Wireless Power Transfer: From Far Field to Near Field

Prof. Jenshan Lin

University of Florida

Outline

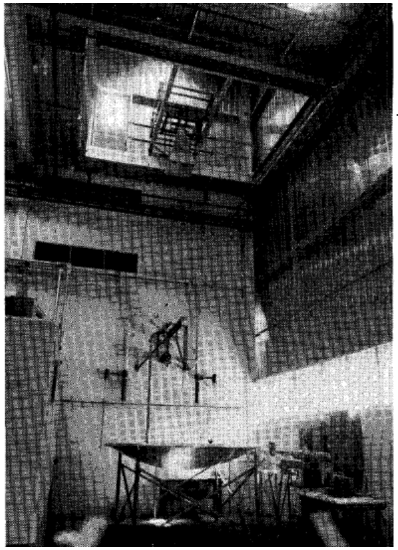
- Far-field WPT – an overview of historical developments
- Challenges of far-field WPT
- From far-field WPT to near-field WPT
- Near-field WPT
  - Overview
  - Difference between far-field WPT and near-field WPT
- Magnetic coupling near-field WPT
  - System architecture
  - Design considerations
  - Examples
- Commercialization and standards
- Conclusion

Far-Field Wireless Power Transmission

- Nicola Tesla proposed it in 19th Century to transmit electric power without using wires.
- Hot topic in 1960's-70's – NASA/DOE's interest to collect solar energy in space and beam it to earth.
- Several potential applications (some might sound crazy):
  - Remote transmission of energy for space applications
  - Remote charging of bio-implanted devices
  - Remote powering of unmanned aircrafts, vehicles, robots
  - Remote powering of wireless sensors, especially for sensors located in hard-to-reach environment
  - An extension of existing power grid system
  - Controlling the destructive storms, e.g. the path of hurricane

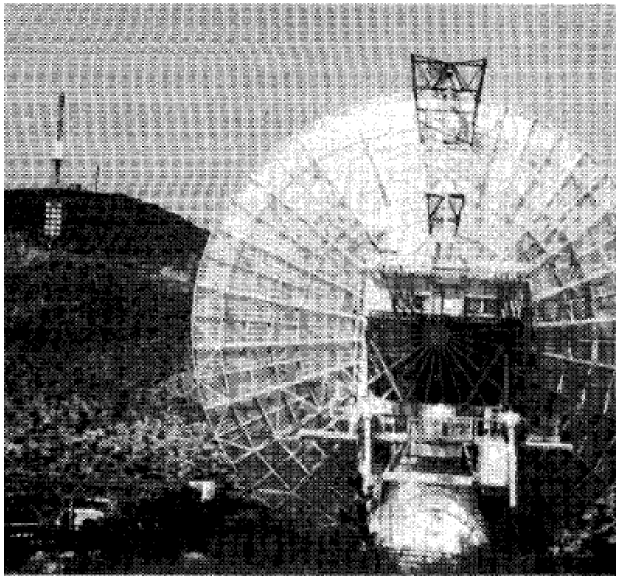
WPT History - more than one century

- **1899** – Tesla's first experiment to transmit power without wires. **150 kHz**.
- **WWII** – **high power microwave tubes** developed.
- **1958** – 1st period of microwave WPT development. Raytheon, Air Force, NASA.
- **1963** – **Brown** in Raytheon demonstrated the **first microwave WPT system**.
- **1975** – **54% dc-to-dc efficiency** was achieved, receiving **496 W @ 170 cm**.
- **1975** – **30 kW dc received @ 1 mile**
- **1977** – 2nd period of microwave WPT development. NASA/DOE sponsorship. More companies involved. Solar Power Satellite (SPS)
- **1995** – NASA Space Solar Power (SSP) Program



First microwave WPT
100 W dc output, 13% dc-to-dc efficiency

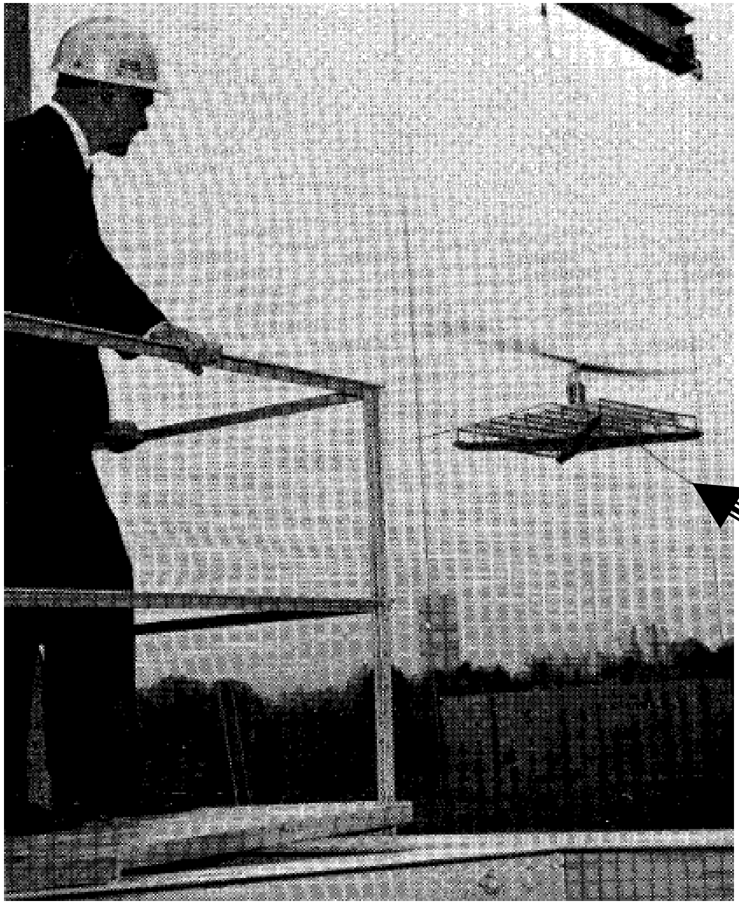
1975 demonstration
30 kW dc output @ 1 mile



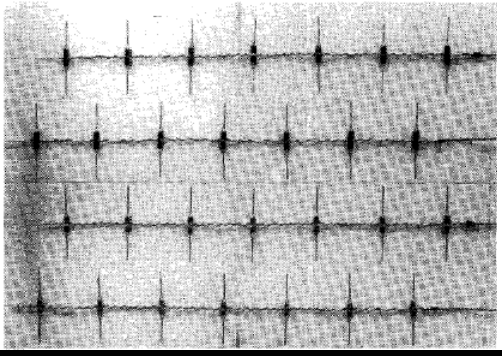
* W. C. Brown, "The History of Power Transmission by Radio Waves," IEEE Trans. Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230-1242, Sept. 1984.

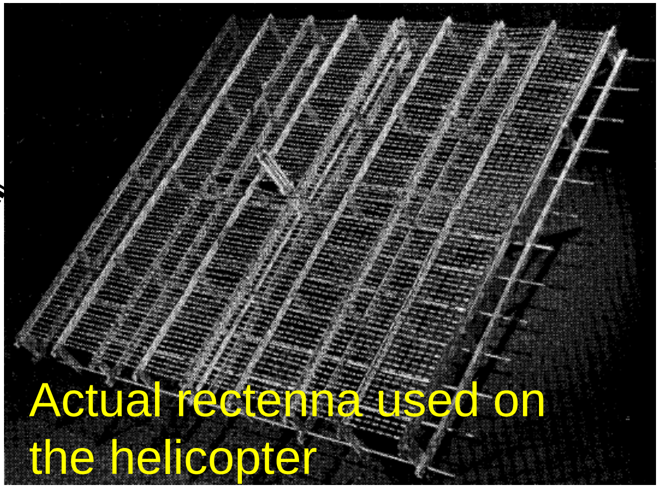
Remote Powering of Helicopter (UAV)

Microwave-powered helicopter flying 60ft above transmitting antenna. 10 hr sustained flight was achieved in 1964.



First “rectenna” – rectifying antenna integrating **solid-state diodes**, 1963. (replacing vacuum tube diodes)

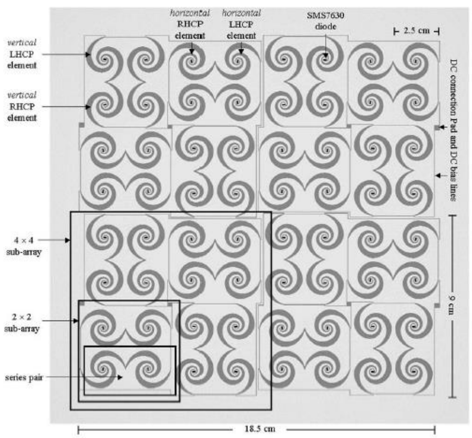


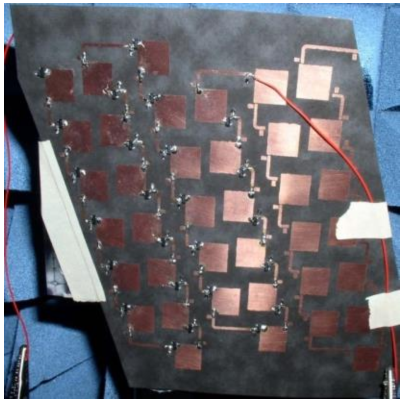


Actual rectenna used on the helicopter

RF Energy Harvesting

- From ambient RF emissions (broadband) or from a remote RF source (narrow band)
- Suitable for **low power** applications, e.g., **sensor network**
- Recently became a very active research area
- Several new techniques have been proposed (Class-F, harmonics termination, wideband, multi-sine, etc.)





* J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic´, "Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays," IEEE Trans. Microwave Theory and Tech., vol. 52, no. 3, pp. 1014-1024, March 2004.
* C. Walsh, S. Rondineau, M. Jankovic, G. Zhao, Z. Popovic, "A Conformal 10 GHz Rectenna for Wireless Powering of Piezoelectric Sensor Electronics," IEEE MTT-S International Microwave Symp., pp. 143-146, June 2005.

Long Distance Wireless Power Grid

- Microwave travels through earth atmosphere twice – overall path ~ 200km
- If using high voltage power line, the path would be several thousands km – more environmental effect
- λ=5000km @ 60Hz – power line becomes good antenna at long distance.

* A. P. Smakhtin, V. V. Rybakov, "Comparative analysis of wireless systems as alternative to high-voltage power lines for global terrestrial power transmission," Proceedings of the 31st Intersociety Energy Conversion Engineering Conference (IECEC 96), vol. 1, pp. 485-488, 11-16 August 1996.

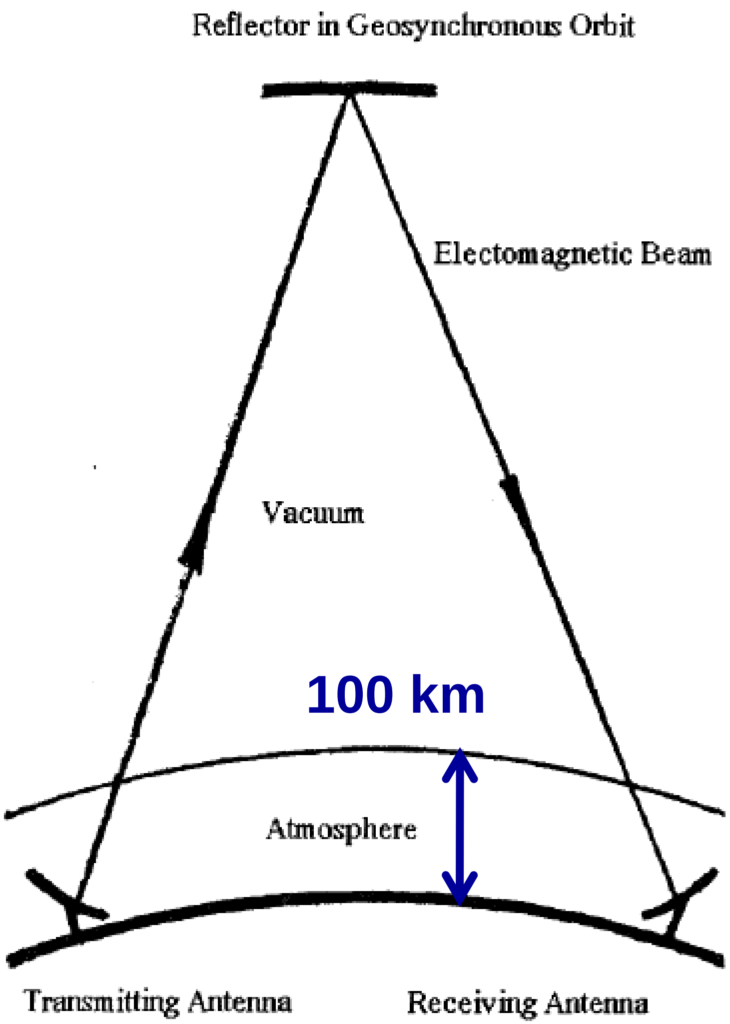
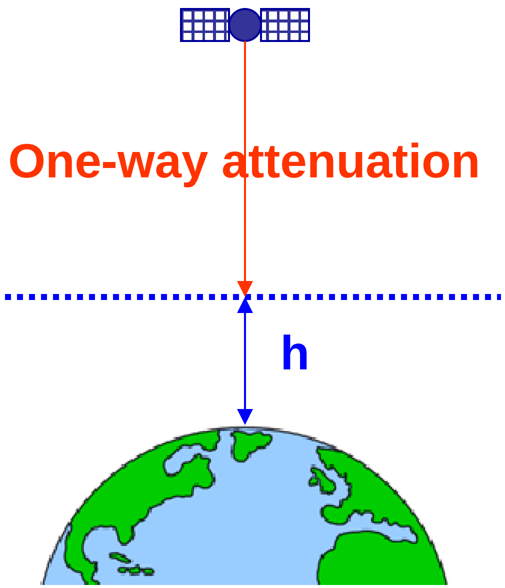
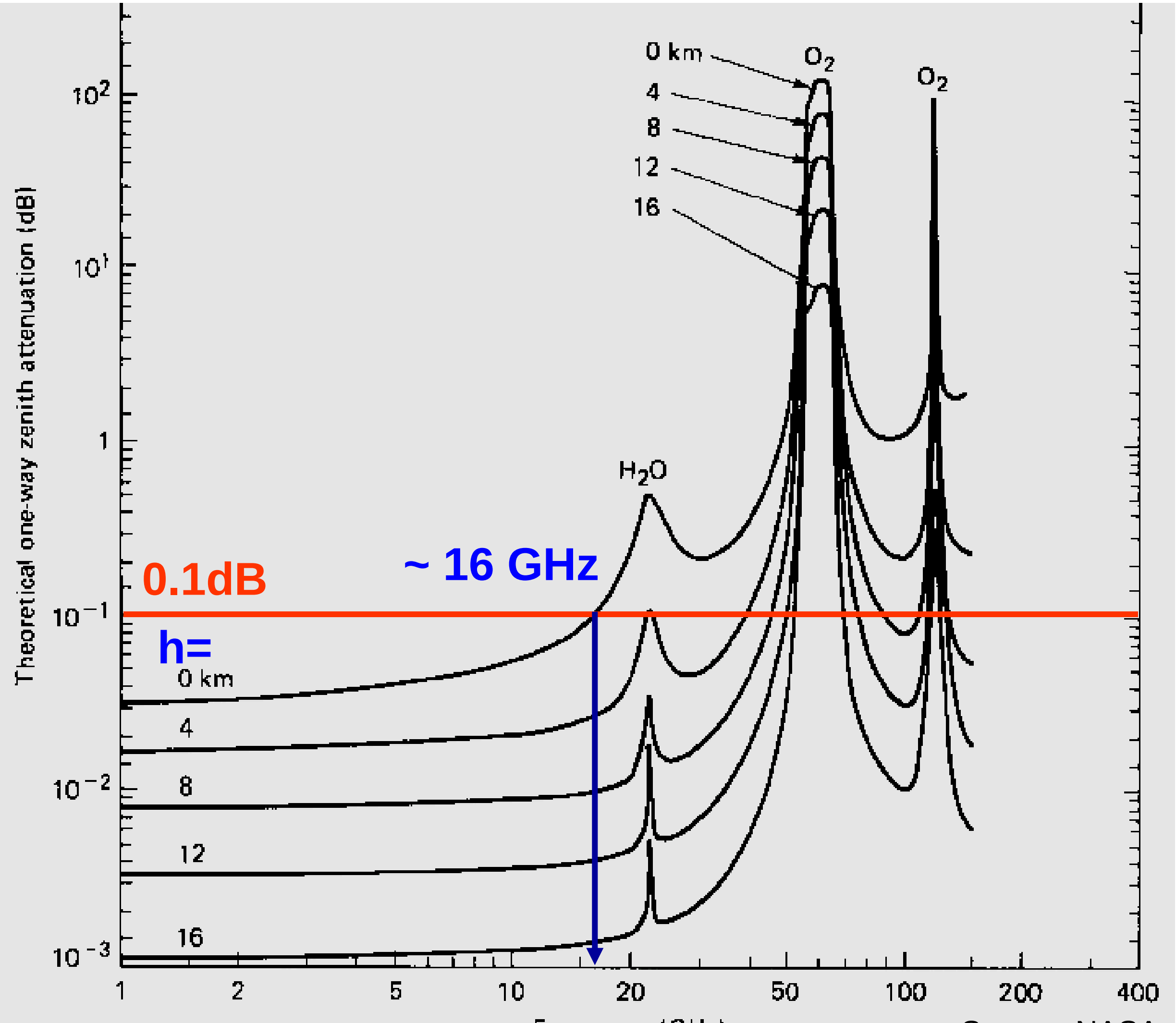


