MedCOMM
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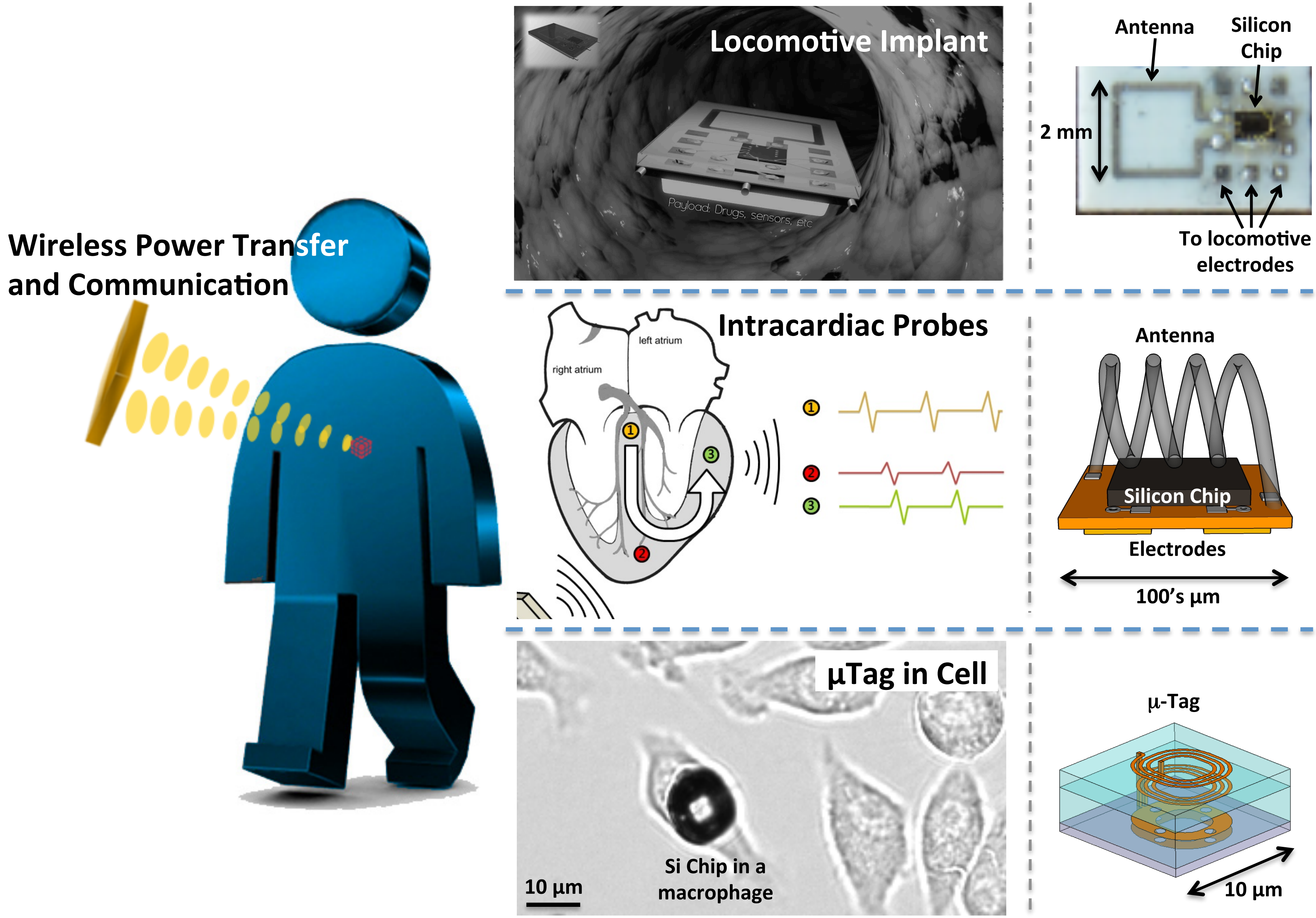
Emerging Wireless Applications in Biomedicine

Ada Poon
Stanford University



Wireless Power Transfer and Communication
Locomotive Implant
Payload: Drugs, sensors, etc
Antenna
Silicon Chip
2 mm
To locomotive electrodes
Intracardiac Probes
left atrium
right atrium
1
2
3
Antenna
Silicon Chip
Electrodes
100's µm
µTag in Cell
Si Chip in a macrophage
10 µm
µ-Tag
10 µm

Some Background

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

$$\nabla \times \mathbf{E} = i\omega\mu_0\mathbf{H}$$

- 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.
- Recently, we included the displacement current and performed full-wave analysis.
  - Optimal frequency lies in the sub-GHz to the low GHz-range depending on the dimension of the transmit antenna.
  - We built a prototype power receiver at 1 GHz that is 100× smaller at the same power transfer efficiency and range.

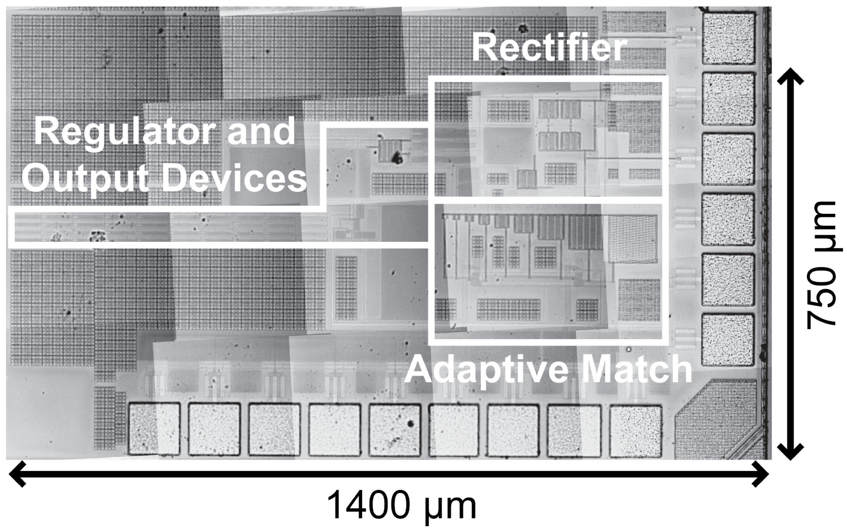
Optimal Frequency for Wireless Power Transfer in Homogeneous Medium

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

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

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

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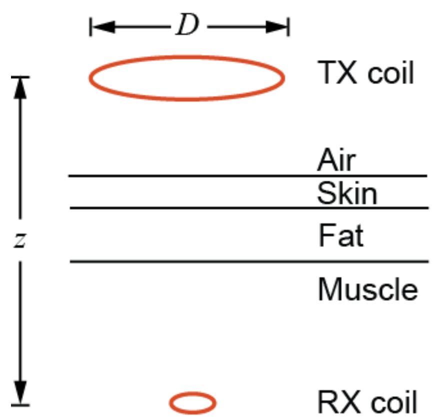
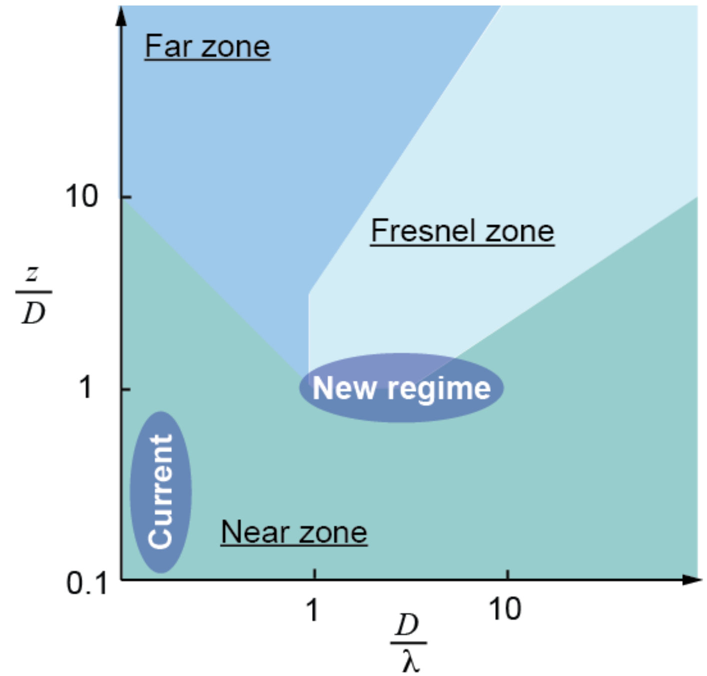
- Unique features
  - Adaptive conjugate matching
  - Highly efficient rectifier
- Coil dimension is 2 mm × 2 mm which is **100 times smaller** than previous designs in the literature at the same power transfer efficiency and range.

