Energy Harvesting Systems

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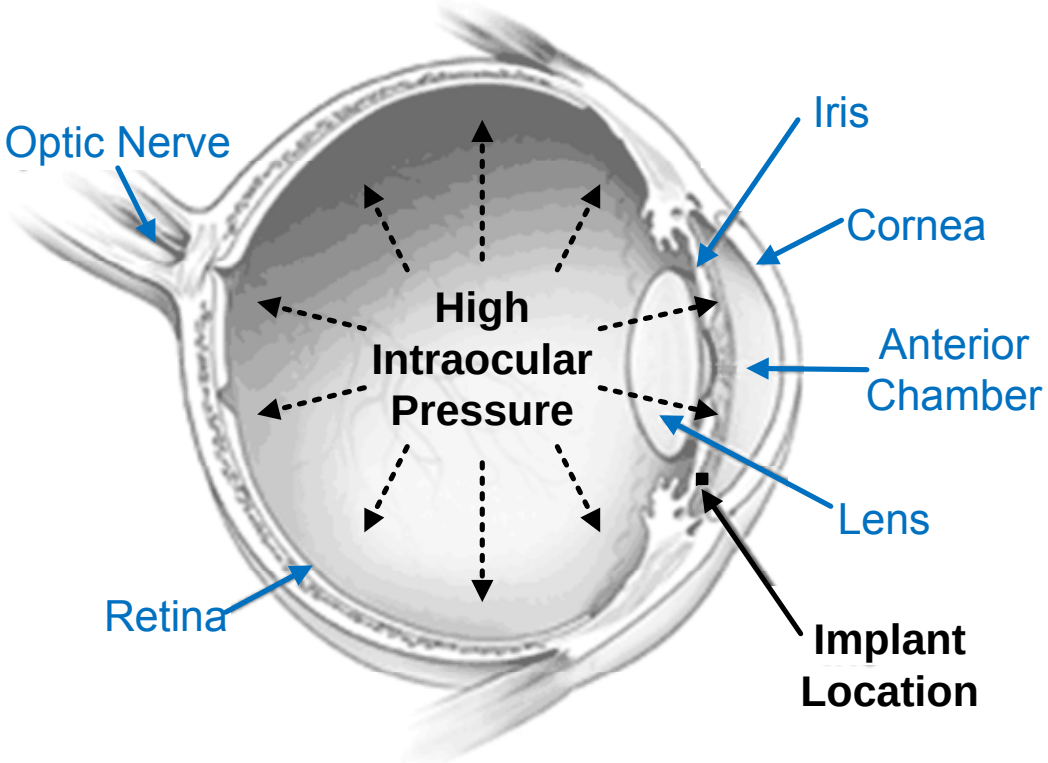
Outline

- In this presentation we will discuss specific designs of energy harvesting systems for two applications:

- Intraocular pressure sensor for monitoring internal eye pressure
  - Gregory Chen, Hassan Ghaed, Razi-ulHaque, Michael Wieckowski, YejoongKim, GyouhoKim, David Fick, DaeyeonKim, MingooSeok, Kensall Wise, David Blaauw, Dennis Sylvester (University of Michigan)

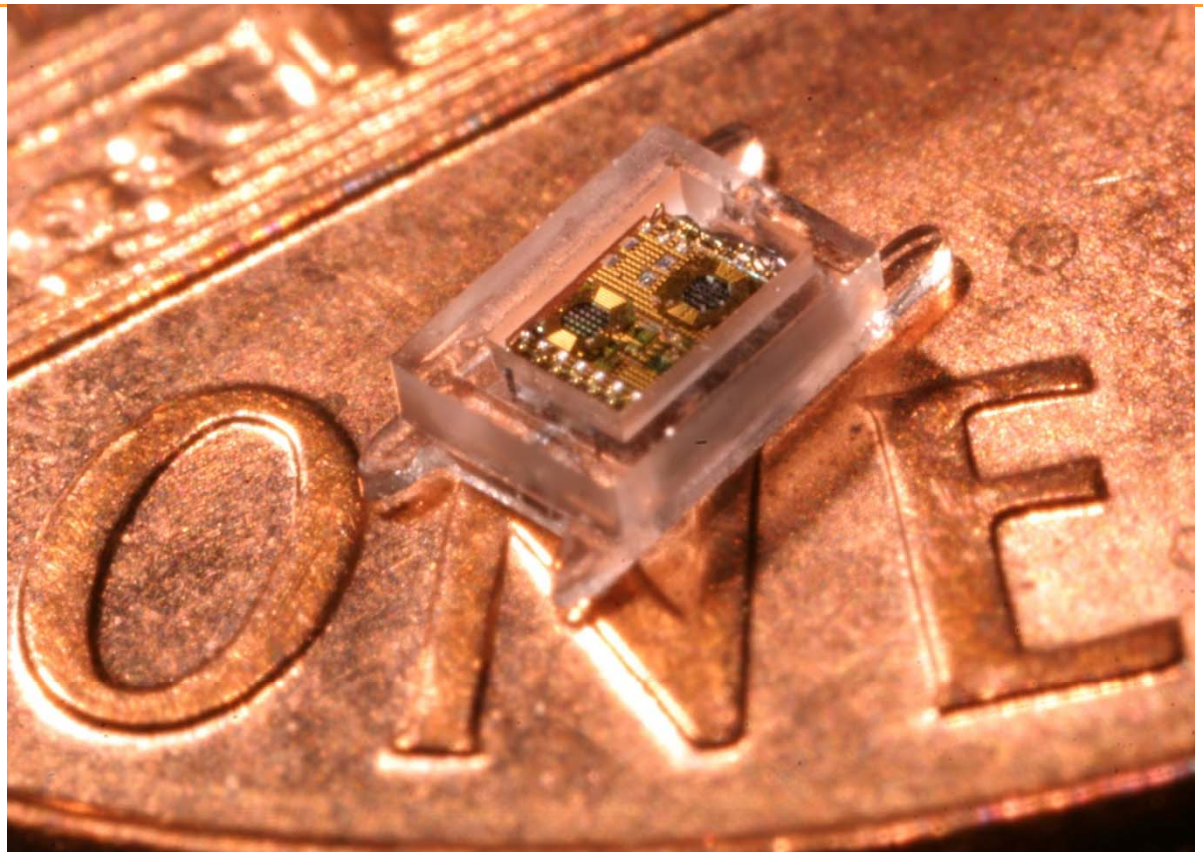
- Energy harvesting backpack for powering military radios in the field
  - Aaron Stein, Heath Hofmann (University of Michigan)
  - Lawrence Rome (University of Pennsylvania, LightningPacks)
  - Cheng Luo, Guanghui Wang (Penn State University)

Continuous IOP Monitoring



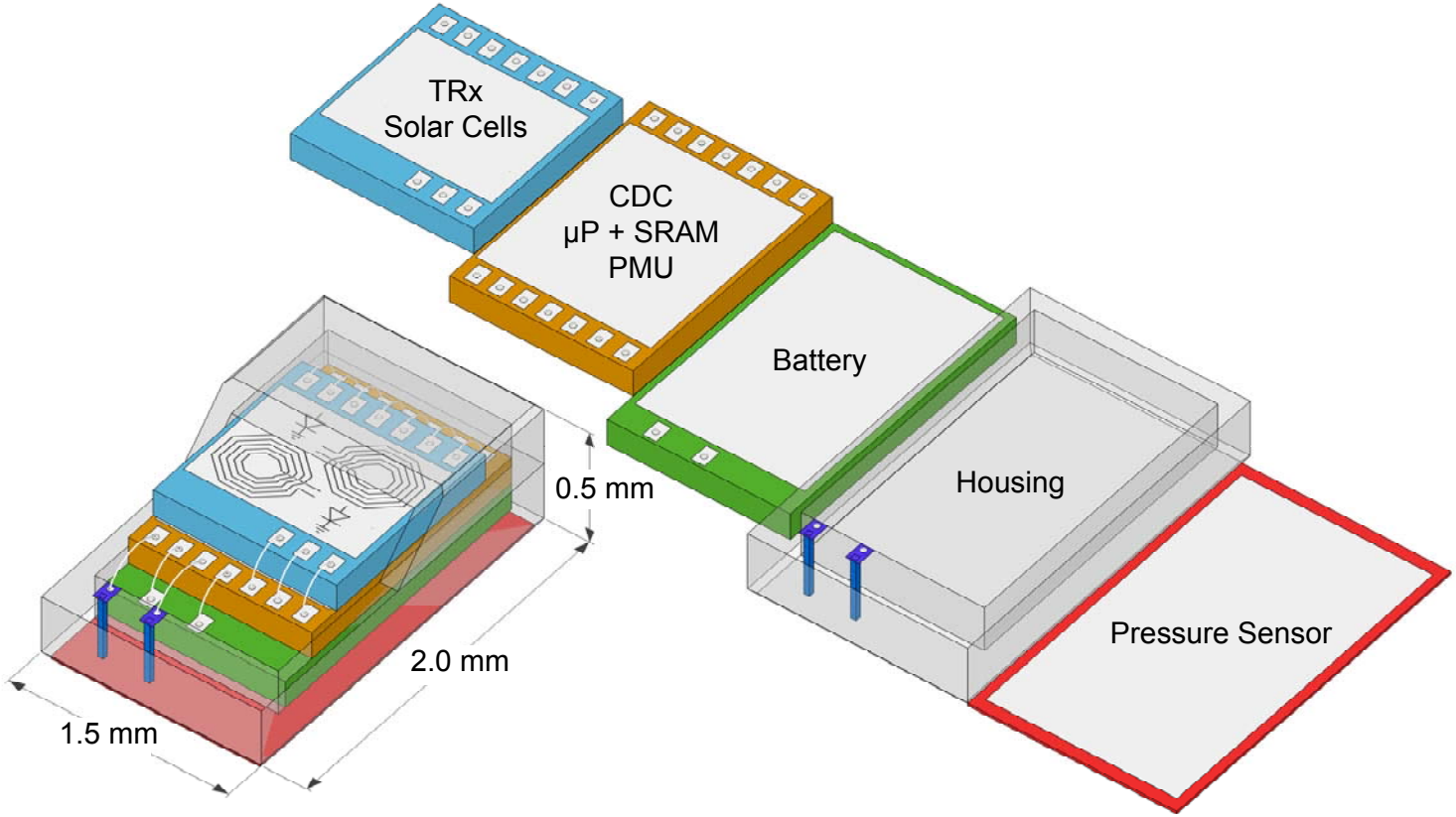
- Glaucoma
  - Second leading cause of blindness affects 60 million people
  - Progress checked by measuring intraocular pressure
- Continuous monitoring with an implanted microsystem
  - Gives doctors a more complete view of disease
  - Faster response time for tailoring treatments

