Wireless Power Transmission: From Far-Field to Near-Field

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IEEE MTT Society

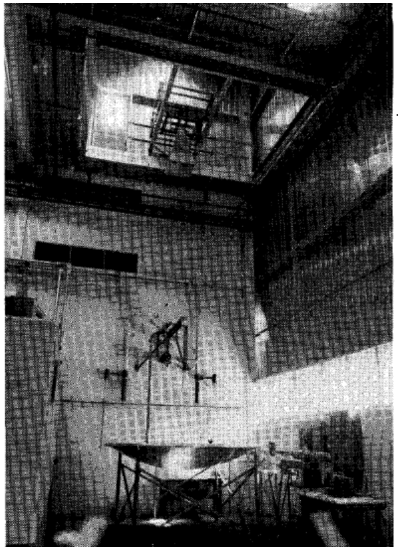
- **5th largest in IEEE**
- **Financially healthy**
- **Volunteer-based society board (AdCom) and conference committees**
  - **Technical Coordinating Committee (TCC) under AdCom**
  - **27 Technical Committees under TCC**
  - **MTT-24 RFID**
  - **MTT-25 RF Nanotechnology**
  - **MTT-26 Wireless Energy Transfer and Conversion**
  - **MTT-27 Microwave Technologies in Automobile Applications**

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:
  - Remote transmission of energy for space applications
  - Remote powering of unmanned aircrafts, vehicles, robots
  - An extension of existing power grid system
  - Controlling the destructive storms, e.g. the path of hurricane
  - Remote powering of wireless sensors, especially for sensors located in hard-to-reach environment
  - Remote charging of bio-implanted devices

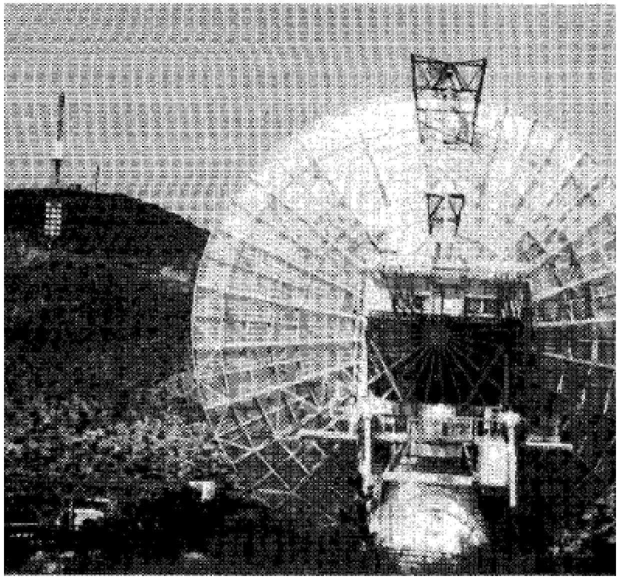
WPT History - more than one century

- **1899** – Tesla's first experiment to transmit power without wires. 150 kHz.
- **WWII** – high power microwave tubes developed.
- **1958** – 1st period of modern WPT development began. 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 modern 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

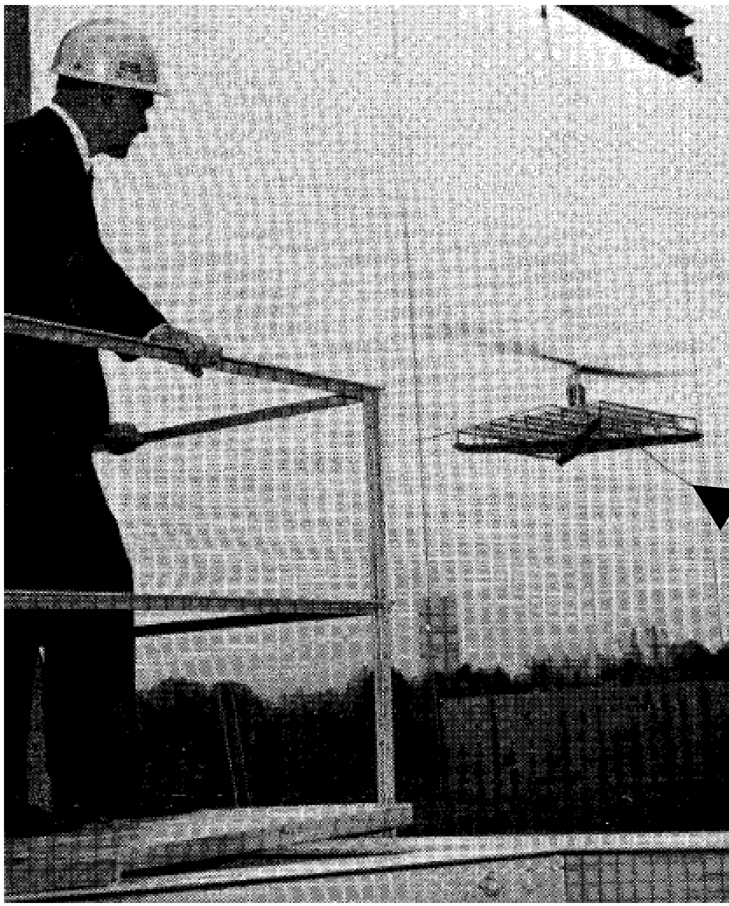
1975 demonstration
30 kW DC output @ 1 mi



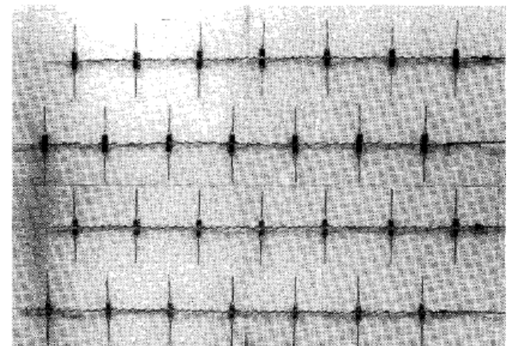
*** W. C. Brown, "The History of Power Transmission by Radio Waves," IEEE Trans. Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230-1242, Sept. 1984.**

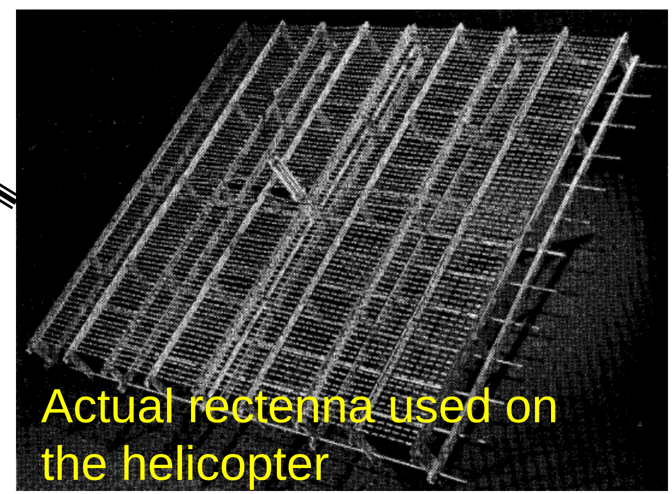
Remote Powering of Helicopter

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)





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.**

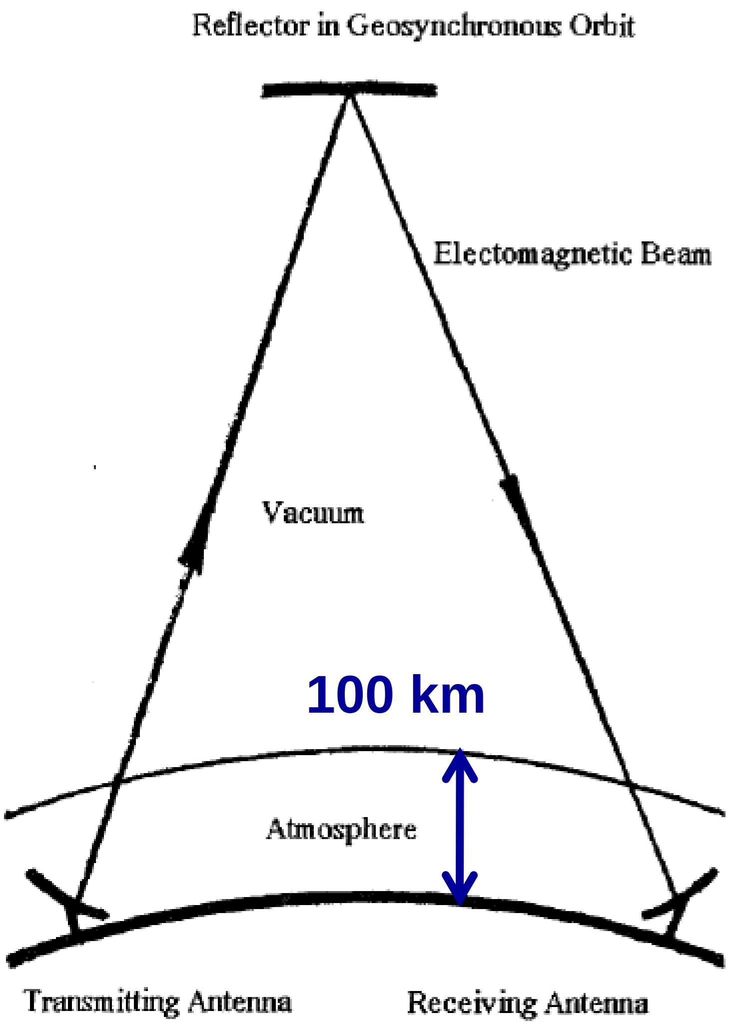
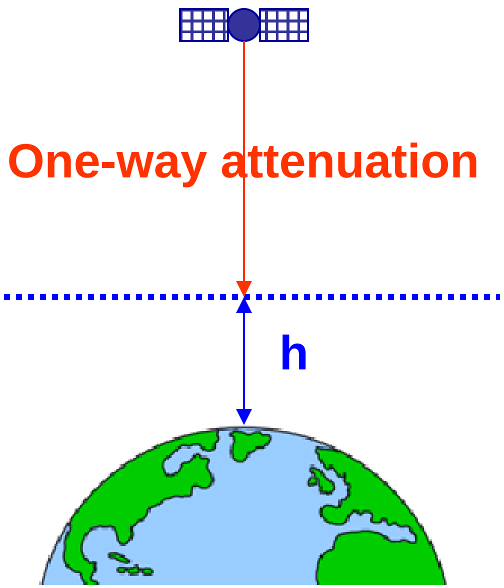
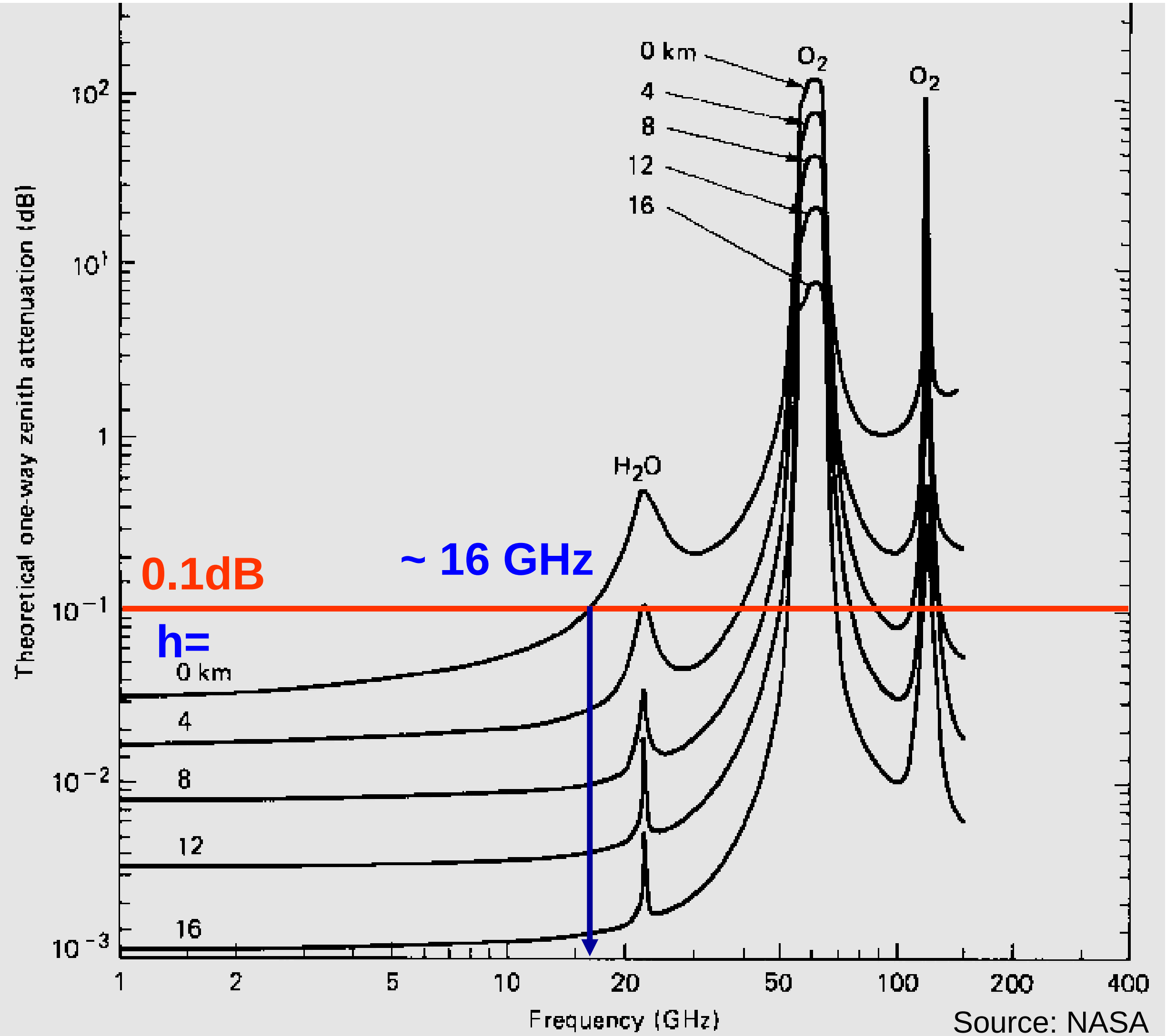


