Observed ESD Transient Fields Near by Rolling Metal Spheres

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***Abstract*—Transient fields associated with ESD events between two rolling metal spheres (diameter:4.0mm -12.7mm) in a plastic box (material: polystyrene) are experimentally analyzed using a short monopole antenna, which located near by the spheres. A very strong and ultra fast impulsive field (amplitude: 10V-25V at 50ohm, pulse width: some 60ps) is observed nearby the rolling spheres. Observed impulse polarity (positive going or negative going) will be governed by movement direction (fixed unidirectional current) of the spheres against the antenna.**

***Index Terms*—ESD, rolling metal spheres, transient fields, ultra fast impulse, impulse polarity**

INTRODUCTION

In electrostatic and electromagnetic view point, real electrostatic discharge (ESD) phenomena will be occurred following dynamical situations.
/ A person stood up from a steel piped chair and away.
/ Then, the chair is electrified due to friction between person's cloth and chair's sitting surface. The charge voltage generate around 1kV ~ 10kV depends on friction speed, materials, humidity and leakage resistance to ground. The chair's charge polarity has usually minus (-). (Depend on triboelectric series between 2-materials)
/ The other person moves adjacent non-charged chair incidentally collide or bump with each other.
/ At this moment, ESD (spark discharge) happens between both chair's metal parts.
/ With ESD events, intense transient electromagnetic fields are emanated to the surrounding space.
/ In some cases, field couples to an electronic system such as network control computer placed near by the chairs causes severe malfunction.

To simulate this EMI (electromagnetic interference) phenomenon caused by ESD, an ESD-gun specified by IEC 61000-4-2 is usually used. However, this testing method only gives applicable in situation of direct discharge from a charged human body. No discharge current is injected to the victim system at indirect ESD [1] phenomena such as above situation. Author has been experienced that the EMI occurrence caused by chair's ESD was strong depends upon the chair's movement direction to the victim system. To prove the EMI phenomena due to indirect ESD in moving conditions, especially in view of impulsive fields polarity, small metal-metal collision system, which behaves more repeatable and quantitative rather than chair's collision trials, was constructed.

I. EXPERIMENTAL SYSTEM

A. Charge-discharge Object

Two metal spheres, which diameter (D) from 4.0mm and 12.7mm made by brass or steel, were used as a charge-discharge object. To generate ESD, these 2-metal spheres housed in a polystyrene plastic box (W94mm x D60mm x H14mm) slant some 5 degrees to roll and collide them at the edge (corner). Fig.1. Measured and calculated capacitance of the sphere are listed in Table 1. The polystyrene has charged always negative by friction (rolling) with metal (brass, iron) spheres. The sphere charge polarity is always plus.

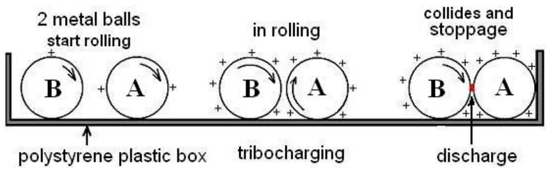

Fig.1. Two metal spheres in the polystyrene box.

Two metal balls (A and B) set tandem in the polystyrene box and slant to move. Left: Start rolling, Middle: In rolling, Right: stop and collides at the corner. At the collision, discharge occurred.

TABLE 1
Sphere diameter, material and capacitance.

Diameter [mm]	Material	Capacitance [pF]	
		Measured	Calculated*
4.0	Brass	0.2	0.22
6.0	Steel	0.3	0.28
6.35	Brass	0.35	0.35
9.52	Brass	0.5	0.53
11.0	Steel	0.55	0.61
12.7	Brass	0.65	0.71

*Capacitance to the free space is calculated by following equation.

$$C = 4pe_0 r = 2pe_0 D \quad [F]$$

ε_0 = 8.8542 x 10 $^{-12}$ [F/m] --- permittivity of vacuum
r: radius of sphere [m]
D: diameter of sphere [m]

B. Electrostatic Measurement Instruments

Static charge
1) ME M-284 Nano Coulomb Meter + Faraday Cup
2) KSD NK-1001 Nano Coulomb Meter
3) ADVNTST TR8652 Digital Electrometer

Charge voltage
1) SSD Statiron DX Surface Voltmeter

C. Electromagnetic Measurement Instruments

Oscilloscope
1) Tektronix TDS6804B DC-8GHz, 20GS/s
2) Tektronix DSA71254 DC-12.5GHz, 50GS/s