New Regime of Operation

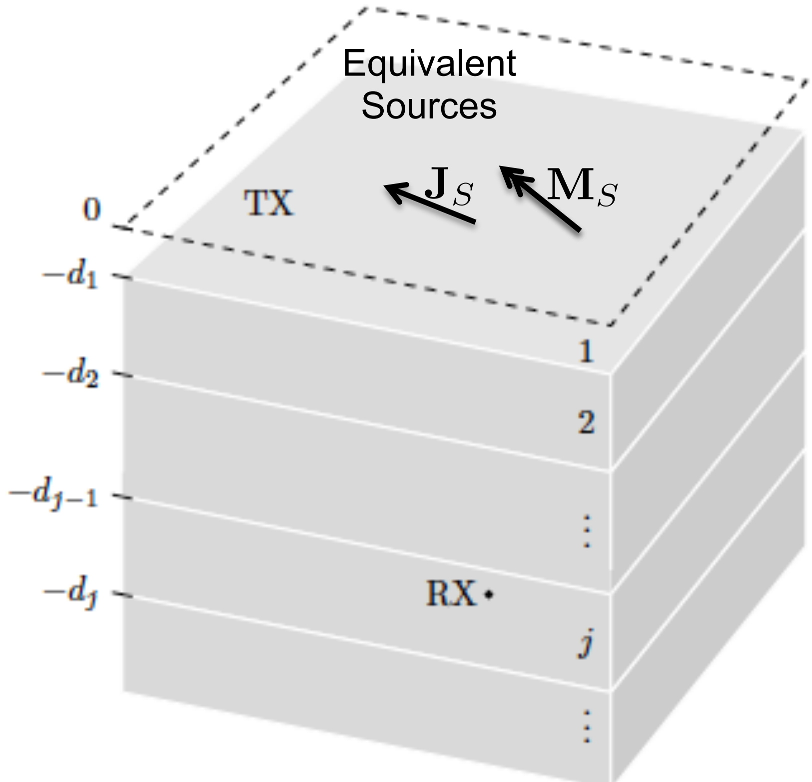
λ_{muscle} @ 1 GHz = 4 cm
~ Tx-Rx separation
~ Tx dimension

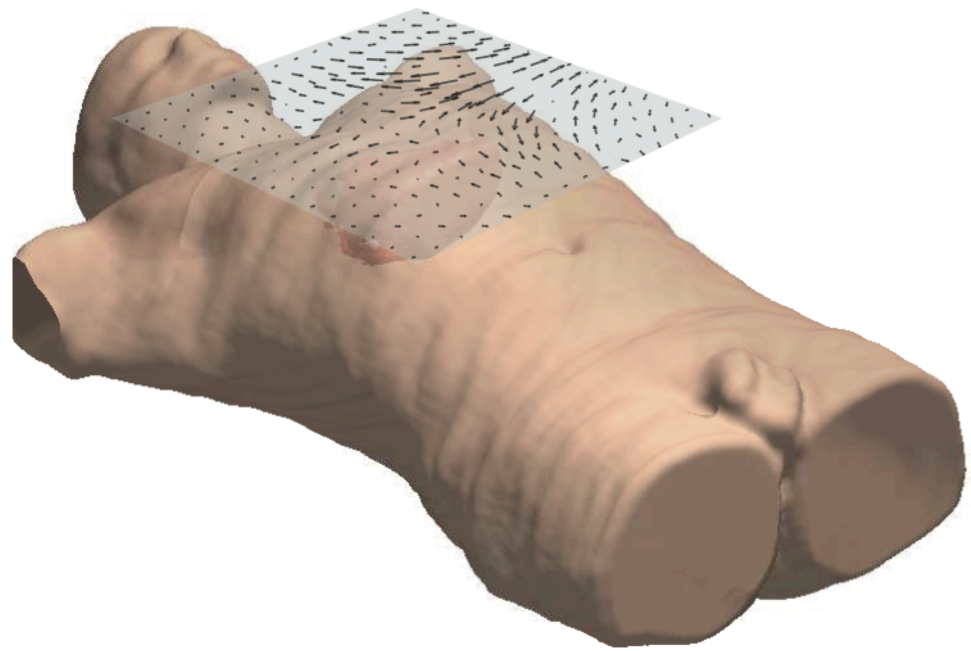




- EM fields can be focused to the implant to further maximize power transfer efficiency and desensitize the system to effects of receiver misalignment.
- Both evanescent and propagating fields contribute.

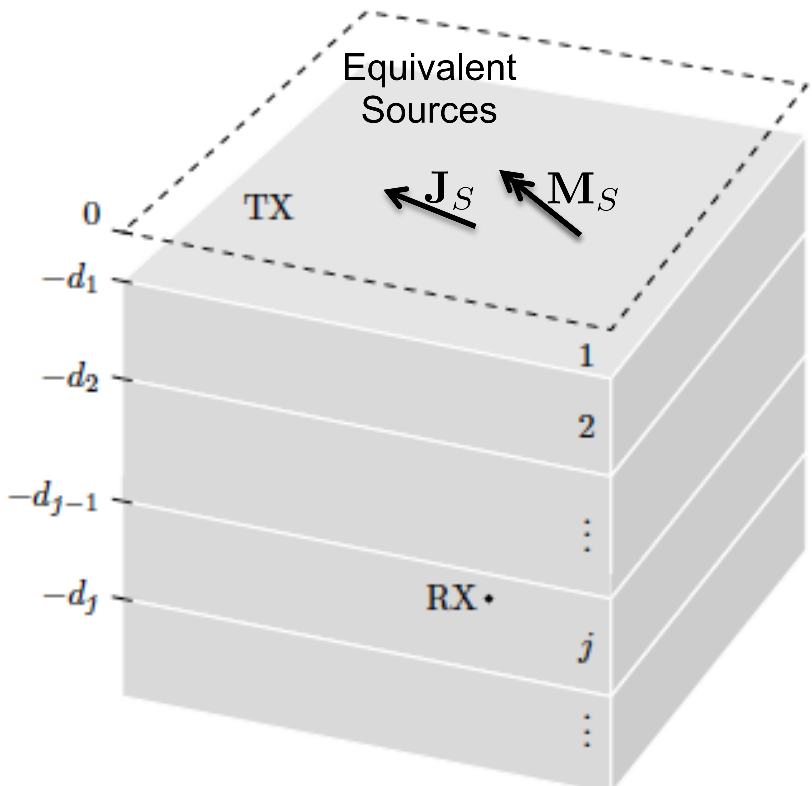
Optimal Power Transfer

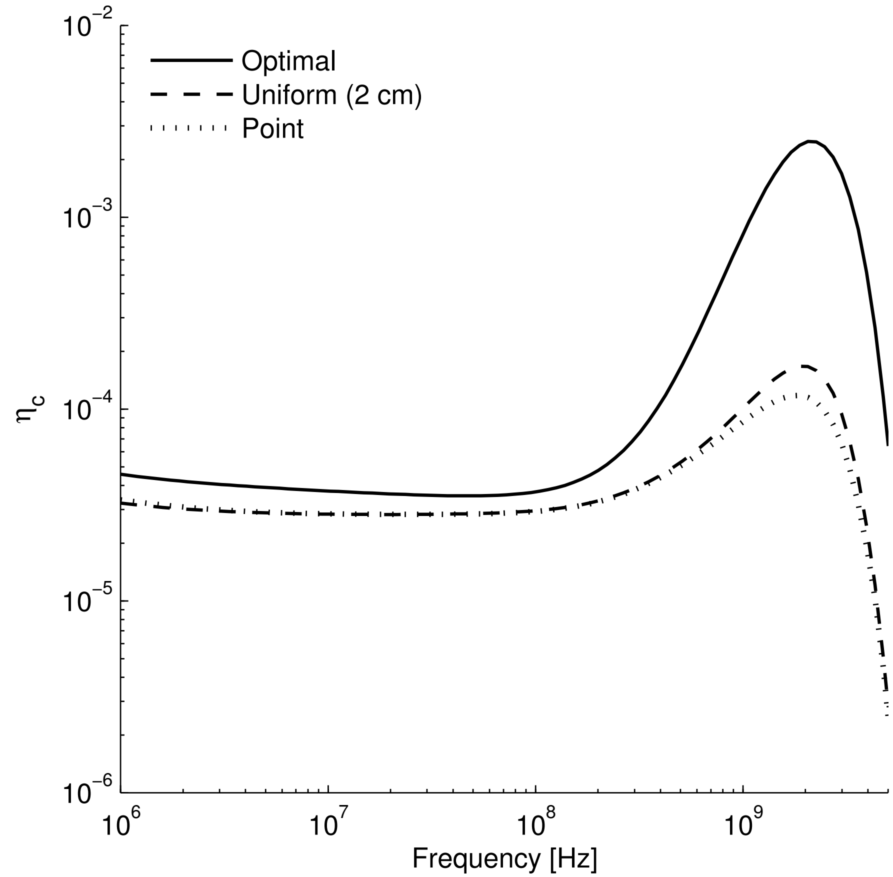




- If we are allowed to choose any transmitter, *is there an upper limit on the power transfer efficiency?*

