Wireless Plug-in Electric Vehicle (PEV) Charging

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Project ID: VSS061

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Overview

Timeline

- Start – Oct. 2010
- Finish – Sept. 2013
- 84% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received for FY11
  - $400K

Partners/Advisors

- ORNL Fusion Energy RF experts

Barriers and Opportunity

- Plug-in Electric Vehicles (PEV) are burdened by the need for cable and plug charger, galvanic isolation of the on-board electronics, bulk and cost of this charger and the large energy storage system (ESS) packs needed.
- Wireless charging opportunity:
  - Provides convenience to the customer.
  - Inherent electrical isolation.
  - Regulation done on grid side.
  - Reduce on-board ESS size using dynamic on-road charging.
- Program targets
  - Level II charging at 3.6kW to 19kW level
  - On road stationary charging
  - On road dynamic charging (vehicle in motion)

Objective

Objective for FY11

- Develop an efficient method for transferring large power levels over moderate distances in stationary setting
  - Loosely coupled magnetic resonant transformers have the potential to accomplish this goal.
  - Target for Vehicle application: Level II 3.6kW, 200mm gap @ >90% efficiency

Overall program

- Wireless charging of PEV stationary and dynamic conditions
  - Demonstrate 90% transfer efficiency from plug to battery at SAE J1772 Level II power of 3.6kW to 19kW.
  - Comply with SAE J2954 Wireless Power Transfer (WPT) emissions guidelines of 500uT in active zone and <62.5mG outside the active zone.
  - Target for Vehicle application: Level III >60kW to vehicle in motion.

Milestones

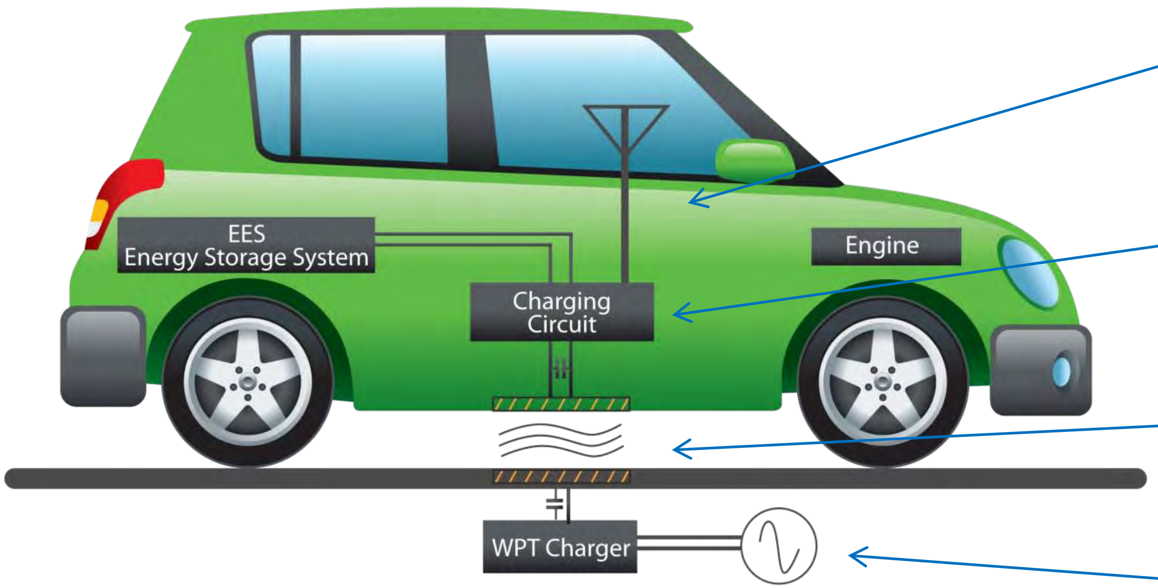
Month/Year	Milestone or Go/No-Go Decision
Sept-2011	Milestone: Completed three (3) iterations of antenna design Milestone: Completed skin and proximity effect model and simulation to understand power loss mechanisms Milestone: Completed current sensor scale calibration
May-2012	Milestone: Demonstrate antenna design with field shaping and shielding sufficient to meet ICNIRP field levels Go/No-Go Decision: Functional prototype meets field constraints and coil-to-coil efficiency >96%
Sept-2012	Milestone: Complete integration of wireless power transfer (WPT) into battery electric vehicle. Milestone: Complete integration of one (1) WPT into solar canopy charging station at ORNL.