Antenna
1) IPL SMA-05 E-field, 5mm, Ultra Broad Band
2) IPL SMA-10 E-field, 10mm, Ultra Broad Band

Microwave Coaxial Cable
1) Jyunkosha DGM024-1000 DC-18GHz, 1m, 50ohm
2) HuberSuhner Sucoflex 103 DC-30GHz, 1m, 50 ohm

RF Attenuator
1) HP 8493A DC-12.4GHz, 10db 2W (avg) ,100W(peak)

ESD Detector
1) IPL ES-98P ESD detector (impulsive signal receiver)

D. Transient Field Measurement Methods

To capture transient fields near by spheres, a 10mm length short monopole antenna is set at distance d from the polystyrene box end. Fig.2. The box's one end lifts some 5-degrees, two balls (A and B) start to roll. The balls are toward to the box end and stop/collide. Final velocity of the rolling balls just before the collision is around 30cm/s.(max 31cm/s @4mm, min 26cm/s @12.7mm) At this collision, a tiny spark discharge between ball A and B could be occurred. To place an ESD detector near by the box, it is easy to detect /recognize discharge event without monitoring the oscilloscope trace.

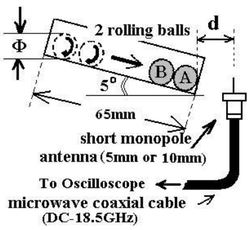

Fig.2. Two balls (A and B) in the polystyrene box and antenna position (distance d from the box end).

Since radiated transient field [2] has very fast and strong, a short monopole antenna [3], 5mm or 10mm, is used in this measurement. The 5mm antenna's frequency characteristic is shown in Fig.3. It is noted that the antenna's frequency characteristics show ultra broad bands, some 100MHz to 3GHz with + - 3db flatness, and its usable up to at least 10GHz.

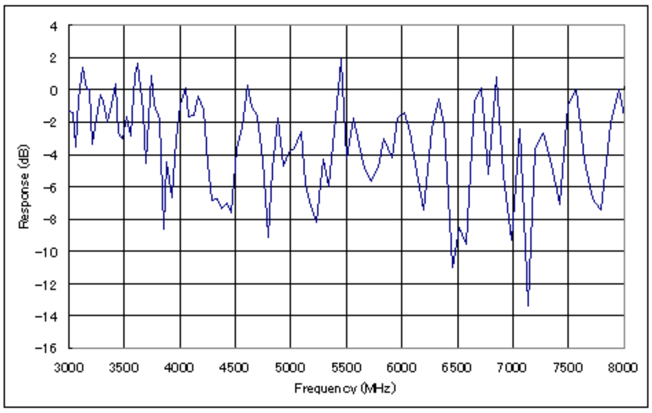

Fig.3. A 5mm antenna's frequency response chart. (3000MHz to 8000MHz)

Due to strong impulsive signal reception on the antenna, which placed near by a radiation source (ball A and B), a 10db (some 1/3.16) microwave attenuator is used to reduce the signal amplitude. And also, to avoid signal distortion on a transmission line, a broadband microwave coaxial cable, such as DC to 30GHz with 2.92mm (f) connector is used.

II. Experiment Results

A. Charge by Friction (rolling)

Measurement of the of sphere's charge by rolling (travel distance=65-2D) on the polystyrene surface (angle=5degree) is made using a Nano-Coulomb meter (with a Faraday cup). The charge polarity of the sphere is always plus in this experiment. The measurement is made 20 times in each trial (2 balls both rolling and 1 ball rolling in each diameter). The measured data (averaged) and calculated voltage difference are listed in Table 2.

TABLE 2
Measured charge and calculated voltage difference.

Diameter [mm]	2 balls [nC] q_2	1 ball [nC] q_1	$\Delta q = q_2 - q_1$ [nC]	$\Delta V = \Delta q / C$ [Volt]
4.0	0.18	0.13	0.05	225
6.0	0.30	0.14	0.16	480
6.35	0.39	0.21	0.18	510
9.52	0.87	0.45	0.42	794
11.0	1.13	0.60	0.53	867
12.7	1.36	0.71	0.65	922

Note: The charge polarity of a ball is plus.

