High Voltage Automotive EMC Component Measurements Using an Artificial Network

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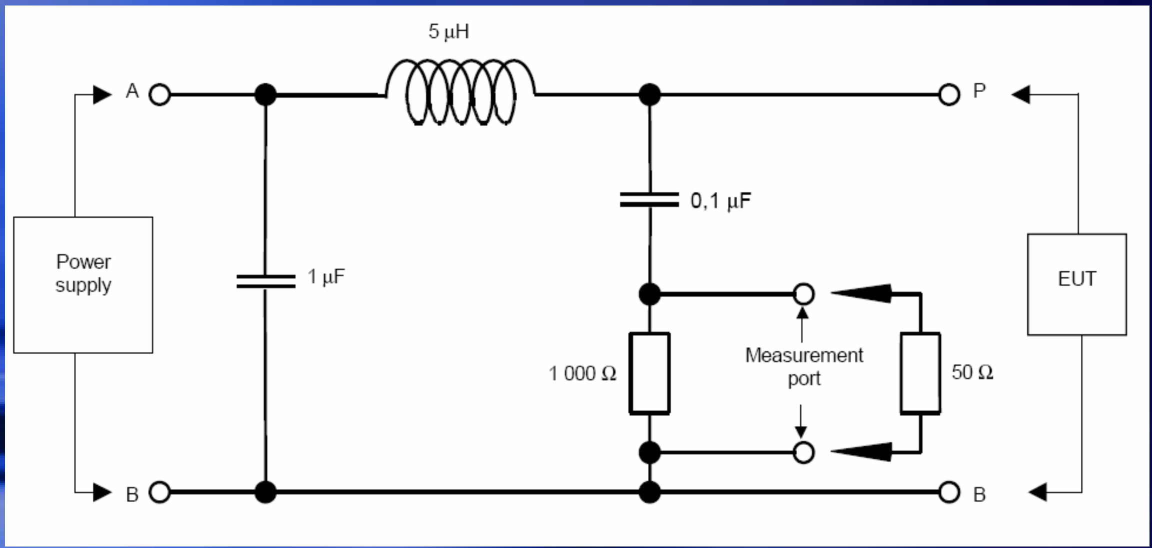
High Voltage Artificial Network Summary

- Based on experimental and simulation results:
  - It is not recommended to use an AN as defined by CISPR for HV conducted emissions voltage validation.
  - It is not recommended to use an AN as defined by CISPR during current probe measurements on HV lines.
- HV AN can be useful for development and simulations.
- A new AN for HV applications should be defined if HV conducted emissions voltage validation is required.

Functions of an Artificial Network

1. Provide a defined impedance over a given frequency range at the power terminals of the equipment under test (EUT)
2. Allow for the disturbed voltage to be measured
3. Isolate the EUT from undesired power supply disturbances



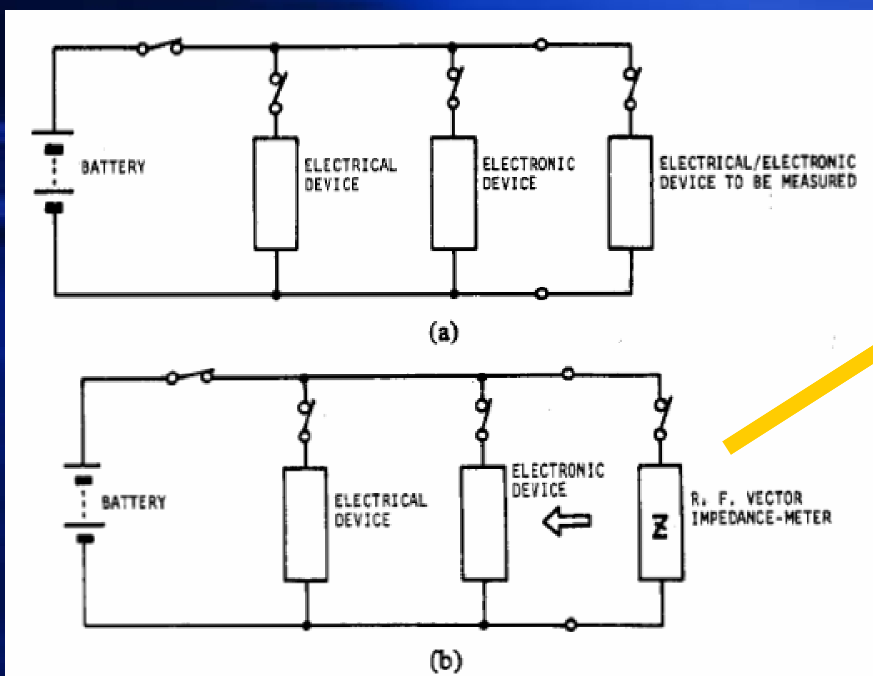
CISPR 25: 0.1 to 100 MHz

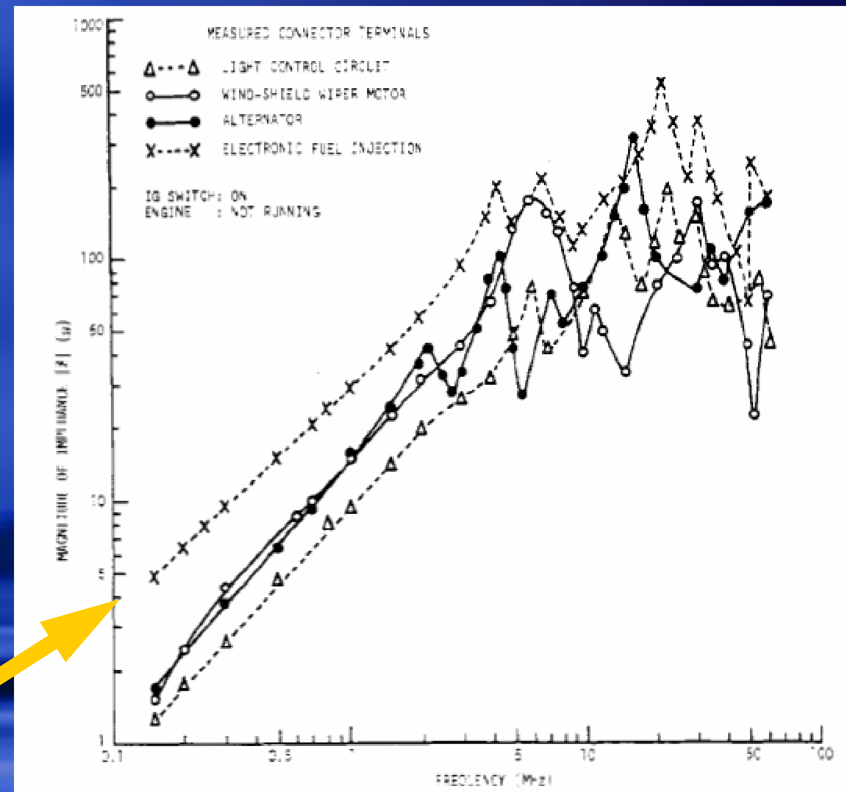
CISPR 16-1: “Specification for radio disturbance and immunity measuring apparatus and methods – Part 1: Radio disturbance and immunity measuring apparatus”, Second edition 1999-10, IEC.

Early Studies of Artificial Networks

Presented in 1983 IEEE Transactions Paper:

- Impedance measurements of the electrical network for 6 different vehicles.
- At most 8 electrical components were on vehicles: horn & light control circuits, ignition coil, alternator, windshield washer & wiper motors, EFI, and radio





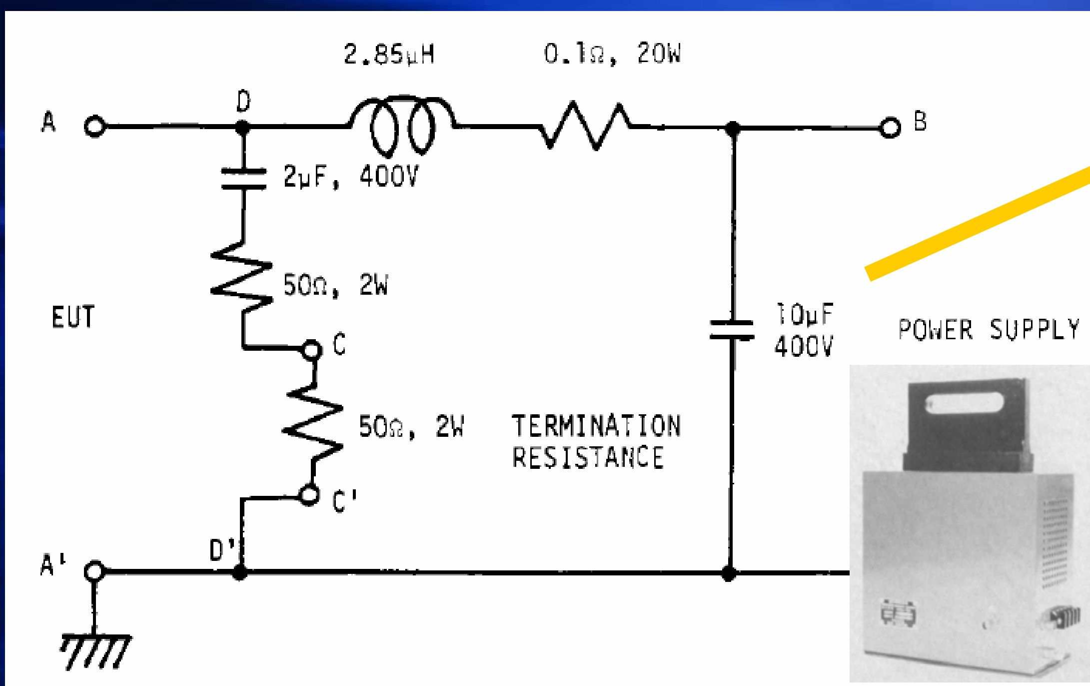
Example measurements of one vehicle.

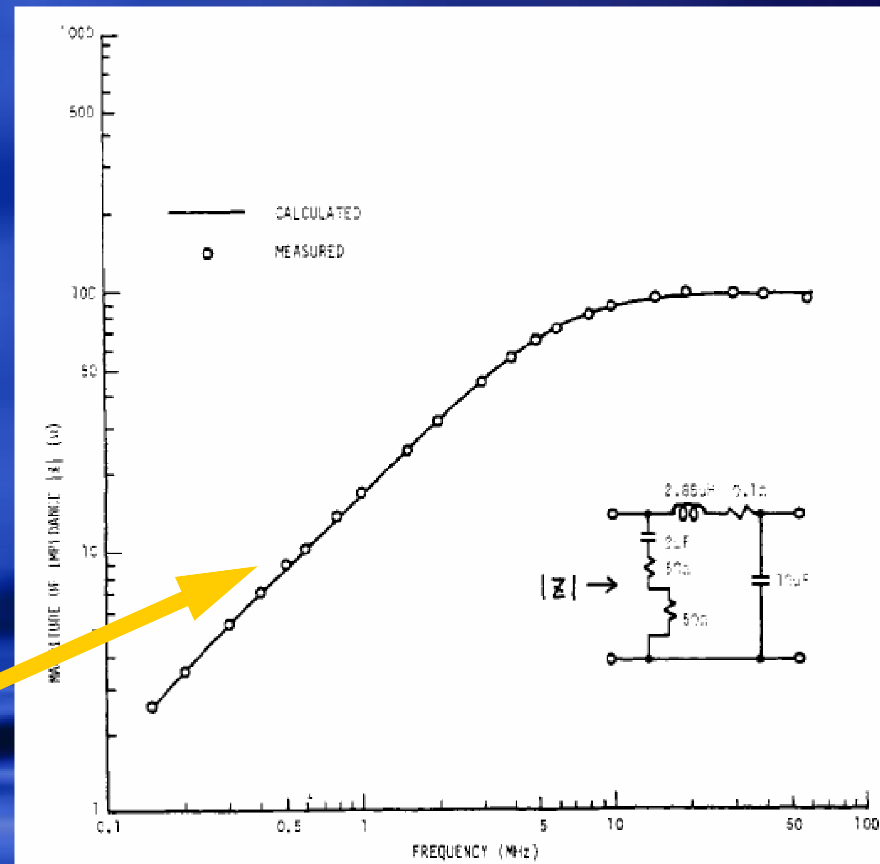
S. Yamamoto and O. Ozeki, "RF Conducted Noise Measurements of Automotive Electrical and Electronic Devices Using Artificial Network," IEEE Trans. Veh. Technol., vol. VT-32, no. 4, pp. 247–253, Nov. 1983.