FIGURE 1. CONCEPTUAL SCHEME OF ELECTROMAGNETIC BEAM POWER TRANSMISSION ON EARTH

Attenuation Through Atmosphere

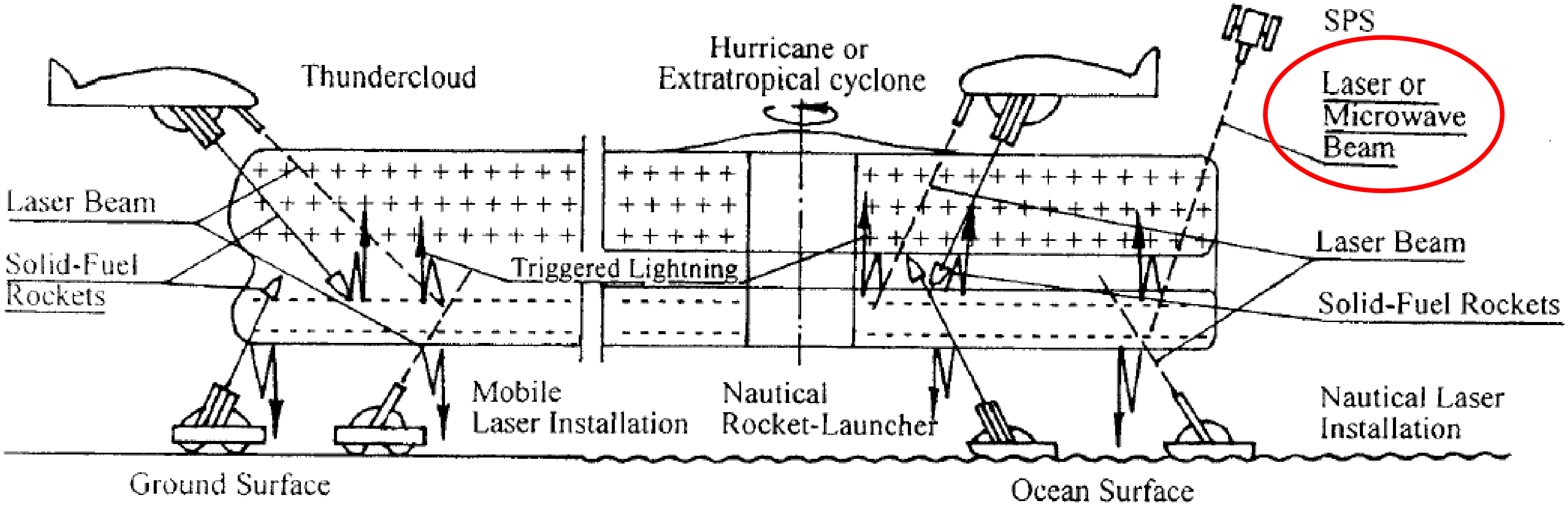




Source: NASA

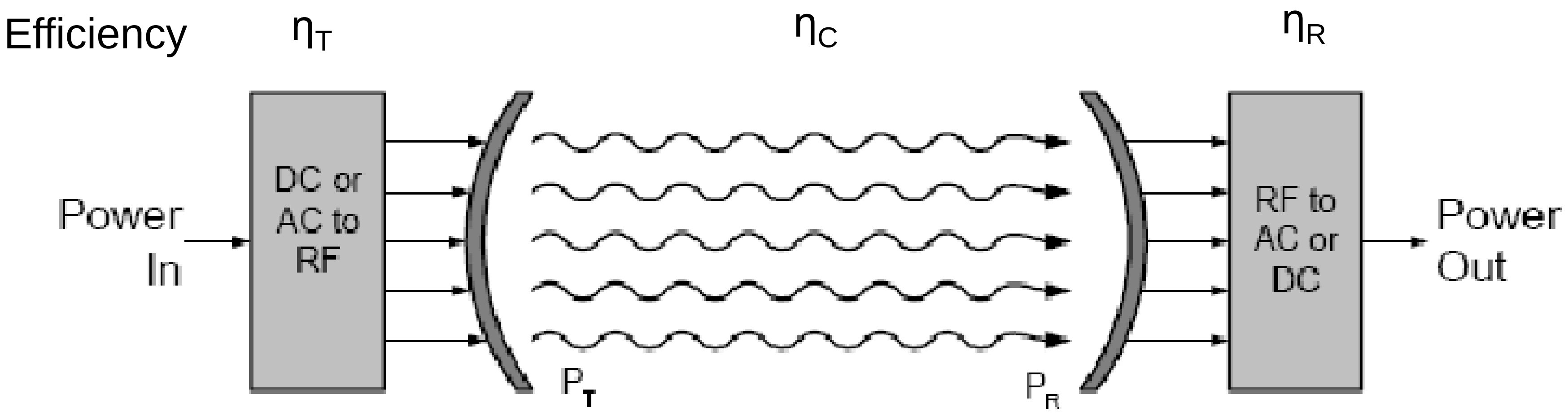
- One-way attenuation < 0.1dB for f < 16GHz

Manipulating tropical storms



E. Yu. Krasilnikov, “Prevention of destructive tropical and extratropical storms, hurricanes, tornadoes, dangerous thunderstorms, and catastrophic floods,” Nonlinear Processes in Geophysics (2002) 9: 51–59

WPT System



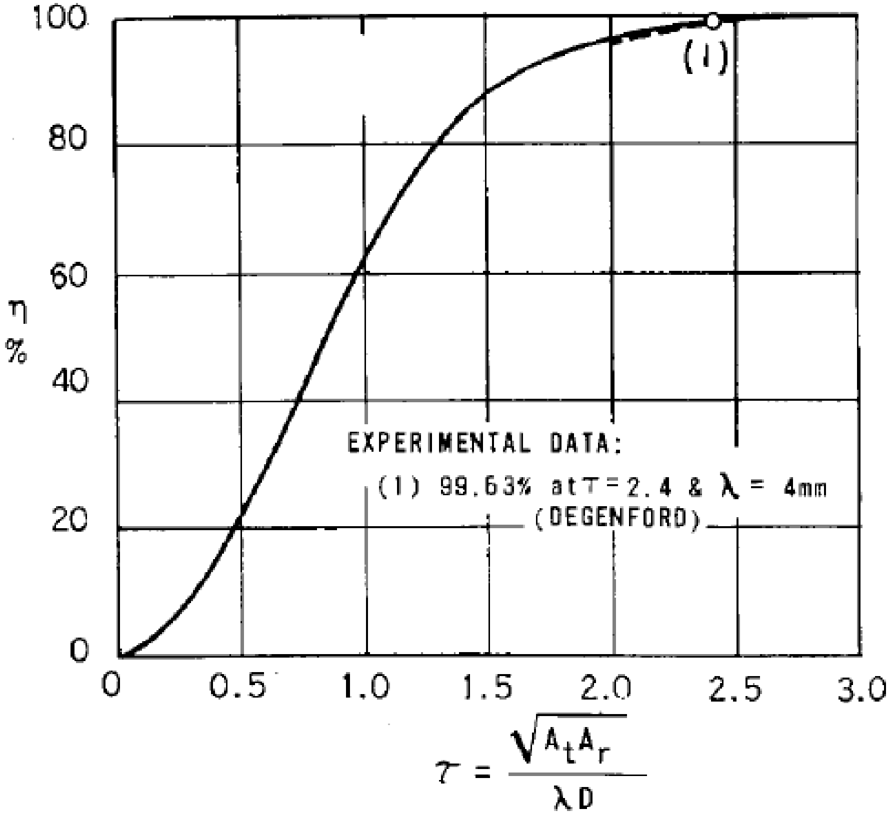
- dc or ac power is first converted to RF power.
- RF power is transmitted by TX antenna to the receiver.
- RF power is received by the RX antenna and rectified to dc power which can further be converted to ac power.
- Total system efficiency = (η_T)x (η_C)x (η_R)

Challenges of WPT

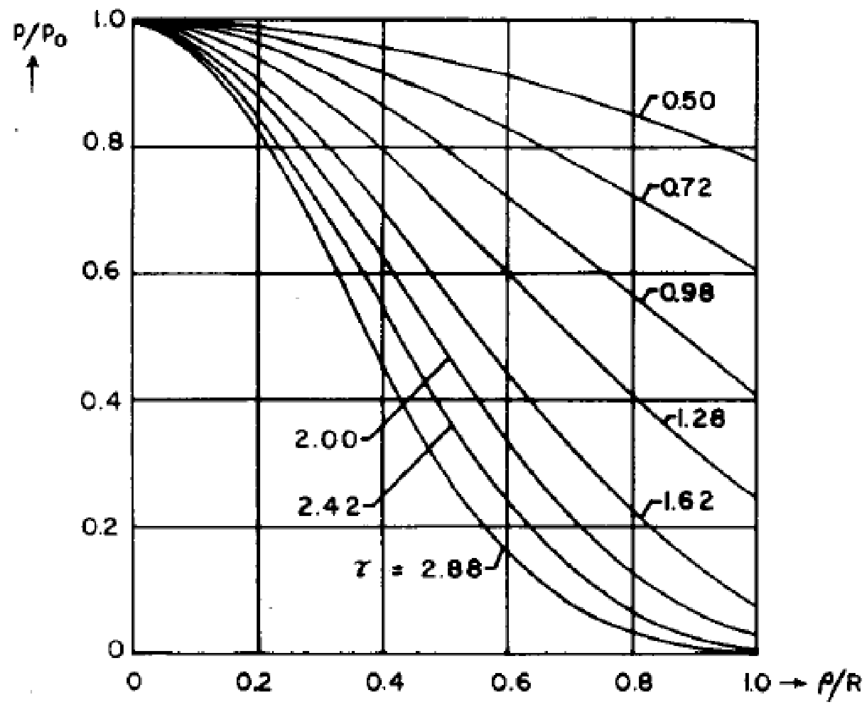
- Technical Issues
  - Beam-forming antennas for directed microwave beam
  - High efficiency microwave power source (transmitter)
  - High efficiency microwave rectifier (receiver)
  - All have to be lightweight to reduce deployment cost
- Environmental Issues
  - Safety concern
  - Ecological effect
- Economic Issues
  - Cost of the system
  - Cost of the development
  - Cost of the deployment

Beam-Forming Antennas

Transmission Efficiency η as a function of τ for optimum power density distribution across the TX antenna aperture as shown on the right.



Relative cross-sectional power density distribution across the TX and RX apertures for various values of τ



<u>Need large antenna aperture or higher frequency to achieve high efficiency.</u>

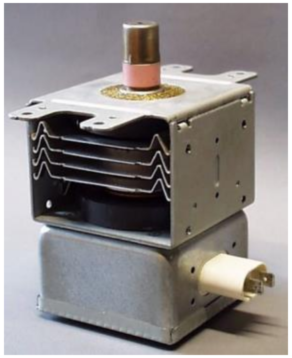
* W. C. Brown, E. E. Eves, “Beamed Microwave Power Transmission and its Application to Space,” IEEE Trans. Microwave Theory and Techniques, vol. 40, no. 6, pp. 1239-1250, June 1992, quoting G. Goubau and F. Schwering, “On the guided propagation of electromagnetic wave beams,” IRE Trans. Antennas Propagat., vol. 9, pp. 248-256, May 1961.

High Efficiency Microwave Power Source

- Find devices to generate high power RF.
  - High efficiency
  - Low cost
  - Lightweight
- Efficiency is particularly important at high power level. 90% efficiency of 9 W output means 1 W is lost to heat, whereas 90% efficiency of 90 W output means 10 W is lost to heat.
- If efficiency is not high, heatsink will be needed and that will also increase the cost and weight.
- Cost of microwave power amplifier goes up with power level. Where do you find the cheapest high power source at 2.4 GHz that can generate 100 W – 1000 W?

High Efficiency High Power Microwave Source

- Microwave tubes have been used to achieve high efficiency and very high output power
  - magnetron, klystron, traveling wave tube (TWT), etc.
  - Magnetron has the highest efficiency and been used in microwave oven. (>80% at several kW demonstrated). Low cost too.
  - However, they are bulky and heavy. For very high power, cooling is still an issue.

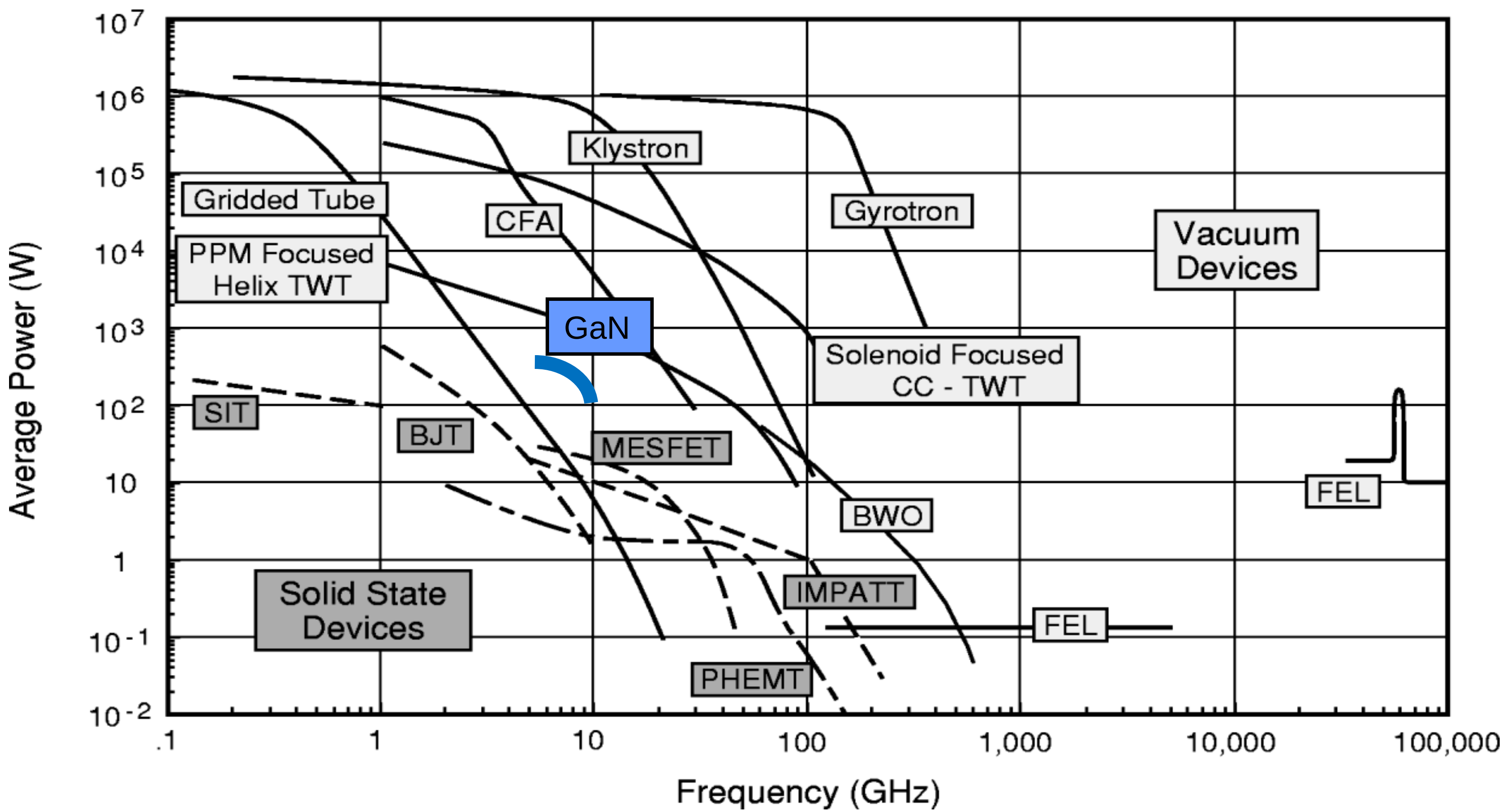


Magnetron inside microwave oven
2.4GHz, ~1kW, ~65% efficiency

Toshiba Klystron
5.7GHz, 50MW, 47%, 0.0125% duty cycle

Microwave Power Source

➢ **Solid-state devices still have not displaced microwave tubes yet.**

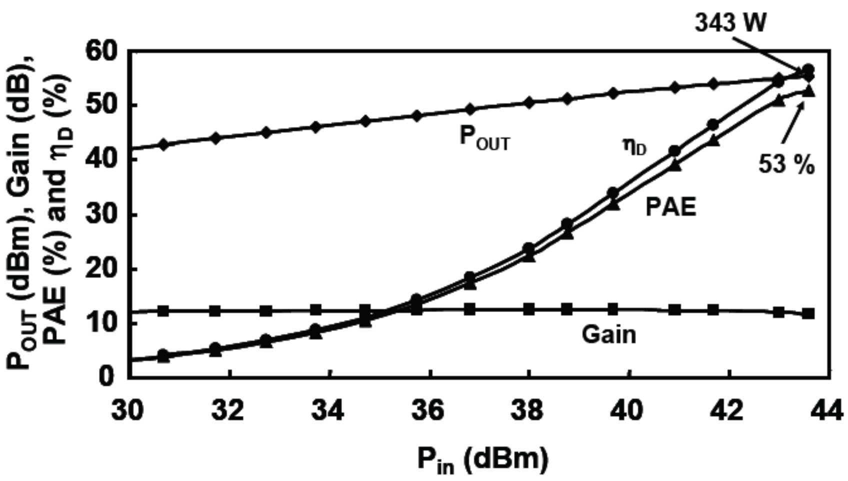


* V. L. GRANATSTEIN, R. K. PARKER, C. M. ARMSTRONG, "Vacuum Electronics at the Dawn of the Twenty-First Century," Proceedings of the IEEE, vol. 87, no. 5, pp. 702-716, May 1999.

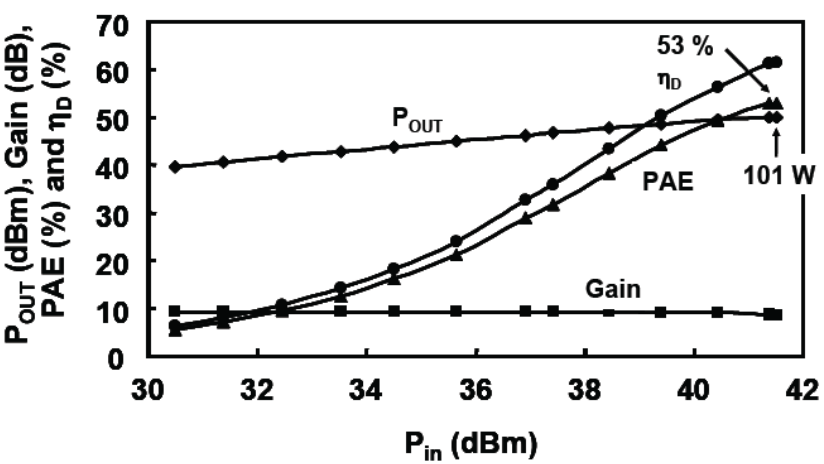
Solid-State Microwave Power Source

- GaN technology is the best candidate at high frequency.
- Spatial power combining of GaN power sources might be a solution.

343 W @ 4.8 GHz (C-Band)



101 W @ 9.8 GHz (X-Band)

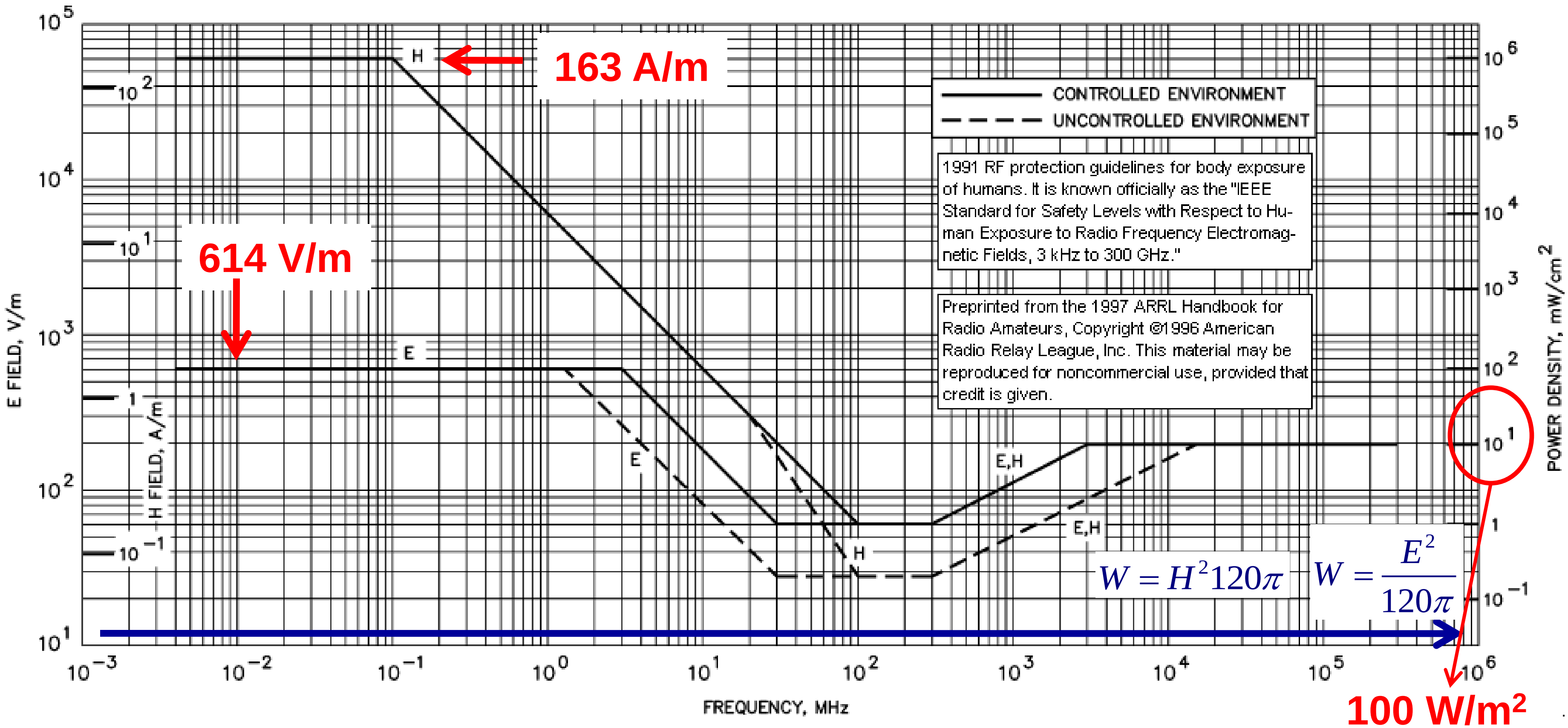


- Shigematsu, H.; Inoue, Y.; Akasegawa, A.; Yamada, M.; Masuda, S.; Kamada, Y.; Yamada, A.; Kanamura, M.; Ohki, T.; Makiyama, K.; Okamoto, N.; Imanishi, K.; Kikkawa, T.; Joshin, K.; Hara, N.; , "C-band 340-W and X-band 100-W GaN power amplifiers with over 50-% PAE," *Microwave Symposium Digest, 2009. MTT '09. IEEE MTT-S International* , vol., no., pp.1265-1268, 7-12 June 2009
- 10 µs pulse width and 10% duty cycle.

