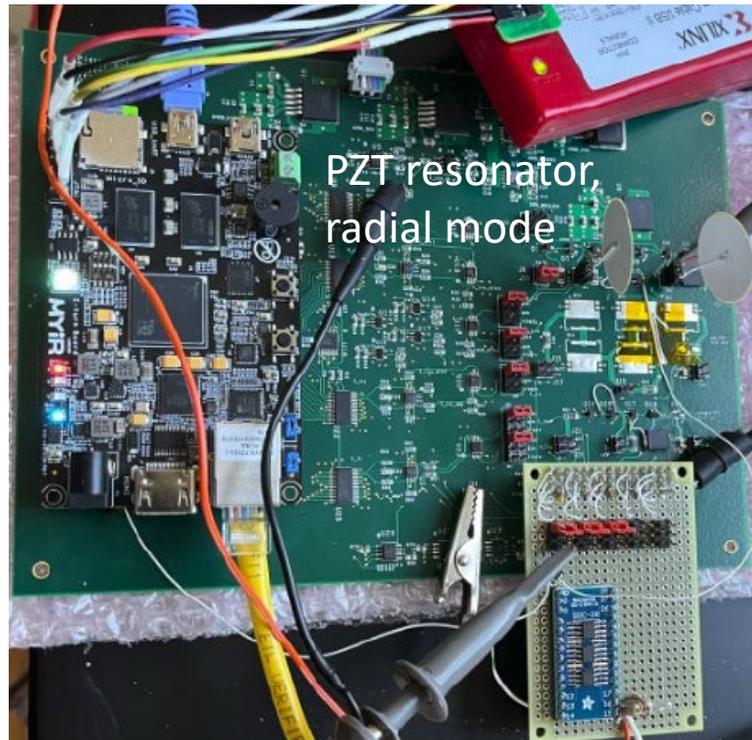 - Control must operate at higher frequencies if resonator is miniaturized

Microresonator Butterworth Van Dyke (BVD) equivalent circuit model

(illustration courtesy Troy Olsson)

$$R_x = \frac{1}{\omega_0 C_S K^2 Q}$$

ZVS switch points

Inductive regime

Y-Parameters for 85kHz resonator

X 85375
Y 0.47618

X 99937.5
Y 0.000399387

STEMiNC SMD25T02411S

8

Prototyping

- 1-5V piezoelectric DC-DC boost conversion demonstrated with macroscale PZT prototypes
  - Application of boost converters: extend to SiPMs (~50V)
  - Also investigating buck

- Questions:
  - Can we continue to miniaturize?
  - What are ultimate performance limits in buck and boost mode?
  - EMI, radiation and magnetic tolerant DC-DC converters for HEP?

PZT resonator, radial mode

PZT resonator, thickness mode

1-5V

1-5V, higher Power, ~MHz

Power converter research in general

- Efficient energy storage elements (resonators in our case)

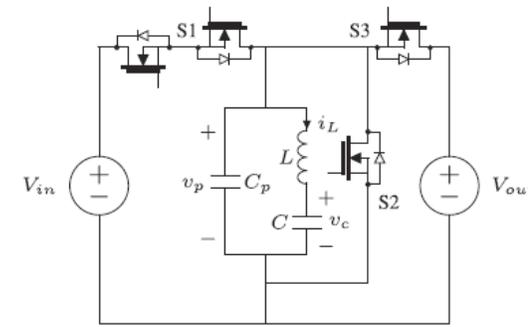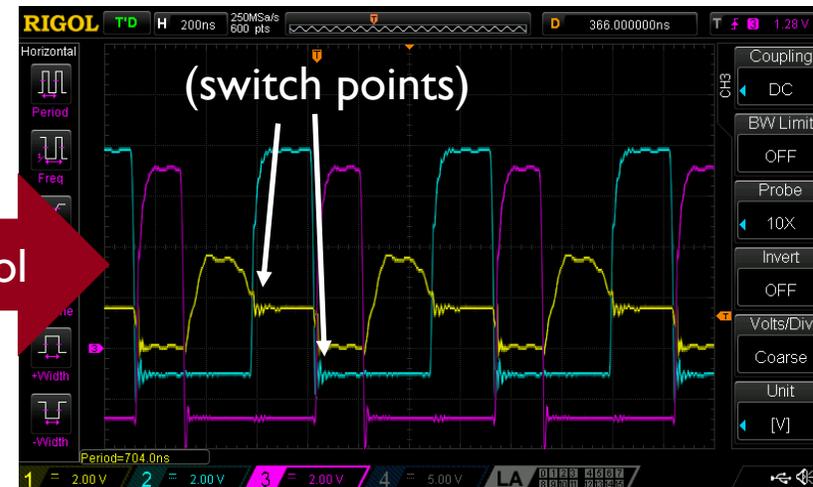- Efficient switches