Early Studies of Artificial Networks – Cont.

Experimental Results:

- Battery cables were < 0.3 Ω.
- From 150 kHz to several MHz, the inductance range from 1.1 – 6.4 μH
- From several MHz to 60 MHz the inductive and capacitive impedance ranged from 20 to 740 Ω

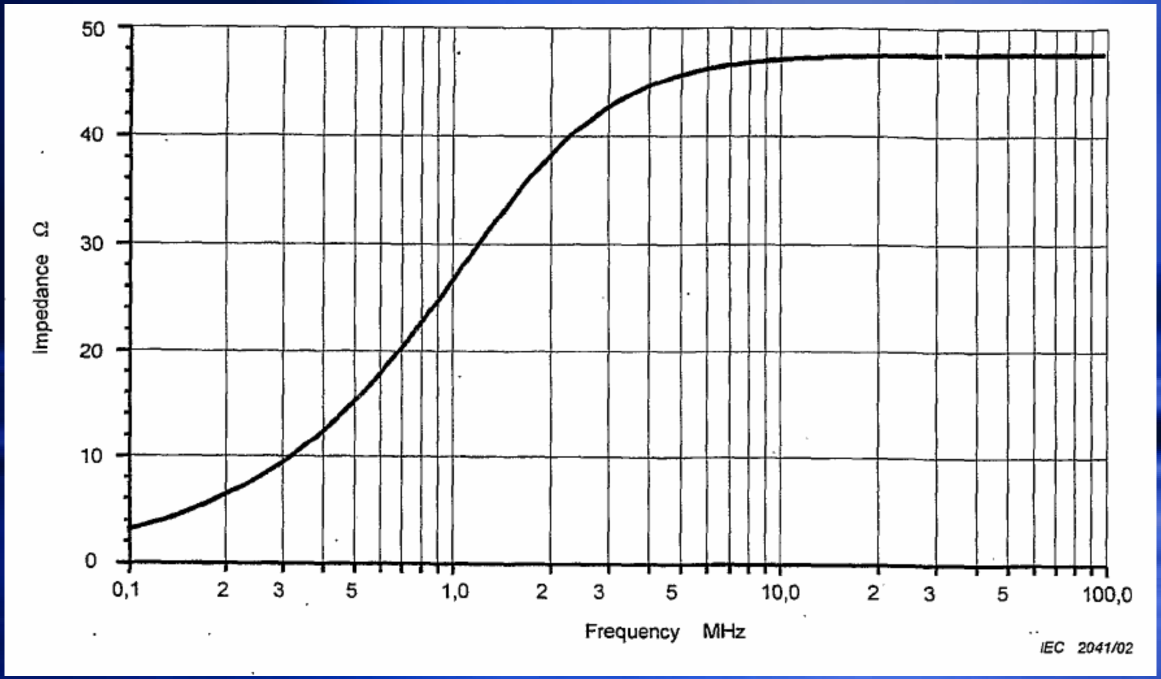




Based on empirical measurements an AN was developed from 150 kHz to 60 MHz with a <u>2.85 μH</u> inductor and <u>10 μF</u> capacitor.

Comparison – AN 1983 vs. AN Today

CISPR 25: Characteristic impedance



	1983	Today
Capacitance	10 µF	1 µF
Inductance	2.85 µH	5 µH
DC Blocking	2 µF	0.1 µF
Resistance	0.1 Ω	0 Ω
Frequency	0.15 – 60 MHz	0.1 – 100 MHz

Early Studies Using HV Artificial Networks

A number of papers exist using an AN for higher than 12 V automotive applications, but none question its functionality:

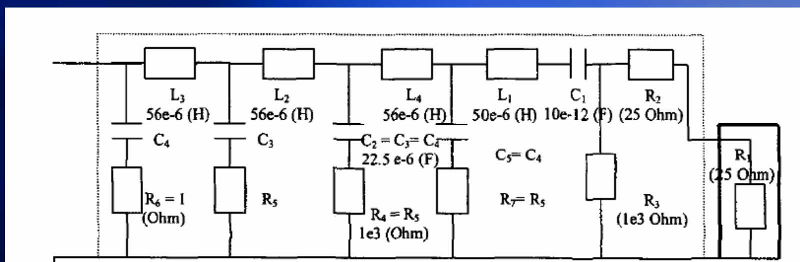
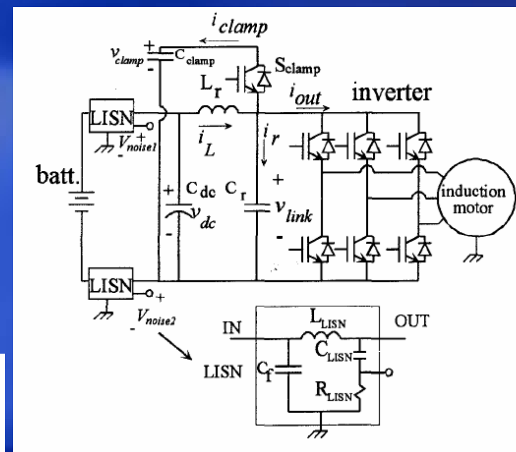
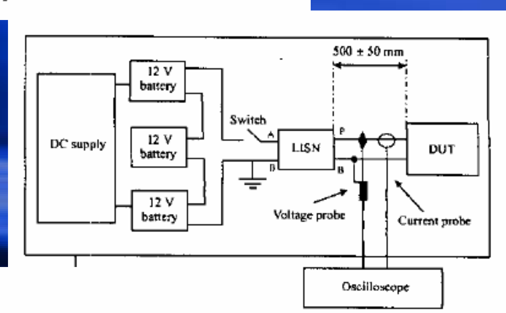
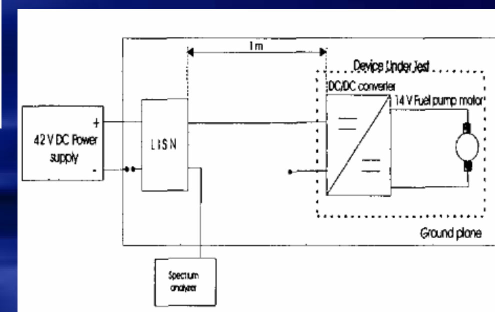
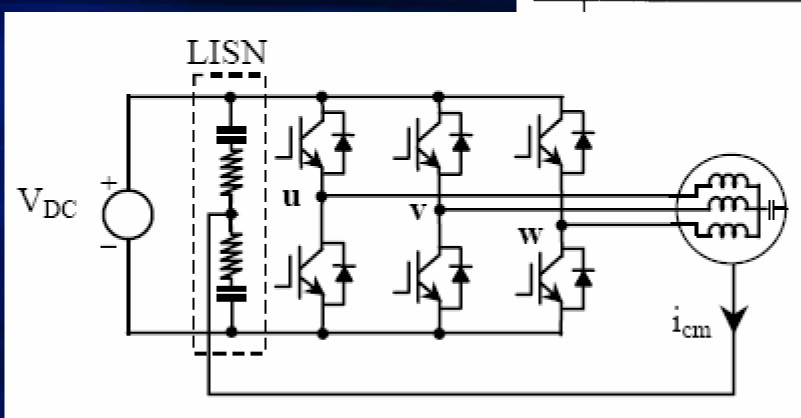


Fig. 3. Single phase schematic of Triple-LISN









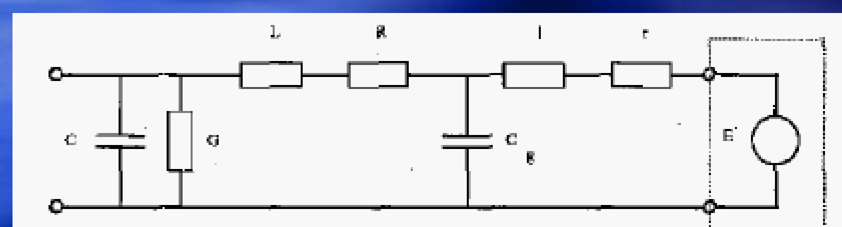


Fig. 4. ATLN circuit (1 cell) with ideal power supply

Refer to paper for references.

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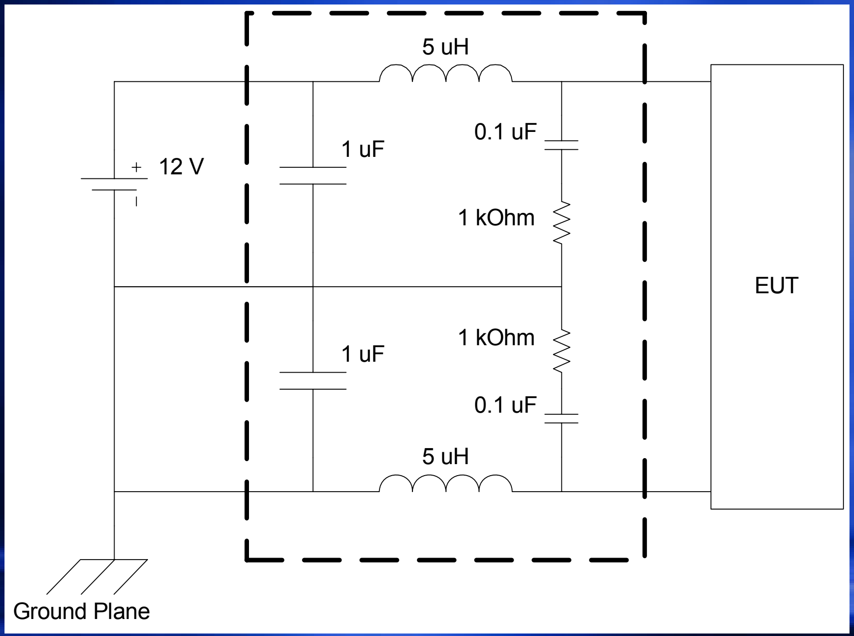
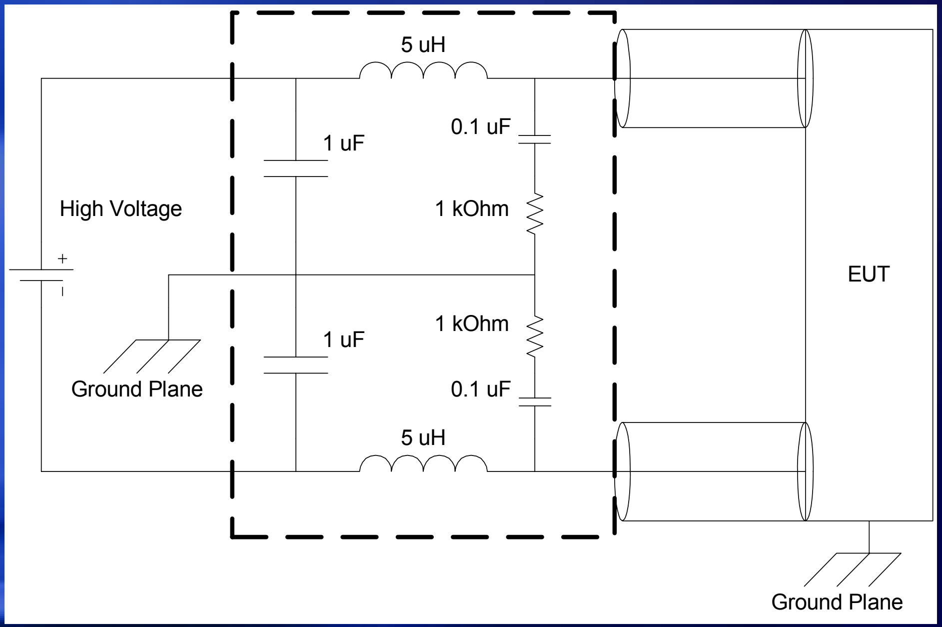
Typical Automotive AN Setup Comparison