Approach

- Design a system that first targets efficiency and then power levels:
  - Optimum operating points for maximum efficiency are quite different than for maximum power.
- Simulate circuit to find “best” operating region and to identify its required operating parameters.
- Target methods for best magnetic coupling over moderate distances and verify in the lab.
  - Vehicle ground clearance requirements:
    - U.S. 200mm and European vehicles 150mm gap
  - Dedicated power inverter needed
    - Design, analyze, simulate LCL inverter concepts at 3.6kW
  - Design and demonstrate grid side vs. vehicle side controls
    - Energy Storage System (Battery) regulation and communications needs.

Approach (contd.)

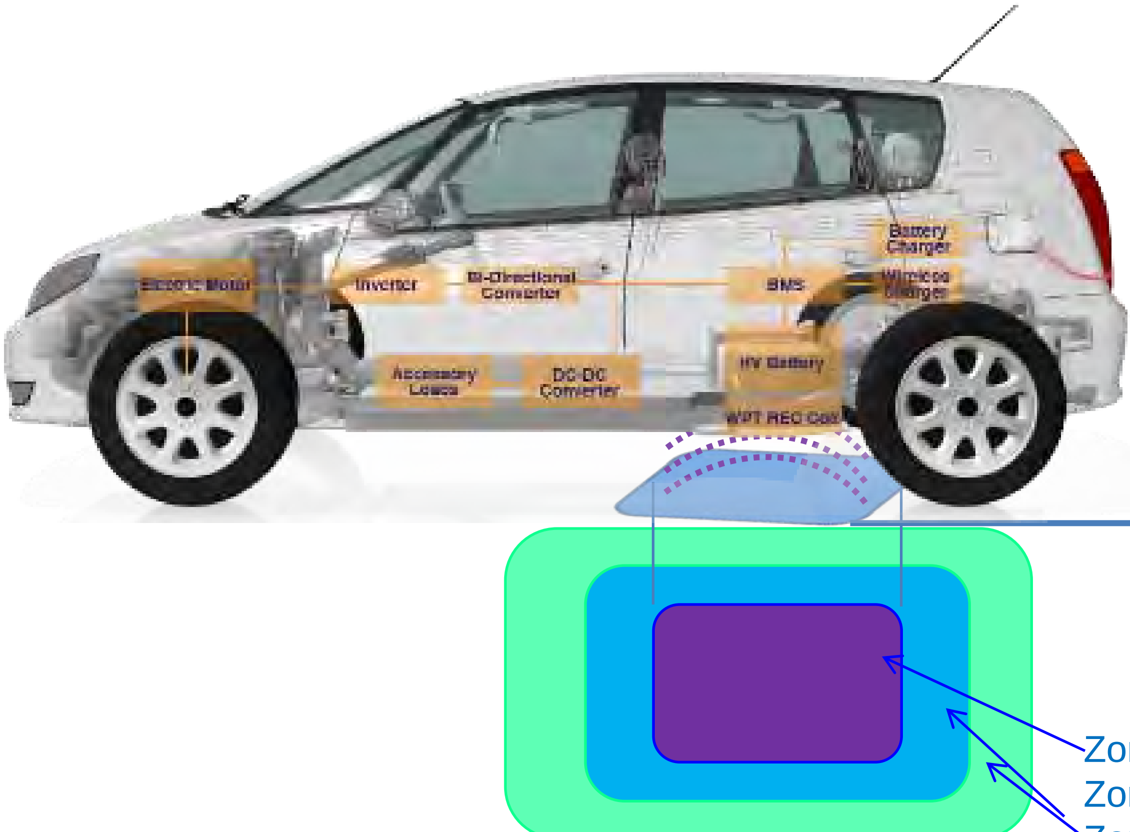
- Design and develop antenna system suitable for vehicle integration for stationary, on-road stationary and on-road dynamic charging at high power levels.
  - Technically: a non-radiating, near field reactive zone power transfer method
  - Practically: a convenient, safe and flexible means to charge electric vehicles.

