

High efficient energy harvesting using piezo macro fiber composites on vibrators with optimized energy transfer

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Smart Material Corp.

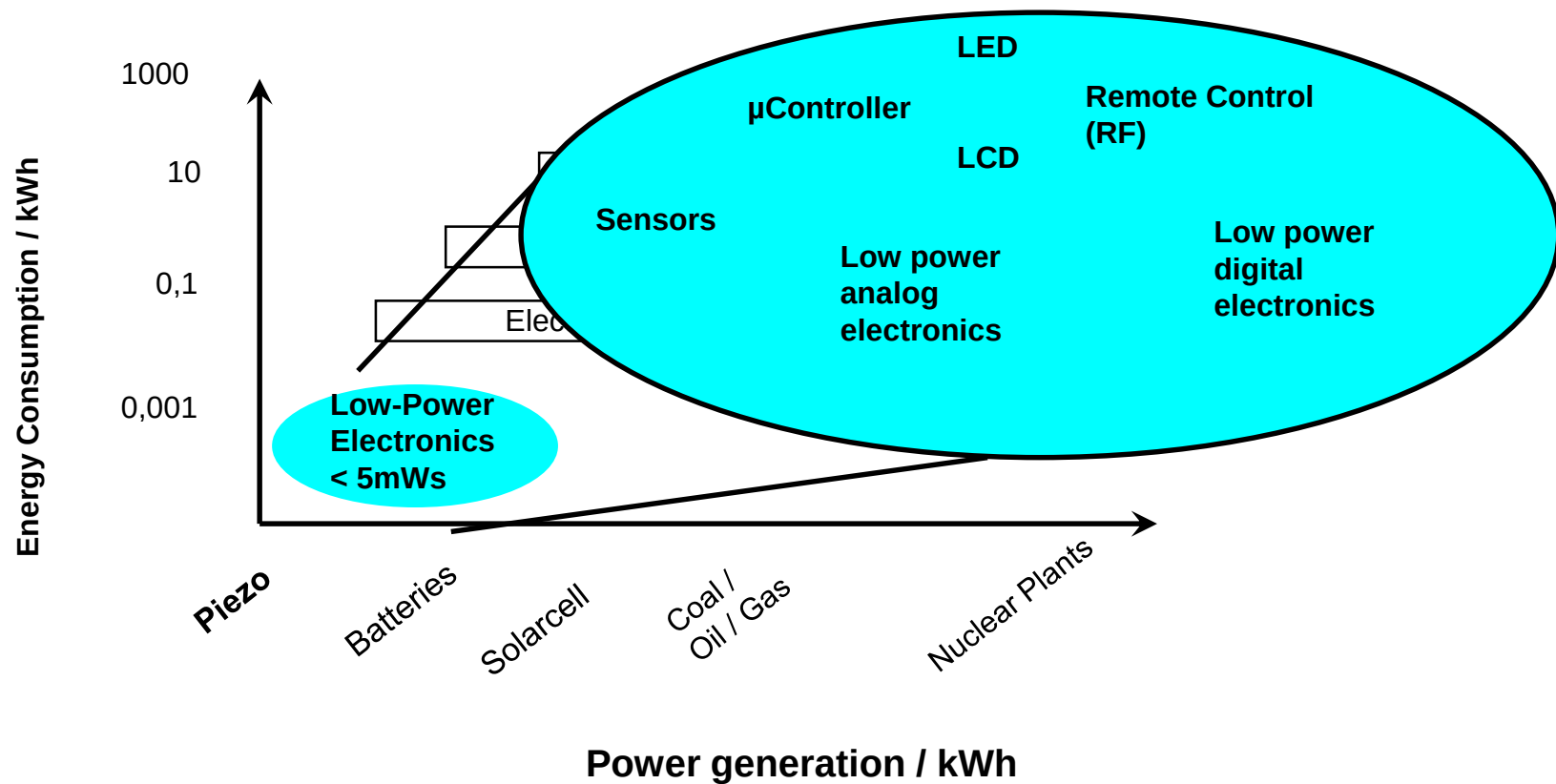
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Outline

- Introduction
- Basics of using MFCs for Energy harvesting
- Test Setup and Components
- Results and Measured Data
- Recommendations and Conclusion

Piezo ceramic energy harvesting = LOW POWER



Vibration Harvester – Typical Design & Challenge

Vibration Harvester –

Piezo ceramic device,
resonant with Cantilever,
non resonant

Integrated Energy Management - Conditioner

Rectifier, Impedance Matching,
Energy Storage, Stabilizer

Electronic Consumer -

Sensor, Amplifier, Micro
Controller, Radio
Transceiver

Strain, Acceleration,
Frequency

Power Output ?

Custom design or
Off the shelf
Conditioners ?

Power Consumption
over time, operating
voltage

Power requirement and Vibration Modes

Vibration Synchronous

Power requirements are synchronous with Vibration and maximum power needed is always **< harvested energy**

simple sensors, RFIDs, Visual feedback applications

Vibration Synchronous & Burst

Power requirements are synchronous with Vibration but power intermittent powers bursts requiring **energy storage**

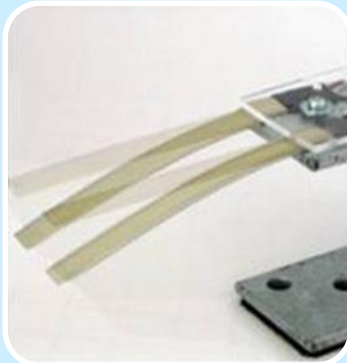
Intermittent Radio transmitter “telemetry” devices, SHM

Vibration Asynchronous

Power requirements continuously, Vibration is intermittent and/or varies over time, **long term energy storage and management**

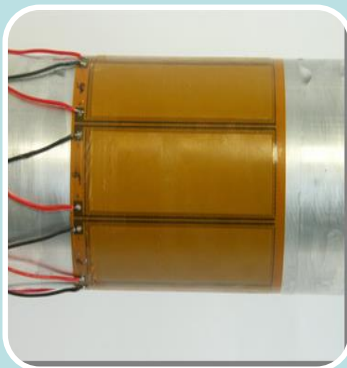
Complex Structural Health Monitoring Devices, Storing RFIDs, Event Monitoring Devices

Resonant vs. Non-resonant Vibration Harvesting



Resonant – mechanical transfer of vibration, Cantilever

- Acceleration (G's) and frequency main design input
- Mechanical transfer allows to adapt operation based on prevalent vibration frequency
- Optimum energy harvesting at discrete frequencies
- Often bulky device, not suitable for large frequency range



