Renewable Energy Sources for the Future of Mobile & Embedded Computing

A Whirlwind tour...

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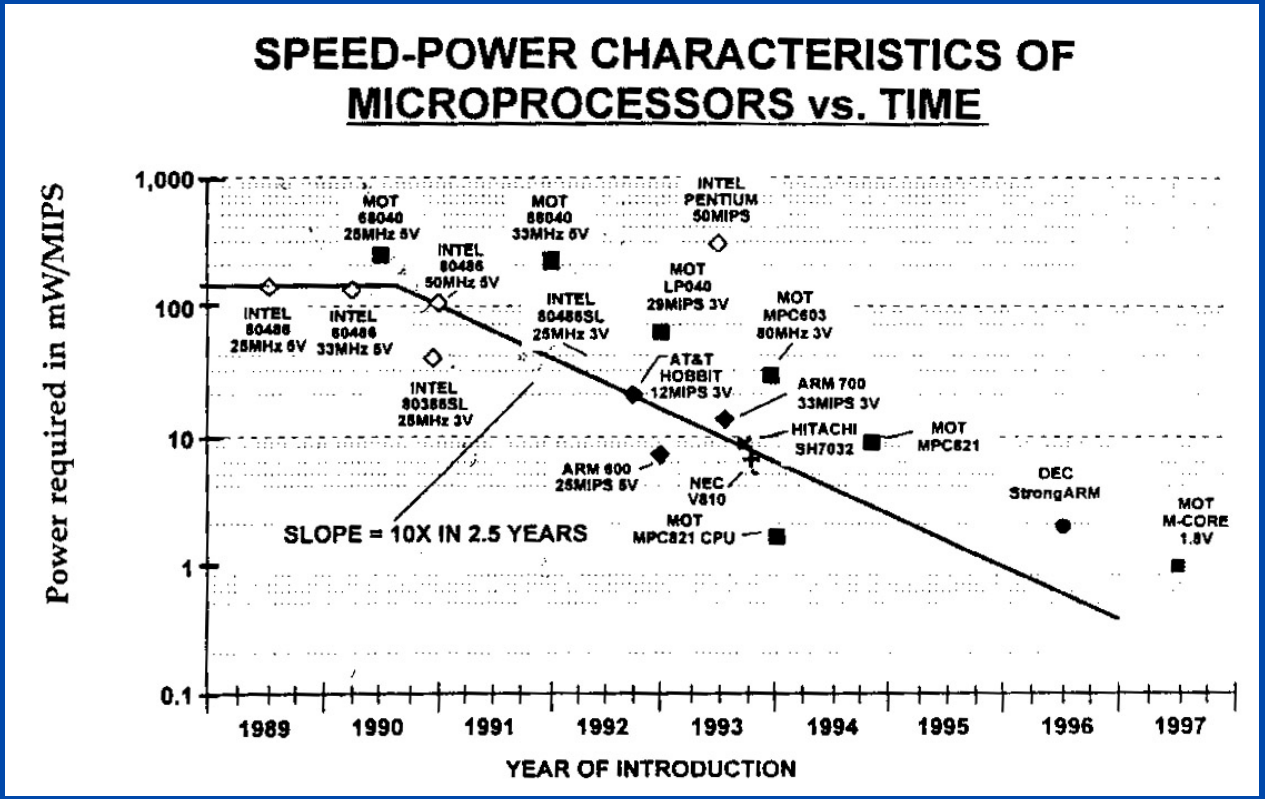
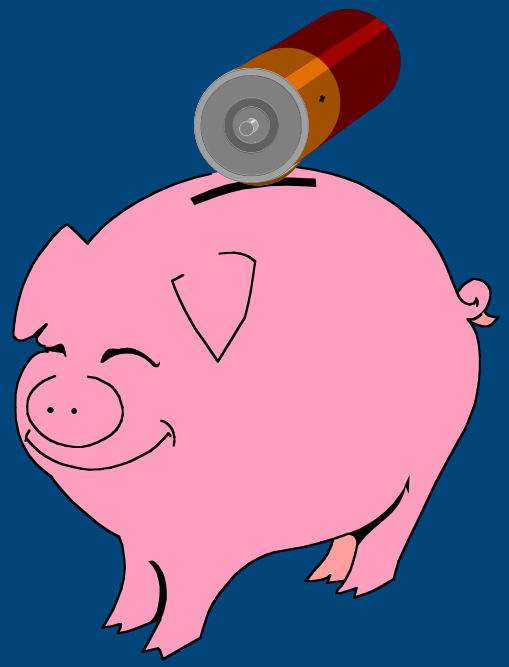
CC - March 2000

Power Management



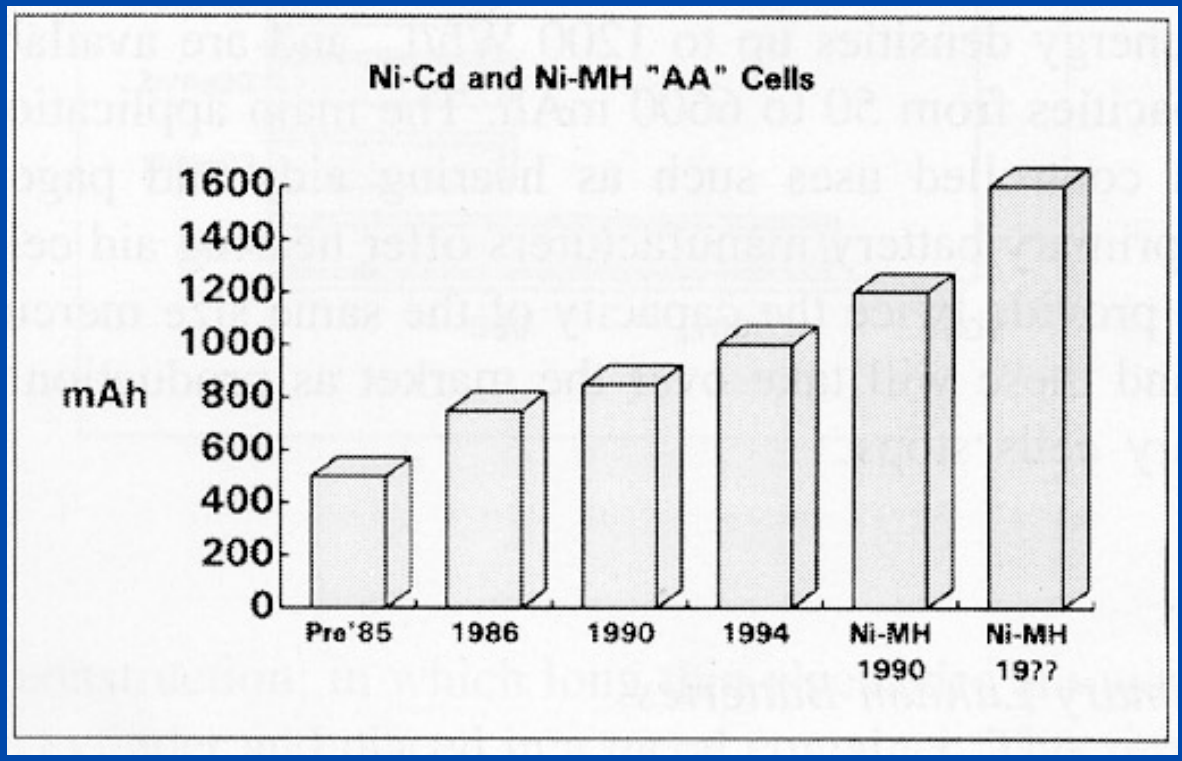
- Specific power decreasing
  - Clever on-chip power management schemes
  - New processes, smaller features, lower parasitics
  - Lower voltages (approach to adiabatic computing)

Slowly Growing Power Pigs



- Laptop power edges slowly upward
  - MIP-hungry applications, etc.
- Internet wireless PDA's a problem?
  - As bandwidth increases towards 100's of kb/sec
    - RF power amplifiers modified to be more linear
    - Pulse-power loads reduce battery life faster
      - Shorter range (e.g. Bluetooth) helps?
      - Otherwise, batteries take it on the chin
- Just more and more wireless devices (and batteries)!!

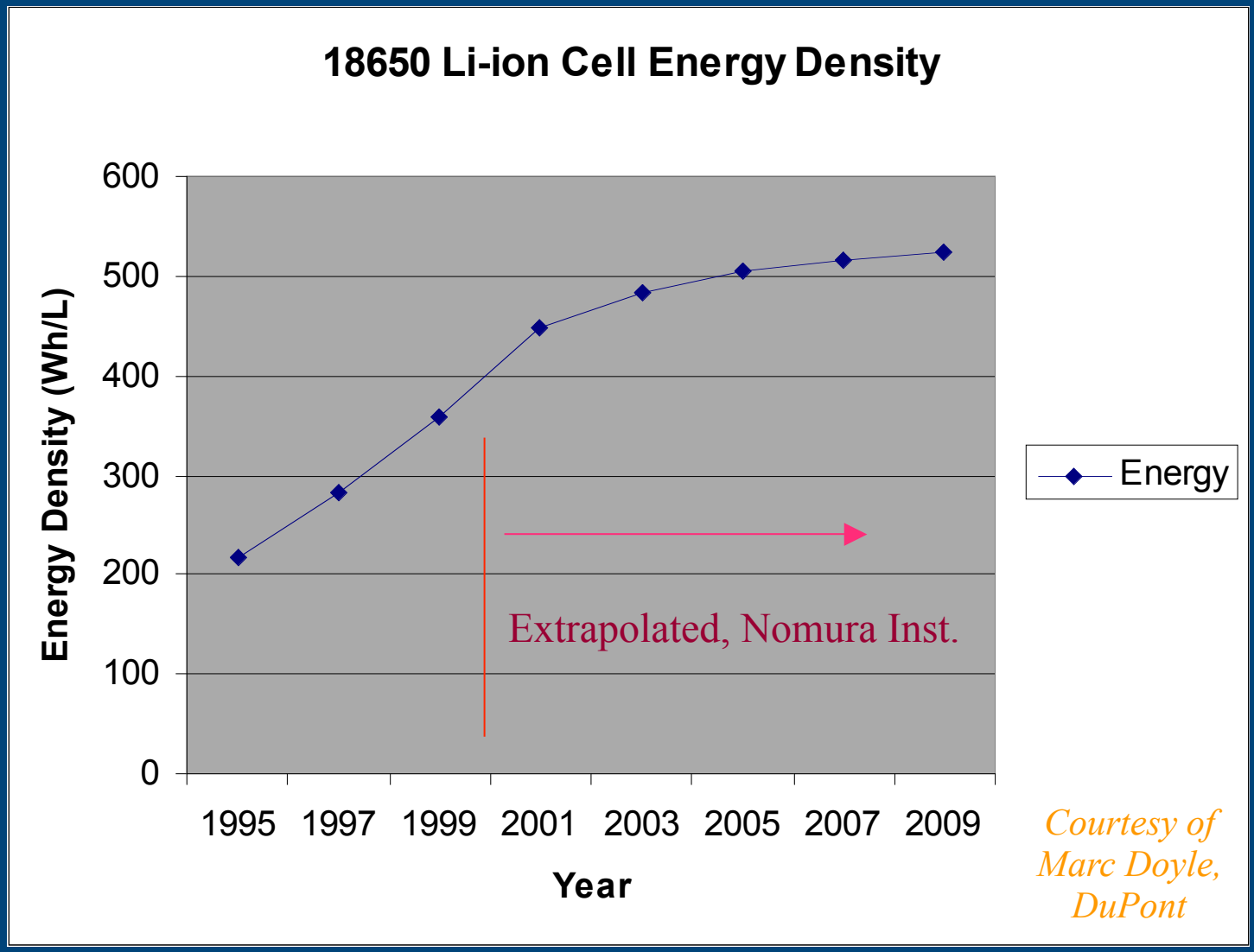
Evolution of Batteries



IEEE Proceedings, 1995

- Slow improvement
  - Certainly not on Moore's Law!

Development of Li-ion battery cells



Highest energy density of today's rechargables

Rechargeable Battery Capabilities Naturally Plateau as Systems Develop - *No Moore's Law Doubling on a Regular Basis*

Need higher energy density

DOD Study

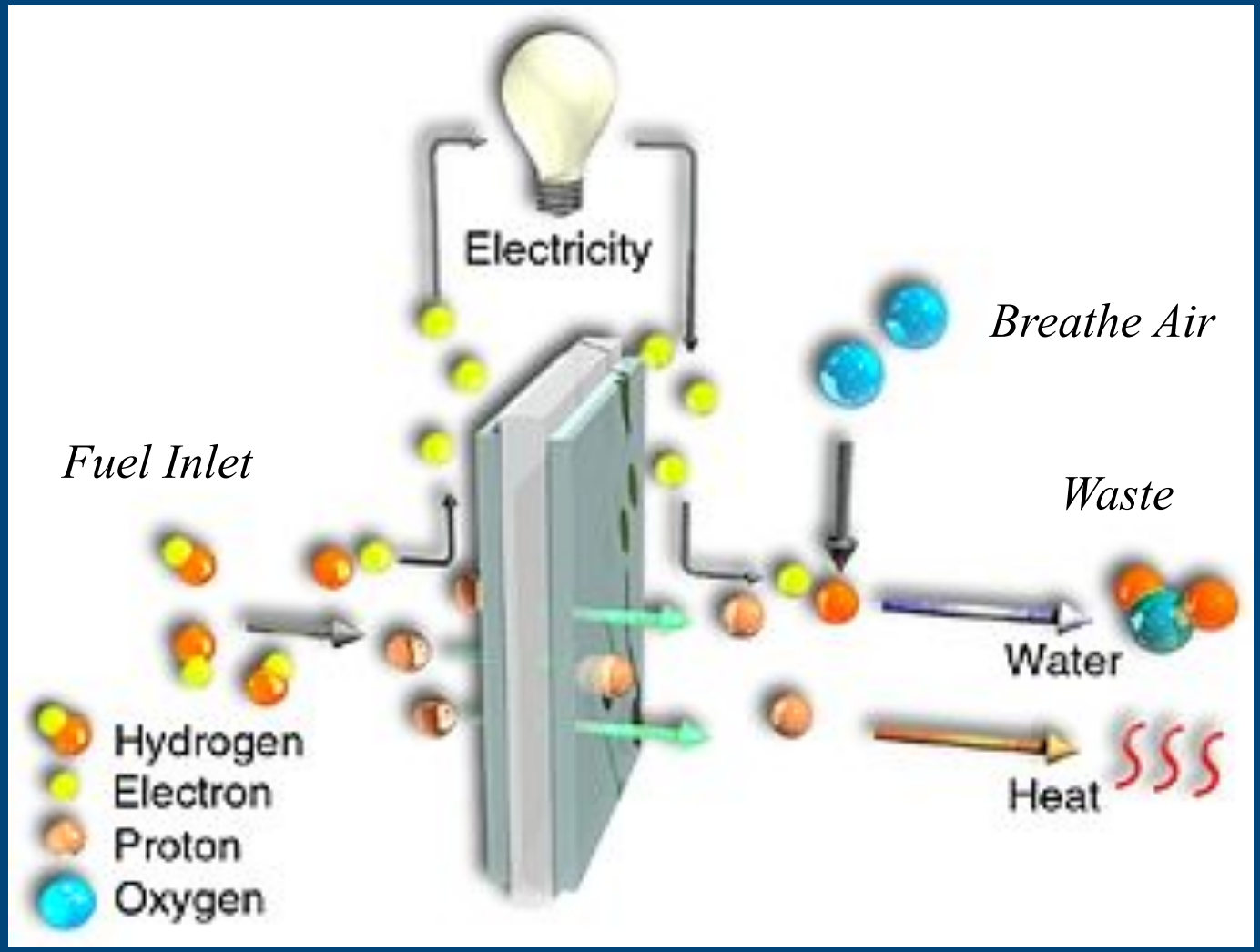
Energy Density of Selected Fuels and Batteries

Fuel:	Energy Density
Diesel Fuel/Jet Fuel	12,000 Wh/kg
Methanol	5,000
High Explosive	1,000

Battery:	
Primary Battery (est. max.)	500
Rechargeable (est. max.)	200
Li/SO_2 Battery (primary)	176
Alkaline Battery (primary)	80
Nickel-Cadmium (secondary)	40

Consume a substance with higher specific energy

Fuel Cells - Renewable energy source



www.plugpower.com

- Membrane splits electrons off hydrogen
  - Electrons recombine with proton on other side in catalyzed reaction w. oxygen to form water
    - …After they are routed through external circuit

Fuel Cells...

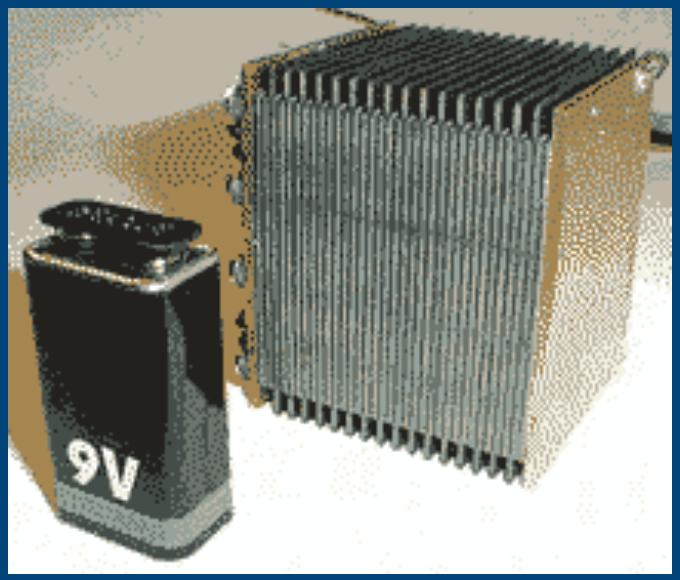
Chicago Transit Authority

- Date from 1839 (William Grove)
- Used heavily by NASA (1960's) for manned spacecraft power
- Polymer Electrolyte Membranes (PEM) enabling practical devices
  - DuPont *Nafion*
- Research programs power terrestrial vehicles, buildings, etc.
- Hydrogen fuel cells produce only water and heat
  - Not "zero-emission" depending on how H_2 is made...
  - Reformers can burn many other fuels
    - Strip off hydrogen (messy, inefficiency?)
  - Direct Methanol fuel cells here now

Fuel Cells...

www.hpower.com

The fuel cell shown here is rated at 50 watts, which is 50 times more powerful than the typical 9 Volt battery

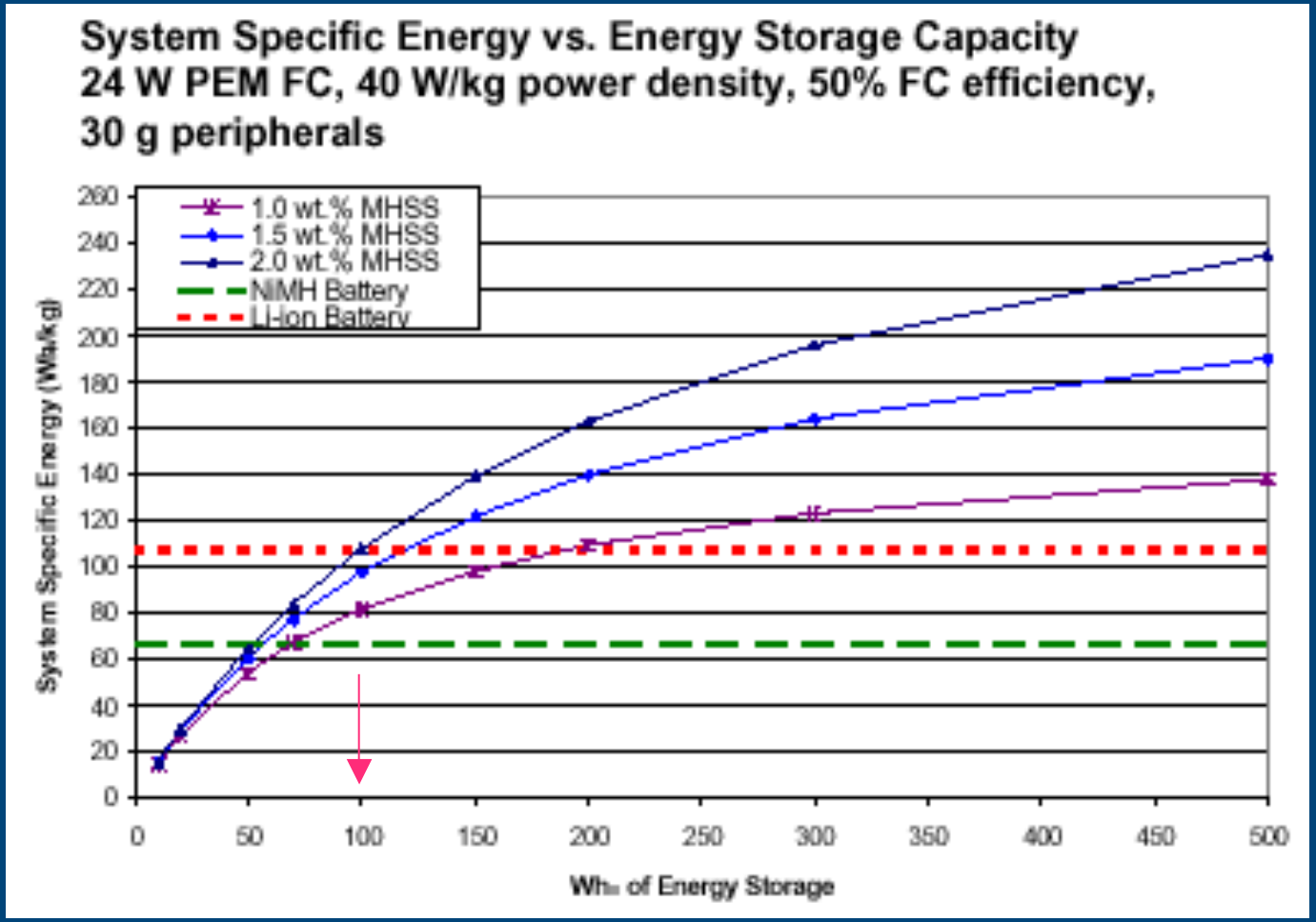


35 W
12 V
3.5 kg
Metal Hydride Storage

- **Want to run at elevated temperatures**
  - **e.g., around 80 deg C**
- **Even at these temperatures, need Pt-coated electrodes**
  - **Expensive**
    - **New porous carbon structures minimize platinum**
- **Significantly more complicated than batteries**
  - **Pumps, fuel storage containers, fans, temperature control, sensors, endplates, etc.**
    - **Most engineering here (fuel storage/handling)**
  - **Sensitive to tilt, etc. (flow issues)**

Fuel Cell Scaling

www.ovonic.com



- Because of added hardware mass, current fuel-cells inferior to best rechargable battery until after 100 Watt-hr energy source (Metal Hydride storage)
  - Considerably bigger than a laptop batery!

