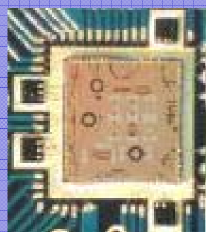
Wireless Sensor Networks

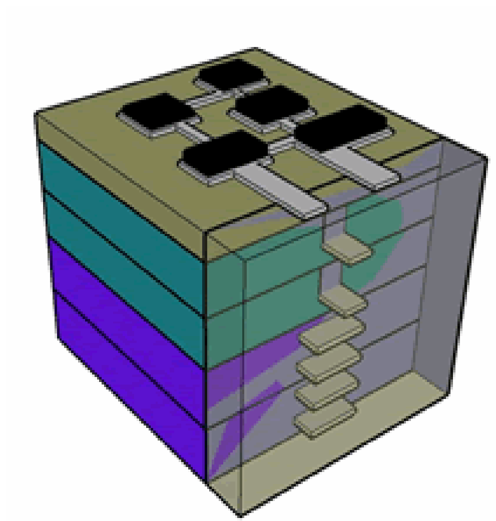
Low Power Radio



"Disappearing Computer"

B. Gates, *Economist* (2003)

Energy Storage



"Picocube"

Sensor

Renewable Power Supply

MEMS Sensors for Electric Power Measurement

Eli Leland, Giovanni Gonzalez, Christopher Sherman, Peter Minor

Presentation to the DR-TAC

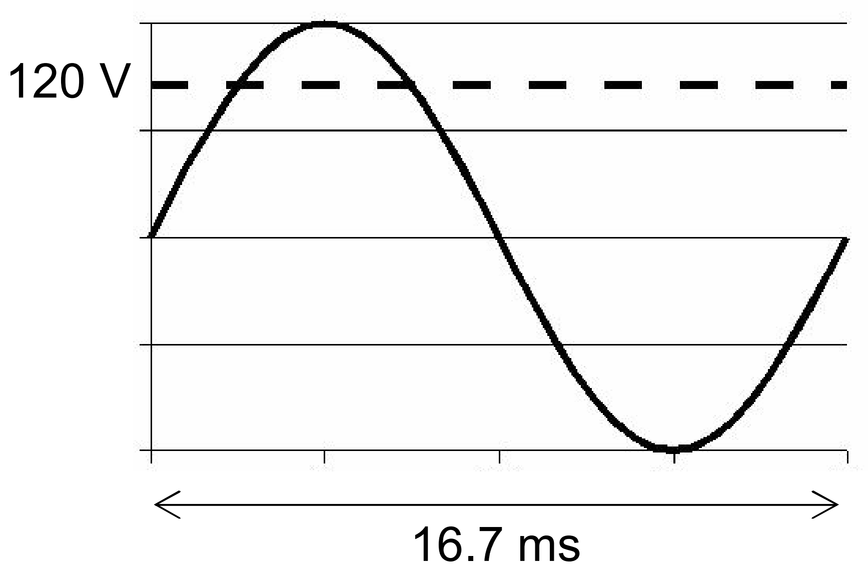
February 19, 2008

If you remember nothing else…

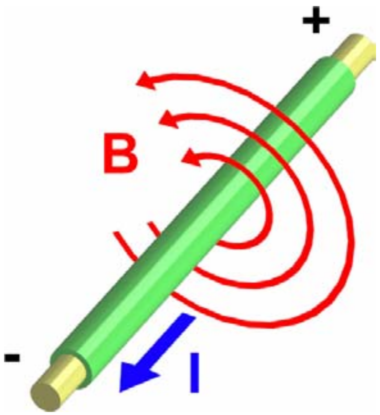
- Passive, proximity-based electric current sensors work at the meso-scale
- MEMS-scale devices are feasible in theory, and we're working on the cleanroom process
- Sensors for distribution cable monitoring and AC voltage sensing are under development

