DC-DC Converters Using New Materials and Architectures

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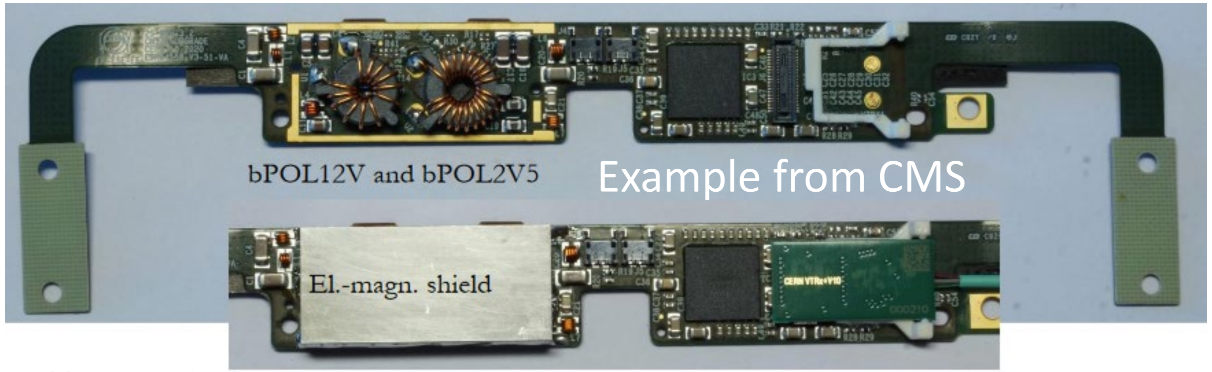
Problem

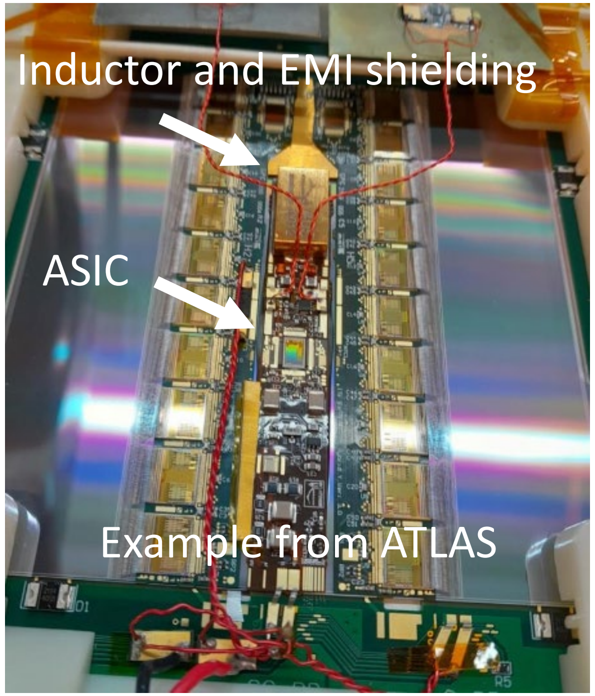
- DC-DC converters in HEP often use inductors
  - These generate electromagnetic interference (EMI) and must be shielded if in a magnetic field
  - They are physically large
- Converter may need to be radiation tolerant
- May not be desirable to have a large number of discrete components
- Other powering schemes:
  - Serial powering [4] 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



