INL'S TESTING & EVALUATION RESULTS:
ORNL'S WIRELESS CHARGING SYSTEM FOR FOA-667

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SAE INTERNATIONAL

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INL Scope of Testing and Evaluation

Evaluate the ORNL Wireless Charging System (FOA-667)

- Characterize the performance:
  - Charging Efficiency
  - EM-field
  - Power Quality

- Characterize impact from:
  - X and Y misalignment
  - Z gap (coil to coil gap)
  - Input voltage
    - 208 vs. 220 vs. 240 V
  - Output voltage
  - Charge Power level
  - EM-field in and around all parts of the vehicle

Measurement equipment

- Efficiency and Elec. Power Quality
  - Hioki 3390 Power Meter
    - 0.15% accuracy
    - 4 channels
      - Voltage
      - Current Probes

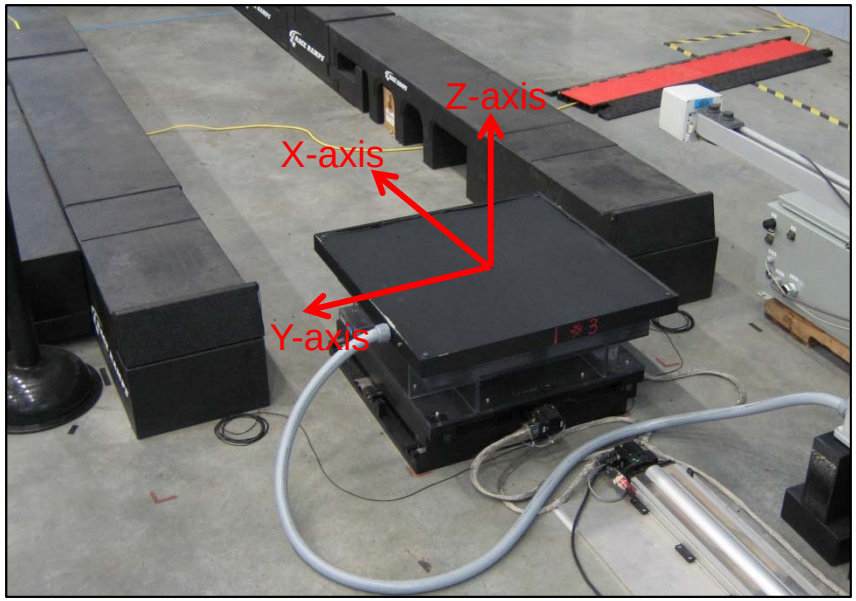
- Electro-magnetic field
  - Narda EHP-200a
    - 9 kHz – 30 MHz

- Surface Temperature
  - FLIR SC640 infrared camera connected to PC

- Custom LabVIEW host control and data acquisition

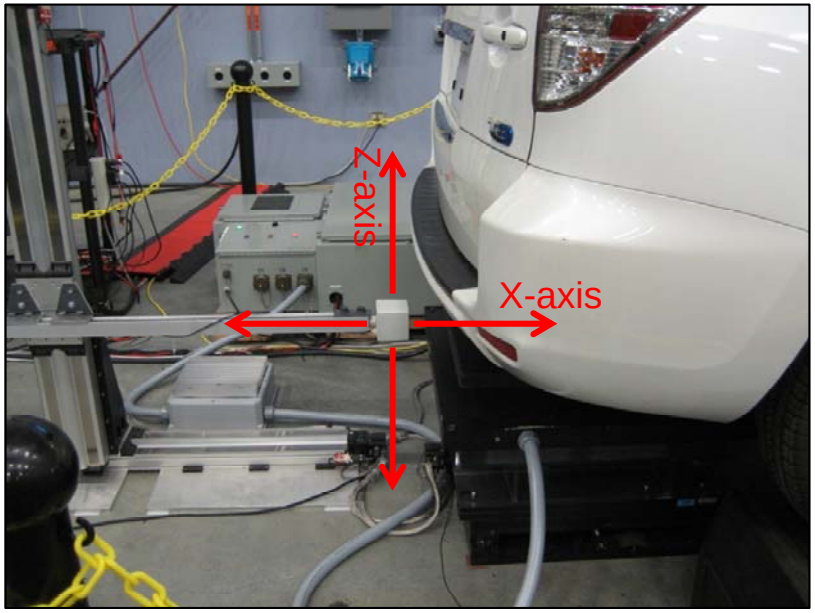
Coil positioning system

- Servo-motor driven positioning system for primary coil (ground assembly)
  - Enables accurate coil misalignment
    - Move primary coil with respect to vehicle coil
- Vehicle is stationary
  - Non-metallic vehicle ramps used to elevate vehicle to provide necessary space for the coil positioning system



Magnetic and Electric Field scan at rear bumper

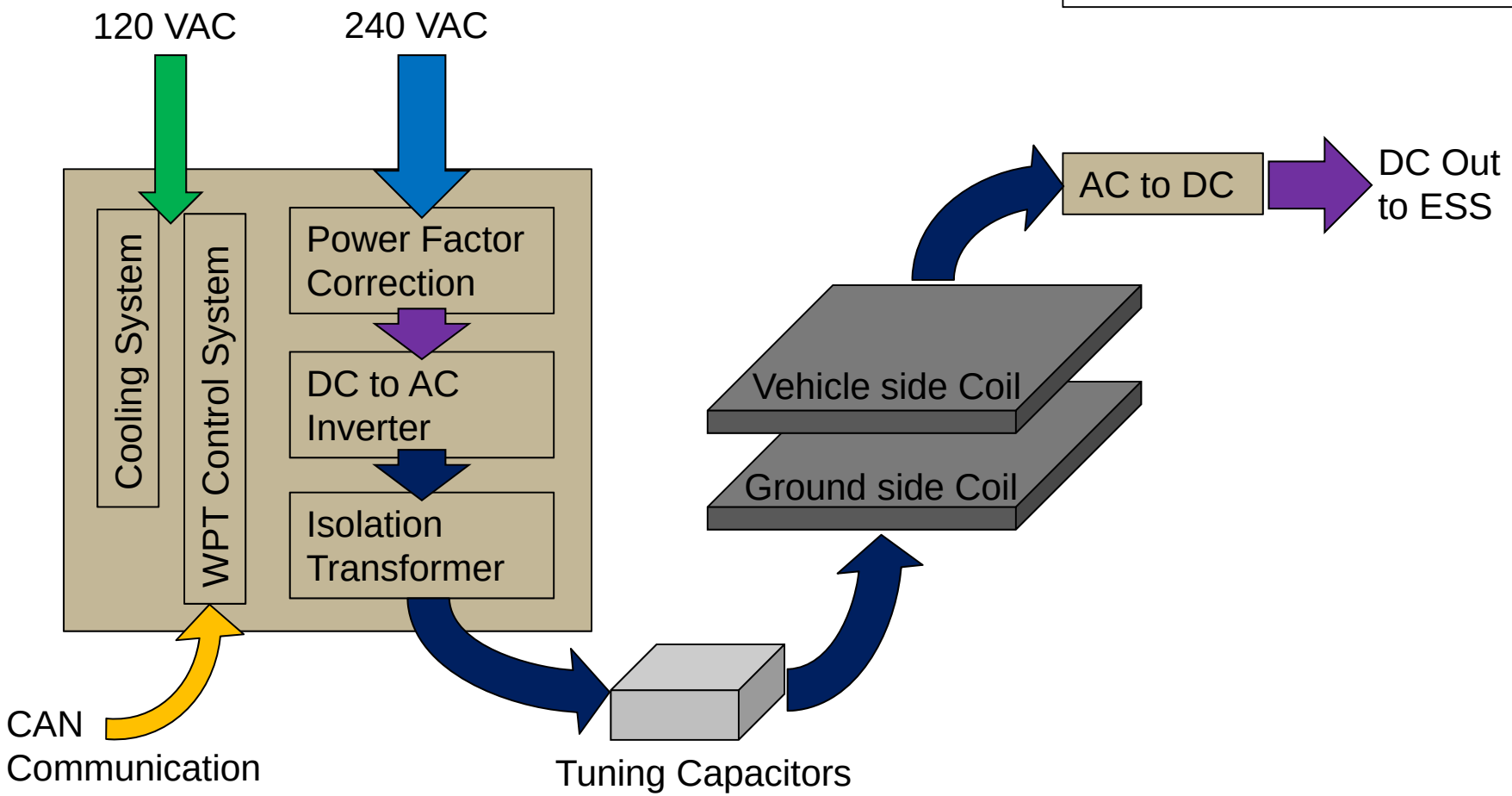
- 2-axis positioning device used to position Narda EM-field meter
  - Precise positioning
  - Quasi-static scan of region



Schematic of ORNL WPT system

- Two AC inputs (120 VAC and 240 VAC)
- One DC output (nominal 350 VDC)