Wires and magnetic fields

- Electric power is 60 Hz AC in the Americas, 50 Hz in Europe
- Voltage and current are sinusoidal – rated value is root-mean-square (rms)
- Magnetic field surrounding a current-carrying wire is circumferential (right-hand rule) and alternating



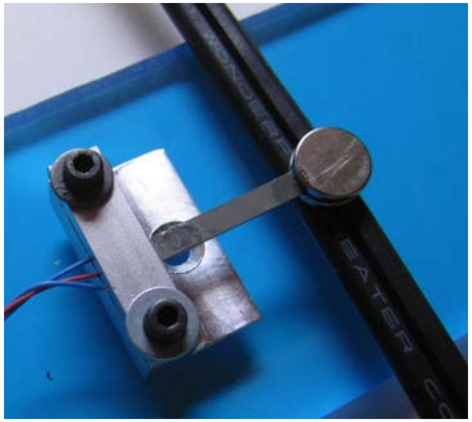
$$P_{avg} = V_{rms} I_{rms} \cos(\phi)$$

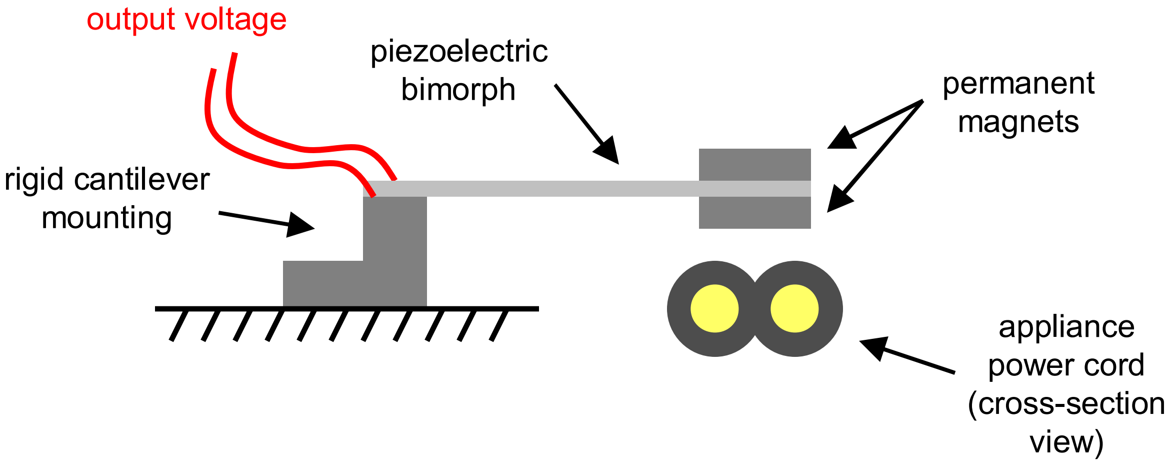


$$B_{air} = \frac{\mu_0 i}{2\pi r}$$

Current sensor design concept: Permanent magnets and piezoelectric materials

- Permanent magnets can couple to the magnetic fields surrounding AC current carriers
- Piezoelectric materials can transduce the forces on the permanent magnet to an output voltage
- Sensor device does not require power supply or wraparound of conductor





What do these fields and forces look like?

- Zip-cord magnetic intensity field
  - Currents 180° out of phase
  - Fields add along vertical line at center
  - Fields cancel as distance increases