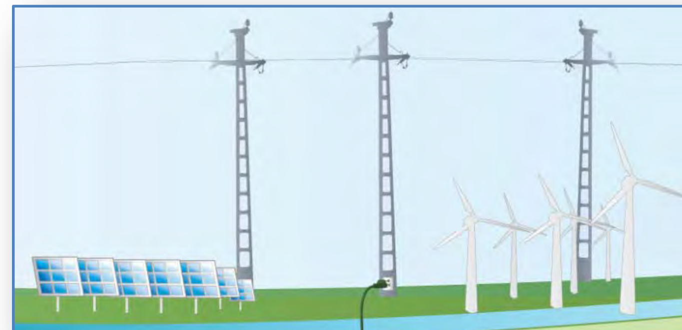


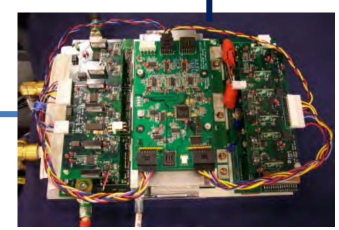
Graphic: Lindsey Marlar ORNL graphics services

Approach (contd.)

- Wireless charging technical challenges:
  - Antenna coil field shaping, vehicle chassis/wiring shielding, alignment tolerance
  - Maximum power across active zone and minimal side lobe emissions







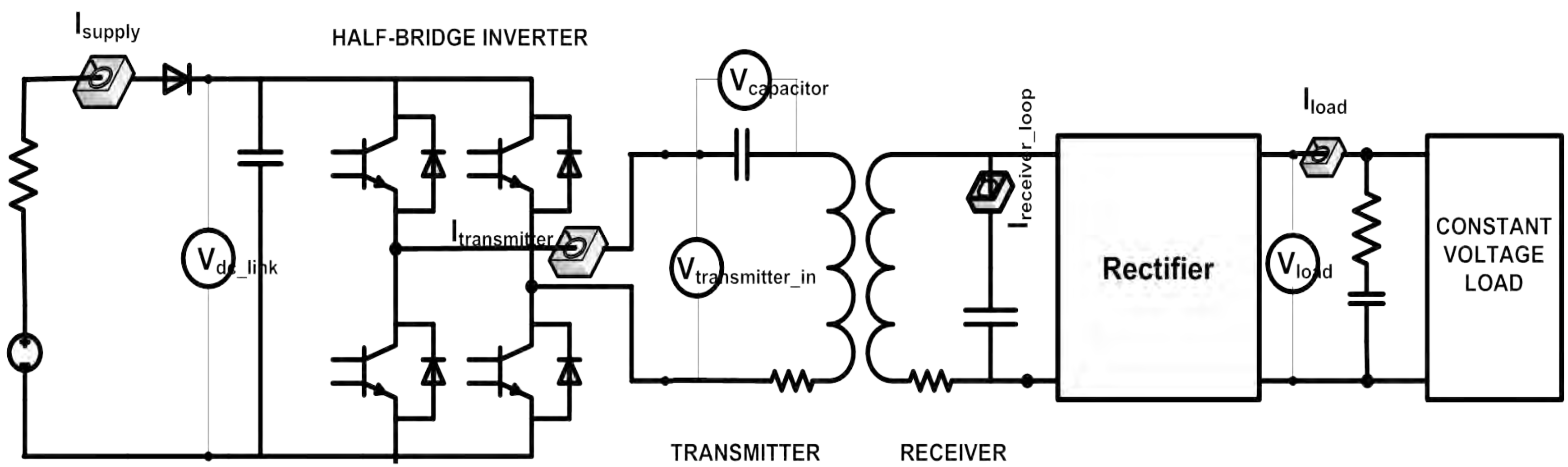
ORNL developed power inverter courtesy Gui-Jia Su.

Zone 1: Active field, ~1m2, <500uT
Zone 2: Transition:300mm boundary
Zone 3: Public zone: Field focusing & shielding <62.5mG (incl. cabin)

Vehicle graphic Lindsey Marlar, ORNL

Approach (contd.)

- Wireless power transfer using magnetic resonance coupling of air core transformer.
  - Power converter to regulate and drive resonant coil system
  - Simple uncontrolled rectifier on secondary
- Prototype hardware identified sensor accuracy issue
  - Current sensors, especially flux nulling type, suffer from scale error in this application.



Circuit diagram obtained from Dr. Matthew Scudirie of ORNL

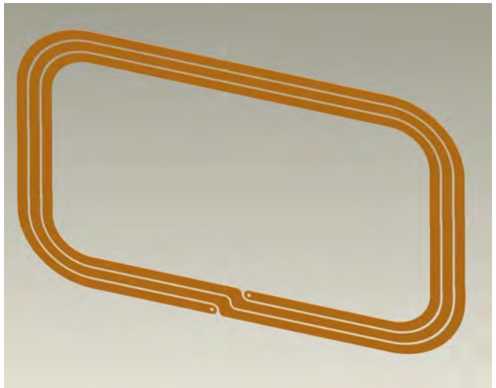
Approach (contd.)

