HBM Tester RC Elements Extracted from the Rise Time of the Total Charge

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Abstract – The standard 0-ohm HBM waveform can be integrated, usually on the oscilloscope being used, and the 10-90% rise time of the resulting charge Q(t), along with final value Q(∞), used to determine an exact R and C for the discharging network. The measured rise time of $I_0(t)$ (required to be 2-10 ns) is used to formulate a reduction chart that transforms the 10-90% Q(t) rise time into the RC time constant. This measurement is nearly effortless and could be used as a quick check or even as a standard for waveform acceptance.

If the Human Body Model (HBM) waveform is modeled as a double exponential, the current $I_0(t)$ is the step response of a series RLC circuit having negative real poles $p_{1,2}$ such that

$$P_{1,2} = \omega(-D \pm \sqrt{D^2 - 1}) \quad (1)$$

where $\omega = 1/\sqrt{LC}, D = \omega RC/2$ [1]. Let $p_{1,2}$=-$P_{1,2}$. For HBM, D is substantially greater than one, meaning that one time constant τ_1 (=1/p_1) is near the required 150 ns decay constant, and the other, τ_2, determines the rise time of 2-10 nsec. Figure 1 shows the relation between that short time constant τ_2 and the $I_0(t)$ rise time, calculated using a computer from the (normalized) double exponential expression

$$I_0(t) = [\exp(-p_1 t) - \exp(-p_2 t)]/(\tau_1 - \tau_2). \quad (2)$$

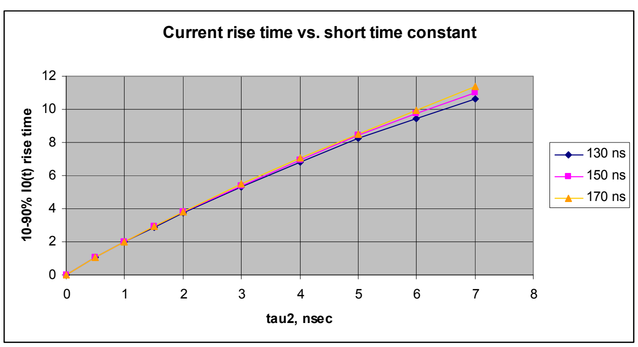

Figure 1. $I_0(t)$ rise time vs. short time constant τ_2.

It is a consequence of the 2-pole RLC solution that $\tau_1+\tau_2$ =RC [1,2]. Note in Fig. 1 that for RC ranging from 130 to 170 ns, there is not much difference among the curves for the $I_0(t)$ rise time, so the τ_2 associated with a rise time is nearly unique. This is a promising sign given our objective.

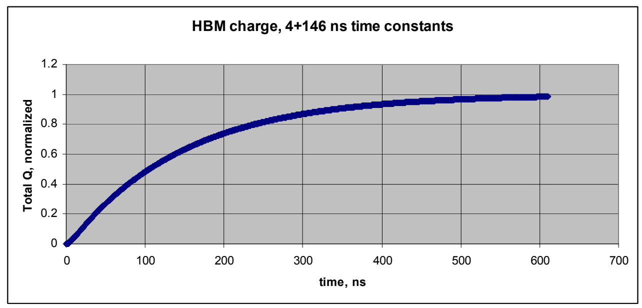

Figure 2. Integrated current for an $I_0(t)$ having 7 nsec rise time (τ_2=4 ns) and RC=150 ns; 10-90% points are from 19.5-340.5 ns, giving 321 ns as a charge rise time.

Figure 2 shows an integrated current for a double exponential as in (2) with τ_1=146 ns, τ_2=4 ns. We note a charge rise time of 321 ns is associated with RC=150 ns; therefore a reduction factor of 2.14 is applied to the Q rise time to get RC. The total charge Q_t, of course, normalized to 1 in these calculations, gives the effective capacitance C (expected to be ~100 pF in HBM), so the RC time constant then gives R, expected to be ~1500 ohms.

The methods of Fig. 2 and the discussion above can be applied to a set of HBM conditions to derive a chart of reduction factors for the Q rise time that result in a value for RC. The reduction factor chart is shown in Figure 3. These reduction factors do not vary by much, changing from no more than 2.183 to no less than 2.09 as the $I_0(t)$ rise time goes from 2 to 10 nsec, the allowed range.

Next we want to apply Fig. 3 to some real HBM waveforms and compare with a more rigorous way [2] of extracting the RC time constant, i.e., by finding the centroid of the waveform as in Figure 4. Results are shown in Table I. The true RC time constant as found from Q(t) rise time is usually accurate to within 1%.

