Year-In-Review: Relationships and Interactions Between ESD and EMC

Alan Righter
Analog Devices
San Jose, CA

ESD and EMC Year-In-Review Outline

- Motivation
- Ways that ESD and EMI interact or are used together
- Recent Work - Literature Review
  - Relating ESD and EMC in Tests and Measurements
- IEC 61000-4-2 and related tests – impact of EMI on testing variability
- Summary

Year in Review Motivation

- It is known that ESD events generate EMI, which can cause damage in devices beyond the ESD event itself.
- Much work in process to better understand the relationship between different ESD tests and EMI / EMC
- Including how EMC-centric tests such as transient and surge extend the realm of understanding effects on ESD devices and systems (boards).
- One example – the IEC 61000-4-2 test, different results between guns and pulsers, ICs versus systems, waveform description / characterization
- This Year-in-Review will review recent works in journals and ESD/EMC related conferences focusing on these topics

Ways that ESD and EMI Interact Or Are Used Together

- ESD events generating detectable EMI in manufacturing
- Commonalities of ESD and EMC Tests
- ESD Protection Impact on EMC Performance
- Issues with EMC Injection During System Level ESD
- Modeling of Different ESD and EMC Events
- Understanding System Level ESD Performance of TVS Diodes
- Issues with System Level ESD Testing of Components

ESD Events Generating Detectable EMI (1)

The Case for Measurement and Analysis of ESD Fields in Semiconductor Manufacturing

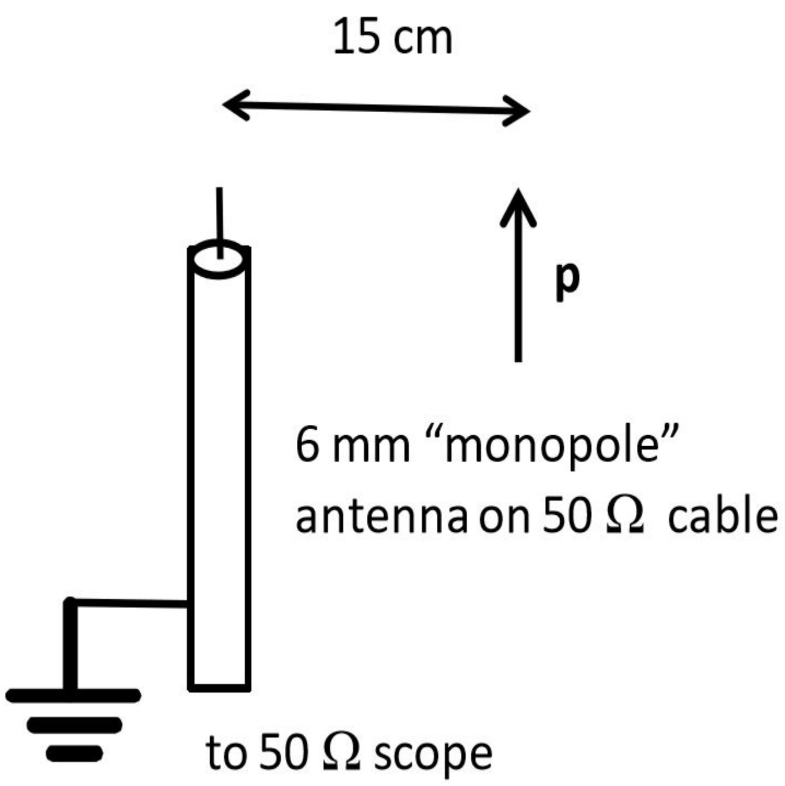
2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI)

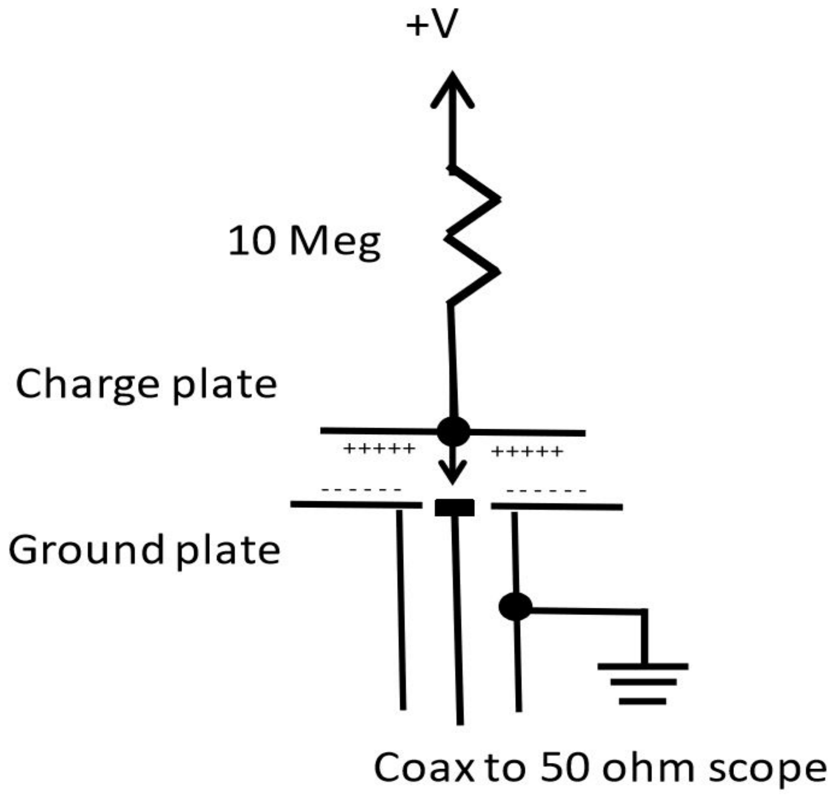
Authors: Tim Maloney, *Fellow, IEEE*

Abstract - **A destructive Charged Device Model electrostatic discharge event** can happen in semiconductor manufacturing and **should be detectable from radiation that results from collapse of an electric dipole.** The **analytically describable radiation field pulse of CDM** can be readily produced with **a new instrument (CDM Event Simulator or CDMES) that creates dipole collapse at will**. A coaxial monopole E-field antenna's transfer function gives the antenna signal in near-field, and experiments compare well with theory. These and other instruments for CDM ESD monitoring and process control are described in a newly-issued patent, reviewed here.

ESD Events Generating Detectable EMI (2)

- ❑ 6 mm "Monopole" Antenna and CDM pulse generator used to create source and detection method separately (US Patent 9671448, Maloney et al.)
- ❑ Can calibrate to different detection levels for manufacturing line CDM events





ESD Events Generating Detectable EMI (3)

- Pulsed Hertzian dipole theory used to develop equations for electric field and antenna response to E-field from ESD-induced EMI events (ref. [5] in paper).
- Derives the “equatorial” polar E-field E_θ, aligned with the current source and electric dipole moment vector (z-direction), as this induces the largest signal in the antenna. In the s-domain:

$$E_\theta(s) = \frac{I(s)\sin\theta}{4\pi\varepsilon_0 s r^3} dl \cdot (1 + s\tau + s^2\tau^2), \tau = \frac{r}{c}$$

where polar angle T = θ/2 at the equator, r = distance from the source,

c = speed of light, dl = length of the dipole.

- A signal is generated as the E-field induces an electric dipole in the antenna tip, driving the 50-ohm load.

- Ref. [5] in paper: T.J. Maloney, "Easy Access to Pulsed Hertzian Dipole Fields Through Pole-Zero Treatment", cover article, IEEE EMC Society Newsletter, Summer 2011, pp. 34-42. See http://ewh.ieee.org/soc/emcs/acstrial/newsletters/summer11/index.html

ESD Events Generating Detectable EMI (4)

A simple circuit model gives the transfer function of such an antenna (ref. [12] in paper), and it can be derived from information in refs. [3-5] in paper to give measured voltage V_m as

$$\frac{V_m(s)}{E_{-z}(s)} = -\frac{l_m Z_0 C_m s}{1 + Z_0 C_m s + L_m C_m s^2}$$

Z_0 = cable impedance (usually 50 ohms)
C_m and L_m are the inductive and capacitive equivalents resp. of the probe wire

l_m is the length of the probe wire

field $E_{-z} = E_0$ when maximum at the equator, $\theta = \pi/2$

ESD Events Generating Detectable EMI (5)

- Measured current and antenna response from defined antenna 15 cm away from event, 3 GHz BW scope