- Robust control schemes for wide load ranges

Image: J. D. Boles, J. J. Piel and D. J. Perreault, "Enumeration and Analysis of DC–DC Converter Implementations Based on Piezoelectric Resonators," in *IEEE Transactions on Power Electronics*, vol. 36, no. 1, pp. 129-145, Jan. 2021, doi: 10.1109/TPEL.2020.3004147.

Digital control

(switch points)

Analog v. power electronics

- Analog:
  - Transistor is biased at an operating point
    - Not always considering switching loss, R_{on}
  - Think of FET as a voltage controlled device
  - Relatively small drain currents (uA or mA)
  - Relatively low voltages (under ~3.3V)
  - Signals almost always referenced to ground

- Power:
  - Transistor is either completely on or off
    - Switching loss extremely important
  - Gate current is important
  - Relatively large drain currents (tens of Amps)
  - Relatively high voltages (5V → hundreds of Volts)
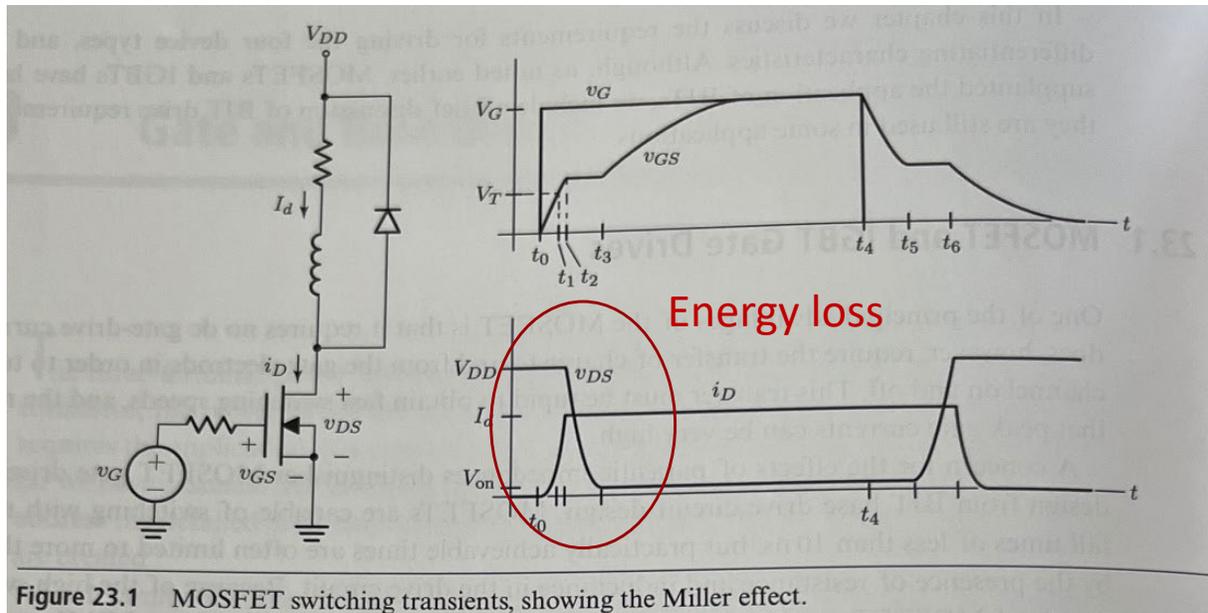 - FETs floating w.r.t. ground