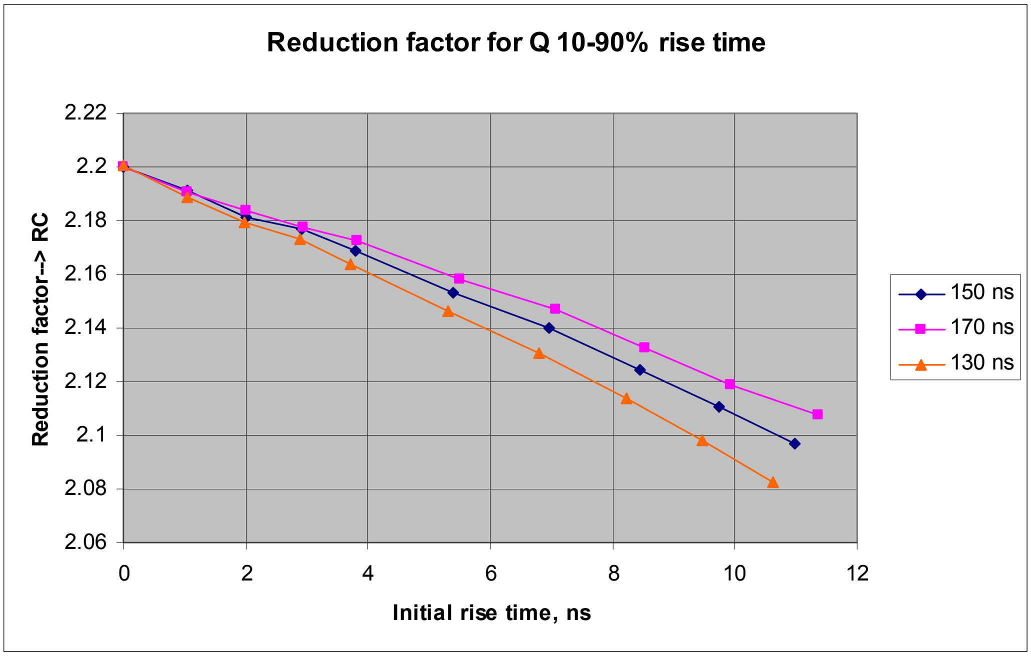

Figure 3. Reduction factor chart for HBM total charge rise times. Reduce the 10-90% rise time by the factor on the vertical axis when the $I_0(t)$ rise time corresponds to the value on the horizontal axis, to give RC. The three curves are for final values of RC within the expected range, so some iteration can increase accuracy.

The measurements in Table I were made with the CT2 current probe [2], but the CT1 may also be suitable, as it even gives a crisp cutoff point for total charge Q_t. Further study could also assure, rigorously, that slight ringing early in the pulse, caused by the C_1 across R [2,3], fits within the model described. In such a case, there is a 3-pole solution [3], with a complex conjugate pole pair replacing τ_2. It can be shown that for damping factor $0.5<D_2<1$ for this pole pair ("mild" ringing), Fig. 3 would be nearly unchanged.

Table I. RC element extraction for several testers.

Tester & voltage	Qt→ cap(pF)	RC, ns (centroid)	RC, ns (10-90%)	ΔRC, % difference
1kV, 256 Zapmaster	114.4	161.8	160.9	0.57
2kV, 256 Zapmaster	112.4	152.0	151.7	0.18
1kV, 512 Zapmaster	105.7	144.0	145.0	-0.64
1kV, MK-4	115	161	160.1	0.55
4kV, MK-4	114.2	149.2	147.7	1.01

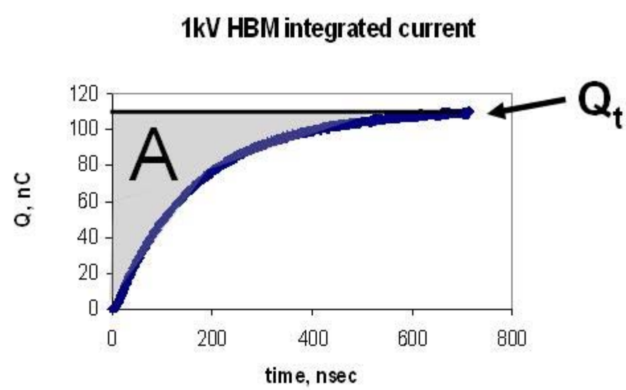

Figure 4. Integrated current for an HBM waveform, converging to total charge Q_t. The centroid of the original $I_0(t)$ waveform is computed from A/Q_t, where A is the area above the curve. Further discussion in [2].

References

[1] Y. Ismail, et al., "Equivalent Elmore Delay for RLC Trees", ACM DAC, 1999.

[2] T.J. Maloney, "HBM Tester Waveforms, Equivalent Circuits, and Socket Capacitance", EOS/ESD Symposium Proceedings, 2010.

[3] K. Verhaege, et al., "Analysis of HBM ESD Testers…", EOS/ESD Symposium Proc., 1993.

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Timothy J. Maloney--biography

Timothy J. Maloney received an S.B. degree in physics from the Massachusetts Institute of Technology in 1971, an M.S. in physics from Cornell University in 1973, and a Ph.D. in electrical engineering from Cornell in 1976, where he was a National Science Foundation Fellow. He was a Postdoctoral Associate at Cornell until 1977, when he joined the Central Research Laboratory of Varian Associates, Palo Alto, CA. At Varian until 1984, he worked on III-V semiconductor photocathodes, solar cells and microwave devices, as well as silicon molecular beam epitaxy and MOS process technology. Since 1984 he has been with Intel Corp., Santa Clara, CA, where he has been concerned with integrated circuit ESD protection, CMOS latchup testing, fab process reliability, signal integrity, system ESD testing, and design and testing of standard IC layouts. He is now a Senior Principal Engineer at Intel. He has received the Intel Achievement Award for his patented ESD protection devices, which have achieved breakthrough ESD performance enhancements for a wide variety of Intel products. He now holds thirty-one patents, with several more pending.

Dr. Maloney received Best Paper Awards for his contributions to the EOS/ESD Symposium in 1986 and 1990, was General Chairman for the 1992 EOS/ESD Symposium, and received the ESD Association's Outstanding Contributions Award in 1995. He has taught short courses at UCLA, University of Wisconsin, and UC Berkeley. He is co-author of a book, "Basic ESD and I/O Design" (Wiley, 1998), and is a Fellow of the IEEE.

Abstract

The standard 0-ohm Human Body Model waveform can be integrated, usually on the oscilloscope being used, and the 10-90% rise time of the resulting charge Q(t), along with its final value Q(∞), used to determine an exact R and C for the discharging network. The measured rise time of $I_0(t)$ (required to be 2-10 ns) is used to formulate a reduction chart that transforms the 10-90% Q(t) rise time into the RC time constant. This measurement is nearly effortless and could be used as a quick check or even as a standard for waveform acceptance.