RF Safety – 1999

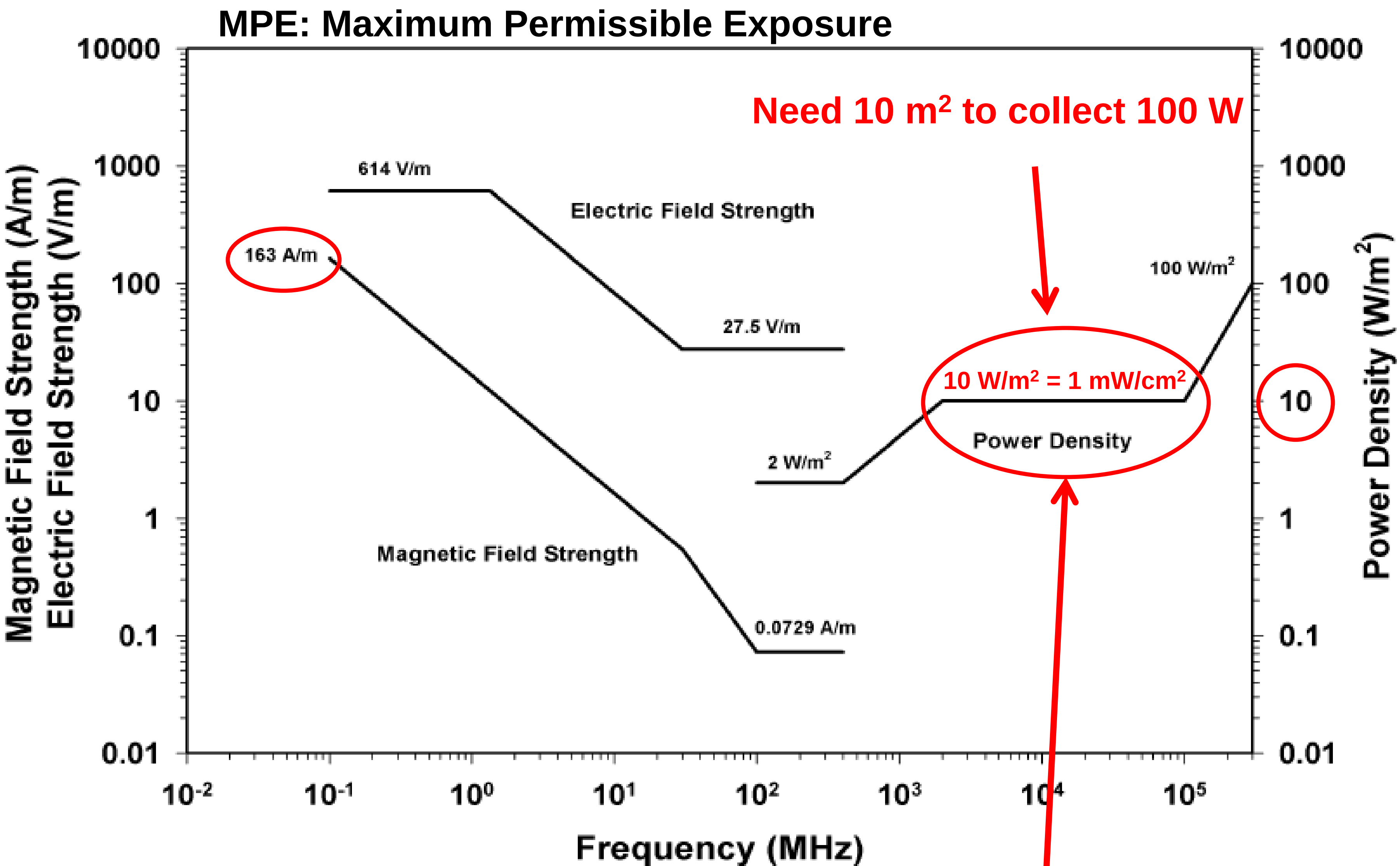
IEEE Std C95.1 – 1999

IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz



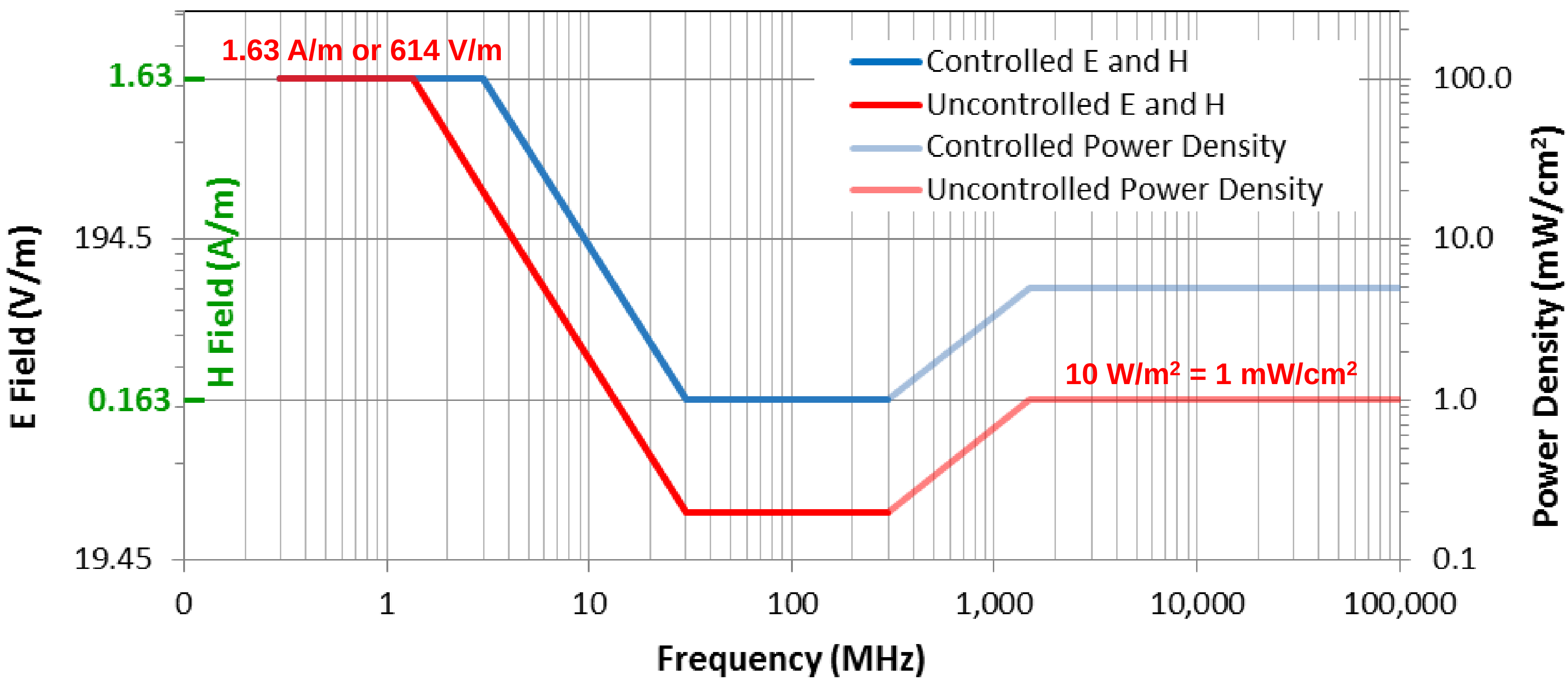
- **Transmitted power density is limited by safety standard.**
- **Magnetic field at low frequency has higher equivalent plane wave power density**

RF Safety – 2005, General Public



10x more stringent than 1999 Standard

RF Safety – 2013 (FCC 13-39)



- Key changes from 2005 to 2013:
  - E and H field MPE limits at low RF become the same, in terms of equivalent power density.
  - This means H field limit is tougher than before.

From Far-Field WPT to Near-Field WPT

- Far-field WPT has limitations but has applications
  - Very low power devices or sensor network, where efficiency and safety would not be concerns
  - High power space, military, or industrial applications not sensitive to cost
- However, when it comes to consumer applications such as charging cellular phones, laptops, and other portable electronic devices, or even electric cars, far-field WPT is not suitable because of <u>efficiency</u> and <u>safety</u>.
  - Near-field WPT is a better choice.
  - <u>Low-frequency magnetic field</u> can be used to allow higher equivalent plane wave power density.

Demand driven by portable devices…

http://www.treehugger.com/2009/10/25-week/

http://community.crutchfield.com/blogs/av_tips/archive/2008/07/22/monster-power-outlets-to-go-went-well.aspx

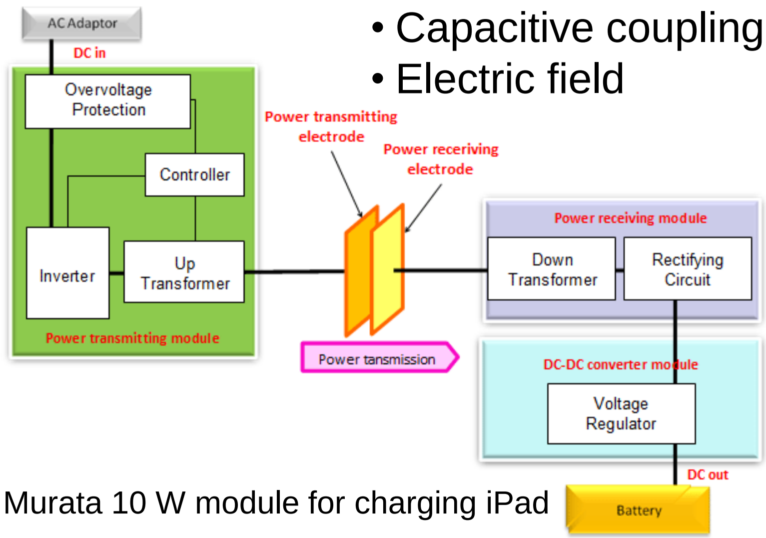
- **Many of them are wireless devices, but they are not completely wireless – still many power chargers and many cables!**
- **A traveler knows the pain of carrying all these chargers.**
- **Standardized USB charging connector could be a solution but there are still proprietary connectors/chargers, and wires are still there.**
- **Wireless power is the ultimate solution – cut the last cable.**

Near-field Wireless Power Charger

- Magnetic coupling
- Higher efficiency than far-field
- Low frequency electronics → high efficiency
- Less safety concern

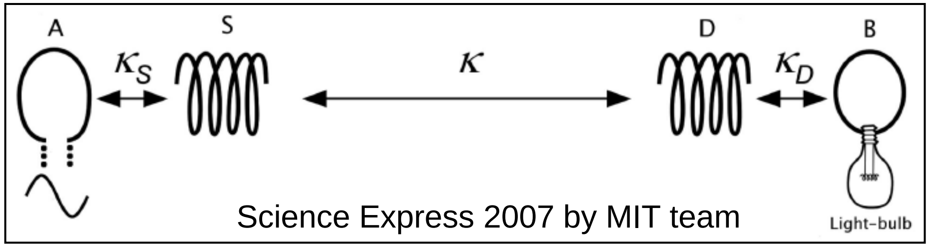
Types of Near-Field Wireless Power

- Capacitive coupling
- Electric field

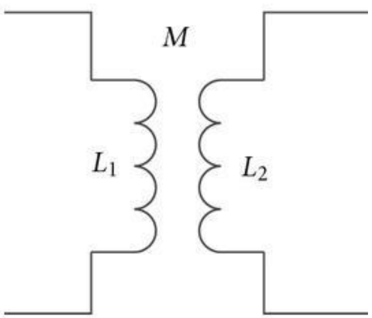


Murata 10 W module for charging iPad

- Magnetic resonance
- Magnetic field
- Four coils



Science Express 2007 by MIT team



- Inductive coupling, or magnetic coupling
- Magnetic field
- Strong coupling or weak coupling
- Many technologies and many companies

The following discussions will focus on magnetic coupling.

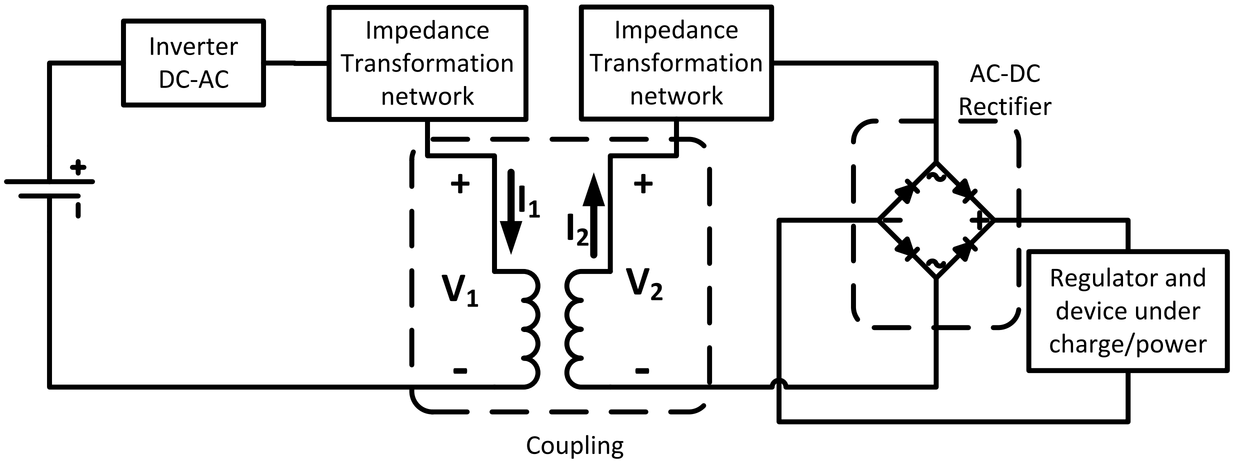
Inductive Coupling

- Magnetic coupling to transfer power has been around for quite many years. Rechargeable electric toothbrush is an example.
- So what's the challenge?
- It uses spilt ferrite core to achieve strong coupling
- It requires careful alignment
- To have <u>higher power transfer</u> with <u>lateral movement freedom</u> yet keeping <u>high efficiency</u> and <u>without using ferrite core</u>, is a challenge.
- Charging multiple devices is another major challenge.

Electric toothbrush

Flexibility of Wireless Power

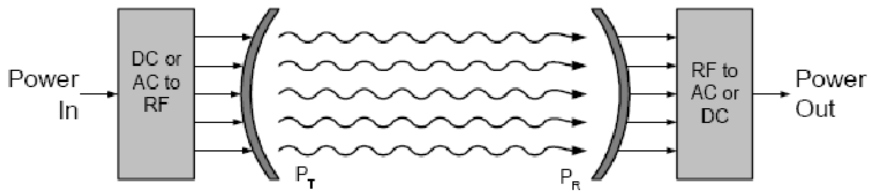
Near-Field WPT System



- **<u>Inverter (or transmitter, power amplifier)</u>**
  - Convert dc power to ac power
  - Need to have high efficiency
  - Switch-mode preferred, e.g., Class-D or Class-E
- **<u>Impedance transformation network and loosely-coupled inductive coils</u>**
  - Transform load impedance to a range the inverter (PA) can handle
  - Ensure correct power delivery when load is varying (a major challenge)
- **<u>Receiver</u>**
  - Rectify ac power to dc power
  - Voltage regulator is used to ensure stable dc output

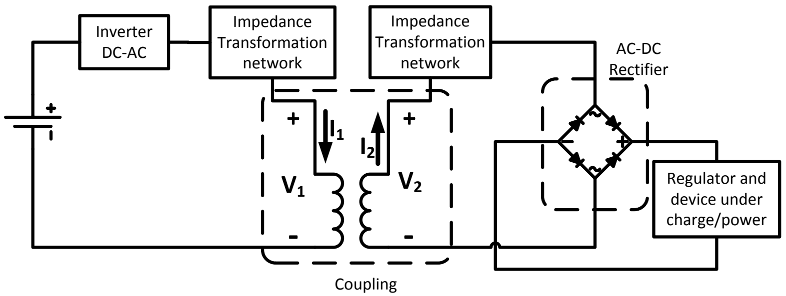
Difference Between Far-Field WPT and Near-Field WPT

Far-Field WPT



system efficiency = (η_T)x (η_C)x (η_R)

Near-Field WPT

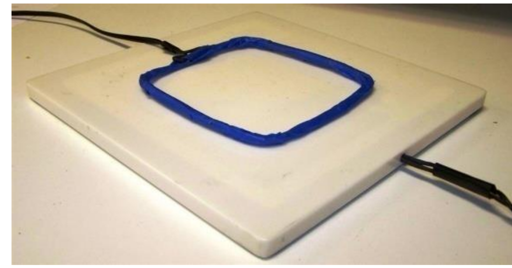


system efficiency = ?

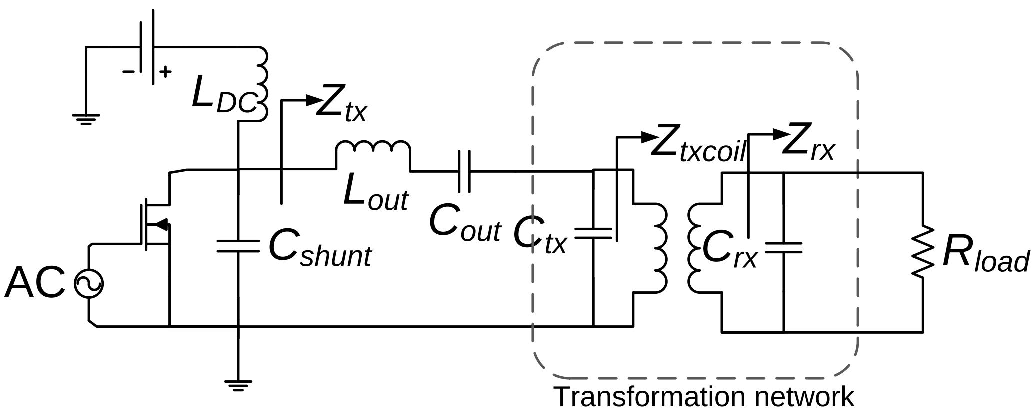
- ❑ Because it is near-field coupling, transmitter and receiver are no longer decoupled. Transmitter efficiency depends on the coupling and the load at receiver.
- ❑ Because the coupling and the receiver load might change (vs. time or location), the transmitter will see a variable load.
- ❑ Essentially, this becomes designing a power amplifier with variable load!
- ❑ Need complete system optimization. Optimizing coil-to-coil coupling efficiency alone will not result in an optimized system efficiency.