120 VAC at 60 Hz
240 VAC at 60 Hz
High Freq. AC (~25 kHz)
DC voltage



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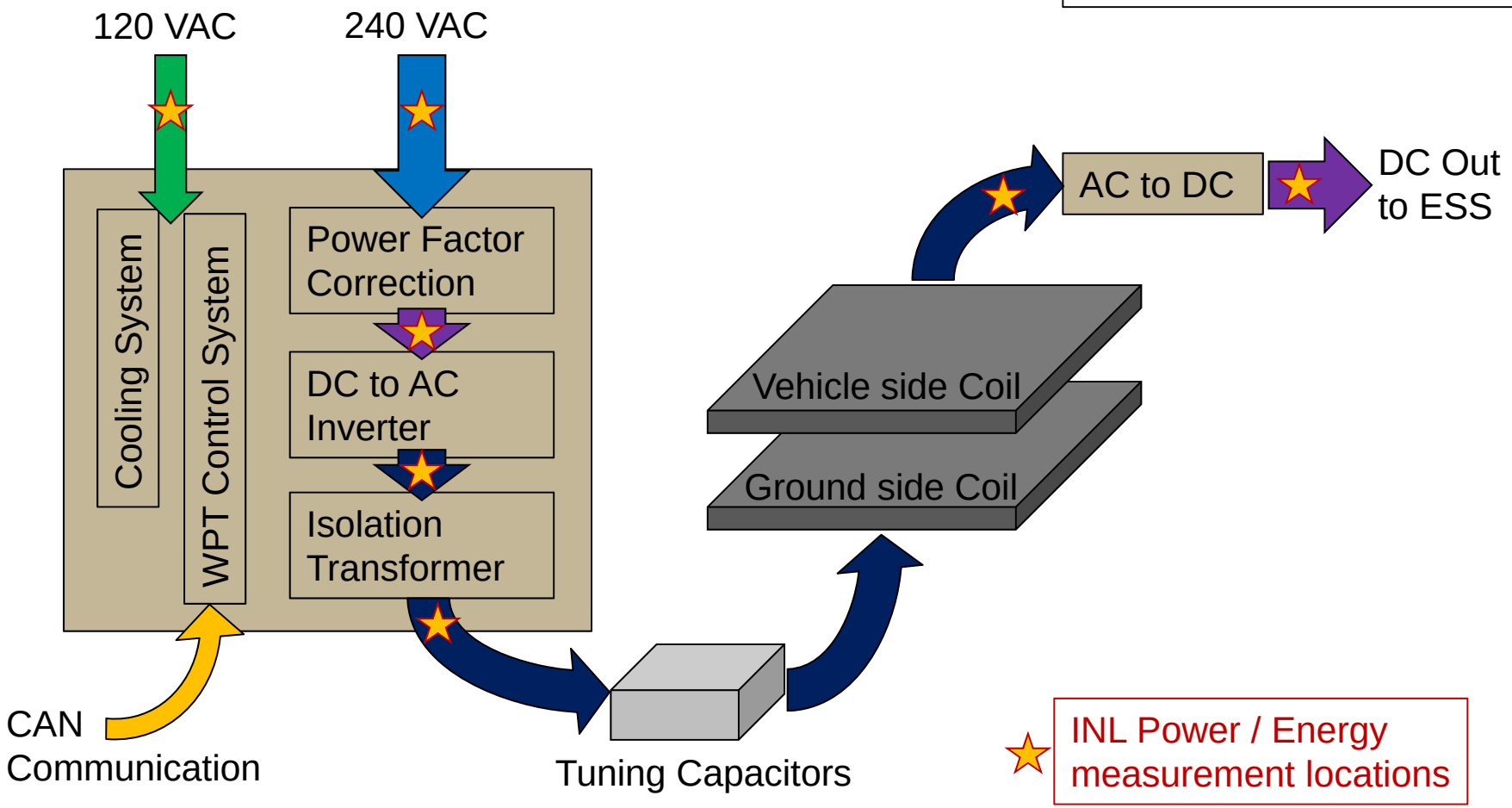
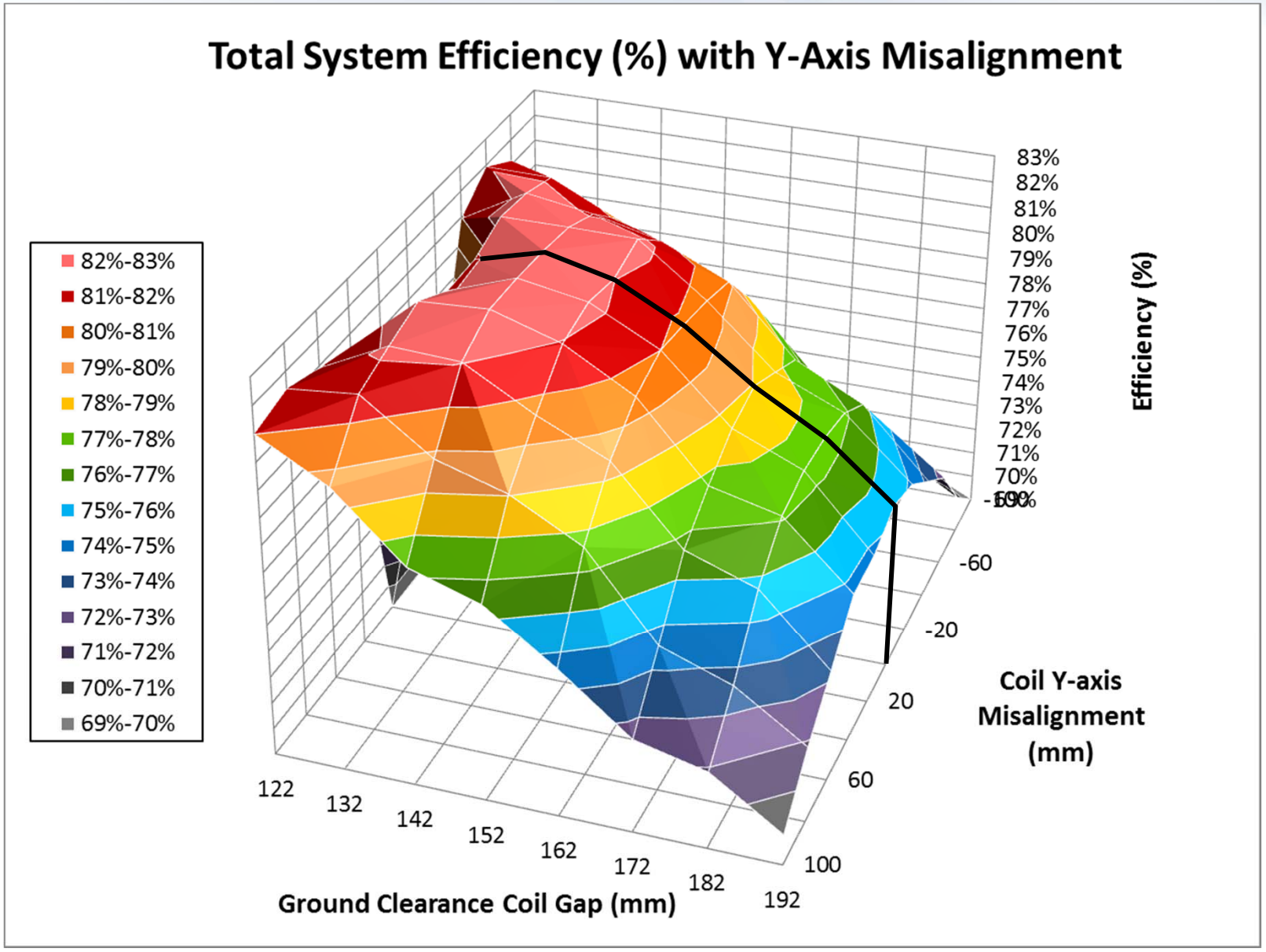


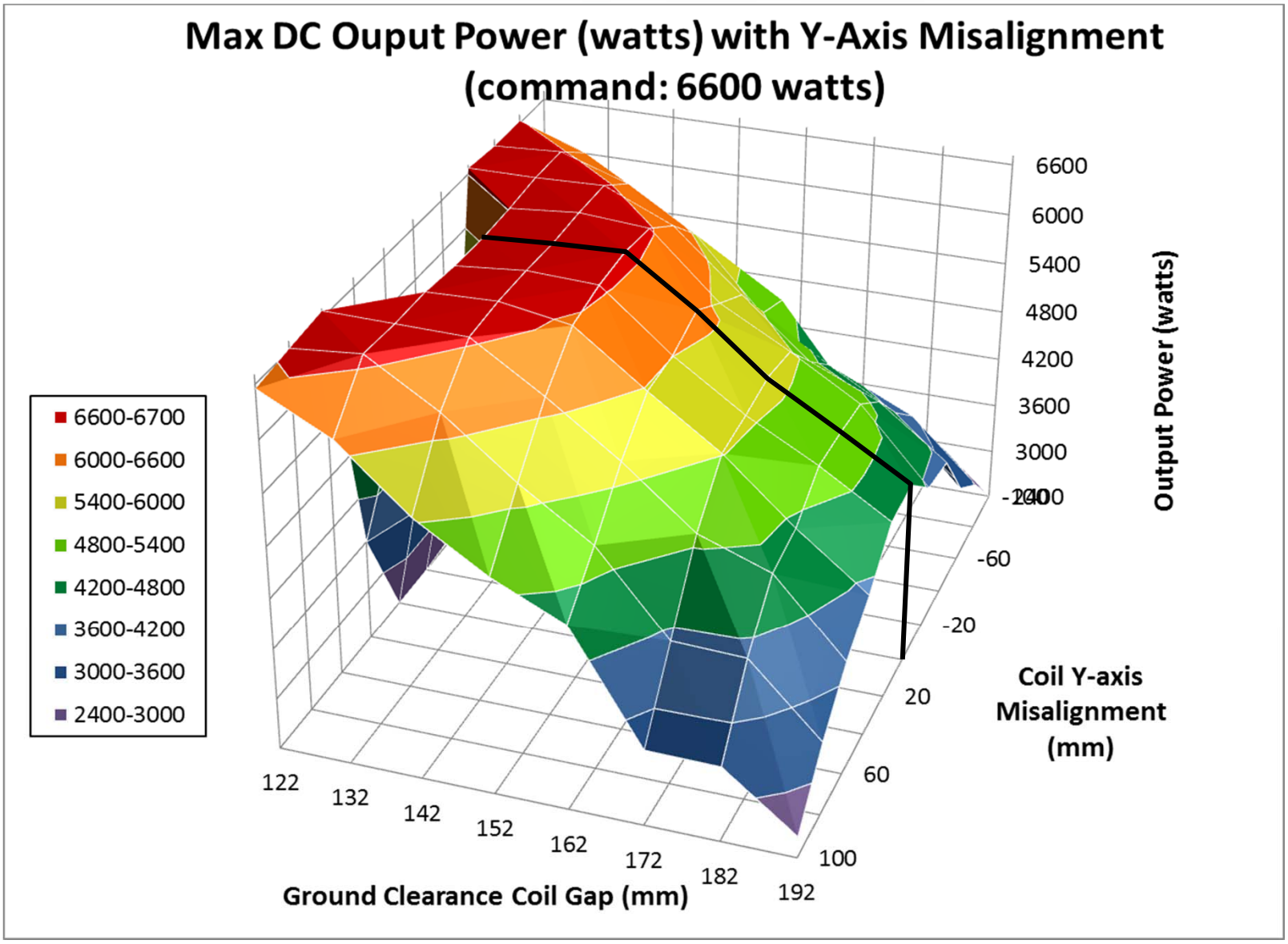
Performance Results with Coils in Alignment (0,0)

Ground Clearance	152mm
Magnetic Gap (Z)	160mm
Max. Total System Efficiency	82.2%
Max. End to End Efficiency	85.2%
Max. DC to DC Efficiency	86.4%
Max. Output Power	7.0 kW
Magnetic field at rear bumper (coils aligned)	132 A/m
Electric field at rear bumper (coils aligned)	105 V/m
Input Current Total Harmonic Distortion (THD)	60%
Input Power Factor	0.94
Operating Frequency	24.5 kHz