A 20-90% Q(t) rise time may better indicate RC if there is early oscillation of the HBM waveform.

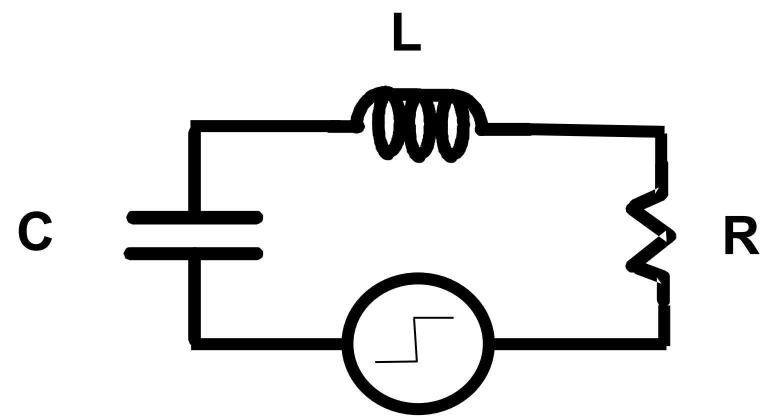
A simple expression for rise time of $I_0(t)$ is derived from a 4-element HBM circuit model with 3-poles and a zero, as approximate values of the elements are known.

2-pole HBM solutions

- The poles are $P_{1,2} = \omega\left[-D \pm \sqrt{D^2 - 1}\right]$
- where $D = \dfrac{RC}{2\sqrt{LC}}$ the damping factor, and
- $\omega = \dfrac{1}{\sqrt{LC}}$ the characteristic frequency

For HBM, R≈1500 ohms, C≈100 pF, L≈3-15 uH

$$Y(s) = \frac{Cs}{LCs^2 + RCs + 1},$$



Current I = VY

V(s) ≈ Vo/s

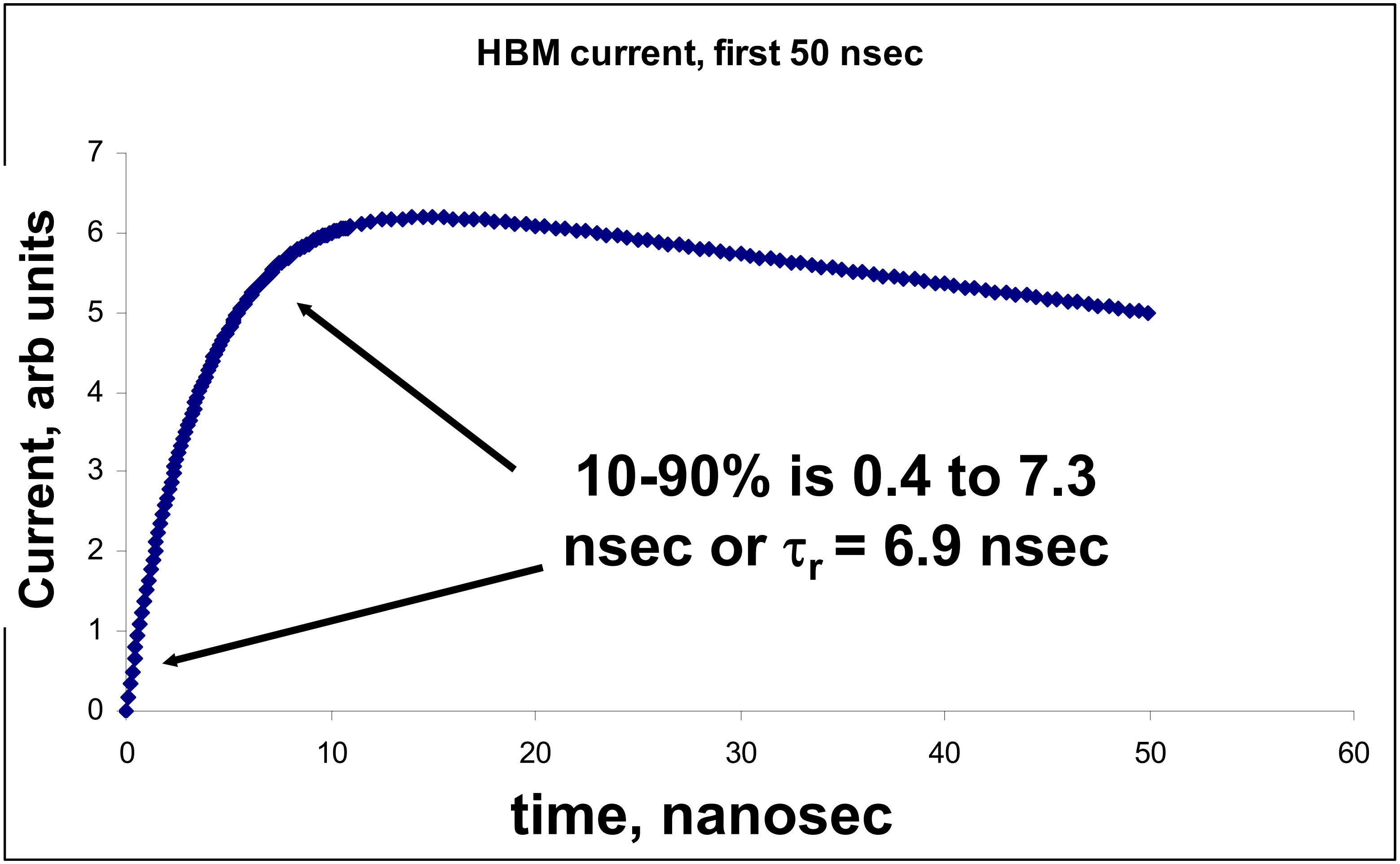
Ref: see [1,2]