Standard 12 V Automotive AN Setup



- Measures DM voltage: 150 kHz < V_{out} < 100-200 MHz
- 1 µF on return generally shorted
- AN defined to represent system impedances
- Generally no shielding

Example HV Automotive AN Setup

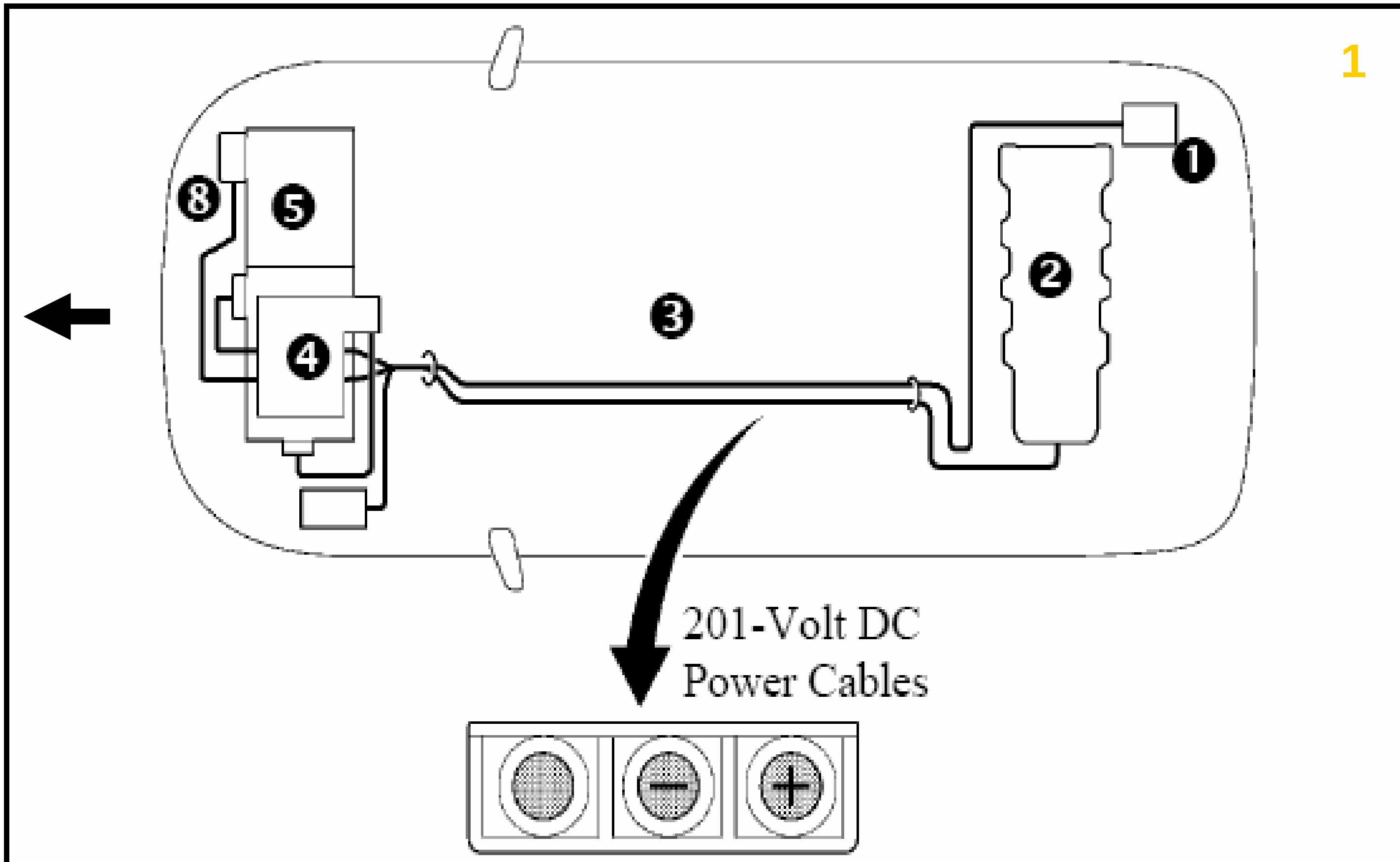


- Measures CM voltage, generally between inner conductor and shield
- 1 µF generally much larger than HV cable shield capacitance
- 5 µH generally much larger than coaxial cable inductance
- Shielding termination not defined

Common Hybrid Electric Vehicle Layout

2004 Toyota Prius HV Layout

Component
12-Volt ❶ Auxiliary Battery
Hybrid ❷ Vehicle (HV) Battery Pack
Power ❸ Cables
Inverter/ Converter ❹
Gasoline ❺ Engine



Components (Top View) and High Voltage Power Cables

[1] 2004 Toyota Prius Emergency Response Guide

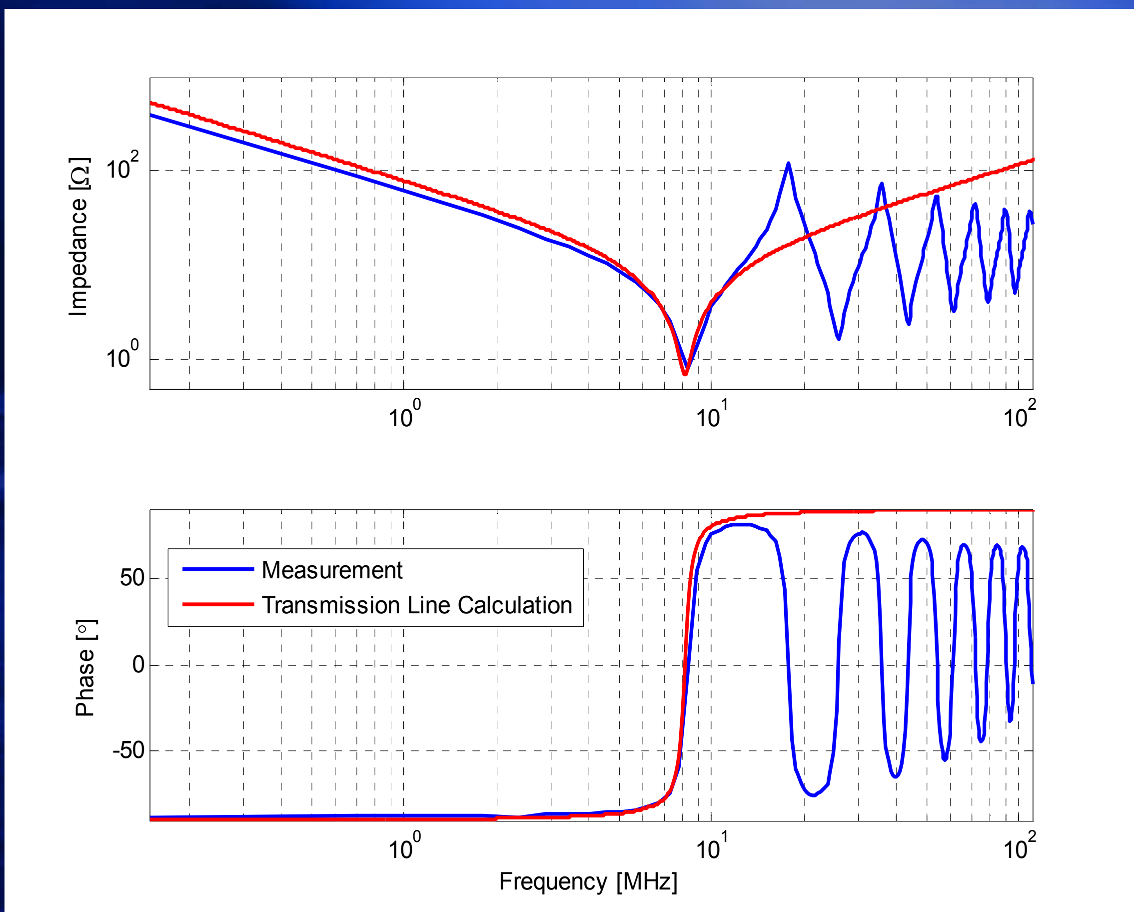
Consequences of HV Shielded Cables

- Shield current is dependant upon the amount of intercable coupling and electrical terminations of shield at the ends of the cable.

- Utilization of different geometries for cables will also affect current path characteristics; shield diameter vs. inner conductor diameter, different dielectrics of isolation material

HV Shielded Cable Example

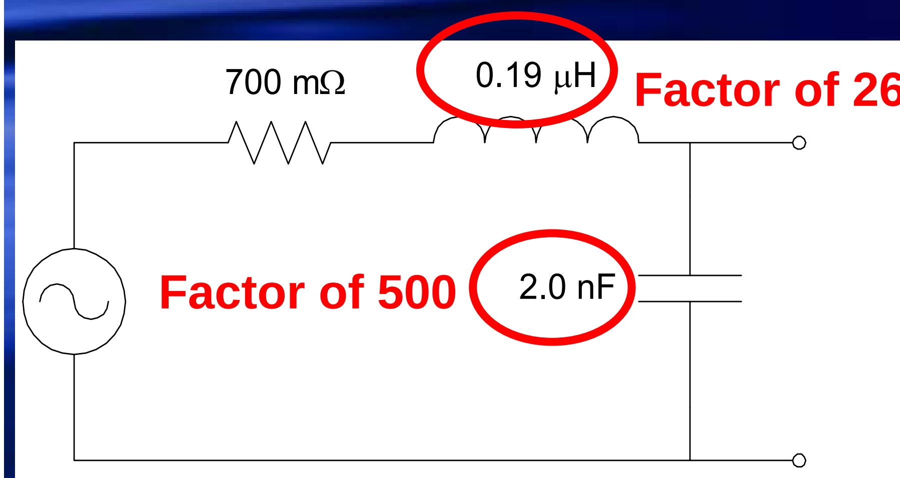
5 m long HV shielded cables measured with Network Analyzer and first resonance calculated with transmission line equations.



Per unit calculations for a coaxial transmission line:

$$l = \frac{\mu_0}{2 \cdot \pi} \ln\left(\frac{D}{d}\right)$$

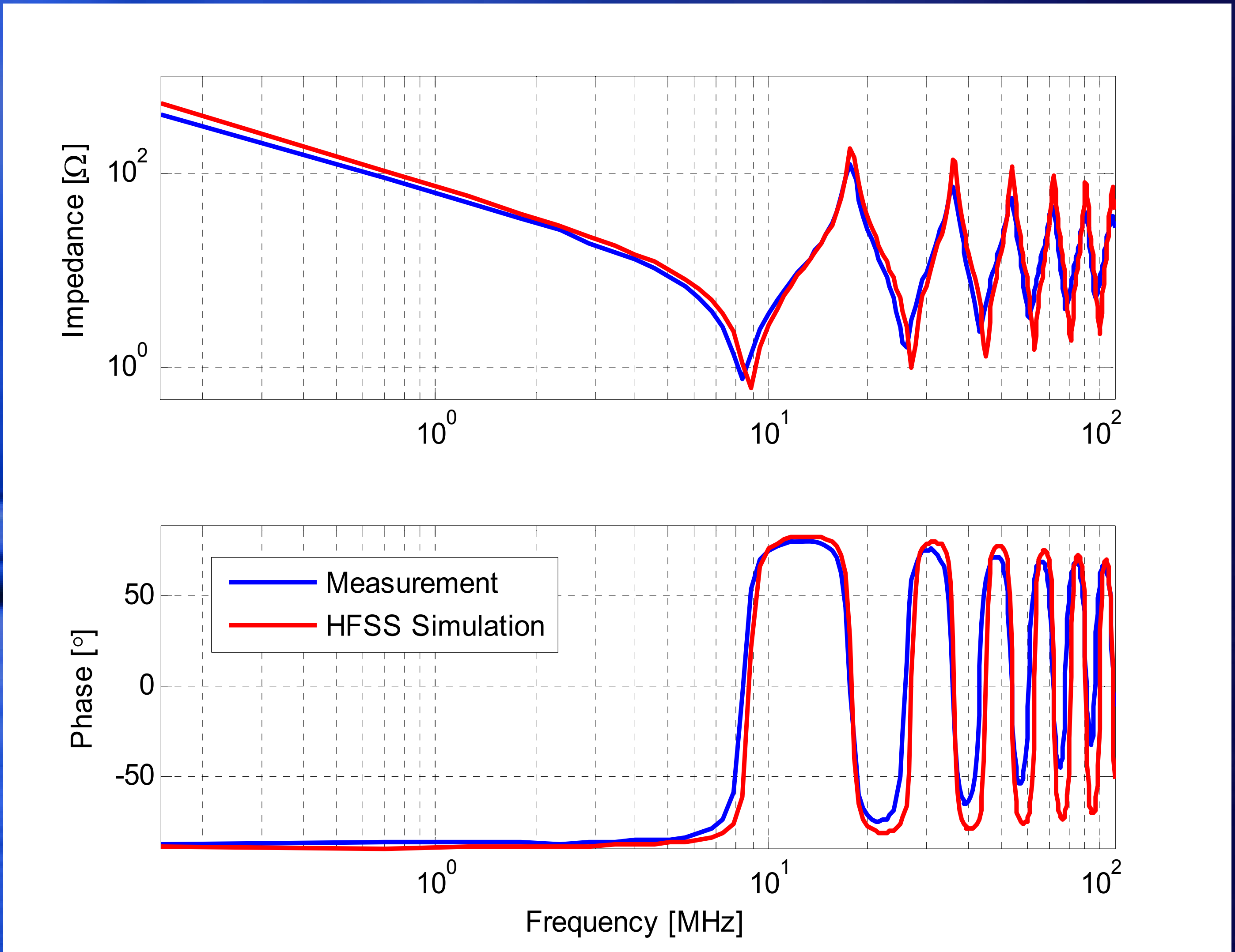
$$c = \frac{2 \cdot \pi \cdot \varepsilon_r \cdot \varepsilon_0}{\ln\left(\frac{D}{d}\right)}$$



Ansoft HFSS HV Cable Simulation

If it is desired to simulate the system to several MHz, a better cable model than transmission line is required.

HFSS simulation, based on Finite Element Method (FEM) with adaptive meshing, was used to create HV shielded cable simulation model.

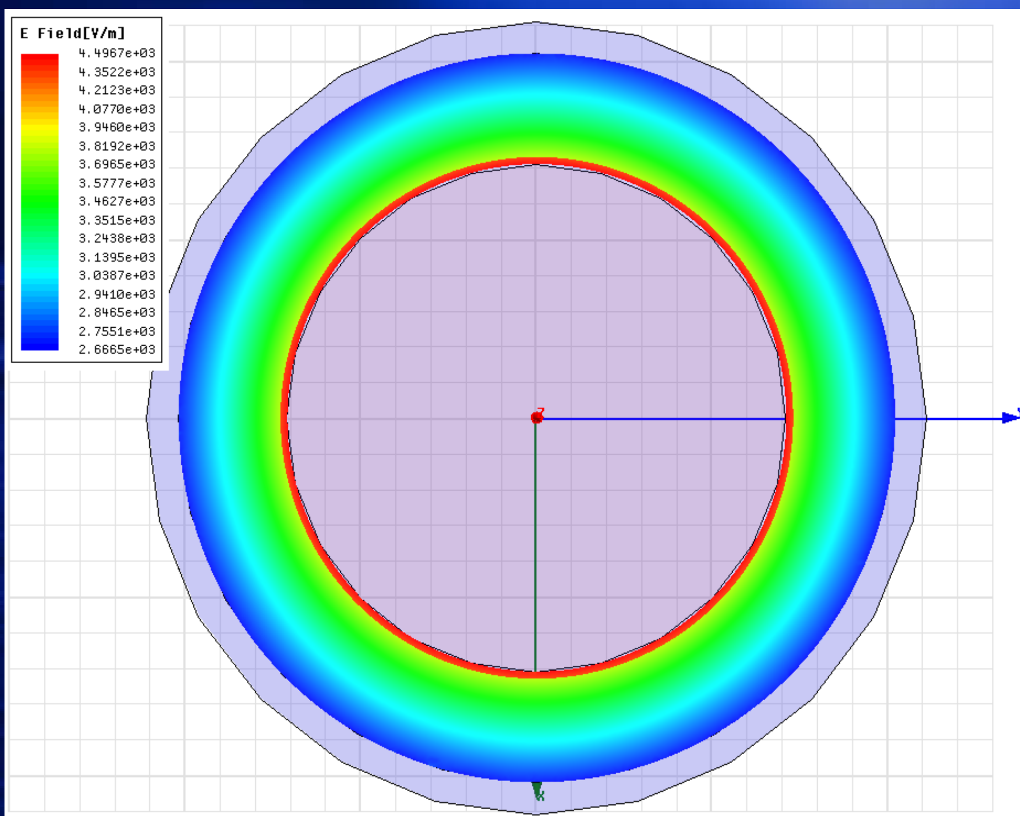


HV Cable Simulation – E & H-Fields

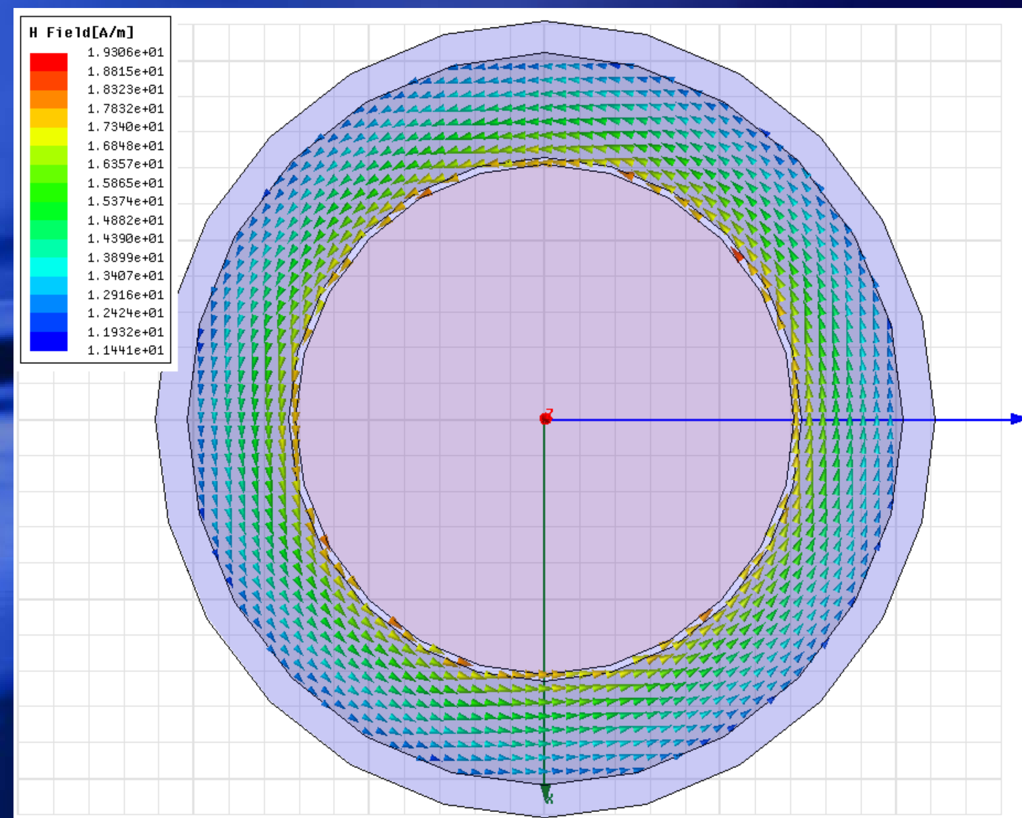
HFSS simulation calculates the simulated near fields within the boundaries of the HV coaxial shielded cable.

Model was created assuming a perfectly shielded coaxial cable - No fields outside of shield

