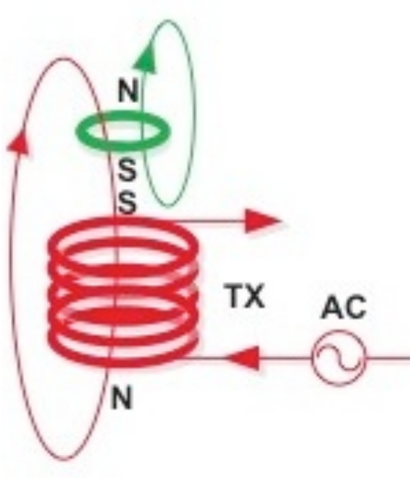
Examining Wireless Power Transfer

John Rice

Agenda

- **Introduction** **5 min.**
  - Foundational principles of electromagnetics
  - Power transfer - near and far field
- **Existing and Emerging Wireless Power Standards** **5 min.**
  - WPC, PMA, A4WP comparison
  - Electromagnetic field safety implications of WPT
- **Theory of Operation** **20 min.**
  - Considering loosely coupled coils
  - Modeling resonant power transfer
  - Magnetic link efficiency
  - Topological analysis with SPICE and FEA
- **Design Considerations** **20 min.**
  - RX to TX communication
  - Intelligent voltage positioning and load response
  - EMI, efficiency/loss measurement
  - Foreign object detection – eddy loss detection
  - Single coil, 5 W WPC design example

Notable Dates in Wireless Power Transfer



- **1820:** Biot–Savart **/** André-Marie Ampère / H. Oersted discover and quantify relationship between electric current and magnetic fields
- **1831**: Michael Faraday / H. Hertz discover electromagnetic induction
- **1834:** Lenz (Lenz's law) → N. Callan invents the electrical transformer
- **1864:** James Clerk Maxwell synthesizes previous observations and mathematically models electromagnetic radiation
- **1891-1917:** Nicola Tesla – enormous contribution to the practical application of resonant power transfer and electromagnetic induction; numerous discoveries and patents

↓

- **2007:** WiTricity research group, led by Professor Marin Soljacic advances magnetic resonance to wirelessly power a 60 W light bulb with 40% efficiency at 2 m using 60 cm-diameter coils

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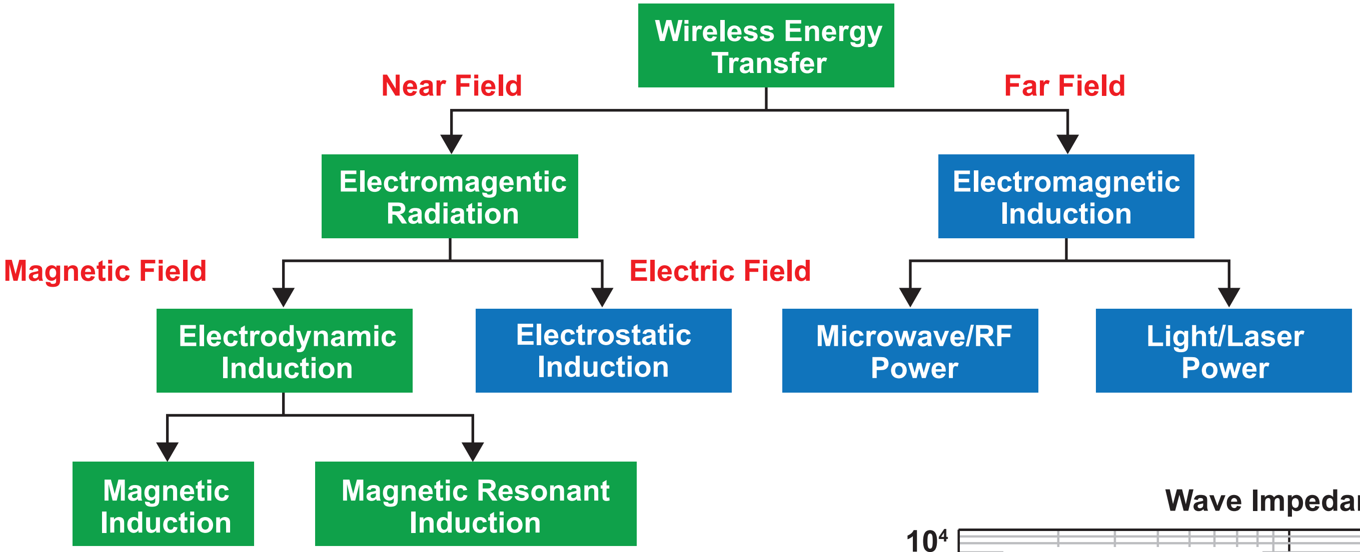
- **2008/9:** A consortium of companies called the Wireless Power Consortium (WPC) announces the evolution of a industry standard for low-power (5 W) inductive charging

Electromagnetic Wave Propagation


Wireless Energy Transfer

Near Field

Far Field

Electromagnetic Radiation

Electromagnetic Induction

Magnetic Field

Electric Field

Electrodynamic Induction

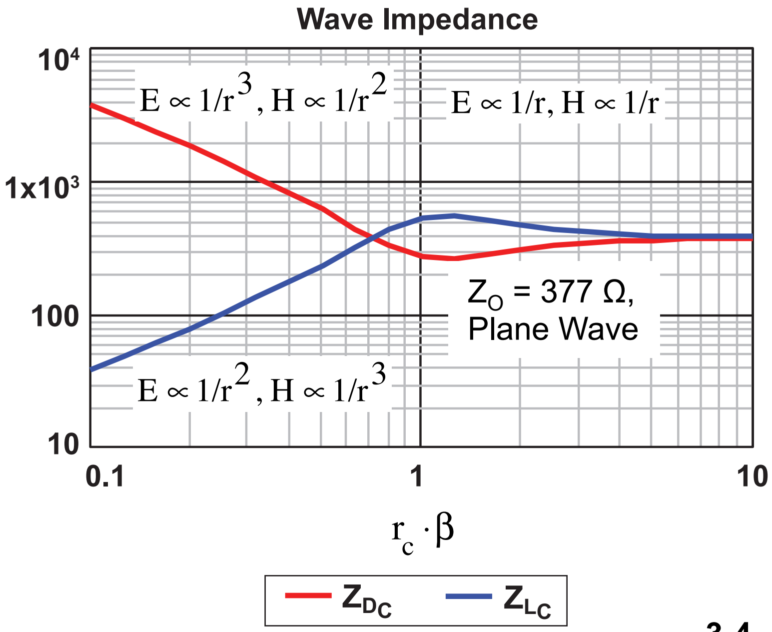
Electrostatic Induction

Microwave/RF Power

Light/Laser Power

Magnetic Induction

Magnetic Resonant Induction



- Field defined by antenna and distance from source
- Dipole(red) and loop(blue) antennas shown
- Wave impedance = E/H, converges at $\lambda >> 1$
- Reactive near field below $\lambda/2\pi$ is non-radiative

Race for a Wireless Charging Standard

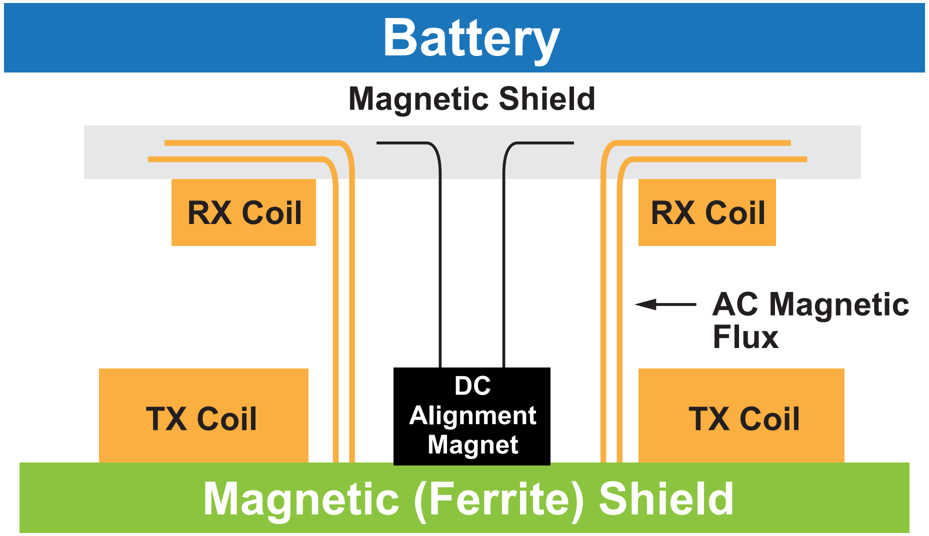
Safety, Performance, Reliability and Interoperability

WIRELESS POWER CONSORTIUM

Power Matters Alliance

rezence

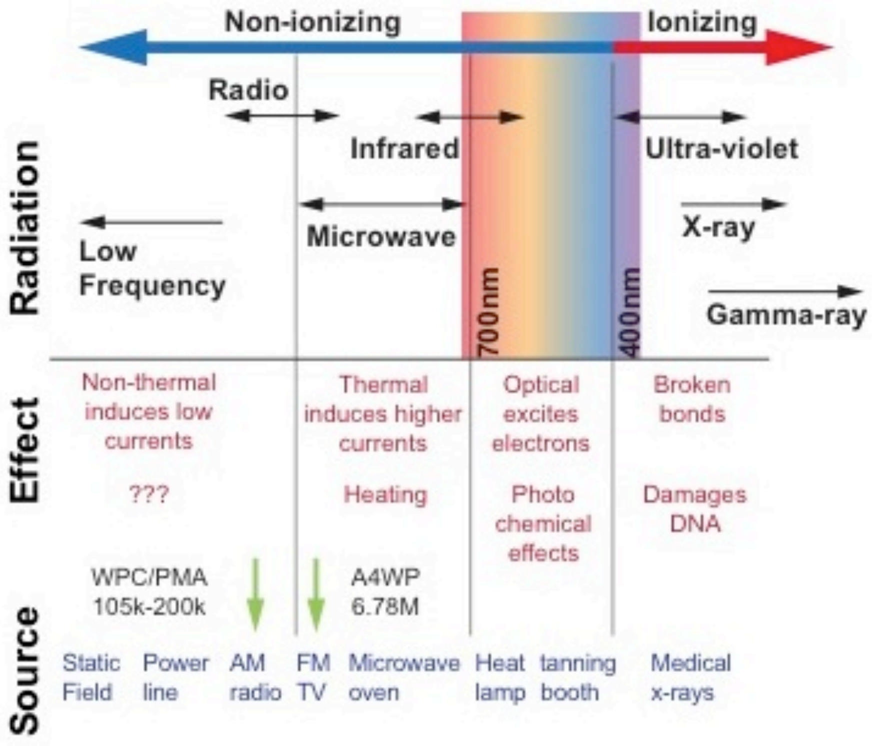
Alliance for Wireless Power



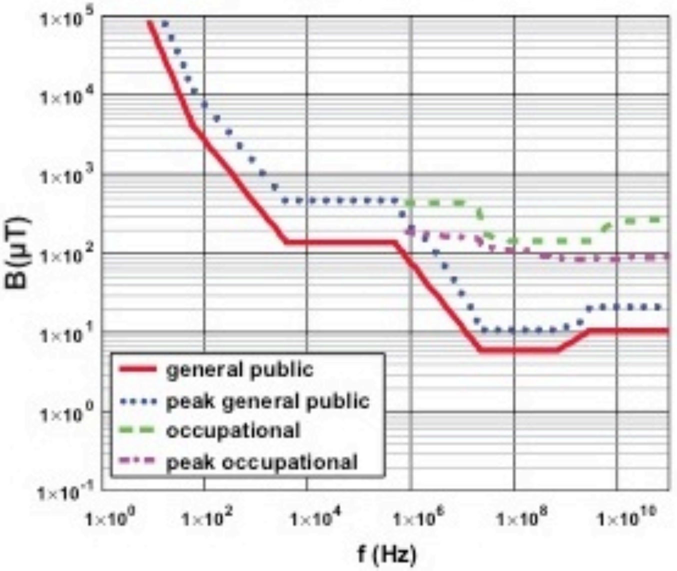
Protocols	Power Frequency Band	Communication Frequency Band	Range of Coupling
Wireless Power Consortium (WPC)	105-205 kHz	Same as power transfer band	0.4 to 0.7
Powermat (PMA)	277-357 kHz	Same as power transfer band	0.6 to 0.8
Alliance for Wireless Power (A4WP)	6.78 MHz	2.4GHz ISM (ZigBee or BLE)	0.1 to 0.5

Safety Considerations
Electromagnetic Radiation Effect

Electromagnetic Spectrum



International Commission on Non-Ionizing Radiation Protection (ICNRP) Magnetic Flux Limit



Frequency Range	E-field (V/m)	H-field (A/m)	B-field (μT)
0.025-0.8 kHz	250/f	4/f	5000/f
0.15-1 MHz	87	0.73/f	0.92/f
1-10 MHz	87/f^0.5	0.73/f	0.92/f

Theory of Operation

$$\oint E \bullet dA = \frac{\Sigma Q}{\varepsilon_0}$$

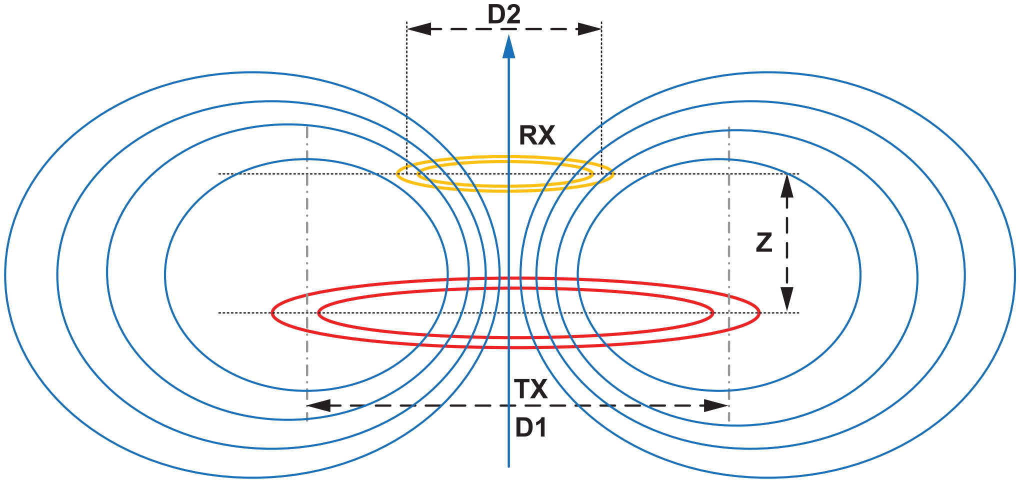
$$\oint B \bullet dA = 0$$

$$\oint E \bullet dl = -\frac{d}{dt}\oint_S B \bullet dA$$

$$\oint B \bullet dl = \mu_0 Ienc + \mu_0 \varepsilon_0 \frac{d\varphi_E}{dt}$$

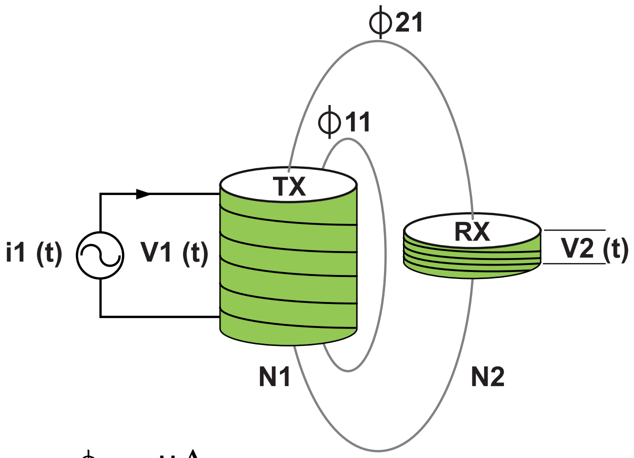
$$\mu_0 = Vacuum\_permeability$$

$$\varepsilon_0 = Vacuum\_permittivity$$



Loosely Coupled Coils
Self and Mutual Inductance

Physical representaion of flux coupling



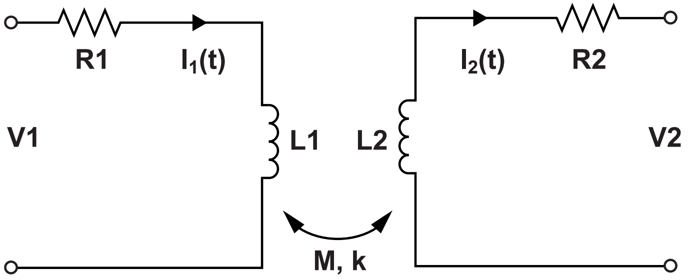
$$P = \frac{\phi}{Ni} = \frac{\mu A}{l}, \phi = PNi$$