2-pole HBM current solution

$$I_0(t) = \frac{[\exp(-p_1 t) - \exp(-p_2 t)]}{(\tau_1 - \tau_2)}, \tau_1 = \frac{1}{p_1}, \tau_2 = \frac{1}{p_2}.$$

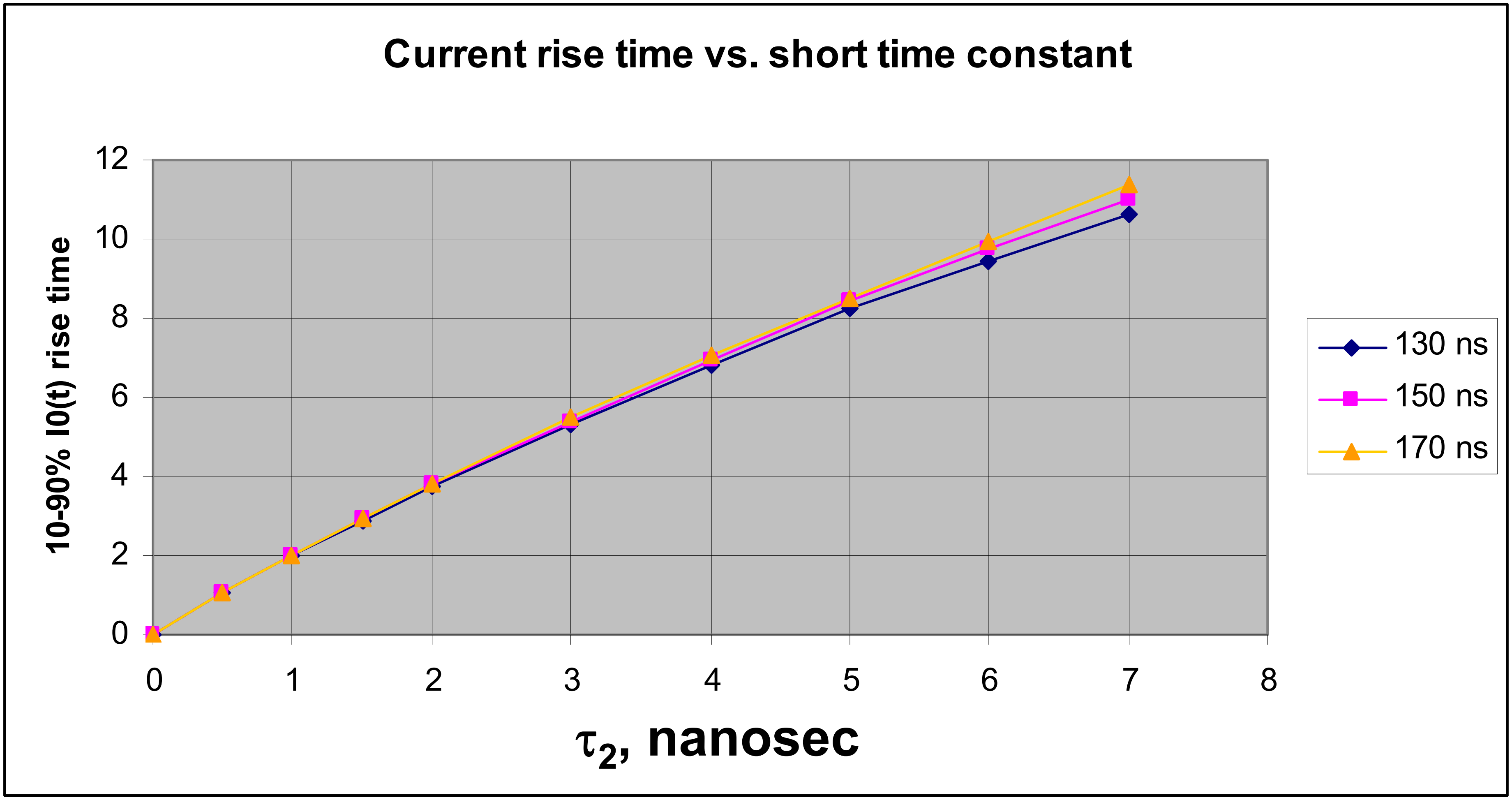
- **Let $p_{1,2}$=-$P_{1,2}$ (positive real numbers)**
- **τ_1 is close to required 150 nsec**
  - **this means D is large**
- **τ_2 determines rise time (next pages)**
- **$\tau_1 + \tau_2$ = RC [1,2]**