[1] 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

[2] 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

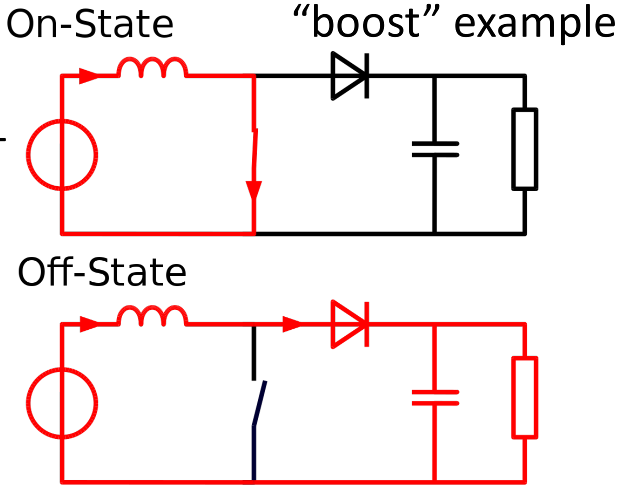


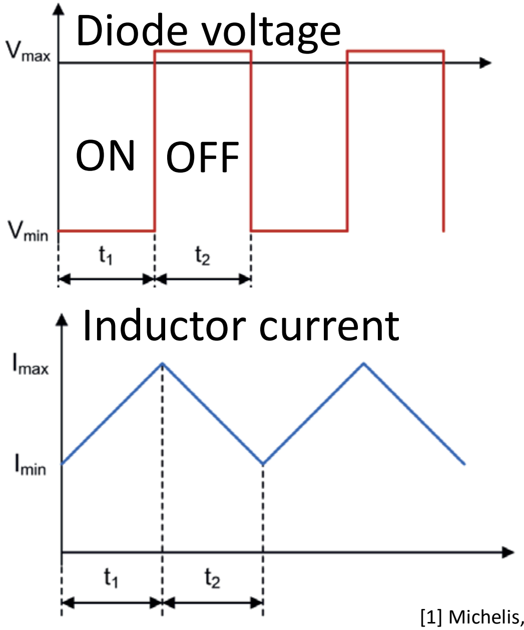
[4] Chan, Jay, “Serial Powering for ATLAS ITk Pixel Modules”, 10th International Workshop on Semiconductor Pixel Detectors for Tracking and Imaging (PIXEL 2022), Santa Fe, USA, 11 - 16 Dec 2022, https://cds.cern.ch/record/2845615

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

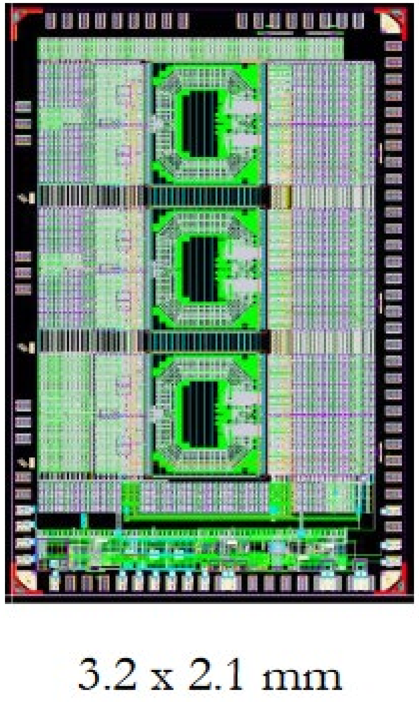
Example: Classic DC-DC Converter

- Energy stored in magnetic field
- MANY topologies! (boost, buck, buck-boost …)
- “Hard-switched”
- Applications: nearly ubiquitous
- Advantages: simplest and lowest cost (usually)
- Generally: difficult to integrate into ASICs