B. Transient Fields by Collision

Transient electromagnetic fields caused by 2-spheres collision (discharge) are measured using a 5mm or a 10mm short monopole antenna, which located distance d from the box. The antenna receives E-field of the transient fields. The antenna is connected to the high speed digital oscilloscope by using a microwave coaxial cable (length 1m).

1) Antenna induced voltage at relatively distant point.

To get total view of the transient fields caused by two spheres (12.7mm) collision, a 5mm antenna is placed a relatively distant point (d) from the box (discharge point). Fig.4.

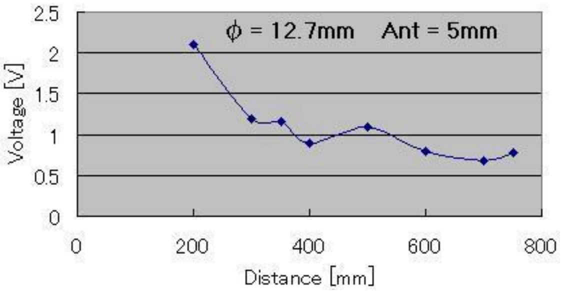

Fig.4. Antenna induced voltage as a function of distance d. Sphere diameter: 12.7mm, Antenna: 5mm, Induced voltage: peak to peak, Distance d: 200mm to 750mm

The measured data show that the induced voltage V_{pp} (peak to peak) of the antenna which located at relatively distant point hold small fluctuations with distance increasing from d=200mm (V_{pp} = 2.1V) to d=750mm (V_{pp} =0.81V).

2) Antenna induced voltage near by the box.

The antenna-induced voltage (zero-peak) near by the box in each diameter is measured. Antenna:10mm, Distance d:5mm. Fig.5.

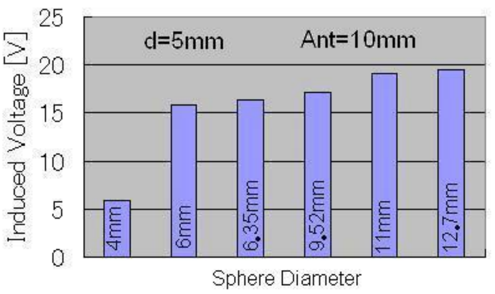

Fig.5. Antenna induced voltage (zero-peak) as a function of sphere diameter. Antenna:10mm, Induced voltage: zero to peak, Distance d: 5mm.

The antenna-induced voltage (zero to peak) increases with increasing diameter but gradually saturates 11mm and 12.7mm. Fig.5. For the voltage level of diameter 12.7mm, some 20V can be observed in this experiment conditions, in contrast with the 5mm antenna induced voltage some 2V at distance 200mm as shown in Fig.4.

3) Antenna Induced Waveforms

It is confirmed that the induced voltage of the short monopole antenna, which located near by the box show impulsive waveforms in any sphere diameters. Fig.6. However, in some cases, the waveforms tend to be ringing with a specific frequency. Fig.7.

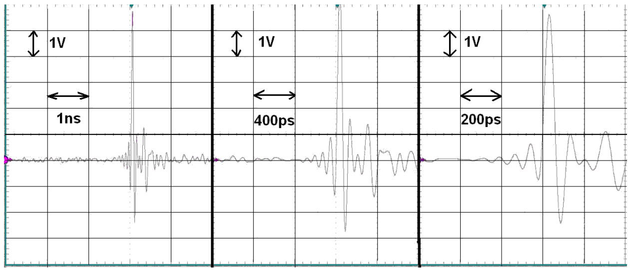

Fig.6. Typical impulsive waveforms. Sphere diameter: 4mm, Antenna: 10mm, Distance d: 10mm. V:1V/div, H:1ns/div (Left), 400ps/div (Center), 200ps/div (Right) Note: These waveforms are merged with 3-different discharge events (different time).

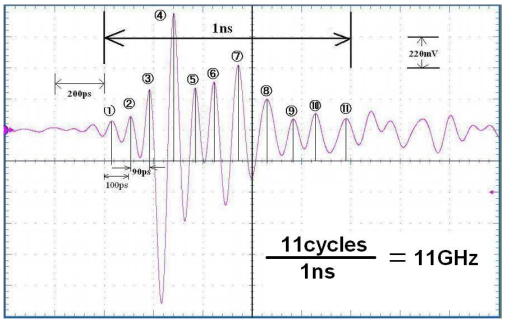

Fig.7. Ringing waveform. Sphere diameter: 4mm, Antenna: 10mm, Distance d: 10mm, Attenuator:10db, V:220mV/div, H:200ps/div, Oscilloscope: DSA71254 12.5GHz, 50GS/s.