Intraocular Pressure Monitor



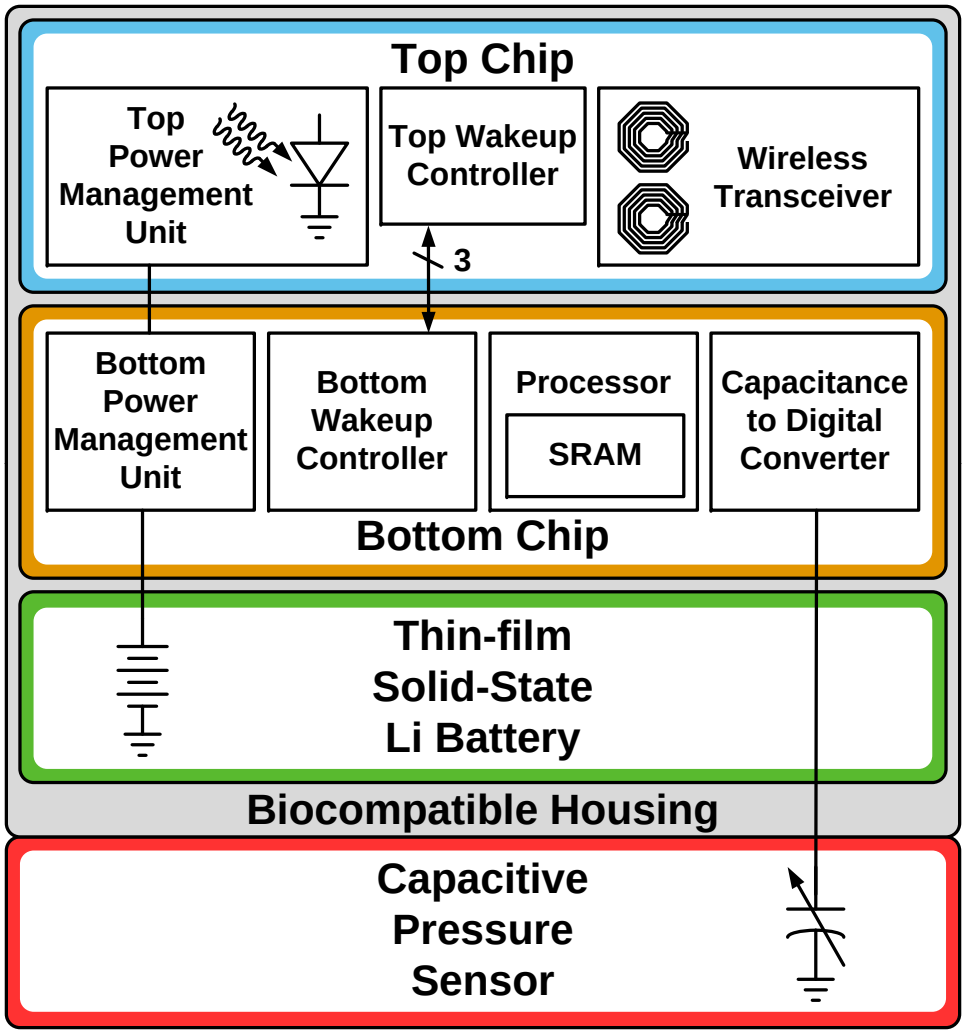
- Continuously monitors IOP
- Processes and stores medical information
- Wirelessly transmits data to an external wand
- Harvests solar energy to autonomously power circuits

Intraocular Pressure Monitor



- Two integrated circuit chips
- 1mm^2 1µAh thin-film solid-state Lithium battery
- Assembled in a glass housing with pressure sensor (Razi)
- Connected using wire-bonds and through-glass vias (Razi)

