Project ID: VS102

High Efficiency, Low EMI and Positioning Tolerant Wireless Charging of EVs

Principal Investigator
Rakan Chabaan
Senior Research Engineer
Hyundai America Technical Center Inc (HATCI)

8 April, 2016

2016 DOE Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

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

Overview

Timeline
- Start date – Oct. 2012
- End date – Dec. 2016
- Percent complete – 80%

Budget
- **Total Budget: $6,014,868**
  - DOE share: $4,215,593
  - Hyundai share: $1,799,275

- Expenditure of DOE share in
  - FY13: $721,632.12 (10/12-9/30)
  - FY14: $993,035.37 (10/1-9/30)
  - FY15: $1,260,820.00 (10/1-9/30)
  - FY16: ~$427,000 (10/1-3/31)

Partner:
Mojo Mobility
Santa Clara, CA

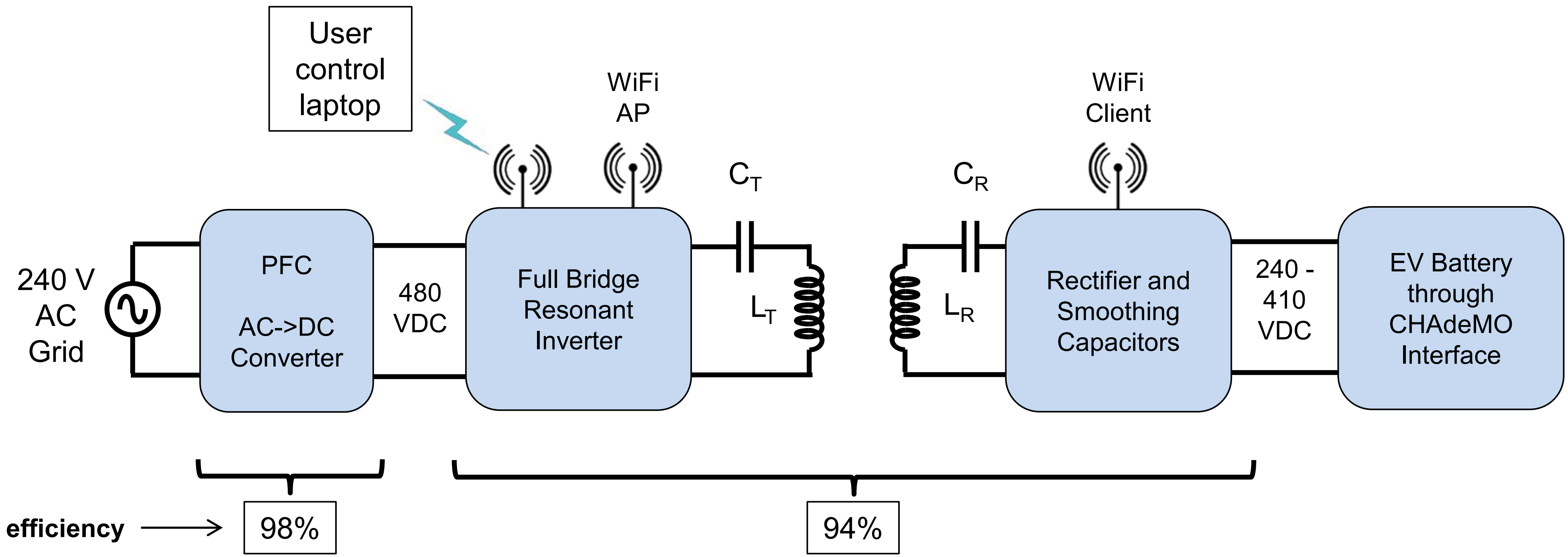
Technical Objectives:

- Transfer power at over 6.6kW.
- Total system efficiencies of more than 85%.
- Greater than 20 cm coil to coil gap.
- Electromagnetic emissions below ICNIRP limits.

Milestones

Month/ Year	Milestone or Go/No-Go Decision	Description	Status
02/2013	Milestone	Design of Initial WPT Prototype System.	☑
06/2013	Milestone	System Test and Corrections.	☑
07/2013	Milestone	Design of Second Generation WPT Prototype System.	☑
09/2013	Milestone	System Test and Corrections.	☑
02/2014	Go/No-Go Decision	Demonstrate the wireless power transfer system and perform a power transfer of at least 6.6 kW with an efficiency of at least 85% with at least a 20 cm coil to coil gap.	☑
09/2014	Milestone	Design of Third Generation WPT Prototype System.	☑
04/2015	Milestone	Vehicle Integration and Test.	☑
05/2015	Go/No-Go Decision	Demonstration of the wireless power transfer system integrated into an electric vehicle with performance as defined in phase 1 Go-No-Go criteria.	☑
05/2016	Milestone	The Project team will deliver one WPT-enabled EV and wireless charging station to the Department of Energy for National Laboratory testing.	☑
08/2016	Milestone	The Project team will build remaining WPT-enabled EVs based on the EV and WPT chargers using system specifications developed in Phase II.	⟳
10/2016	Milestone	Hyundai team will finish testing on the complete wireless charging system, including overall performance, electrical endurance, vehicle durability, and EM emissions.	⟳
10/2016	Milestone	Final system demonstration to DOE observers at Hyundai Technical Center.	⟳

System Overview



Efficient High Power System

- Designed for 19 kW capability, demonstrated up to 10kW thus far (AC mains to EV battery)
- High efficiency (93% Grid to Battery)
- High Position Freedom

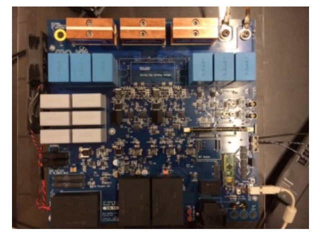
Phase 1-2 Development

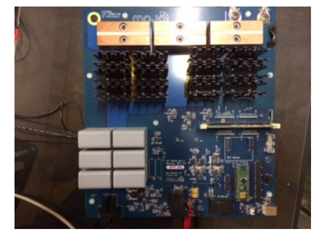
Development Stages

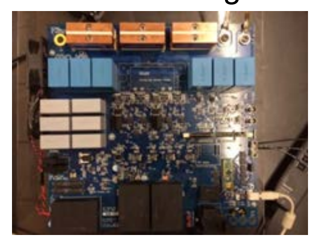
- First Generation WPT Prototype System (phase 1)
  - Initial proof of concept
  - Variable DC power supply in place of PFC
  - Identical transmitter and receiver coil design
- Second Generation WPT Prototype System (phase 1)
  - Reduced PCB size due to design optimizations
  - Increased transmitter coil size for larger position freedom
- Third Generation WPT Prototype System (phase 2)
  - Custom PFC AC/DC front end (>20 kW output design)
  - Redesign charger for integration with PFC
  - Redesign receiver for EV integration
  - Redesign receiver and charger coil; design housing and mounting for EV integration


Gen. 1 Charger


Gen. 1 Receiver


Gen. 2 Charger


Gen. 2 Receiver

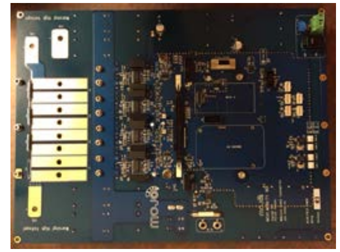

Gen. 3 Charger


Gen. 3 Receiver Housing and Coil

Phase 3 Development

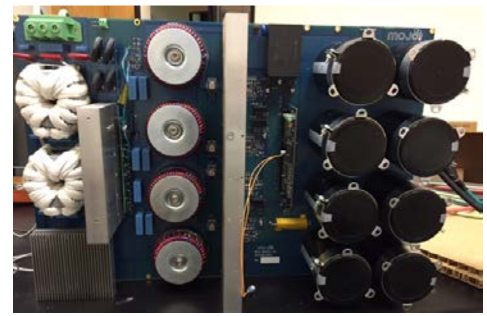
Phase 3

- New design necessary in phase 3 to fix issues found in phase 2; also includes design improvements for safe testing, and cost reduction.