4) Antenna position and observed impulse polarity

The polarity of impulsive waveform follows antenna position to the two spheres is confirmed. Based on the experiments, the polarity (plus or minus) decision factor is as follows.

Plus (positive going from steady level): The antenna locates sphere-B side (or sphere-A and B away from the antenna and collide/discharge). Fig.8. Top

Minus (negative going) impulse occurrence: The antenna locates sphere-A side (or sphere-A and B approach to the antenna and collide/discharge).). Fig.8. Bottom

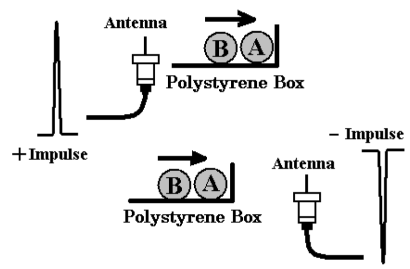

Fig.8. Antenna position to the spheres and observed impulse polarity. + impulse=sphere-A side, - impulse= sphere-B side. (rolling direction: sphere-A leads, sphere-B follows)

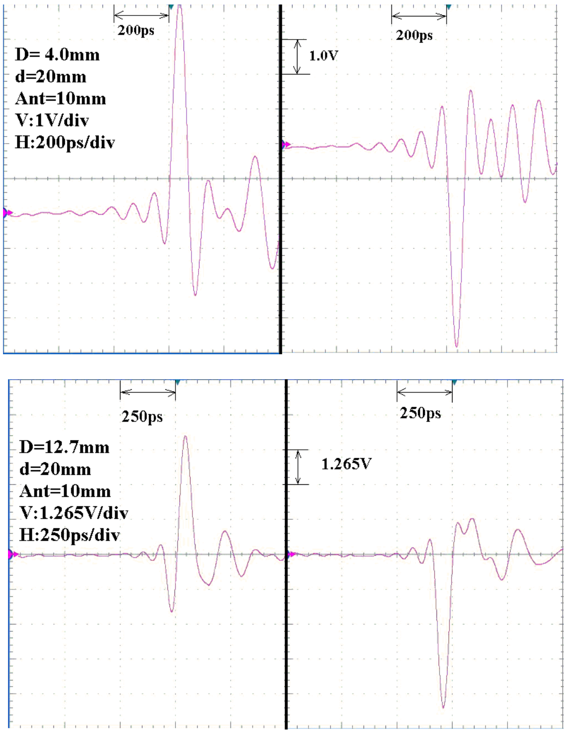

Fig.9. Observed impulse polarity. Ant=10mm, d=20mm
Top: Diameter D=4mm, Left: Antenna B-side,
Right: Antenna A-side, 2-different collision/discharges
Bottom: Diameter D=12.7mm, Left: Antenna B-side
Right: Antenna A-side, 2-different collision/discharges

5) Impulse rise/fall time estimation using oscilloscope's sampling data

Observed impulsive waveforms show ultra fast rise/fall times and high amplitudes. For example, as Fig.9, pulse width some 60ps or less is obtained. This value 60ps indicates oscilloscope bandwidth (12.5GHz). In case of diameter 6.35mm, some 26V(peak to peak) is induced on a 10mm antenna, which located 10mm from sphere-B. The waveform is mono-pulse like as shown in Fig.10 (EXCEL Graph). An enlargement graph of the rise/fall part modified by linear interpolation (1ps interval) is shown in Fig.11.

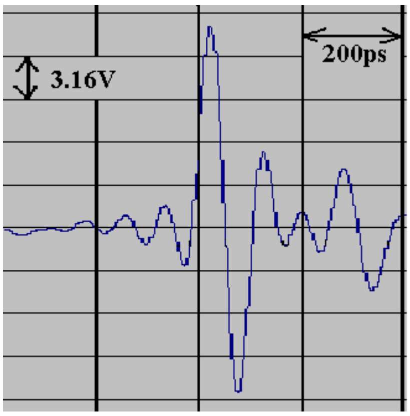

Fig.10. A 10mm-antenna induced voltage waveform. D=6.35mm, d=10mm, V:3.16V/div, H:200ps/div.