Optimal Power Transfer

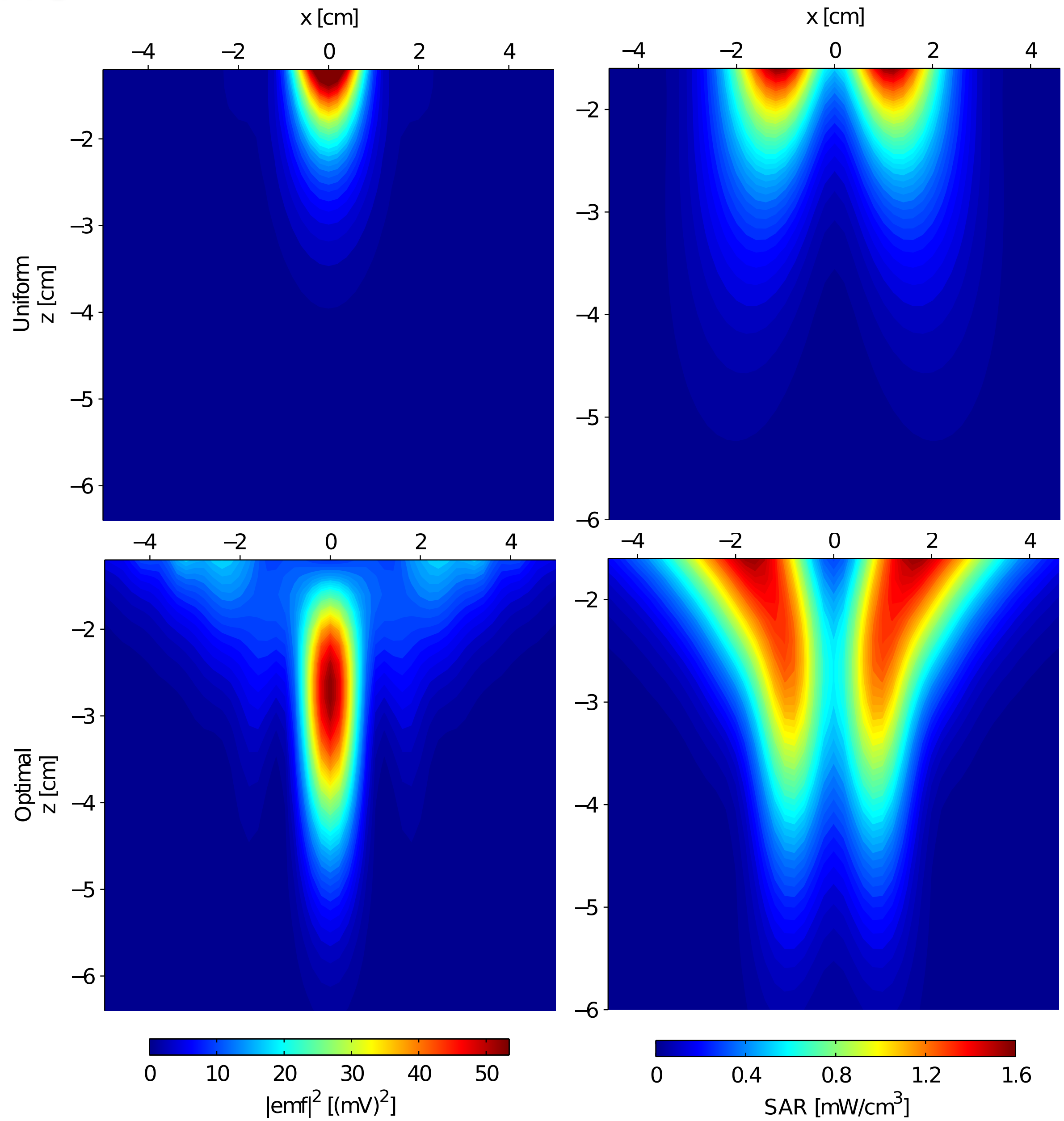




- Yes, there is a theoretical upper limit on the power transfer efficiency.

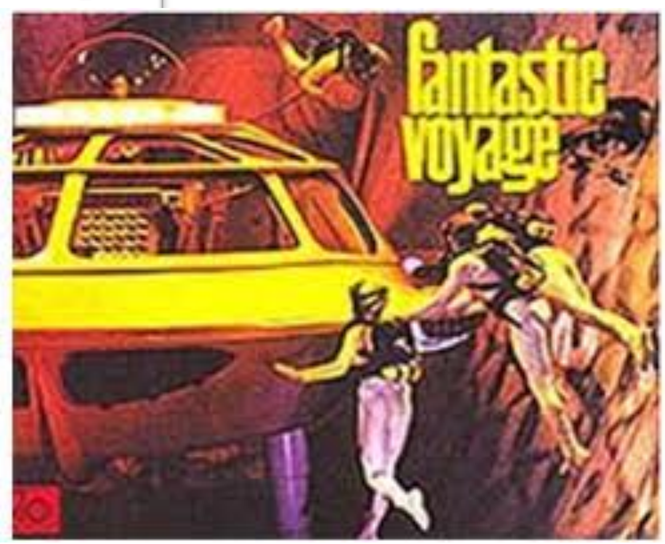
Field Distributions

Optimal source focuses EM fields to the implant antenna to maximize the received power while re-distribute the SAR to minimize tissue absorption.



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.



Wireless Locomotive Implant

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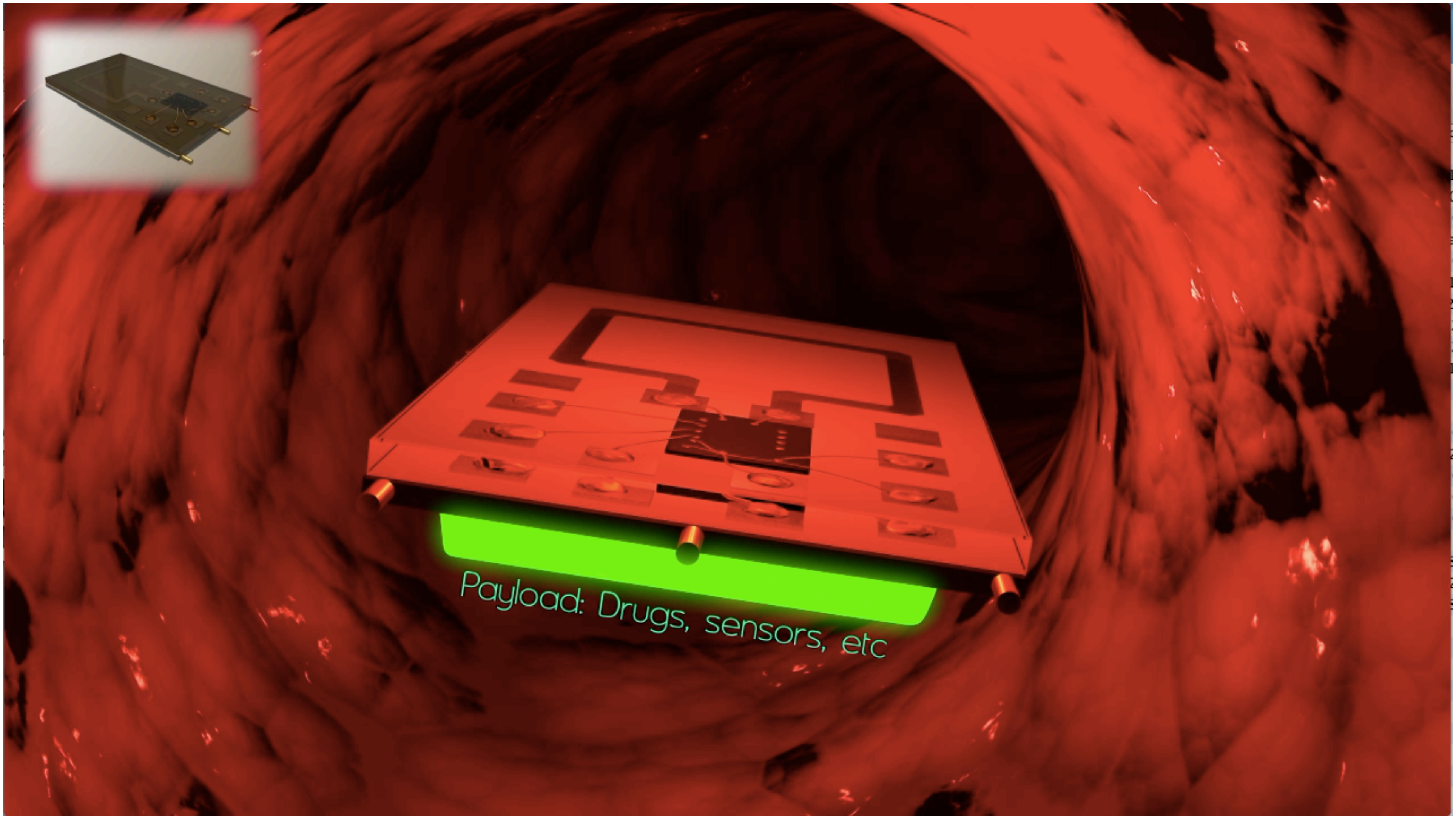
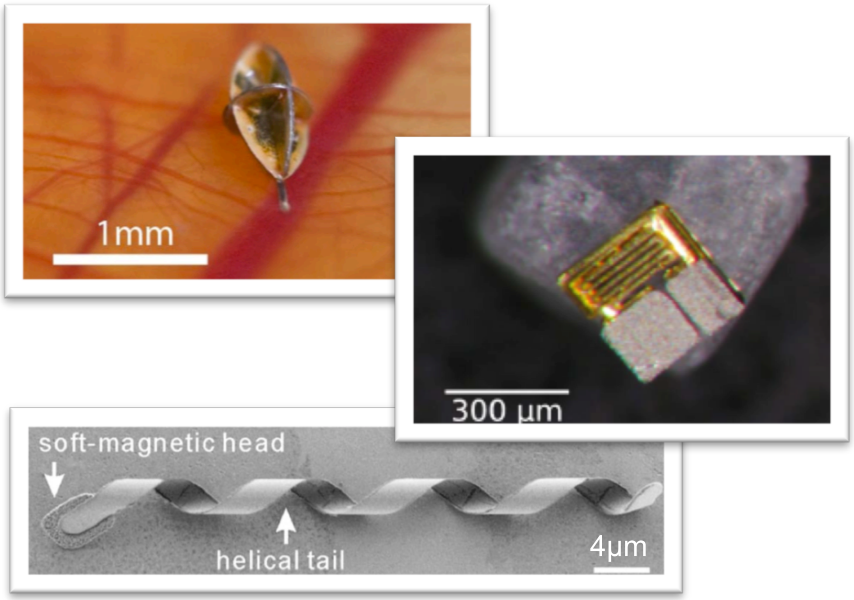
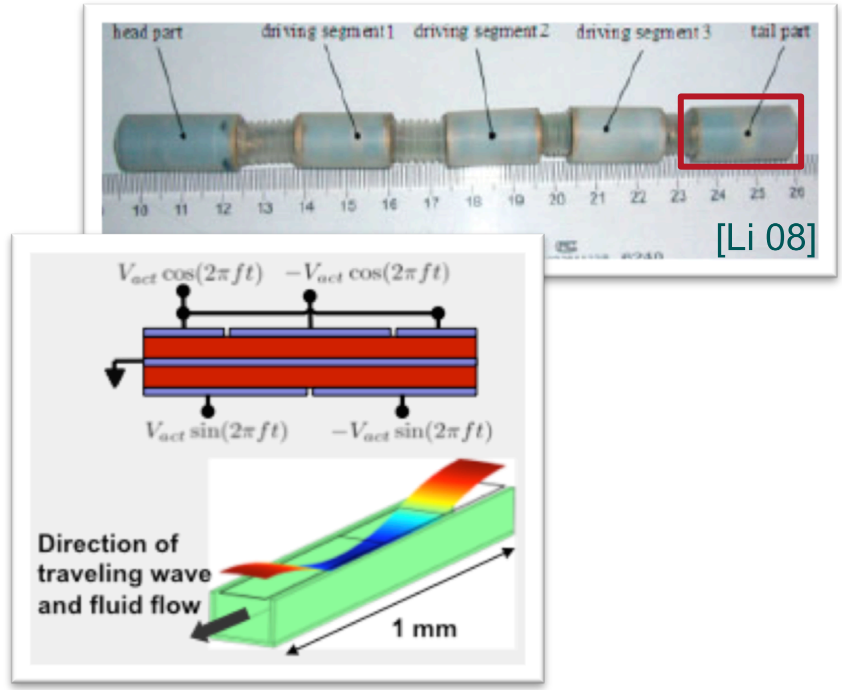


