# Charged Device Model (CDM ) Metrology: Limitations and Problems

Leo G. Henry
Advanced Micro Devices
1 AMD Way, M/S 66
P.O. Box 3453
Sunnyvale, CA 94088-3453
Phone: 408-749-3447
FAX: 408-749-2841
E-Mail leog.henry@amd.com

Hugh Hyatt
Hyger Physics, Inc.
537 Constitution Ave.
Suite E
Camarillo, CA 93012
Phone: 805-388-7884
FAX: 805-388-0624
E-Mail: hygerphy@aol.com

Jon Barth
Barth Electronics
1589 Foothill Drive
Boulder City, NV 89005
Phone: 702-293-1576
FAX: 702-293-7024
www.barthelectronics.com

Michael Stevens
Motorola
Mail Drop G385
2501 S. Price Road
Chandler, AZ 85248-2899
Phone: 602-732-3720
FAX: 602-732-5861
E-Mail r20543@email.sps.mot.com

Tom Diep
Texas Instruments
P.O. Box 660199
MS 8640
Dallas, TX 75266-0199
Phone: 214-480-6689
FAX: 214-480-6659
E-Mail: tdti@msg.ti.com

## ABSTRACT

*The inconsistent performance of various CDM test heads indicates severe metrology problems exist. Test head-to-test head response times vary by factors of two to three and no independent calibration method exists. CDM waveforms depend upon the total measurement system. This paper discusses the problems and methods necessary to the capture of believable CDM waveforms.*

## INTRODUCTION

Charged Device Model (CDM) testing standards attempt to define the ESD susceptibilities of integrated circuits (i.e., IC's, devices or chips). For many years computers and other fully assembled systems underwent various levels and classes of simulated Human ESD tests in an attempt to harden the equipment against upset and damage. Concurrently, integrated circuit manufacturers found individual components sustained damage, not solely from interaction with a human operator, but from triboelectric charging and resultant discharges occurring as the IC moved through the manufacturing or printed circuit board process. [1][2]

The ESD Association CDM Standards: Working Group (WG 5.0) addresses testing to qualify device hardness to CDM events. Creating standards depends upon the accuracy of available CDM data and measurements. In an effort to answer the metrology questions arising because different simulators create different results Working Group WG 5.0 established a Round Robin series of tests to define explicitly CDM measurement limitations and problems, and correct those that could be corrected. The Round Robin used a total of six commercial and in-house designed CDM test heads as well as the fast oscilloscopes, cables, attenuators, and calibration pulsers. [3][4][5][6][7]

Major discrepancies exist between simulators designed for Charged Device Model (CDM) ESD failure analysis. Lack of repeatability in the current measurement produced only order of magnitude guesses about device failure thresholds. Order of magnitude guesses can yield gross estimates of problems with gross improvements in devices. *What is missing is the ability to do real physical analysis of device failures based upon realistic quantitative not qualitative data.* We present calibration results for six separate CDM test heads and describe methods for improvement in all measurement areas. A specific method for CDM test head calibration is presented. [8]

Current levels and waveforms differ from test head to test head, independent of other components in the measurement. Test head bandwidth limitations obscure some discrepancies by filtering the CDM waveforms. Combining the non-repeatability of an air discharge events with existing CDM test head dissimilarities makes data validation impossible with existing techniques and equipment.

## THE CDM DIAGNOSTIC CHAIN

To make the discussion explicit all references to the CDM diagnostic chain refer to the entire set of components used to conduct the CDM signal to the oscilloscope, including the oscilloscope. *Specifically, it includes all cables, attenuators, power splitters, delay lines, current monitors connectors and the oscilloscope.*

Input to the diagnostic chain, the CDM test head, typically consists of a 1.0 Ω current monitor. For slow varying waveforms a one volt signal translates to a one amp current through the test head, however for CDM events the test head exhibits non-linear impedances and losses. The 1.0 Volt/Amp calculation used without correction gives highly inaccurate results. The signal at the oscilloscope combines all the losses from each of the distinct components superimposed on the CDM waveform. Ideally, a diagnostic chain would transport the signal to the oscilloscope with a minimum of loss and/or distortion.[9] In the CDM case, both signal attenuation and distortion dominate the waveform due to the very fast event transition times.

The source of the inaccuracies comes from a combination of problems in the design and construction of very fast sensors. Resistors purchased off-the-shelf no longer act as pure resistances, but exhibit inductances and stray capacitances that effect the signal. Oscilloscopes fast enough to capture the CDM event have 50 Ω input impedances. Matching cable impedances to the oscilloscope and to the current monitor becomes mandatory to avoid reflections. In general losses in a diagnostic chain can take several forms:

- Improperly matched CDM test heads cause waveform distortion due to internal reflections in the test head.
- Variations in the 1.0 Ω resistors yield incorrect results which cannot be correlated from test head to test head without calibration.
- Observed current levels differ by nearly a factor of two. When the limited risetime response of the diagnostic chain is introduced into the anlysis the data suggests that portions of the waveform may be in error by factors as large as 5-10.
- High frequency information losses due to low bandwidth diagnostics, commonly called bandwidth limited measurements obscure the *true* signal.
- Skin effect losses in cables and cables with severe bandwidth limited response attenuate the high frequency components of the CDM event.
- Incorrectly calibrated attenuators yield incorrect waveform amplitudes.
- Reflections due to mismatched components in the diagnostic chain other than the CDM test head interfere with the primary waveform generating data errors.
- And, for one CDM test head the energy from the calibration pulse caused the 1.0 Ω resistor to vary as a function of the number of pulses, indicating resistor breakdown.

*One comment on attenuators is pertinent at this point. By the time the diagnostic chain was fully calibrated, it became apparent that certain attenuators caused the least of the problems. Choosing very high bandwidth attenuators (18.0 - 26.4 GHz) with power rating sufficient to handle the peak power of the calibration pulser, in general, made losses small enough that attenuator corrections could be ignored.*

## DIAGNOSTIC CHAIN CALIBRATION

To see the CDM diagnostic chain response to fast signals requires using signal sources faster than the expected response time of the diagnostic chain. The Round Robin team acquired three well defined fast risetime voltage sources. Each pulser provides a unique capability for analyzing diagnostic chain response. The instruments and waveforms were:

- A .20 volt, 30 picosecond risetime. Time Domain Reflectometer (TDR) output of the Hewlett-Packard HP54120/54121 Digital Sampling Oscilloscope (See igure 1.0).
- A -9.0 volt, 15 picosecond transition time voltage pulse from a Picosecond Labs pulser (See Figure 2.0), and
- A high voltage, 50 picosecond risetime pulse from a Barth Model 732 Transmission Line Pulser (See figure 3.0).