Total System Efficiency

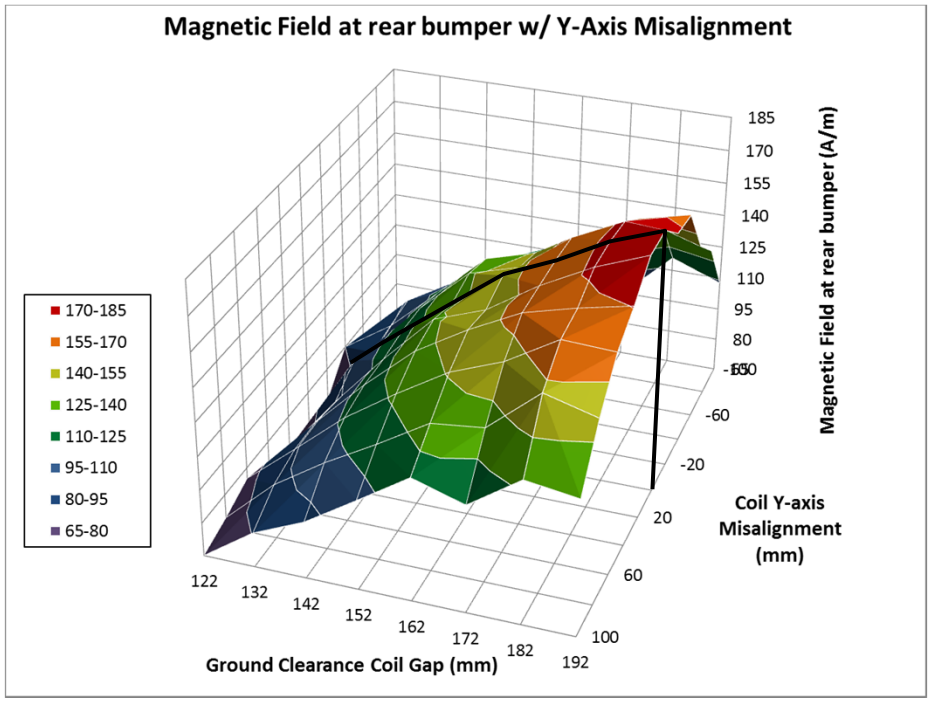


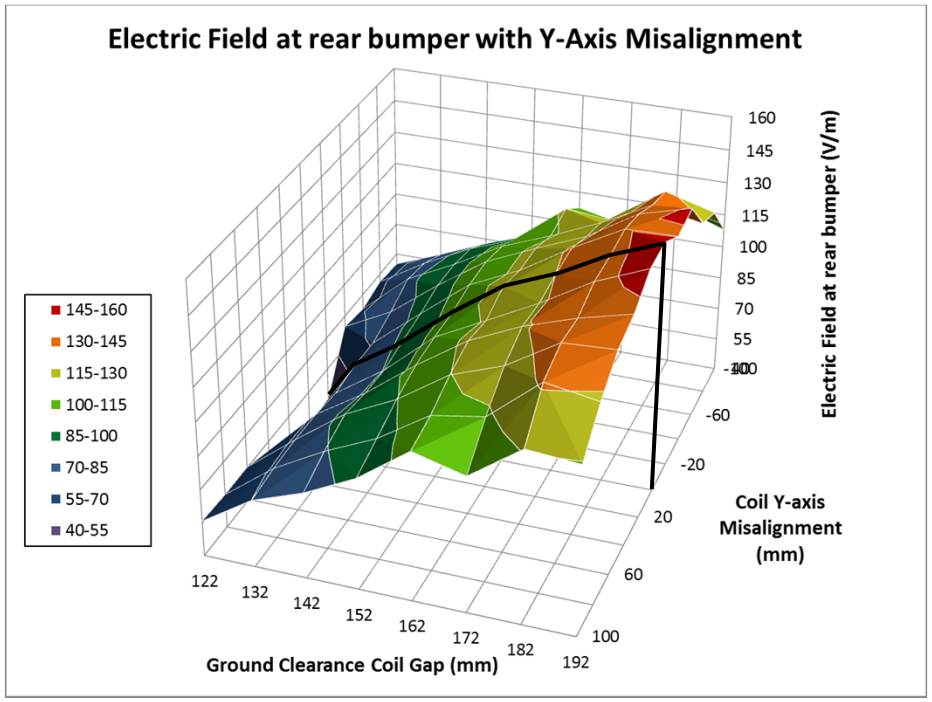
Maximum Output Power (watts)



Magnetic and Electric Field Strength

- Measured near rear bumper (510 mm from coil center)
- Centered vertically between coils

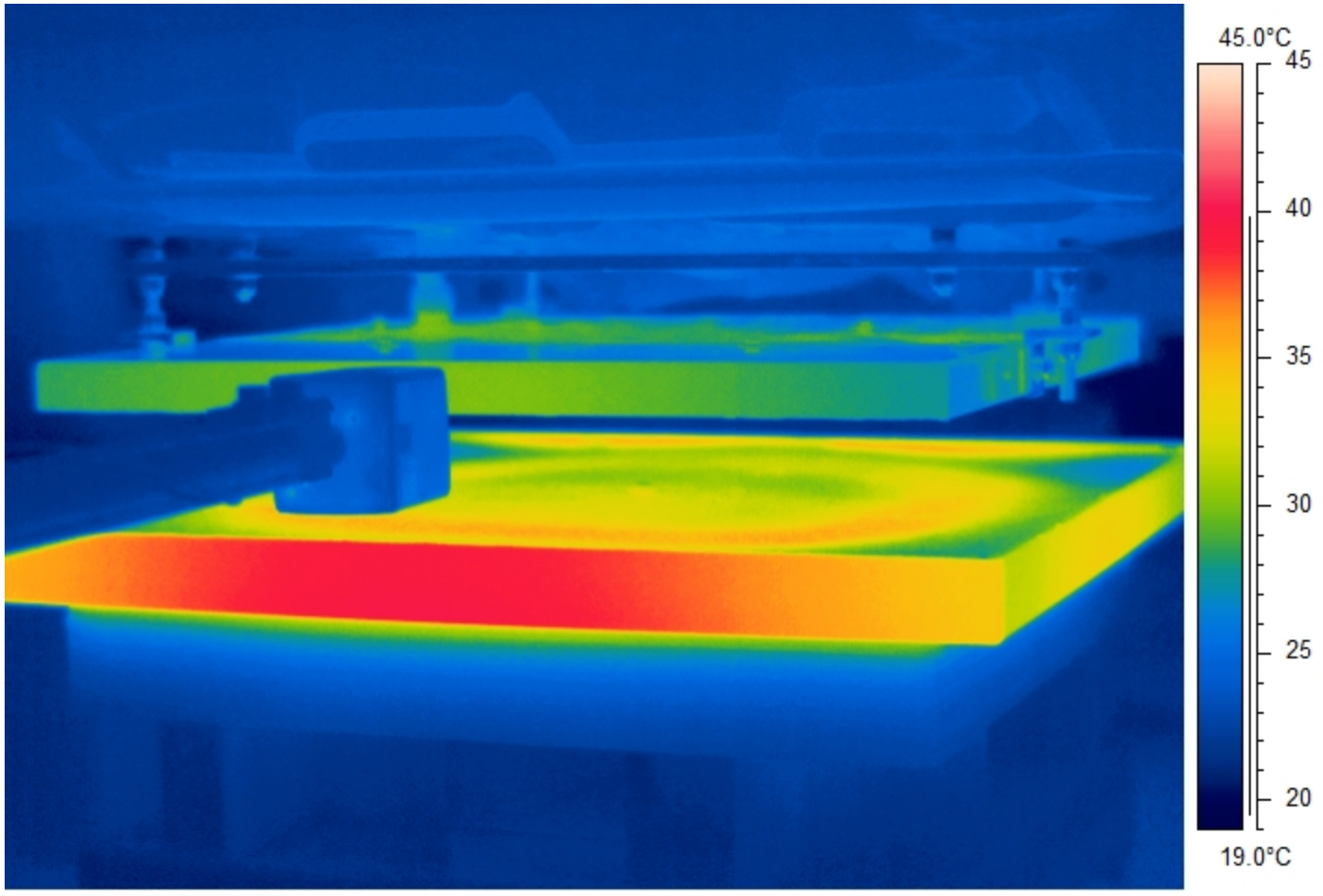




- EM-field strength increases as coil gap increases
- EM-field strength decrease w/ misalignment due to reduced power capability

Surface Temperature during Testing

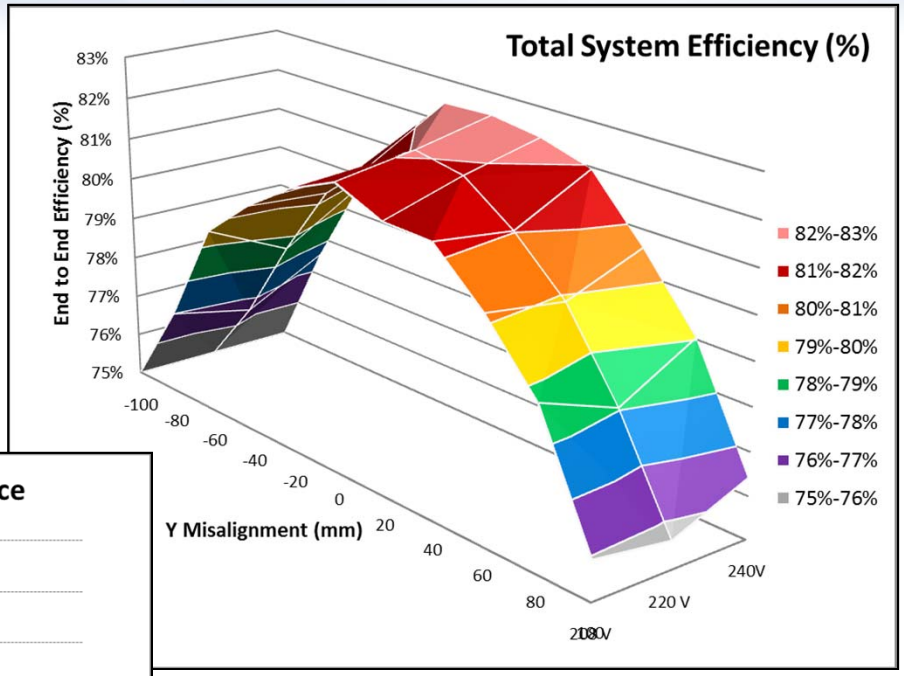
- Temperature monitored through out testing
- Maximum surface temperature through all phases of testing:
  - Below 55 ^{o}C (safety surface touch limit)

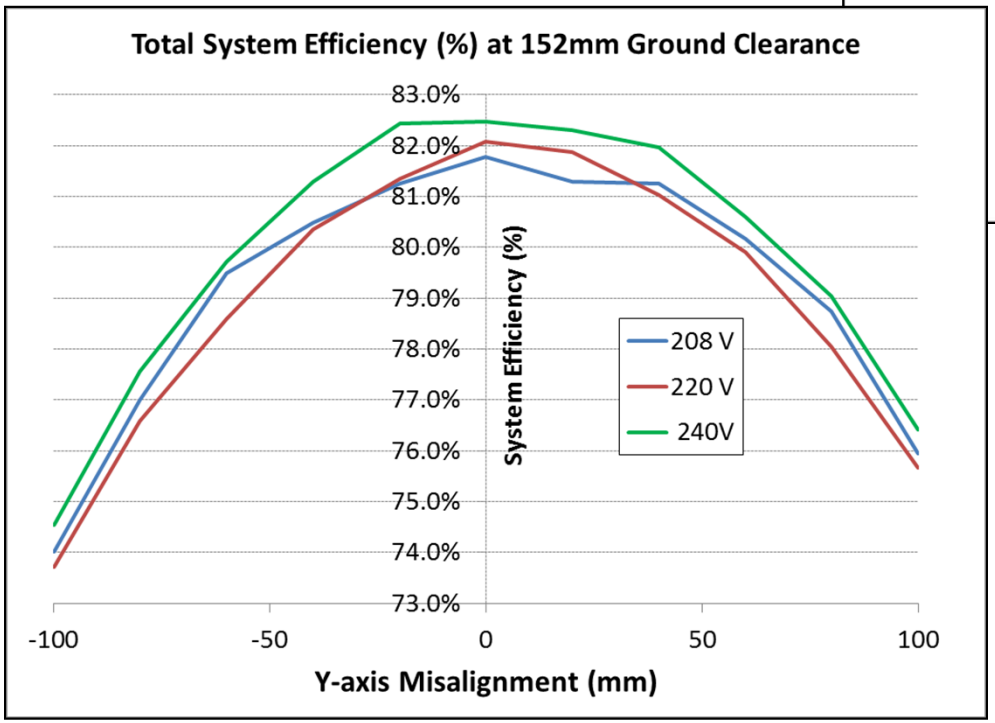


In-depth Testing at 152mm Ground Clearance

Impact of Input Voltage on System Efficiency

- Higher Input voltage results in:
  - Slightly Higher efficiency when coils are aligned