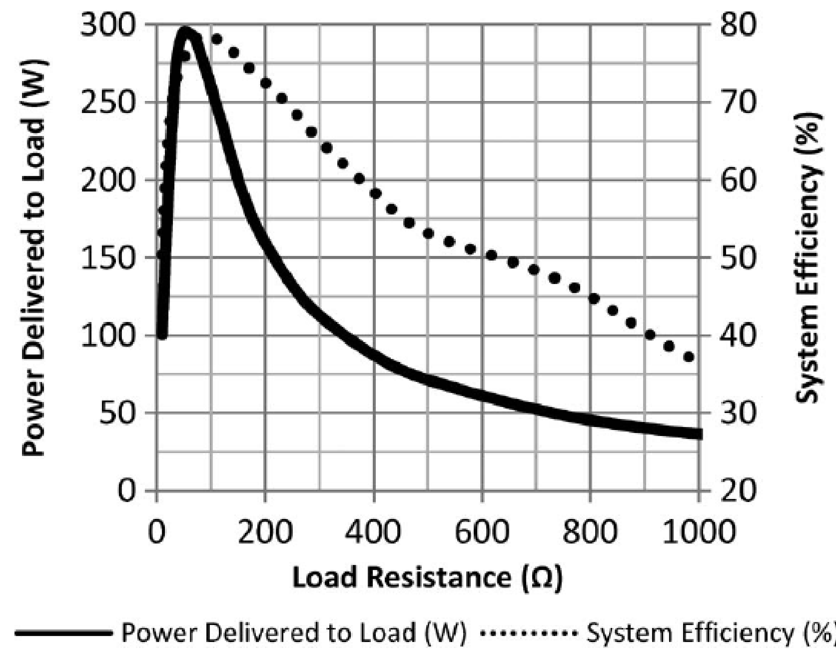
Near-Field WPT – Loosely Coupled

- High power (295 W) delivery with high end-to-end system efficiency (>75%)
- Class-E transmitter operating @ 134 kHz
- Varying location of RX on TX → Power delivery variation 5%
- Coupling coefficient ~ 0.37 (>0.25 to avoid TX heating)



- TX coil 21cmx21cm
- RX coil 13cmx13cm
- Separation 1cm





Z. N. Low, R. A. Chinga, R. Tseng, and J. Lin, "Design and Test of a High-Power High-Efficiency Loosely Coupled Planar Wireless Power Transfer System," *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 5, pp. 1801-1812, May 2009.

Why Class-E?

- Compared to Class-D:
  - Simple single transistor topology
  - Single gate drive instead of out-of-phase gate drive
  - Higher power delivery with same supply voltage
  - Disadvantage: Higher device stress

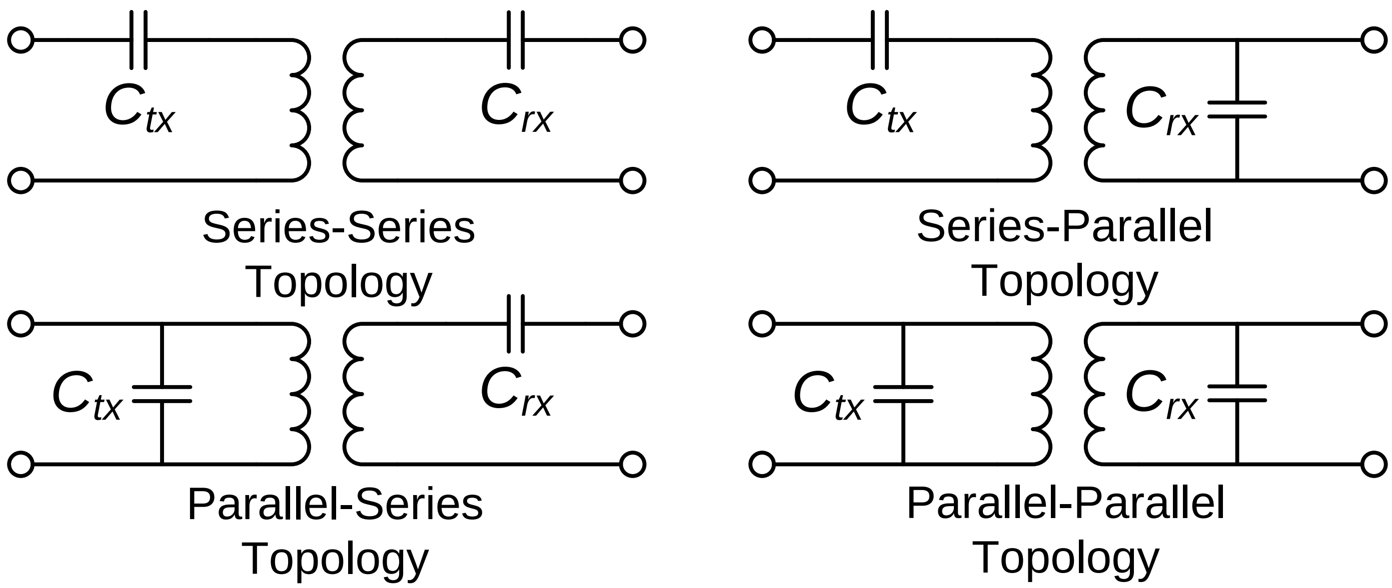
$$P_{out-ClassE} = \frac{8}{\pi^2+4}\frac{V_{CC}{}^2}{R} = 0.5768\left(\frac{V_{CC}{}^2}{R}\right)$$

$$P_{out-ClassD} = \frac{2}{\pi^2}\frac{V_{CC}{}^2}{R} = 0.2026\left(\frac{V_{CC}{}^2}{R}\right)$$

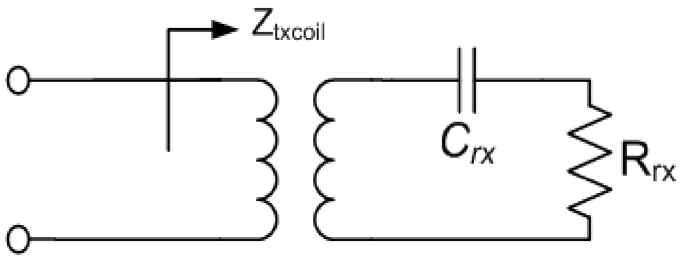
For the same …	**Compare …**	**Ratio (Class-E/Class-D)**
Supply voltage	Power delivery	2.847
Power delivery	Supply voltage	0.593
Power delivery	Drain voltage stress	2.112
Supply voltage	Drain voltage stress	3.562

Impedance Transformation Network

- Capacitors are preferred over inductors because they are smaller and less lossy.
  - Also achieve resonance to increase efficiency.
- Single element impedance transformation is used to achieve low component count and simplicity.
  - More complex network can be used, but loss may increase.
- Purpose of the network is to achieve
  - high efficiency coupling between the coils
  - desirable phase response/power delivery trend.



Receiver Capacitor in Series



X-Series Topology

$$Z_{txcoil} = \frac{\omega^2 M_{12}^2 R_{rx}}{R_{rx}^2 + \left(\omega M_{22} + X_{rx}\right)^2} + j\left(\omega M_{11} - \frac{\omega^2 M_{12}^2 \left(\omega M_{22} + X_{rx}\right)}{R_{rx}^2 + \left(\omega M_{22} + X_{rx}\right)^2}\right)$$

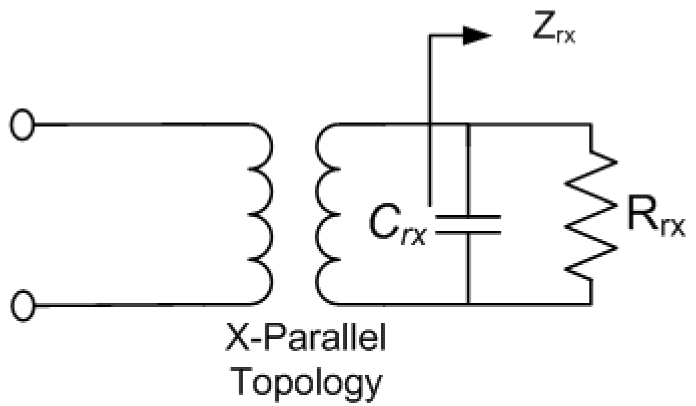
$$Z_{txcoil} = \frac{\omega^2 M_{12}^2 R_{rx}}{R_{rx}^2} + j\omega M_{11}$$

$$Z_{txcoil} = \frac{\omega^2 M_{12}^2}{R_{rx}} + j\omega M_{11}$$

$$Z_{txcoil} = \frac{A}{R_{rx}} + j\omega M_{11}$$

1. A is small due to loose coupling
2. Z_{txcoil} will be small unless
   - Operating frequency is high, or
   - Receiver coil is large
3. Resulting in high loss across parasitic resistance of transmitting coil and LC filter network.

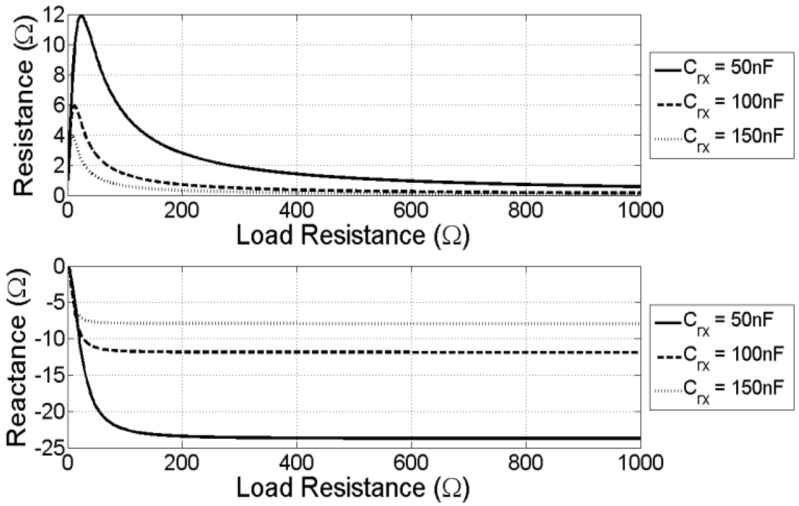
Receiver Capacitor in Parallel



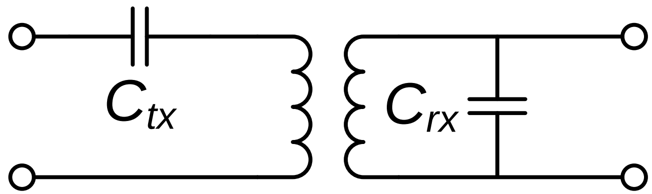
$$Z_{rx} = \frac{R_{rx}}{1+\omega^2 C_{rx}^{\ 2} R_{rx}^{\ 2}} - j\frac{\omega C_{rx} R_{rx}^{\ 2}}{1+\omega^2 C_{rx}^{\ 2} R_{rx}^{\ 2}}$$

1. Resistance R_{rx} is "compressed" by a factor of **$1/(1 + \omega^2 C_{rx}^2 R_{rx}^2)$**, the equivalent resistance R_{rx} decreases with increasing load resistance.

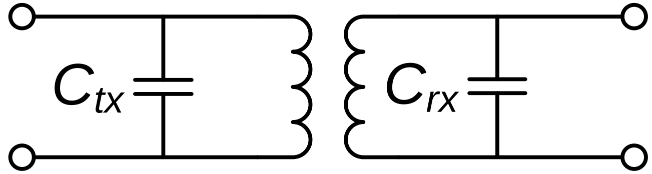
2. The reactive term decreases nonlinearly from null with increasing load resistance with an asymptote of **$-1/\omega C_{rx}$**. This is used to compensate the receiving coil inductance.



Impedance Transformation Network



Series-Parallel Topology



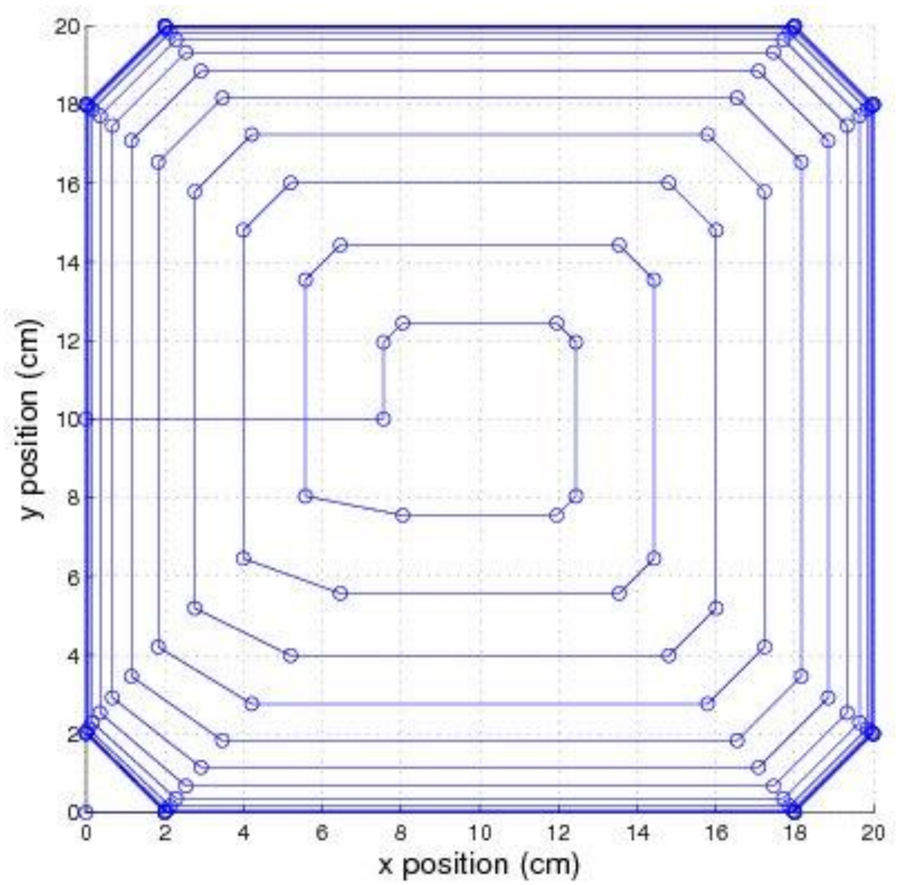
Parallel-Parallel Topology

- On receiver side, parallel capacitor is better than series capacitor.
- On the transmitter side, either series or parallel topology can be used.
- C_{rx} is selected to reflect maximum resistance looking into the transmitting coil. If the variation of resistance looking into the transmitter coil is too large, it is preferred that a parallel capacitor is used on transmitter side to further compress the resistance → Parallel-Parallel Topology
- Series-Parallel Topology has an advantage: C_{tx} can be absorbed into C_{out} (reducing one component)

TX Coil Design for Uniform Field

- **Rectangular spiral of N turns**
- **Spacing increases approaching the center.**
- **Width of turn n to turn n+1 related by ratio f**
- **Corners blunted by fraction Δ to reduce field peaks**
- **Coil is fully described by length, width, N, Δ, k.**

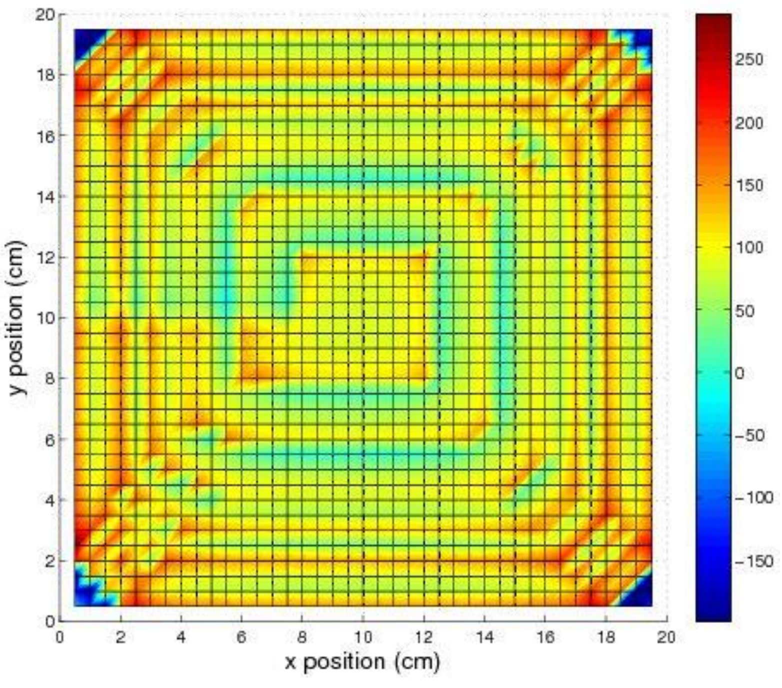
$$f = 1 - (1 - (N - n + 1)/N)^k$$



J. J. Casanova, Z. N. Low, J. Lin, R. Tseng, "Transmitting Coil Achieving Uniform Magnetic Field Distribution for Planar Wireless Power Transfer System," *Proceedings of IEEE Radio and Wireless Symposium*, pp. 530-533, January 2009.