current

-0.496 A max

-166.4 pC

antenna, 15 cm

125 mV =Vp-p

1.664 pF

-100V pulse

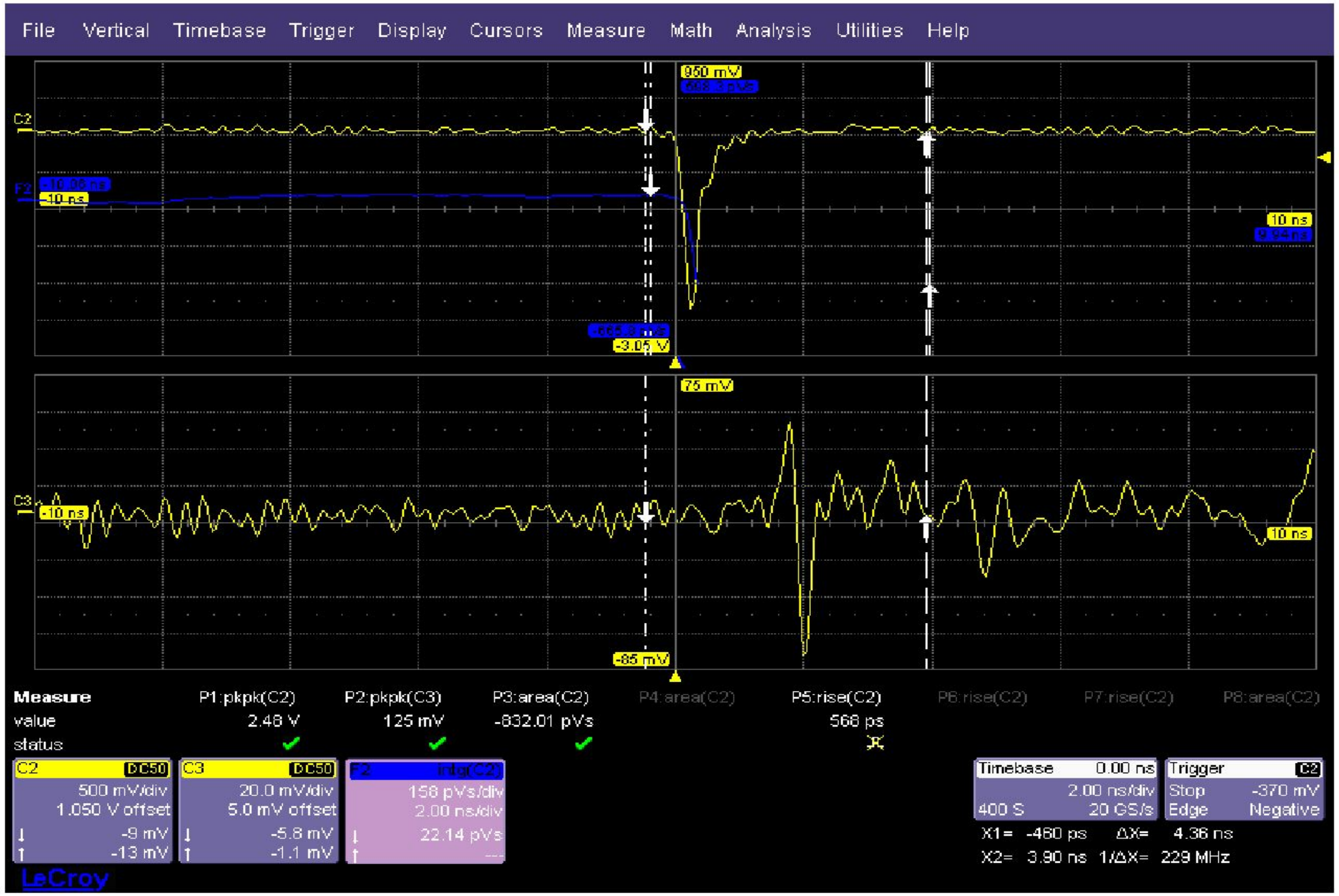
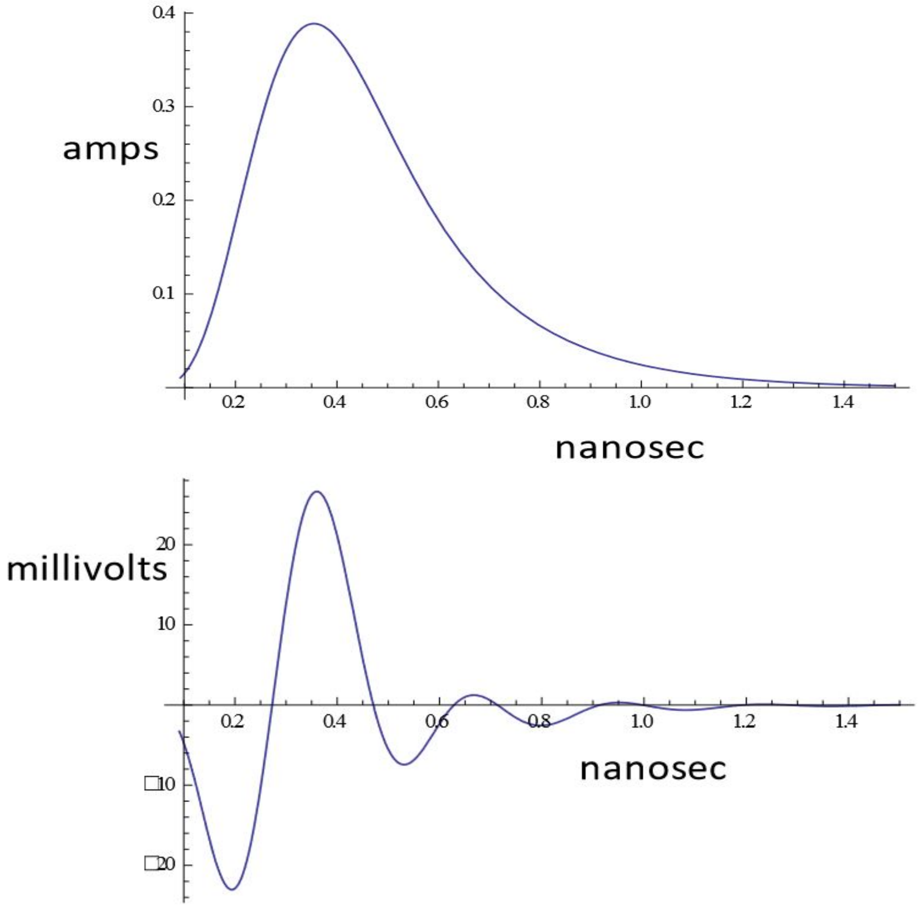
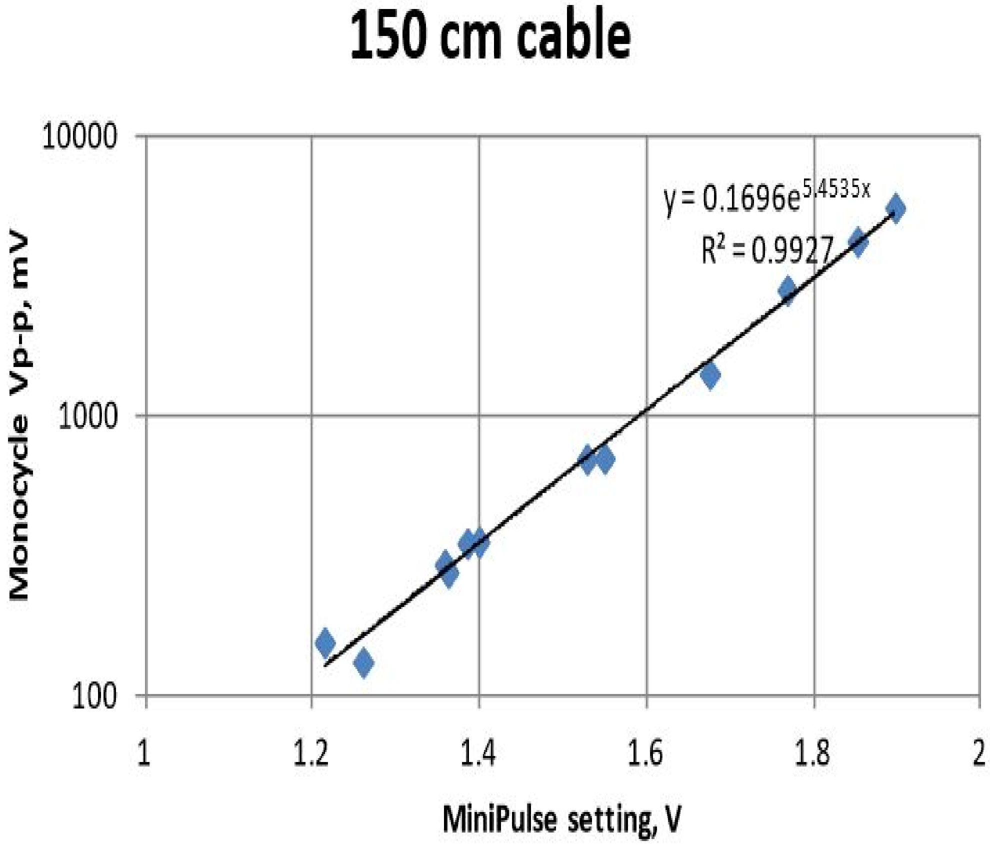


Fig. 3. Measured current (top) and antenna response (bottom) to E-field at 15 cm, using artificial CDM source; 2 nsec/division, 3 GHz scope. Setup as in Fig. 1, current polarity negative. Integrated current gives -166.4 pC of charge; 10x attenuation used.

ESD Events Generating Detectable EMI (6)

- CDM current pulse approximated from previous measured current pulse
- Calculated antenna response shows excellent agreement to measured data





Commonalities of EMC and ESD Tests

Relating the Commonalities and Robustness Characteristics of EMC and ESD Tests

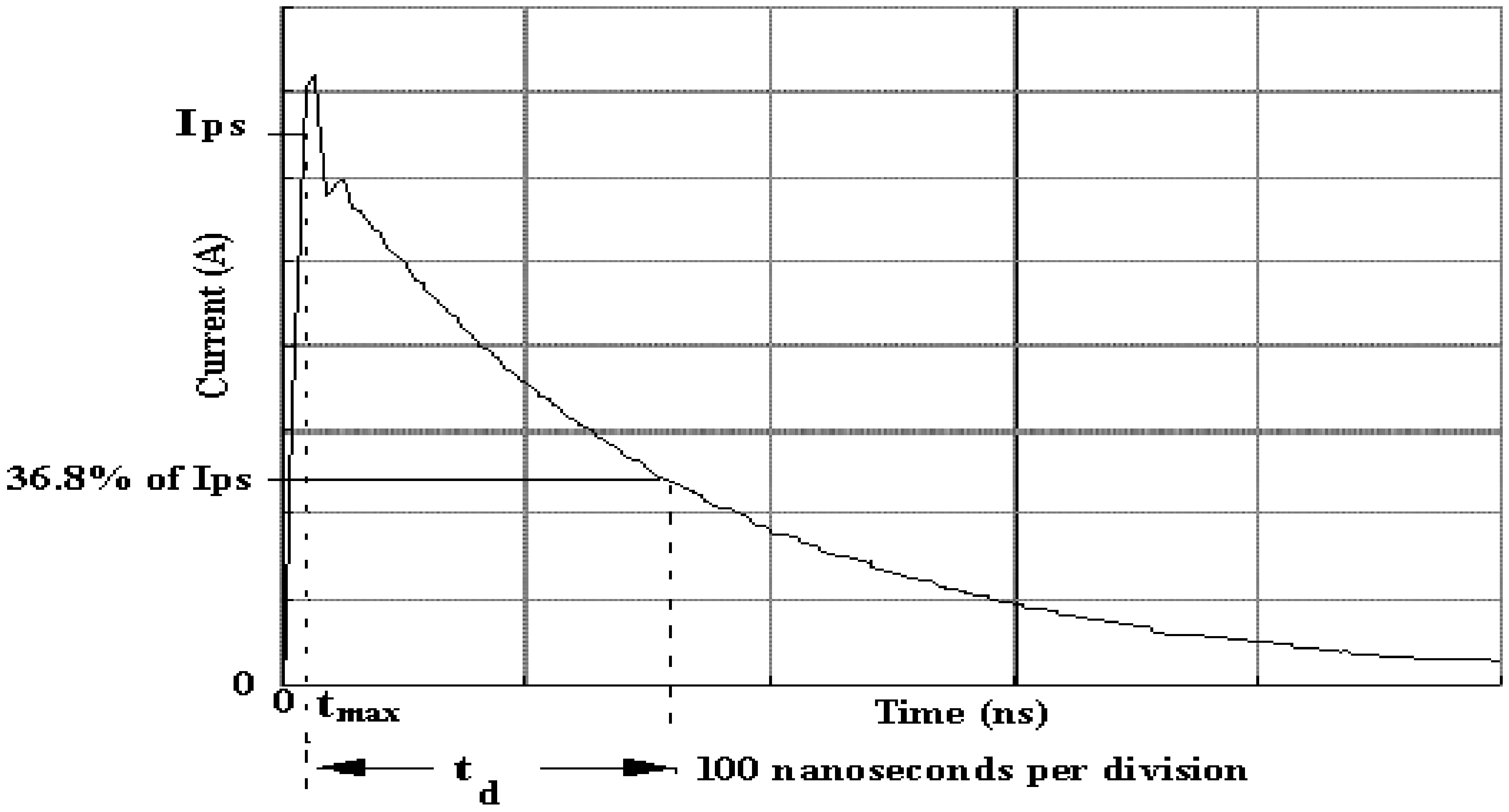
2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI)

Author: Alan Righter, *Analog Devices*

- ❑ Components and systems must be qualified in terms of a set of electrical robustness characteristics.
- ❑ **The various test methods of ESD and EMC will be related in terms of their application to various electronic entities, certain robustness environments and energy profiles, and transport / interaction with electronics.**
- ❑ These include but not necessarily be limited to **HBM and CDM component level, IEC 61000-4-2, -4-4, -4-5; ISO 10605, and ISO 7637-2 and -3**.