HBM $I_0(t)$ rise time, calculated



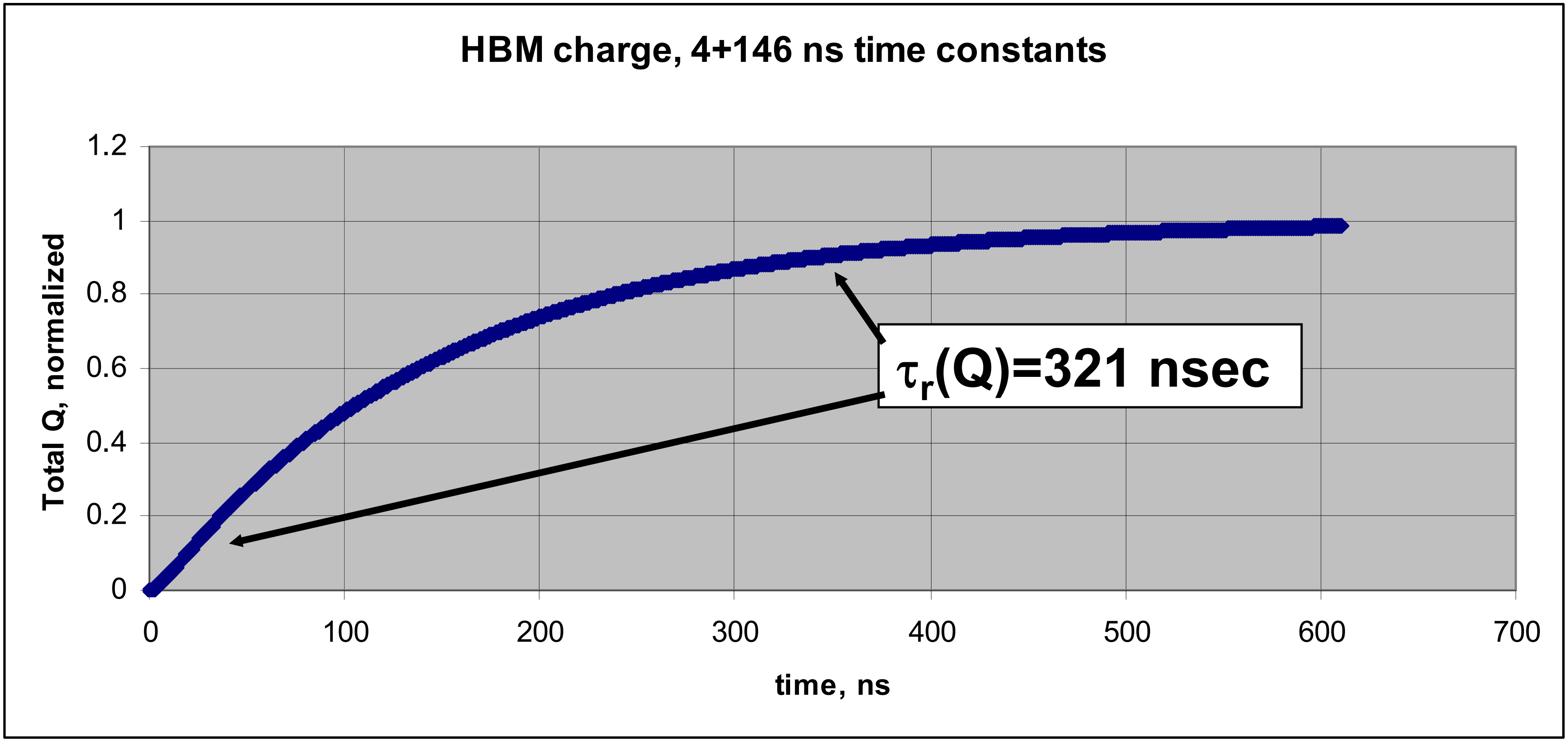
τ_2 of 4 nsec→ τ_r of 6.9 nsec

HBM current rise time → τ_2



Fairly consistent relation within the range of acceptable RC decay constants

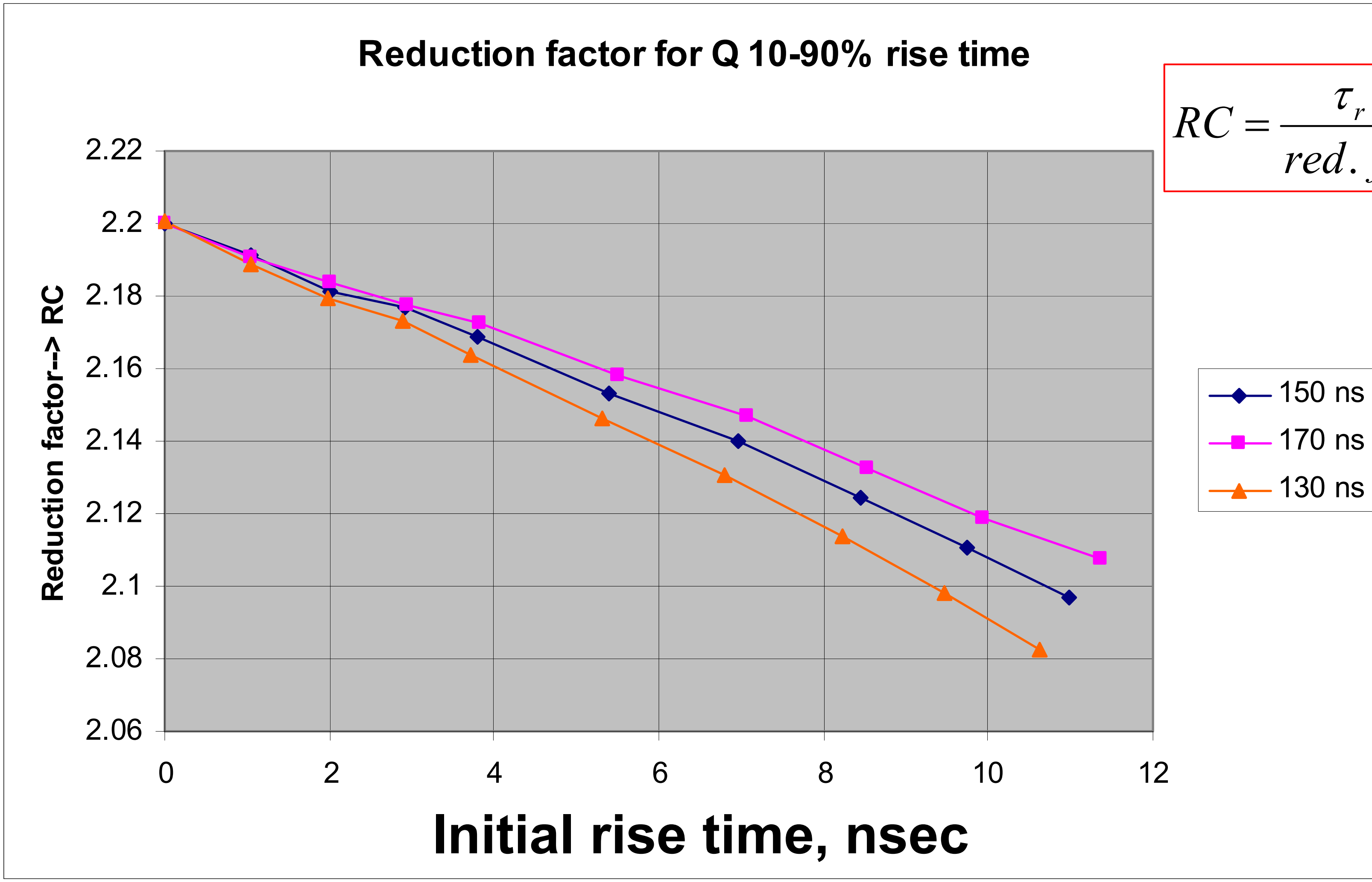
Integrated current Q(t)→ RC



10-90% Q(t) rise time maps back to RC=150 nsec (= $\tau_1 + \tau_2$)