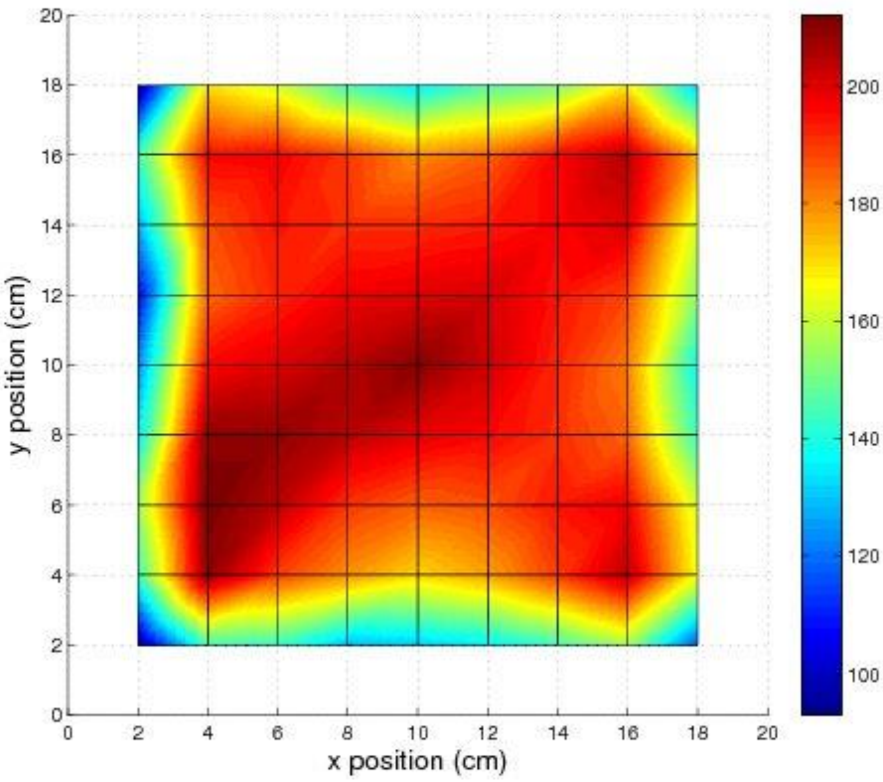
Magnetic Field Distribution

Calculation (Magnetic Quasi-Static)



H (A/m) based on 1 A current on coil

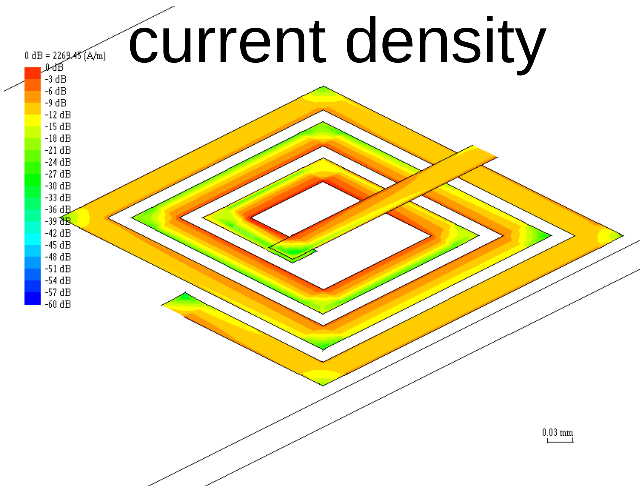
Measurement

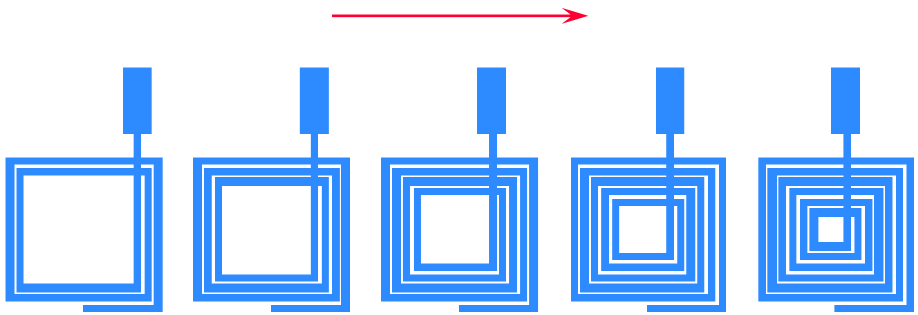


Voltage (mV) on the field probe

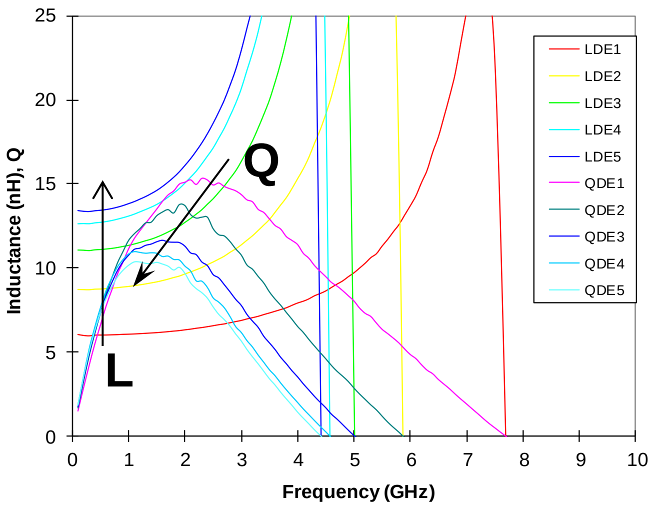
RFIC Inductors – a comparison

current density

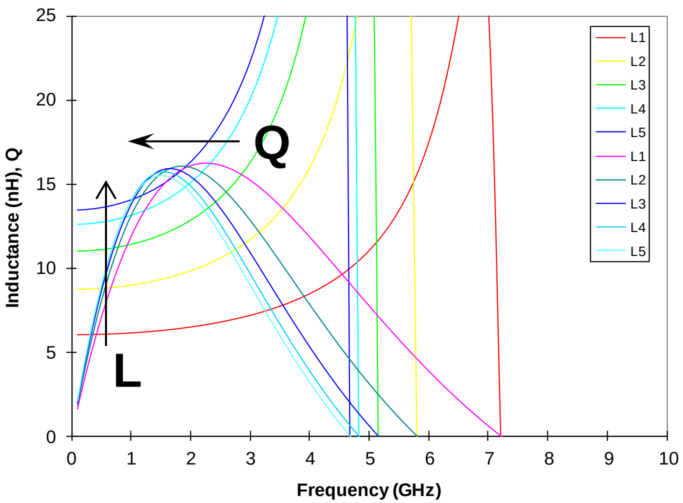




measured



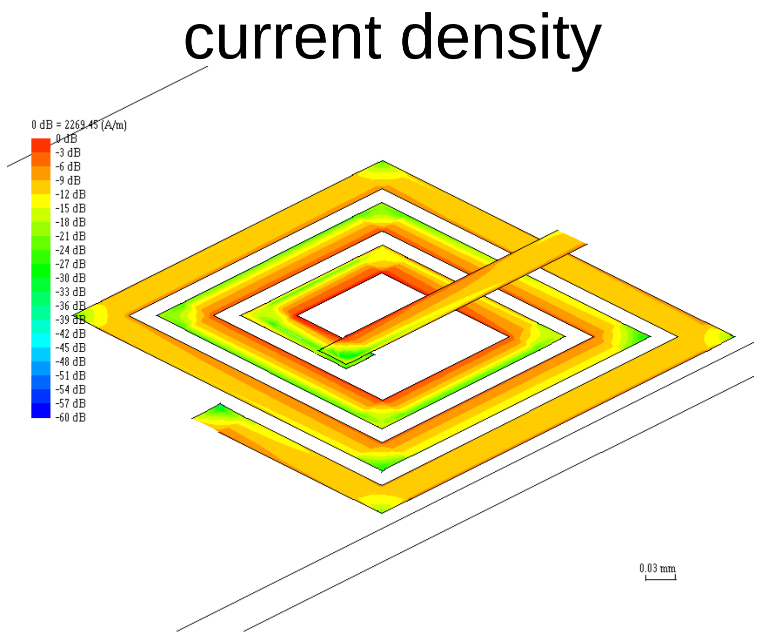
simulation without current crowding effect

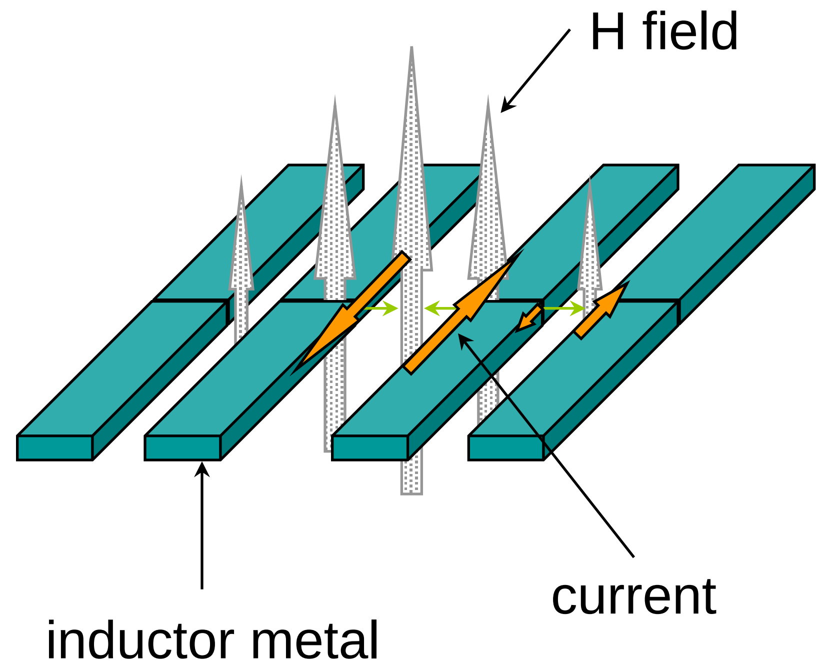


Boundary Conditions

	General	Perfect Electric Conductor
Tangential E	$\hat{n}\times(\vec{E}_2-\vec{E}_1)=-\vec{M}_s$	$\hat{n}\times\vec{E}_2=0$
Tangential H	$\hat{n}\times(\vec{H}_2-\vec{H}_1)=\vec{J}_s$	$\hat{n}\times\vec{H}_2=\vec{J}_s$
Normal D	$\hat{n}\cdot(\vec{D}_2-\vec{D}_1)=q_{es}$	$\hat{n}\cdot\vec{D}_2=q_{es}$
Normal B	$\hat{n}\cdot(\vec{B}_2-\vec{B}_1)=q_{ms}$	$\hat{n}\cdot\vec{B}_2=0$

Current Crowding Effect
(Proximity Effect)



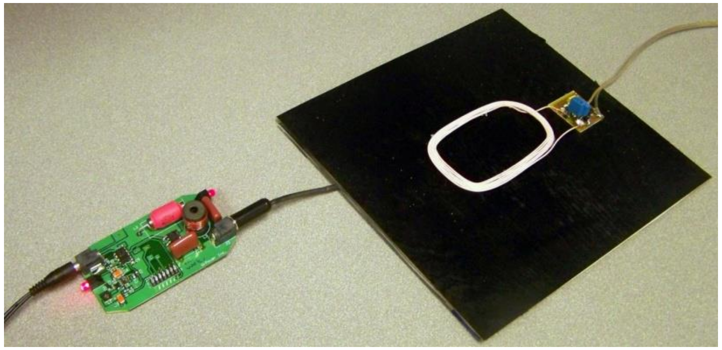


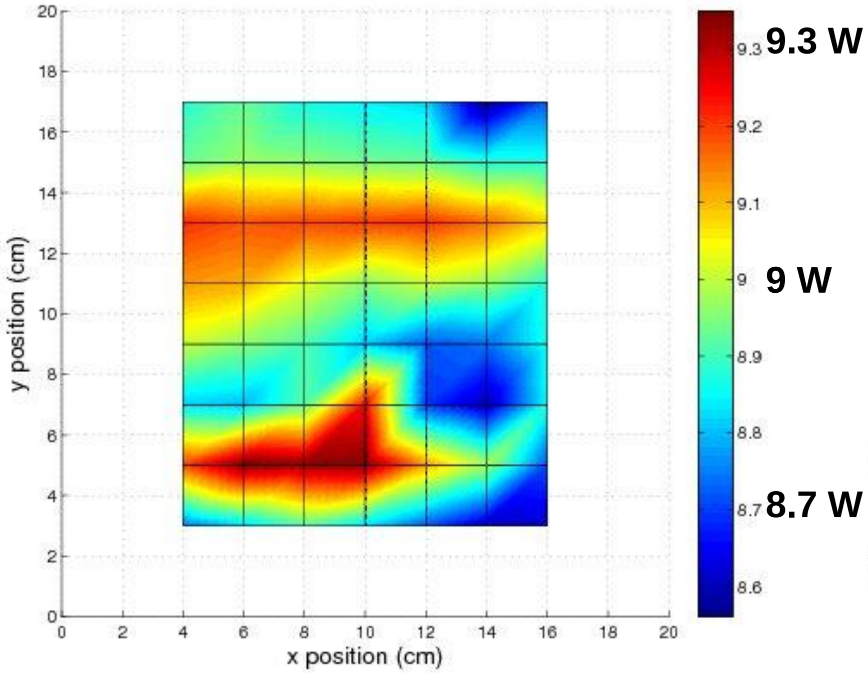
Dense inductor with many turns
→ Building strong magnetic field at center
→ Current concentrating at inner edge near center
→ Lower the Q

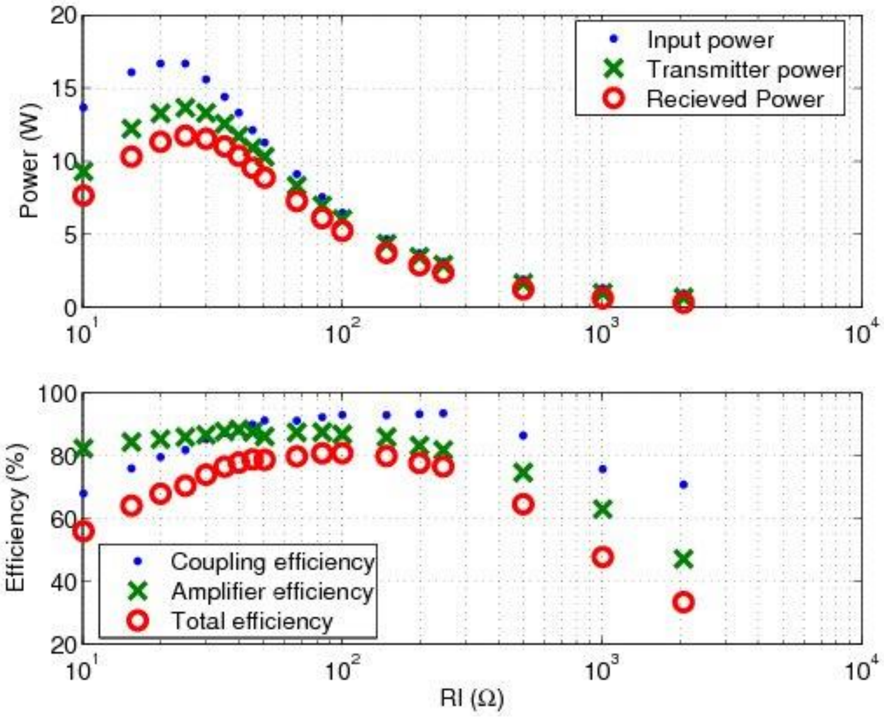
To avoid this, RFIC inductors usually have a hollow center.

10 W System with 80% Efficiency

- Transmitter 20 cm x 20 cm, 13 turns
- Receiver 6 cm x 8 cm, 6 turns
- 100 strand/40 AWG Litz wire for both coils
- Operating frequency 240 kHz, Vcc 12 V
- Peak delivered dc power = 11.8 W
- Peak coupling efficiency = 88.4%. Peak dc-to-dc efficiency = 80.9%
- Power delivery variation vs. location < 10%

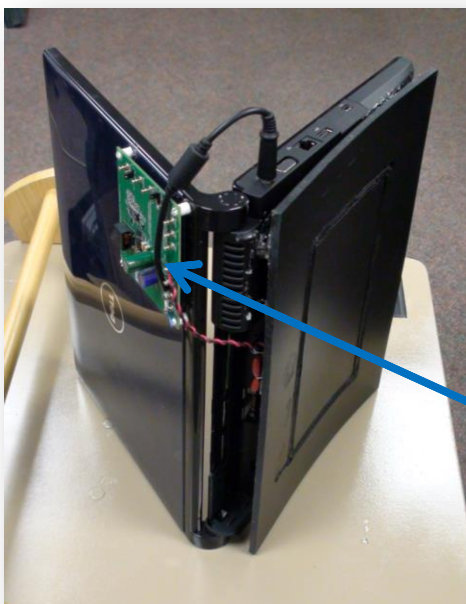


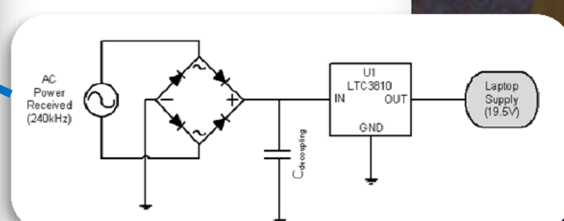




Wireless Laptop Charging Station

- Dell Vostro 1310 laptop
- Battery removed from laptop → Power from the wireless power receiver only
- Total power required: 32 W
- TX coil size: 35 cm x 25 cm
- RX coil size: 20 cm x 12 cm



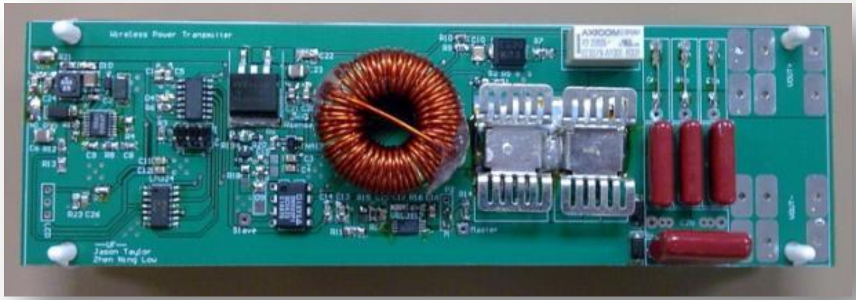


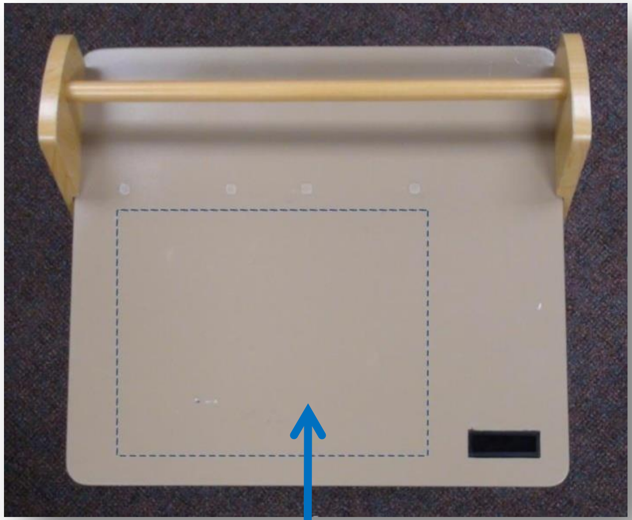
LCD

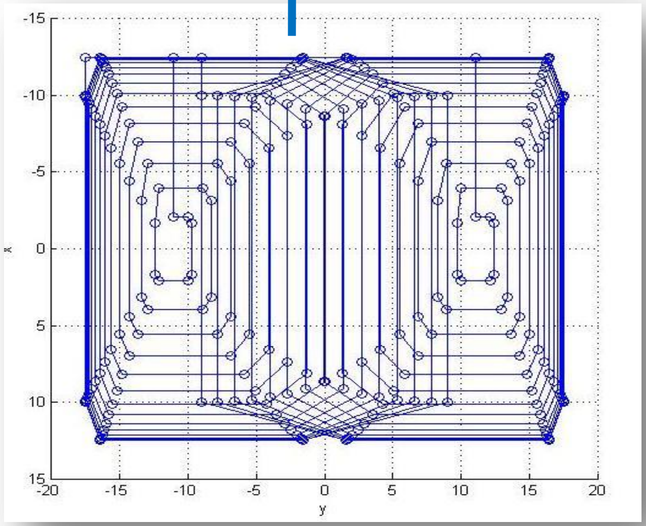
J. A. Taylor, Z. N. Low, J. J. Casanova, J. Lin, "A Wireless Power Station for Laptop Computers," *Proceedings of IEEE Radio and Wireless Symposium*, pp. 625-628, January 2010

Transmitter Design

- TX coil is embedded into the desktop (blue dashed outline).
- Two parallel overlapping coils created uniform magnetic field distribution.
- TX coil size: 35 cm x 25 cm
- TX board size: 5 cm x 17 cm
- Operate at 240 kHz