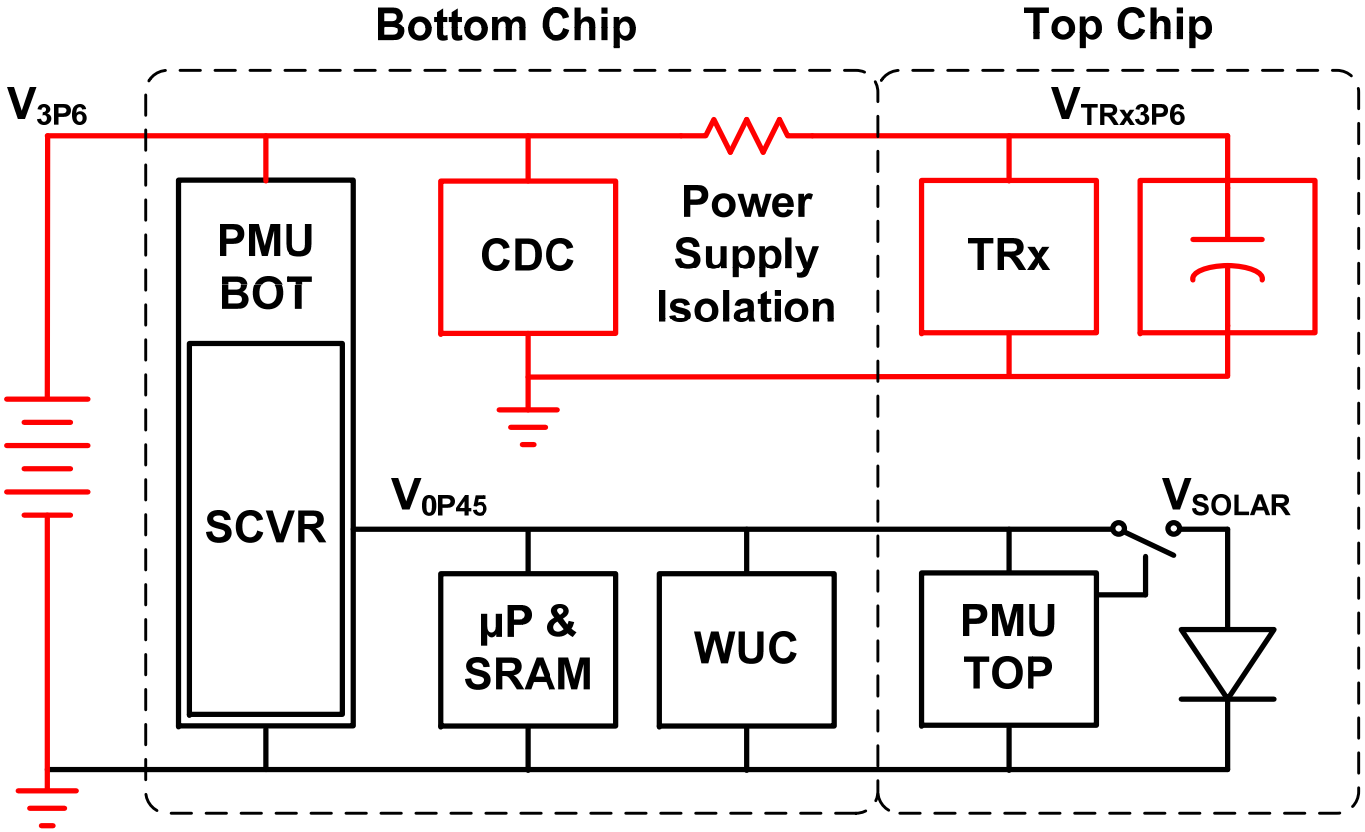
IOP Monitor Block Diagram



- Cross sectional view of microsystem

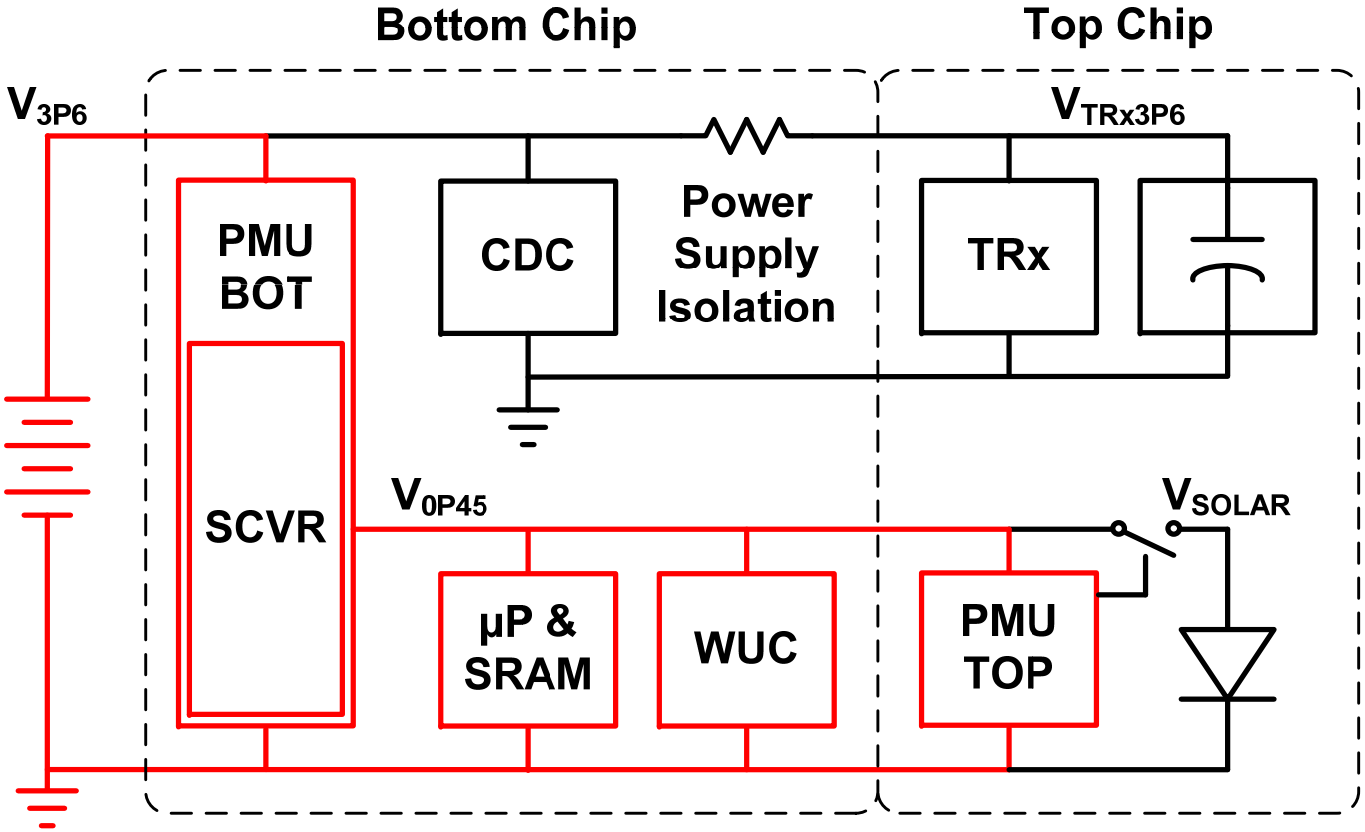
Power Delivery and Management

- Battery powers CDC and wireless TRx
- Isolated local TRx power supply prevents catastrophic V_{DD} drop
- CDC and TRx designed with high-V_{TH} thick-t_{OX} IO devices and no bias currents for low leakage during standby mode



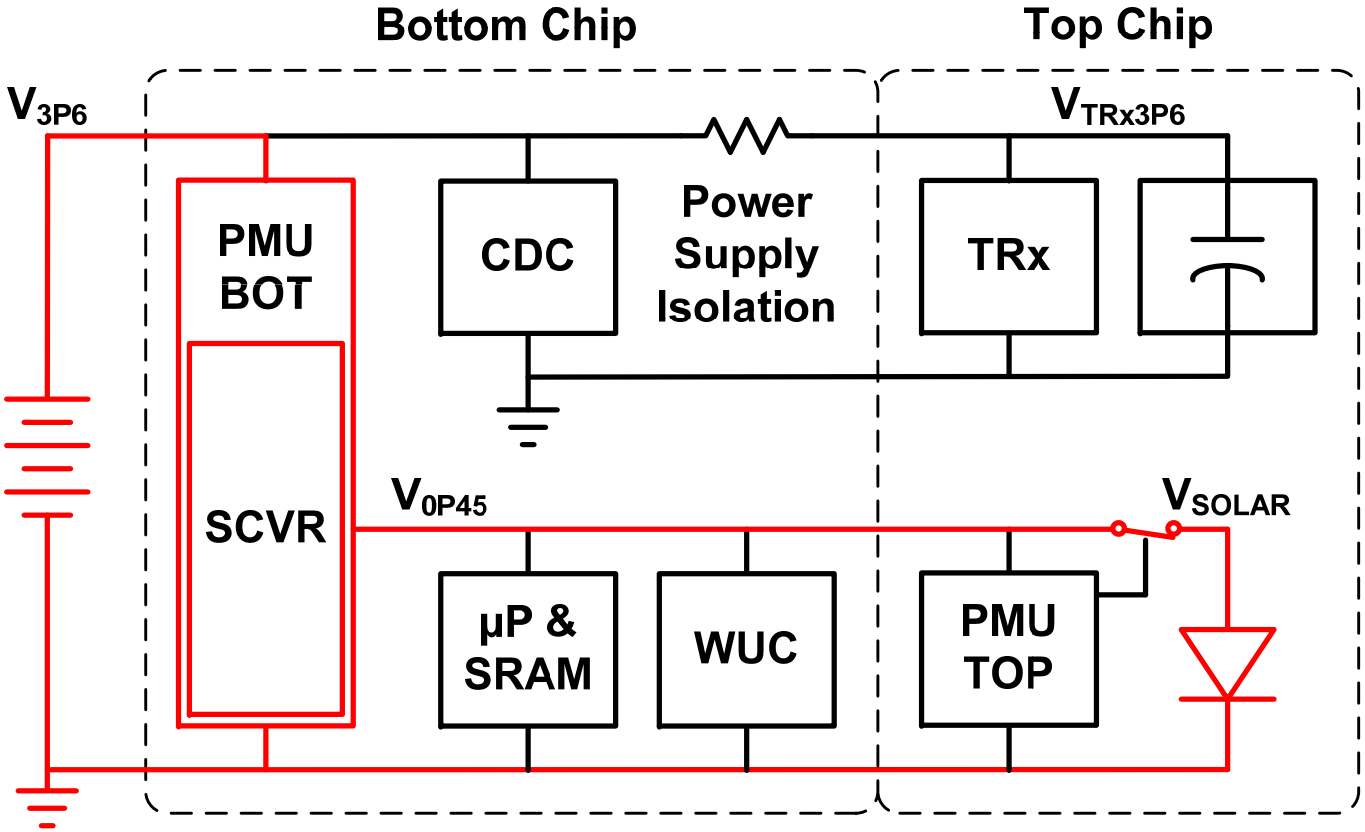
Power Delivery and Management

- 8:1 Switch Cap Voltage Regulator (SCVR) delivers 0.45 V
- µP is power gated in standby mode and uses logic devices
- SRAM and WUC use IO devices for low standby leakage
- SCVR clock is reduced to 50 Hz clock in standby mode