[6] “Boost Converters”, Wikipedia https://en.wikipedia.org/wiki/Boost_converter

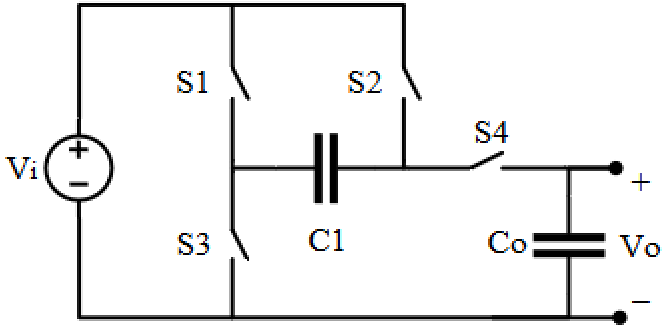


On-chip buck inductor example (Udine/CERN) with 1V @ 500mA output

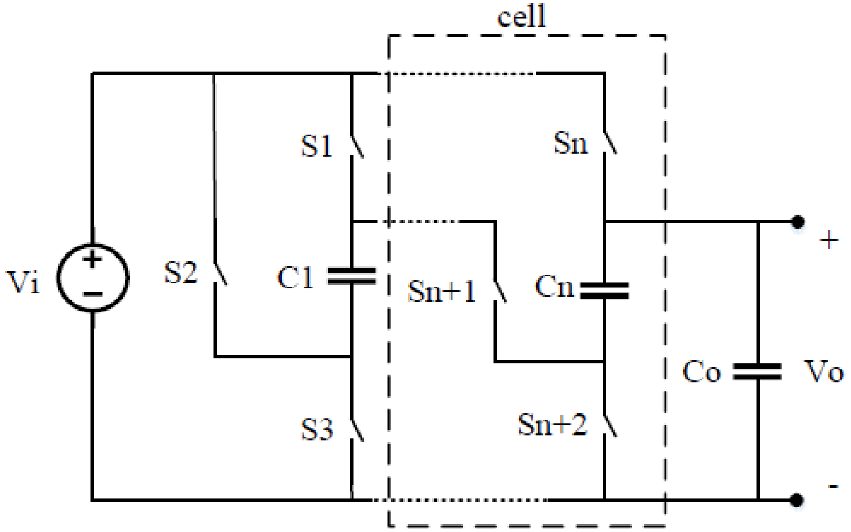
[1] Michelis, S., “Powering Next Generation Detector Systems”, Implementing DRD7: an R&D Collaboration on Electronics and On-detector Processing, 2nd Workshop, https://indico.cern.ch/event/1318635/contributions/5551795/attachments/2720651/4726975/WP7.1b_2023_09_25.pdf

Example: Switched Capacitor (SC) Converter

- Charge pump principle, descended from voltage doubler
  - Energy stored in electric field instead of magnetic
  - MANY topologies
- Advantages:
  - Higher **energy density** than inductors
  - **Monolithic integration into ASICs** (compatible with common process nodes)
  - **Lower EMI** than inductors
- Applications:
  - Embedded systems
  - Low power: biomedical, battery management, energy harvesting
  - High power: photovoltaics (PV) and renewable energy



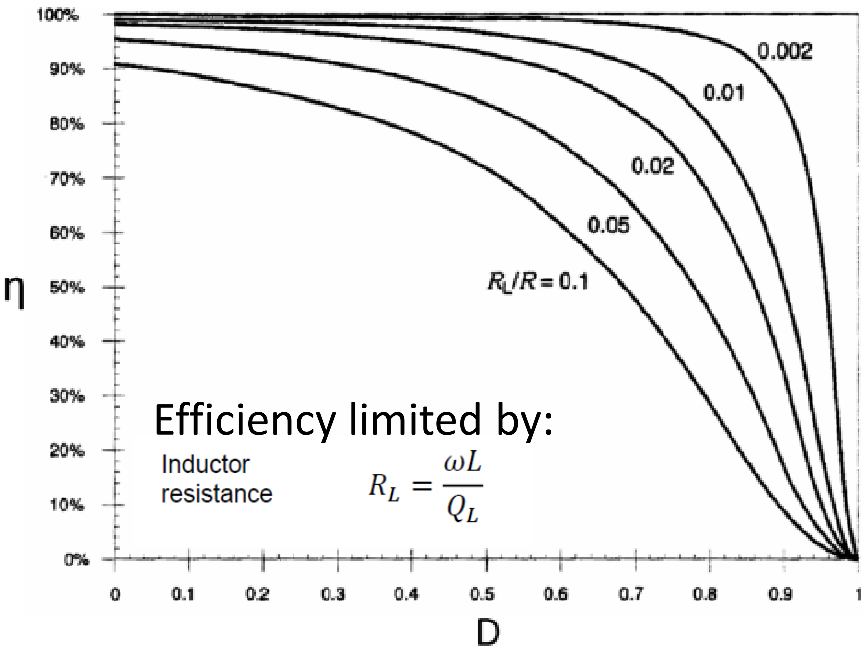
[7] de Souza, A.F., Tolofi, F.L., Ribeiro, E.R., "Switched Capacitor DC-DC Converters: A Survey on the Main Topologies, Design Characteristics, and Applications", MDPI Energies 2021, 14(8), 2231; https://doi.org/10.3390/en14082231