Non Resonant - directly attached to strain area

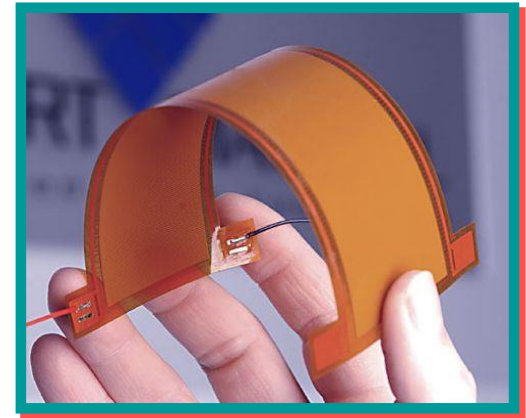
- Strain and frequency is main design input
- Piezo harvester is attached directly to maximum strain – area, very small mechanical harvester possible
- Normally not operating at resonance – lower yield
- Capable of harvesting from broad frequency spectrum

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- **Basics of using MFCs for Energy harvesting**
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MFC - good match for vibration energy harvesting

- MFC – Macro Fiber Composites developed at NASA LaRC during the late `90s
- **Actuator** (1Hz to 10kHz)
- **Sensor** (0.5 Hz up to 500kHz)
- **Flexible** and **robust**, ready to use package, overcomes disadvantages of solid PZT plates or patches based on solid wafers
- **Reliable**, > 10^9 cycles as actuator and > 10^{10} cycles for energy harvesting
- Broadband, allows for easy **non-resonant** and **resonant** energy harvesting applications
- Encapsulated and fault tolerant
- Integration of electronic components possible



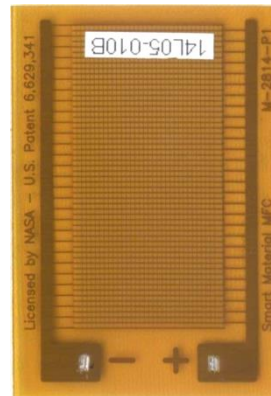
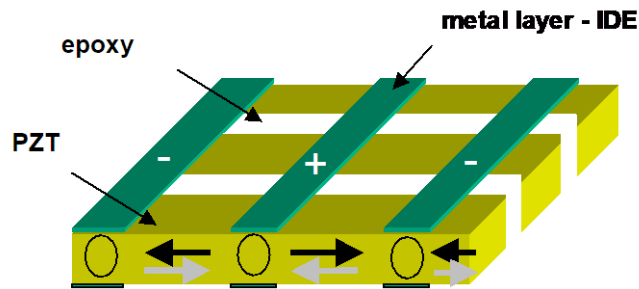
Typical Applications for MFCs

- Vibration and Noise Control
- Strain gauge
- Health Monitoring Systems
 - Passive and active acoustic emission spectroscopy
 - Resonance shift detection
- Adaptive Structures
 - Morphing and Shaping of structures
- **Energy Harvesting from Environmental Vibrations**



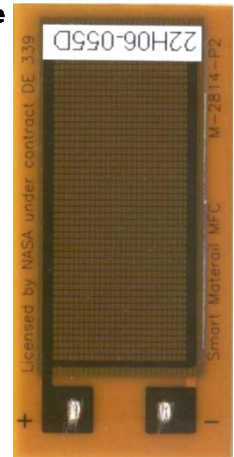
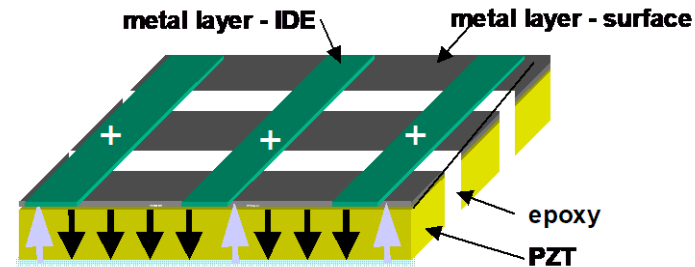
MFC – available in d33 and d31 operational mode

P1-Type MFC (d33)



Elongator

P2-Type MFC (d31)



Contractor

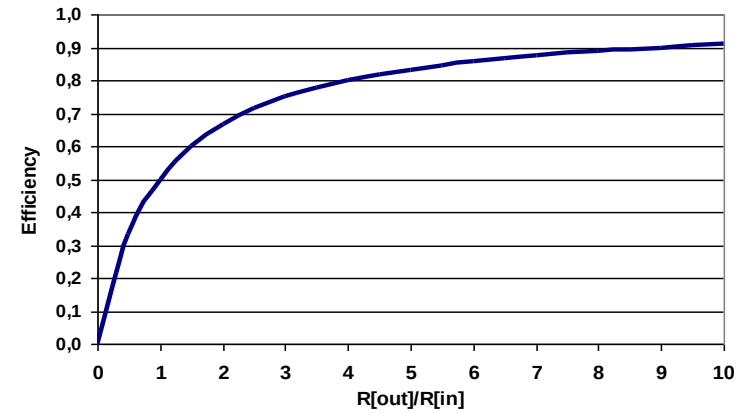
Device	Operation voltage		Capacity	Sensor characteristic		Actuator characteristic	Generator characteristic
	V_{op}^+ [V]	V_{op}^- [V]		d_{33}^{eff} [pC / N]	d_{31}^{eff} [pC / N]		
3-3 MFC	1500	-500	0,42 [nF / cm ²]	460	-	Strain / Volt. [μstrain / V] 0 ... 1500V	Charge/Strain [pC / ppm] [> 100V]
3-1 MFC	360	-60	4,5	-	-370	- 2 [0 ... 360 V]	3250 [< 100 V]