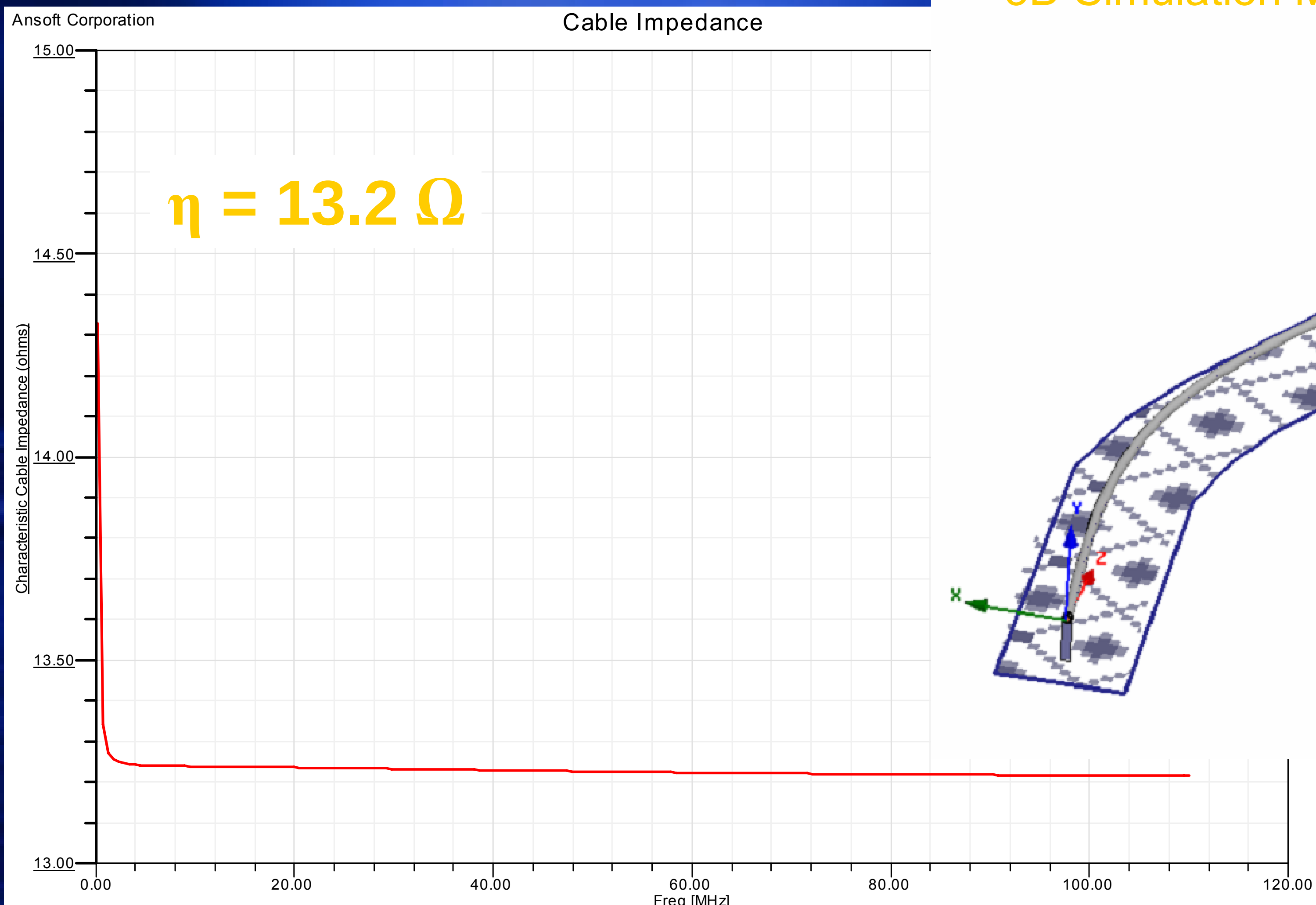
E-Field

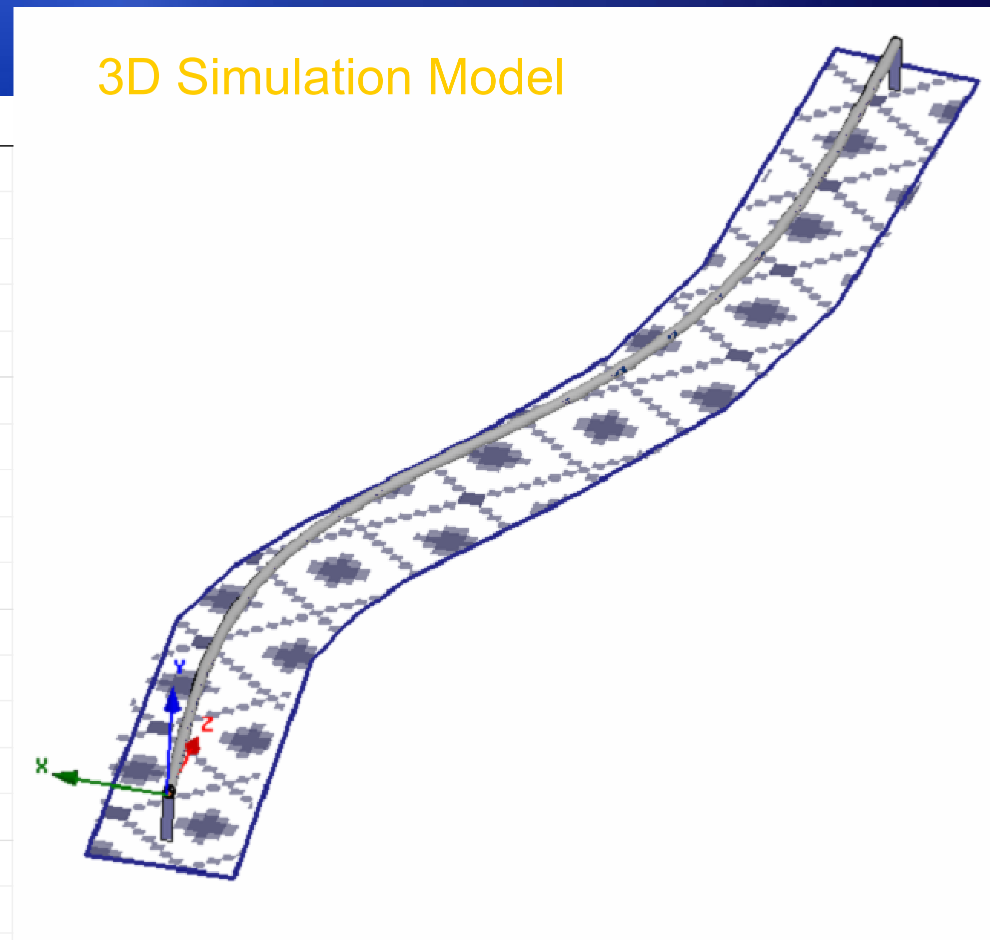


H-Field

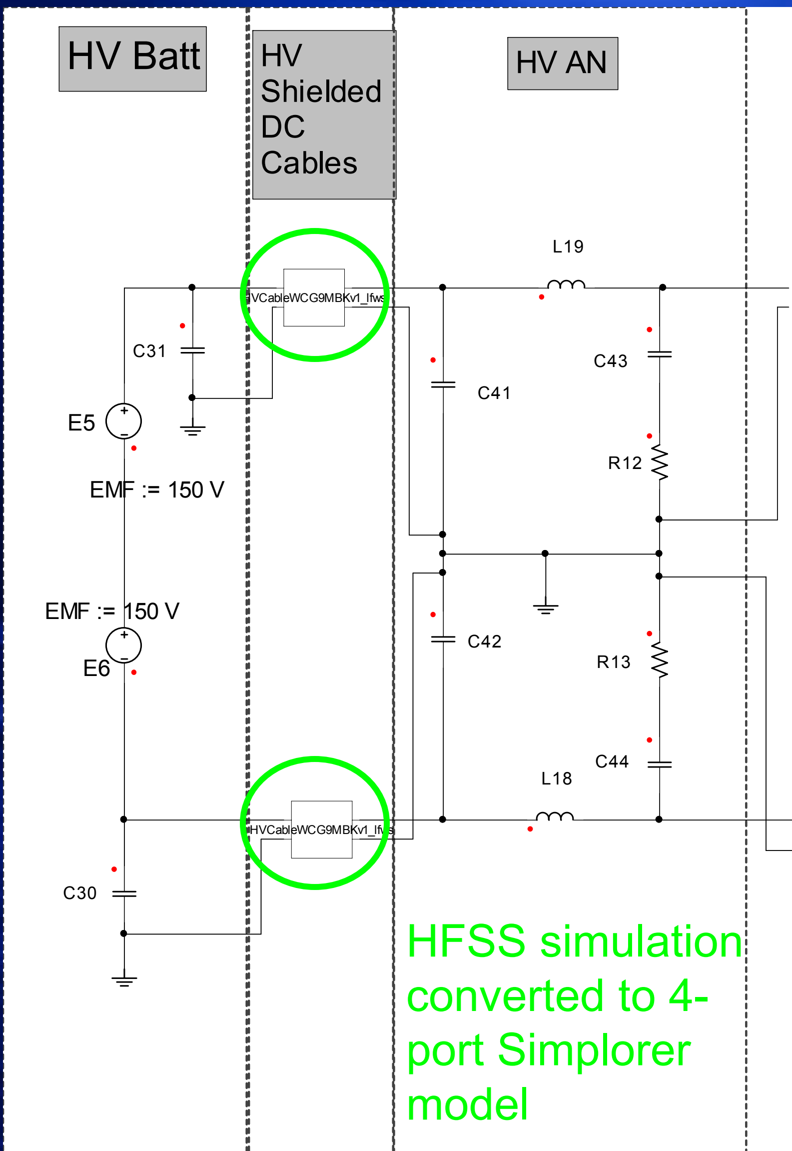


HV Cable Simulation – Wave Impedance

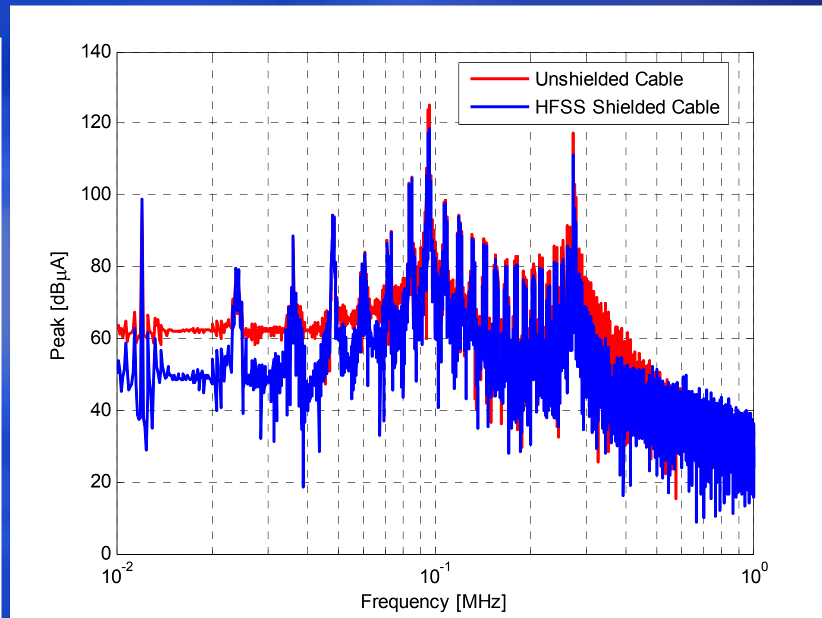




HFSS Simulation to Simplorer Model



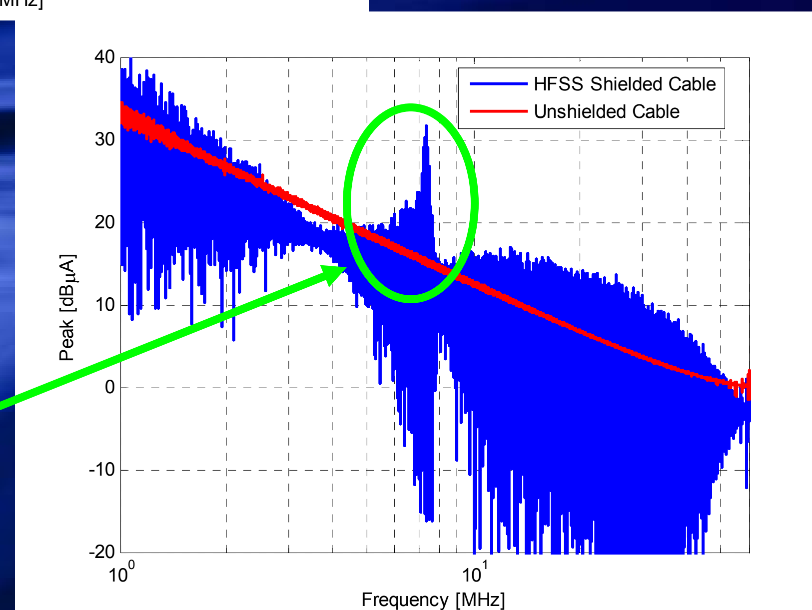
HFSS simulation converted to 4-port Simplorer model



Improvement due to impedance of shielded cable realized; shielding effectiveness not part of simulation

Higher frequency content realizable with HFSS model

1st resonance of cable seen



Benefits of Simulation for this Work

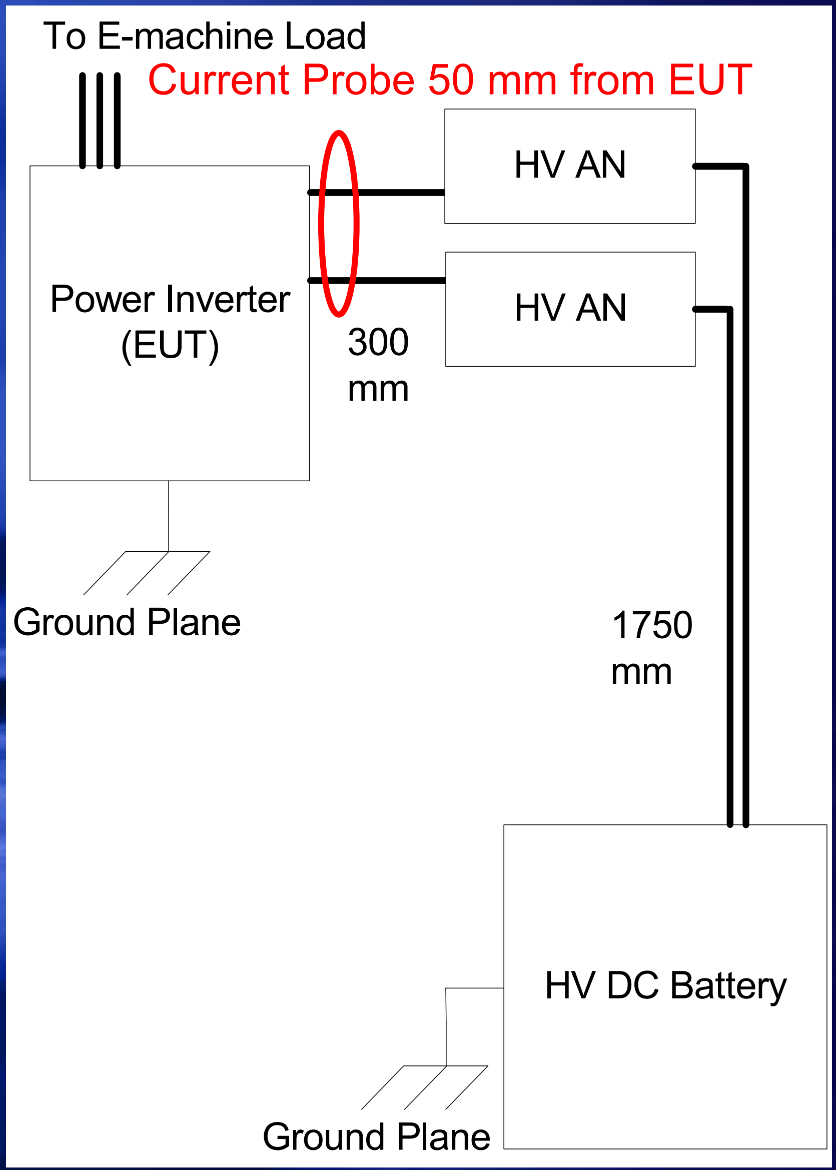
Complex physics of this need to be understood, such as the frequency dependent characteristics unique to this type of problem.

