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Leadership Starts Here

Wireless Charging of Electric Vehicles Current Status and Future Trends

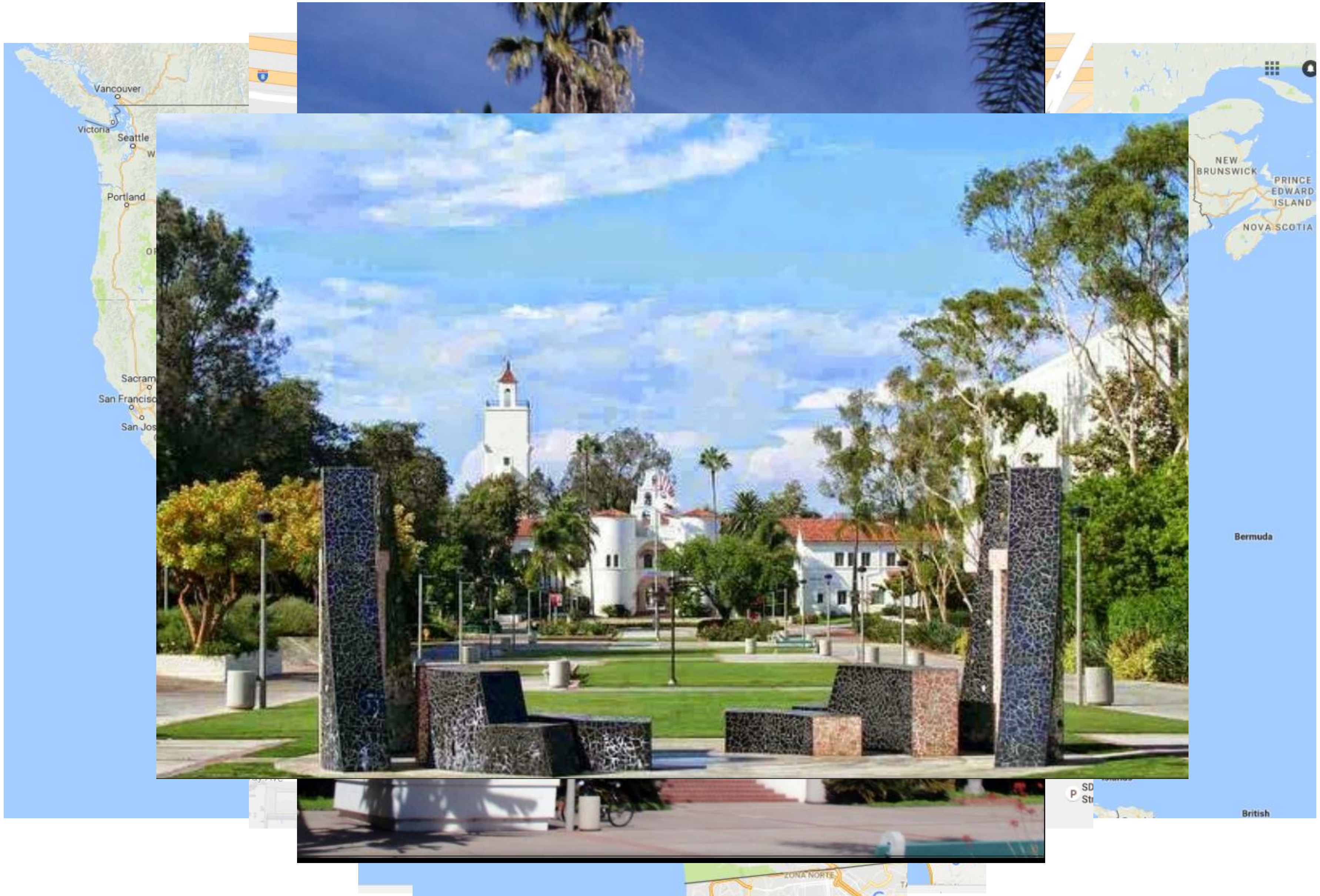
Chris Mi, Ph.D, Fellow IEEE, Fellow SAE

Professor and Chair, Dept. Electrical and Computer Engineering

Director, DOE GATE Center for Electric Drive Transportation

San Diego State University, (619)594-3741; mi@ieee.org

San Diego State University, California, USA



Presentation Outline

- Definition, history and application of wireless power transfer
- Principle of inductive wireless power transfer
- Safety of wireless power transfer
- J2954 recommended practices
- Topologies for Inductive WPT
- Capacitive wireless power transfer
- Other developments and applications of WPT
- Conclusions

Definition of Wireless Power

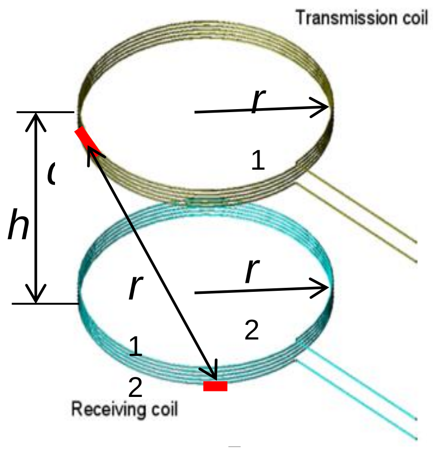
- The essential principles of WPT are
  - Given a distances over which the power is transferred through air or other non-conductive medium
  - The coupling is almost always less than a quarter wavelength, so the fundamental operation of all of these systems can be described by simple coupled models
- Contactless power system (CPS)
- Inductive power transfer (IPT)
- Capacitive wireless power transfer
- Strongly coupled magnetic resonance
- Wireless energy transfer

Tesla Broadcast Tower 1904

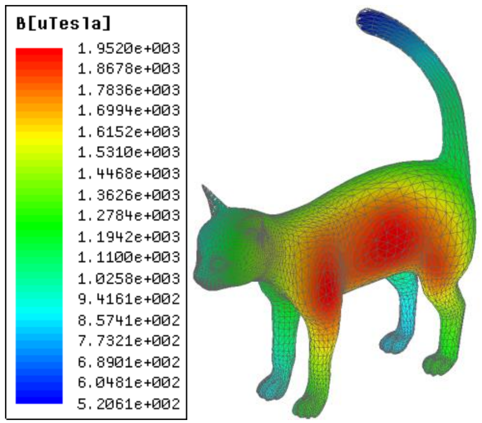
Ref: Grant Covic and John Boys, “Modern Trends in Inductive Power Transfer for Transportation Applications,” IEEE journal of emerging and selected topics in power electronics, vol. 1, no. 1, march 2013

Methods of Wireless Power Transfer

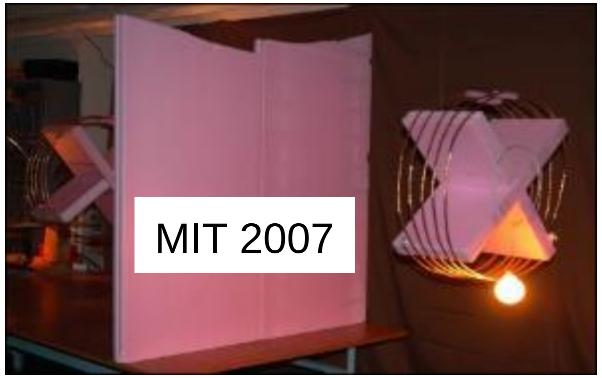
- **Wireless Power Transfer** 电能的无线传输
  - **Electromagnetic Induction** 电磁感应式
  - **Radiation** 辐射式
    - **Radio wave** 无线电波
    - **Microwave** 微波
    - **Laser** 激光
    - **Ultrasound** 超声波
  - **Electromagnetic Resonance** 电磁谐振式



- Most WPT is to effectively transfer heat
- Microwave has been used in our homes/offices
- Induction heating is popular in industrial applications



Applications of WPT



MIT 2007

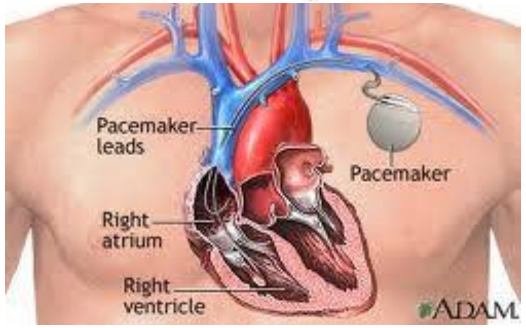
Leaf 2012

Intel 2008

Korea KAIST

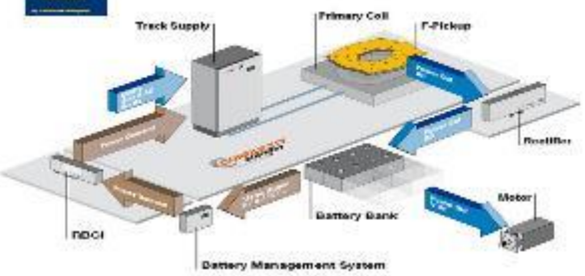
Witricity/Delphi

Japan



Tokyo 2009

conductix-wampfler

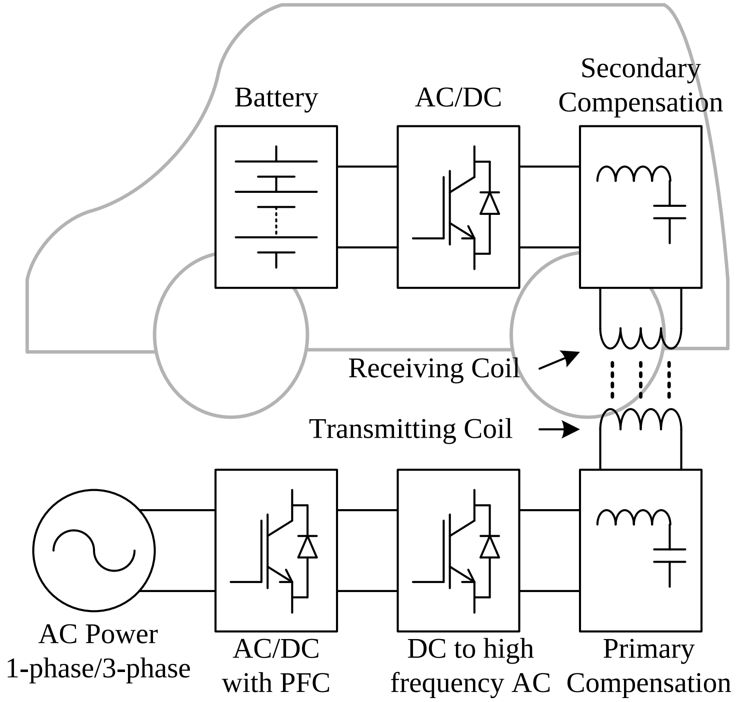


Issues of Conductive Charging and Battery Swapping

Electric safety is of concern: electric shock due to rain, etc.

Charge station, plug and cable can be easily damaged, stolen

Charge/swap station takes a lot of space and affect the views

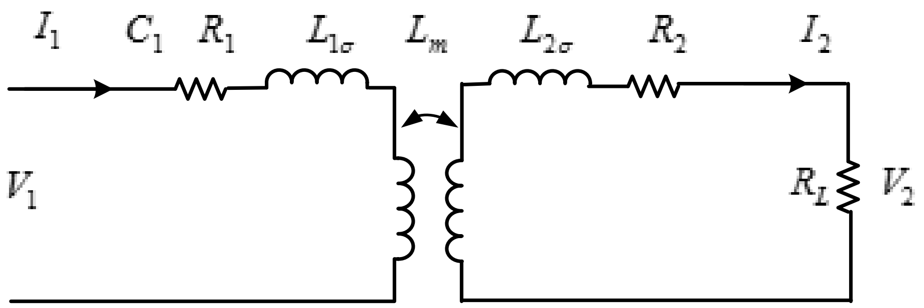


Possible Solution:

Wireless Charging

Principle of Inductive WPT Technology

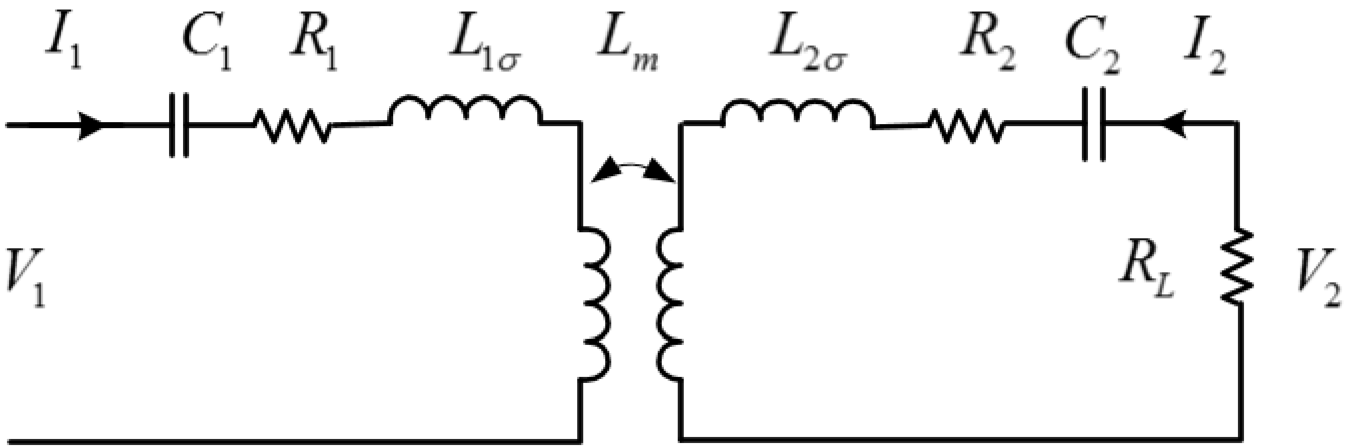
- Inductive WPT systems works like a transformer
- But loosely coupled between the primary and secondary
- Result: mutual coupling coefficient is only 10~20%