FIGURE 1. CONCEPTUAL SCHEME OF ELECTROMAGNETIC BEAM POWER TRANSMISSION ON EARTH

Attenuation Through Atmosphere

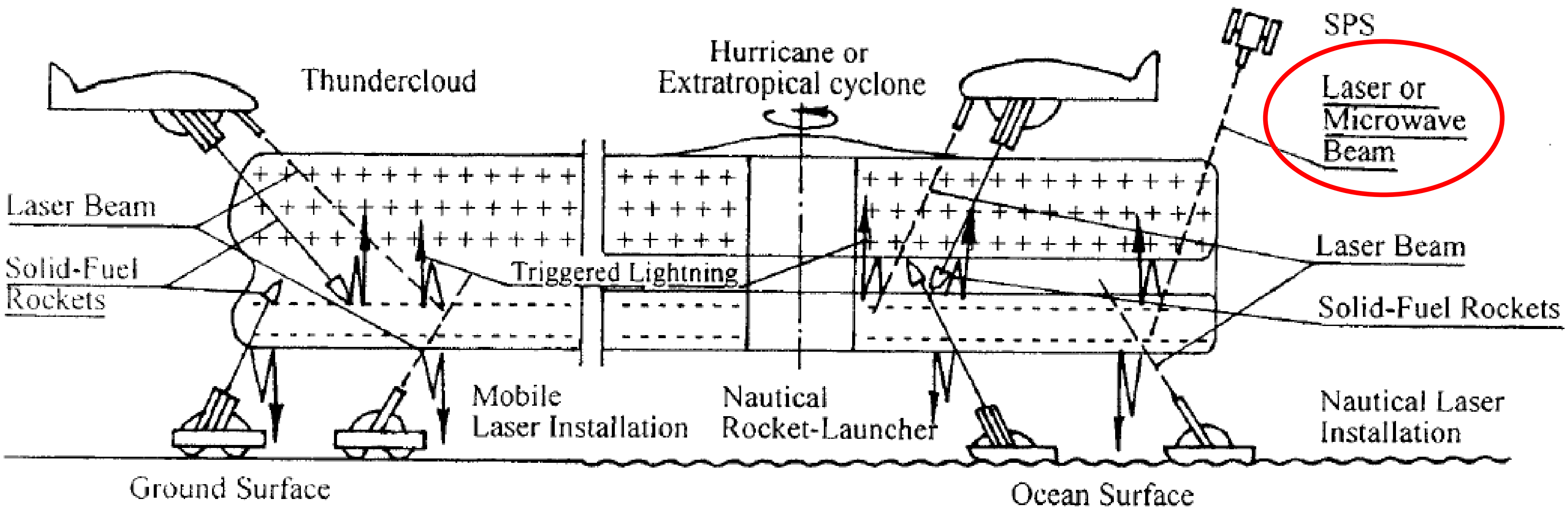




Source: NASA

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

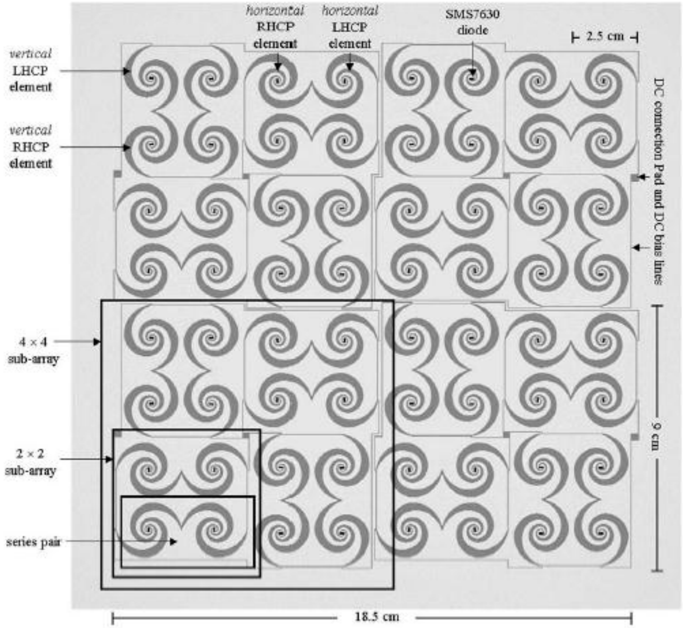
Manipulating tropical storms

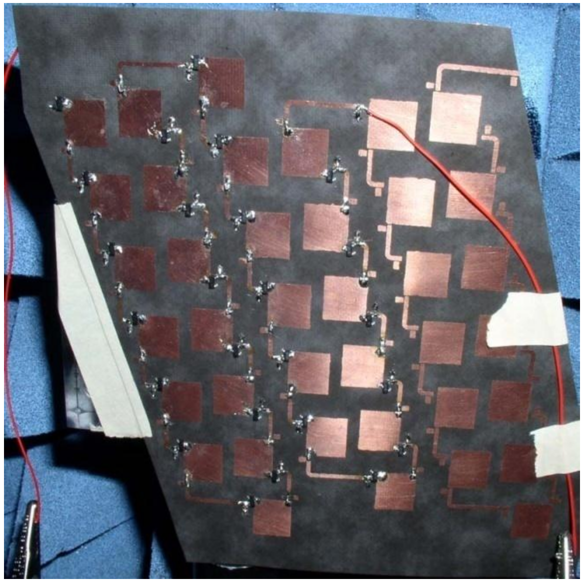


E. Yu. Krasilnikov, "Prevention of destructive tropical and extratropical storms, hurricanes, tornadoes, dangerous thunderstorms, and catastrophic floods," Nonlinear Processes in Geophysics (<u>2002</u>) 9: 51–59

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**

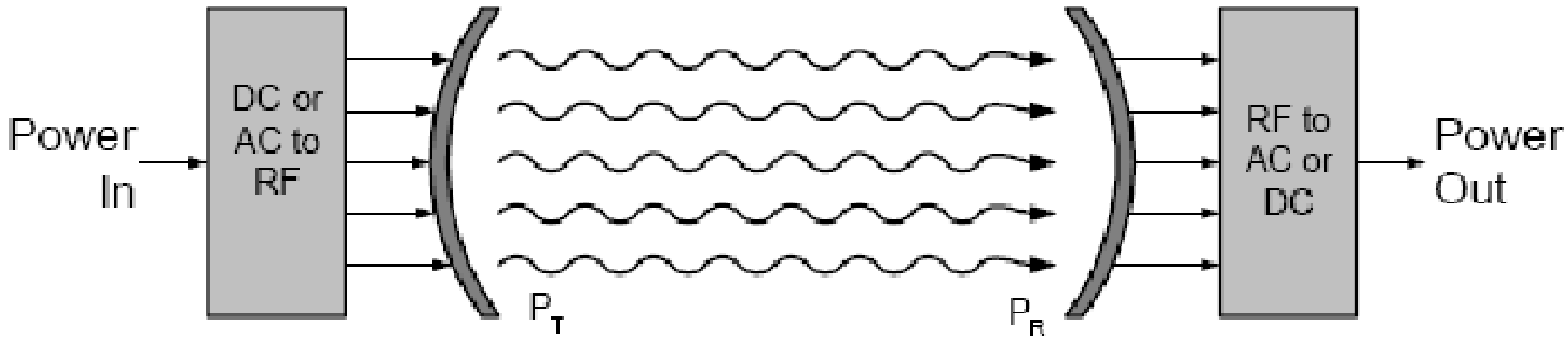




*** J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic´, "Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays," IEEE Trans. Microwave Theory and Tech., vol. 52, no. 3, pp. 1014-1024, March 2004.**
*** C. Walsh, S. Rondineau, M. Jankovic, G. Zhao, Z. Popovic, "A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