Basics of power transfer in active dipoles - Compromise

Efficiency

$$\eta = \frac{P_{out}}{P_q} = \frac{R_{out}}{R_{in} + R_{out}}$$

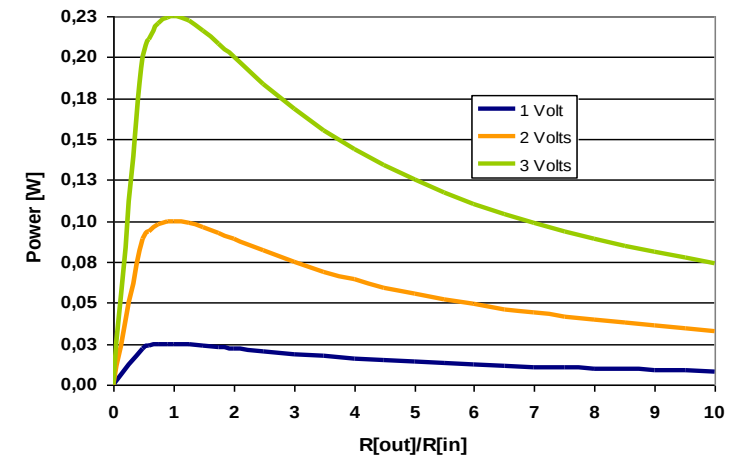
$$R_{out} \gg R_{in}$$



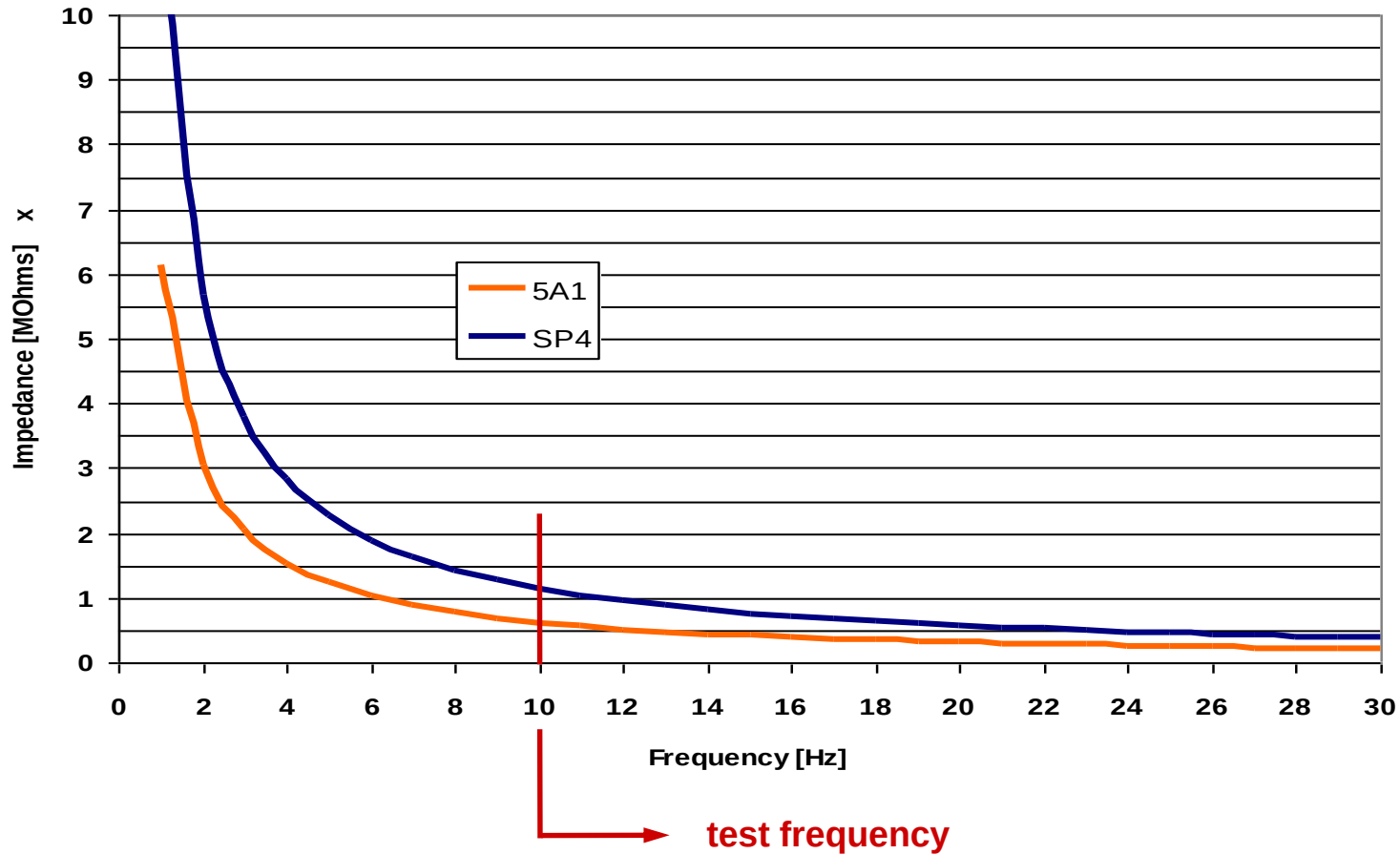
Energy Transfer

$$P_{out} = U_q^2 * \frac{R_{out}}{(R_{in} + R_{out})^2}$$

$$R_{out} = R_{in}$$



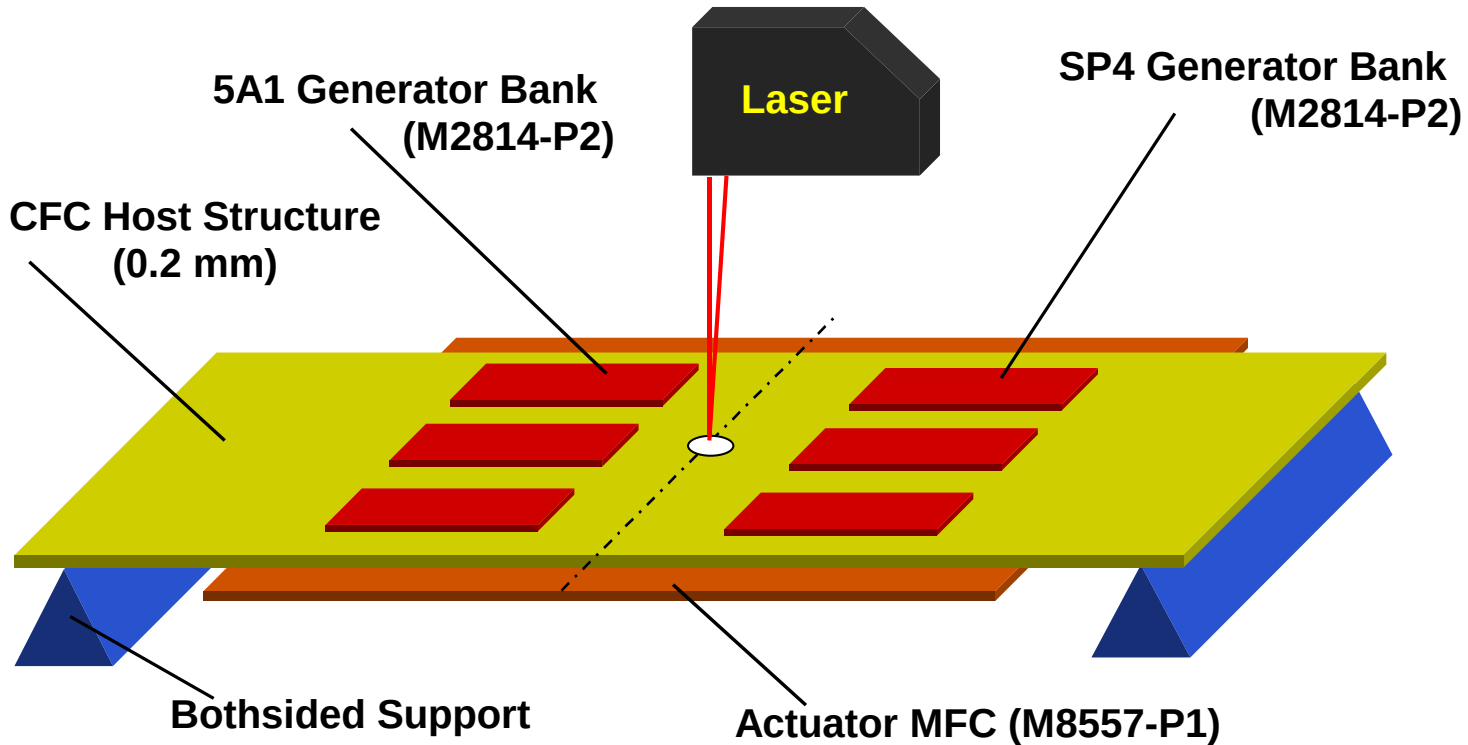
Dynamic impedance behavior for the M2814P2 (4 cm²)