Simulation could be used to provide insight into the physical behavior without affecting system operation due to testing with standard methods.

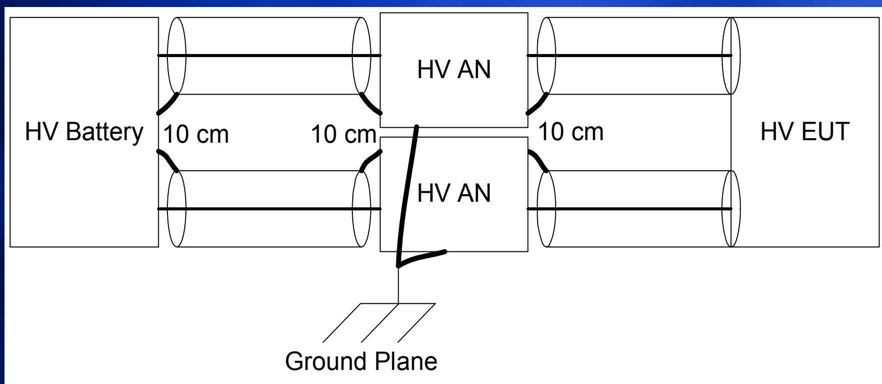
HV AN Experimental Test Setup

An experimental test setup was created to demonstrate the effects of the HV AN

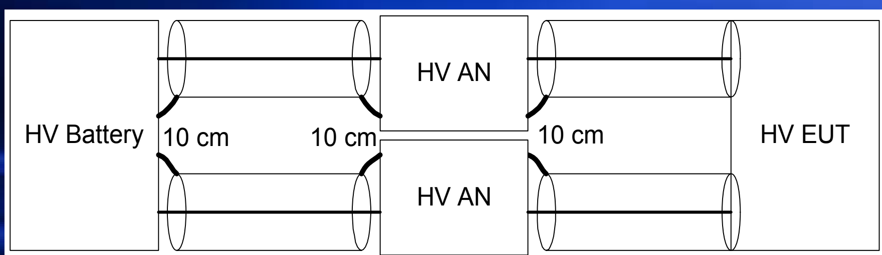
- Mounted on real vehicle chassis
- Routing similar to actual HEV
- Maintained CISPR setup requirements
- All tests performed at 500 rpm, 5 N·m
- Current probe measurements taken 50 mm from EUT (CM)
- Voltage measurements measured from output of HV AN



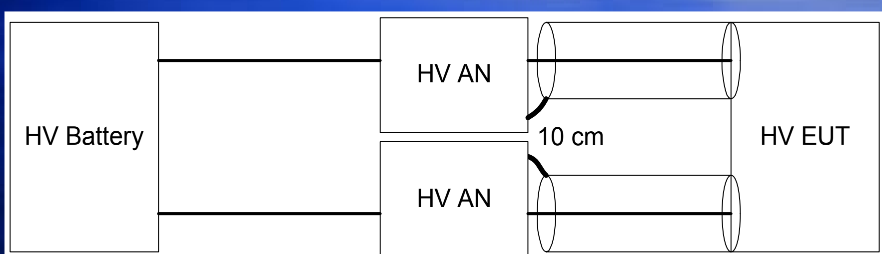
HV AN Test Configurations*



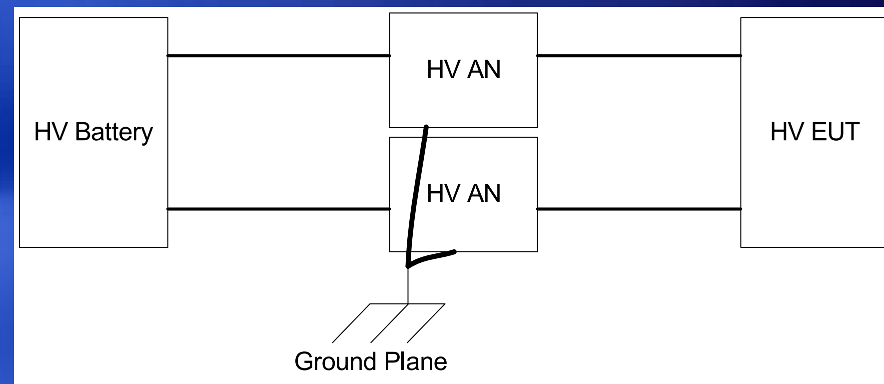
Test 1



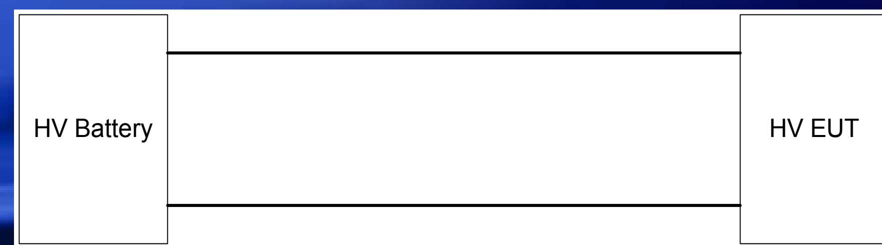
Test 2



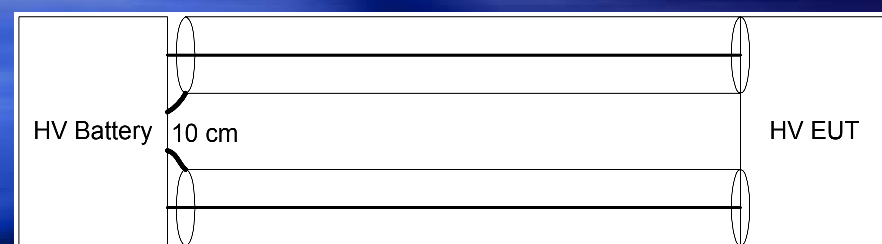
Test 3



Test 4



Test 5



Test 6

***HV Battery and HV EUT grounded in all tests.**

HV AN Test Configurations Example

Test 1

HV AN Test Configurations Example

Test 2 & 3

HV AN Test Configurations Example

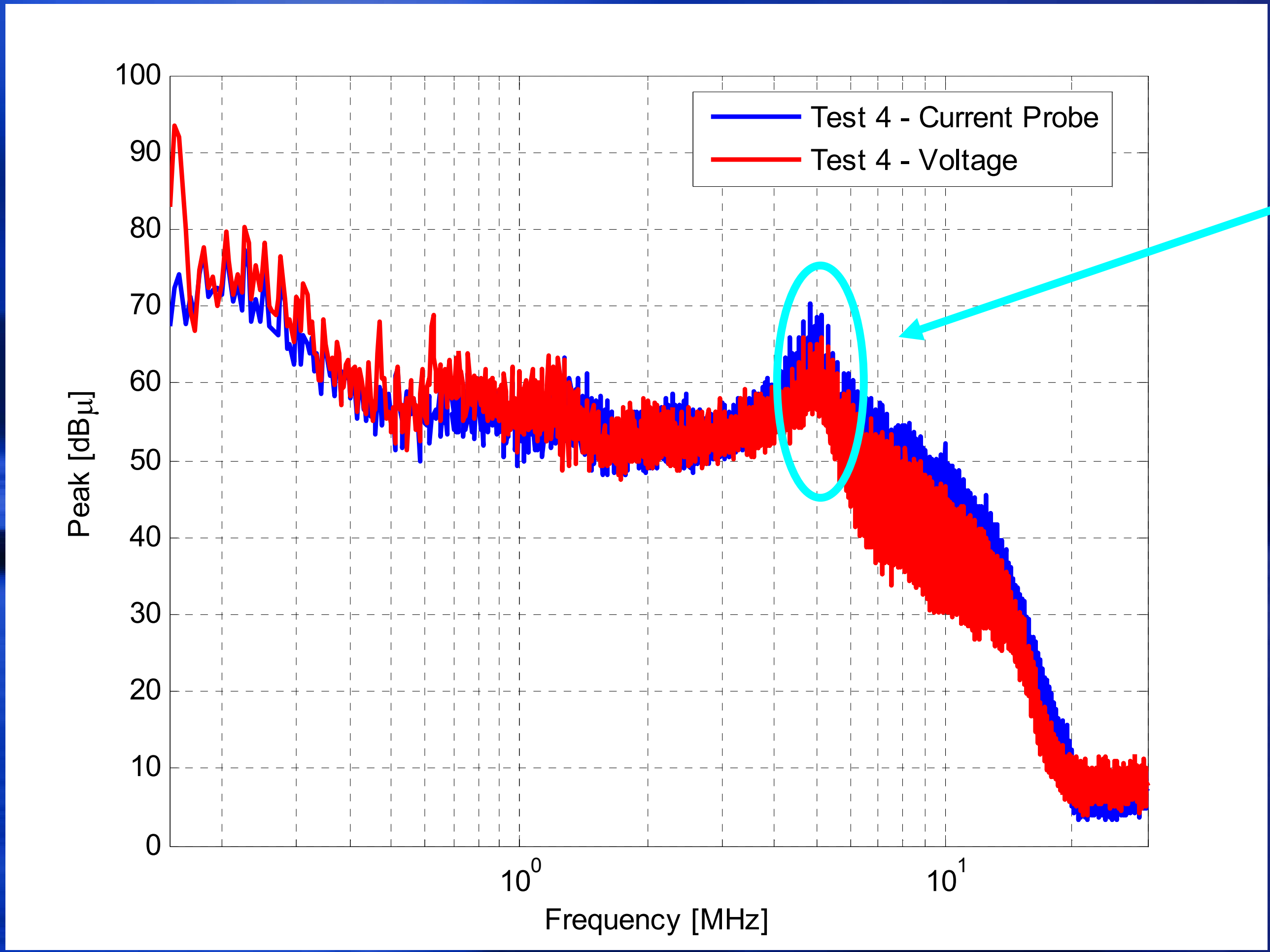
Test 1, 2, & 3

Test 4

Current Probe vs. HV AN Voltage

Test 4 (Unshielded Cables)

