NSF Workshop on Biologically-Enabled Wireless Networks Design and Modeling
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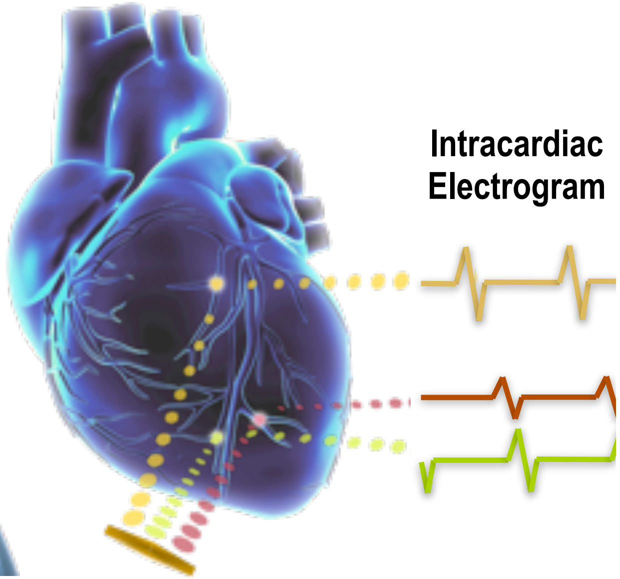
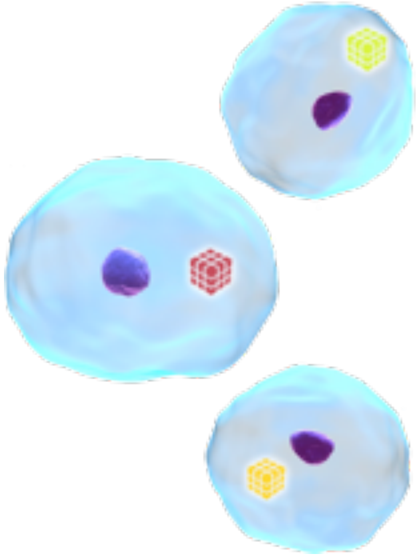
Future Implantable Systems

Ada Poon
Stanford University

Real Time, Distributed *In Vivo* Diagnostics





- Moving implants
- Wireless endocardial pacing and sensing

- Multielectrode epicardial mapping for EP study

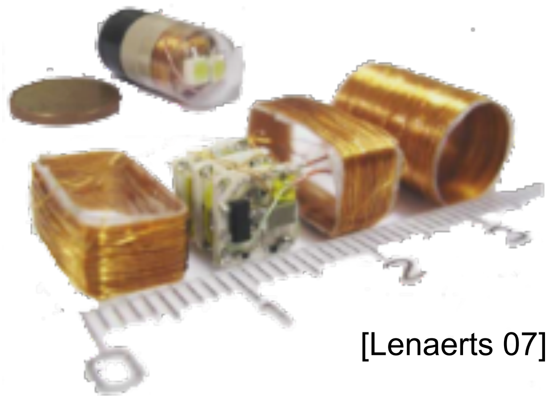
- Chip in cell for cellular-level monitoring and therapeutic treatments

1 mm → 100 μm → 10 μm

Implant Dimension

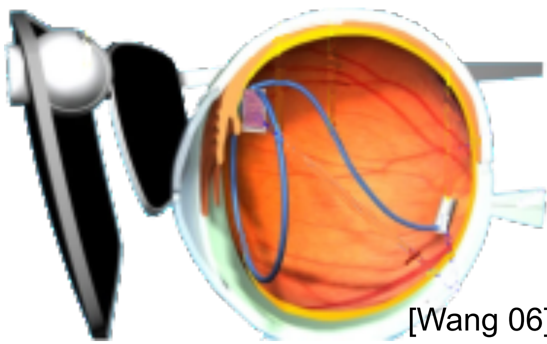
Current Autonomous Implants

Endoscope



[Lenaerts 07]

Retinal implant



[Wang 06]

Cochlear implant

- Use remote power source to remove the battery partially or completely.
- Power transmission is like a transformer – **inductive coupling**.
- Power receiver is large – 1 to a few cm.
- Extremely short distance (almost touching)
- Coil alignment is critical.
- **Still, we haven't solved the problem of miniaturization.**

Can we do better than inductive coupling?

Back to Physics …

$$\nabla \times \mathbf{H} = -i\omega\epsilon_0\epsilon_r\mathbf{E} + \sigma\mathbf{E}$$
$$\nabla \times \mathbf{E} = i\omega\mu_0\mathbf{H}$$

In the past 50 years, analyses on wireless power transmission within biological tissues omit the displacement current – the term Maxwell added to Ampere's Law and resulted in the Maxwell equations.

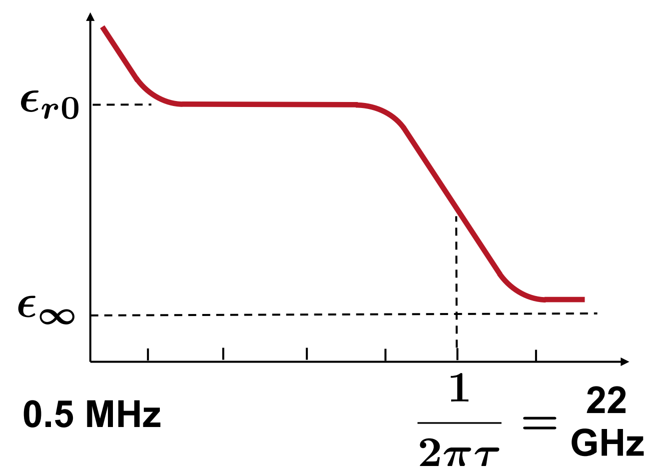
- Lower frequency is better!
- Most systems operate at 10 MHz or lower.

YES when we take into account the displacement current.

Tissue Model: Relaxation Loss

- Occur at high frequency in dielectrics, for example, biological media.
- Efficiency would not increase indefinitely with frequency. An optimal frequency exists.
- We are interested in where it is, **MHz-range or GHz-range**.
- Use Debye relaxation model:

$$\epsilon_r(\omega) = \epsilon_\infty + \frac{\epsilon_{r0} - \epsilon_\infty}{1 - i\omega\tau} + i\frac{\sigma}{\omega\epsilon_0}$$



An efficiency metric that is valid in all field regions and is not contaminated by circuit parameters.

$$\eta = \frac{\left|\text{Induced emf}\right|^2}{\text{Total tissue absorption}}$$

$$= \frac{\left|\omega \int_{\text{Implant}} \textbf{Magnetic flux} \cdot \hat{\mathbf{n}}\, da\right|^2}{\omega \int_{\text{Tissue}} \epsilon_{im} \left|\textbf{Electric field}\right|^2 d\mathbf{r}}$$

- Both magnetic flux and electric field are derived from vector field analysis, that is, no far-field or near-field approximation.