Gen. 4 Charger

Gen. 3 Receiver Housing and Coil

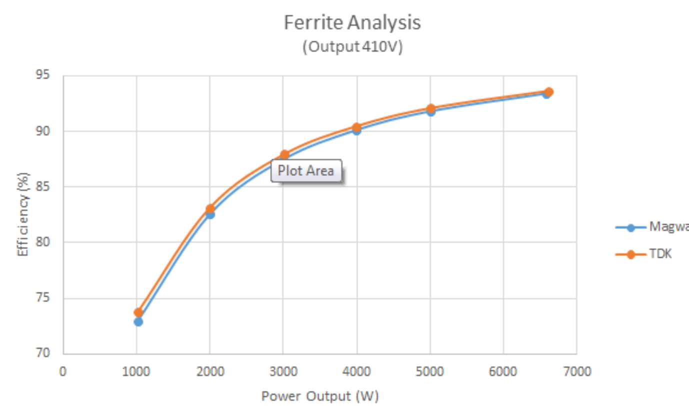


Gen. 2 PFC

A. New PFC (Gen. 2)
   - Fixed design issue with Gen. 1, inductors saturated at high current.

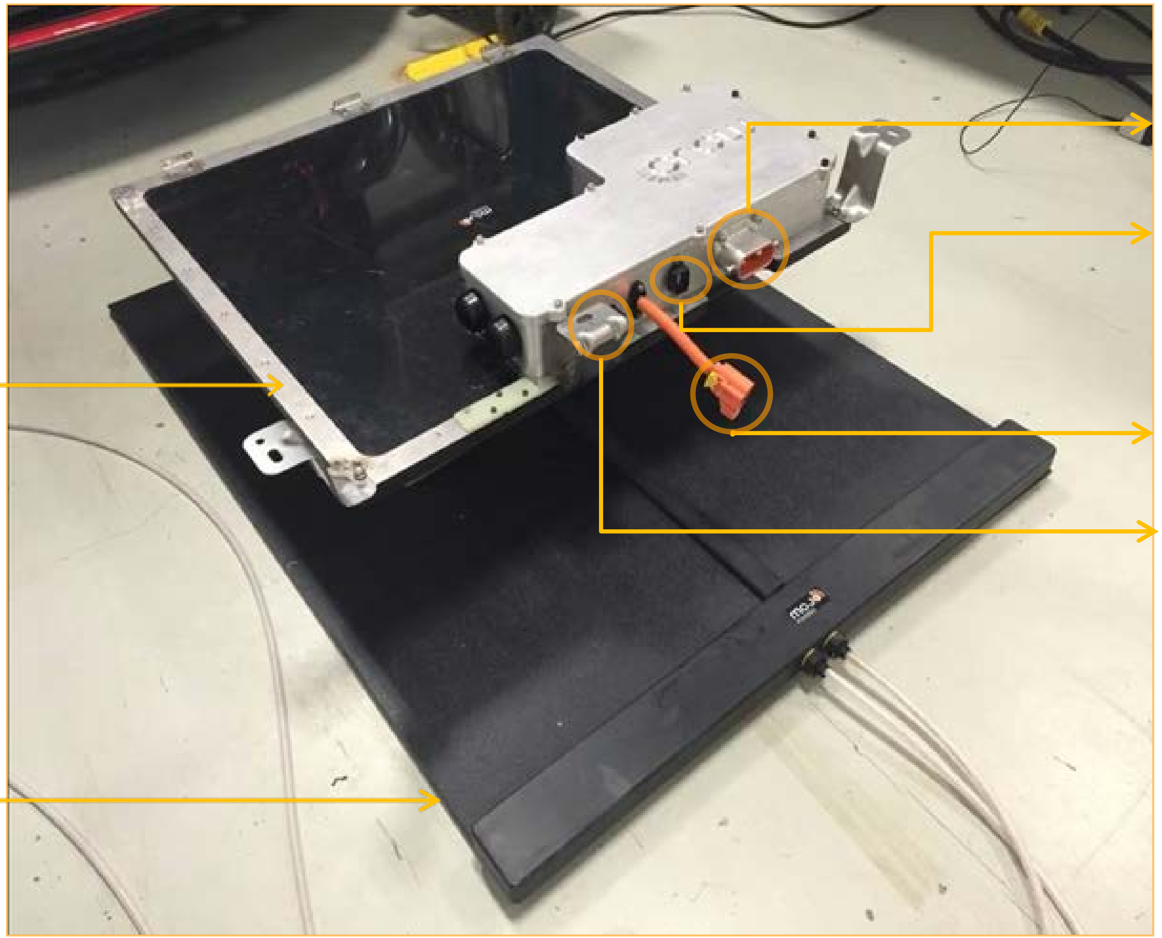
B. New Tx (Gen. 4 Charger)
   - New gate drivers and FET design result in improved safety/protection, and better thermal management
   - Uses a second WiFi connection to connect to user control laptop.

C. Receiver (Gen. 3 from Phase 2)
   - Used same design as Phase 2, except using lower cost Ferrite (1/10 cost from new source), with same performance as before



