Wireless Charging of Electric Vehicles

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Oak Ridge National Laboratory

U.S. DOE Vehicle Technologies Office
2015 Annual Merit Review and Peer Evaluation Meeting

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Program Overview

Timeline

- Project start date: Oct. 2012
- Project end date: Scheduled for April 2016
- 98% Complete (reporting, papers, etc.)

Barriers

- Transfer from laboratory set-up to integration prototype development
- Ability and availability of components for WPT requirements
- Interoperability with different vehicle energy storage system requirements.
- Lack of Standardized Test Protocols

Budget (DOE share)

- DOE funding : $8.0M
- Partner funding : $2.6M

Partners

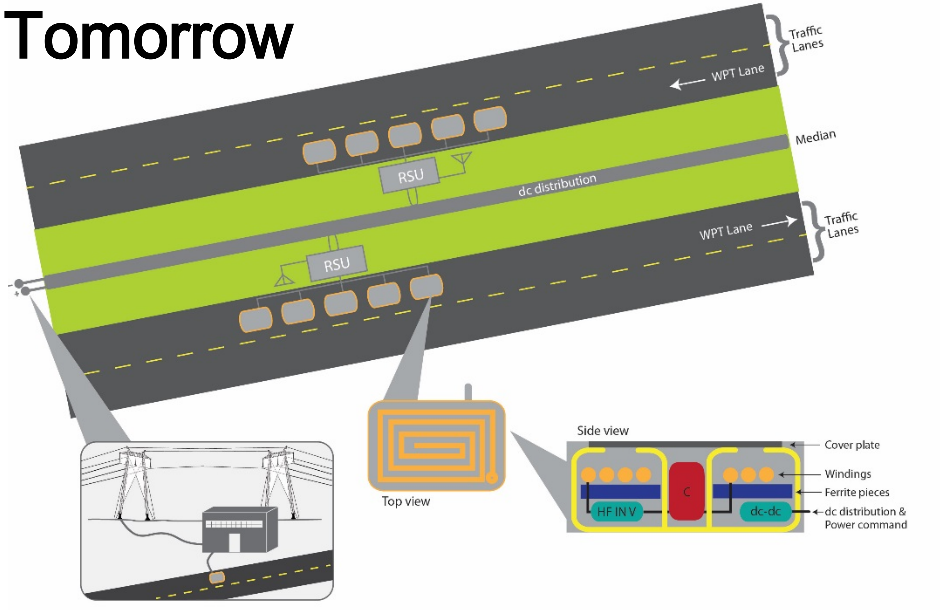
- Oak Ridge National Laboratory (Project Lead)
  - Power Electronics & Electric Machinery Group
  - Center for Transportation Analysis
- Toyota (CRADA)
- Evatran (Plugless power)
- Clemson University – ICAR Center

Project Objective and Relevance

- Advance technology maturity, identify commercialization, standardization and safety of wireless charging technology
- **Supports major LD Vehicle Systems (VS) powertrain electrification goals:**
  - Demonstrate market readiness of grid-connected vehicles
  - Develop methods to reduce impact on infrastructure due to EV charging.
  - Address codes and standards needed to enable wide-spread adoption of electric-drive transportation technologies.
- **Directly supports VS component and systems evaluation.**
  - Supporting J2954 standards
  - Component efficiencies highlighting system efficiencies and project deliverables

Today

Tomorrow

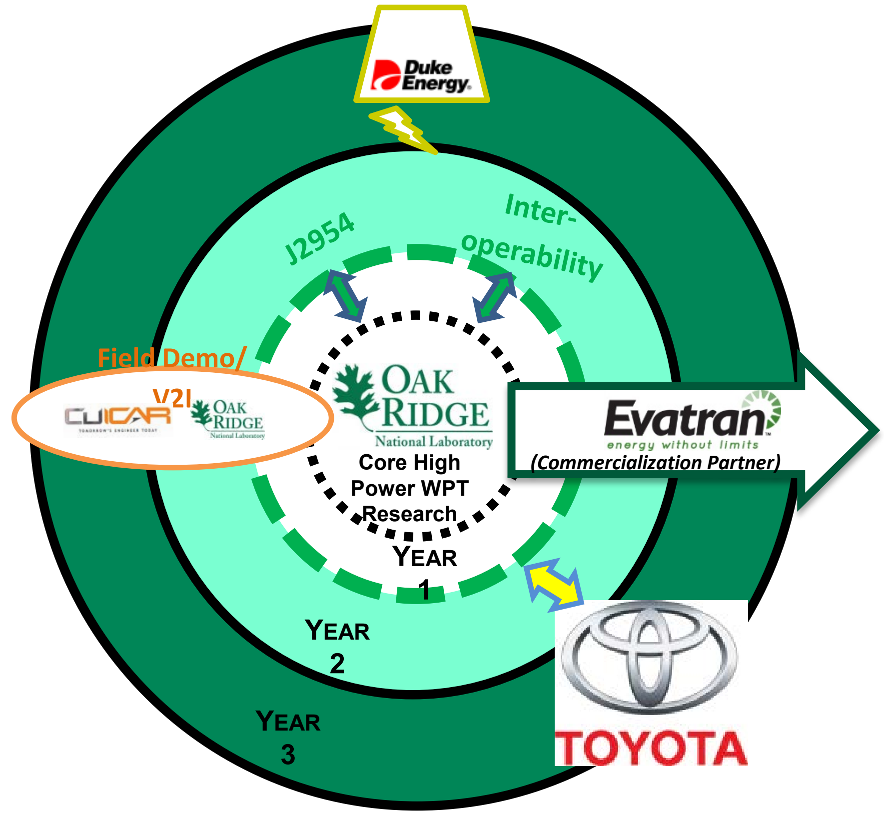


Objective and Outcome

Overall goal: **Coordinate multi-party team activities to integrate the technology developed in the lab to the vehicles with different WPT charging levels (WPT Level I-II) and different vehicle ESS and interface requirements.**

Overall Program Outcome:

- **Develop fundamental knowledge base for the technology to fill the gaps for commercialization.**
- **Work with partners to overcome the challenges of vehicle integration.**
- **Validate system through testing and generate valuable research data.**
- **Provide unbiased data to promote technology standards.**



Partners / Collaborators

Organization		Type of Collaboration/Coordination
Evatran energy without limits	Evatran - Plugless Power	WPT packaging, vehicle integration, vehicle testing
CU-ICAR TOMORROW'S ENGINEER TODAY	Clemson University ICAR	Communications technology, demonstration site
TOYOTA	Toyota Motor Corp	Demonstration vehicles (Prius Plug-in, Scion IQ-EV, RAV4) and integration support, CAN
Duke Energy	Duke Energy	Grid readiness and interaction
CISCO	CISCO Systems	DSRC Communications

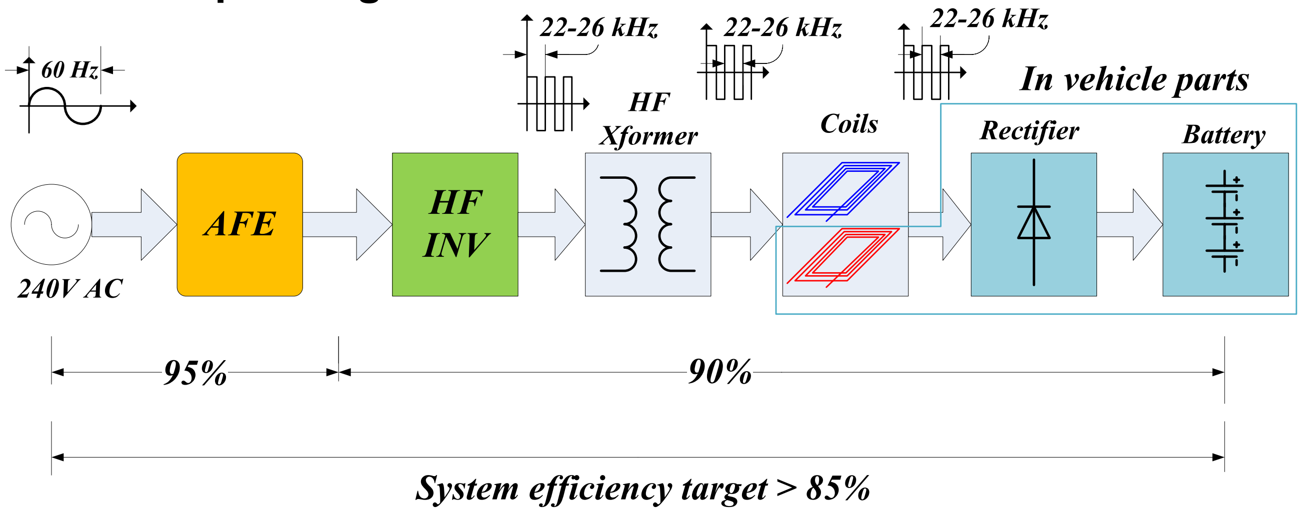
- **ORNL supports SAE J2954 Wireless Charging Standards Development Committee and its subcommittees.**

Milestones

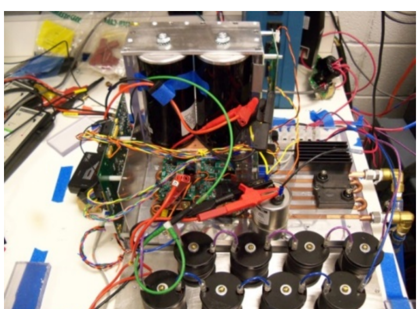
Date	Milestones and Go/No-Go Decisions	Status
Nov-2013	Milestone: WPT efficiency >85% wall to battery (or equivalent) at 6.6 kW power.	Successful demonstration of bench top prototype technology at ORNL ➢ *> 85% @6.6kW (required)* ➢ *Demonstrated 10kW (progress towards high power)* ➢ *Met the IEEE and ICNIRP standards*
July 2015	Milestone: Integrate WPT System into commercial PEV's. Demonstrate 85% efficiency is retained at >160mm airgap at >6.6kW power transfer to the load.	ORNL, Evatran, and Cisco completed integration of WPT system into Toyota vehicles (Prius and Scion iQ). Demonstrated interoperability with two vehicles Closed loop automated charging process operation with 85%@6.6 kW was demonstrated at ITIC facility
November 2015	Milestone: Evaluation of the OEM vehicle with fully integrated WPT system by an independent laboratory	INL independently tested the system at different test conditions and validated: • Power transfer level (>6.6kW), • Efficiency target (>85%), • Misalignment tolerant (up to +/- 40mm), • Electric and magnetic fields (<6.25uT, <87V/m).
March 2016	Milestone : Demonstrate progress toward 20 kW static and dynamic wireless charging using an OEM vehicle	Excluding PFC, DC-to-DC efficiency >95%, power transfer >20kW Electric and magnetic fields (<6.25uT, <87V/m).

