Wireless Charging

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Project ID: VSS103

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start – Oct. 2012
- Finish – Sept. 2015
- 22% complete

Budget

- Total project funding $11.3M
  - DOE share – 72.9%
  - Cost share – 27.1%

DE-FOA-000667 Wireless Charging for Electric Vehicles

Barriers

- Diverse, early stage, products beginning to proliferate in marketplace due to lack of standardization
- Uncertainty in product offerings regarding control method (grid-side, vehicle-side, or both), coupling coil field pattern (polarized or not), and data communications
- Safety protocol: Is primary pad isolation needed?

Targets Addressed

- Match J1772 conductive charging efficiency of >85%

Partners/Collaborators

- **ORNL Team Members:** David Smith, PT Jones, Paul Chambon, Omer Onar, Cliff White, Chester Coomer, Steven Campbell, Lixin Tang, Puqi Ning,
- **Commercialization Partner:** Evatran Plugless Power
- **Communications Partner:** Clemson-ICAR
- **Automotive OEM:** GM and Toyota
- **Supporting partners**: Duke Energy, International Rectifier

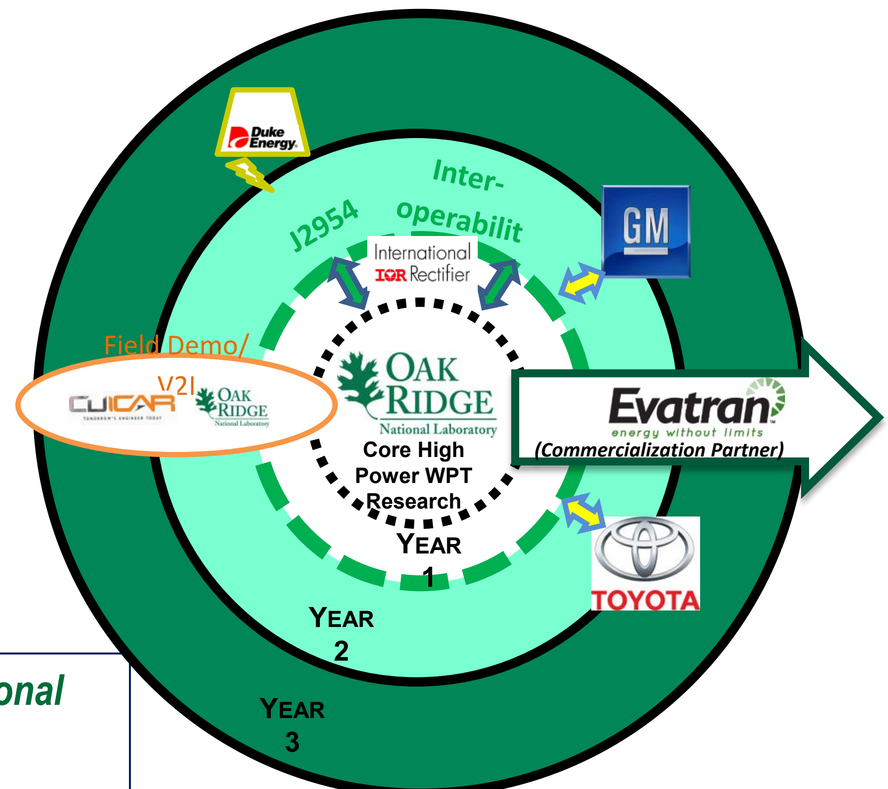
Objective

Objective for FY13

- **Coordinate multi-party team, develop 10 kW capable wireless power transfer (WPT) apparatus, and demonstrate on bench at full power.**

Overall program

- **With Evatran, CU-ICAR, GM and Toyota Motor Co. to integrate ORNL developed WPT technology into demonstration vehicles and validate at independent testing laboratory.**



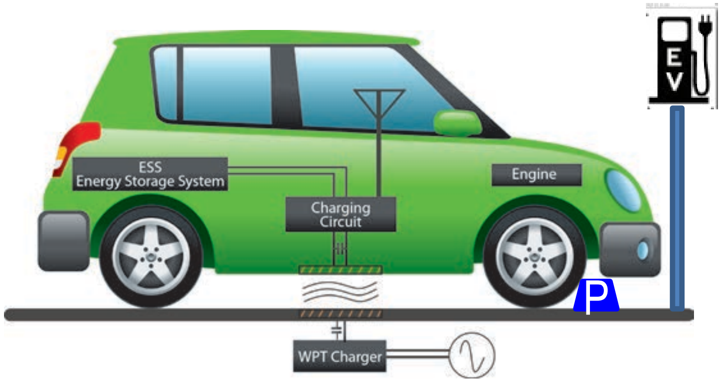
ORNL's technology meets international standards on high frequency electromagnetic fields.

Project drives standardization with SAE J2954 WPT Task Force for 2015 guideline

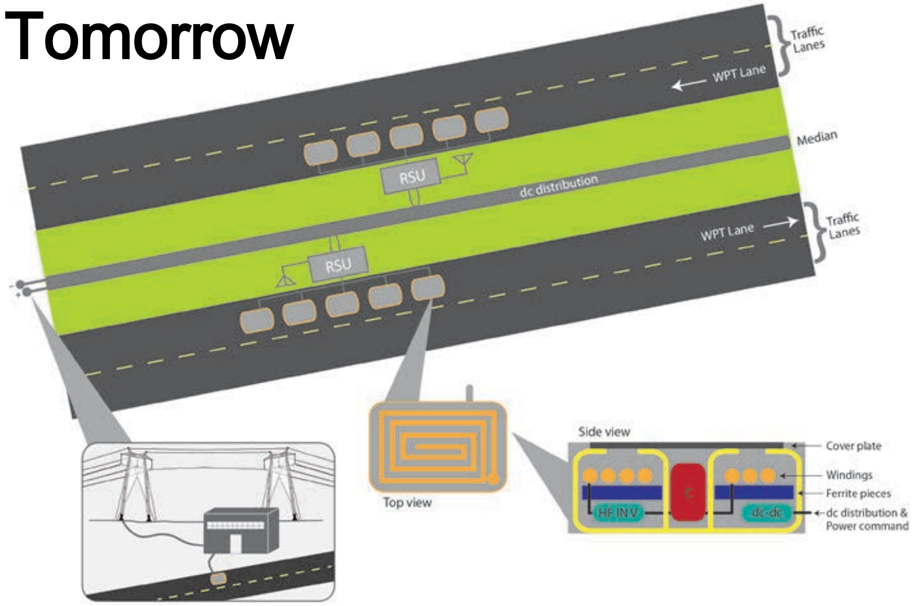
Project Focus

- Advance the knowledge, standardization, commercialization, and safety of wireless charging technology

Today



Tomorrow



ORNL wireless charging focuses and shields the active zone magnetic field to insure fringe fields are well within international standard limits (ICNIRP)

Milestones

Date	Milestones and Go/No-Go Decisions	Status
Sept-2013	Milestone: WPT efficiency >85% wall to battery (or equivalent) at 10 kW power Go/No-Go Decision: Achieves 10 kW continuous power at >85% efficiency	On track toward 2013 bench demonstration with new coil design, active front end power factor corrector, radio comm. and controls
Sept-2014	Milestone: Integrate product intent WPT into 3 each, GM and TMC, commercial PEV's. Go/No-Go Decision: Vehicle battery charging power regulation performed using dedicated radio communications and message set	
Sept-2015	Milestone: Deliver one each WPT equipped vehicle to independent testing laboratory.	

Note: FY12 milestone: Completed hardware design, fabrication and basic controls for 6.6 kW successful vehicle demonstration on Equinox PHEV with Nickel Metal Hydride (NiMH) battery pack.

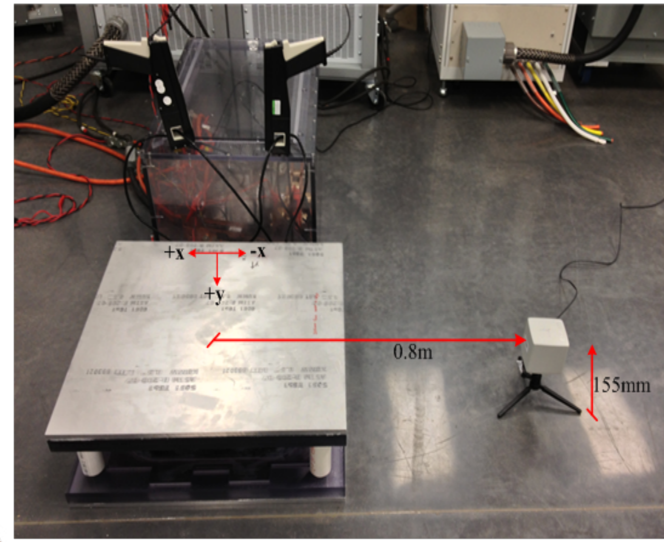
Approach

- **Develop WPT Charging Technology for Bench Demonstration that Achieves:**
  - **Continuous throughput power of 10 kW into 370V nominal load (e.g. Volt pack under charge 370 +/- 25V)**
  - **Targeting a dc-to-dc efficiency >90% and 240Vac grid input power to dc load power efficiency >85%**
  - **Validate grid input stage power factor controlled to >98%**
  - **Coupling coils that meet ICNIRP2010 magnetic field <6.25 uT[1] and electric field < 87 V/m at 0.8 m lateral from coil center**
  - **Control strategy that tracks variations in coil spacing, k(z), and load variation due to battery state-of-charge (SOC)**
  - **Radio communications that closes the load voltage (power) to grid converter loop and effectively manages charging power.**

[1]Source: NRL-National Radiation Laboratory, the magnetic field of the earth (static field) at its surface ranges from 25 uT to 65 uT whereas the magnetic field from a 60 Hz residential power transformer (pad mounted along street) has a mean value of 16 uT at its enclosure and 2.8 uT at 1m. Directly beneath a 230 kV transmission line at 1m from ground the field is 13 uT (but electric field is ~2,500 V/m).