- Force proportional to *grad(H)*

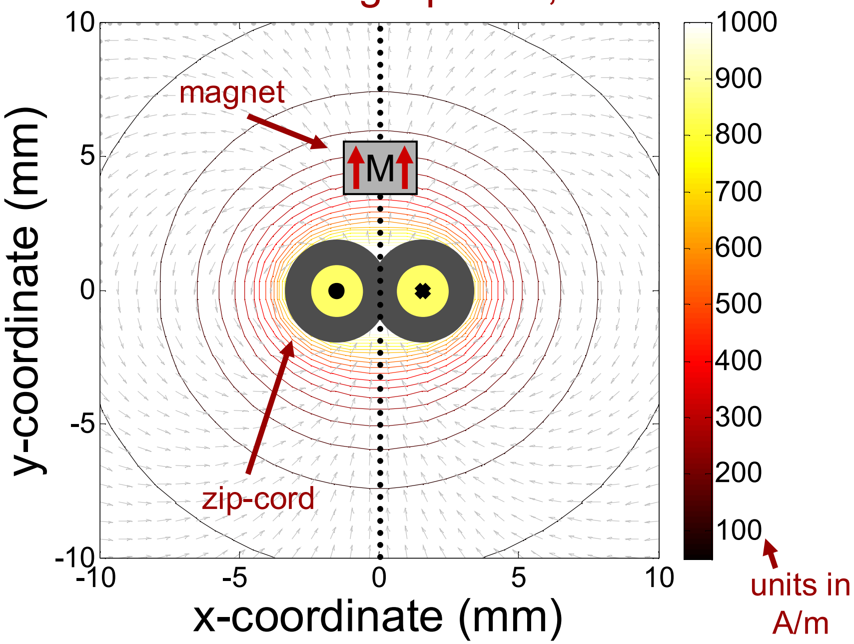
$$F_y = B_r \int \frac{d(H_y)}{dy} dV$$

- *grad(H)* proportional to current

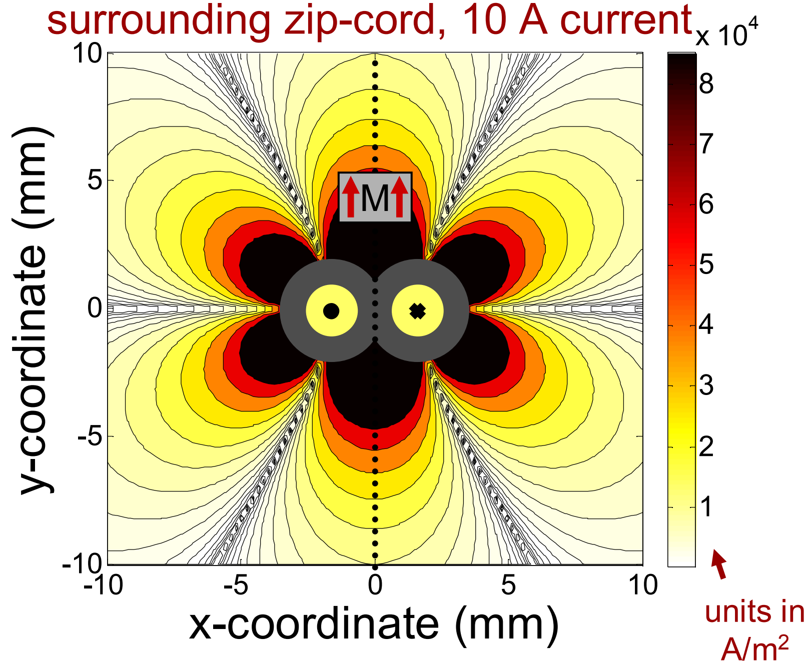
$$\frac{d(H_y)}{dy} = -\frac{i}{\pi}\frac{2dy}{(y^2+d^2)^2}$$

...so force is linearly proportional to current!