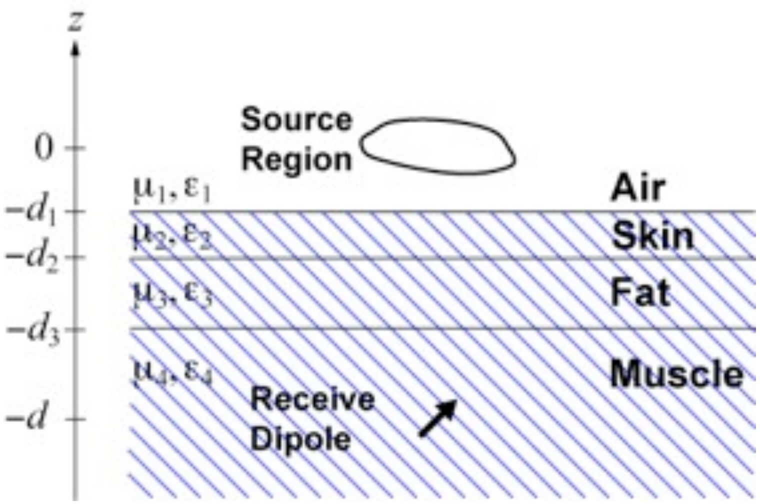
Optimal frequency

$$\omega_{opt} = \sqrt{\frac{c\sqrt{\epsilon_{r0}}}{d\tau(\epsilon_{r0} - \epsilon_{\infty})}} \cdot \sqrt{1 - \frac{4a_{\perp}^2 + \left(\sigma d\sqrt{\frac{\mu_0}{\epsilon_0 \epsilon_{r0}}} - 1\right)a_{\parallel}^2}{\left[\frac{d\epsilon_{r0}^{3/2}}{c\tau(\epsilon_{r0} - \epsilon_{\infty})} + 1\right]a_{\parallel}^2}}$$

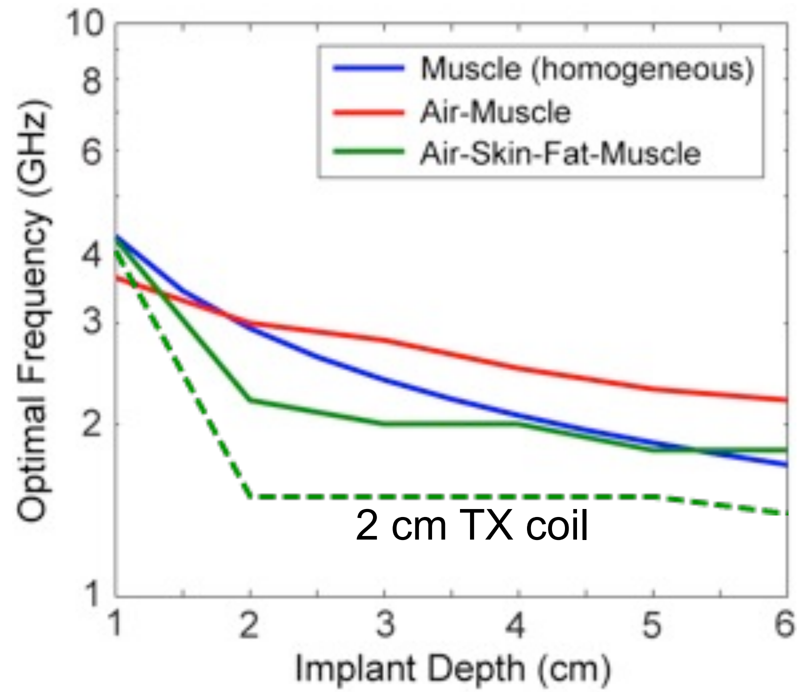
Tissue Type	Freq (GHz)
Blood	3.54
Bone (cancellous)	3.80
Bone (cortical)	4.50
Brain (grey)	3.85
Brain (white)	4.23
Fat (infiltrated)	6.00
Fat (not infiltrated)	8.64
Heart	3.75

Tissue Type	Freq (GHz)
Kidney	3.81
Lens cortex	3.93
Liver	3.80
Lung	4.90
Muscle	3.93
Skin	4.44
Spleen	3.79
Tendon	3.71