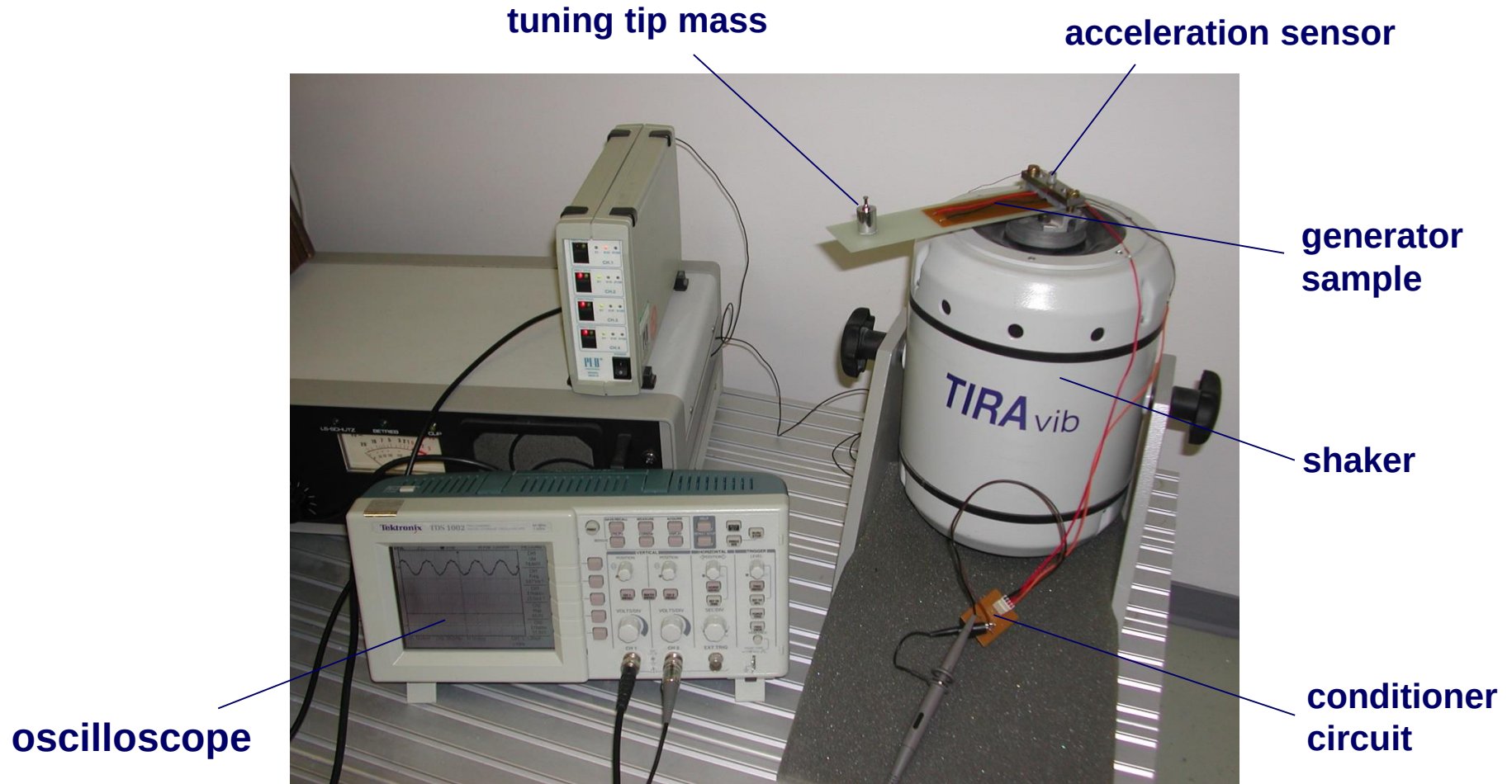
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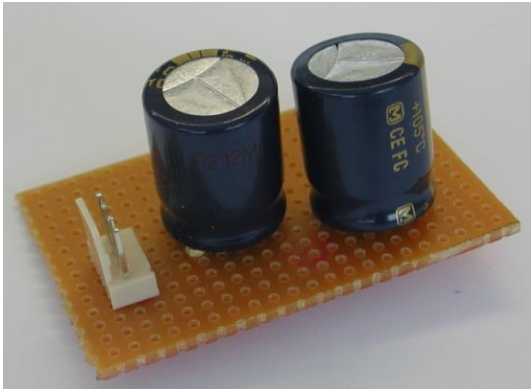
Setup for Strain measurements – non resonant



Setup for acceleration – resonant with cantilever



Conditioner – critical for optimized energy transfer

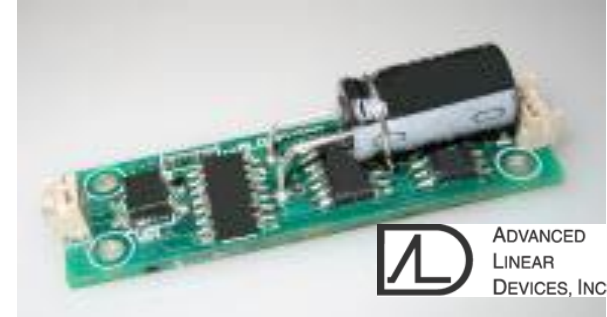


Schottky rectifier / 609 μ F

Simple circuit but good for
basic measurements

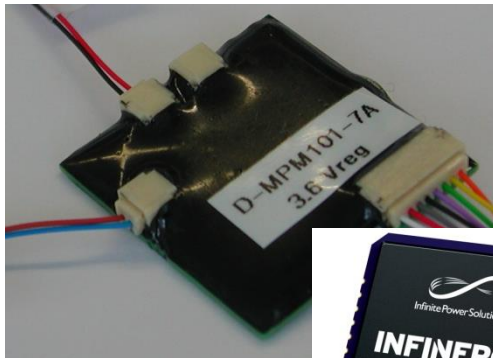


dynamic input impedance for
good power matching



EH 300

ADVANCED
LINEAR
DEVICES, INC.