WPT System

Efficiency η_T η_C η_R



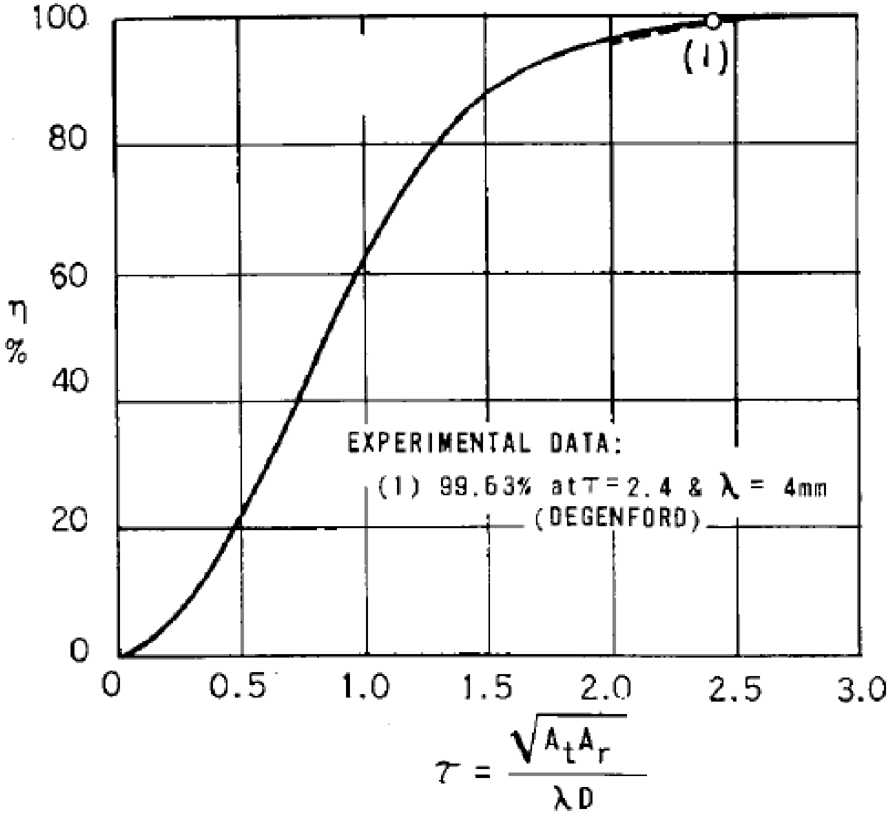
- DC or AC power is first converted to RF power.
- RF power is transmitted by TX antenna to the receiver.
- RF power is received by the RX antenna and rectified to DC power which can further be converted to AC power.
- Total system efficiency = (η_T)x (η_C)x (η_R)

Challenges of WPT

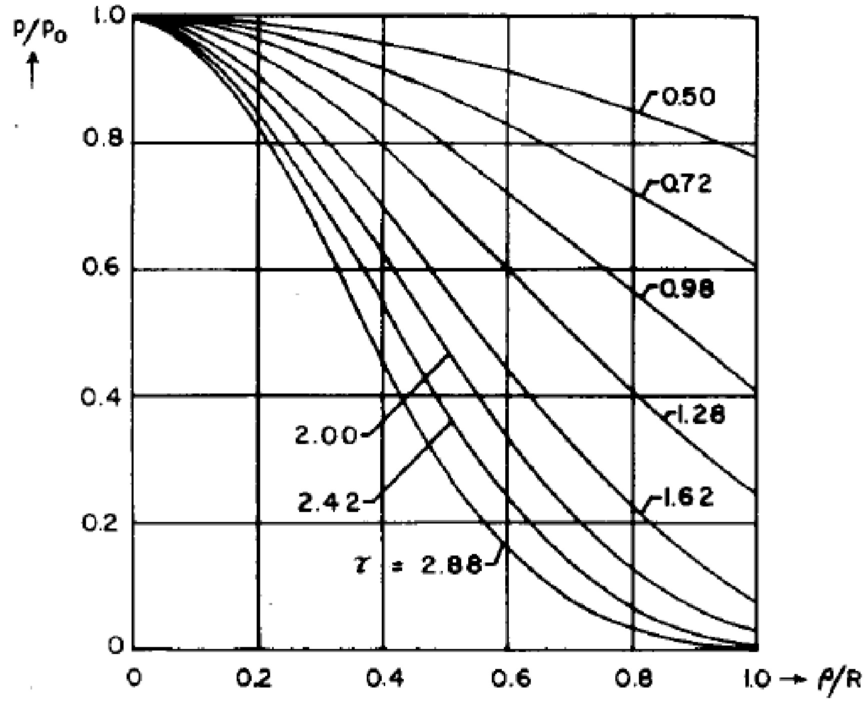
- Technical Issues
  - Beam-forming antennas for directed microwave beam
  - High efficiency microwave power source (transmitter)
  - High efficiency microwave rectifier (receiver)
  - All have to be lightweight to reduce deployment cost
- Environmental Issues
  - Safety concern
  - Ecological effect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

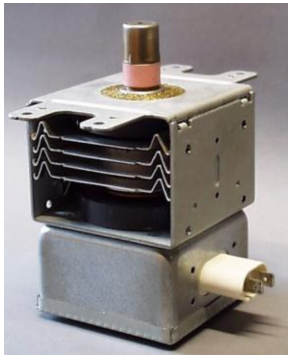
* W. C. Brown, E. E. Eves, “Beamed Microwave Power Transmission and its Application to Space,” IEEE Trans. Microwave Theory and Techniques, vol. 40, no. 6, pp. 1239-1250, June 1992, quoting G. Goubau and F. Schwering, “On the guided propagation of electromagnetic wave beams,” IRE Trans. Antennas Propagat.,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

High Efficiency Microwave Power Source

- Find devices to generate high power RF.
  - High efficiency
  - Low cost
  - Lightweight
- Cost of microwave power amplifier goes up with power level. If efficiency is not high, need heatsink.
- Where do you find the most affordable high power source at 2.4 GHz that can generate 100W-1kW?

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.

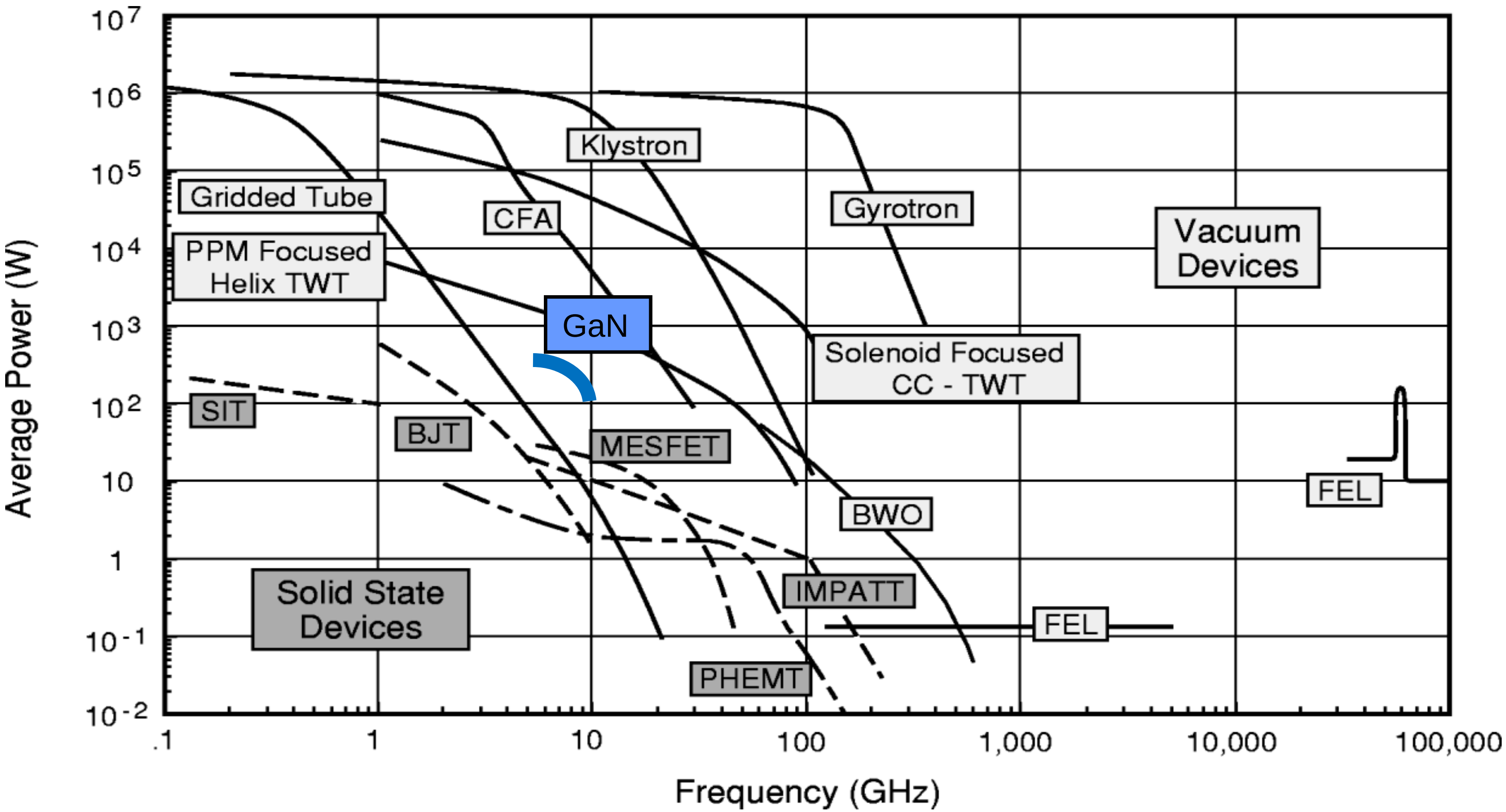


Magnetron inside microwave oven
2.4GHz, ~1kW, ~65% efficiency

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

Microwave Power Source

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

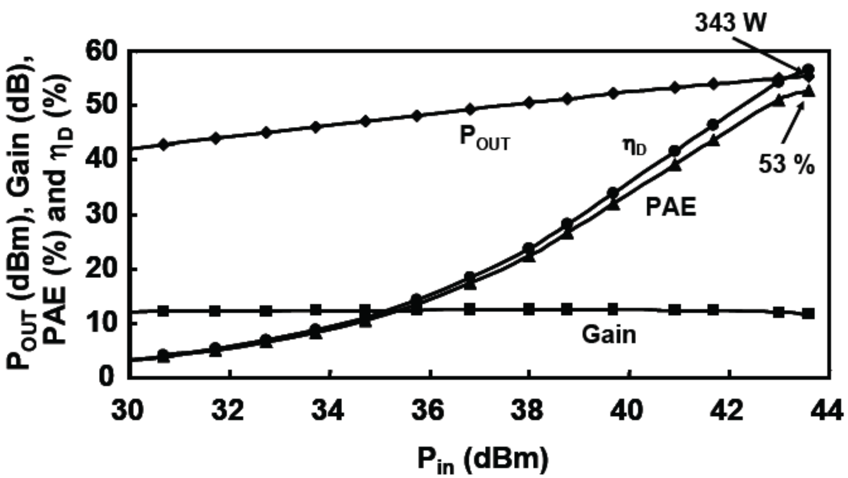


* V. L. GRANATSTEIN, R. K. PARKER, C. M. ARMSTRONG, “Vacuum Electronics at the Dawn of the Twenty-First Century,” Proceedings of the IEEE, vol. 87, no. 5, pp. 702-716, May 1999.