Fuel Cell Issues

- **Energy Storage:**

Methanol	Metal Hydrides	Liquified H2	Compressed H2	Li-Ion Rechargable
4500 Watt-hr/L	2000-5000 Watt-hr/L	2400 Watt-hrL	600 Watt-hr/L	400 Watt-hr/L

- **Direct methanol attractive for several reasons**
  - **Fairly easy to produce and transport**
    - **BioProduction possible at zero emission**
  - **Clean waste products (H_2O, CO_2)**
  - **Potentially safer to store**
    - **Corrosive, poisonous**
  - **Now prime candidate for future mobile platforms**
    - **Interest in US for using gasoline w. reformer**
- **Polymer membrane inefficient!**
  - **Methanol ions can leak across**
    - **Dilute Methanol fuel used now**
    - **Energy storage drops to 160 Watts/L!**
      - **Ongoing work!**

Fuel Cells for Mobile Platforms

A laptop computer using a fuel cell power source can operate for up to 20 hours on a single charge of fuel. (Courtesy: Ballard Power Systems)

Photo showing conceptual Motorola/LANL fuel-cell-phone

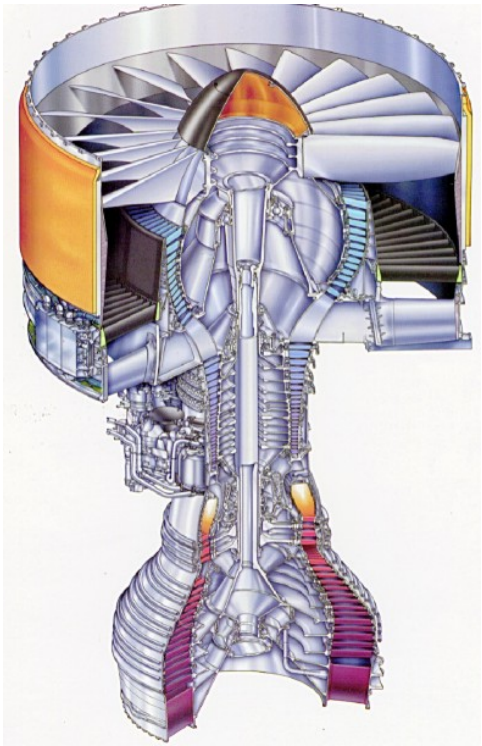
Motorola Mobile Charger:

2” x 4” x 0.5” (10/01)
Belt holder
1 month of calls per charge
2-4 years
200 million units by 2010
Other players:
NEC,
Mechanical Technology,
Manhattan Scientifics
Fraunhofer Institute

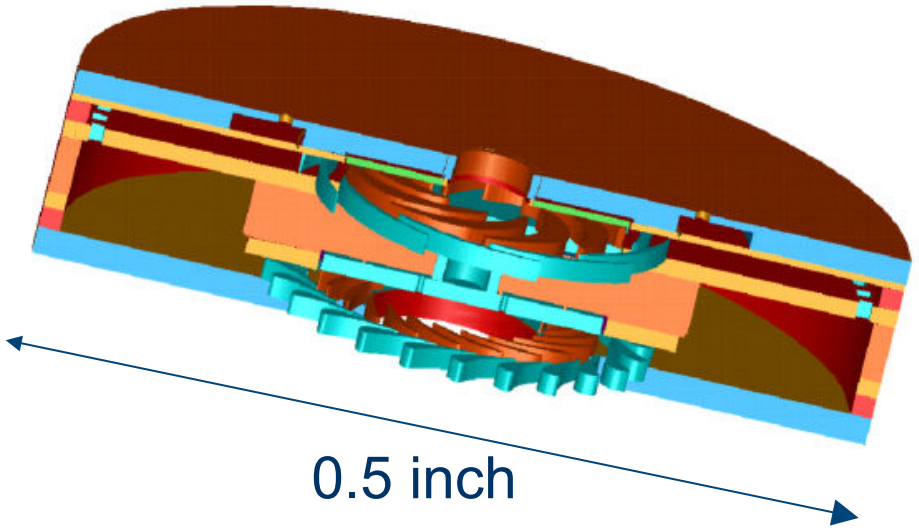
- **Superior to batteries at 100 Watt-hr (Metal hydride)**
  - **Fuel cell technology improves at approx. 10 watt-hr/yr**
    - **Parity with laptop batteries in 5 Years**
    - **Cell phones (2-5 Watt-hr) soon to follow (another 4-5 years)**
      - **Motorola/LANL collaboration**
        - **Direct Methanol**
        - **Battery-FC hybrid (FC at 1 Watt charges battery)**
        - **Same form factor**
        - **Power phones for over a month?**
    - **Replacable cartridge to feed fuel, collect water…**

MIT Micro Gas Turbine Generator

112 inch



Microturbine with electric-field induction generator

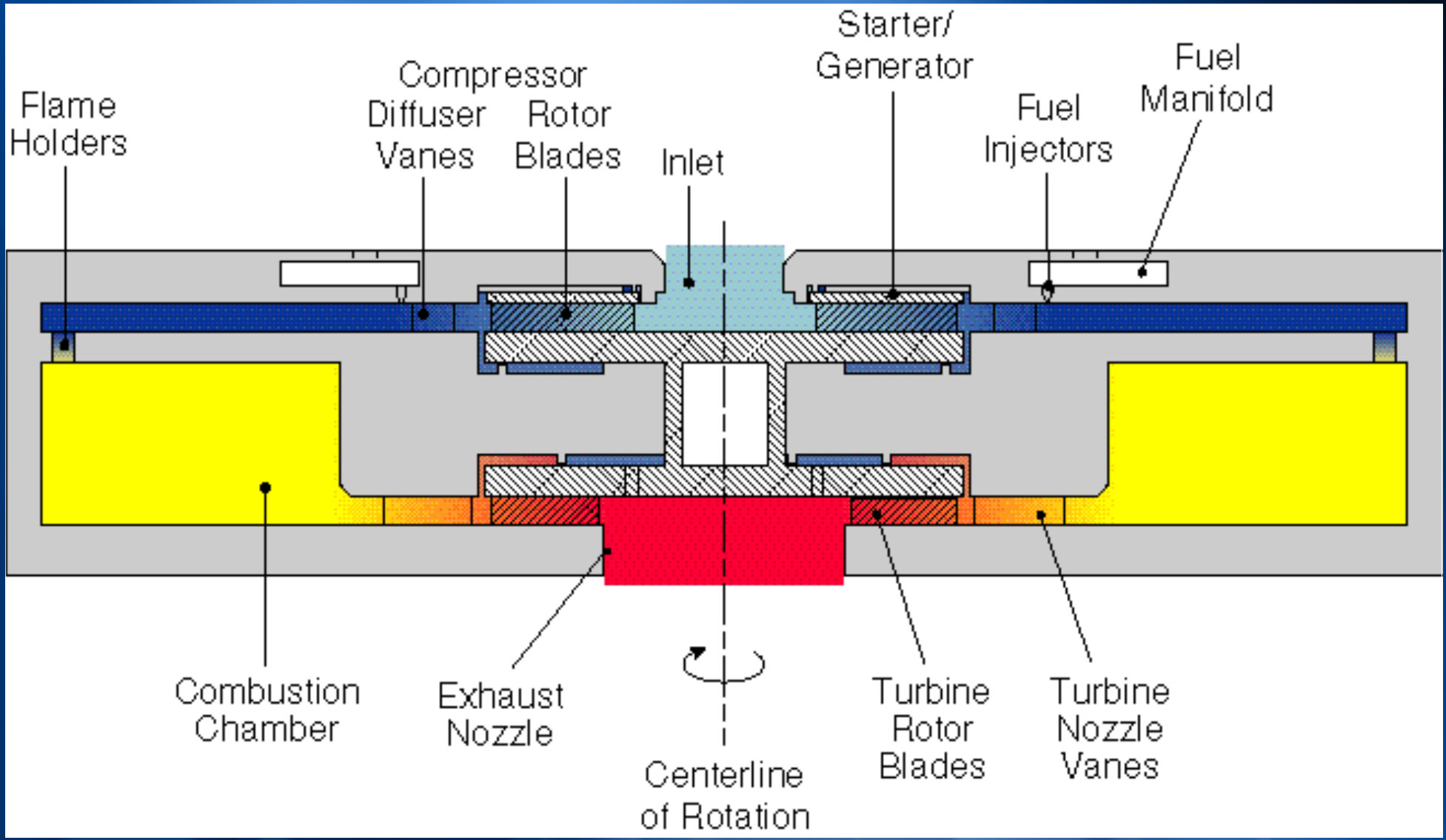


	Micro Turbo Generator	LiSO2 Battery (BA5590)
Power Output	50 W	50 W
Weight	50 grams	1000 grams
Specific Energy	3500 W-hr/kg	175 W-hr/kg

- A portable power source with ten-fifty times the power density of state-of-art batteries
- …In the size of a shirt button...

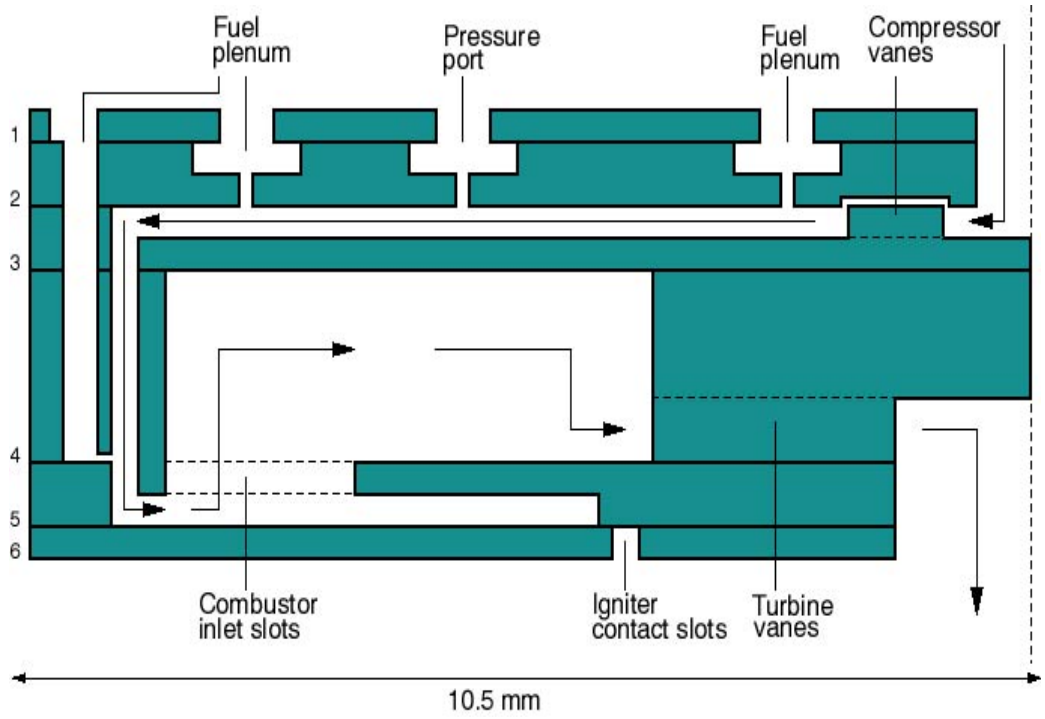
Marty Schmidt and collaborators, MIT Microsystems Technology Laboratory (MTL)

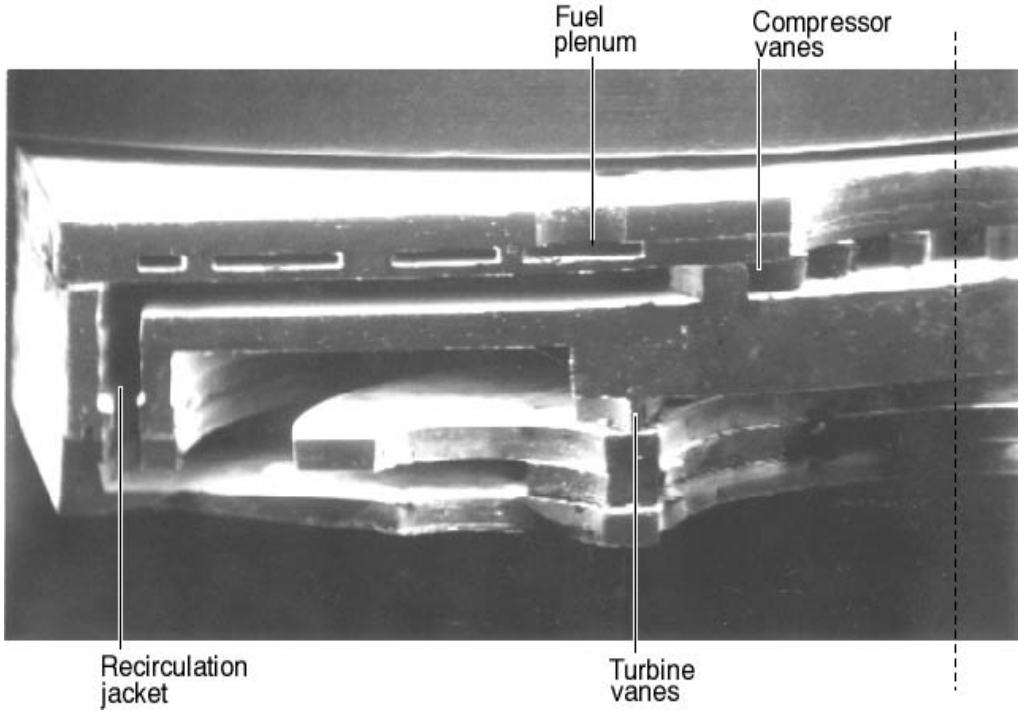
MIT Microengine



Six-Wafer Microcombustor

A. Mehra and I. Waitz

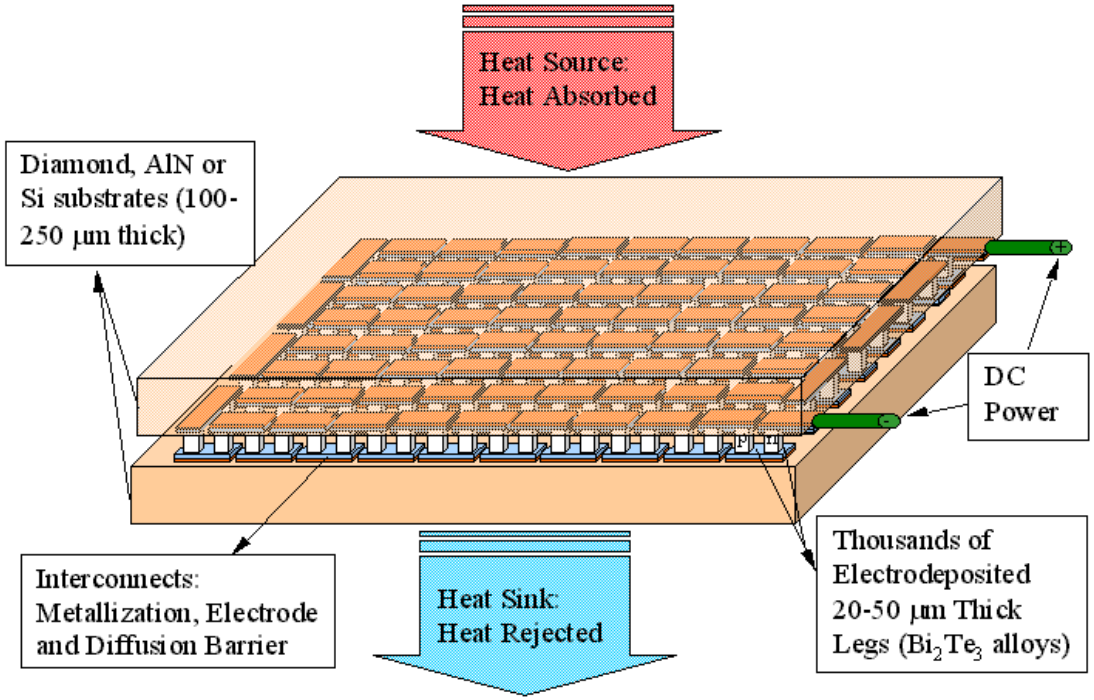




15 masks, 12 deep etches through 3.8mm, 5 aligned wafer bonds

- **2.4 MRPM (1.2 now; geometry/precision)**
  - **Rotor breaks the sound barrier**
  - **Rotor supported on laminar air bearings**
- **Silicon carbide parts where higher temperature**
- **Combustion in Silicon (this year?)**
- **And, of course, making generator work!**

Thermoelectric Energy Conversion



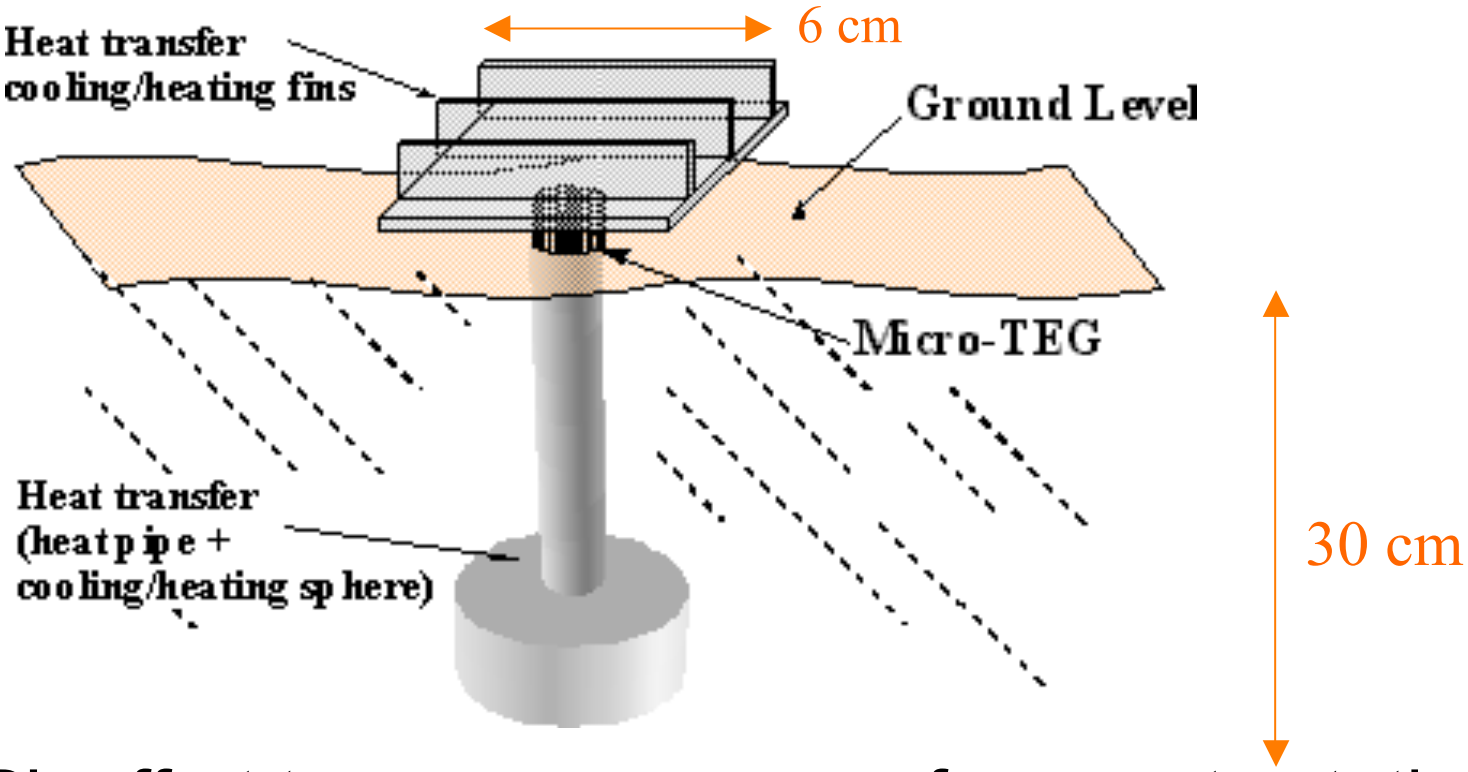
- Miniature thermoelectric generators
- Directly convert heat to electricity with array of vertically-integrated thick-film thermocouples on thin, high thermal conductivity substrates
- DARPA effort to generate 5 Watts from a catalytic combustor

Jean-Pierre Fleurial, NASA/JPL

Energy from the Environment...

- Vibration/acoustic/turbulence
  - MEMs devices
  - Piezoelectric pickups
    - Places where loud noise and strong vibration present
      - Ships, machinery, underwater
- Thermal
  - Need large surface area, big ΔT
- Ambient electromagnetic
  - AM radio
    - Need big dipole…
- Ambient chemical
  - Seabed, in-vivo

Environmental Heat Harvesting

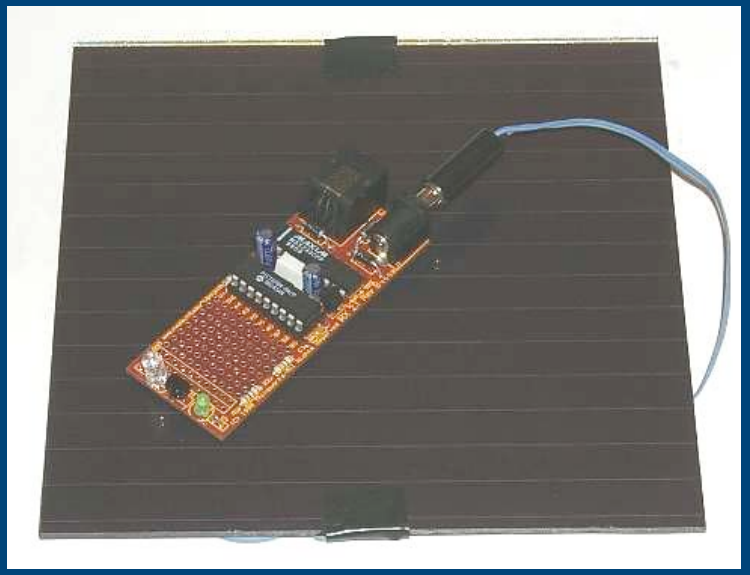


- DARPA-JPL effort to scavenge power for remote stations
- Unit will sit atop the ground
  - 8.5 deg C temperature difference between top and bottom
    - 0.5% efficiency
  - 22 mW average produced at 4.1 Volts
  - 100 mW at 10% duty cycle (best conditions)
- See also SII's (Seiko Instruments) thermally-powered watch

Jean-Pierre Fleurial, NASA/JPL

Solar Photovoltaic

Solar roofs in Japan



Media Lab's Locust Position Beacon

Franhofer ISE Freiberg
1 Watt under halogen
20% eff.