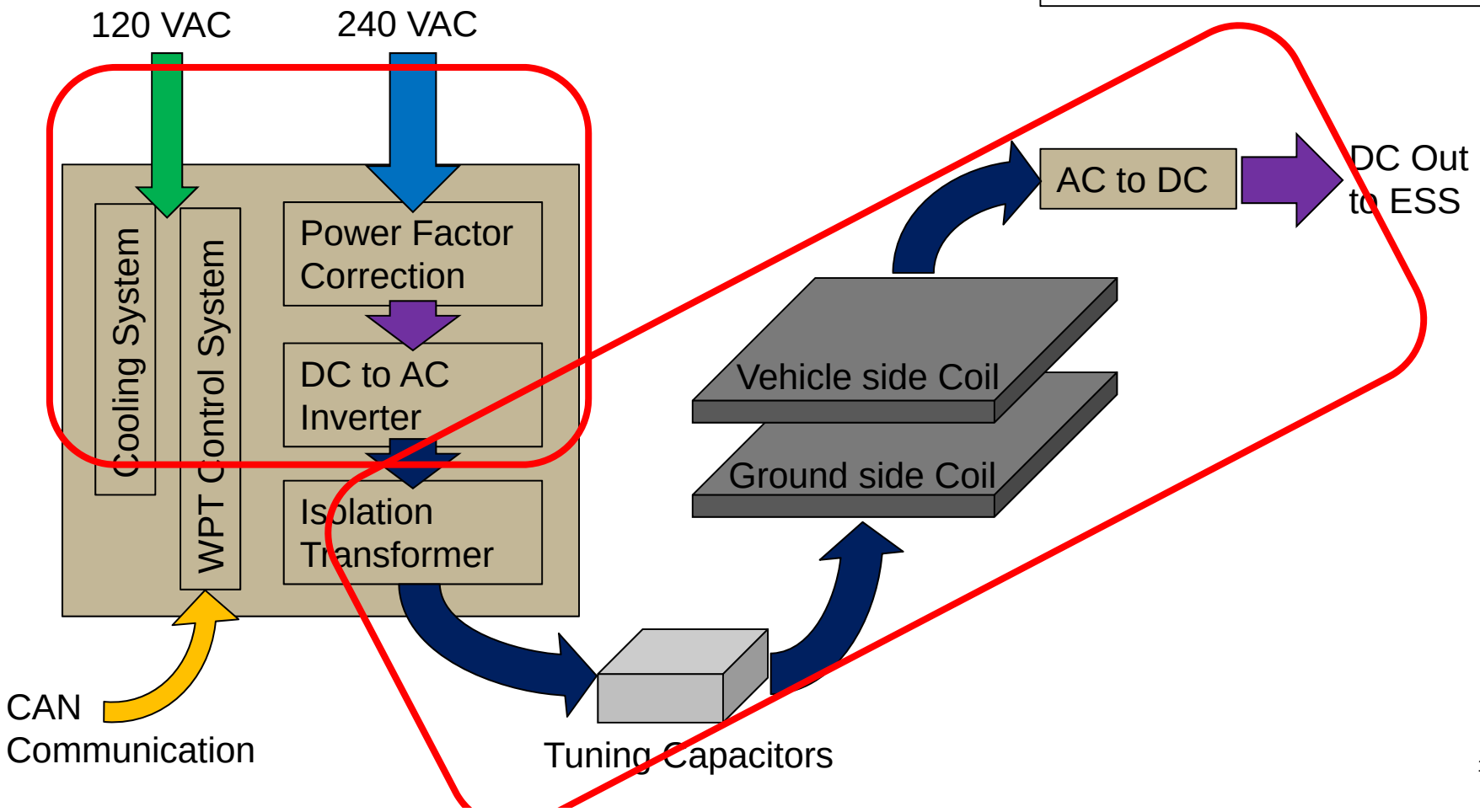




Impact of Input Voltage

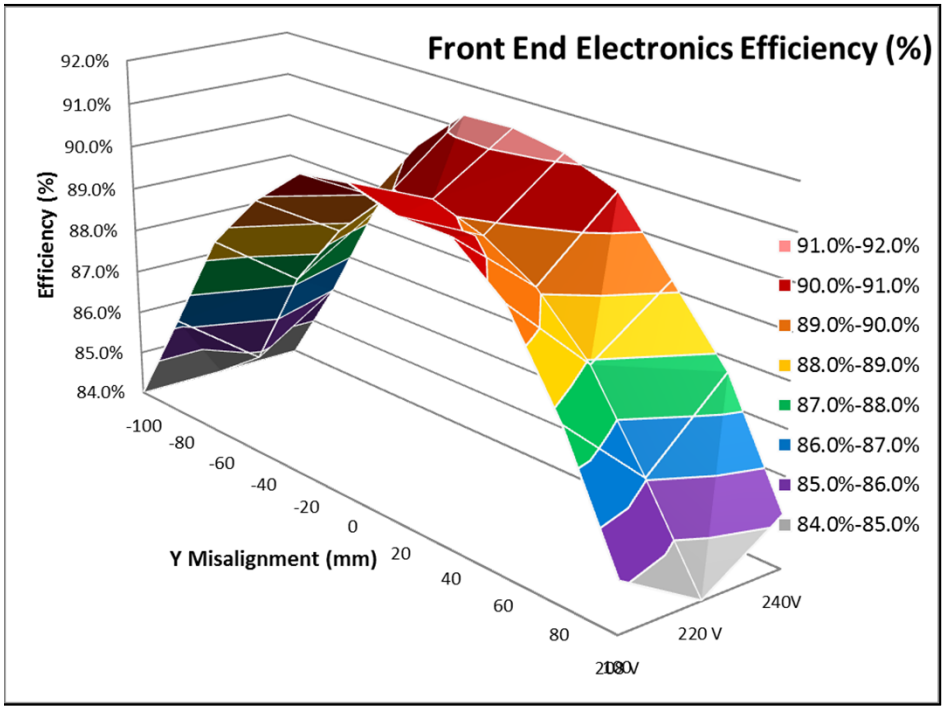
- Analyze Efficiency of sub-systems
  - Front End Power Electronics (60 Hz to 25 kHz)
  - 25 kHz to Batt DC (Iso. Trans. + Caps + Coils + Rect.)

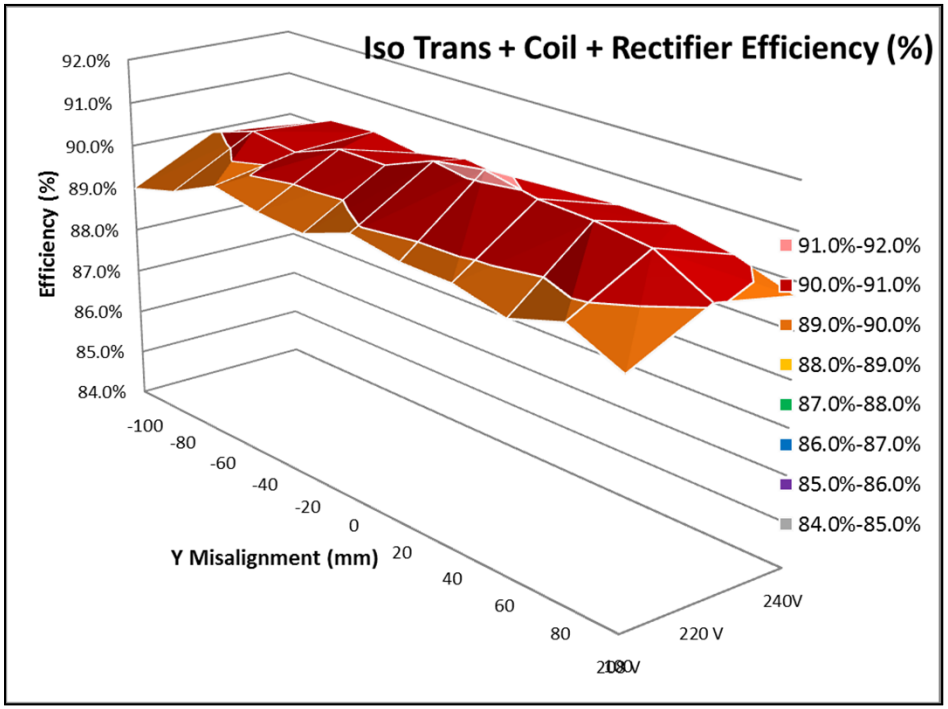
120 VAC at 60 Hz
240 VAC at 60 Hz
High Freq. AC (~25 kHz)
DC voltage



Impact of Input Voltage

- Input Power Electronics
  - PFC (60 Hz AC to DC)
  - Inverter (DC to 25 kHz AC)
  - 120V aux. loads
    - cooling + controls
- Output High Freq. Components
  - Isolation transformer
  - Tuning capacitors
  - Ground coil to vehicle coil
  - Rectifier





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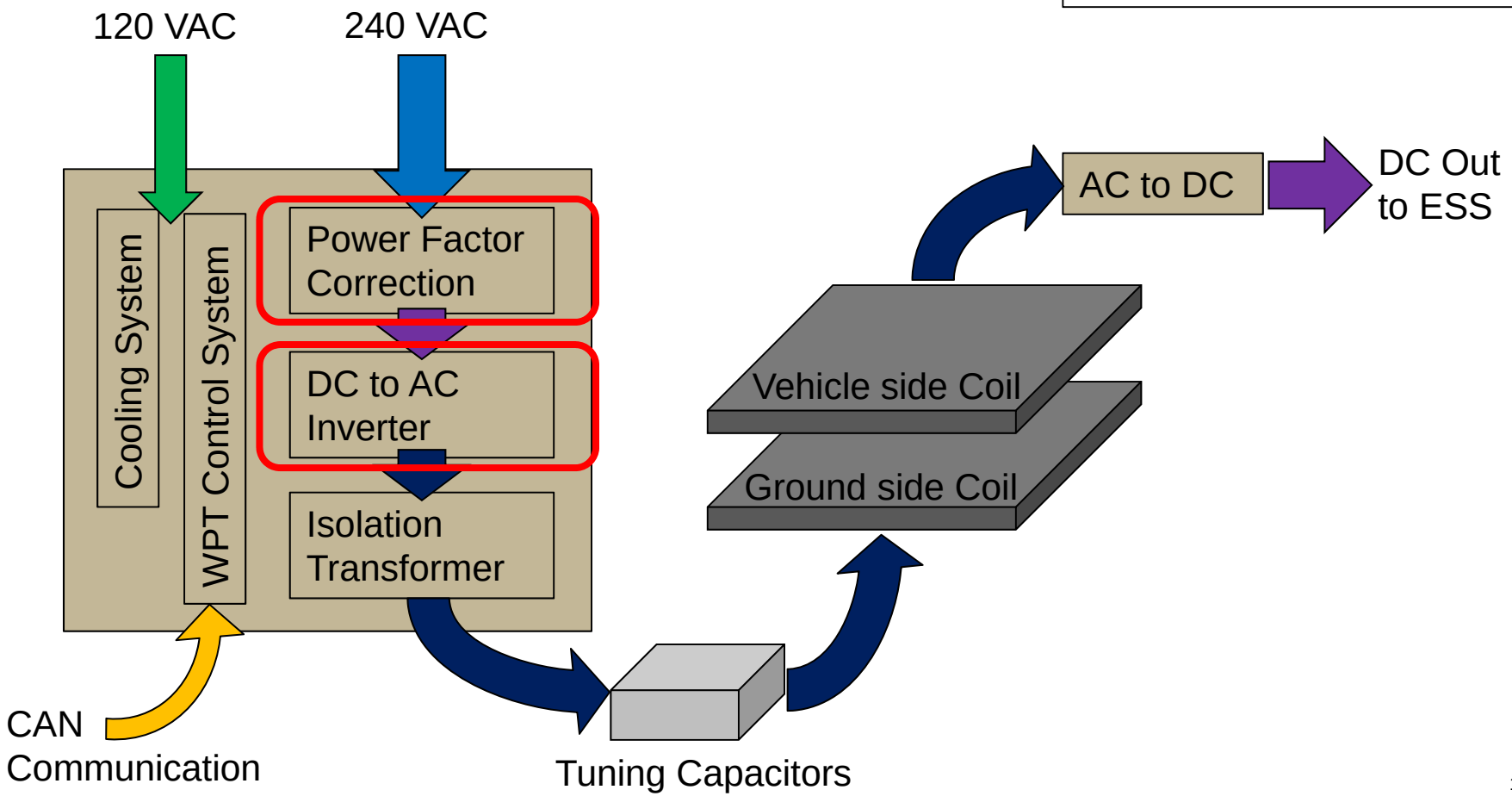
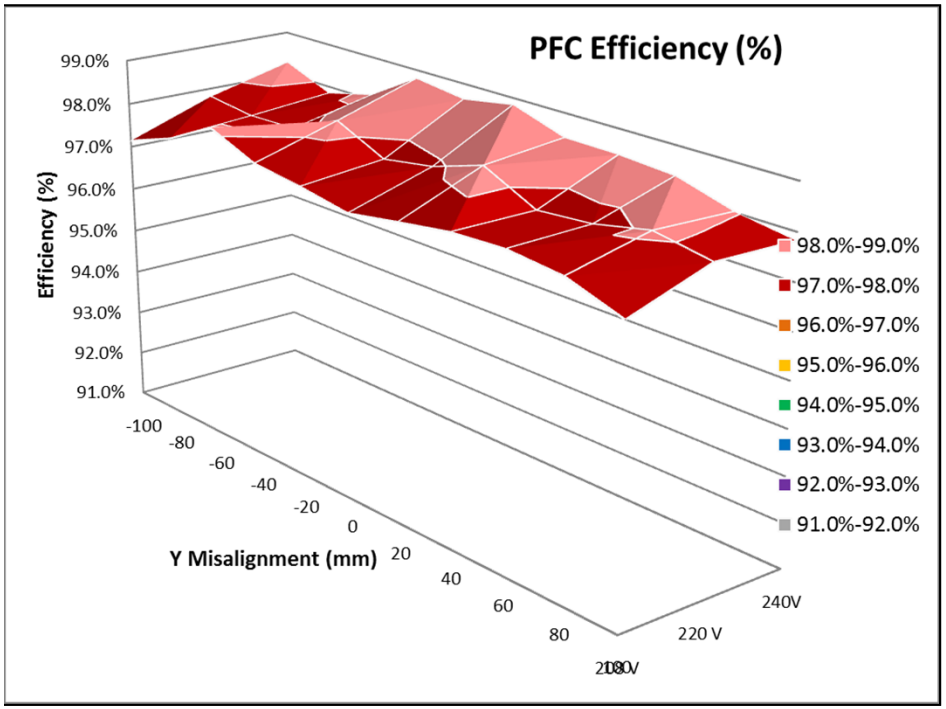
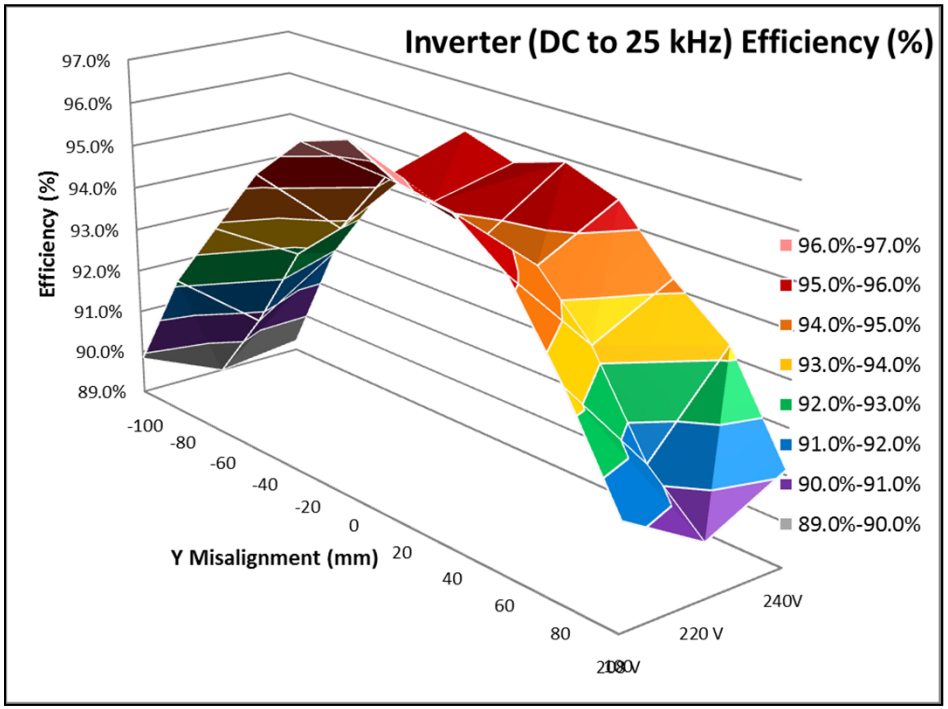