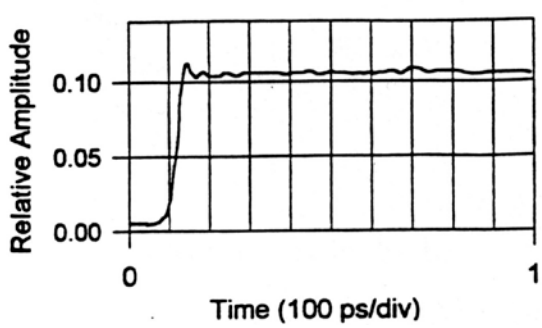


**Figure 1:** *The .20 volt, 30 picosecond risetime TDR output from the Hewlett-Packard HP54120 / 54121 Digital Sampling Oscilloscope. All components measured with this waveform show some effect on the risetime and waveshape.*

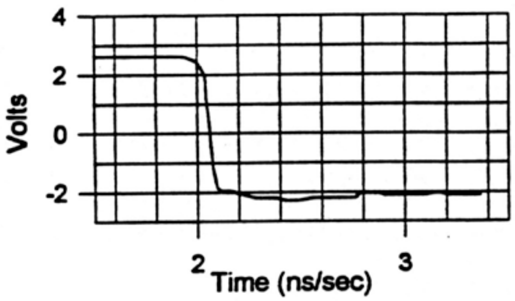


**Figure 2:** *The –9.0 volt, 15 picosecond transition time voltage pulse from the Picosecond Labs pulser on the SCD5000. The effect of the SCD5000 bandwidth limitation clearly shows in the 80-90 picosecond fall time of the waveform.*

These three instruments produce voltage impulses with transitions faster than the risetime of the CDM diagnostic chain allowing direct calibration of the diagnostic chain response. The instruments produce stable, repeatable pulses from well matched 50Ω sources, and each works well with either single shot oscilloscopes or digital sampling oscilloscopes (DSO's).

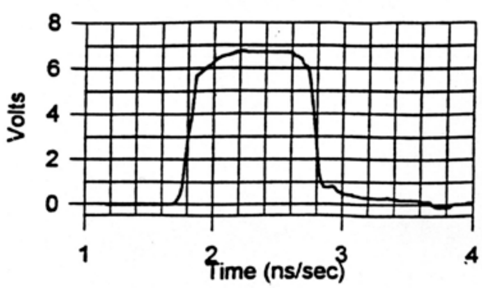


**Figure 3:** *A 7.0 volt, 50 picosecond risetime pulse from the Barth Model 732 Transmission Line Pulser.*

Why three separate fast risetime pulsers? One important reason is comparisons between pulsers. By applying the three pulser outputs to a component and observing that consistent results occur for each type of waveform, gives a first type of calibration validation. It also provides a check on calibrationpulsers insuring that the pulsers performs consistently throughout the calibration procedure. Additionally, the lower voltage calibration pulsers allow measurements to be made with fewer attenuators installed between the signal source and the oscilloscope. The fewer components in the diagnostic chain, the less distortion on the waveform.

The high voltage calibration source (Barth Model 732 Transmission Line Pulser) serves a unique purpose in these tests. The CDM event occurs from a high voltage electrostatic discharge producing relatively high currents. A complete calibration needs to drive comparable currents through the CDM sensors. Using a 50 Ω transmission line source capable of producing the 10-30 Amps typical of CDM measurements allows stressing sensors to levels similar to actual events. Any high voltage non-linearities show clearly with this pulse calibration technique. The low voltage pulsed sources do no stress the CDM test heads sufficiently to eliminate possible high current or voltage variances in the test head output.

Although the Round Robin's goal was to explain inconsistencies seen in the various CDM simulators, it became obvious with the very first measurements that many of the diagnostic chain components were inadequate for capturing the very fast CDM events. Before data collection could start on the CDM simulators, it became necessary to select the best set of cables and attenuators. Several cables were tested and completely rejected due to their distortion and mis-matched performance. Two sets of cables eventually were compared, with the fastest set of cables used for the data presented here.

First calibrations looked at the cables alone. TDR and pulser waveforms varied from cable to cable. Figure 4.0 shows three cables originally considered during the Round Robin testing, but eliminated due to excessive losses. Cables can easily cause problems in the measurement because so many failure modes exist. For example, the connectors become damaged when used again and again, leading to problems such as discontinuities at the connector or resistive pin-to-pin contacts.

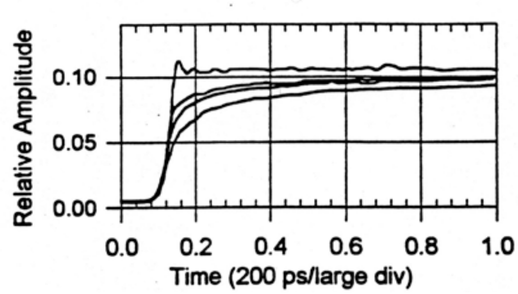


**Figure 4:** *Shows three cables originally considered for the Round Robin testing, but eliminated due to excessive losses. Each of the cables shown in this figure are microwave rated to 18.0 GHz, considered low loss and represent typical cabling available.*

Philosophically, calibrating very fast measurement equipment involves determining the impulse response of the measurement chain by inputting signals with faster risetimes than the diagnostics to be calibrated, looking at the signal after it passes through the equipment and comparing input waveform to output waveform.

Two theoretically equivalent calibration methods exist. One method measures the spectral response of the diagnostic system with very high frequency spectral analysis equipment such as network analyzers or spectrum analyzers then by performing a Fourier Transform on the data to predict the trasient, or time domain response. The other method measures the time domain response directly using very fast pulsers. The Round Robin chose to do time domain calibrations for several reasons:

- CDM data captured on single shot oscilloscopes always appears as time domain data so time domain calibrations directly conform to the data type without resorting to computation or data translation.
- CDM measurements involve high voltages (up to 2000 volts). Spectral analysis equipment uses low voltages to characterize the diagnostic chain components and may not stress the measurement system at levels sufficient to observe non-linear responses and voltage dependent breakdown.
- Calculation of attenuation factors, risetime limits on total diagnostic chains and system losses becomes a simple calculation of ratios or reading risetimes directly from the captured oscilloscope data.