Planarly Layered Body Model

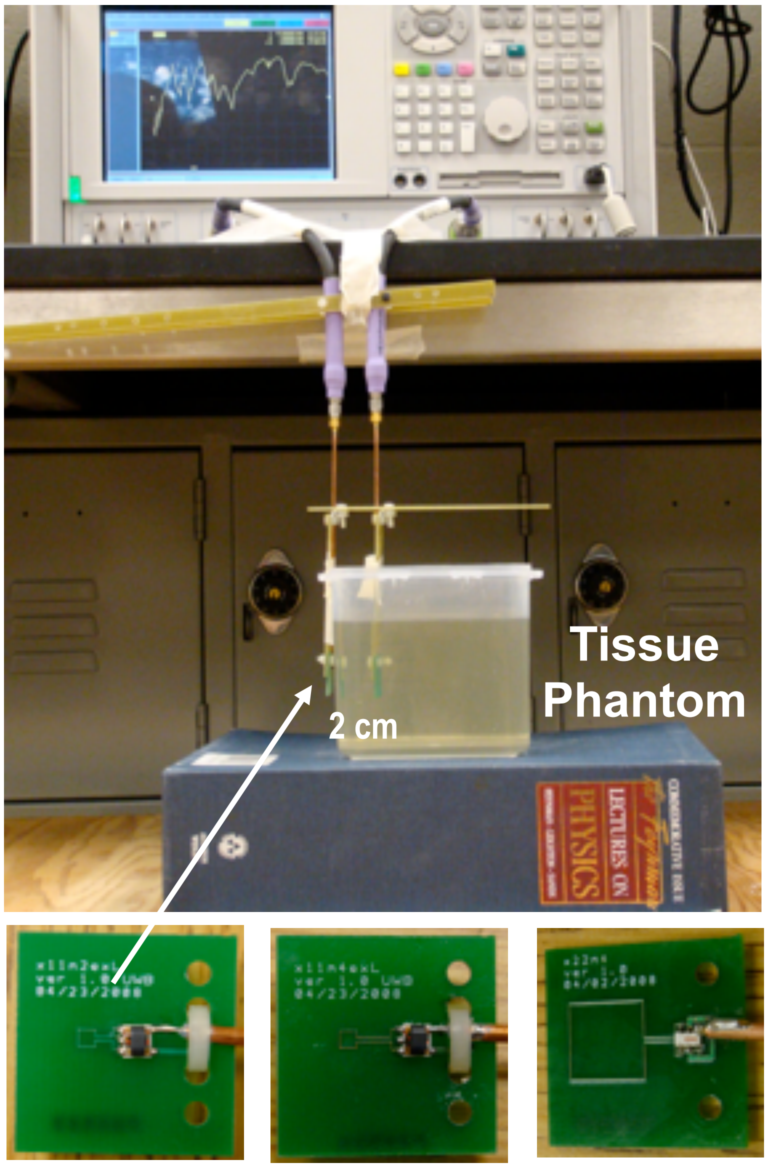


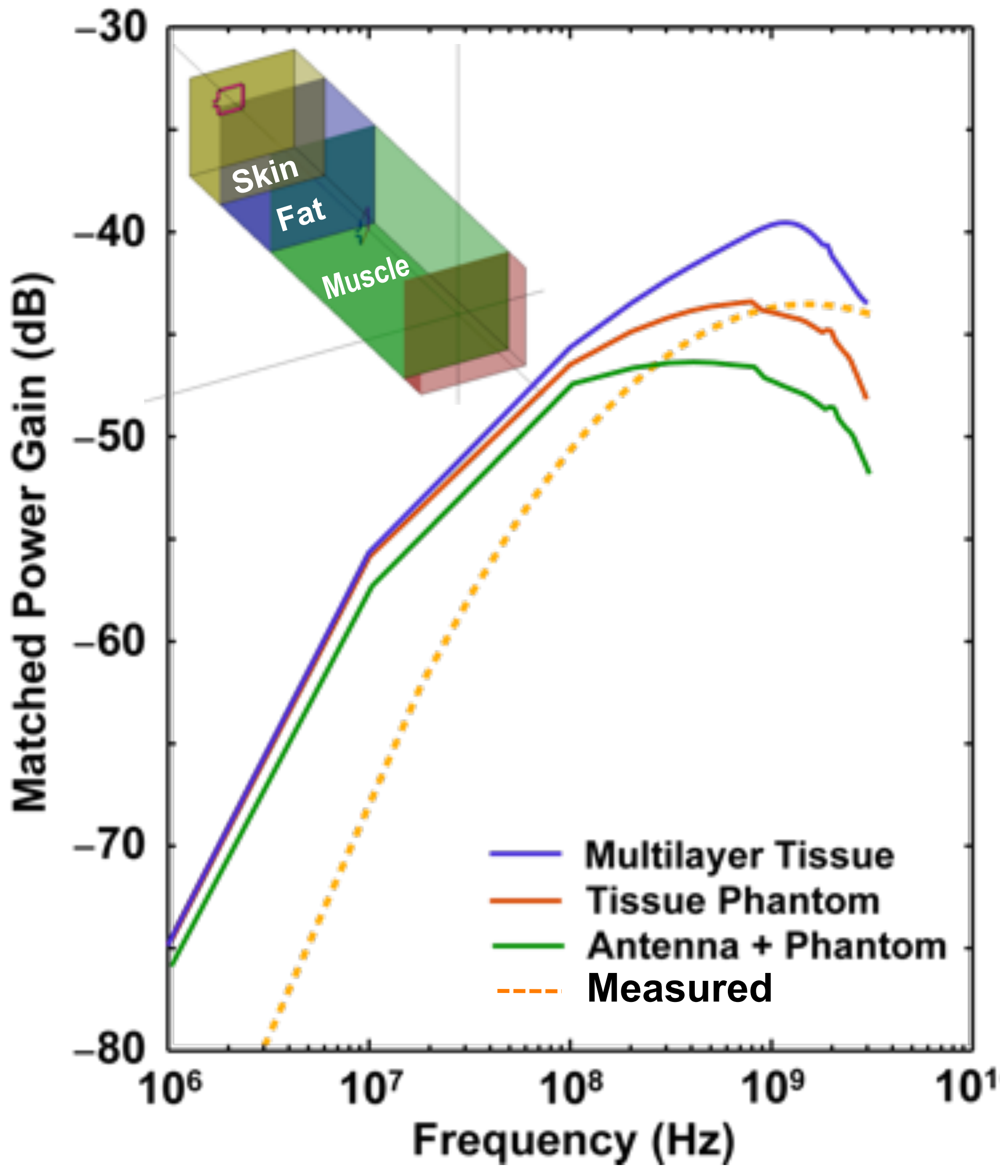
d_1 = 10 mm, skin thickness 2 mm, fat thickness 5 mm



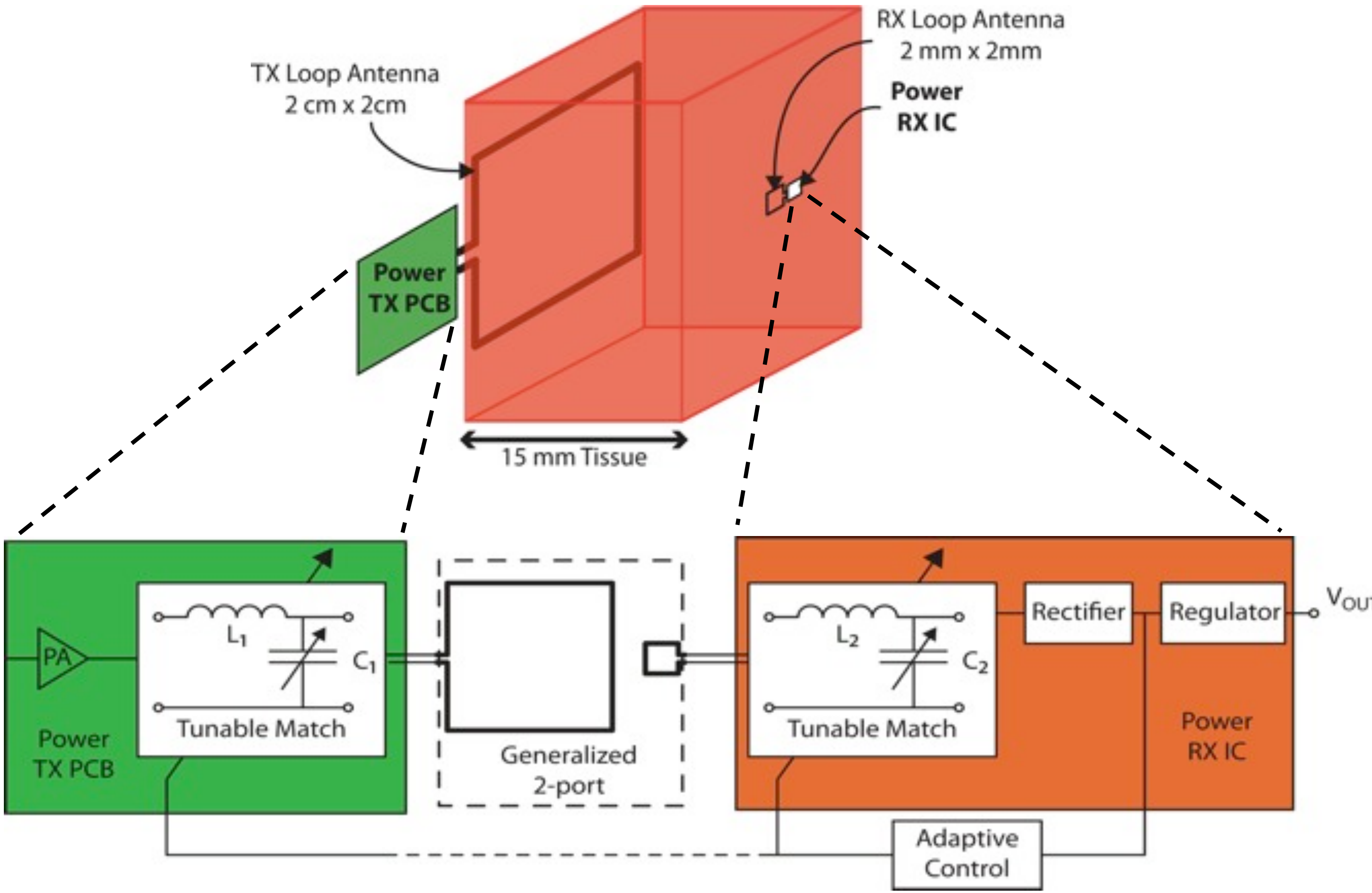
- Sommerfeld integration
- Optimal frequency remains in the GHz range.
- $\eta_{opt} \propto \frac{1}{d^3}$