$$V_c = N\frac{d\phi}{dt} = N\frac{d(PNi)}{dt} = N^2\frac{\mu A}{l}\frac{di}{dt} = L\frac{di}{dt}$$

$$L = \frac{N\phi}{i}, \phi_1 = \phi_{11} + \phi_{21}$$

$$V_2 = N_2 N_1 P_{21}\frac{di_1}{dt} \rightarrow M = N_2 N_1 P_{21}$$

Electrical representation of flux coupling

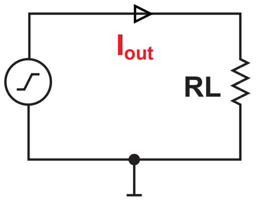


$$V_1(t) = R_1 i_1(t) + L_1\frac{di_1(t)}{dt} + / - M\frac{di_2(t)}{dt}$$

$$V_2(t) = R_2 i_2(t) + L_2\frac{di_2(t)}{dt} + / - M\frac{di_1(t)}{dt}$$

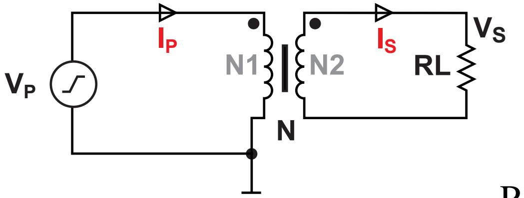
Power Transfer, Wired and Wireless

Wired/
Tightly
Coupled



$$P_{out} = \frac{V^2}{RL}$$

Ideal Transformer k = 1

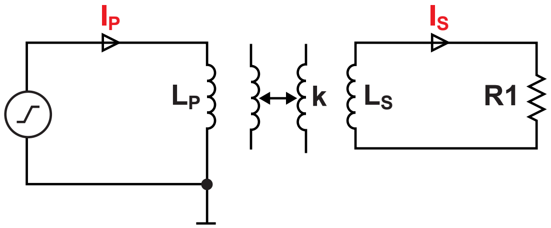


$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S}$$

$$P_{out} = \frac{{V_P}^2}{RL} \bullet \left[\frac{N_S}{N_P}\right]^2$$

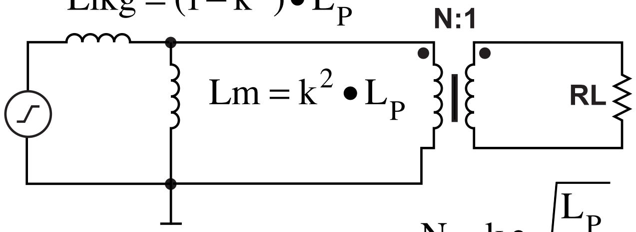
Loosely
Coupled
WPT

Non-Ideal Transformer k<<1



Cantilever Transformer Model

$$Llkg = (1 - k^2) \bullet L_P$$

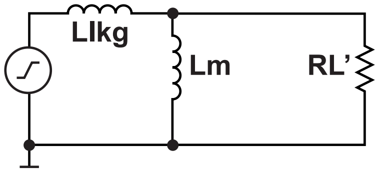


$$Lm = k^2 \bullet L_P$$

$$N = k \bullet \sqrt{\frac{L_P}{L_S}}$$

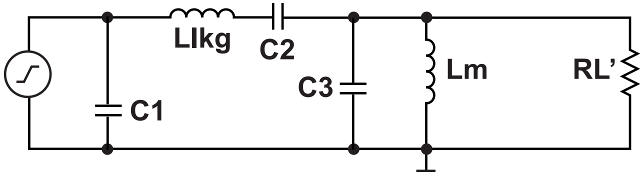
Load
Reflected
to Primary

Load Reflected to Primary is Propotional to k^2

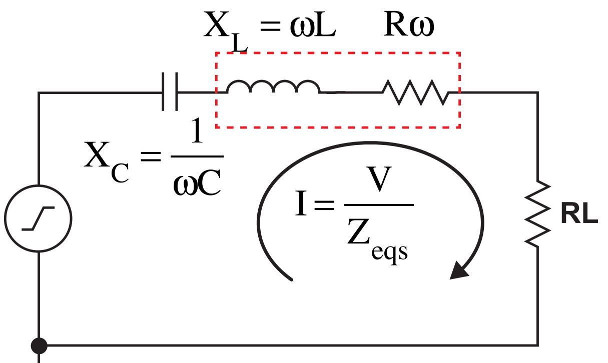


$$RL' = N^2 \bullet RL = RL \bullet k^2 \bullet \frac{L_P}{L_S}$$

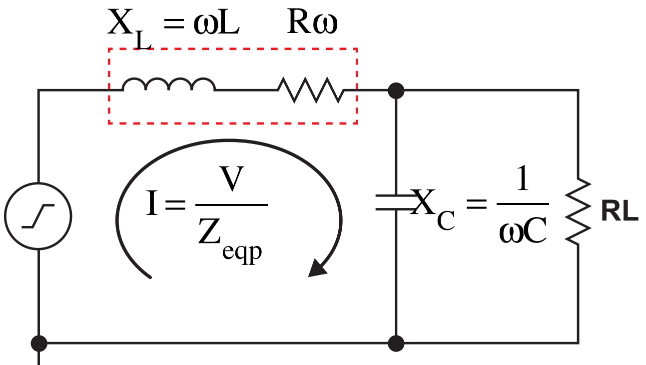
Leakage Impedance Cancelation



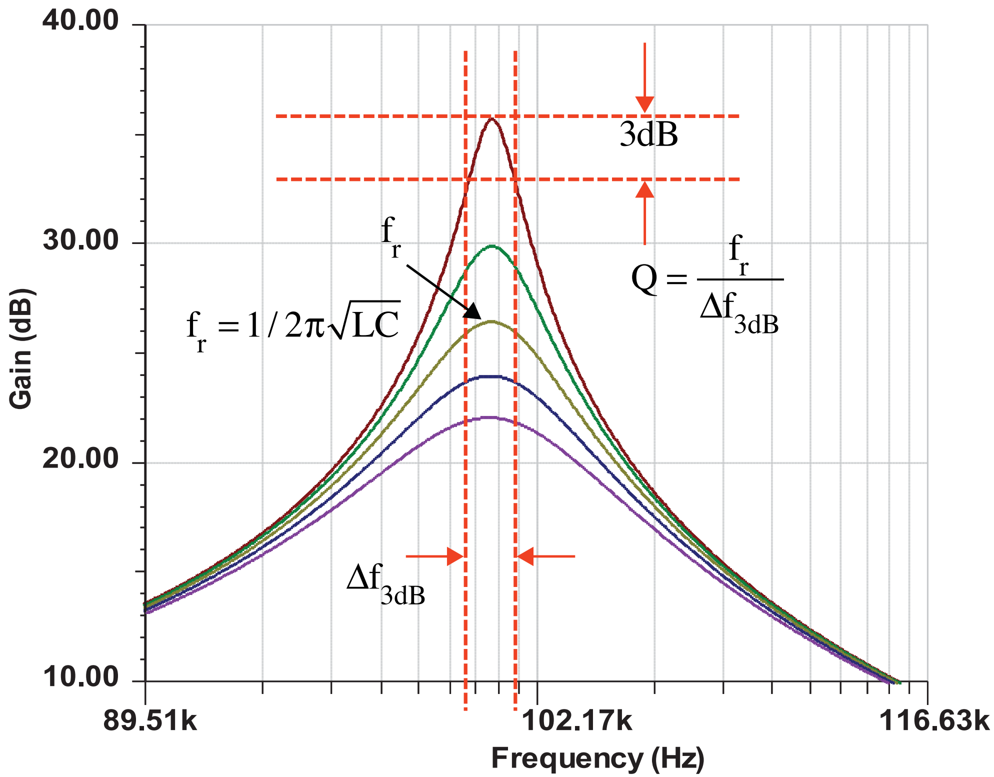
Considering Resonance



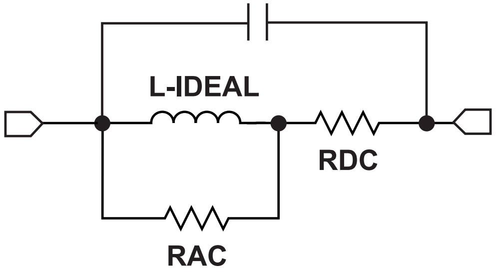
Series Resonant Tank



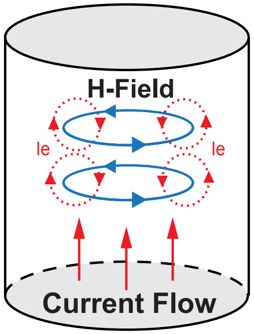
Parallel Resonant Tank



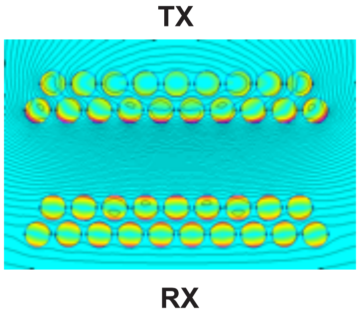
Coil Skin and Proximity Losses (Eddy Induced Losses)



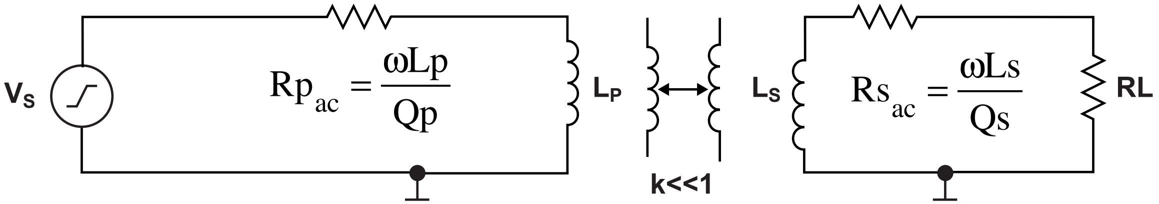
Non-Ideal TX/RX Inductor



Skin Effect

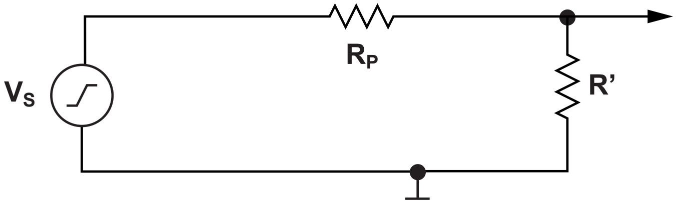


Proximity Effect



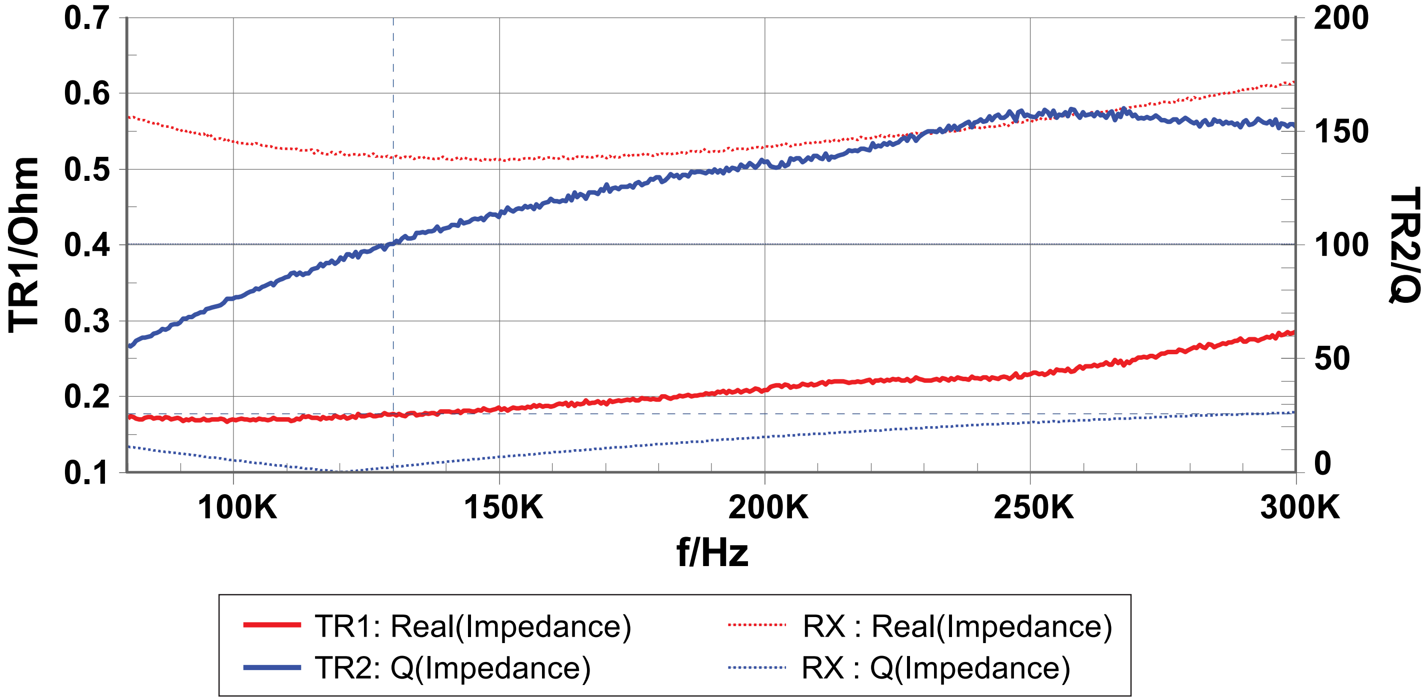
$$Rp_{ac} = \frac{\omega Lp}{Qp}$$

$$Rs_{ac} = \frac{\omega Ls}{Qs}$$



$$R' = k^2 \bullet \frac{Lp}{Ls}(Rs + RL)$$

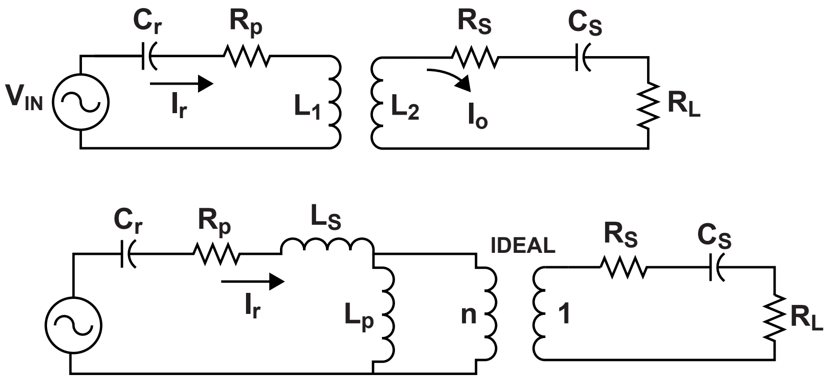
Typical WPC TX/RX Coil Q and Skin/Proximity Effect