H-field surrounding zip-cord, 10 A current



Magnitude of gradient of H_y surrounding zip-cord, 10 A current

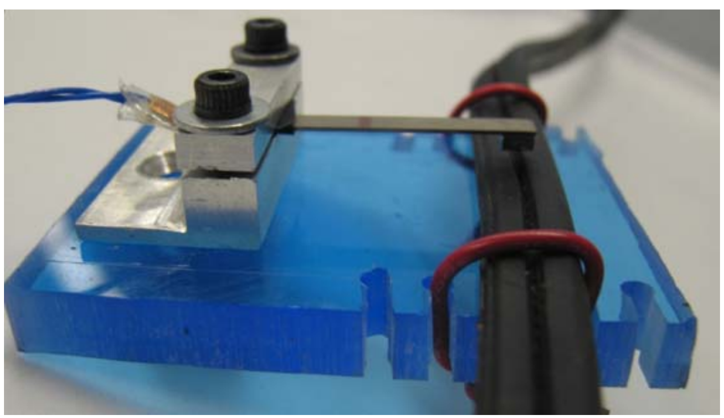


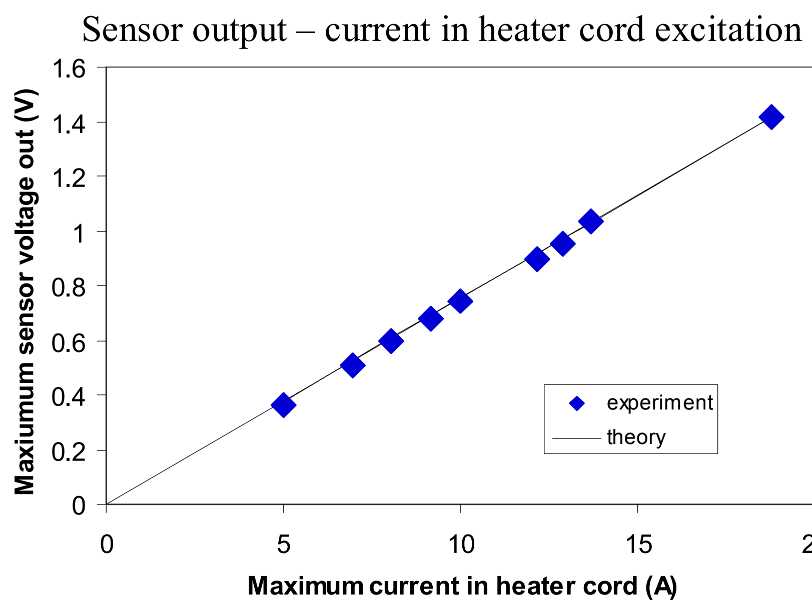
These sensors work, and they show linear behavior

Voltage frequency response function:

$$V_{oc} = F_{in} \frac{c_p d_{31} t_p a_3}{\varepsilon k_2 m a_2} \cdot \frac{1}{\omega_n^{\,2}\left(1 - \frac{c_p d_{31}^{\,2}}{\varepsilon}\right) - \omega^2 - j\left(2\zeta_m \omega_n \omega\right)}$$

For a constant frequency input of 60 Hz (*w = 2p × 60*), the voltage output is a linear function of magnetic input force





Everybody loves PZT, but Aluminum Nitride may be better for this application

	PZT		Aluminum Nitride	
	1 mm cantilever	500 µm cantilever	1 mm cantilever	500 µm cantilever
resonance frequency (Hz)	281	927	434	1425
sensitivity (mV/A)	0.59	0.28	2.4	1.2