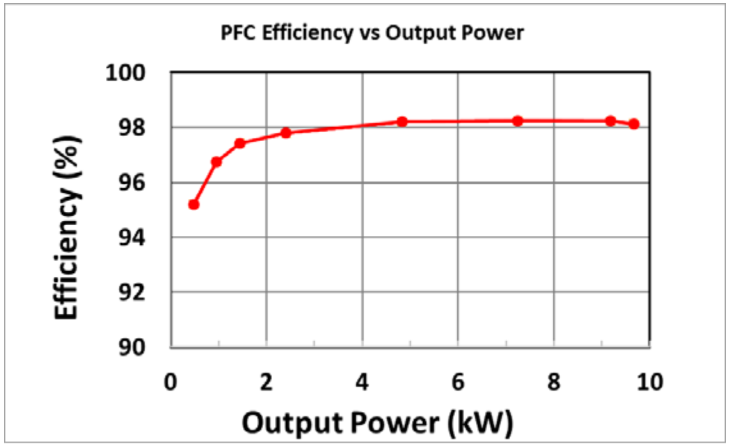
Tx and Rx Assembly

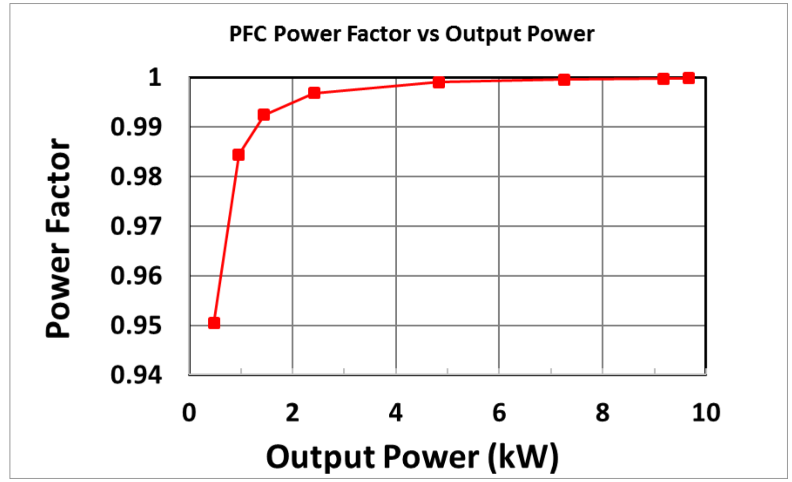
Transmitter assembly includes coil and capacitors.
Receiver assembly includes coil, and electronics housing with capacitors and rectifier.



Phase 3 Development

High Efficiency (98.3%) AC/DC Power Factor Correction (PFC) front end:

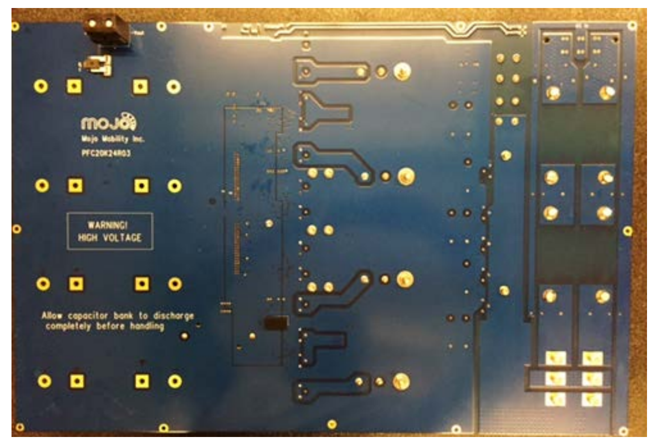




- 240 V AC input to 480 V DC output
- Designed for > 20 kW output
- **0.9998 Power Factor**

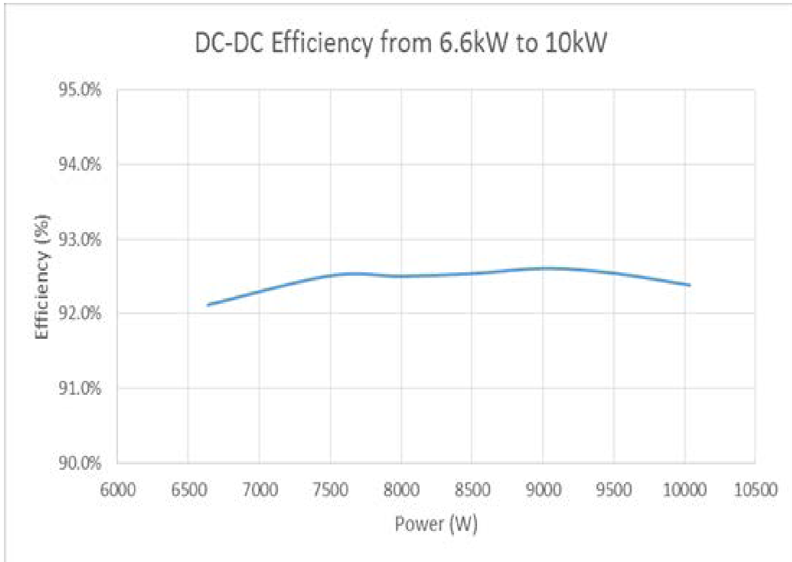
- Interleaved 4 phase operation
  - Reduced current through each switch
  - Reduced output ripple of PFC

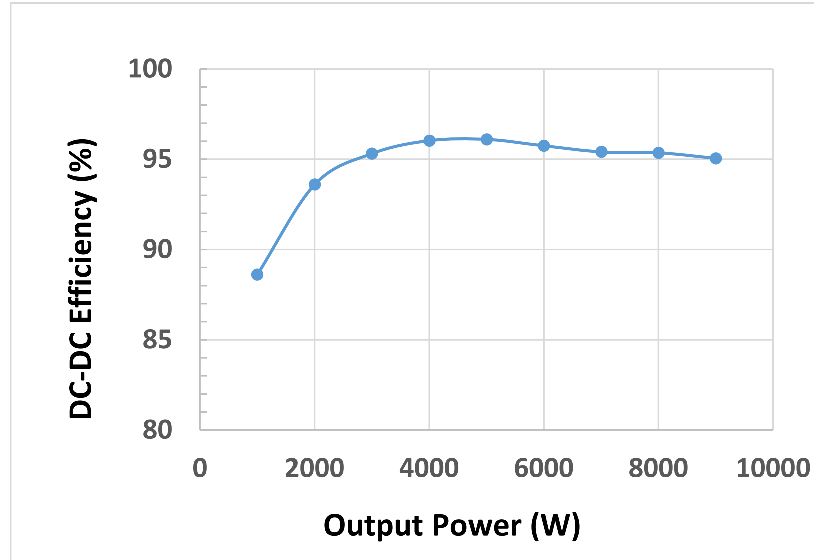
- Single Board construction (60x40x12 cm)
- Record Efficiencies