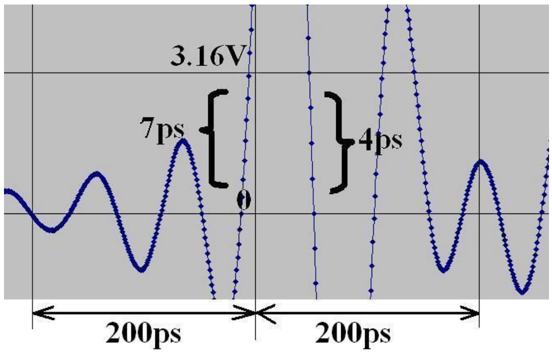

Fig.11. Enlargement of the most fast rise/fall part of Fig.10. Spacing between dot and dot is 1ps. Rise part: 3.16V/7ps, Fall part: 3.16V/4ps.

6) In phase captured waveforms in different discharge events

In order to compare waveforms in each collision/discharge events, some specific data has extracted and overlaid. As a result, very unique figures are obtained. Fig.12. & Fig.13.

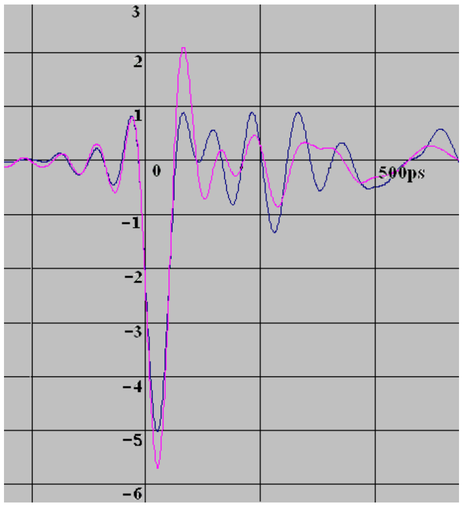

Fig.12. Two overlaid waveforms of 2 different collision/discharges. D=4mm, d=10mm, V:1V/div, H:250ps/div.

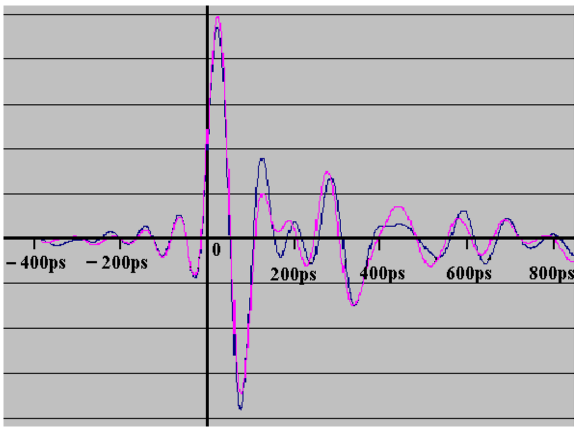

Fig.13. Two overlaid waveforms of 2 different collision/discharges. D=6.35mm, d=10mm, V:3.16V/div, H:200ps/div.

III. DISCUSSION

A. Sphere's Electrostatic Energy and Kinetic Energy

Sphere A and B get both electrostatic energy (W_e) and kinetic energy (W_k) during rolling due to tribo-charge (q) and momentum (p). Lead sphere-A collides to the polystyrene wall and give a temporary displacement to the wall by W_k but remain charge (polarity+). Follow sphere-B collide to sphere-A then deposits both W_e and W_k to sphere-A. To compare sphere's W_e and W_k just before the collision/discharge, calculation is made using following equations. Results are shown in Fig.14. and Fig.15.

$$W_e = \frac{CV^2}{2} = \frac{qV}{2} \quad [J]$$

where;
C: capacitance of a sphere [F]
V: charge voltage of a sphere [V]
q: tribo-charge of a sphere [C] --- + polarity

$$W_k = \frac{mv^2}{2} = \frac{pv}{2} \quad [J]$$

where;
m: mass of a sphere [kg]
v: velocity [m/s] --- proportional to sin θ
p: momentum [kgm/s]

$$W_0 = W_k + W_e \quad [J]$$

W_0: total energy of sphere-B just before the collision

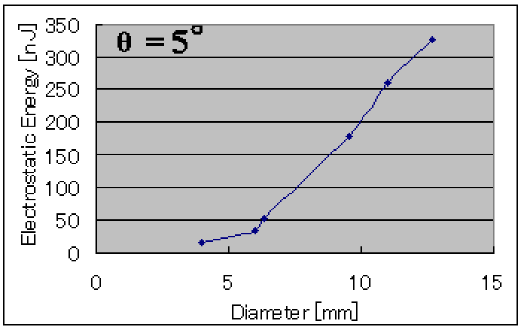

Fig.14. Electrostatic energy as a function of diameter. (raw data =Table 2)