Technical Accomplishments: Test Bench Demo- FY13/14 Milestone: Overall System Architecture

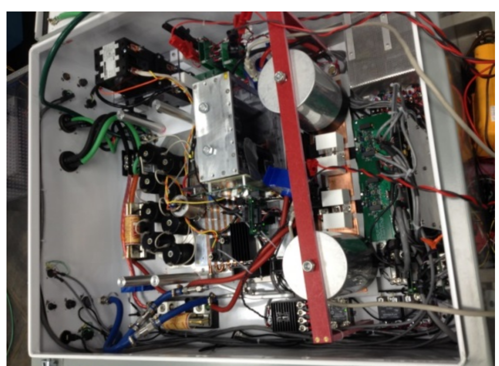
- **Targeting grid side regulation with a single grid side unit adapting the requirements from different vehicles with minor hardware modifications on each vehicle.**
- **Built a control system that allowed fully automated operation, control, monitoring, and switch between operating modes.**



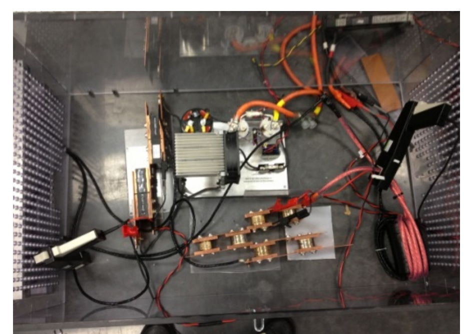
AFE with PFC



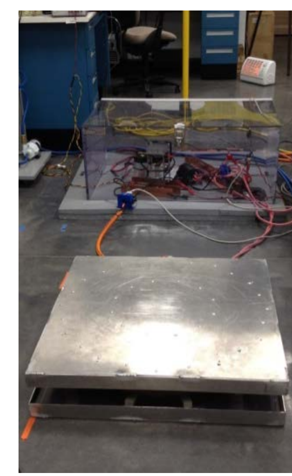
PFC and inverter



Trx., tuning, rectifier



Coils

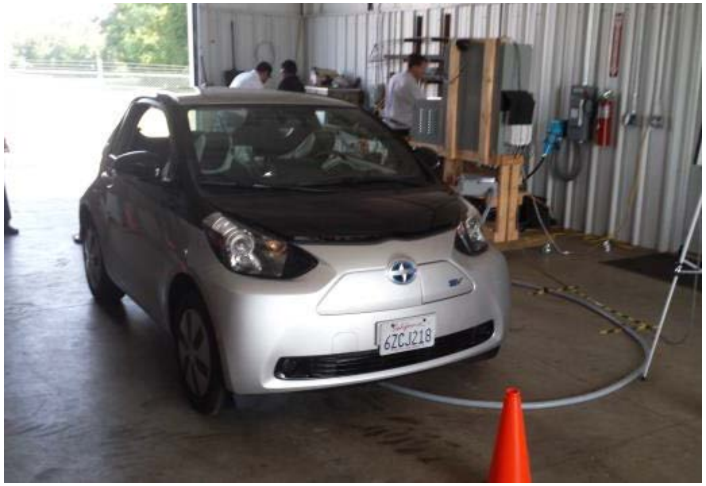


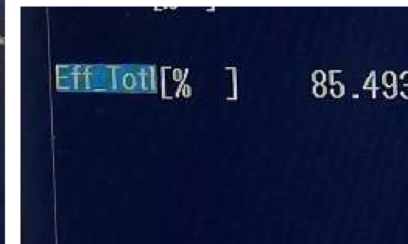
Vehicle Integration : Summary and Testing

- System designed during the initial phase integrated into the vehicles with all functionalities including:
  - Alignment (Evatran system leveraged and integrated)
  - Radio communications for vehicle side feedback and controls (Cisco and Clemson University ICAR)
  - Start and stop charge
  - Orderly and emergency shutdown procedures
- Demo at ITIC facility in July 2015.

Vehicle Integration : Summary and Testing

- **Performed the Phase #2 demos in July 2015 with Prius Plug-in and Scion iQ**

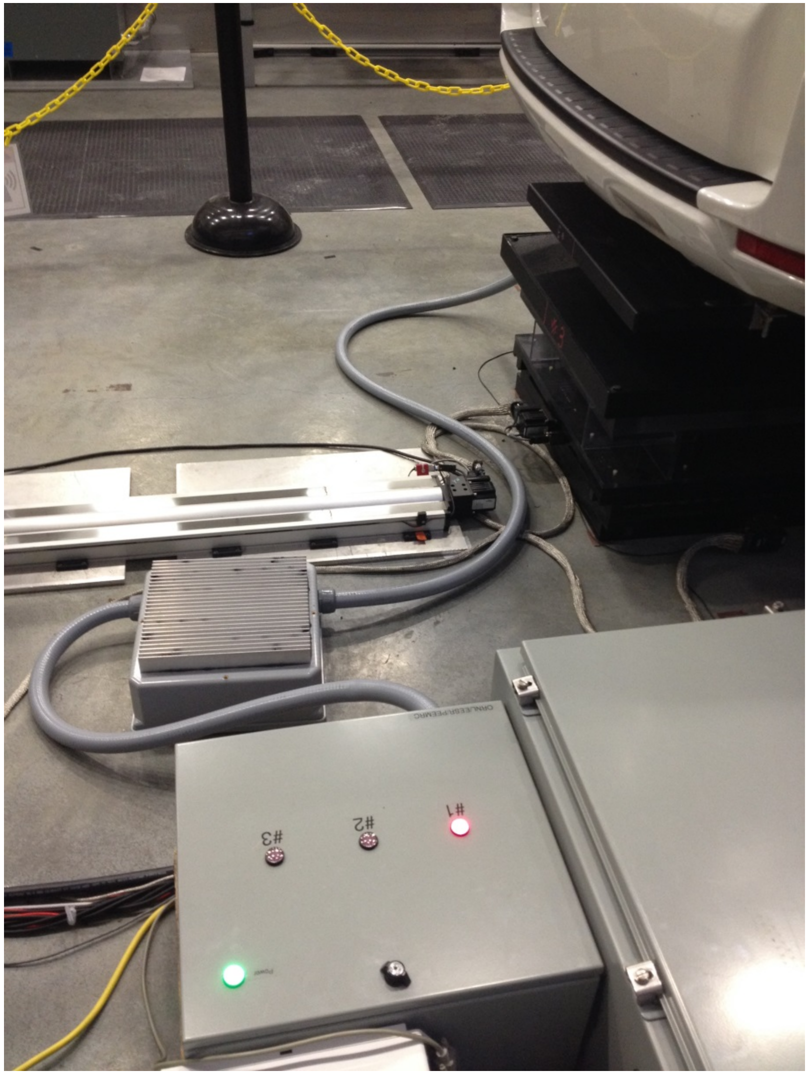




- **Demonstrated fully automated operation, 6.9kW power transfer at 160 mm airgap, 85.4% efficiency (208-209Vac)**

INL Testing Summary

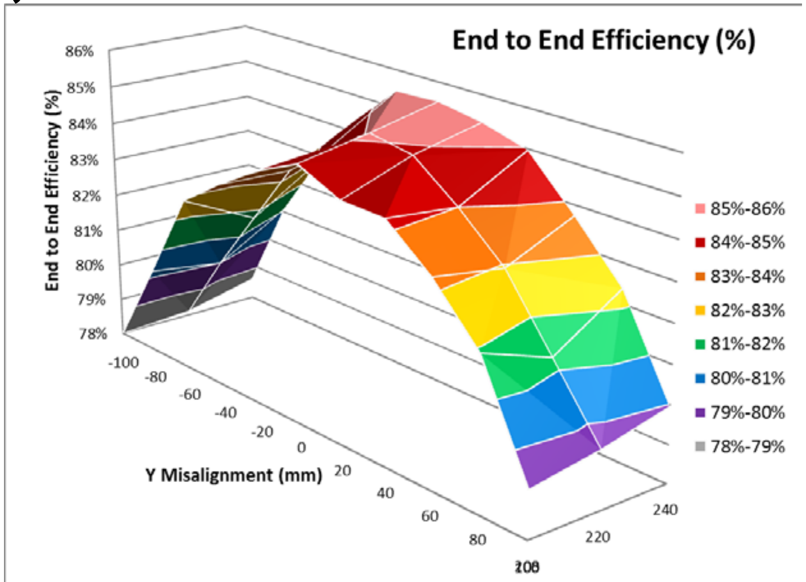
Test setup:

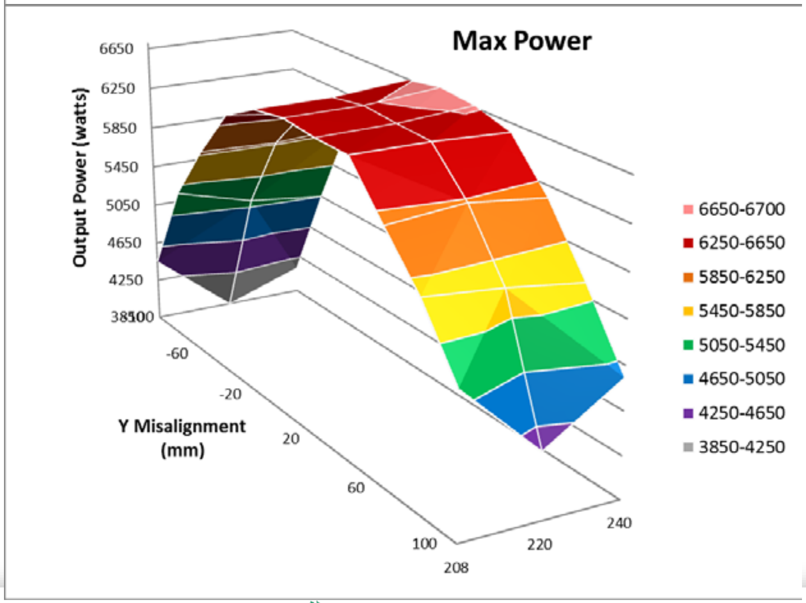


INL Testing Summary

– 6.6kW, 160mm magnetic airgap, 85.50% end-to-end efficiency (up to 6.8kW tested)

Misalignment [mm]	Output (battery) power [W]	Efficiency [%]
-100	4104	78.57
-80	5054	81.10
-60	5920	82.88
-40	6348	84.36
-20	6642	85.44
0	6715	85.50
20	6667	85.31
40	6567	84.97
60	6143	83.74
80	5573	82.38
100	4938	79.95