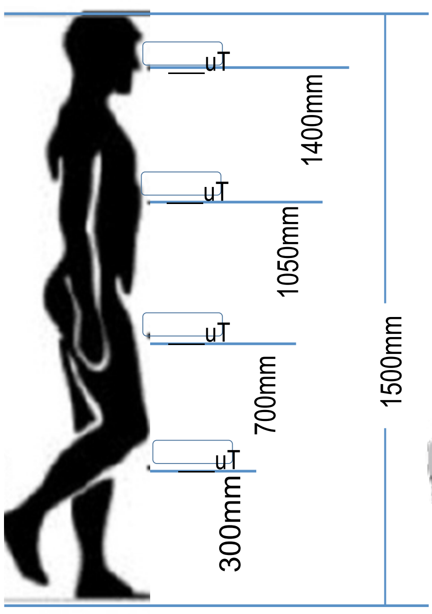
Approach (contd.)

- **<u>Health and safety</u> paramount in all aspects of WPT development work: high voltages, magnetic fields, high power**

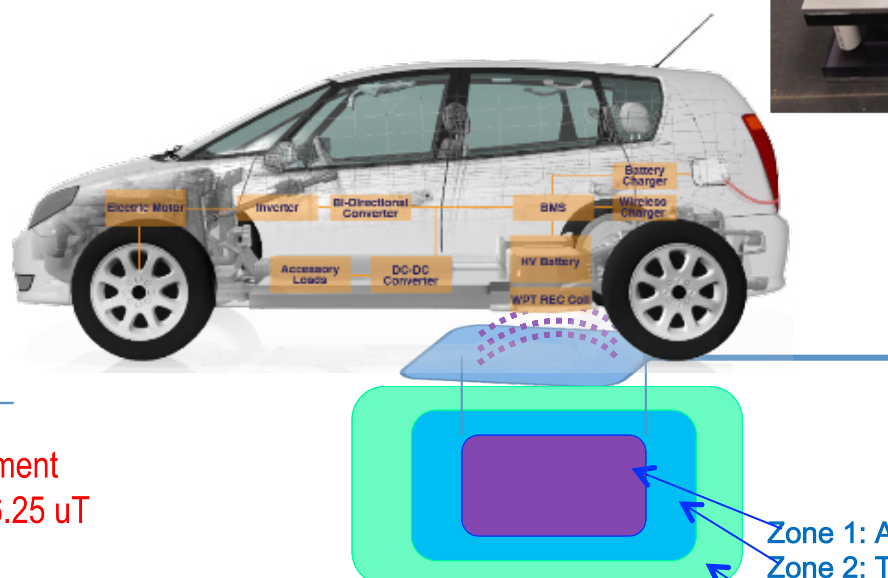


<u>Closest Approach Boundary</u>

- Validated x=0.8m, z=155 mm, P=5 kW, f=23 kHz
- At test position: B=5.36uT, E=52.1 V/m
- At P=7 kW sensor moved to x=0.9m
- Then: B=4.86 uT, E=52.6 V/m



Record average of 4 measurement points and validate ______ < 6.25 uT whole body average

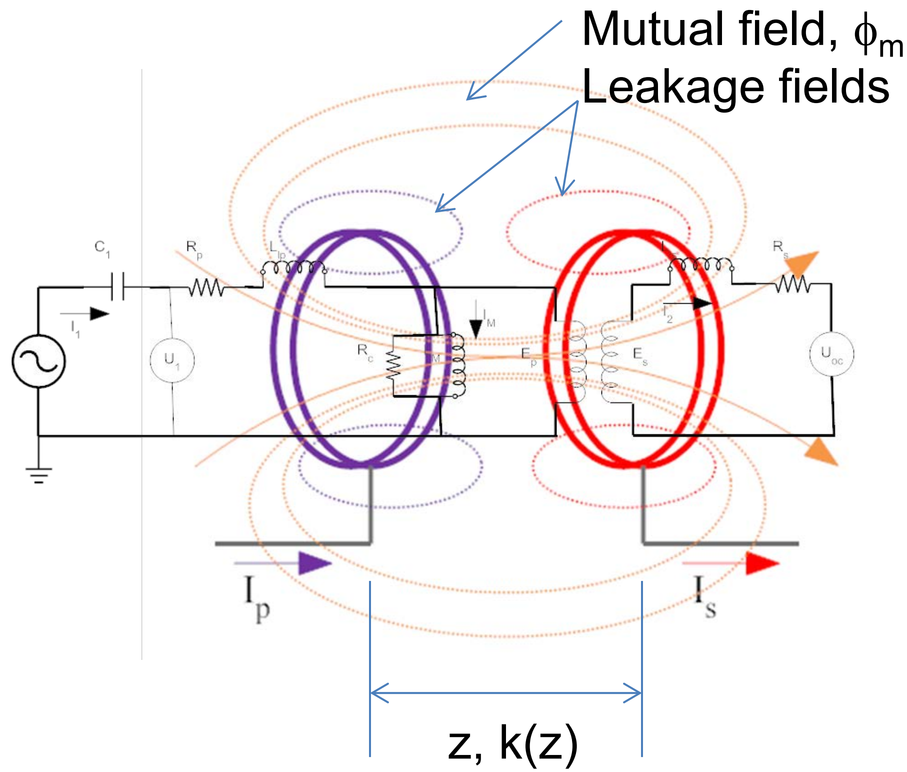


Zone 1: Active field, within confines of coils
Zone 2: Transition to closest approach boundary
Zone 3: Public zone:, outside up to closest approach boundary (including passenger cabin)

Approach (contd.)

- Basics of WPT are understood from FY12 analysis and experimental work – expand on these basics.

$$\bar{A} = \hat{\varphi}\frac{\mu_0 a_1^2 I_p \sin(\theta)}{4\sqrt{z^2 + a_2^2}} \qquad \varphi_m = \oint \bar{A}\cdot\bar{dl} \qquad E_m = -N_s \oint \frac{\partial \bar{A}}{\partial t}\cdot\bar{dl}$$

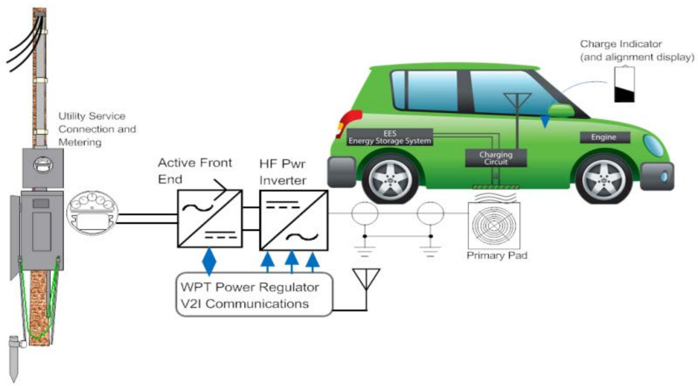


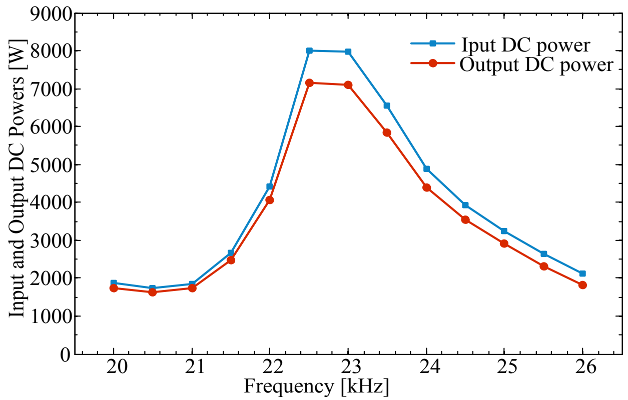
WPT Basics:

- The mutual field transfers power from grid to vehicle
- Primary current, I_p, establishes the total field, mutual + leakage
- Leakage fields are highly gap (z) dependent and diminish the coil coupling coefficient k(z)
- The mutual field at secondary produces a voltage, E_m, that supplies charging current
- Primary tuning capacitor, C_1, resonates out primary leakage thereby facilitating high primary current I_p from source, U_s.