- Conventional Transformer
- Leakage is ~2%
- Operate at 50/60Hz

- Wireless less power
- Leakage is >80%
- Operate at KHz ~ MHz

Capacitor Compensation – Resonance



L_1, L_2 – Self inductance

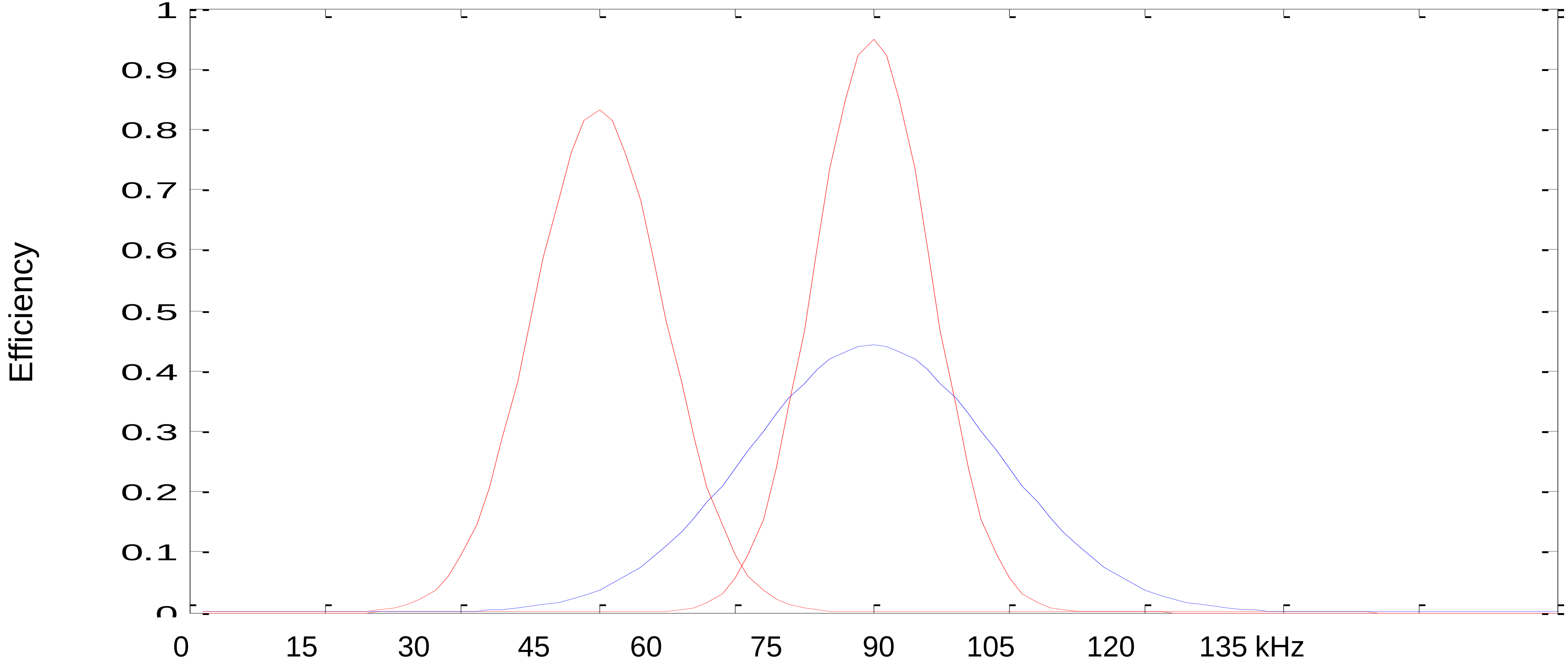
L_m – Mutual inductance

$L_1 = L_{1\sigma} + L_m$; $L_2 = L_{2\sigma} + L_m$

Series-Series Resonance Structure

$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(\omega L_1 - \dfrac{1}{\omega C_1}) & -j\omega L_m \\ -j\omega L_m & R_L + R_2 + j(\omega L_2 - \dfrac{1}{\omega C_2}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

Efficiency of WPT Systems

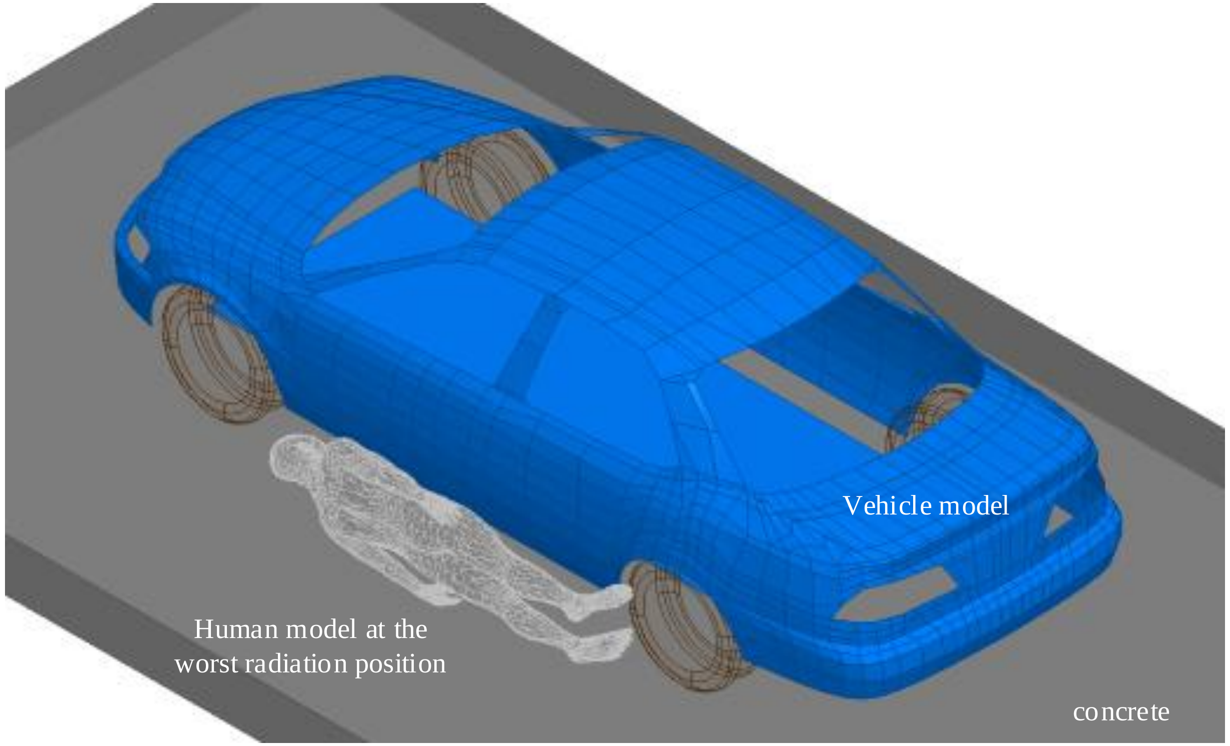


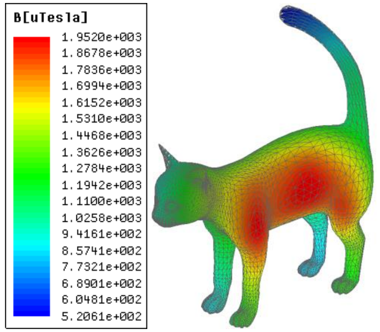
$$\eta = \frac{P_2}{P_1} = \frac{(\omega L_m)^2 R_L}{|Z_2[Z_1 Z_2 + (\omega L_m)^2]| \cos\varphi}$$

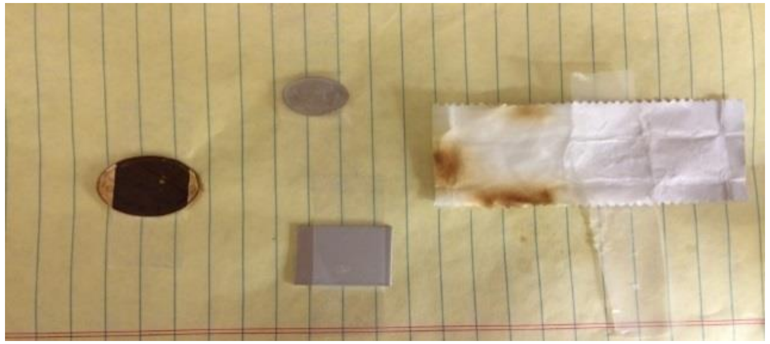
Safety Issues of WPT Systems

Safety Issues

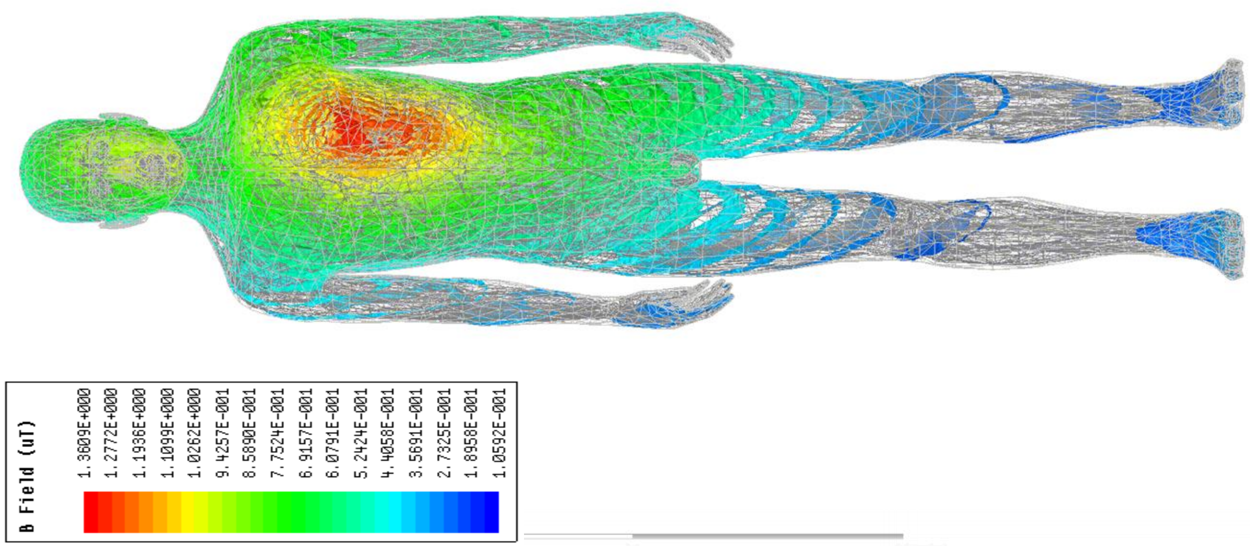
- Simulation study of a typical WTP
- 6.6 kW charging power
- Coil is 500×500 mm
- Worst case is human lay down next to the car and facing the car
- The worst radiation is well below the ICNIRP regulation







EM Field in Humans



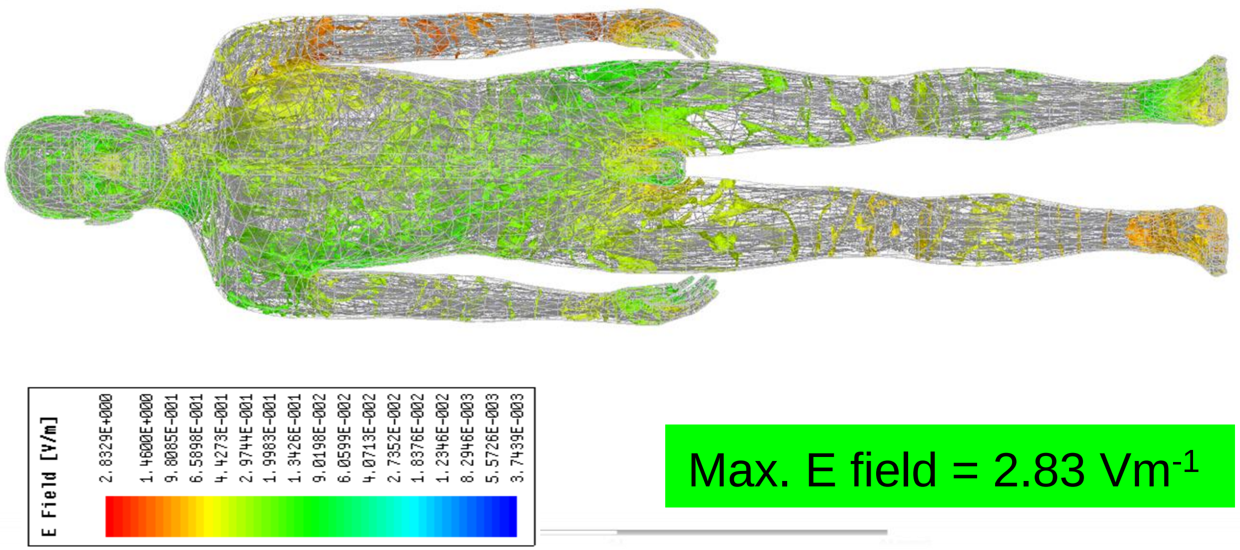
ICNIRP Guideline:

B field of human tissue < 27μT

B field of pacemaker < 6.25μT

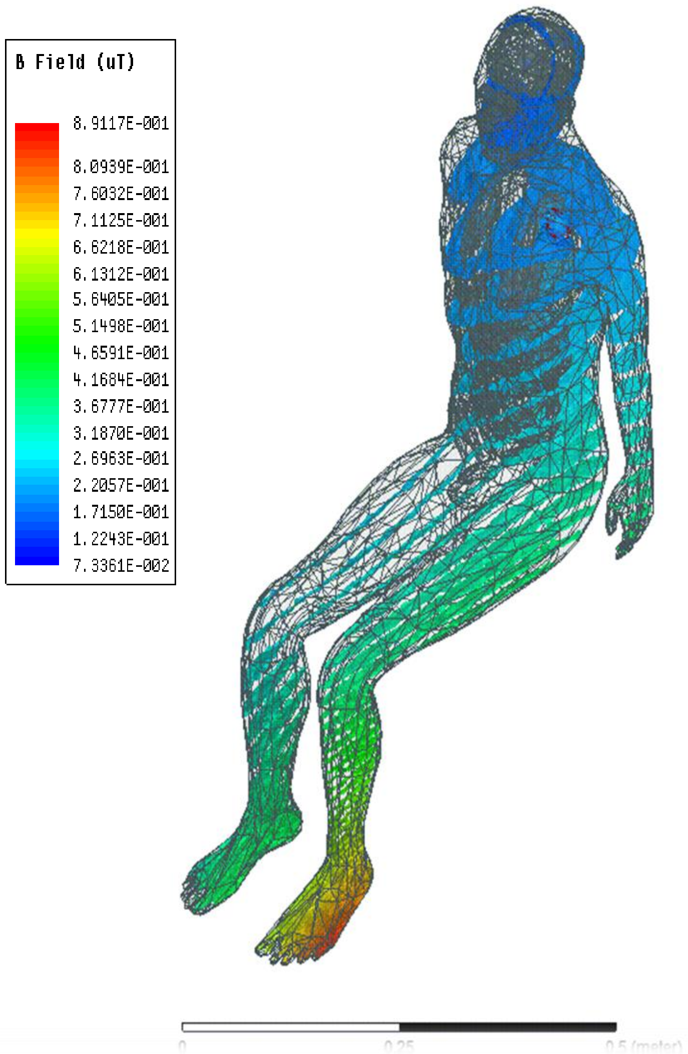
E field < 83 Vm^{-1} @85kHz

Max. B field = 1.36 μT



Max. E field = 2.83 Vm^{-1}

EM Field Inside Car



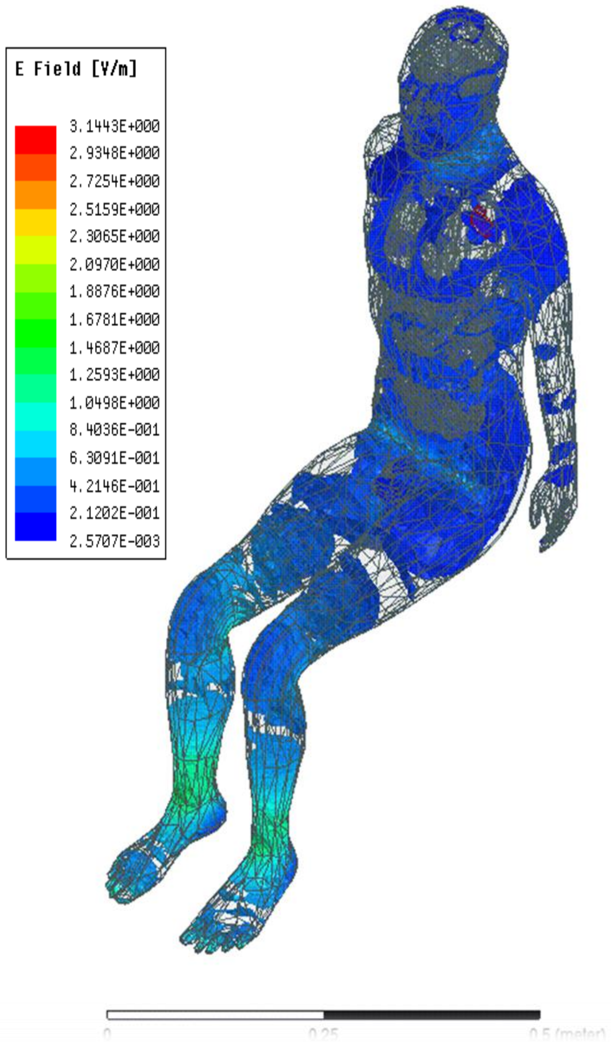
Max. B field = 0.89 μT

ICNIRP Guideline:

B field of human tissue < 27μT

B field of pacemaker < 6.25μT

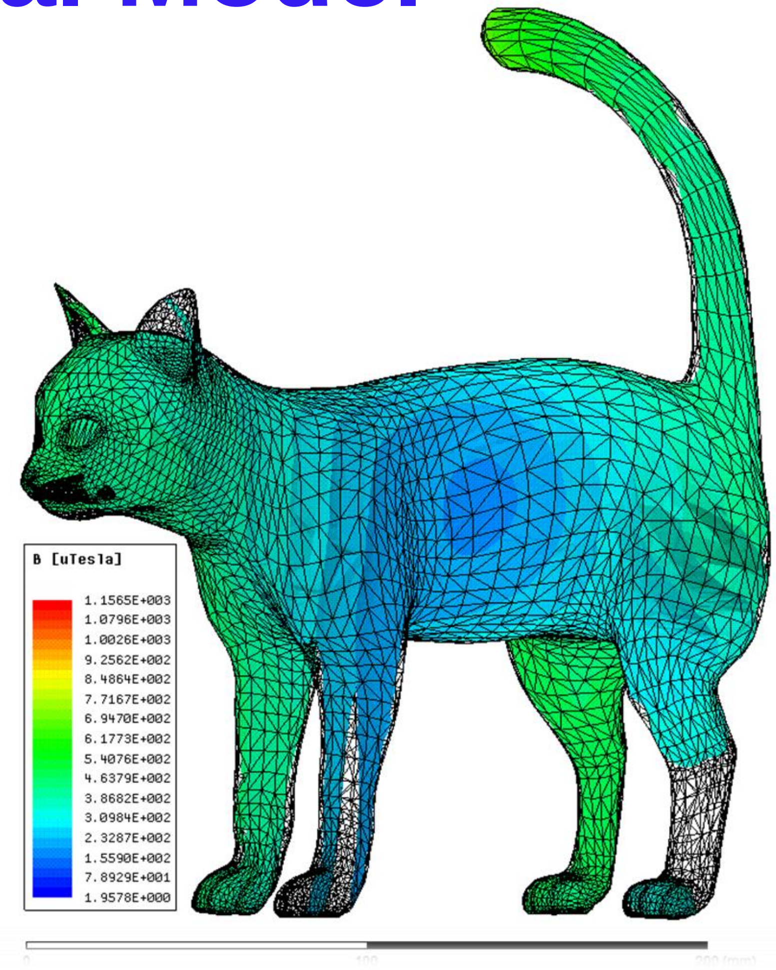
E field < 83 Vm^{-1} @85kHz



Max. E field = 3.14 Vm^{-1}

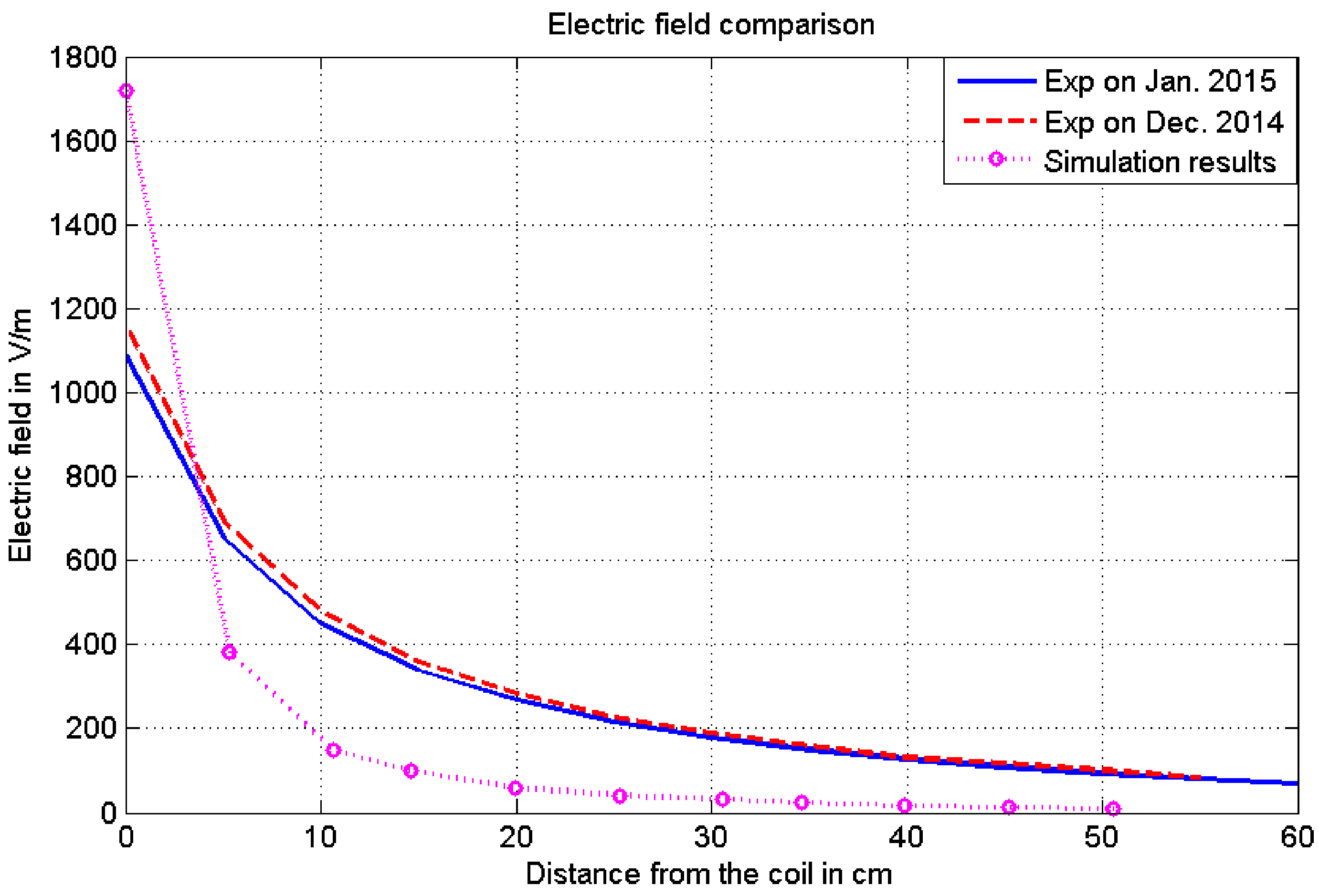
Animal Model

- Cat under the car
- 1.156 mT of magnetic field is observed which is not longer safe