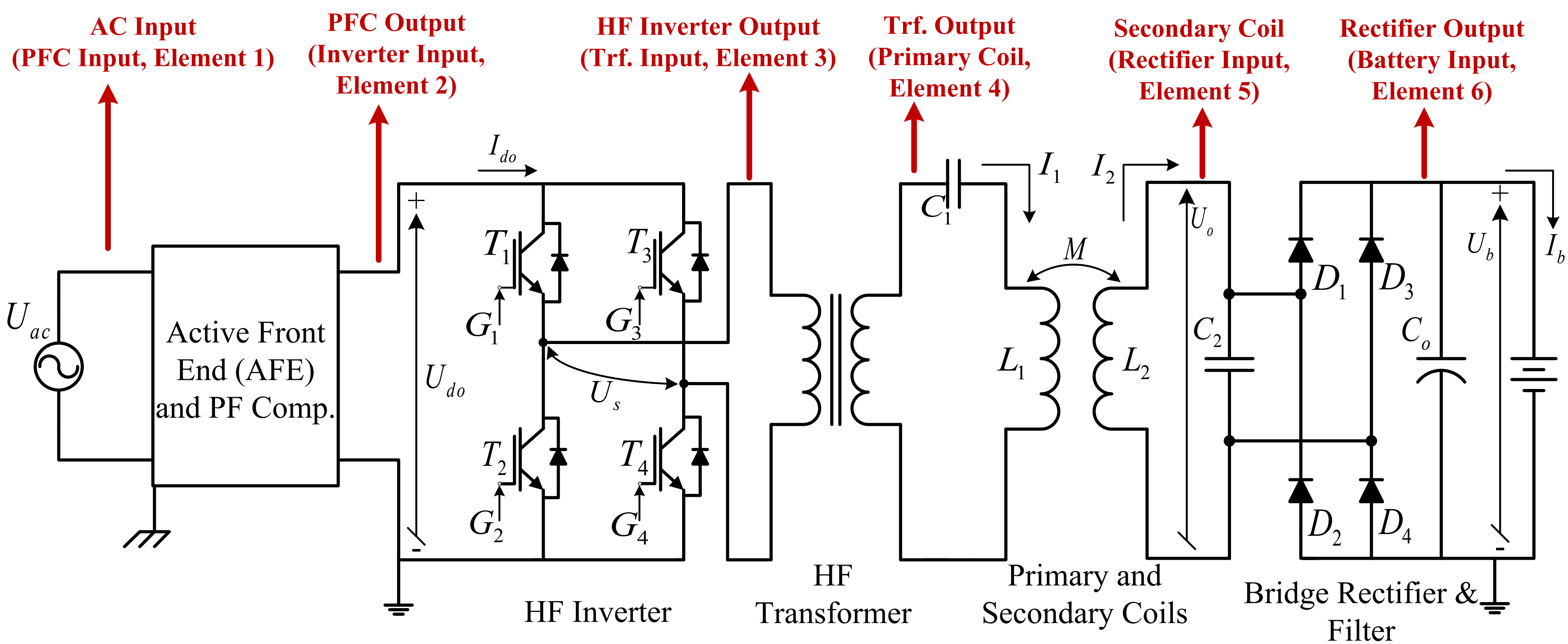




Static WPT Demonstration -6.6kW at ORNL – With Interoperable Coils

η_{PFC}=**97.409%** η_{INV}=**97.936%** η_{TRF}=**97.049%** η_{COILS}=**94.174%** η_{RECT}=**97.691%**

7.761 kW 7.560 kW 7.404 kW 7.185 kW 6.767 kW 6.661 kW



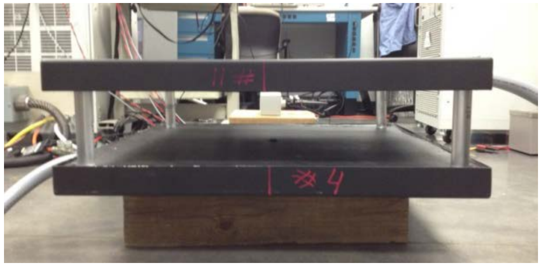
$\eta_{END\text{-}to\text{-}END}$=**85.176%** $\eta_{DC\text{-}to\text{-}DC}$=**89.508%**

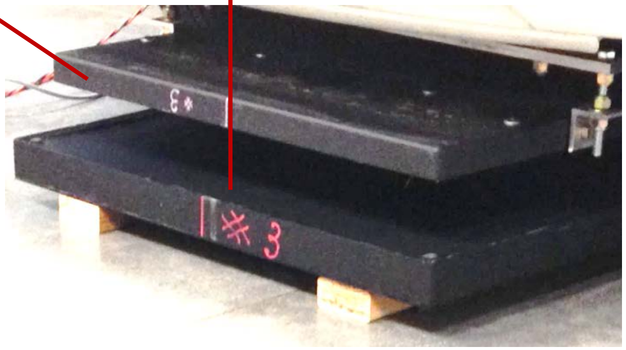
Static WPT System Improvements at ORNL

- All power conversion stages are at least 97% or more efficient except coil-to-coil efficiency.
- ORNL evaluated that reduced coil-to-coil efficiency is due to the dimensional difference in primary and secondary coils.
- According to SAE definition, unmatched coils are interoperable coils.
- Efficiency expectation of systems with interoperable coils is 80% instead of 85%.
- Due to the smaller size secondary coil, <u>not all the field generated by primary coil can be captured by secondary.</u>
- This results in higher fringe field emissions (Magnetic field).

Secondary coil lip length is half the primary coil lip length.

Secondary coil is shorter by ~2 inches from each side (which reduces efficiency)

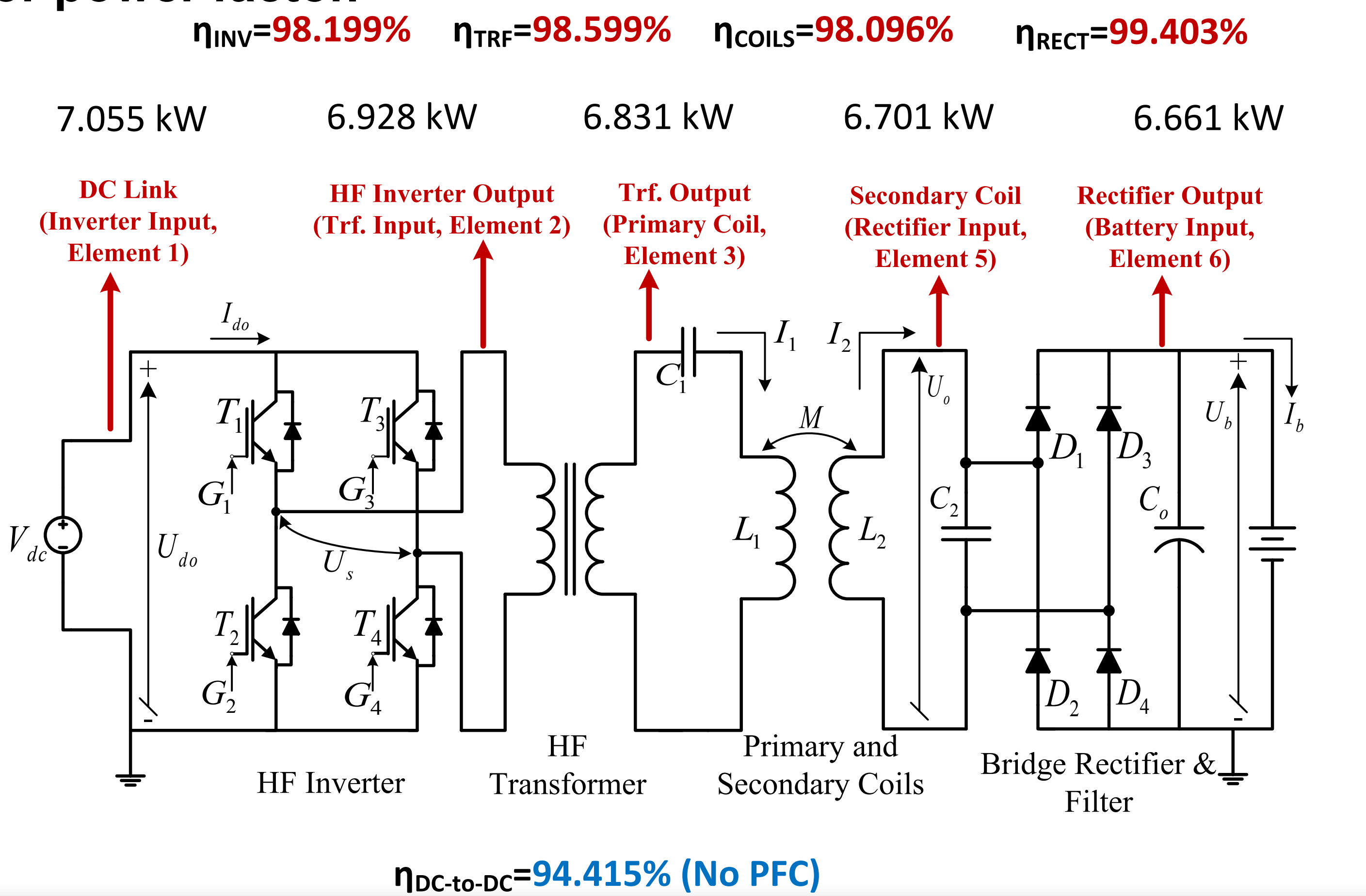




SOLUTION: MATCHED PRIMARY AND SECONDARY COILS

Static WPT Demonstration -6.6kW at ORNL – With Matched Coils

- **Coil-to-coil efficiency: 94.17% to 98.1%.**
- **Other stages such as vehicle side rectifier and grid side inverter efficiency also improved due to the reduced reactive power that they had to handle earlier with poor power factor.**



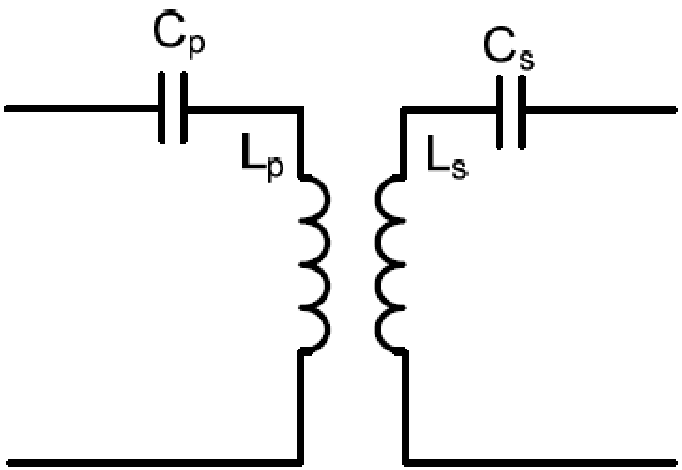
Interoperability with Different Coils

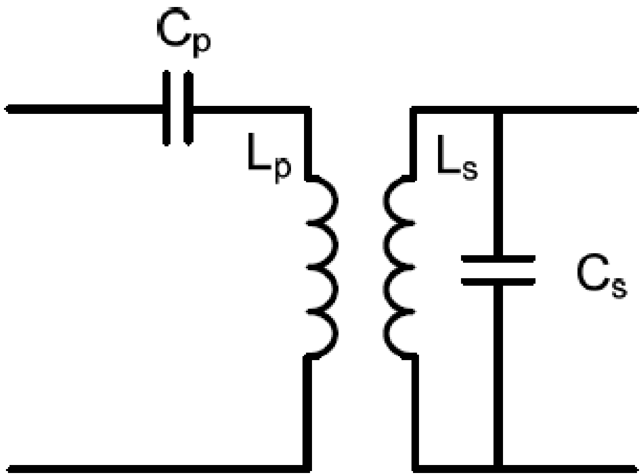
- SAE J2954 efficiency requirements
- Interoperable refers to the coils of different dimensions, types, and manufacturers.