Simulated & Measured Optimal Frequency

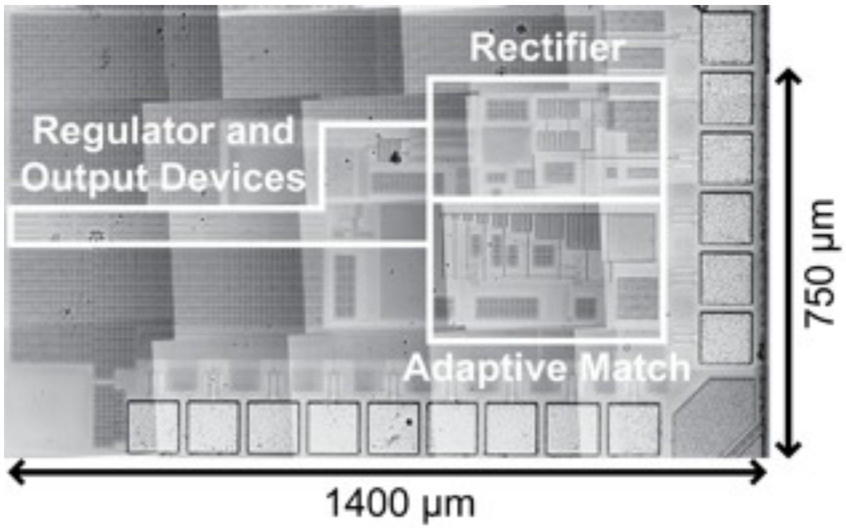




Implemented System



Prototype Receiver at .13 μm CMOS



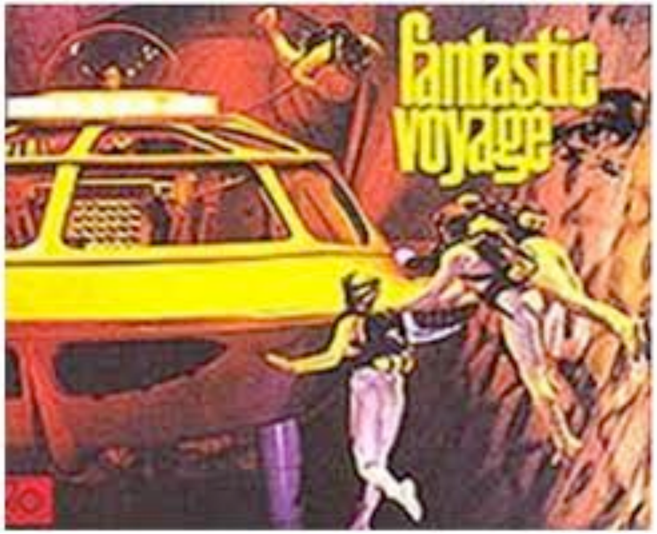
Operating frequency	915 MHz or 1 GHz
TX antenna size	20 mm × 20 mm
RX antenna size	2 mm × 2 mm
Inter-antenna dielectric	15 mm, bovine muscle tissue
Startup time	4 μs
Rectifier efficiency	65%
Regulator efficiency	70%
Gain of link + rectifier + regulator	-33.2 dB (theoretical 31.0 dB)
DC output power	140 μW @ 1.2 V regulated

ISSCC 09

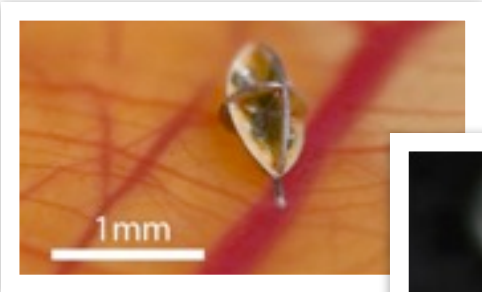
- Unique features
  - Adaptive conjugate matching
  - Highly efficient rectifier
- Coil dimension is 2 mm × 2 mm which is **100 times smaller** than previous designs in the literature at the same power transfer efficiency and range.

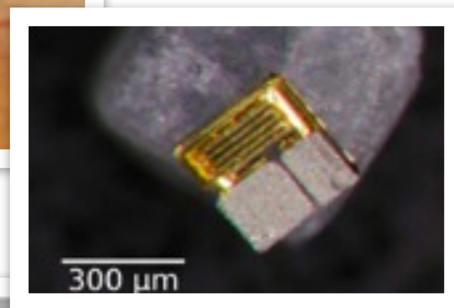
1959, Richard Feynman, *Plenty of Room at the Bottom*:

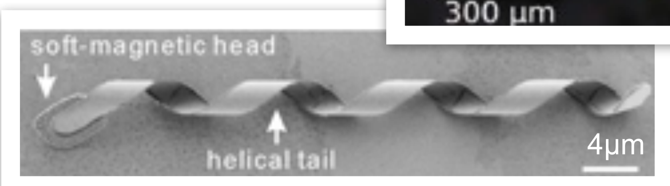
A friend of mine (Albert R. Hibbs) suggests a very interesting possibility for relatively small machines. He says that, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and "looks" around. (Of course the information has to be fed out.) It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately-functioning organ.

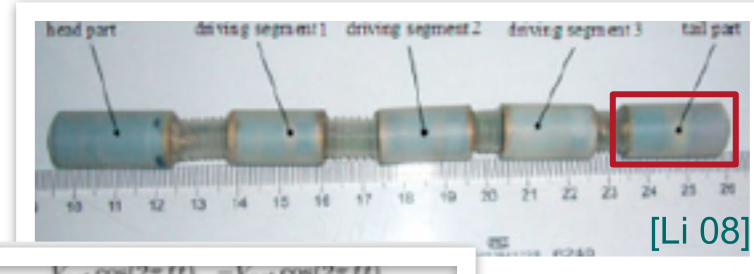


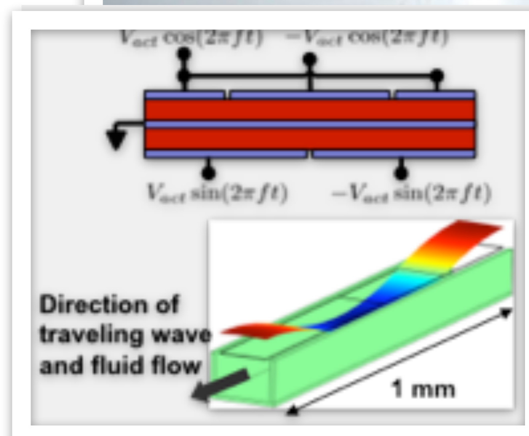
Current Propulsion Methods











Passive methods

- Requires complex field generation e.g. gradient, rotating, and oscillating fields.
- Requires precise 3D control of fields.
- Slow at small sizes

Mechanical methods

- Suffers from low conversion efficiency from mechanical motion to forward thrust.
- Requires high power e.g. 1 mW for 1 cm/s
- Moving parts increase complexity.

Convert Electrical Power *Directly* to Thrust

Mechanical methods

Wireless Power Source → Electrical Energy to Mechanical Motion → Mechanical Motion to Thrust

Introduces Loss (Electrical Energy to Mechanical Motion)

Very Inefficient at Low Reynolds (Mechanical Motion to Thrust)

Proposed electromagnetic method

Wireless Power Source → Electrical Current to Thrust Force

How does it work?