Although the Round Robin studied individual elements in the diagnostic chain, final calibration consists of connecting the entire chain together, injecting a very fast risetime pulse into one end of the total chain, and monitoring the result at the other end. The time domain calibration procedure requires two independent steps:

### Calibration Step 1:

Connect the fast risetime pulser with the shortest, fastest response cables possible directly to the oscilloscope making certain to provide the appropriate attenuation, dependent upon the pulser used. Capture the direct coupled waveform and record the results. This waveform becomes the calibration reference.

### Calibration Step 2:

Then insert the diagnostic chain or component of the diagnostic chain to be calibrated between the fast transient voltage source and the oscilloscope. A direct measurement of signal losses results.

Overlaying the calibration waveform with the reference waveform directly identifies all errors in the measurement. Calculating complete diagnostic chain attenuation factors becomes a simple exercise of ratioing the reference waveform with the diagnostic chain waveform.

To be precise in this measurement, each attenuator must be calibrated independently, and its effect on the observed waveforms used with corrections if necessary. The requirement to independently specify attenuator performance comes from the need to change attenuation levels when moving the high voltage pulser from the HP54120/54121 DSO to the SCD5000. The HP54120/54121 can only handle .20 volts maximum, where the SCD5000 can handle signals of over 9.0 volts. Signal levels are adjusted by varying either attenuators or changing the pulser output voltage.

This calibration technique defines the total diagnostic chain response to a fast transient simply installing the complete CDM diagnostic chain into the calibrated waveform path gives, in one measurement, all the information needed to evaluate diagnostic performance.

## SCD 5000 CALIBRATION

This technique allows calibration of oscilloscopes as well. In particular, the response of the SCD5000 Digital Sampling Oscilloscope used to capture the single shot, non-repeatable CDM events was calibrated by first looking at each of the fast transient pulsers on the 20GHz, HP 54120/54121 DSO. The HP 54120/54121 DSO can resolve transitions of approximately 17 picoseconds. By generating the reference waveform on the 20GHz system, then transferring the pulser, and all relevant attenuators and cabling to the Tektronix SCD5000's leads to a direct measurement of Tektronix SCD5000 transient response. Both the Picosecond Lab pulser and the Barth 732 determine the *SCD5000 response to be approximately 80-90 picoseconds*, (See Figure 5.0 and Figure 6.0).

What does it mean to say the SCD5000 impulse response cannot exceed 80-90 picoseconds. It means that any signals with risetimes faster cannot be properly captured and displayed. It is important to understand this means loss of all information faster than the approximately 90 picosecond risetime limit. Specifying a fast oscilloscope alone does not determine the speed (impulse response or bandwidth) of a total measurement chain. The total diagnostic system response time can only be determined by calibrating the complete system in the configuration it will be used. [10]

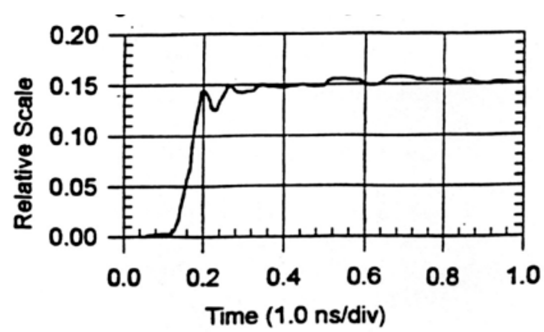


**Figure 5:** *The Barth Model 732 pulse as displayed on the HP 54120/54121 showing approximately 59 picosecond risetime time.*

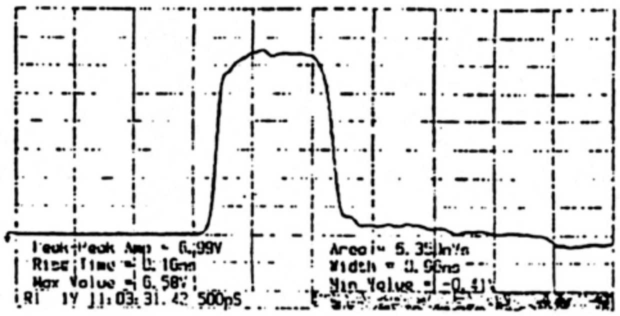

**Figure 6:** *The Barth Model 732 pulse as displayed on the SCD5000 giving a direct minimum risetime measurement of approximately 90 picoseconds.*

One additional comment must be added to the description of the SCD5000. Work at Sandia National Laboratories lead to a technique for extending the bandwidth capability of the SCD5000 to over 15 GHz. To achieve such high single-shot bandwidths, equivalent to 23 picosecond response times, additional calibrations and a data convolution must be performed. It is the intent of the CDM working group to carry the CDM measurements to this higher bandwidth, but was beyond the scope of the equipment available at the time the data presented here was collected. See the reference for more information. [11]

Although this may seem like a lot of work to determine the response of a fast oscilloscope, the CDM waveforms are faster, in relationship to the fastest measurements capable with this equipment.

## CDM TEST HEAD CALIBRATIONS

Combining the SCD5000 response with the bandwidth limited response of the total CDM diagnostic chain implies system 10%-90% response times of 100-250 picoseconds. See Figures 7 and 8 which slow the six test heads with the full diagnostic chain connected, calibrated with the 50 picosecond high voltage pulse at 500 volts and 1000 volts, respectively. [12][13] Clearly slower risetimes and distortion appear on the high voltage calibration pulse for every test head studied. This same distortion modifies any CDM waveforms captured in normal testing. All measurement of a CDM event with any of these test heads must consider the total diagnostic chain response and where possible corrections should be made to the final data. The test head calibrations identified at least four distinct distortions from nominally square wave calibration pulse:

- Ringing on the early portion of the waveform which implies resonances in the CDM test head structure, and implies that the CDM response varies directly with how well the CDM event matches the resonances in the test head. Response amplitude for these distortions varies with the spectral content of the input waveform.
- High frequency roll off, seen as deviation from a smooth fast risetime edge primarily a skin effect loss, leads to increased attenuation in the high frequency components of the input waveform.
- Inconsistent attenuation factors from test head to test head means data from one simulator to another will not correlate. If all were exactly 1.0 Ω current sensing devices, the six curves shown would all reach the same level.
- Over the first 1.0 nanoseconds these calibrations the test heads impose very large deviations from a linear response on the input calibration pulse, with attenuation varying as a function of time from the onset of the pulse.