Current Propulsion Methods





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

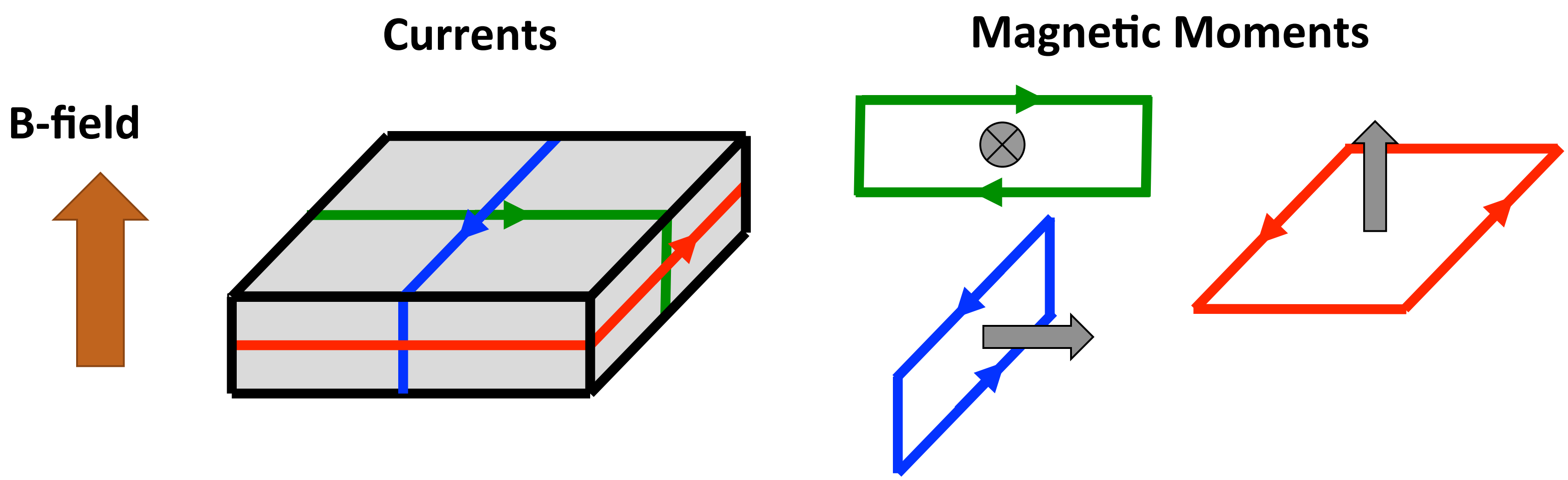
Introduces Loss

Very Inefficient at Low Reynolds

Proposed electromagnetic method

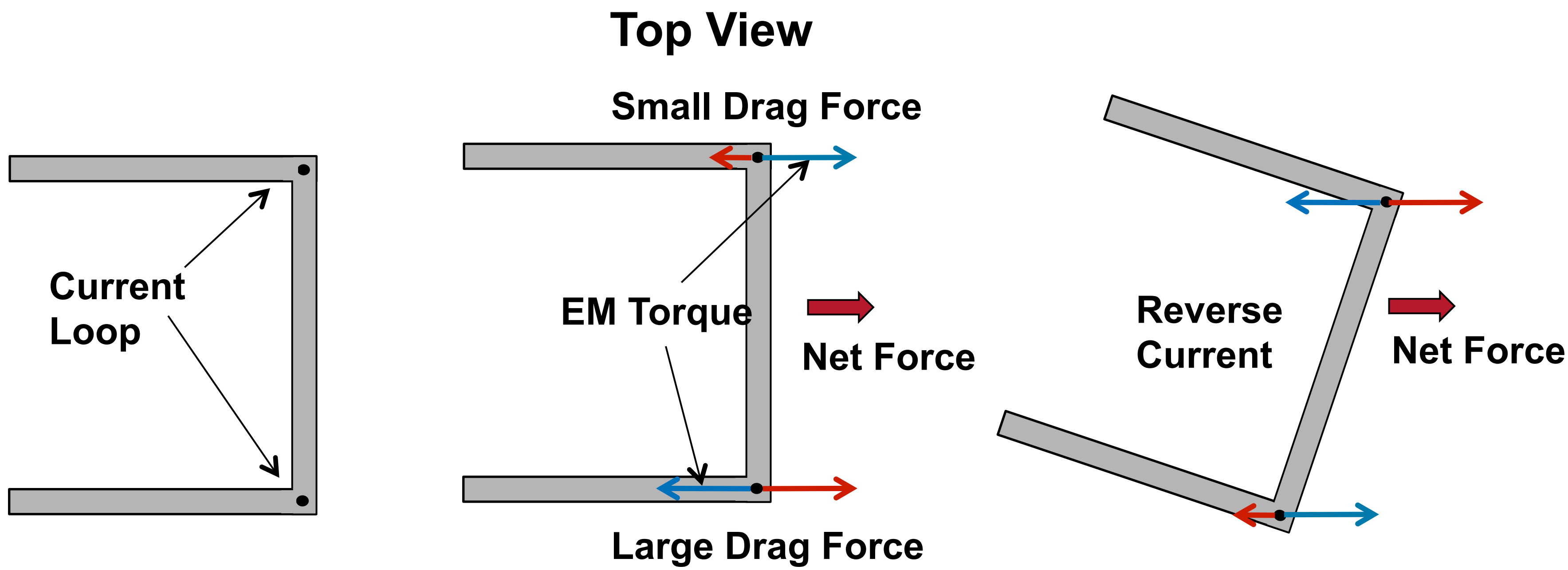
Wireless Power Source → Electrical Current to Thrust Force

