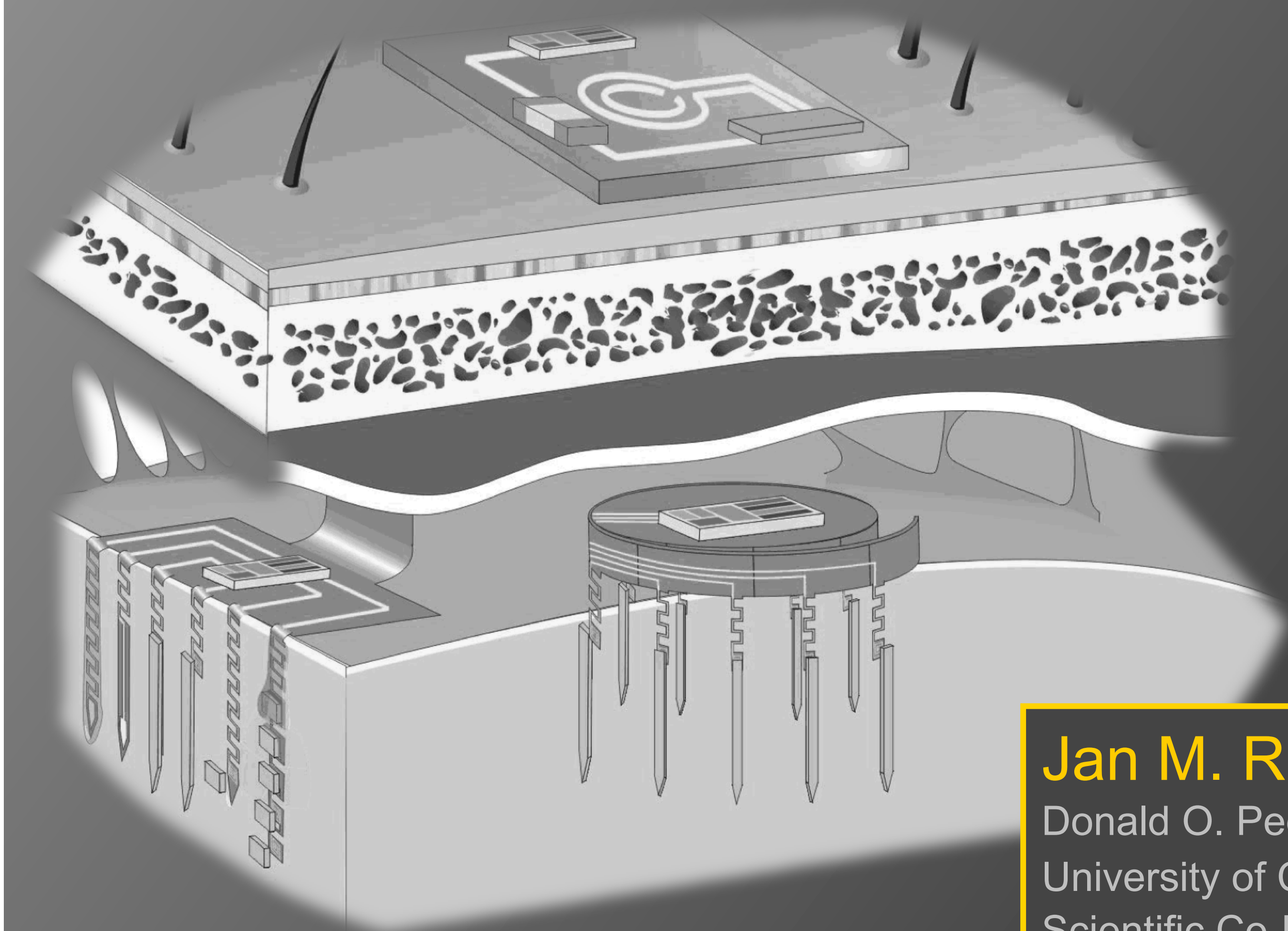
POWERING MINIATURE BIOMEDICAL IMPLANTS



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Scientific Co-Director BWRC

Director Swarms Lab at Berkeley

PwrSOC 2012

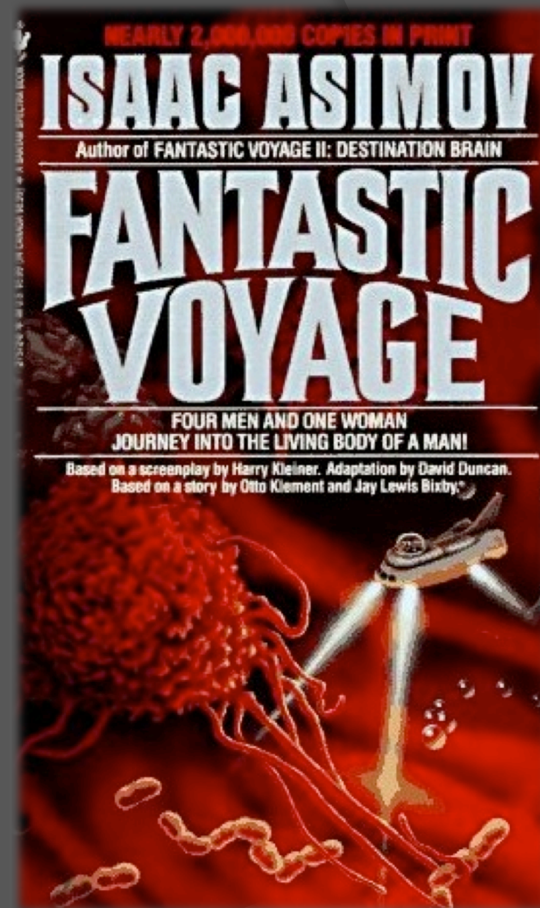
San Francisco, Nov. 2012

ULP Platforms for Human Enhancement

- Extreme miniaturization combined ultra-low power circuitry pave the way for "nanomorphic" bio-interfaces

  "The Nanomorphic Cell is a conception of an atomic-level, integrated, self-sustaining microsystem with five main functions: internal energy supply, sensing, actuation, computation and communication" [REF: Wikipedia]

- Opportunities: observing living cells in vivo (diagnostics, stimulation), brain-machine interfaces

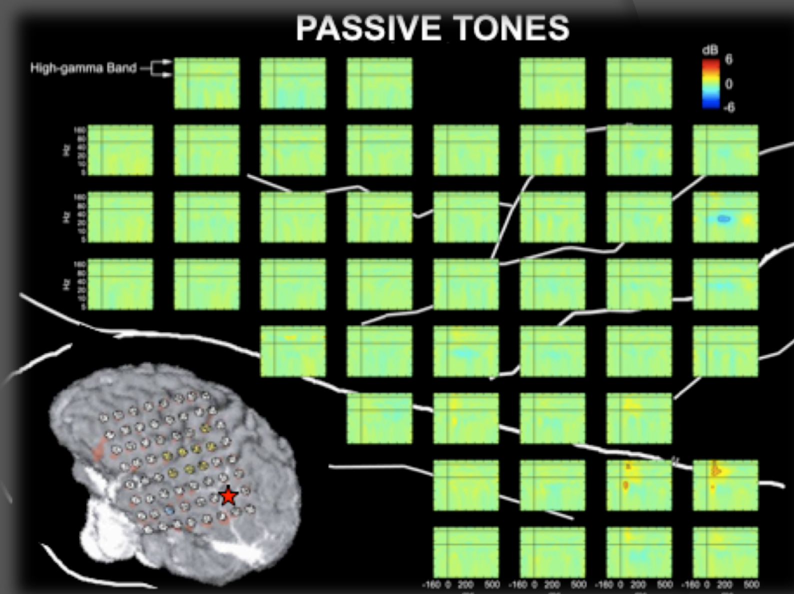


Other readings:
M. Crighton,
N. Stephenson

The Instrumentation of Neuroscience

Learning about the operational mechanisms of the brain

- Only marginally understood
- Potential benefits to humanity hard to overestimate
  - Addressing neural impairments Cochlear implants, artificial retina, Deep-brain stimulation, neuro-prostheses
  - Human enhancement

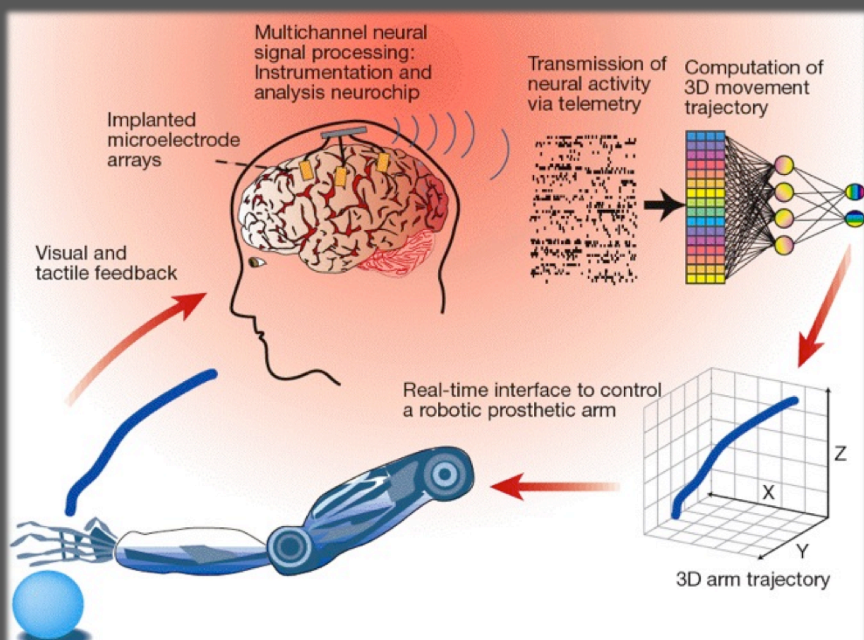


The Decade of Neuroscience?