## CDM MEASUREMENT SYSTEM

Typical CDM measurement systems (diagnostic chain) consists of four main components a) the CDM current monitor or test head, b) cabling and attenuators, c) the oscilloscope or digital sampling oscilloscope, and d) the Device Under Test (DUT). Most CDM test heads use a 1.0 Ω disk resistor, a pogo pin to contact the integrated circuit, a reference ground plane, charging plate, and a transition from the 1.0 Ω disk resistor to an SMA connector. Cabling must be 50 Ω very wide bandwidth.

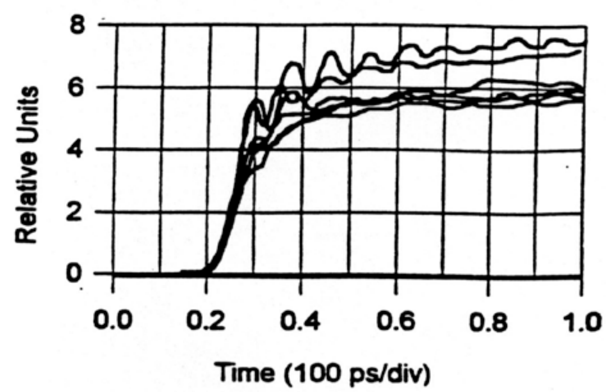


**Figure 7:** ***500 volt calibration data for the six CDM test heads scaled and overlaid. These figures clearly display the test head to test head dissimilarities.***

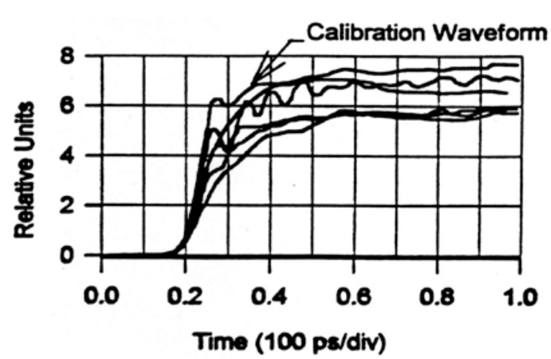

**Figure 8:** *1000 volt calibration data for the six CDM test heads scaled and overlaid. These figures clearly display the test head to test head dissimilarities. Additionally, the top trace in this figure shows the calibration pulse from the high voltage pulser. Deviations from the top waveform are diagnostic errors.*

CDM testing consists of charging the DUT to a given voltage, discharging it through the 1.0 Ω current viewing resistor to gound, while monitoring the discharge, or at least counting the discharges, then inspecting the device for functionality. If operational paramenters stay within specified limits the device passes. Conceptually a very simple sounding test. Charge, discharge, charge discharge pin by pin. Then examine the component for functionality. In actuality, the test is far from simple as the calibrations above imply.

## THE CDM ROUND ROBIN DATA

Small printed circuit board (PCB) disk capacitors provided a consistent calibrated CDM event reference for each CDM test head calibrated. The printed circuit board wafers are gold plated disks with 0.350 inch and 1.000 inch diameters, respectively. Each copper disk is about 1.0 mil thick on a 1/32 inch substrate of FR-4 material. The metal circle forms a capacitor plate with the high voltage charging plate of the CDM simulator. The smallest disk exhibits approximately 4.0 picofarads of capacitance and the large disk is approximately 30 picofarads. The 500 volt, raw data for the 4.0 pf and the 30pf wafers are shown in Figures 9 and 10. The 1000 volt, raw data for the 4.0 pf disk is shown in Figure 11. [14] Raw data appears exactly as the SCD5000 recorded the waveform. In this form the data needs to be scaled accounting for attenuators included in the measurement, and ideally for any other losses discovered during the calibration processes. Previously, these measurements would have been considered adequate indications of the current generated in the CDM event, only requiring a correction for attenuation factors.

Digitizing the CDM data leads to the following observations: See Figure 12, 13, and 14 which show the overlaid digitized and scaled CDM events at 500 and 1000 volts from the 4.0 picofarad disk and at 500 volts from the 30 picofarad disk, respectively.

Apparent current levels have a range of approximately 6.0-10.0 Amps for the 4.0 picofarad disk at 500 volts, 11-19 Amps for the 4.0 picofarad disk at 1000 volts and 17-25 for the 30 picofarad disk at 500 volts. Although not shown, the 1000 volt, 30 picofarad current data scales by factors of two as does the 500 volt, 4.0 picofarad currents.

The data has only been scaled for known attenuation factors in the diagnostic chain, no attempt was made to correct for the non-linear responses of the CDM test heads.

By overlaying data, several distinct problems become clear.

- CDM current risetimes approximately equal the total diagnostic chain response time.
- CDM waveforms typically appear as damped sinusoids, showing little structure on the leading edge of the waveform, supporting the argument that the diagnostic chain filters the waveform.
- The CDM current derivative (di/dt) can exceed 110 x $10^9$ Amps/second, a very large current risetime for any technology.
- There is no corresponding voltage measurement associated with the current measurement, making full analysis of the discharge circuit uncertain.
- 4.0 pf calibration wafers produce typical transients with less than 1.5 nanoseconds duration and 30 pf wafers transient duration seldom exceeds 2.5 nanoseconds.

CDM current risetimes, as captured by the CDM diagnostic chain using the 4.0 pf calibration disk, in some cases are exactly the same as the total diagnostic chain response time within the measurement error. To see this is true compare waveform risetimes to the response times found during calibration of the test heads. Figures 15 and 16 show the same CDM event overlaid with the reference diagnostic chain calibrations. These pictures show the major errors apparent in the diagnostic chain.

A close look at the test head and event overlays show that the current waveform occurs at exactly the most non-linear part of the diagnostic chain's impulse response. All amplitudes captured in this time frame are attenuated by very large factors. Factors of 3-5 over the expected 1.0 Ω response of the test head appear for signals in the 80-110 picosecond range. For signals much faster than 80 picoseconds, the attenuation factors become arbitrarily large.