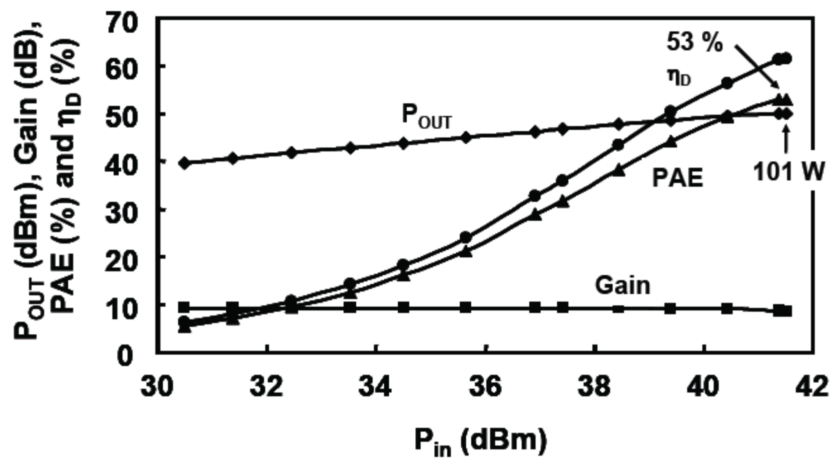
Solid-State Microwave Power Source

- 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)

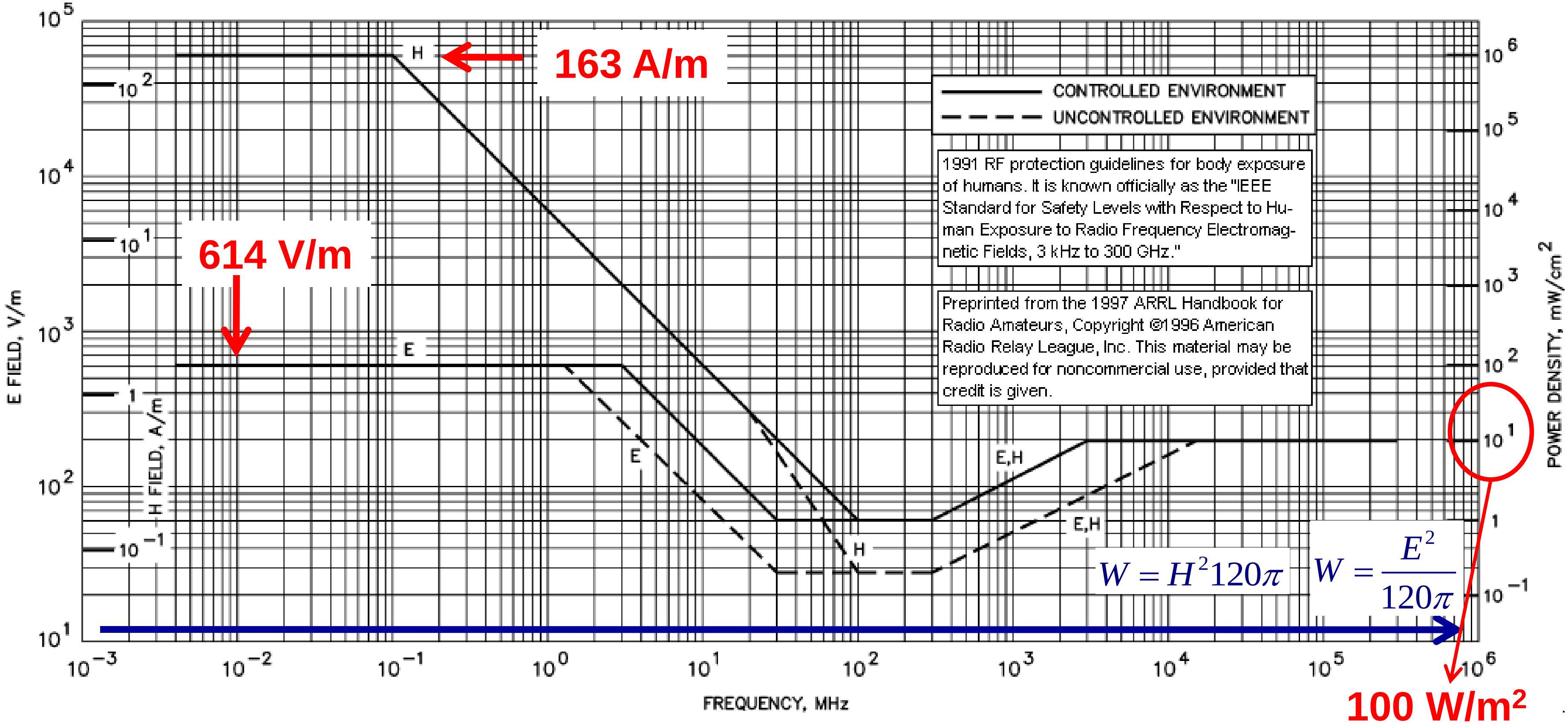


- Shigematsu, H.; Inoue, Y.; Akasegawa, A.; Yamada, M.; Masuda, S.; Kamada, Y.; Yamada, A.; Kanamura, M.; Ohki, T.; Makiyama, K.; Okamoto, N.; Imanishi, K.; Kikkawa, T.; Joshin, K.; Hara, N.; , "C-band 340-W and X-band 100-W GaN power amplifiers with over 50-% PAE," *Microwave Symposium Digest, 2009. 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