- Antenna (coil) design is crucial to this program
  - Meeting plug to battery efficiency target demands very high coil-to-coil efficiency

1st Gen

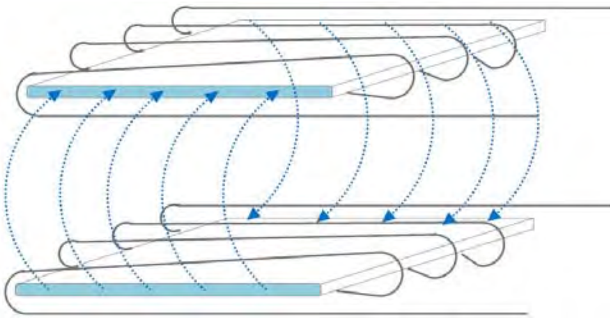
Copper tube (0.635mm), 2 in parallel, 3 turns overall:
Rac = 16mOhm
Ls = 15.3 uH

2nd Gen



Copper plate (2.37mm thich by 25.4mm width), 3 turns overall:
Rac = 11mOhm
Ls = 15.3 uH

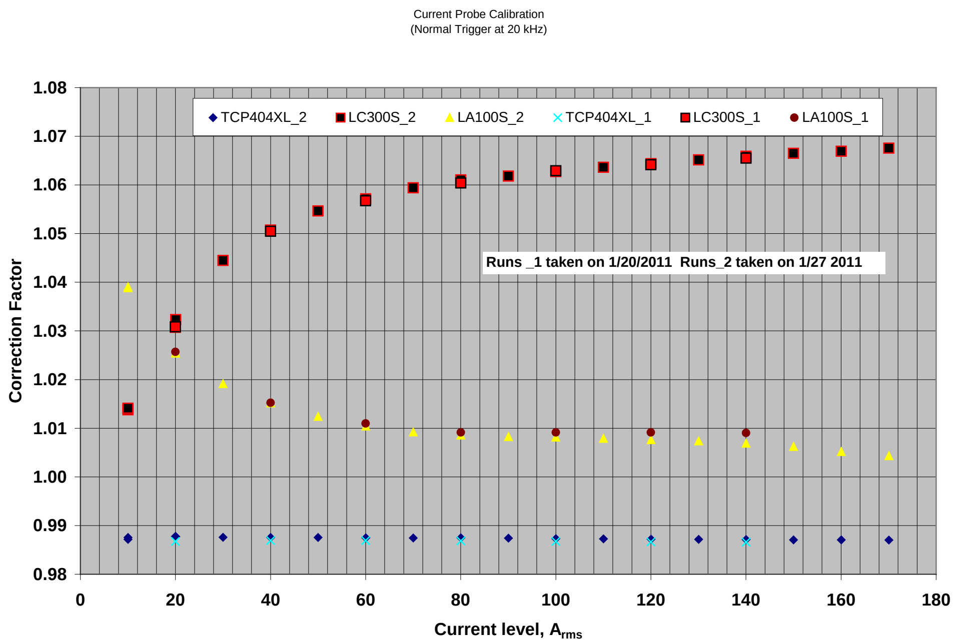
3rd Gen

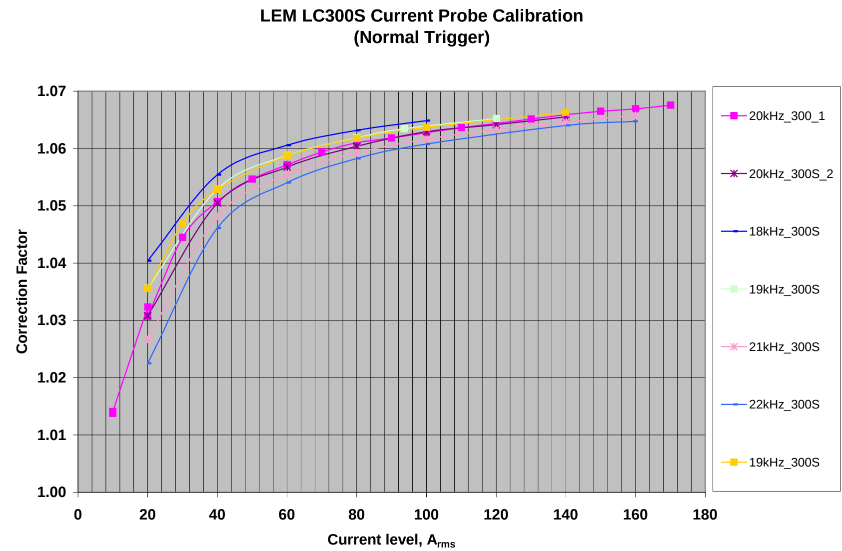


Copper tube (0.635mm) around plexiglass core for field shaping materials, 4 turns overall
Rac = xx mOhm
Ls = yy uH

Approach (contd.)