	J2954 Proposed WPT Power Class			
	WPT1	WPT2	WPT3	WPT4
Maximum AC input power	3.7kVA	7.7kVA	11.1kVA	22kVA
Load power	~3-3.3kW	~6.6kW	~9.4kW	~18.7kW
Minimum target efficiency with matched coils	>85%	>85%	TBD	TBD
Minimum target efficiency with interoperable coils	>80%	>80%	TBD	TBD

Progress Towards High Power > 20 kW: Resonant Tuning Configurations and Impact

- **Series-series (SS) and series-parallel (SP) configurations**





- **SP is ideal for voltage driven vehicle side (vehicle side OBC, CHAdeMO needing voltage for start-up, etc.)**

- **SS can be used for direct battery connected systems.**

- **SS results in lower primary coil current → Less B-field and E-field, higher overall power rating without hitting limits of the system**

Static WPT Test Setup – System Descriptions

Laboratory setup with RAV4 updated with Matched Coils

RAV4 vehicle

Receive coil

1st and 2nd transmit coils

Ramp platform

DC power supply

Power analyzer

HF power inverter

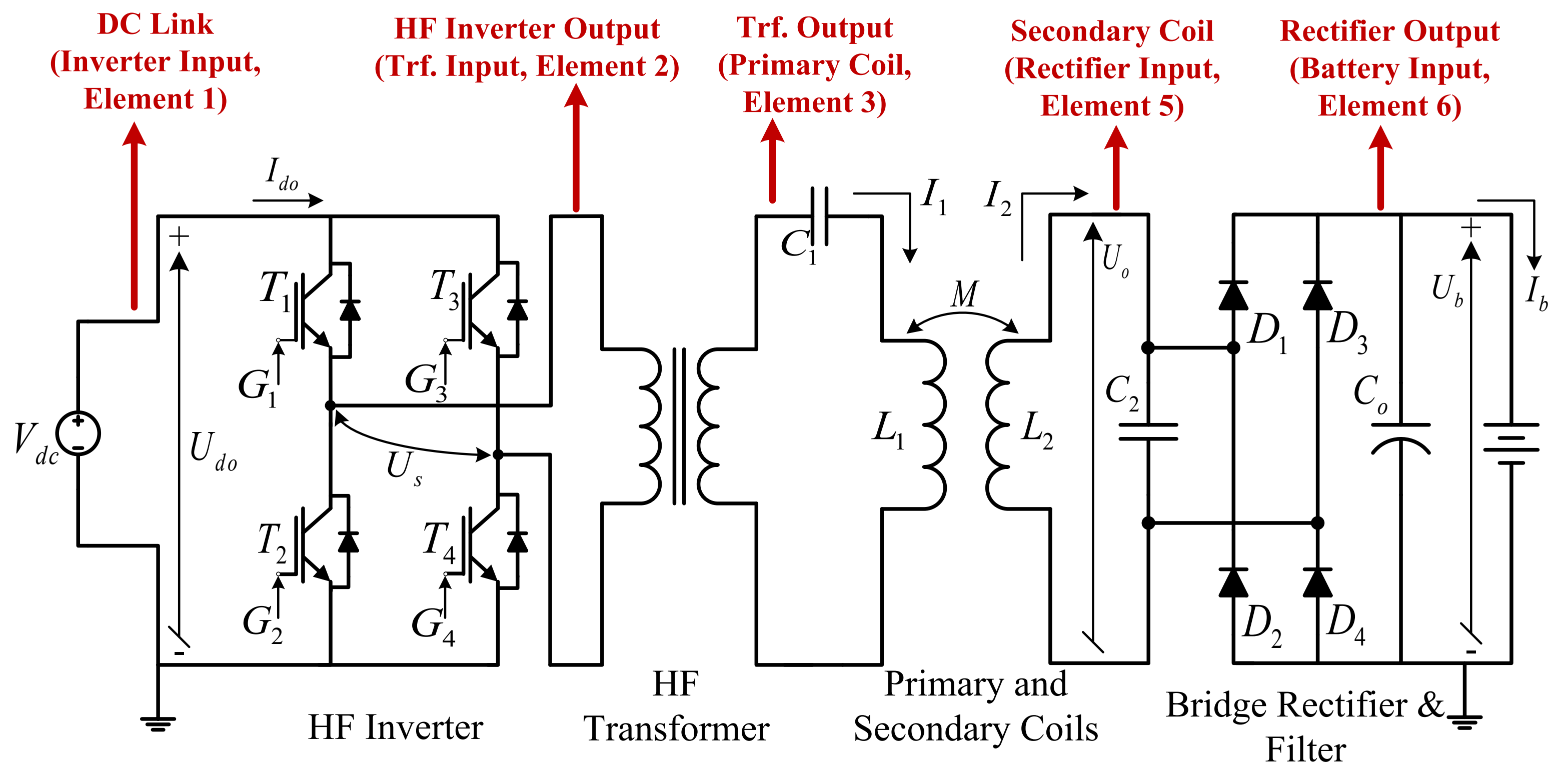
Switchbox for testing both static and dynamic

Static WPT Demonstration >20kW power transfer to RAV4

- **Power flow and power conversion stage efficiencies:**

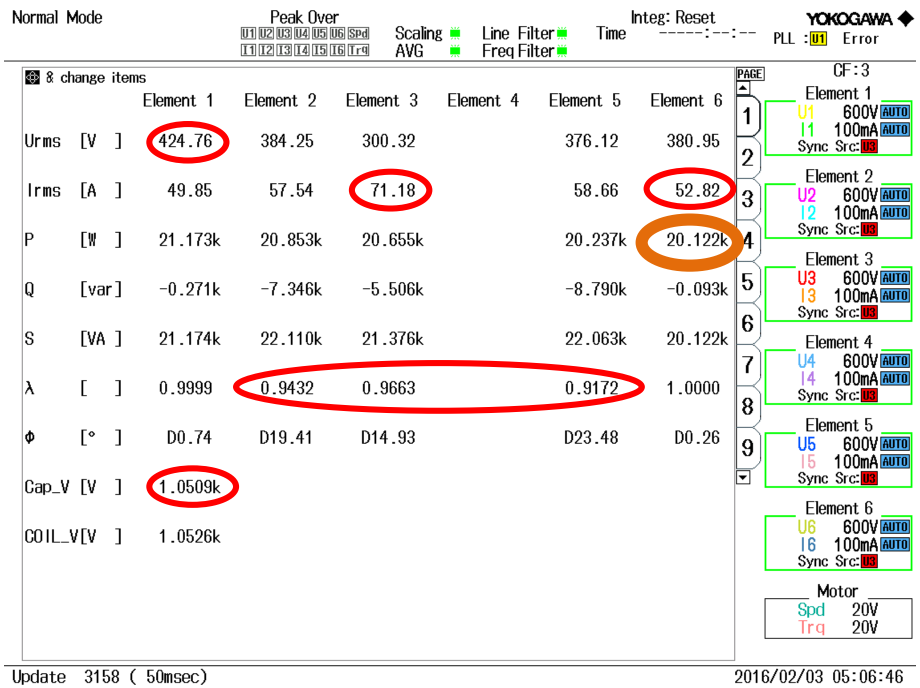
η_{INV}=98.493% η_{TRF}=99.048% η_{COILS}=97.297% η_{RECT}=99.431%

21.173 kW 20.853kW 20.655 kW 20.237 kW 20.122 kW

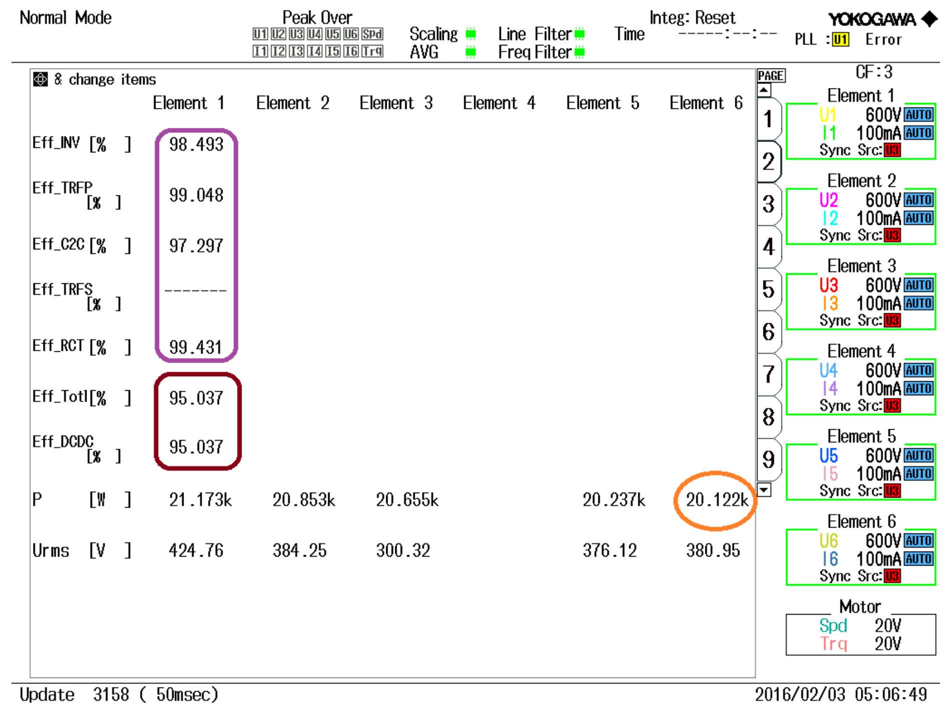


$\eta_{DC\text{-}to\text{-}DC}$=95.037% (No PFC)

Static WPT Demonstration >20kW power transfer to RAV4



	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Urms [V]	424.76	384.25	300.32		376.12	380.95
Irms [A]	49.85	57.54	71.18		58.66	52.82
P [W]	21.173k	20.853k	20.655k		20.237k	20.122k
Q [var]	-0.271k	-7.346k	-5.506k		-8.790k	-0.093k
S [VA]	21.174k	22.110k	21.376k		22.063k	20.122k
λ [ ]	0.9999	0.9432	0.9663		0.9172	1.0000
Φ [°]	D0.74	D19.41	D14.93		D23.48	D0.26
Cap_V [V]	1.0509k					
COIL_V[V]	1.0526k					