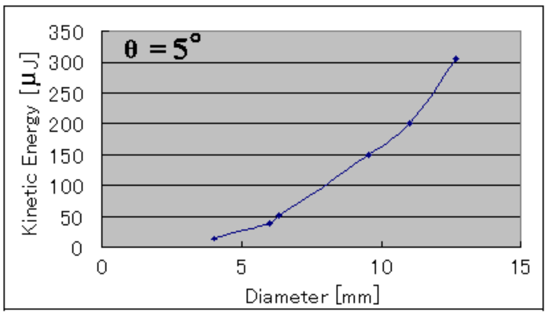

Fig.15. Kinetic energy as a function of diameter.

It also confirmed that the kinetic energy (W_k) is overwhelmingly large than the electrostatic energy (W_e) at the collision. The ratio W_k / W_e will have some 1000 or more greater. Since charge polarity of sphere-A and B is same (plus, in this experiment), repulsion force just before the collision will be excited. On the other hand, the sphere-B approach to sphere-A pushing by mechanical force against repulsion force, a new charge (excessive plus charge) will be induced on sphere-A. This means that a direct energy conversion from mechanical force to electricity is exists. In total, the electrostatic energy of this system (consider as a parallel-plate capacitor) is increase with distance decrease. These theoretical results are consistent with experiment results.

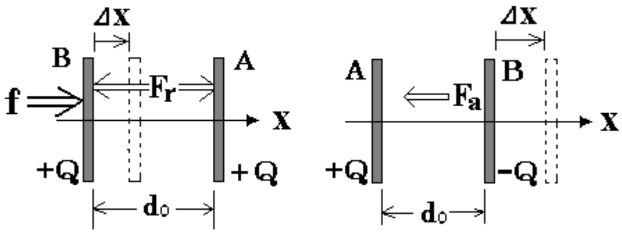

Fig.16. Increment of electrostatic energy due to displacement of plate in constant-charge condition. Left: Repulsion force (F_r) appearance between plates caused by same charge polarity (+Q and +Q) in a parallel-plate capacitor. Right: Attraction force (F_a) appearance between plates caused by opposite polarity (+Q and -Q). f: mechanical (compression) force by movement, F_r: repulsion force by Maxwell stress, F_a : attraction force, d_0: initial distance, Δx: displacement by mechanical force.

$$W = \frac{QV}{2} = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}\frac{Q^2 d_0}{e_0 S} \quad [J]$$

$$\Delta W = \frac{1}{2}\frac{Q^2 \Delta x}{e_0 S} = F\Delta x \quad [J]$$

$$W_E = W + \Delta W = \frac{1}{2}\frac{Q^2}{e_0 S}(d_0 + \Delta x) \quad [J]$$

$$F = \frac{1}{2}\frac{Q^2}{e_0 S} \quad [N]$$

where;
W: initial electrostatic energy at distance d_0
W_E : total electrostatic energy
Q: initial charge
V: voltage
C: capacitance
ε_0 : permittivity
S: area of a plate
d_0: initial distance
Δx: displacement by mechanical force
ΔW: increment of electrostatic energy
F: repulsion/attraction force by Maxwell stress

B. *Generation of Unidirectional Current Flow*

Due to a limited charge (an order of pico Coulomb) stored to sphere surface and a limited discharge time derived from even voltage between two spheres, duration of discharge current will be narrowed. In order to modeling of these situations, a momentary switch (S_{gap}) adapts in between two spheres. Then, discharge happens (S_{gap} "on"), momentary and unidirectional current can be generated. Fig.17.