$$V_{out} \approx F_{in}\left(\frac{d_{31}}{\varepsilon}\right)K$$

	PZT	AlN
d_{31} (pm/V)	-138	-3
ε_r	1800	9
d_{31}/ε	8.66 x 10^{-3}	37.7 x 10^{-3}

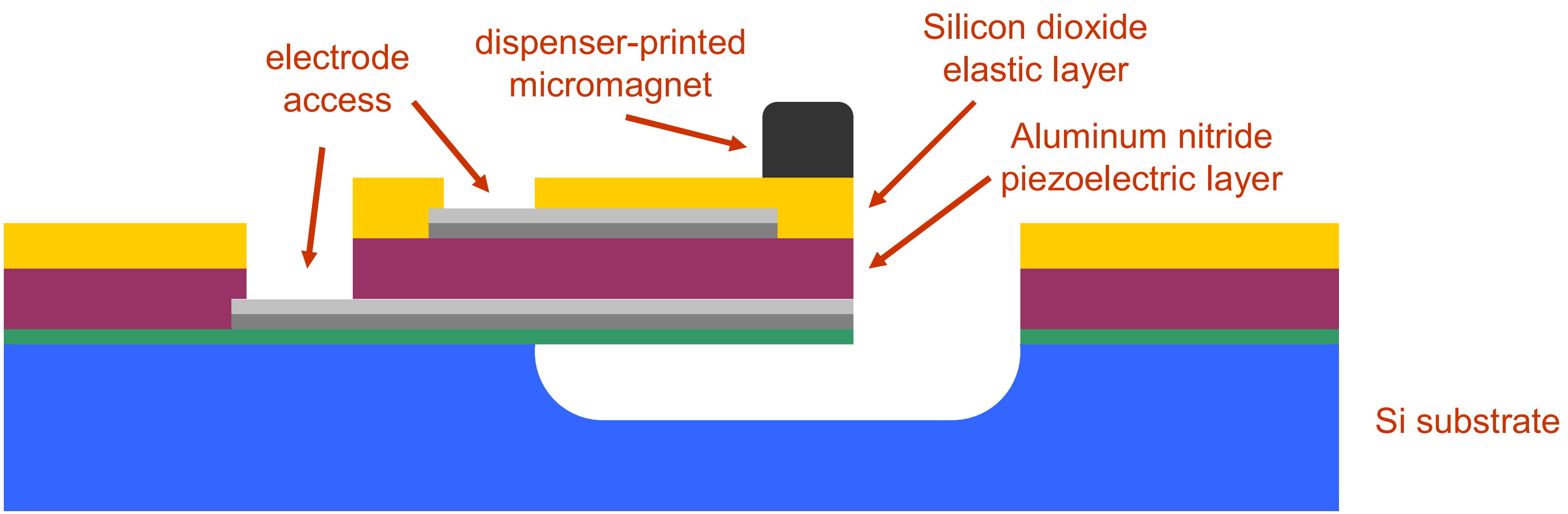
about 4.3x greater for AlN

- Aluminum nitride sensitivities are about 4x those of PZT
- Many AlN devices have been fabricated successfully in the Microlab (UC Berkeley cleanroom)
- Geometry can be optimized to maximize voltage output

Notes: All simulations used 1µm platinum elastic layer and 1µm piezoelectric layer (AlN or PZT). 100µm cantilever width and 100µm x 100µm x 100µm magnet size for all simulations. PZT properties: d_{31} = -141 pm/V, ε_r = 1800, density = 7800 kg/m³, c_p = 66 GPa. AlN properties: d_{31} = -3 pm/V, ε_r = 9, density = 3200 kg/m³, c_p = 350 GPa. Magnet properties: density = 7500 kg/m3, B_r = 0.4 T. Pt properties: c_p = 171 GPa, density = 21450 kg/m³.

Recipe for a MEMS AC current sensor

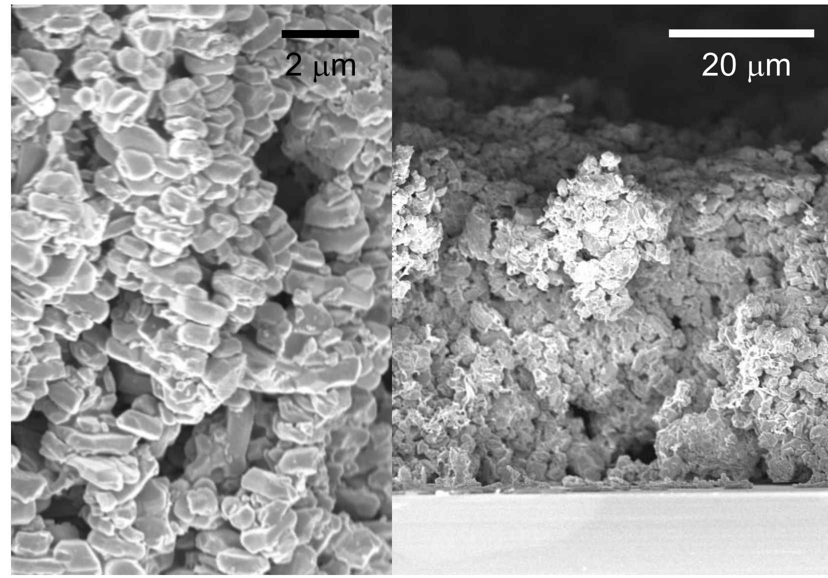
- MEMS sensor fabrication process based on well-characterized recipe for AlN devices (G. Piazza, et al, 2004)
- Magnet can be printed and magnetized before release step