Could have huge impact in totally different domains (e.g. neuro-inspired computation)

BMI for Motor Control

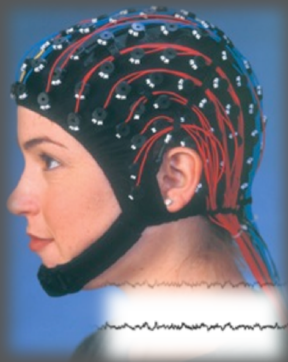
- **Spinal cord injuries/amputees** (upper-limb prosthesis)
  - Estimated population (US) of 200,000 people
  - 11,000 new cases in the US every year

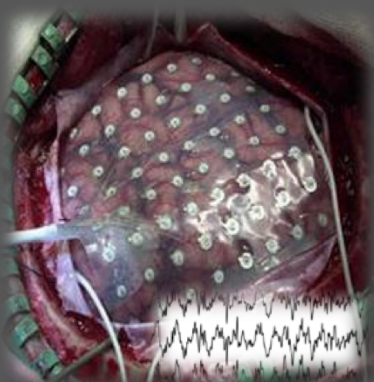


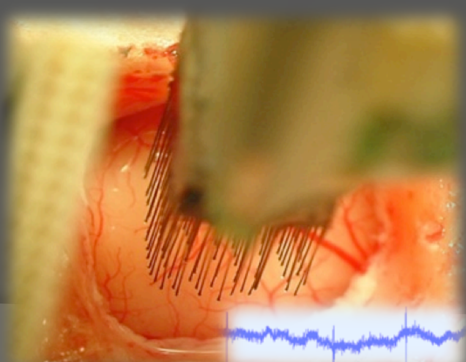
[MAL Nicolelis, Nature, 18 January 2001]

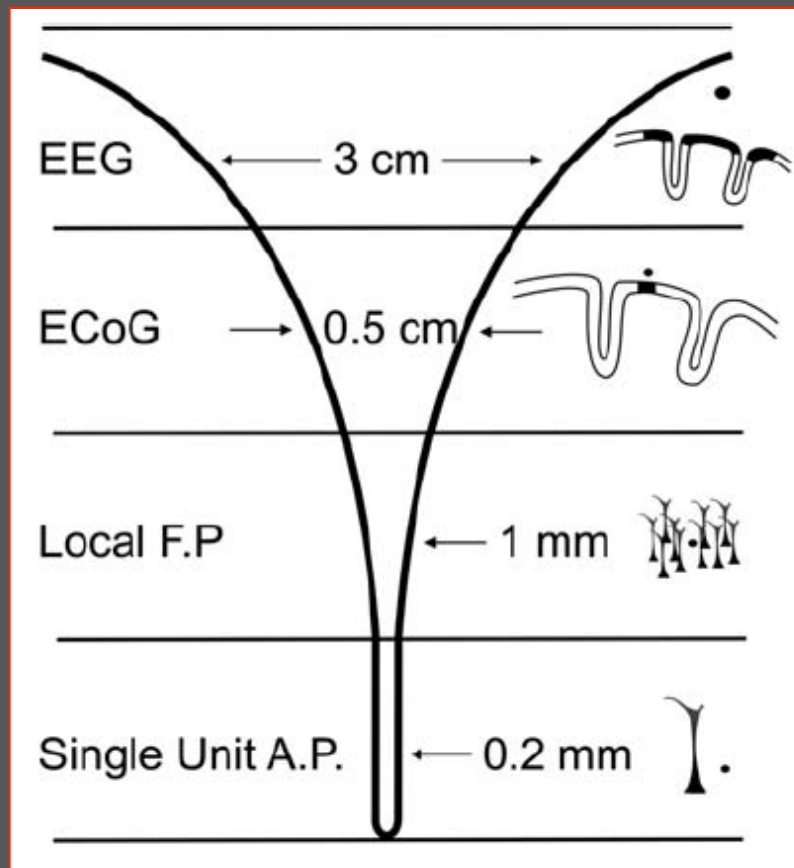
[Lebedev, 2006]

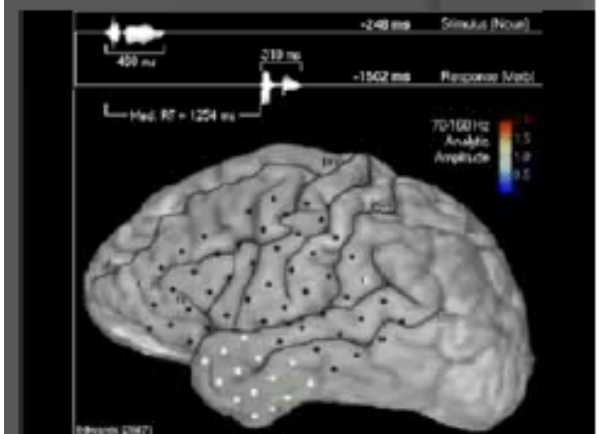
The BMI Spectrum





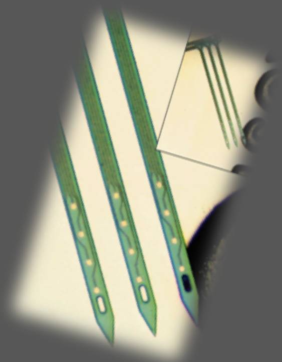


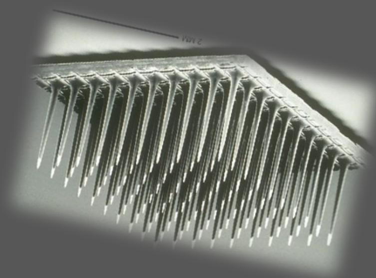


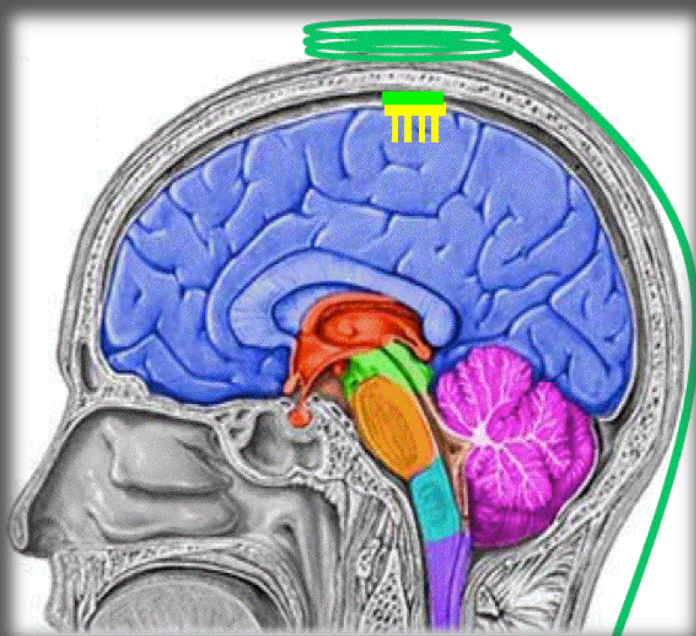


[Schwartz et al. Neuron, 2006]

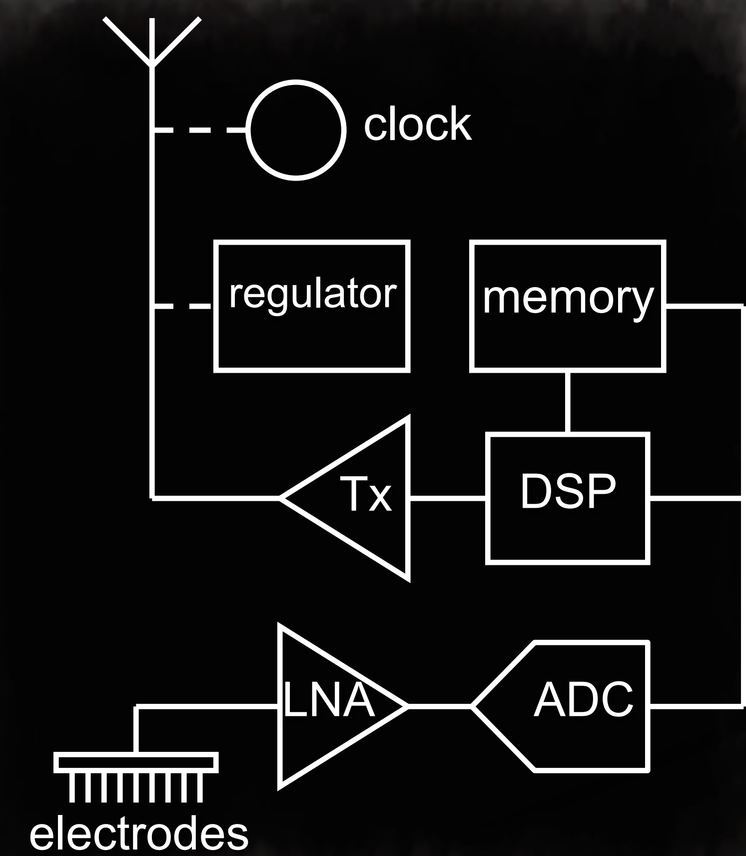
Towards Integrated BMI Interface Nodes







[Illustration art: Subbu Venkatraman]

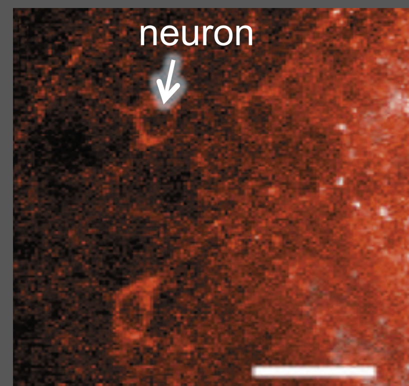


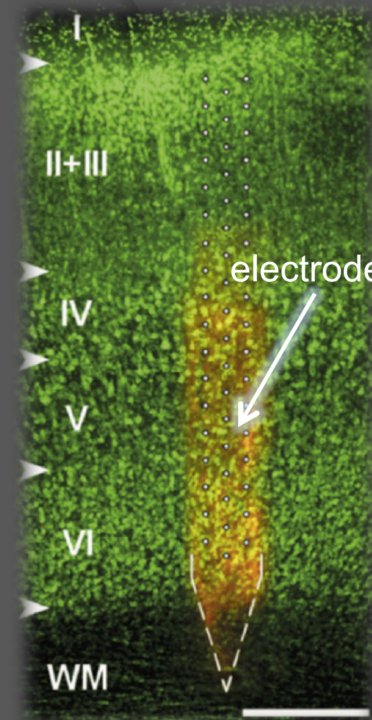
* “Michigan” and “Utah” Electrode Arrays shown

Why Extreme Miniaturization?