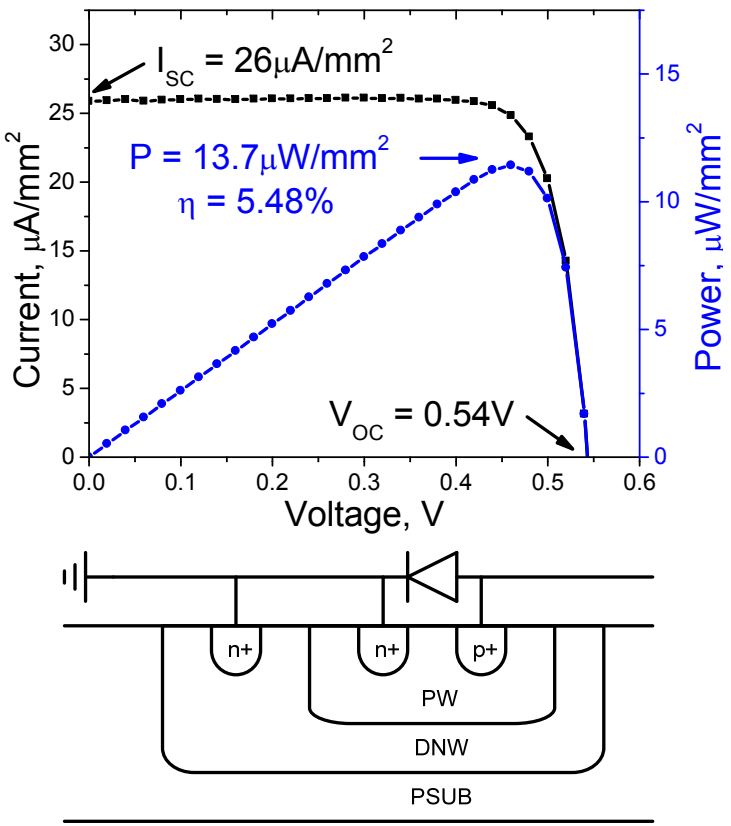


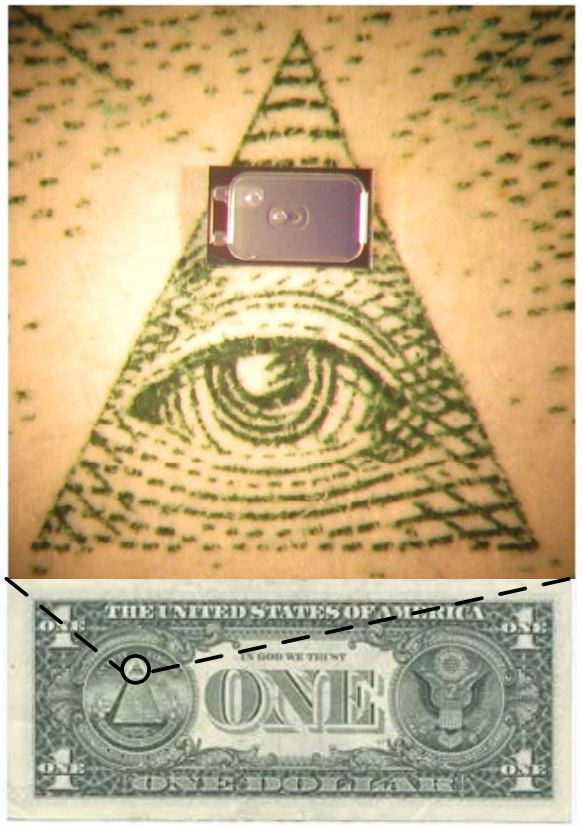
Power Delivery and Management

- Solar cell connected when open circuit V_{SOLAR} exceeds V_{0P45}
  - Check voltage on solar cell with small replica
  - Compare using clocked variable offset comparator
- SCVR up-converts solar energy to recharge the battery



Power Sources

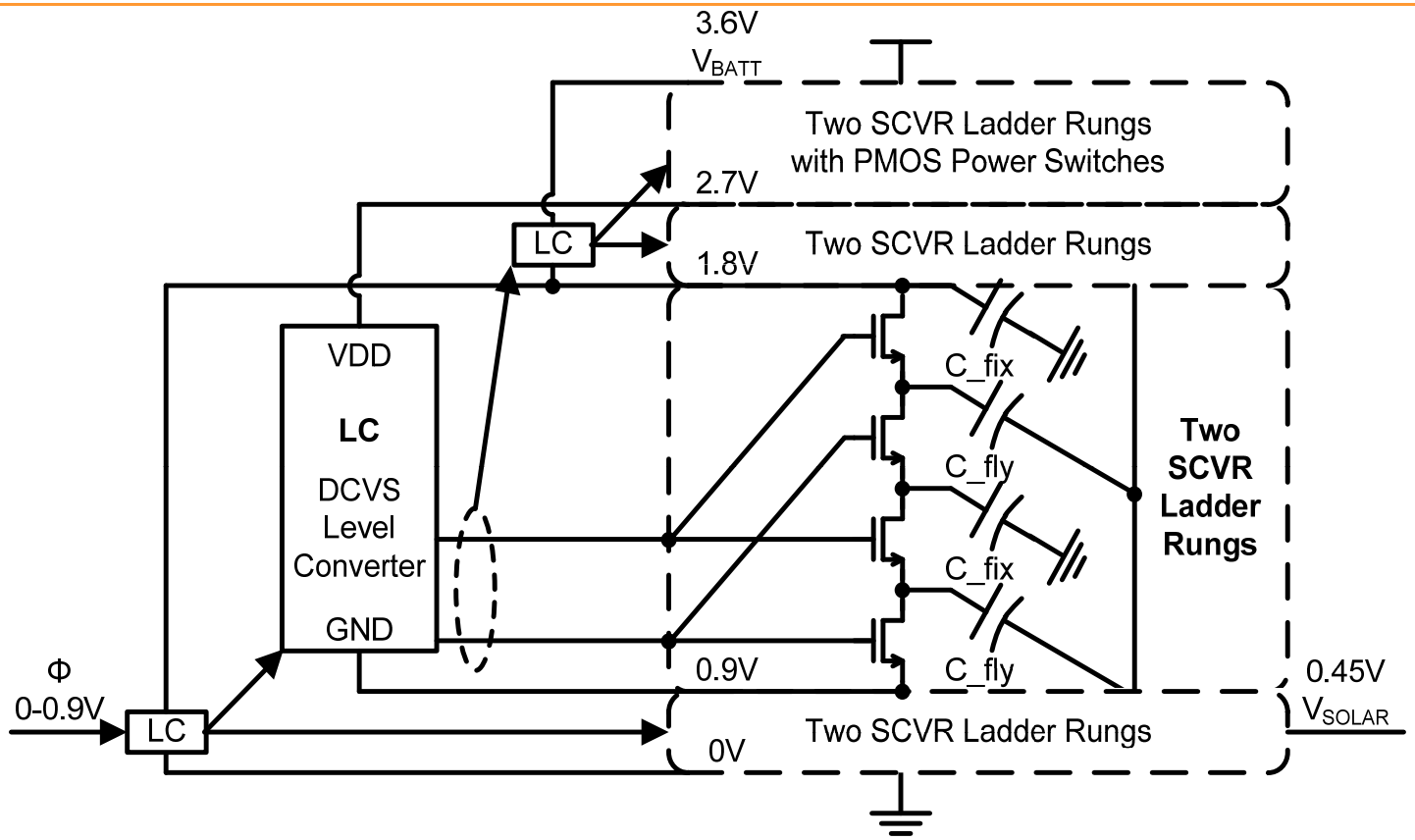




- 0.07 mm² solar cell
- 0.18 μm CMOS
- No post-processing
- 5% solar efficiency

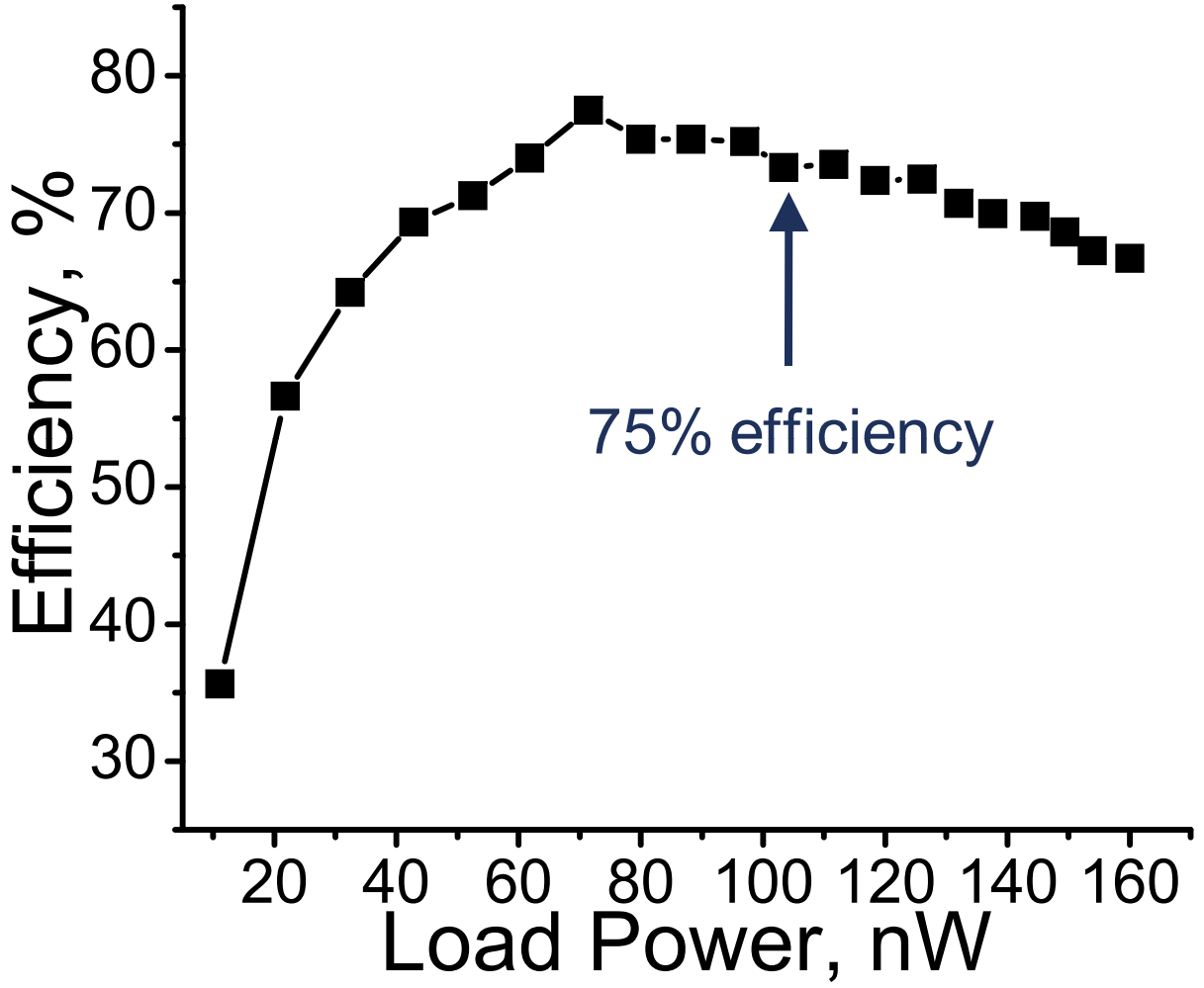
- Cymbet thin-film Li battery
- 1 mm² custom size
- 1μAh capacity
- 40μW peak power