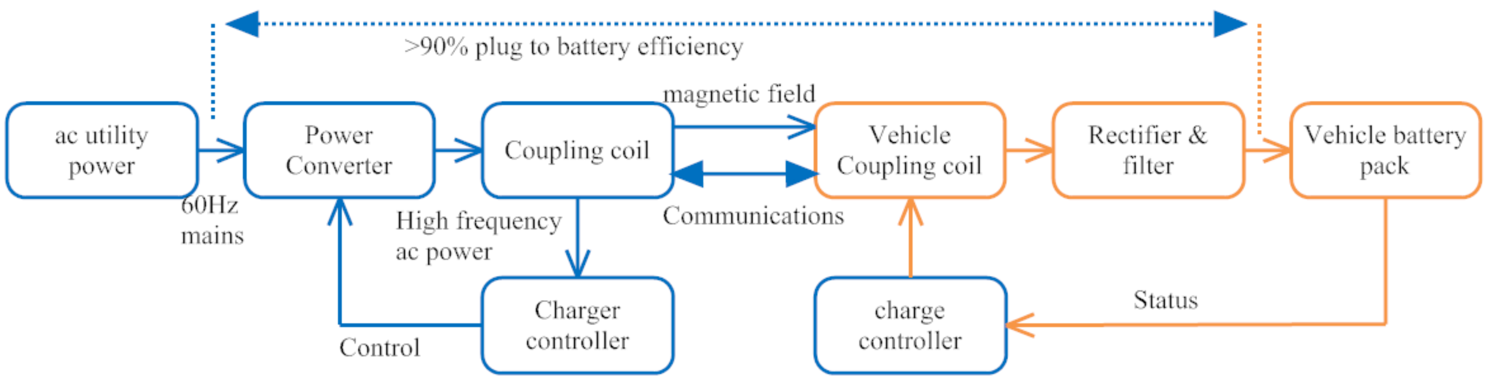
Technical Accomplishments and Progress - Overall

- ORNL team demonstrated WPT charging of GM Equinox test vehicle (280V NiMH pack) at >6.6kW level.
  - Implemented basic grid-side converter power flow control



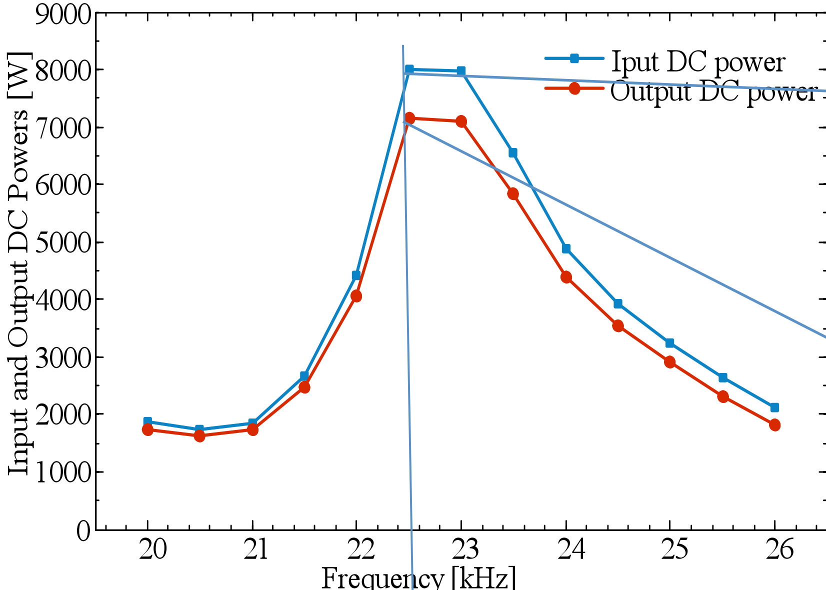


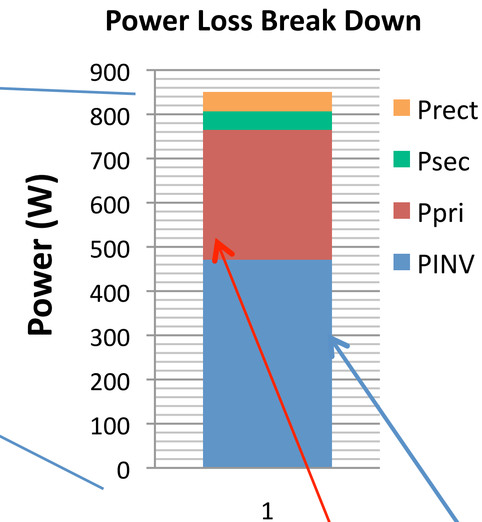
- Overall WPT system functional design remains unchanged

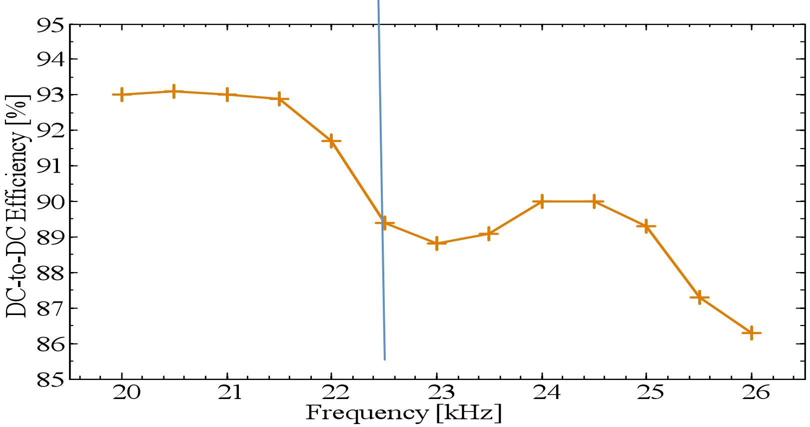


Technical Accomplishments and Progress – FY13 (contd.)

- **Assessment of dc-dc efficiency**







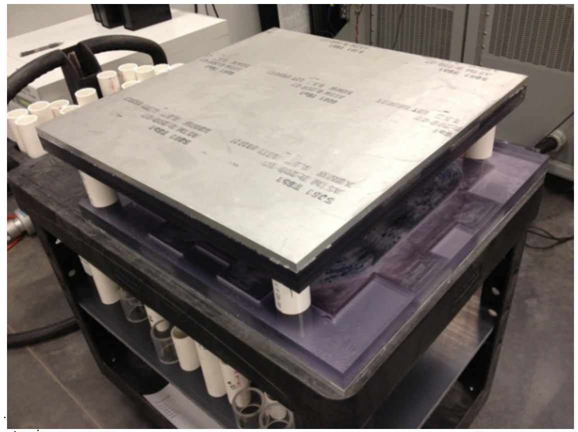
$$P_{pri} = I_p^2 R_{dc}\left[1 + 0.175\sqrt{f_{kHz}}\right]$$

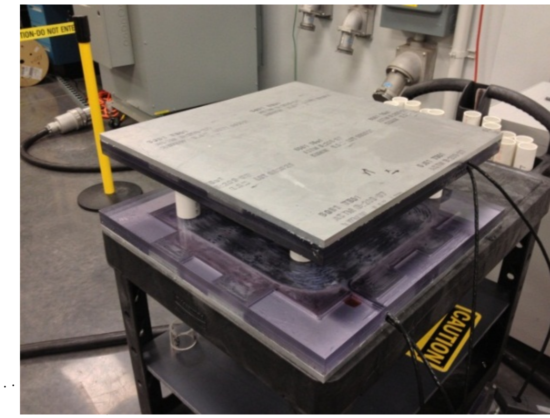
$$P_{INV} = 2V_{CE}(ON)I_p + 2(E_{ON} + E_{OFF})f$$