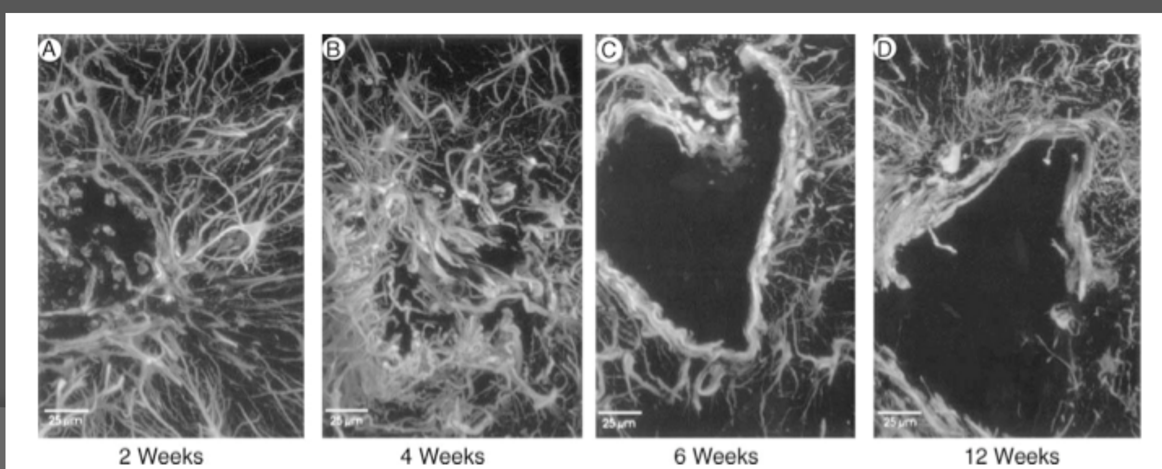
- Resolution – observations at the cellular level
  - Need spatial measurement resolutions on the scale of 100 μm or below

[Pictures courtesy of T. Blanche, UCB]





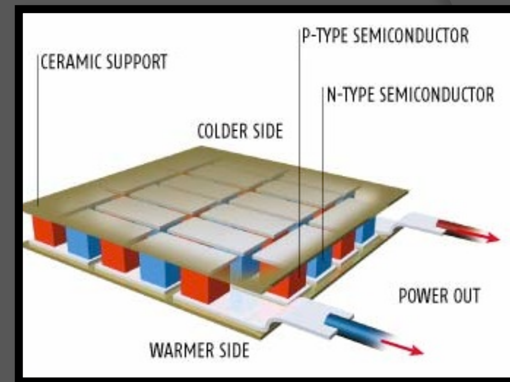
- Reliability and longevity



  - Scarring reduces sensitivity and cause failure
  - Maybe addressed by “truly untethered” free-floating nodes

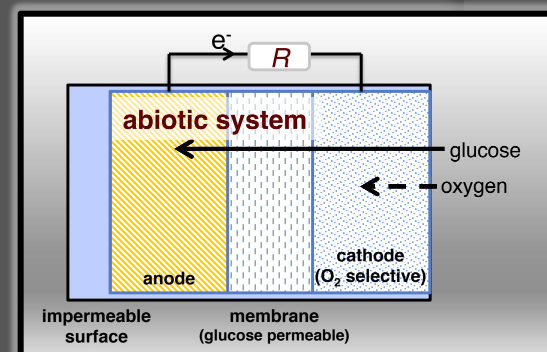
Miniaturization - It's All About Energy!

- Batteries
  - problems:
    - size
    - replacement

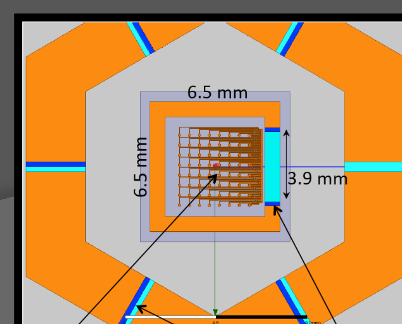


New Scientist, June 2004

- Energy scavenging inside the body
  - a relatively young research area
  - e.g. utilizing body heat (thermoelectric)
    0.6 µW / mm^2 @ ΔT=5° [Paradiso05]
  - Glucose biofuel cells attractive,
    but need improvement (up to 0.7 µW / mm^2 today)



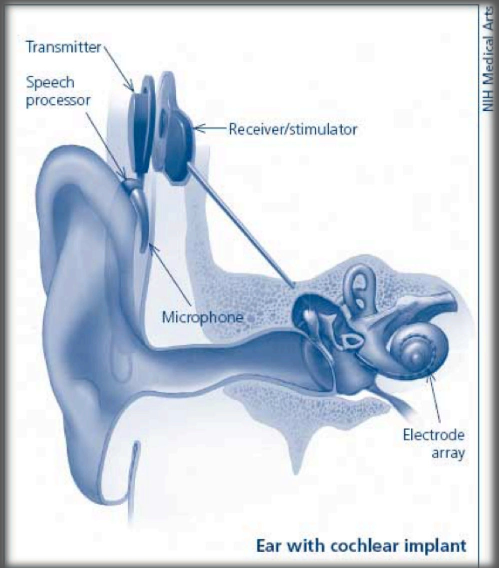
- (Electro-)Magnetic Powering
  - advantages:
    - energy source sits outside the body
  - limitations:
    - possible health risks of EM radiation



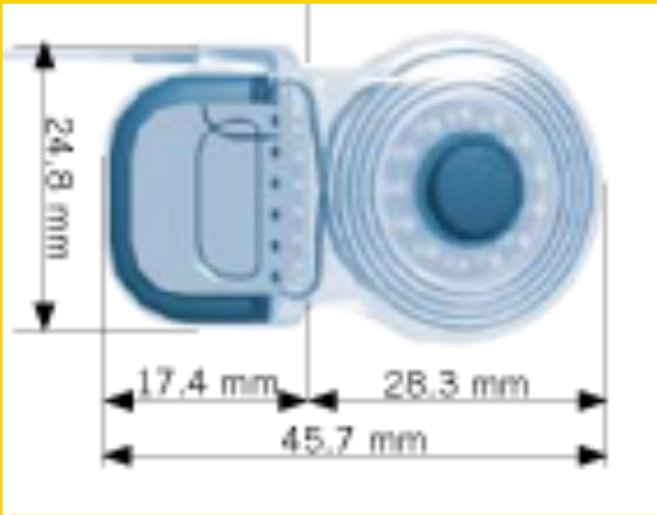
Example of Wireless Powering

Deafness (cochlear implant)

- ~250 million deaf people worldwide, 2/3 in developing countries
- > 100,000 cochlear implant users worldwide
- 22,000 adults and 15,000 children live in the US
- **Cost: US$ 40-60K**



Ear with cochlear implant

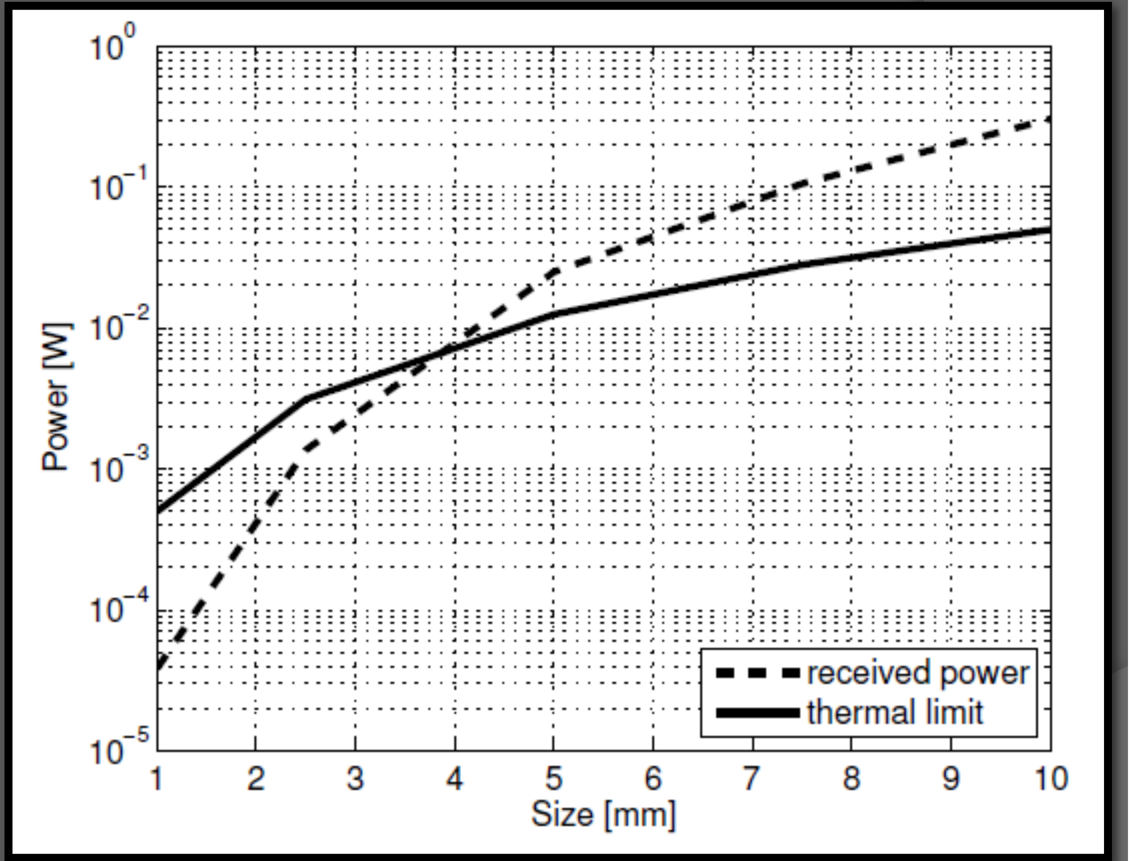


[Sources: National Institutes of Health, Neurology journal]

Wireless Power and Size

- Specific absorption rate (SAR) sets the limit on external power
- Thermal considerations limit power dissipated by implant
- Available power drops with size by d^4 or more