8:1 Ladder SCVR



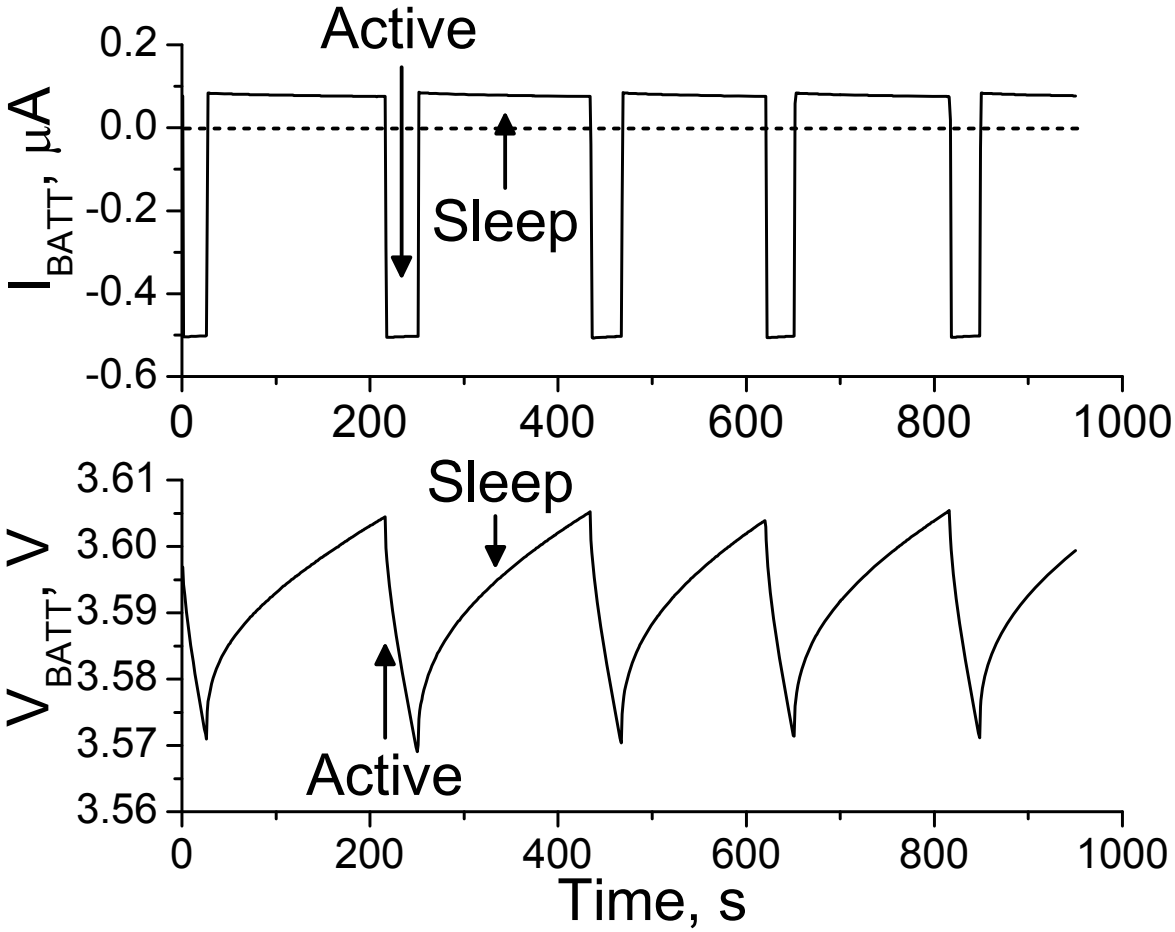
- 0.32 mm^2 with 35 pF MOS fixed caps, 45 pF MIM flying caps
- Low switching losses: 1.8 V clocks with level converters
- Low conduction losses: High switch overdrive and low currents
- Low leakage: Minimum-sized IO power switches

SCVR Measurements



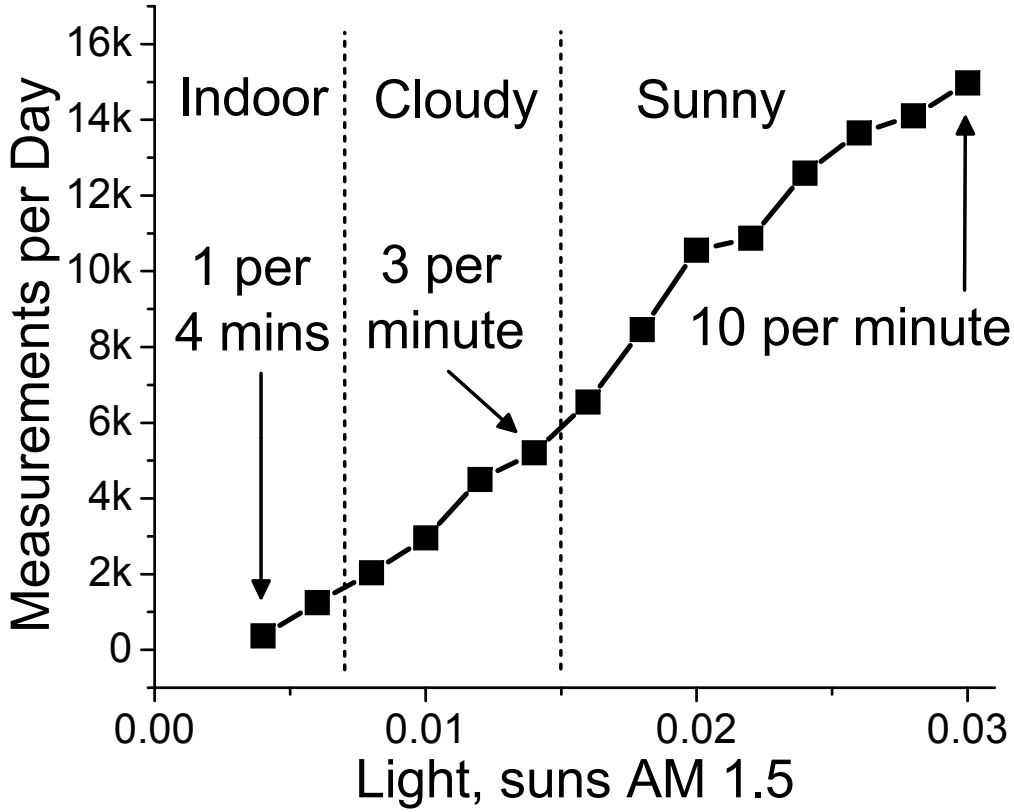
- 75% efficiency with 100 nW processor load in active mode
- 40% efficiency with 72 pW load in standby mode

Energy-autonomous Operation



- Measured battery voltage and current
- Energy consumed by microsystem is recharged in sleep mode
- No net drain of battery energy

Energy-autonomous Operation



Mode	Harvesting	Discharge Rate
One measurement every hour	No	20%/year
Idle lifetime	No	11%/year
Up to 10 measurements per minute	Yes	0%/year