Power-Efficient Torque Generation



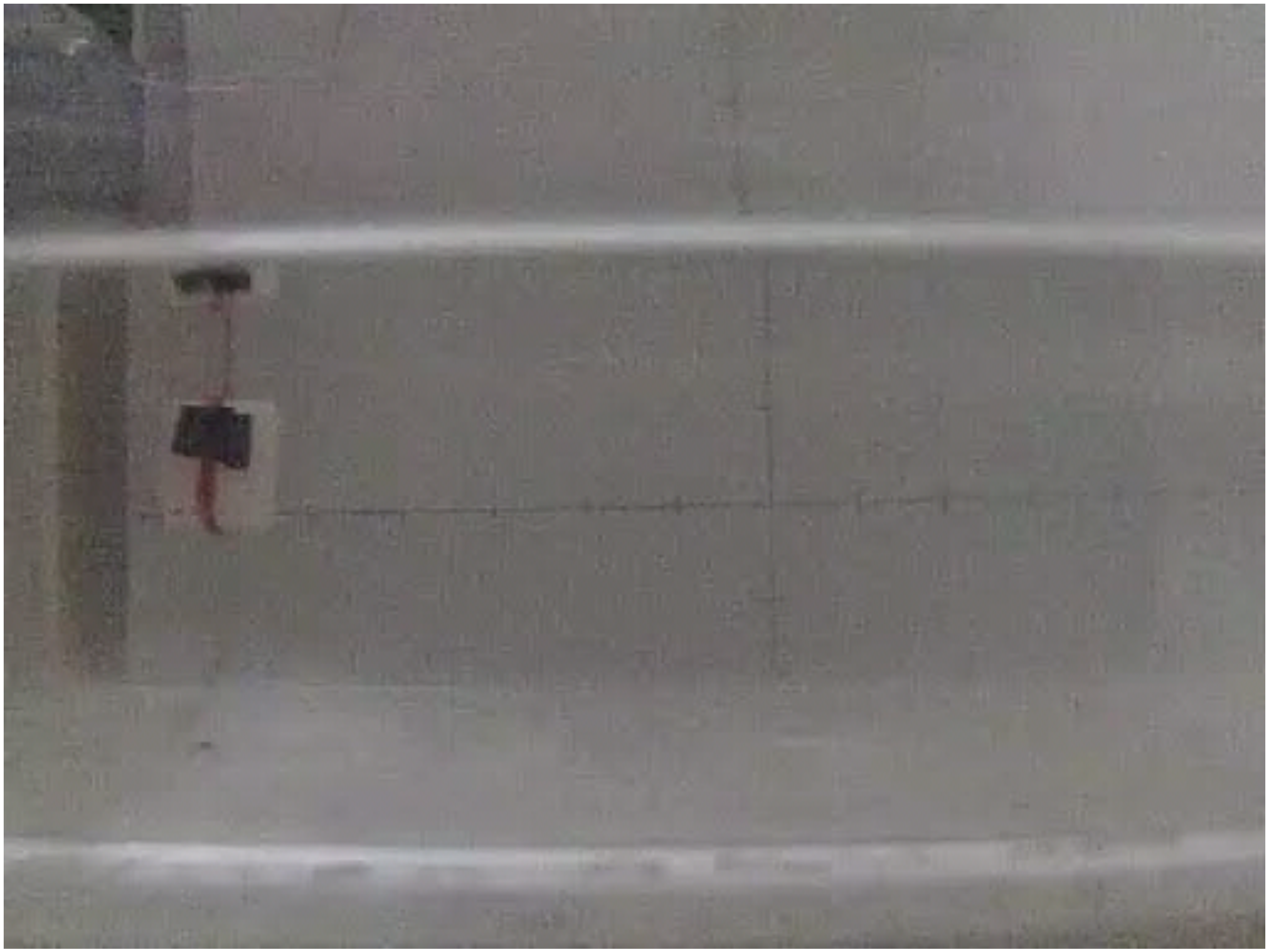
- Current loops on the implant can generate magnetic moment in any 3D direction.
- Generated magnetic moment experiences a torque to align it with an external static magnetic field.

Translating Torques into Motion

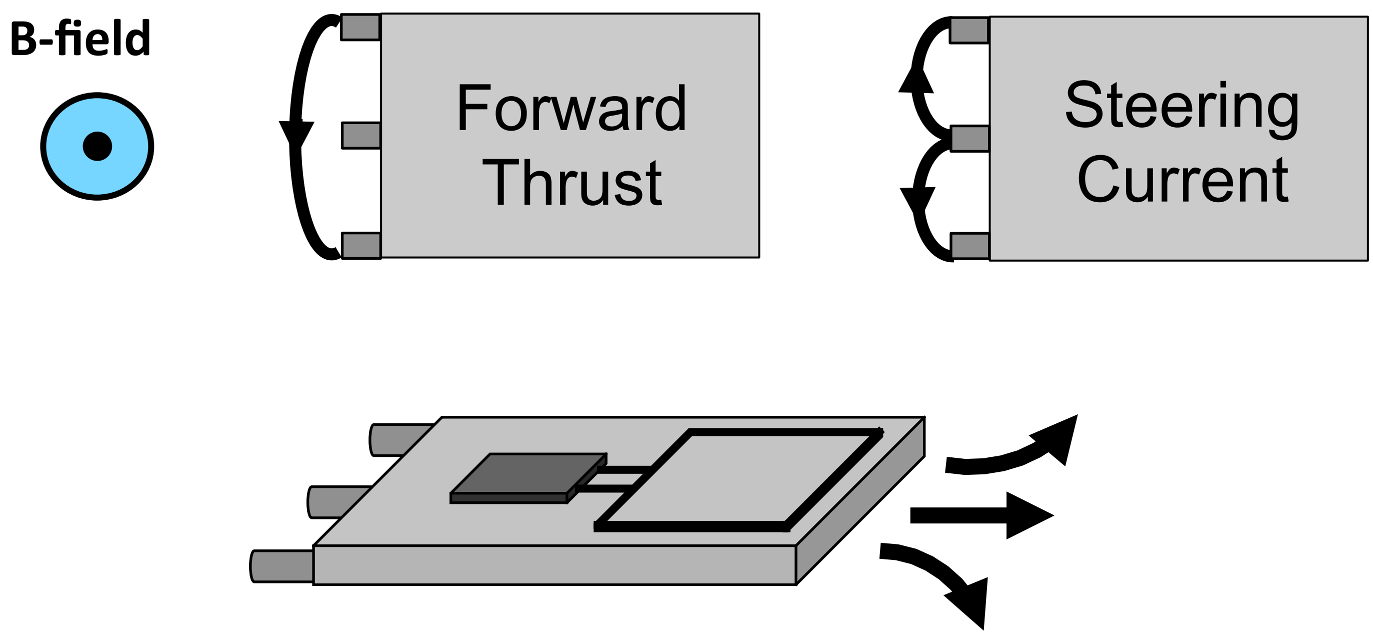


- Idea is similar to the paddle in kayaking.
- Asymmetrical shape produces asymmetrical drag forces.
- Alternate direction of EM torque results in net forward force.
- Device can be optimized in terms of shape, frequency of current switching, and magnitudes of currents.