Power Available at Matched Input Terminal



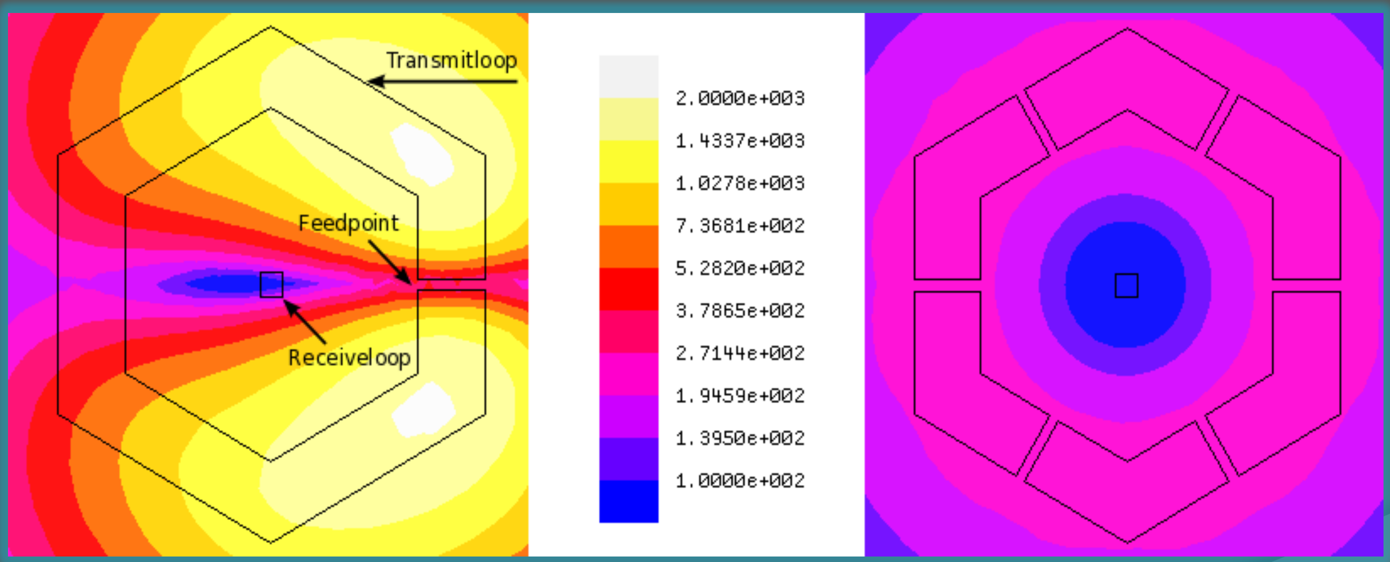
[Rabaey, Mark, et al., DATE 2011]

Ultra Low-Power Design Essential!

Efficiency: Maximizing Power that can be Applied

- ***Externally applied power*** limited by health concerns
- Limit set by Specific Absorption Rate (SAR)
- ***1.6 W / kg averaged over 1 g of tissue (in US)***

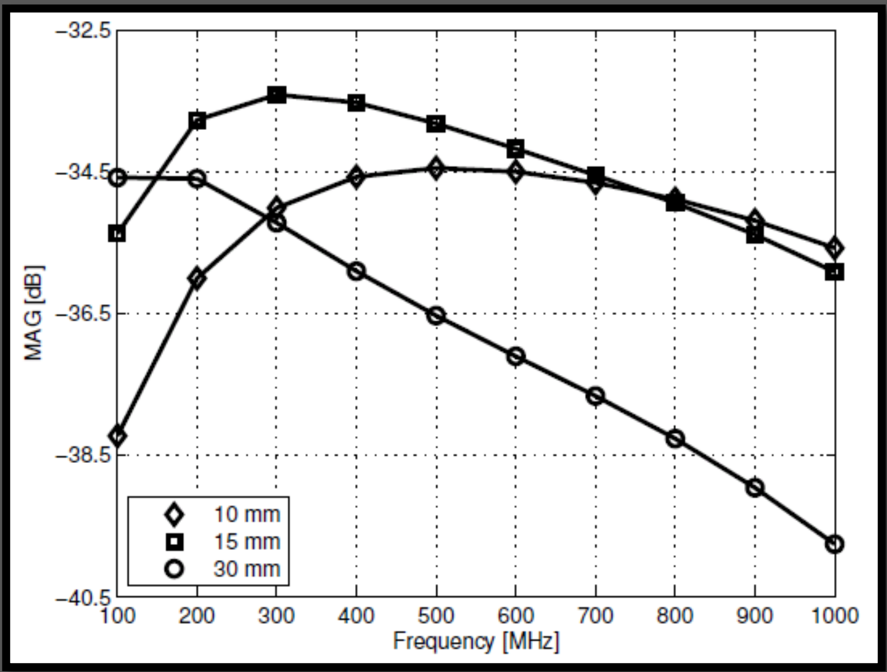
$$SAR = \frac{\sigma|E|^2}{\rho}$$



[Mark, Bjorninen et al., Biowireless 2011]

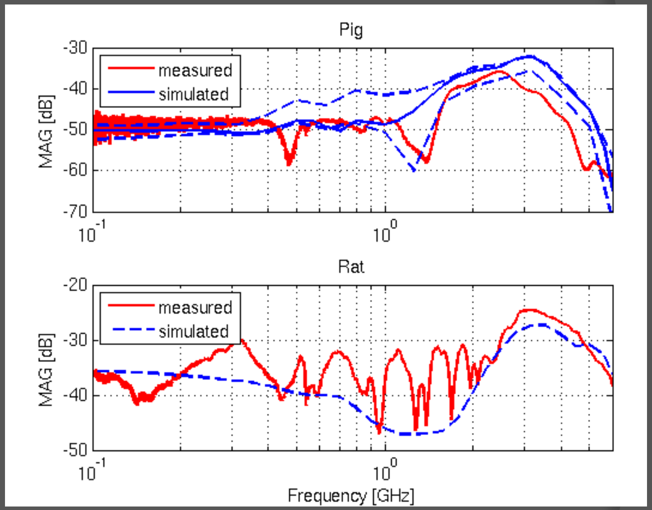
- Segmented transmit loop increases power available to the implant by 47 % (at 500 MHz)

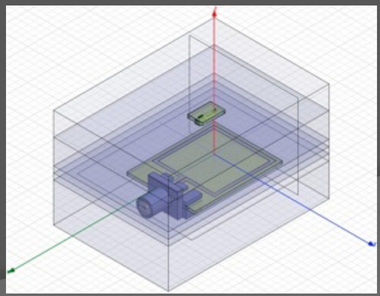
Efficiency – Optimization of RX Antenna Size and Frequency

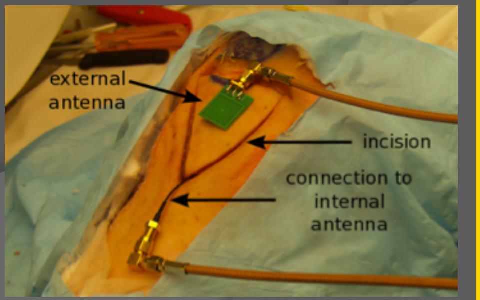


Maximum Achievable Gain vs. Frequency

Simulations (HFSS) match in-vivo measurements

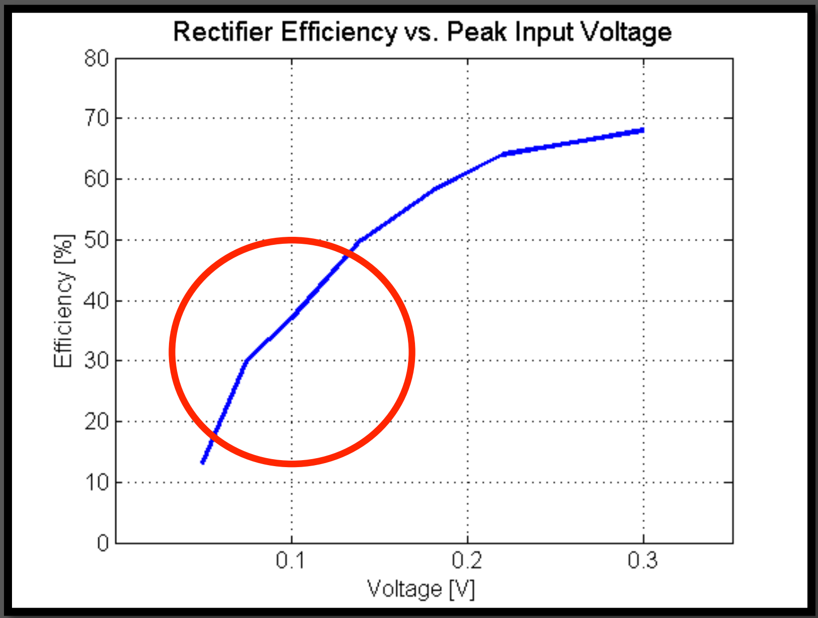




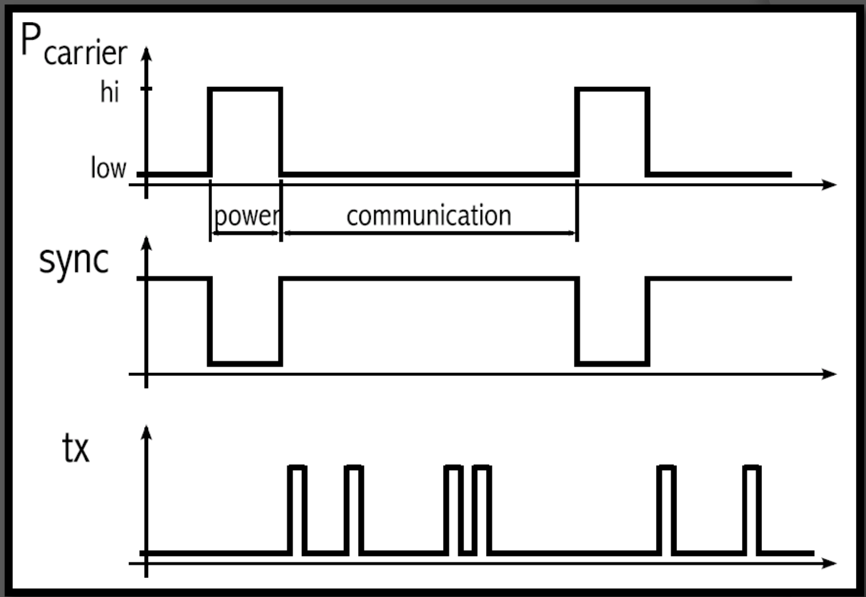


(shown for a single turn 1 mm x 1 mm implanted antenna)

Boosting the Rectifier Efficiency



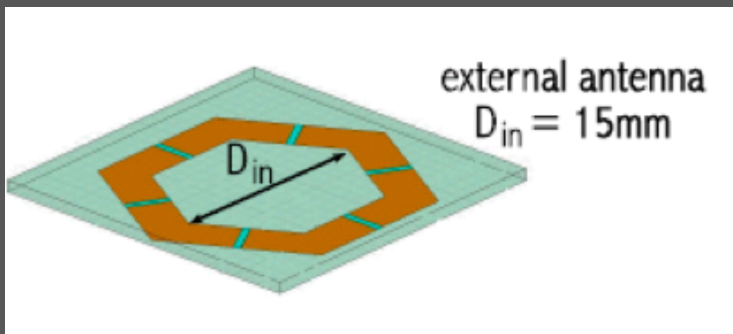
At 500 MHz for 1mm antenna
Max input voltage: 145 mV