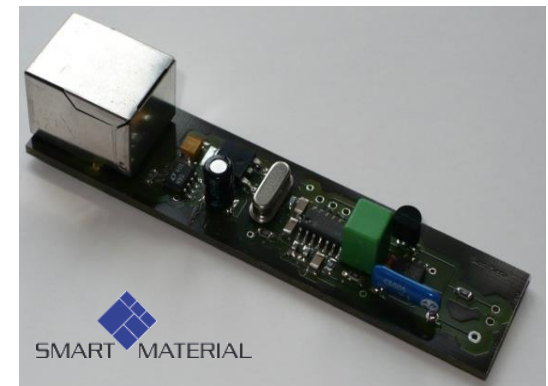


MPM101-7A

excellent leakage-free
battery cell



Special input impedance matching
for MFC generators



Smart EH Module

SMART MATERIAL

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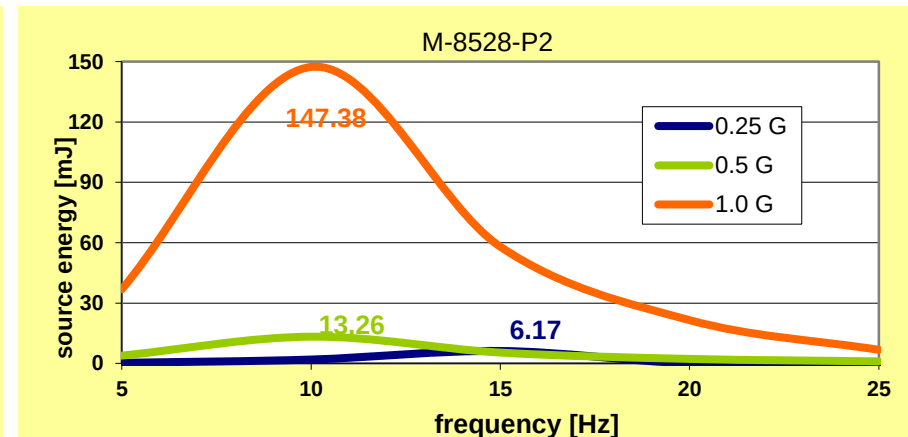
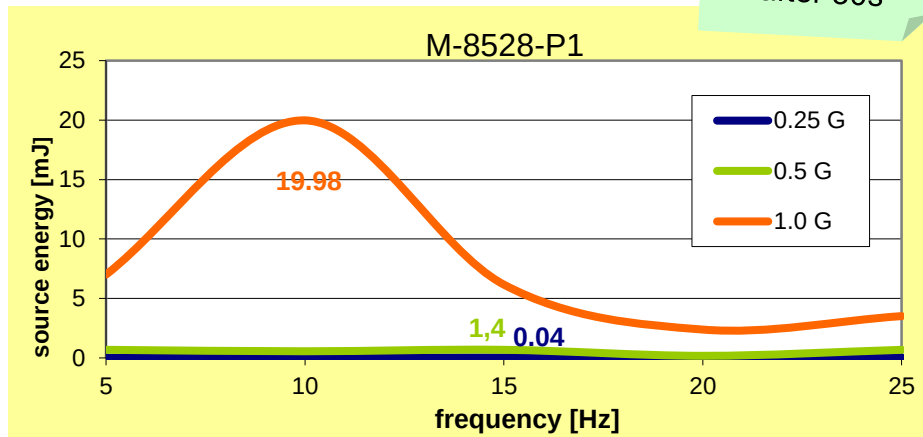
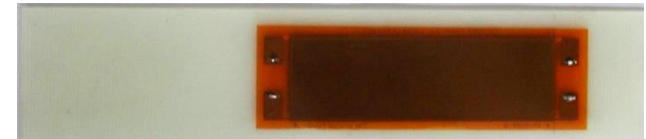
Generator characterization – resonant mode

d_{33} generators (P1; interdigitated electrodes) vs. d_{31} generators (P2; surface electrodes)



Energy:

609 μF
capacitor
after 30s



➤ P2 type MFCs (d_{31} effect) about 7 times better generators due to larger surface and lower source impedance

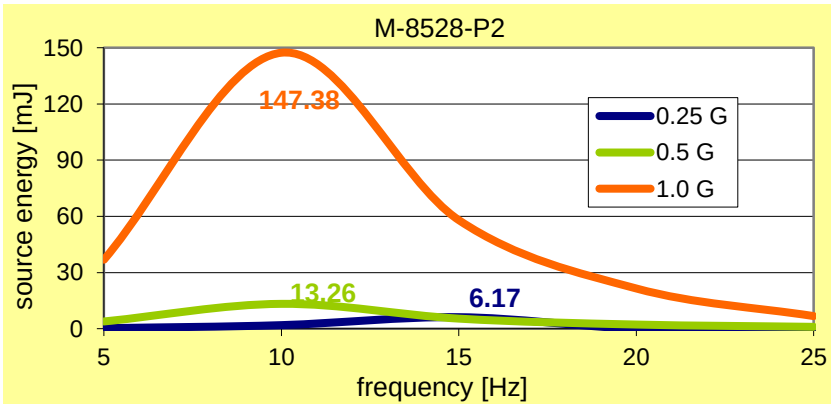


➤ Output energy is a function of

- frequency
- source impedance matching
- Deflection as a function of acceleration/frequency

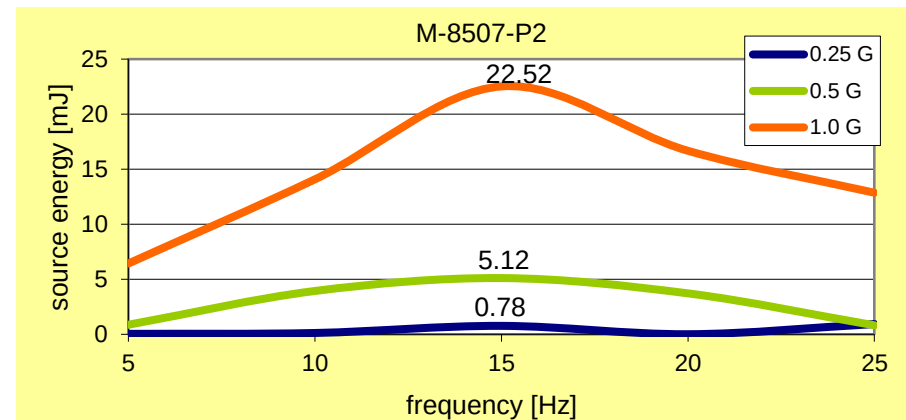
Different sized Generators – Size matters