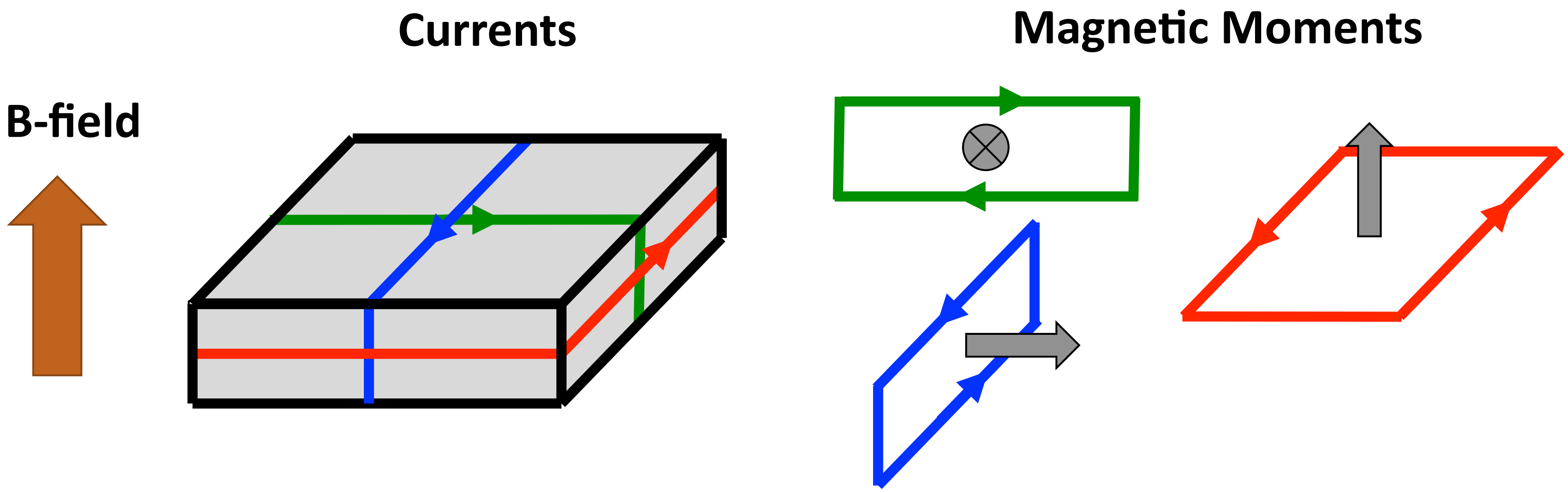
Inspired by product rule in differentiation …

$$\mathbf{F} = \nabla(\mathbf{m} \cdot \mathbf{B})$$

$$\sim \nabla\mathbf{B} \cdot \mathbf{m} + \nabla\mathbf{m} \cdot \mathbf{B}$$

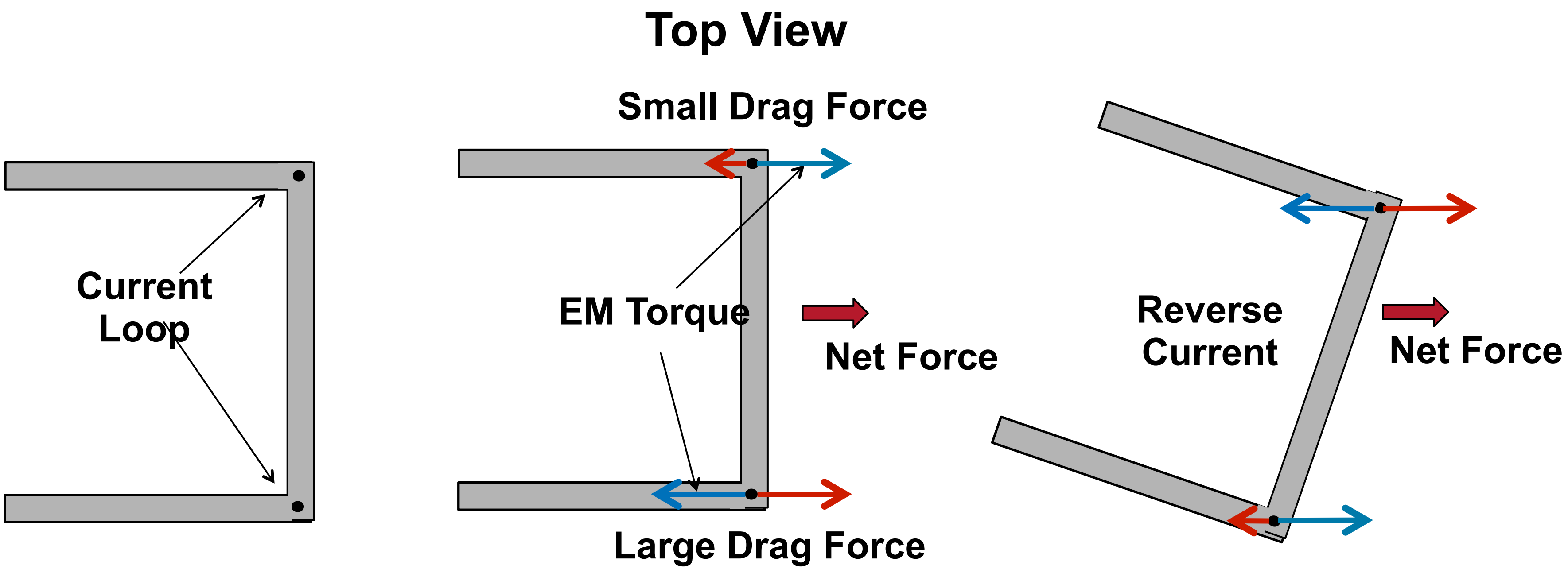
- In the passive propulsion method, we keep $\mathbf{m}$ constant and vary $\mathbf{B}$. It circumvents the power and efficiency issues but require a precisely controlled, large field gradient.
- Now, we vary $\mathbf{m}$ and keep $\mathbf{B}$ constant.

Power-Efficient Torque Generation



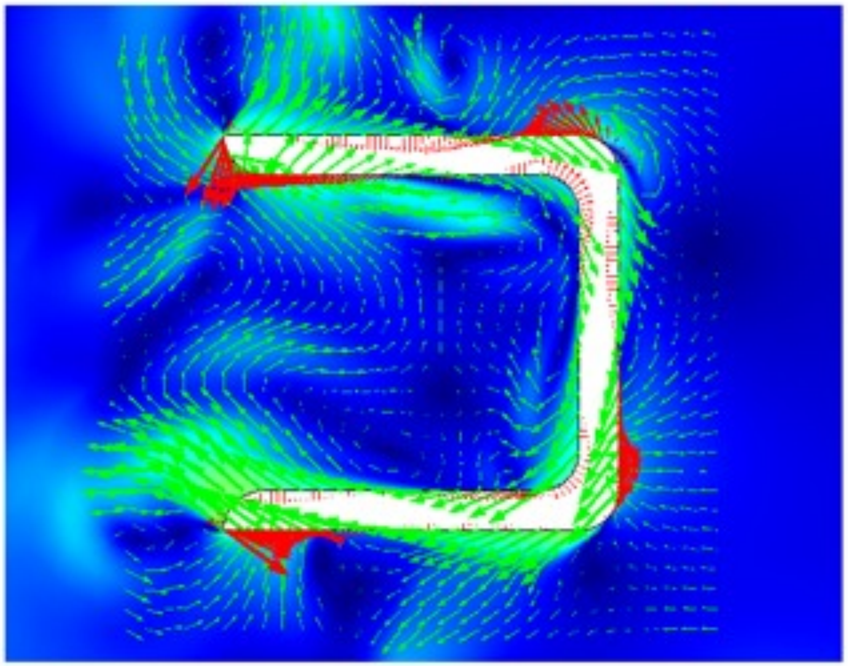
- Current loops on the implant can generate magnetic moment in any 3D direction.
- Generated magnetic moment experiences a torque to align it with an external static magnetic field.