Limitations of Inductive and SC Converters

- Inductive disadvantages:
  - Quality inductors are **difficult to miniaturize**
    - L, Q (and R_L) decrease with volume
  - Inductors are lossy
    - Resistance dissipates some energy as heat
    - Magnetic hysteresis
  - Hard switched -> **electromagnetic Interference (EMI)**
  - Discontinuous conduction mode and synchronous rectification are more complex

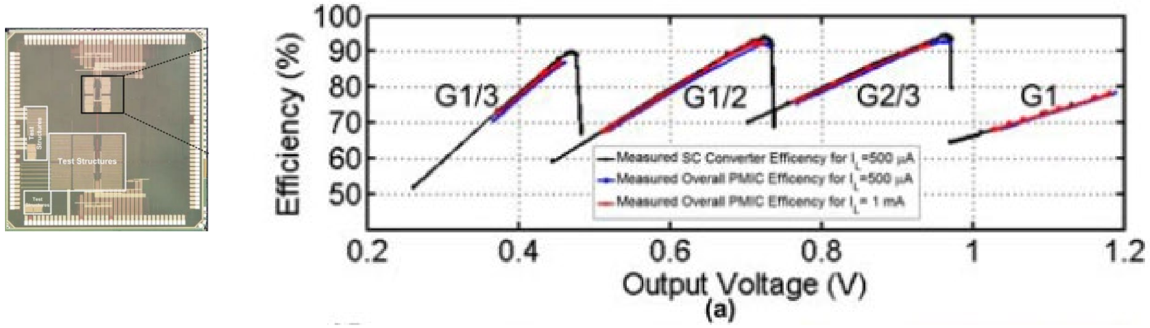
- SC disadvantages:
  - Voltage **regulation is more difficult** than inductor based converters
    - Discrete gain ratios (unless dynamic topology change)
    - Duty cycle does not linearly relate to output voltage
    - Difficult to control charge balance with multiple capacitors
  - FET switching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



Efficiency limited by:

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

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

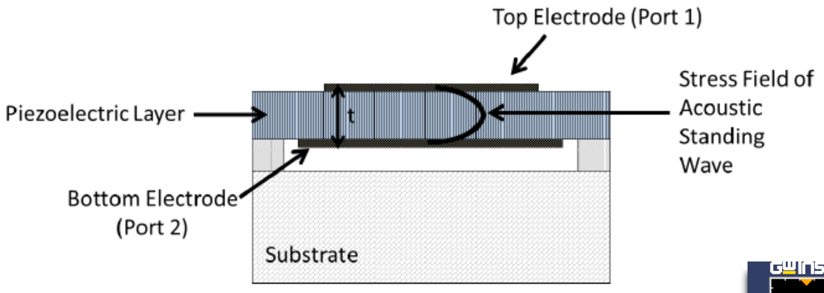


Gains and efficiency in a ferroelectric SC ASIC

[8] 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.