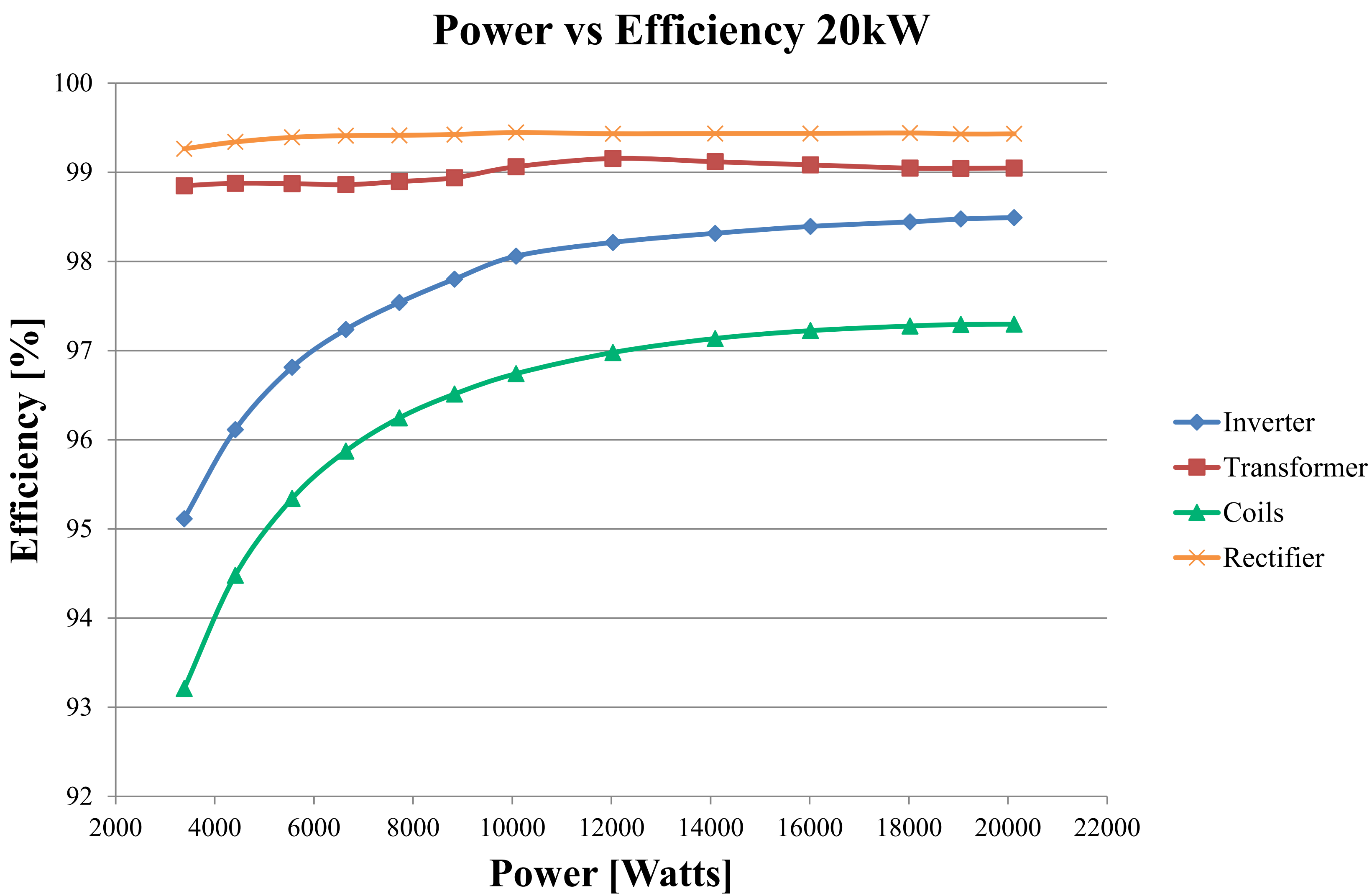


	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Eff_INV [%]	98.493					
Eff_TRFP [%]	99.048					
Eff_C2C [%]	97.297					
Eff_TRFS [%]	-------					
Eff_RCT [%]	99.431					
Eff_Totl[%]	95.037					
Eff_DCDC [%]	95.037					
P [W]	21.173k	20.853k	20.655k		20.237k	20.122k
Urms [V]	424.76	384.25	300.32		376.12	380.95

Power across each stages

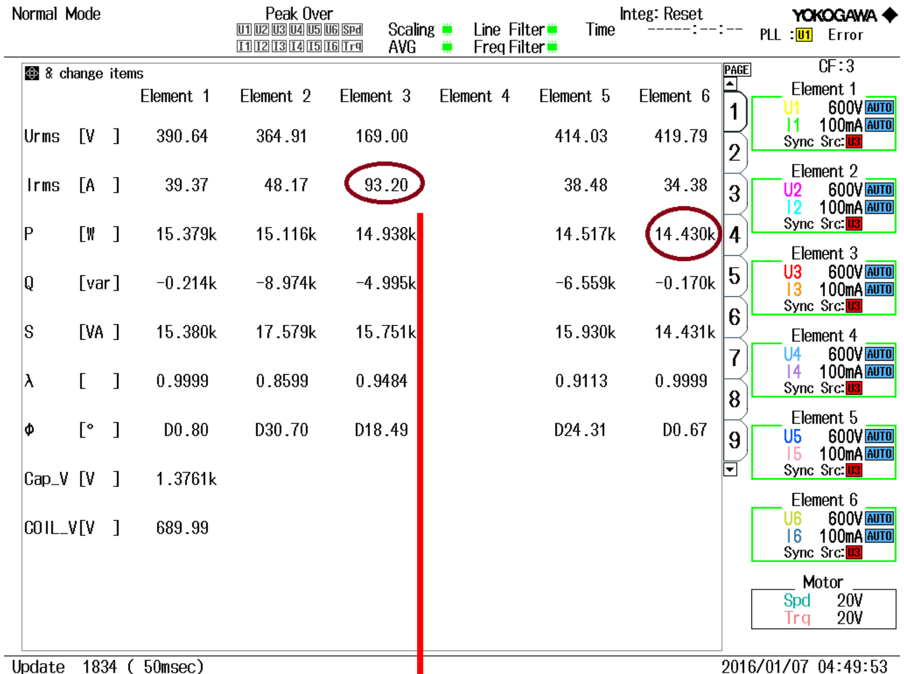
Efficiency across power conversion stages

Progress Towards High Power: Comparisons (ii)



Higher Airgap Separation Test Results:

- 184mm airgap



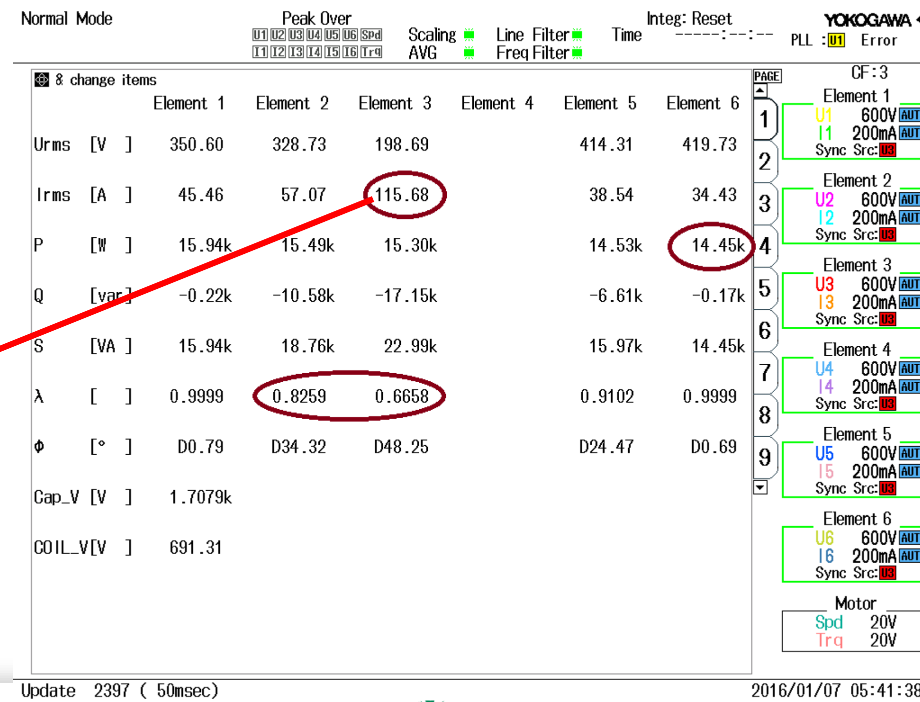
93.20A, more room to increase airgap without hitting the limit