Commonalities: Human Body Model (HBM)

HBM ESD Current Waveform into a Short-Circuit:

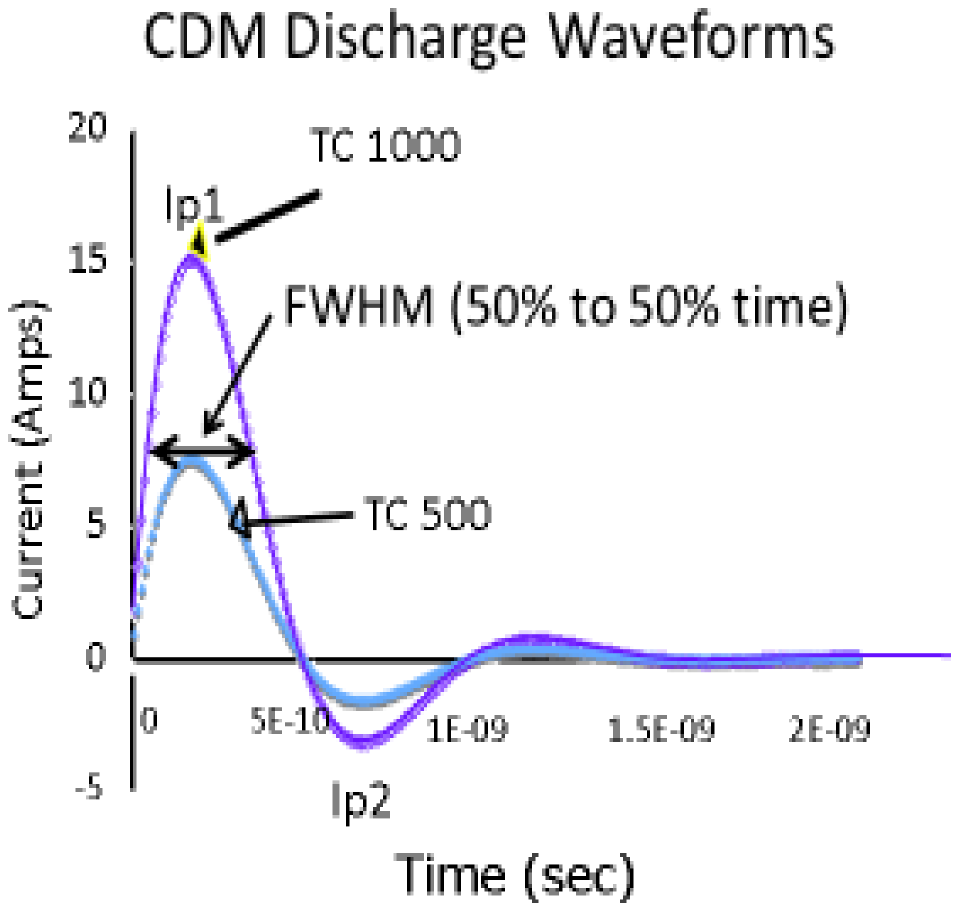


Commonalities: Charged Device Model (CDM)

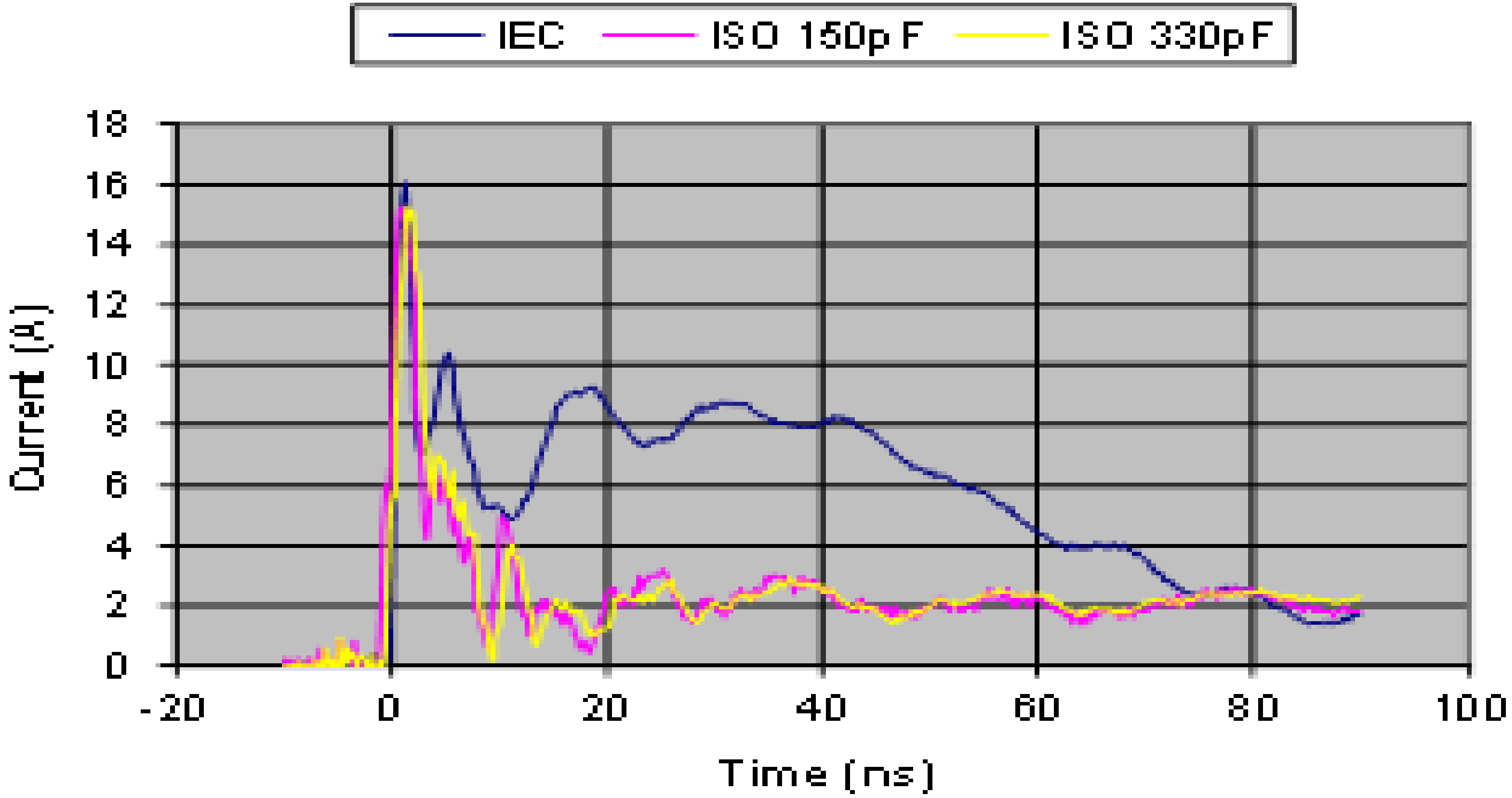
CDM Event - Current Waveform

CDM Event:

1. Very Fast rise times (< 100-400 ps)
2. Extremely high first peak (Ip1) currents (> 3-15 Amps)
3. Short pulse duration (< 1 ns pulse width)
4. Full width at half height (FWHM)



4 KV ISO 61000-4-2 Compared to ISO 10605 Waveforms of 150 pF / 330 pF Capacitances

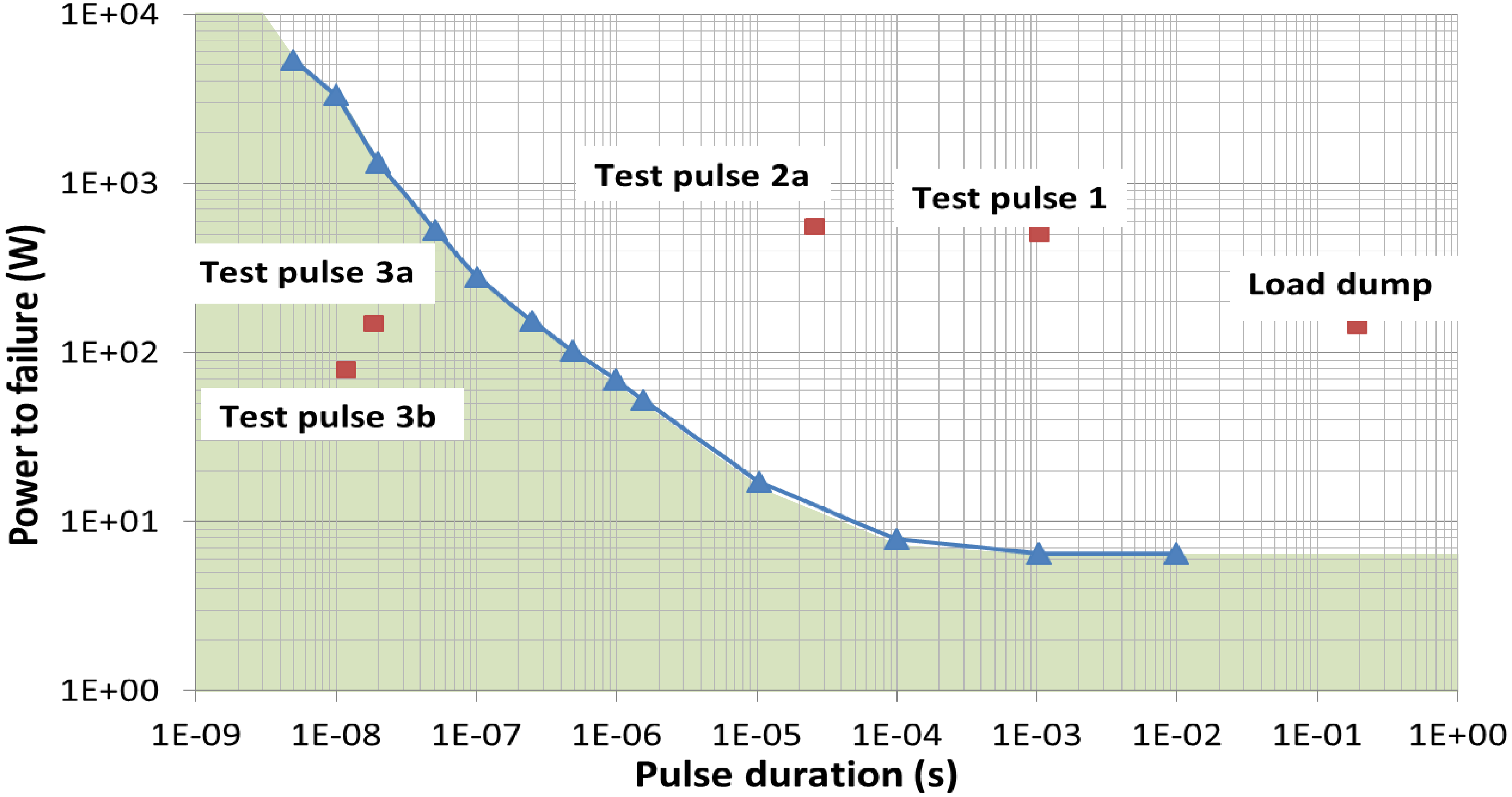


- **ISO 150pF and 330 pF simulate different automotive ESD environments**

Automotive Transient Charge Multiple Relation

Standard	Application	V [Volts]	Duration (10-90%)	Ipeak [A]	Charge	Charge multiple of 61000-4-2
IEC 61000-4-2	System	8k	120ns	~33	1.2 µC	1
ISO 7637: 1	System	~150	~2ms	~15	20 mC	1.6 E+4
ISO 7637: 2a	System	~112	~50µs	~56	0.5 mC	4.2 E+2
ISO 7637: 3a	System	~220	~150ns	~4.5	300 nC	0.25
ISO 7637: 3b	System	~150	~150ns	~3	200 nC	0.16
ISO 16750-2 (load dump)	System	~101	~40-400ms	~50	1.7 C	2.1 E+6