Current probe (+34 dB shift) and HV AN produce similar waveforms

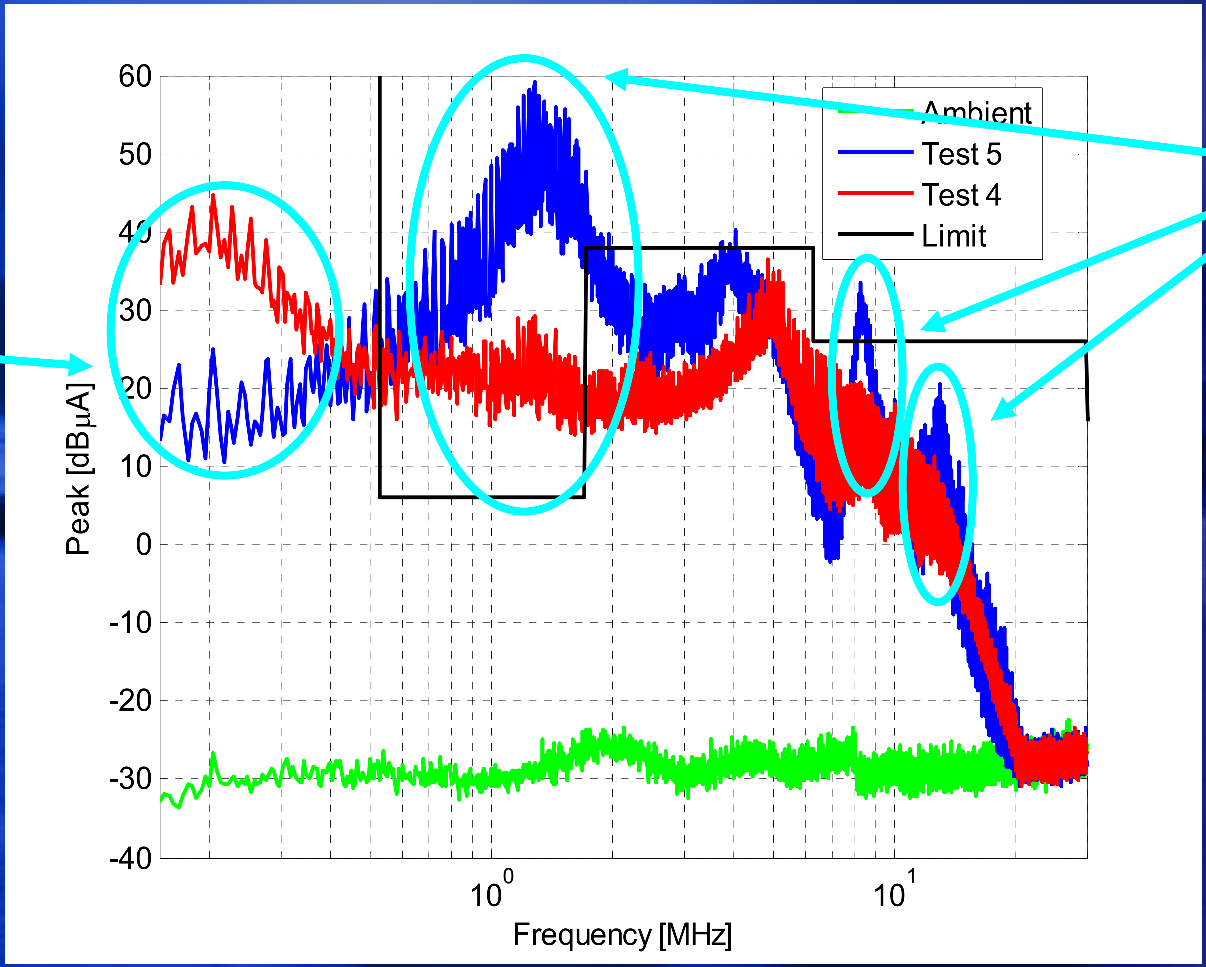


Created by power switch slew rate of approximately 1500 V/µs

Current Probe – HV AN Influence

Test 4 (Unshielded with AN) vs. Test 5 (Unshielded without AN)

Increased noise due to AN 1 µF capacitance connection to ground plane which completes CM path from inverters through motor stray capacitance



Noise path is through HV battery Y-capacitance (stray or intentional)

Reduction due to additional capacitance on HV battery side, AN with ground connection, or shielding.

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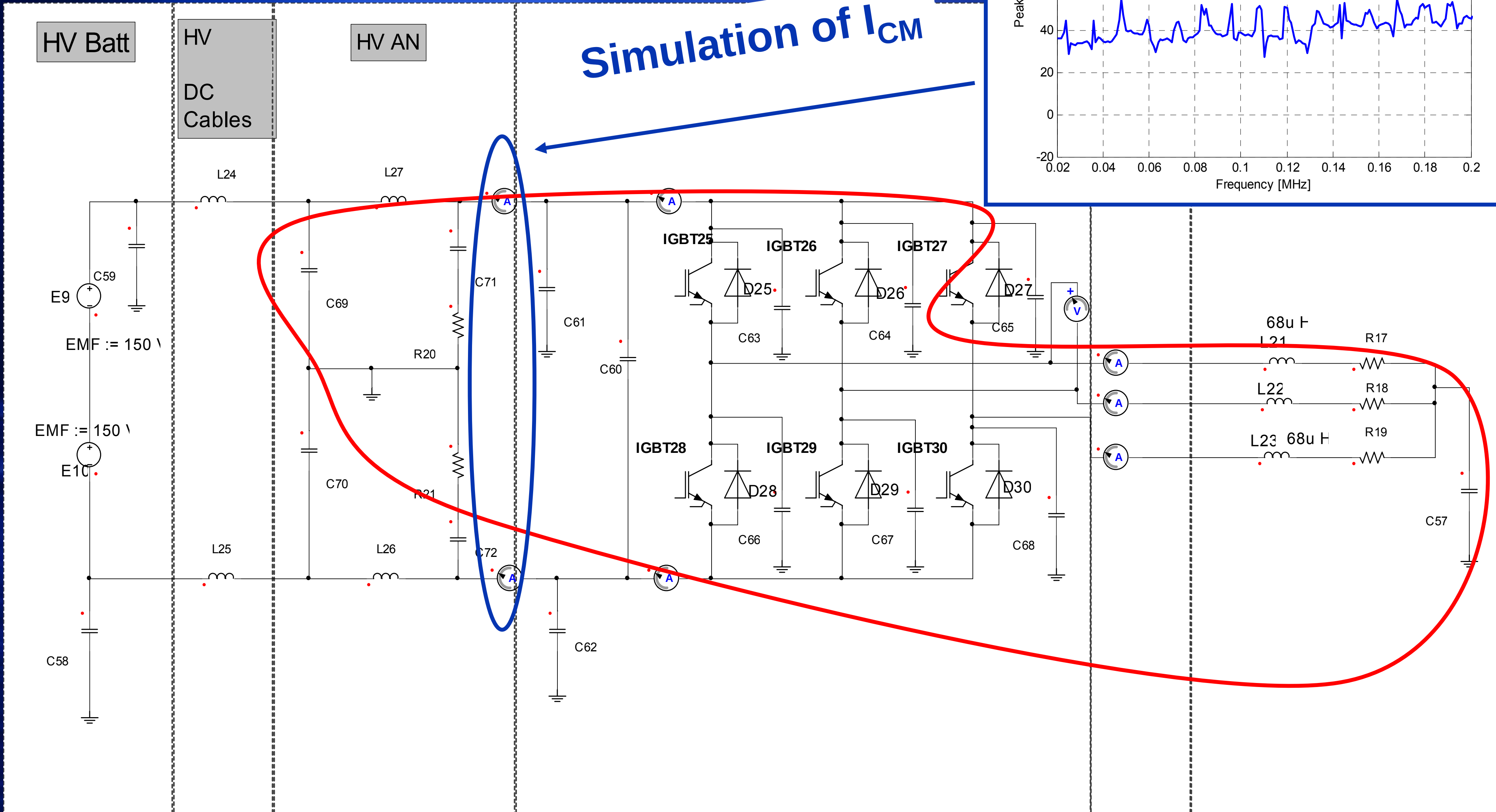
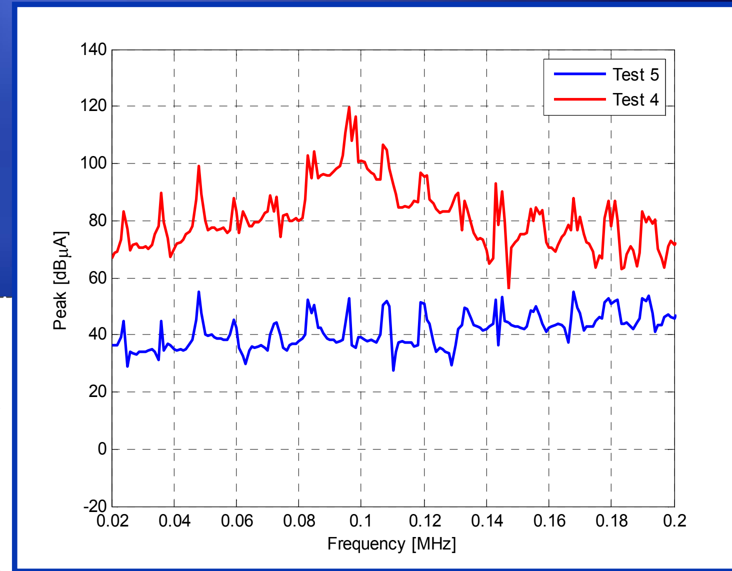
Simulation of 1 µF Effects

Test 4

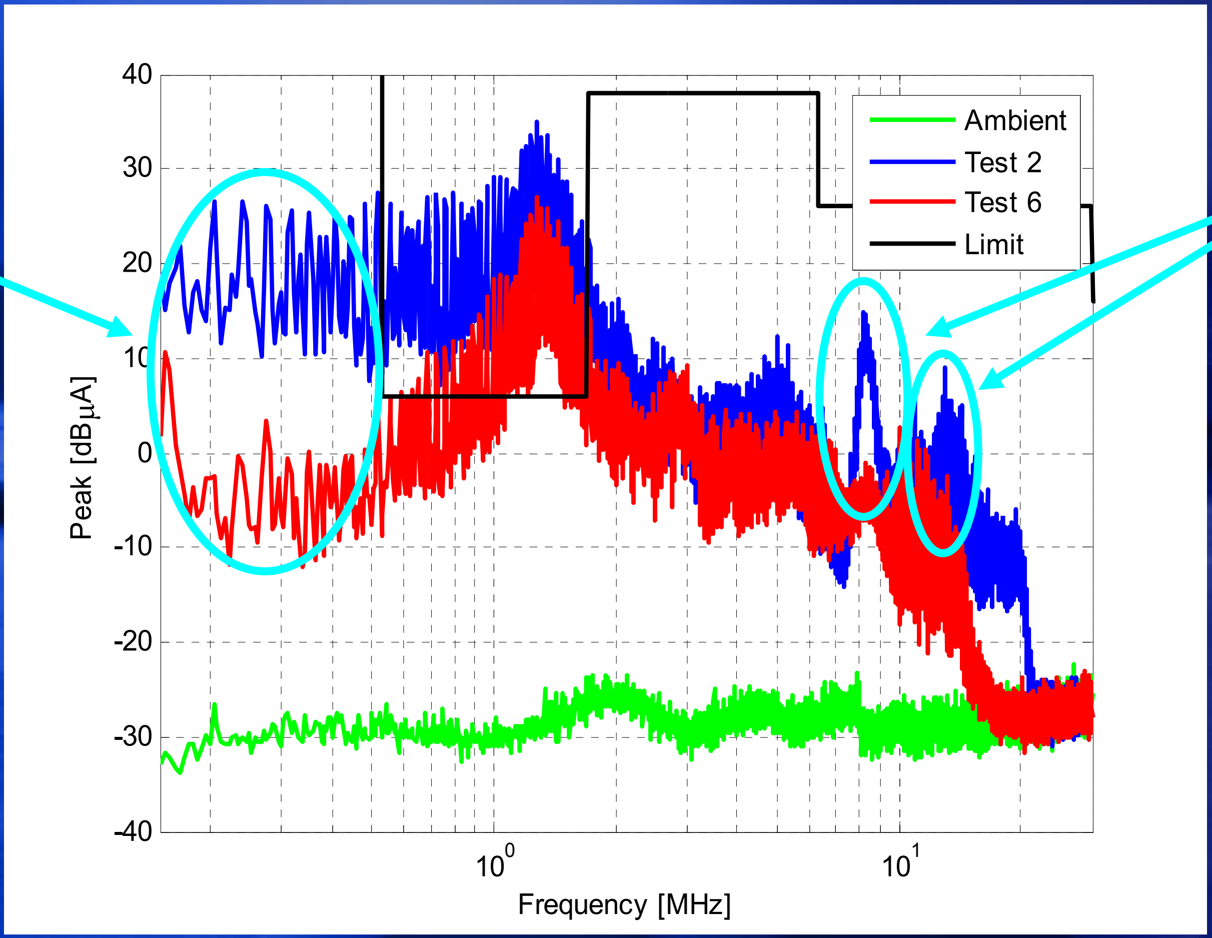




Current Probe – HV AN Influence

Test 2 (Shielded with AN) vs. Test 6 (Shielded without AN)

Same as previous, increased noise due to AN 1 µF capacitance connection to ground plane (through shielding connections to HV battery and HV DUT which are grounded)