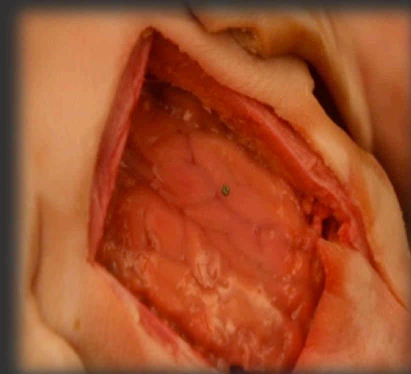


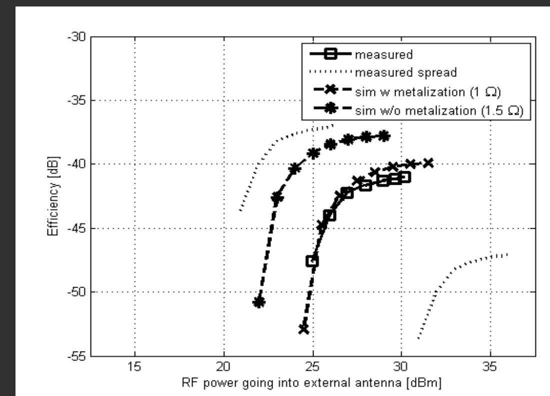
Solution:
Pulsed power transmission

Keeps average SAR while increasing efficiency by 25%

Proof of Concept:
1 mm^3 Wirelessly-Powered Node

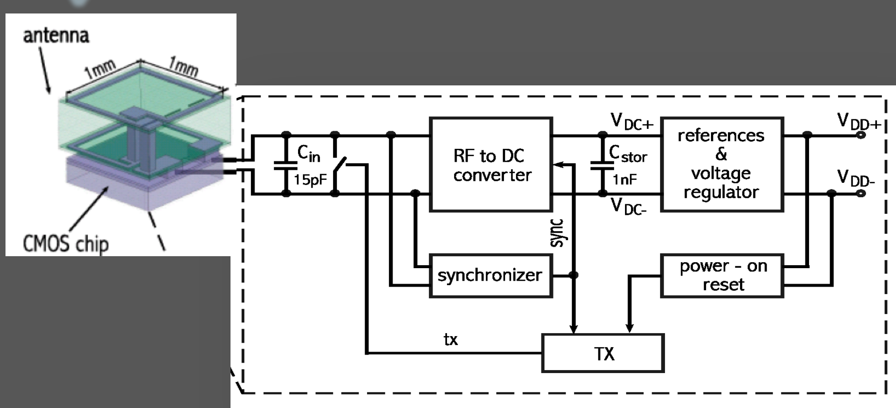


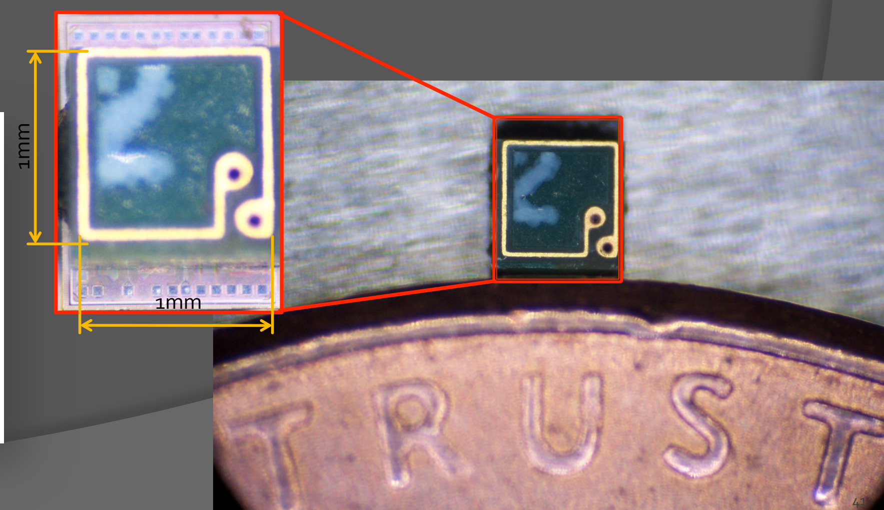




Delivers 26 uW or 8 uW of power (IEEE, FCC)

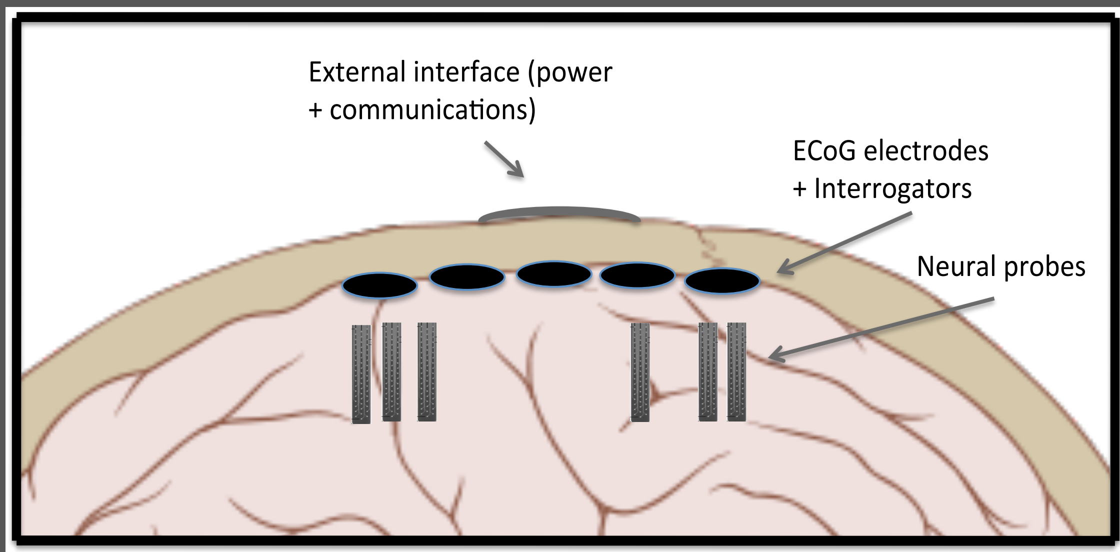
1 cm of skin, fat, bone

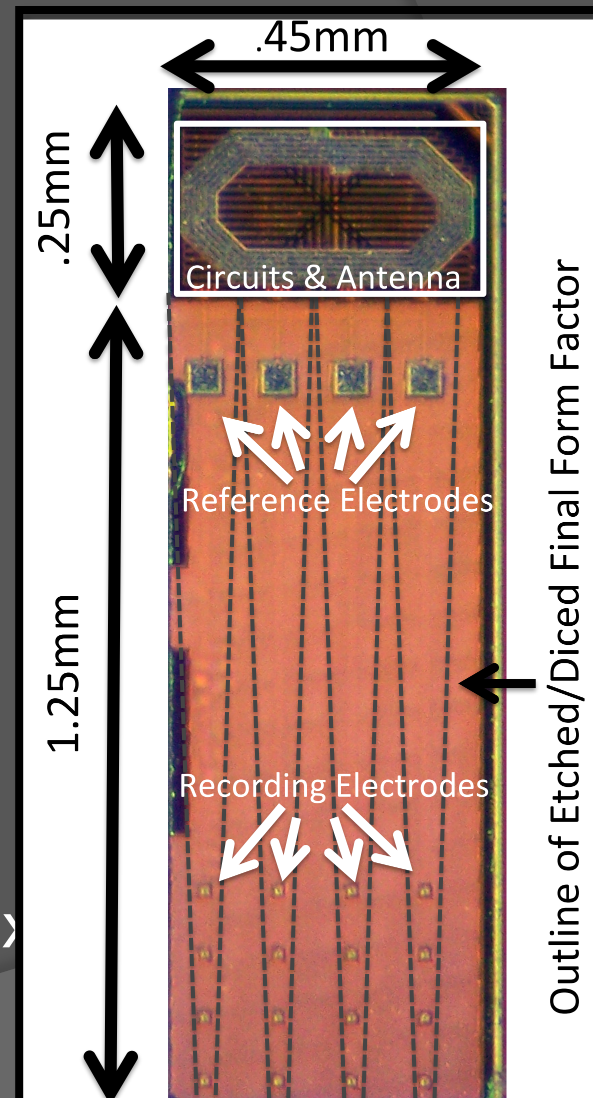




[Mark, Chen, et al., VLSI 2011]

Next step– “Neural Dust”

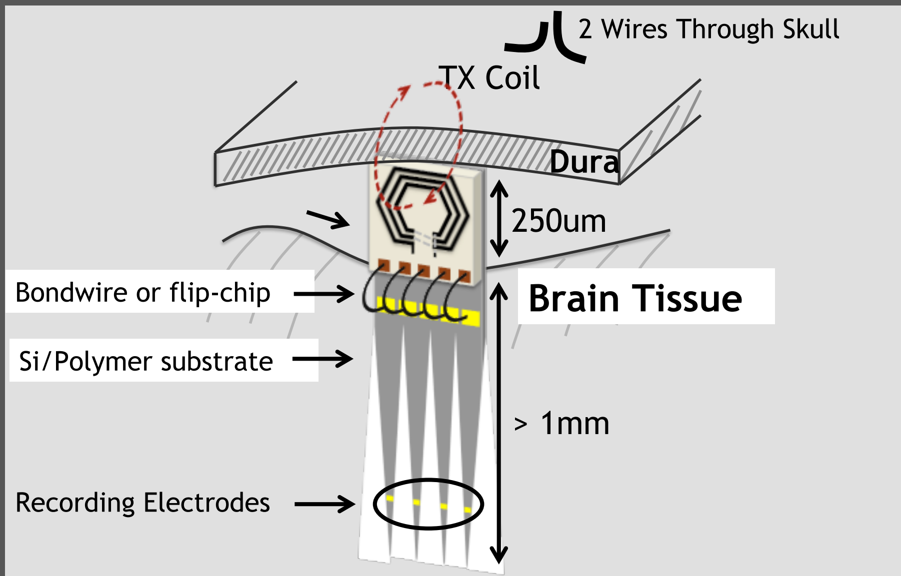


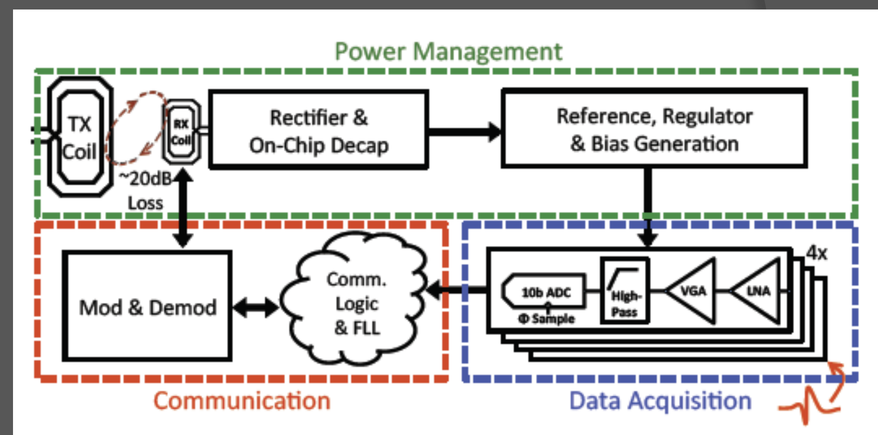


- Thousands of “sensing nodes” freely embedded in neo-cortex
- Interrogated by array of nodes located neo-cortex surface
- Communicating with and powered by ex cranial interfaces