85mm by 28mm
active area

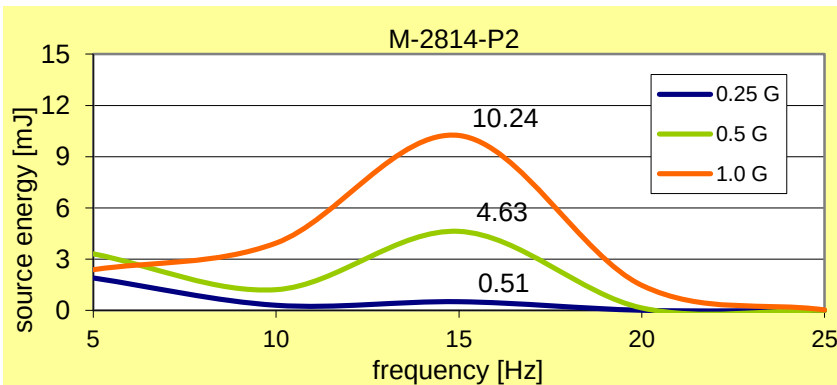


energy across
a 609 μF capacitor
after 30s

85mm by 7mm
active area

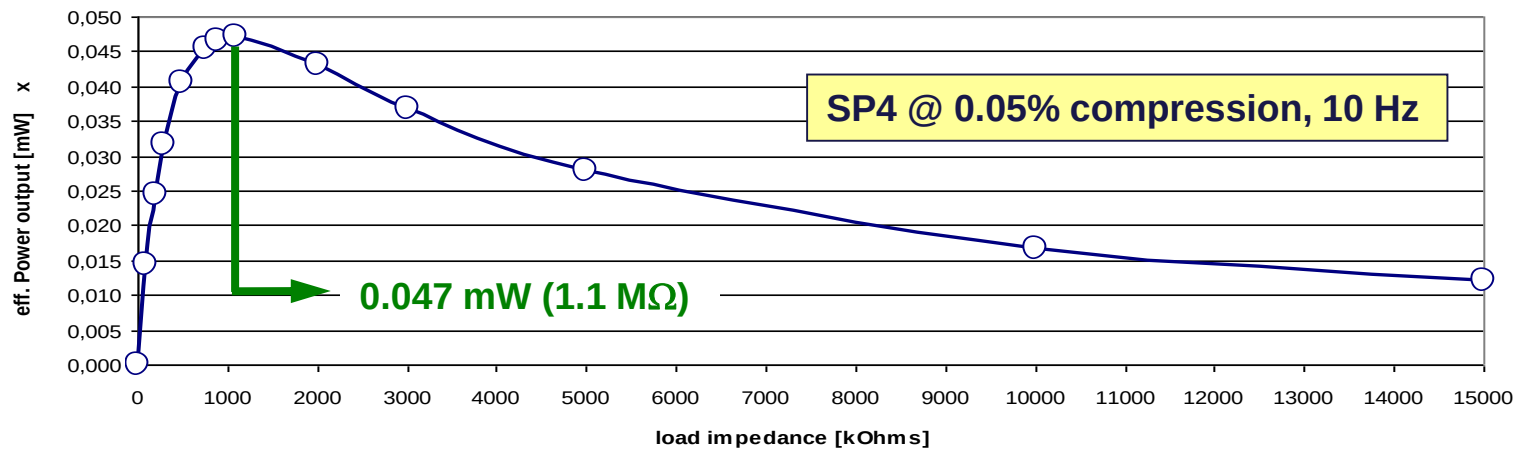
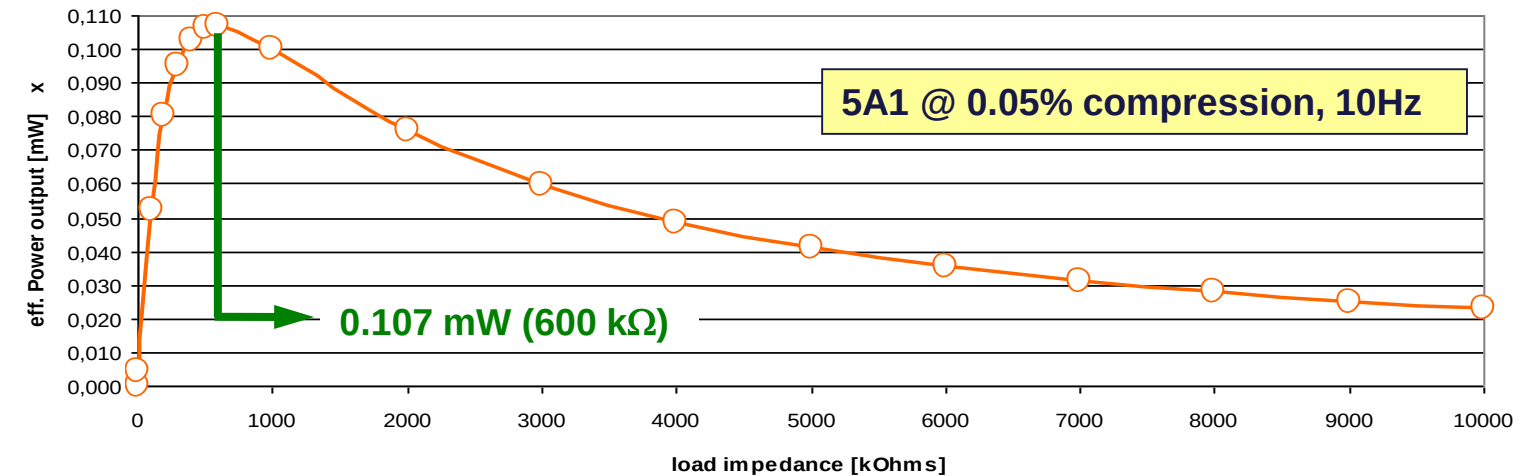