The 30 picofarad wafers show slower risetimes, and suggesting that the waveform may be more nearly correct, however correct peak amplitudes still exceed the 17 – 25 Amps by possibly as much as factors of 1.5 to 2.0.

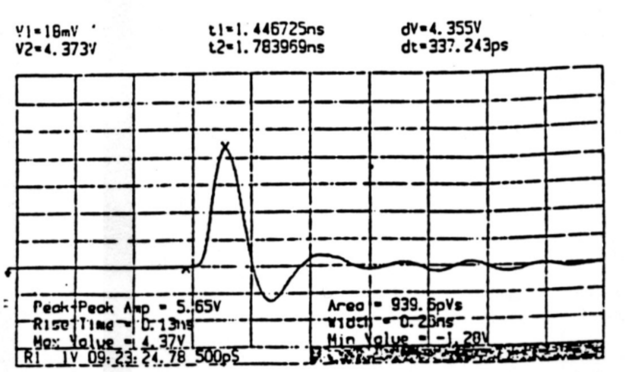


**Figure 9A**

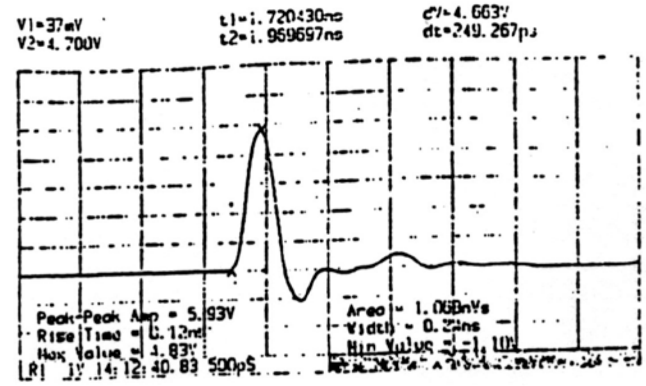


**Figure 9B**

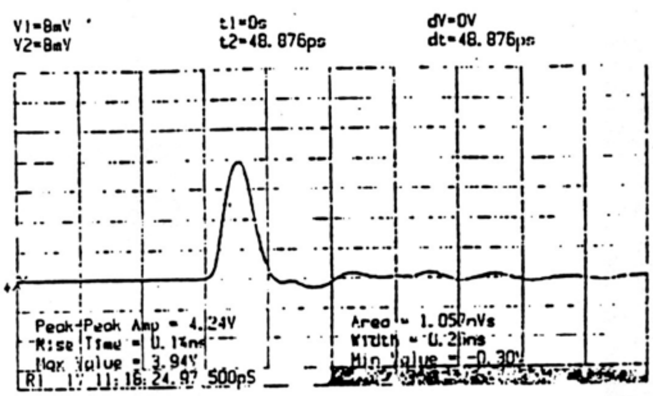


**Figure 9C**

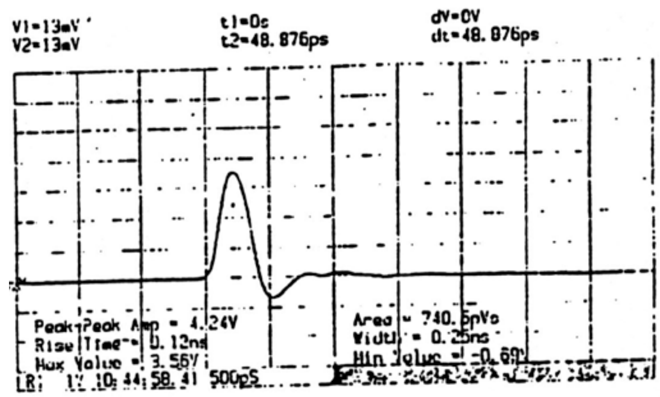


**Figure 9D**

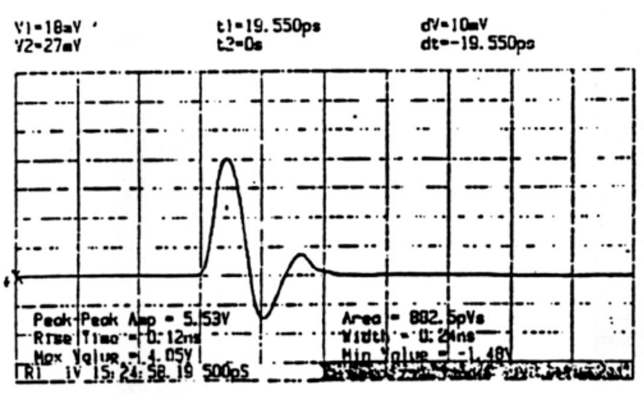


**Figure 9E**

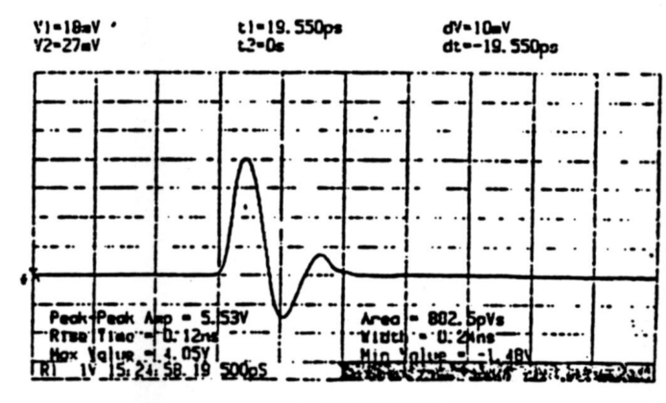


**Figure 9F**

Figure 9A through F: *The 500 volt raw data for the 4.0 picofarad disk data as displayed on the SCD5000. To reduce waveforms for comparison and analysis, the data was re-digitized converting the CDM and calibration waveforms to X, Y data sets (See Figures 12, 13 and 14).*