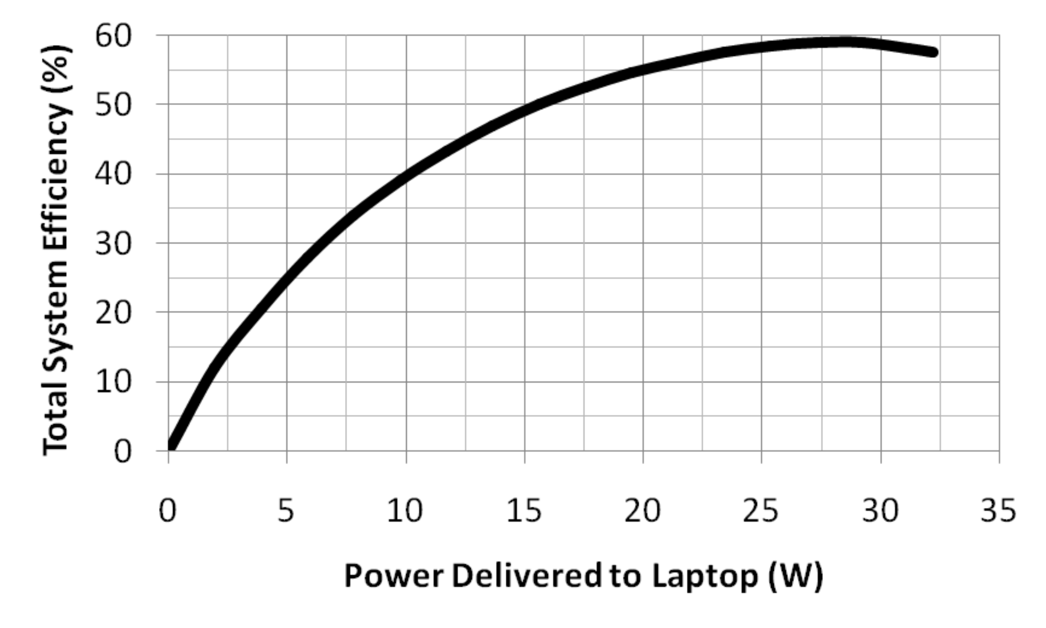


High-power Class-E Inverter

Low-power control circuit

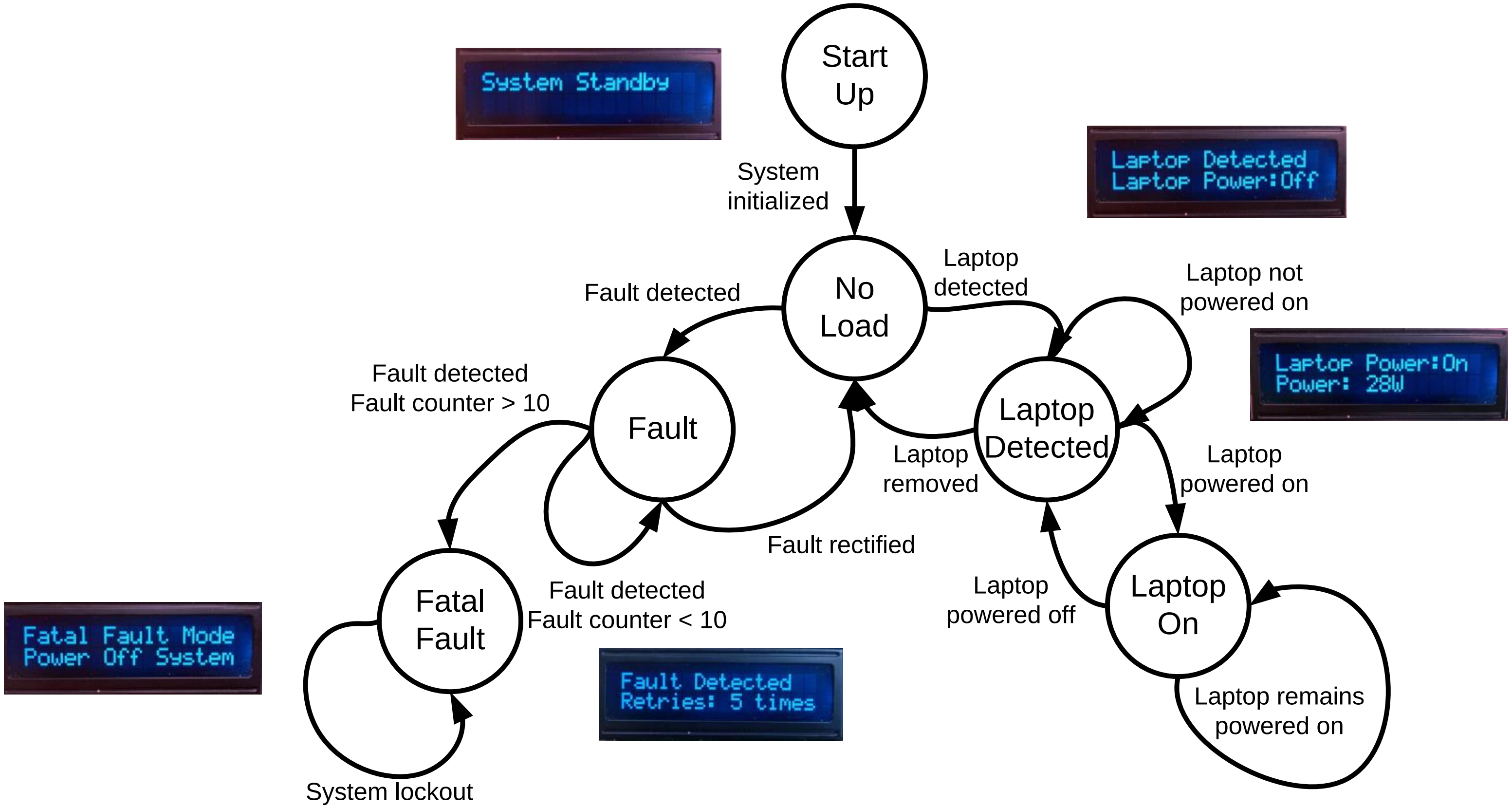
Measurement Result

- Better than 50% for power above 15 W.
- Peak efficiency near 60%.
- Total system efficiency includes the receiver regulator, detection and control circuitry, with respect to the power delivered to the laptop.
- Voltage regulator conversion efficiency: 90%
- Class E amplifier drain efficiency: > 90% for most load conditions



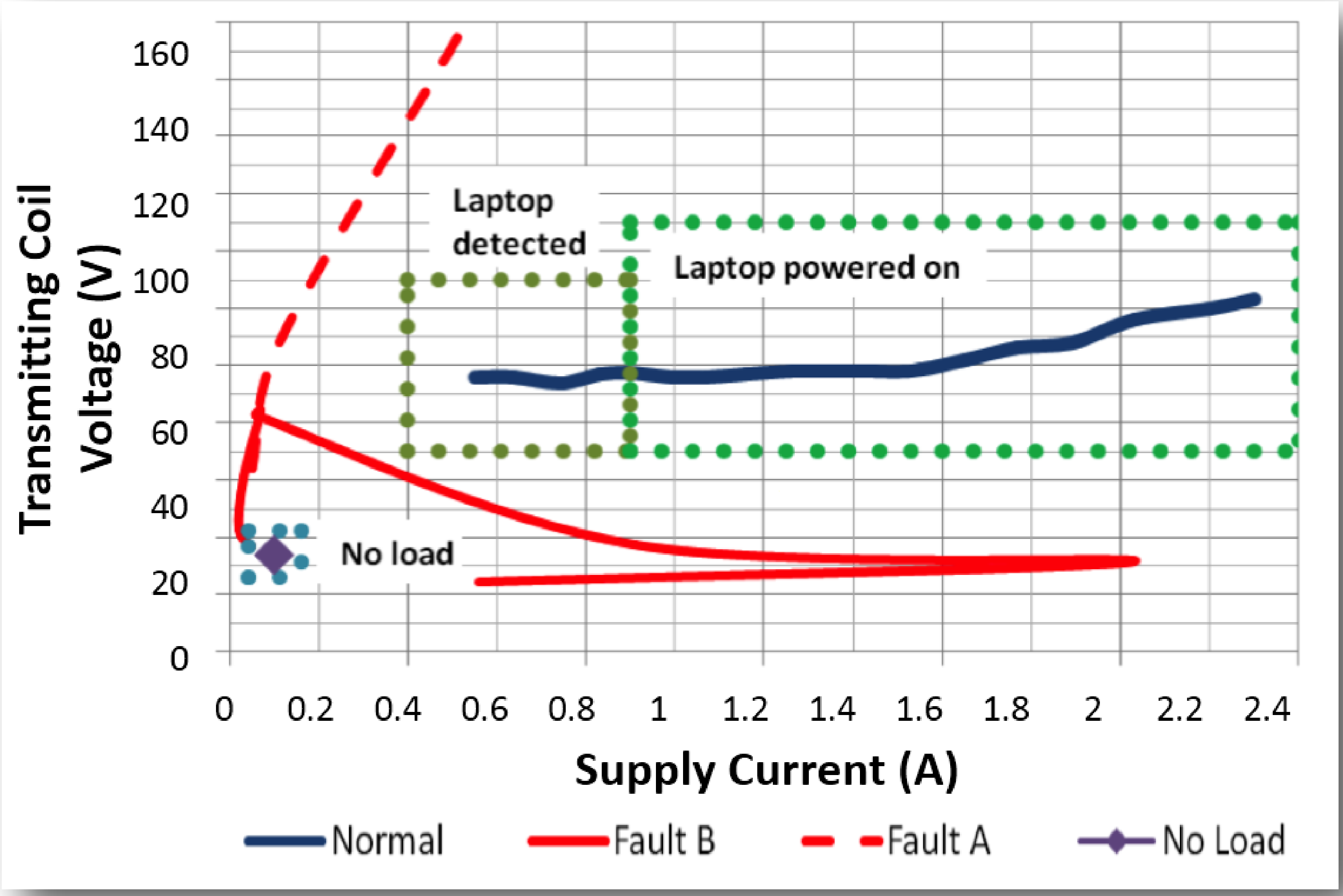
- Since the laptop generates more heat than the wireless power receiver, temperature increase is not observed after high power operation of more than 2 hours.
- Most of the heat is generated at the ferrites and voltage regulator which can be easily dissipated to the environment

Software Control and Load Detection



- Initial start-up: no load state.
- Supply current and coil voltage sampled by A/D converter
  → determine the system state.
- If no load is detected, the system enters into a low duty cycle state to save power by turning off the system most of the time and only probes the system once every two seconds.
- For simplicity, the fault state (foreign object detection) is only considered if a piece of metallic or magnetic material of significant size is placed in the vicinity of the transmitting coil.

Load Detection

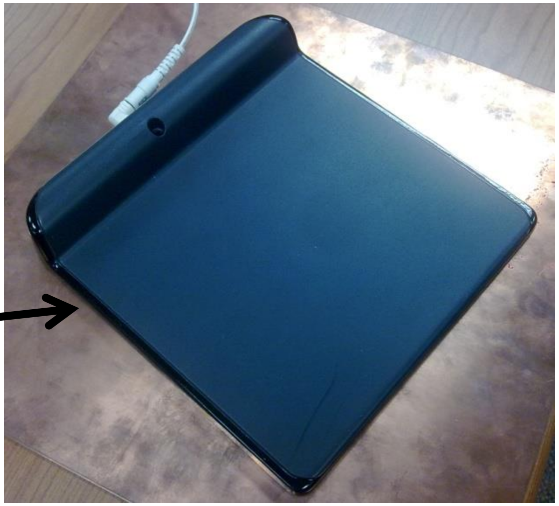


Z. N. Low, J. Casanova, P. Maier, J. Taylor, R. A. Chinga, J. Lin, "Method of Load/Fault Detection for Loosely Coupled Planar Wireless Power Transfer System with Power Delivery Tracking," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1478-1486, April 2010

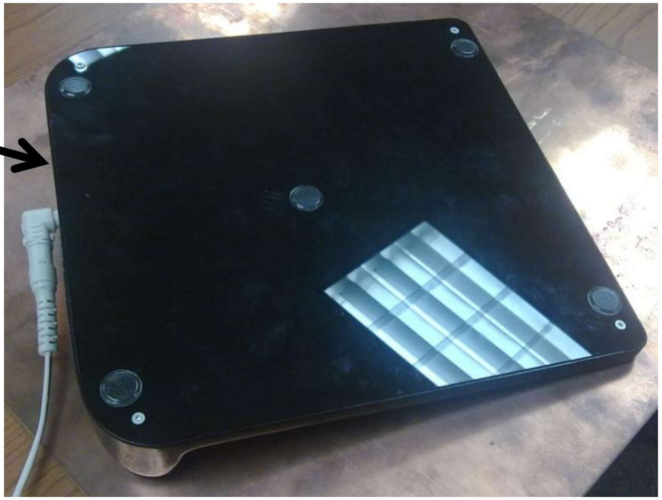
Load/Fault Detection

Large amount of metallic objects on transmitting coil

Transmitter without shielding placed on top of metallic object

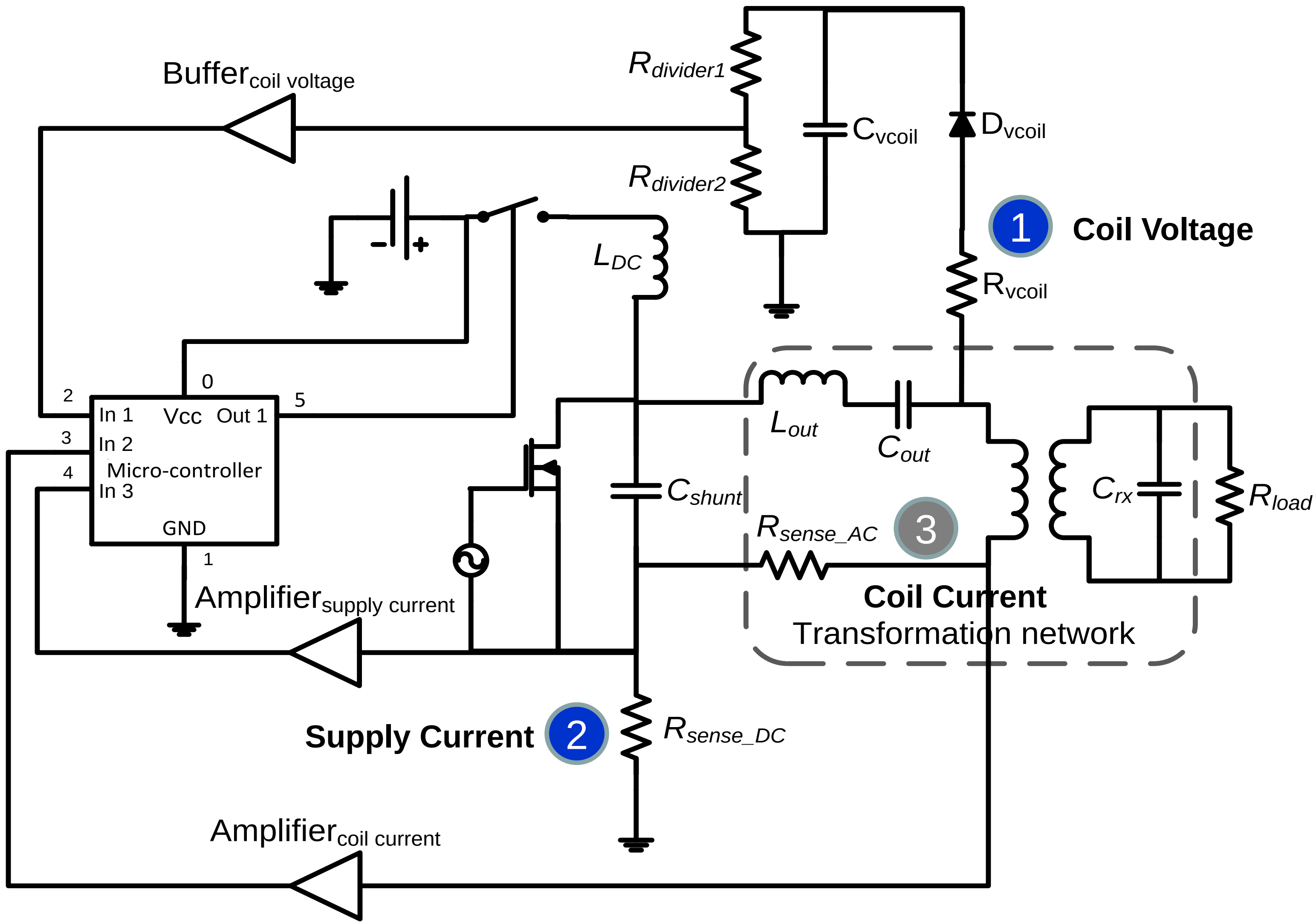


Transmitter flipped over and placed on top of metallic object



- Conductive or magnetic objects at the vicinity of the transmitting coil:
  - Affect self-inductance of the transmitting coil.
  - ZVS/ZDS operation does not hold.
- Need to protect the transmitter from damage due to over-voltage and excessive heating.

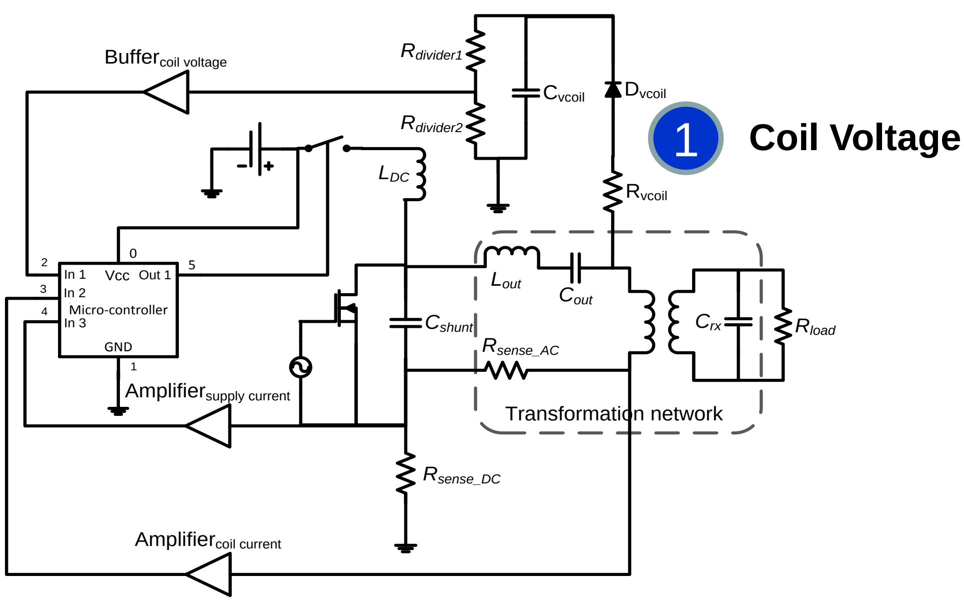
Load/Fault Detection Scheme



All detections except #3 are done in DC so that a low speed ADC can be used.

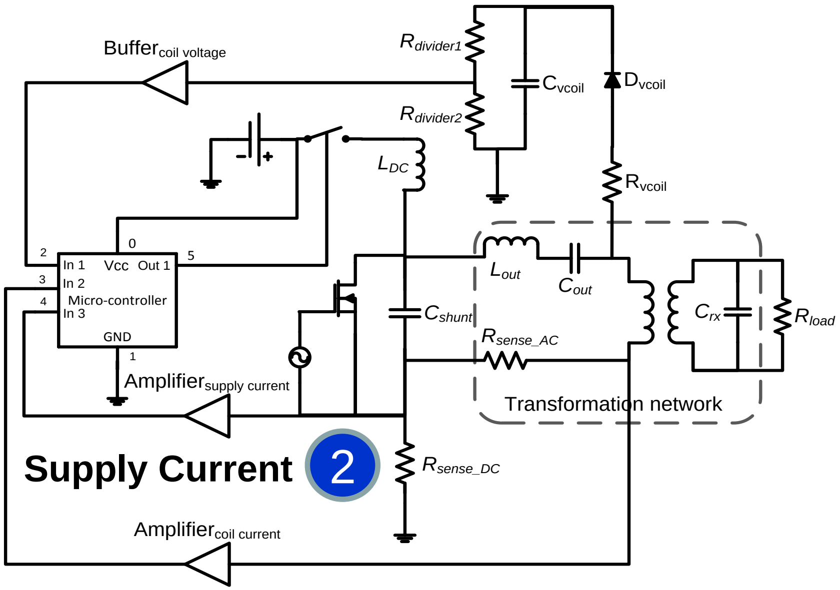
Load/Fault Detection Scheme #1

- Half wave rectifier D_{vcoil} is used to convert the ac waveform to dc
- R_{vcoil} is used to regulate the current across the diode so that the coil does not see a low impedance path through the diode and capacitor C_{vcoil}
- C_{vcoil} is used as a charge holding capacitor
- $R_{divder1}$ and $R_{divder2}$ is used to step down the voltage so that it will not damage the input of the ADC
- A buffer (voltage follower using an op-amp) is used for both buffering purpose as well as low pass filter to further reduce the high frequency noise.