Preliminary Experiment

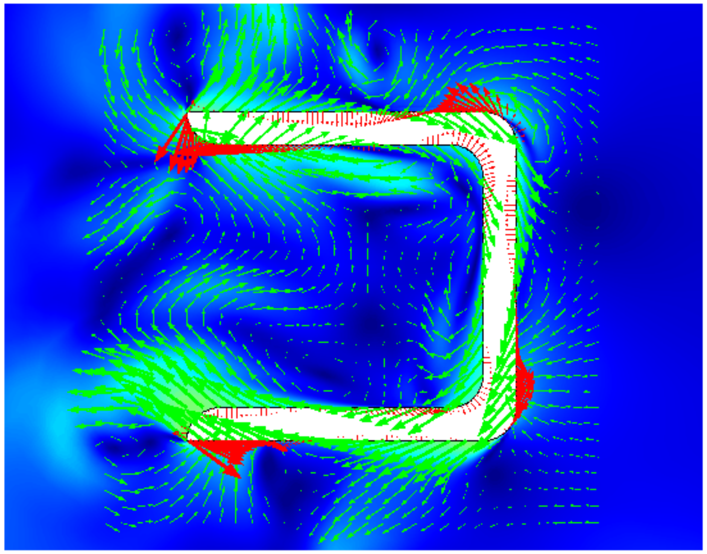


Another Propulsion Method: Magnetohydrodynamic (MHD) Propulsion

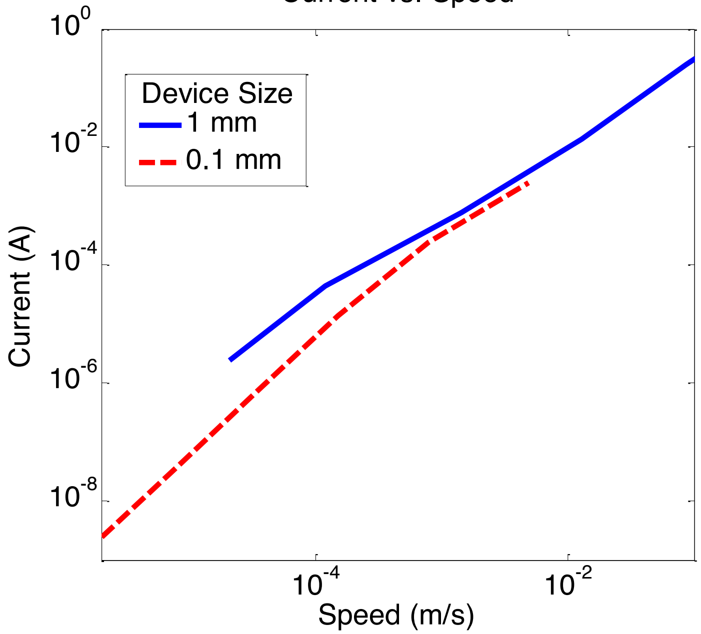


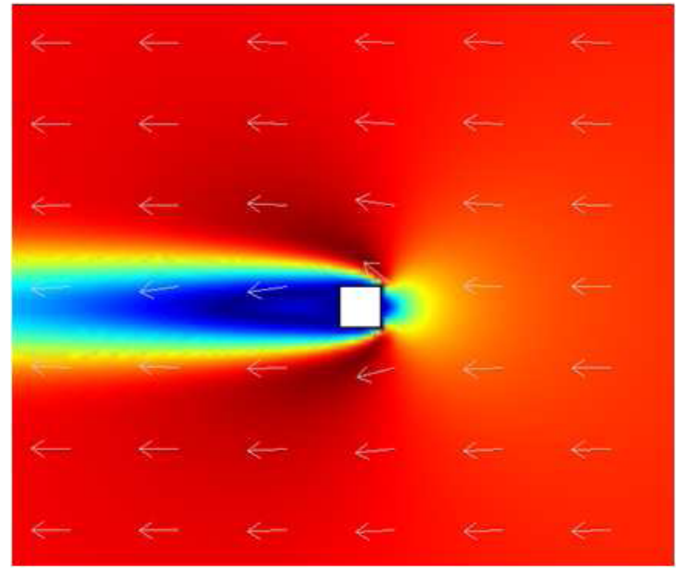
- Precise motion control by directing currents at the fluid electrodes.
- Requires conductive fluid

mA of current achieves speed of cm/sec

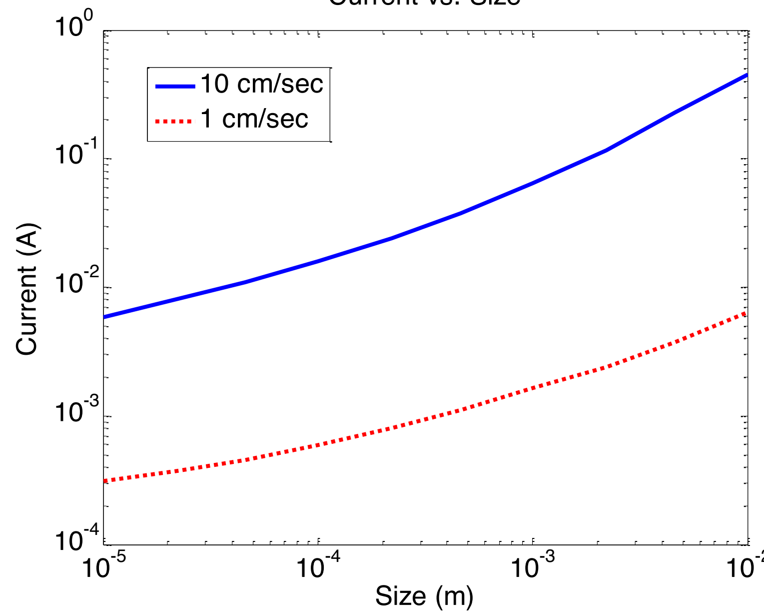


Current vs. Speed

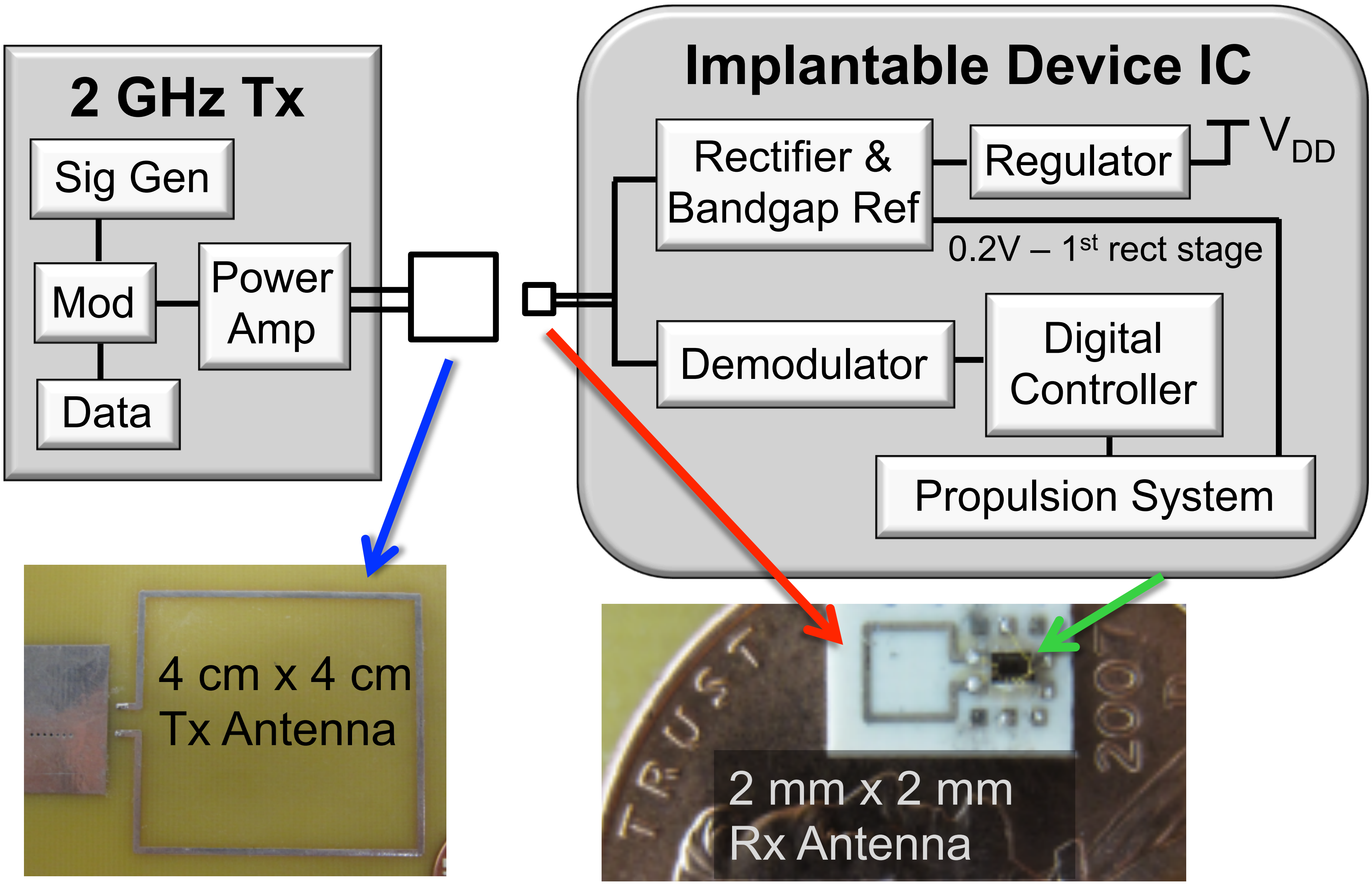




Current vs. Size



Prototype IC



Circuit Performance and Chip Layout

Power Breakdown	
Bandgap Reference	5μW
Regulator	5μW
Demodulator	5μW
Digital Controller	2μW
Fluid Propulsion System	250μW
Total	**267μW**