Energy loss

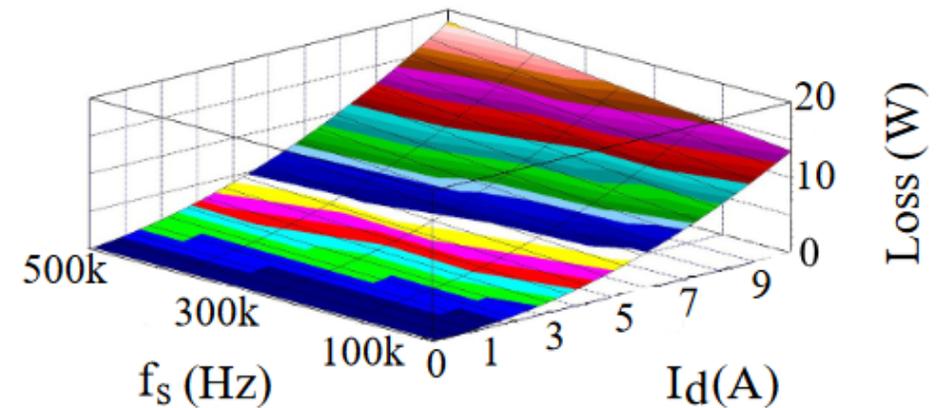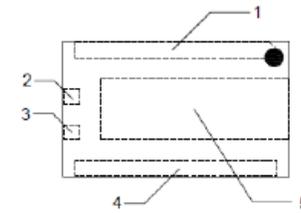Figure 23.1 MOSFET switching transients, showing the Miller effect.

Figure 10. Behavior of switching and conduction losses in MOSFET IRFP460.

J. G. Kassakian, D. J. Perreault, G. C. Verghese, and M. F. Schlecht, *Principles of Power Electronics*, 2nd ed. Cambridge: Cambridge University Press, 2023.

"Switched Capacitor DC-DC Converters: A Survey on the Main Topologies, Design Characteristics, and Applications "https://www.mdpi.com/1996-1073/14/8/2231
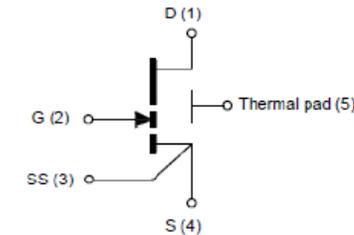
Considerations after PCB prototyping

- Commercial transistors not tailored for our applications
  - Much higher I_D and $V_{DS,max}$ than needed
  - Higher C_{gs} than desired → limits frequency of operation

- Commercial resonators not tailored for this application
  - Higher than expected R_x → limits efficiency
  - Difficult to mount/anchor → spurious modes, losses
  - Power handling not understood

- PCB high frequency behavior will be limited by parasitics
  - Need to scale to higher frequency for high Q resonator
  - Frequency drift of drive circuitry affects boost ratio

Package Outline   Circuit Symbol

https://www.infineon.com/assets/row/public/documents/24/49/infineon-gs61008p-datasheet-en.pdf

- GaN FET:
  - I_D = 90A !
  - R_{on} = 7 mΩ !
  - But C_{in} = 600pF / Q_g=8nC

- Gate charge and risetime relationship:
  - Desired risetime: 10ns
  - 8 nC / 10 ns = **0.8A** into gate!

CMOS v. DMOS

Double-diffused MOSFET

- Smaller L reduces R_{on}

$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})}$$

- Use lowest BV_{DS} possible for the application

- (Other processes available …)

Single 6V FET layout in BCD (bipolar-CMOS-DMOS) process

Many fingers, multiplied

Large area → low R_{on}
Control C_{gs}

Wide metal → high drain and gate current

Inversion layer

Narrow "L" region

NMOS   PMOS   DMOS

Marco Berkhout, Tutorial: Analog Circuit Design in Bipolar-CMOS-DMOS (BCD) Technologies, https://ieeexplore.ieee.org/document/11005819

