Triboelectric generation of x-rays: Predictions and Results

Eli Van Cleve, Benjamin Lucas, Zach Gamlieli, Eric Wong, David Kamkar, Gilberto Jimenez, Pedro Cortes Jr, Nikhil Mehta, Justen Harper, Dan Cuadra, Michael Hennessey, Jon Fong, Mark Valentine, Dale Fox, and Carlos Camara
Tribogenics Inc.
phone: (949) 981-5224
e-mail: eli@tribogenics.com

***Abstract*— It has recently been shown that triboelectric charging can be used to charge a surface for the production of x-rays. The nature of the x-rays that are produced is dependent on the electric field experienced by the electrons. This field will vary due to both the geometry of the system and the change in the charge density. In this paper we present a simple model for the charge density on the band. A simple apparatus has been constructed to test the model through the production of x-rays. The theoretical charge density of 1.3×10^{11} electrons/cm^2 will generate the measured 35 kV energy, which is consistent with the charge density reported in the literature.**

I. INTRODUCTION

Although the generation of charge through rubbing two materials together, tribocharging, has been known for over 300 years, it was only recently discovered that this process could also be used to generate X-rays [1]. Tribocharging has been used to generate X-rays in several different embodiments [1-3]. This method of generating X-rays allows for direct conversion of mechanical motion into X-ray emission. Here we describe a device based on this principle. The effect is driven by triboelectrification: the conversion of friction into a charge imbalance between contacting materials. Tribocharging can be realized by tapping, rolling or sliding dissimilar materials [4]. In the X-ray source described here, the charge generation takes place by the sliding contact between a polymer and a metal [5].

II. MODEL OF THE SYSTEM

A. Fundamental Model:

The details of the charge density on a surface that has been tribocharged is dependent on many factors: 1) the initial charge accumulated on the system due to contact electrification, 2) the geometry surrounding the surface, 3) the electrostatic potentials surrounding the tribocharged surface and 4) the details of the chemistry of the surface. The initial charge buildup and the chemistry of tribocharging has been extensively studied [2,3,6-8]. Until now the effect of geometry and electrostatic potentials on the charge on the surface of the system after the two surfaces have been released in vacuum has not been studied, although some work has been done in nitrogen environments [9,10]. Here we present a simple model of the charge density on the surface as a function of time.

An electron on the surface of a charge will experience two forces, the electrostatic force pulling it off the surface that is generated by the surrounding electrons, and the binding force between the electron and the surface itself. The surface charge density, in vacuum, can be represented by a simple rate equation:

$$\frac{d\sigma[t]}{dt} = -q\lambda E[\sigma[t]] + F_b\delta \tag{1}$$

where $\sigma[t]$ is the charge density of the surface as a function of time, q is the charge of the electron, $E[\sigma[t]]$ is the electric field felt by the electron, F_b is the binding force between the electron and the surface and λ and δ are related to the probability of the particle staying on the surface or leaving it.

When the electron is sufficiently close to the surface, the electrostatic field that it experiences is nearly equivalent to that of an infinite plate. The field will become more complex as the distance between the electron and the surface grow. For this work we use the parallel plate approximation. This assumption makes it possible to find an analytic solution to equation (1). The equation for the electric field over a single charged plane is:

$$E = \frac{\sigma[t]}{2\varepsilon_0} \tag{2}$$

where ε_0 is the electric permittivity of vacuum. By combining equations (1) and (2), setting the initial conditions such that $\sigma[0] = \sigma_0$ and solving the differential equation, the charge density is:

$$\sigma[t] = \alpha F_b\delta + e^{-t/\alpha}(\sigma_0 - \alpha F_b\delta) \tag{3}$$

where $\alpha = 2\varepsilon_0 / q\lambda$ which is the time constant for the electron emission off of the surface. This model is valid in vacuum but not in any gaseous environment where the discharge is dominated by Paschen's curve, such as in the experiments conducted by Smith and Horn [9]. The dielectric nature of the air will prevent electron field emission and promote discharge events, which is not included in the model.

B. Experimental Apparatus

A simple apparatus is used to test the use of a charged insulator to produce x-rays. A diagram of the apparatus shown in fig 1.

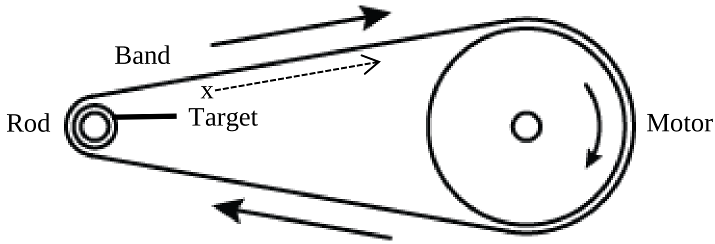

Fig 1: A diagram of the apparatus used to produce x-rays from a tribocharged insulating band. The band is constructed of insulating polymer. It is run over a stationary metallic rod. A small metal target is placed near the rod and below the insulating band. The band is moved around the stationary rod via a motor at 1000-10,000 rpm while the system is held at a pressure below 10^{-4} torr.

At a pressure of 10^{-4} torr the mean free path of nitrogen molecules is about 770 mm, much larger than the distance from the band to the target, therefore the ambient pressure in the chamber should not impact the performance of the system. It is possible that, due to the rubbing and emission of the electrons, the local pressure near the band was higher and impacted the X-ray production and emission. Very little is known about the effect of pressure on the efficiency of X-ray production and we will not address it in this work.