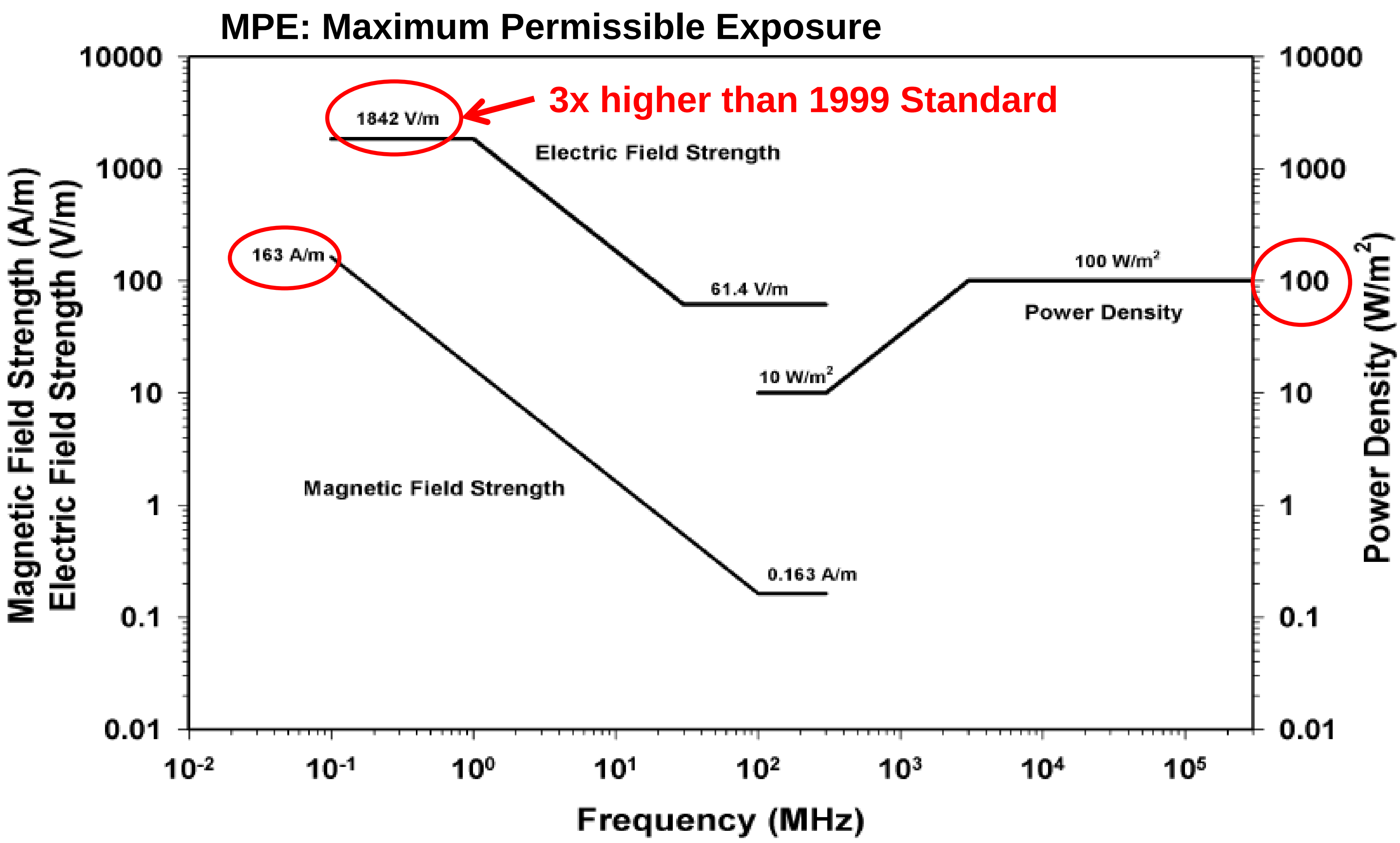
IEEE Std C95.1 – 1999

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

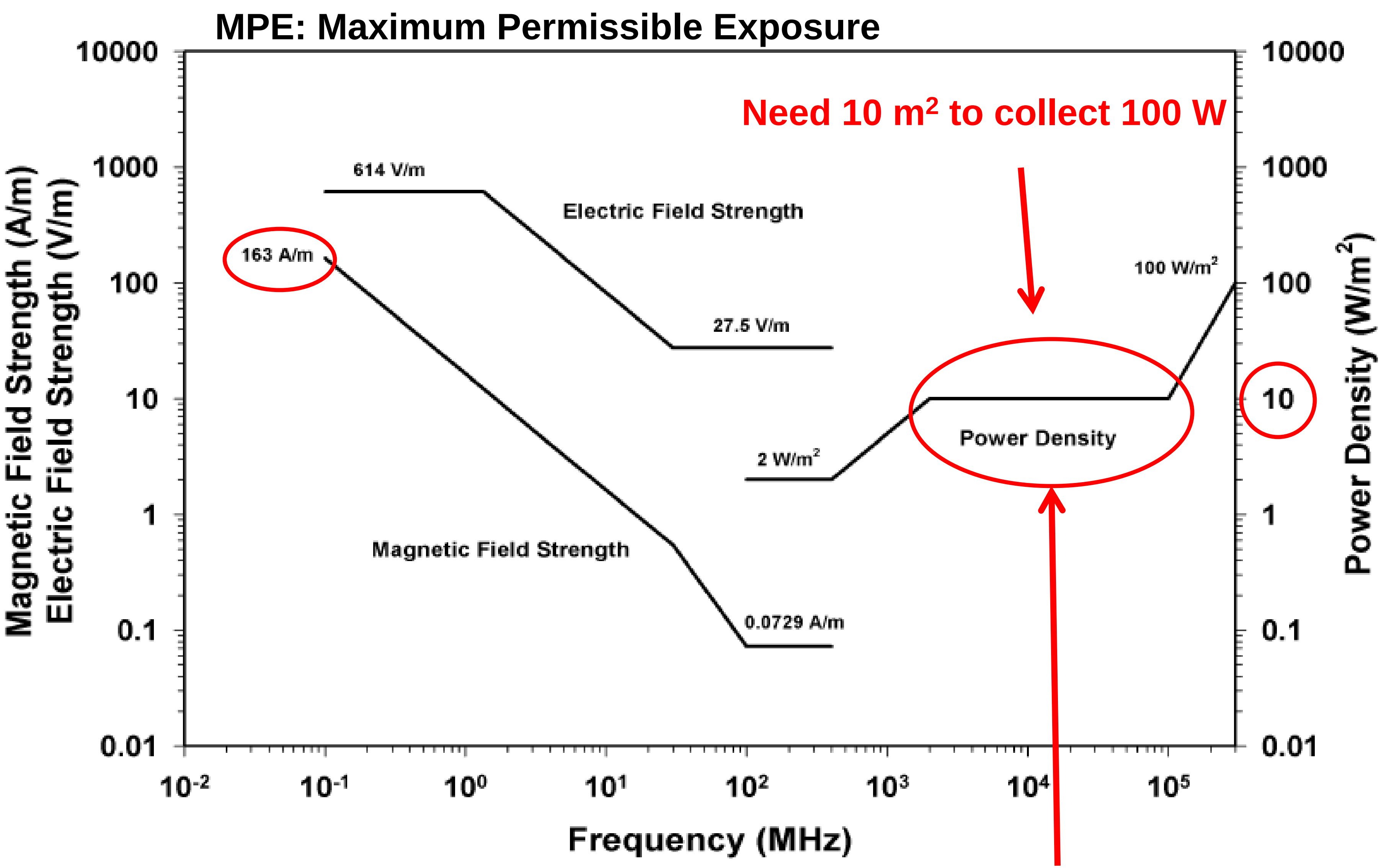


- **Transmitted power density is limited by safety standard.**
- **Magnetic field at low frequency has higher equivalent plane wave power density**

RF Safety – 2005, Controlled



RF Safety – 2005, General Public



10x more stringent than 1999 Standard

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 efficiency and safety limit.
  - Near-field WPT is a better choice.
  - Low-frequency magnetic field can be used to allow higher equivalent plane wave power density.

Problem with Portable Consumer Electronic Devices

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

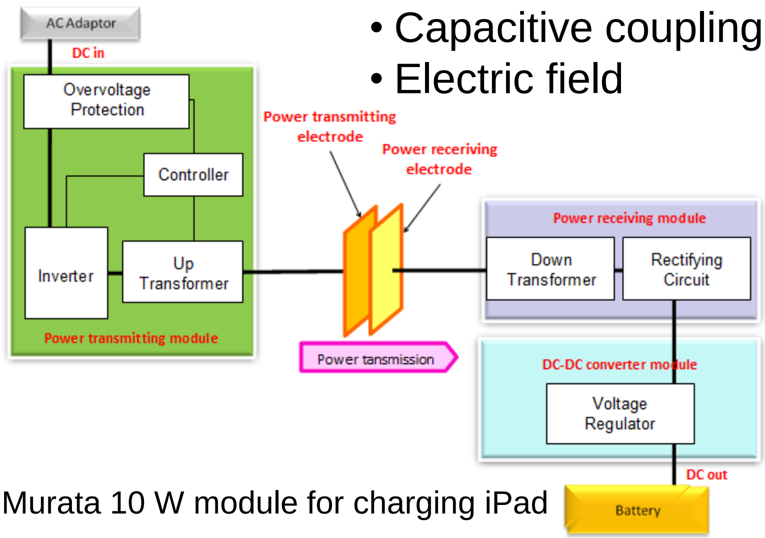
http://community.crutchfield.com/blogs/av_tips/archive/2008/07/22/monster-power-outlets-to-go-went-well.aspx

- **We have many power chargers for many electronic devices.**
- **Too many chargers and cables!**
- **A traveler knows the pain of carrying all these chargers.**
- **Standardized USB charging connector is a solution but there are still proprietary connectors/chargers.**
- **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**

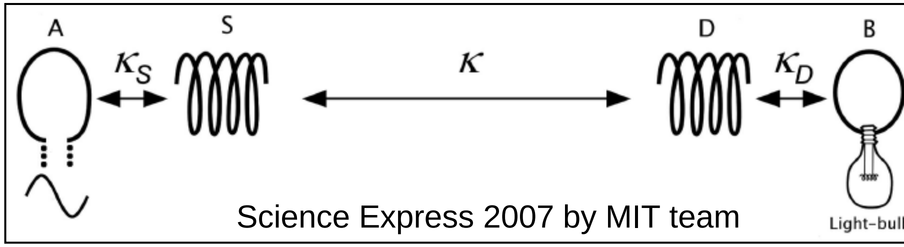
Types of Near-Field Wireless Power



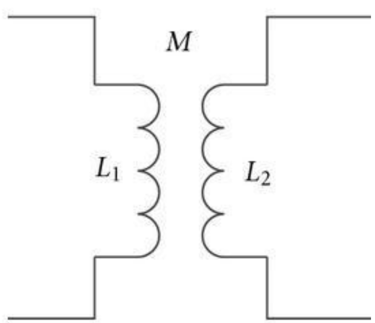
- Capacitive coupling
- Electric field

Murata 10 W module for charging iPad

- Magnetic resonance
- Magnetic field
- Four coils



Science Express 2007 by MIT team



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

The following examples focus on inductive coupling.

Inductive Coupling

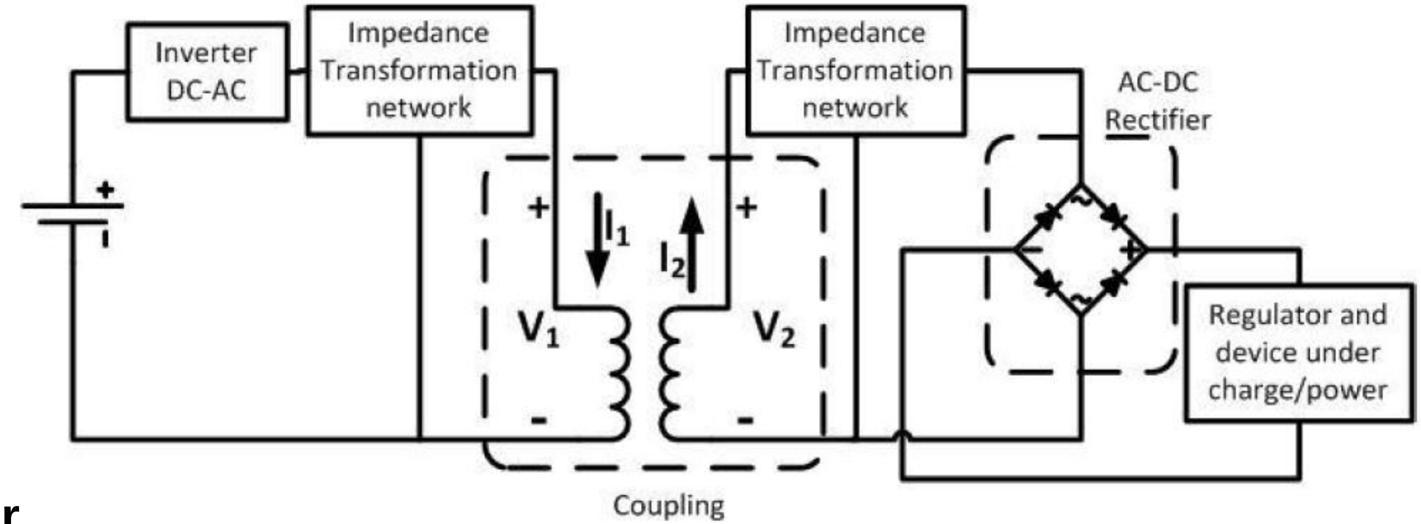
- Inductive coupling to transfer power has been around for quite many years. Rechargeable electric toothbrush is an example.
- So what's the challenge?
- It uses spilt ferrite core to achieve strong coupling
- It requires careful alignment
- It is low power and has slow charging rate
- To have higher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

Electric toothbrush

Flexibility of Wireless Power

[Video]

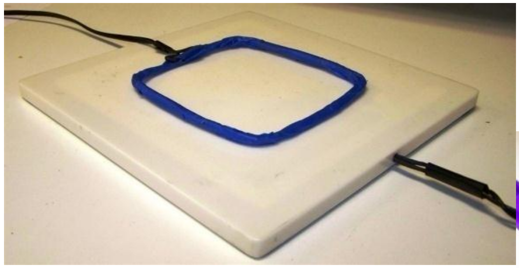
Near-Field WPT System Diagram

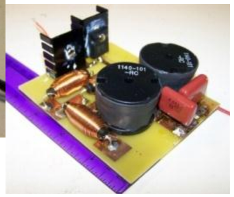


- **<u>Inverter</u>**
  - Convert DC power to AC power
  - Need to have high efficiency
  - Switch-mode preferred, e.g., class D or class E
- **<u>Impedance transformation network and loosely-coupled inductive coils</u>**
  - Transform load impedance to a range the inverter can handle
  - Ensure correct 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

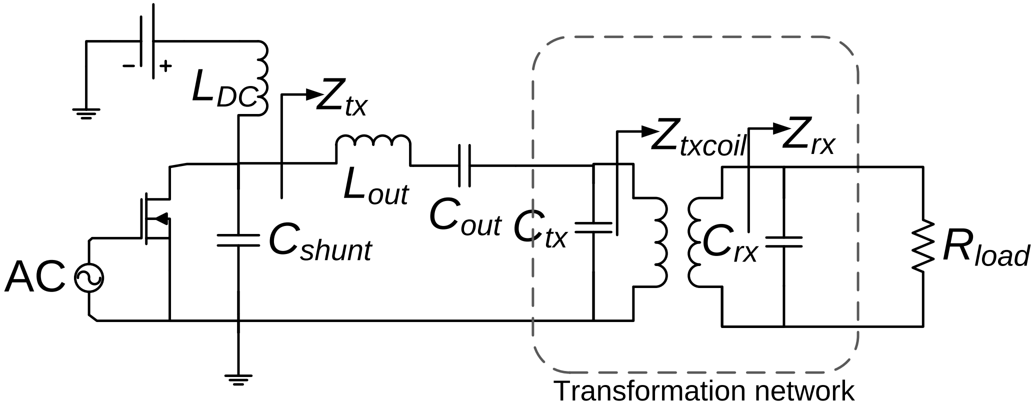
Near-Field WPT – Loosely Coupled

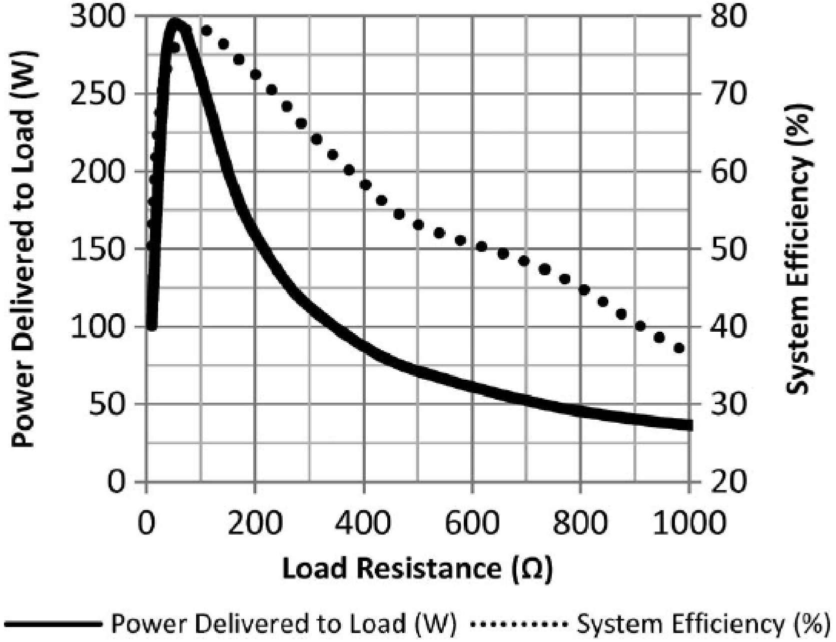
- High power (295W) delivery with high end-to-end system efficiency (>75%)
- Class-E transmitter operating @ 134kHz
- Varying location of RX on TX → Power delivery variation 5%
- Coupling coefficient ~ 0.37 (>0.25 to avoid TX heating)





