

# 3D detector with highly resistive electrodes: An electrical model.

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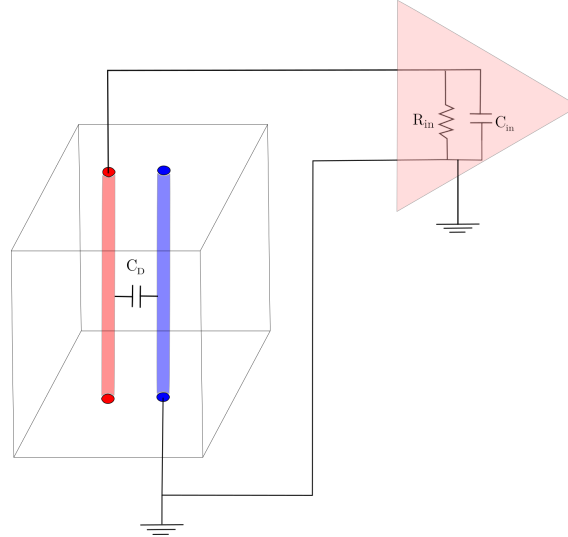
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## Electrical model for 3D column detector

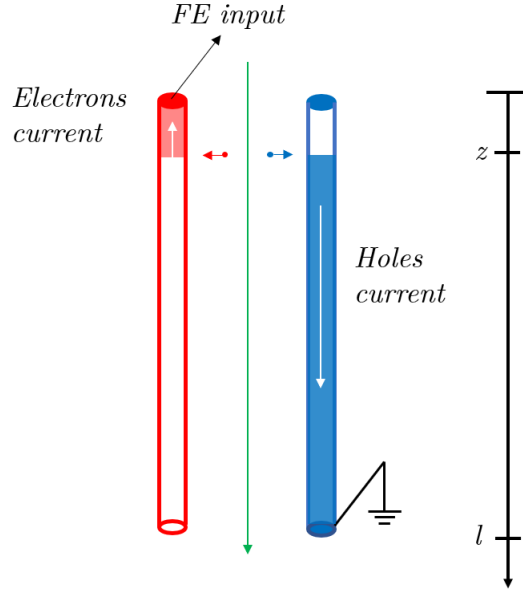
Let's consider a 3D detector with columns with radius  $r = 3.5\mu m$ , distance  $d = 55\mu m$  and length  $l = 500\mu m$ . In this condition for a diamond detector, the capacitance would be around  $C_D \sim 30fF$ . Normally the effect of the detector on signal shape is model considering only the capacitance of such detector and assuming ideal electrodes with no resistance. The voltage at the input of a front-end connected to the detector in this case, would be given by the convolution of the current with a transfer function that, at first order, is a RC low pass filter where the resistance is the input resistance of the electronics  $R_{in}$ , while the capacitance is the sum of the one of the detector  $C_D$  and the input capacitance of the front-end  $C_{in}$  (Figure 1).



**Figure 1.** Simplest description of a detector connected to a front-end electronics

If the detector has highly resistive column this model has to change considering the shaping effect of such electrodes. If we consider a particle with a track parallel to the columns (Figure 2), we can assume that charges produced at different  $z$  induce a current that “sees” a different resistance in series depending on whether they are electrons or holes. The resistance can be written as a function of  $z$ :

$$R_n(z) = R_N \cdot \frac{z}{l} \quad (0.1)$$



**Figure 2.** Model for 3D detector with highly resistive columns .

$$R_p(z) = R_p \cdot \frac{l - z}{l} \quad (0.2)$$

where  $R_n(z)$  is the resistance seen by the electron at  $z$  and  $R_p(z)$  is the one seen by the hole. The electrical model for the electron in position at  $z$  is shown in (Figure 3). With ideal electrodes the transfer function would be:

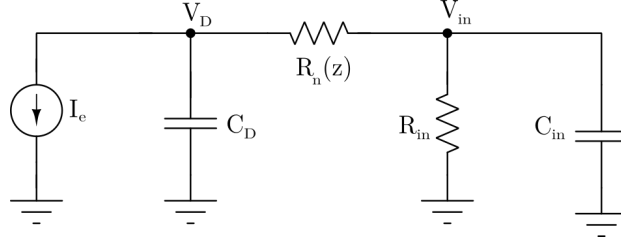
$$V_{in-e}(s) = I_e(s) \frac{R_{in}}{1 + s\tau^*} \quad (0.3)$$

where  $\tau^* = R_{in}(C_{in} + C_D)$ .

If the resistance is considered, the transfer function becomes:

$$V_{in-e}(s, z) = I_e(s) \frac{R_{in}}{sR_{in}C_D + (1 + s\tau)(1 + s\tau_N(z))} \quad (0.4)$$

where we have introduced  $\tau_N(z) = R_n(z)C_D$ .