28mm by 14mm
active area



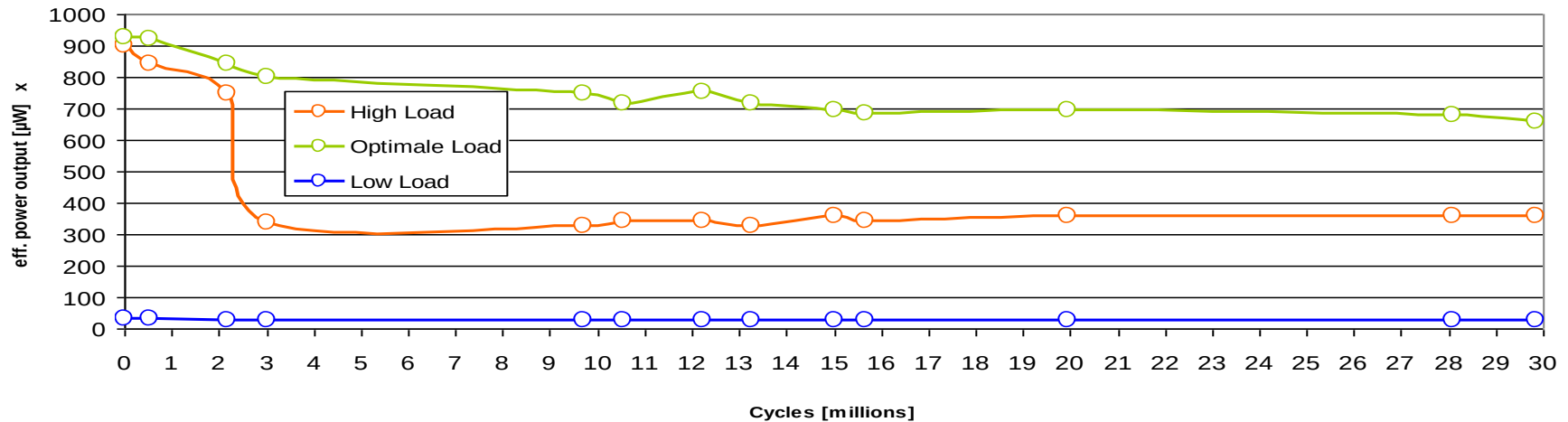
- harvested energy ~ to size
- select width over length
- position at max. strain position