- **Limited Efficiencies**

  Amorphous Silicon 13% **Crystalline Silicon 22%** **III-V devices, concentrators, etc. 30%**

- **DOE goal to get amorphous Si cells to 15% (circa 2005)**
  - **0.0021 W/cm^2 at moderate latitudes**
- **Multiple junction devices, GaAs, concentrators get 30-34%**
  - **Still in Lab**
- **In most places, not readily suitable for mobile devices**
  - **Need the sunlight, Need the area…**
  - **Possible for some low-power embedded sensor packs**

Direct Energy Conversion : IR/Optical Rectannas

OBJECTIVE:

• **Development of a power generation device which directly converts available electromagnetic radiation into electric power at >40% efficiency**

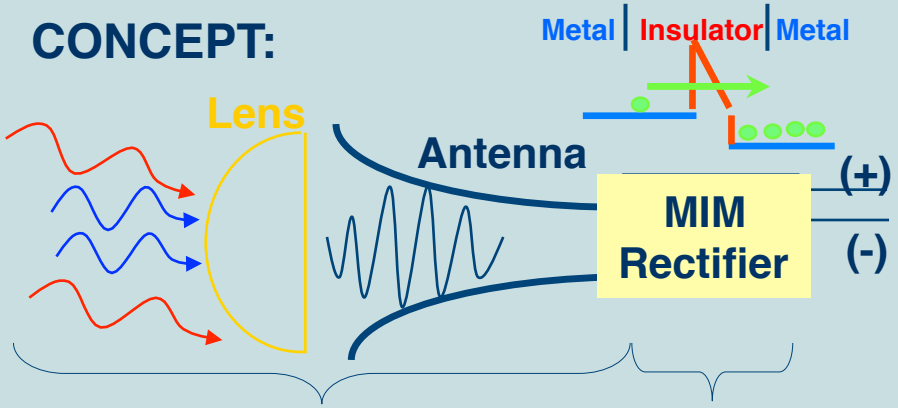
RECENT ACCOMPLISHMENTS:

• 2-D Grid antenna array that will receive and rectify (AC-to-DC) a dual polarized wave consisting of many non-directional waves, at >75% efficiency for low frequencies; 10 and 30 GHz

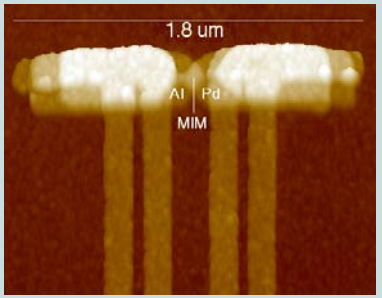
• First time ever demonstration of room temperature optical rectification with a non-linear, unbiased planar Nb/NbOx/Ag quantum tunneling diode at 60 THz (10 μm); >73% quantum efficiency (10% power efficiency).

• Fabrication of resonant diode structures with low-cost, parallel processing techniques; dipole a) and MIM diode b) shown at right.

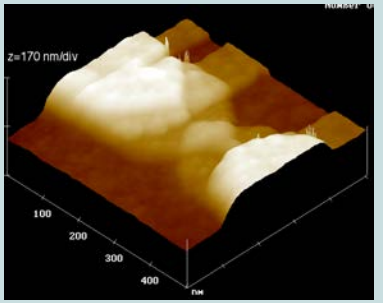
CONCEPT:



Solar Concentration/Focusing **AC → DC Rectification**



a)



b)

• **Use of grid antenna array for energy concentration/transport in combination with a MIM tunneling diode for energy extraction**

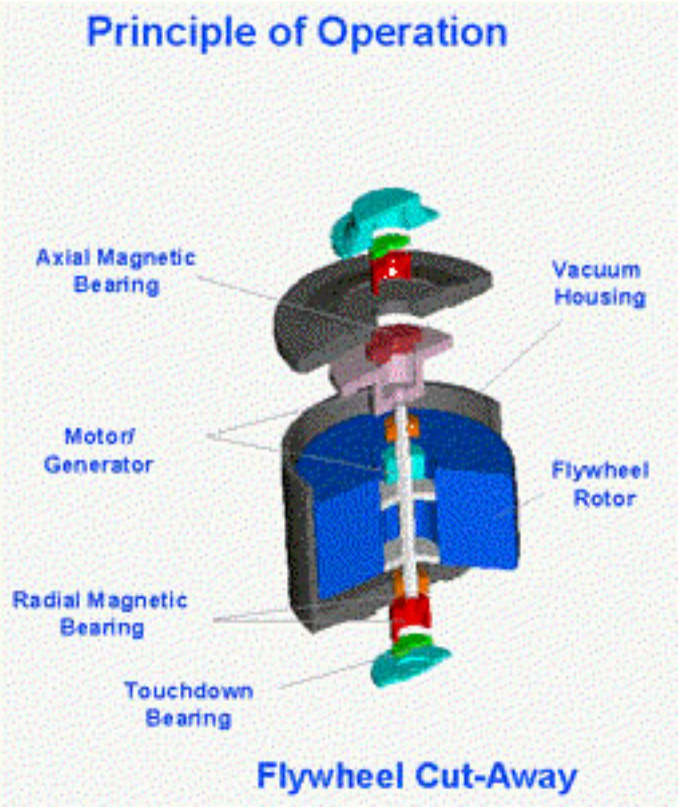
Bruce Lanning (ITN), Eric Grossmann (NIST)

Flywheels…

20C1000 Series Cable/Telcom System

Beacon Power Systems (SatCon subsidiary)

Power:	1 kW
Duration:	2Hr
Usable Energy:	2kWhr
Output Voltage:	36V or 48V(dc)
Recharge Time:	5Hrs
Weight:	260 lbs



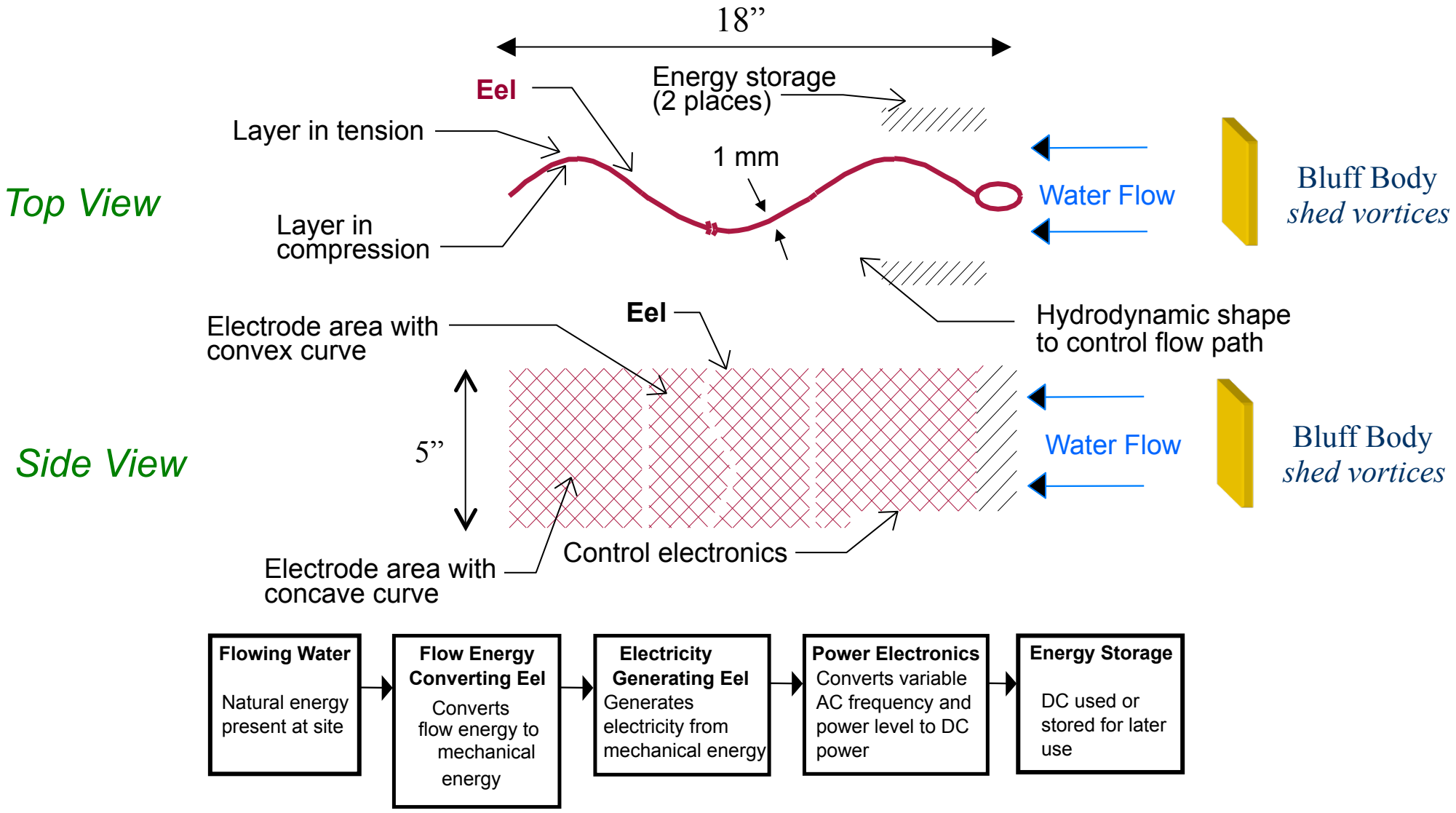
http://www.satcon.com/sub/beacon/index.html

- **Store kinetic energy in massive (and/or fast) rotor**
  - **Old idea (e.g., Austrian busses)**
  - **New composites make faster rotor possible**
    - **Less massive, not lethal during failures**
    - **Magnetic, frictionless bearings**
  - **Devices now for vehicle, residential, backup use**
    - **Scaling difficult for portable, battery-equivalents**
      - **Losses, intrinsic equipment give high zero-power mass**
        - **Sensors, vacuum, bearings, active control...**

OPT Eel - Program Approach

- The Eel utilizes a regular pattern of bending and unbending of a piezoelectric or electrostrictive material caused by moving water and converts it to electrical power.
- By inserting a vortex generator upstream of the Eel-like device a vortex street is generated.
- The forces generated by the traveling vortices on either side of the Eel produce a forcing field on the body. Current simulations are underway to reveal the optimum cross sectional Eel geometry based off of these forcing fields.
- The Eel currently is made up of piezoelectric PVDF, electrostrictive PVDF:TrFE copolymer is being concurrently bench tested. The copolymer will be fully integrated into the system during the next year.

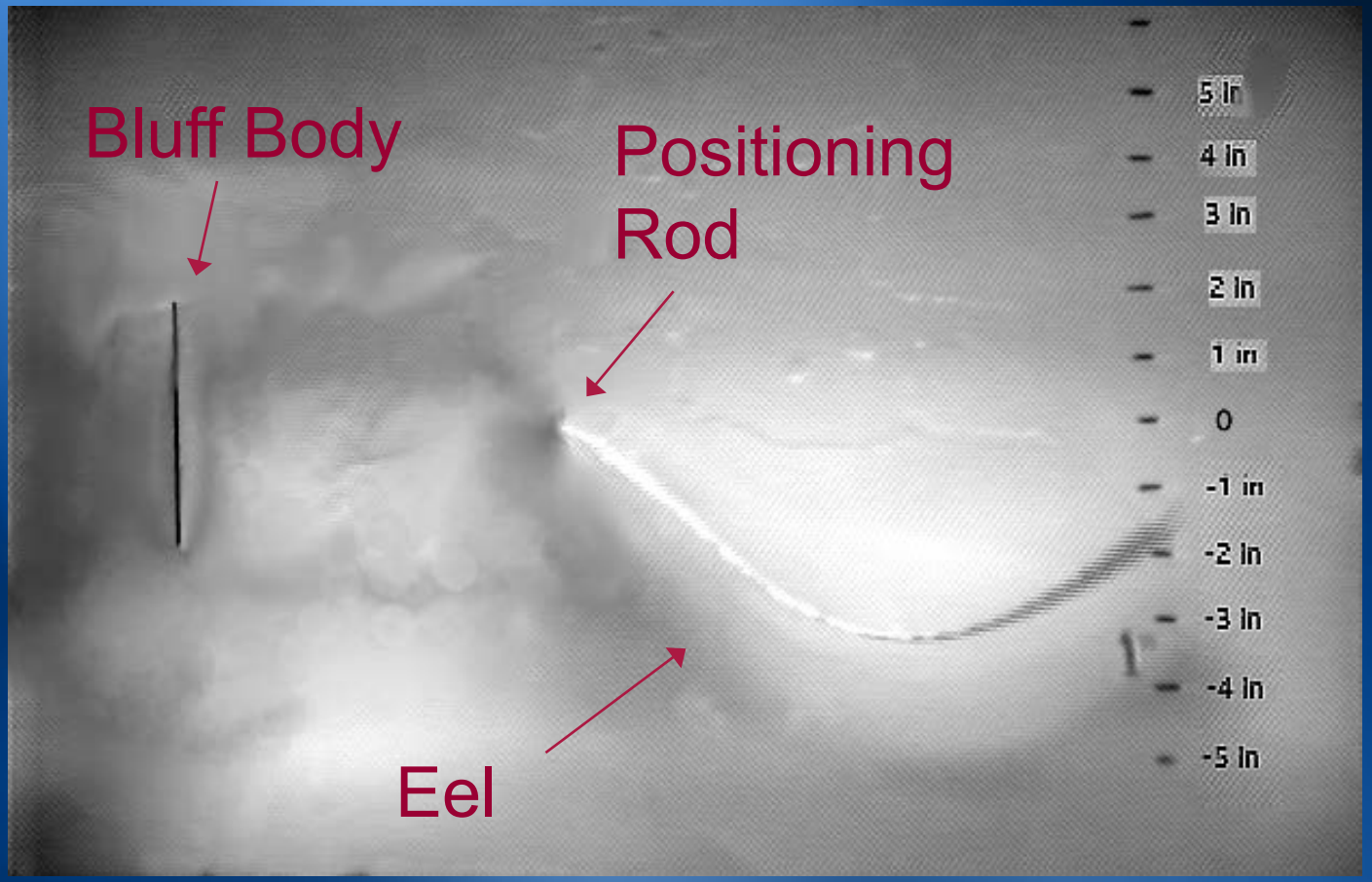
Illustration of the OPT Power Eel Concept



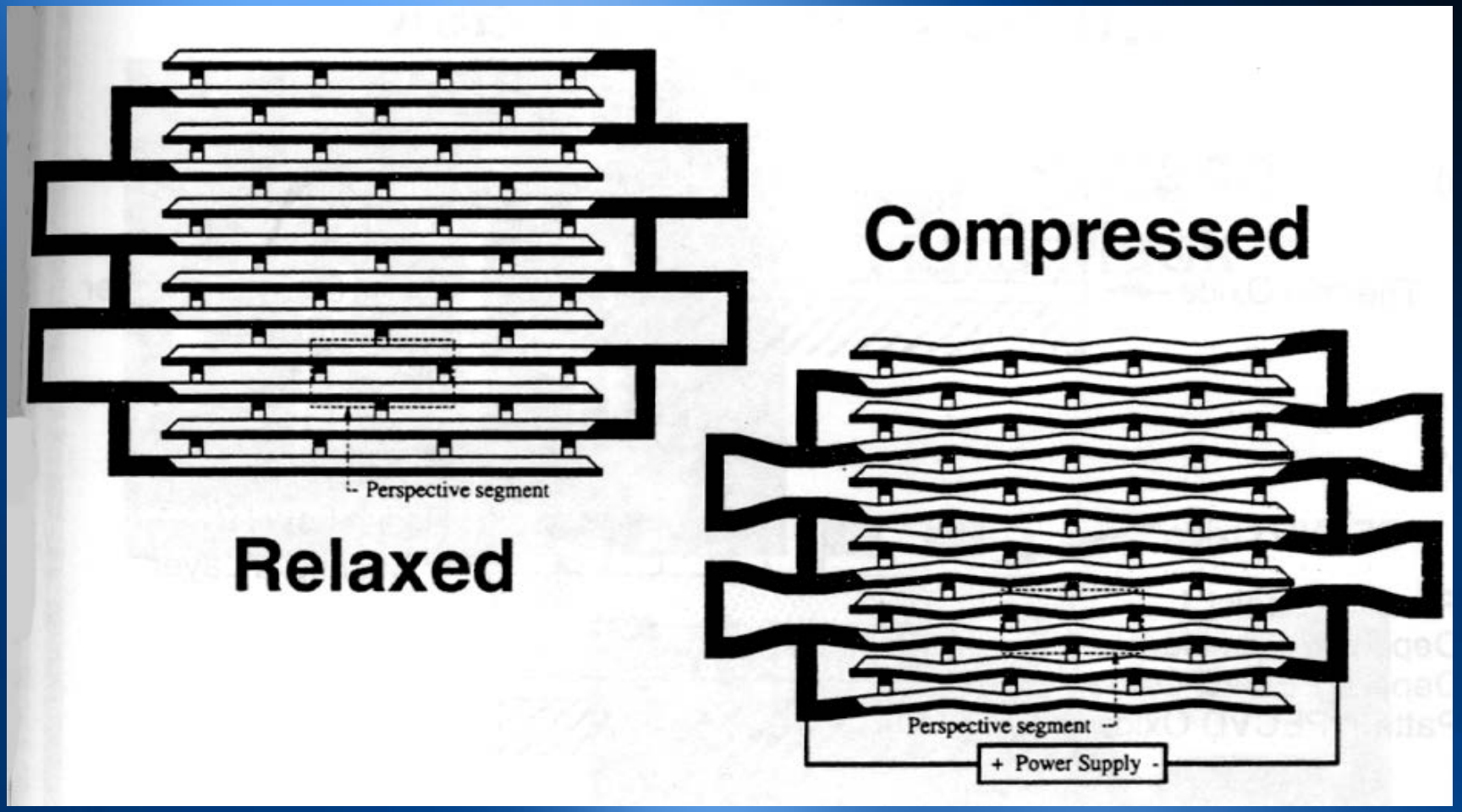
- **Eel now PVDF - Will become piezo copolymer or electrostrictor**
- **Anticipate 0.5 Watts from 18” eel in 1 m/sec flow**
- **Demonstration in 12-15 months**

Ocean Power Technologies, New Jersey, oceanpwr@aol.com

Eel Body in flow tank at .5 m/s

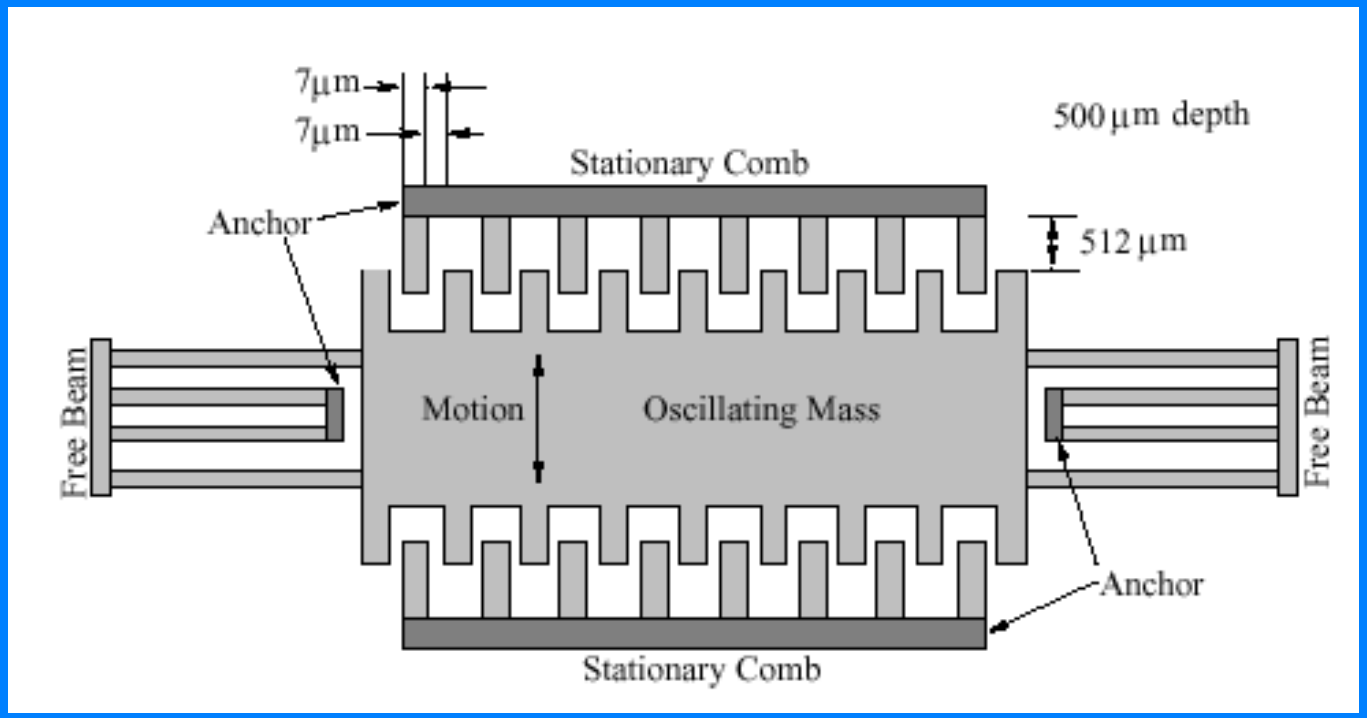


Microstructures for Vibrational Energy Recovery



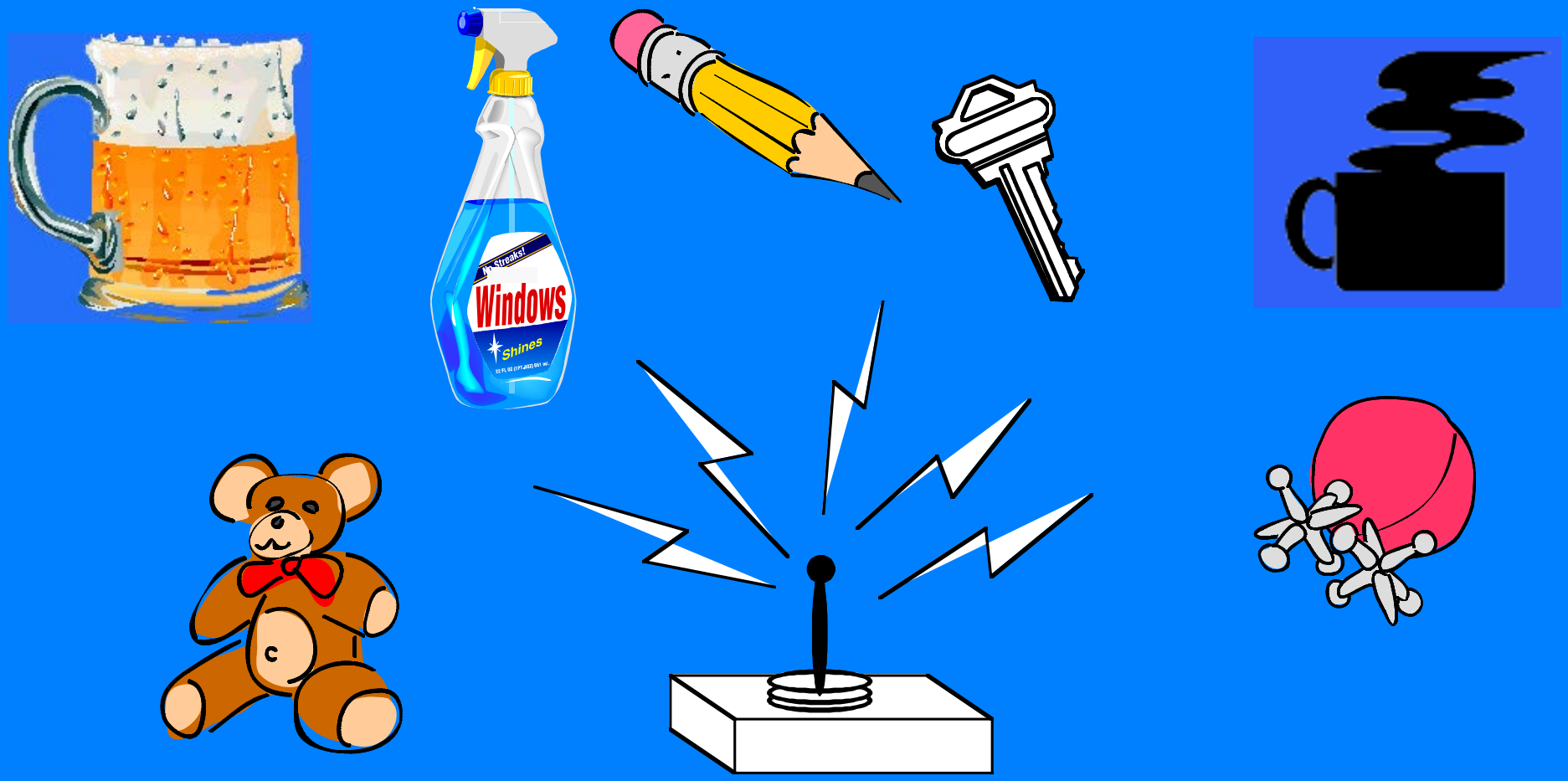
- MEMs Electrostatic Force Arrays
  - Work like condensor microphone
  - Voltage across plates creates current as they deflect
  - Need battery or other bootstrap

MEMs Driven Condensor Power Supply



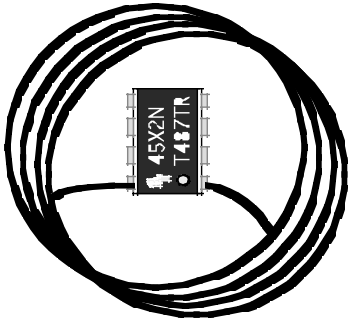
- MEMs motor in reverse…
  - Special power-control electronics designed & fabbed
  - MEMs now under fab
  - Expect 8 uW
  - Could tile for more power
  - Will provide power for their sub μW "picoJoule DSP"
    - Embedded low-power sensing applications
      - Vibrating bulkheads (ships), mechanics, etc.