Example: Piezoelectric (PR) DC-DC Converter

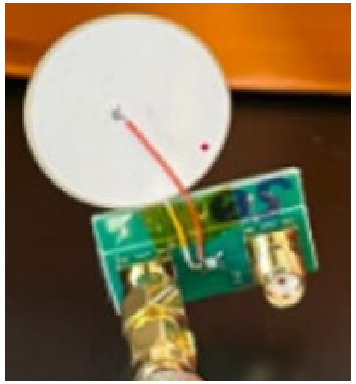
- Long history of piezoelectrics in power conversion [9]
- But recent advances in resonant PR converters are promising [10,11,12]
  - “Soft-switched” (sinusoidal current)
  - No fixed conversion ratios
  - Less concern about ripple?
- Energy storage is mechanical, not magnetic
  - Low EMI
- For equivalent inductor volume:
  - **High quality factor (Q)**
  - Low series resistance
- Can be **integrated into ASICs**



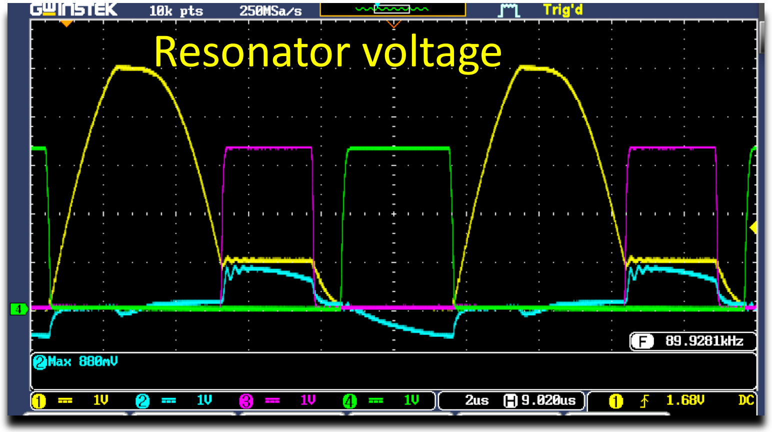
BAW cross section

PR resonator mounted on substrate

(illustration courtesy Troy Olsson)



Commercial lead zirconate titanate (PZT) resonator



A piezoelectric conversion cycle

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[9] Carazo, A., Piezoelectric Transformers: An Historical Review “, MDPI *Actuators* 2016, *5*(2), 12; https://doi.org/10.3390/act5020012

[10] 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.

[11] 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.

[12] 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.

Modeling PR 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

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

Strain coeff. (pm/V)

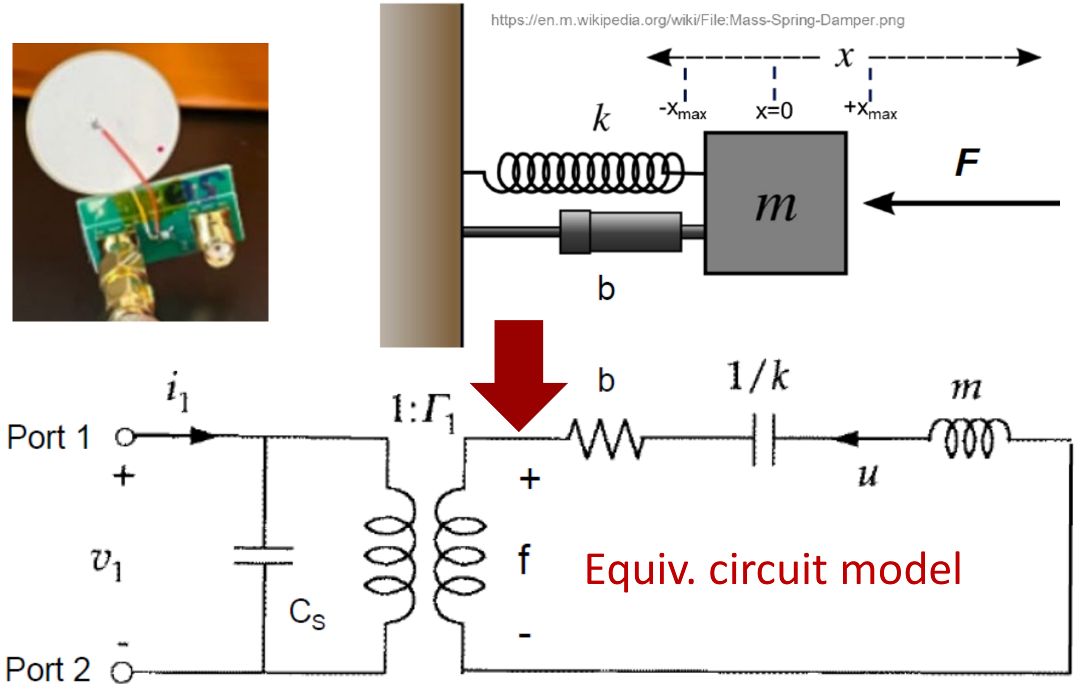
Young’s modulus (GPa)