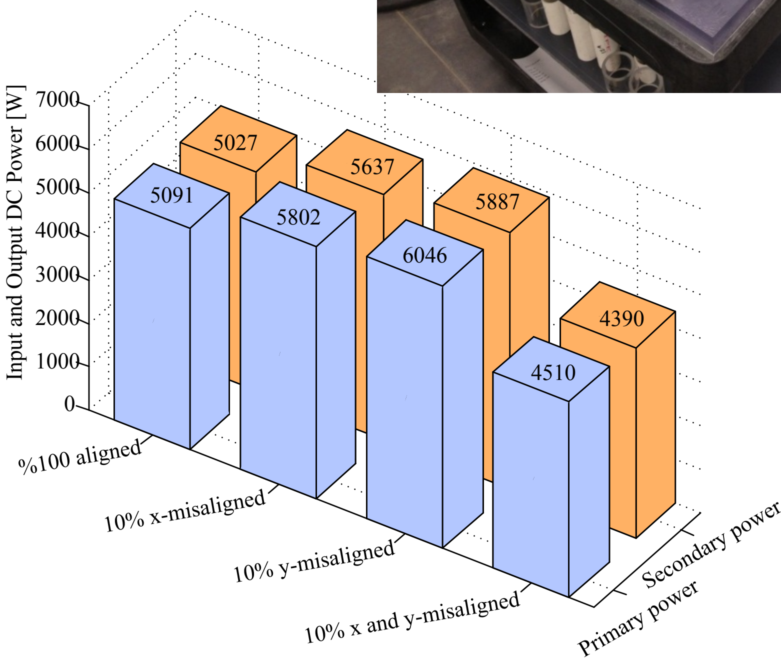
Key factors in frequency determination

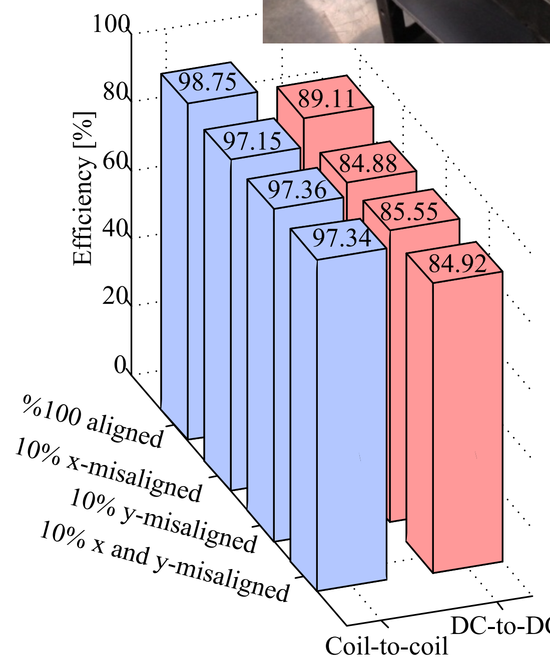
Technical Accomplishments and Progress – FY13 (contd.)

- Misalignment tests at Po=5 kW, +/-10% Δx, +/-10% Δy



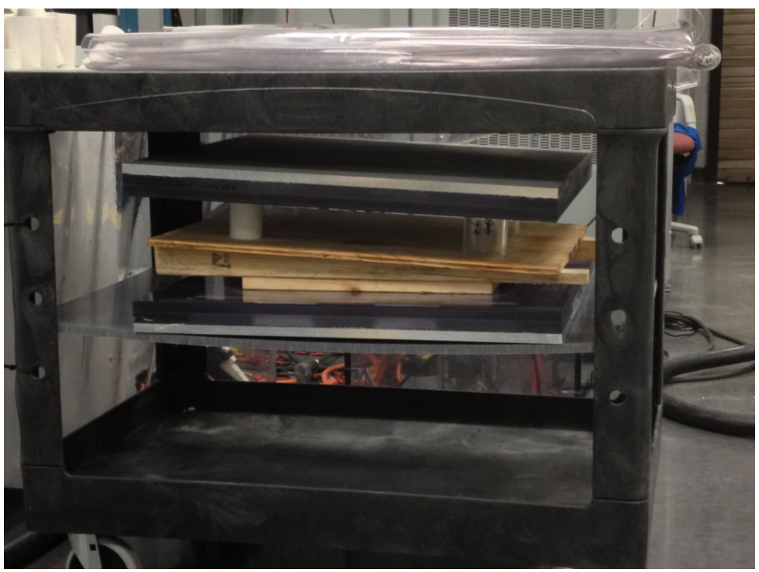


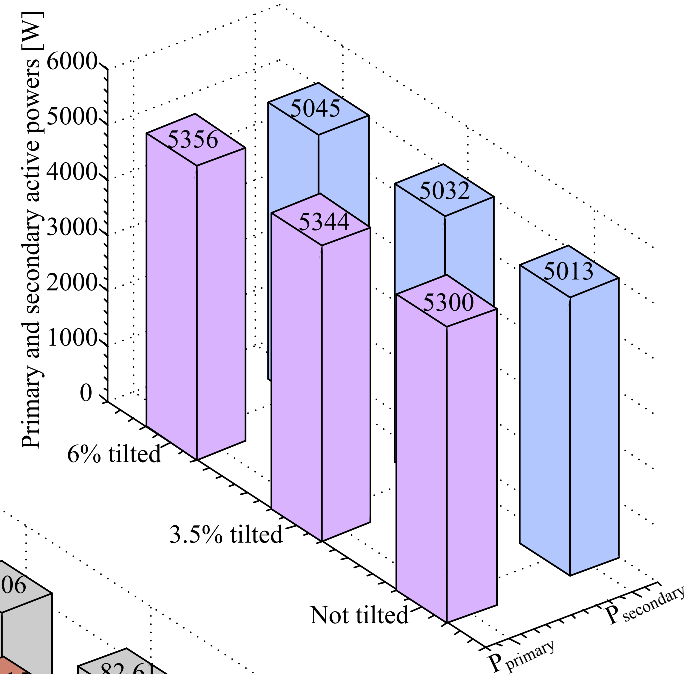


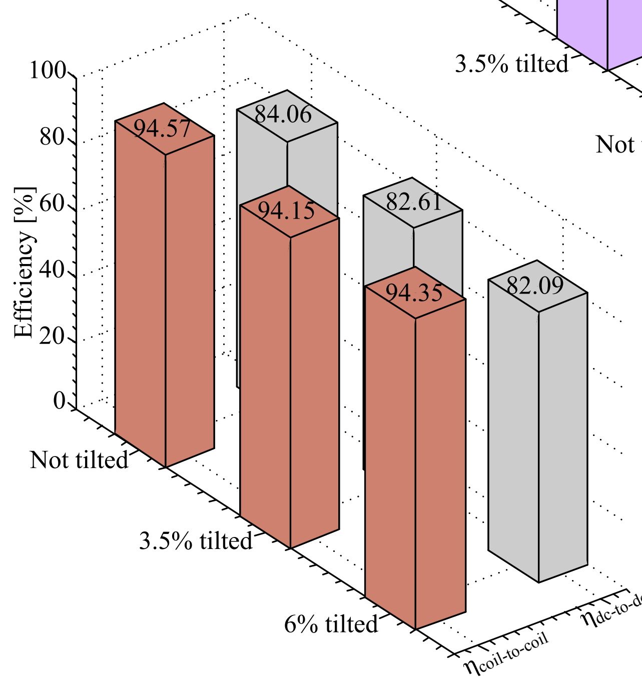


Technical Accomplishments and Progress – FY13 (contd.)

- **Tilt tests at Po=5 kW**
- Gap: z=150mm (magnetic airgap, measured from center to center at all cases including not tilted and ~3.5% and ~6% tilted conditions), Load voltage: V_{batt}=420V, Duty cycle: d=70%, C_{series}=0.39μF, switching frequency: f_s=23.5kHz

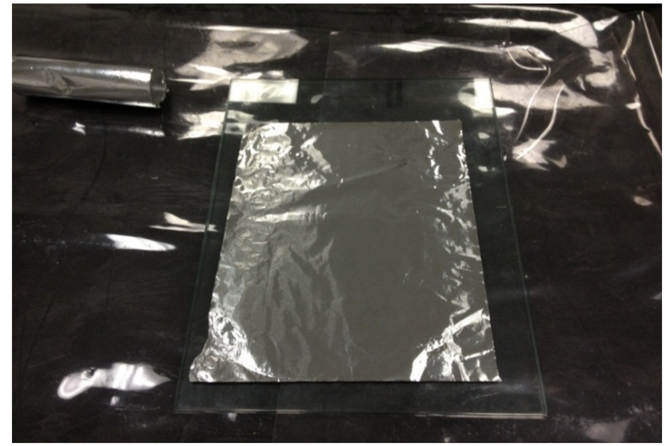




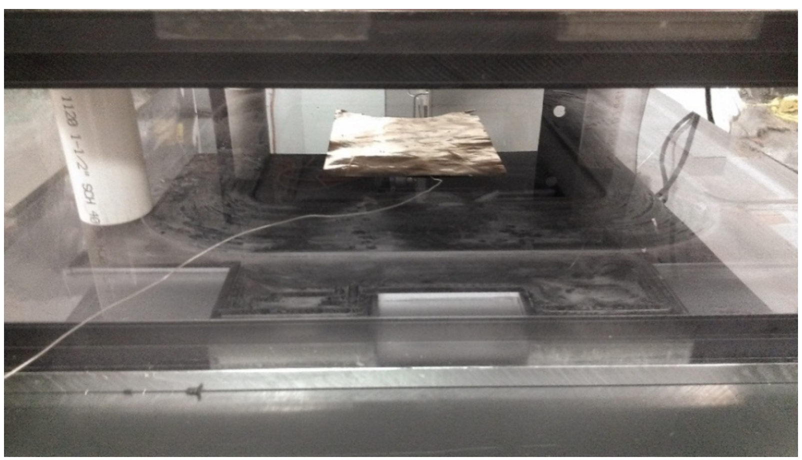


Technical Accomplishments and Progress – FY13 (contd.)