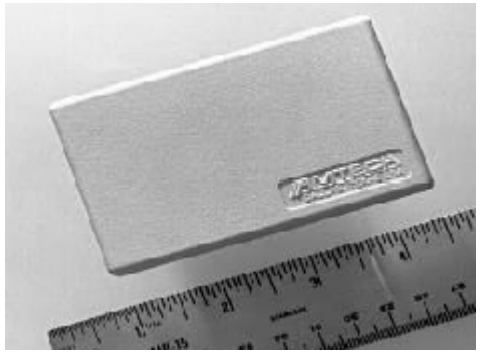
Transponders: Smart, Passive Objects



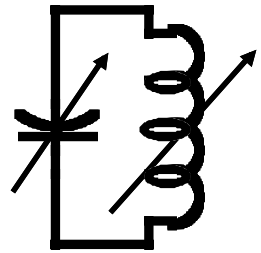
- ***ID, sensors in passive objects remotely interrogated***
  - **Tangible bits with no batteries, wires, line-of-sight!**
  - **Energy coupled via E,B Field, RF, optics, acoustics**

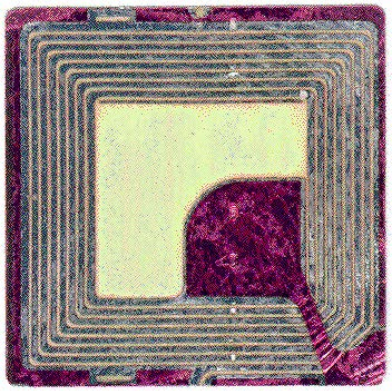
Noncontact ID and Sensing - RF Tags



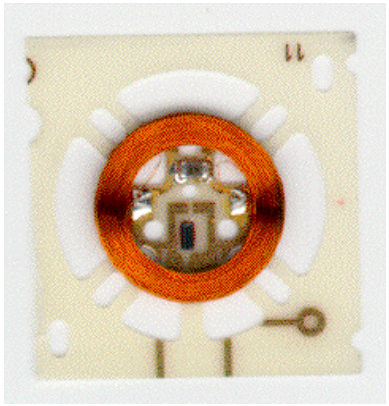


RF Coupled (Amgen)





LC Tag



Inductively coupled

Electrostatically Coupled
(Motorola Bistatix)

Magnetostrictor

Chip Tags

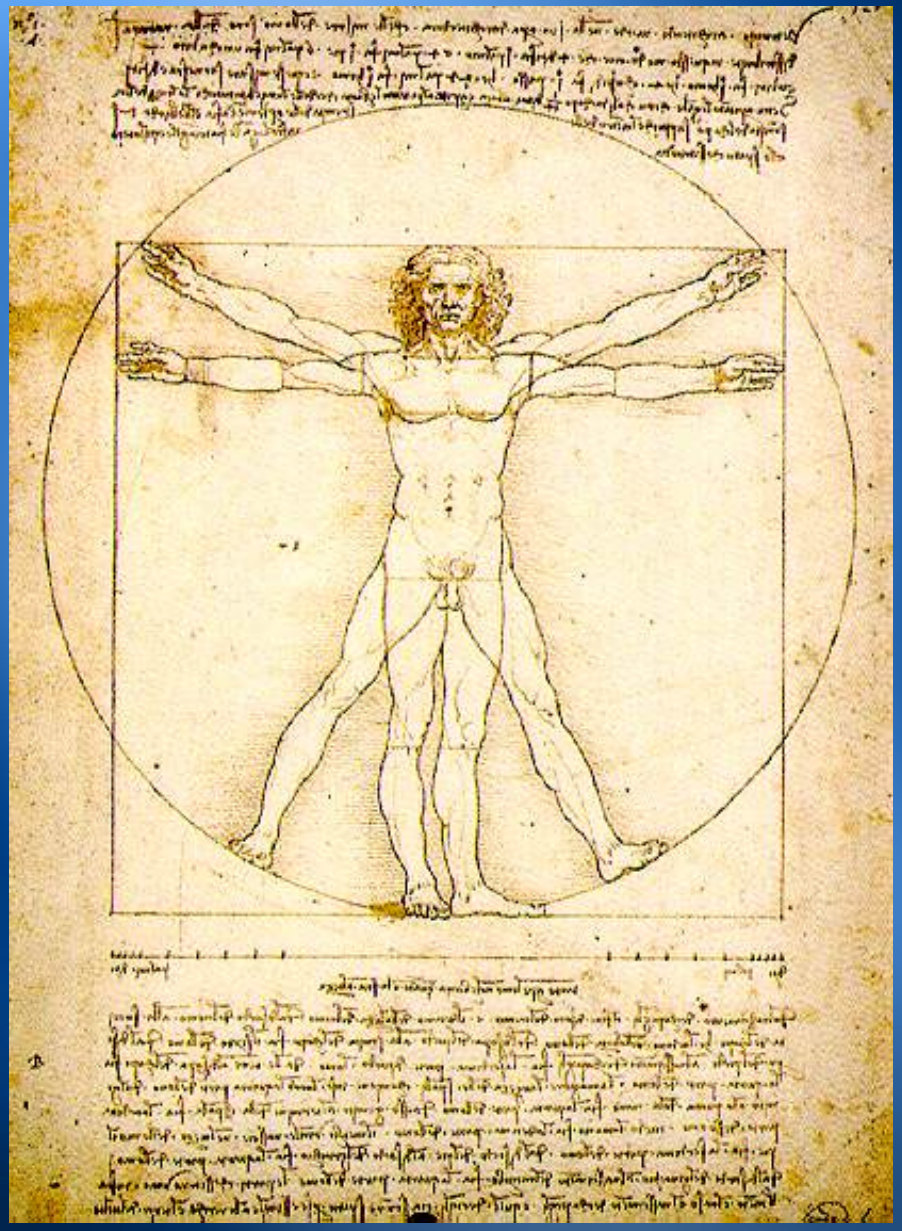
Printed Electronics!

Shoplifting Tags

Resonance = f(T,P,F,a,...)

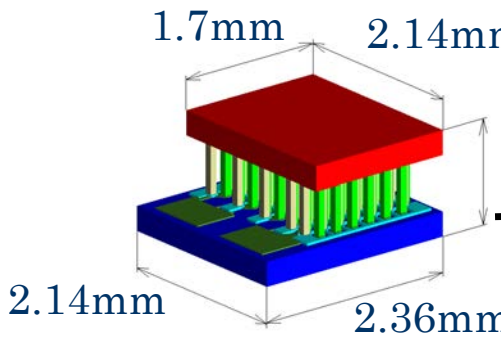
Close Proximity - Limited bandwidth

Human-Powered Systems

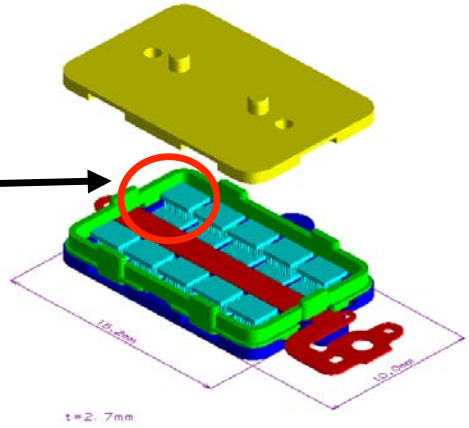


Seiko SII Thermal Energy Watch

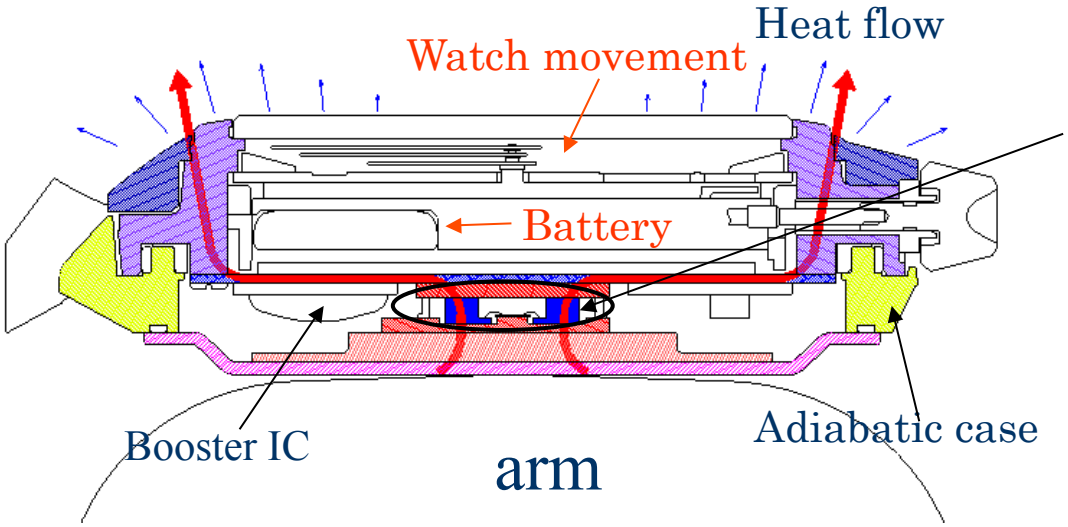
Thermal energy watch

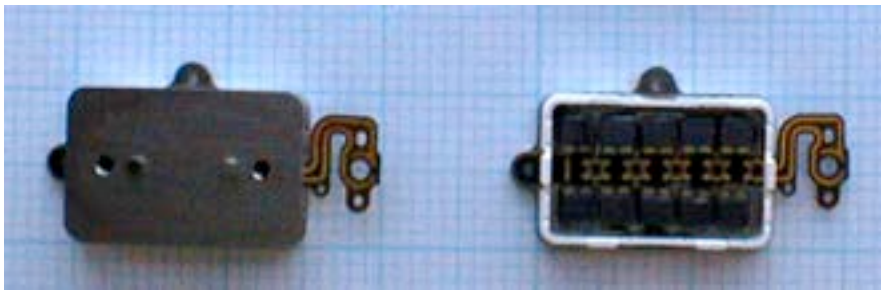


Thermoelectric module



Thermoelectric unit



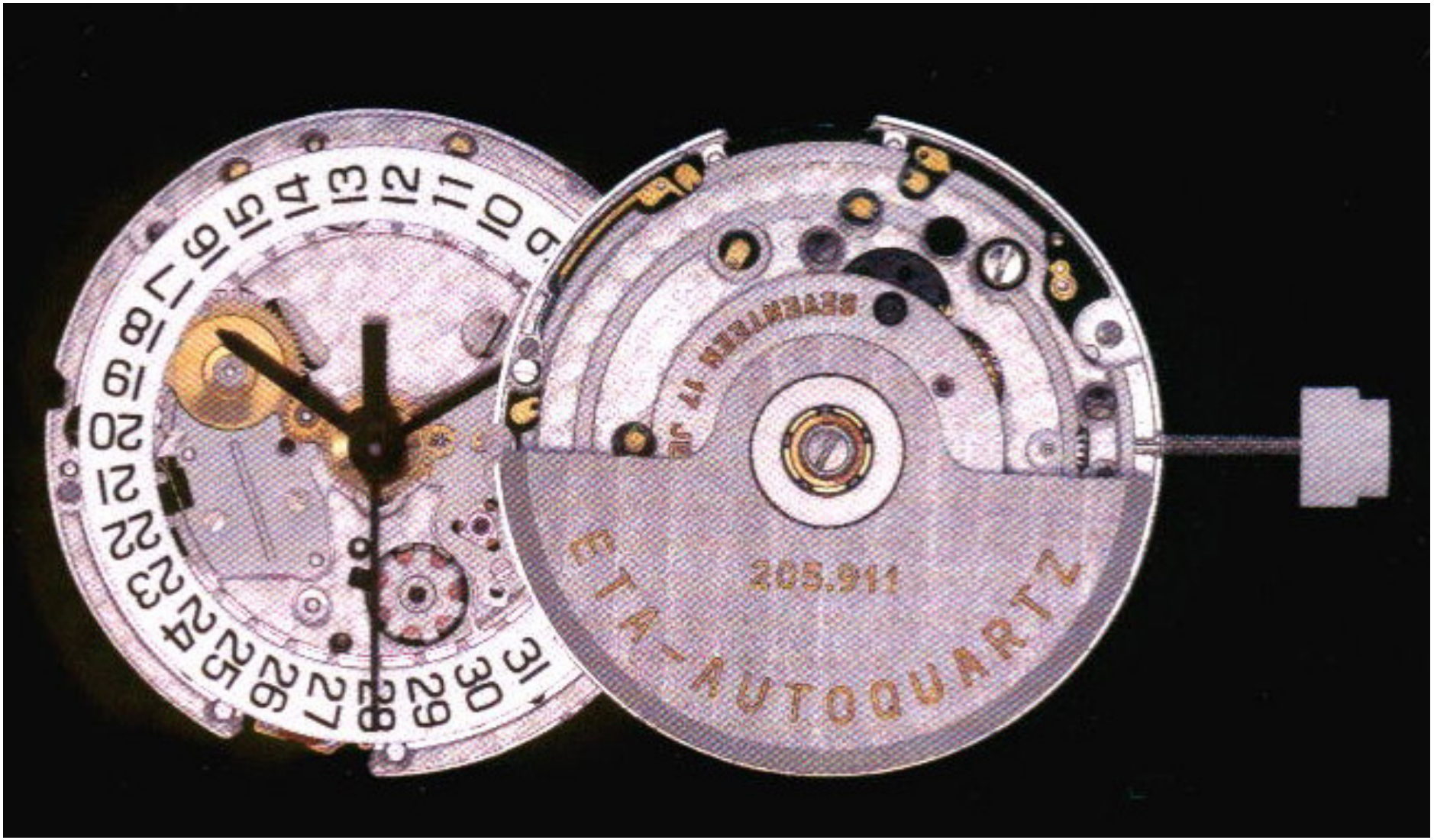


Thermoelectric (Photo)

- Uses 10 Thermoelectric modules and a booster IC
- Runs off body heat

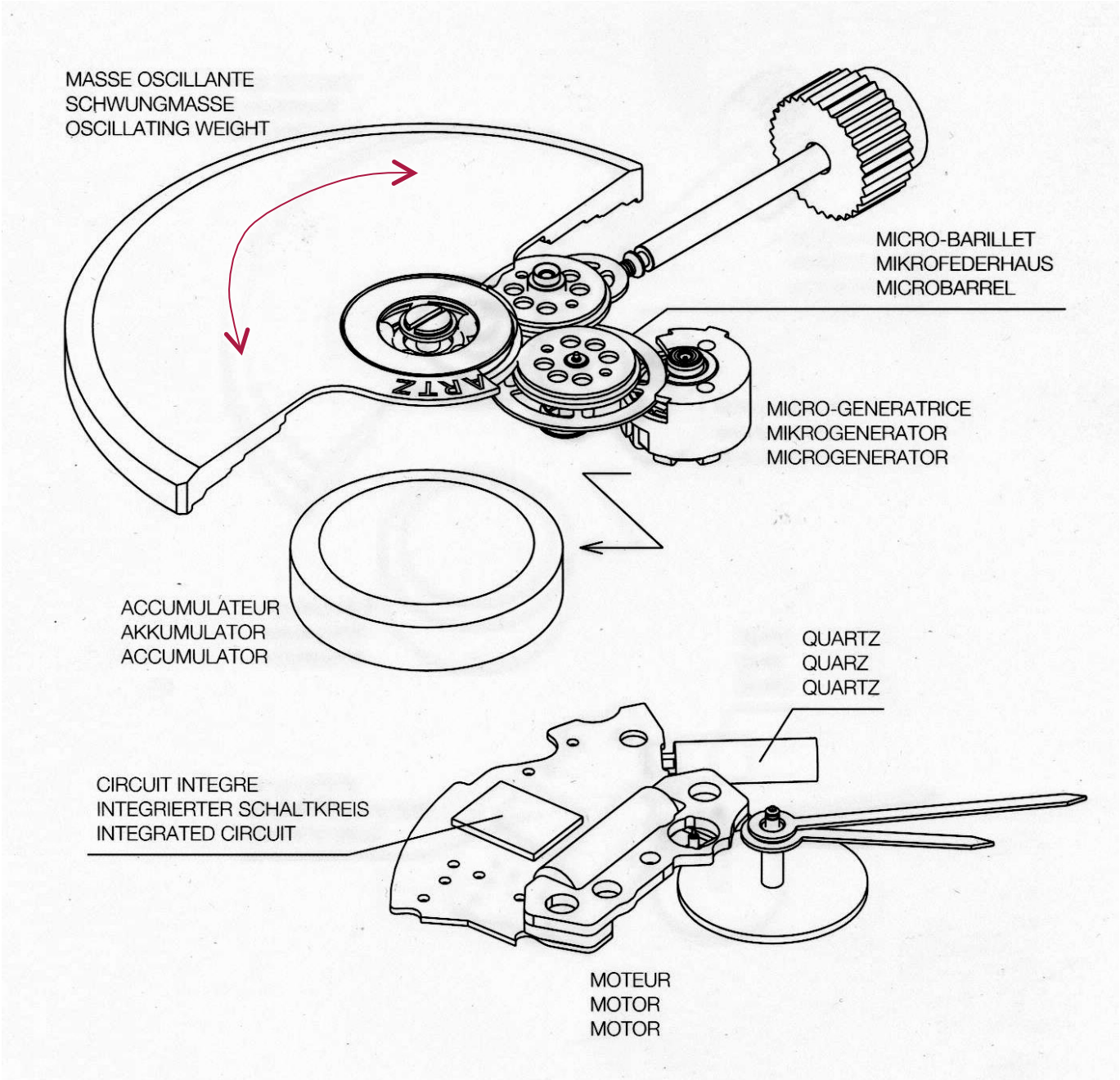
Low ΔT, limited surface area, low efficiency -> Microwatts…

The ETA Autoquartz Self-Winding Electric Watch



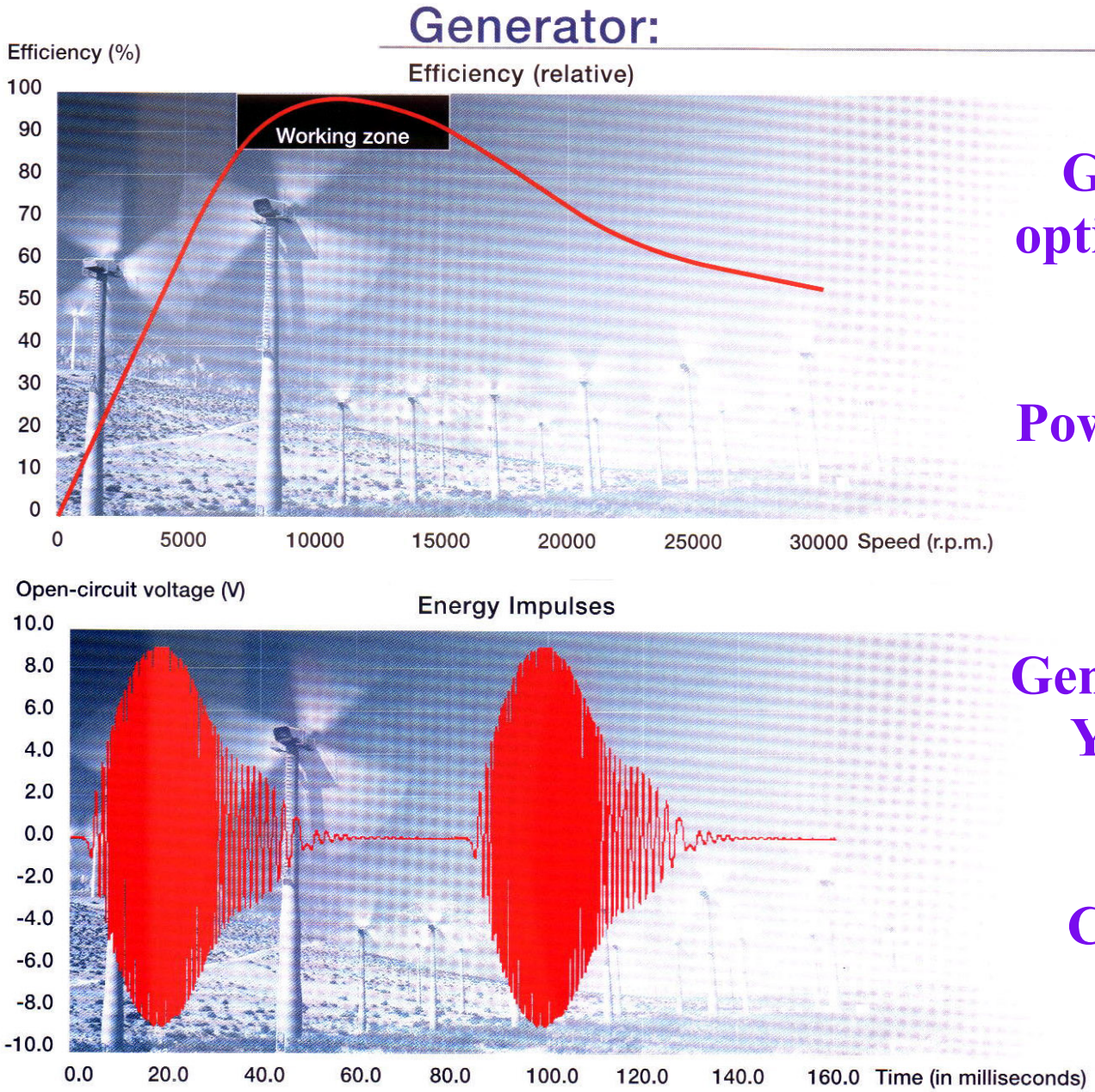
The Swatch Group (SMH)