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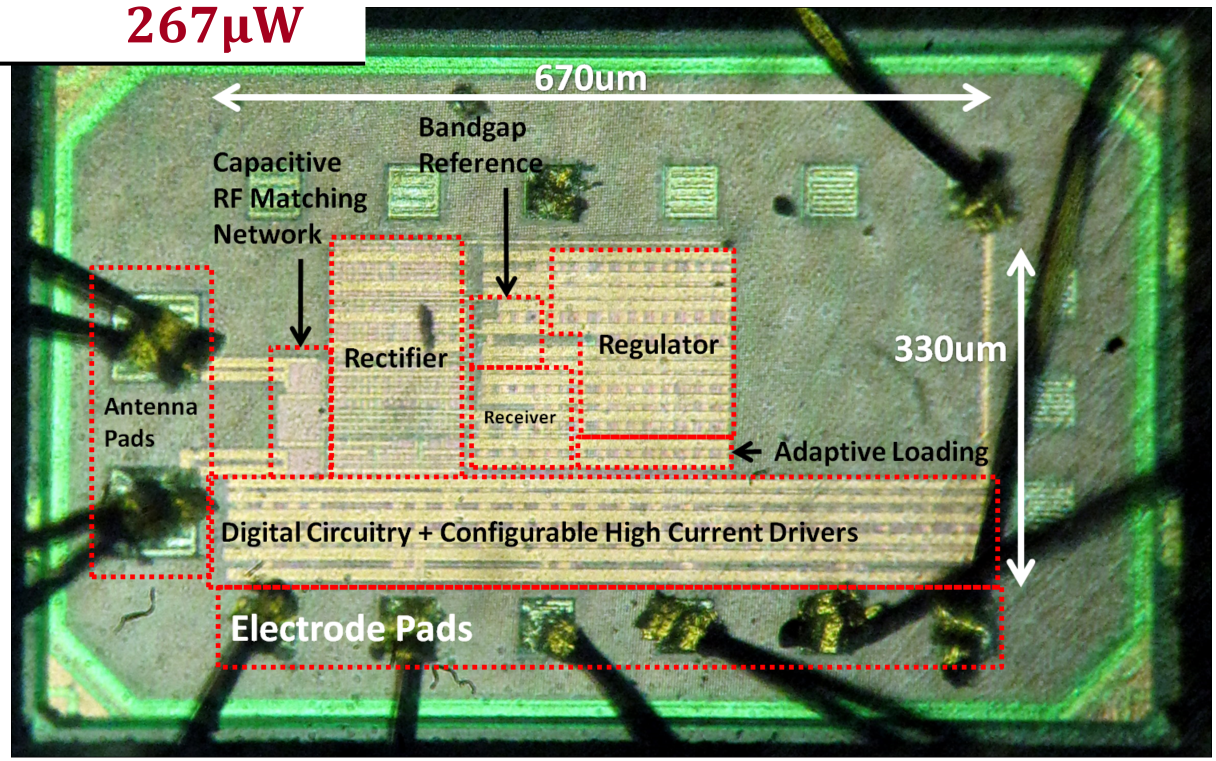
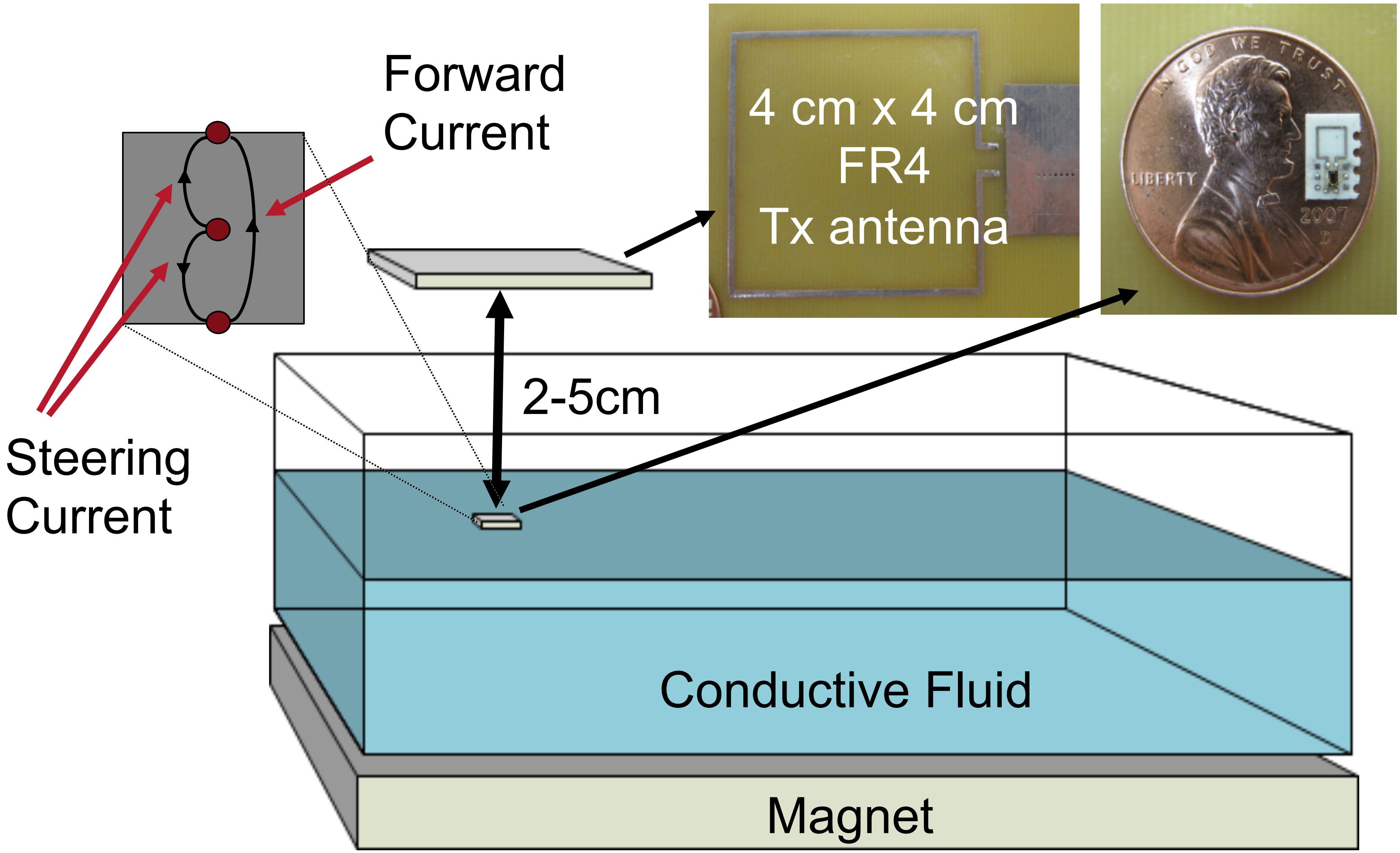
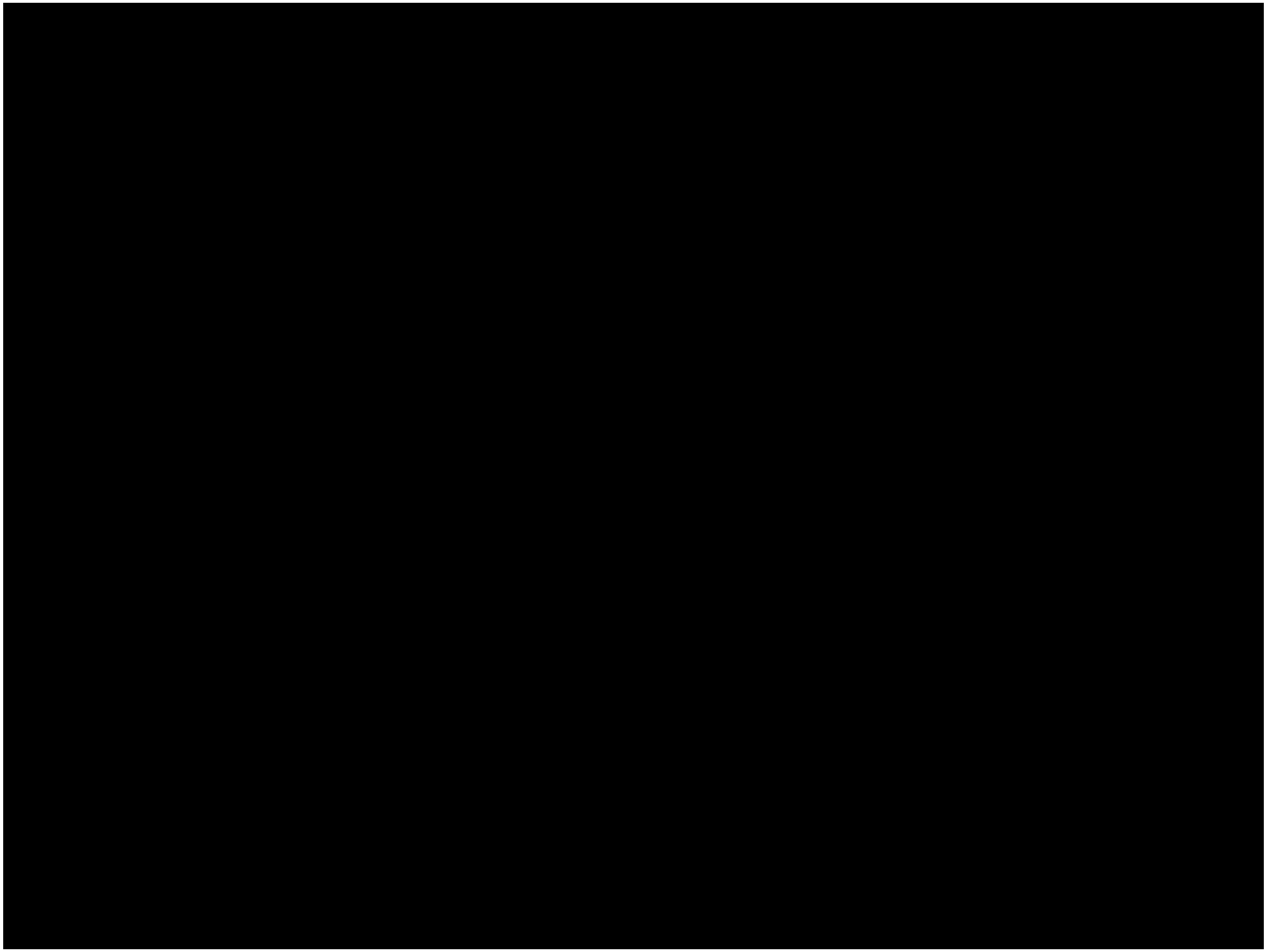