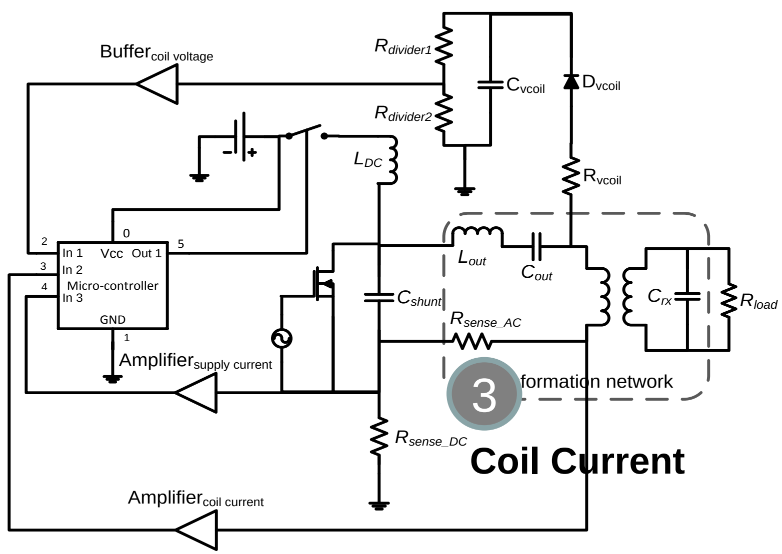
Load/Fault Detection Scheme #2

- Can be implemented by placing a small current sense resistor (typically less than 0.1 Ω) at the high side or low side.
  - High side: Require a high voltage differential amplifier, but signal less noisy.
  - Low side: Single ended buffer/op-amp can be used, signal more noisy due to ground noise in a high voltage and current system. Since dc is measured, noise can be removed by a low pass filter.



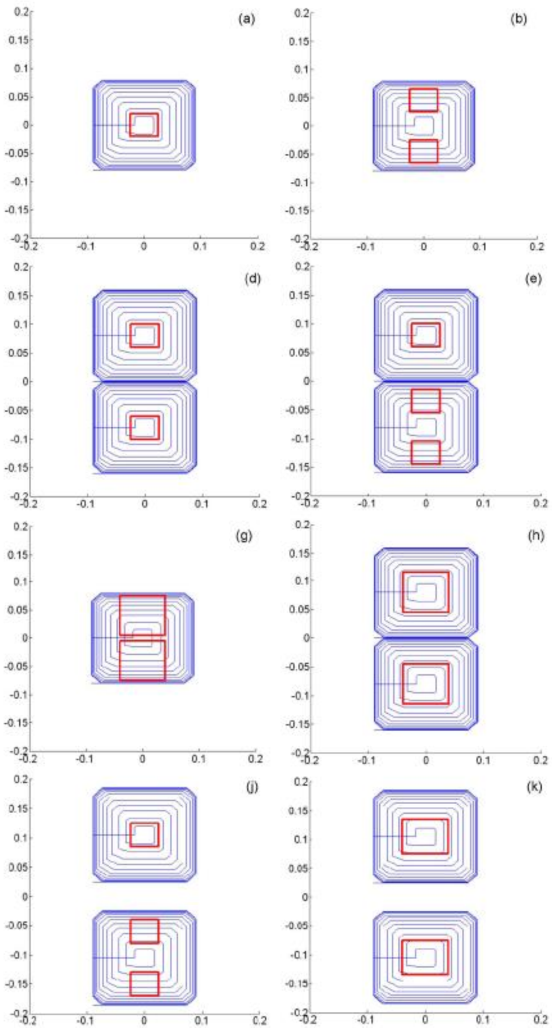
Load/Fault Detection Scheme #3

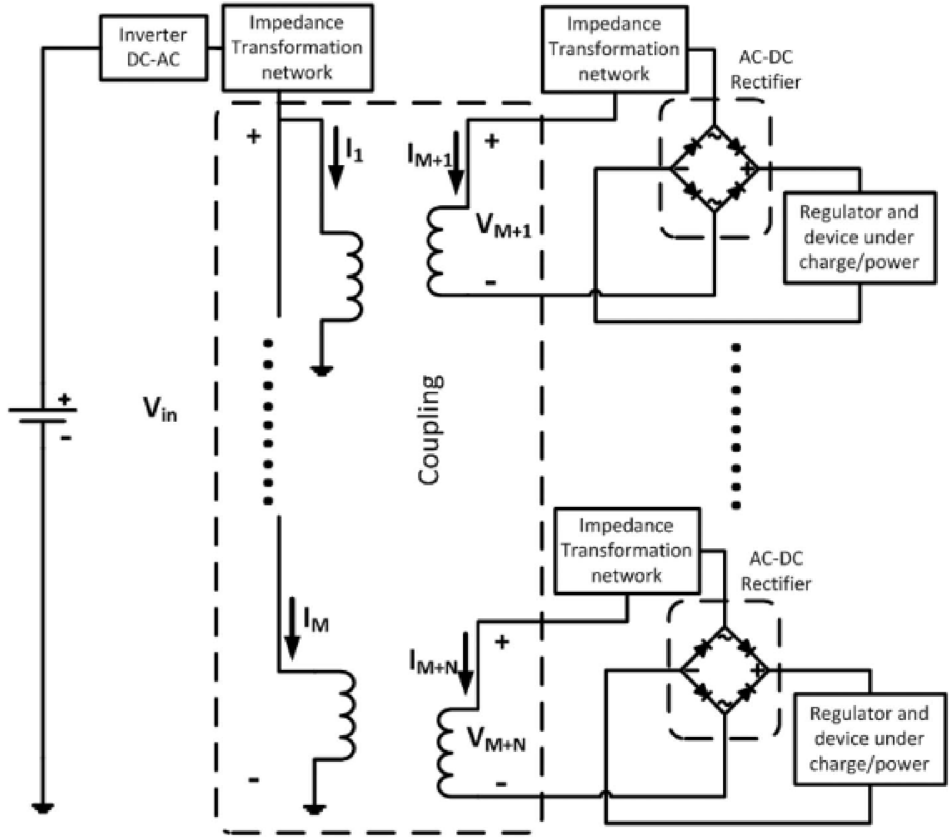
- Can be implemented by placing a small current sense resistor (typically less than 0.1 Ω) at the high side or low side, or using a current sense transformer.
  - High side: Requires an extremely high voltage (>100 V) high speed differential amplifier, but signal less noisy.
  - Low side: Single ended buffer/op-amp can be used, signal more noisy due to ground noise in a high voltage and current system. Noise cannot be remove because of ac measurement.
  - Current sense transformer are typically bulky and have frequency response less than 100 kHz. In addition, the current sense transformer will pick up the high voltage and current signals on the PCB as noise.



Challenge: Charging Multiple Receivers

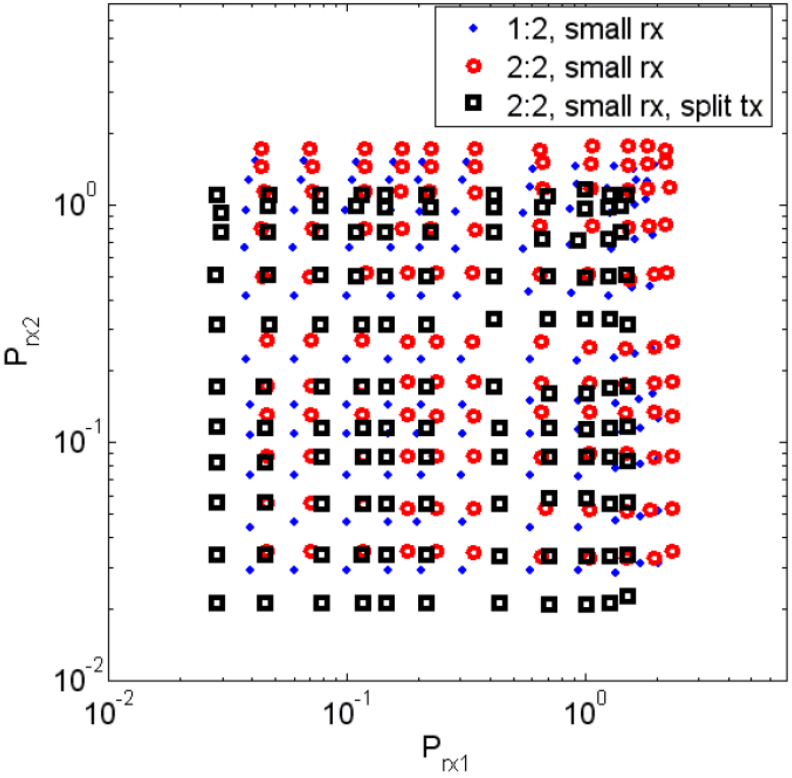
Multiple TX coils (in parallel) transferring power to multiple RX coils

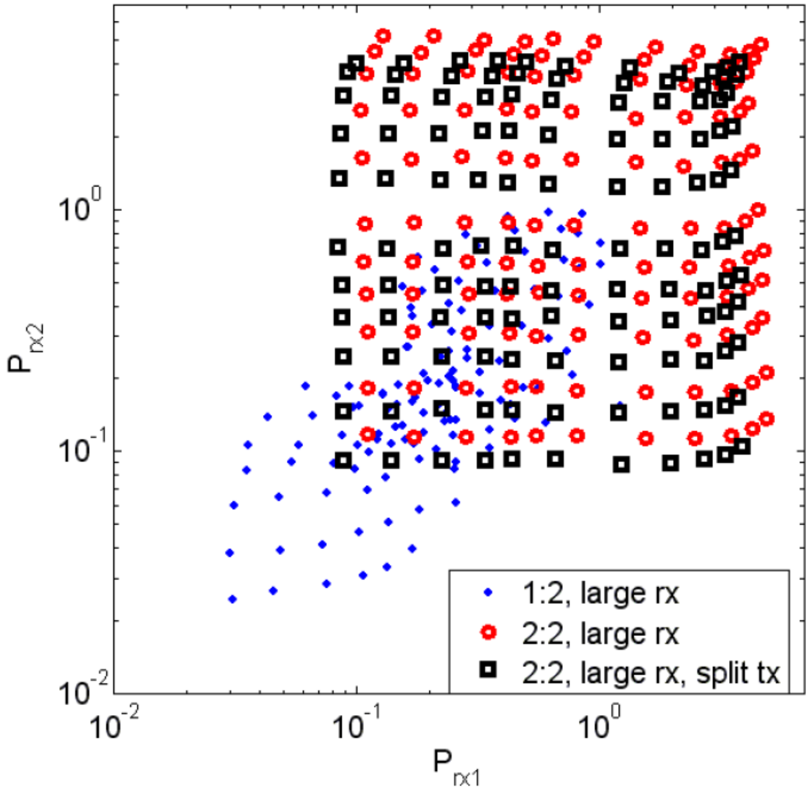




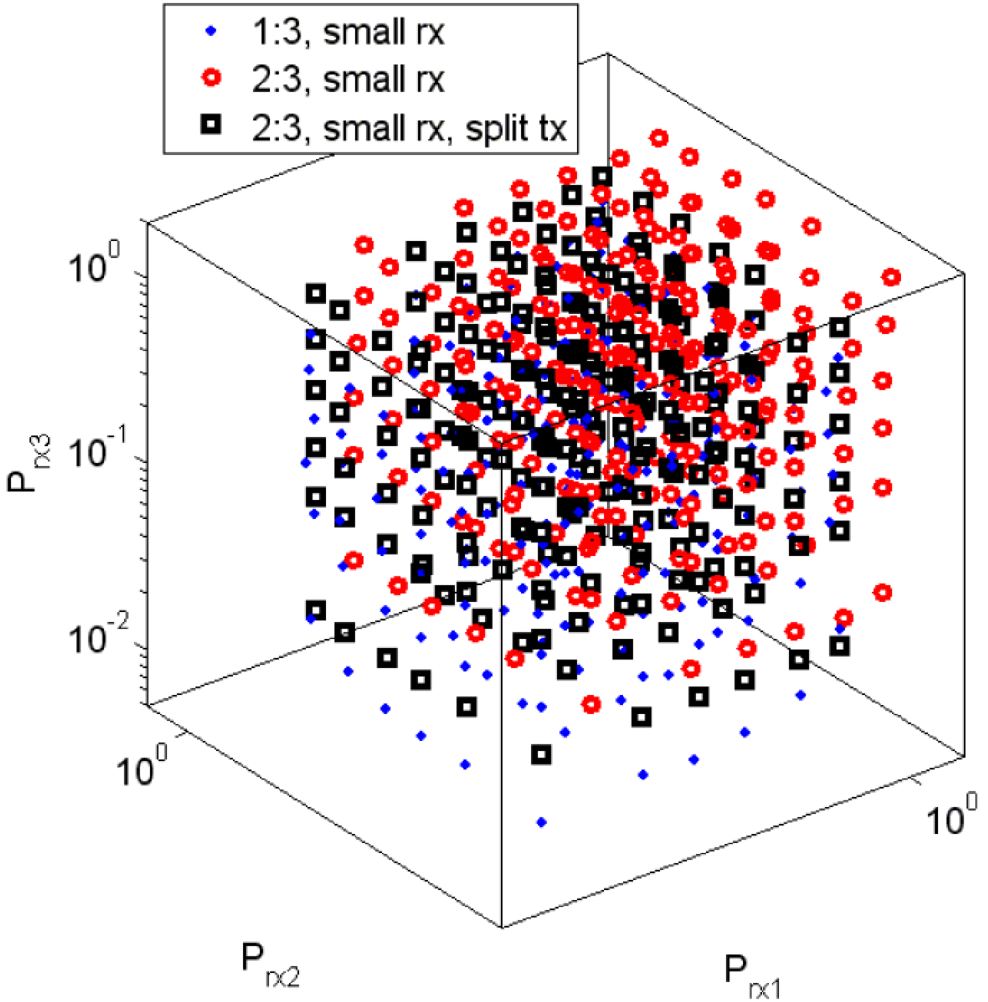
Blue: TX coil (large)
Red: RX coil (small)

Charging Two Receivers





Charging Three Receivers



Challenge of Multiple Variable Loads

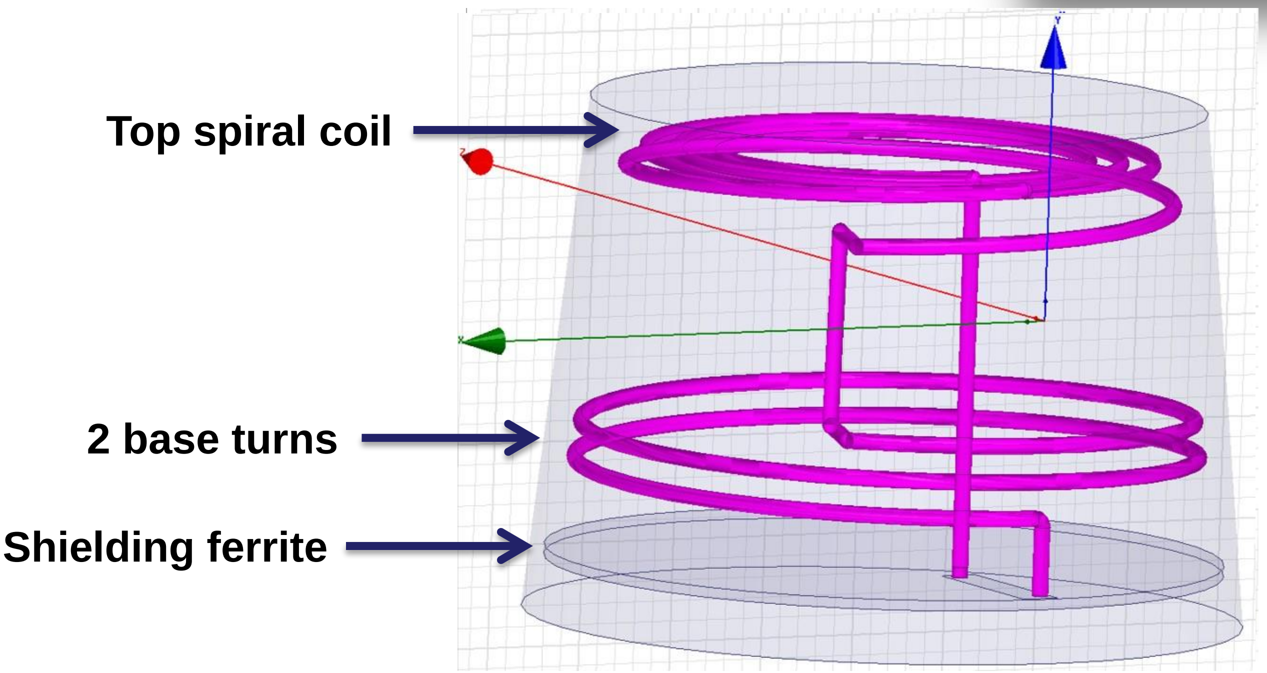
maximum received power and maximum efficiency

Arrangement	Max P_{rx} (W)	Max η_c (fraction)
1:2, small-rx	3.44	0.75
2:2, small-rx	3.88	0.75
2:2, small-rx, split-tx	2.60	0.68
1:2, large-rx	1.82	0.82
2:2, large-rx	9.45	0.88
2:2, large-rx, split-tx	7.86	0.87
1:3, small-rx	1.91	0.74
2:3, small-rx	3.08	0.74
2:3, small-rx, split-tx	2.40	0.67

J. Casanova, Z. N. Low, J. Lin, "A Loosely Coupled Planar Wireless Power System for Multiple Receivers," *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 8, pp. 3060-3068, August 2009