Calculated Peak Power Values Related to Automotive Transient Pulses of LDMOS



ESD Protection Impact on EMC Performance (1)

Impact of ESD Strategy on EMC Performances - Conducted Emission and DPI Immunity

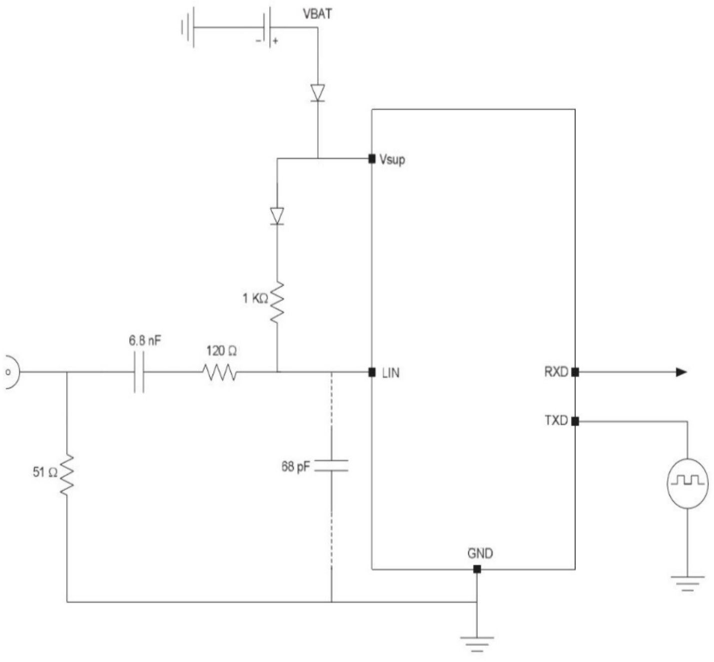
EMC Compo 2011 - 8th Workshop on Electromagnetic Compatibility of Integrated Circuits, November 6-9, Dubrovnik, Croatia

Authors: K. Abouda, P. Besse and E. Rolland

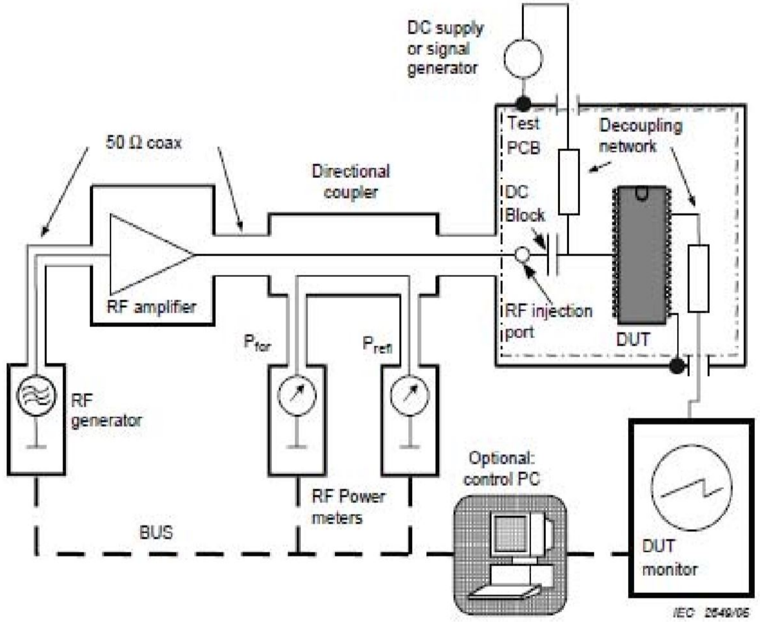
- System-level stresses such as EMC stress (Direct Power Injection, Bulk Current Injection, and Radiated Field) and ESD gun stress are directly applied to ICs with no external protections.
- The ESD strategy / ESD protection architecture significantly impacts EMC performance
- Simulation of functional performances during EMC and ESD events very challenging for analog products over frequency domain, regarding high injection mechanisms.
- This paper describes two case studies where ESD protection impacted the conducted emission (CE 150ohm: first case study) and the conducted immunity (DPI: second case study) performance. Failure mechanisms are explained / design optimizations fixing EMC issues (as measured) will be presented.

ESD Protection Impact on EMC Performance (2)

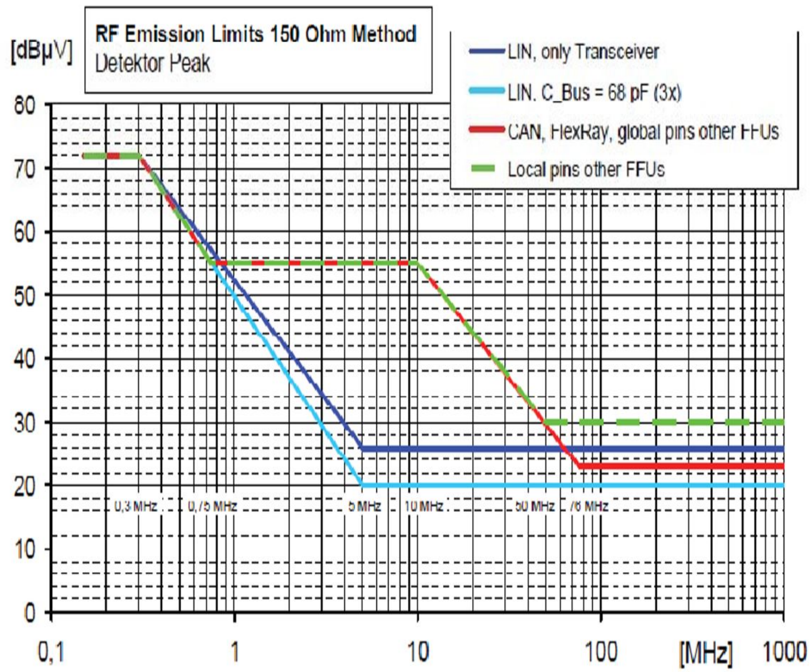
LIN conducted emission setup



DPI injection setup



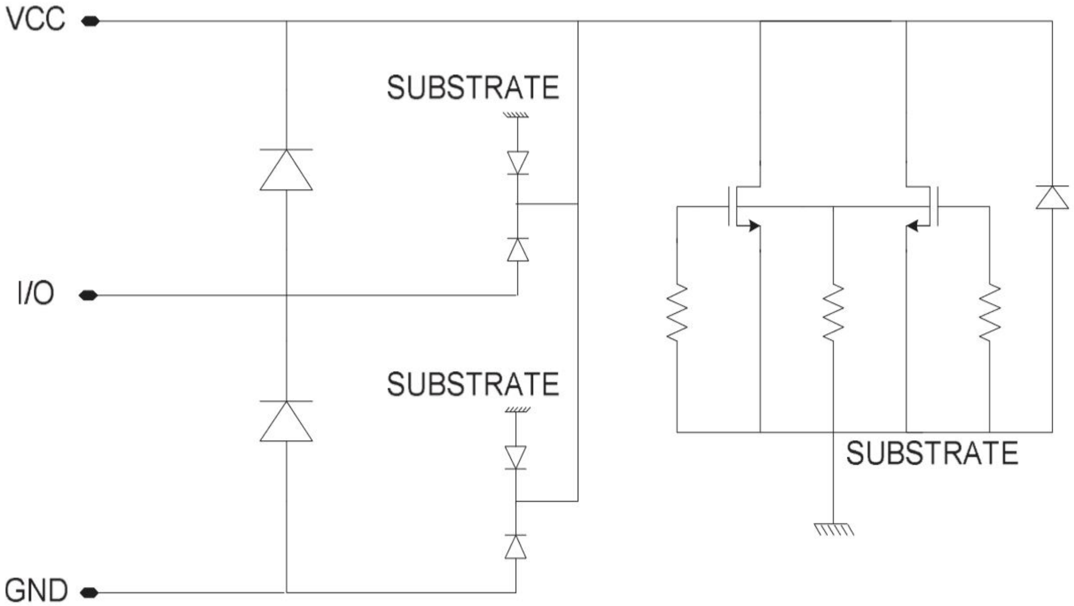
Emission Profile

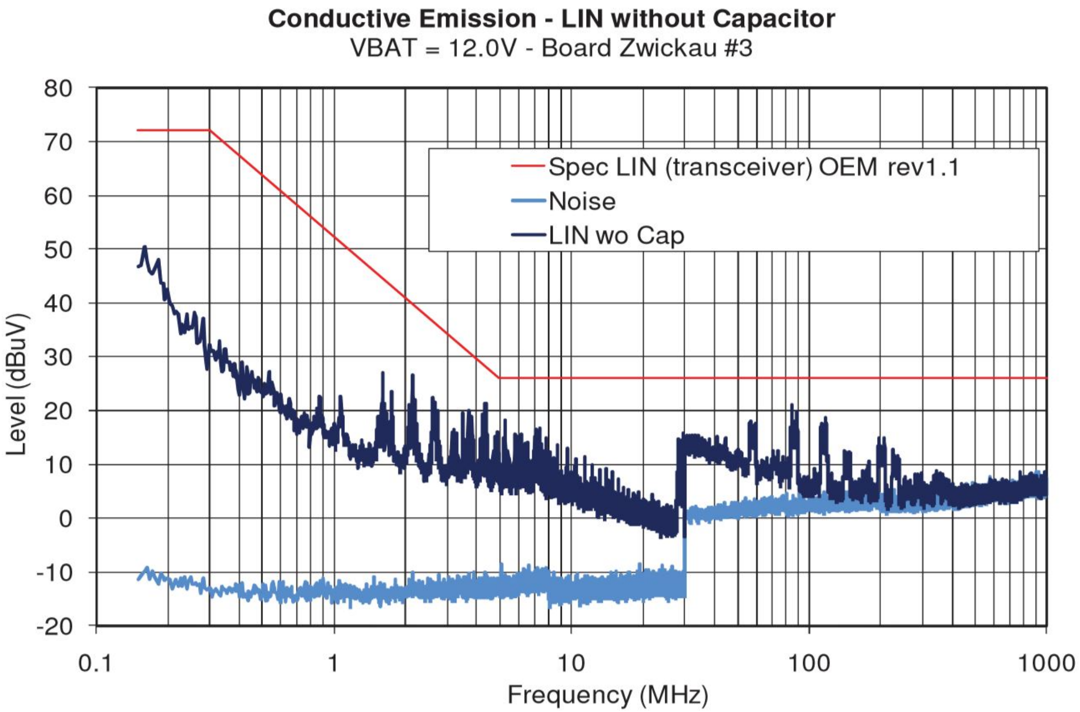


- Three case studies involving LIN architecture, test setups / simulation models for IEC and DPI to predict response / compare with measurement

ESD Protection Impact on EMC Performance (3)

- TV2 case study - ESD protection effect on emission profile using dv/dt trigger clamp vs. junction breakdown clamp
- Adding low resistance between grounds reduced substrate noise injection, improving emission profile
- LIN pin secondary protection design must consider emission injection to substrate as well





Issues with EMC Injection During System Level ESD (1)