M2814P2 power matching results at Nominal Strain

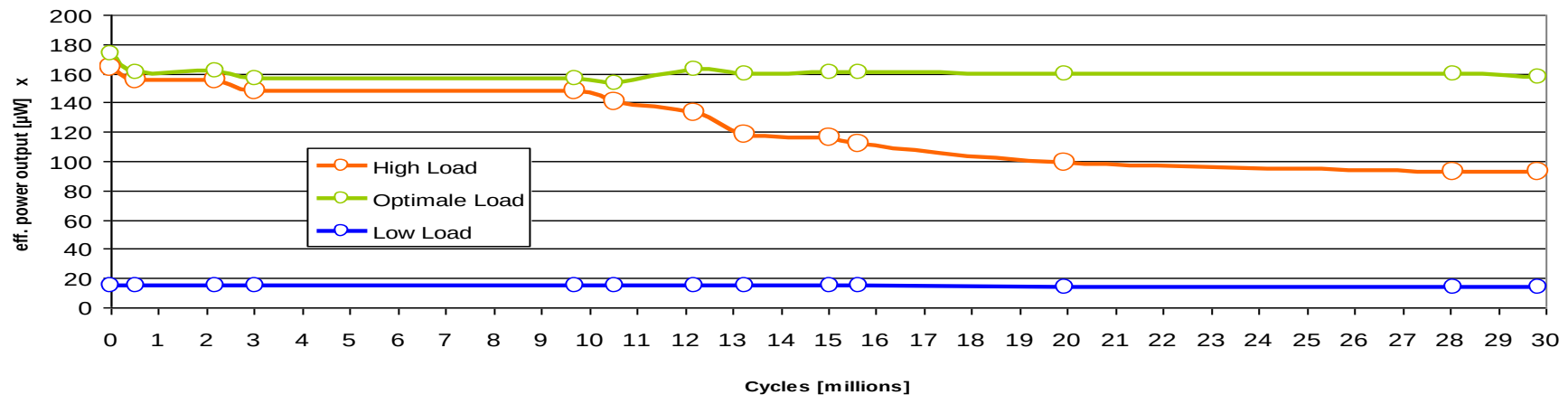


Power output @ 0.15 % compression and 10Hz

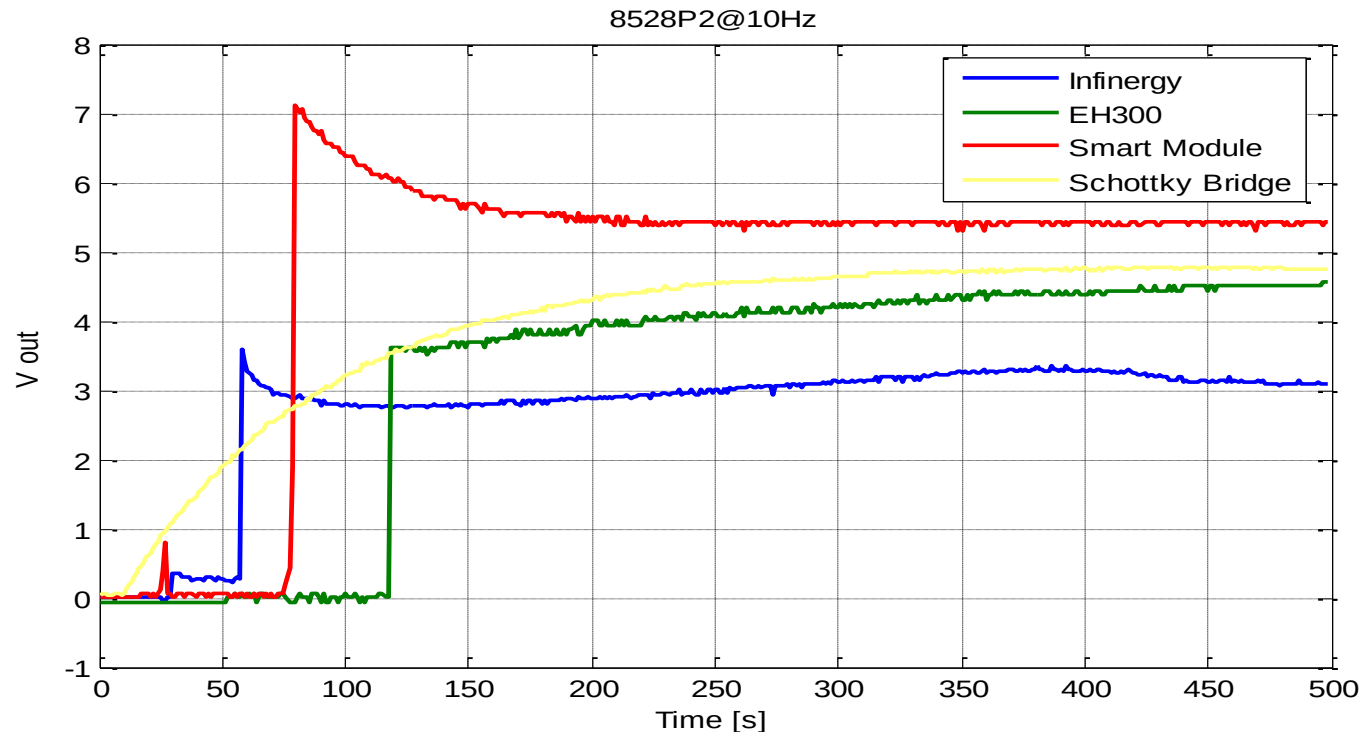
M2814 P2 - 5A1



M2814 P2 - SP4



Conditioner at 10Hz – good performance for all



- At 10Hz, 1G the M8528P2 is providing approx. 4mWs
- All managed circuits have discrete “on” voltage threshold
- Time between beginning of harvesting and first “switch on” difficult to determine for battery based systems => unknown charge status
- Better impedance matching of the Smart Module allows for highest power transfer

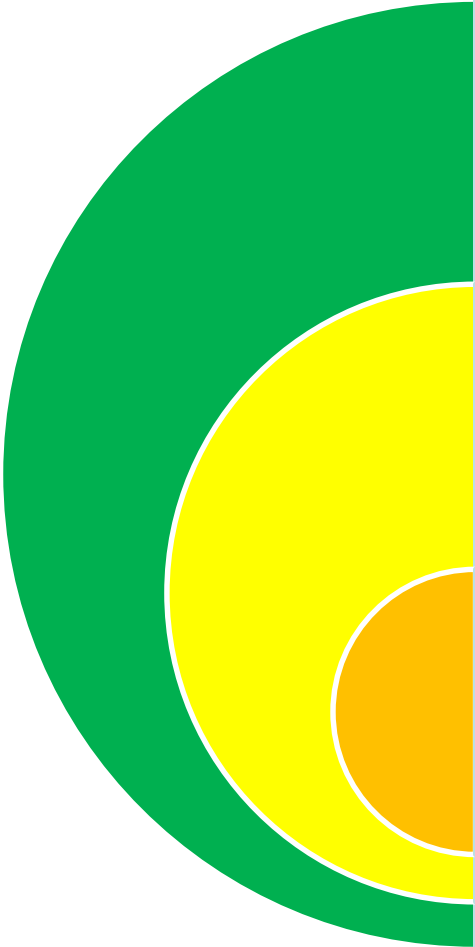
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Basic Design Rules for harvesting from environmental vibration

1. **Non resonant approach:** Check for typical strain and frequency using strain gauge and/or laser vibrometer, locate nodes of high strain best suited to attach MFCs
2. **Resonant approach:** Check for acceleration at single frequency using accelerometer, clamp cantilevered MFC at point of highest acceleration
3. For long life (> 10 years) best strain range for P2 MFC is 100 to 500ppm. Strain up to 1500ppm is permissible at reduced life expectancy. Maximum tensile strength is 4000ppm.
4. Best frequency range for low dynamic impedance (R_{in}) and life time is 10Hz to 500Hz
5. Adjust MFC size and PZT material according to required charge generation, complex relation but ballpark estimate
 - At 500 ppm, 10Hz, approx. $30\mu\text{Ws}/\text{cm}^2$ (5A1 PZT)
 - At 1G, 10Hz resonant mode approx. $200\mu\text{Ws}/\text{cm}^2$ (5A1 PZT)
6. **Adjust rectifier/load balancing electronic, i.e. Conditioner** for optimal load impedance, typical use of harvested energy to select available intelligent rectifier electronics

Storage retention, energy density => Battery



Thin film Batteries	• < 8% self discharge p.a. • highest energy density, size
Super Caps, Multi Layer Tantals	• Self discharge to 60% in 30 days • $\frac{1}{4}$ energy density of battery
Standard electrolytic capacitors	• Self discharge to 60% < 3 hours • $\frac{1}{8}$ energy density of battery, inexpensive

Best (cost, efficacy) Conditioner applied

Vibration Synchronous

Power requirements are synchronous with Vibration and maximum power needed is always **< harvested energy**

Schottky Bridge with Cap

Vibration Synchronous & Burst

Power requirements are synchronous with Vibration but power intermittent powers bursts requiring **energy storage**

Schottky Bridge, EH300 device with Super Cap

Vibration Asynchronous

Power requirements continuously, Vibration is intermittent and/or varies over time, **long term energy storage and management**

Infinite Power, Battery Technology

Conclusions

- **Design of Piezo Harvester** requires specific and careful adaptation to each targeted vibration source for maximum efficacy and energy transfer.
- **Correct impedance matching of Piezo Harvester** single most important design input for optimized energy transfer
- Many standard available Conditioners are designed to accommodate a variety of energy harvesting components (i.e. solar, electro magnetic, etc) => **sensitive impedance matching** for piezo ceramic devices is often not optimized (yet).
- **Thin film battery solutions** appear to be the best approach for long term managed energy storage especially in asynchronous energy harvesting applications
- Non-resonant applications still require system design for the Conditioner for optimum efficacy
- A **simple and well designed Schottky bridge** with capacitor can still be the best solution for synchronous applications!
- A good Conditioner for a piezo ceramic harvester will **require adaptive or adjustable impedance matching** and a combination of cap and battery storage with a smart charging management

Supporting Slides

Testing the Conditioners - parameters

- Acceleration constant 1G
- Frequency 5Hz, 10Hz, 15Hz based on power distribution for energy harvester

Energy Harvester

- M8528P2
- mounted on glass fiber cantilever
- Optimum energy output at about 10Hz@1G

Conditioner

- output voltage between 3V – 6V

Consumer

- resistive 15kOhm load
- at 3-6V simulates 650 μ W to 1.6mW consumer

Emerging Applications using PZT Harvester

- Telemetry and Condition (Health) Monitoring, typical 100-400 μ Ws
 - airplanes, helicopters
 - automotive crash sensors
 - wind generator blades
 - bridges and other high rise structure with “vibrations”
 - medical devices used by patients



Applications cont'd

- Backup chargers for applications using rechargeable batteries, typical $500\mu\text{Ws}$
 - Buoys
 - Active RFIDs
- “wake-up” circuits for dormant electronic circuits, typical $< 100\mu\text{Ws}$
 - Sealed and/or submersed Alarm systems
 - Door entries