Energy Harvesting Backpack

Marines carry large weights

Large forces cause reduced mobility and endurance

Large forces result in acute and long term musculoskeletal injuries

Affects force readiness and retention

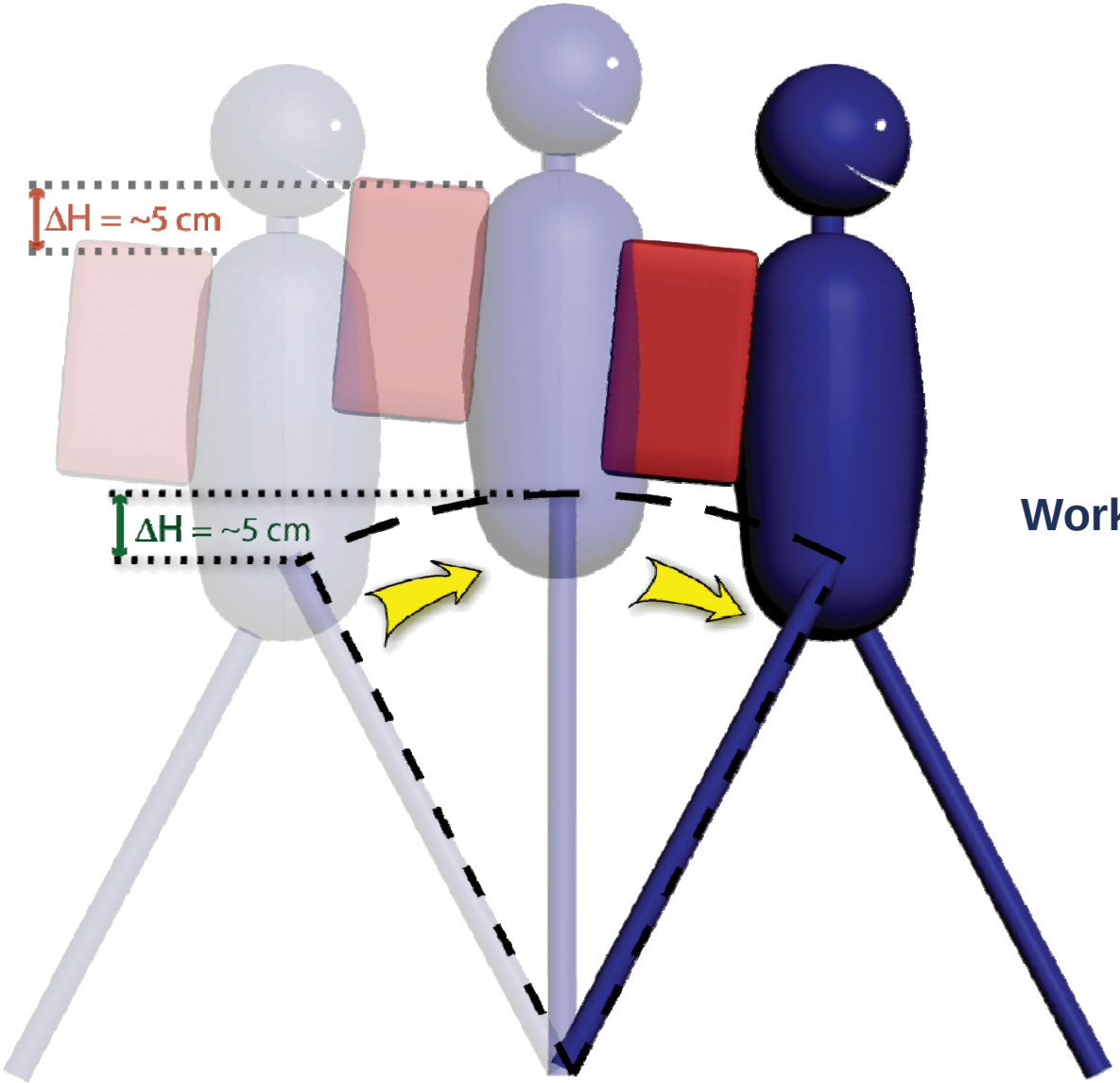
Modern warfare requires electrical energy (batteries)

Disposable batteries add considerable weight (up to 20 lbs) to already heavy packs (> 80 lbs)

Dependence on disposable batteries limit mission duration.

Disposable batteries are very costly and difficult to supply and dispose of

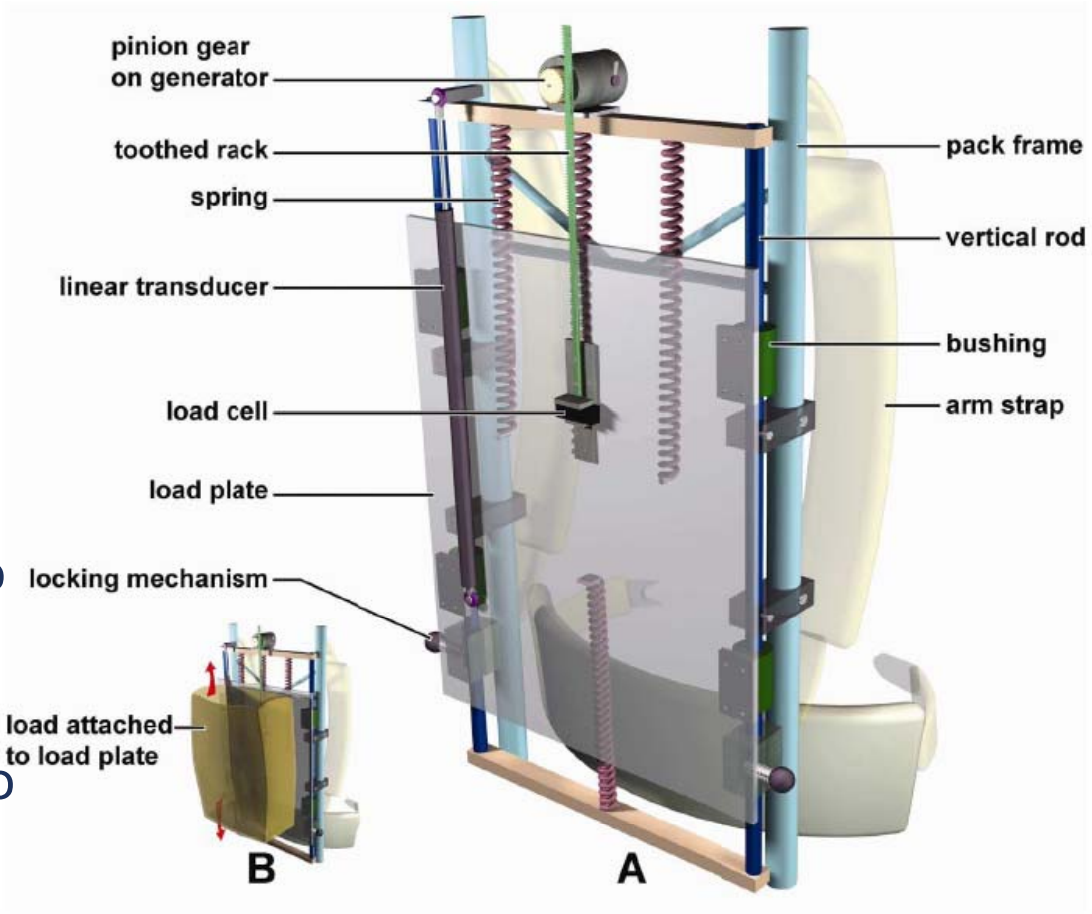
Solution Make the problem work for you!



Work generated with an 80lb load

Force=40kg*g= 400 Newton
Work=400N*0.05m= 20 Joules
Power=20J* 2step/s=40 Watts

Energy Harvesting Backpack

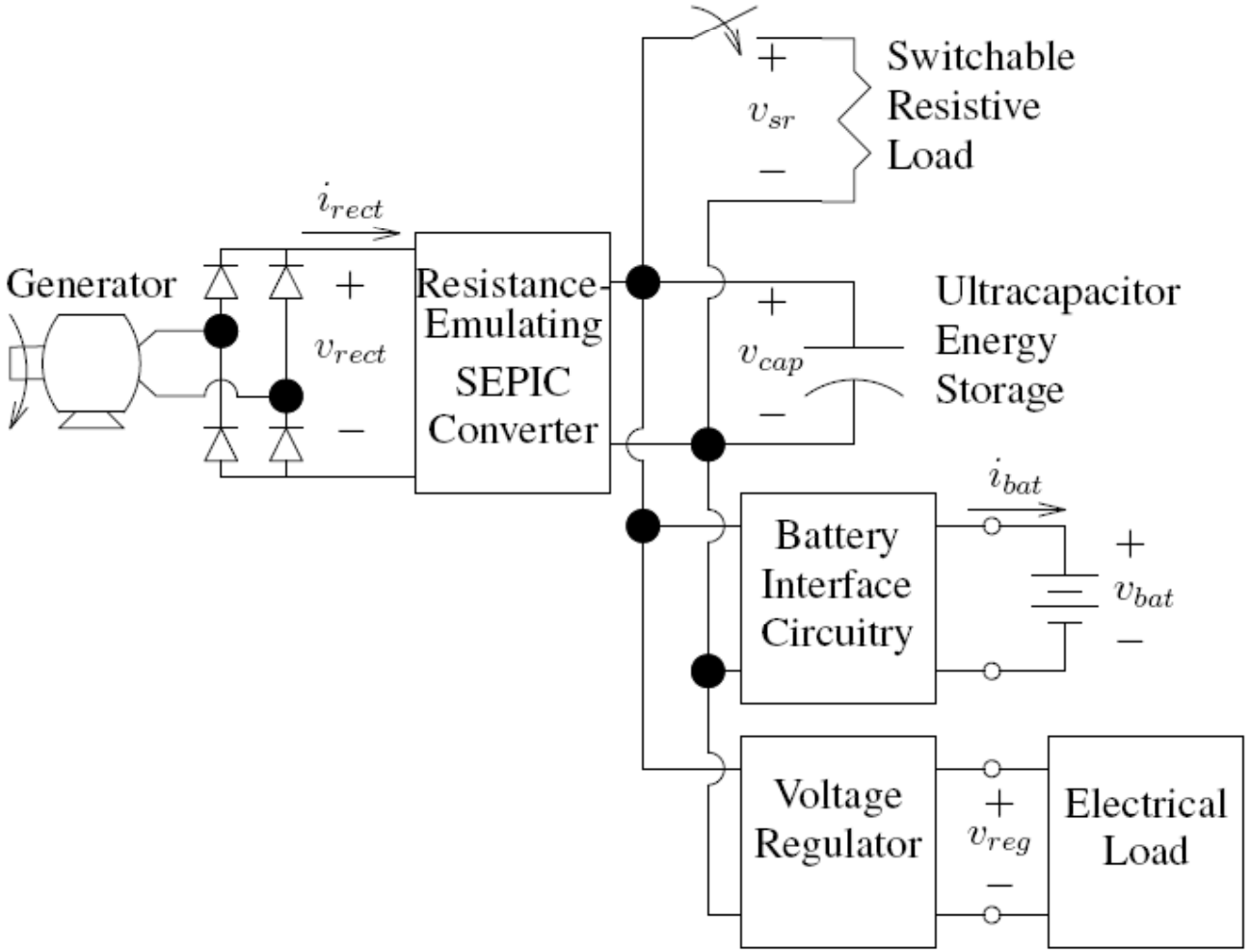


- Load of backpack attached to frame via springs
- Resulting spring-mass resonance frequency tuned to human walking gait
- Resulting large displacements of load used to generate electricity