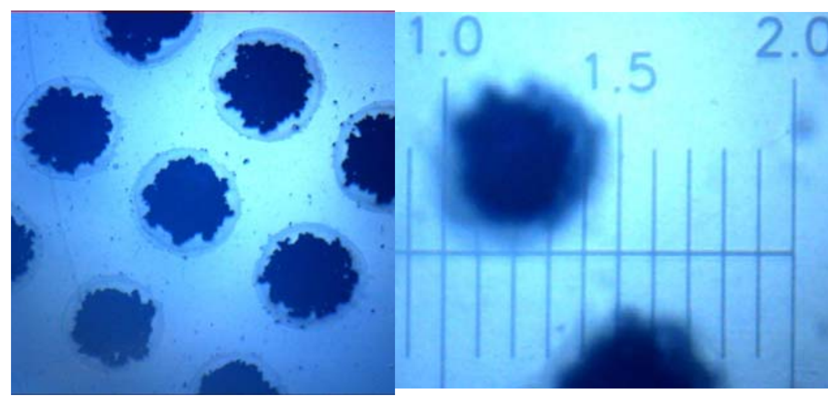


What is a dispenser-printed micromagnet?

- We have made composite magnets using the dispenser printer (Steingart, et al)
- Magnetic powder (SrFe, SmCo and NdFeB) in a PVDF polymer matrix
- They stick to steel!
- They need to be charged with magnetic intensity $H = 2\text{-}3\text{x } H_{ci}$
    - NdFeB: 2-3 Tesla(!!!)
    - Ferrite: 0.4-1 Tesla
    - What's the best way to do this?
- Curing the magnets in an external field may enhance magnetic properties