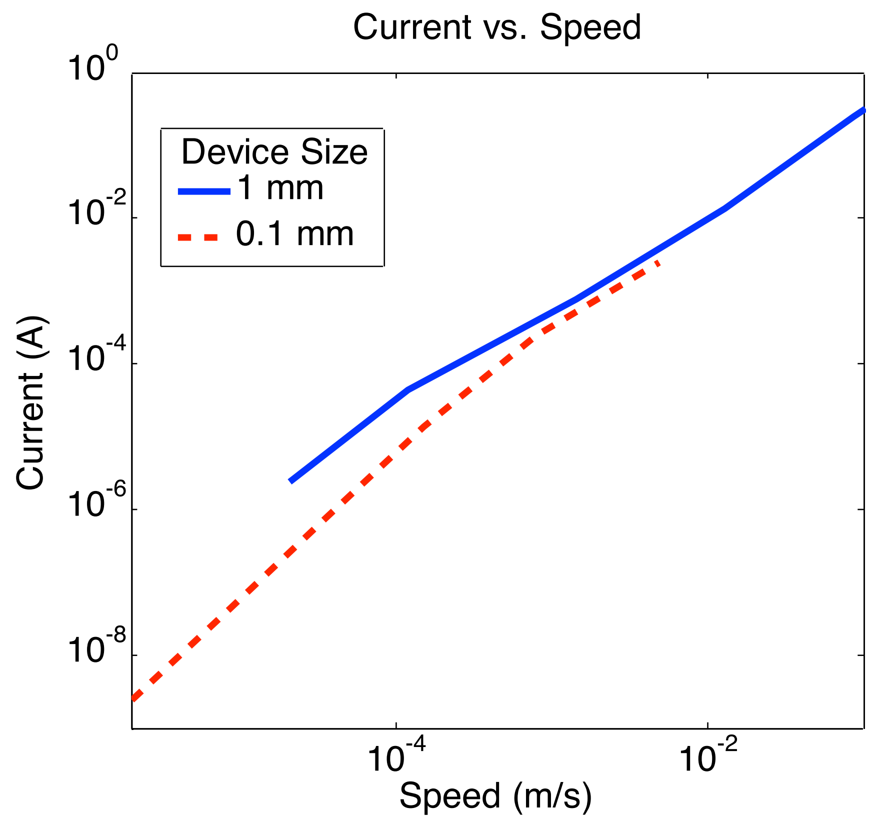
Translating Torques into Motion



- Idea is similar to the paddle in kayaking.
- Asymmetrical shape produces asymmetrical drag forces.
- Alternate direction of EM torque results in net forward force.
- Device can be optimized in terms of shape, frequency of current switching, and magnitudes of currents.