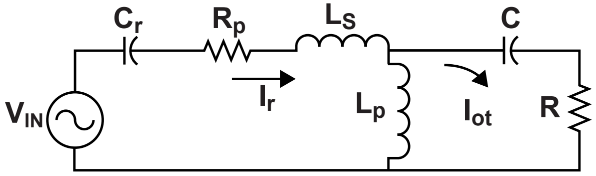


TX:
43 mm diameter with shield
Litz wire, 105 strand
20 turns, 2 layers
Q = 100 @ 130 kHz
R_{ac} = 176 mΩ

RX:
40 x 30 mm with shield
Litz wire, 2 strands
14 turns, 1 layer
Q = 2.3 @ 130 kHz
R_{ac} = 515 mΩ @ 130 kHz

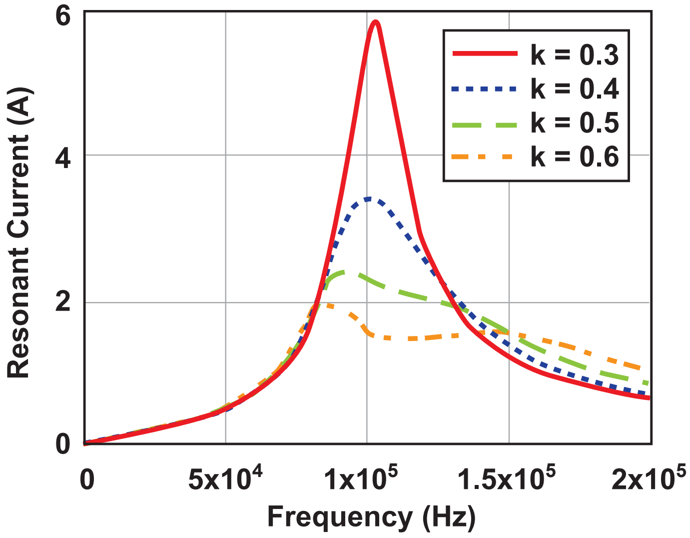
Primary Current vs. Frequency and Coupling Coefficient





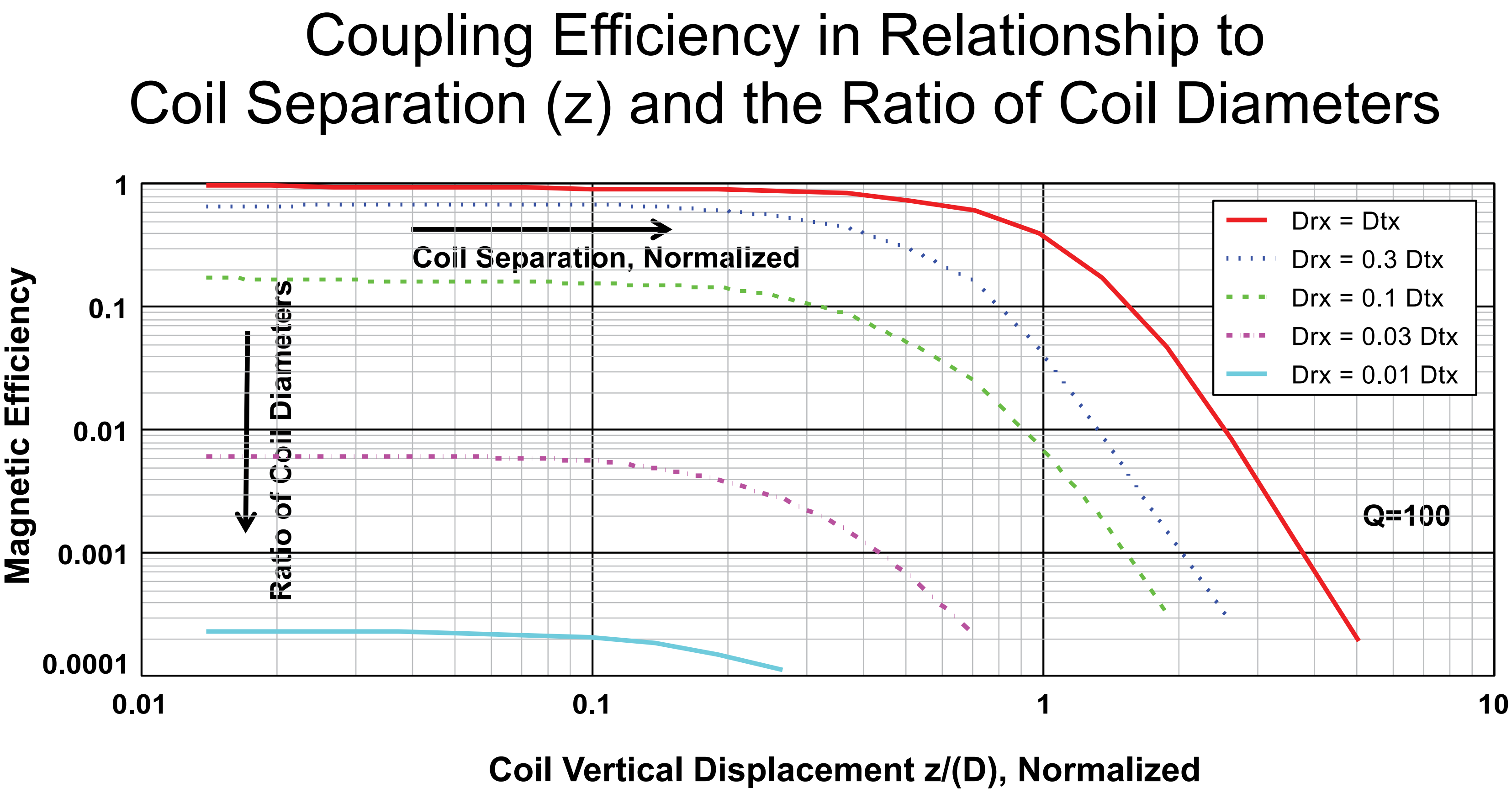
$$R(k) = (R_S + R_L) \times n(k)^2$$

$$ir(f,k) = \frac{V\text{fundamental}}{Z_{IN}(f,k)}$$



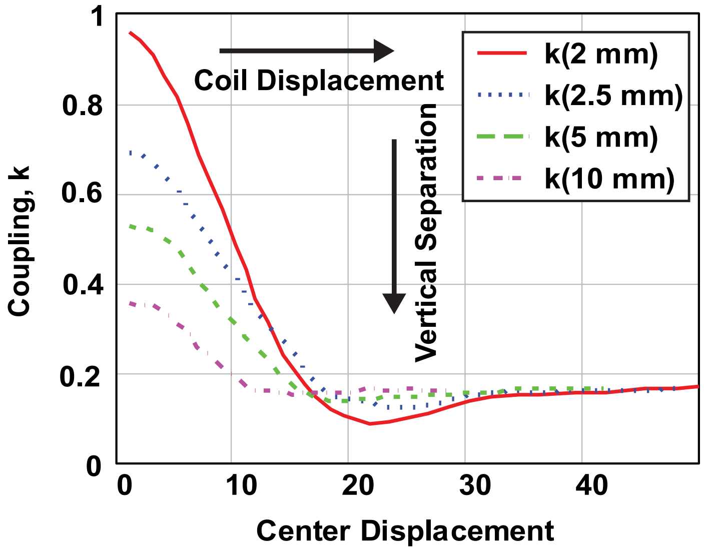
$$Z_{IN}(f,k) = R_P + R(k) \bullet \frac{Q_P(f,k)^2}{1+Q_P(f,k)^2} + j(XL_S(f,k) - XC_r(f) + R(k) \bullet \frac{Q_P(f,k)}{1+Q_P(f,k)^2})$$

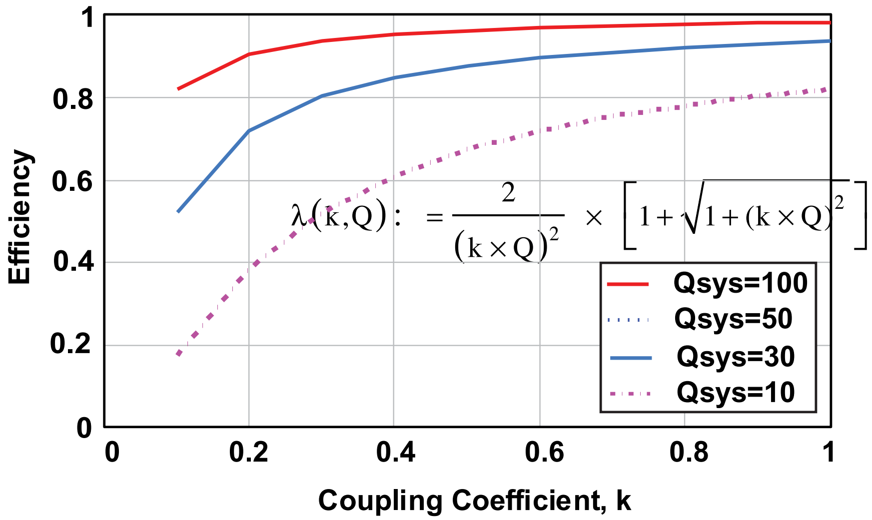
Coupling Efficiency



Magnetic Figure of Merit F(k,Q)

30 mm Planar Coils





$$\lambda(k,Q) := \frac{2}{(k \times Q)^2} \times \left[1 + \sqrt{1 + (k \times Q)^2}\right]$$

- Q = geometric mean of coil quality factors = $\sqrt{Q_p \times Q_s}$
- Q influenced strongly by skin and proximity effect

- High Q compensates for poor coupling
- High Q requires greater control bandwidth

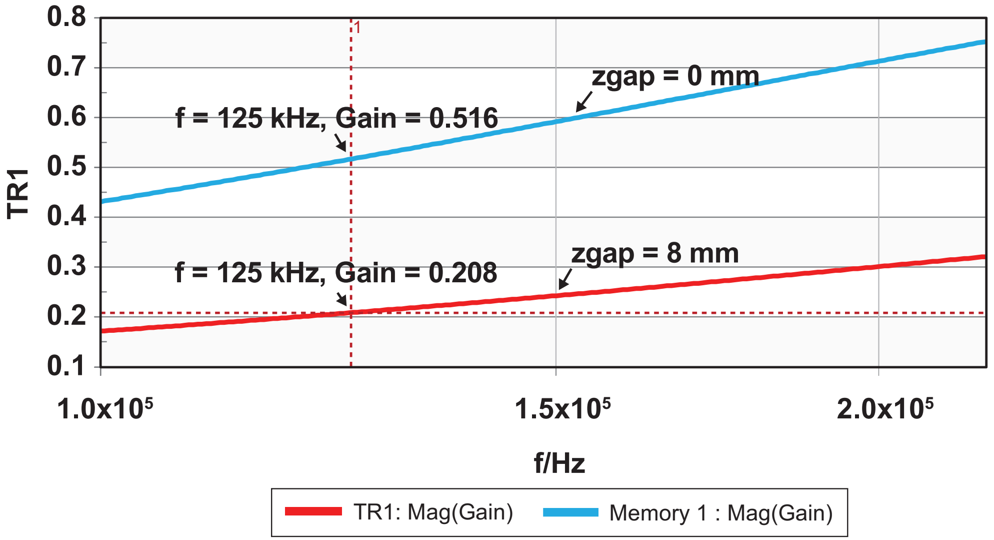
Coupling Coefficient and Mutual Inductance from Transfer Gain

$$k = \sqrt{\frac{\text{Lrx}}{\text{Ltx}}} \bullet \frac{\text{Vtx}}{\text{Vrx}} = \frac{\text{Gain}}{\sqrt{\frac{\text{Lrx}}{\text{Ltx}}}}$$

$\text{Lrx} = 10.8\ \mu\text{H}$

$\text{Ltx} = 25\ \mu\text{H}$

$$M = k \bullet \sqrt{\text{Lrx} \bullet \text{Ltx}}$$

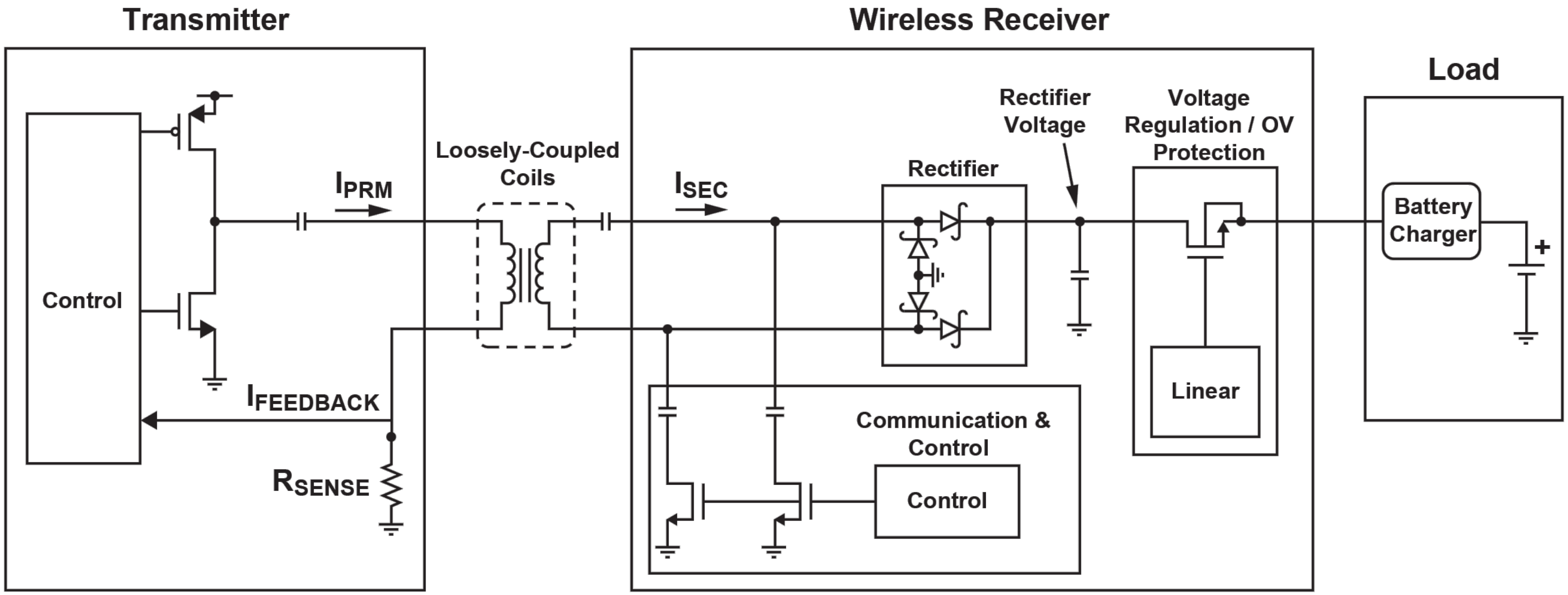


Typical 5 W coils
Connected to a VNA

$$k(\text{gap} = 0\ \text{mm}) = \frac{0.516}{\sqrt{\frac{\text{Lrx}}{\text{Ltx}}}} = 0.83,\ M = 13.6\mu$$