Image Copyright 2005 AAAS

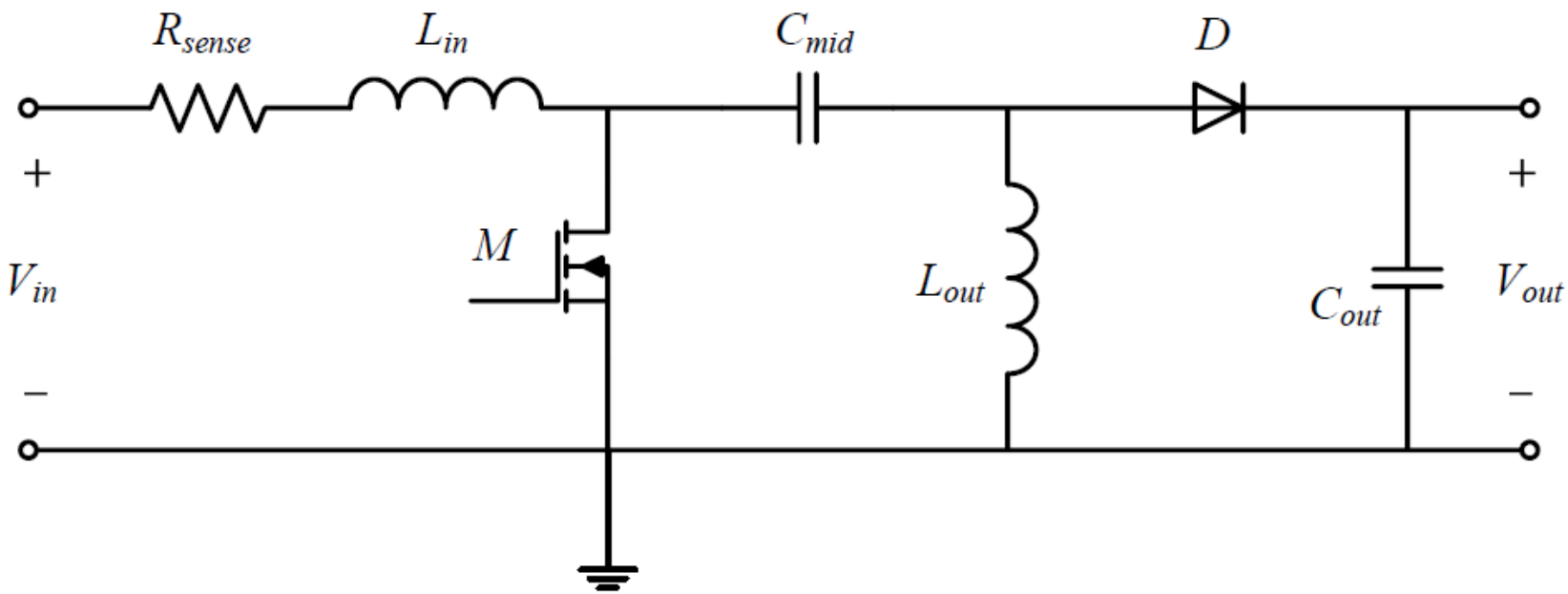
- Resonant motion of backpack also has ergonomic benefits

Energy Harvesting Backpack Circuit



Goal of circuit: to emulate generator load which maximizes efficiency of energy transfer to battery, load

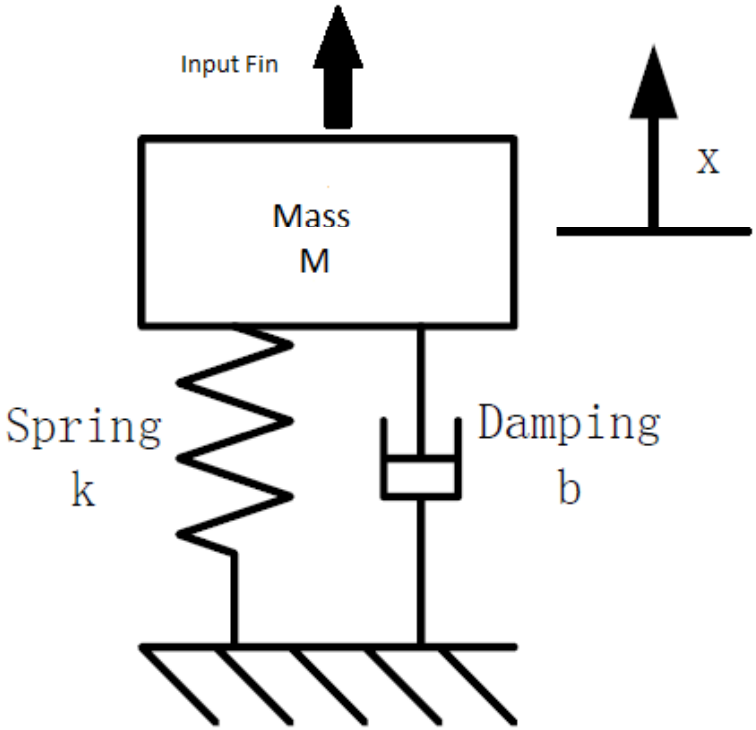
Resistance-Emulating SEPIC Converter



- Buck-boost converter topology
- Inductor at input allows regulation of input current
- Input current is regulated to be proportional to input voltage,
  - Converter emulates a resistance *R* at its input terminals

Effects of Resistive Load Emulation

- Resistive load at terminals of generator results in a linear damping of the mechanical dynamics.
- Equivalent mechanical damping constant *b* determined from resistance *R*, torque/speed constant c_{tw} of generator, and gearing constant g_{rp} of rack-and-pinion gear.



$$b = \frac{c_{tw}^2}{g_{rp}^2 R}$$

System Response

- Mechanical Dynamics:

$$m\ddot{x} + b\dot{x} + kx = f_{in}$$

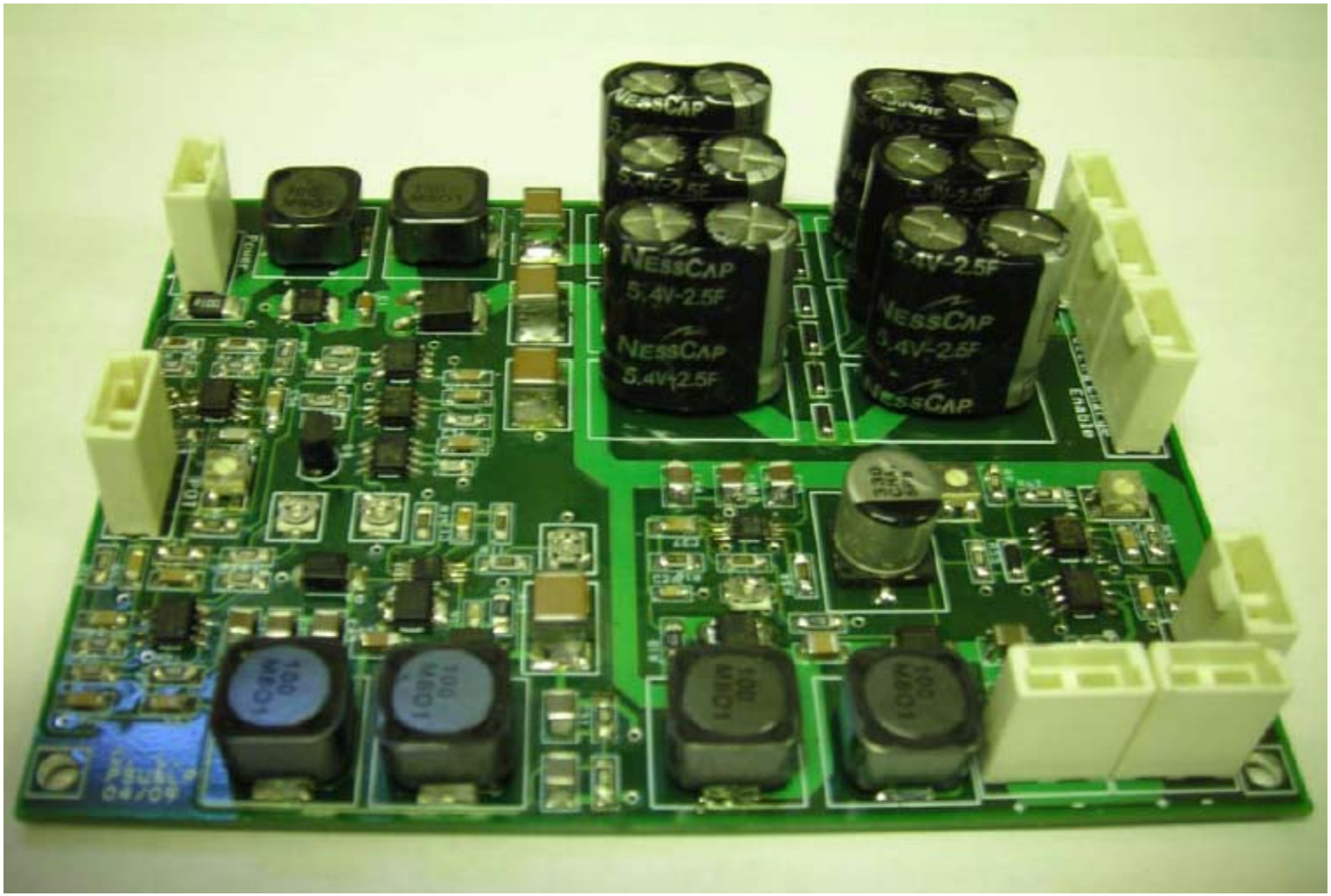
$$x(s) = \frac{f_{in}(s)}{ms^2 + \frac{c_{tw}^2}{g_{rp}^2 R}s + k}$$