Top View of PFC

Phase 3 Development





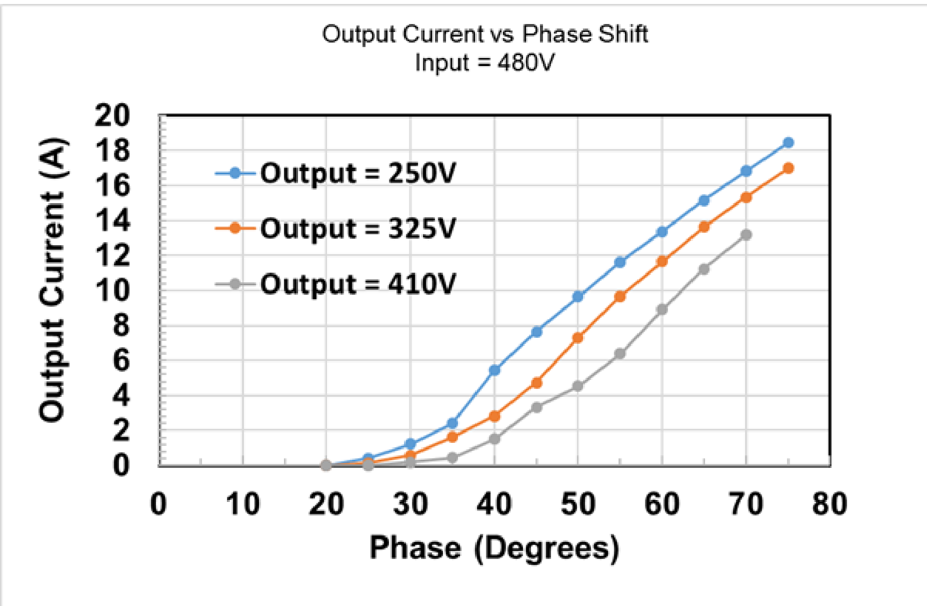
Phase 1 → **Phase 2 & 3**

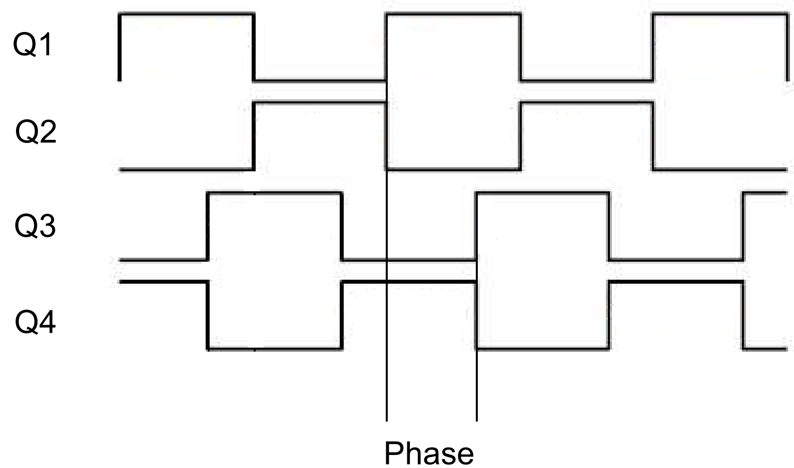
- In Summary, we have decreased size of Tx coil in Phase 2; maintained size in Phase 3
  - Results in 3% efficiency increase
  - Smaller X-Y positioning, but sufficient for most applications (> ±20 cm)
- Output power limited by electronic load. Higher powers can be reached with 2 loads in series.

Phase 3 Development

Controlling Current into EV

- EV battery requires 240 to 410 V WPT output to charge
- Required current is requested by EV through CHAdeMO every 200 msec.
- WPT receiver receives CHAdeMO messages and sends to Transmitter through WiFi
- Transmitter calculates required phase through PID control and adjusts Resonant Converter Phase delay to desired output current

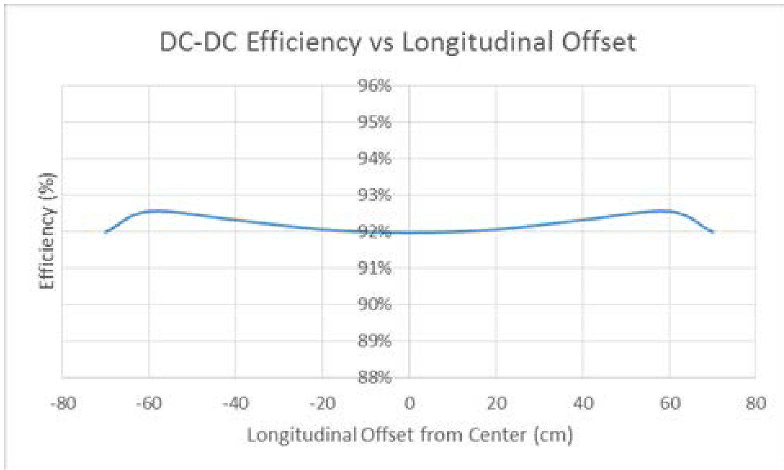




Phase 3 Development

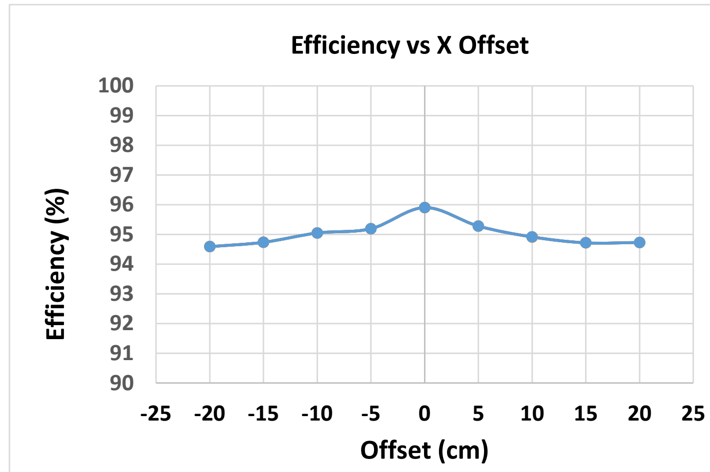
WPT DC-DC Efficiency vs Coil Offset

X Offset



Phase 1

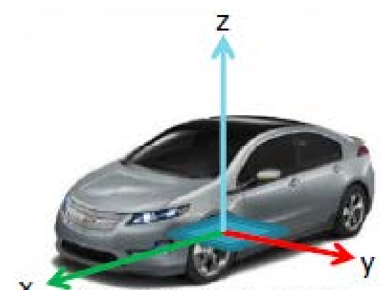
X Offset



Phase 2 & 3

Conditions:

- 87kHz switching frequency
- 20cm coil to coil separation
- 5kW input power



(image provided by SAE J2954)

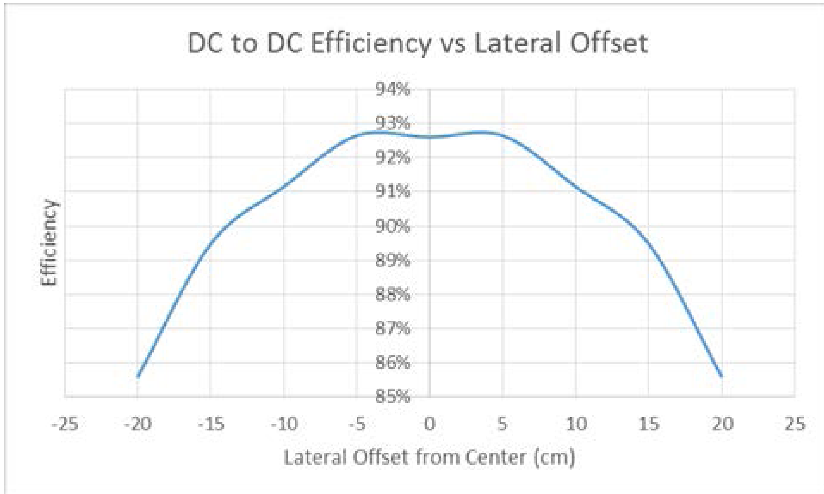
Notes:

- Phase 2&3 utilize a smaller coil design

Phase 3 Development

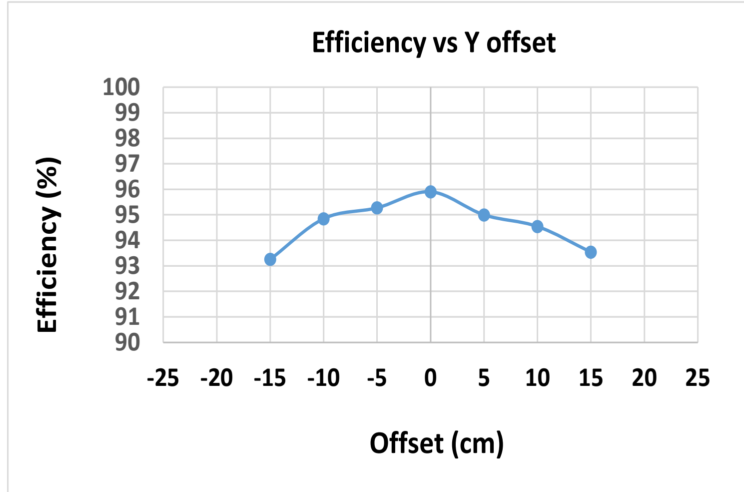
WPT DC-DC Efficiency vs Coil Offset

Y Offset



Phase 1

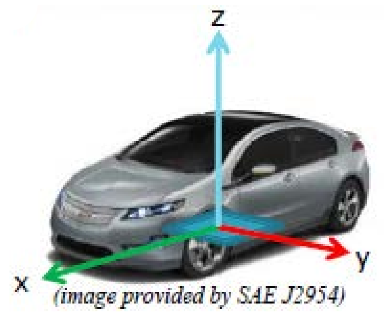
Y Offset



Phase 2 & 3

Conditions:

- 87kHz switching frequency
- 20cm coil to coil separation
- 5kW input power



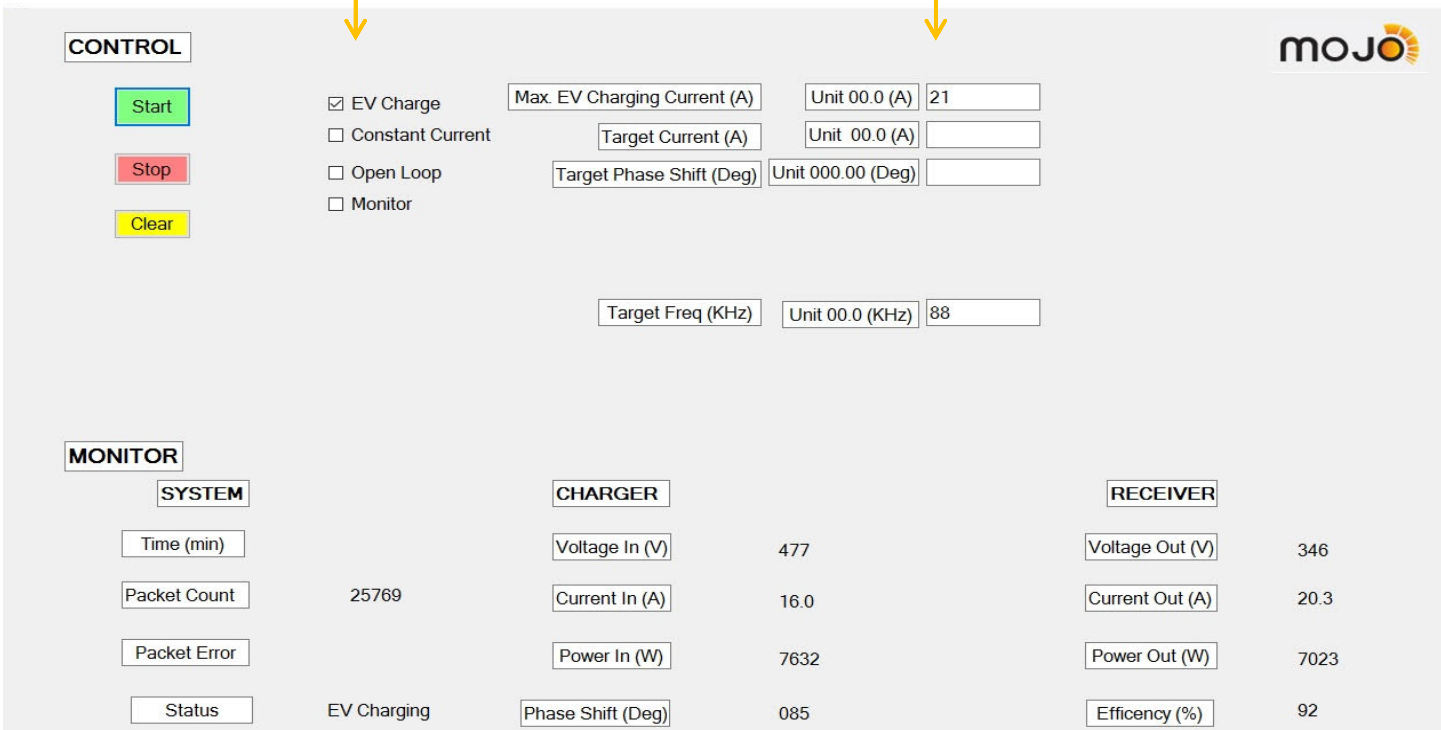
Notes:

- Phase 2&3 utilize a smaller coil design

Phase 3 Development - User Interface Software

User chooses operating mode

Configurable fields to control the power



- User interface software (UI) runs on PC laptop and connects to Tx through PC WiFi Controls all functions of Tx
- Can run in Constant Current, Open Loop, and EV charge modes
- In EV charge mode, the max. EV charge current can be typed in and charging started.
  - The Tx transmits the value to Rx and Rx negotiates through CHadeMO with EV and starts charging with EV controlling supplied current.

Phase 3 Development - Results

RECEIVER	
Voltage Out (V)	380
Current Out (A)	26.3
Power Out (W)	9994
Efficency (%)	94

Final results in Phase 3:

- Charging of EV with Rx integrated into car.
- 10 kW power transfer into EV at 20 cm coil to coil z-gap
- 94% DC-DC efficiency; ~ 92% efficiency Grid to EV
- Input and output conditions shown on UI

Phase 3 Development - Results

Stepping Up Power Level:

- Charging of EV with Rx integrated into car at 20 cm coil to coil gap.

- 6.3 kW with 92% efficiency
  9.0 kW with 95% efficiency
  10 kW with 94% efficiency
  (DC-DC efficiencies)

- To reach over 9.0 kW, input voltage into transmitter was increased from 480VDC to 550VDC.

- Higher than 10kW power levels are possible with further testing and development.