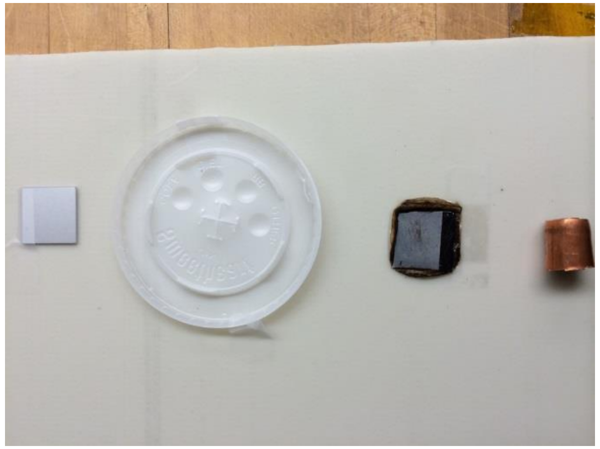
Maximum B field = **1156** µT

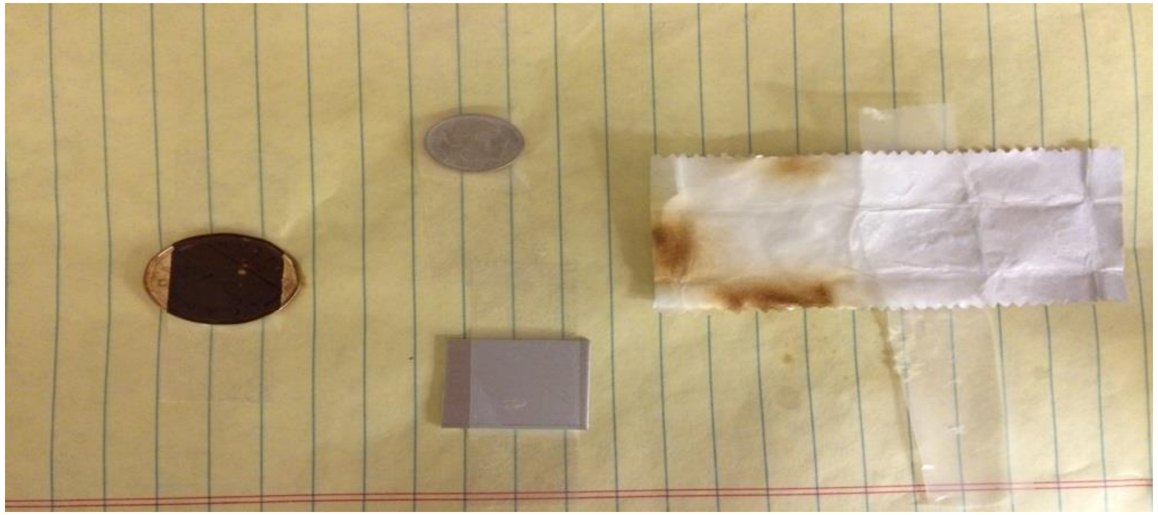
EM Field Measurement



- ✓ Simulation tool: Maxwell+HFSS
- ✓ Measuring Equipment: Narda EHP – 200A

Results of Foreign Object Test #1

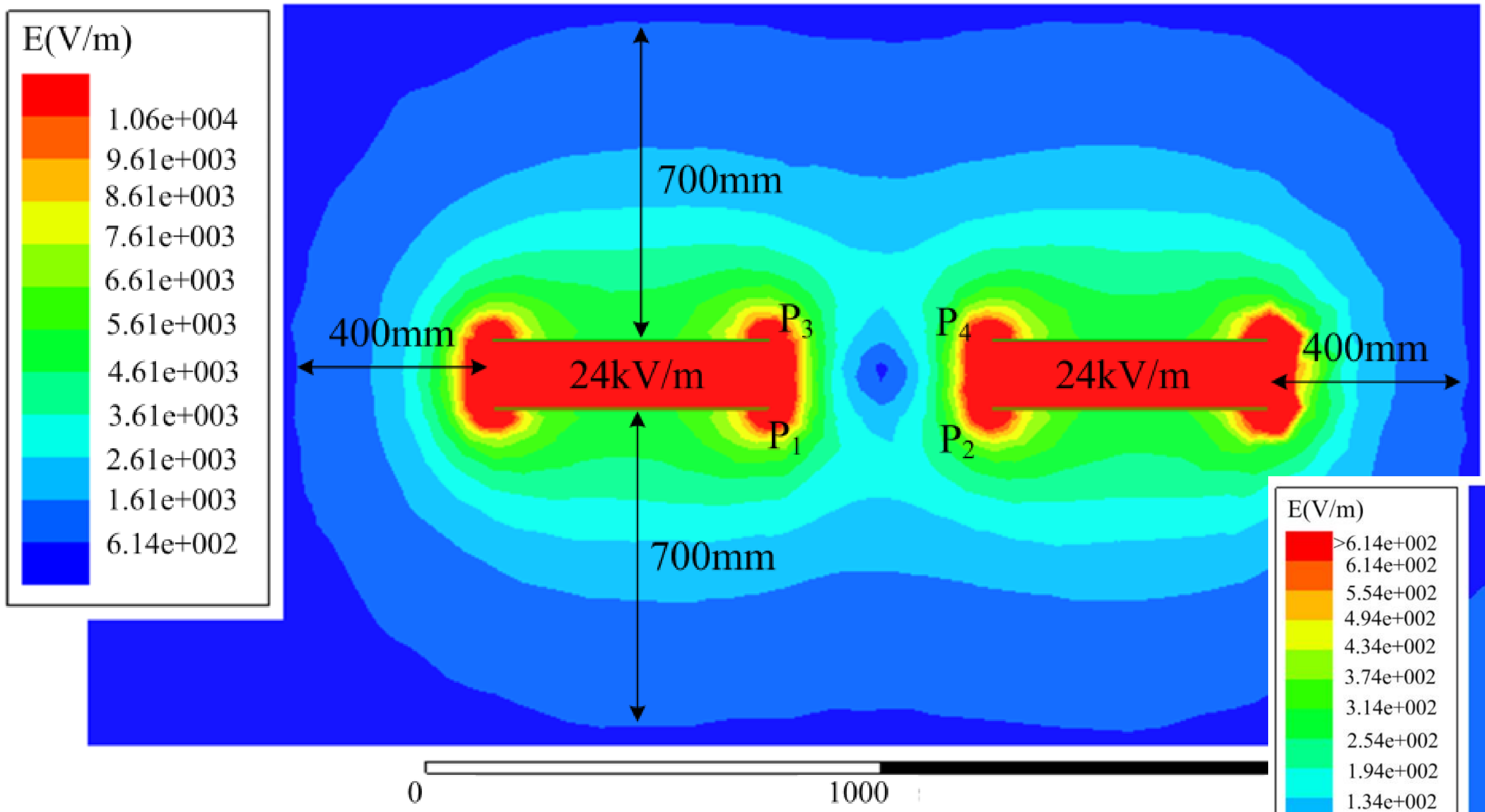




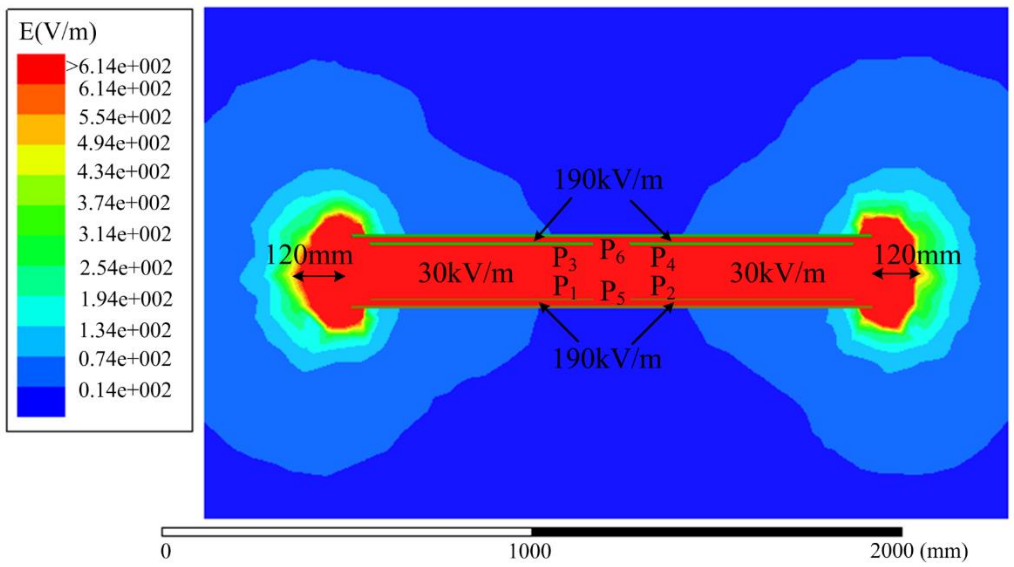
Experiment Result: the gum wrapper was burned and there left an imprint, which means the temperature is high.

Safety of Capacitive Wireless Power Transfer

- $|V_{C1}|=|V_{C2}|=5.2$ kV, $|V_{14}|=|V_{23}|=4.2$ kV, and $|V_{13}|=|V_{24}|=3.1$ kV



➢Further research shows safe range is 400 mm from the edge with 300mm misalignment



➢ Safe range is 700mm from the edge of plates

SAE J2954 - Wireless Charging of Electric and Plug-in Hybrid Vehicles

- Started in November, 2010 (Monthly meetings)
- General aspects of WPT, establish acceptable criteria for interoperability, electromagnetic compatibility, minimum performance, EMC, safety and testing

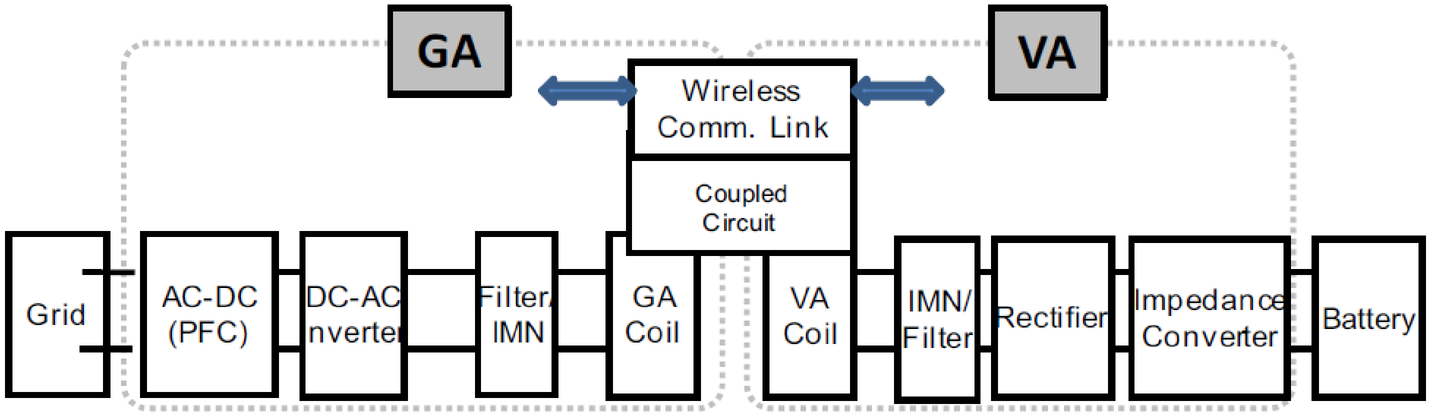


Figure 1 - SAE J2954 WPT flow diagram

SAE J2954 - Wireless Charging of Electric and Plug-in Hybrid Vehicles

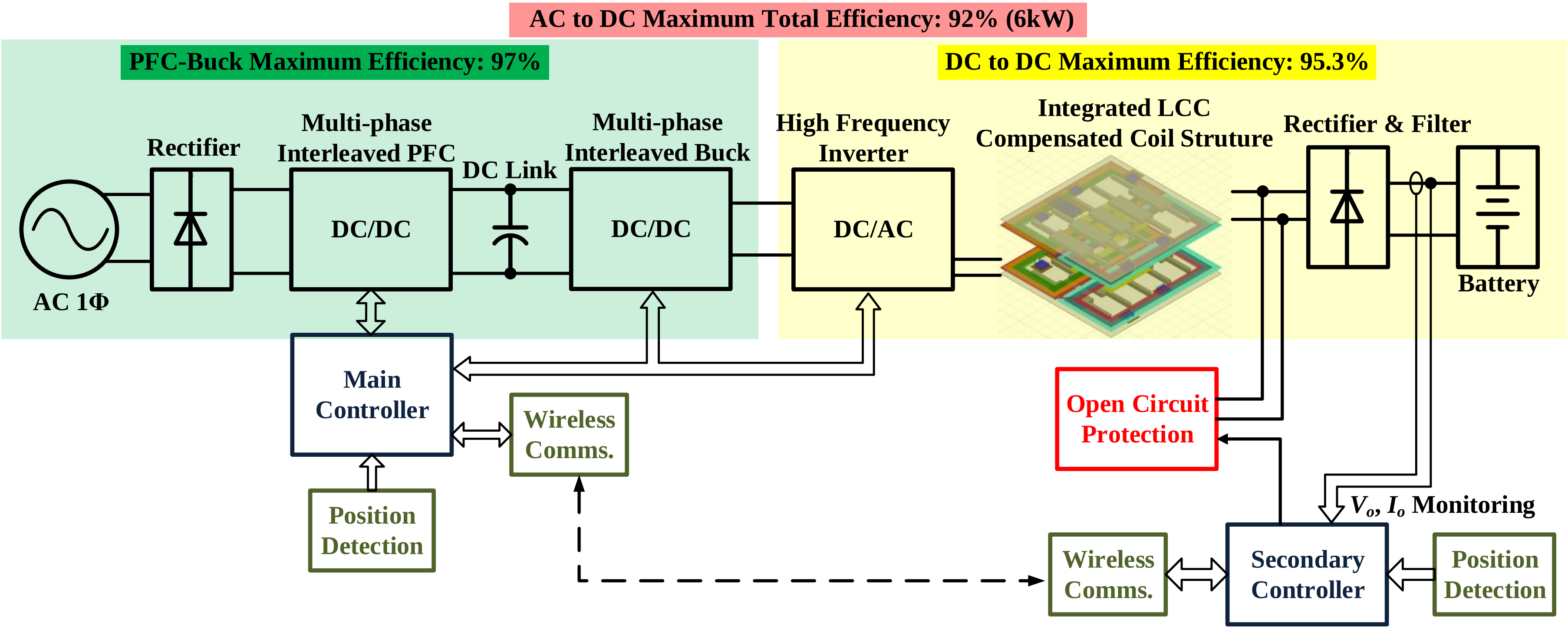
- 3.7 kW to 11.1 kW, and up to 22-kW developmental systems
- Frequency band: 81.39 - 90kHz
- Misalignment:75mm x direction and 100mm y direction
- Vertical distance: 100-250mm, Z1, Z2, Z3 classes
- Location of receiver and size limits of receiver
- Minimum efficiency: 85% aligned and 80% misaligned
- Communication method between transmitter and receiver
- Foreign and live object detection (FOD, LOD) methods

SAE J2954/2TM
Heavy Duty Wireless Power Transfer

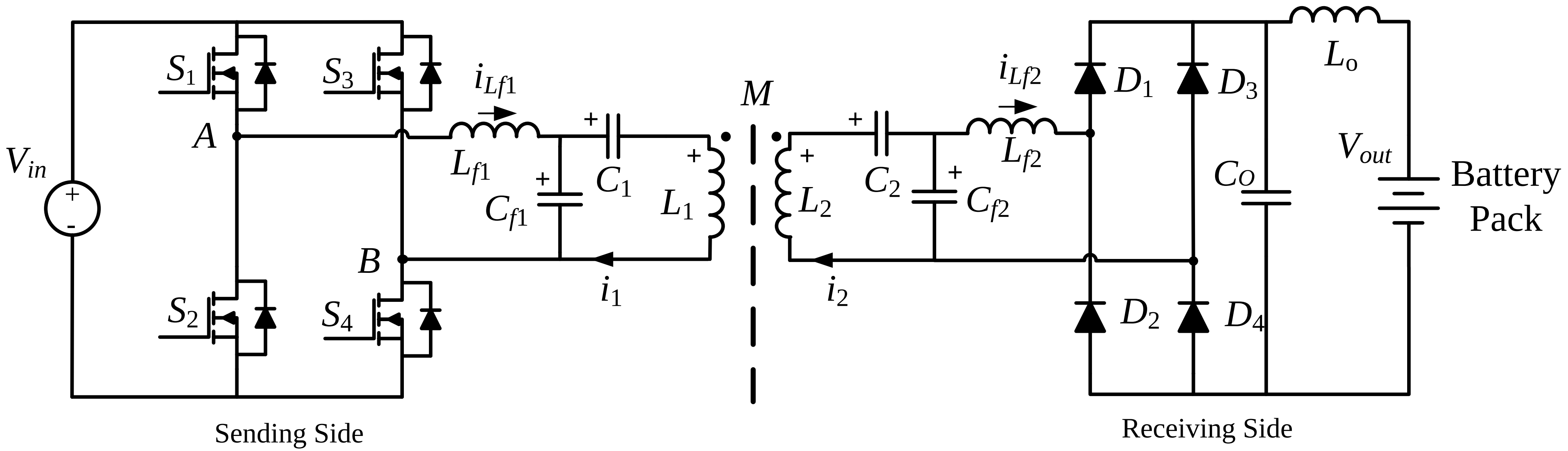
- Frequency: 21-38kHz
- Power class: 50kW – 500kW (Typical 200kW)
- Urban & On-Road Route Profiles
- Assumptions include 4kWhr/mile, 2 & 3 kWhr/mile
- Efficiency; Topology
- Communications
- Interoperability
- Safety related limitations to high-power WPT

Double-Sided LCC Topology

- Key inventions:
  - Optimized multi-coil design for maximum coupling, with bipolar architecture
  - LCC topology for soft switching to further increase efficiency and frequency
  - Distributed circuit parameters to minimize the capacitor size and voltage rating
  - Foreign object detection and electromagnetic field emissions for human and animal safety for the developed system.