Impact of Input Voltage on Sub-systems

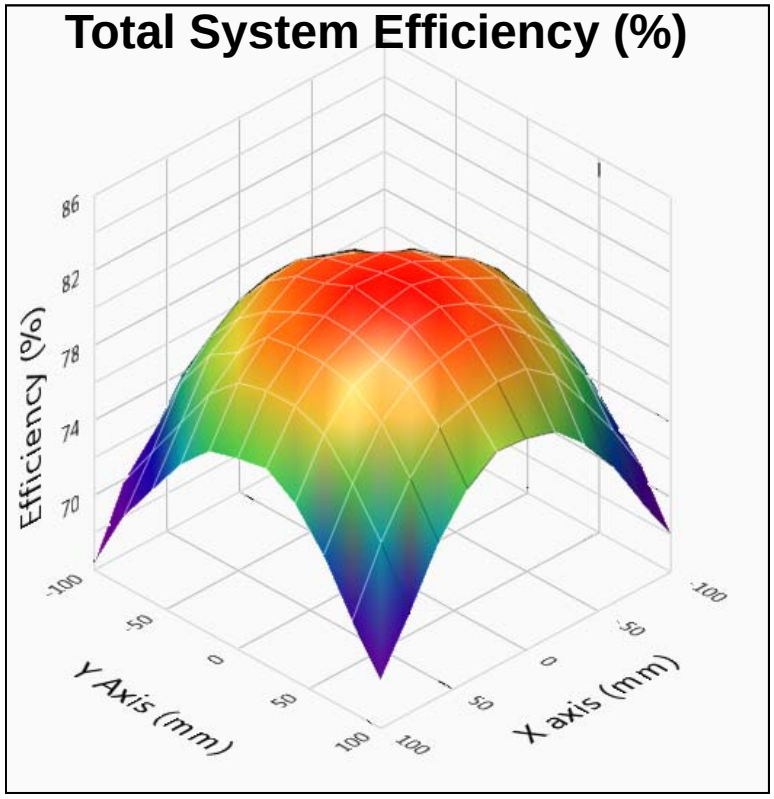
- Power Factor Correction
  - 60Hz to DC link
- Inverter
  - DC Link to 25 kHz