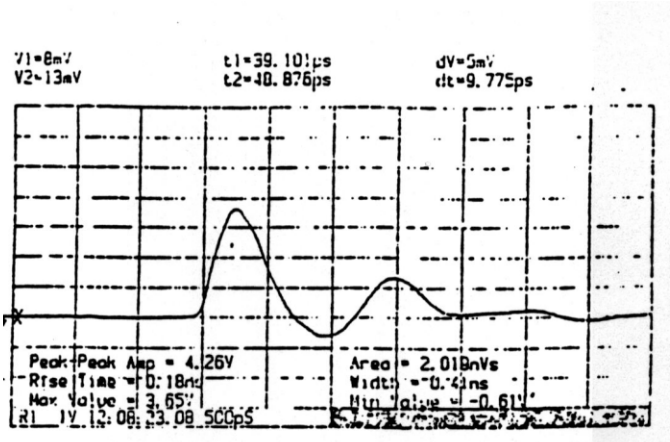


**Figure 10A**

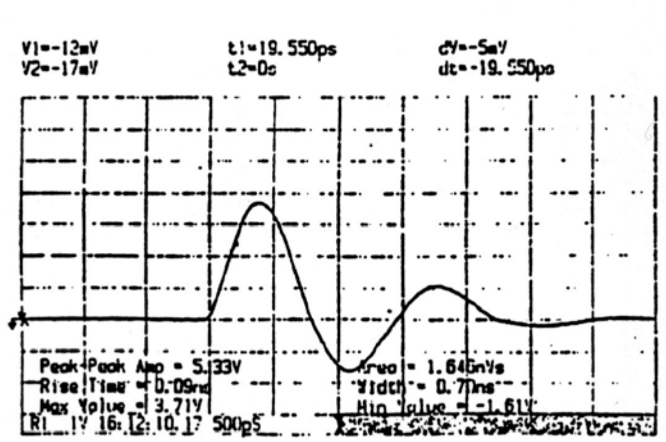


**Figure 10B**

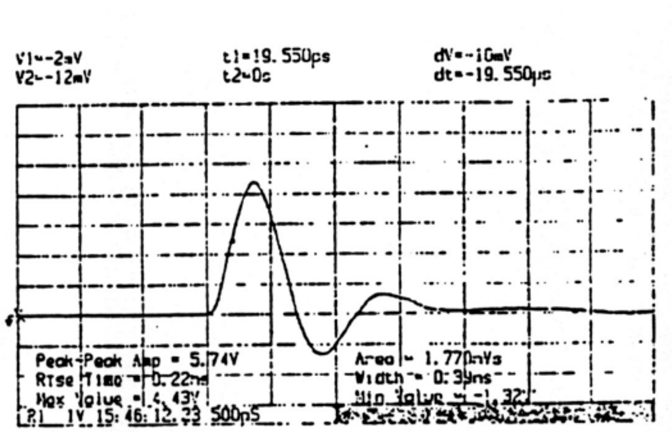


**Figure 10C**

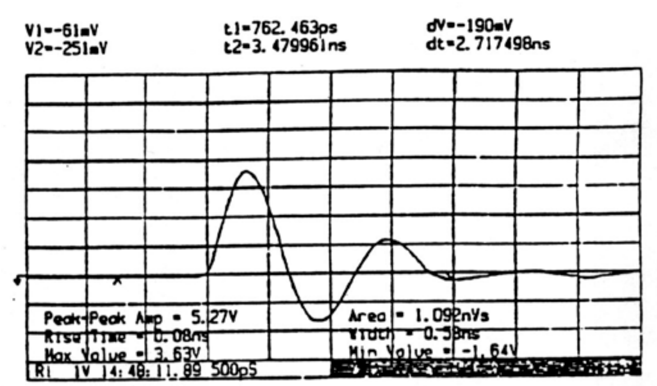


**Figure 10D**

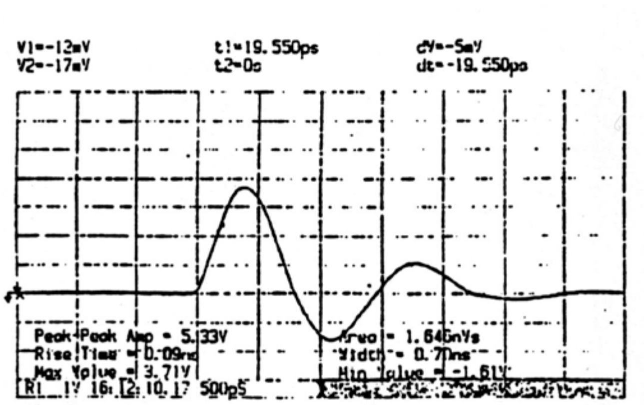


**Figure 10E**

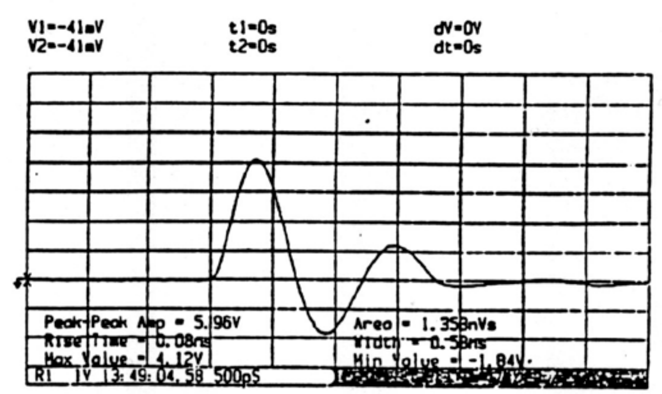


**Figure 10F**

Figure 10A through F: *The 5oo volt raw data for the 30 picofarad disk as displayed on the SCD5000. To reduce the waveforms for comparison and analysis, the data was re-digitized converting waveforms to X, Y data sets (See Figures (12, 13 and 14).*