- Current sensor issue added unanticipated tasks
  - Can exhibit significant scale error at operating frequency
  - Tests performed at 20kHz over full range of current for the following sensors:
  - LEM LA100S; LEM LC300S; Tektronix® probe TCP404XL





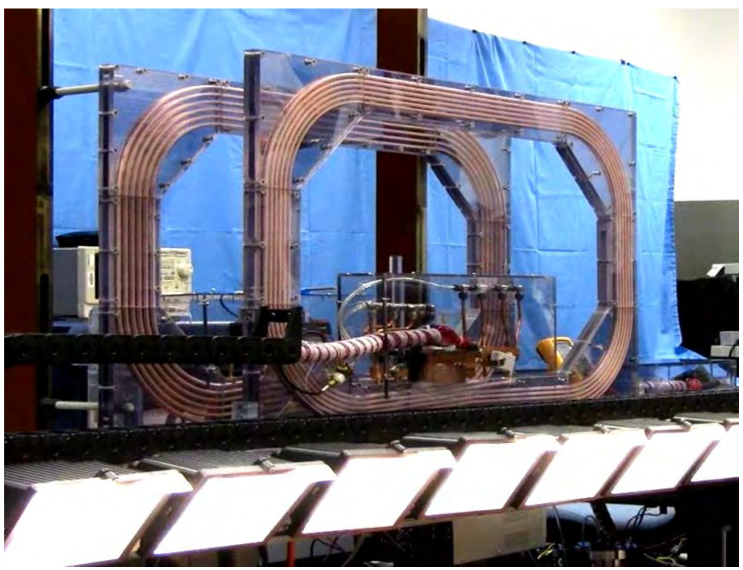
Scale error is repeatable
Tektronix current probe stable with current magnitude.

Correction factor necessary for LEM

Charts courtesy of Dr. John McKeever of ORNL

Technical Accomplishments and Progress - Overall

- Completed fabrication of laboratory test apparatus
  - Two antennas are mounted vertically to allow easier access for experimental work.
  - The closer “mobile” antenna rides in a track that translates it in the direction of travel to measure longitudinal displacement effects.
  - The transmitting antenna in the back could be adjusted to measure coil spacing (d) and lateral displacement effects to study variation of coefficient of coupling (k).



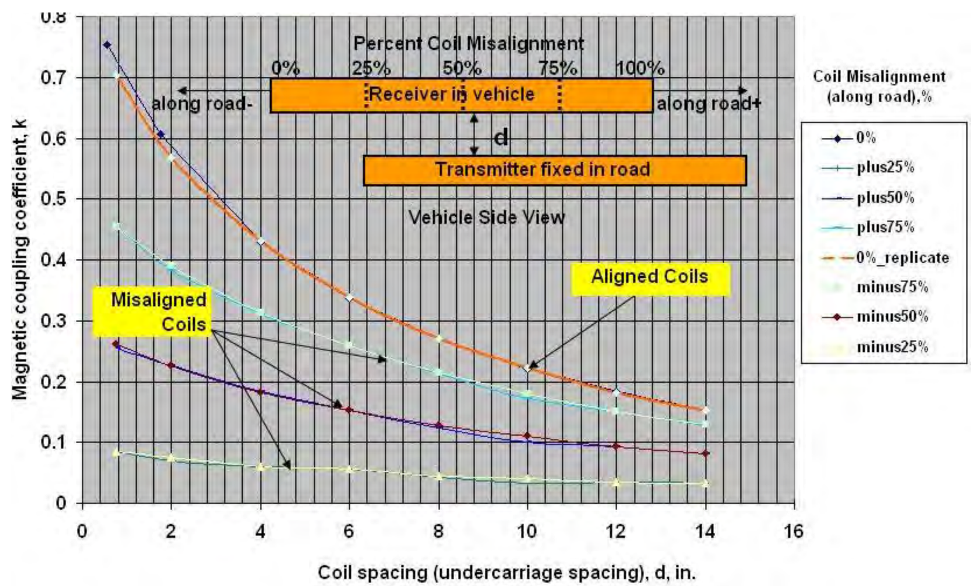
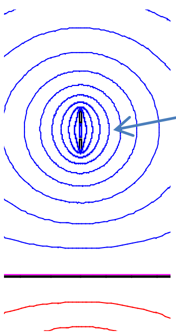
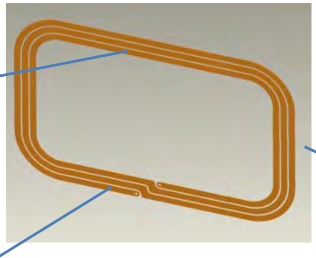