Airgap	DC-to-DC efficiency @14kW
162mm	95.16%
184mm	93.83%
206mm	90.69%

1.33% reduction 22mm airgap increase

3.14% reduction 22mm airgap increase

- 206mm airgap



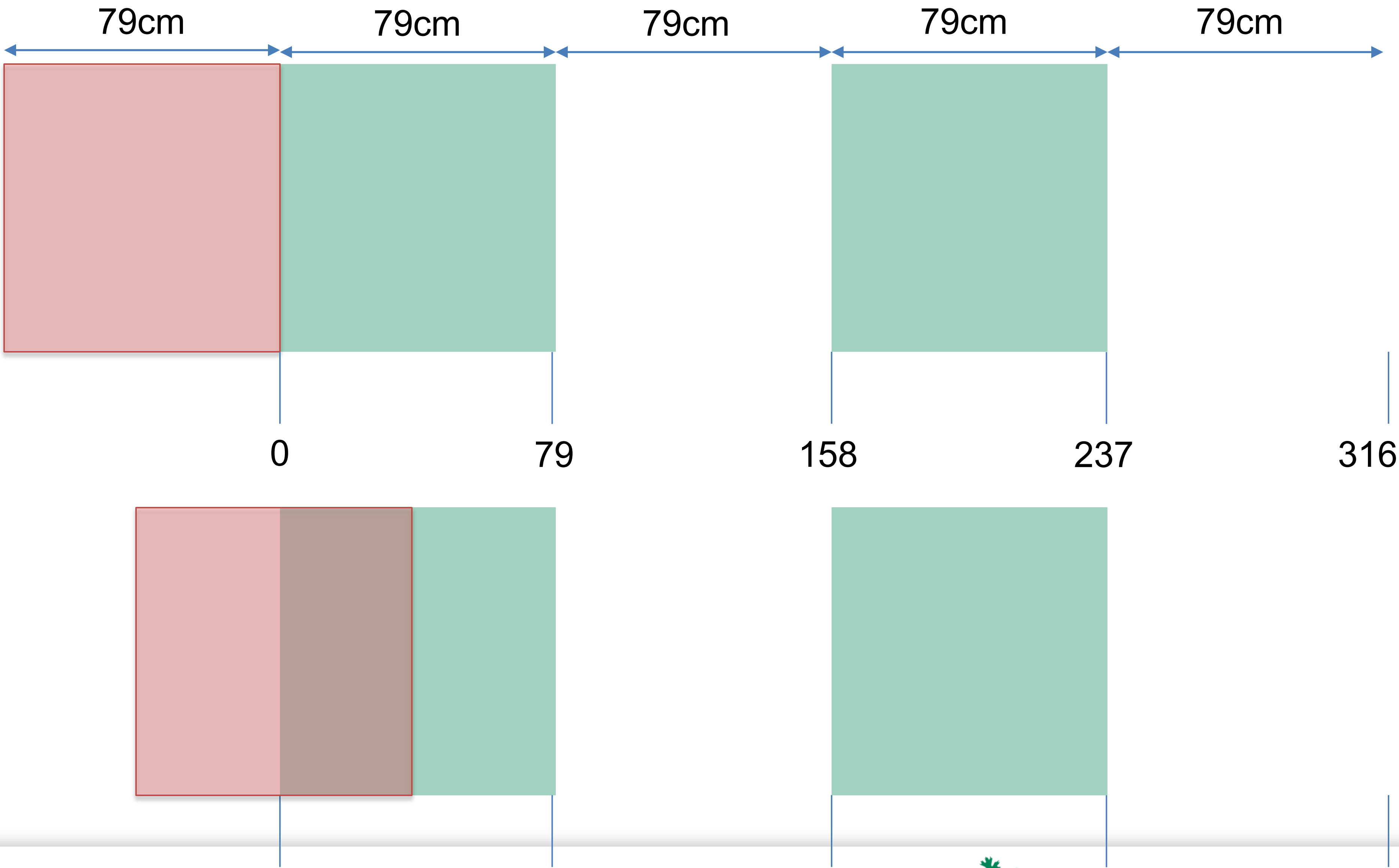
115.68A even at the worst case, more room to increase airgap without hitting the limit

Step-by-Step Manual Testing for D-WPT

- **Step by step manual dynamic WPT experiment and data collection**

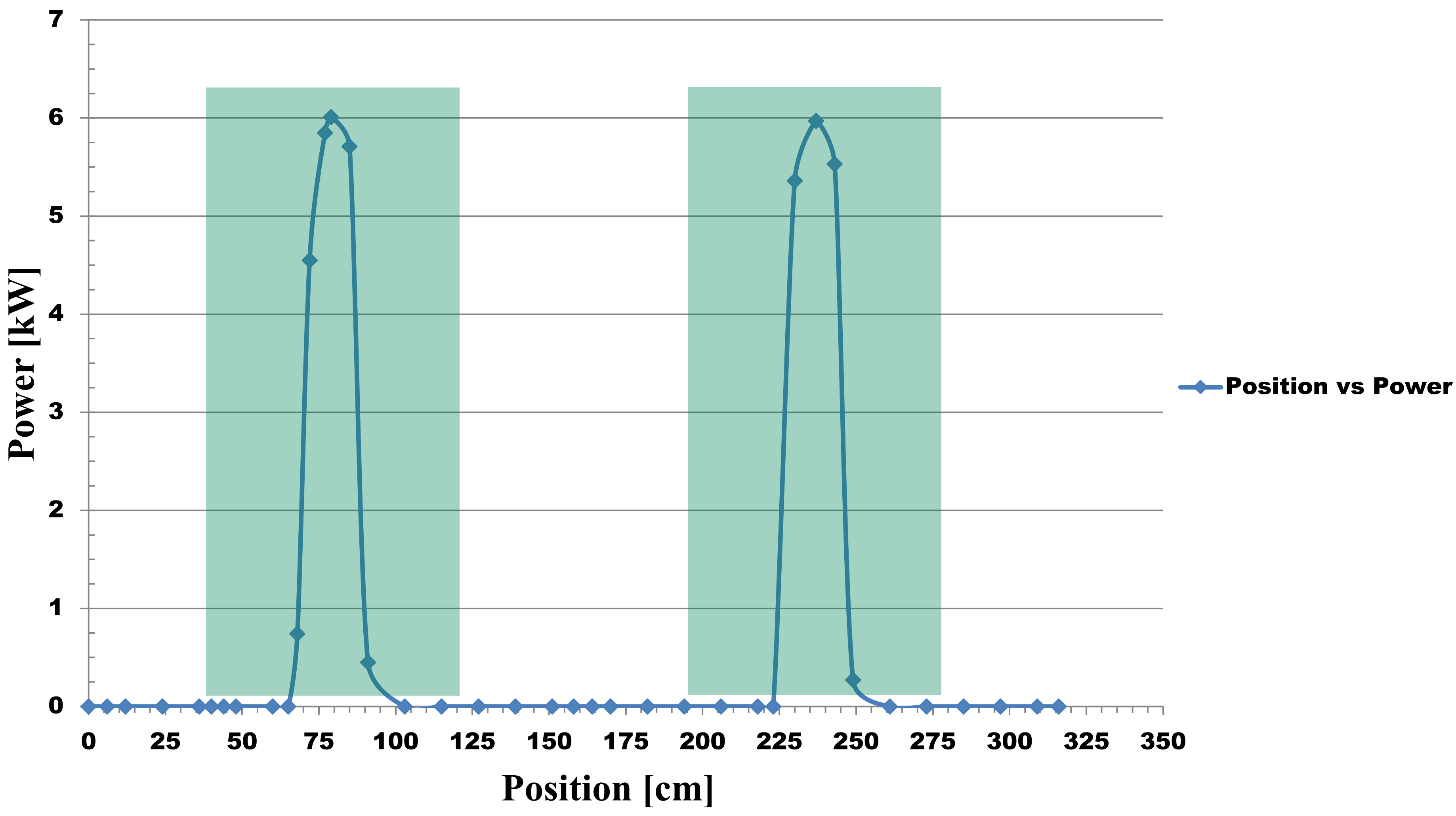
Dynamic WPT Demonstration: Lab Tests

- **Lab test setup for tests:**



Dynamic WPT Demonstration: Lab Tests

- **Lab test results – Series-series Tuning configuration:**



Dynamic WPT Demonstration: Lab Tests

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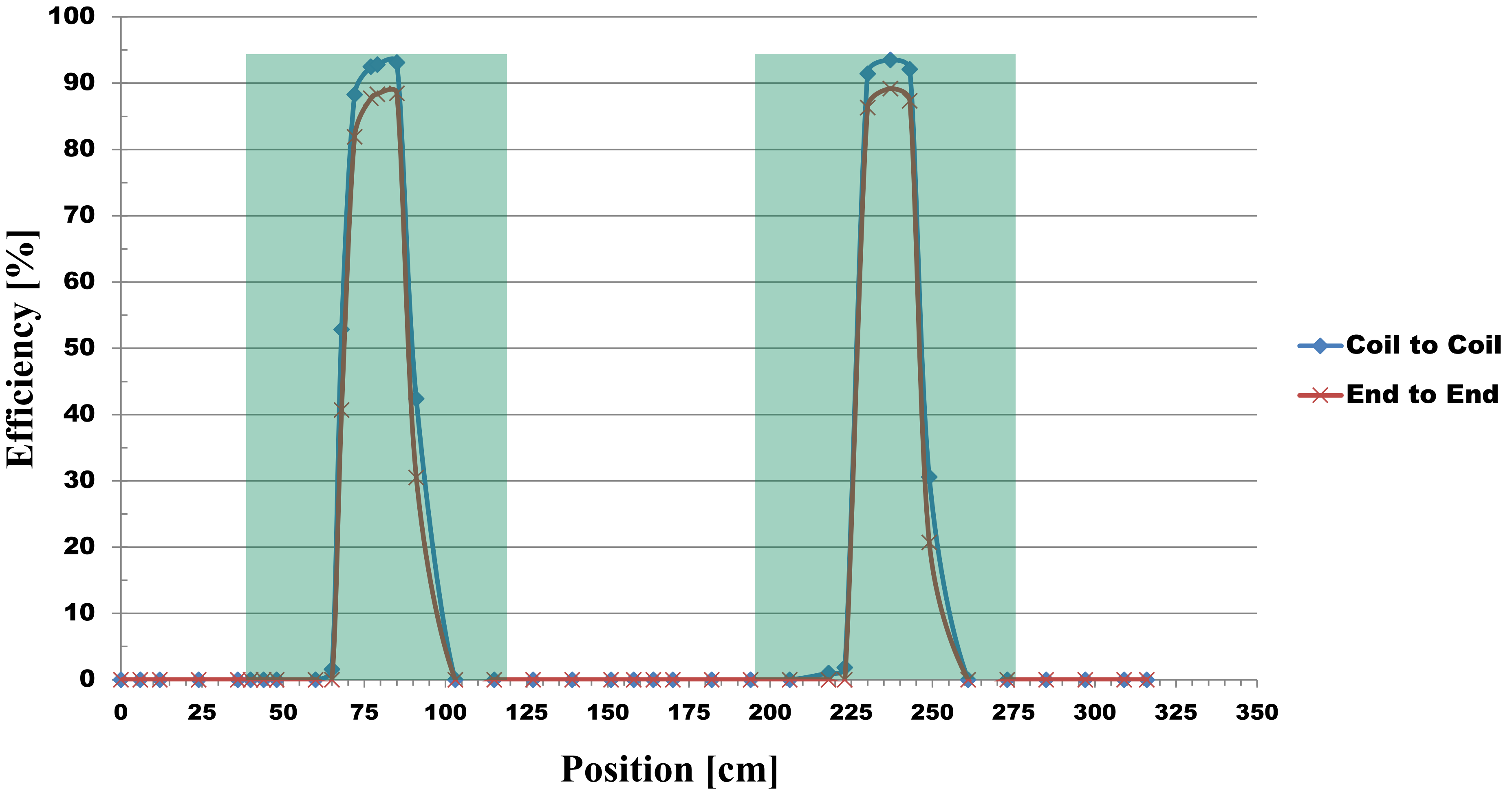
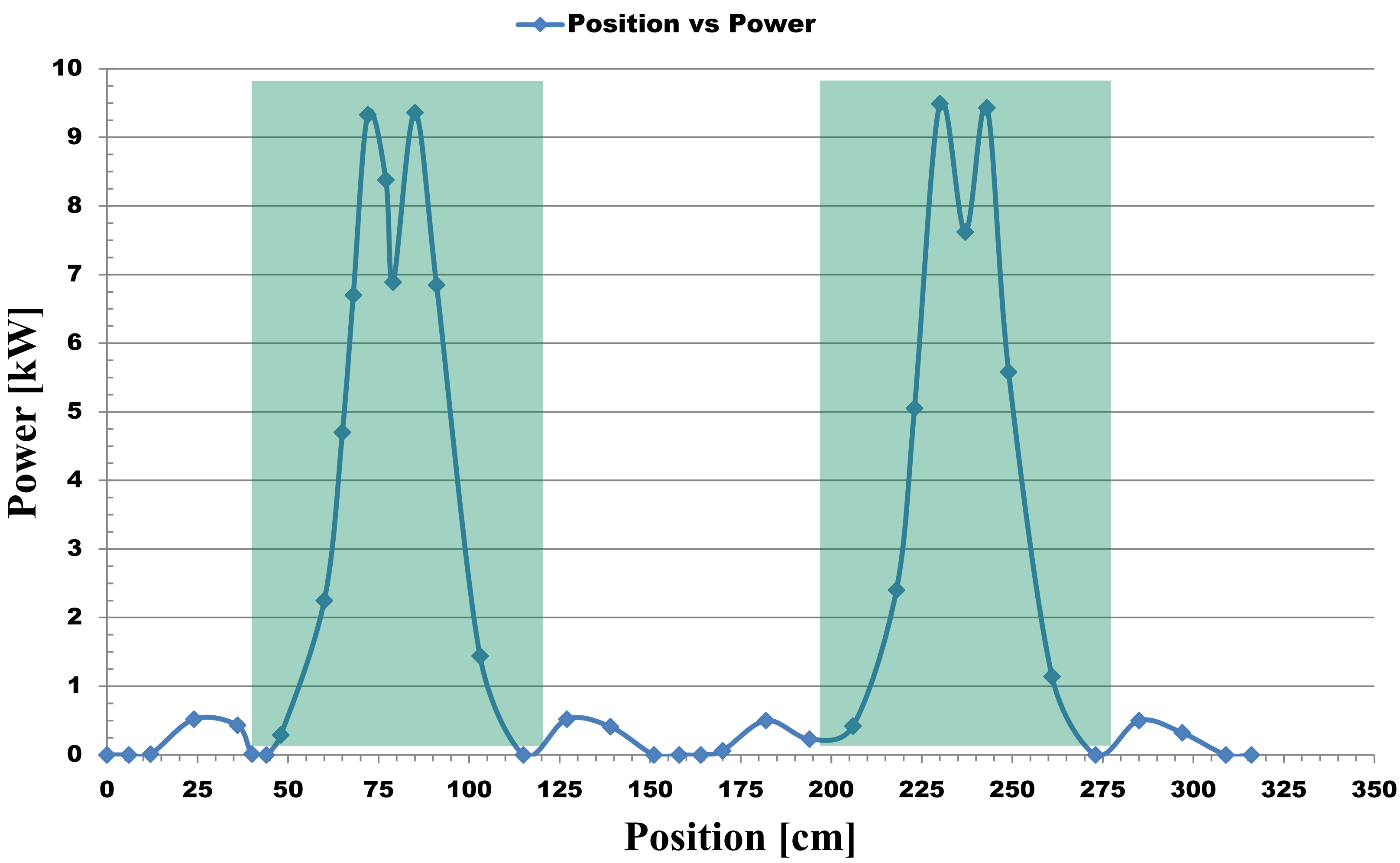