Systematic Evaluation of Soft Failures in System-Level ESD Transient Events

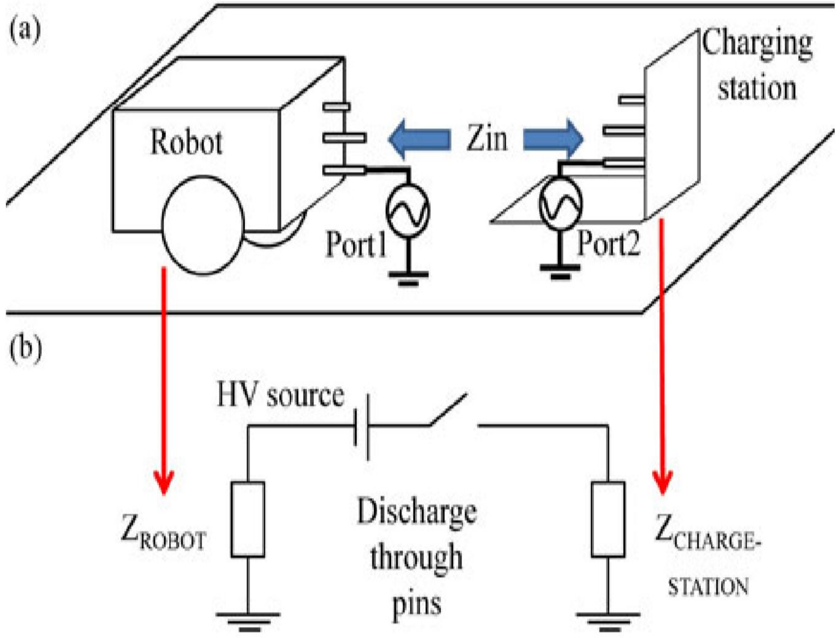
IEEE Trans. On Electromagnetic Compatibility, Vol. 60, No. 5, Oct. 2018

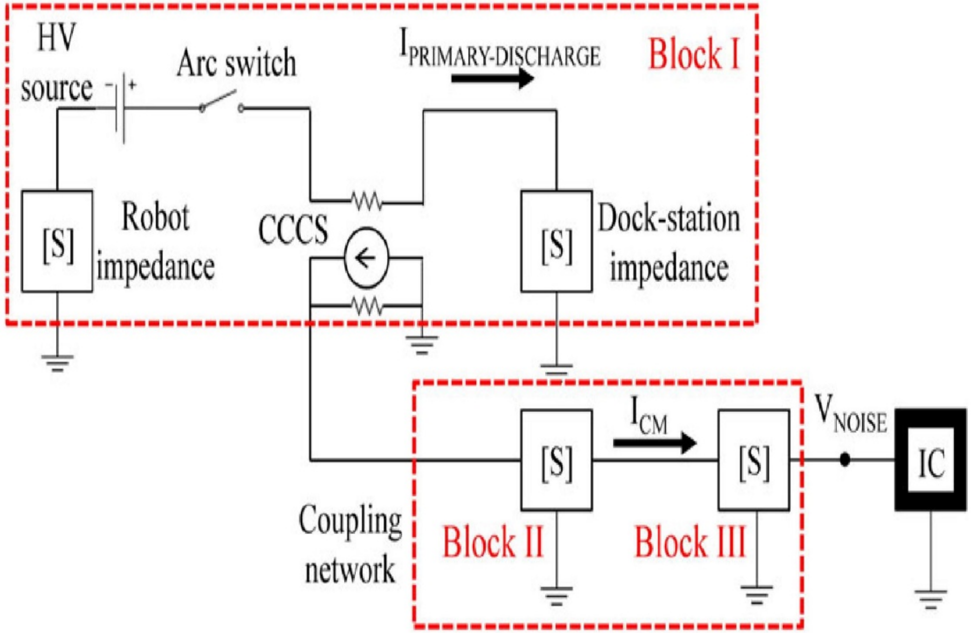
Authors: A. Patnaik, W. Zhang, R. Hua, L. Chuang, A. Huang, H. Lin , B-C. Tseng, and D. Pommerenke, Fellow, IEEE

- A human-assisting robot consisting of many subsystems such as sensors, display, motors, and control was created to assess impact of ESD on subsystems.
- This paper analyzed ESD events beginning at the robot tribo-charging through the sensor disruption.
- Based on the charge voltage, the discharge current is simulated using a simple switch model along with the loop impedance limiting the current.
- Discharge current coupling to the sensor is represented as S-parameters obtaining the noise voltage at the sensor.
- This noise voltage is compared to the sensor's noise sensitivity threshold to reproduce the disruptive event. The simulation model can help system designers assess ESD risks / efficiently design filtering networks.

Issues with EMC Injection During System Level ESD (2)

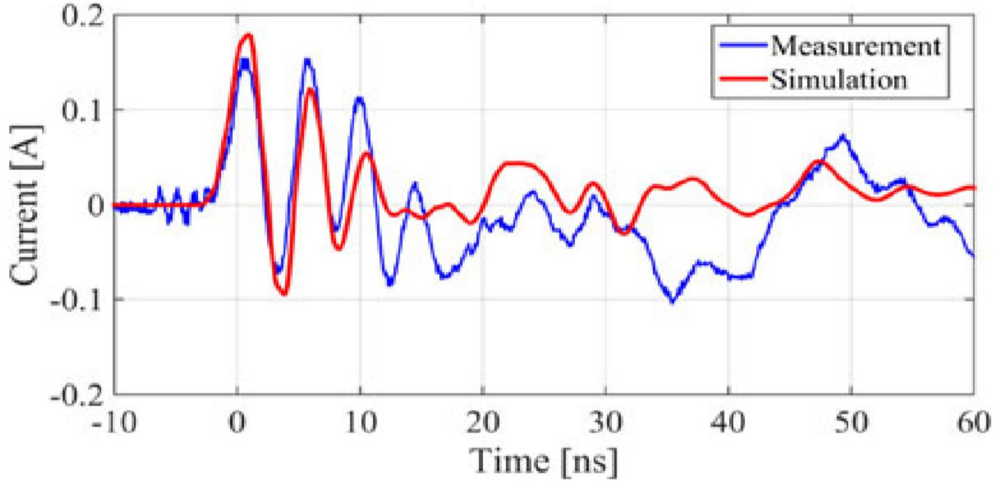
- "Human assisted robot" - Rolling wheels charge the robot - discharge occurs when it reaches the charging station
- 5 kV IEC 61000-4-2 -> 10 kV/m pulse @ 0.1m distance
- Fields couple into wires / traces -> noise injection -> soft errors
- Evaluated different materials for tribocharging / simulation of robot sensor actuation / soft failure

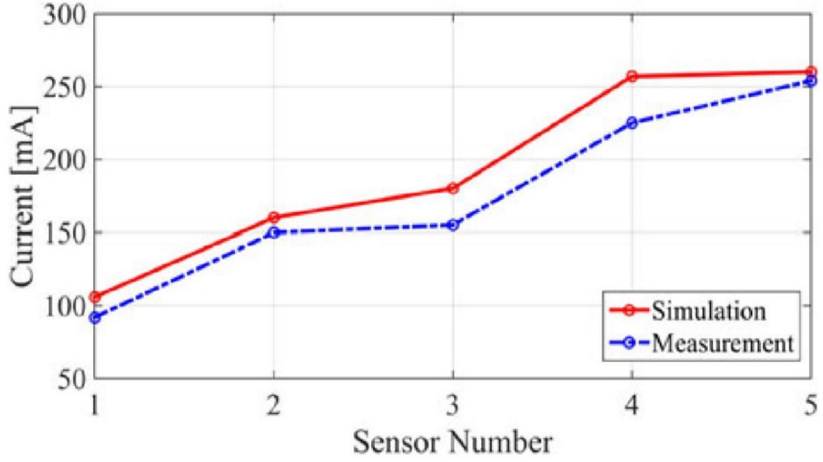


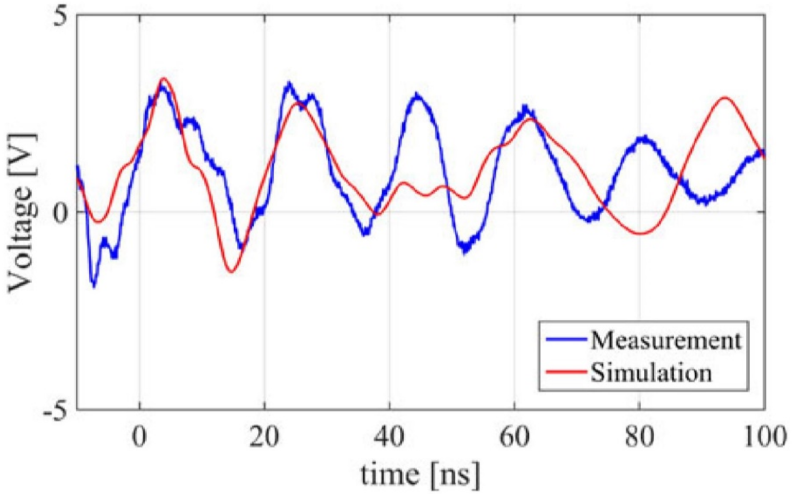


Issues with EMC Injection During System Level ESD (3)

- Five "sensor bundles" designed, to soft fail at different charging voltages
- Simulations showed good agreement with waveforms







Modeling of Different ESD and EMC Events (1)

Implementation Methodology of Industrial and Automotive ESD, EFT and Surge Generator Models which Predict EMC Robustness on ICs and Systems

2017 EOS/ESD Symposium Proceedings

Authors: C. Leveugle and T. Weyl, Analog Devices

Abstract - This paper presents a novel methodology to **develop and validate disturbance generator models for a virtual EMC lab**.

New simulation models for ESD, EFT and Surge stimuli were created and verified on a wide range of load conditions.

Modeling of Different ESD and EMC Events (2)

- ❑ Novel “disturbance generator” SPICE platform simulation models for IEC ESD, EFT, Surge to form a “Virtual EMC Lab”
- ❑ IEC 61000-4-2 Stimulus – Comparing TESEQ NSG438 Gun / Langer P331 Probe into different R, C loads

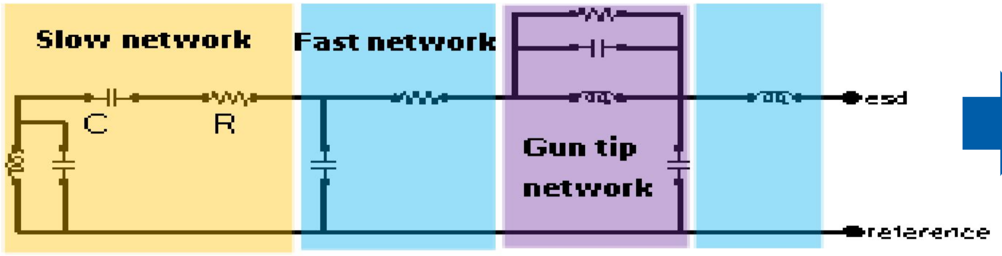
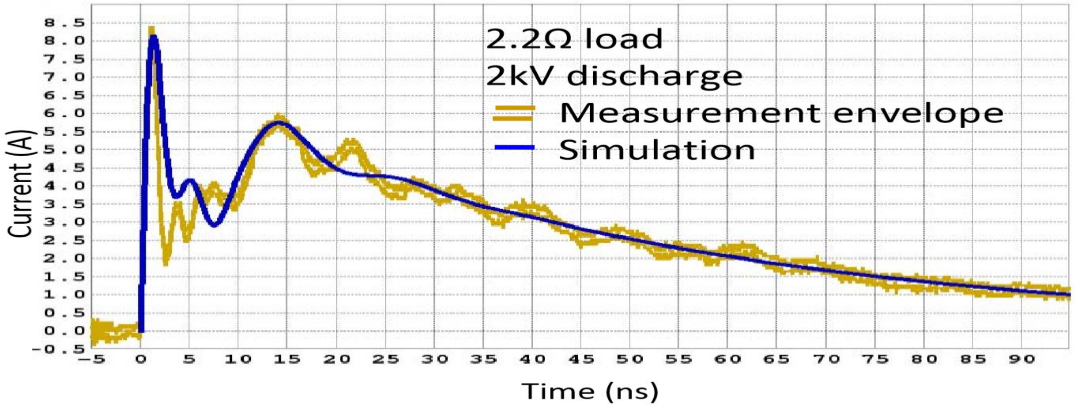


Figure 5: Simplified ESD TESEQ NSG438 gun model schematic.