- Objects in WPT active zone



Aluminum foil (1mil) before test

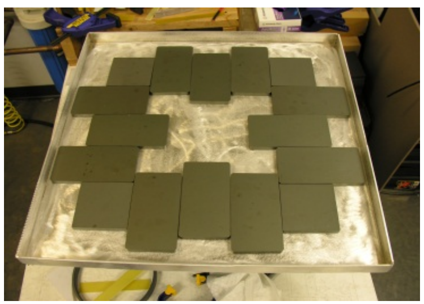
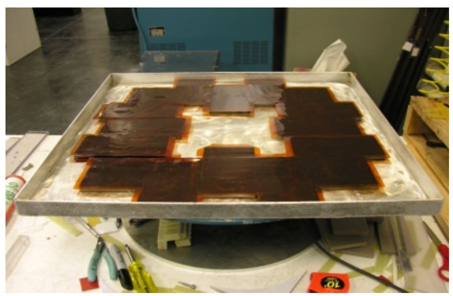
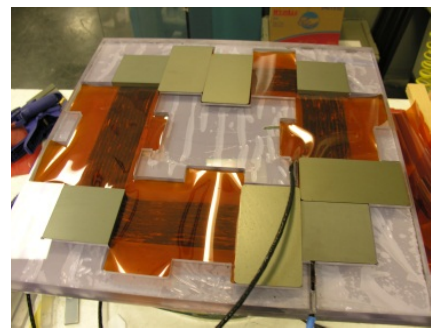
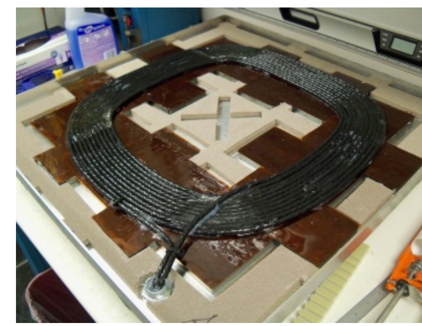
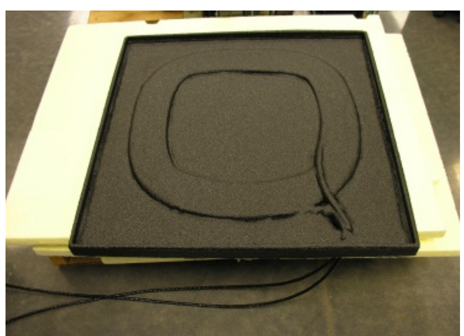


Copper foil (2mil) heated quickly to red hot

Aluminum foil after test – curled up

Technical Accomplishments and Progress – FY12 (contd.)

- Coupling coil design
- Primary coil with #2AWG Litz, Ferroxcube 3C94 flux guides, conformal coating, and Lexan cover plate
- Assembly sequence using ferrite flux guide plates

Experimental coil: 2 ft square x 1½" tray. Coil is approx 16" diameter

Technical Accomplishments and Progress – FY13 (contd.)

- Coupling coil performance evaluation: k(z) and R_{ac}

Parameters

a=533 mm width

b=558 mm length

r_{eq}=300 mm equiv radius

S=0.297 m^2 net area

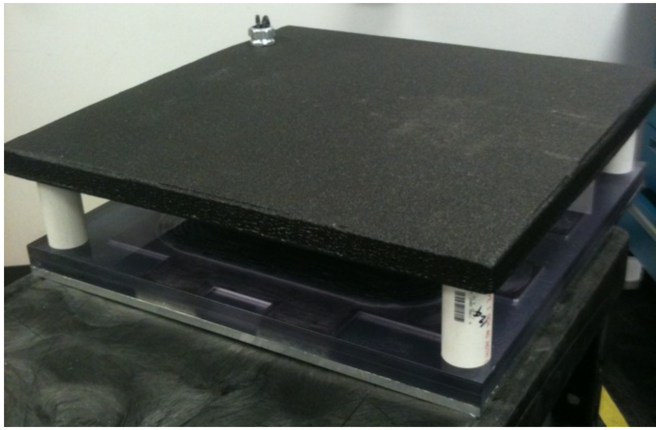
D/4=150 mm ¼ diameter

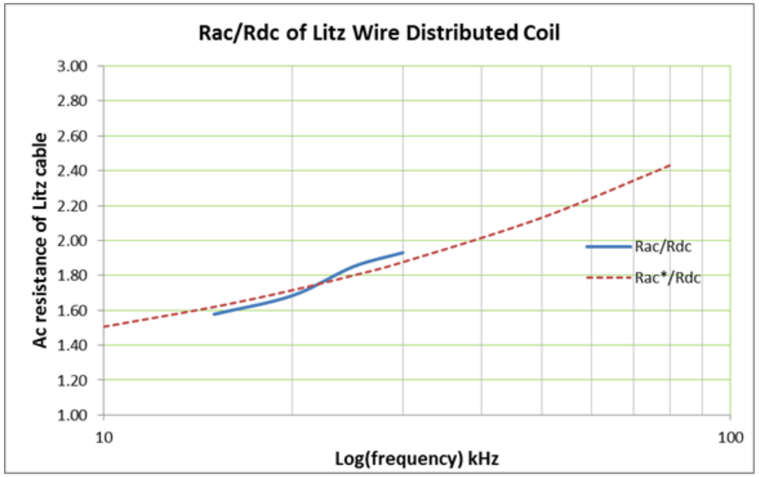
R_{dc}=22 mΩ coil resistance

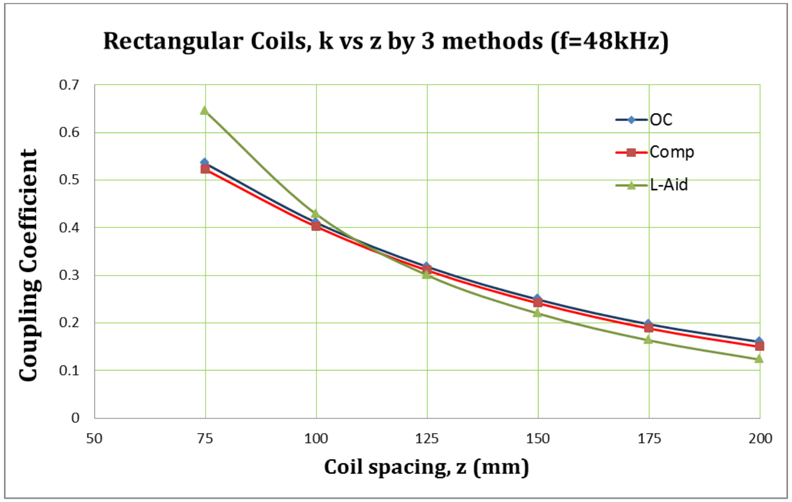
R_{ac}(48kHz)=64 mΩ

L_{11} = 122 mH coil inductance

Nc=11 coil turns







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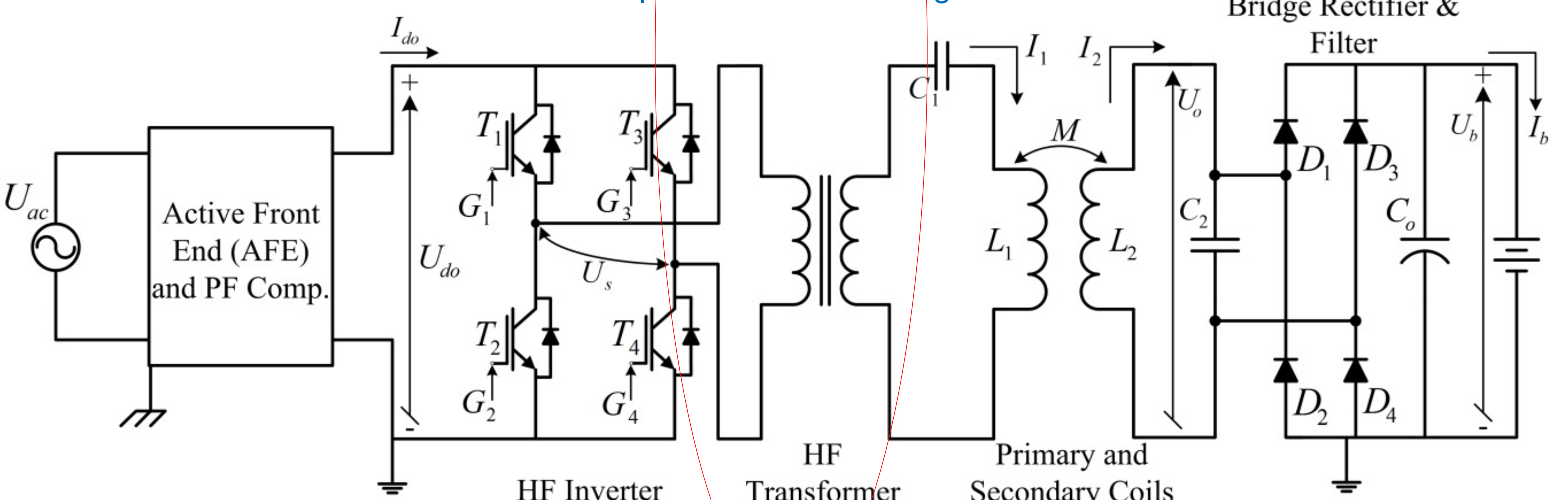
Technical Accomplishments and Progress – FY13 (contd.)