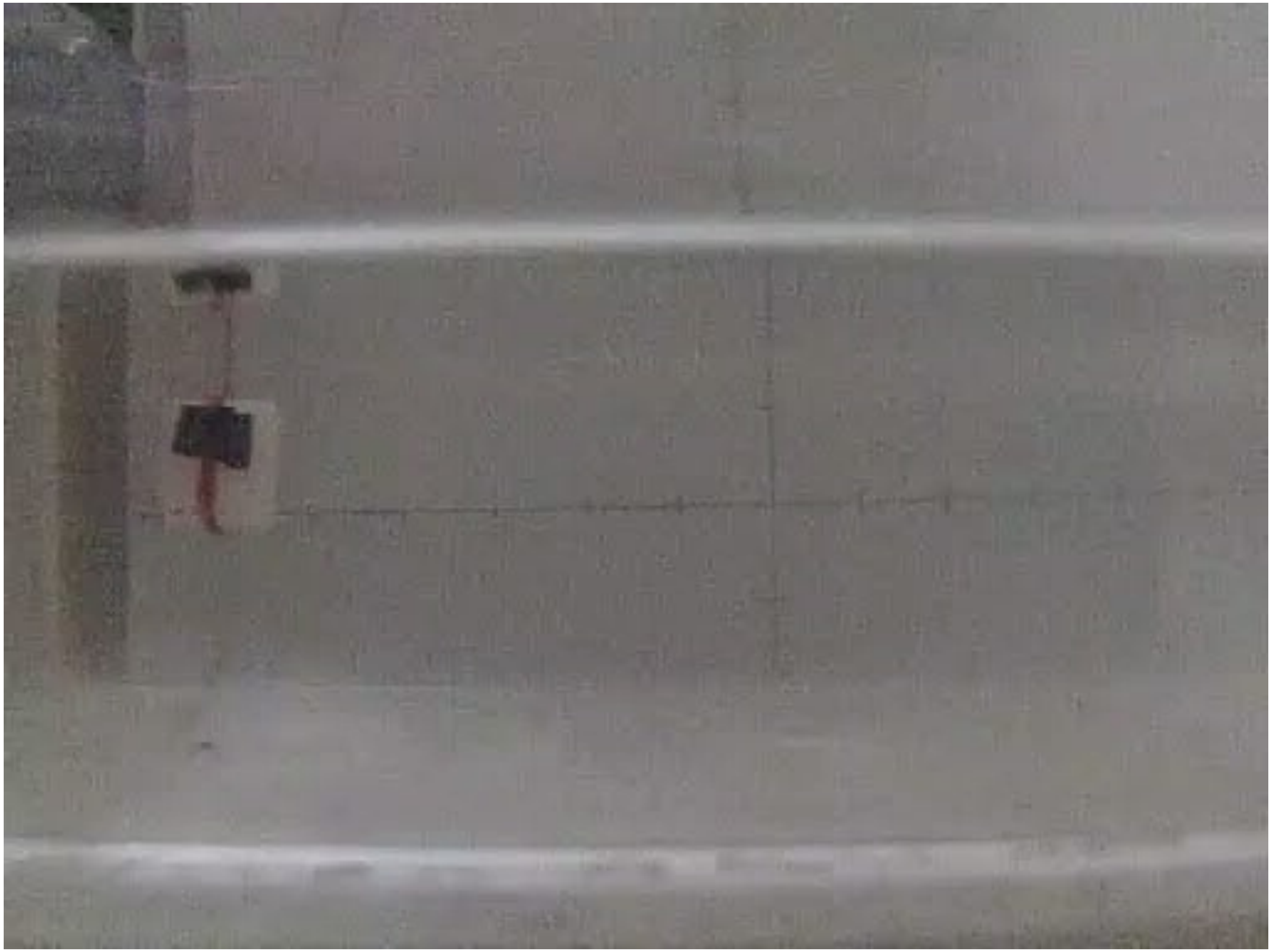
Fluid Simulation



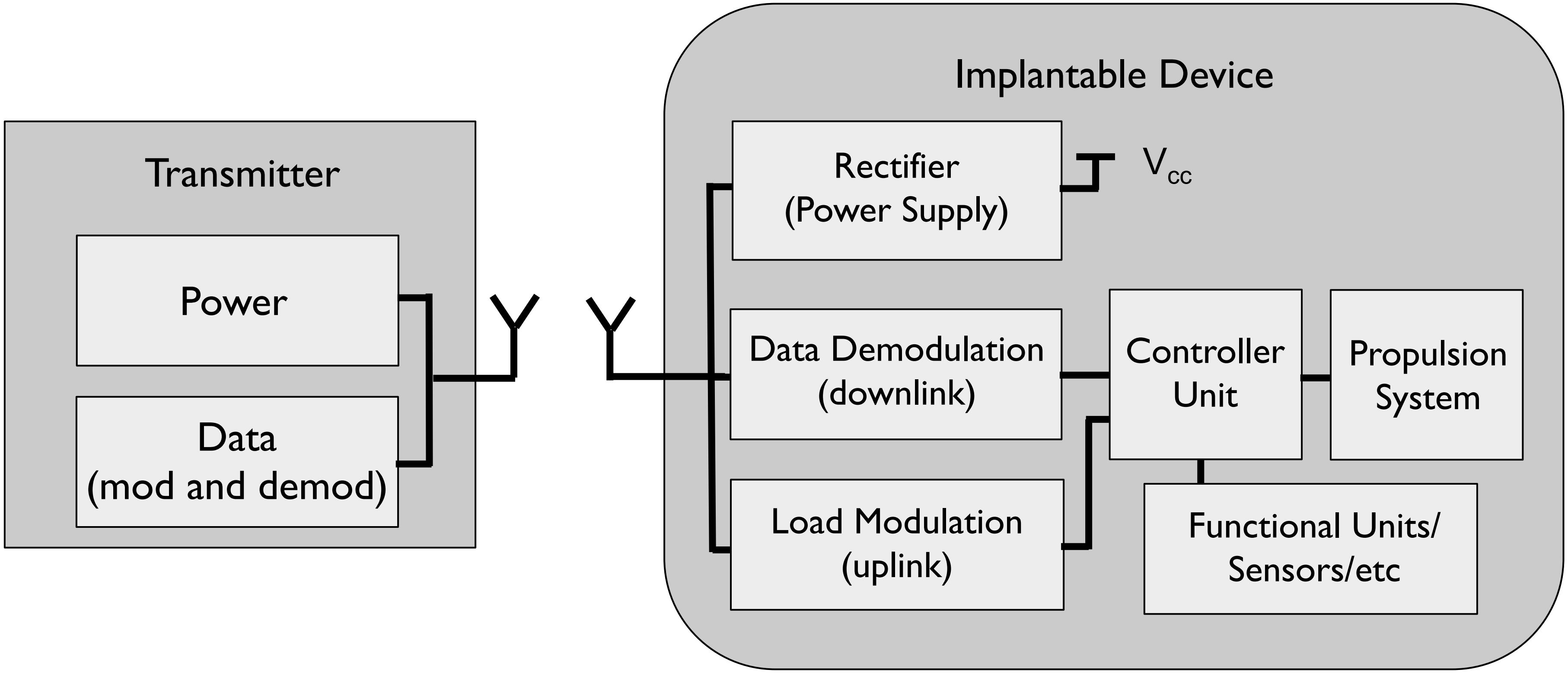


- For a 1-mm device in a 0.5-T static field, the current to achieve an angular frequency of 10 Hz is about 10 mA.
- Thrust force produced corresponds to stead-state velocity of 1 cm/s.
- Current required corresponds to power consumption of 100 μW.

Preliminary Experiments



System-Level Block Diagram

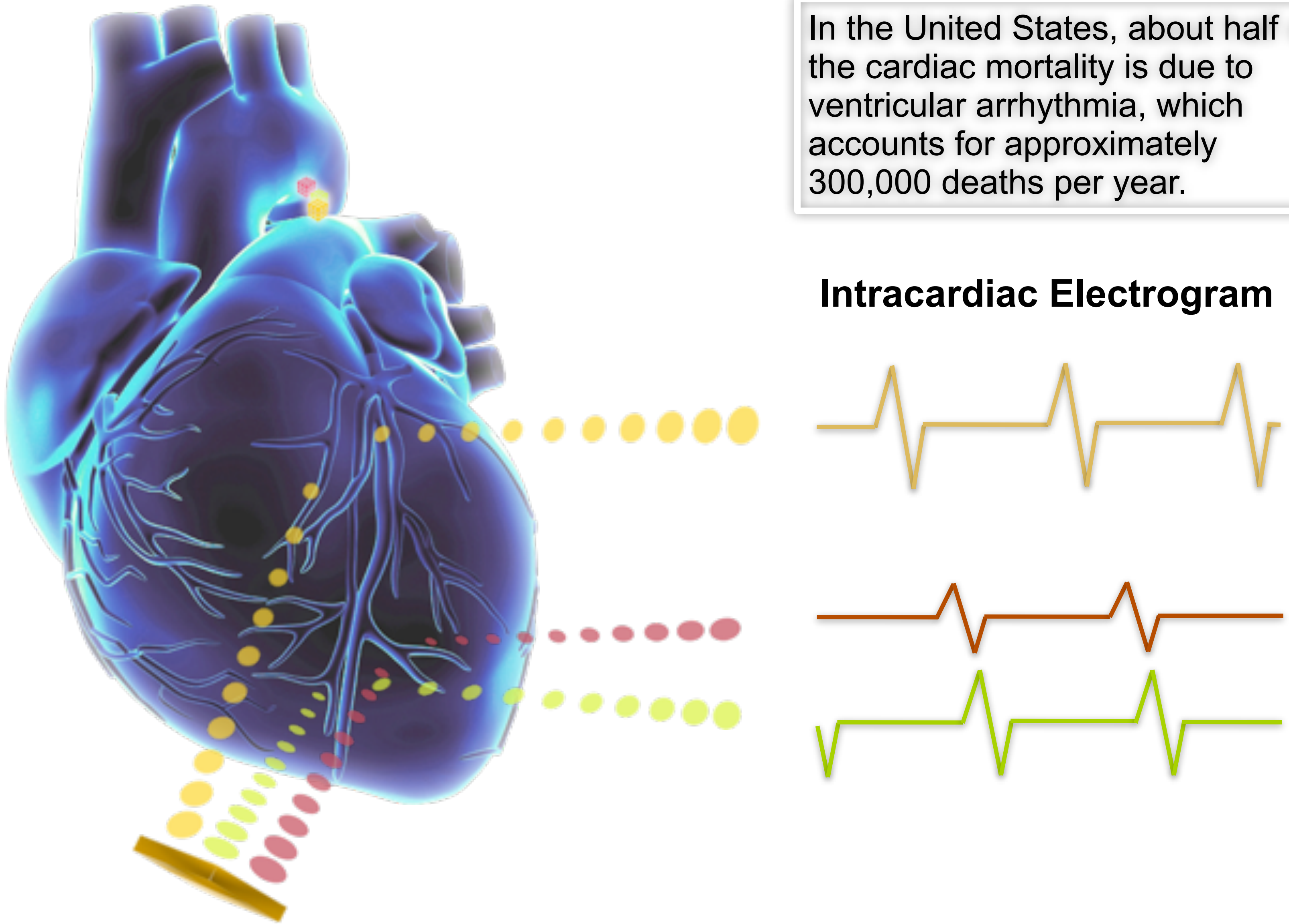


- Power and data are transmitted from same antenna
- Propulsion dominates power consumption, and must be efficient.
- Taped out in June