The ETA Autoquartz Mechanism



Proof Mass winds spring, which pulses generator

The Autoquartz Generator Performance



Generator always run at optimum rate (10-15K RPM)

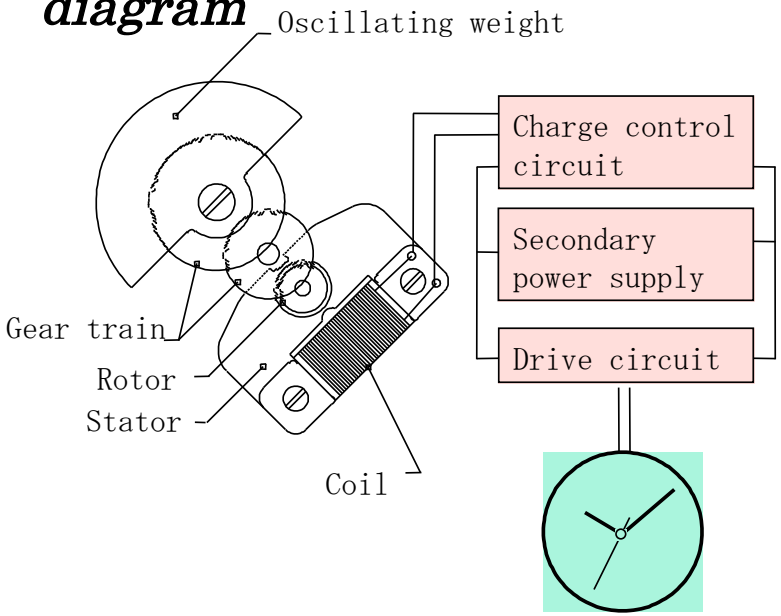
Power stored on spring until threshold is exceeded

Generator pulsed for 50 msec Yields 6 mA at >16 Volts

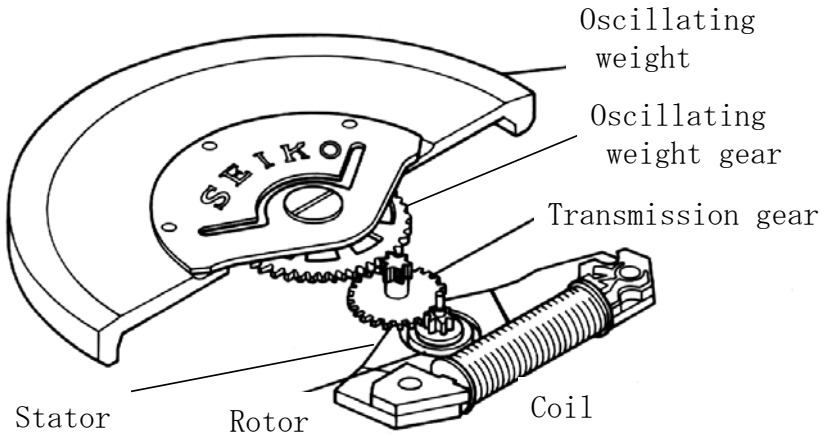
Current integrated onto capacitor

Seiko AGS System

KINETIC outline diagram

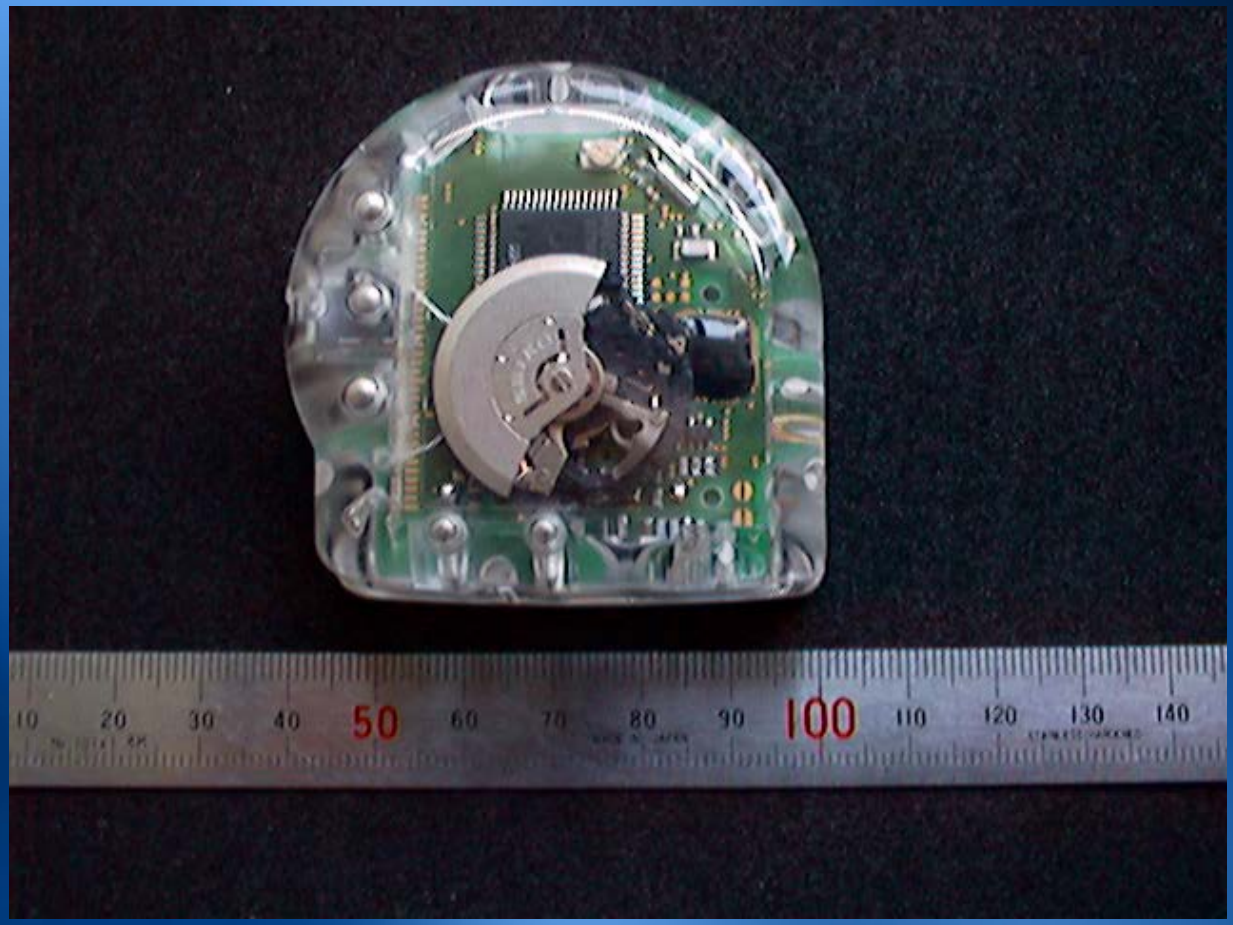


Oblique view



- Proof mass oscillation directly cranks generator rotor
  - Little intervening mechanics
  - Charge accumulated on capacitor
- Power Output:
  - 5 μW average when the watch is worn
  - 1 mW or more when the watch is forcibly shaken

Seiko Experimental AGS for Marine Mammals



- Uses watch AGS components
  - Power Output is 5 to 10 mW

Modern Magnetic Generator Products

Shake!

- 60 turns (1 min) stores 0.6 Watt-hr
  - 40% efficient
- Today's laptop supply roughly 50 W-hr
- Wrists?

Step!

STEPCHARGER® PAT.

Trevor Baylis (Baygen)

Crank!

Squeeze!

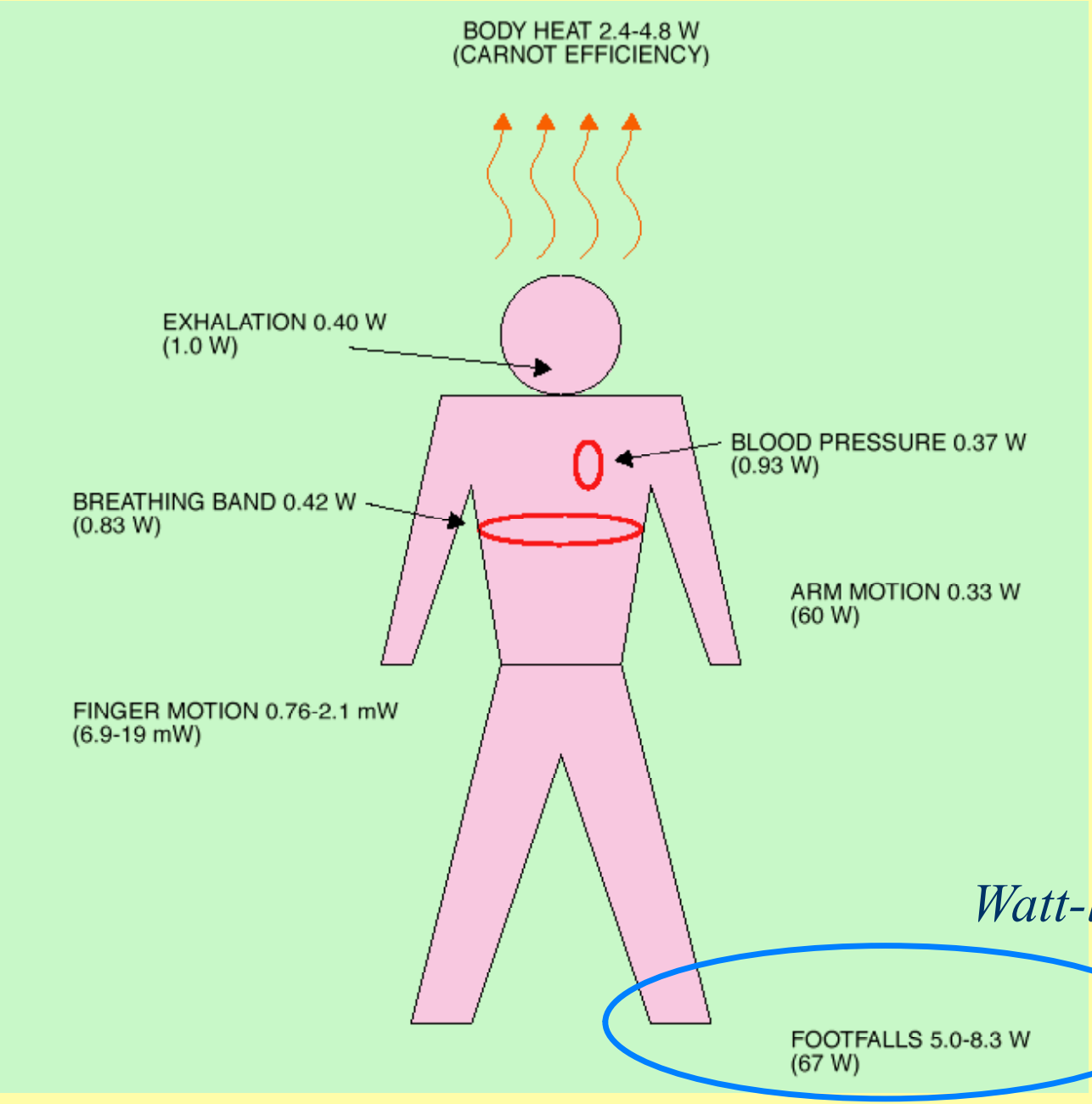
ALADDINPOWER PAT

- Freeplay/Motorola windup cellphone charger (30 sec = 6 min for $49.)
- Windup Landmine detector

The Electric Bolo

- Saul Griffith (MIT Media Lab)
- Claims approx. 5 Watts...

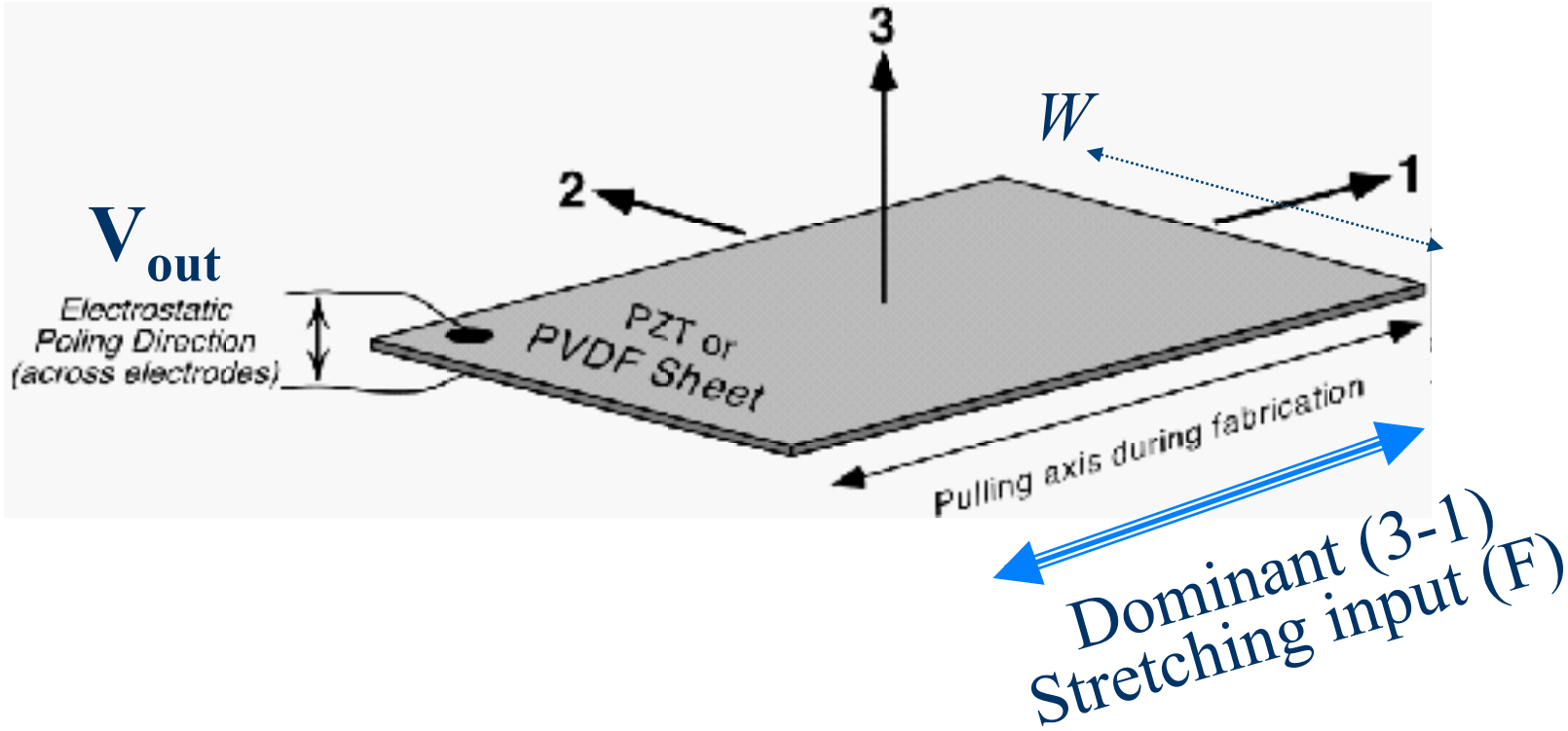
Harvesting at the Foot



Watt-level available

Thad Starner, Human-Powered Wearable Computing, IBM Systems Journal 35, pp. 618-629 (1996).

Piezoelectrics

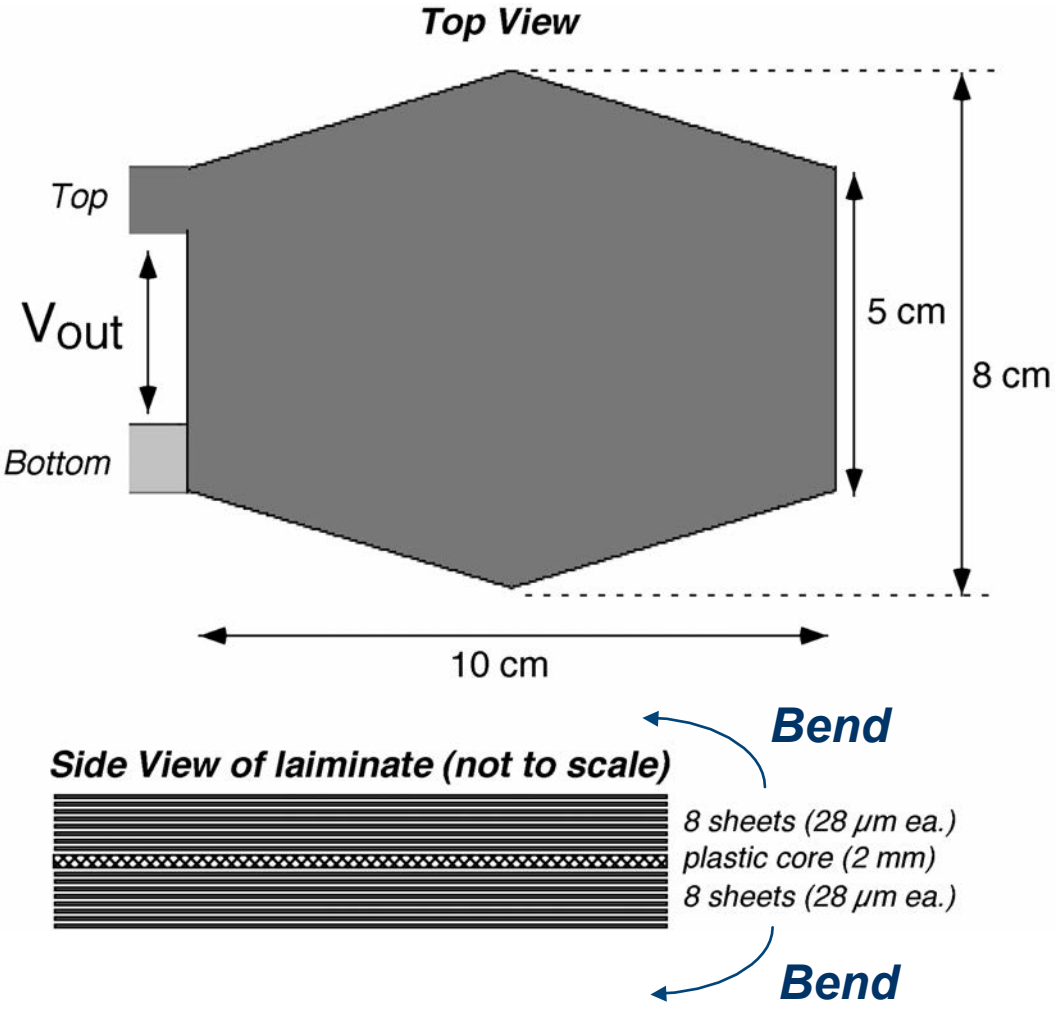


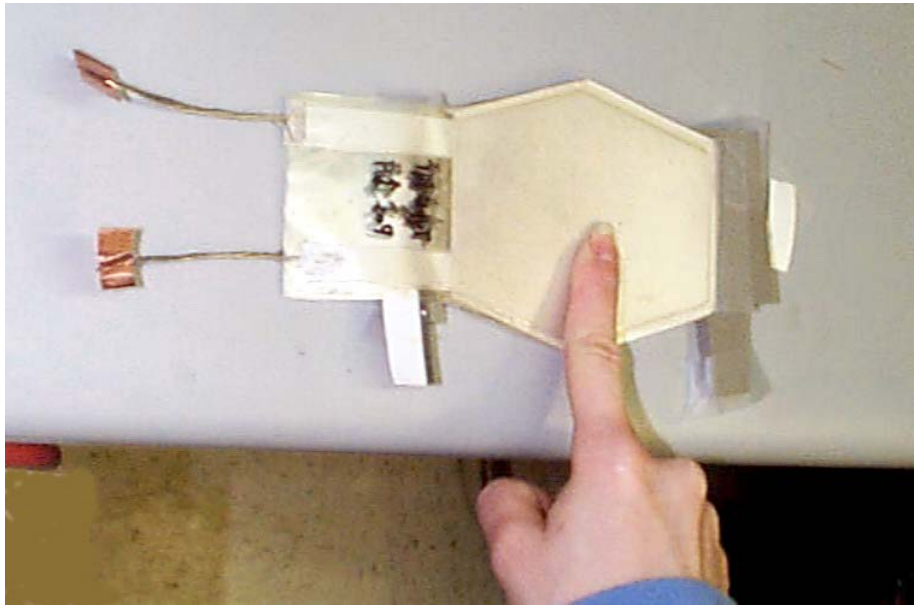
Piezoelectric materials respond mainly to tension and compression along their pulling (1) axis

$$V_{out} = g_{31} \frac{F}{W}$$

Piezoelectric Voltage Constant
(Mechanical-to-Electrical conversion)