Here, reduction factor ≈ 2.14

Reduction factor chart

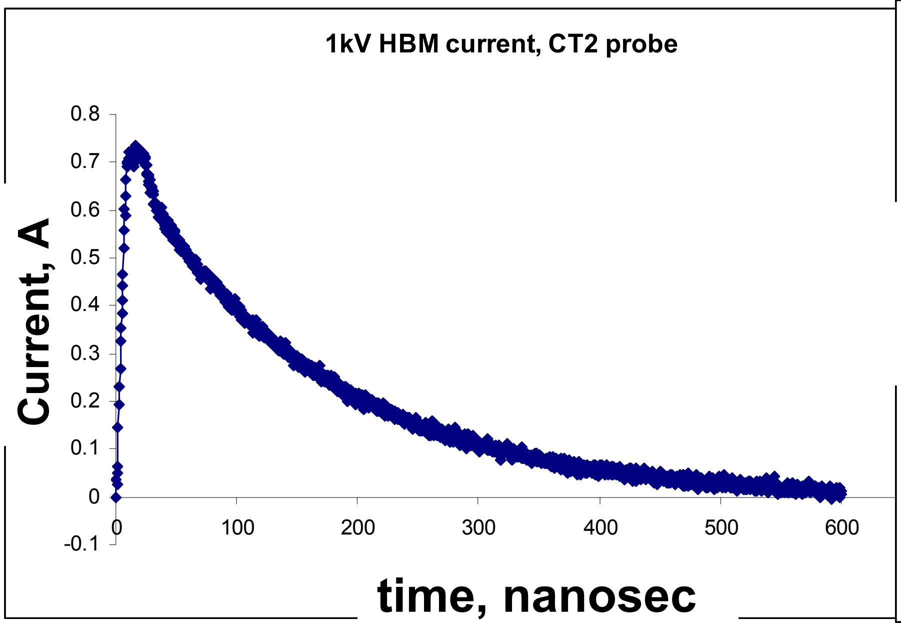


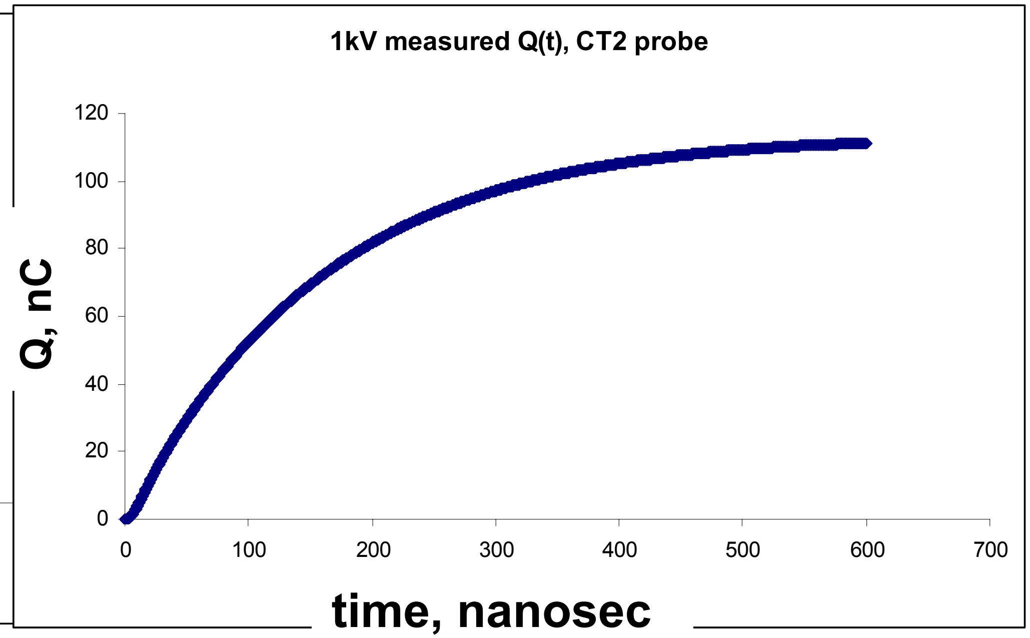
$$RC = \frac{\tau_r(Q)}{red.\ factor}$$

Covers acceptable range of $I_0(t)$ rise times and RC

Iteration increases accuracy

Example: 256-pin Zapmaster



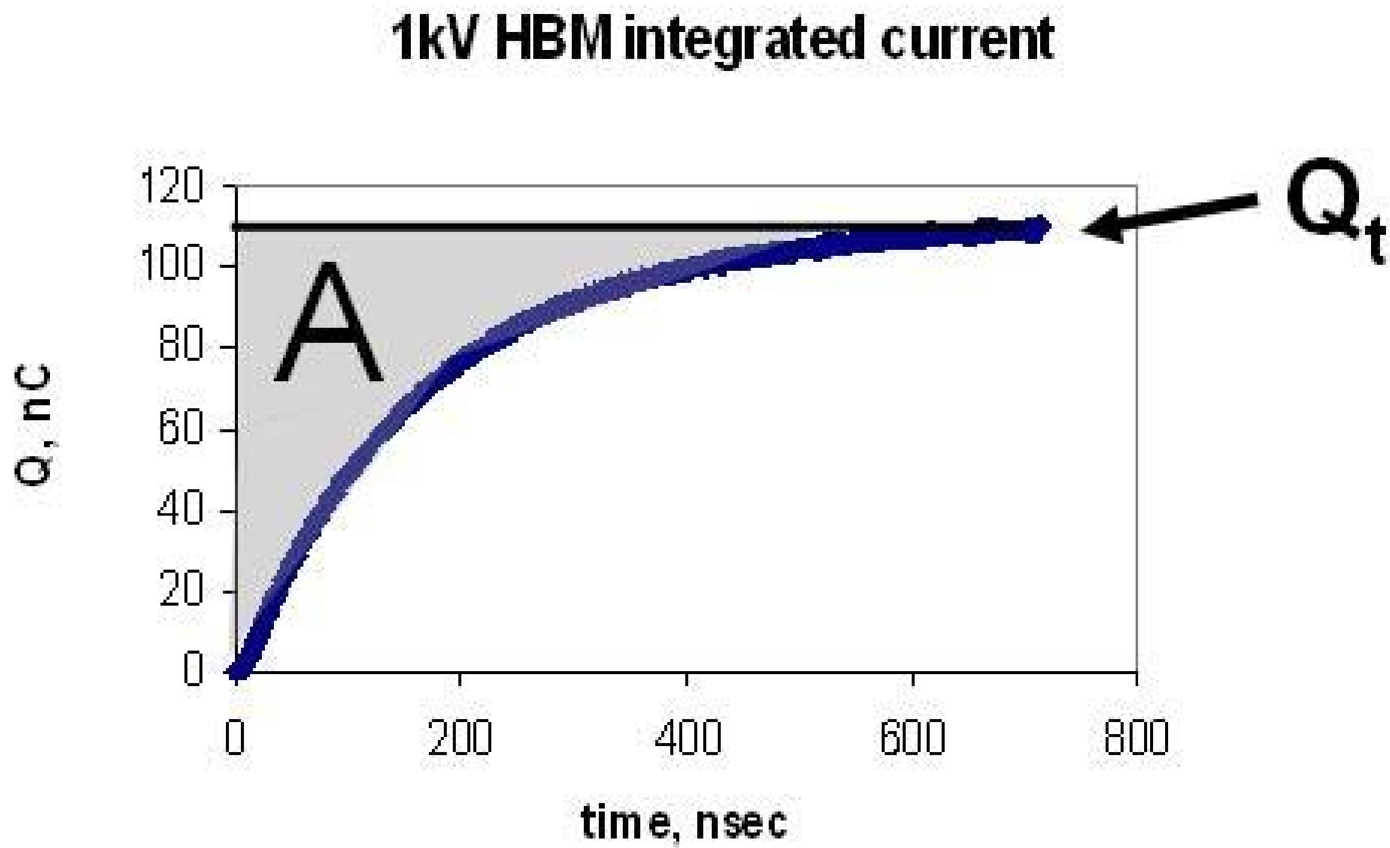


$I_0(t)$; τ_r=6.76 nsec

$Q(t)$; $\tau_r(Q)$=345 nsec

Most scopes can readily produce both waveforms