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

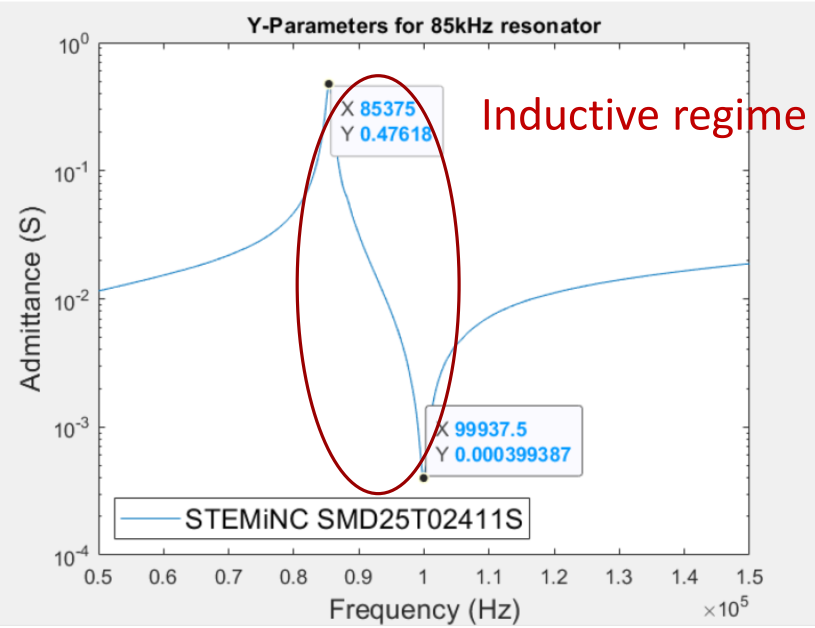
$$L_x = \frac{m}{\Gamma^2}$$

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

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

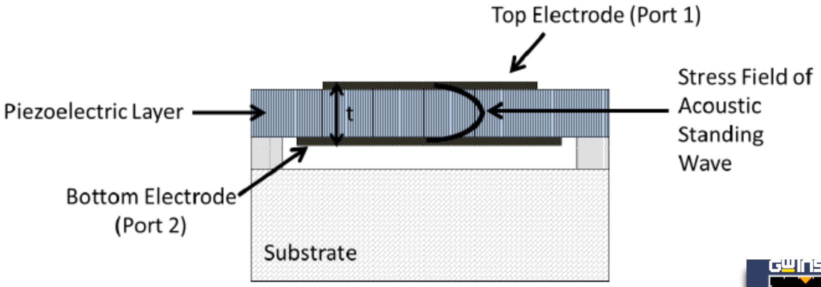


[13] H.A.C. Tilmans, “Equivalent Circuit Representation of Electromechanical Transducers: I. Lumped-parameter Systems”, J. Micromech. Microeng. 6 157, 1996, doi: 10.1088/0960-1317/6/1/036
Illustration adapted by Troy Olsson



PR Limitations

- Shunt C_s
- Also desire low series resistance to maximize voltage gain efficiency
- Operates near resonance
  - Load change -> freq change
- Control depends on **zero volt switching (ZVS)**
- Can control scale control to high frequencies?