The PVDF Stave





PVDF = Polyvinylidineflouride

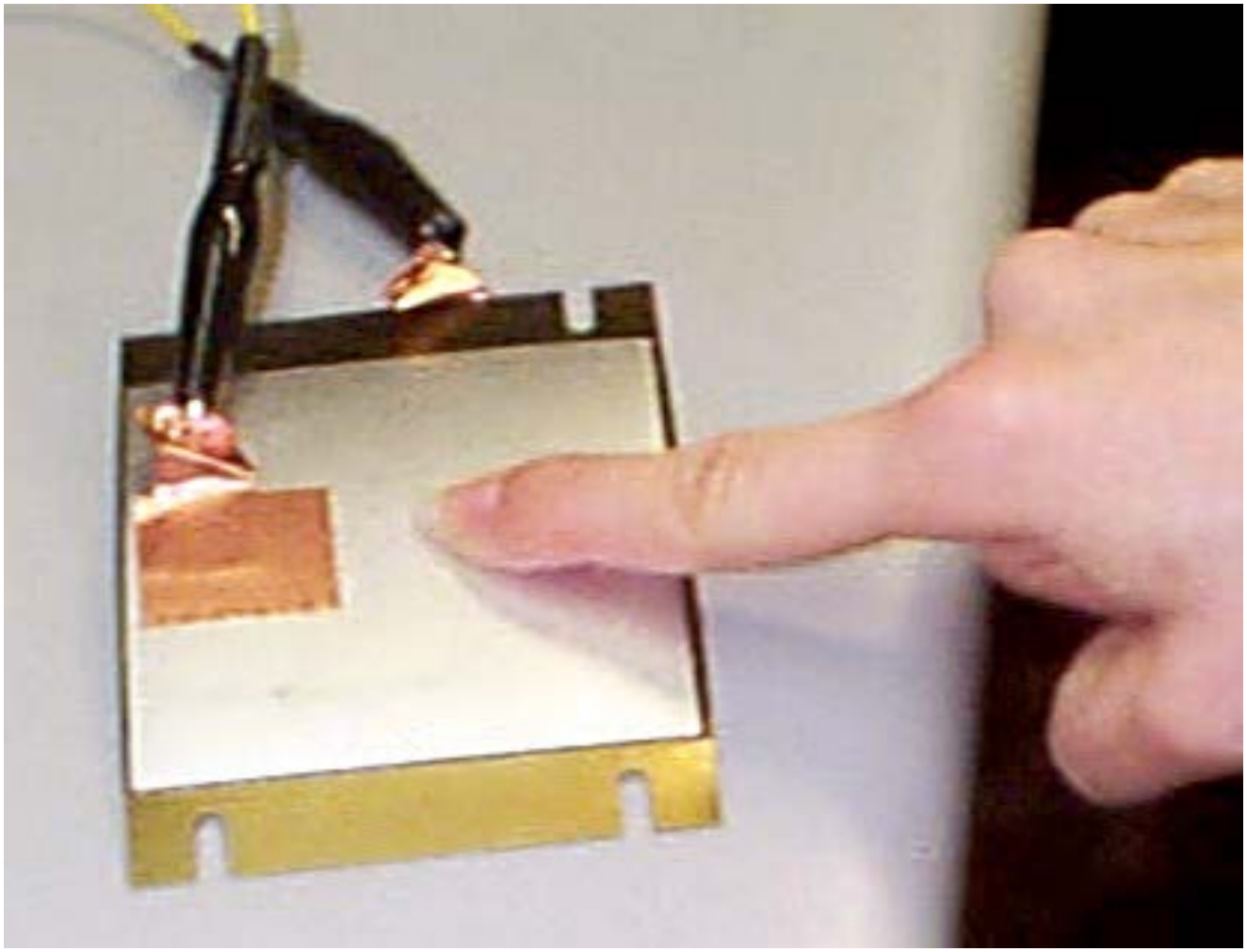
Piezoelectric Film material

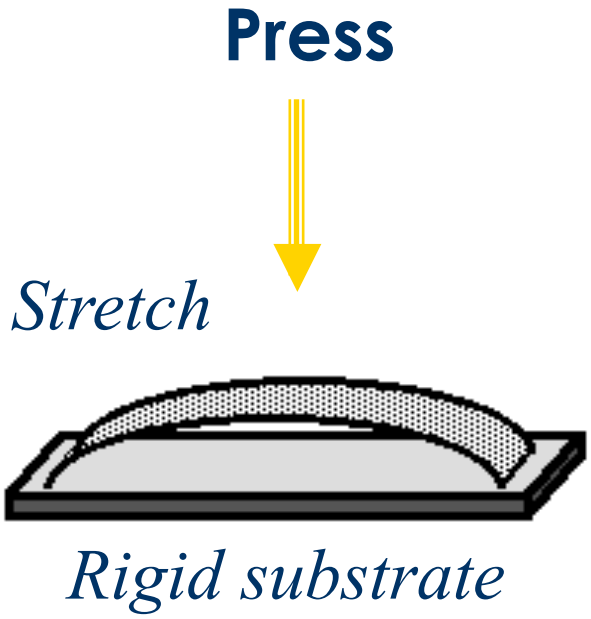
8 layers of PVDF foil laminated on both sides of 2 mm spacer

When bent, outer layers in expansion & inner in compression

Thanks to K. Park and M. Toda at AMP Sensors (now Measurement Specialties)

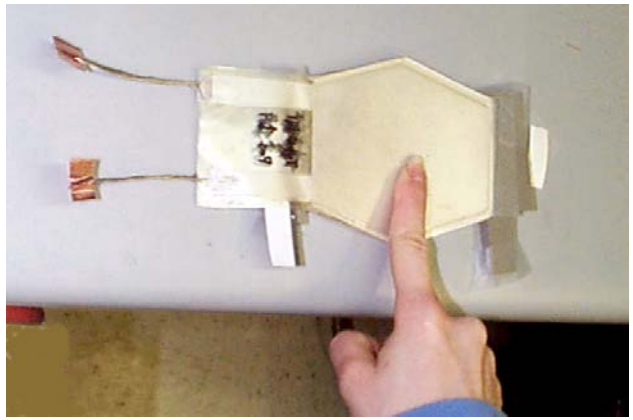
The PZT Unimorph





- Thunder™ sensor/actuator from Face Technology
  - PZT material integrated into semiflexable cloth matrix
  - Order of magnitude higher g_{31} than for PVDF
  - Generate voltage when pressed flat (break when reversed)

Power Harvesting Shoes



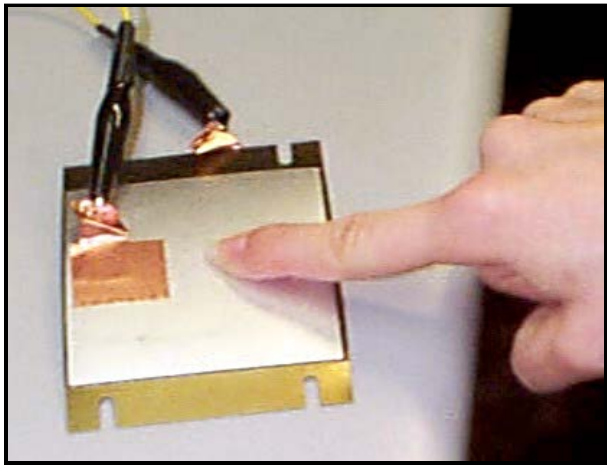
PVDF Stave

Molded into sole

Energy from bend

$P_{peak} \cong 10$ mW

$\langle P \rangle \cong 1$ mW



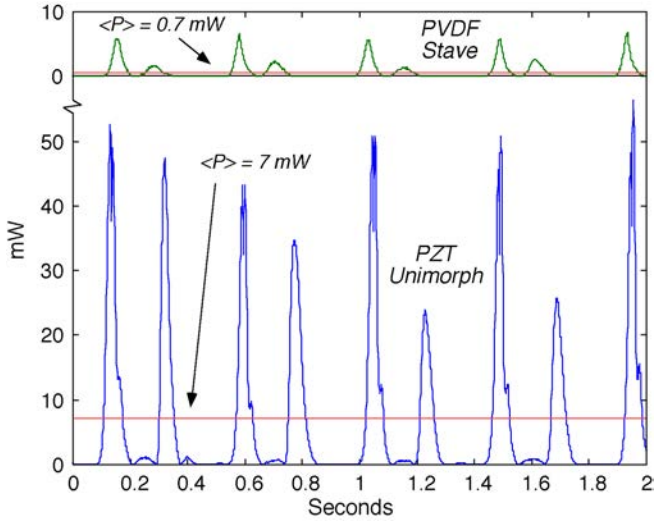
Flex PZT Unimorph

Under insole

Pressed by heel

$P_{peak} \cong 50$ mW

$\langle P \rangle \cong 10$ mW



Raw Power

circa 1% efficient

unnoticable

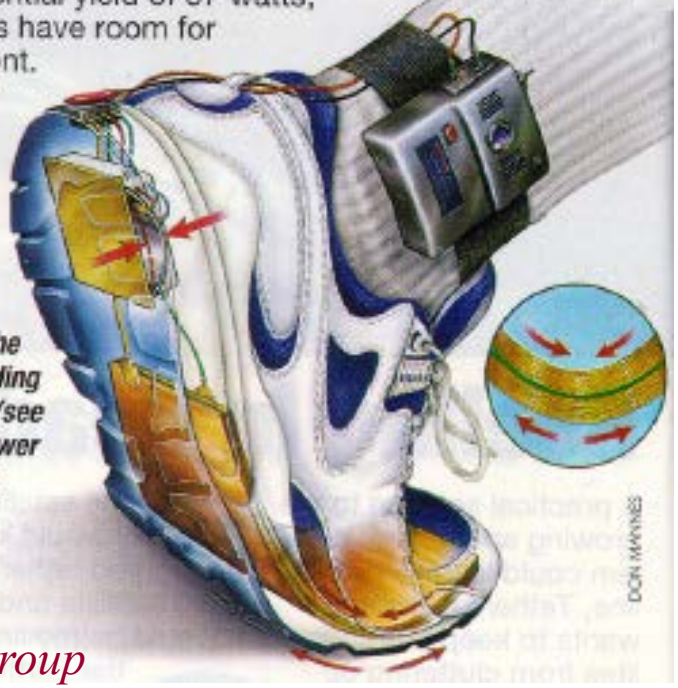
Walking Powers Electronics

High-tech shoes harvesting old-fashioned foot power could someday generate enough electricity for portable phones and computers.

MIT scientists led by Joseph Paradiso, technical director of The Media Laboratory's Things That Work Consortium, have powered simple electronic identification tags with two different devices that resemble cushioned shoe inserts.

Both use the piezoelectric principle by which a physical distortion to a substance produces an electrical potential between its surfaces. One device harvests heel strikes' energy with a stiff piezoceramic material. The other device turns the flex in a sneaker's insole into electric power via a multilayered laminate of piezoelectric foil.

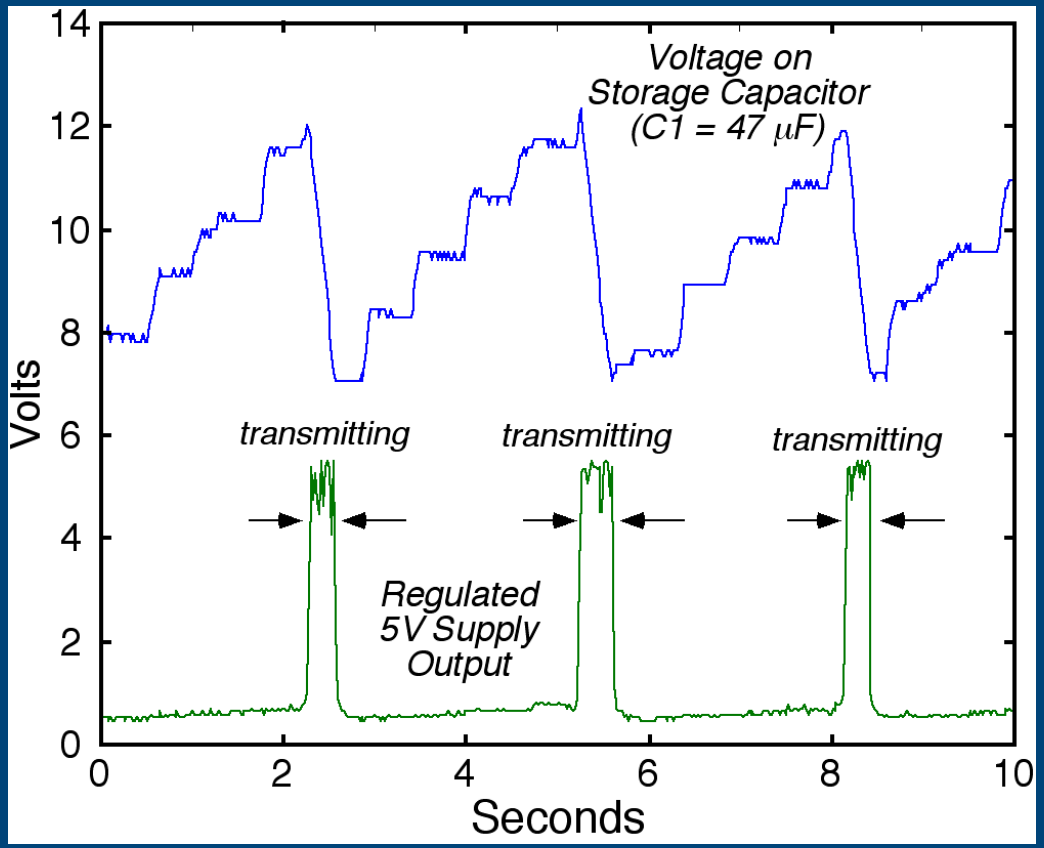
Power is measured in milliwatts. With a potential yield of 67 watts, researchers have room for improvement.



Pressure at the heel and bending at the insole (see inset) can power an electronic ankle ID tag.

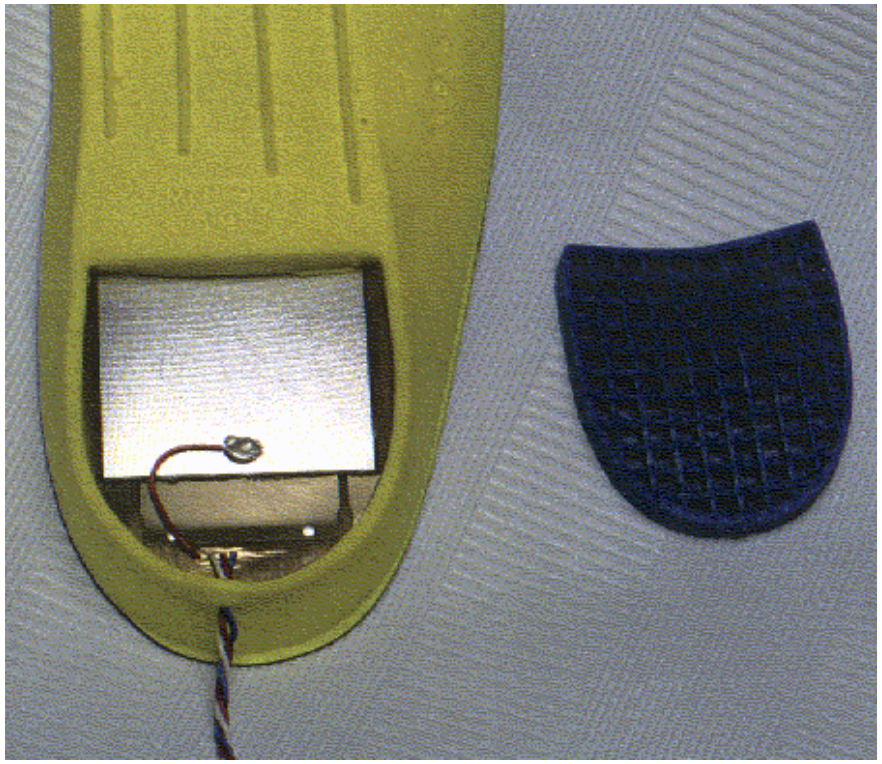
Responsive Environments Group
MIT Media Lab
1998 IEEE Wearable Computing Conference

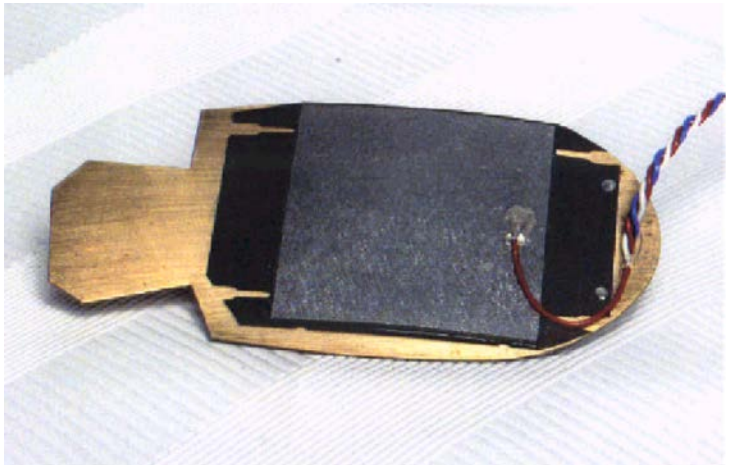
Application: Batteryless RFID Tag



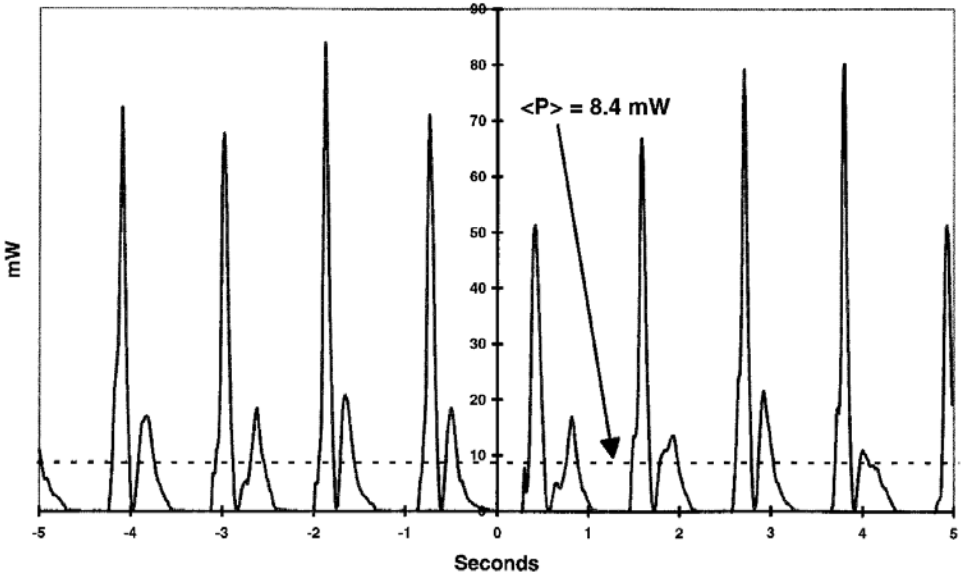
- Use Piezo-shoes to charge up capacitor after several steps
- When voltage surpasses 14 volts, activate 5 V regulator
  - Send 12-bit ID 6-7 times with 310 MHz ASK transmitter
- After 3-6 steps, we provide 3 mA for 0.5 sec
  - Capacitor back in charge mode after dropping below output

PZT Bimorph in an Navy Boot





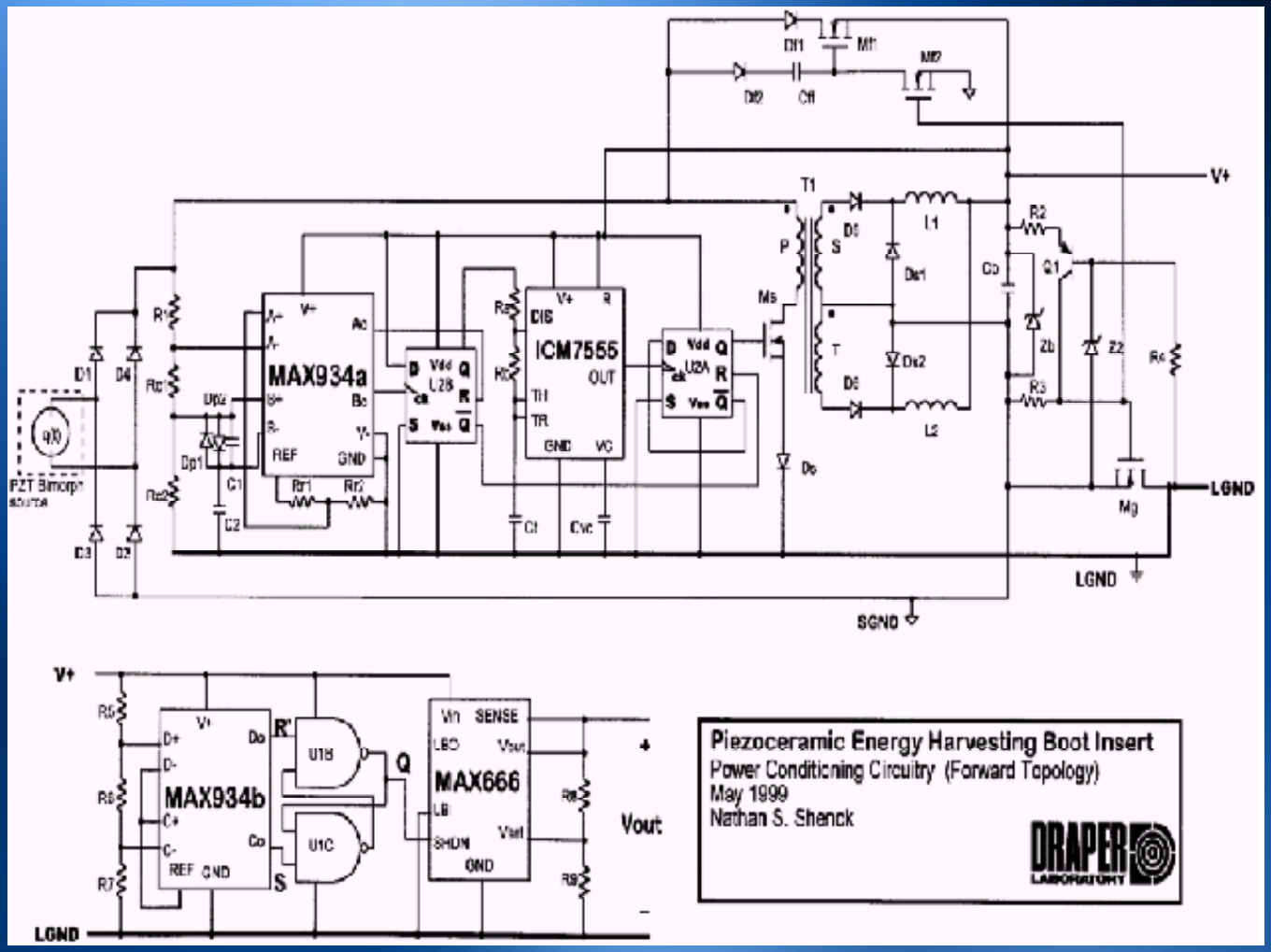
Power into 500 kOhm Resistive Load



- *Larger, bimorph device - raw power more than doubled.*
  - *Circa 20% efficient*

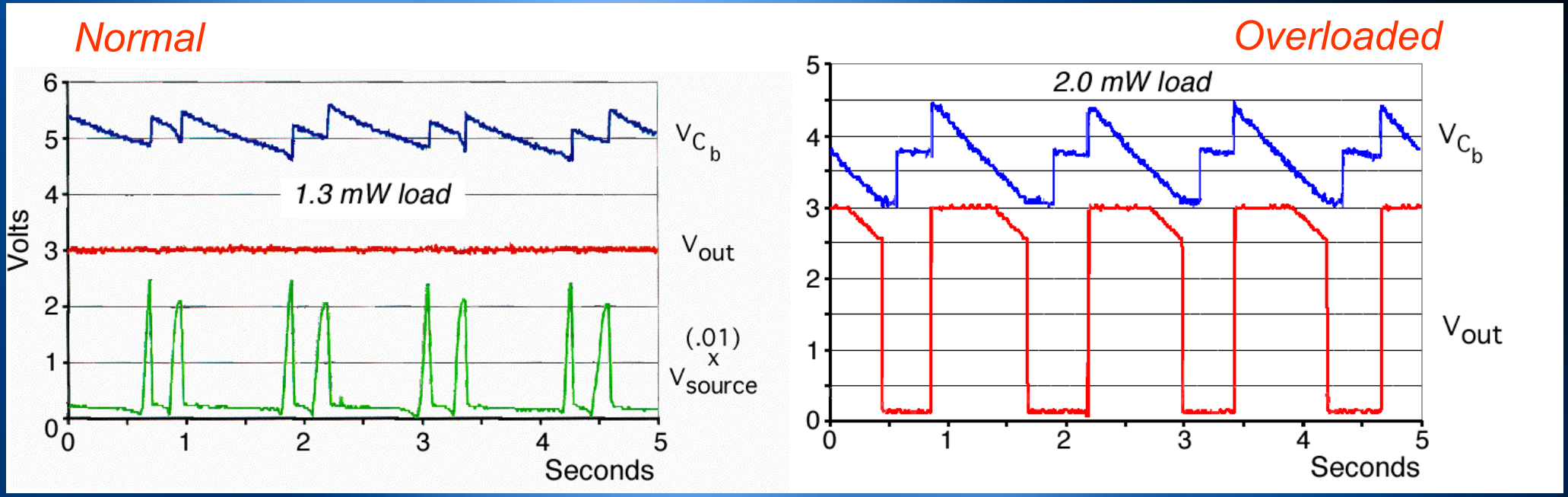
Nate Shenck - Draper Fellow and Media Lab Student

Nate's Forward-Converting Switching Regulator



- Bootstraps via previous "bucket" circuit
- Switcher waits for peak charge before activating ($^1/_2$ CV^2)
- High freq. (25 kHz) chop into transformer
  - No direct connection of bucket cap to piezo after bootstrap

Regulator performance



- Switcher drops ~100 V source down to ~5 V
- Subsequent low-power linear regulator gives stable 3 V
- Provides 1.3 mW of stable, regulated 3 V at 0.8 Hz walk
  - Converter is 20% efficient
  - Losses in transformer, MOSFET parasitics
  - More than twice as efficient as bucket scheme

A Mechanical Solution...