The Langer probe model is shown in Figure 6.

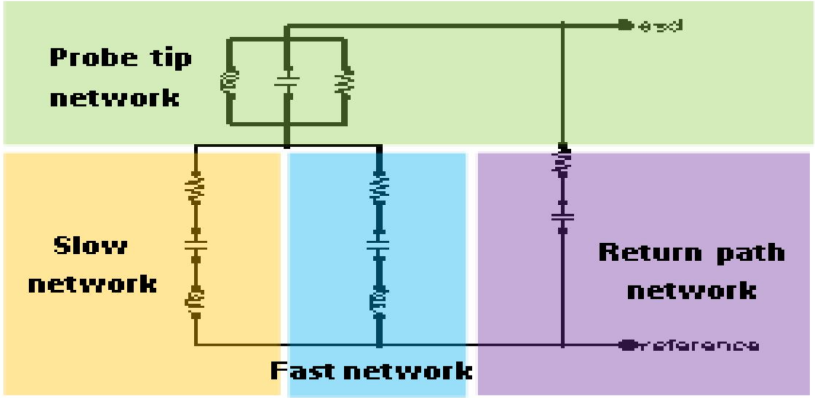
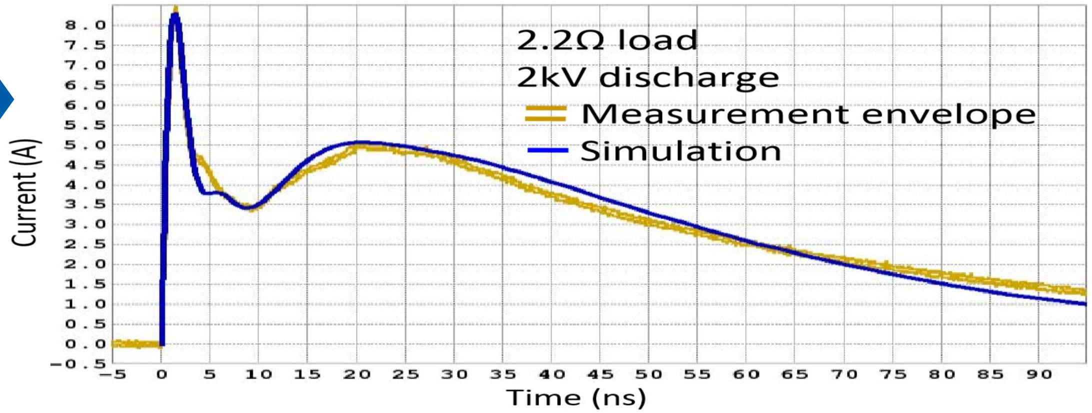


Figure 6: Simplified ESD Langer P331 probe model schematic.



Modeling of Different ESD and EMC Events (3)

- IEC 61000-4-4, ISO7637-2 / -3 Stimulus Schematic / Results

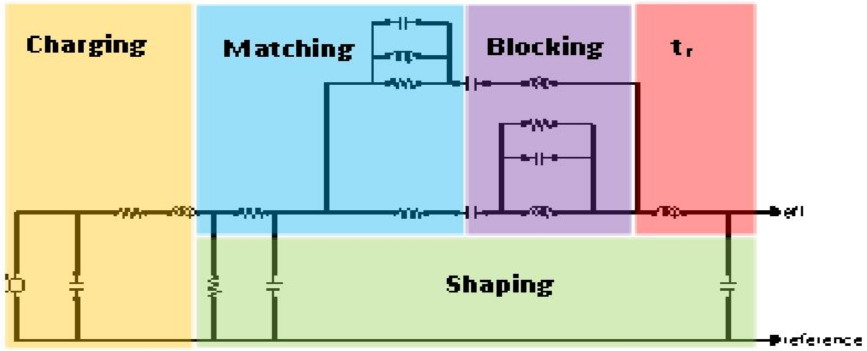
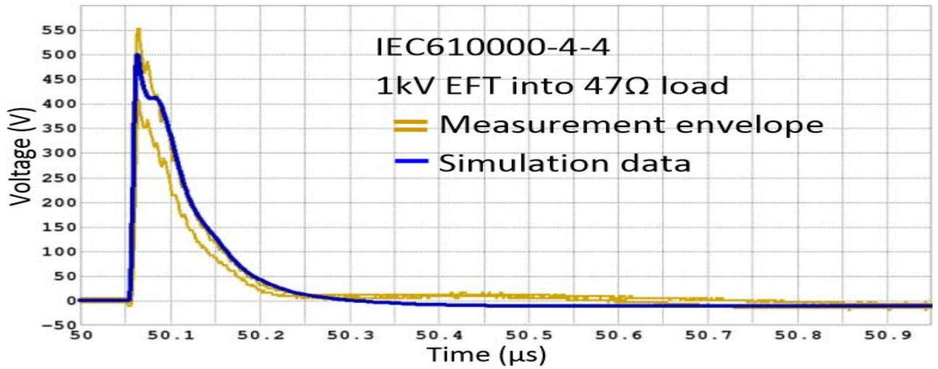


Figure 19. Simplified IEC61000-4-4 EFT generator model schematic.



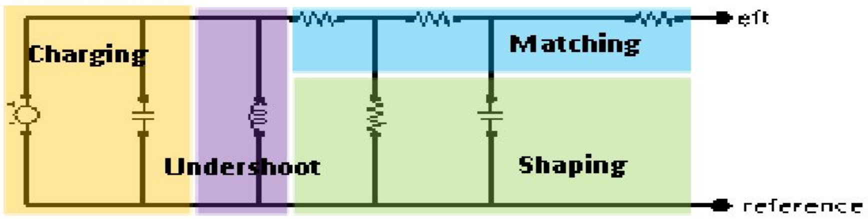
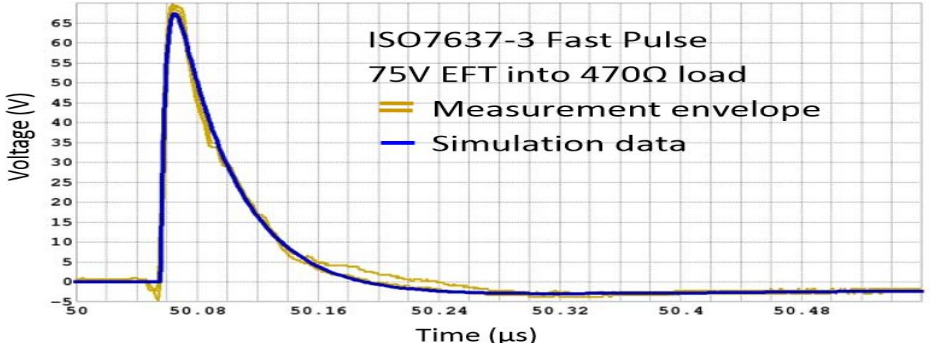
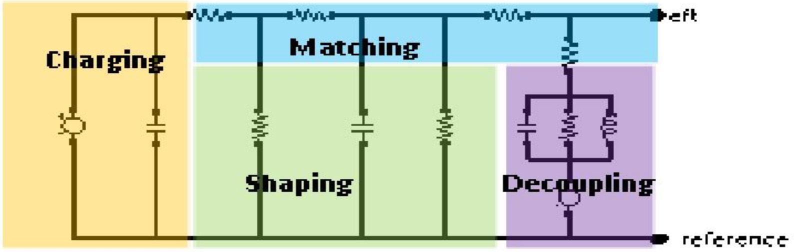
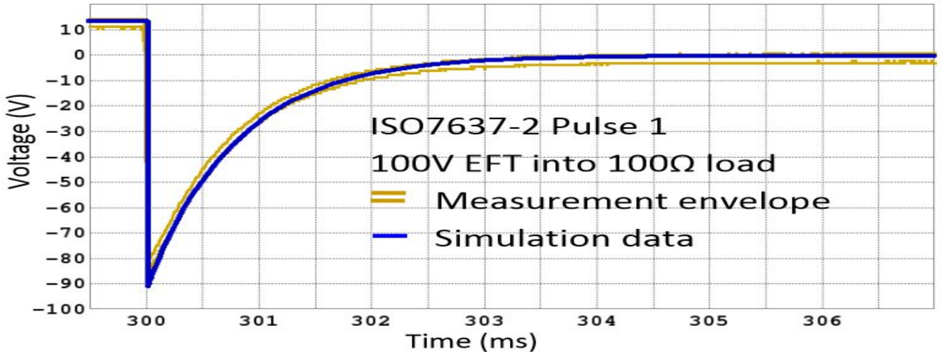


Figure 20: Simplified ISO7637-3 Fast EFT generator model schematic.

