DC-DC Converters Using New Materials and Architectures

CPAD Kickoff Meeting

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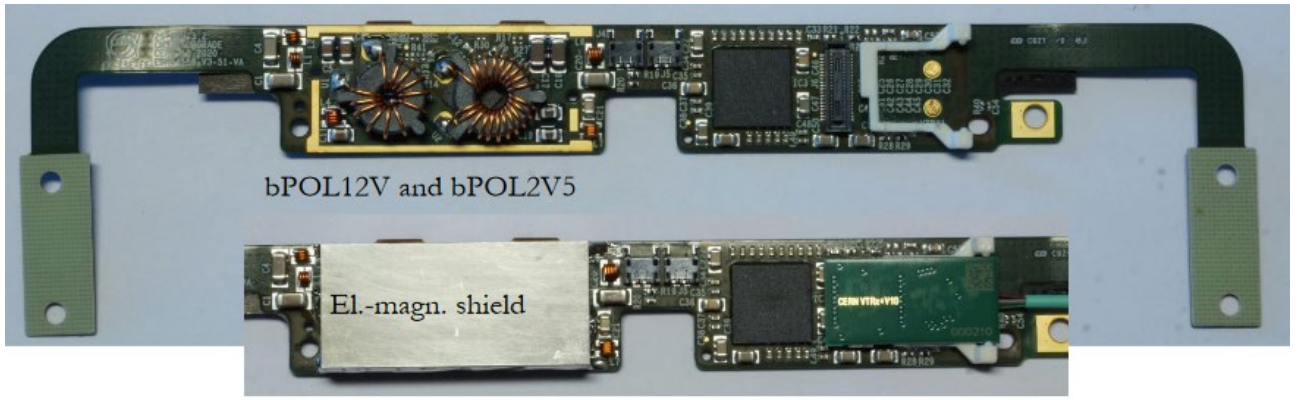
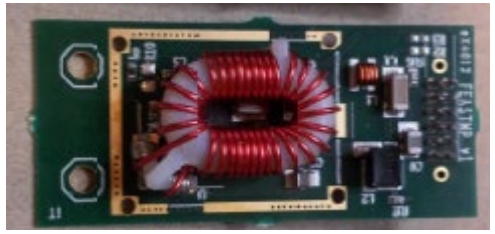
Problem

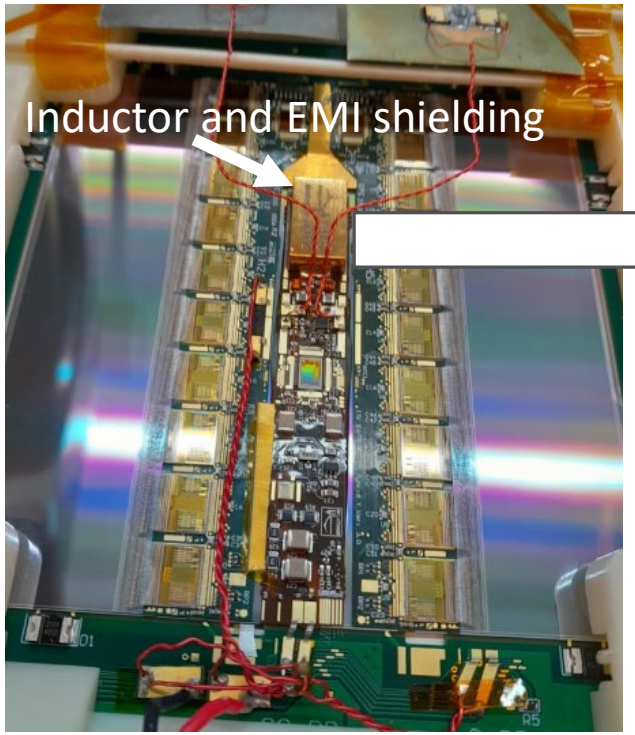
- DC-DC converters in HEP use inductors
  - These generate electromagnetic interference (EMI) and must be shielded
  - They are physically large
- Often need to be radiation tolerant
- There may be problems with using large discrete inductors and capacitors
  - System level interactions (see example)