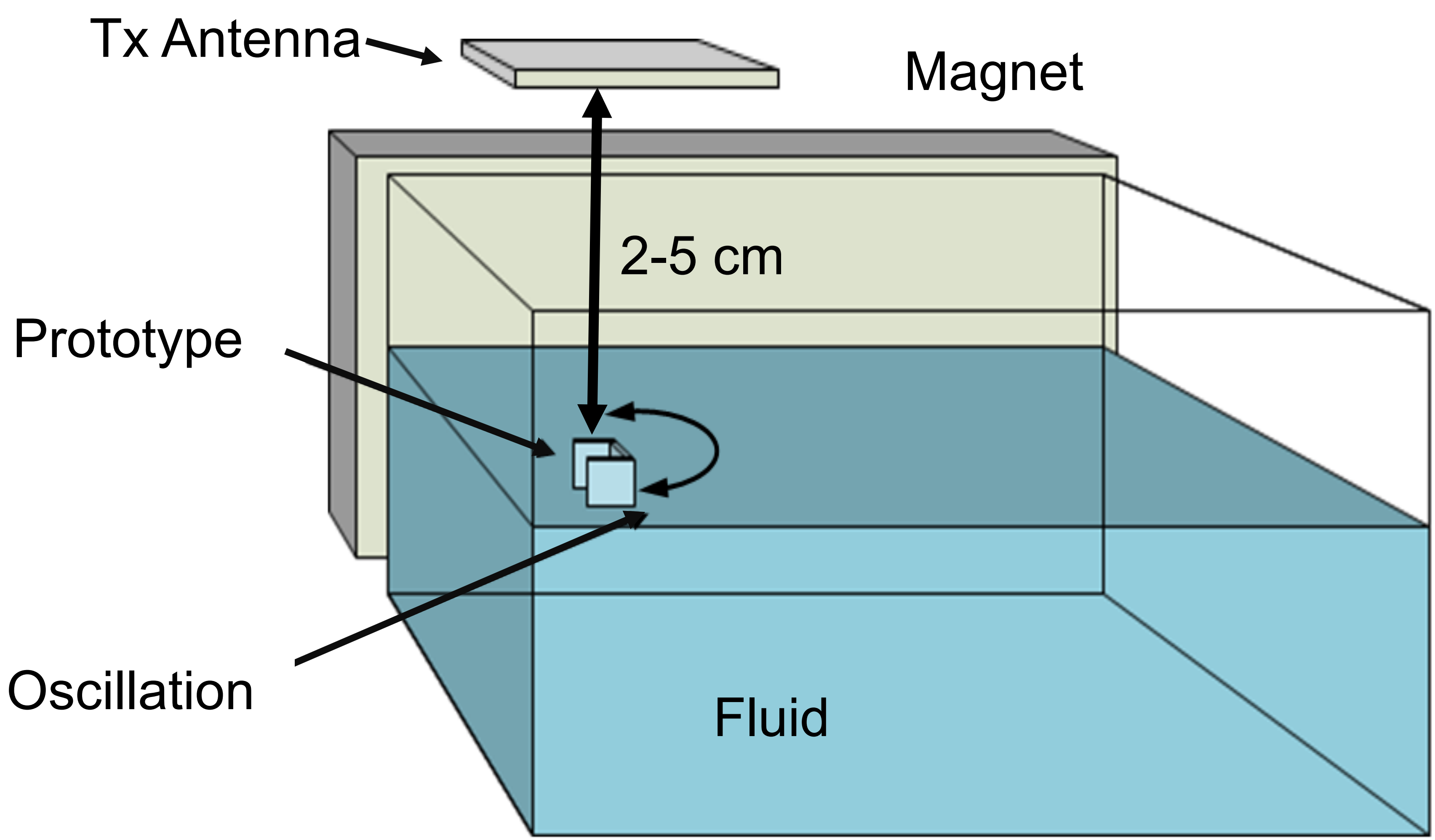
Method 1: MHD Propulsion



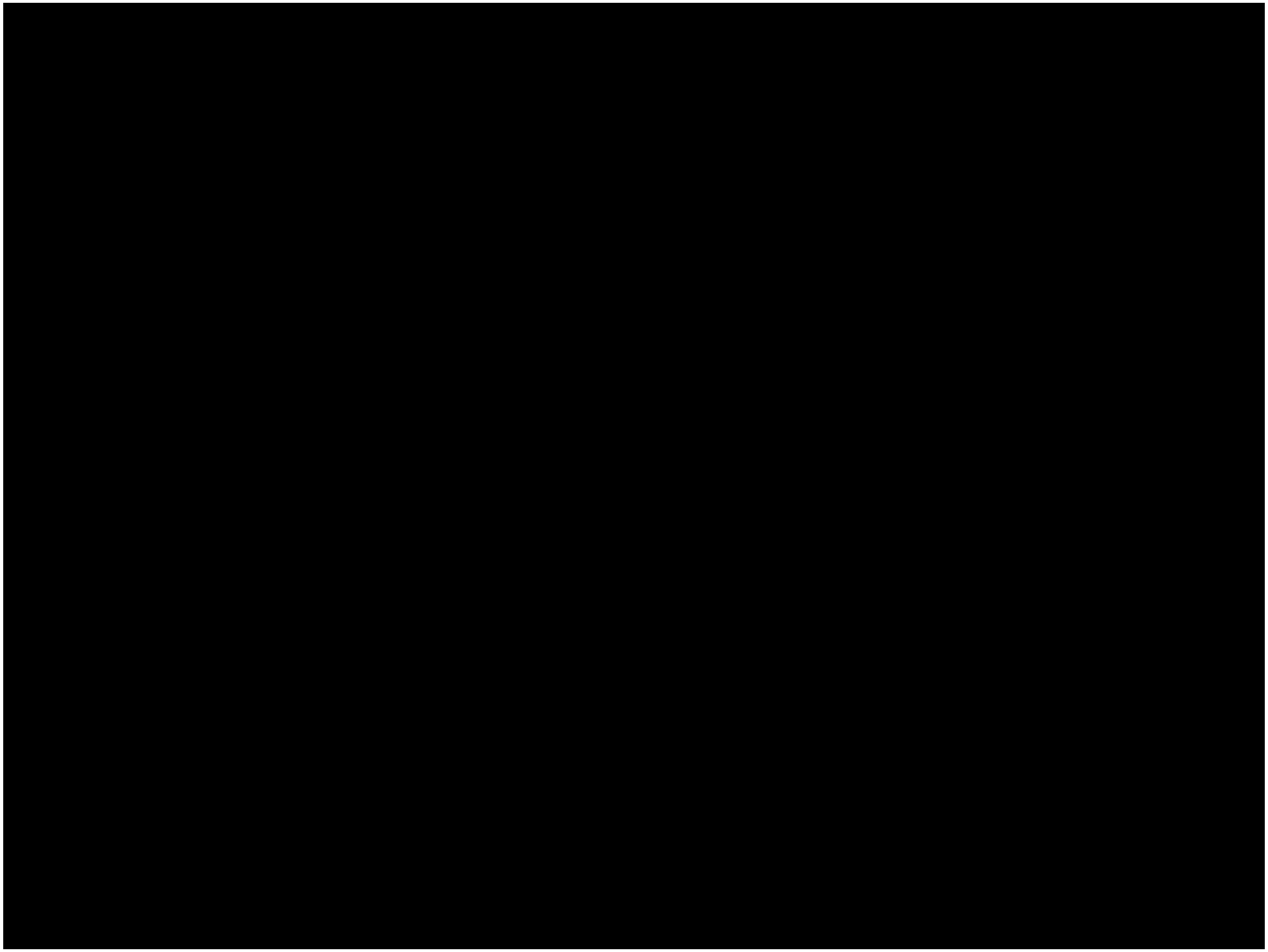
Method 1: Demonstration



Method 2: Asymmetric Drag Propulsion



Method 2: Demonstration



Conclusions

- Use high-frequency power carrier to reduce the size of implant.
- Focused wireless power transfer shows promise in achieving high transfer efficiency for miniature implants.
- Demonstrate a mm-sized wirelessly powered and remotely controlled locomotive implant.