RC from centroid [2]



RC=A/Q_t, even if >2 poles in the circuit model [2]

Compare our estimates with this more rigorous method

HBM Testers Compared

Tester & voltage	**Qt→ cap(pF)**	**RC, ns (centroid)**	**RC, ns (10-90%)**	**ΔRC, % difference**
1kV, 256 Zapmaster	114.4	161.8	160.9	0.57
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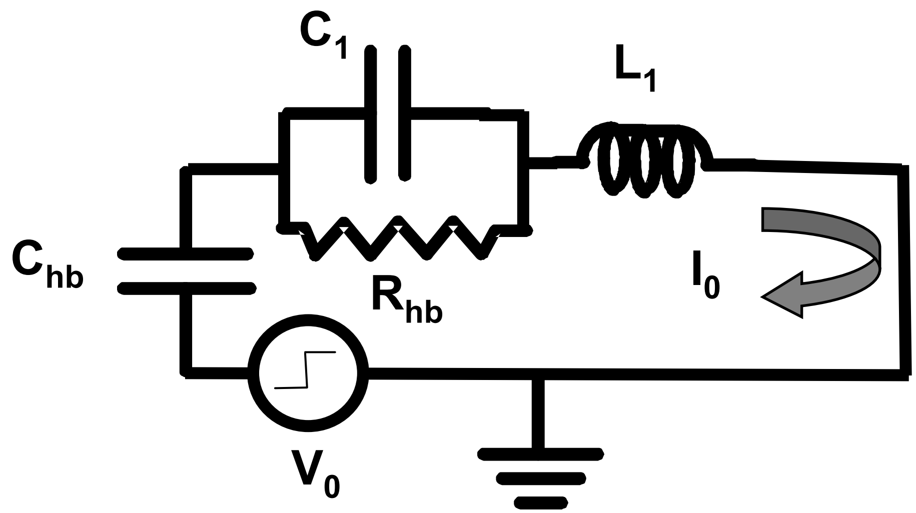
4kV, MK-4	114.2	149.2	147.7	1.01