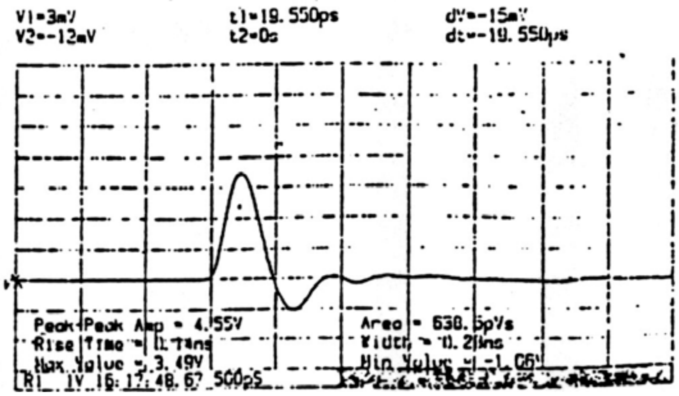


**Figure 11A**

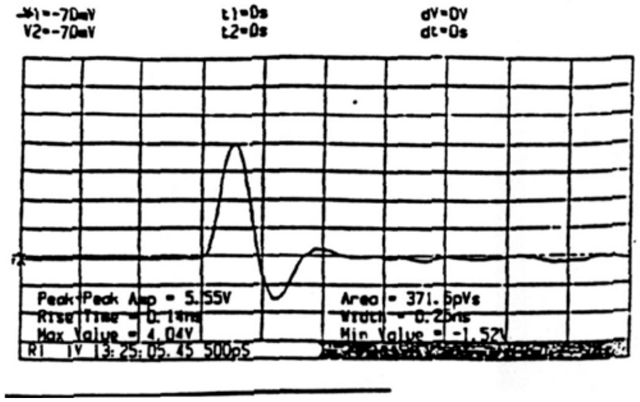


**Figure 11B**

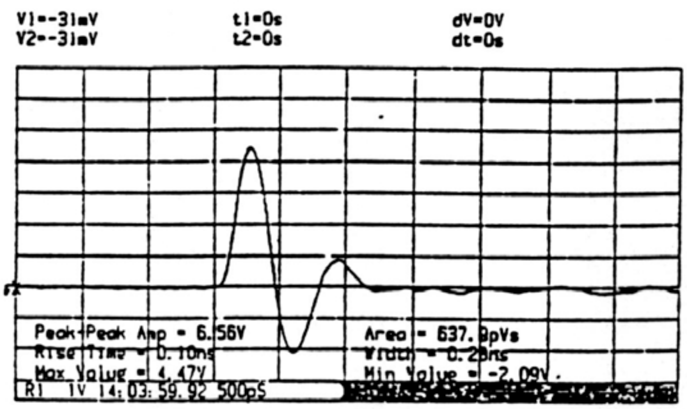


**Figure 11C**

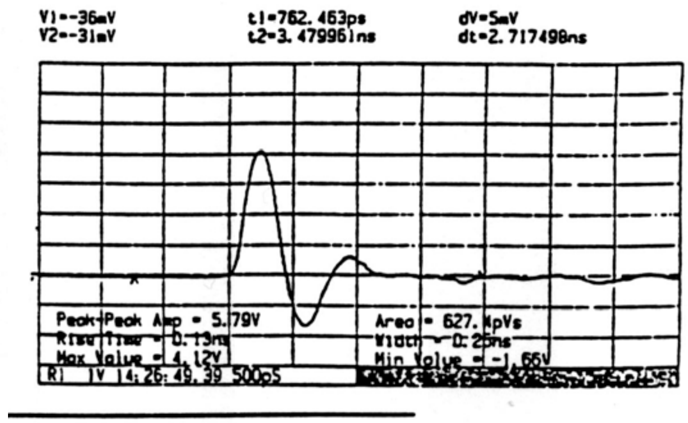


**Figure 11D**

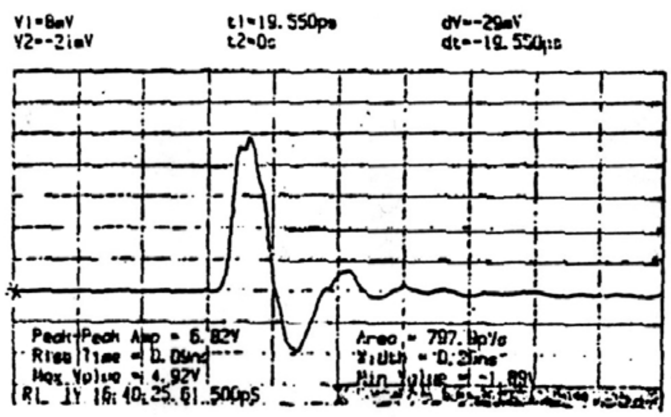


**Figure 11E**

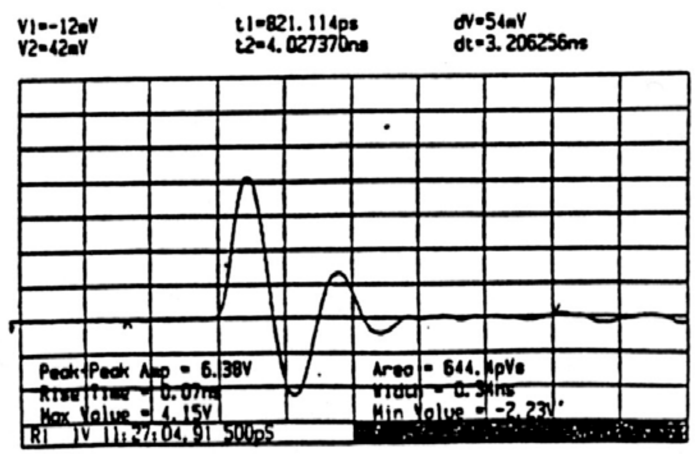


**Figure 11F**

Figure 11 A through F: *The 1000 volt raw data for the 4.0 picofarad disk as displayed on the SCD 5000. To reduce waveforms for comparison and analysis, the data was re-digitized converting waveforms to X, Y data sets (See Figures 12, 13 and 14).*