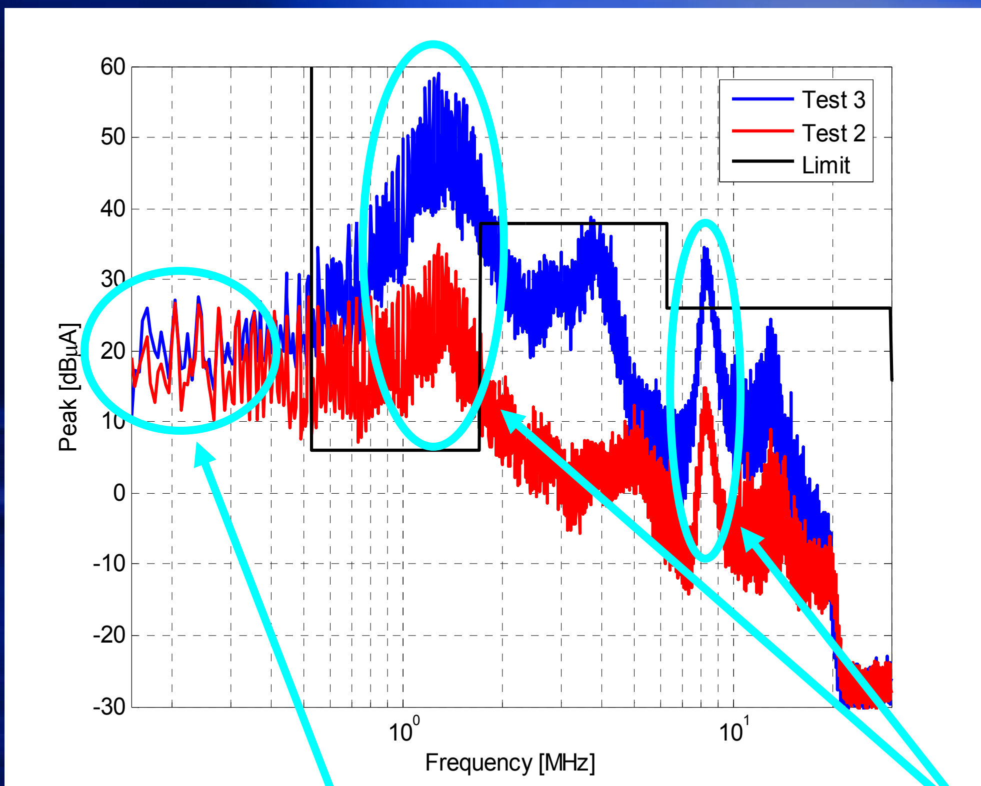


Noise appears due to non-ideal shielding terminations

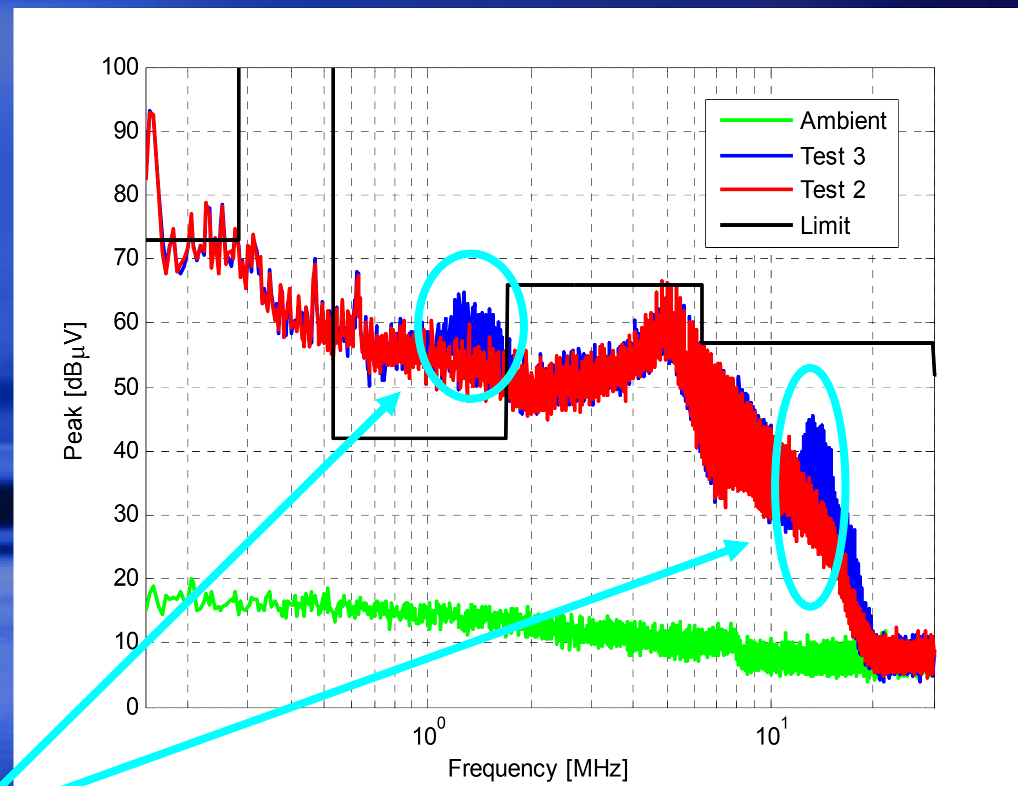
HV Battery Shield

Test 2 (With Batt Cable Shield) vs. Test 3 (Without Batt Cable Shield)

Current Probe



HV AN Voltage



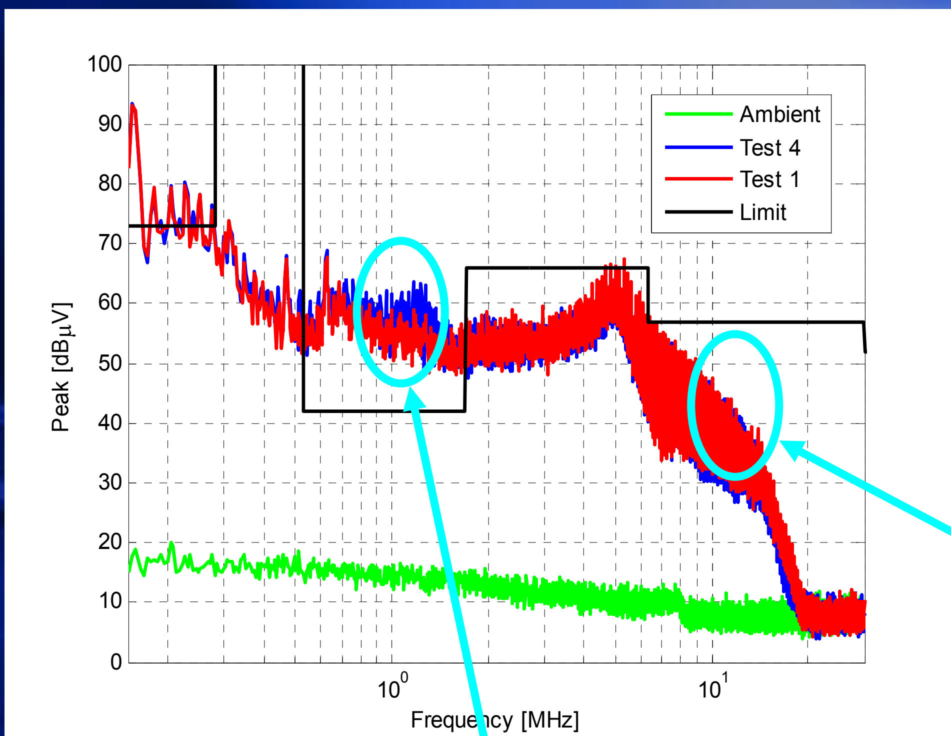
Same since path between motor stray capacitance is same

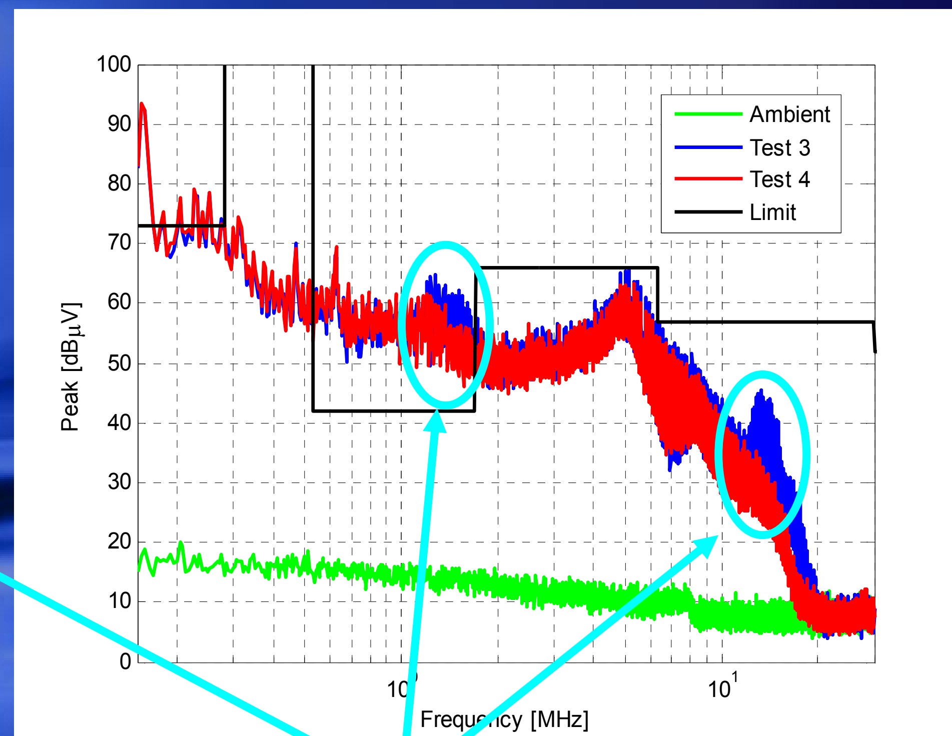
Attenuation due to cable shield and Y-capacitance between HV battery and AN

HV AN and Shielding Influence

Test 4 (No Shield, AN GND) vs. Test 1 (Full Shield, AN GND)

Test 4 (No Shield, AN GND) vs. Test 3 (Partial Shield, AN ISO)





Attenuation due to cable shield between HV battery and AN

Noise reduction due to grounding of AN which provides additional Y-capacitance to HV battery side

Summary of Experimental HV AN Tests

- "Grounded" HV AN affects results:
  - The 1 μF capacitor creates a current loop from electric machine stray capacitance
  - The 1 μF capacitor creates a current loop from HV battery Y-capacitance

- Cable shields and their connections impact the results

- AN inductance has smaller impact than the AN capacitance

- Most comparable to real vehicle configuration (Test 6 with shielded cables) is configuration with AN isolated and shielding on both sides (Test 2); however, shielding terminations are critical for higher frequency and 1 μF negatively impacts lower frequency band.

Comments for New HV AN

1. Provide a defined impedance over a given frequency range at the power terminals of the equipment under test (EUT)
   - Impedance of shielded cable and HV battery should be considered.
   - Shielding connections should be same as for vehicle.
2. Allow for the disturbed voltage to be measured
   - Need to protect test equipment from potentially high CM voltage pulses. Depending on configuration, can be 100's of Volts DC.
3. Isolate the EUT from undesired power supply disturbances
   - Use actual battery or build HV battery pack from series Lead-acid batteries. Then isolating power supply is not required.

Items for Future Study

Consists of both testing and simulation:

- Construct matrix of different shield termination methods and impact upon CE measurements.
- Measure common mode current on external surface of shield due to non-ideal shield coverage.
- Analysis of effects due to complex impedance of sources and loads.

Conclusion of Study

- Based on experimental and simulation results:
  - It is not recommended to use an AN as defined by CISPR for HV conducted emissions voltage validation.
  - It is not recommended to use an AN as defined by CISPR during current probe measurements on HV lines.
- HV AN can be useful for development and simulations.
- A new AN for HV applications should be defined if HV conducted emissions voltage validation is required.

Final Remarks: New Systems – New Questions !

Can measurement of CE be used for these types of systems?

Are there other EMC test methods that need to be reviewed for HV systems of the new generation of vehicles?

Should a new standard be created for HV CE measurement methods and required performance levels?