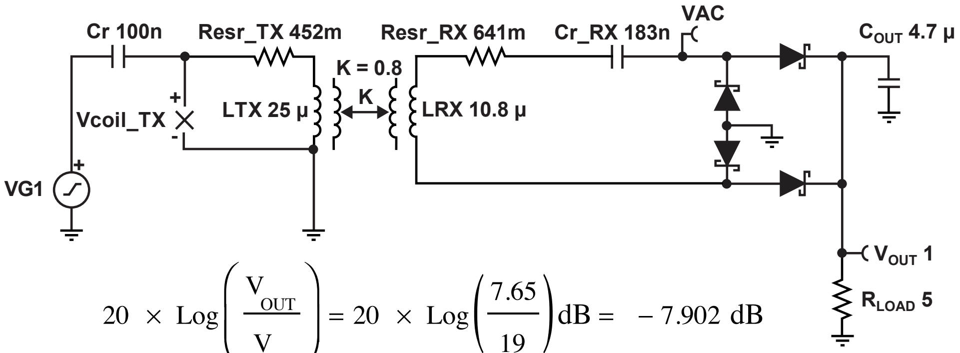
$$k(\text{gap} = 8\ \text{mm}) = \frac{0.208}{\sqrt{\frac{\text{Lrx}}{\text{Ltx}}}} = 0.321,\ M = 5.27\mu$$

Intelligent WPT
Digital Power, Resonant Battery Charger



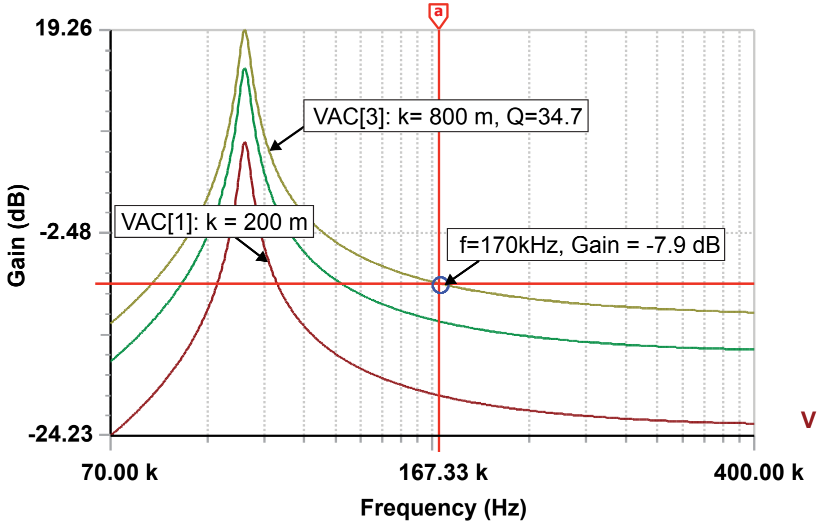
- A transmitter (TX) driving a resonant coupled inductor
- A receiver (RX) with rectification, load modulation and post regulation
- A load, commonly a single cell, secondary battery pack

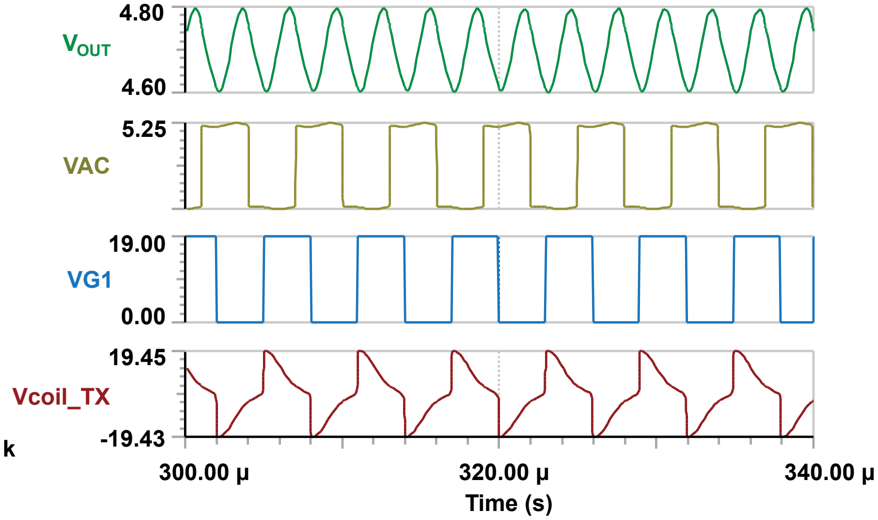
Resonant Circuit Analysis



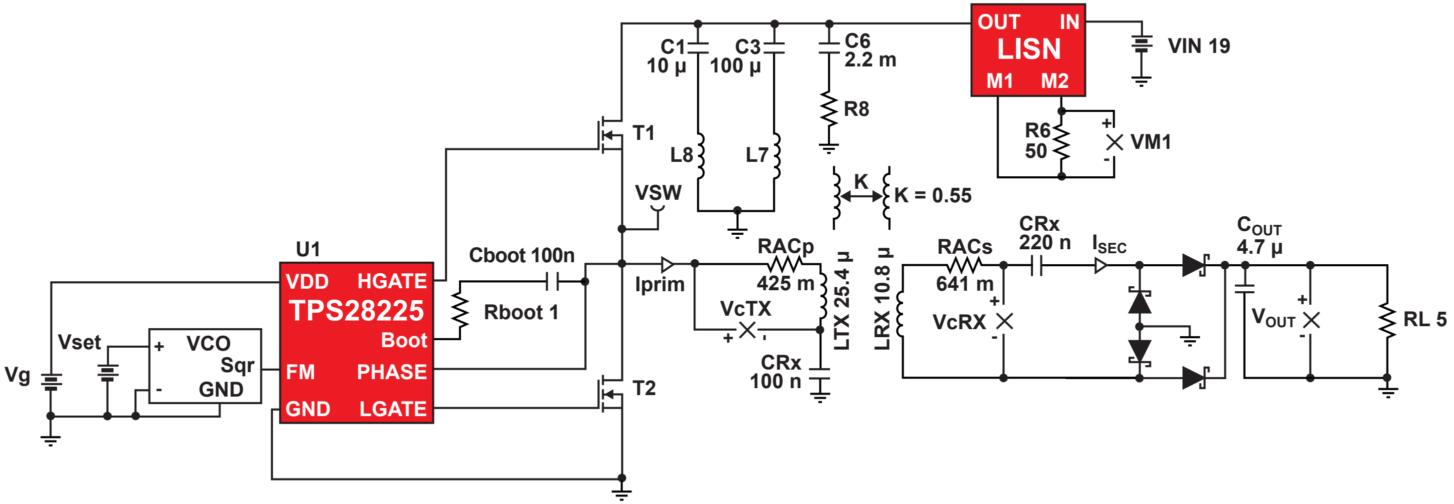
$$20 \times \text{Log}\left(\frac{V_{OUT}}{V_{IN}}\right) = 20 \times \text{Log}\left(\frac{7.65}{19}\right)\text{dB} = -7.902\text{ dB}$$

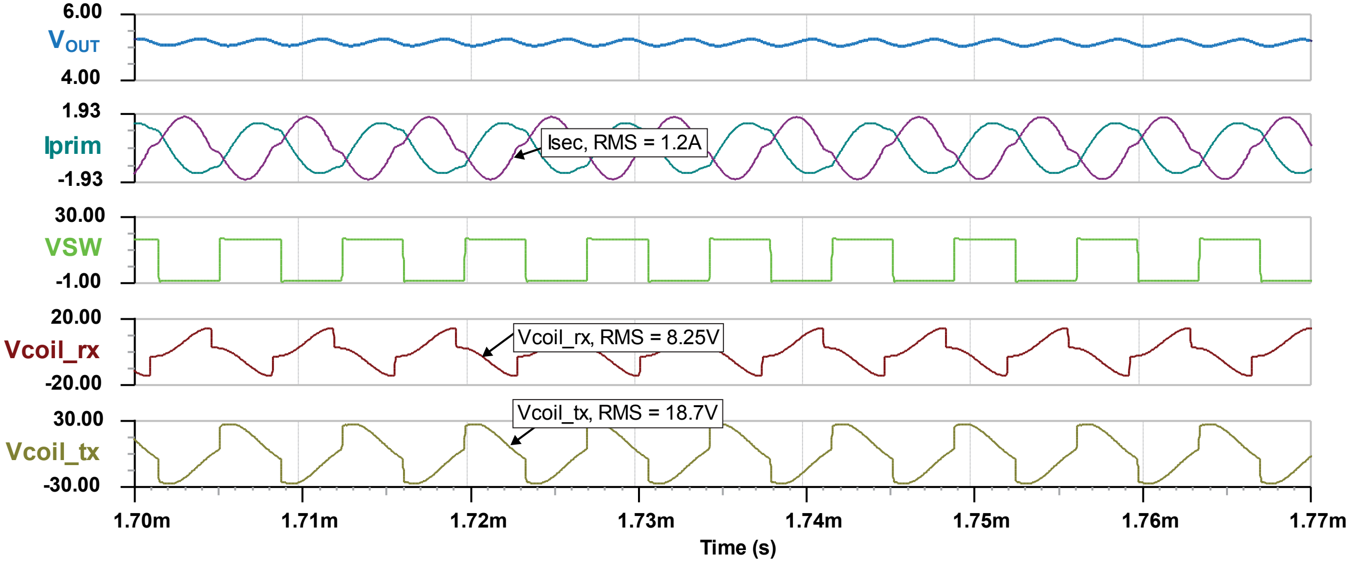
- VG1 is a variable frequency AC signal in frequency domain
- VG1 is a 50% duty cycle, 19 V square wave in the time domain
- Power regulated by changing the frequency or voltage





Examining Circuit Behavior in SPICE





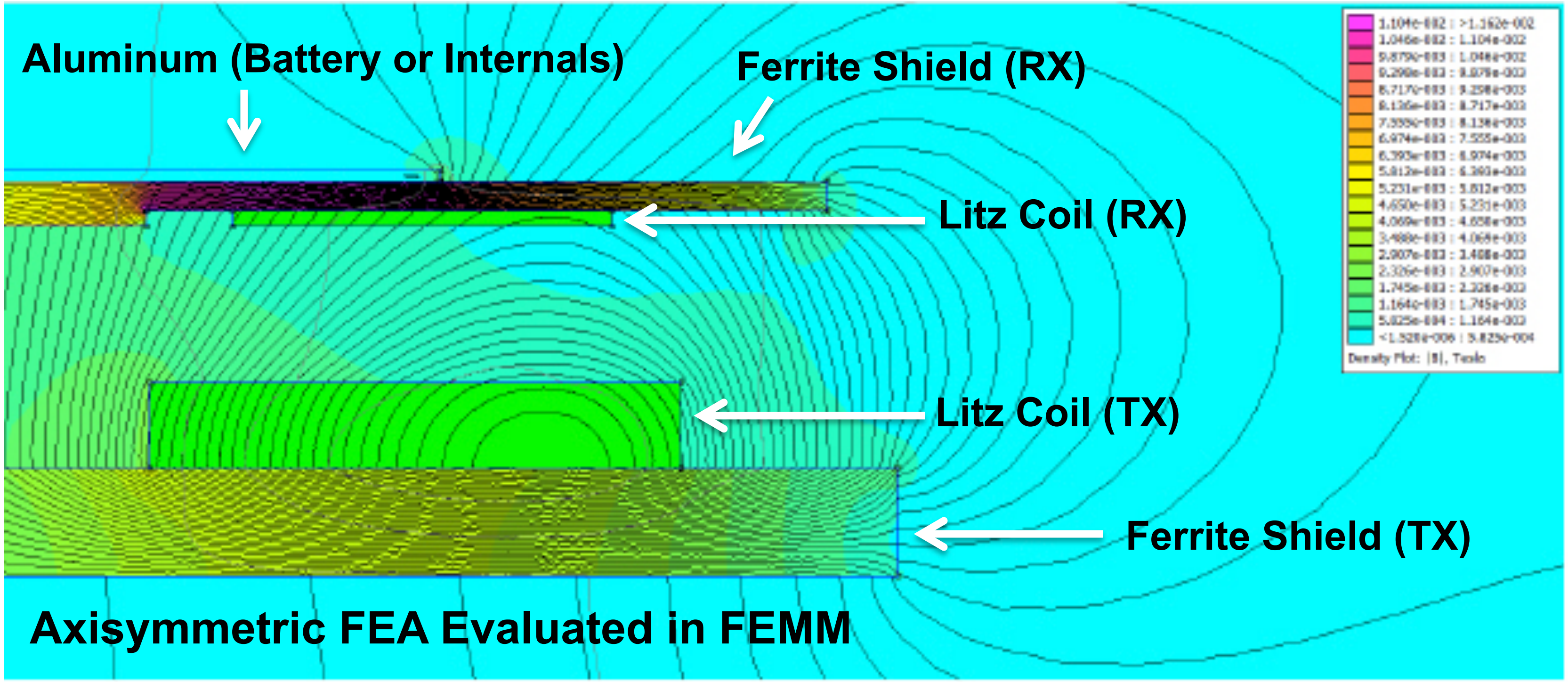
Isec, RMS = 1.2A

Vcoil_rx, RMS = 8.25V

Vcoil_tx, RMS = 18.7V

2-D FEA Plot of Magnetic Flux Between TX/RX Coils

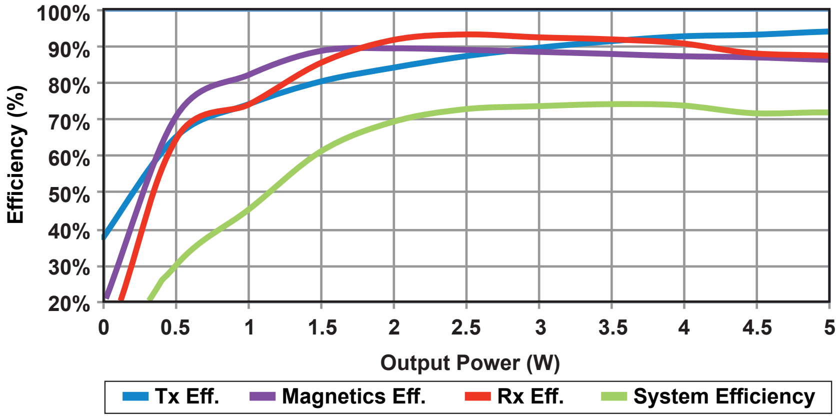
- Receiver side shielding is important
- Poorly designed shields expose battery and external circuits to magnetic field
- AC/DC winding losses of TX/RX coils correspond with empirical results = 0.32 W