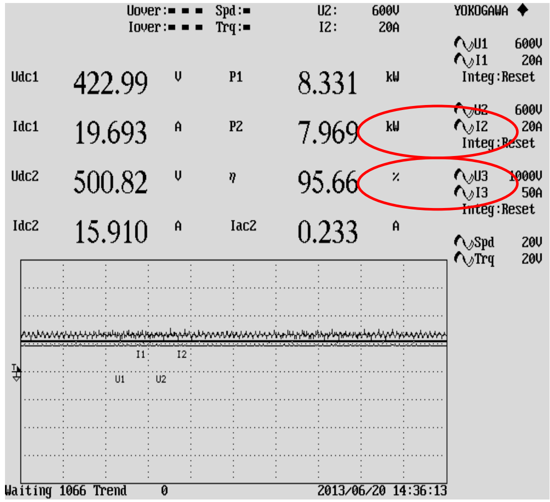


Double-sided LCC Compensated Wireless Power Transfer

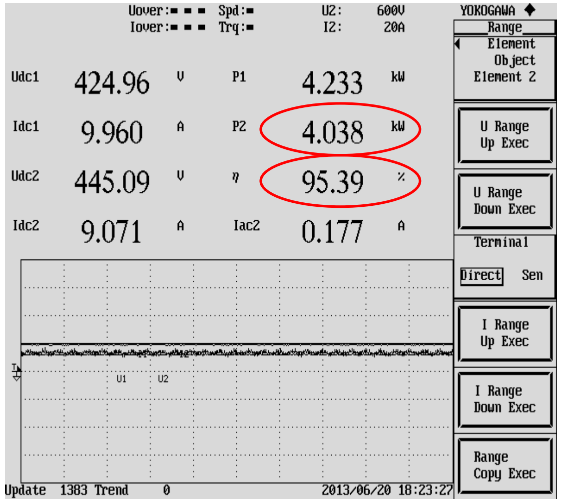


- Important Characteristic:
- The output current at resonant frequency: $I_{Lf2} = I_{Lf2\_1} = \frac{U_m}{\omega_0 L_f} = \frac{L}{\omega_0 L_f^2} \cdot k \cdot U_1$
- The output power can be expressed as: $P = U_2 \cdot I_{Lf2\_1} = \frac{L}{\omega_0 L_f^2} \cdot k \cdot U_1 \cdot U_2$