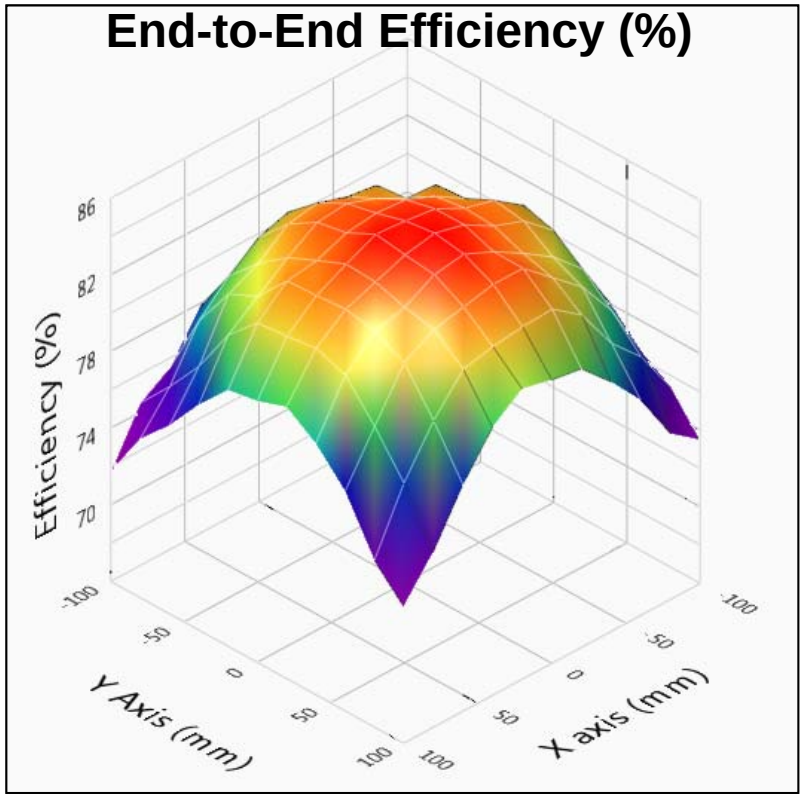


Further In-depth Testing at 152mm Ground Clearance across X, Y misalignment

Total System Efficiency and End-to-End Efficiency

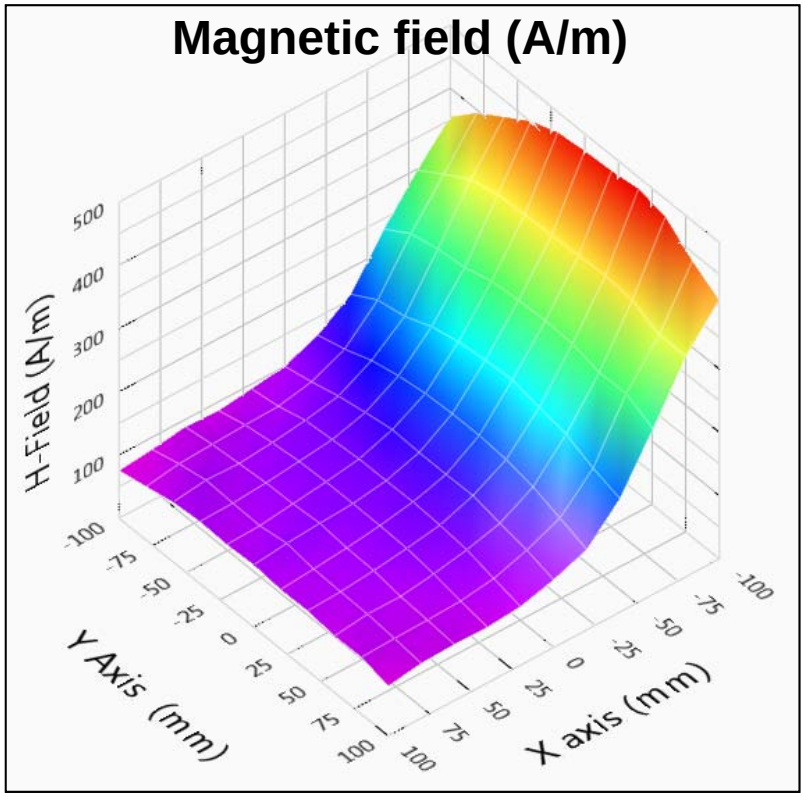


Max. = 82.2 %

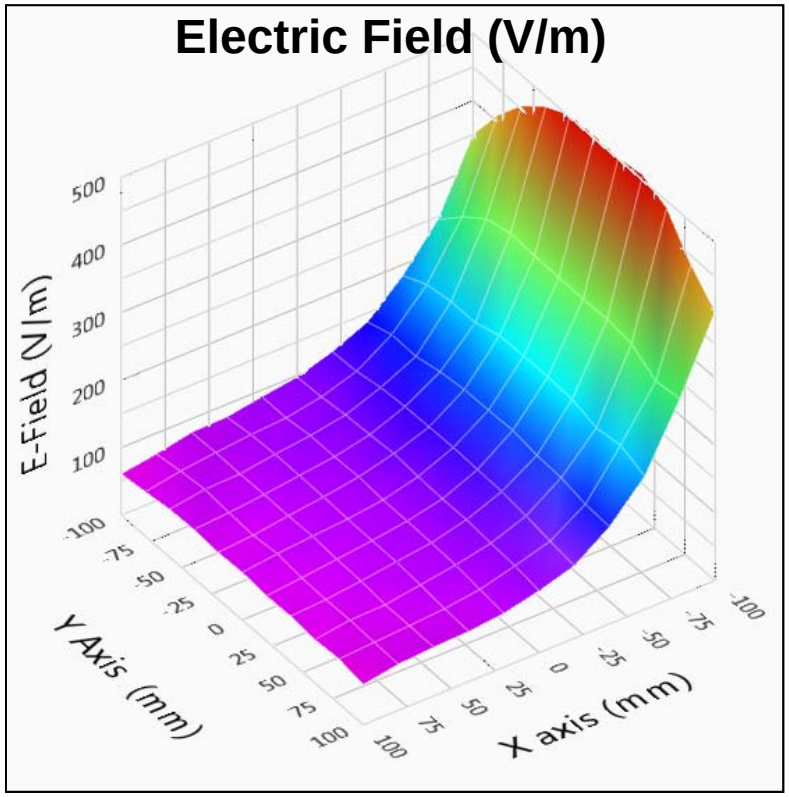


Max. = 85.2 %

EM-field near vehicle's rear bumper



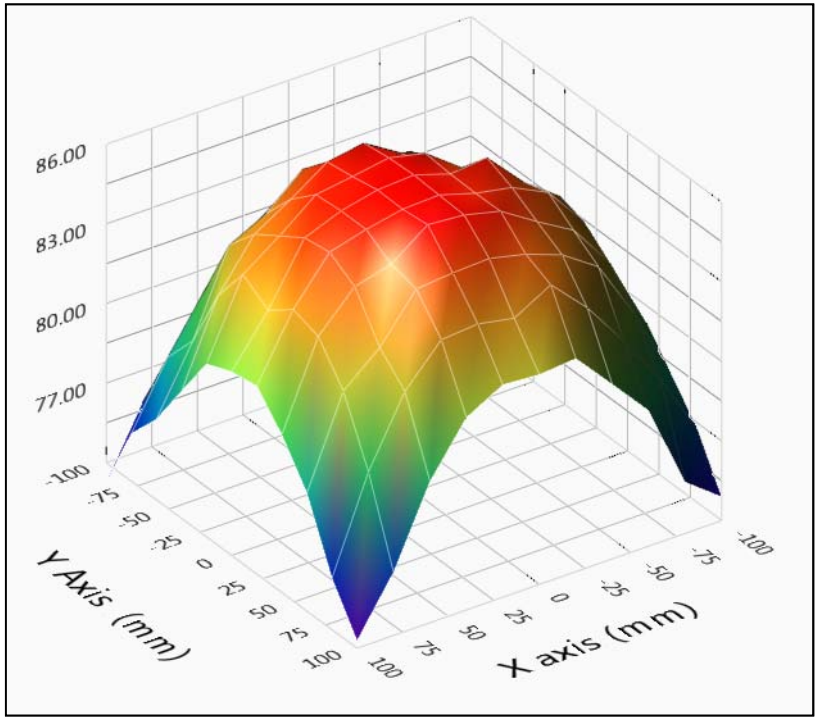
Coils Aligned= 136 A/m
Max. = 482 A/m



Coils Aligned = 106 V/m
Max. = 507 V/m

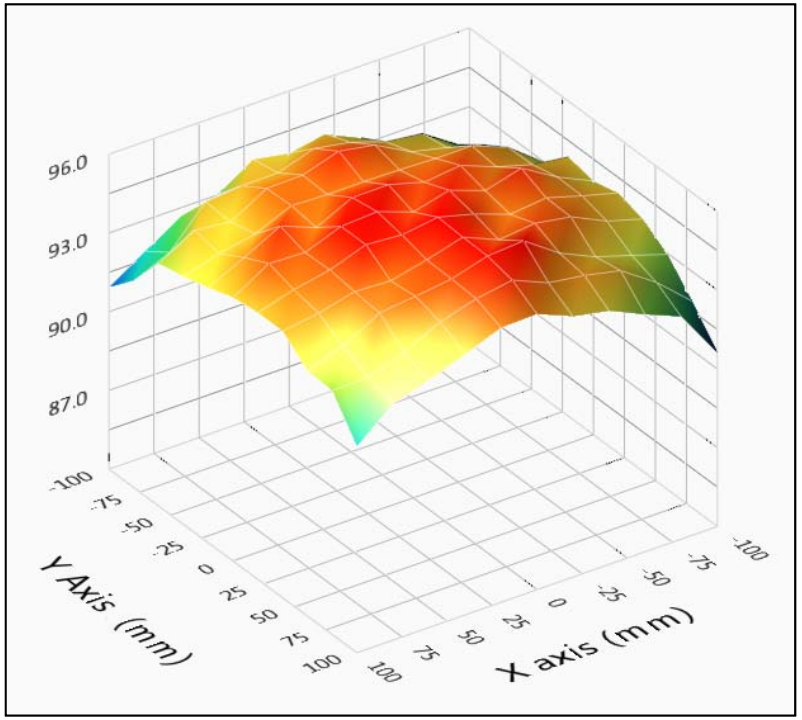
Sub-system Efficiency

DC to DC Efficiency (%)



Max. = 86.4 %

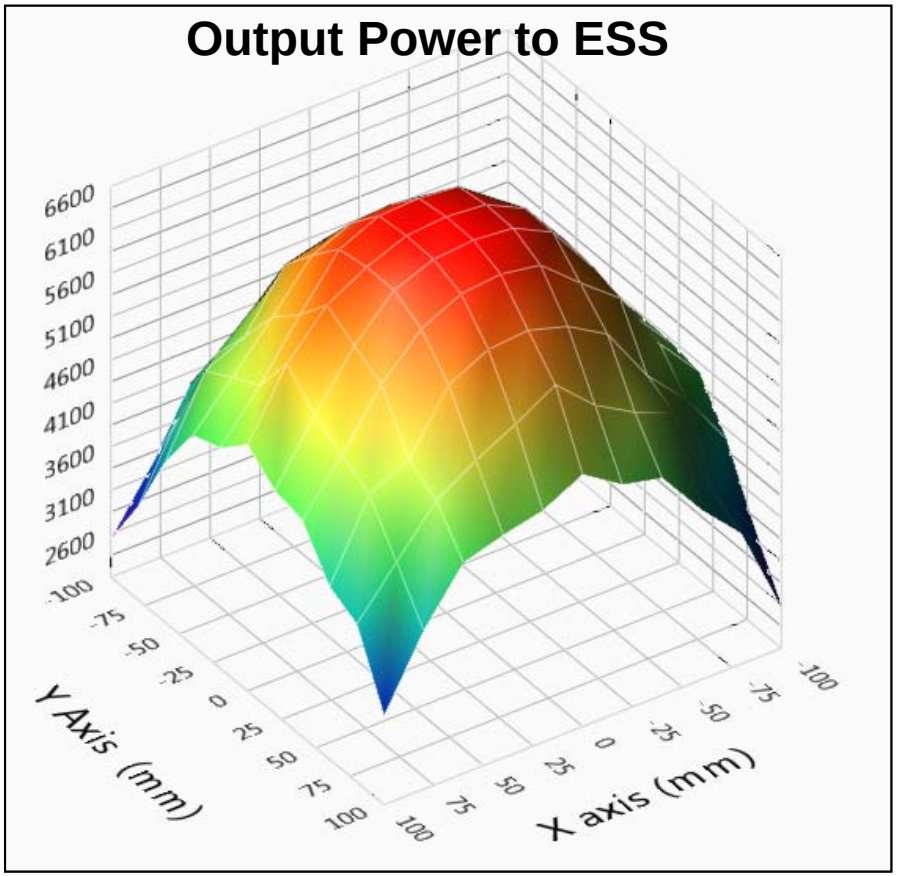
Inverter plus Aux. Load Efficiency (%)



Max. = 95.4 %

Output Power Capability

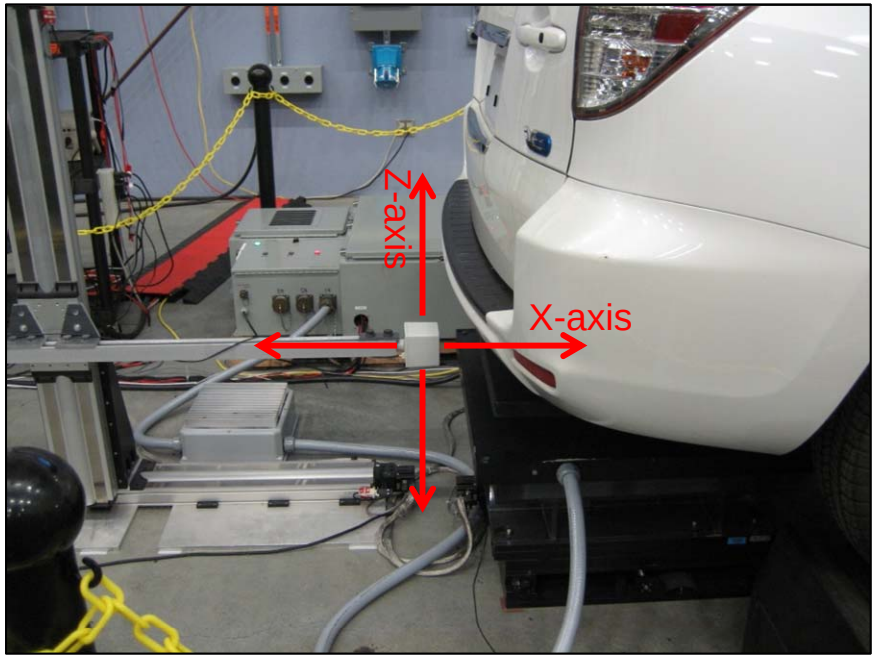
- Commanded output power
  - 6600 watts



Max. = 6.6 kW

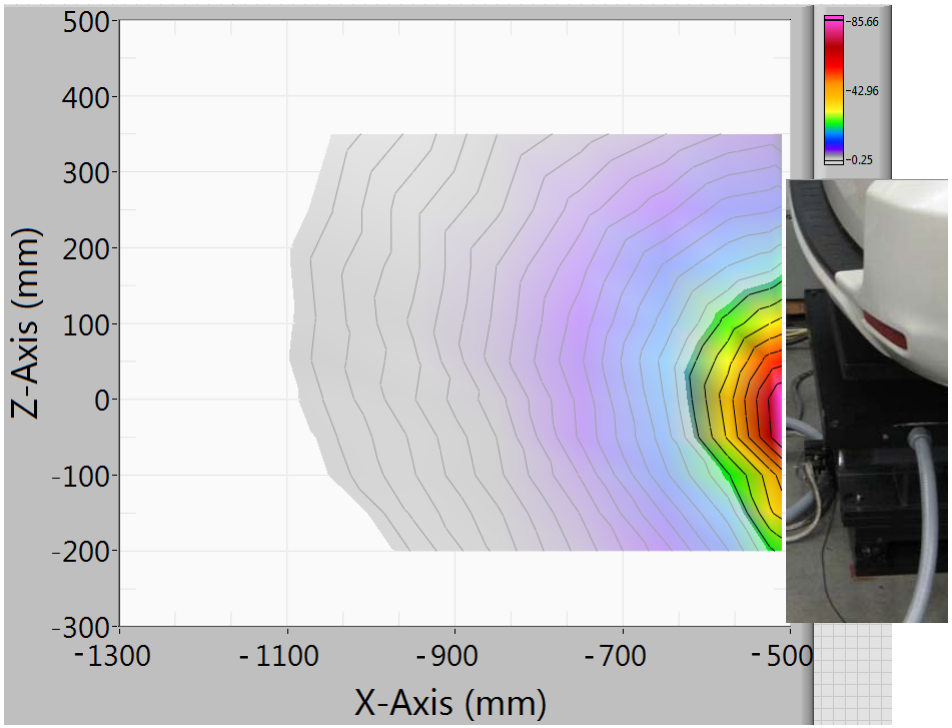
EM-field Scan in X, Z plane near rear bumper