**Figure 3.** Equivalent circuit for the voltage induced by an electron at  $z$ .

Electrons at different heights  $z$  would induce the same current  $I_e(t)$  but the shaping would be different because of the different resistance in series. We can factorize the transfer function as the following:

$$V_{in-e}(s, z) = I_e(s) \frac{R_{in}}{(1 + s\tau)} \frac{1}{\frac{sR_{in}C_D}{(1+s\tau)} + (1 + s\tau_N(z))} \quad (0.5)$$

We assume as negligible the term:

$$\frac{sR_{in}C_D}{(1 + s\tau)} \quad (0.6)$$

(at low frequency tends to zero while at high frequency tends to the ratio  $C_D/C_{in}$ , so for  $C_{in} > C_D$  the assumption can be reasonable or a factor can be introduced to adapt to the specific case .)

The voltage at the input produced by the induction of the single electron at  $z$  can be written:

$$V_{in-e}(s, z) = \frac{I_e(s)}{(1 + s\tau_N(z))} \frac{R_{in}}{(1 + s\tau)} \quad (0.7)$$

so it can be expressed as the current:

$$I_e(s, z) = \frac{I_e(s)}{(1 + s\tau_N(z))} \quad (0.8)$$

that has to be convoluted with the input impedance of the front-end with no contribution from the detector (the influence of the capacitance  $C_D$  is

already taken into account in the current).

The total current induced by all the electrons at different  $z$  is then:

$$I_{e,TOT}(s) = I_e(s) \sum_{z=0}^{z=l} \frac{1}{(1 + s\tau_N(z))} \quad (0.9)$$

considering also the holes contribution:

$$I_{TOT}(s) = (I_e(s) + I_h(s)) \sum_{z=0}^{z=l} \left( \frac{1}{(1 + s\tau_R(z))} \right) \quad (0.10)$$

Where we have assumed that the same total resistance  $R$  for both columns. The transfer function that models the effect of the highly resistive column in the 3D detector is then:

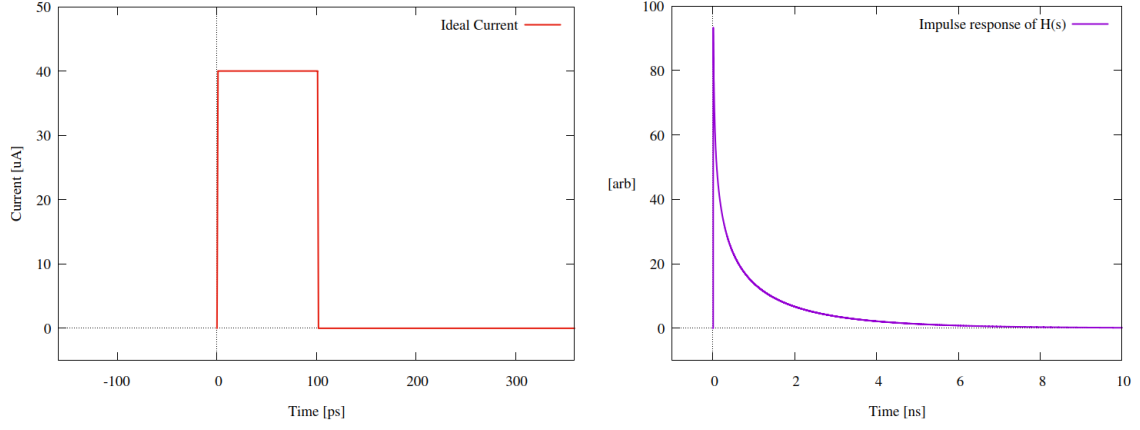
$$H(s) = \sum_{z=0}^{z=l} \left( \frac{1}{(1 + s\tau_R(z))} \right) \quad (0.11)$$

This can be calculated in the time domain as:

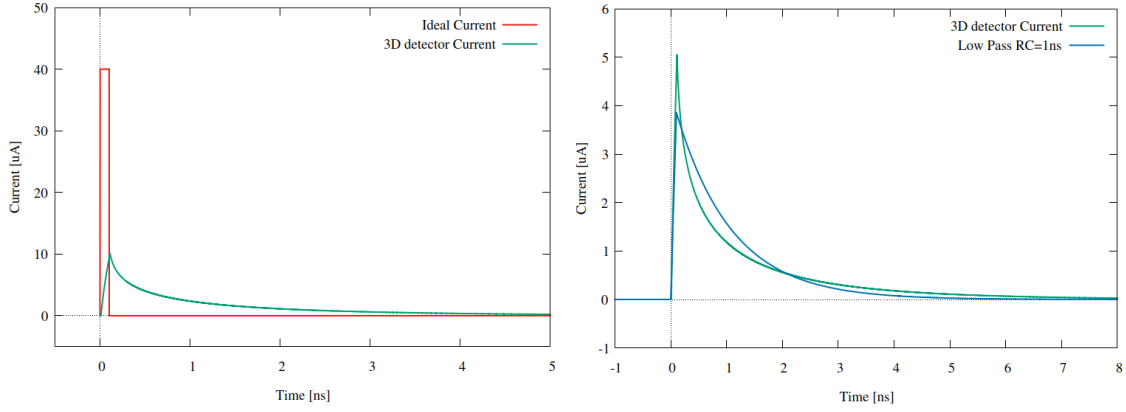
$$H(t) = \frac{1}{k} \left[ \frac{e^{-\frac{t}{\tau_R(z_1)}}}{\tau_R(z_1)} + \frac{e^{-\frac{t}{\tau_R(z_2)}}}{\tau_R(z_2)} + \dots + \frac{e^{-\frac{t}{\tau_R(l)}}}{\tau_R(l)} \right] \quad (0.12)$$