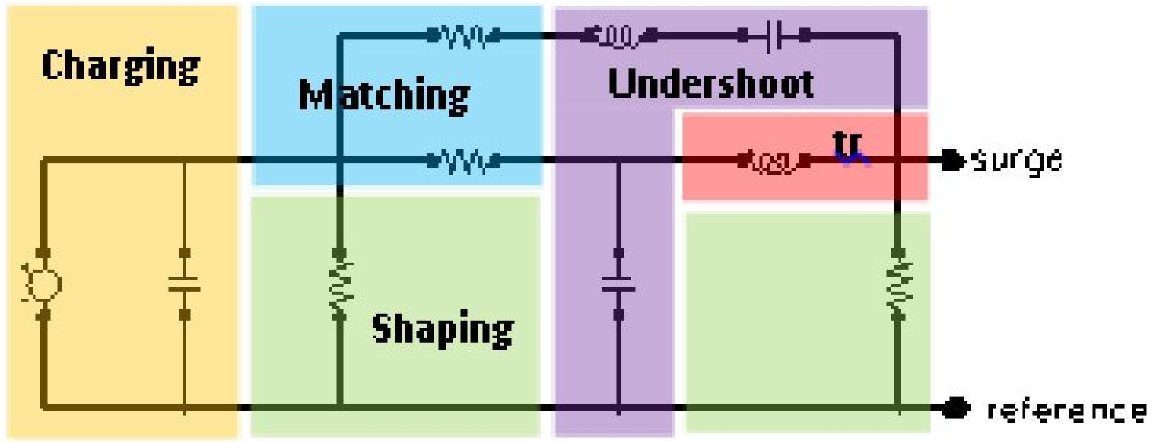


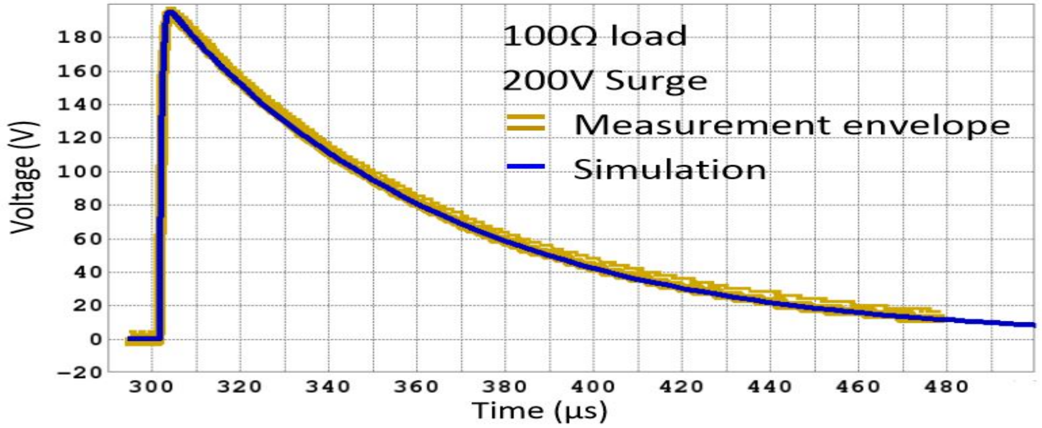


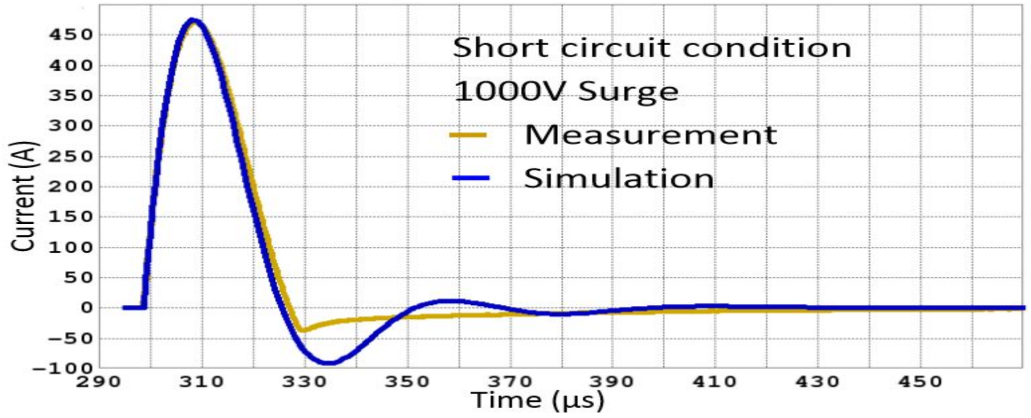


Modeling of Different ESD and EMC Events (4)

- Surge (IEC 61000-4-5) – Measurements performed using a TESEQ multifunction generator system NSG3040
- Currents measured using a TESEQ MD300 current probe – 100V into 100 ohms (upper), 1000V into short (lower)







Understanding System Level ESD Performance of TVS Diodes (1)

A Study on ESD Protection Characteristic Difference By Measurement of TVS Diodes by VNA

2017 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI)

Authors: T. Yoshida and M. Endo

- Protection performance of an ESD protection device changes when the device is implemented in a circuit at a system level.
- Additionally, the operating characteristics / protection performance of an ESD-protection device may differ from device to device even if the device specifications are the same.
- Develop evaluation / simulation method expressing realistic differences in the ESD-protection-performance of devices relying on TVS diodes.
- Protection characteristics of TVS diodes evaluated with a vector network analyzer - measured and compared four types of TVS diodes that have very similar specifications.
- Proposed method can express the differences between the four similar TVS diodes in terms of the attenuation of the pass frequency responses. In addition, the reproducibility of the measurement for different PCB patterns is also confirmed.

Understanding System Level ESD Performance of TVS Diodes (2)

- Evaluation and simulation method using VNA
- PCB and system connections (three different PCB types)

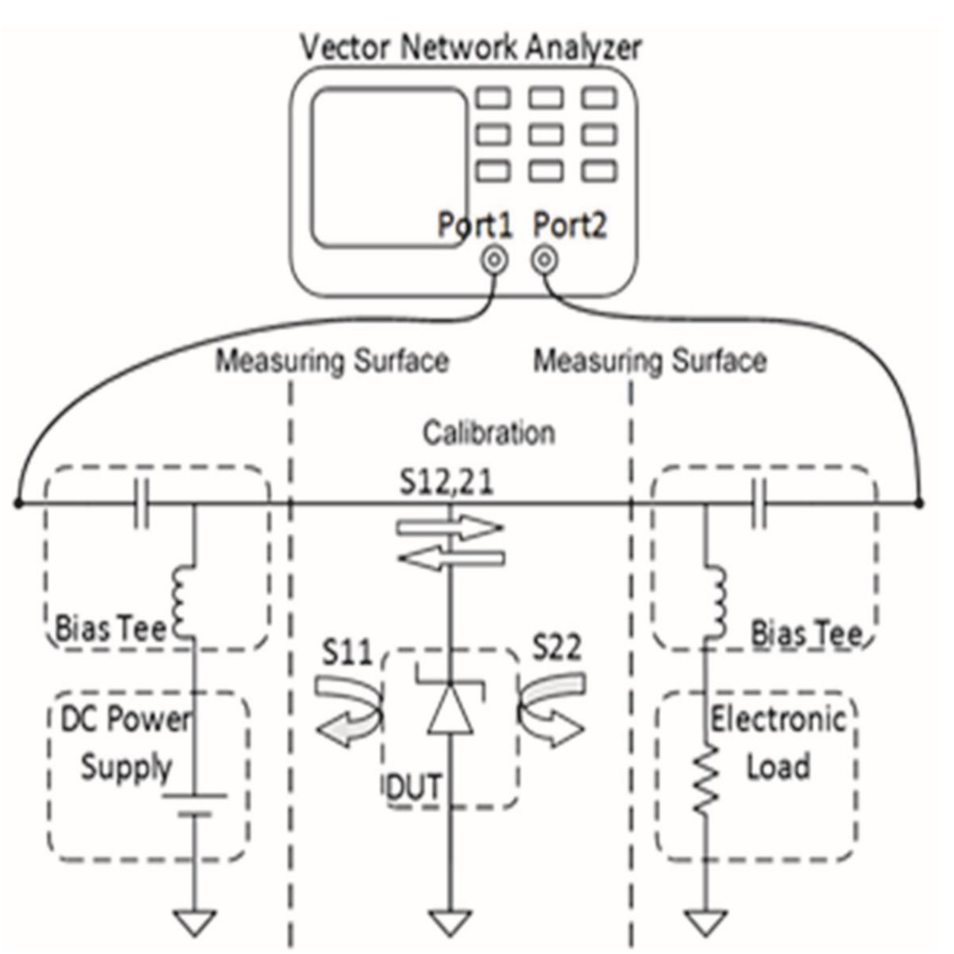
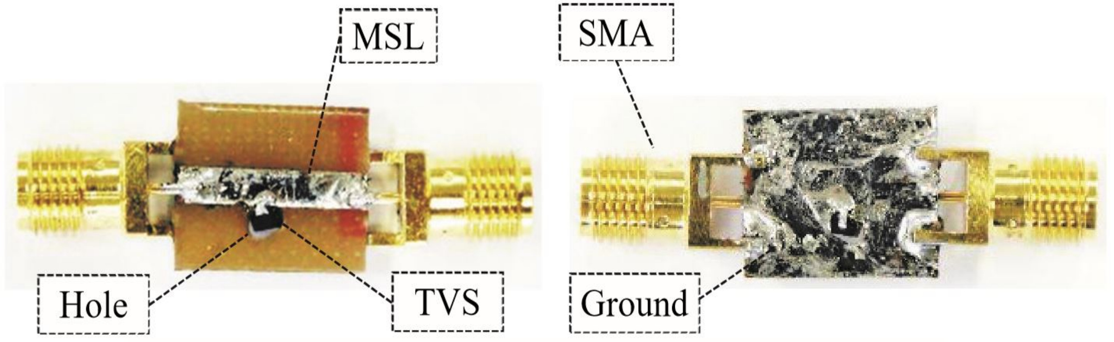


TABLE I. SPECIFICATION OF THE TRANSIENT VOLTAGE SUPPRESSOR (TVS) DIODES

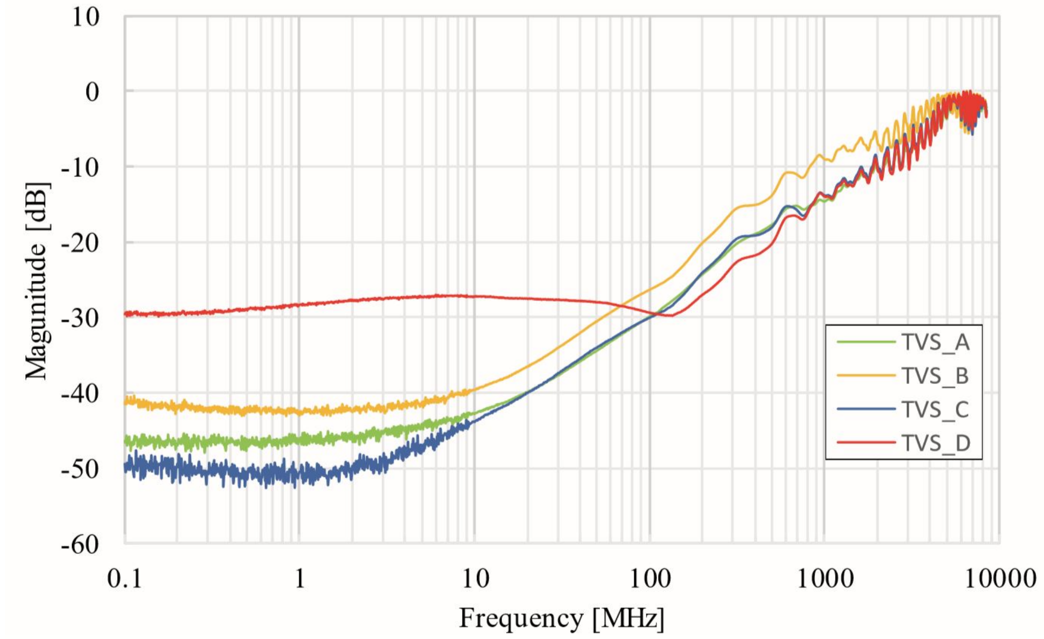
TVS model	Maker	P_{pk} [W]	Min_V_{BR} [V]	V_C [V]
TVS_A	A (Japan)	200	6.4	9.2
TVS_B	B (US)	200	6.4	9.2
TVS_C	C (Europe)	200	6.4	9.2
TVS_D	D (Europe)	200	6.4	13