13

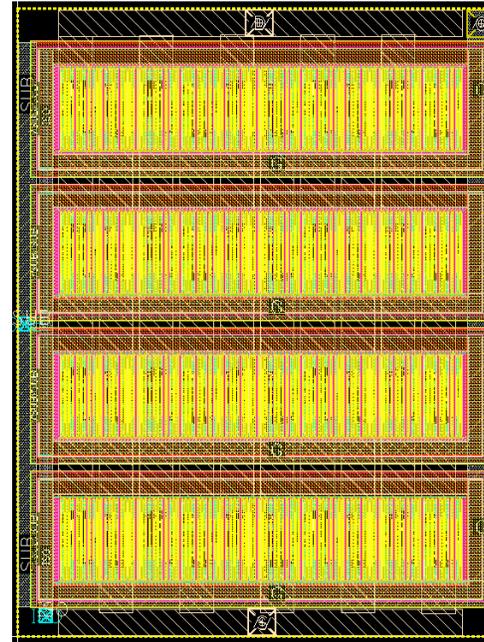# CMOS v. DMOS

- Smaller L reduces R_{on}

$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})}$$

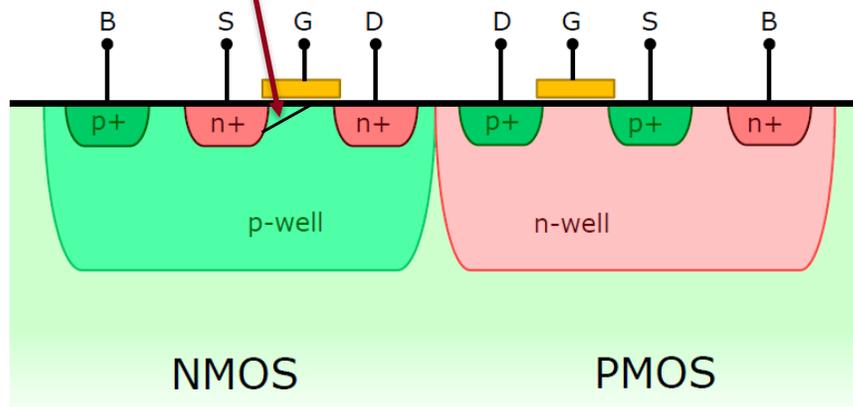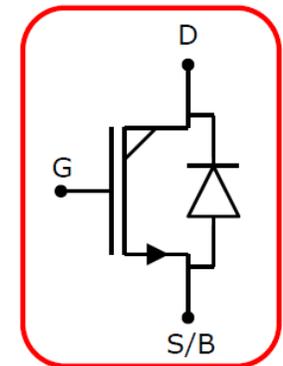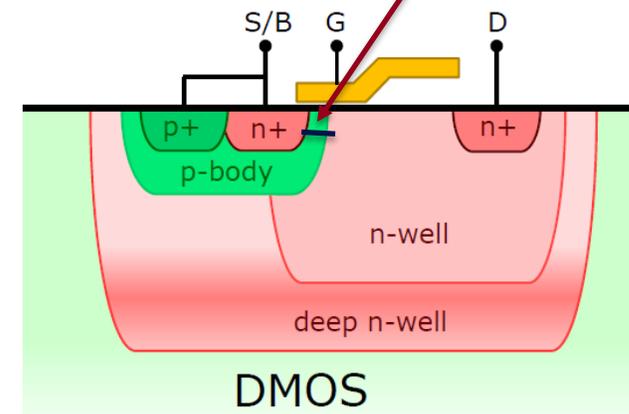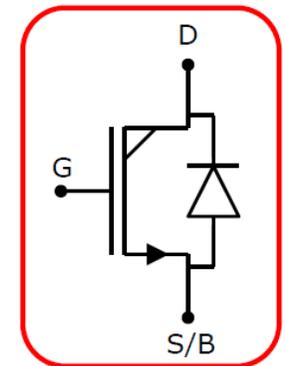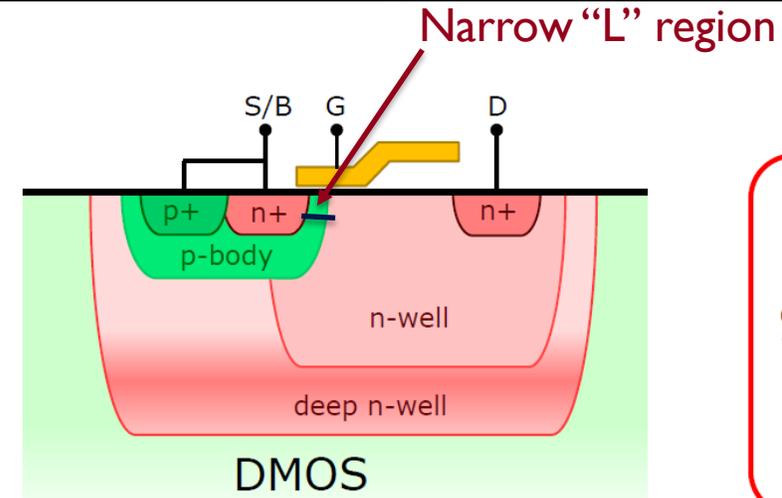- Use lowest BV_{DS} possible for the application

- (Other processes available …)