[W. Biederman and D. Yeager, UCB, VLSI12]

Free-floating AP Acquisition Electrodes



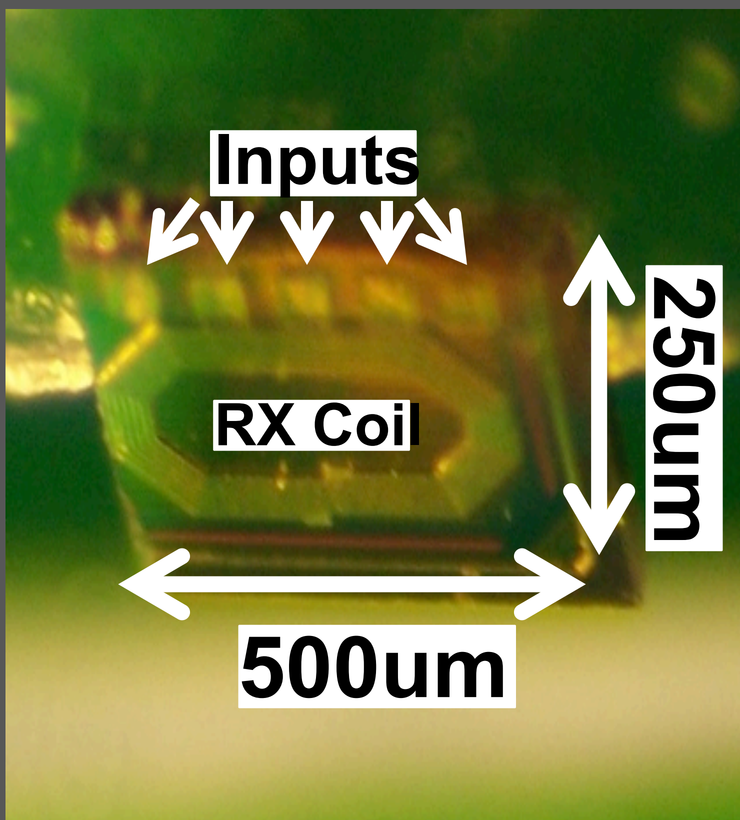


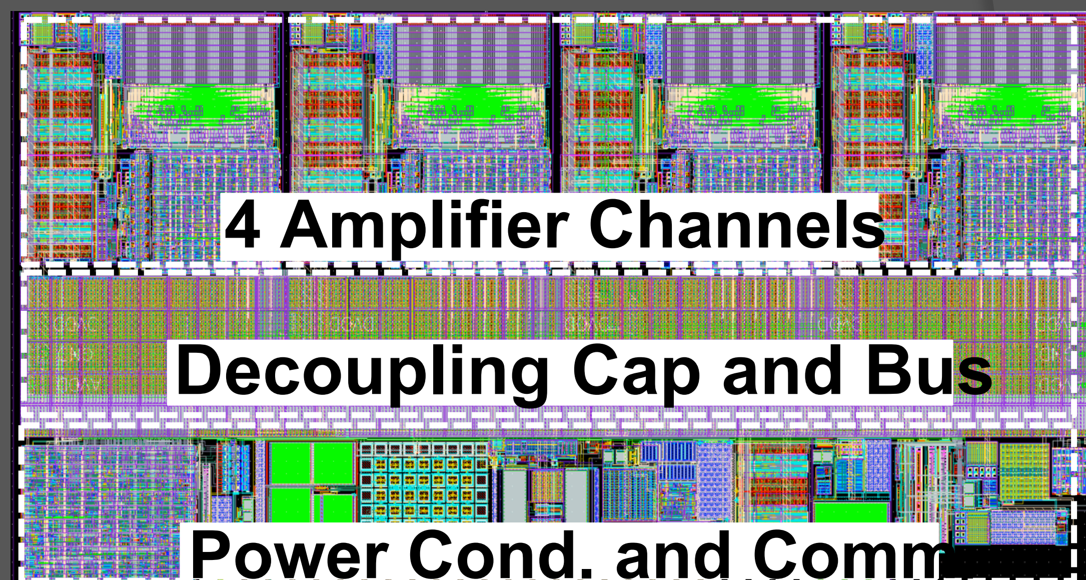
	Simulated Power	Layout Area (um^2)
4 Neural Amplifiers	6 uW	100 x 450
Total System:	9 uW	220 x 450

[Courtesy: W. Biederman, D. Yeager, VLSI 2012]

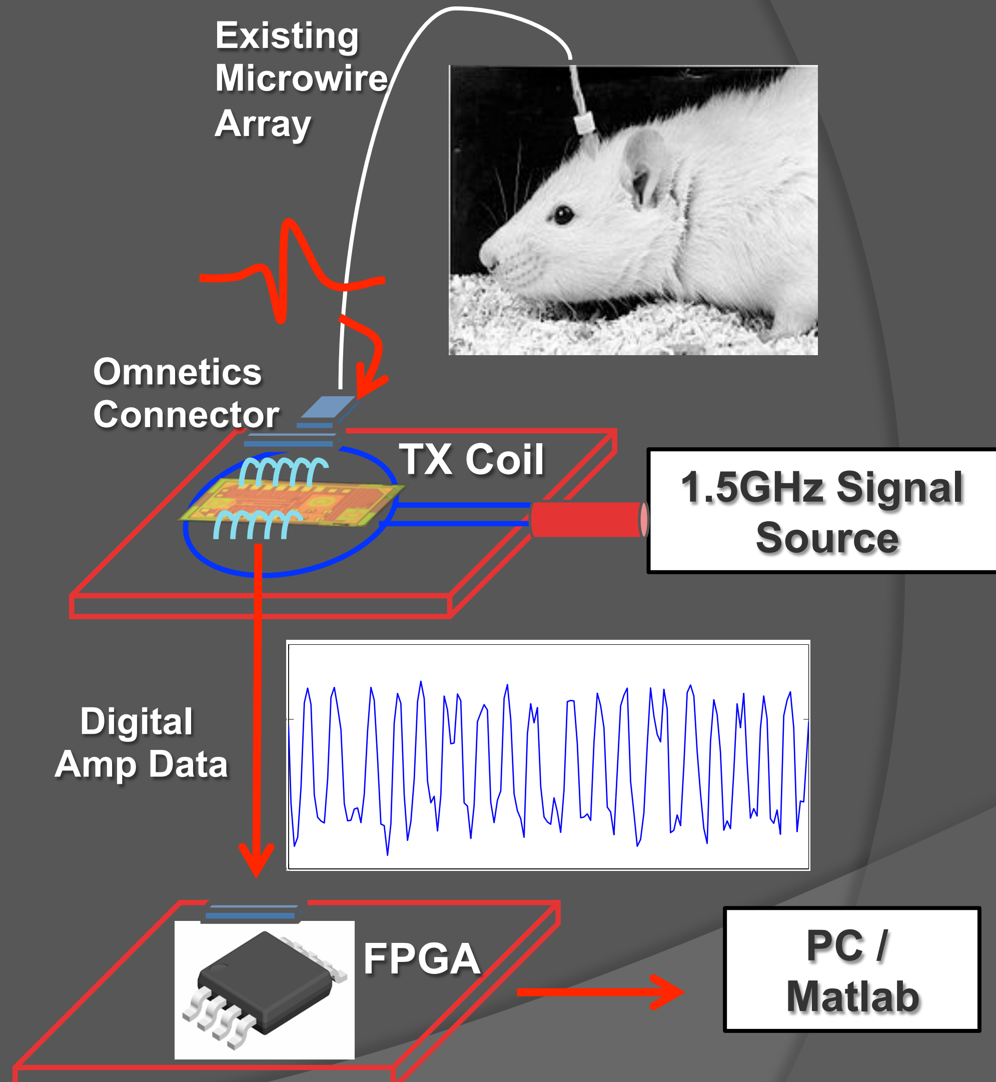
IC Fabrication

- Fabricated in 65nm CMOS
- Consumes $0.125mm^2$ (500µm x 250µm) of active area
- RX Coil in Al layer over active circuitry