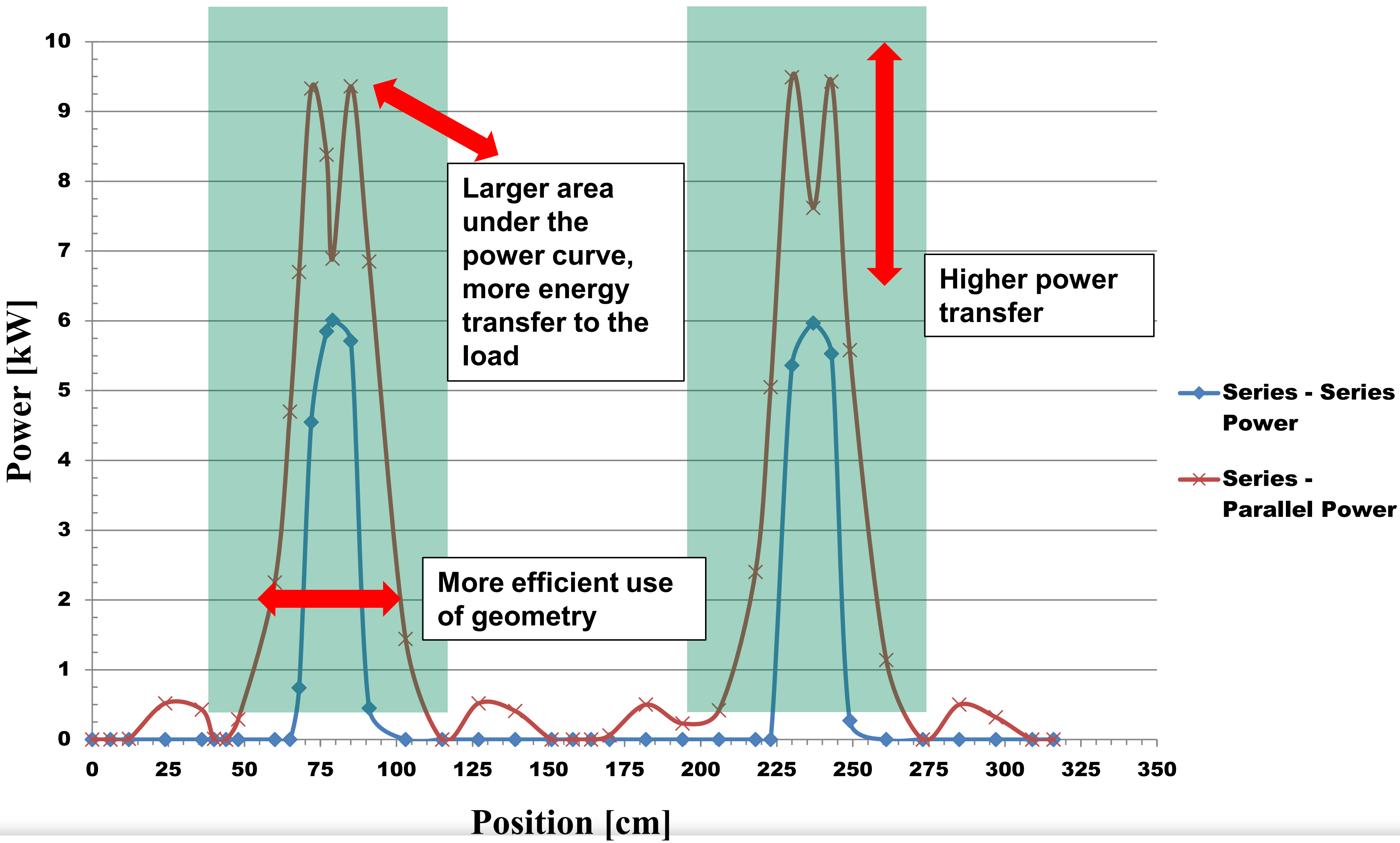
Dynamic WPT Demonstration: Lab Tests

- **Lab test results – Series-parallel Tuning configuration:**



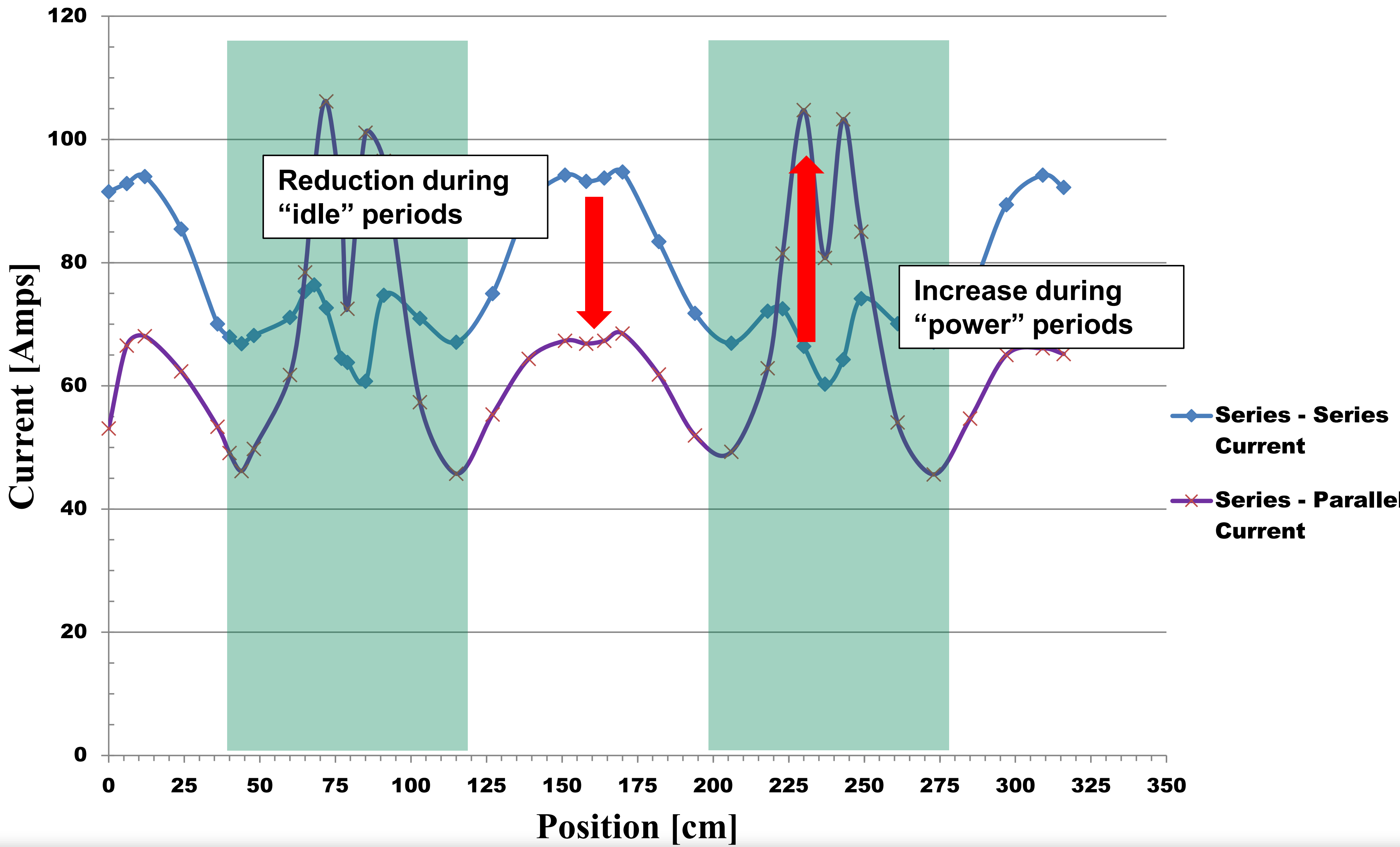
Dynamic WPT Demonstration: Lab Tests

- Lab test results –Tuning configuration comparisons:



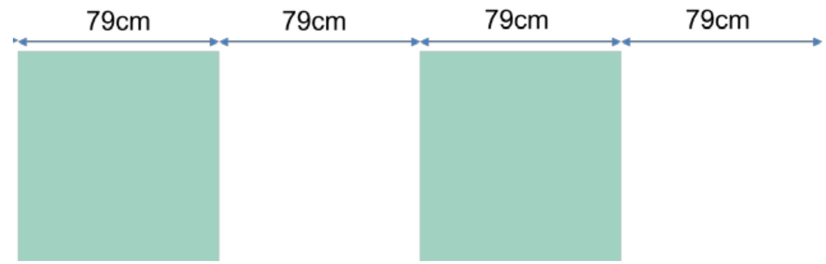
Dynamic WPT Demonstration: Lab Tests

- Lab test results –Tuning configuration comparisons:



Dynamic WPT Demonstration: Energy Transfer Discussion

- Energy transfer: Time integral of power vs. time curve.
- Power vs. time curve is directly related to the power vs. position curve if speed is constant.



$$E = \int_0^t P(t)dt$$

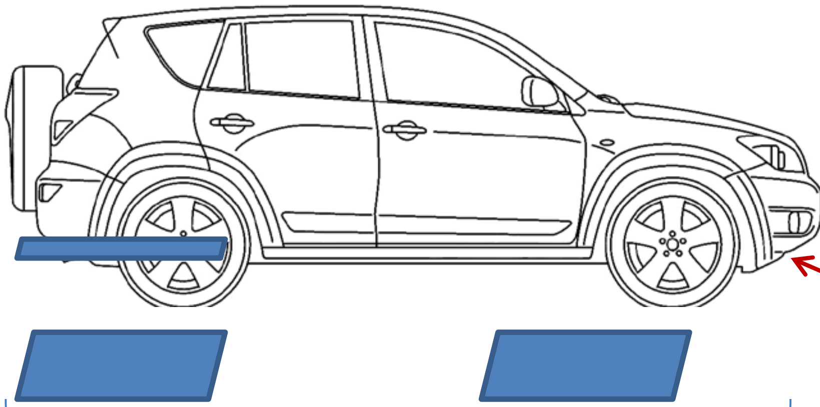
- 50 miles per hour → 2235 cm per seconds
- It takes 141ms to complete the track of 2 coils with a total length of 316cm

- For series-series tuning **E1=<u>97.2 Watt-seconds</u>** (joules) (time integral of 'power vs. time curve')

- For series-parallel tuning **E2=<u>281.08 Watt-seconds</u>** (joules) → **<u>Three times more energy transfer to the vehicle battery</u>**

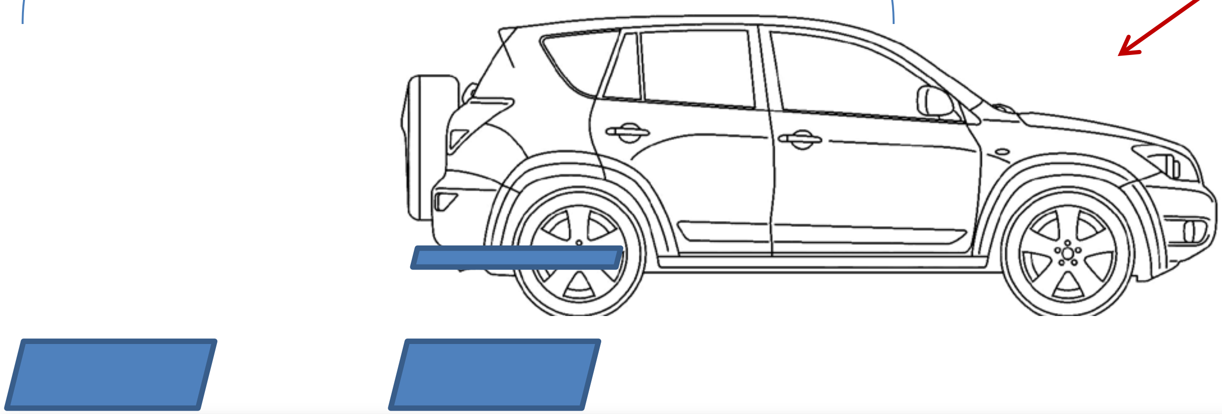
Dynamic WPT Demonstration: Lab Tests

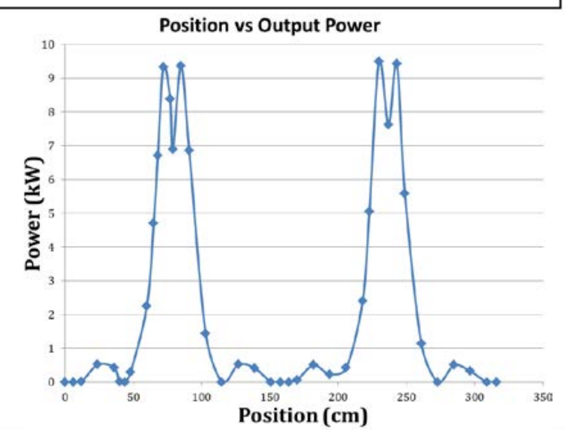
- Battery power variation with vehicle



Vehicle body interfering

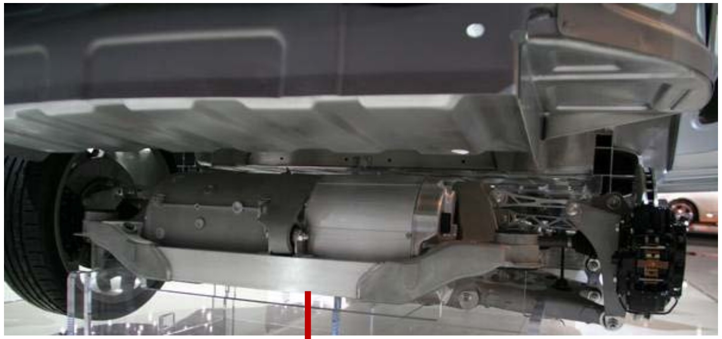
Vehicle body not interfering





Vehicle body Interference Discussions

- Lab test results –with the vehicle



Dual motor mechanical support. Thick steel plate.

Toyota RAV4 vehicle frame to protect battery pack on the floorboard (Tesla designed).

Tesla designed dual motor traction drive system

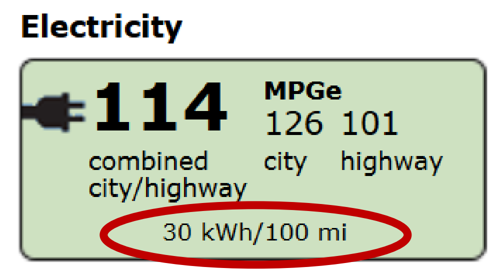
Dual motor enclosure and frame housing.

Dynamic WPT Demonstration: Energy Transfer Discussion

- Assuming a typical mid-size sedan vehicle, 0.3kWh (300Wh) is needed to drive 1 mile (1609 meters). Track length with two coils: 0.316 meters
- Therefore:

$$\mathit{Tavel\ distance\ worth\ energy\ captured\ from\ two\ coils} =$$

$$0.316\ [meters] = E\ [Watt - hours] \times \frac{1609\ [meters]}{300\ [Watt\ - hours]}$$

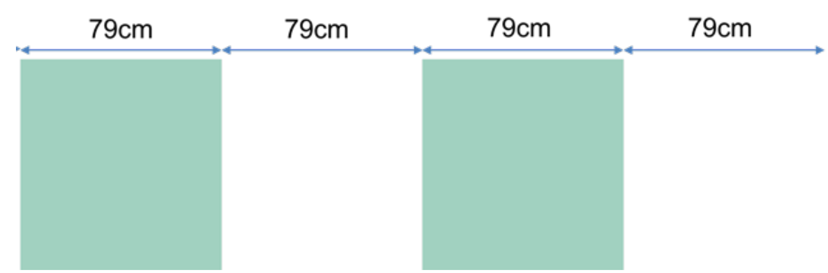


$$E = 0.316\ [meters] \times \frac{300\ [Watt - hours]}{1609\ [meters]} = 0.06\ Watt - hours$$

$$E = \int_0^t P(t)dt$$

!! This energy gives the ability to drive in "**charge sustaining mode**"

- Currently, we gain **E2=281.08 Watt-seconds** (joules) → 0.08 Watt-hours
- 75% of a highway should we covered with coils with 9.28kW peak power
- With 100kW power transfer, only 7.5% of the roadway should be WPT installed.



Response to Previous Year Reviewer's Comments

- **Q1)** One of the reviewers stated that there appears to be a good level of collaboration in this project; however, the reviewer wondered why INL has not been brought into this project with their wireless charging test setup. The reviewer asked if this is something that ORNL plans going forward.
- **A1)** In fact, an independent laboratory testing, to be performed by INL, was included in the program objectives. In October 2015, INL received a Toyota RAV4 vehicle with ORNL, including a grid side unit. INL conducted extensive testing of the system and evaluated the performance under various operating conditions (misalignment, airgap, battery voltage, input AC voltage, various power levels, etc.). INL testing helped ORNL evaluate the system characteristics and ORNL was able to improve system efficiency and maximum power substantially.
- **Q2)** The reviewer pointed out that the technical accomplishments were being met and that the project was on track. One thing that was not clear was whether the SAE decision to go with a different frequency would negatively impact this project going forward and whether Evatran would abandon the technology in favor of one that adheres to the SAE standard. The reviewer suggested that providing evidence of a contingency plan for this situation and a discussion of what the reasons are for the SAE decision would be good additions to future presentations.
- **A2)** ORNL is currently working on wide bandgap device technologies what will meet the 85kHz center frequency as indicated in the SAE J2954 TIR. Currently, ORNL designed SiC power converter is one of the very few developments that can meet high frequency requirements while still allowing to transfer high power (WPT Level-2) at target efficiencies. The inverter was tested at 10kW at 85kHz with an efficiency of >98%.

Proposed Future Work

- FY2016 (remainder)
  - Software improvements in the system to further improve the vehicle agnostic (interoperable) operation of the system
  - Complete additional testing to demonstrate system operation that is independent of the battery voltage, state-of-charge, and reference (target) power to the vehicle battery pack.
  - Submit additional technical papers for journals and upcoming conferences.

Conclusions for Static WPT Development and Testing

- WPT system explained including functional diagram and test setup
- Matched / interoperable coil impact on maximum power and efficiency
- SS and SP tuning impact
- Progress towards high power WPT
- **Summary of FOA requirements and current status**

	FOA Project Requirement	Current Status
Airgap:	160mm	162mm nominal, also tested 184 and 206mm
Efficiency	85%	~92-93% (with estimated PFC eff.)
Maximum load power	6.6kW	20.2kW

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