Cadence simulation in BCD process

Resonator voltage

Gate drive voltages

Input/output currents

Inversion layer

Narrow "L" region

B   S   G   D   D   G   S   B

p+   n+   n+   p+   p+   n+

p-well   n-well

NMOS   PMOS

S/B   G   D

p+   n+   n+

p-body

n-well

deep n-well

DMOS

D

G

S/B

14

Resonator design

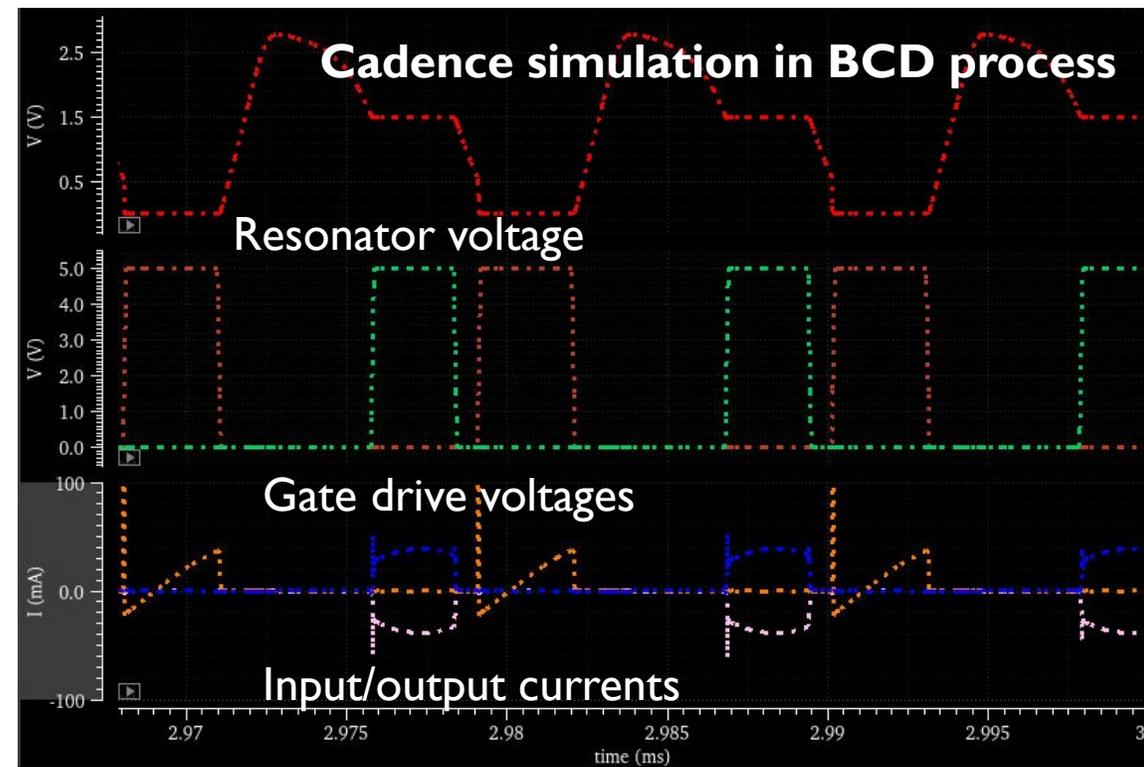- Spurious mode avoidance: careful electrode design, easier to control over larger inductive region

- Overtone resonators: optimize resonator impedance to load impedance

- Mass augmentation: increases effective inductance, but need to be mindful of series R_x

- Lithium niobate:
  - high Q
  - In shear mode: higher K^2 (electromechanical coupling), no thermoelastic heating (no tension and compression forces)

- Piezoelectric transformers: historically have been used for high voltage gain, but few miniaturized examples, and drive circuitry may need to be improved

COMSOL modeling

Resonator fabrication by Xu Zhao in Penn Singh Center

Packaging considerations

UTM

M3

M2

M1

Marco Berkhout, Tutorial: Analog Circuit Design in Bipolar-CMOS-DMOS (BCD) Technologies, https://ieeexplore.ieee.org/document/11005819

- Must consider wirebonding for higher current applications

- Consider effect on energy transfer, resonator performance

CURRENT (A) VS. WIRE DIAMETER (MILS)