CHARGER		RECEIVER	
Voltage In (V)	474	Voltage Out (V)	377
Current In (A)	14.4	Current Out (A)	16.8
Power In (W)	6825	Power Out (W)	6333
Phase Shift (O)	103	Efficency (%)	92

CHARGER		RECEIVER	
Voltage In (V)	474	Voltage Out (V)	379
Current In (A)	19.7	Current Out (A)	23.6
Power In (W)	9337	Power Out (W)	8944
Phase Shift (O)	180	Efficency (%)	95

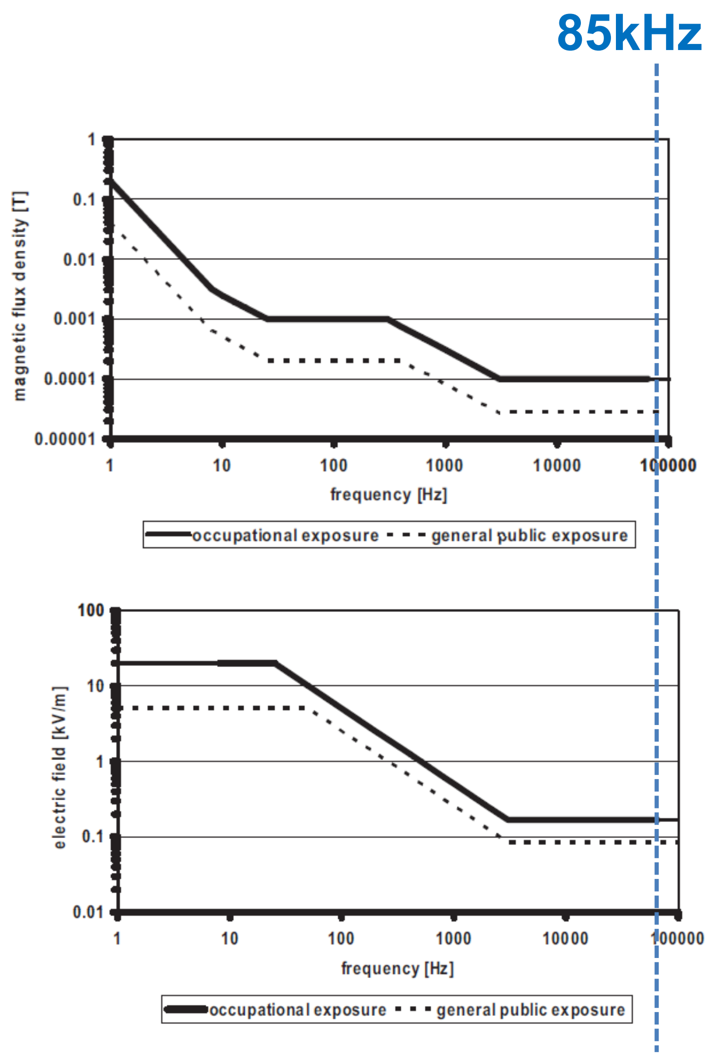
CHARGER		RECEIVER	
Voltage In (V)	541	Voltage Out (V)	380
Current In (A)	19.5	Current Out (A)	26.3
Power In (W)	10549	Power Out (W)	9994
Phase Shift (O)	154	Efficency (%)	94

E&M Field Emissions - Requirements

ICNIRP Electromagnetic Emission Safety Guidelines

ICNIRP 2010 Guidelines for Safe Exposure to Electric & Magnetic Fields in Frequency Range of 80kHz to 90kHz:

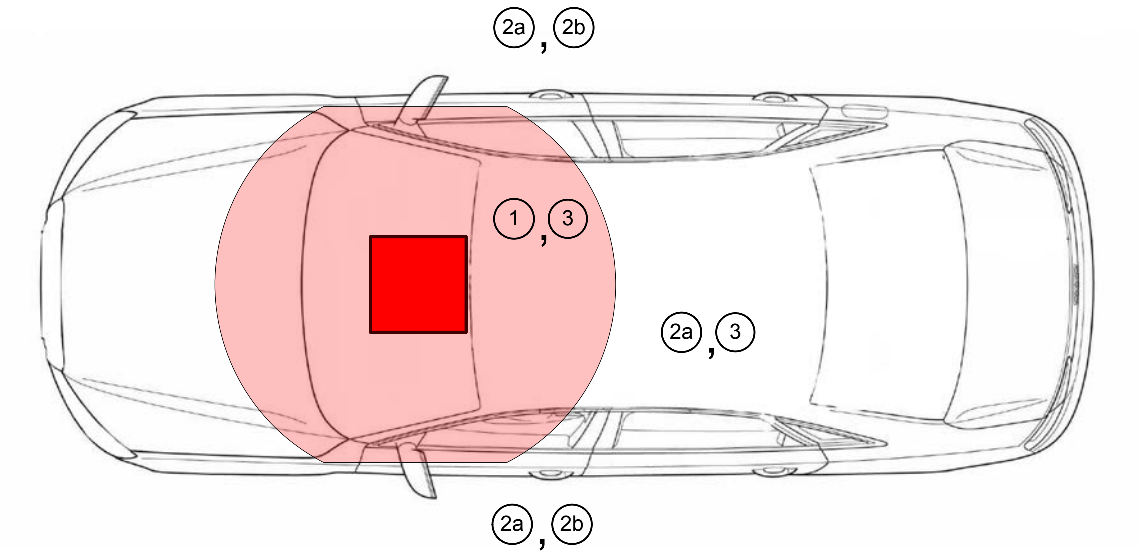
- 100 uT & 170 V/m for Occupational Exposure
- 27 uT & 83 V/m for General Exposure

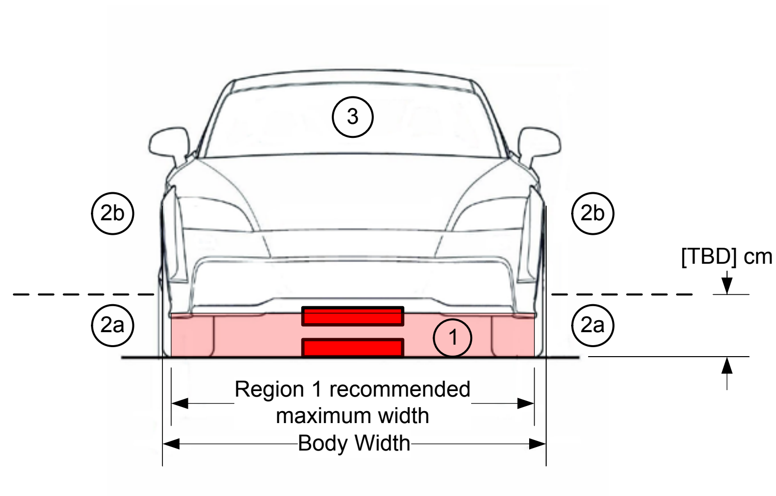


E&M Field Emissions - Test Method

EMF Exposure to Humans & Implanted Medical Devices

SAE J2954 TIR





SAE has been working hard to define EMF exposure limits as it relates to the automotive environment.

Region 1: Underneath the vehicle and near the wireless power pads.