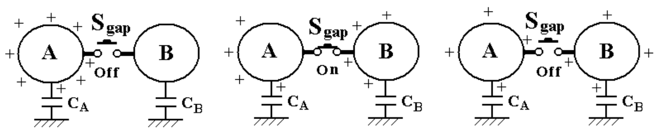

Fig.17. A momentary switch between 2-spheres.
Left: before discharge (off), Center: at discharge (on), Right: after discharge (off)
C_A : sphere-A's capacitance,
C_B : sphere-B's capacitance, $C_B = C_A$
S_{gap}: momentary switch ("off-on-off")

C. *Ultra Fast Rise Time*

Since charge (q) distribution over a sphere (sphere-A, radius r) is complete uniform and point-symmetry construction at any point of the sphere surface, inductance (L) along the current path (length=π r) can be ignored. As for a charge-receptor (sphere-B, r = a) side, same situation occurs. Therefore, at the sphere-sphere discharge, unidirectional and ultra fast rise time current will be occurred. Experiment results show that the rise time of transient field received by a short monopole antenna some 30ps is observed and this value equals to system rise time of an oscilloscope (12.5GHz) to be used.

For sphere diameter (D) is 4mm, an estimated discharge time (Δt) has 20.9ps, in terms of charge (along with length π r) transfer velocity equals to light speed (c). If spark resistance (R) has always fixed 80Ω [4][5], an estimated discharge time (Δt) would have 17.6ps, in terms of time constant (τ=CR) equals to Δt. For D=12.7mm, Δt=66.5ps (π r /c) and Δt=56.8 ps (CR). According to experiment results, which waveforms obtained by a 12.5GHz oscilloscope, the 4mm sphere's pulse width has some 60ps and the 12.7mm sphere has some 80ps.

D. *Impulse Polarity of Transient Fields*

Charge polarity of sphere A and B always measured plus and no negative charge is observed. Table.2. On the other hand, transient fields forms impulsive has own polarity, which depend on antenna location against sphere-A side or sphere-B side under a given rolling direction.

In the experiment, rolling direction sphere-A leads sphere-B follows, a negative going impulse is observed at the antenna, which located sphere-A side. The sphere-A's charge polarity be assumed plus. Because, a sudden static potential drop of the sphere-A at collision/discharge creates a negative dynamic field (-E). On the contrary, for the sphere-B, which accepts positive charge from the sphere-A creates a positive dynamic field (E). Then, antenna at the sphere-B side, a positive going impulse will be received.

E. *In Phase Waveforms by Different Discharge Events*

In spite of different discharge events, matched waveforms are captured using a 12.5 GHz oscilloscope. Fig.12. Fig.13.It is seen that there are quite large rise time differences exist between discharge events and system bandwidth (f_{BW}) of the oscilloscope to be used. In reality, 2-overwrapped first leading edge of impulse waveforms extremely matched within 1ps to 2ps. This value (only 1ps to 2ps difference) is hard to explain by ordinal discharge mechanism under finite and scalable charge. However, if the rise time of discharge (t_r) far beyond from the oscilloscope's rise time (28ps=0.35/ f_{BW}), it is explainable. The captured waveform indicates as an extremely fast impulse response of the oscilloscope.

IV. Conclusion

Transient fields associated with sphere-sphere ESD is experimentally analyzed. Charging process during rolling phase also investigated in terms of force-energy conversion. In just before the collision, electrostatic energy could be increased due to compression force applied against electrostatic repulsion force to be appeared between spheres (same charge polarity). The discharge current rise time will be far beyond oscilloscope's rise time 28ps (12.5GHz bandwidth). Observed impulse polarity can be explained by the unidirectional discharge current flow due to the fixed potential difference between leading and following spheres at the moment of collision.

References

[1] M. Honda, "A New Threat - EMI Effect by Indirect ESD on Electronic Equipment", IEEE Trans. IAS, Vol. IA-25, pp.939-944.Sept/Oct. 1989.

[2] P. Wilson and M. Ma, "Fields radiated by electrostatic discharge," IEEE Trans. EMC. EMC-33,1. 1991.

[3] M. Honda, "Indirect ESD Measurement Using A Short Monopole Antenna," IEEE Proceedings of the 1990 International Symposium on EMC, pp. 641-645, 1990.

[4] Y. Taka, I. Mori, and O. Fujiwara, "Characteristic Measurement for Air Discharge through Hand-Held Metal Piece from Charged Human Body," IEICE Technical Report, EMCJ2005-40, pp. 109-114. 2005.

[5] S. Isofuku, "Voltage Dependent of Spark Resistance at Low-Voltage ESD in Air and Reed Switch," EOS/ESD Proceedings, EOS-28, pp. 267-274. 2006.