- Power harvested at resonant frequency:

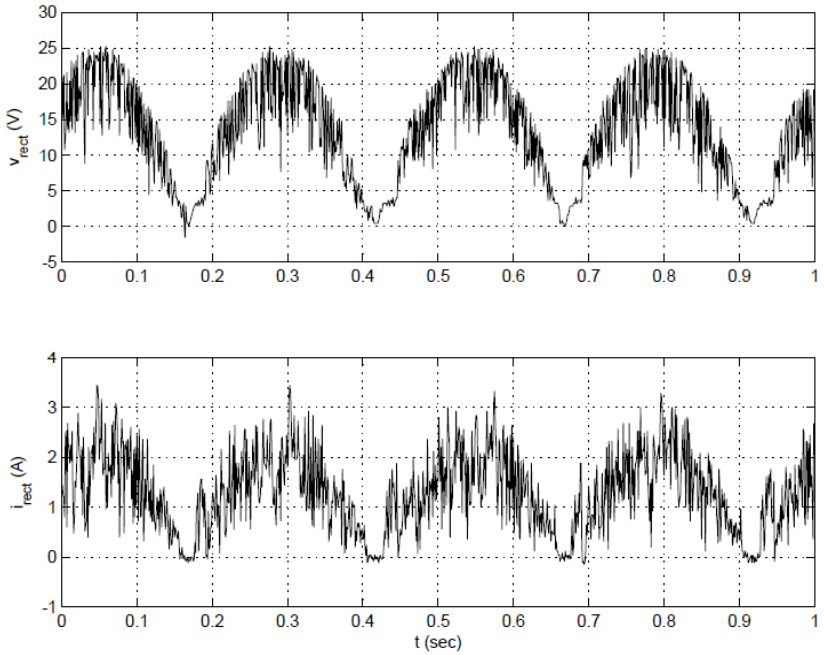
$$P = \frac{F_{in}^2}{2b} = \frac{g_{rp}^2 R}{2c_{tw}^2} F_{in}^2$$

- Resistance R is chosen to satisfy a combination of requirements:
  - Energy harvesting
    - Harvest sufficient power
  - Ergonomic
    - Constrain displacement of backpack to a level that is acceptable to wearer
  - Damping
    - Reduction of quality factor Q of mechanical resonant system makes power harvesting less sensitive to excitation frequency

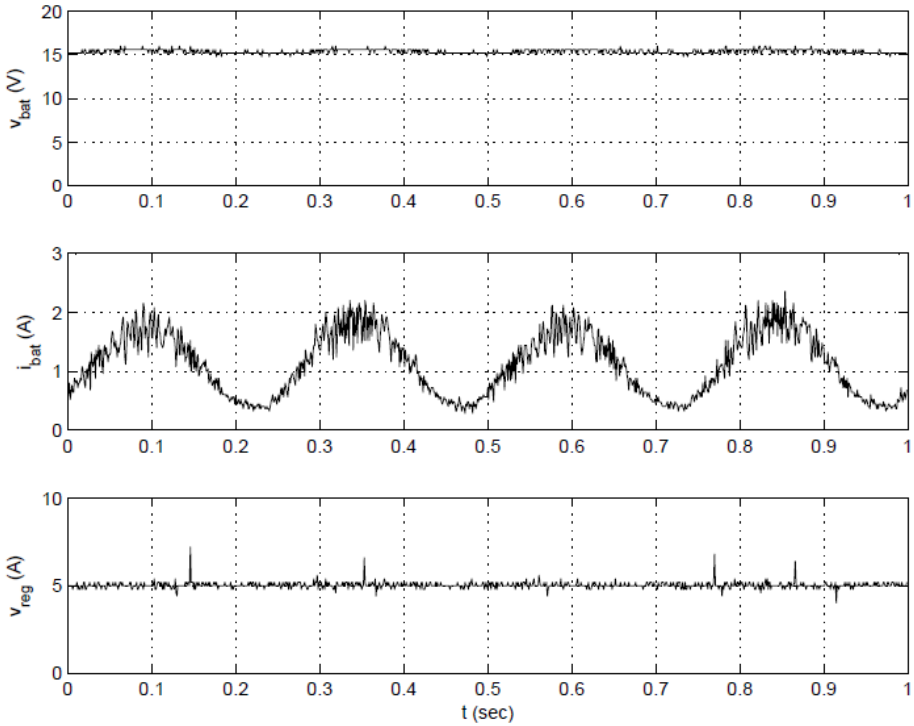
Energy Harvesting Backpack Circuit



Energy Harvesting Circuit Waveforms



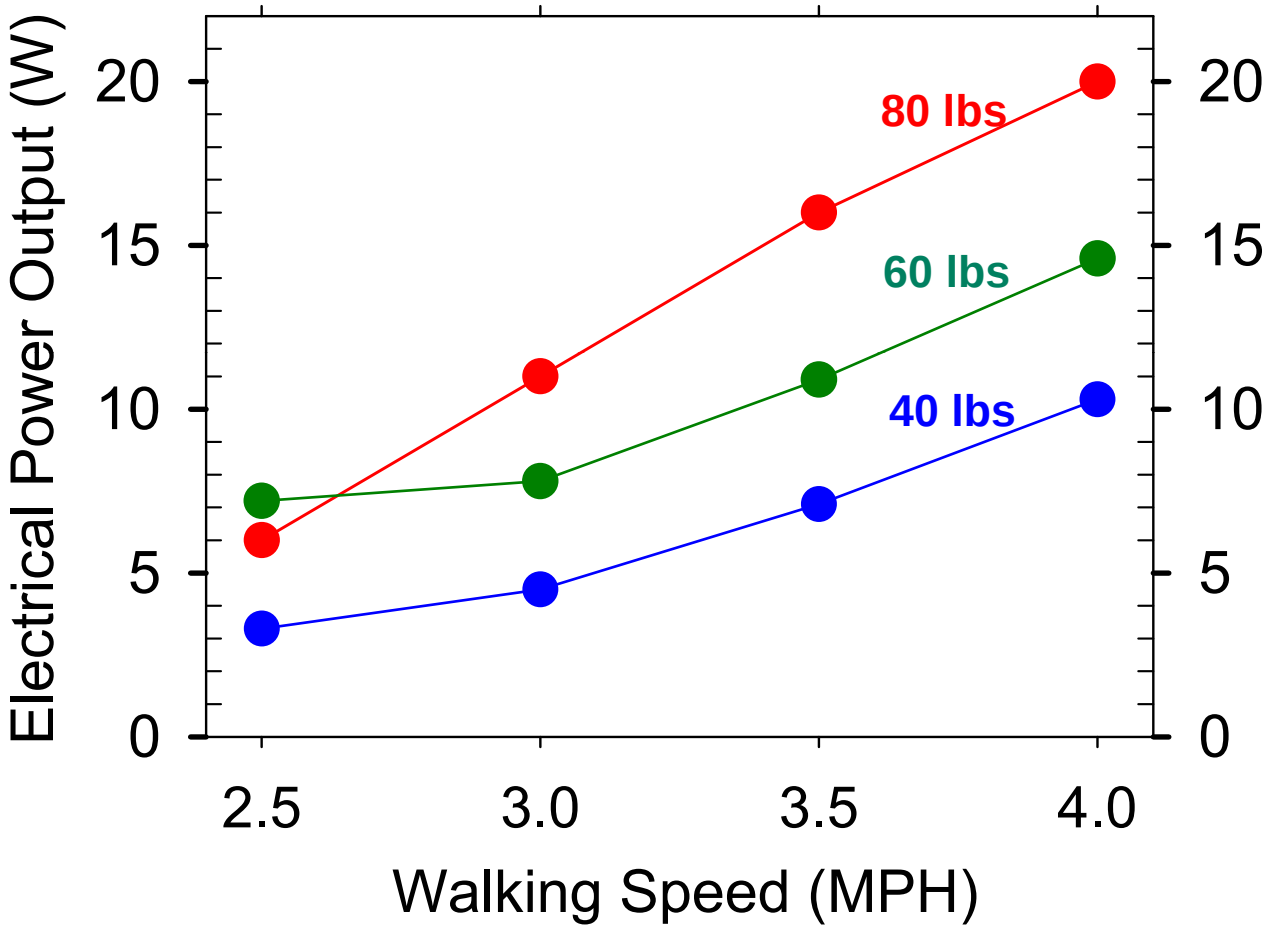
Input voltage and current waveforms



Output waveforms, top to bottom: battery voltage, battery current, regulation voltage (with 10Ω load)

G. Wang, C. Luo, L. Rome, and H. Hofmann. "Power Electronic Circuitry for Energy Harvesting Backpack ", ECCE 2009.

Electricity Generation During Walking



Questions?