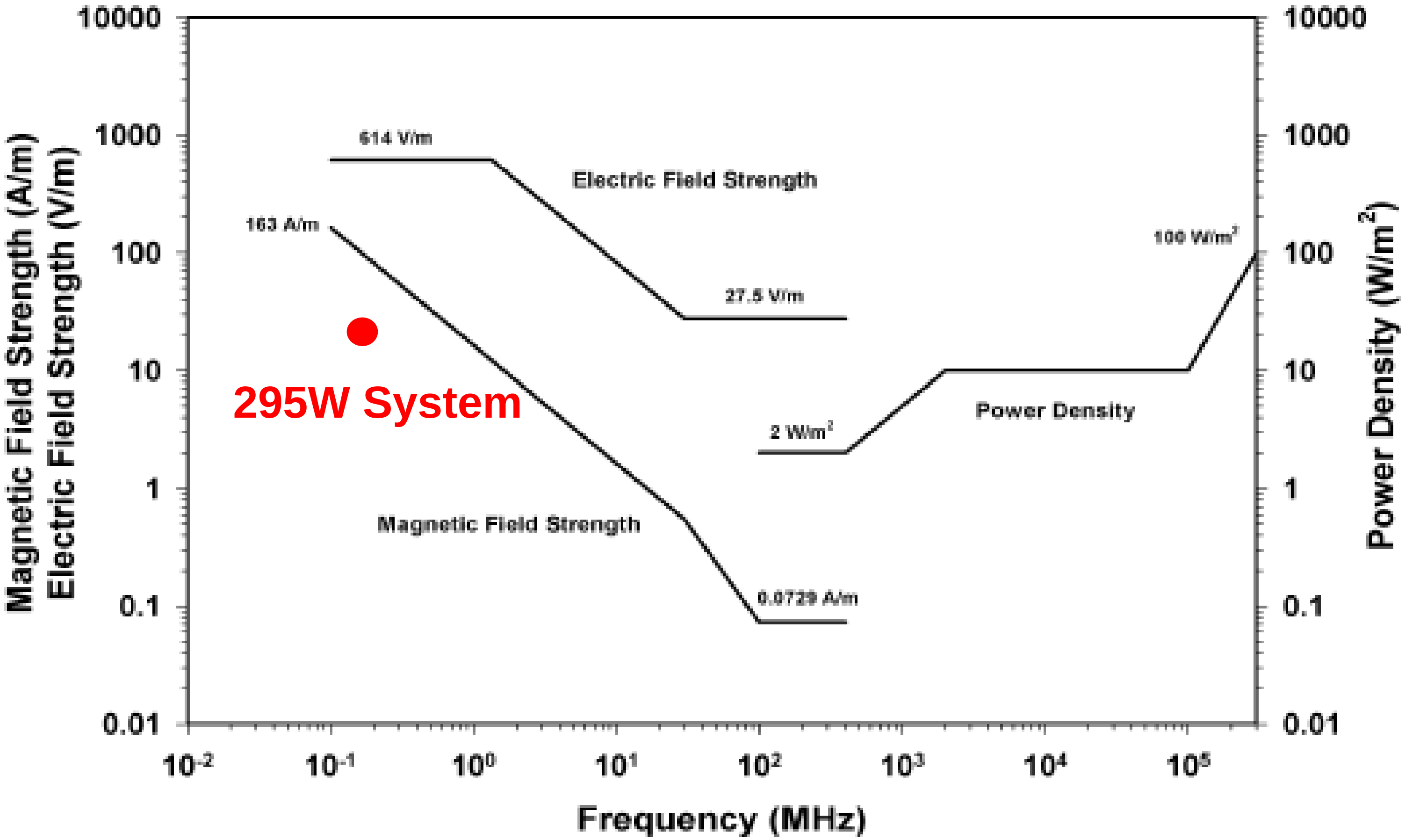
- TX coil 21cmx21cm
- RX coil 13cmx13cm
- Separation 1cm





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.

Safety Check



- **Maximum Permissible Exposure for magnetic field @134 kHz:**
- **121.64 A/m measured at 0.2 m from the field source**
- **Estimated system magnetic field strength at 0.2m above TX: 24 A/m**

- **Near-field H field from magnetic dipole** $\propto \dfrac{1}{r^3}$ **Much faster than in far-field**

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

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

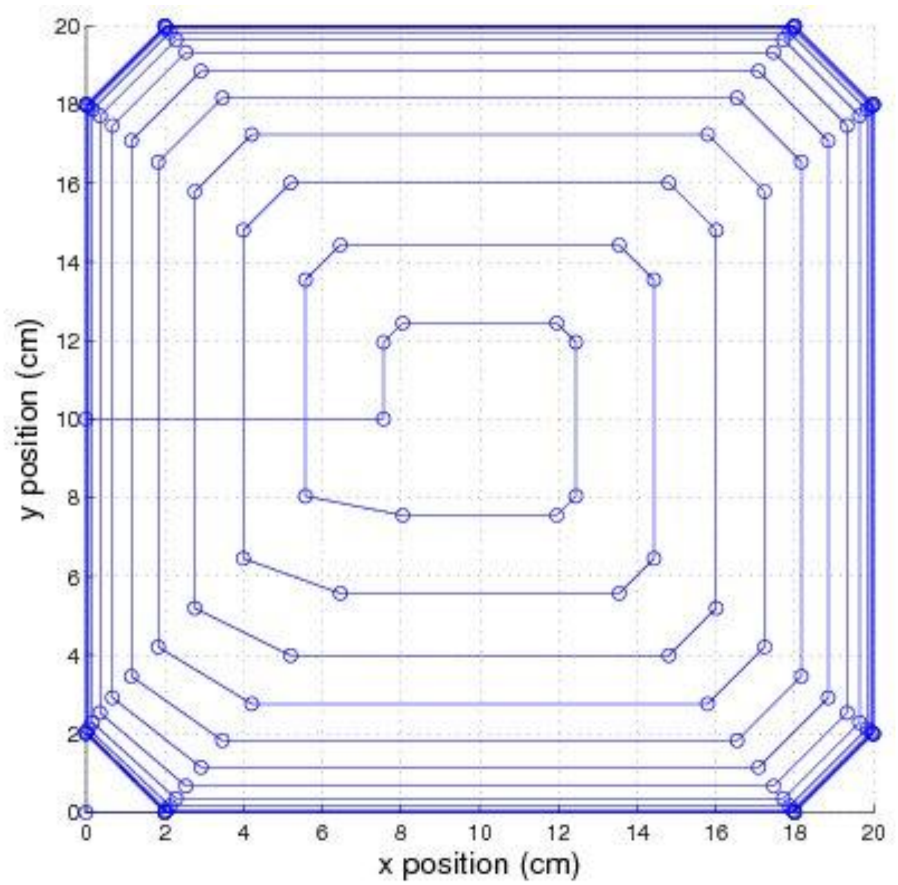
$$P_{out-ClassD} = \frac{2}{\pi^2}\frac{V_{CC}^2}{R} = 0.2026\left(\frac{V_{CC}^2}{R}\right)$$

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

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.

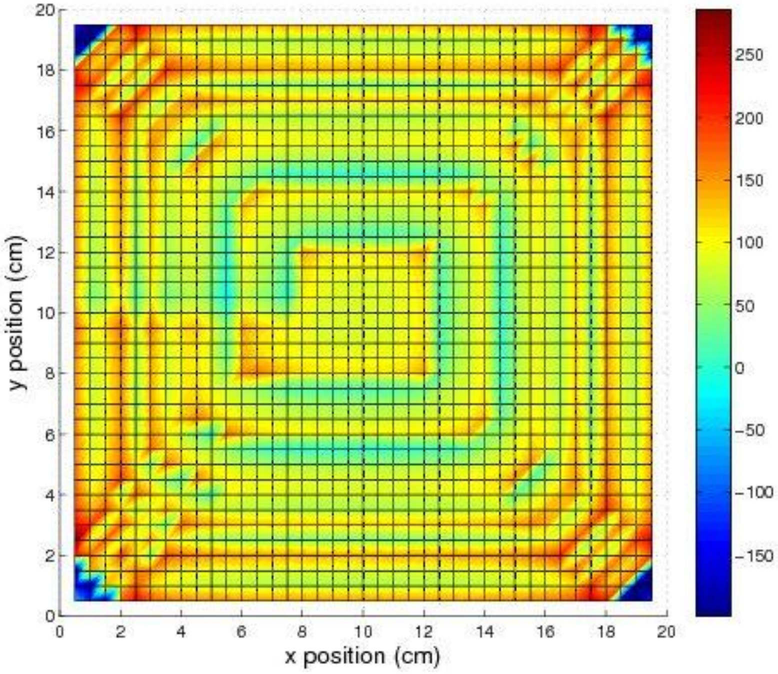
$$f = (1 - (N - n - 1) / N)^k$$



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.