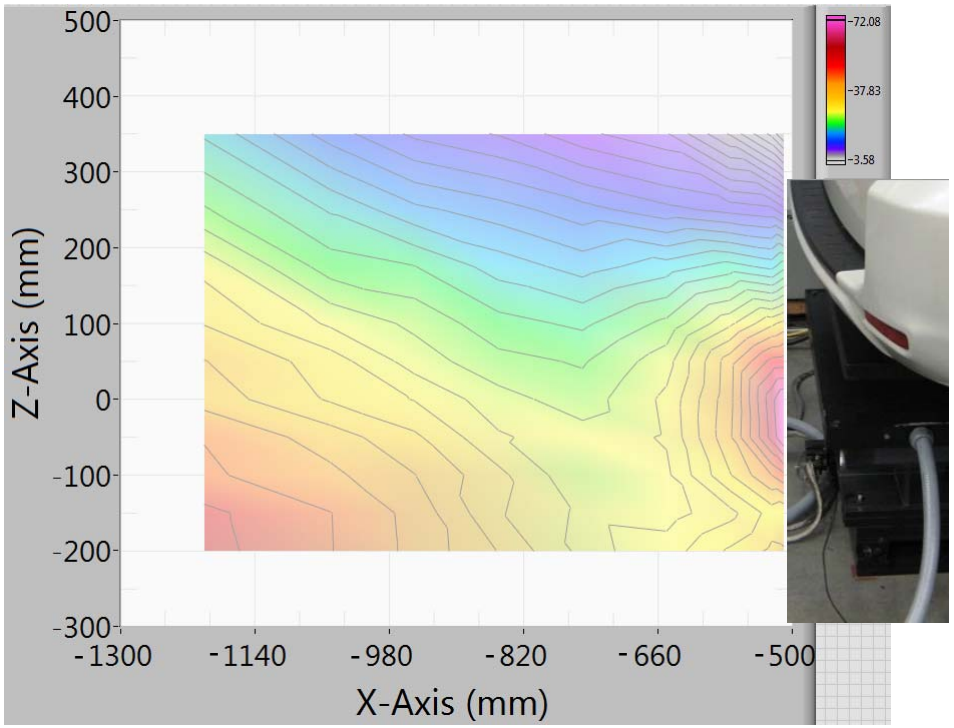
- Coils Aligned (0,0)
- Full power: 6600 watts output
- Input voltage: 240 V RMS
- Output Voltage: 366 VDC



Magnetic and Electric Field at 132mm coil gap

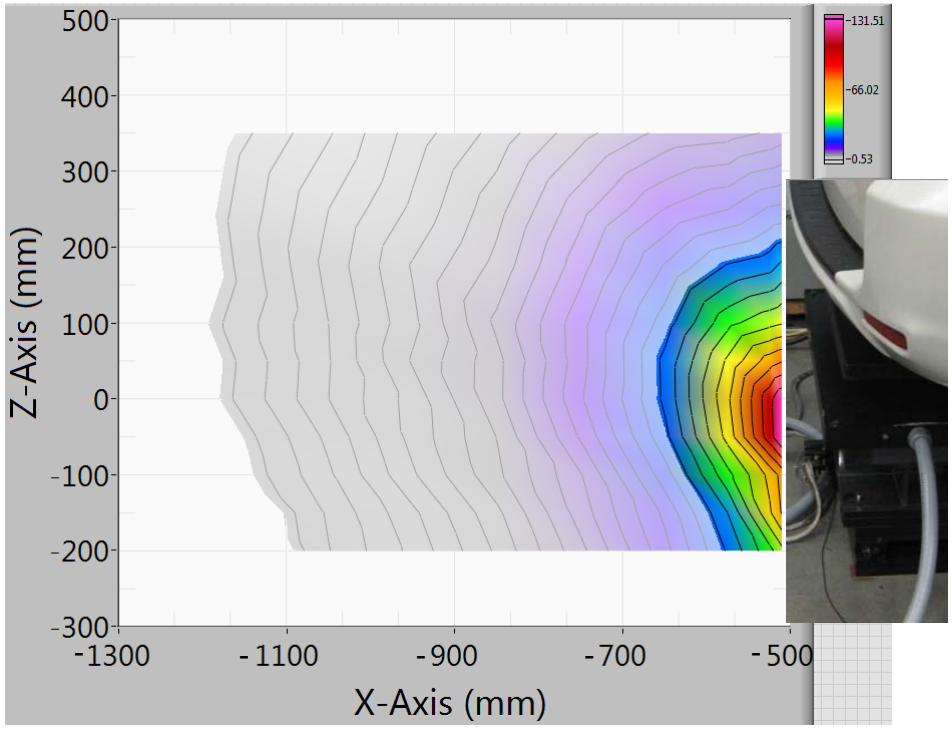
- Bright color area is above ICNIRP 2010 levels (general public exposure)
- Magnetic field (A/m)
  - Large area near bumper at ankle height shows peak of 85.7 A/m
- Electric field (V/m)
  - All areas measured around rear bumper are below ICNIRP 2010

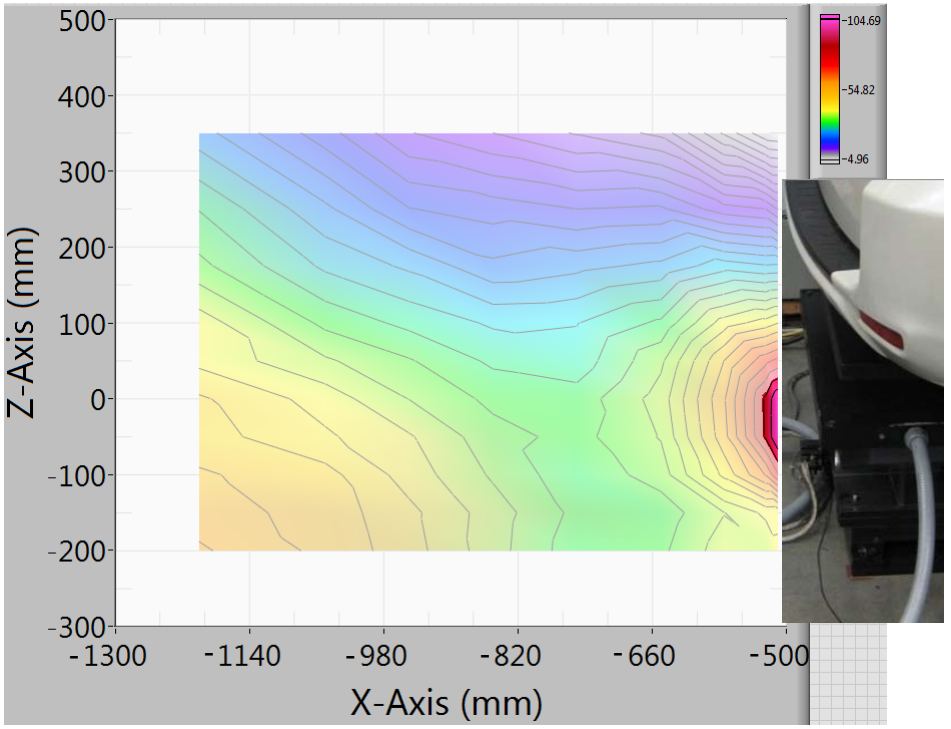




Magnetic and Electric Field at 152mm coil gap

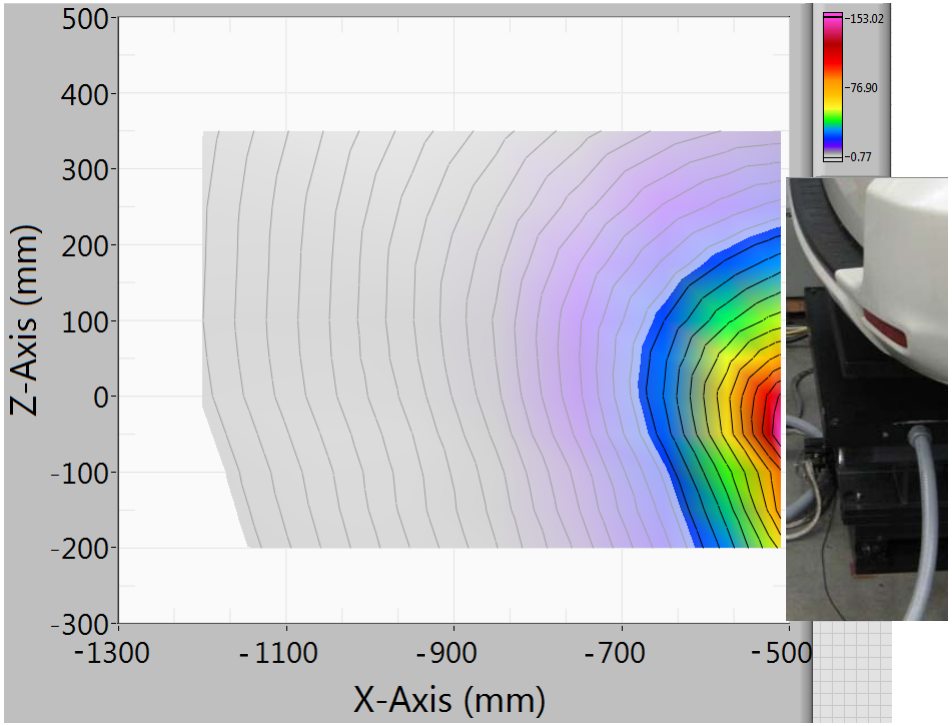
- Bright color area is above ICNIRP 2010 levels (general public exposure)
- Magnetic field (A/m)
  - Large area near bumper at ankle height shows peak of 132 A/m
- Electric field (V/m)
  - Small area near bumper at ankle height shows peak of 105 V/m