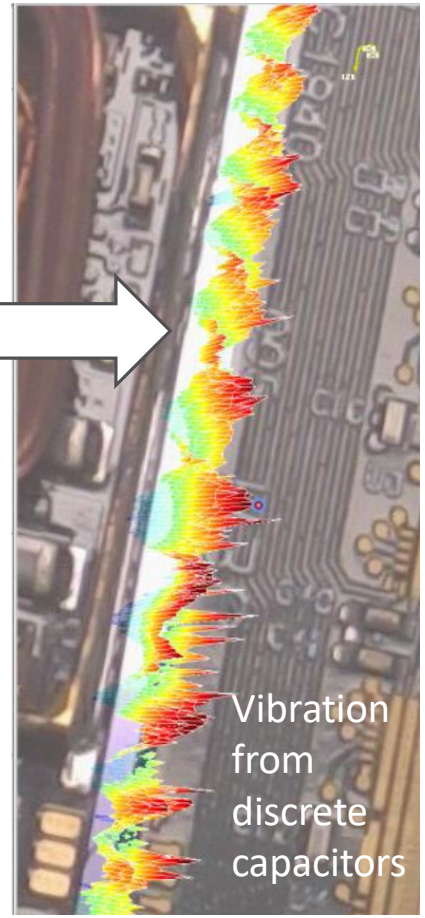


Example from CMS [1]



FEAST/bPOL, 0.35um rad hard [2]

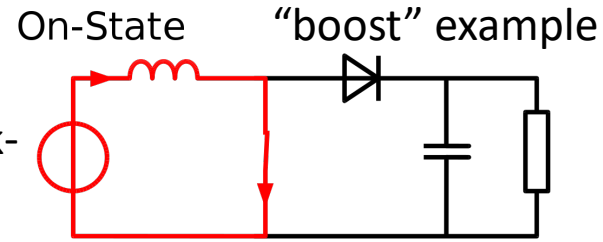


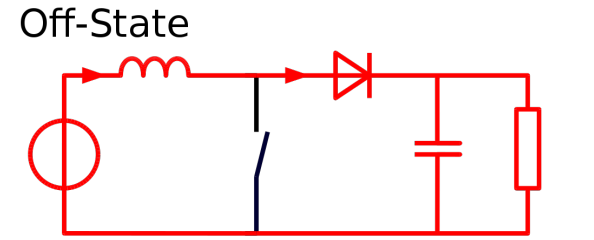


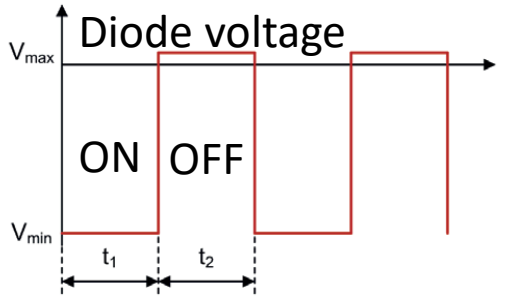
Example from ATLAS [3]

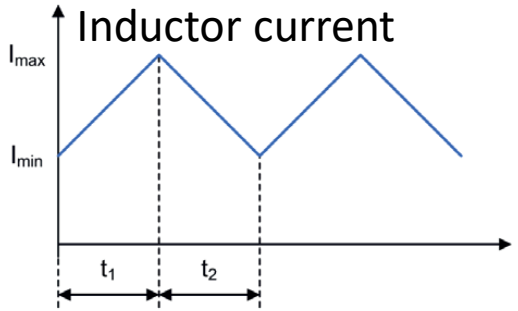
Example: Classic DC-DC Converter

- Energy stored in magnetic field
- MANY topologies! (boost, buck, buck-boost …)
- EMI from “hard-switching”
- Need inductor with low series resistance to get high efficiency [4], but real inductors are lossy
- Difficult to miniaturize inductors (inductance and quality factor decrease with volume)
- Generally: work well only for narrow bands of power
- Generally: difficult to integrate into ASICs