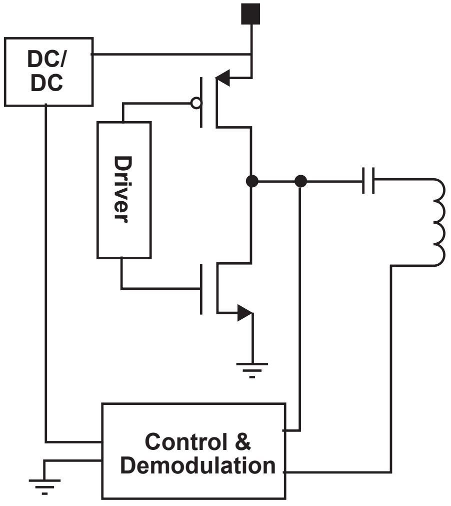


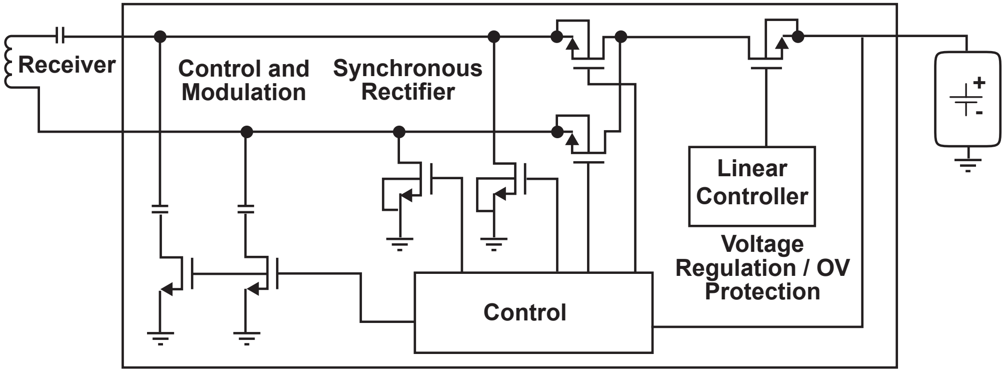
Axisymmetric FEA Evaluated in FEMM

Quantifying Losses – Typical 5 W Wireless Power Transmitter/Receiver

$$\eta = \frac{P_{OUT}}{P_{OUT} + P_{RX} + P_{TX}}$$





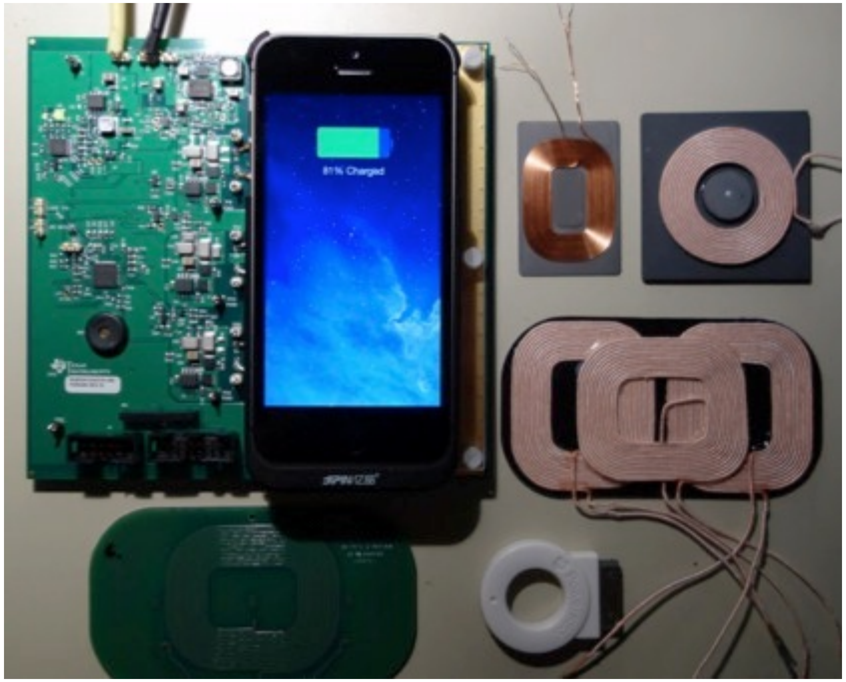


$$P_{TX} = P_{TXcoil} + P_{Bridge} + P_{control} + P_{DC-DC}$$

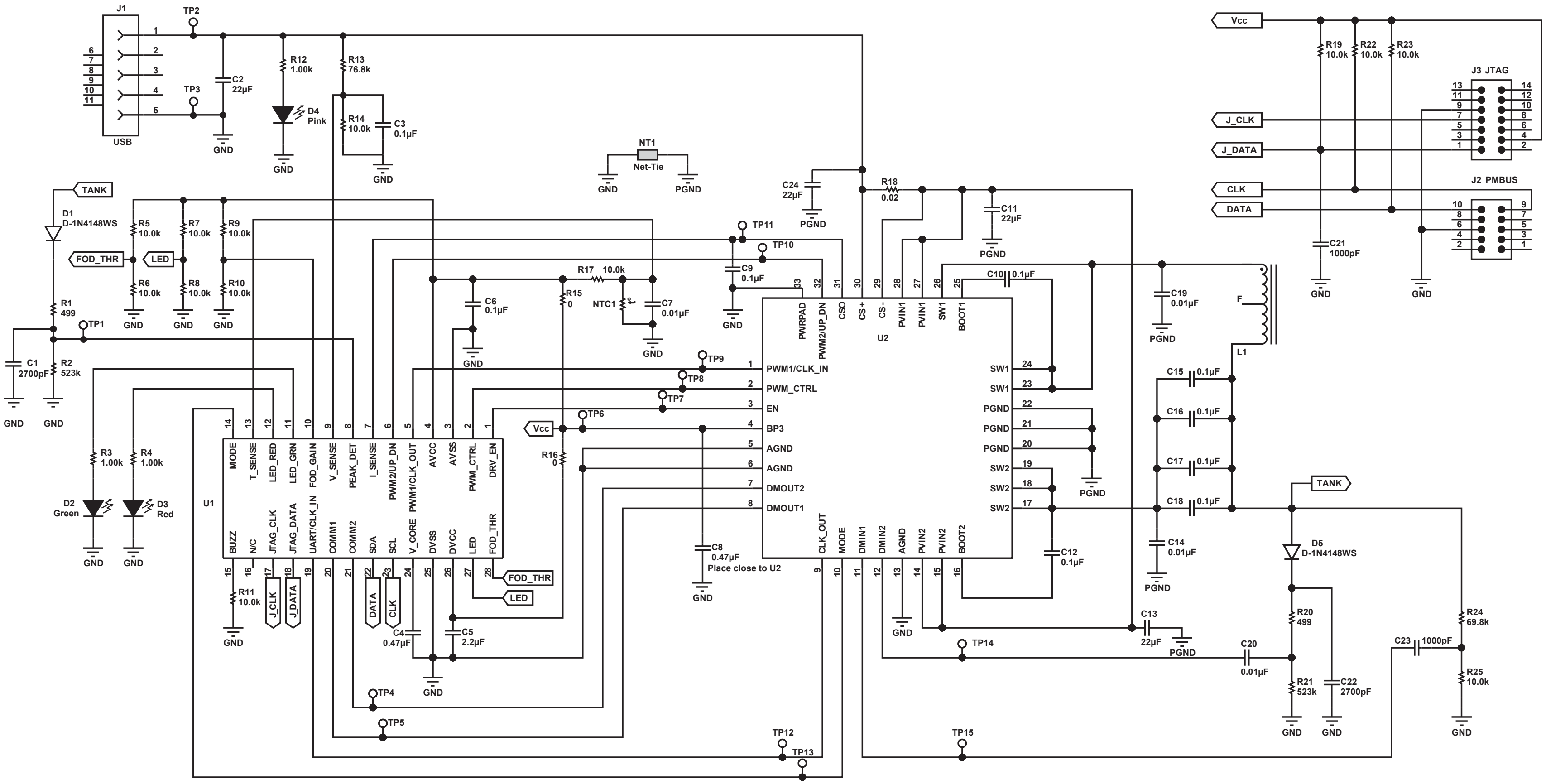
$$P_{RX} = P_{RXcoil} + P_{rectifier} + P_{Ido} + P_{comm}$$

Design Considerations, WPC

- Feedback communication
- Loop response
- Foreign object detection
- Electromagnetic compatibility
- System efficiency

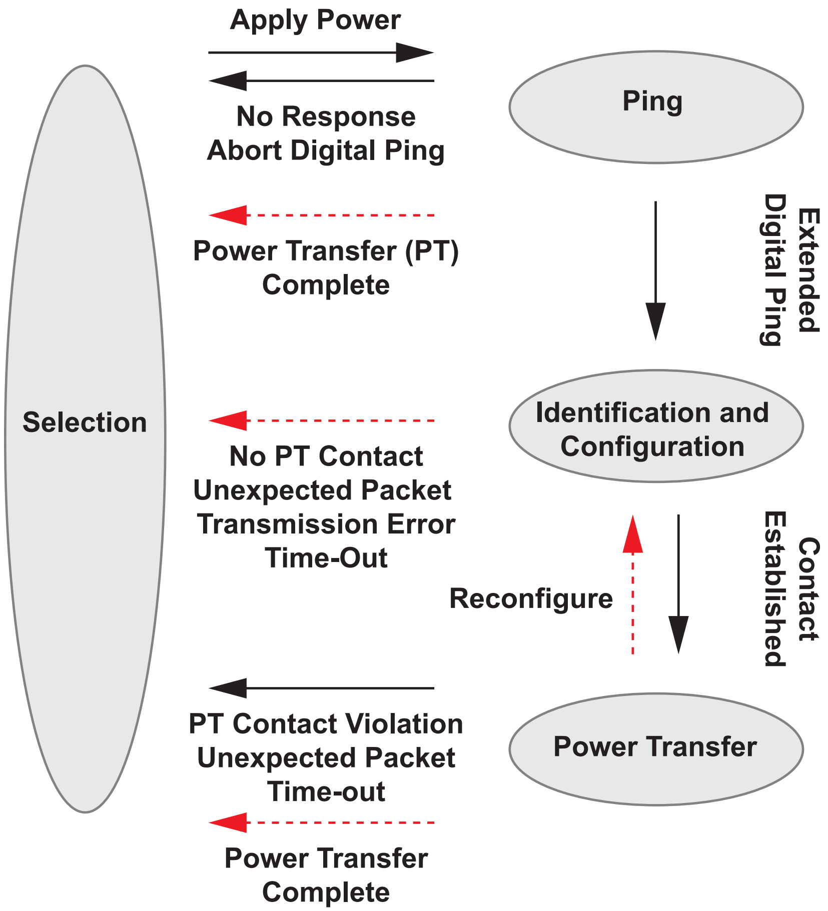


WPC 1.1 Compliant
5 W TX Reference Design



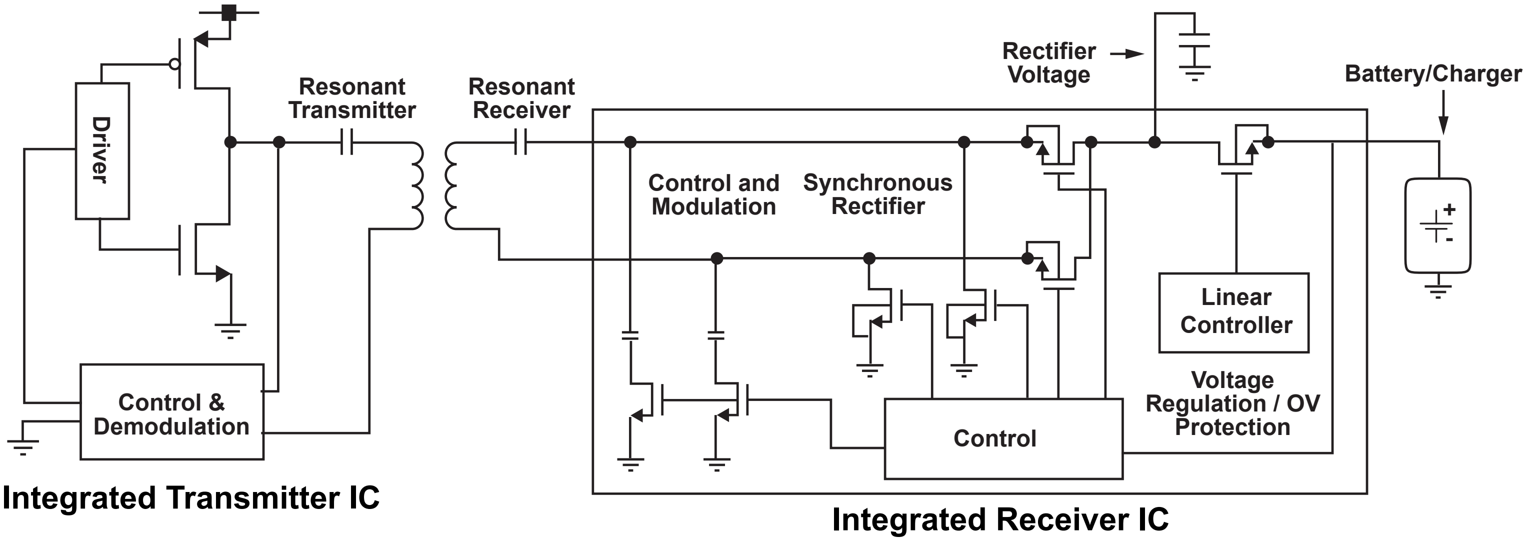
Qi Power Transfer Communication Protocol

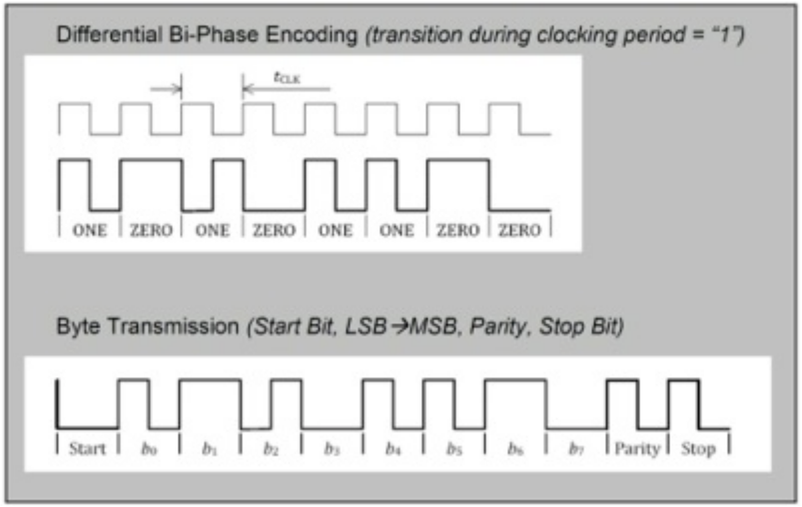
- **TX generates a shared magnetic field**
  - TX coil creates magnetic field
  - Magnetic field induces current in RX coil
- **Communication in power field**
  - TX waits until its field perturbed by RX
  - TX sends seek energy "ping"
  - TX waits for a digital response
  - If digital response is valid, transfer power
- **Power transferred at level needed**
  - RX reports power received/needed
  - TX adjusts power based on RX feedback
  - If feedback is lost, power transfer stops