The X-ray emission from the source was measured with a single photon counting solid state X-ray detector (Amptek CdTe 123). In order to prevent pile-up (i.e. simultaneous photon counts that lead to erroneously high energy readings), the detector was placed 90 cm from the target, and a lead pinhole with an aperture of 0.28 mm^2 was placed in front of the detector. At this distance the single photon count rate in the detector was in the order of 1 kHz. Given that the detector has a detection speed of 20 μs, the probability of counting two independent photons at the same time is $4x10^{-4}$. To correct for solid angle we take the ratio of the area of the detector, a, to the area over which the total X-ray flux is distributed, A. The X-rays will be distributed over a half sphere with area $A = 2\pi R^2$, where R is the distance from the focal spot on the anode target. Taking R = 90 cm, A = $5.1x10^4$ cm^2. The detector area is a = $2.8x10^{-3}$ cm^2 and the calculated solid angle is $5.5X10^6$. This means that a total flux of $1x10^9$ X-rays per second results in 550 X-ray counts on the detector. Using this geometry we have measured a total flux corrected for solid angle of about $7x10^8$ X-rays per second. The energy of the output photons was measured to be 35 kV.

C. Numerical Model:

Equation (3) is not in a useful form for this system. We are primarily interested in the charge density as a function of the distance from the point of separation, not time. In order to correct for that we can rewrite equation (1) noting that by the chain rule

$$\frac{d\sigma[t]}{dt} = \frac{d\sigma[x]}{dx}\frac{dx}{dt} = \frac{d\sigma[x]}{dx}v \qquad (4)$$

where v is the velocity of the band. Plugging equation (4) into equation (1) and solving using the electric field in equation (2) we get:

$$\sigma[x] = \alpha F_b \delta + e^{-x/(\alpha v)} (\sigma_0 - \alpha F_b \delta) \qquad (5)$$

where the variables in this equation are the same as they are in equation (3). We set $F_b \delta = \lambda_f$ because it will be impossible to separate those two variables during any experimental fit.

In order to fit the variables, data was taken from figure 9 in [11]. We fit equation (3) to the data to obtain the binding force for the system, λ_f , which came out to be 1.41x10^{-7} C /(s*m^2).

Previous measurements have been made of the initial charge density on metal polymer pairs due to contact electrification [4, 5] (9.4x10^{10} electron/cm^2 and 1.4x10^{11} electron/cm^2 respectively, which is roughly 10^{11} electrons/cm^2). In order to determine the value of α , we calculate the amount of charge being removed from the system from the measured total flux, 6.5x10^8 X-rays/second. During the experiment we were also able to measure the current that was gathered by the target. An ammeter connected to the target and to ground was used to measure the current, which was measured to be on average 7.6 μA. With a total measured flux of 6.5x10^8 X-rays/second we are able to calculate the number of electrons that produce X-rays in our system, which is 72,000 electrons per X-ray, significantly larger than the value of 6,000 electrons required to produce a photon according to Chervenak[12]. The difference most likely implies that only a fraction of the collected current leads to the observed high-energy photons.

Based on our number of electrons per photon, we calculate the electron flux, which is roughly 4.75x10^{13} electrons/second. By dividing the electron flux by the velocity and multiplying by the distance from the rod to the end of the target we can get total number of electrons that are removed, which is 8x10^{10} electrons. By using the above numbers and equation (5) we can then calculate α , which gives us a value of 1.45x10^{-3} seconds.

A plot of the charge density, based on the above numbers placed into equation (5) can be seen in fig. 2.

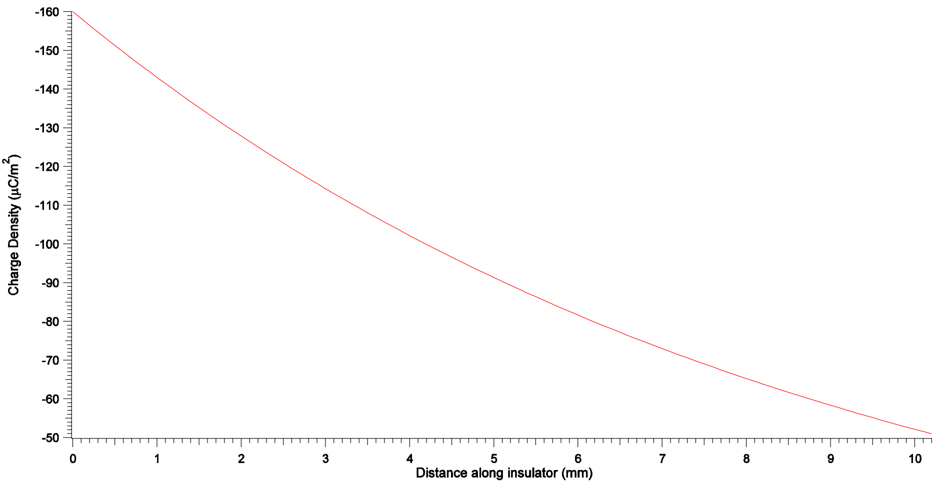

Fig 2: A plot of the charge distribution as a function of distance using a charge density of 1.3×10^{11} electrons/cm^2. This is a standard distance in our system.

Using equation (5) and the above derived values we solved for the charge density as a function of distance along the band. We then combined equation (5) and equation (2) to find the electric field experienced by the electron and hence the electron's energy. The electrons will gain between 15.4 kV and 35 kV when moving from the band to the target.

III. Conclusion

We have presented a simple model based on a decay rate equation to describe the charge density on the surface of an insulating band as it leaves contact with a metal rod. X-ray flux data were taken from the device, and, combined with other measurements to predict the expected maximum photon output energy of our device, which was 35 kV.

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