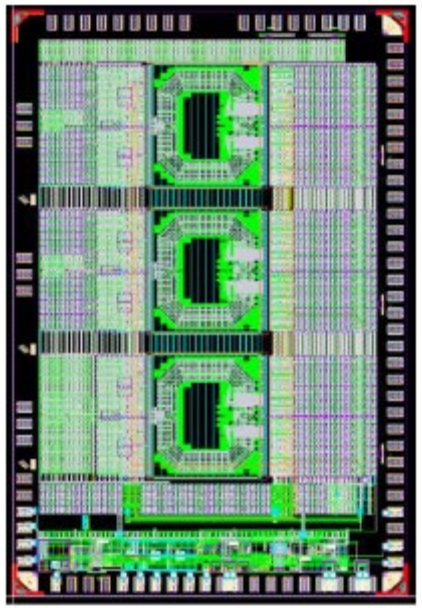








On-chip inductor example [1] with 1V @ 500mA output

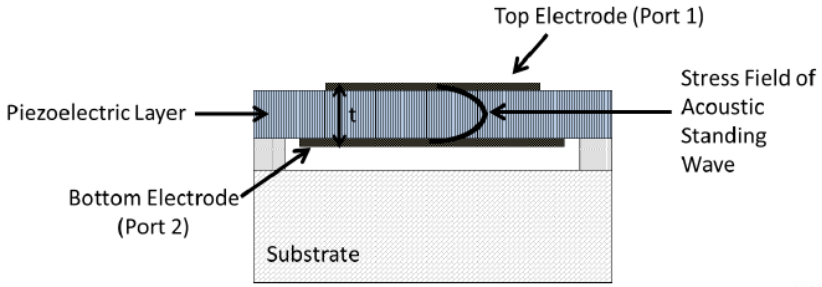


3.2 x 2.1 mm

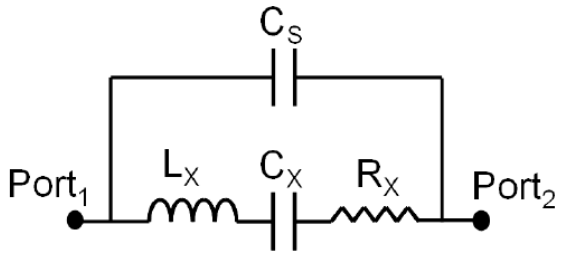
[5]

Example: Piezoelectric DC-DC Converter

- Long history of piezoelectrics in power conversion [6]
- But recent advances in resonant converters are promising [7,8,9,10]
- Energy storage is mechanical, not magnetic
  - Low EMI
  - "Soft-switched"
- For equivalent inductor volume:
  - High quality factor (Q)
  - Lower series resistance
- More easily integrated into ASICs