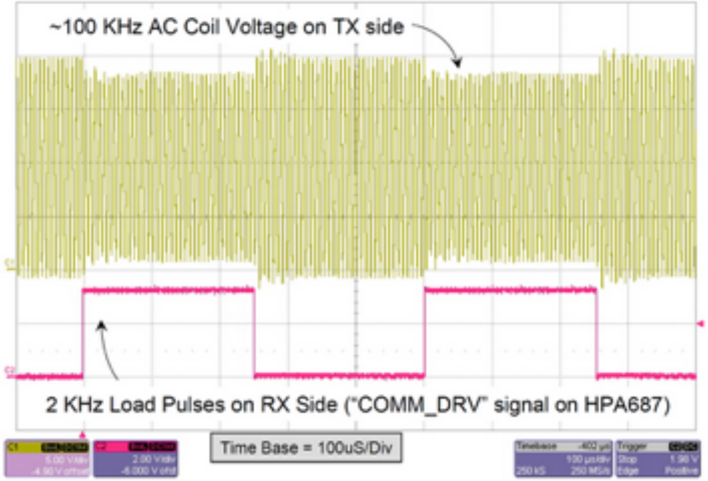
From WPC Qi System Description. Part 1

WPC RX Load Modulation




Differential Bi-Phase Encoding *(transition during clocking period = "1")*

Byte Transmission *(Start Bit, LSB→MSB, Parity, Stop Bit)*

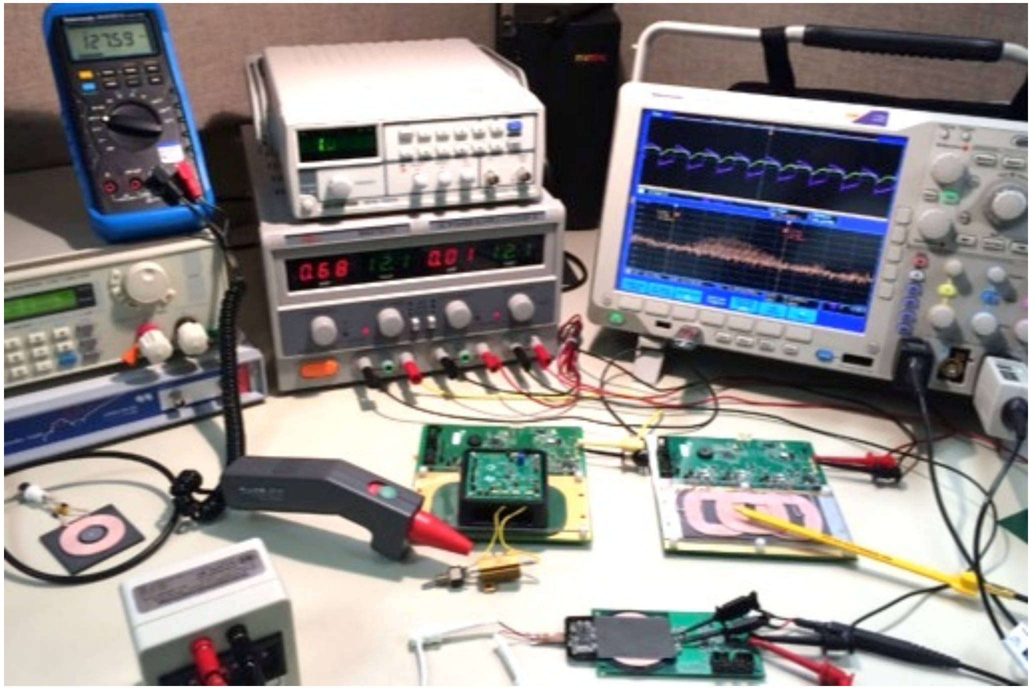

~100 KHz AC Coil Voltage on TX side

2 KHz Load Pulses on RX Side ("COMM_DRV" signal on HPA687)

Time Base = 100uS/Div

Measurement

- Power transfer waveforms
  - Coil resonance
  - Harmonic content
- Load response
- Efficiency –
  - Loss contributors
  - PCB coil vs. Litz
- RX/TX communication
- EMI, FOD
- Spatial freedom

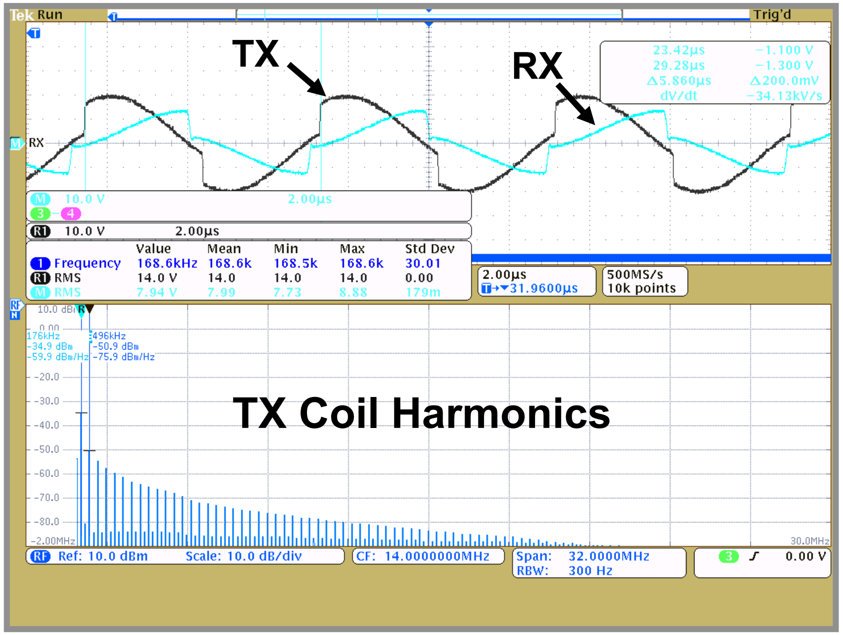


VNA – Bode 100 – Coil gain/impedance characteristics

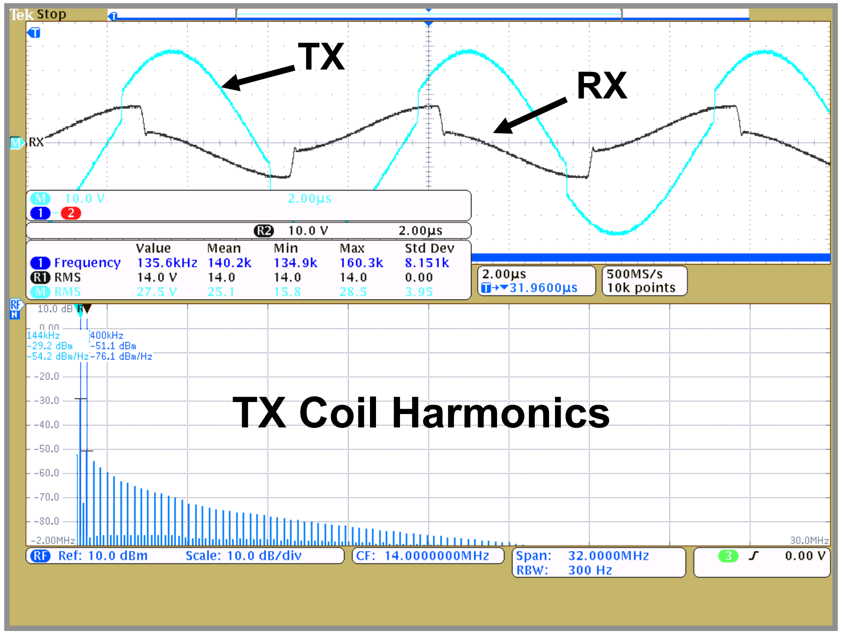
MDO4104 – Mixed domain oscilloscope

Differential voltage probe capable of > 40 V, current probe, IR probe

Reference Design Waveforms at 5 W
Time and Spectrum Domain



	Value	Mean	Min	Max	Std Dev
1 Frequency	168.6kHz	168.6k	168.5k	168.6k	30.01
R1 RMS	14.0 V	14.0	14.0	14.0	0.00
M RMS	7.94 V	7.99	7.73	8.88	179m



	Value	Mean	Min	Max	Std Dev
1 Frequency	135.6kHz	140.2k	134.9k	160.3k	8.151k
R1 RMS	14.0 V	14.0	14.0	14.0	0.00
M RMS	27.5 V	25.1	15.8	28.5	3.95