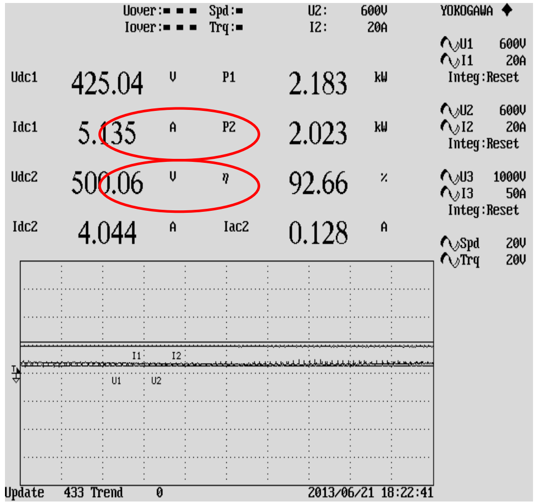
Experiment Results: DC-DC Efficiency



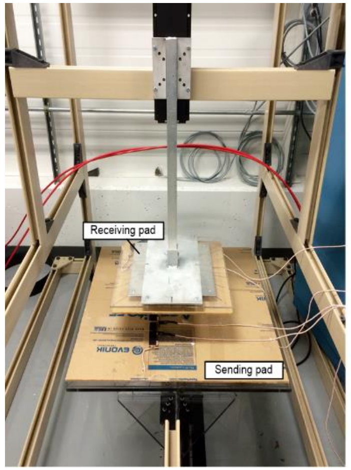
Xmis=0mm, Gap =200mm

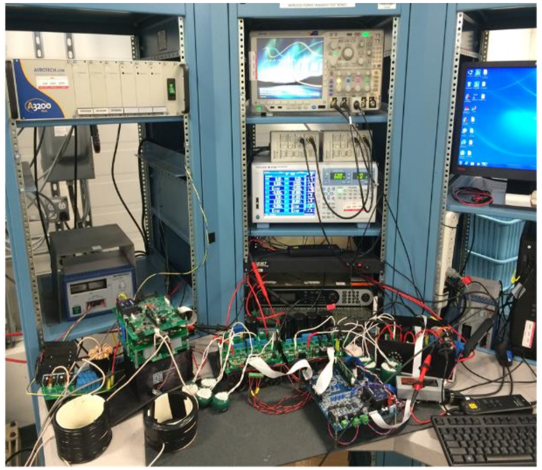


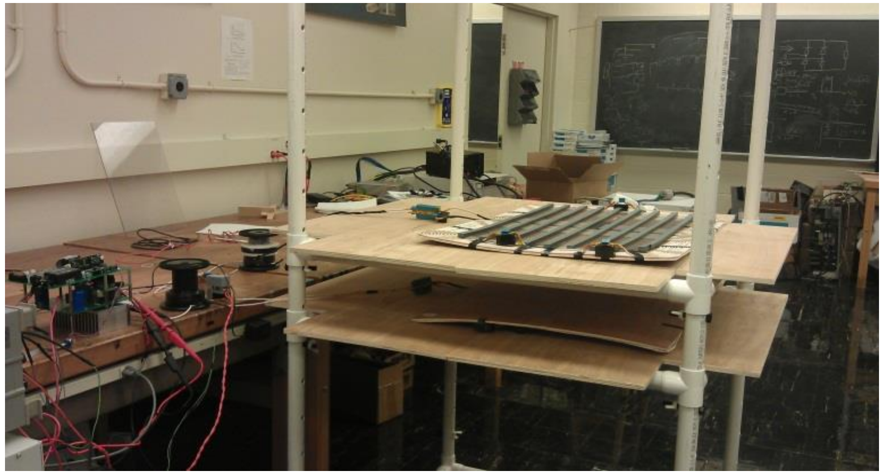
Xmis=300mm, Gap =200mm



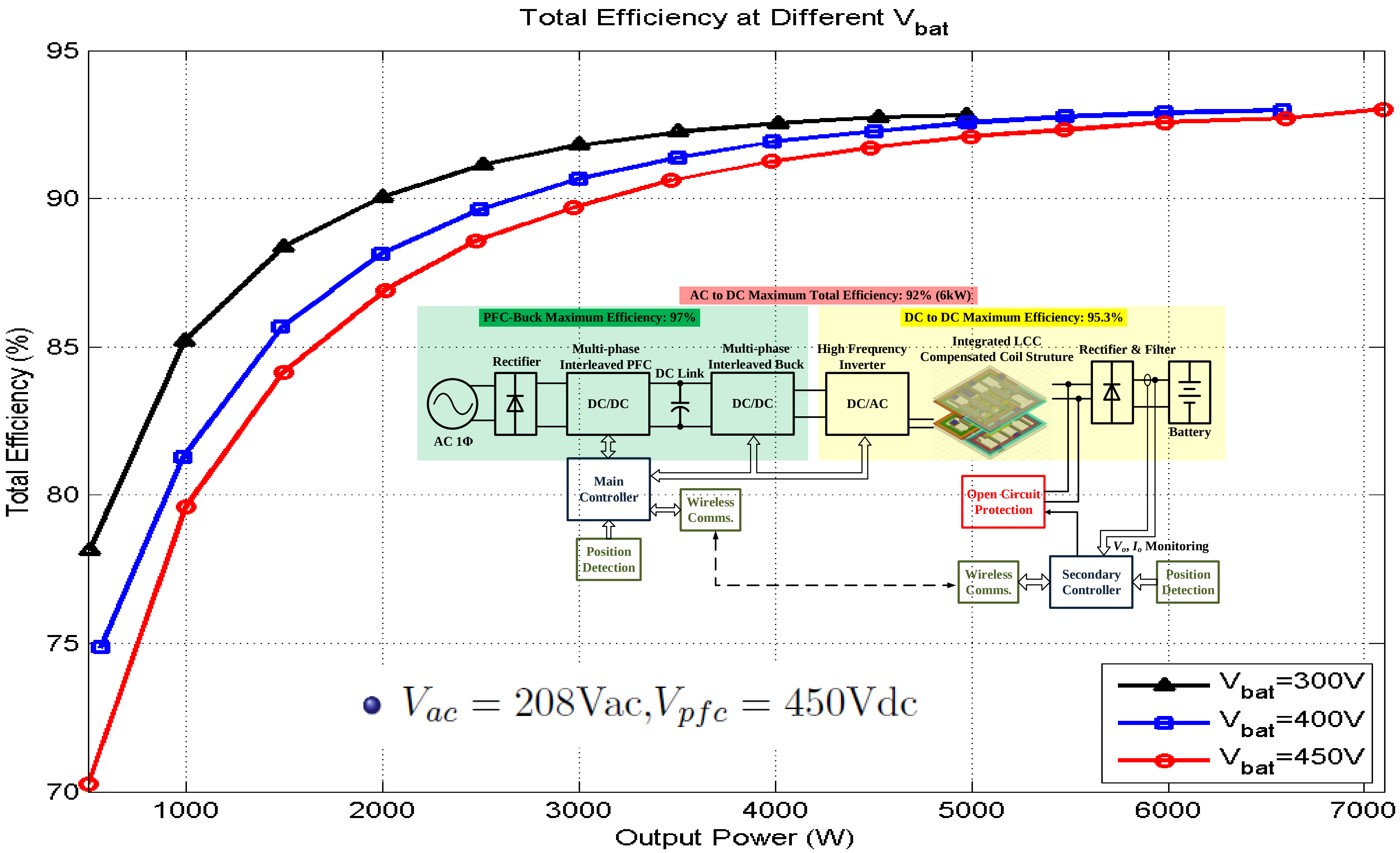
Xmis=125mm, Gap =400mm







System Efficiency

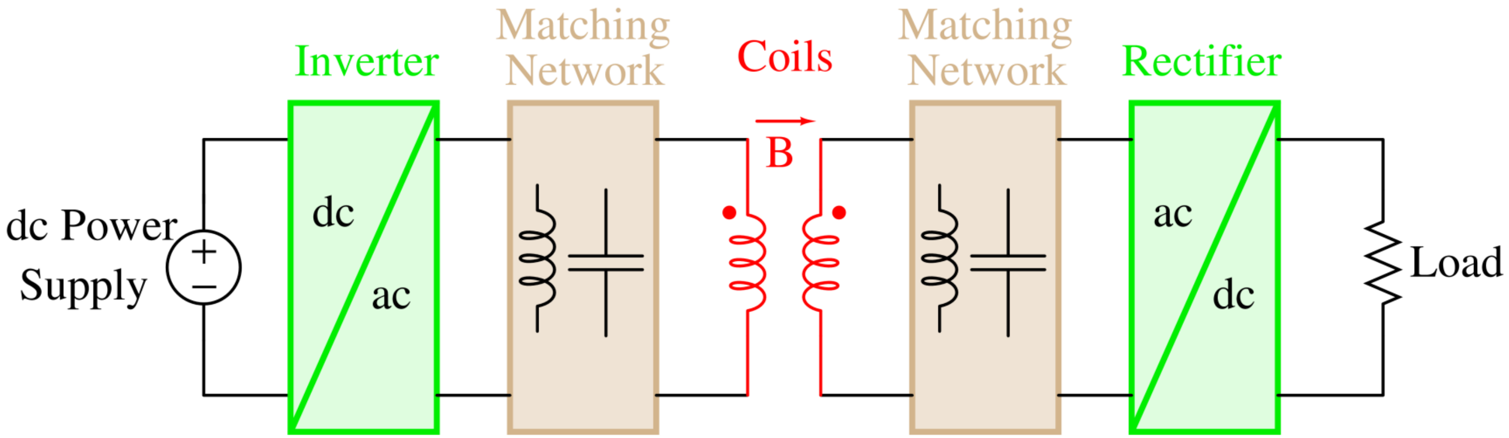


- $V_{ac} = 208\text{Vac}, V_{pfc} = 450\text{Vdc}$

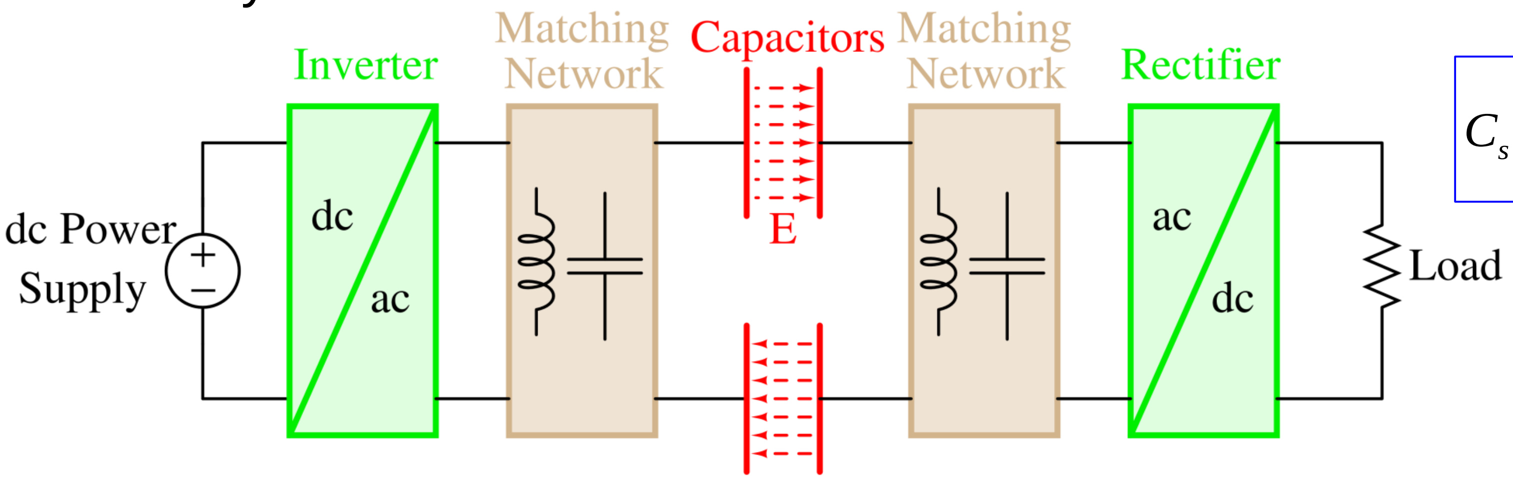
Capacitive Wireless Power Transfer

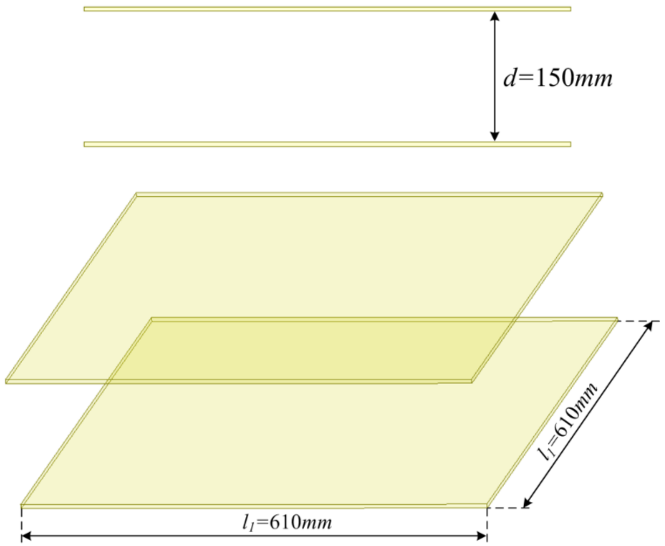
Analogy of CPT and IPT

- IPT System Structure



- CPT System Structure



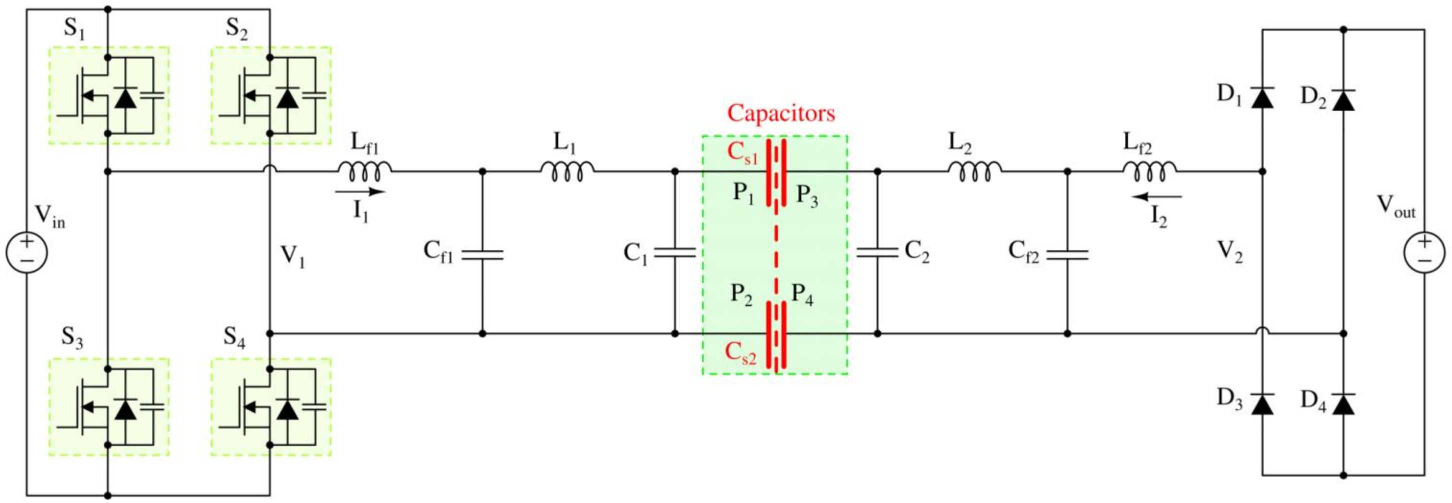


$$C_s = [1 + 2.343 \cdot (d / l_1)^{0.891}] \cdot \frac{\varepsilon \cdot l_1^2}{d} = 36.7\text{pF}$$

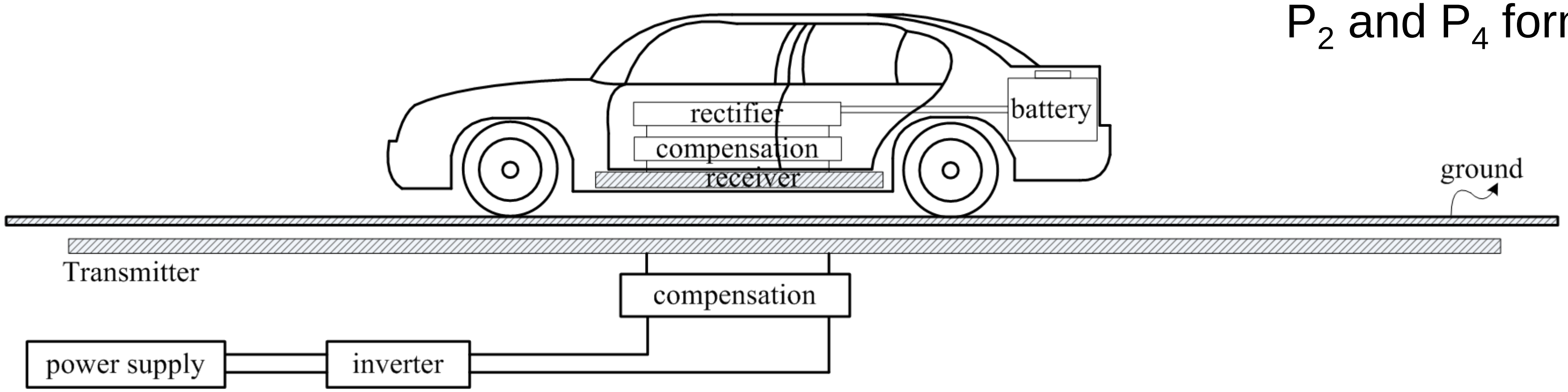
NEW Compensation Topology is Required!

- Electric field is not sensitive to metal material nearby
- Electric field does not generate eddy-current loss in the metal
- CPT coupler uses metal plates, instead of Litz-wire, reduce system cost

Double-sided LCLC Circuit Topology



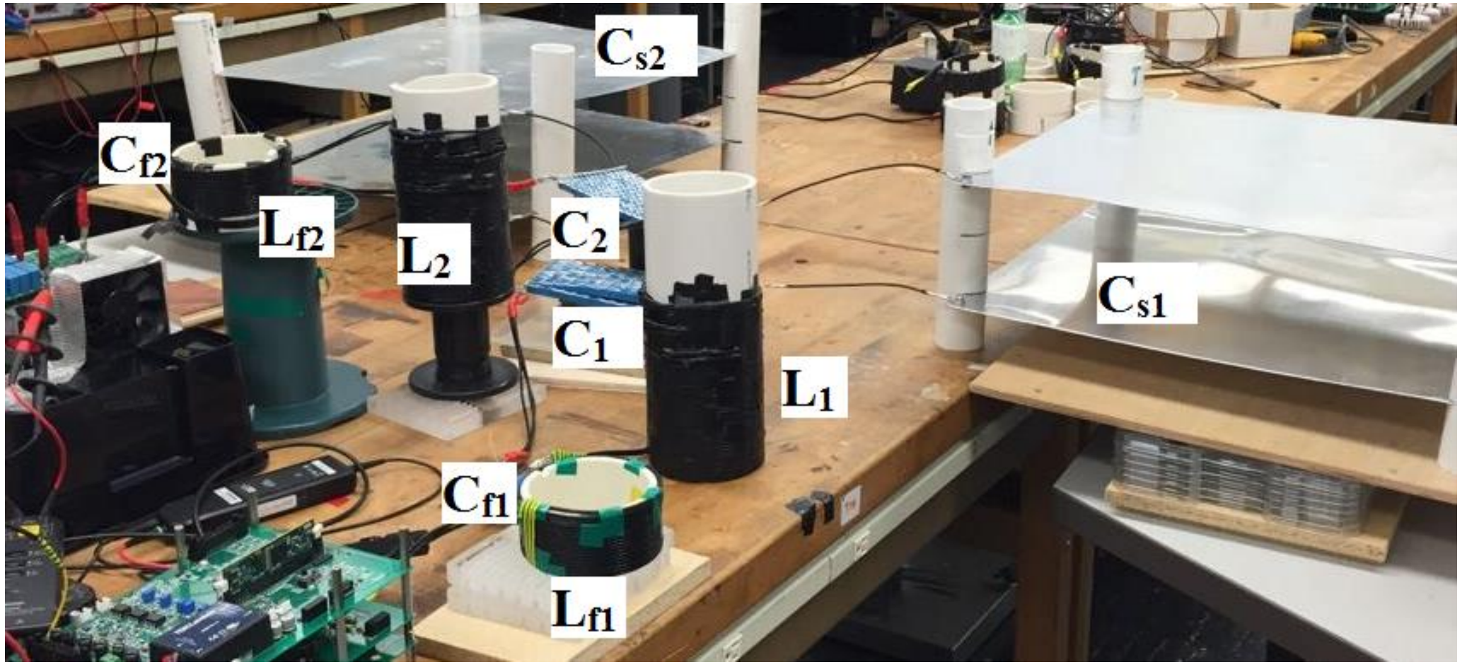
- Two inductors and two capacitors are used at each side
- P_1 and P_2 are at the primary side, P_3 and P_4 are at the secondary side
- P_1 and P_3 form a coupling capacitor, P_2 and P_4 form the other capacitor

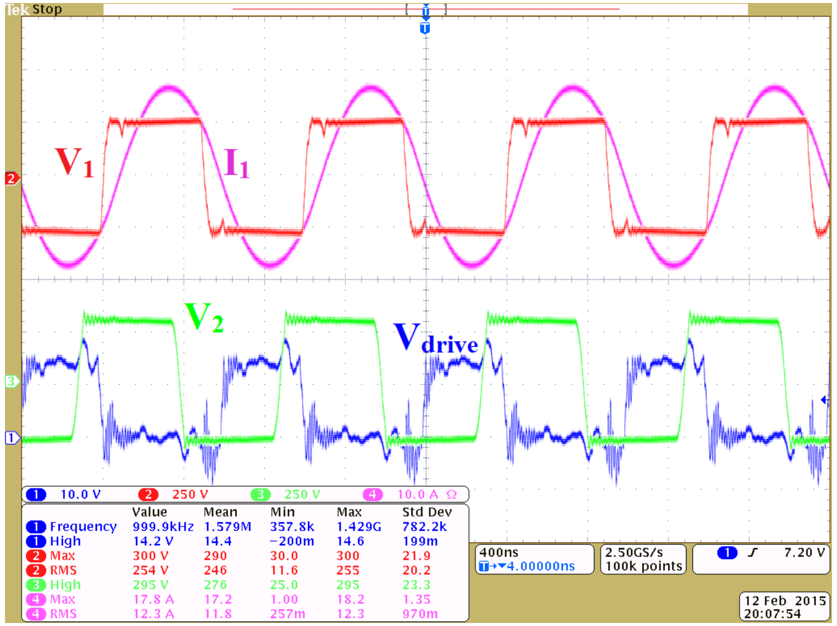


Dynamic CPT

F. Lu, H. Zhang, H. Hofmann and C. Mi, "A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging," in *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6011-6014, Nov. 2015. doi: 10.1109/TPEL.2015.2446891