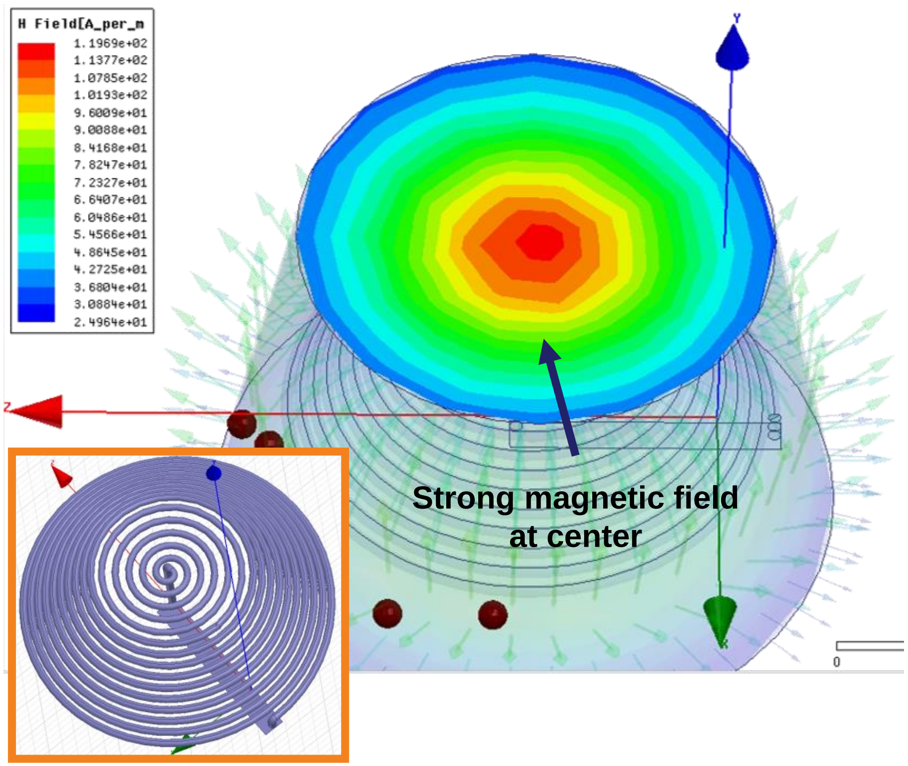
3D Wireless Charging

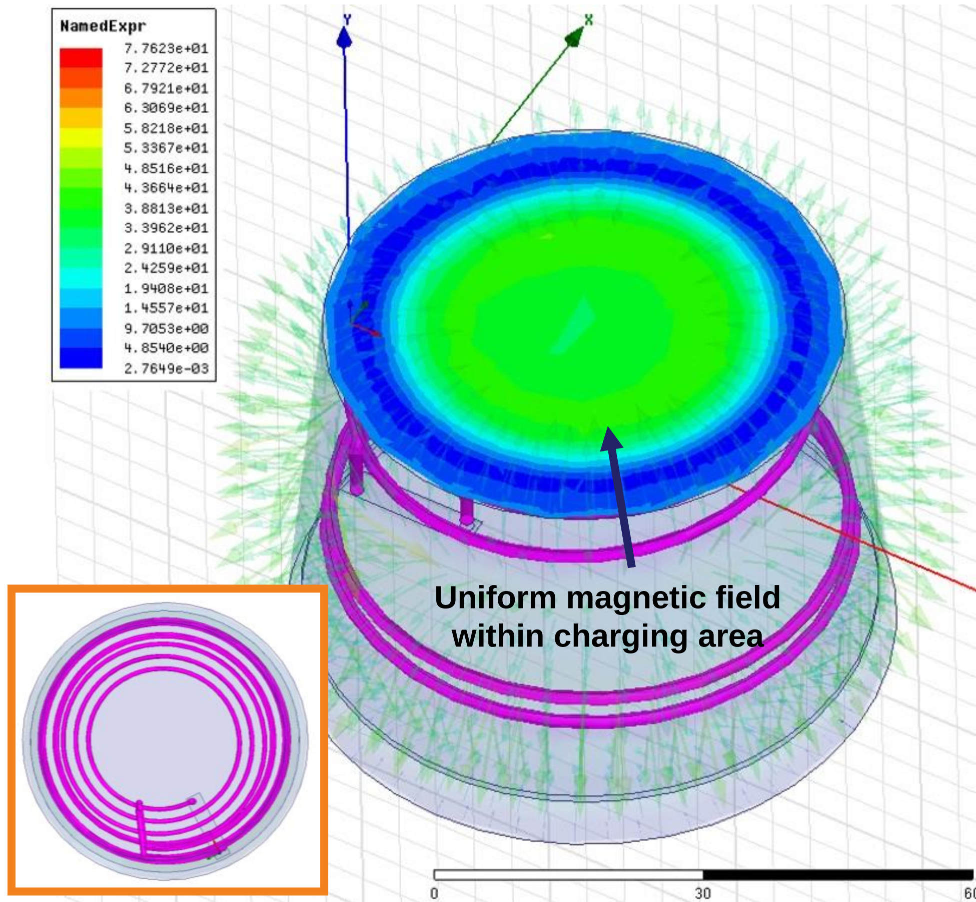
- 360° uniform charging surface
- Free positioning of the wearable device
- Support up to 10 W to the load
- Coil-to-coil efficiency (1 TX coil vs. 2 RX coils) 79.5%



3D Wireless Charging: TX Coil

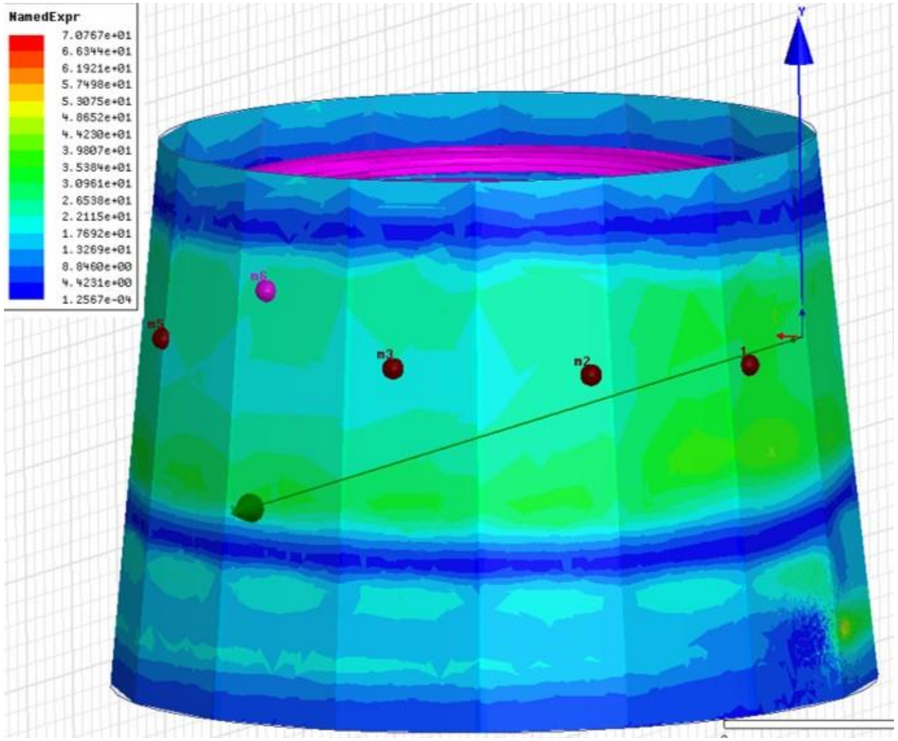
- Cell Phone charging area
  - Reduce central turns to have uniform magnetic field
- Ls= 1.3 μH @6.78 MHz, Q= 250

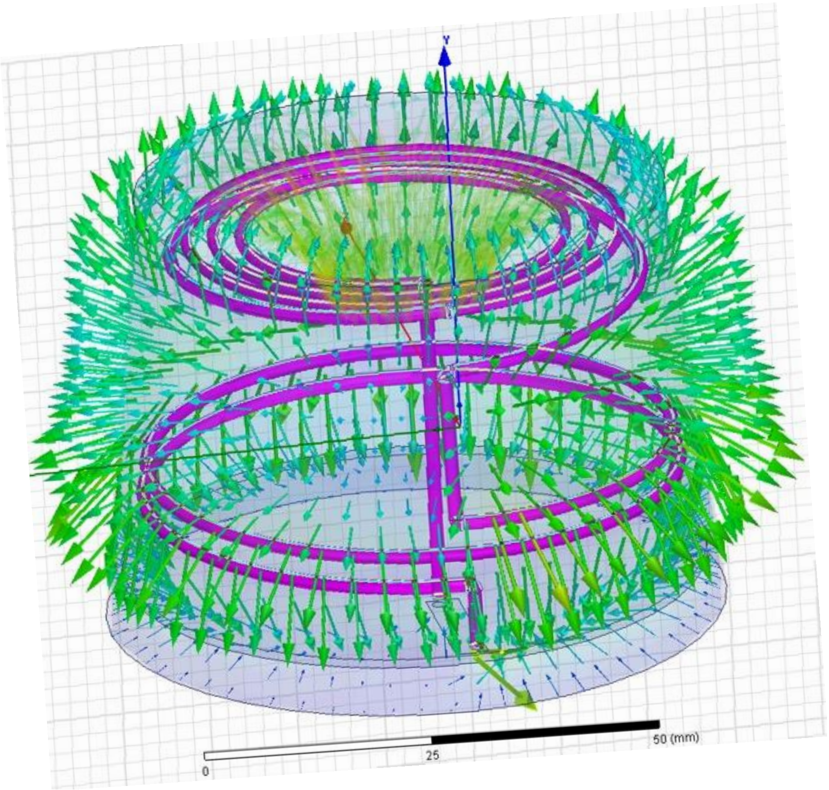




3D Wireless Charging: TX Coil

- Wearable device charging area

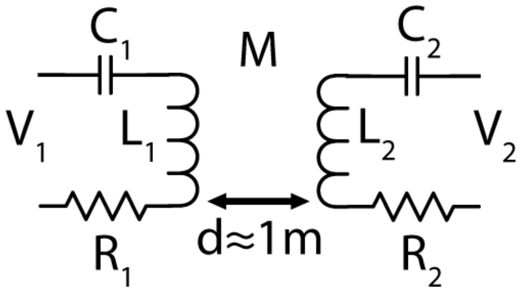


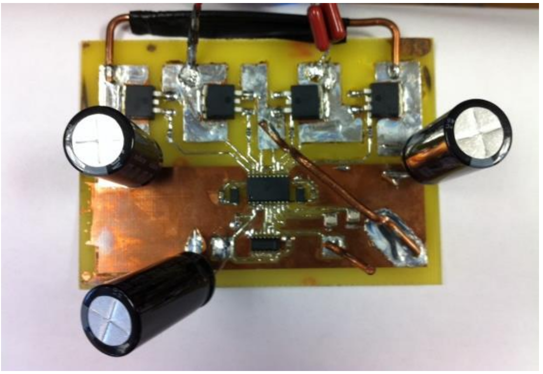


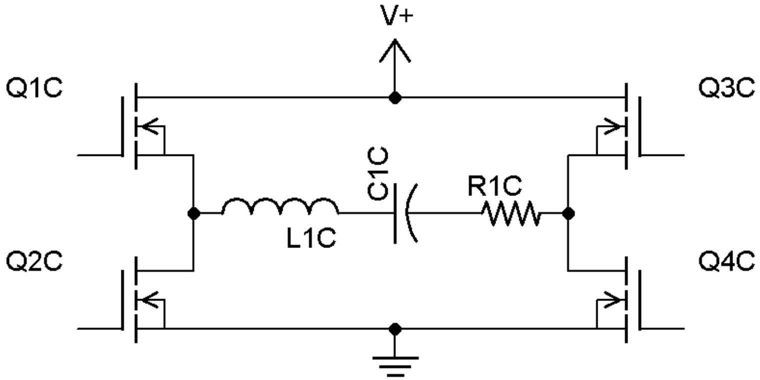
R.-C. Kuo, P. Riehl, Anand Satyamoorthy, W. Plumb, P. Tustin, J. Lin, "A 3D Resonant Wireless Charger for a Wearable Device and a Mobile Phone," IEEE Wireless Power Transfer Conference, May 2015.

A Mid-range WPT System

- Two 1 m x 1 m coils separated by 1 m
- Driven by full-bridge Class-D amplifier
- Frequency: 508.5 kHz

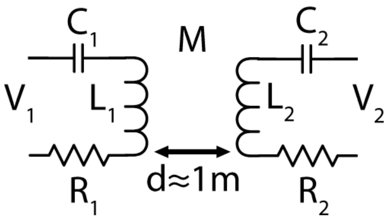






Design Equations

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_1 + j\omega L_1 + \frac{1}{j\omega C_1} & j\omega M \\ j\omega M & R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$



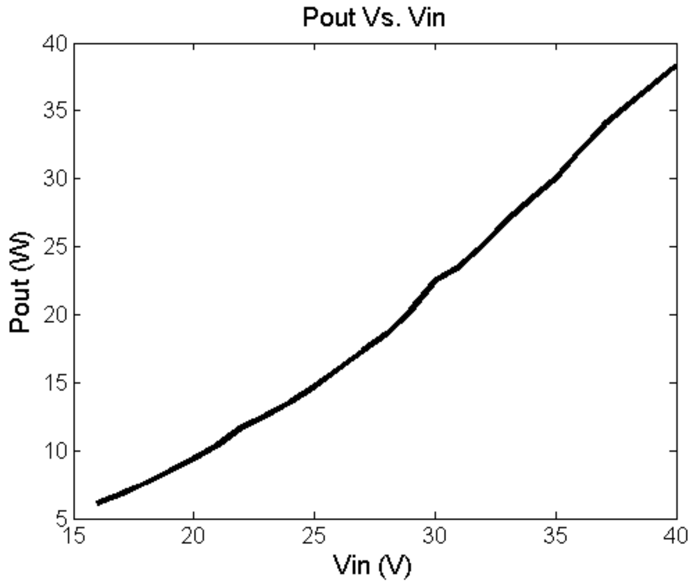
At resonance, $j\omega L_x + 1/j\omega C_x = 0$ ⇨ $\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_1 & j\omega M \\ j\omega M & R_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$

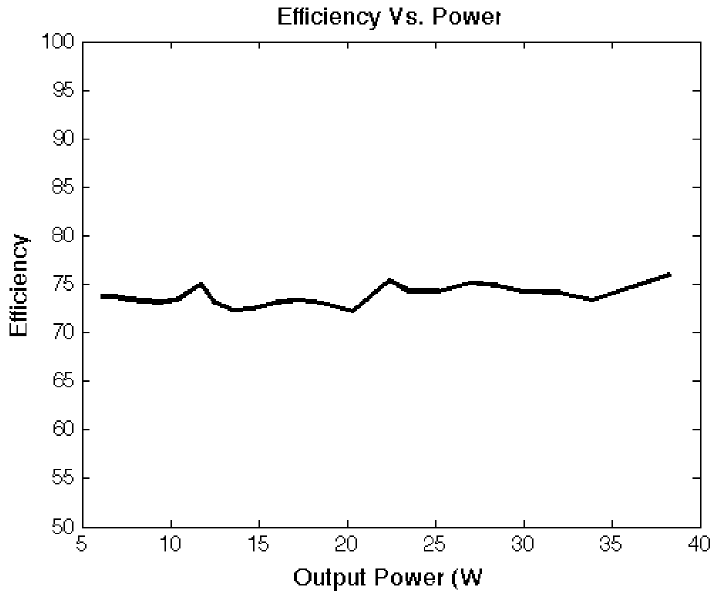
$$P_{\text{out}} = \frac{V_{\text{in}}^2 \omega^2 M^2 R_L}{(R_1(R_2 + R_L) + \omega^2 M^2)^2} \qquad \eta = \frac{\omega^2 M^2 R_L}{R_1(R_2+R_L)^2 + \omega^2 M^2 (R_2 + R_L)} \qquad R_{\text{TX}} = \frac{V_1}{I_1} = R_1 + \frac{\omega^2 M^2}{R_2 + R_L}$$

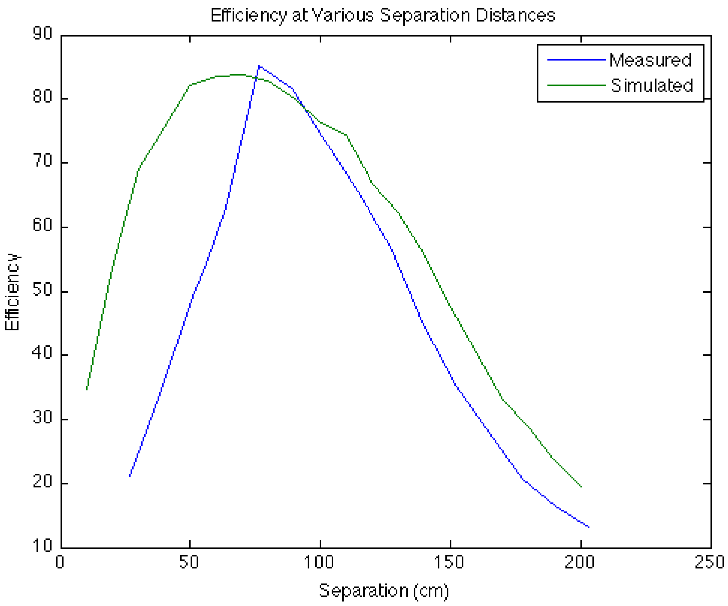
$$R_{L,\text{matched}} = \sqrt{R_2^2 + \omega^2 M^2 \frac{R_2}{R_1}} \quad \Rightarrow \quad \eta_{\text{MAX}} = \frac{\omega^2 M^2 \sqrt{R_2^2 + \omega^2 M^2 \frac{R_2}{R_1}}}{\left(R_2 + \sqrt{R_2^2 + \omega^2 M^2 \frac{R_2}{R_1}}\right)^2 R_1 + \left(R_2 + \sqrt{R_2^2 + \omega^2 M^2 \frac{R_2}{R_1}}\right)\omega^2 M^2}$$

$$\eta_{MAX} = \frac{\alpha^2}{\left(1 + \sqrt{1+\alpha^2}\right)^2} \qquad \alpha = k\sqrt{Q_1 Q_2} \qquad Q_1 = \frac{\omega L_1}{R_1} \qquad Q_2 = \frac{\omega L_2}{R_2}$$

Mid-range WPT System Test Result



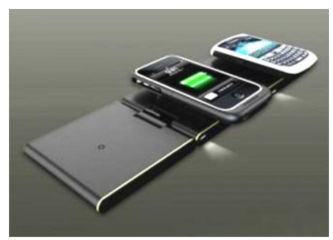




Commercialization and Standardization

- Industry alliances for near-field wireless charging
  - Wireless Power Consortium (Qi):
    est. Dec. 2008, 226 members (11/2015)
  - AirFuel Alliance (195 members, 11/2015) combining
    - Alliance for Wireless Power (A4WP):
      est. 2012, 140 members (4/2015)
    - Power Matters Alliance (PMA)
      est. 2012, 68 members (4/2015)

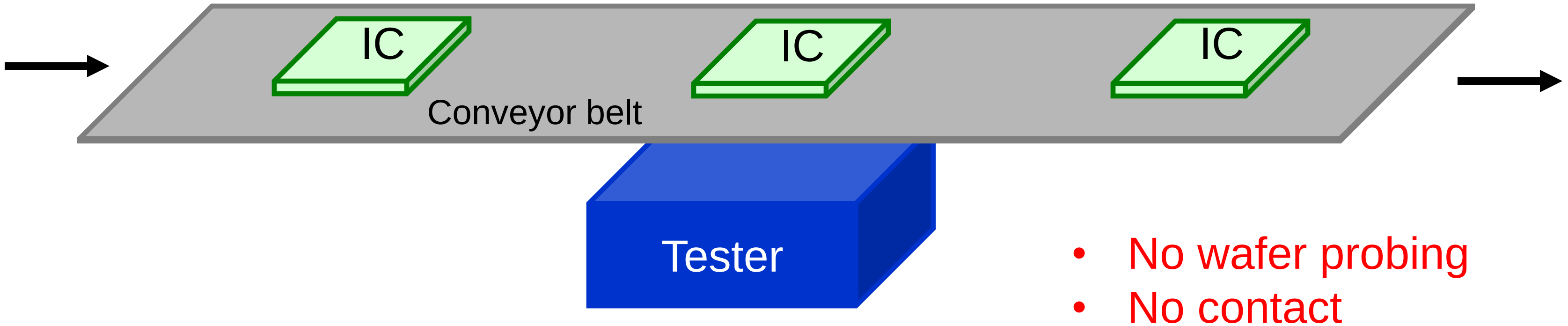
rezence
Alliance for Wireless Power



- A unified standard like IEEE 802.11 (WiFi) would be better
  - Compatibility
  - Unlicensed operation
  - Wireless communications interface for authentication of wireless power transfer

Wireless-Powered IC Chips

- Signals can be transmitted wirelessly, why not do the same for power? Cut the last wire to the chip!
- A chip mounted on PCB without bond wire or flip-chip bump
- Both operating dc voltage and power consumption of IC chips for mobile devices continue to decrease, making this possible in the future.
- Testing, packaging, and system integration of IC chips in the future will be very different.



- No wafer probing
- No contact
- Faster throughput

Future Chip-Scale Wireless Power

- The development of wireless power and other wireless technologies benefited from semiconductor technology.
- In return, wireless power may revolutionize IC testing and packaging in semiconductor industry.

IoT (Internet of Things) → IoC (Internet of Chips)

Conclusion

- Wireless Power in the 21st Century: a mix of both long range and short range, both near field and far field
- Far-field wireless power
  - Long range
  - Lower efficiency
  - Space/military, ultra low power devices, sensor network
  - Energy harvesting
- Near-field wireless power
  - Short range – less safety concern
  - Higher efficiency
  - Wireless charging EV, OLEV, personal equipment, IoT
  - Frequency: kHz, MHz, or GHz
- Large scale to small scale
  - OLEV, EV, UAV, laptop, mobile phone, IC chip, …