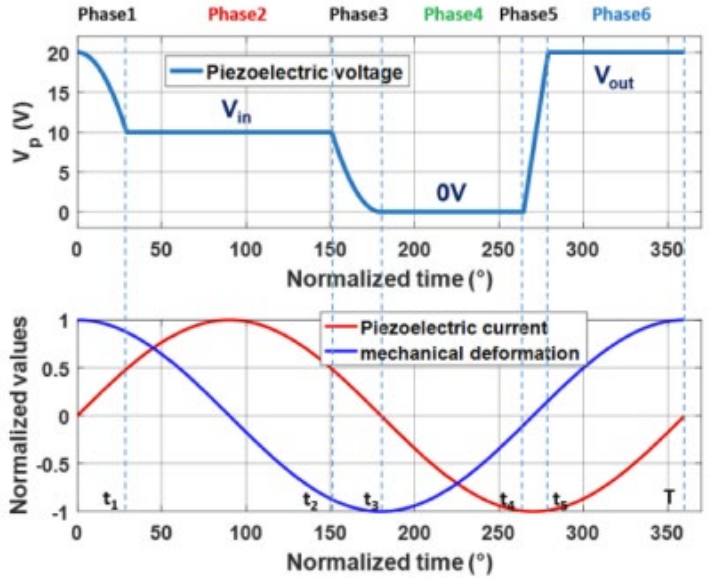


BAW cross section



Microresonator Butterworth Van Dyke (BVD) equivalent circuit model

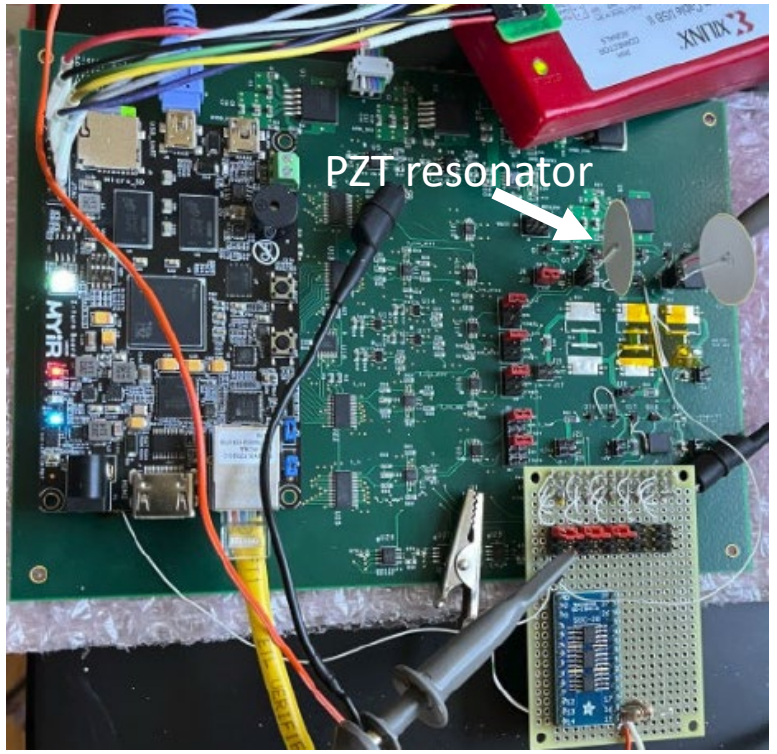
Illustrations courtesy T. Olsson

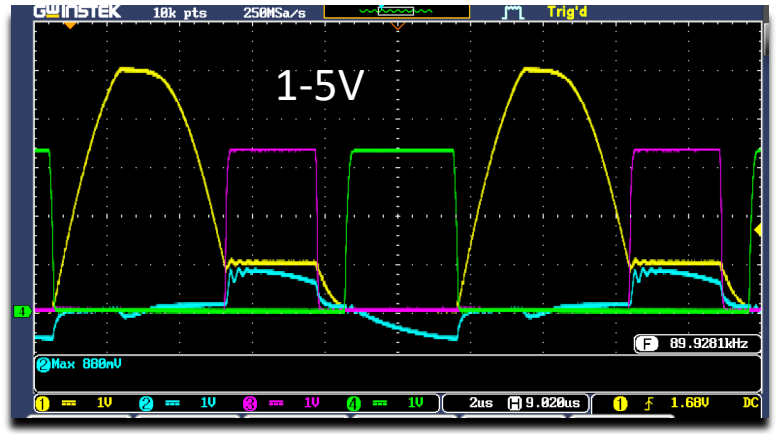


A piezoelectric conversion cycle [7]

Work at Penn, and Proposal

- 1-5V piezoelectric DC-DC boost conversion demonstrated with macroscale prototypes
  - Collaboration between Penn Physics and School of Engineering and Applied Science (SEAS)
  - Uses lead zirconate titanate (PZT) resonator
- Want to extend this to an ASIC using miniaturized resonator
  - SEAS group has experience with miniaturized high quality resonators using aluminum scandium nitride (AlScN) among other materials
- **Develop highly miniature, low EMI, radiation tolerant DC-DC converters for HEP using novel materials and architectures** ← goal
- How is this different from prior work?
  - European groups have not looked into piezoelectrics or ferroelectric capacitors
  - Power electronics community generally not interested in rad tolerant (but there is interest in highly miniaturized and low EMI design)
- Possible hybrid architectures (piezoelectric-switched-capacitor, ferroelectric capacitor [11,12])
- Miniature converters also have broad applications in many HEP and non-HEP systems





Links

- [1] “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
- [2] "FEAST2: A Radiation and Magnetic Field Tolerant Point-of-Load Buck DC/DC Converter" https://ieeexplore-ieee-org.proxy.library.upenn.edu/document/7004569
- [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
- [4] R. W Erickson, “DC-DC Power Converters,” *J. Webster (ed.), Wiley Encyclopedia of Electrical and Electronics Engineering*, pp. 1-18, 2007.
- [5] “Boost Converters”, Wikipedia https://en.wikipedia.org/wiki/Boost_converter
- [6] "Piezoelectric Transformers: An Historical Review” https://www.mdpi.com/2076-0825/5/2/12
- [7] "A New Non-Isolated Low-Power Inductorless Piezoelectric DC–DC Converter" https://ieeexplore-ieee-org.proxy.library.upenn.edu/document/8645685
- [8] "Enumeration and Analysis of DC–DC Converter Implementations Based on Piezoelectric Resonators" https://ieeexplore-ieee-org.proxy.library.upenn.edu/document/9122580
- [9] "Feedback Control for a Piezoelectric-Resonator-Based DC-DC Power Converter" https://ieeexplore-ieee-org.proxy.library.upenn.edu/document/9646012
- [10] "A Piezoelectric-Resonator-Based DC–DC Converter Demonstrating 1 kW/cm3 Resonator Power Density" https://ieeexplore-ieee-org.proxy.library.upenn.edu/document/9931991
- [11] "Switched Capacitor DC-DC Converters: A Survey on the Main Topologies, Design Characteristics, and Applications " https://www.mdpi.com/1996-1073/14/8/2231
- [12] "A 93% efficiency reconfigurable switched-capacitor DC-DC converter using on-chip ferroelectric capacitors" https://dspace.mit.edu/handle/1721.1/95416