BAW cross section

PR resonator mounted on substrate

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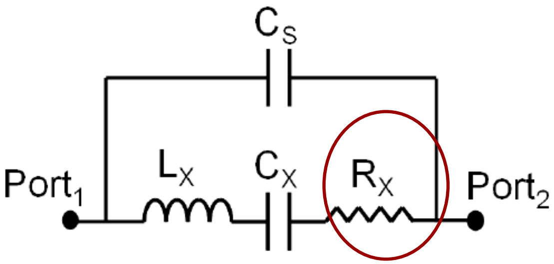
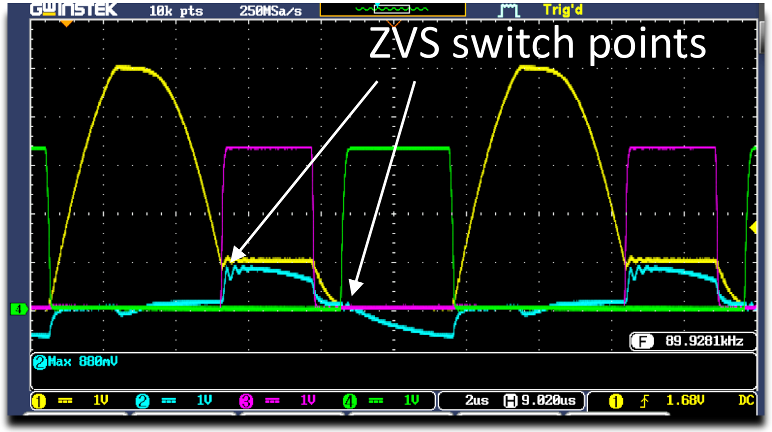


Microresonator Butterworth Van Dyke (BVD) equivalent circuit model

(illustration courtesy Troy Olsson)