Centered coils force operation further from resonance

Vpp_tx = 20 V, f_{SW} = 170 kHz

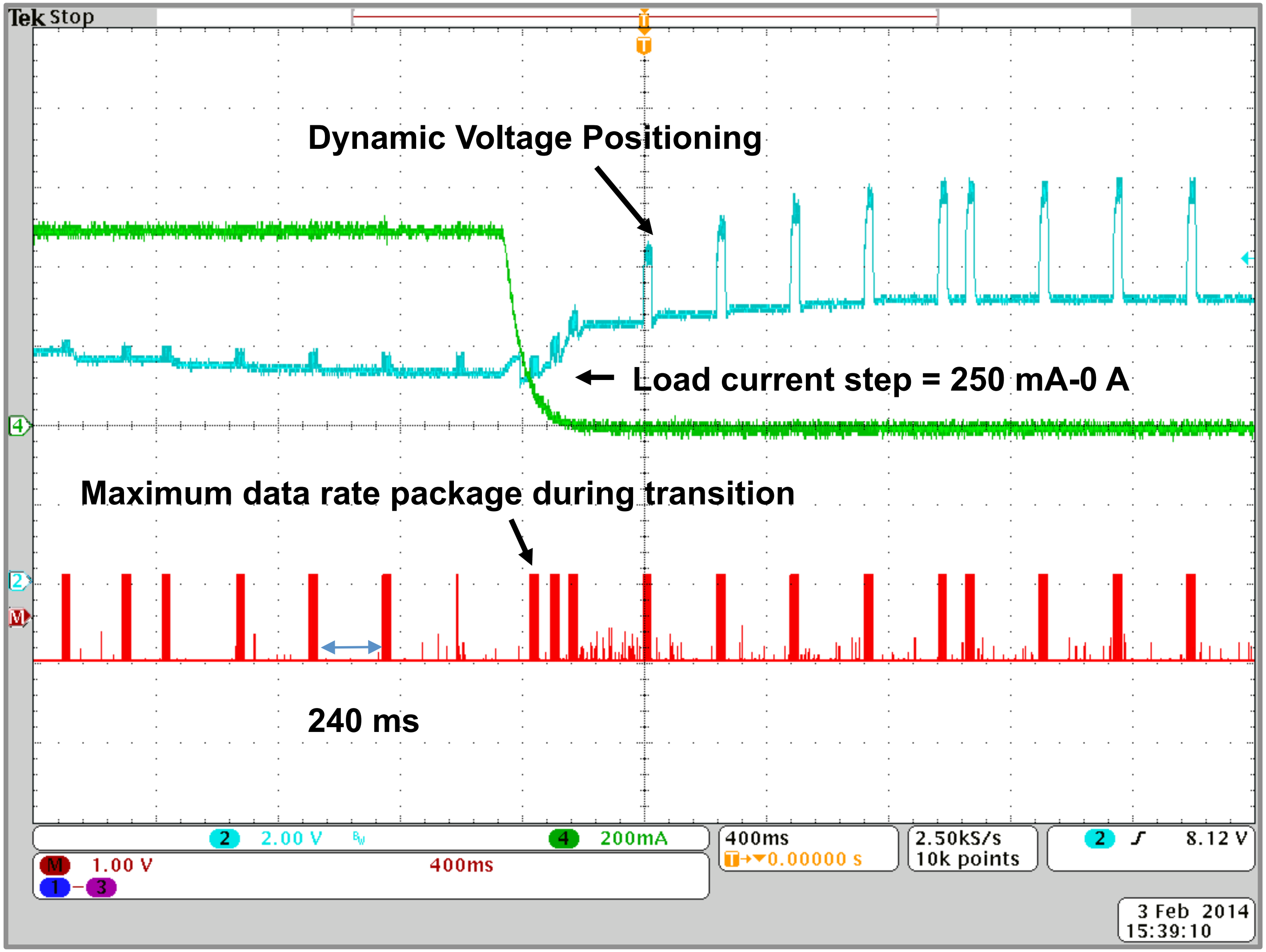
RMS gain = 0.56

Misaligned coils force operation closer to resonance

Vpp_tx = 40 V, f_{SW} = 135 kHz

RMS gain = 0.509

Intelligent Voltage Positioning



Dynamic Voltage Positioning

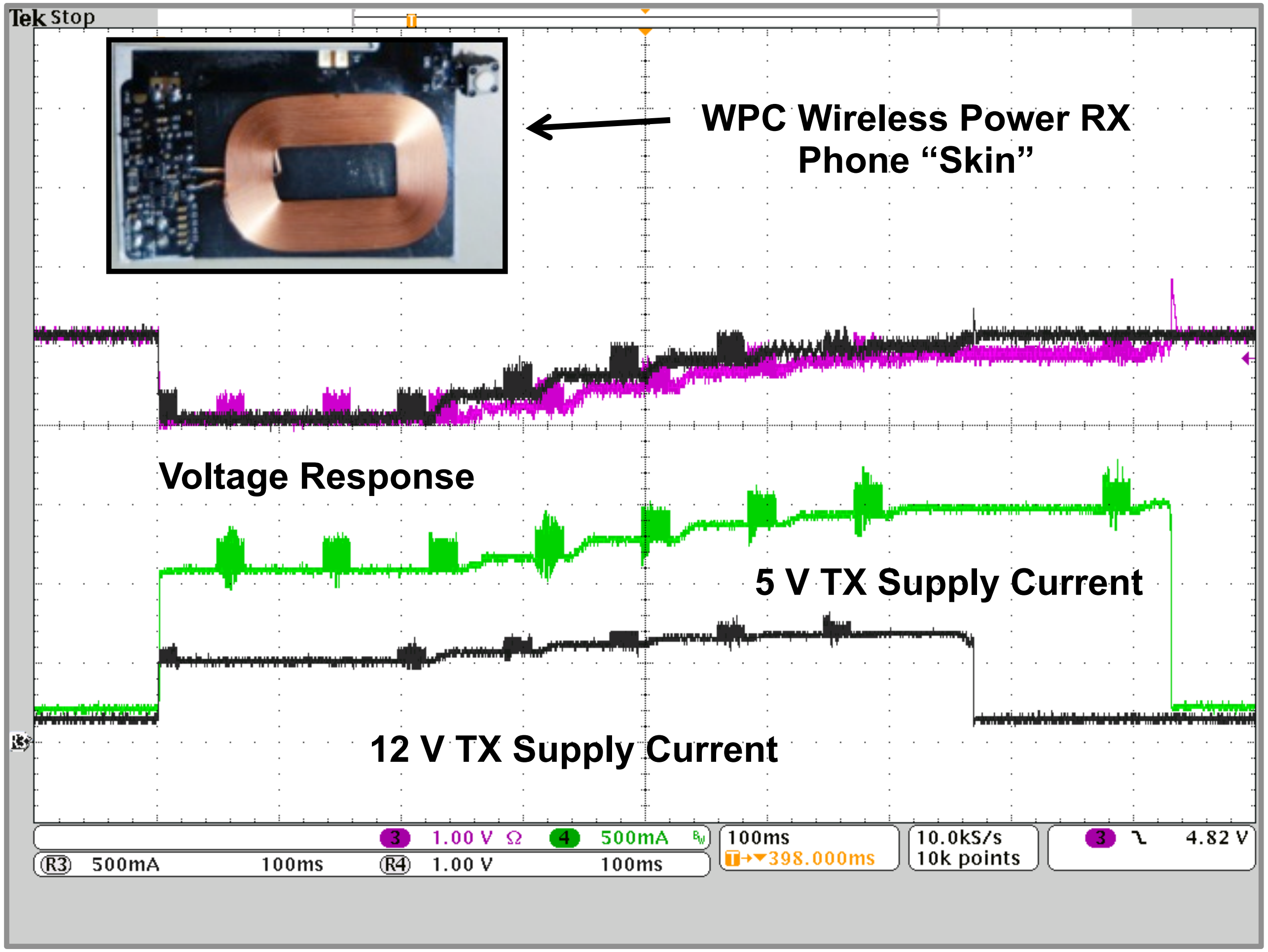
Load current step = 250 mA-0 A

Maximum data rate package during transition

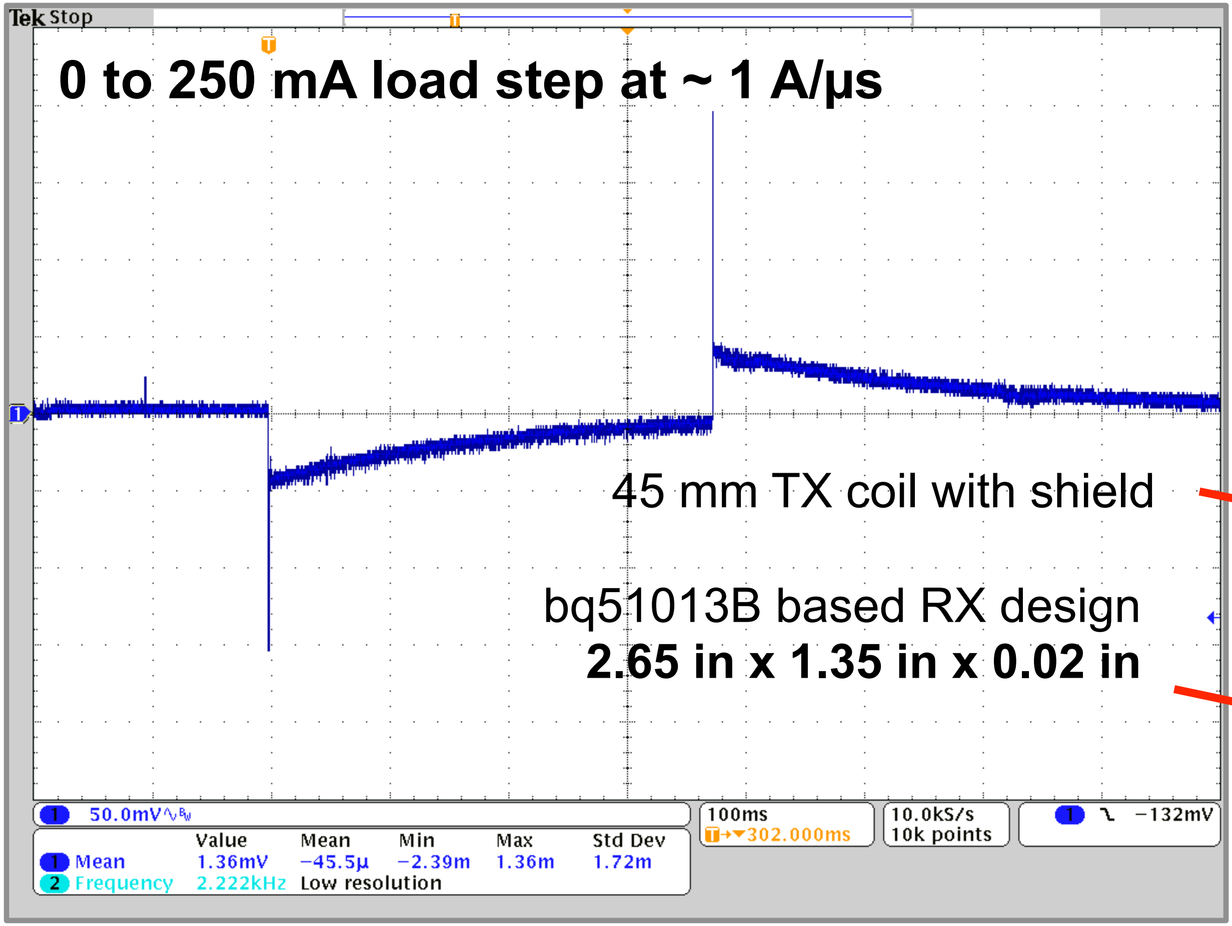
240 ms

Transient Load Response

I_{OUT} = 0 to 1 A



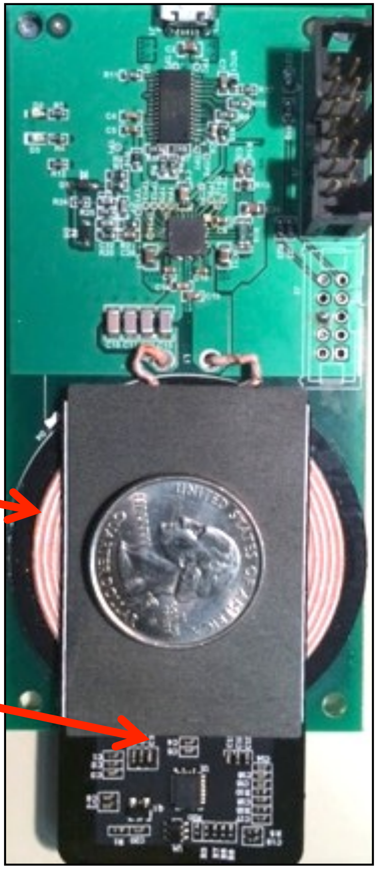
Transient Load Step Response
Litz TX Coil / PCB RX Coil



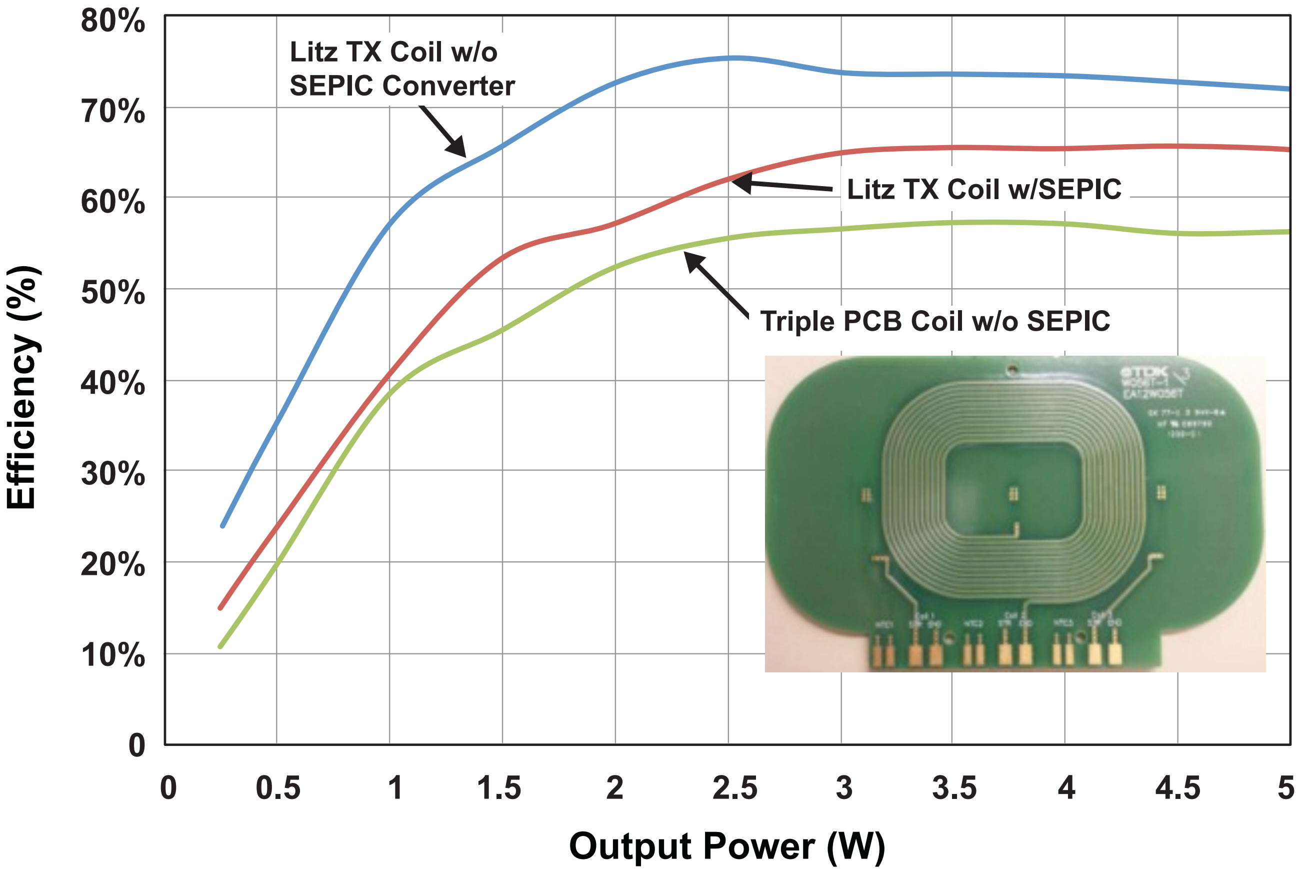
0 to 250 mA load step at ~ 1 A/µs

45 mm TX coil with shield

bq51013B based RX design
2.65 in x 1.35 in x 0.02 in

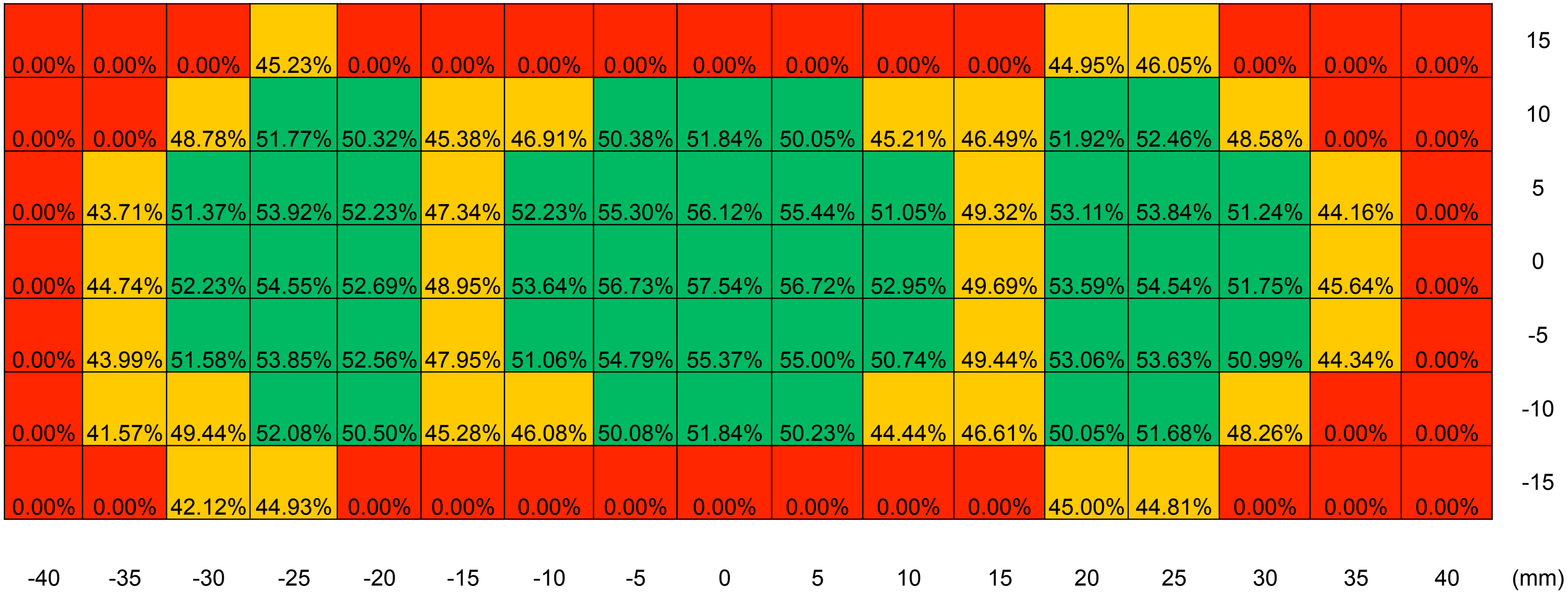


System Efficiency – DC Input to DC Output PCB Coil vs. 105 Strand Litz Coil



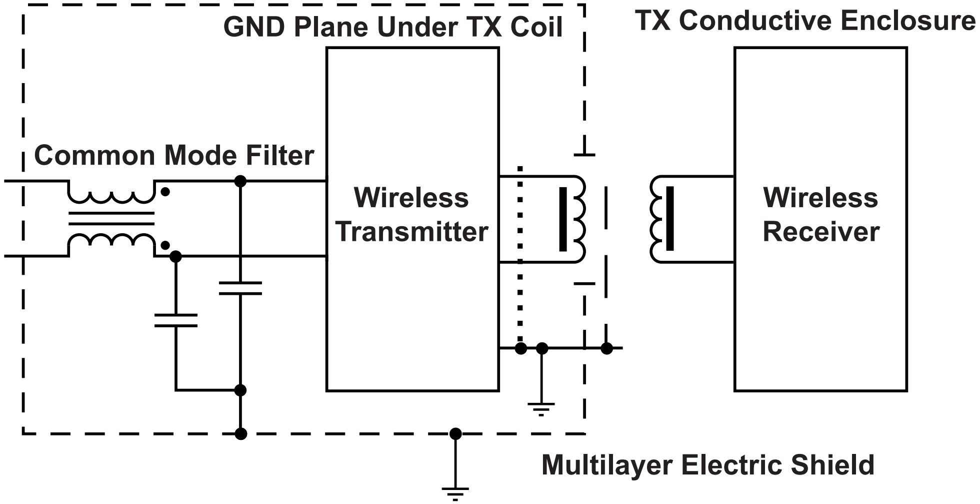
Designing for Spatial Freedom Efficiency Across Charging Area

- Efficiency map at a 5 W load measured over the PCB coil area
- +/- 40 mm in x-direction and 30 mm in y-direction, 5 mm steps



-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	(mm)
0.00%	0.00%	0.00%	45.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	44.95%	46.05%	0.00%	0.00%	0.00%	15
0.00%	0.00%	48.78%	51.77%	50.32%	45.38%	46.91%	50.38%	51.84%	50.05%	45.21%	46.49%	51.92%	52.46%	48.58%	0.00%	0.00%	10
0.00%	43.71%	51.37%	53.92%	52.23%	47.34%	52.23%	55.30%	56.12%	55.44%	51.05%	49.32%	53.11%	53.84%	51.24%	44.16%	0.00%	5
0.00%	44.74%	52.23%	54.55%	52.69%	48.95%	53.64%	56.73%	57.54%	56.72%	52.95%	49.69%	53.59%	54.54%	51.75%	45.64%	0.00%	0
0.00%	43.99%	51.58%	53.85%	52.56%	47.95%	51.06%	54.79%	55.37%	55.00%	50.74%	49.44%	53.06%	53.63%	50.99%	44.34%	0.00%	-5
0.00%	41.57%	49.44%	52.08%	50.50%	45.28%	46.08%	50.08%	51.84%	50.23%	44.44%	46.61%	50.05%	51.68%	48.26%	0.00%	0.00%	-10
0.00%	0.00%	42.12%	44.93%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	45.00%	44.81%	0.00%	0.00%	0.00%	-15