Region 2a: Around the vehicle at heights less than 20cm above the ground.

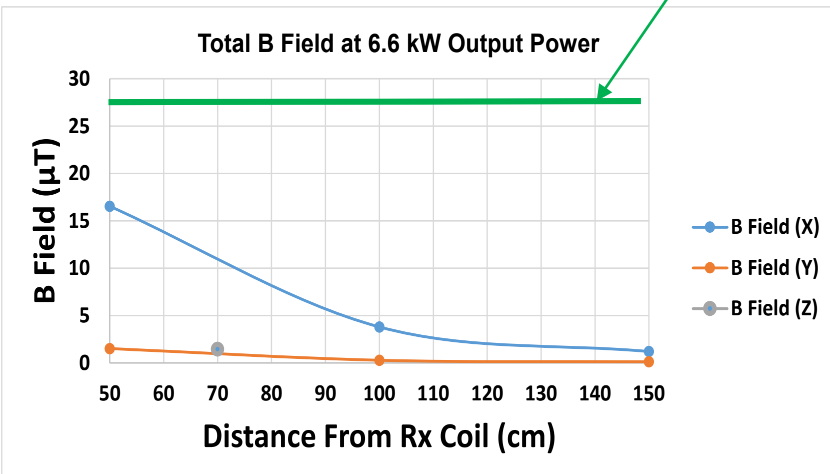
Region 2b: Around the vehicle at heights greater than 20cm above the ground.

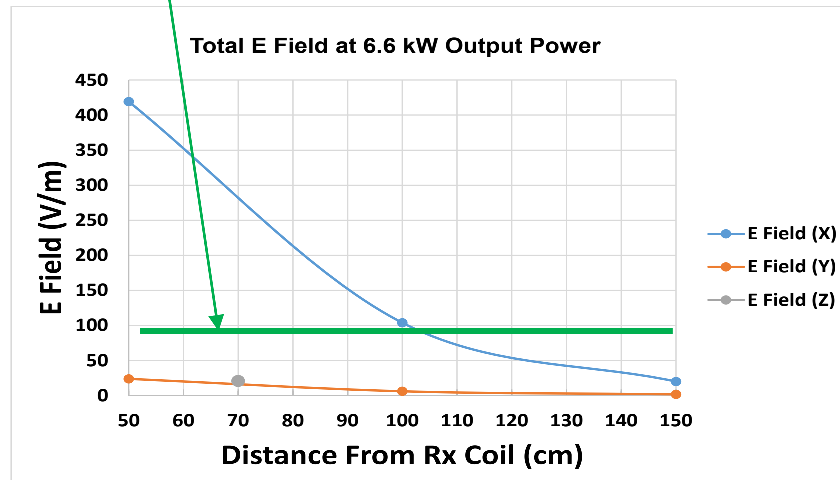
Region 3: Vehicle interior.

E&M Field Emissions – Phase 2 Bench Results

System Emissions Measurements

ICNIRP 2010 Limits for General Public



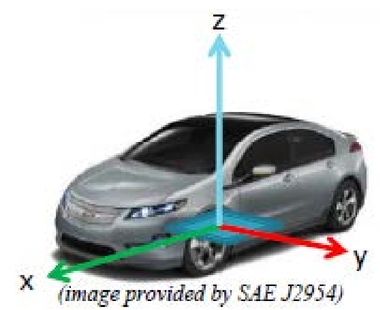


Conditions: Bench system measurements

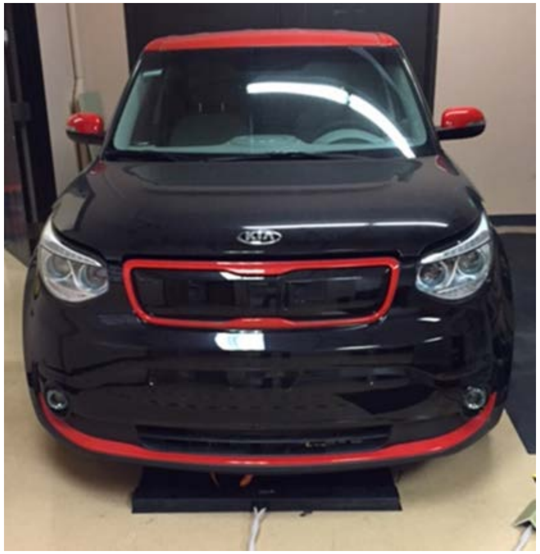
- 82 kHz switching frequency
- 20 cm coil to coil separation

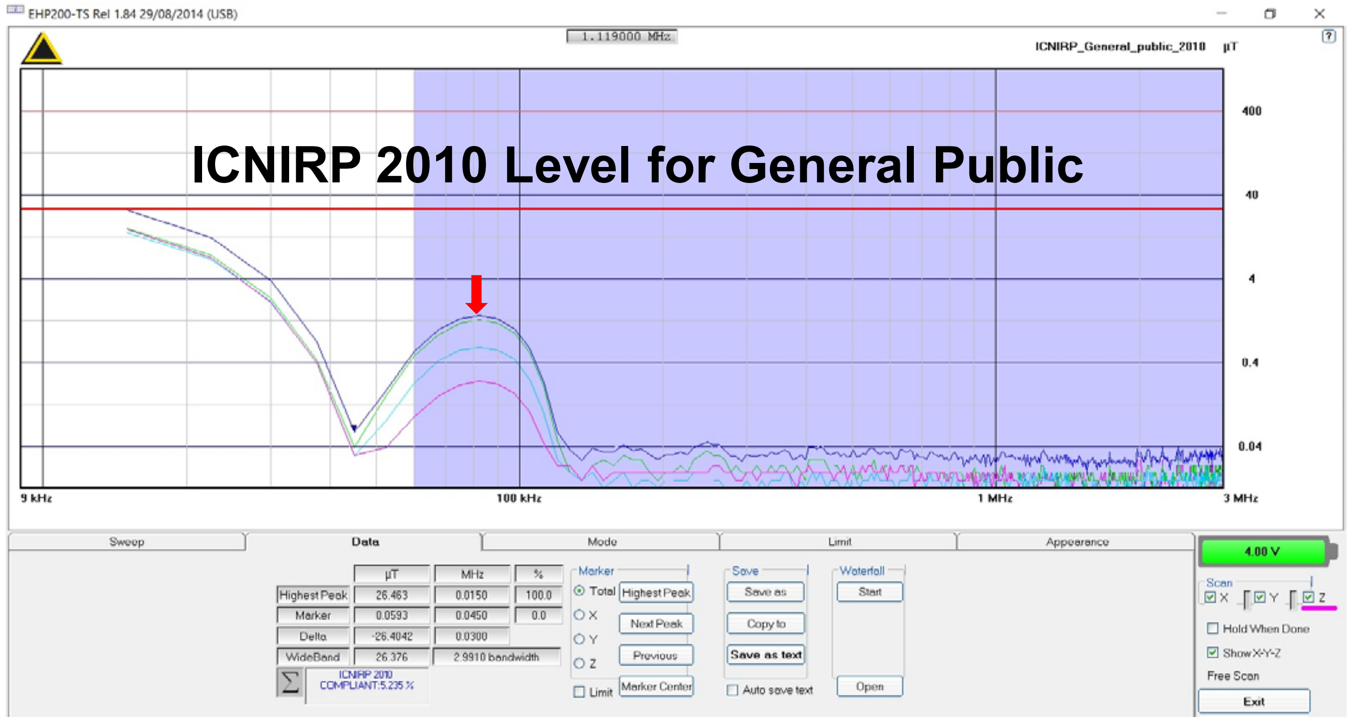
Note:

- Very low lateral emissions (unique design)
- Vehicle length will help shield the x-axis component



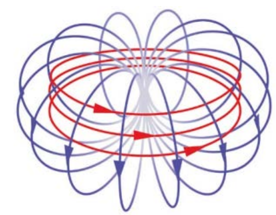
E&M Field Emissions - Phase 3 Vehicle Results





Conditions: Vehicle system measurements (Outside EV)

- Receiver integrated into Vehicle
- Power level: 6.6 kW into EV
- EMI measured at 0.5 m from front of EV; 30 cm above ground

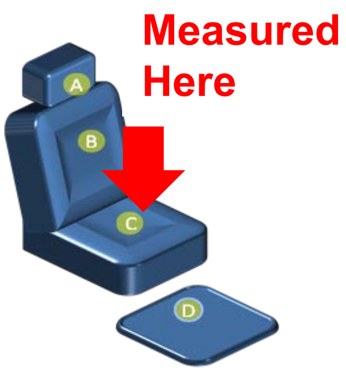


Result: Electric and Magnetic Fields are less than **10%** of ICNIRP limit

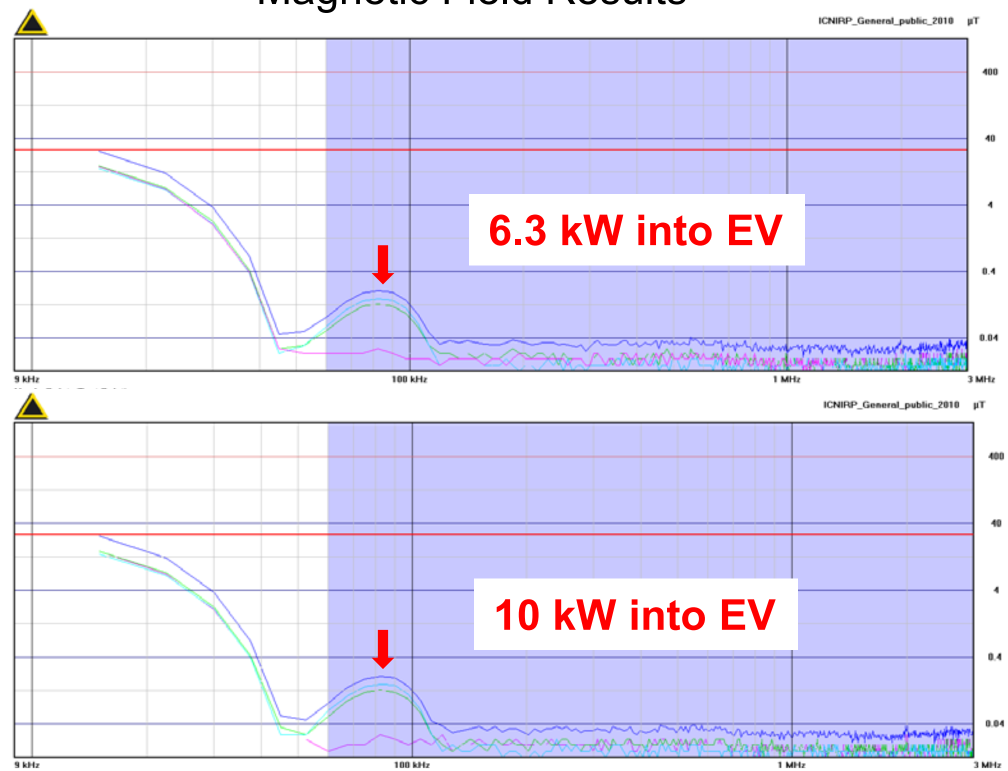
E&M Field Emissions - Phase 3 Vehicle Results

Magnetic Field Results

ICNIRP limit is red line →



Driver seat



Conditions: Vehicle system measurements (Inside EV)

- Receiver integrated into Vehicle
- Little variation in results from 6.3 kW to 10 kW power level

Result: Electric and Magnetic Fields are less than **1%** of ICNIRP limit

Thermal Testing - Phase 3

Conditions:

Plastic Container with Water

No Significant Rise in Temperature

Temperature Reading

Thermal Imaging Camera

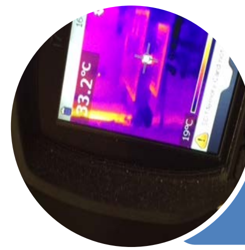
Plastic Container with Water

Thermal Testing - Phase 3

Conditions:

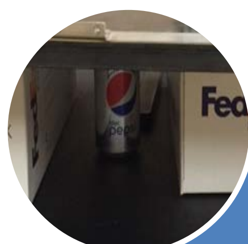
Empty Pop Can

Minimum Temperature Rise



Temperature Reading

Thermal Imaging Camera



Metal Pop Can

Conclusion

Attribute	Project Goal	Achieved
Power Transferred	>6.6 kW	10 kW
Grid to EV Efficiency	>85%	92%
Coil-To-Coil Gap	20cm	20cm
EMI	Below ICNIRP	1% - 10% of ICNIRP

Observations:

- Adhesive materials used in housing assembly have effect on resonant circuit characteristics.
- Unique considerations of closed-loop control system; have to consider WiFi delay and effect of output voltage on system response.
- Good thermal results; minimal temperature rise.
- AM radio interference during power transfer.
- Electromagnetic interference can disrupt test equipment, even user laptop

What Else Do We Want to Learn?

- What are the effects to other wireless communication systems in the vehicle (TPMS, cellular, WiFi, etc.)
- What are the effects on the powertrain components? Important to know if considering dynamic charging.

Next Steps

- Complete fleet build-up
  - Three systems remaining
- Continue to support INL testing
  - System was delivered, testing and analysis in progress
- System testing at Hyundai Technical Center
  - System performance
  - Electrical endurance
  - Vehicle durability
  - Emissions

Collaborations and Coordination with Other Institutions

- Mojo Mobility
  - Sub-recipient of award no. DE-EE0005963.
  - Responsible for design, development of wireless charging system.
  - Currently developing wireless charging systems for consumer electronics, and automotive applications.

- Society of Automotive Engineers (SAE)
  - J2954 Wireless Charging Task Force (Voting Member)
  - J2836/6 Wireless Charging Specific Use Cases (Voting Member)
  - J2847/6 Wireless Charging Specific Messages (Voting Member)
  - J2931/6 Wireless Charging Specific Protocols (Voting Member)

End