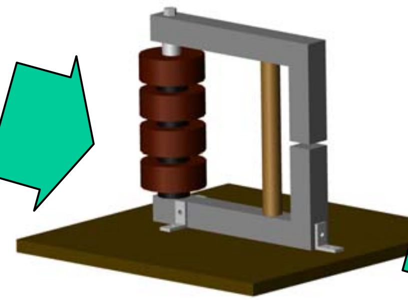
SEM of SrFe-PVDF magnet on Si

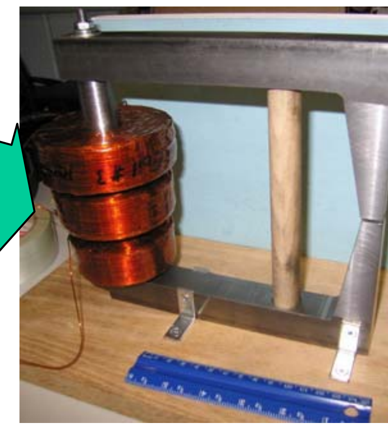




Magnetizing the micromagnets

Following a mishap with the super high-power magnetizing rig…

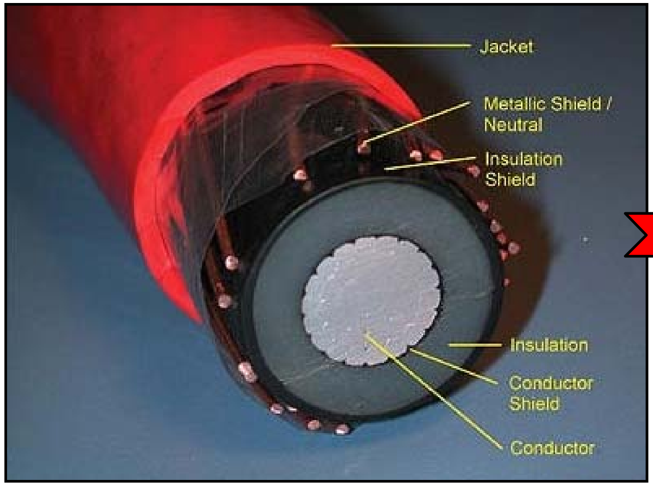


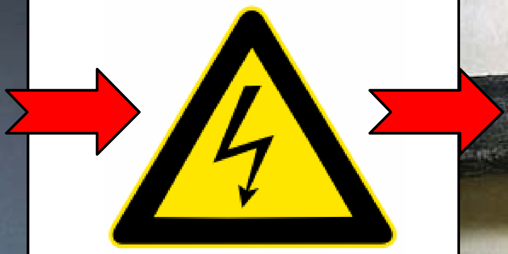


…we decided to take matters in to our own hands and build a benchtop 1 Tesla electromagnet. Sufficient for the ferrite magnets, we'll need to send out the higher-energy samples for magnetization.

Related project: Assessing integrity of high-voltage underground power distribution cables

Goal: To identify cables, operating at 12 kV and above, needing replacement before their failure

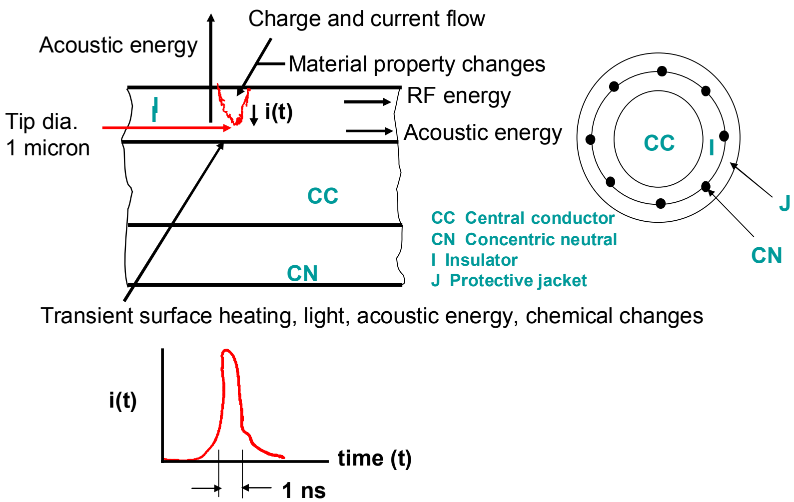


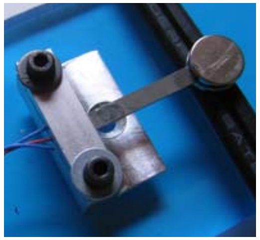


Failure Mechanism: Microvoids and channels form in insulator due to electrical forces, water seeps in and fills them, forms tree-like conducting structure. Ultimately a high-powered brief arc occurs producing damage pictured above.

Proposed cable diagnostic techniques

Distribution Cable, Tree, and Partial Discharge





A. Near cable ends where concentric neutrals are all connected together and grounded, use MEMS-based current sensors to measure current in each concentric neutral (CN) wire. Detects open CNs (no CN current flowing). Asymmetric CN currents may indicate presence of potentially destructive water trees near those CNs.

B. Use concentric neutrals as transmission line to probe cable insulator. Launch test pulse by capacitive coupling of Electrostatic Discharge Simulator (gift from Kikusui Co.) to a CN wire beneath insulating jacket (J). Pulser produces up to 30 kV, 60 ns pulse. Use to sample cable for water trees.

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Thanks!