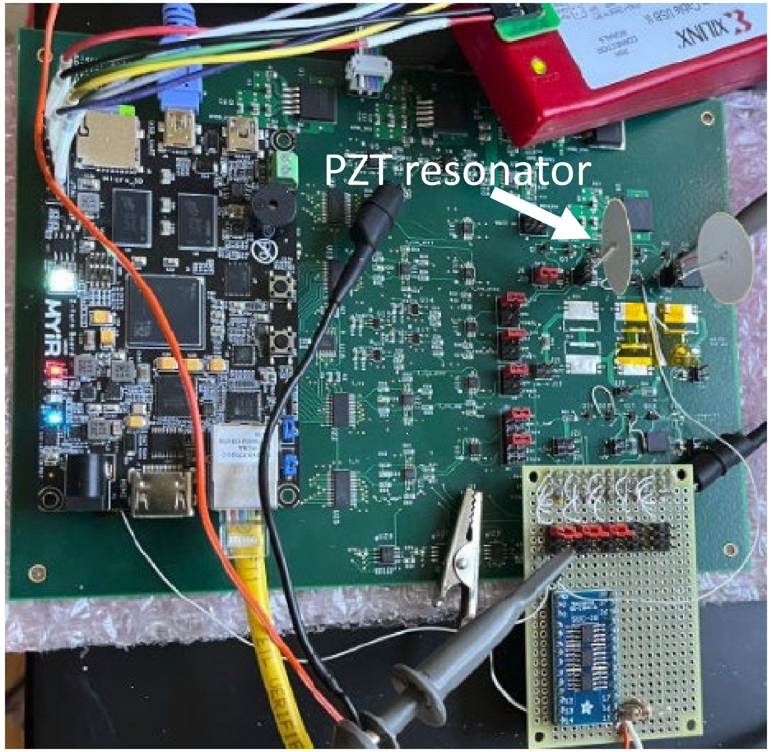
A piezoelectric conversion cycle

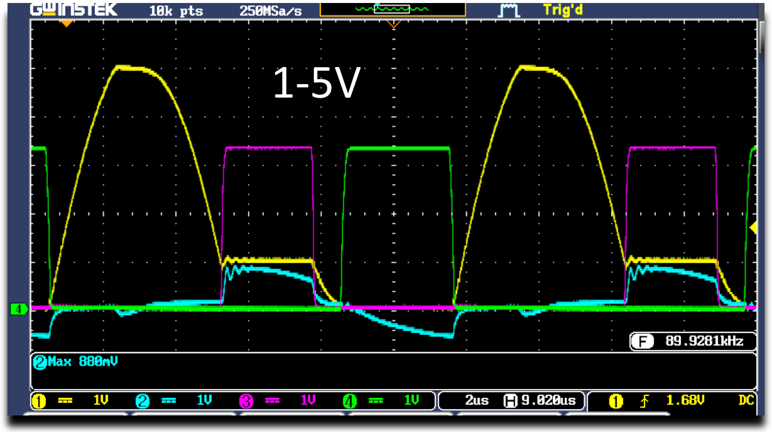
Work at Penn

- 1-5V piezoelectric DC-DC boost conversion demonstrated with macroscale prototypes
  - **Collaboration between Penn Physics and Penn Electrical and Systems Engineering (ESE) Department**
  - Uses commercial lead zirconate titanate (PZT) resonator
- Plan to extend this to an ASIC using miniaturized resonator
  - Olsson group has experience with miniaturized high quality resonators using aluminum scandium nitride (AlScN) among other materials
- **Develop miniature, low EMI, radiation and magnetic tolerant DC-DC converters for HEP using novel materials and architectures**

goal

- How is this different from prior work?
  - European HEP groups have not looked into piezoelectrics
  - Power electronics community generally not interested in rad tolerant (but there is interest in highly miniaturized and low EMI design)





Proposal

	Volume	Monolithic	Voltage regulation	Power	Efficiency	EMI	Rad hard	Mag hard	Reliability	Cost
Inductor	largest	difficult	wide range	medium - high	limited range	most	yes	yes		least
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		

- We believe there is opportunity for innovation in DC-DC conversion using novel materials and architectures, based on prototype results and current knowledge of piezoelectric/ferroelectric converters
  - Unique expertise from Physics HEP and ESE groups
  - Study HEP specific topics (radiation and magnetic tolerance, vibration, extreme environments, etc.)
- Explore possible hybrid architectures (piezoelectric-switched-capacitor, ferroelectric capacitor, multi-phase switched capacitor)
  - Switched capacitor converters are compatible with existing process nodes
  - Piezoelectric resonators can be integrated onto control ASICs on the backend
  - Ferroelectric processes exist from TI/Ramtron and Samsung
- We invite collaborators and efforts along these lines to move chip and module-level powering approaches beyond those of HL-LHC designs
- Miniature converters have broad applications in many HEP and non-HEP systems

control

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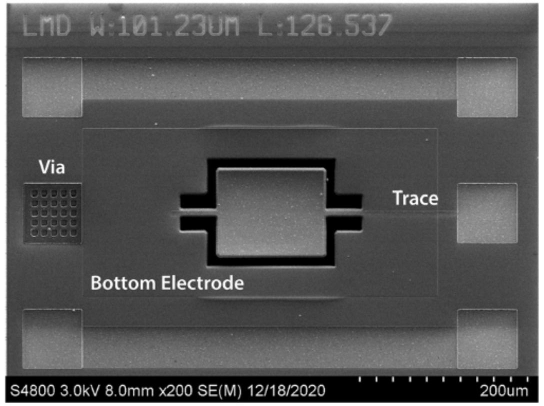

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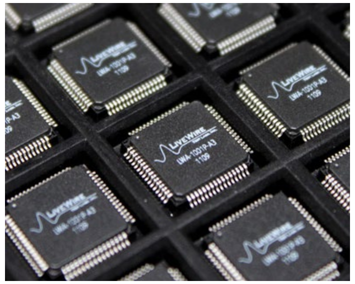
ASIC converter



Example of MEMS resonator

[9] 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