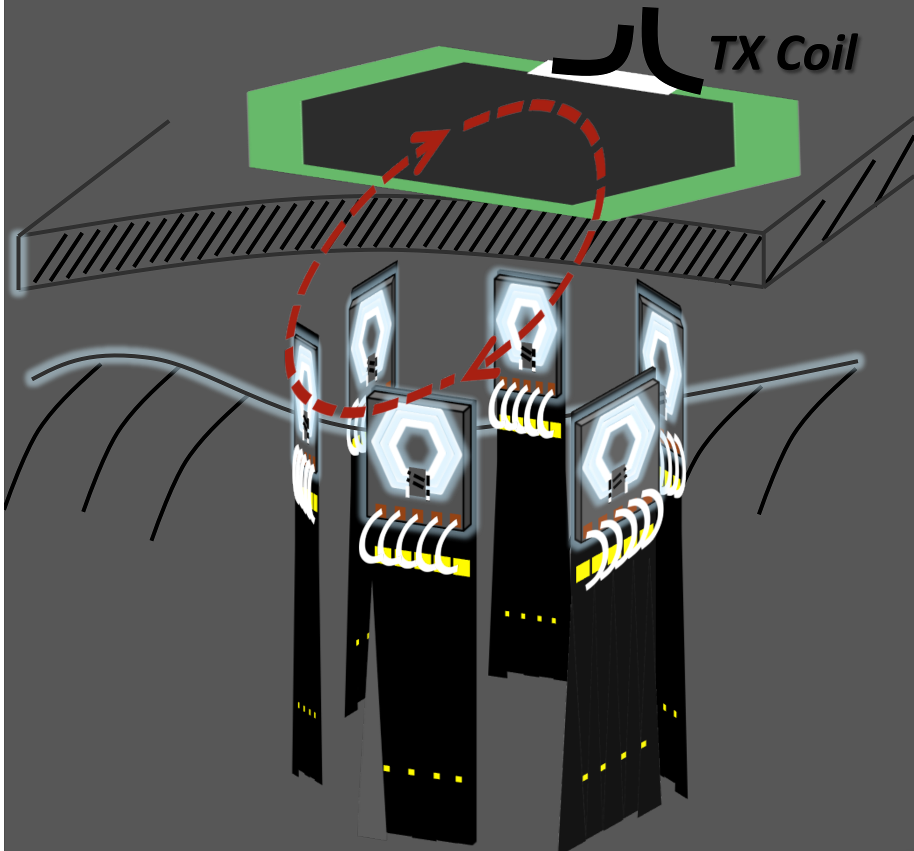


In Vivo Recording Setup

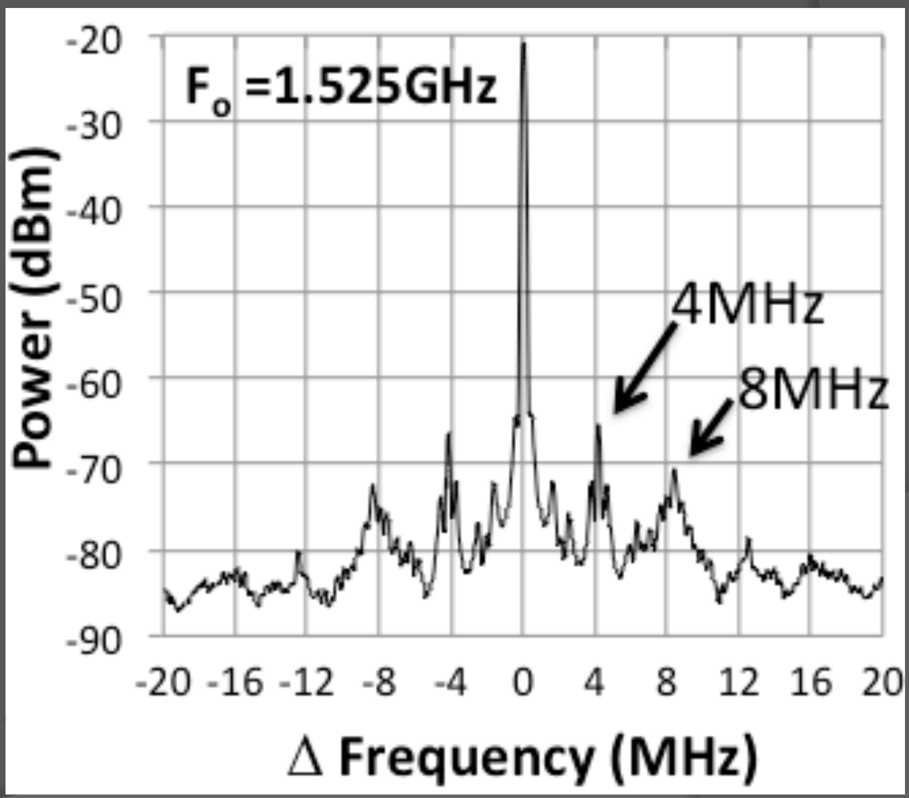


Multi-Node Communication

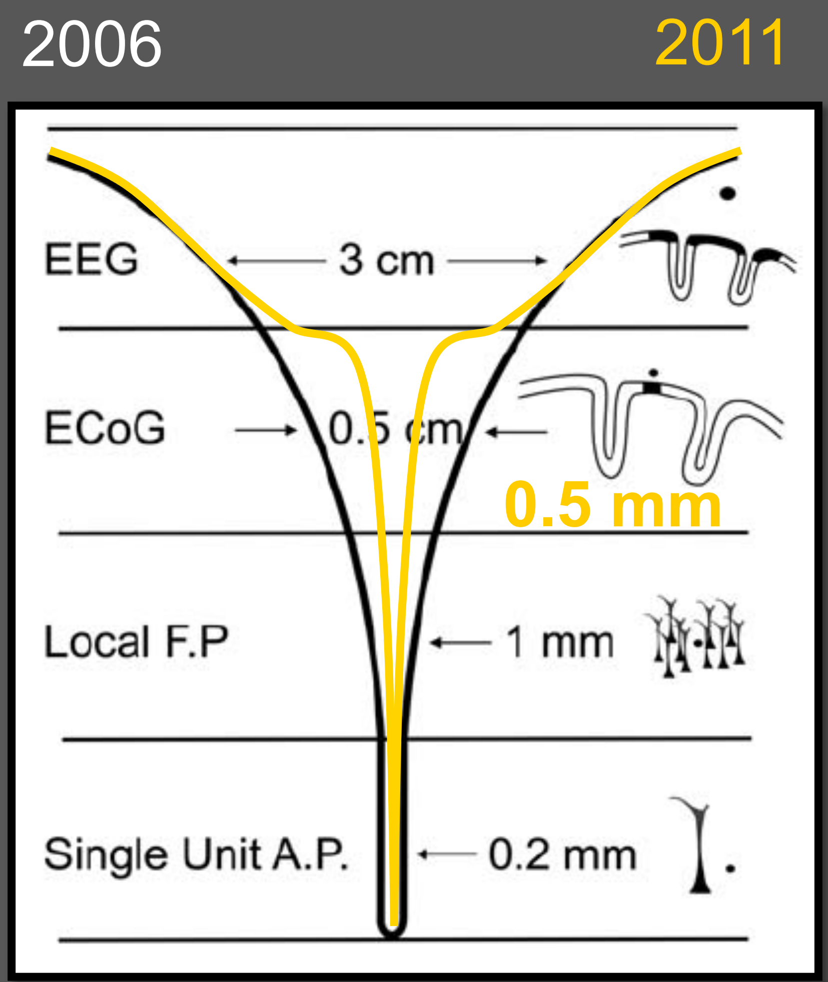
- Programmable Miller subcarrier
  - 1-10 MHz
  - 6 simultaneous sensors

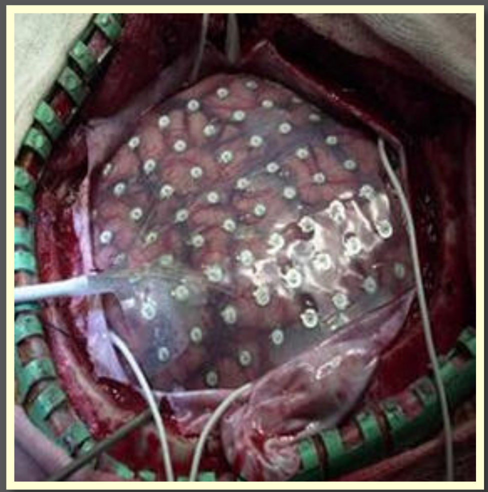


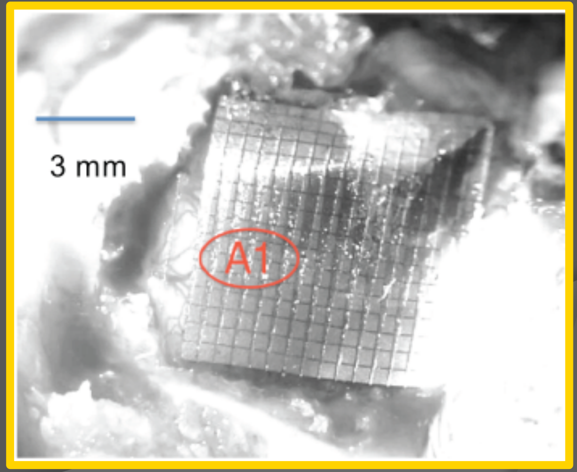
Freq. Spectrum w/ Two Sensors



Exploring Alternatives Routes : µECoG

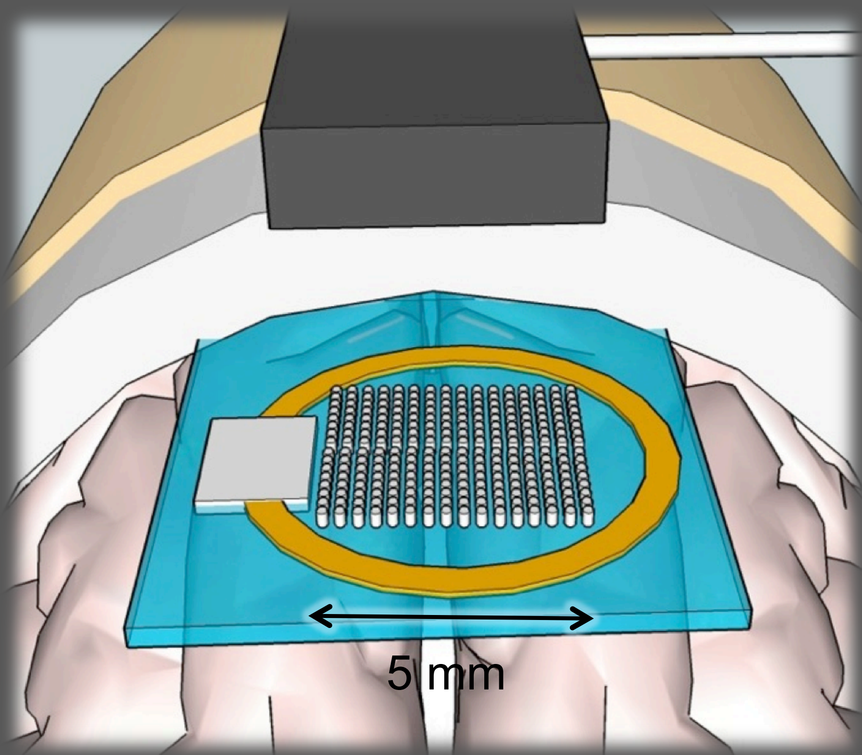




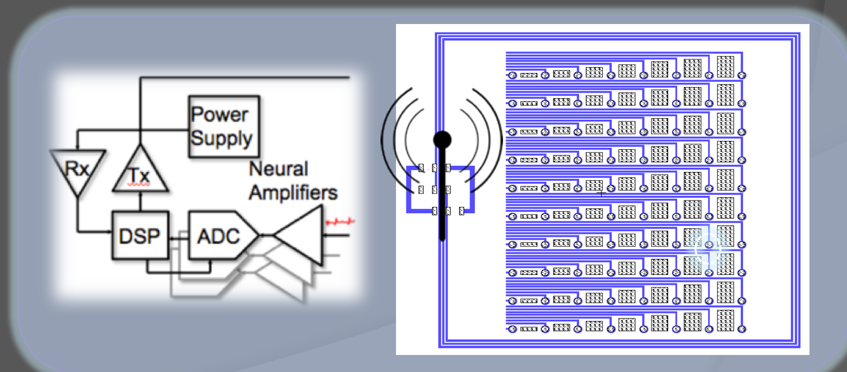


[Courtesy: P. Ledochowitsch, R. Muller]