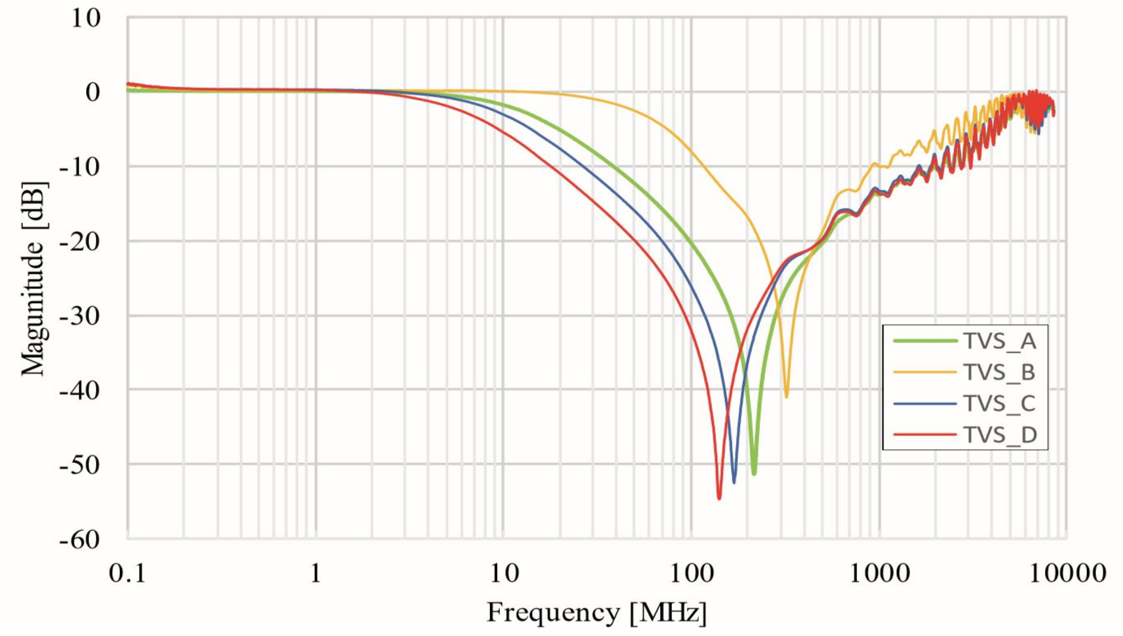
(a) Top view (b) Bottom view

Understanding System Level ESD Performance of TVS Diodes (3)

- Frequency from 100 KHz -> 8.5 GHz, measured in “operating” (<V_{BR}) and “non-operating” (>V_{BR}) states
- Results show very different S_{21} (output vs. input) over frequency range of ESD events



Operating state



Non-operating state

- On a PCB, results over the three different PCB types show TVS devices did show differences in the ESD frequency range for each PCB

Issues with System Level Testing of Components (1)

System Level Testing of Components (IEW 2019 Invited Talk Presentation)
Author / Presenter: Kathy Muhonen, Qorvo

- ❑ This Invited Talk explains recommendations for testing components to the IEC 61000-4-2 standard.
- ❑ While components are not completed systems, OEMs still ask their vendors to test components outside the system according to this standard.
- ❑ There is no real guidance for this in the IEC 61000-4-2 standard - results are not repeatable. This talk gives guidance to those who have to conduct the test regardless.
- ❑ The talk will also review the similarities and differences between testing to the IEC 61000-4-2 standard and the HMM standard practice. The hurdles and pitfalls to system level testing is shown and best practices are outlined.
- ❑ This talk also reviews several controlled experiments to determine the amount of variability that is typical in this type of test.

Issues with System Level Testing of Components (2)

- ❑ This invited talk describes work in the ESDA Standards Working Group 5.6 (HMM, or Human Metal Model)
- ❑ Customers are requiring IC suppliers to apply the IEC 61000-4-2 test to a component
- ❑ HMM is the ESDA Standard Practice (best practice) methodology for applying the IEC 61000-4-2 test to a component
- ❑ Components behave differently when it is on a board / in a system, compared to the component by itself

Issues with System Level Testing of Components (3)

- Design Of Experiments (DOE) on Bench Parameters • Wiring harness, ground location, gun type, point of entry – etc. all make a difference
- Type of IEC gun has large effect on outcome
- ESDA Round Robin for HMM • 12 Sites, different equipment, showed +/-6kV of variability for some device types

Issues with System Level Testing of Components – Initial IEC Waveform Conclusions

- Different shaped guns have different waveform characteristics, but still within Tables 1 and 2 wide limit ranges below, which may lead to different heating stresses
- Different guns produce range of peak currents which may lead to different dielectric breakdown stresses

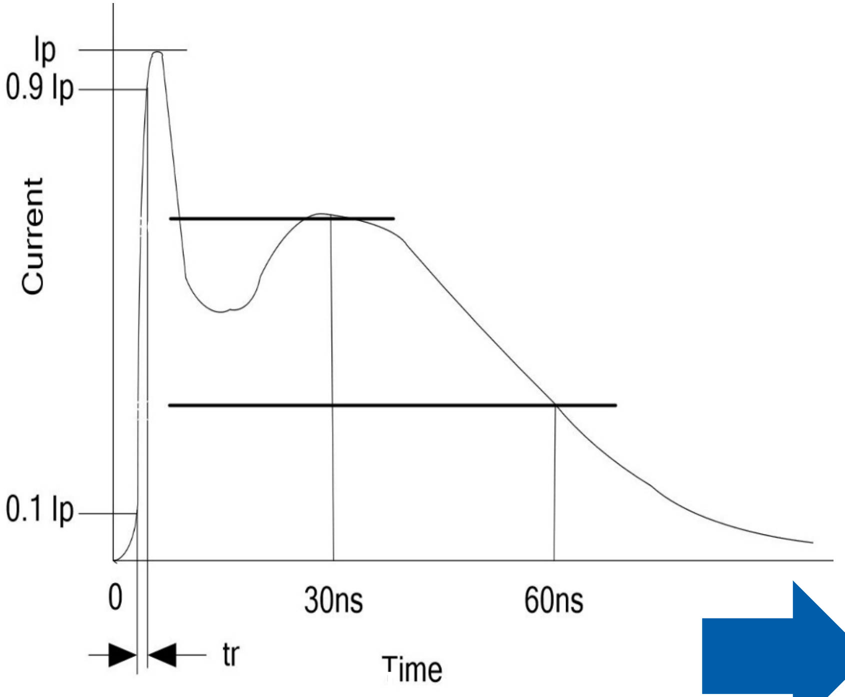


Table 1: General Waveform Properties

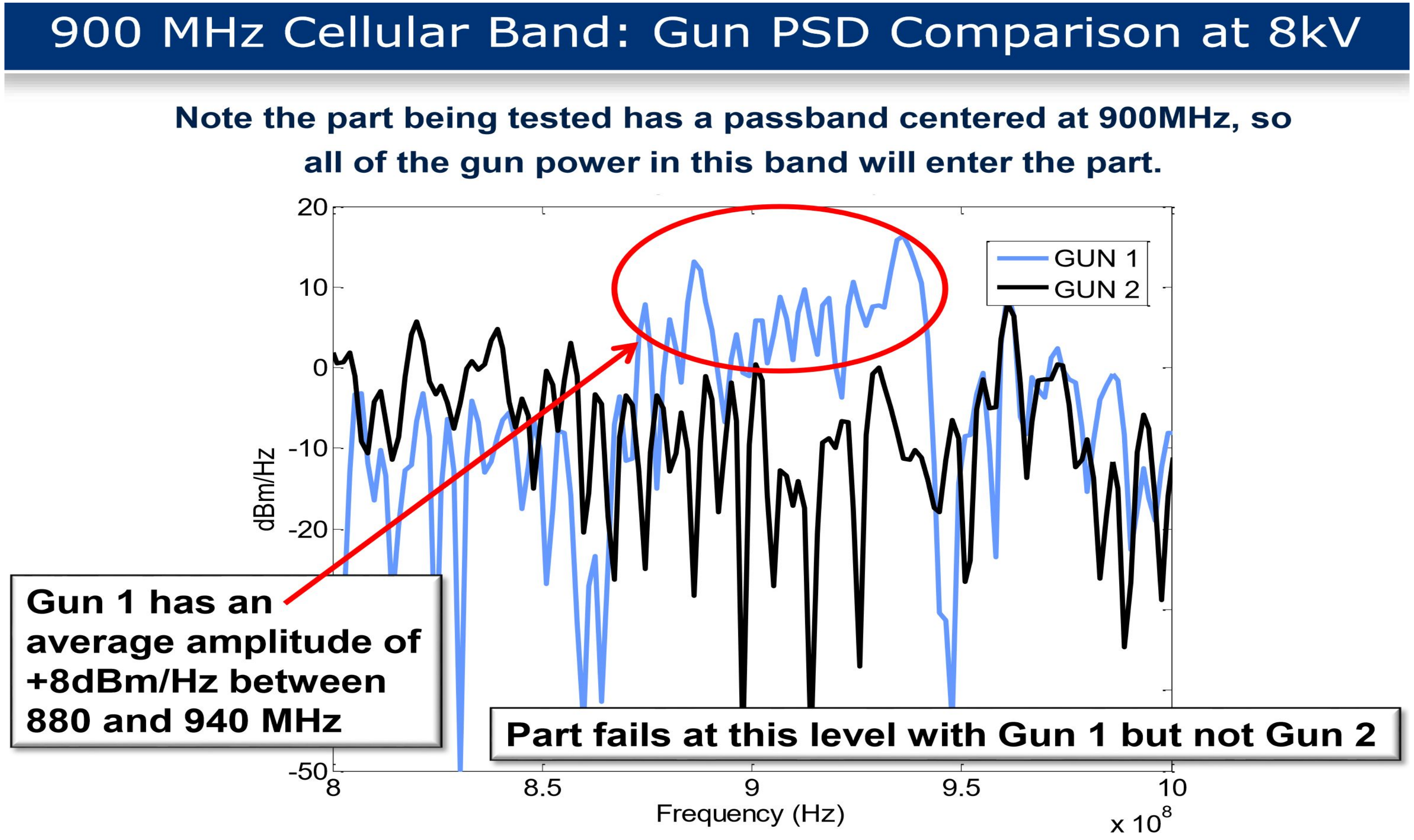
Output voltage contact mode[1]	At least 1 kV to 8 kV, nominal
Tolerance of output voltage	± 5%
Polarity of output voltage	Positive and negative
Discharge mode of operation	Single discharges

Table 2: IEC Pulse Parameters

IEC Pulse Parameters	Value	Unit
10 to 90% Pulse Rise-time	0.8 ± 25%	ns
First peak current of the discharge (Ip)	3.75 ± 15%	A / kV
Current at 30 ns from initial 10% point	2 ± 30%	A / kV
Current at 60 ns from initial 10% point	1 ± 30%	A / kV

Issues with System Level Testing of Components – Spectral Content Failure Dependence

- ❑ Spectral content of IEC guns can cause different failure levels, even if the total energy delivered by each gun is similar
- ❑ 900 MHz operation part example shown from IEW presentation



System Level Testing of Components: Summary

- ❑ The IEC 61000-4-2 test (as is) cannot be applied to components (especially RF components) reliably
- ❑ The IEC waveform parameter tolerances are much too wide to apply to components, and spectral energy frequency adds to variability
- ❑ Possible next steps:
- ❑ Consider the ESDA form a MOU with the IEC to jointly investigate and model / define the spectral energy component and provide guidelines / EMC effects standard for IEC 61000-4-2 of components, benefiting the industry
- ❑ Alternatively, find a way to apply filtering to the 61000-4-2 output to harmonize existing gun energy profiles to ensure uniform gun application to components

ESD and EMC - Year In Review Summary

- ESD and EMC do relate to each other - and often contribute energy from the same event to cause different failure modes
- ESD protection devices can show different protection results in the EMC frequency domains
- Understanding and modeling the profiles for EMC as well as ESD can help in event detection, improving various tests
- Significant research / progress made in ESD / EMC co-design, simulation / modeling, and factory measurement
- More work needs to be done in standards body collaboration to more effectively define and properly apply IEC 61000-2 guidelines for components