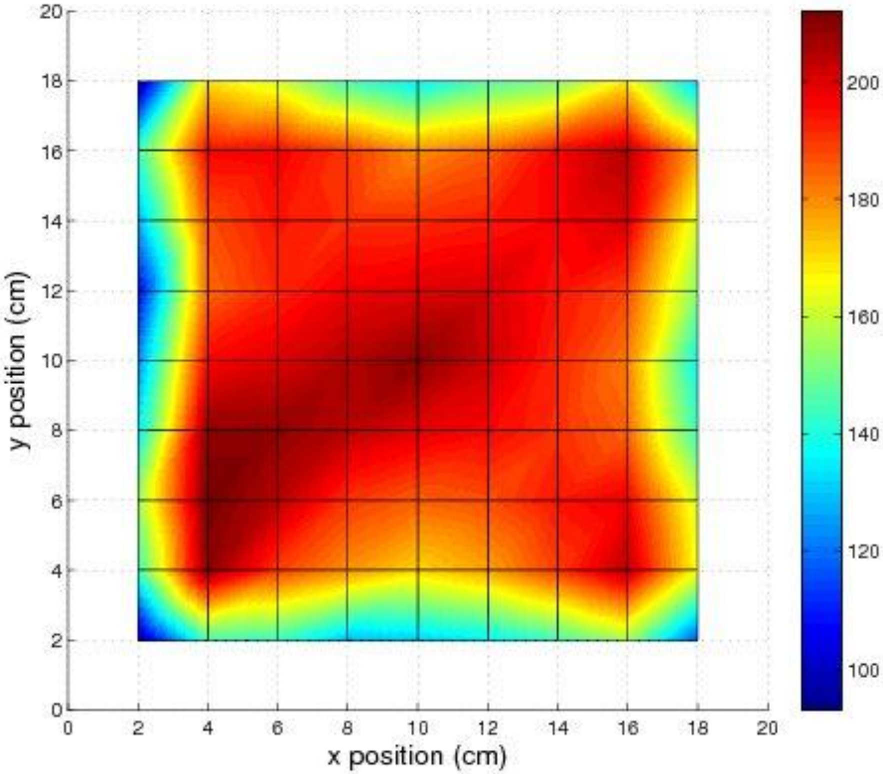
Magnetic Field Distribution

Calculation (Magnetic Quasi-Static)



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

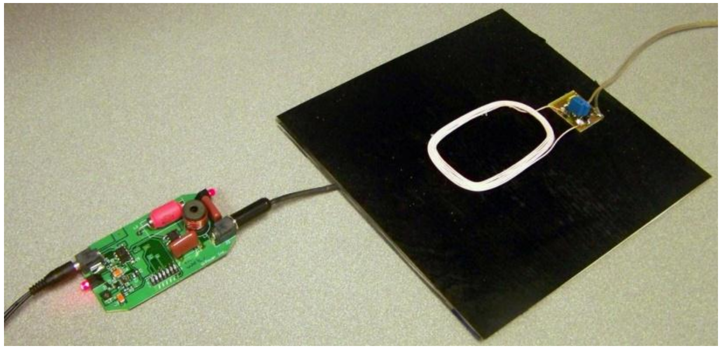
Measurement



Voltage (mV) on the field probe

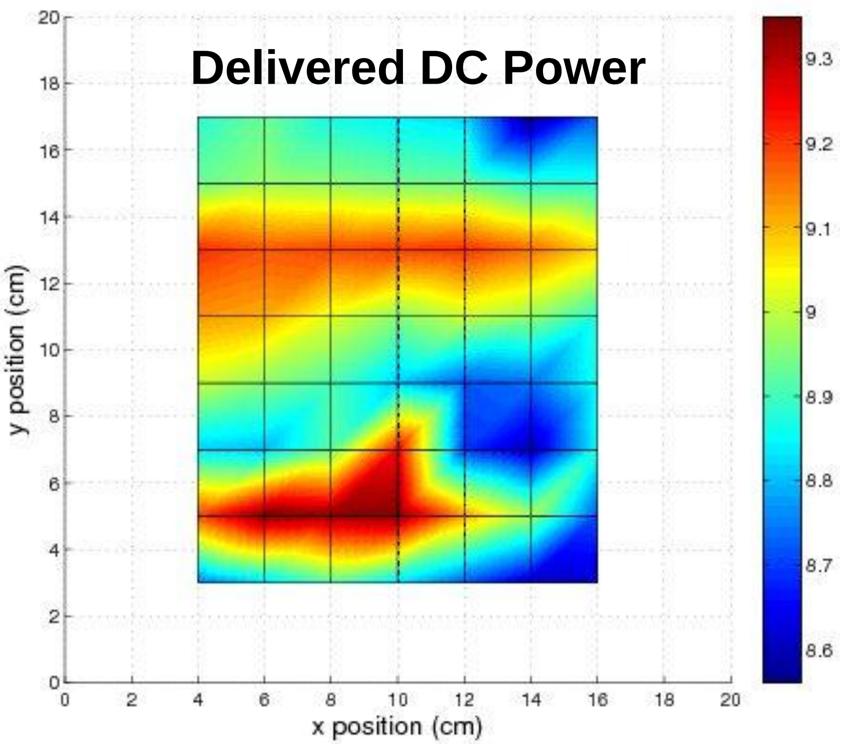
10 W System with 80% Efficiency

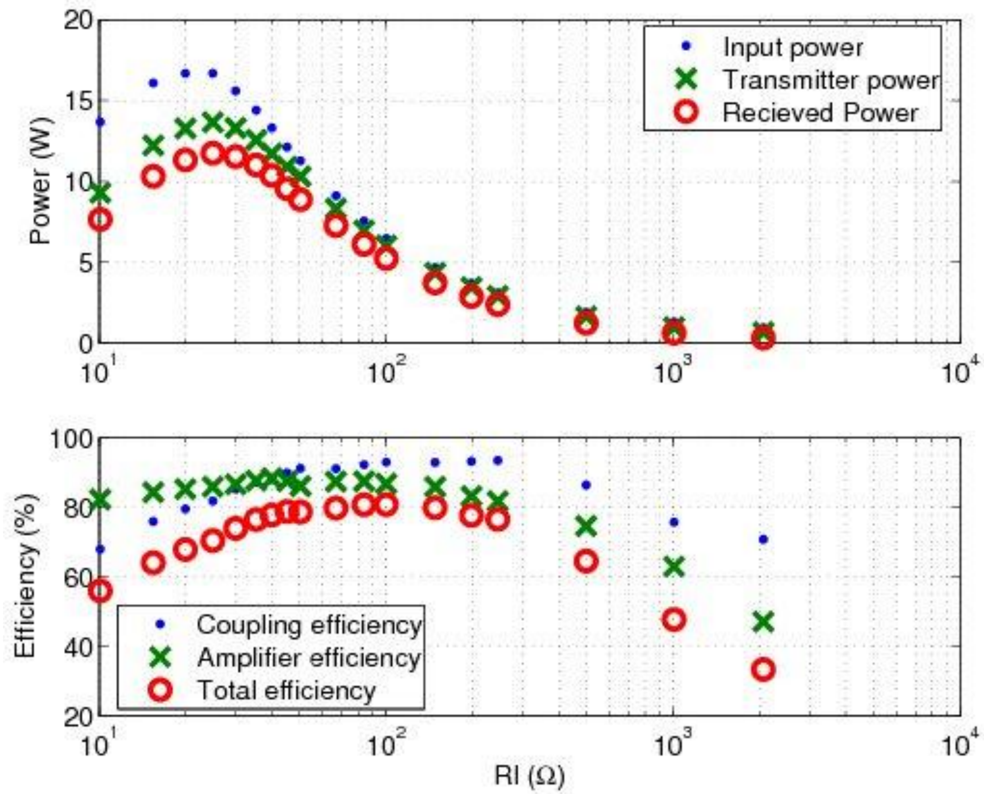
- Transmitter 20 cm x 20 cm, 13 turns, k = 3.0, Δ = 0.1
- Receiver 6 cm x 8 cm, 6 turns
- 100 strand/40 AWG Litz wire for both coils
- Operating frequency 240 kHz, Vcc 12 V
- Measure field strength with field probe
- Fixed load resistance, sweep receiver position over transmitter
- Fixed location, sweep load resistance from 10 Ω to 2000 Ω
- Measure input, transmitted, and received power



Measurement Result

- Peak delivered DC power = 11.8 W
- Peak coupling efficiency = 88.4%. Peak total DC-to-DC efficiency = 80.9%
- Power delivery variation vs. location < 10%





J. Casanova, Z. N. Low, J. Lin, "Design and Optimization of a Class-E Amplifier for a Loosely Coupled Planar Wireless Power System," *IEEE Transactions on Circuits and Systems II*, Vol. 56, No. 11, pp. 830-834, Nov. 2009

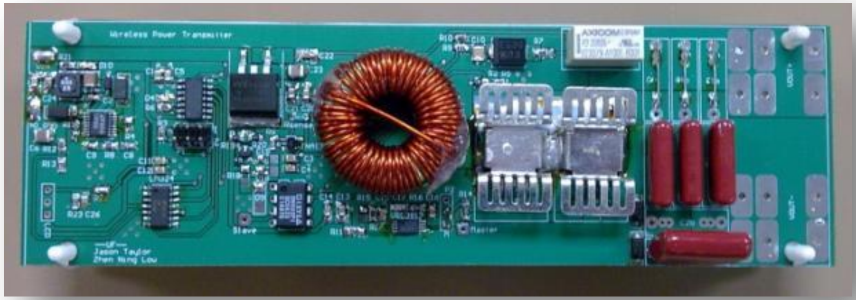
Wireless Laptop Charging Station

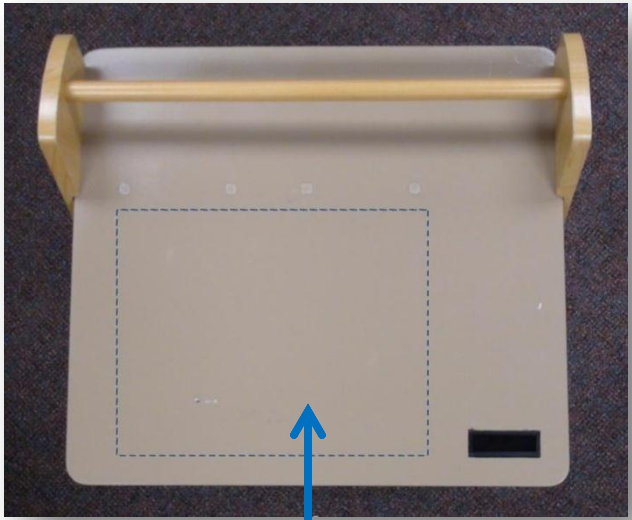
- Dell Vostro 1310 laptop was used in demonstration.
- Battery was removed from the laptop → Power is supplied solely from the wireless power receiver.
- Battery charging circuit is no longer active and the total power required by the laptop is about 32 W.
- Original 19.5 V laptop power supply is used to power the wireless power transmitter → The wireless power system is "transparent" to the laptop.
- A 2x16 LCD was added to display the operating status of the system (load detection).