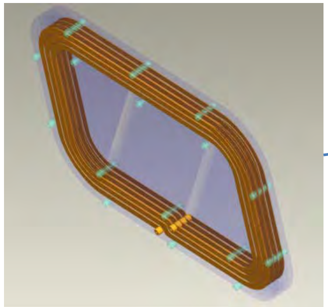
Photo and chart courtesy of Dr. Matt Scudiere of ORNL

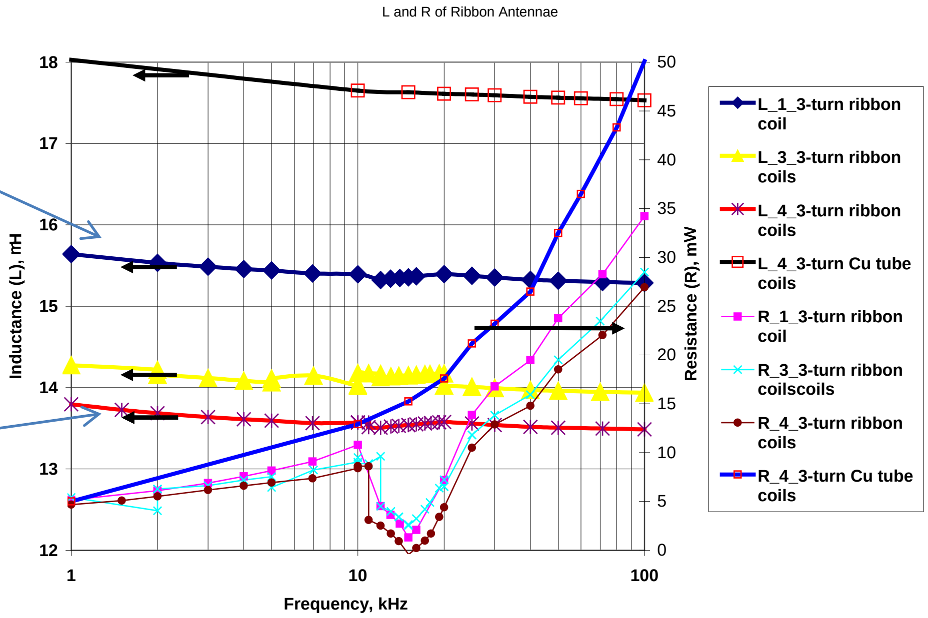
Technical Accomplishments and Progress – FY11 (contd.)

- Evaluation of stacked “ribbon” antennas
  - ORNL evaluated the performance (Rac, Ls) of 1, 3 and 4 antenna coils in parallel
  - Very disappointing results due to substantial proximity effect in 2^{nd} gen ribbon coil antenna.









Plot of coil field at 20kHz excitation in air

Source: coil CAD drawings courtesy Dr. Matthew Scudiere, Laboratory test data Dr. John McKeever
Field flux plot simulation: Dr. Pan-Seok Shin

Technical Accomplishments and Progress – FY11 (contd.)