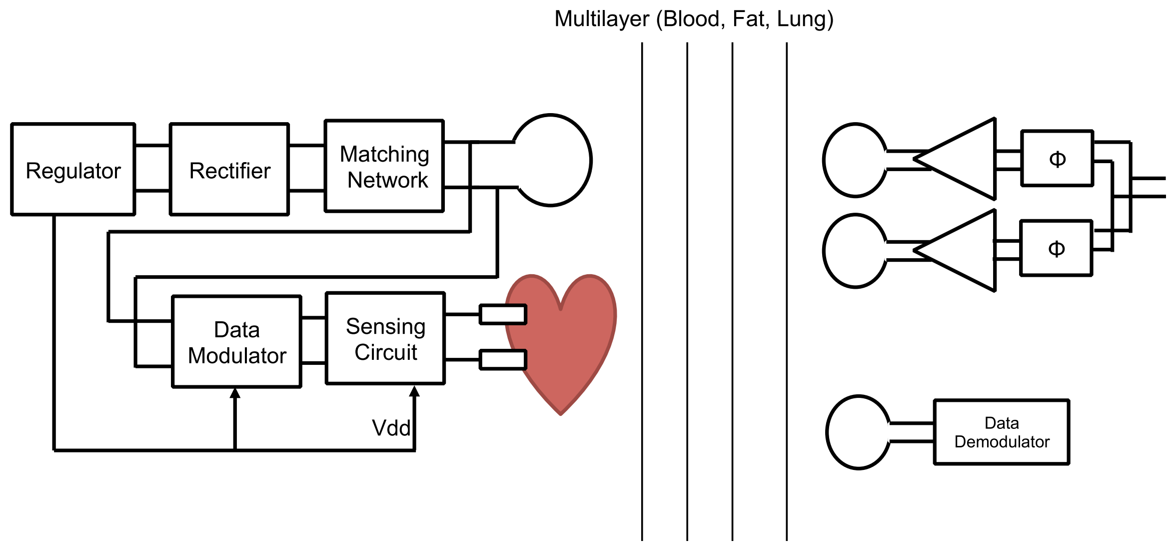
Wireless Probing of the Heart

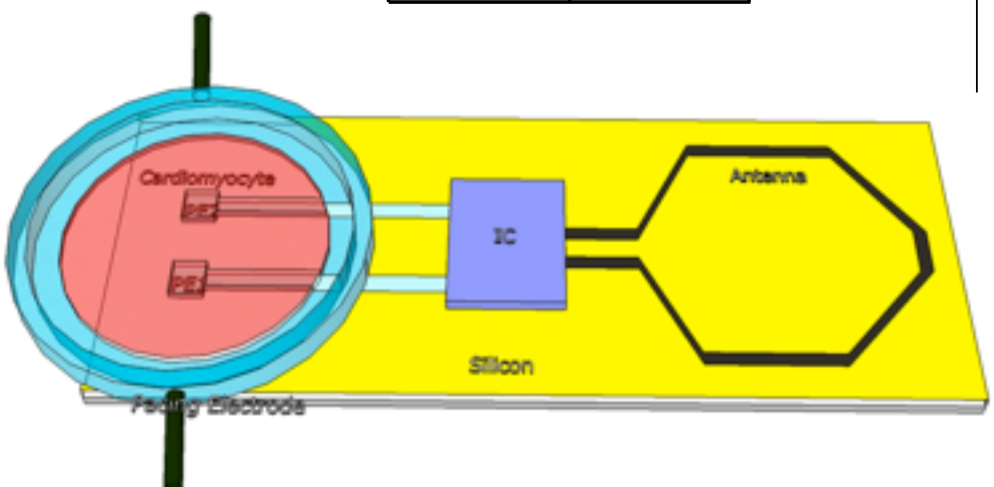
In the United States, about half of the cardiac mortality is due to ventricular arrhythmia, which accounts for approximately 300,000 deaths per year.

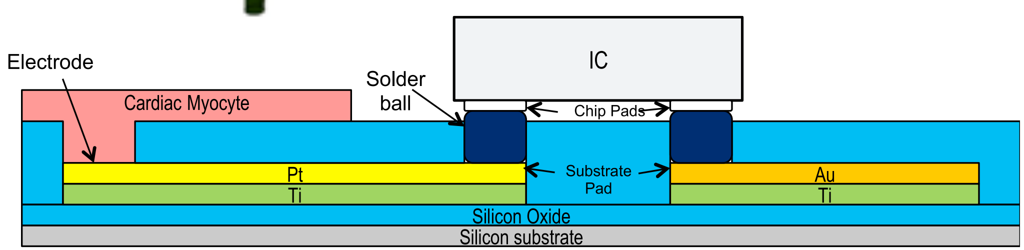
Intracardiac Electrogram



Building Blocks

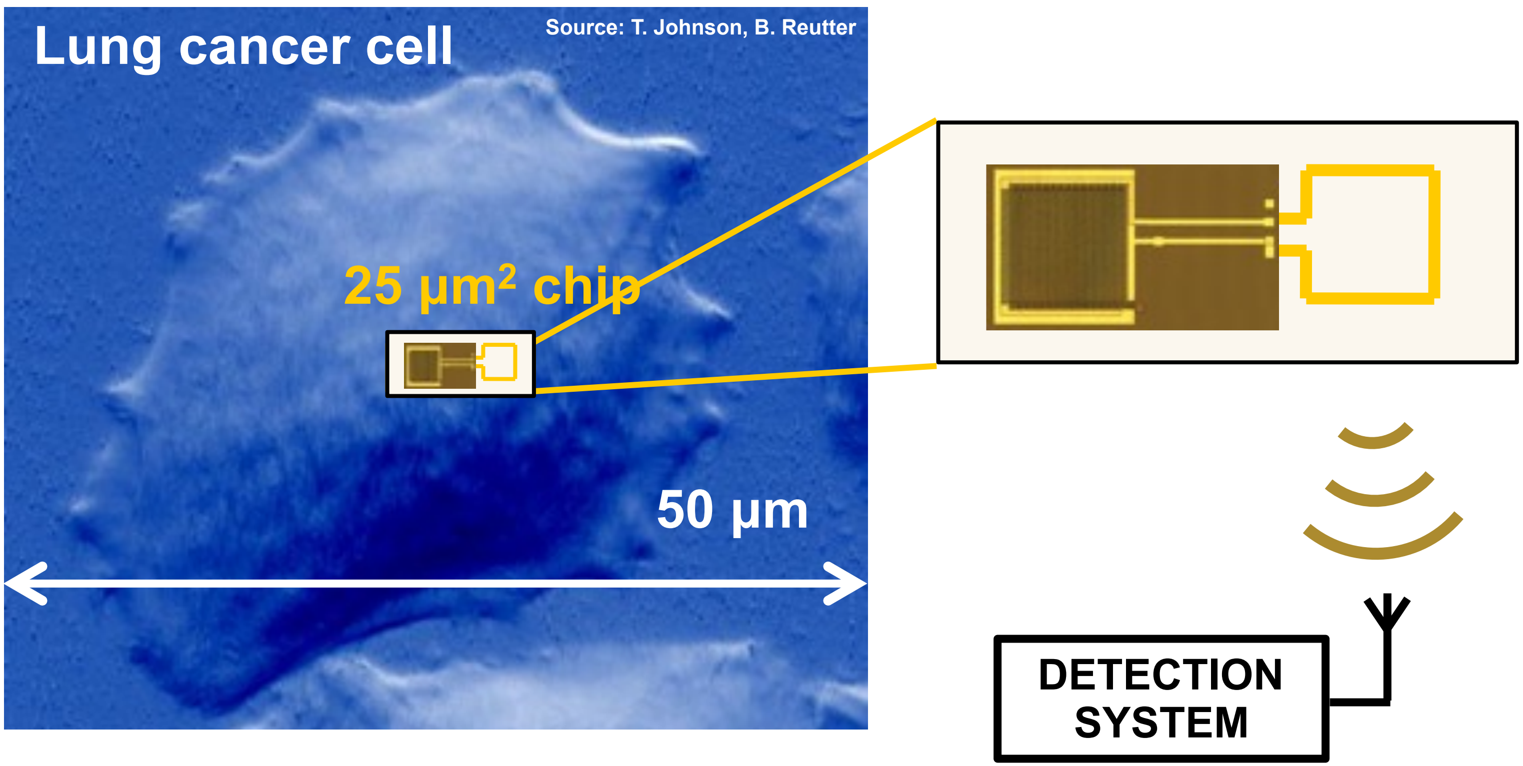






CHIC (CHip In Cell)

- Autonomous, wireless, implantable sensor
- Active, continuous-time monitor of cellular activity



Conclusions

- Optimal frequency for wireless power transfer over biological tissue is about 2 order of magnitude higher than conventional wisdom. As a result, the implant dimension can be reduced by 100 times in area.
- Wireless and miniature implants will introduce a new way to *in vivo* diagnostics and therapeutic treatment.