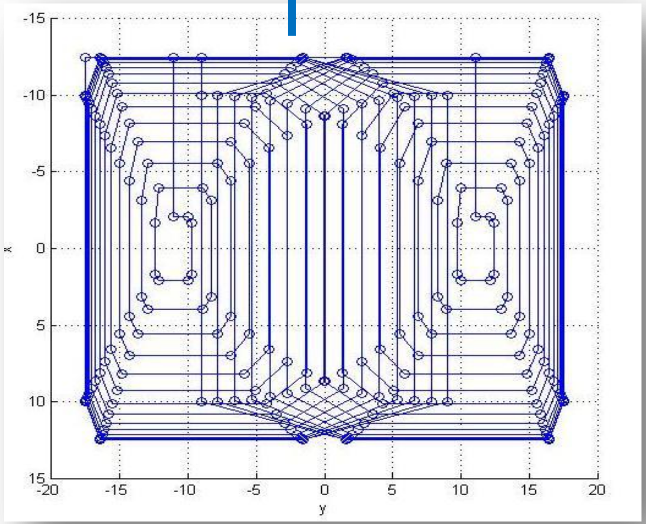
J. A. Taylor, Z. N. Low, J. J. Casanova, J. Lin, "A Wireless Power Station for Laptop Computers," ***Proceedings of IEEE Radio and Wireless Symposium*****, pp. 625-628, January 2010**

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

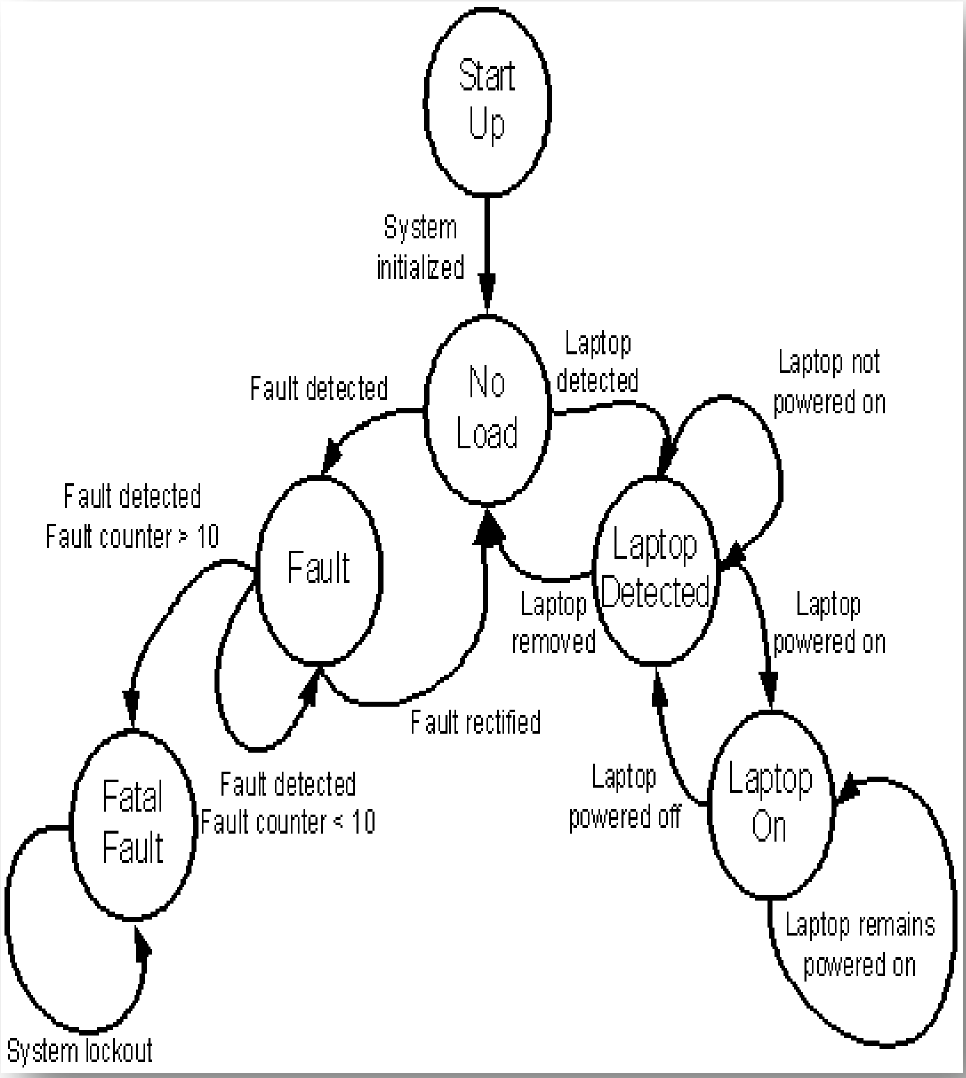
Low-power control circuit

Receiver Design

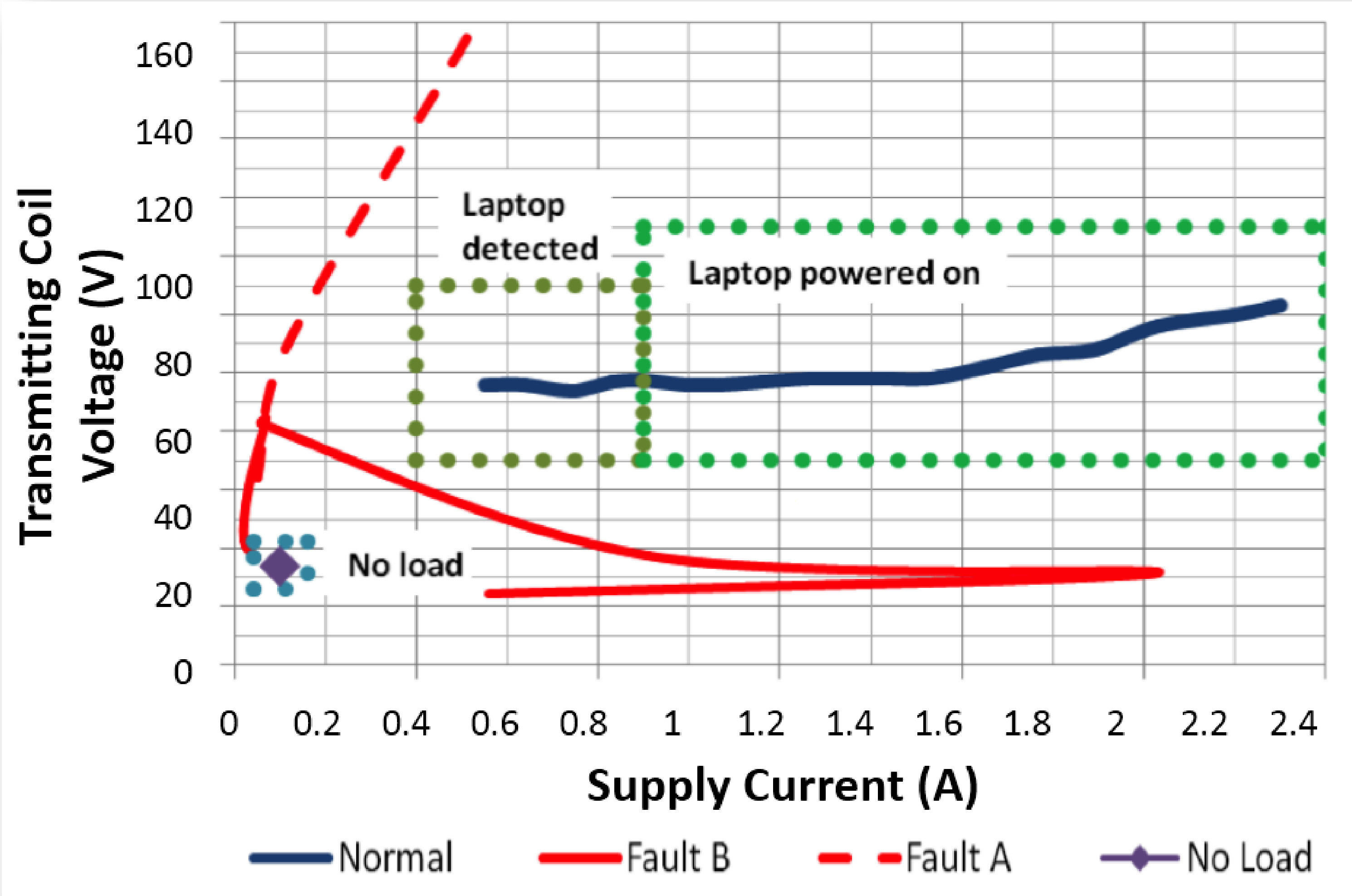
- RX coil size: 20 cm x 12 cm, embedded into a polycarbonate plastic sheet and fastened to the bottom of the laptop
- RX electronics are attached to the back.
- The laptop contains a significant amount of metal so the receiving coil needs to be shielded → ferrite tiles are placed in a ring along the RX coil.
- RX coil is smaller than the TX coil which enables ±5 cm placement tolerance in either x or y direction.
- Received AC power is rectified by a full wave rectifier and regulated by a Linear Technology LTC3810 regulator.

Software Control and Load Detection

- The system starts up in the no load state after initialization.
- Depending on the supply current and coil voltage values captured by the A/D converter, the system falls into various states.
- To reduce no load power consumption, the system enters into an extremely low duty cycle state shutting down the system most of the time and only probes the system once every two seconds.
- For simplicity, the fault state is only considered if a piece of metallic or magnetic material of significant size is placed in the vicinity of the transmitting coil.



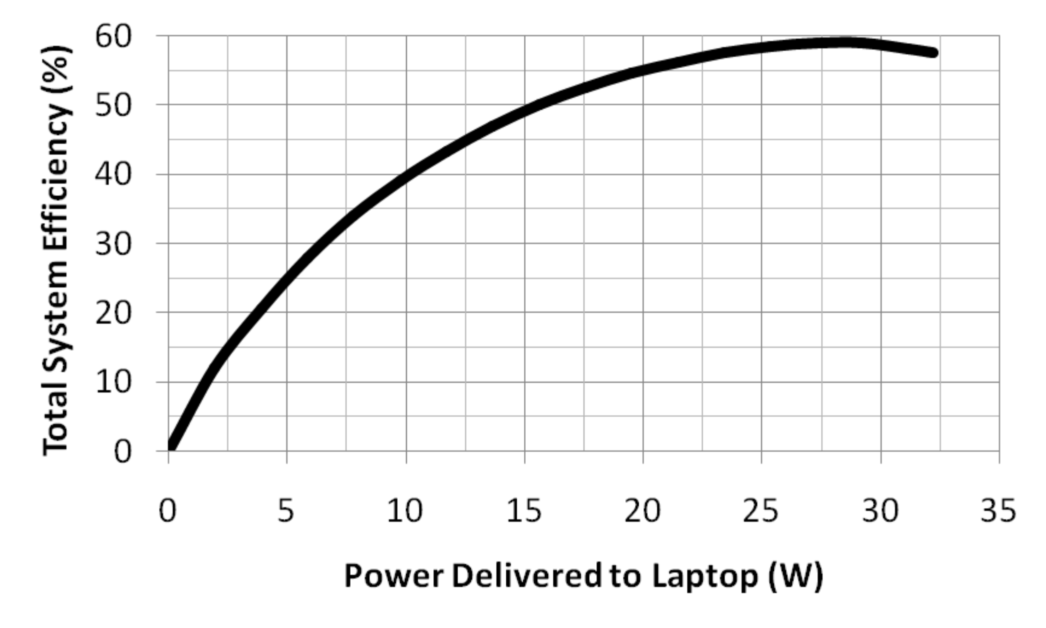
Load Detection



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," published online, *IEEE Transactions on Industrial Electronics*, 2009

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

Commercialization of Wireless Power

- Currently there are two major alliances for near-field wireless power
  - Wireless Power Consortium (older): 137 companies.
  - Alliance for Wireless Power (A4WP)(newer and growing): Qualcomm, Samsung, Broadcom, NXP, SanDisk, Powermat, SK Telecom, …
- A standard like IEEE 802.11 (WiFi) is needed.
  - Compatibility
  - Wireless communications interface for authentication of wireless power transfer
- Technical challenge: EMI/EMC issue

Conclusions

- Far-field wireless power transmission
  - Long distance
  - Safety concern
  - Lower efficiency
  - Space/military, ultra low power devices and sensor network, energy harvesting
- Near-field wireless power transmission
  - Short distance
  - Less safety concern
  - Higher efficiency
  - Consumer applications

Thank you for your attention!