Exploring Alternatives Routes : µECoG



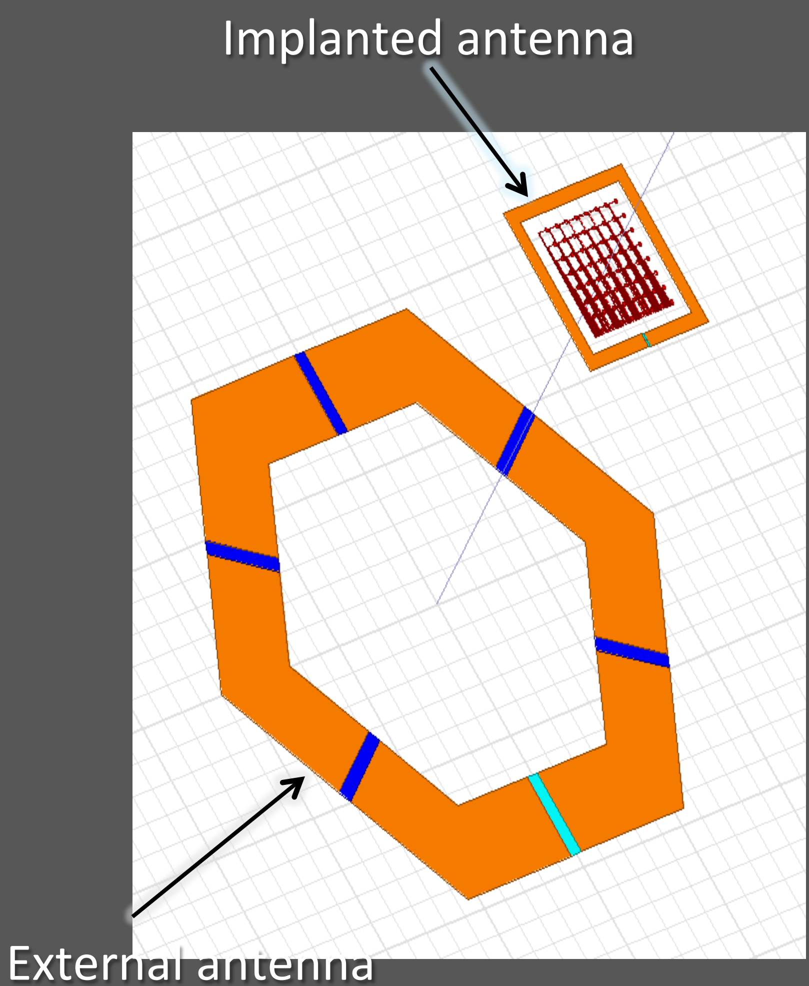
- Wireless µECoG may provide up to 1000 channels with pitch as low as 200 µm.
- Providing unprecedented resolution and offering huge potential for BMI (ALS, Epilepsy).
- Antenna printed on polymer substrate

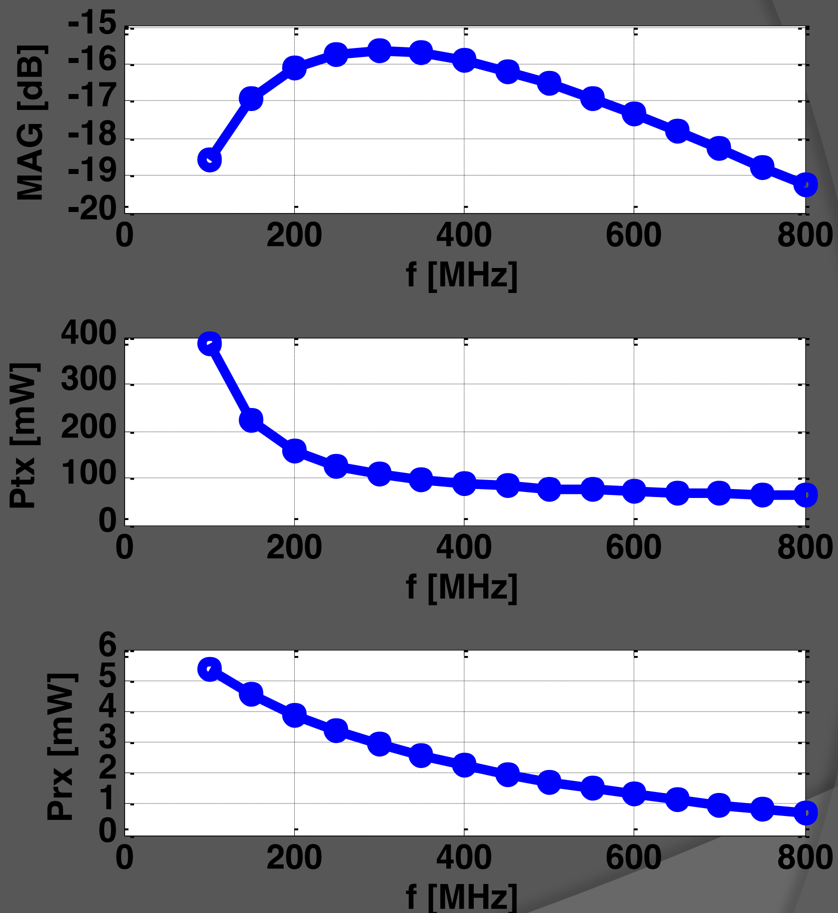


Circuit elements similar to AP sensor nodes

[Courtesy: P. Ledocowich, R. Muller, M. Maharbiz, J. Rabaey]

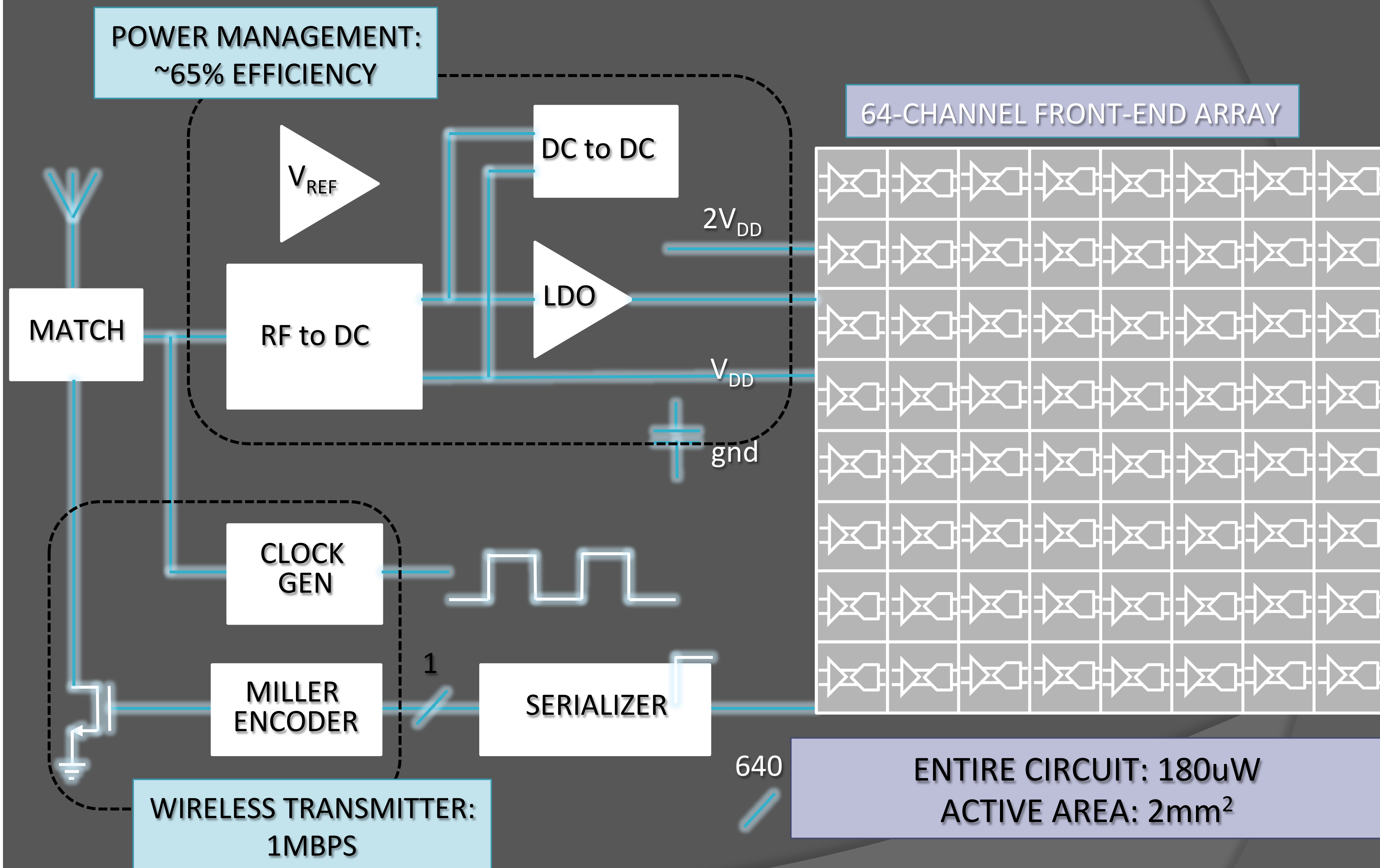
Loop Antenna for Link Optimization





[Courtesy: T. Bjorninen, R. Muller]

Integrated Wireless Acquisition IC



How to scale to 1000 channels?

[Courtesy: R. Muller, W. Li, H. Le, S. Gambini]

Final Reflections ....

- Nanomorphic circuits as a game changer
  - The potential is huge - Societal impact first, human advancement next
- ULP circuit and systems design in concert with innovative technologies to provide “cellular electronics”

- Energy the limiting factor
  - Harvesting within the body is hard
  - (Electro)magnetic currently the only solution
  - In search for other solutions

- Requires broad multi-disciplinary collaboration
  - The new reality of engineering
  - A major attraction to a new generation of engineers and beyond