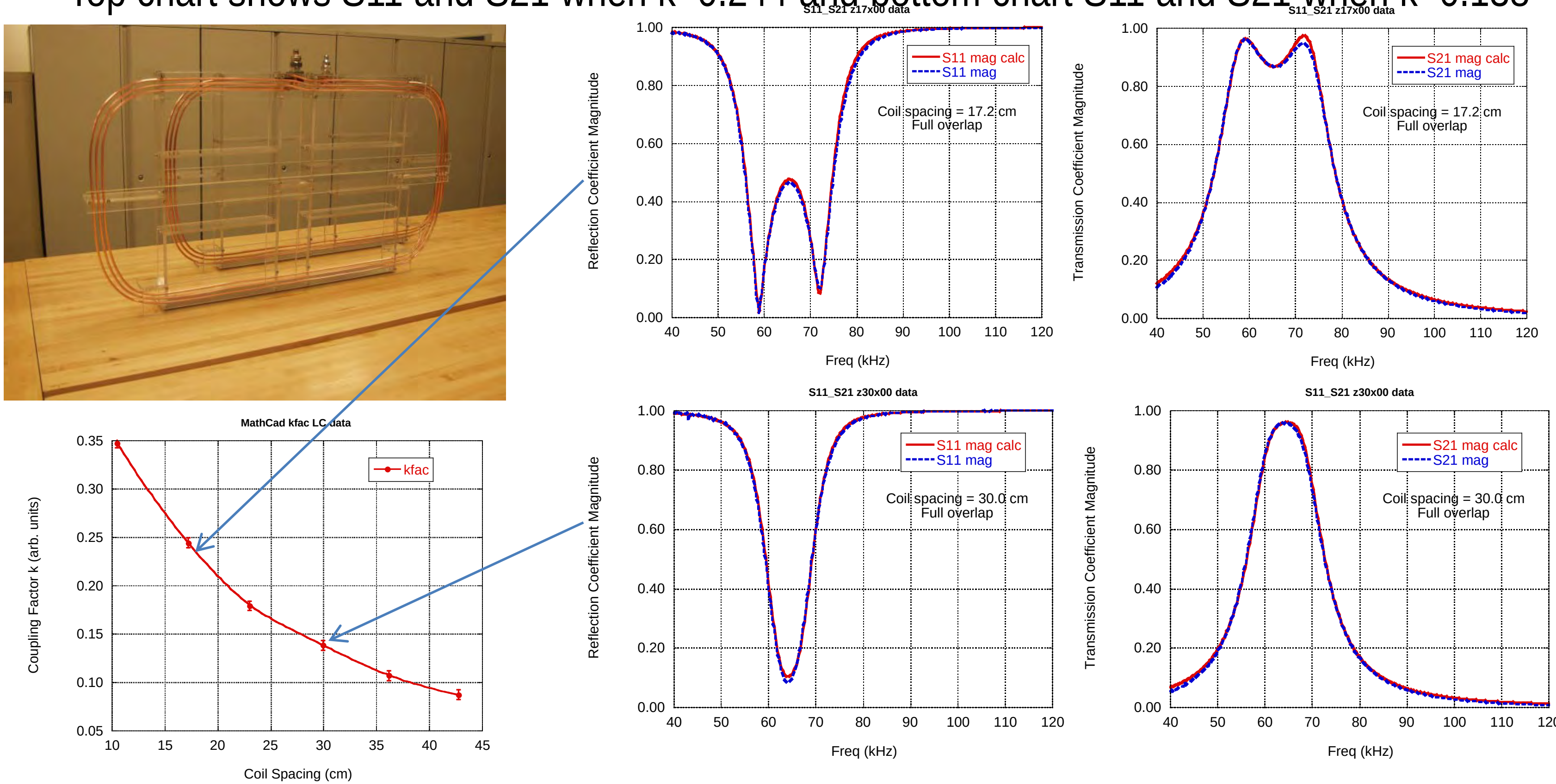
- Experimental finding that multiple “ribbon” antennas operating in parallel offer no benefit in terms of loss reduction.
  - Two such coils in close proximity (~15mm) exhibit virtually unchanged Rac and Ls

Top: End on view of flux lines for 3 turn ribbon coil antenna. Bottom: end on view of ribbon coil conductor current density plots shown extensive skin effect and proximity effects in two outside bars.

Source: Field flux plot simulation: Dr. Pan-Seok Shin

Technical Accomplishments and Progress – FY11 (contd.)

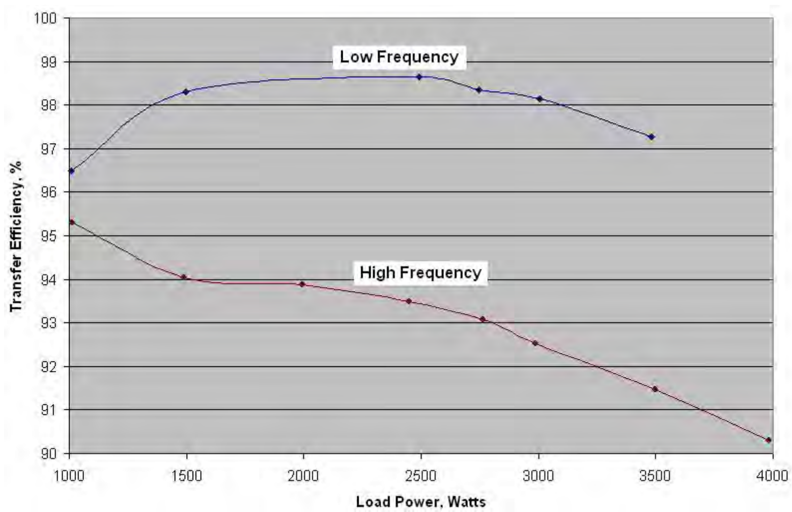
- RF experts at ORNL Fusion Energy modeled and simulated the copper tube antenna system showing coil-coil efficiency ~96% =$(S_{21})^2$
  - Reflection coefficient S11 and transmission coefficient S21 analyzed wrt coil spacing d.
  - Top chart shows S11 and S21 when k=0.244 and bottom chart S11 and S21 when k=0.138