τ_r(Q) gives an excellent estimate of RC

Next topic: 3-pole HBM circuit

- Models stray cap C_1 across R_{hb}
  - Accounts for more waveform details [3]
- What is the effect of C_1?
  - Splits the 2nd pole into two, moves 1st pole slightly
  - Split pole is a complex conjugate pair if C1 is large enough; introduces early ringing
    - But most HBM testers don't ring
- Effect of C_1 and L_1 on rise time can be derived through perturbation and tau sum rule [2]

3-pole HBM model



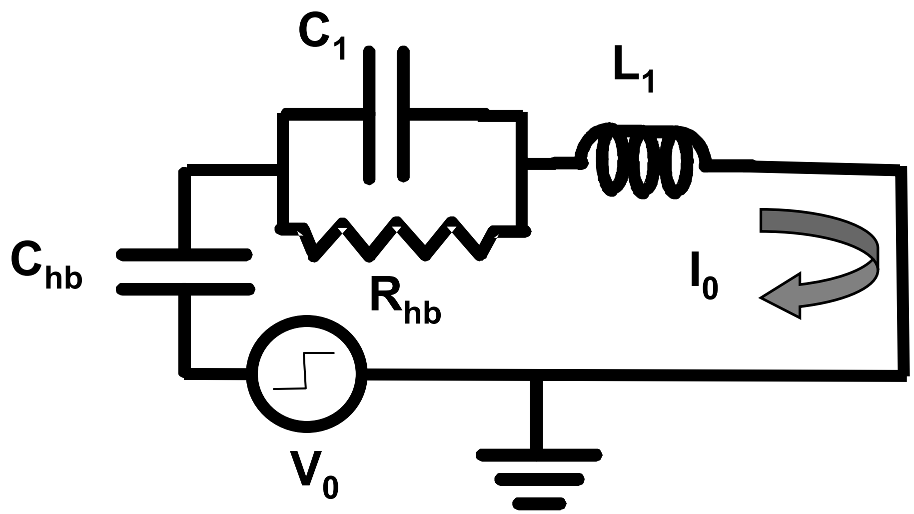
Reduces to 2-pole model for vanishing C_1:

$$I_0(s) = \frac{V_0 C_{hb}(1 + R_{hb} C_1 s)}{1 + b_{1-0}s + b_{2-0}s^2 + b_{3-0}s^3},$$

where $b_{1-0}=R_{hb}(C_{hb}+C_1)$, $b_{2-0}=L_1C_{hb}$, $b_{3-0}=L_1C_{hb}R_{hb}C_1$

Now $b_{1-0}=\tau_1+\tau_2+\tau_3$; sum of reciprocal network poles [2]

Estimating rise time



Suppose L_1=0. Then there is a single pole

$$s_0 = -\frac{1}{R_{hb}(C_{hb}+C_1)} = -\frac{1}{\tau}$$

Now with $L_1 \neq 0$, suppose the still-dominant pole becomes $\frac{1}{s_1} = -\tau + \Delta\tau$. $\Delta\tau$ represents the reciprocal sum of "rise time poles".

Rise time, 3-pole model

- Once again, $s_0 = -\frac{1}{R_{hb}(C_{hb}+C_1)} = -\frac{1}{\tau} \qquad \frac{1}{s_1} = -\tau + \Delta\tau = -\tau_1$

- It can be shown that

$$\Delta\tau = \frac{L_1}{R_{hb}}\left(1 - \frac{2C_1}{C_{hb}} + \frac{L_1 C_{hb}}{R_{hb}^2 (C_{hb}+C_1)^2}\right) + \cdots$$

- This $\tau_2+\tau_3$ maps to initial 10-90% current rise time as in the earlier chart, and then maps to the reduction factor chart. Works best for "small" C_1.

Any pitfalls?

- Be suspicious of early overshoot/ringing
  - C_1 causes this [3] but not on many testers.
    - 20-90% rise time for $\tau_r(Q)$ should be better, as window starts past the ringing
    - Cubic solver shows behavior clearly
    - In short, if there are complex conjugate poles, the reduction factor chart is less accurate if based on $I_0(t)$ rise time alone
      - Could adjust for ringing amplitude too, but there's always the centroid method [2]

Conclusions

- RC element extraction from HBM 0-ohm waveforms is highly accessible
  - $I_0(t)$ waveform and integral can be captured on a scope, rise times and total Q noted
  - These quickly reduce to the principal R and C values for the HBM network, simplifying lab checks
- Applies to HBM models with 3 or 4 elements (2 or 3 poles), parasitic L_1 and C_1 included
  - Rise time expression for 2 or 3-pole model is developed and shows influence of parasitic L_1 and C_1
  - Best if C_1 is “small” but that is true for most HBM testers we use

References

- [1] Y. Ismail, et al., “Equivalent Elmore Delay for RLC Trees”, ACM DAC, 1999.
- [2] T.J. Maloney, “HBM Tester Waveforms, Equivalent Circuits, and Socket Capacitance”, EOS/ESD Symposium Proceedings, 2010, pp. 407-415.
- [3] K. Verhaege, et al., “Analysis of HBM ESD Testers…”, EOS/ESD Symposium Proc., 1993, pp. 129-137.