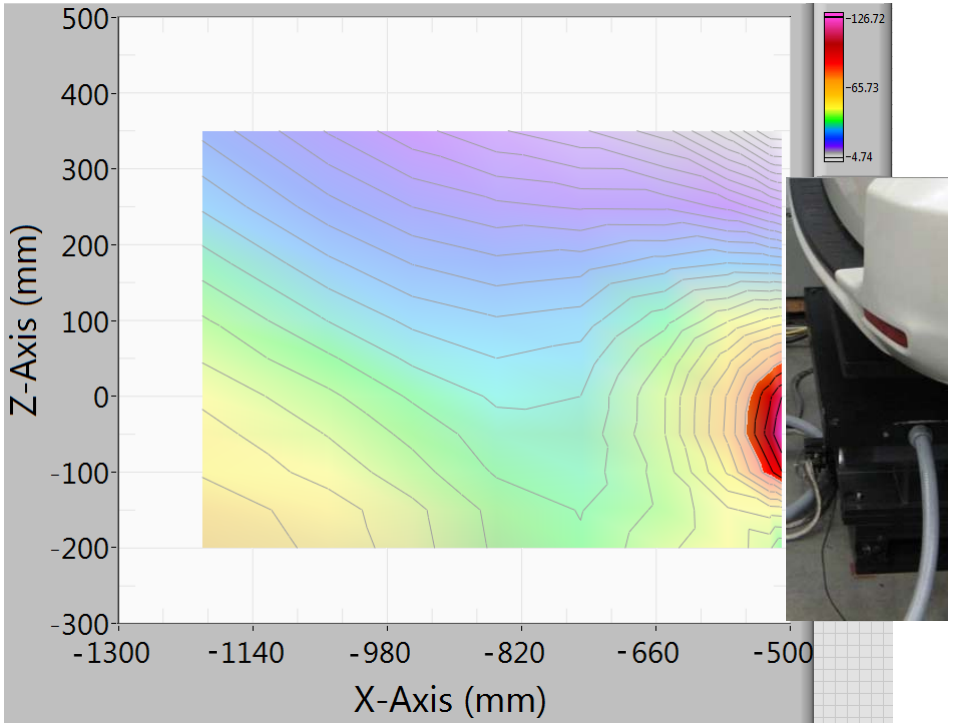




Magnetic and Electric Field at 172mm coil gap

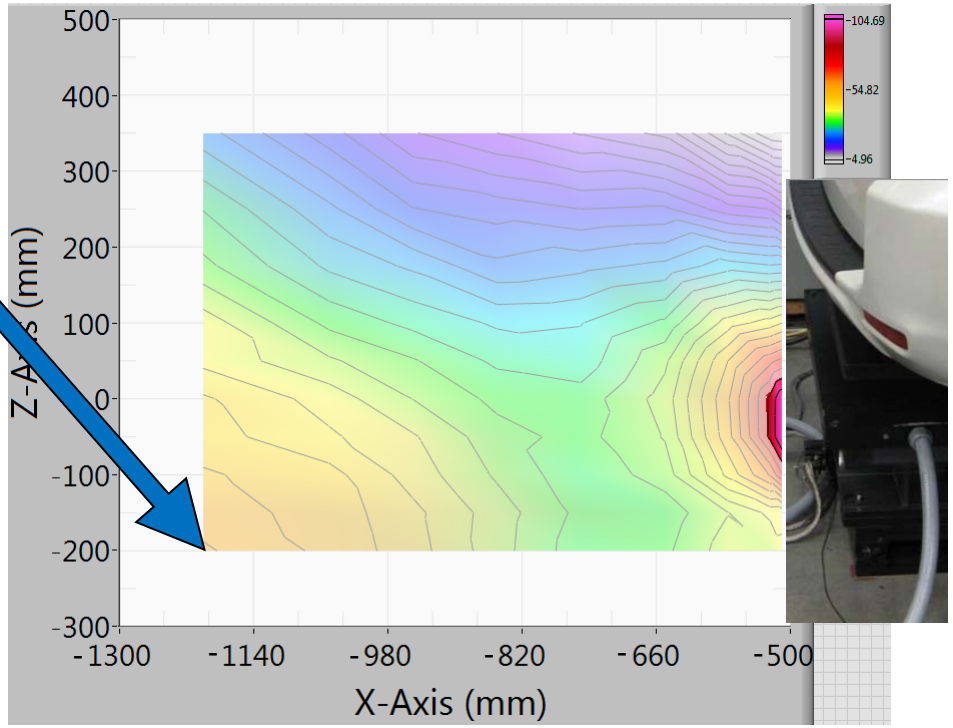
- Bright color area is above ICNIRP 2010 levels (general public exposure)
- Magnetic field (A/m)
  - Large area near bumper at ankle height shows peak of 153 A/m
- Electric field (V/m)
  - Small area near bumper at ankle height shows peak of 127 V/m



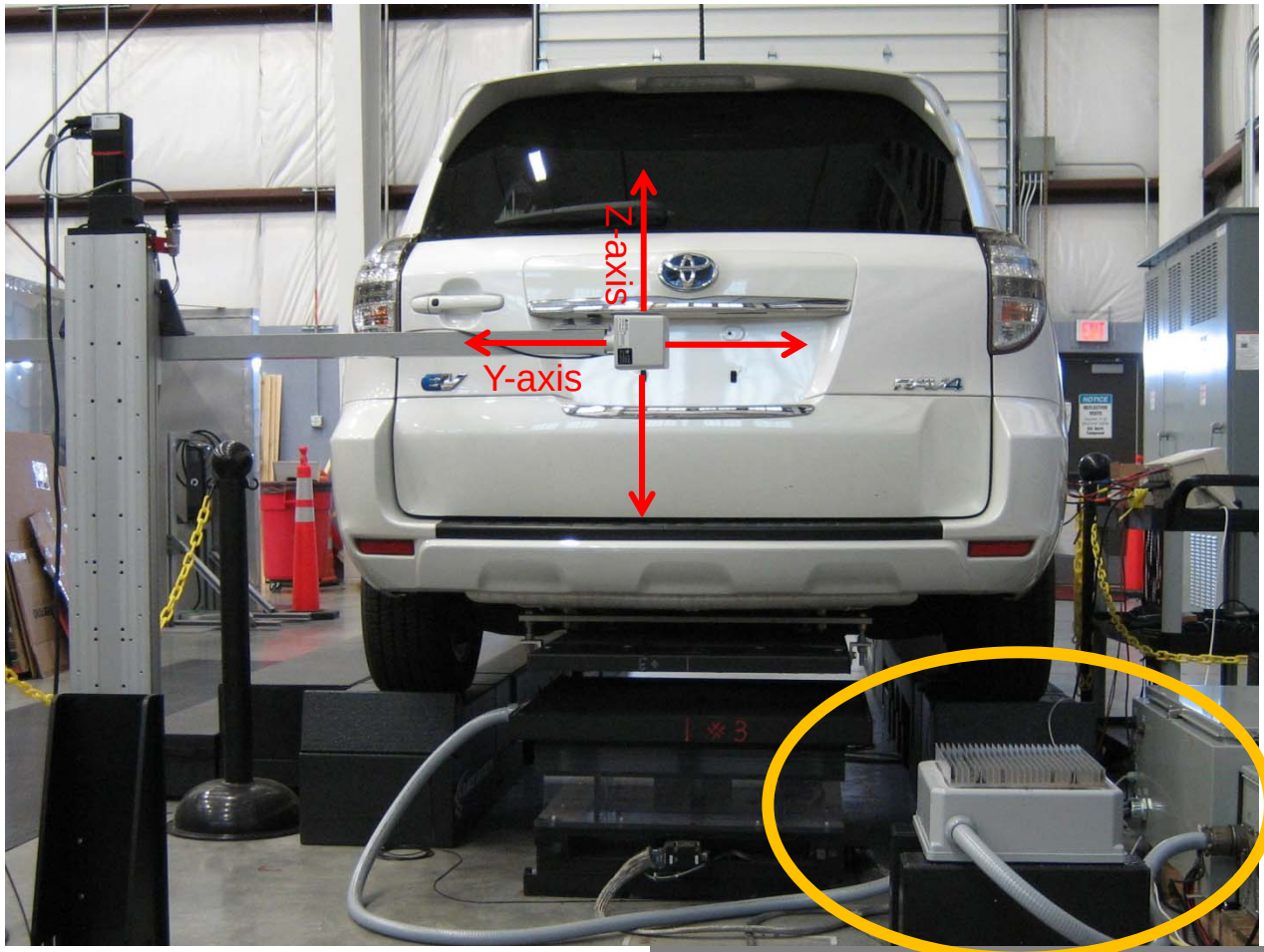


Magnetic and Electric Field at 152mm coil gap

- What is the additional Electric field approximately 1.2m from the coil center?
- Approx. 60 V/m
- This is EM-field generated from the tuning capacitor enclosure between the GSU and the Primary coil

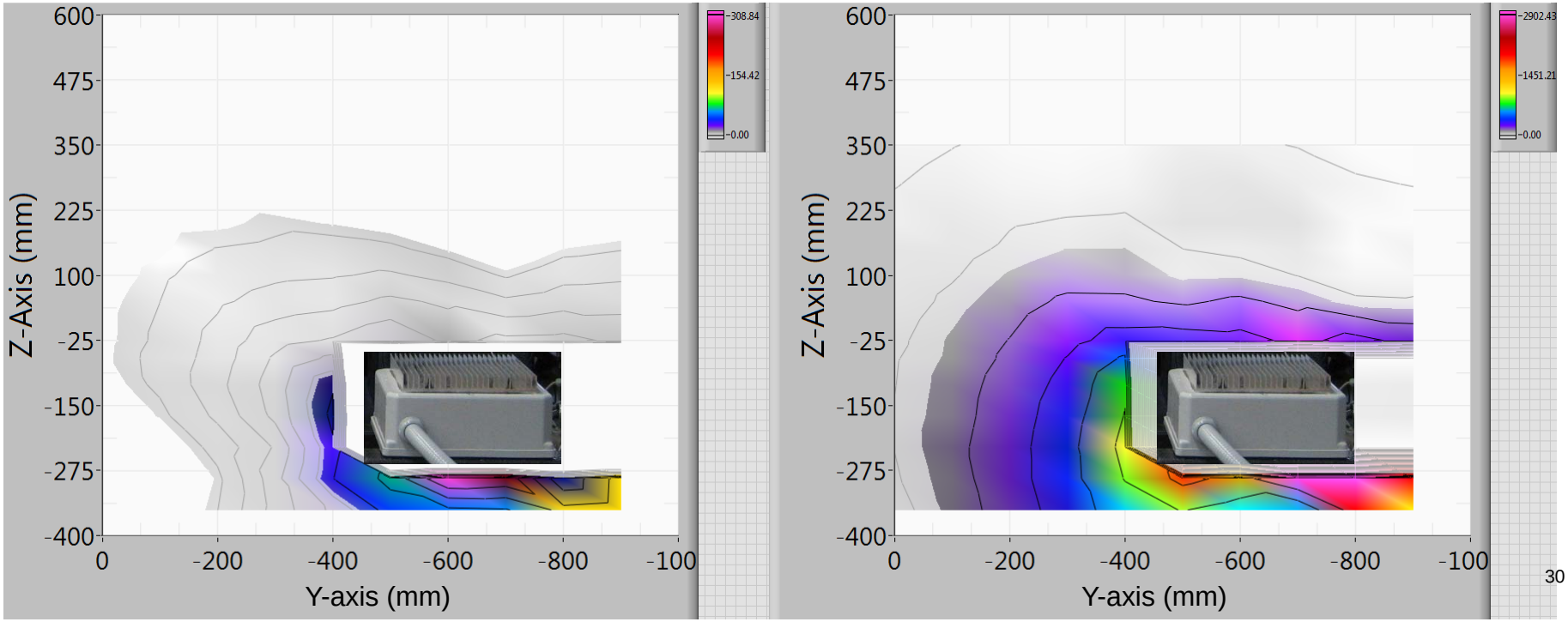


EM-Field near Tuning Capacitor Enclosure
at 152mm ground clearance coil gap



EM-Field near Tuning Capacitor Enclosure
at 152mm ground clearance coil gap

- Bright color area is above ICNIRP 2010 levels (general public exposure)
- Magnetic field (A/m)
  - Shows peak under the enclosure of 309 A/m
- Electric field (V/m)
  - Shows peak under the enclosure of 2,902 V/m



Summary

- Performance Summary at designed Z gap
  - At 152 mm ground clearance (160 mm magnetic gap)
  - At 240VAC, coils aligned (0,0), 6.6 kW output, 366 VDC output
    - Maximum Total Efficiency: 82.2%
    - Maximum End-to-End Efficiency: 85.2%
    - Magnetic field at rear bumper: 132 A/m
    - Electric field at rear bumper: 105 V/m
    - Power Factor: 0.94
    - Operation Frequency: 24.5 kHz
  - Maximum Output Power achieved: 7.0 kW
  - Magnetic field near lower surface of Tuning Capacitor enclosure
    - 309 A/m
  - Electric field near lower surface of Tuning Capacitor enclosure
    - 2,902 V/m

Summary Continued

- Performance Impact (Efficiency and EM-field) from external factors
  - Highest Impacts
    - Coil Gap
      - 8% efficiency decrease from 152 mm to 192 mm gap
      - Mag. field increased 67 A/m for 40mm change in gap
      - Elec. field increased 55 V/m for 40mm change in gap
    - Misalignment
      - 16% efficiency decrease for 100mm misalignment
      - Mag. field increased 346 A/m for 100mm misalignment change
      - Elec. field increased 401 V/m for 100mm misalignment change
  - Lesser Impacts
    - Output Voltage
      - 3% efficiency decrease from 385 VDC to 285 VDC
    - Input Voltage
      - 0.8% efficiency decrease from 240 VAC to 208 VAC
    - Output Power
      - 1.6% efficiency decrease from 3.9 kW to 6.8 kW

Acknowledgement

This work is supported by
the U.S. Department of Energy's
EERE Vehicle Technologies Program

More Information

http://avt.inl.gov