- Grid converter: power factor corrector, high frequency power inverter, and isolation transformer

Metglass tape wound core will be replaced with ferrite ring core stack.

FOA-667 transformer design will rely on ferrite core stack
#6 AWG primary
#2 AWG secondary



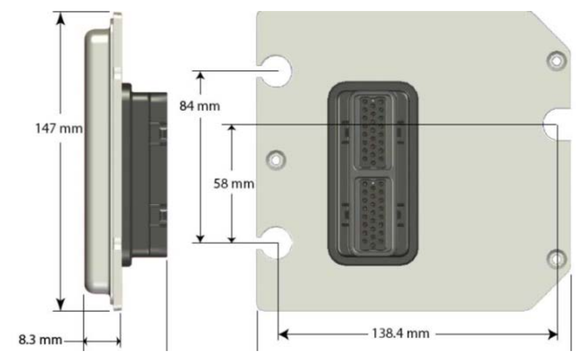
Technical Accomplishments and Progress – FY13 (contd.)

- Communications: B&B Electronics ZP24D-250RM Zlinx-radio-modem
  - For communications interfacing only – FOA hardware will use CISCO DSRC radio
  - RS-232/422/485 serial, 256 bit, Temperature: -40C to +85C; 10Vdc to 48Vdc
  - 2.0 GHz to 2.4385 GHz ISM band with FSK modulation

Grid-side power controller and communications

Vehicle side communications

VWPT – vehicle side WPT
Zlinx wireless modem
Woodward GCM-0563-048



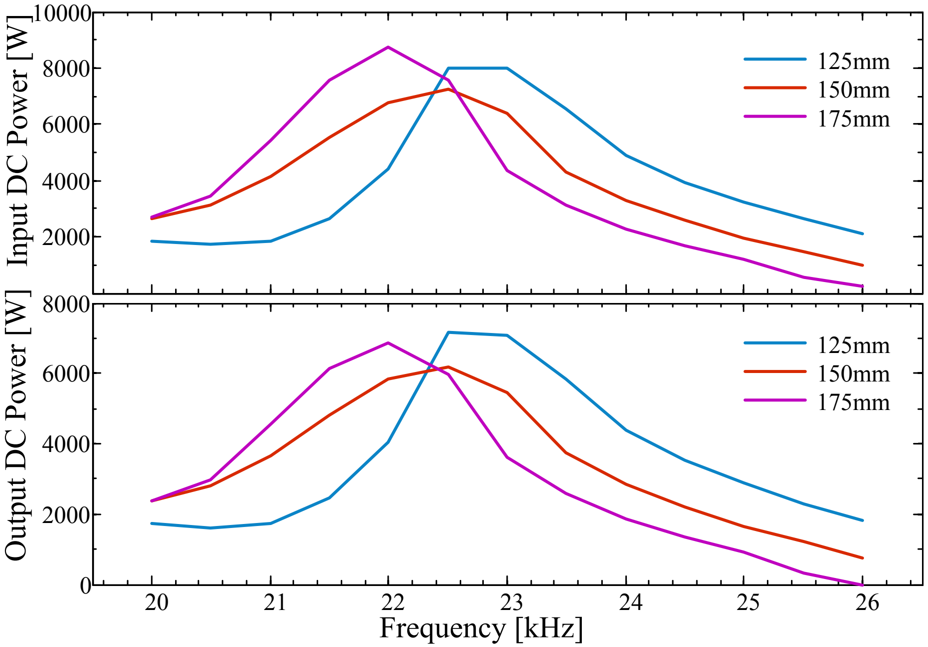
Woodward GCM-0563-048
Freescale MPC563 @ 56 MHz
32k RAM, 64k EEPROM
8-32Vdc, -40C<Top<+85C
11-18 analog input

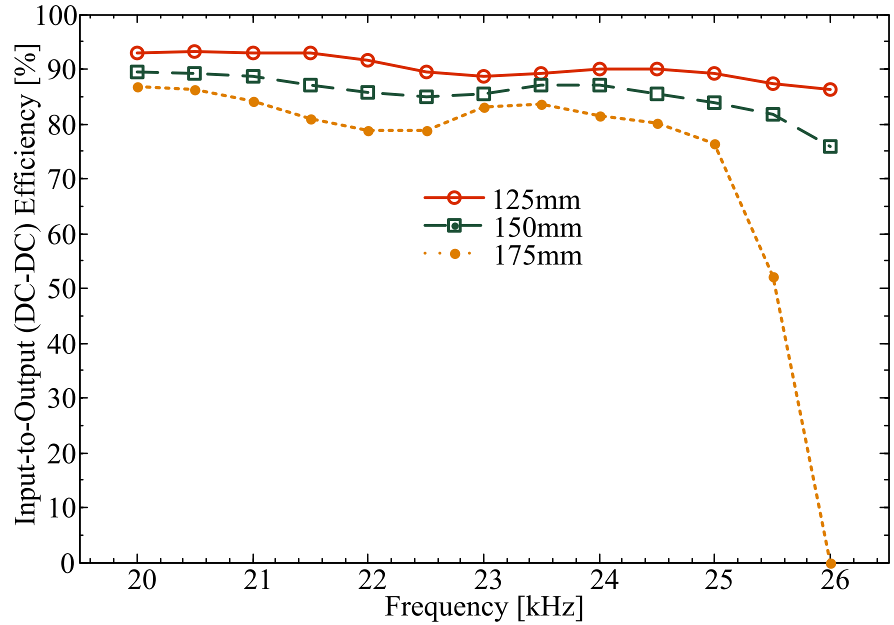
Spectrum Digital E2DSP using
TI-TMS320F28335 core
32bit, 150 MHz, 68k RAM, 256k SRAM
RS232, CAN 2.0, 12bit ADC

Validation tested at ORNL
- Messages of 6 bytes
- Round trip time of ~20 ms
- WPT will require 8 bytes
- Proved interoperable

Technical Accomplishments and Progress – FY13 (contd.)

- Dynamic frequency tracking due to gap changes, k(z)
- **Effect of gap changes on power transfer and efficiency: V_{batt}=420V, DC link voltage: V_{dc}=135V, Duty cycle: d=70%, C_{series}=0.44μF, f_0=21.7 kHz**