CPT Prototype Design and Results





- Plates are made by aluminum sheets
- P_{out}=2.4kW at designed input/output
- Inductors are wound by AWG46 Litz-wire without magnetic core
- High-power-frequency thin film capacitors resonate with the inductors
- Silicon Carbide (SiC) MOSFETs C2M0025120D are used in the inverter
- SiC diodes IDW30G65C5 are used in the rectifier

Comparison of CPT and IPT

	IPT	CPT
Switching frequency	85kHz	1MHz
Coupling field	Magnetic	Electric
Foreign objects (metal)	Will generate heat	Will not generate heat
Material	Litz wires, ferrites	Copper/Aluminum plates
Cost	High	Low
Safety	Good	Excellent
Size	Small	Large
Misalignment	Poor	Good
Efficiency	Excellent	Excellent
Voltage stress	Medium	High
Power level	High	Medium
Stationary or dynamic	Better for stationary	Both

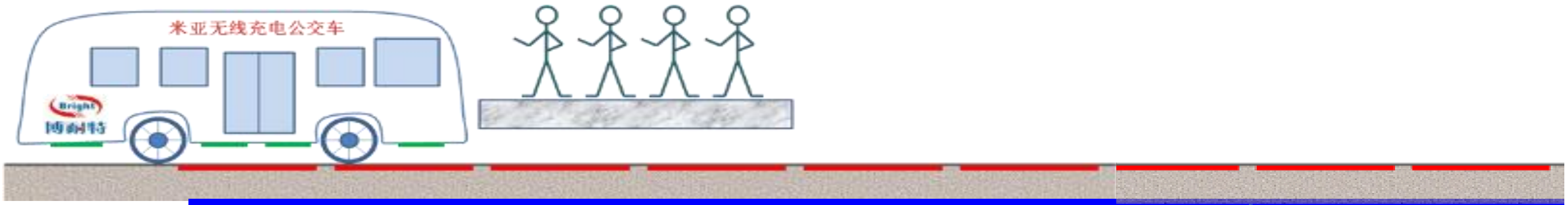
Other Developments and Applications of WPT

Topology, Coil Structure, and Other Issues

- SS and double-sided LCC are among the best choices
- PS, SP, PP and less popular
- SN, LCL, LCC_N etc. are more suited for high power, short distance WPT system
- Unipolar coil, for longer distance, and bipolar for shorter distance WPT
- Mechanical device to move coil position and change distance
- LOD and FOD remains a challenge, both technology and cost
- CPT is on the rise

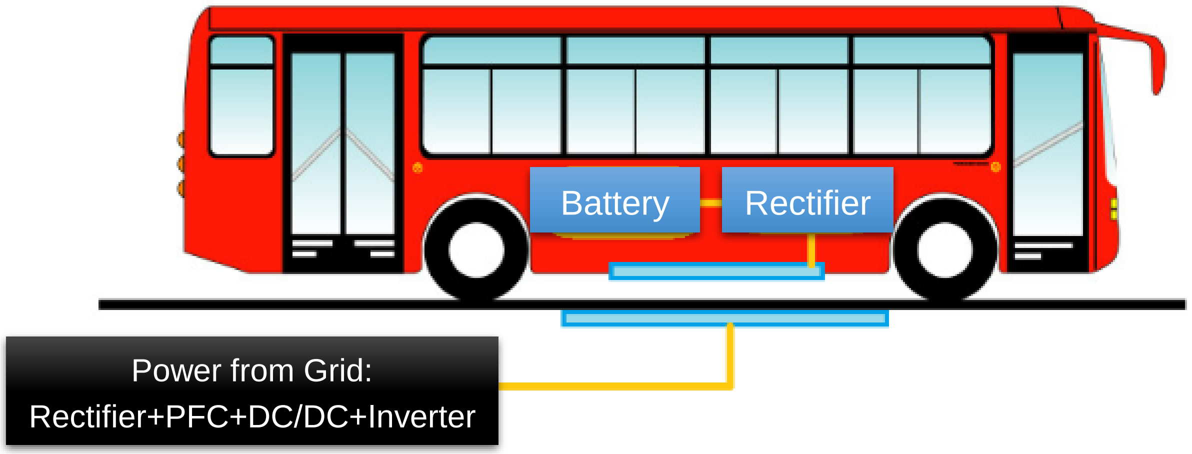
Wireless Charging of Electric Buses

- Charge points are located in the bus stop area



Bus drives in 10 s; Bus stop 20s; bus drive out 10s

Total charging time: 30s



Total energy delivered:

30s/3600s * 120kW

= 999Wh ←→1.6km

Initial Savings – cover initial investment

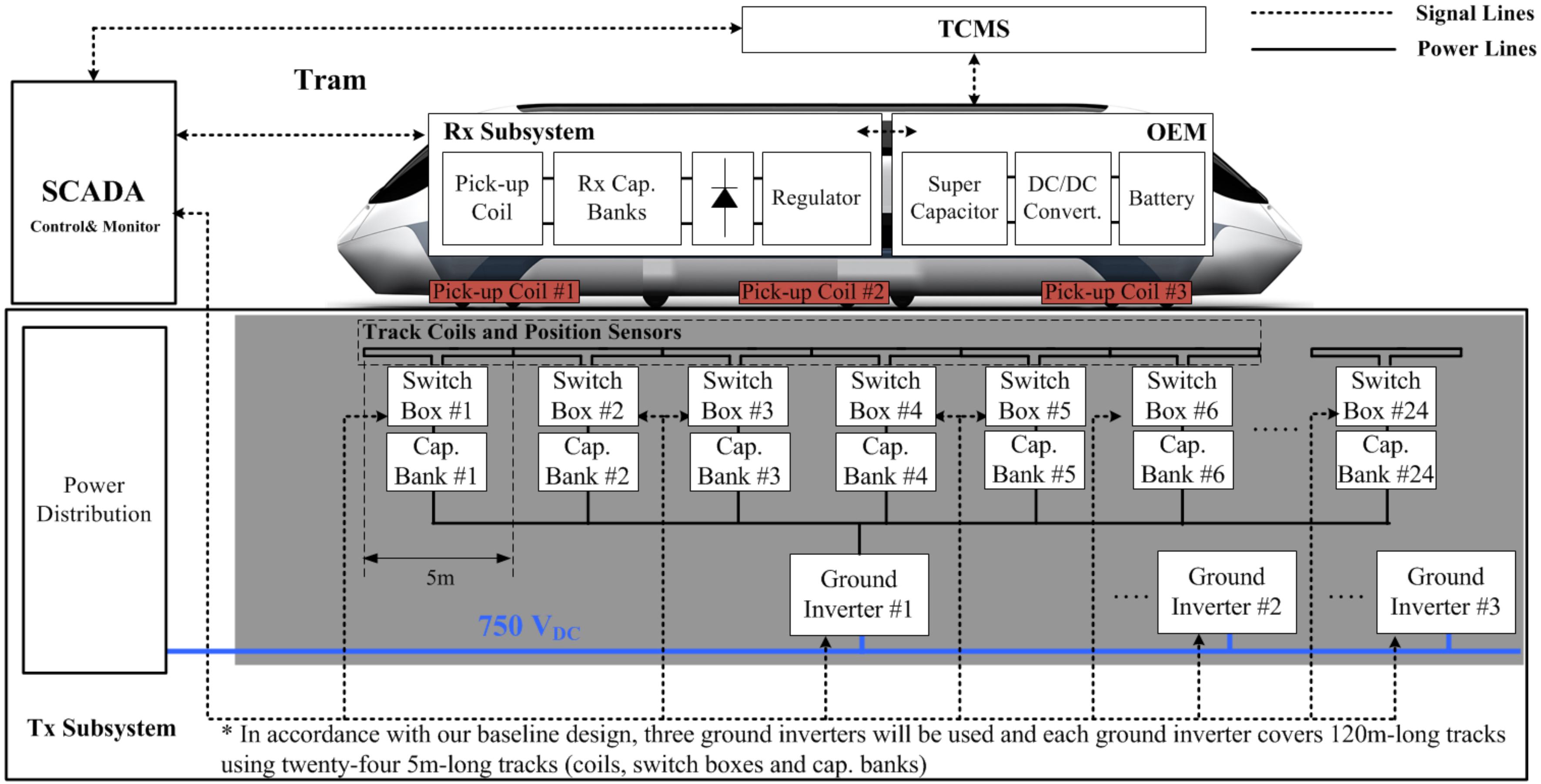
Annual Savings - $ 250k

Economics/Benefits of a Bus Project

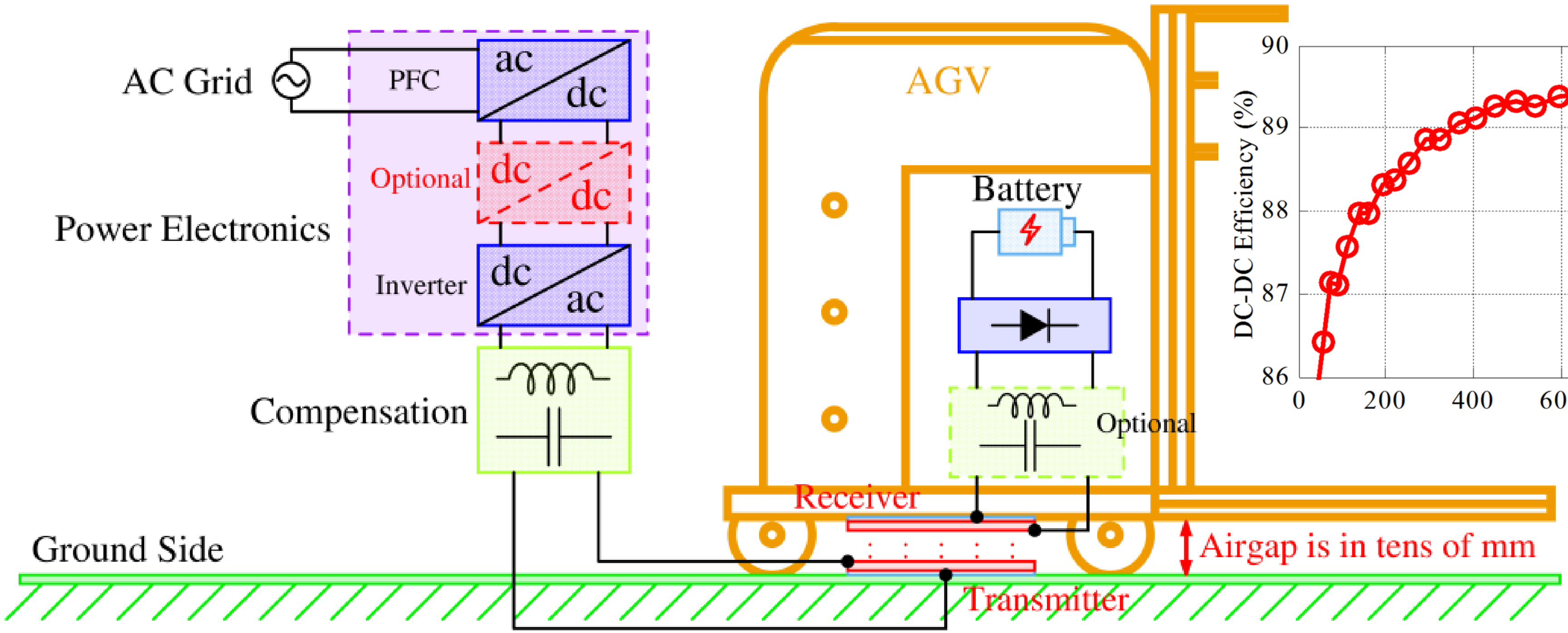
- Saving on board battery
  - Savings of investment of battery: $100k/bus
  - Savings of weight >1 T/bus = 200Wh/mile/bus
- Savings of operating cost
  - Two operators/station is no longer needed: $200k/year
- No need of new land for charge station installations
- Increase battery life due to narrow SOC band is used
  - Top off every time at bus stops, no full discharge of the battery
- More reliable; does not have to deal with hundred of amperes of currents, eliminate spark, eliminate electric shock
- Less maintenance: no tear and wear of cable, plug,