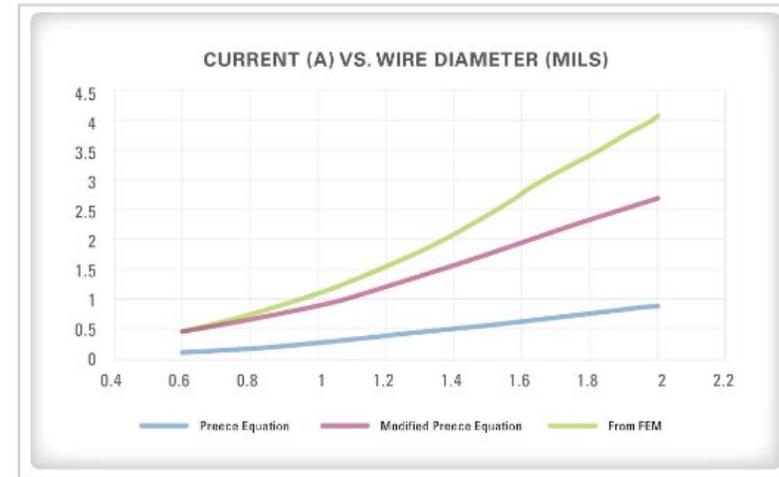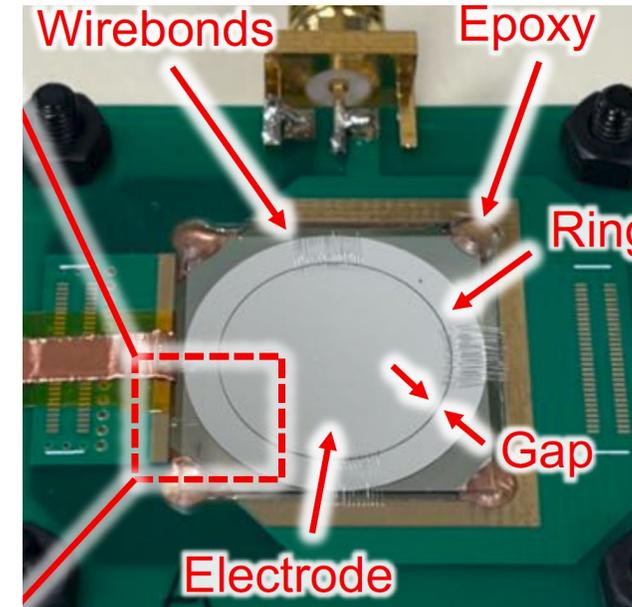Preece Equation — Modified Preece Equation — From FEM

Figure 2: Current-carrying capability of 1-mm-long gold wire using FEM and the Preece equations

Renesas Corporation, ESTIMATING BOND WIRE
CURRENT-CARRYING CAPACITY, Power Systems Design July/Aug 2012. (Retrieved from Renesas website)

Wirebonds   Epoxy

Ring

Gap

Electrode

H. Zhang, M. Berkhout, K. A. A. Makinwa and Q. Fan, "A 121.4-dB DR Capacitively Coupled Chopper Class-D Audio Amplifier," in *IEEE Journal of Solid-State Circuits*, vol. 57, no. 12, pp. 3736-3745, Dec. 2022, doi: 10.1109/JSSC.2022.3207907

K. Nguyen *et al.*, "Spurious-Free Lithium Niobate Bulk Acoustic Resonator for Piezoelectric Power Conversion," *2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, Toyama, Japan, 2023, pp. 1-4, doi: 10.1109/EFTF/IFCS57587.2023.10272177

Summary

	Volume	ASIC integration	Voltage regulation	Power	Efficiency	EMI	Rad. Tolerant	Mag. Tolerant
Inductor	largest	difficult	wide range	medium - high	limited range	most	yes	no
SC	smaller	yes	fixed ranges	wide range	limited range	less	yes	yes
Piezo	smaller	yes	wide range	wide range	to explore	less	to explore	to explore

- This research presents an opportunity for miniaturized power converters tailored for future detector applications

- Possibility of hybrid converters (SC+PR), more exotic technologies (ferroelectric capacitors)

- Opportunities for further miniaturization

- But need to understand high frequency control

Example of MEMS resonator

G. Esteves, T. Young, Z. Tgan, S. Yen, T. Bauer, M. Henry, R. Olsson,
"Al 0.68 Sc 0.32 N Lamb wave resonators with electromechanical
coupling coefficients near 10.28%",
Appl. Phys. Lett. 118, 171902 (2021); doi: 10.1063/5.0047647

- Potential application of boost converters: Silicon photomultipliers (SiPM)
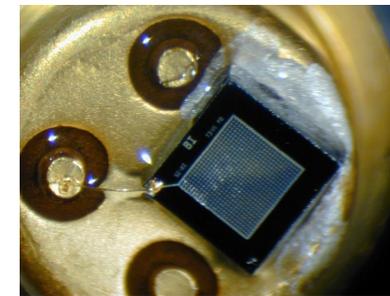 - Bias ~50-70V, very low current

Image: https://en.wikipedia.org/wiki/Silicon_photomultiplier

- Applications of buck converters:
  - Nearly ubiquitous
  - Unique environments (magnetic tolerant, small form factor)

Thank you!