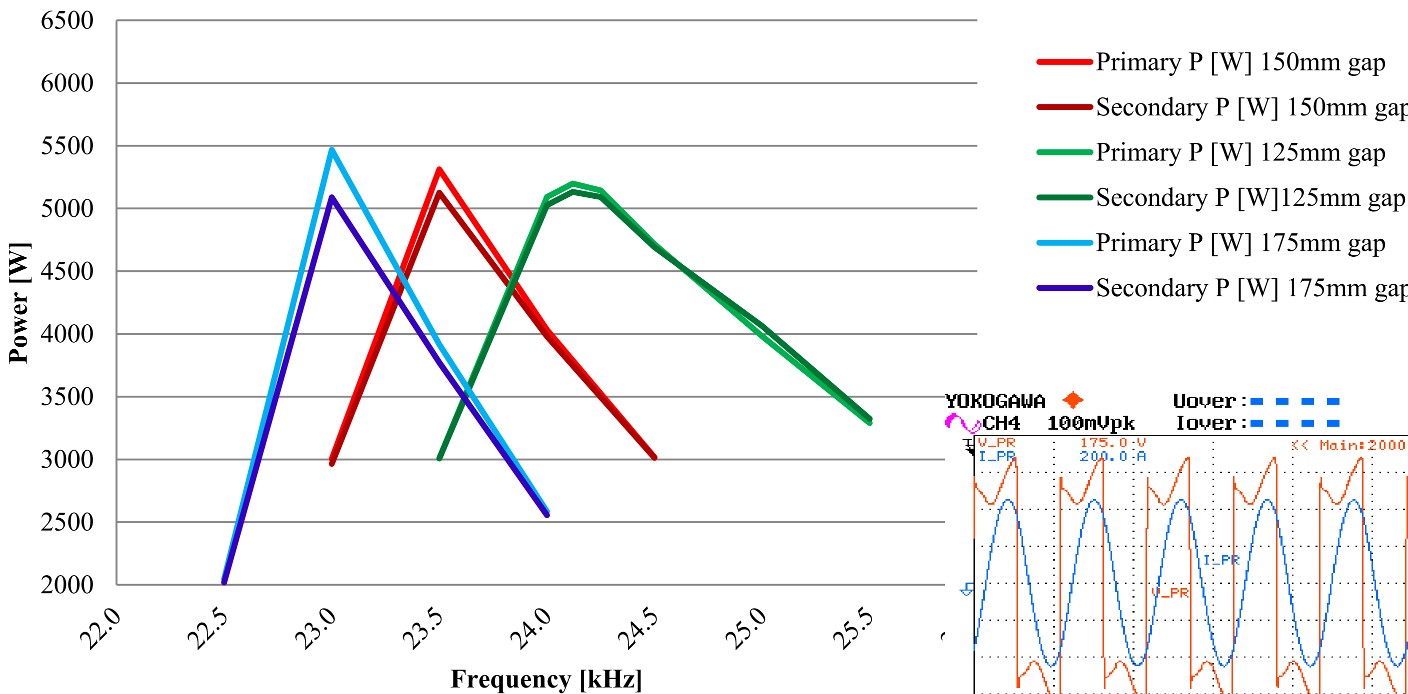


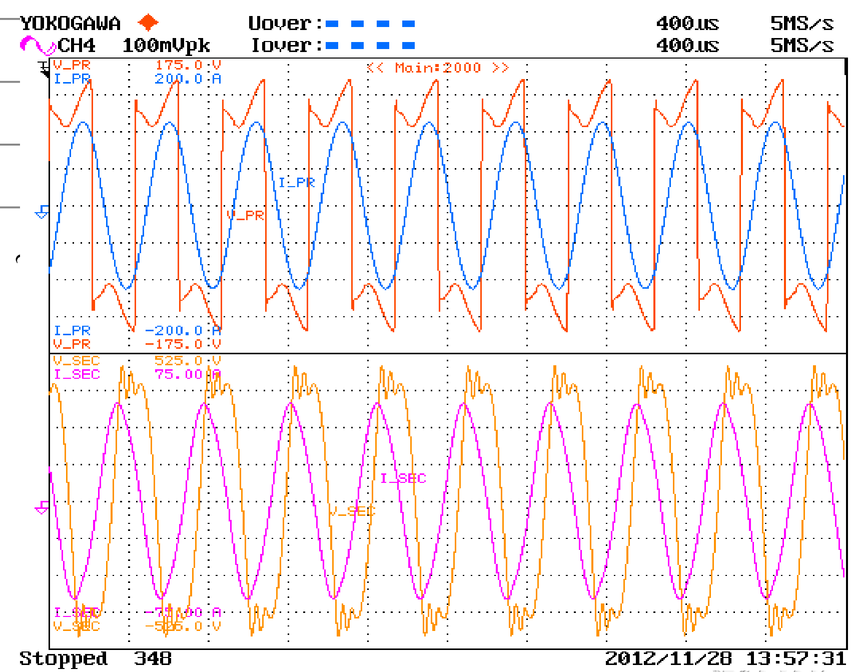


Note: Voltage exposure of the primary tuning capacitor, C1, rated 1,800V was being exceeded in these tests.

Technical Accomplishments and Progress – FY13 (contd.)

- Dynamic frequency tracking due to gap changes, k(z)

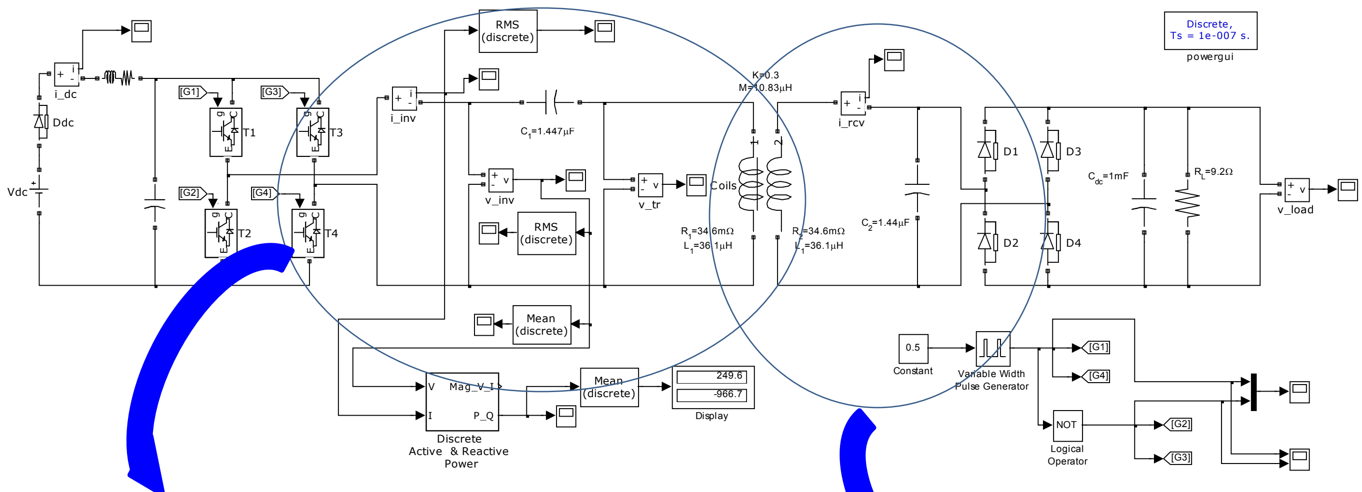




Screen shot for z=150mm, Ub=420Vdc, Pout>5 kW.

Technical Accomplishments and Progress – FY13 (contd.)

- Developed New Theory of WPT Operation and Control
  - High power WPT is a blend of electrical tuned circuit theory and power grid regulation concept of reactive power injection to regulate voltage



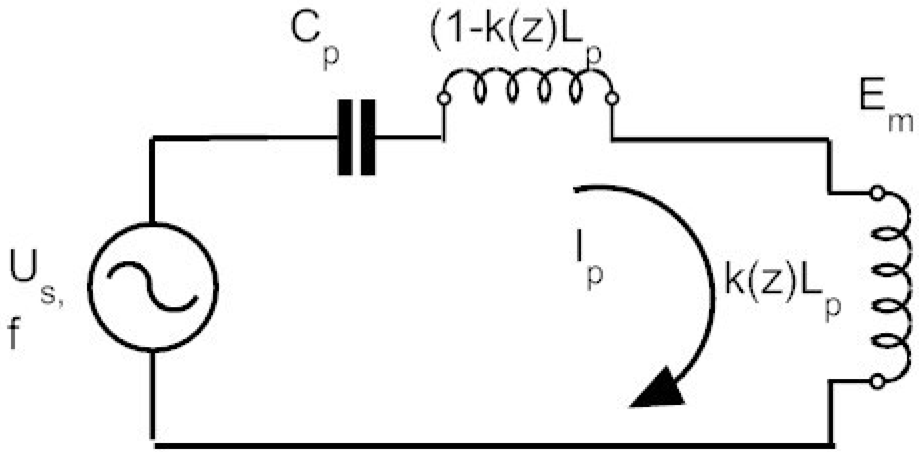
Series tuned primary (Cp, Lp) retains tuned circuit behavior necessary to maximize primary current Ip

Parallel tuned secondary (Cs, Ls) exhibits Grid transmission system behavior of real and reactive power flows

Key insight: Realization that Cs is more than an electronic circuit tuning parameter, it's a VAR source that sustains rectifier input voltage, Ur, to level necessary for transmission of real power.

Technical Accomplishments and Progress – FY13 (contd.)

- Developed New Theory of WPT Operation and Control
  - Primary side requires efficient delivery of current Ip to support potential E_m.
  - Tuning the input achieves this and permits $U_s \sim E_m$

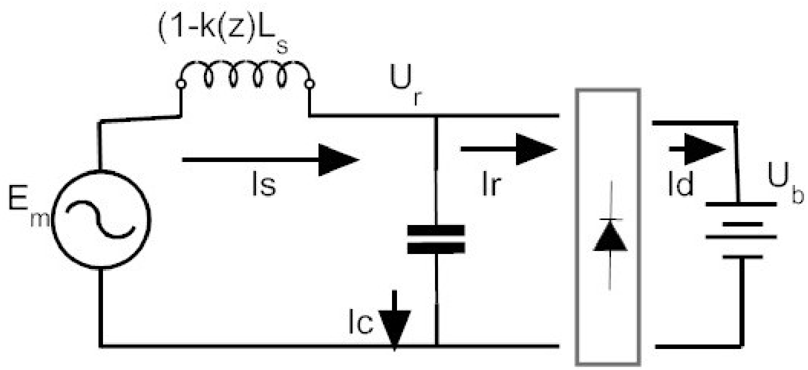


$$\bar{U}_s = \bar{E}_m + \frac{j}{\omega C_p}\left[\left(\frac{\omega}{\omega_{lp}}\right)^2 - 1\right]\bar{I}_p$$

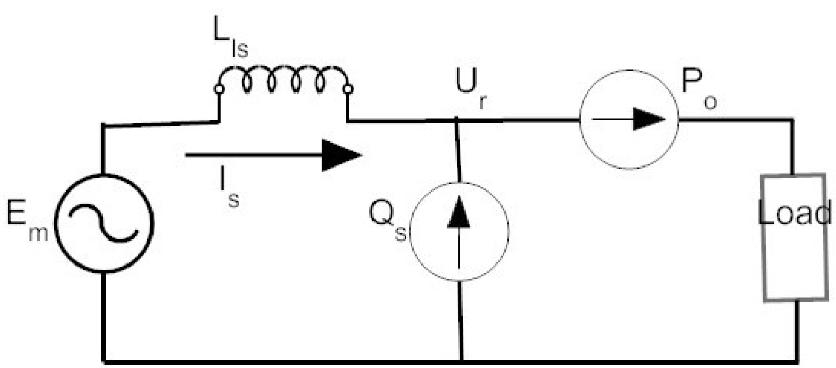
Input current is maximized when the source frequency, f (ω), is matched by the resonant frequency, ω_{lp}.