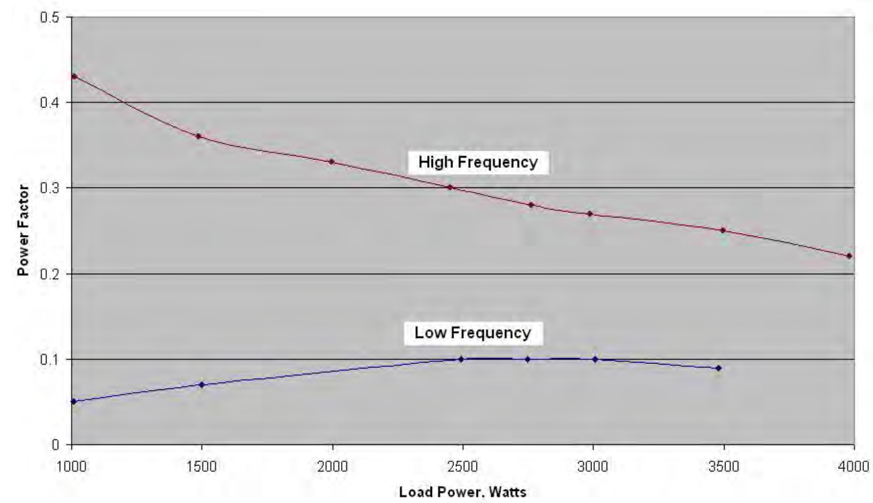


Source: Dr. John Caughman ORNL Plasma Tech. & Appl., Fusion Energy Division (FED)

Technical Accomplishments and Progress – FY11 (contd.)

- ORNL APEEM experimental work measured the transfer efficiency results for the copper tube coil antenna design as function of frequency.
  - Efficiencies >95% were obtained coil-coil, but power factors were low!





  - Power factor versus Transfer Efficiency does not include the H-bridge converter. A commercial, or purpose designed (sister project), inverter will have better efficiency.
  - Low power factor means a larger inverter is necessary, or, the resonant design shifts from the present LC to an LCL design.

Source: Dr. Matthew Scudiere and Dr. John McKeever ORNL APEEM

Collaborations

- ORNL Plasma Energy & Applications, Fusion Energy Division
  - Dr. John Caughman, Dr. Timothy Bigelow, Dr. Phillip M. Ryan
- SAE J2954 Wireless PEV Charging Task Force
  - Mr. Jesse Schneider (BMW) chairman

Future Work

- Remainder of FY11
  - Design, model, simulate and fabricate 3rd Gen antenna and demonstrate coil-coil efficiency, field focusing and shielding.
  - Subtask on dedicated inverter to demonstrate kW/kVA→0.5
  - Demonstrate plug to secondary rectifier output eff>90%

- FY12
  - Design, model, simulate and fabricate strip line power cables
  - Characterize antenna shielding effect in proximity to concrete and vehicle chassis floor pan galvaneal.
  - Refine design for vehicle integration and stationary vehicle charging demonstration.

Summary

FY11 Accomplishments

- This project has demonstrated an efficient wireless power transfer technology capable of transferring large power levels over coil-coil gaps commensurate with vehicle ground clearance.
- Loosely coupled magnetic resonance transformer approach is shown to have the best performance.
- New antenna designs are underway to address shielding and field focusing to minimize emissions.

- Impacts
  - Wireless charging eliminates the inconvenience of plug and cable.
  - Introduces inherent electrical isolation into the charging process.
  - Regulation can be done grid side with short range communications to/from the vehicle over Zigbee, active RFID, others.
  - Opportunity for on-board energy storage system size reduction.