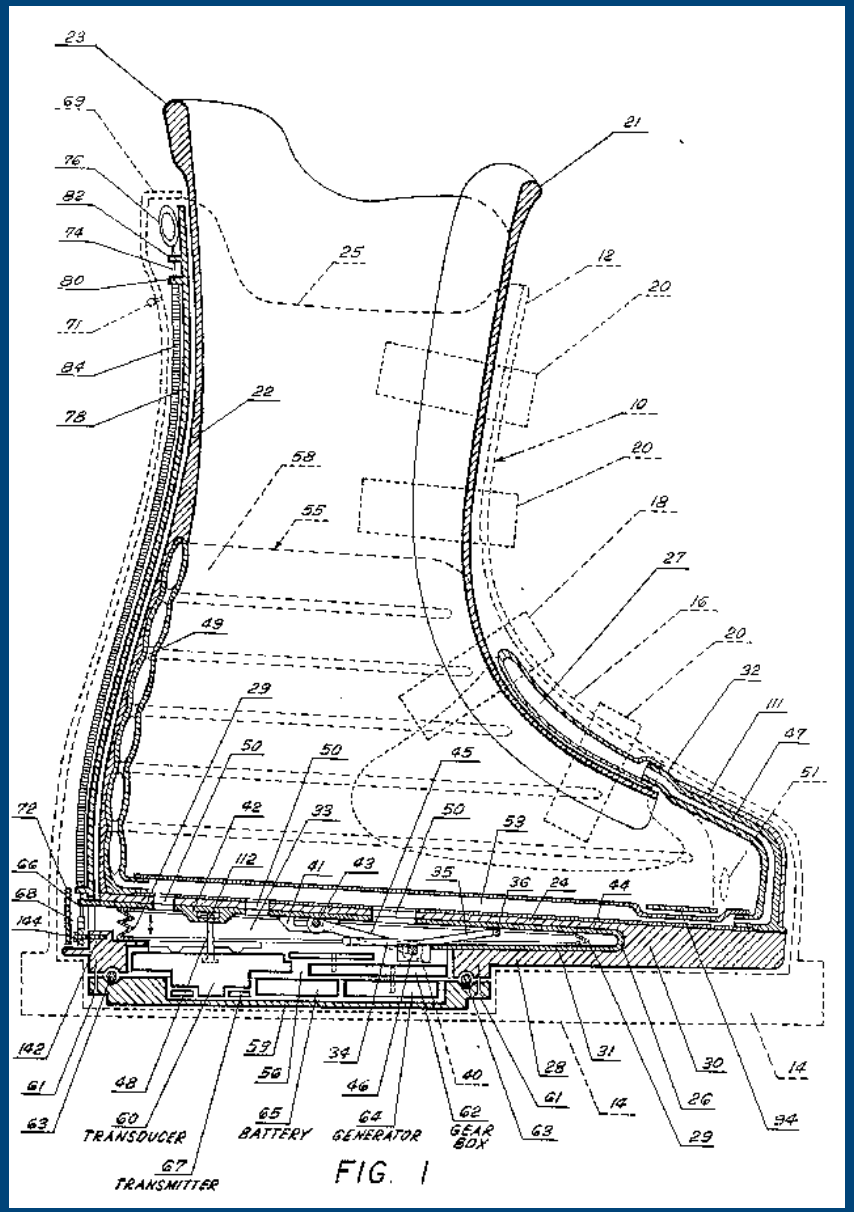


FIG. 1

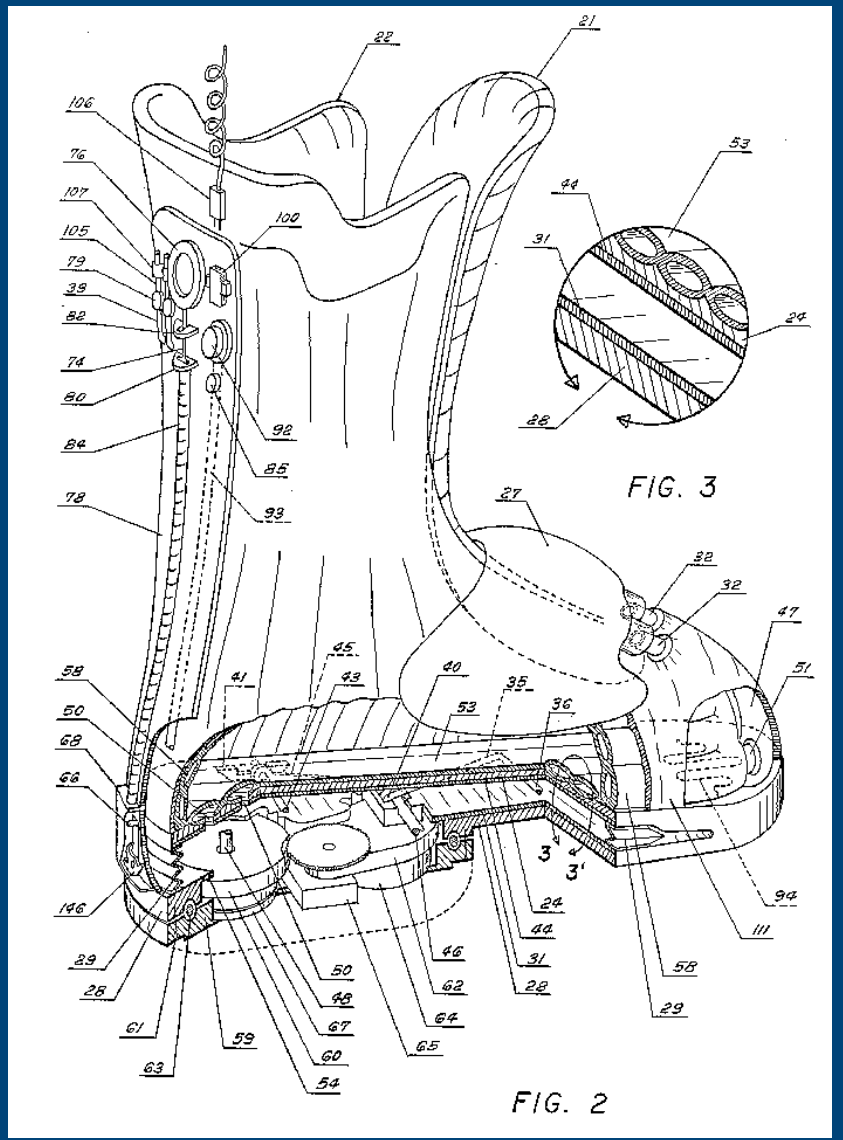


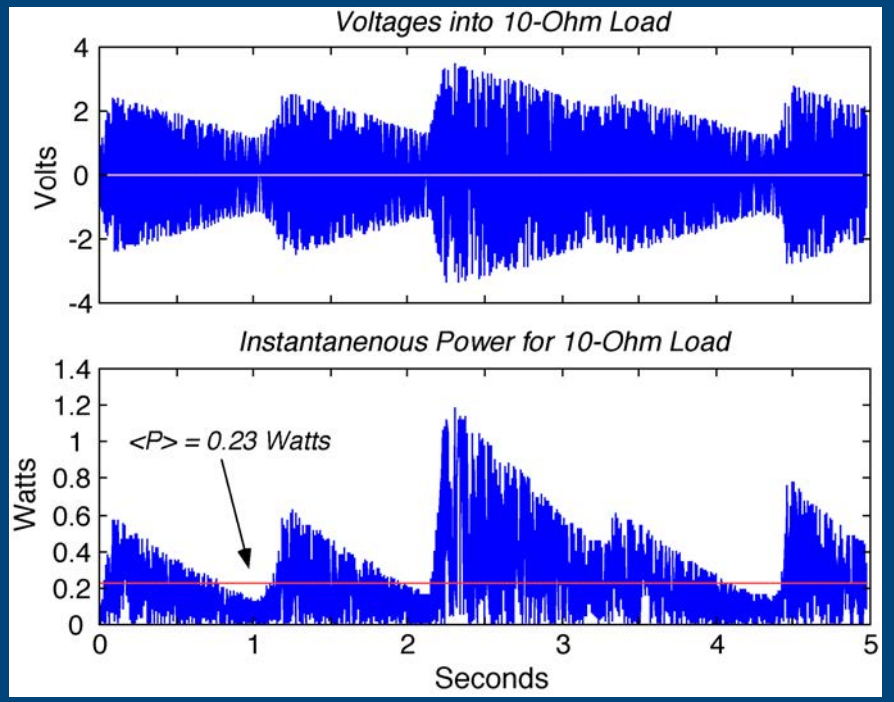
FIG. 3

FIG. 2

A parasitically-powered boot heater, US Patent 4845338, 1989

Rotary Magnetic Generator Retrofit

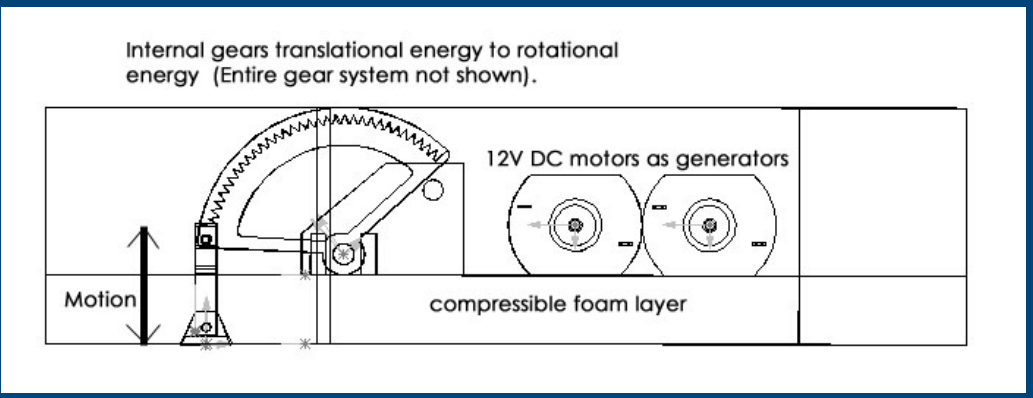
Responsive Environments Group - MIT Media Lab

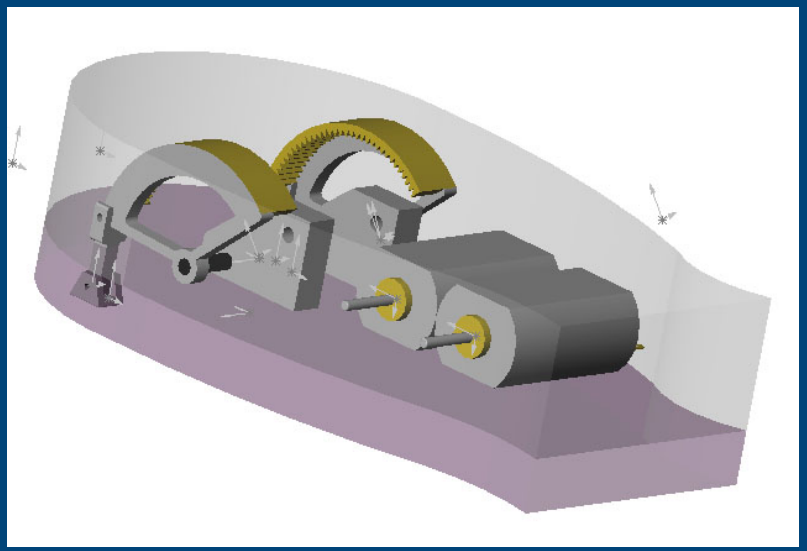


- *Attaches lever-driven flywheel/generator to shoe*
  - 3 cm deflection, bulky
  - Suboptimal (e.g., better integration, hydraulics...)
- ***Produces a quarter watt average (≅ 1 W peak), but very obtrusive!***

Better Generator Integration

Jeff Hayashida's thesis - 1999





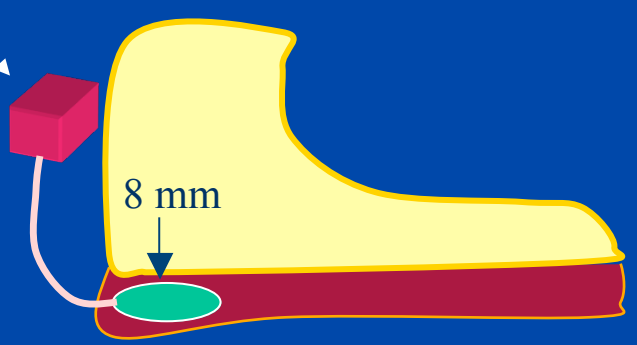
- *Mechanical generators entirely in insole*
- *Produces about 60 mW average power*
- *Use of a spring to store energy between footfalls can bring a Watt*
- *Mechanically complex and fragile…*

More power from the heel strike

DARPA Research Projects

Nesbit Hagood's Lab, MIT Aero/Astro Dept.

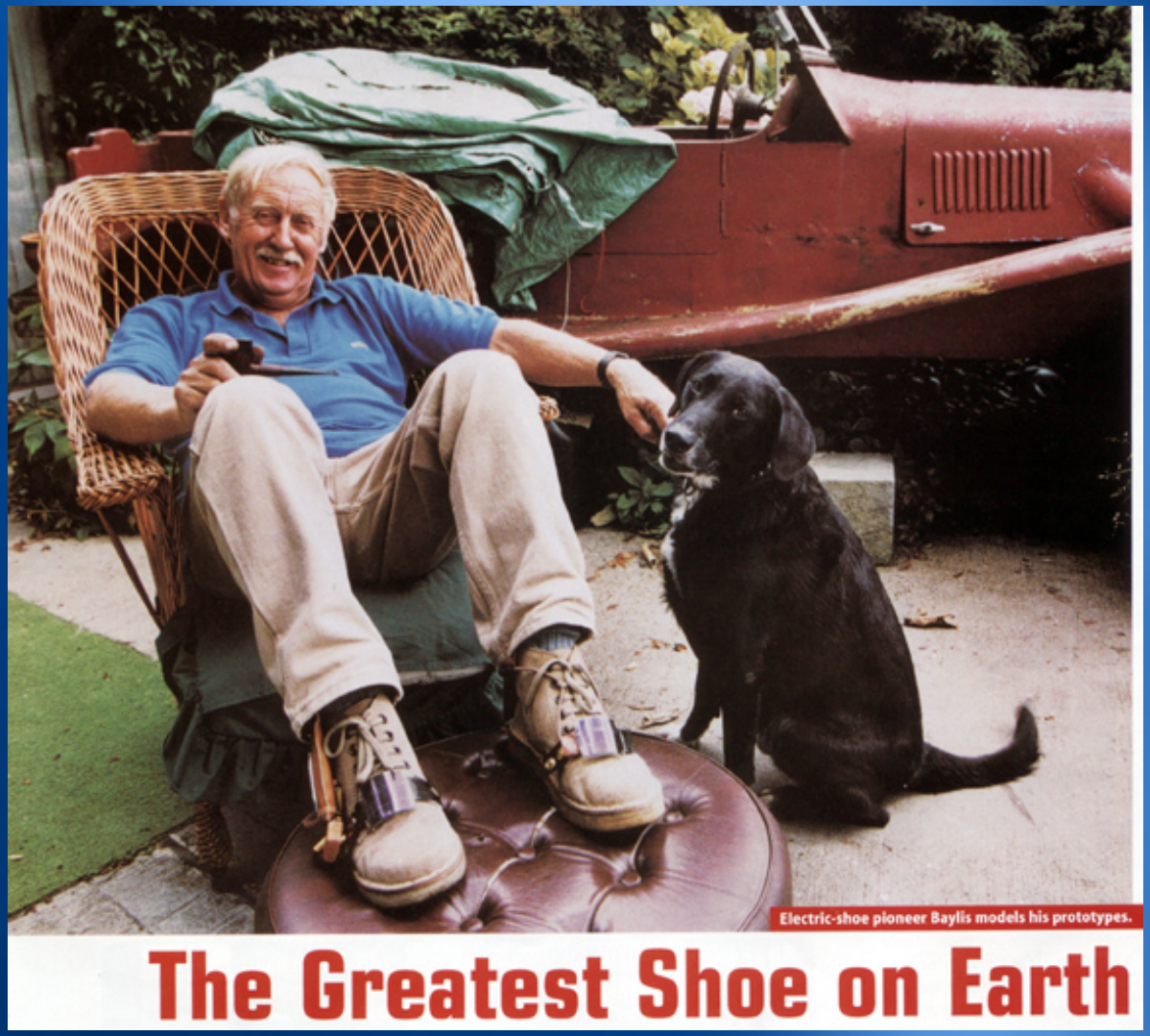
- Heel compresses Hydraulic bladder by 8 mm
  - μ-hydraulic transducers hammer PZT stack
  - Many charge-pump cycles per footstep
  - Piezo driven at resonance frequency (20 kHz)
- PZT generators occupy 1-cm cube
  - Each produces a watt
    - 40% efficiency
  - 3 per shoe gives 3 watts total
- DARPA high-risk program
  - Pieces tested, full-up demo circa October
  - Multi-level PZT stacks can yield more power…



More Power from Heel Strike – Use of rigid piezoelectrics

- Antaki, et al., 1995
  - Passive hydraulic resonant excitation of piezoceramic stack during heel compression
  - Big, kludgy shoe
    - Developed to power artifical organs
    - Developed order of 0.2 Watt average power

Trevor Baylis' Electric Shoe Company



- Piezoelectric "crystal" struck with each footfall
- Claims to generate 100-150 mW
- Used in walk across Namibian Desert, summer 2000
  - Cellphone battery partially (e.g., <half) charged after 5 days of walking

Electroactive polymers under the heel

DARPA Research Projects

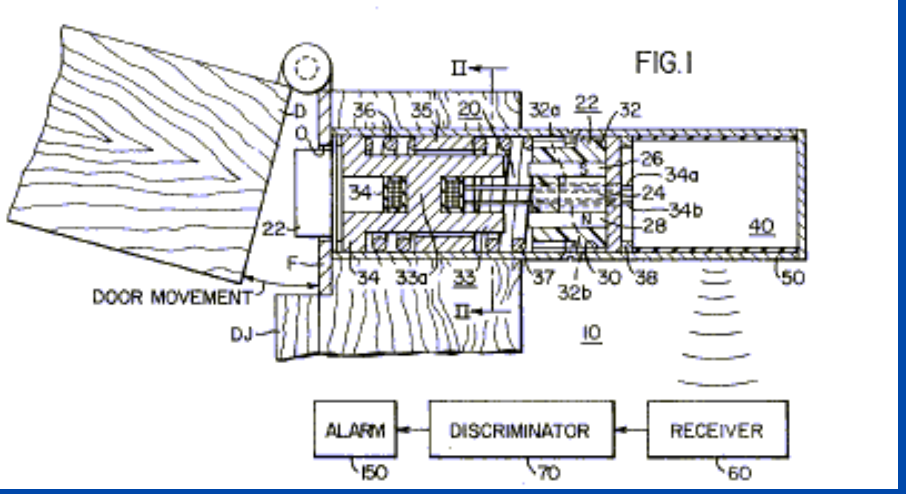
Ron Pelrine, Roy Kornbluh - SRI International

- Electrostrictors are like piezoelectrics, but…
  - Electromechanical coupling function of applied voltage
  - More coupling with more voltage
  - Need to bootstraped
- New “silicone rubber” electrostrictors
  - Placed under heel
  - Squeeze 2-4 mm
  - 4 kV across them!
  - Announced 0.5 Watt (10/01)
  - Looking for 2 Watts in January
  - At least 2 years to product

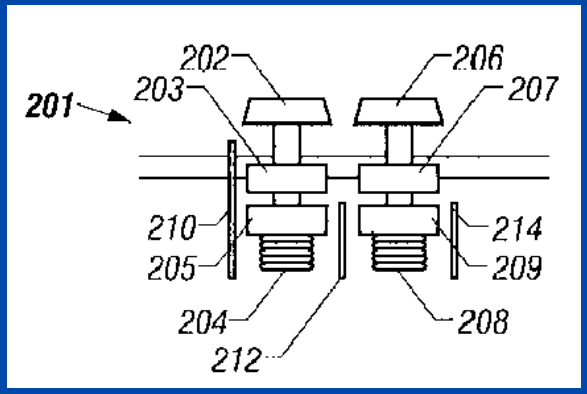
The self-powered wireless switch

- Wireless input device powered by its own activation
- No need for power or signal wiring, batteries, etc.
- Just “drop” into homes, offices, public spaces, vehicles…

Related Efforts



Johnson, et al., Transmitter Circuit, US Patent No. 3,796,958, March 12, 1974.