Technical Accomplishments and Progress – FY13 (contd.)

- Developed New Theory of WPT Operation and Control
  - Secondary side requires efficient delivery of power to load
  - Equivalent to transmission of power through utility grid and the need for reactive power compensation to maintain voltage regulation.



In order to deliver charging current, I_d, to the battery at potential U_b, the voltage Ur must be maintained. The quadrature component of secondary current, I_s, achieves this.



$$S = P + jQ = real\ power + reactive\ power$$

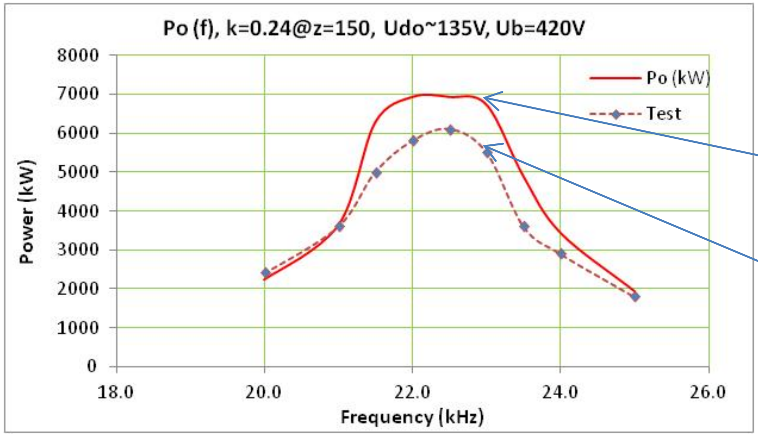
$$P_o = \frac{E_m U_r}{\omega L_{ls}} \sin(\delta)$$

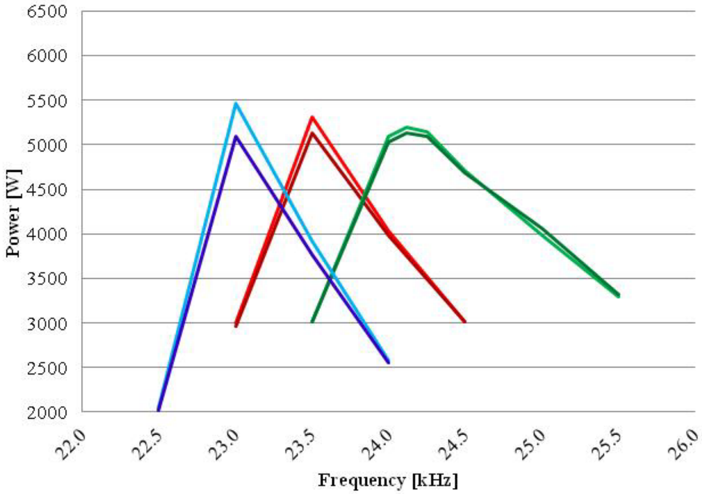
$$P_o = \frac{(\omega k_z M I_p) U_r}{\omega L_{ls}} \sin(\delta)$$

Output power not dependent on operating frequency

Technical Accomplishments and Progress – FY13 (contd.)

- Developed New Theory of WPT Operation and Control
  – Model is idealized at this point
  – Results in good agreement with test

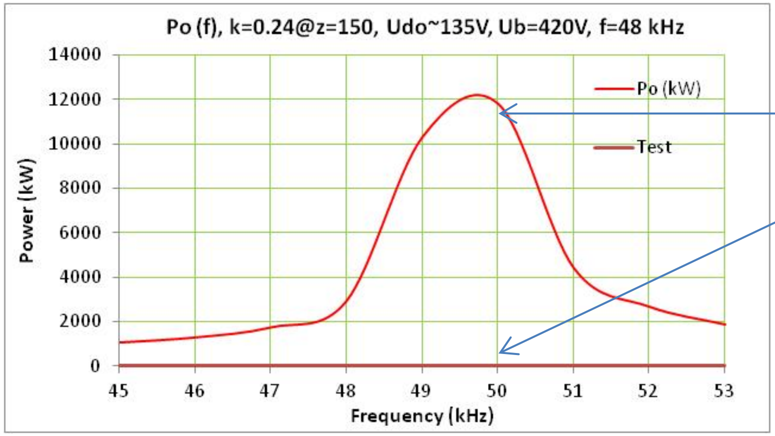




I_p limited

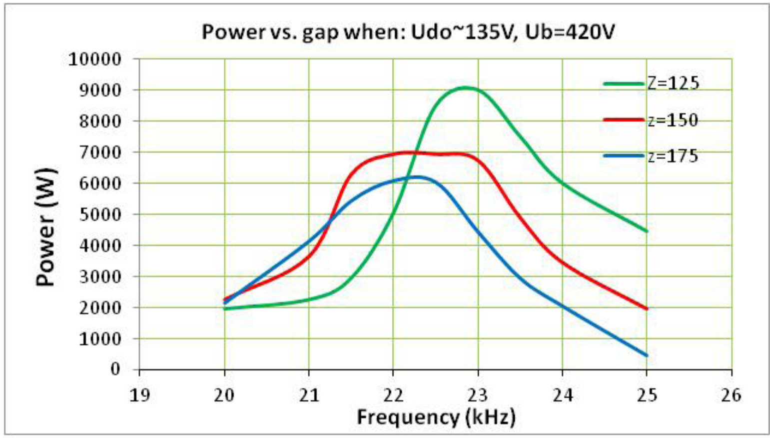
Test data PS Limited

  – Supports SAE frequency determination



I_p not limited

Center frequency does not alter charging power



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Collaboration and Coordination

Organization		Type of Collaboration/Coordination
	Evatran Plugless Power	WPT packaging, vehicle integration, vehicle testing
	Clemson University ICAR	Communications technology, demonstration site
	General Motors	Demonstration vehicles (Volt) and integration guidance, CAN
	Toyota Motor Corp	Demonstration vehicles (RAV4) and integration guidance, CAN
	Duke Energy	Grid interaction
	International Rectifier	High speed power semiconductor

Collaborations

- SAE J2954 Wireless PEV Charging Task Force
  - Jesse Schneider, Chair
  - Grant Covic, Chair, coupling coil interoperability sub-committee
  - Ted Bohn, ANL, test and measurement
- ORNL is a voting member of SAE J2954
  - Keep committee informed on:
    - Center frequency determination,
    - Power flow regulation method,
    - Magnetic and electric field’s, and
    - Communications

Future Work

- Remainder of FY13
  - *Design, fabricate, and test prototype power factor corrector in grid converter*
  - *Complete design of >10 kW capable coupling coils*
  - *Bench demo power flow regulation using CISCO DSRC radio in control loop*
  - *Demonstrate system to DOE and freeze design based on go/no go decision*
  - *Appraise SAE J2954 committee on inter-operability related findings*
- Program Year 2: FY14
  - *Fabricate and deliver 6 coil sets and 2 grid inverters to Evatran*
  - *Evatran integrates all WPT hardware into test vehicles including ORNL controls*
  - *OEM input to guide WPT integration*
- Program Year 3: FY15
  - *Deliver integrated WPT system on 1-each test vehicle to testing laboratory*
  - *Data collection program on WPT vehicles at 2 independent test sites (ORNL campus and CU-ICAR campus)*
  - *ORNL Center for Transportation Analysis leads and delivers economic feasibility study*
  - *Publish final report*

Summary

- **Relevance:** This project focuses on the development of high power stationary wireless charging to production intent level.
- **Approach**: The approach pursued addresses technology barriers that limit market acceptance of wireless charging.
  - *Development of advanced soft magnetic materials as low loss flux guides,*
  - *Improved rectifier plus filter stage on-vehicle to enhance end-to-end efficiency,*
  - *Alternatives to Litz cable for all high frequency components and interconnects.*
- **Collaborations:** The program team consists of ORNL as technology development lead, a commercialization partner, OEM's to supply test vehicles, a leading university for standardized communications apparatus, one utility and one semiconductor manufacturer.
- **Technical Accomplishments:**
  - *Established technical criteria to guide frequency determination (22 kHz vs 48 kHz)*
  - *Completed misalignment, tilt, variable gap, and objects in gap tests*
  - *Implemented high frequency isolation transformer for inverter optimization*
  - *Developed new theory of WPT operation to guide power regulation controller algorithm*
  - *Developed coupling coil design methodology*
- **Future Work:** Complete development of WPT to design freeze stage so that effort may focus on vehicle integration, standardization, inter-operability, and real world data collection.