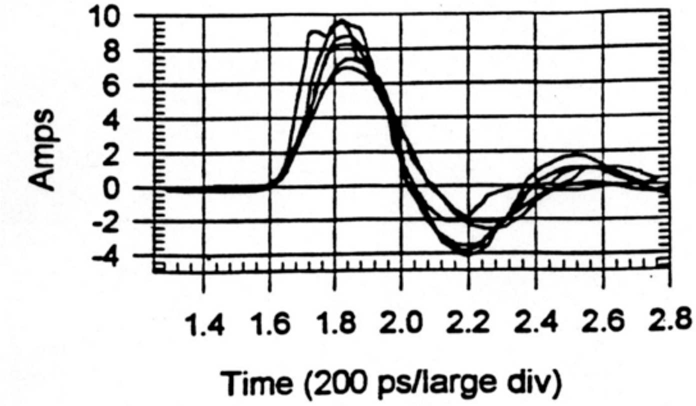


**Figure 12:** *500 volt, 4.0 picofarad disk, scaled and overlaid CDM event data from each of the six test heads.*

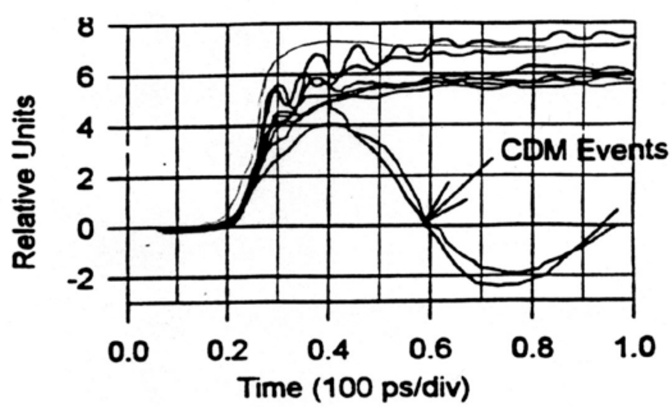


**Figure 13:** *1000 volt, 4.0 picofarad disk, scaled and overlaid CDM event data from each of the six test heads.*

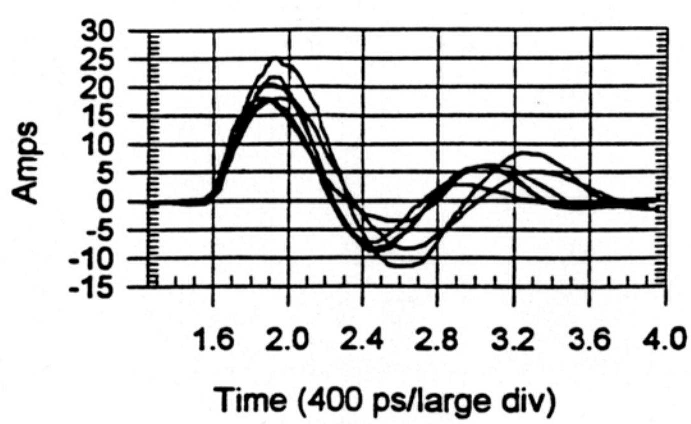


**Figure 14:** *500 volt, 30.0 picofarad disk, scaled and overlaid CDM event data for each of the six test heads.*

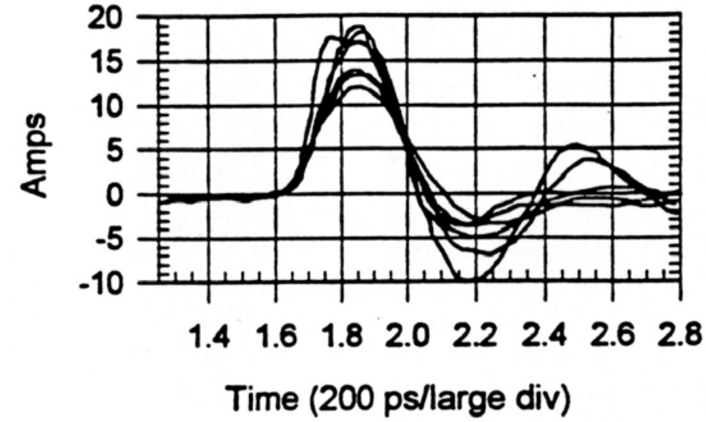


Figure 15: Overlay of the test head calibration curves with 500 volt, 4.0 picofarad CDM event data.

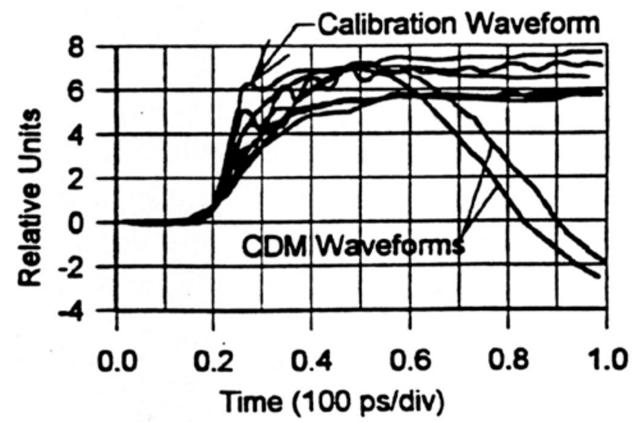


**Figure 16**: *Overlay of the test head calibration curves with 500 volt, 30.0 picofarad CDM event data.*

## SUMMARY

Presently, CDM diagnostic chains cannot precisely measure the fastest events. The current waveform produced by CDM simulators, using a verification disk, is faster than some of the test heads in the diagnostic chain can resolve.

Analysis of the CDM events demonstrate that the variations are due to bandwidth limited equipment and discharge heads. The overlay of the CDM events and the leading edge of the test head pulse response waveforms show that the speed of the measurement system must be faster than 100 picoseconds to accurately display fast CDM events. Test heads or recording instruments slower than this require a calibration factor to achieve correlation for the faster pulses. Our measurement system was not fast enough to yield:

- Risetime of 4 pF CDM verification disk events.

- Accurate peak currents for these events.
- High frequency components of waveforms.

It is important to remember that although the waveforms shown have the current scaled in Amps, the actual current will be somewhat higher than shown depending on the bandwidth limiting of the discharge head and recording system. The data does indicate that a somewhat faster measurement system is needed to accurately identify the peak currents and risetimes of the fastest discharges. [15]

Although the CDM Metrology Group tests do not provide the precise answer of CDM event amplitude and risetime, the risetime measurements of the test head indicate that some system risetime improvement can provide the missing data. One possibility is to use the Sandia National Labs 15 GHz software equalization of the Tektronix SCD5000. [11]

Calibrating each test head to determine impulse response, and using faster risetime response heads will allow more accurate peak current information. The total system pulse current measurement accuracy can be improved by the accurate resistive measurement of the nominal 1.0 ohm current sensing resistor and capacitance measurement of the verification disks. [16] Future work must continue to insure device data correlation and to confirm the test methods and metrology. This work must collect device threshold data and compare the failure mechanisms from a controlled sample of devices using many CDM simulators. [17]

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