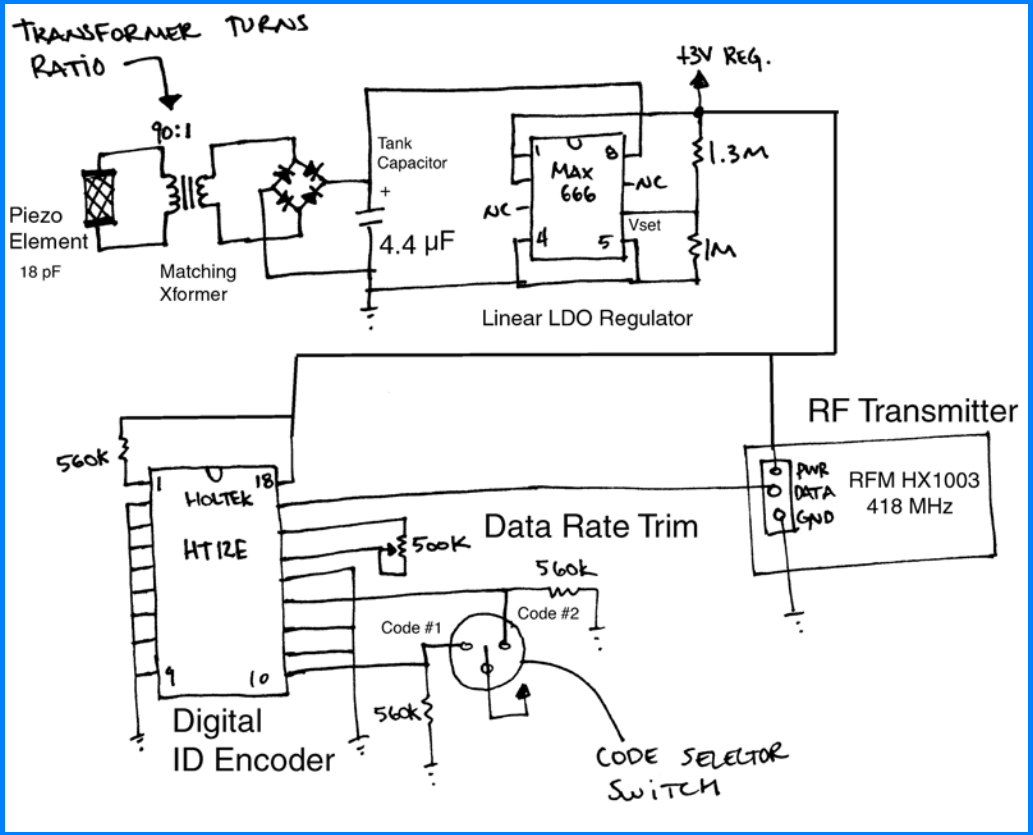


Crisan, A. (Compaq), Typing Power, US Patent No. 5,911,529, June 15, 1999

Zenith 'Space Command"

Pipi "Kodomo No Omocha" pager toy

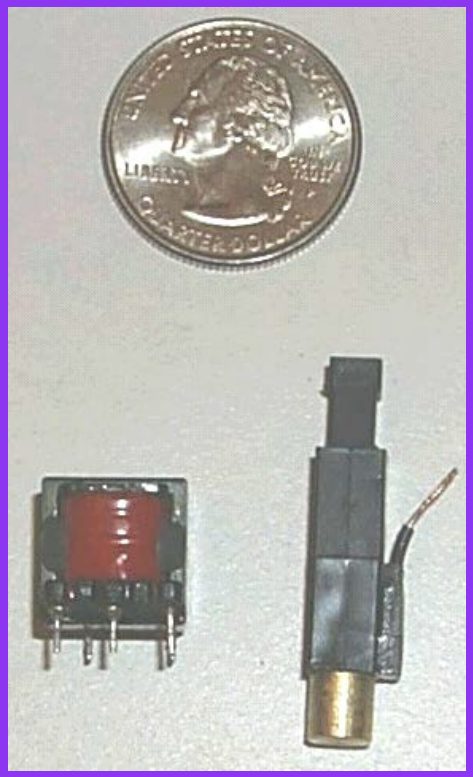
Our Switch Design

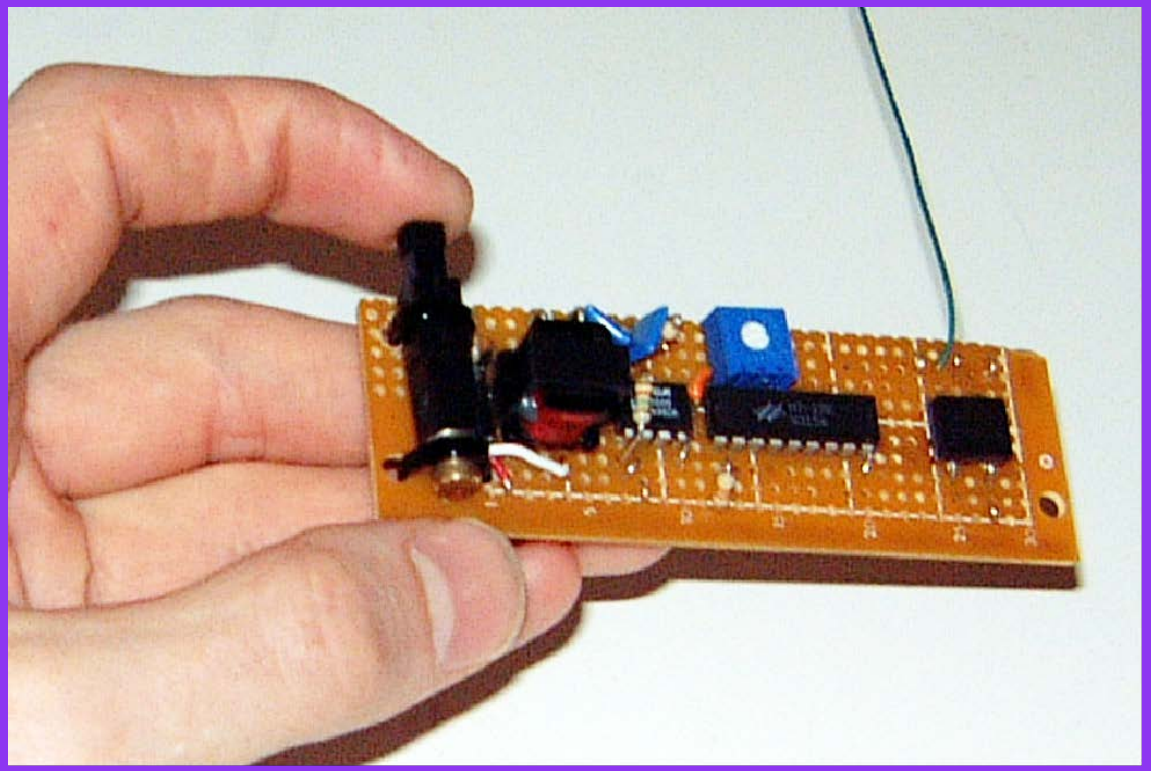


- Small piezoceramic striker
  - Adapted from Scripto lighter (softer strike)
- 90:1 amorphous core transformer gives nearly 1000:1 drop in impedance
  - Matches piezo better - more current, less voltage

- ② *Electric resonance frequency (xformer L, piezo + reflected load C) matched to mechanical piezo resonance frequency*
- Works on 1 push
- Power low-power, LDO linear regulator to provide stable +3 volts
- CMOS 12-bit ID encoder drives OOK RF transmitter

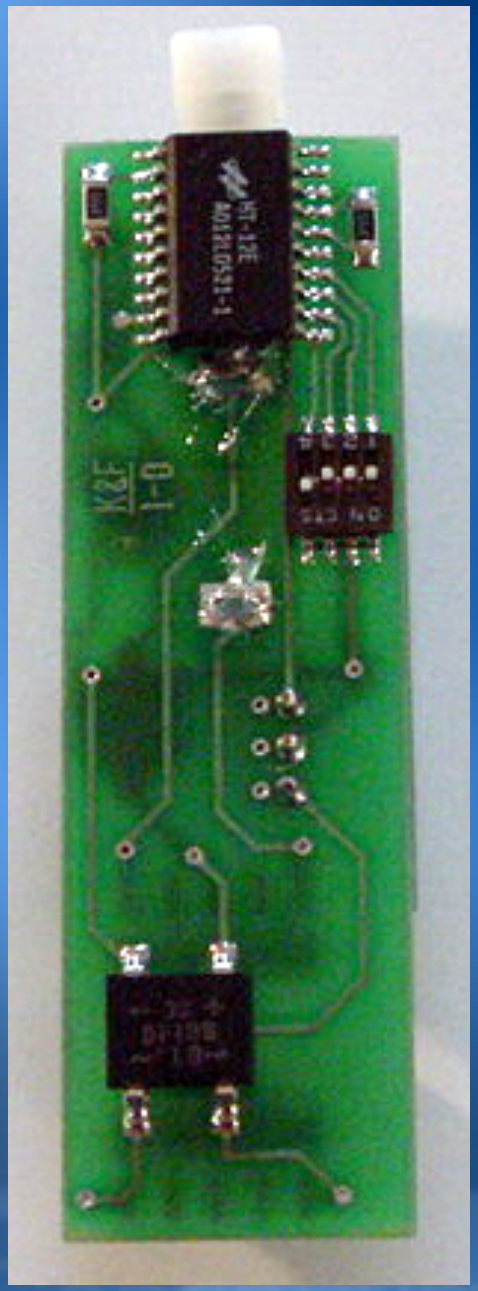
Prototype Device



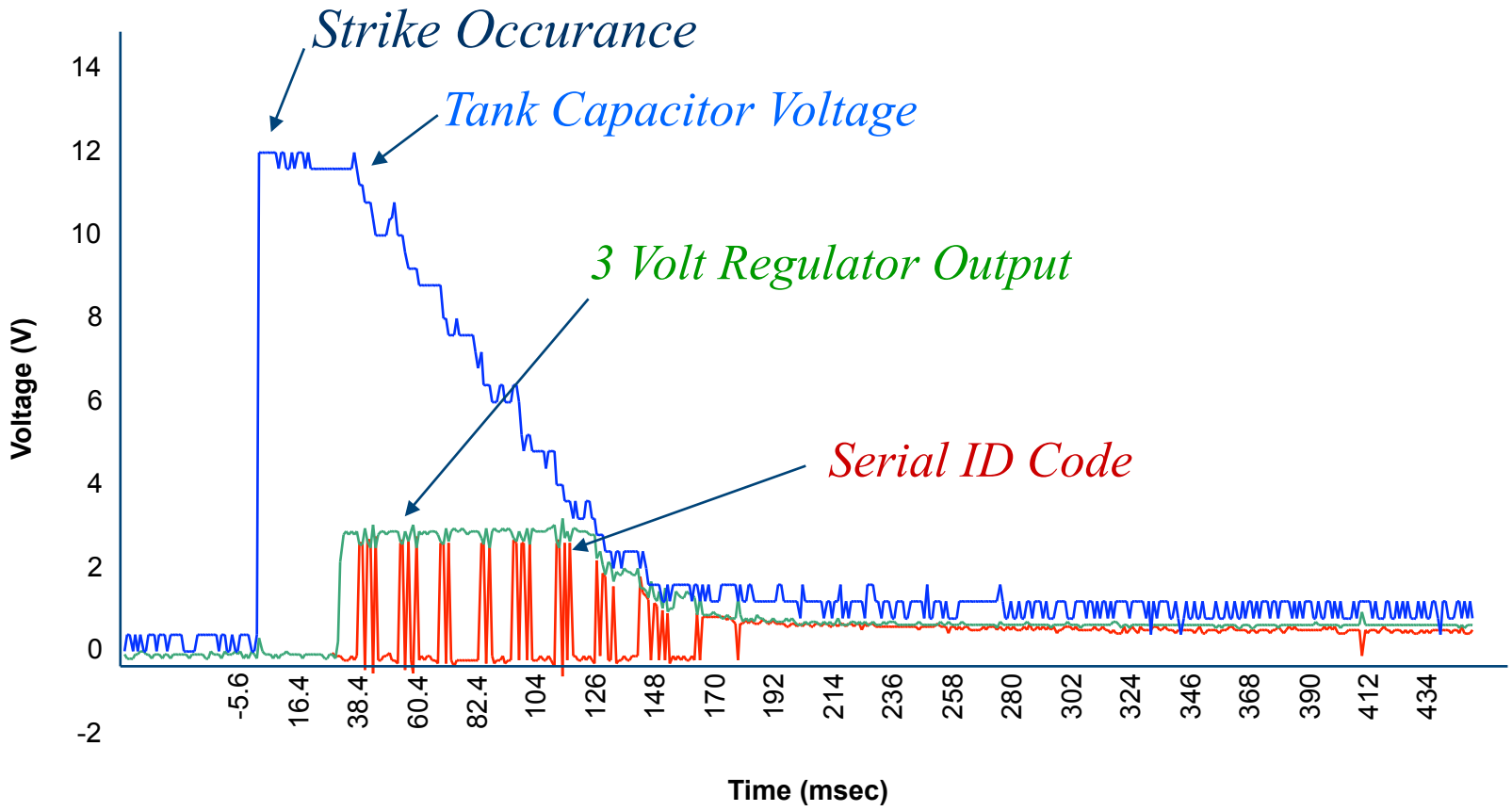


- Minimal Components (8 grams, < $5.)
  - Dominated by xformer and striker
    - Surface mount and tighter mounting easily possible!

Cleaner Prototype (ML sponsor)



Performance



- ~0.5 mJ at 3 Volts per push
- Sends 12-bit RFID 6-8 x throughout wide area (50 ft.)
- More power than needed...
- Demo!!

Improvements...

- We have more power now than needed for the current application, but…
- Power can be increased by:
  - Using a fast-start, high-frequency switching regulator instead of the series regulator
    - More components…
  - Improving strike mechanics and electrical mismatches/losses
- Multiple button layouts
- Handshaking for reliable/secure data xfer?

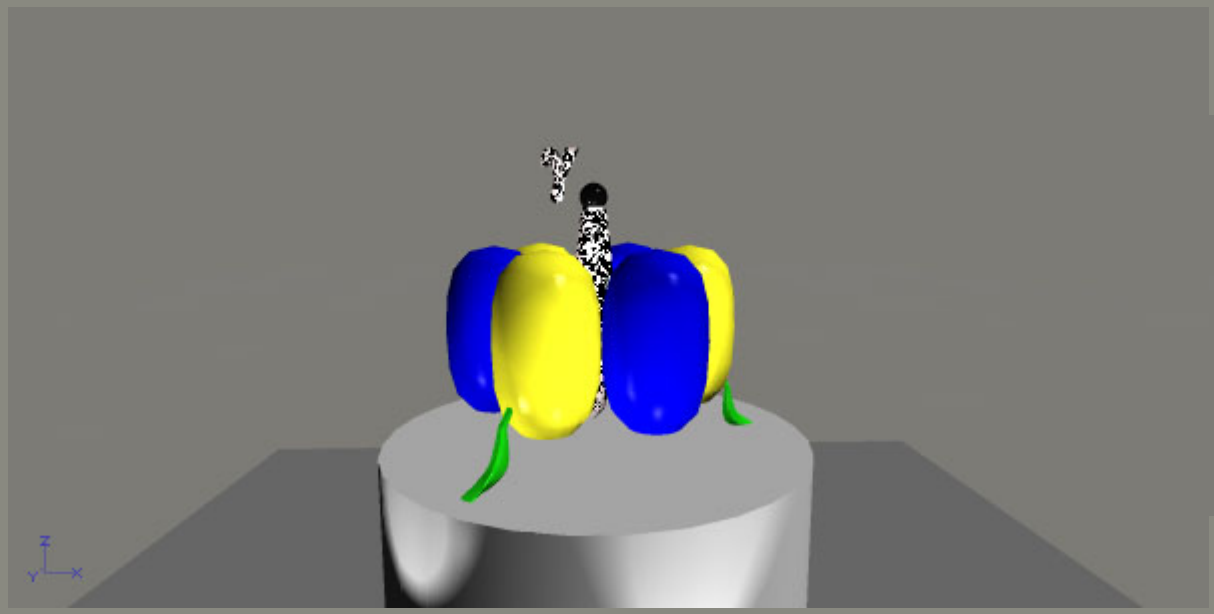
Into the Body...

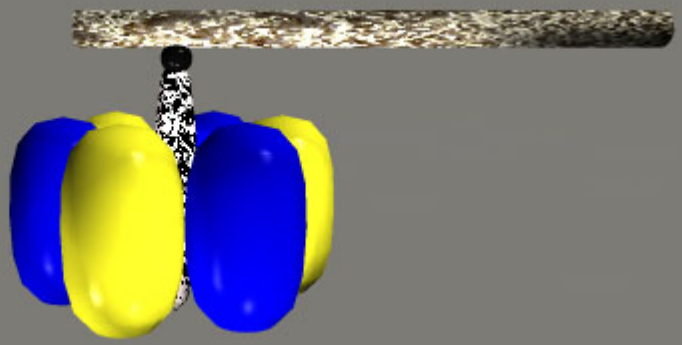
Adam Heller, University of Texas

- Extrapolating from electrochemical detection of glucose
  - Adapt techniques for more power
  - Make a sugar-burning bio fuel cell
- Composite electrodes and conductive gels
  - Biologically transparent system
  - Build into a vascular stent
  - Generate electricity from glucose and O_2 in blood
    - 1 cm long x 4 mm wide
    - Can (theoretically) produce up to 1 mW
      - 1-3 weeks of power from equal-size battery
- In-vitro low power or low duty-cycle medical systems
  - Low-bandwidth biosensors
  - Valve for the incontinent

There's room at the bottom...

Carlo Montemagno, Cornell University

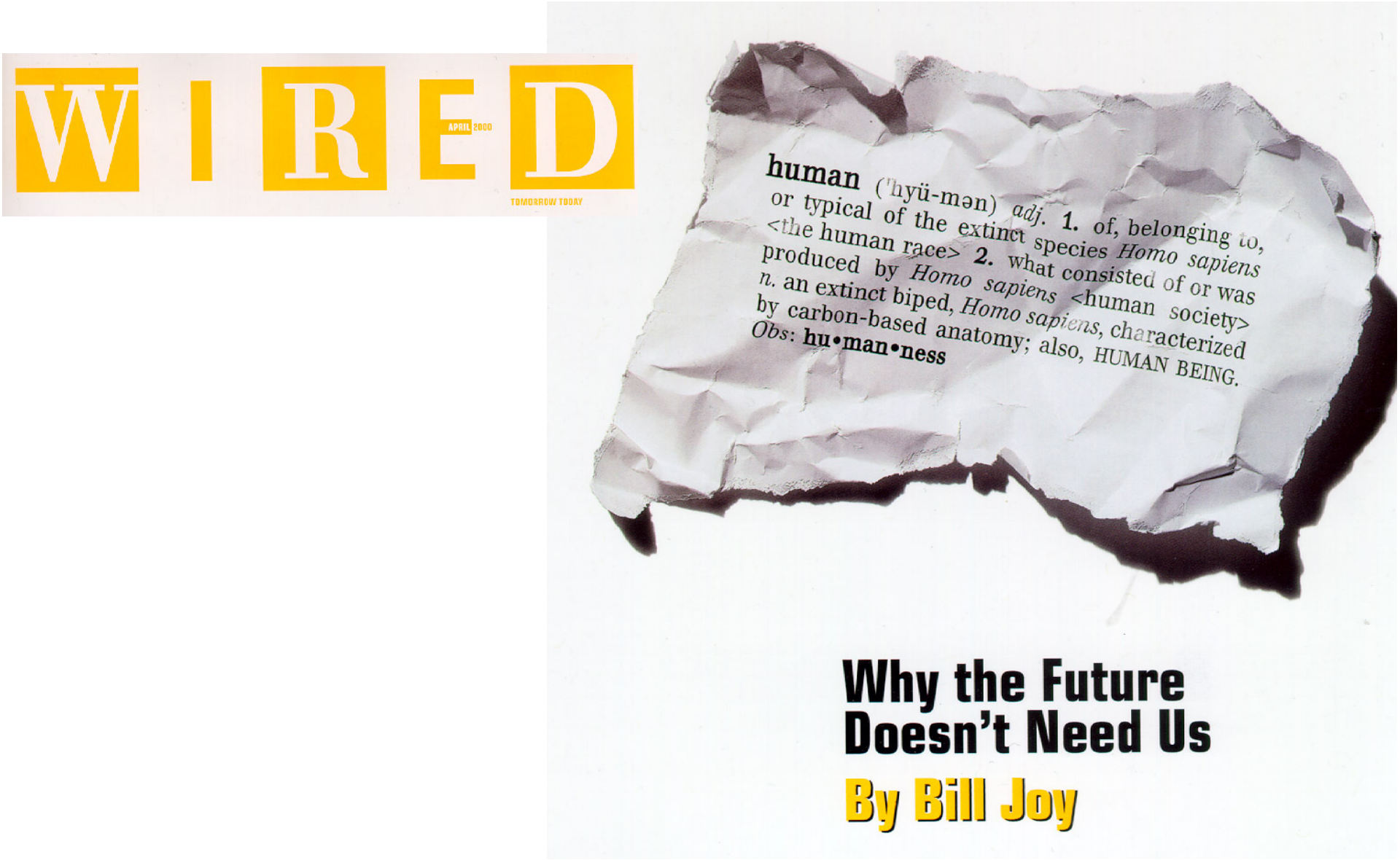




http://falcon.aben.cornell.edu/

- **ATPase Molecular Motors**
  - **Fueled by ATP (adenosine triphosphate)**
  - **Ubiquitous biological carrier molecule**
  - **"Base" attached precisely to sites on lithographed substrates**
  - **Various constructs attached to rotor**
    - **Actin filament, microspheres**
  - **Chemically-controlled rotation**
    - **Seen to run for 40 minutes at 3-4 rps**
    - **Nanovalves, nanopropulsion, ??**

…Where will it end??



Reality Check...

The Matrix, film by the Wachowski Brothers, United Artists 1999

- **We are dim bulbs…**
  - **A resting human dissipates about 100 Watts**

They will use us in more creative ways...

Acknowledgements

- Marc Doyle - DuPont (fuel cells, batteries, solar power)
- Bob Norwak - DARPA (energy harvesting program)
- Marty Schmidt, Anantha Chandrakasan - MIT MTL
- Nesbit Hagood - MIT Aero/Astro
- Kinya Matsuzawa and Masakutsu Saka - Seiko Epson
- Anton Bally - ETA
- Jean-Pierre Fleurial - NASA/JPL
- Bruce Lanning - ITN
- George Taylor - OPT
- Adam Heller - University of Texas
- Rob Pelrine - SRI
- Jerry Hallmark - Motorola Energy Group
- Carlo Matimagno - Cornell University
- Robin Miller - United Technologies Research Center