Design for Electromagnetic Compatibility



GND Plane Under TX Coil

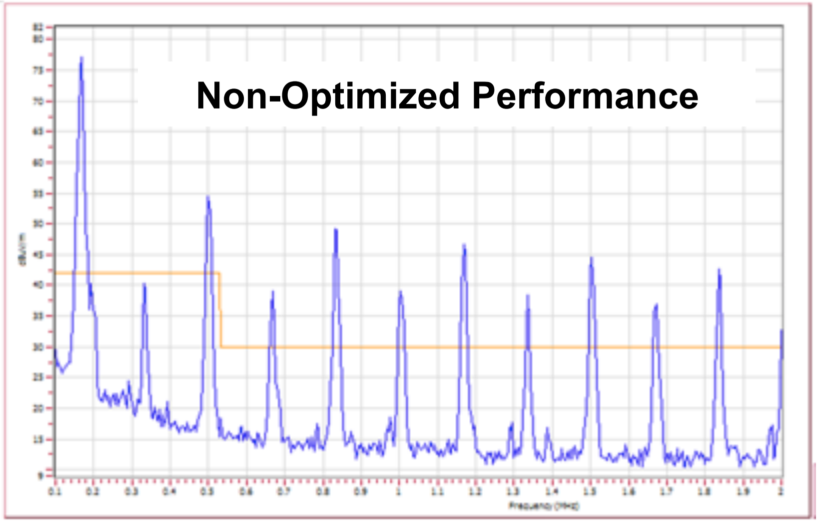
TX Conductive Enclosure

Common Mode Filter

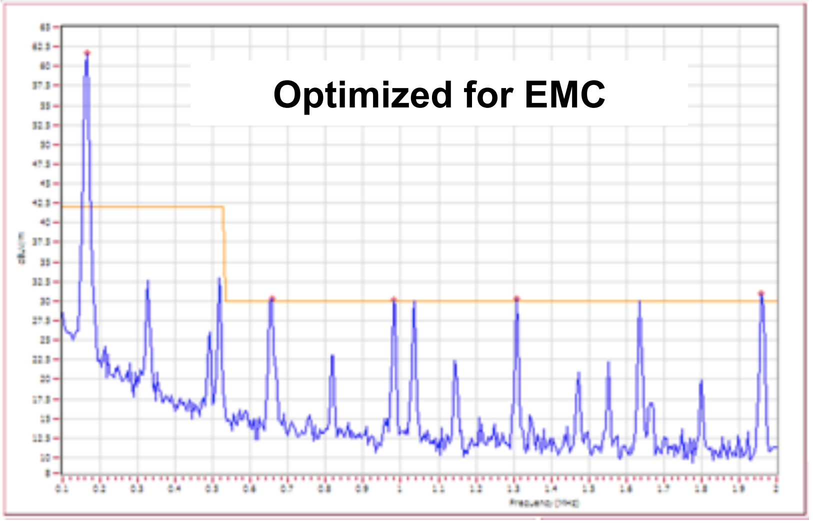
Wireless Transmitter

Wireless Receiver

Multilayer Electric Shield



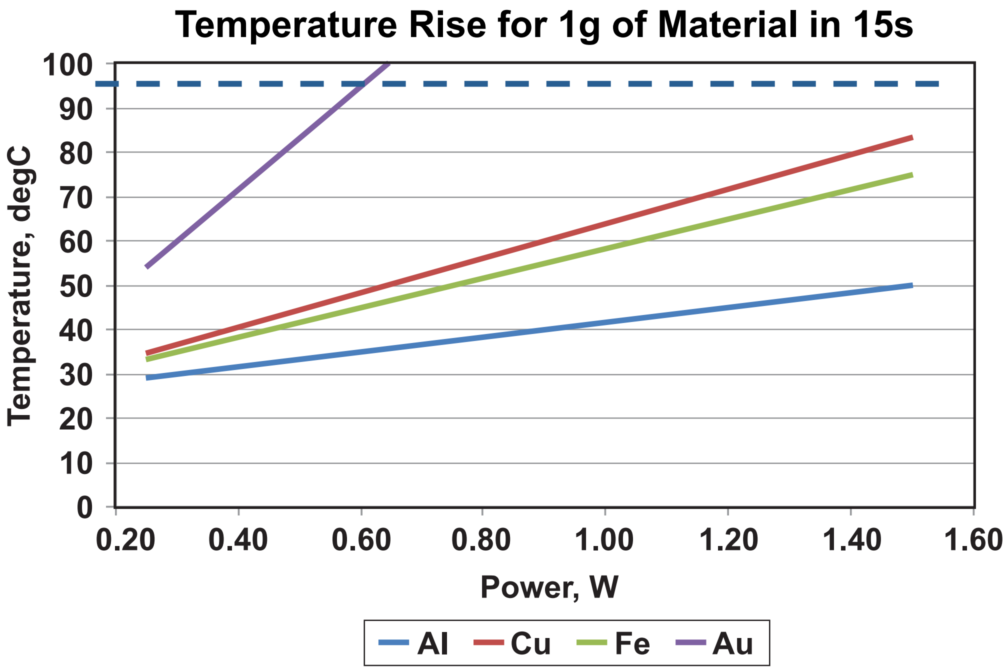
Non-Optimized Performance



Optimized for EMC

Foreign Object Detection

- Metal objects between TX and RX can induce eddy current losses
- Field density of 5 W wireless chargers can result in significant eddy losses
- Depending on specific heat capacity, foreign object temp rise can be > 60°C
- Battery pack is especially sensitive



$$\Delta T = \frac{P \times t}{C \times m}$$

Where:

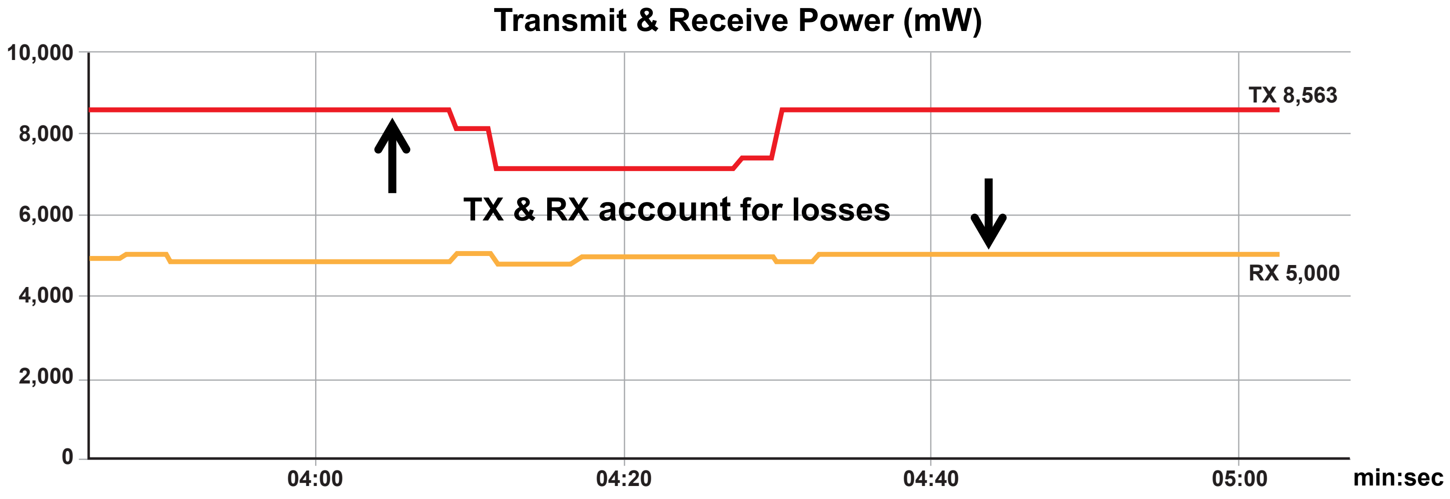
→ P = Power dissipated in FO

→ C = FO specific heat capacity

→ M = FO mass

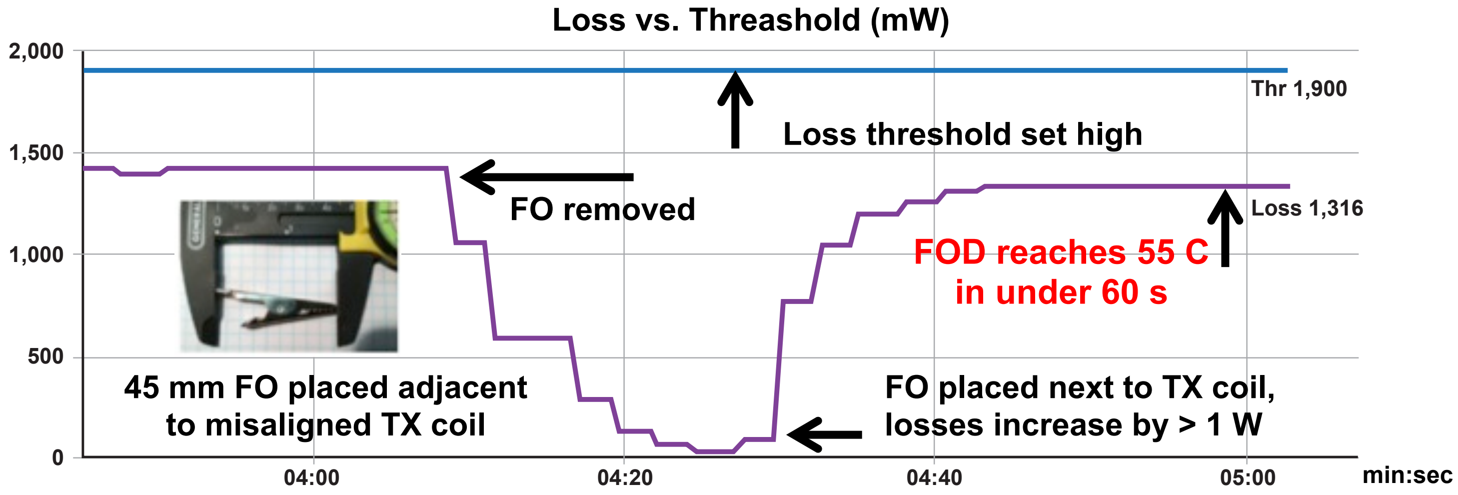
→ t = time

Dynamic RX / TX Loss Accounting



Transmit & Receive Power (mW)

TX & RX account for losses



Loss vs. Threashold (mW)

Loss threshold set high

FO removed

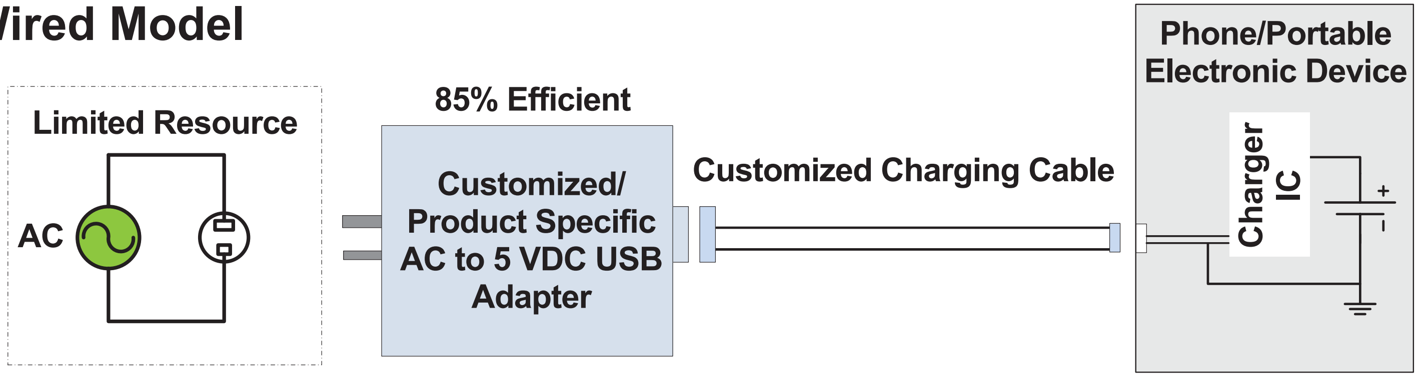
FOD reaches 55 C in under 60 s

45 mm FO placed adjacent to misaligned TX coil

FO placed next to TX coil, losses increase by > 1 W

A Vision for Wireless Power Transfer

Wired Model


Limited Resource

AC

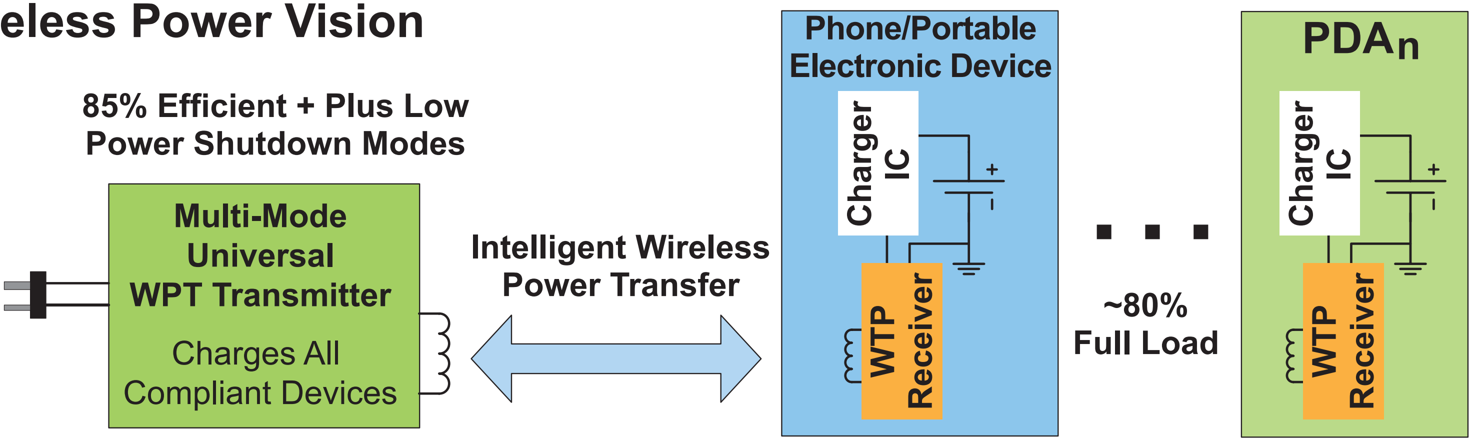
85% Efficient

Customized/ Product Specific AC to 5 VDC USB Adapter

Customized Charging Cable

Phone/Portable Electronic Device

Wireless Power Vision


85% Efficient + Plus Low Power Shutdown Modes

Multi-Mode Universal WPT Transmitter

Charges All Compliant Devices

Intelligent Wireless Power Transfer

Phone/Portable Electronic Device

~80% Full Load

PDAn

Summary

- Market studies project rapid growth in wireless power technology
- Wireless power transfer is useful when a wired solution is **inconvenient, hazardous or impossible**
- WPT standards have emerged to accelerate growth, reliability, acceptance and safety in consumer electronics
- Developing a wireless power solution does not require compliance to any standard other than those affecting consumer safety and EMC
- Standard compliance may provide advantages in marketability (interoperability), performance, reliability and time to market
- Achieving spatial freedom and good efficiency requires a deep understanding of magnetic field theory

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