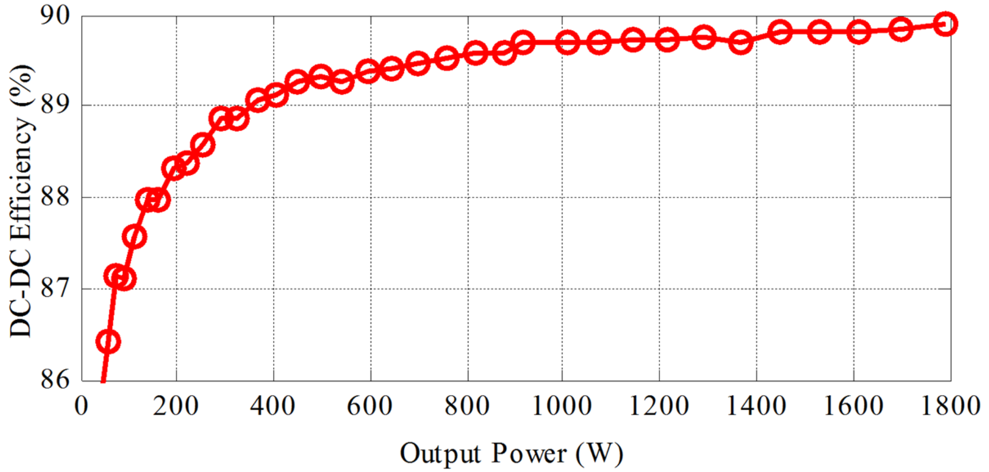
Wireless Power Transfer for Light Rail

- Charge points are located in the Train stops area

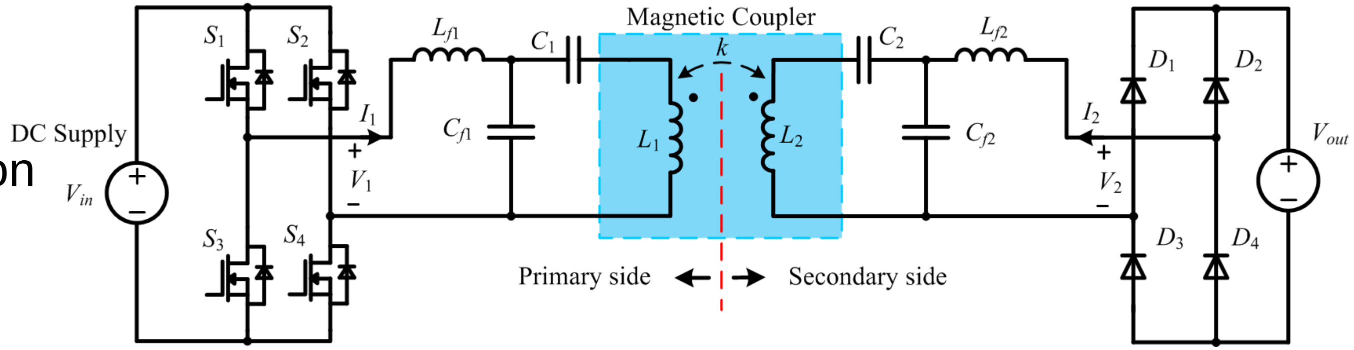


Wireless Charging of AGVs

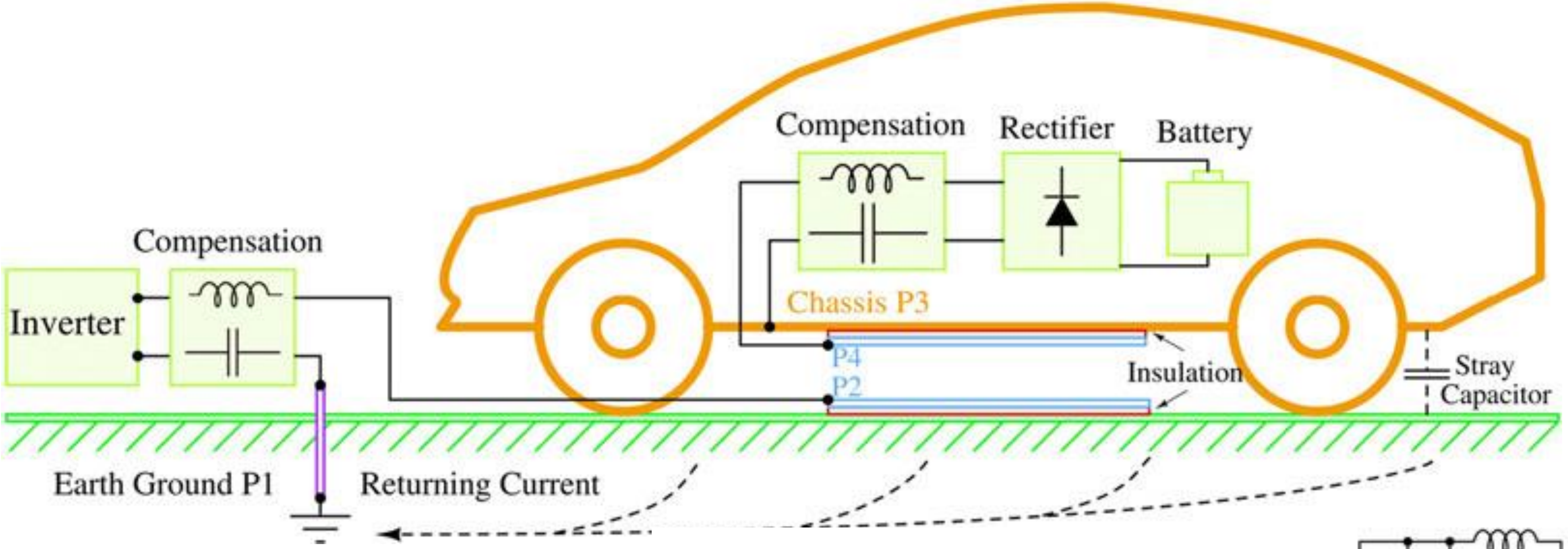




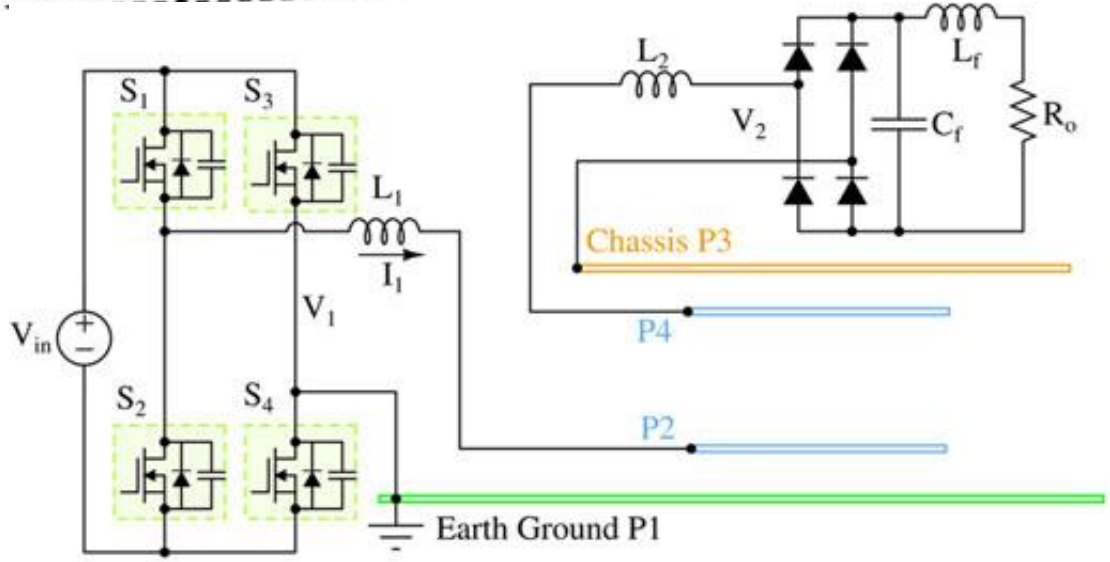
- Properties of an AGV system
  - ➢ Low chassis height: around 10's of mm
  - ➢ Low battery voltage due to safety reason
- Motivations of wireless charging
  - ➢ Increase effective working time
  - ➢ Reduce the size of the onboard battery



Single Ended CPT System

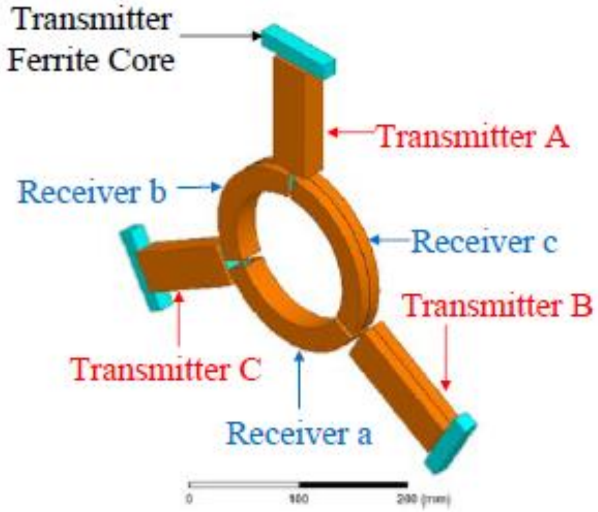


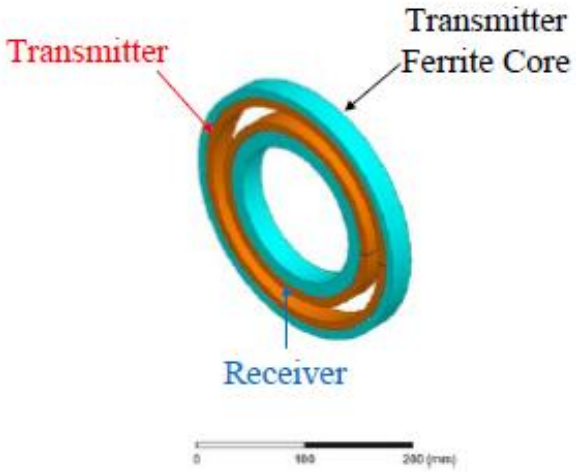
- Two plates only
- Chassis and the earth are the third and forth plates

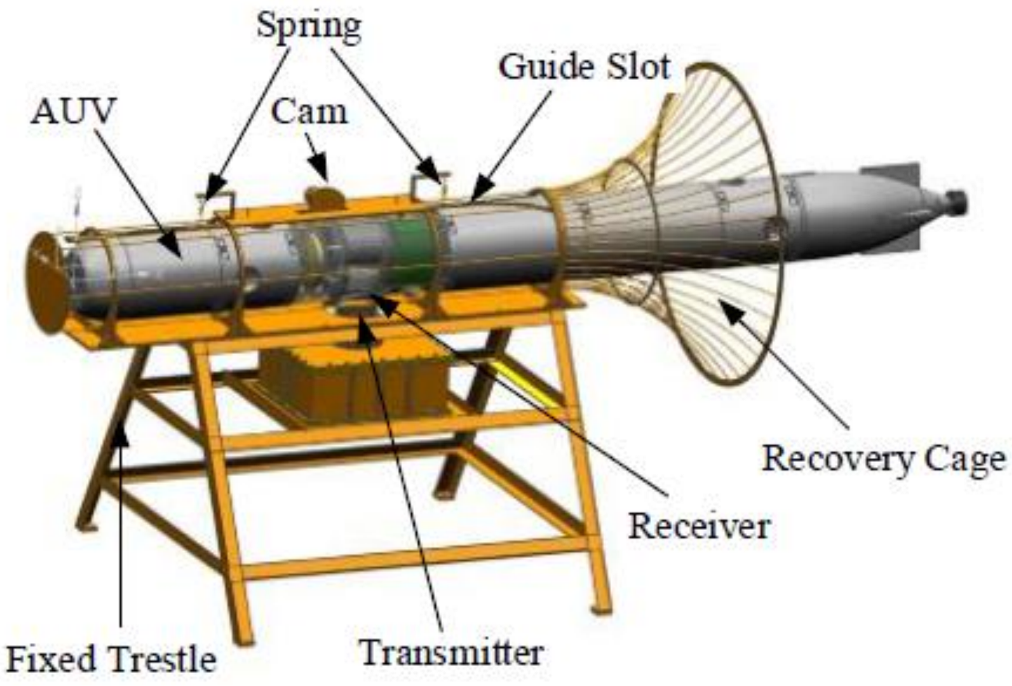


Underwater Vehicle Applications

- Losses due to seawater
- A three-phase system helps improve efficiency and reduce EMC







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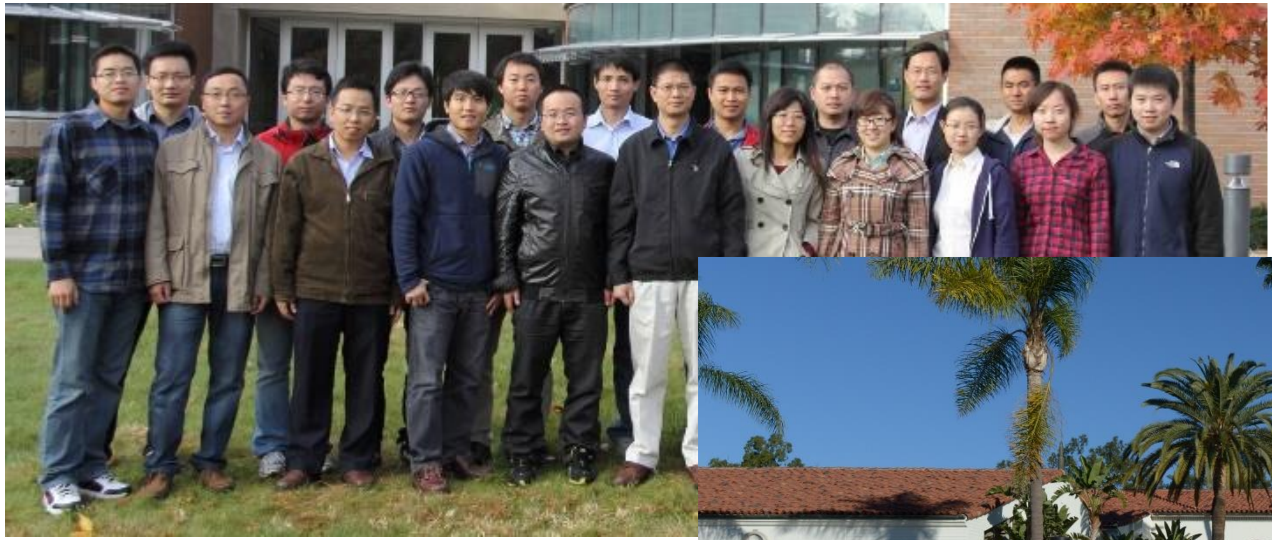

Q & A

Thanks!