where  $k$  is the number of slices used in the sum. As an example we can consider the effect of such transfer function on a rectangular current with duration  $t_c = 100ps$  and magnitude  $I_0 = 40\mu A$  for a total  $4fC$  of charge (Figure 4 left). Let's suppose the detector has  $R_N = R_P = 100k\Omega$  and  $C_D = 30fF$ . The transfer function in the time domain is shown in Figure 4 right. The effect of such transfer function on the rectangular pulse is shown in Figure 5 left. The signal becomes smaller in amplitude and longer in duration. Figure 5 right, shows a comparison with a current obtained doing a convolution of the ideal current with a low pass filter with time constant  $\tau_{LP} = 1ns$ , which is three times smaller of the product  $RC_D = 3ns$ .

In the specific case the resistances of the electrodes could be different, (if for example we have multiple columns connected in parallel in the return



**Figure 4.** Ideal rectangular current (left) and pulse response of the detector with highly resistive columns (right)



**Figure 5.** Comparison between the ideal current and the one of the 3D detector with highly resistive electrodes (left), Comparison of the 3D detector current with the convolution of the ideal current with a low pass filter with 1ns time constant (right).

path). In this case the correct shape of the total current can be obtained considering separately the electrons current and the holes current. There would be two different transfer function  $H(s)_e$  and  $H(s)_h$  and the total current would be given by:

$$I_{e,TOT}(s) = I_e(s) \sum_{z=0}^{z=l} \left( \frac{1}{(1 + s\tau_N(z))} \right) \quad (0.13)$$

$$I_{h,TOT}(s) = I_h(s) \sum_{z=0}^{z=l} \left( \frac{1}{(1 + s\tau_P(z))} \right) \quad (0.14)$$

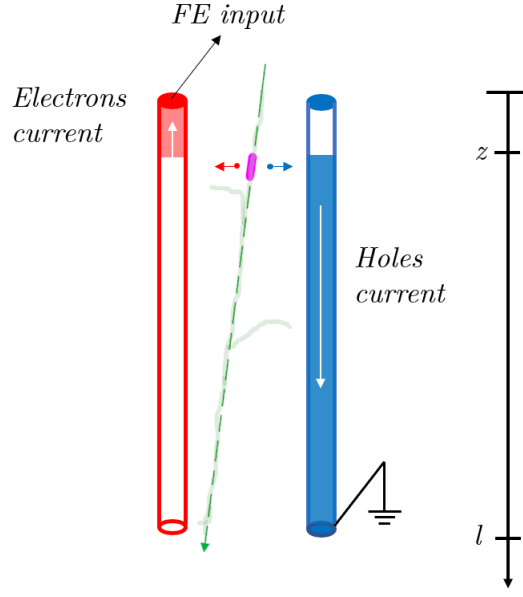
$$I_{TOT}(s) = I_e(s) \sum_{z=0}^{z=l} \left( \frac{1}{(1 + s\tau_N(z))} \right) + I_h(s) \sum_{z=0}^{z=l} \left( \frac{1}{(1 + s\tau_P(z))} \right) \quad (0.15)$$

$$I_{TOT}(t) = I_e(t) \circledast \sum_{z=0}^{z=l} \left( \frac{e^{-\frac{t}{\tau_N(z_1)}}}{\tau_N(z_1)} + \dots + \frac{e^{-\frac{t}{\tau_N(l)}}}{\tau_N(l)} \right) + \\ + I_h(t) \circledast \sum_{z=0}^{z=l} \left( \frac{e^{-\frac{t}{\tau_P(z_1)}}}{\tau_P(z_1)} + \dots + \frac{e^{-\frac{t}{\tau_P(l)}}}{\tau_P(l)} \right) \quad (0.16)$$

The most general case is when we have tracks not parallel to the columns but with an arbitrary direction. We could also have not homogeneous deposition of charge along  $z$ . Considering figure 6, the purple region of the track would have  $dz = \frac{l}{k}$  and position  $z = z_j$  so that the current  $I_{eh}(z_j)$  can be written:

$$I_{eh}(z_j)(t) = \left( I_e(t, z_j) \circledast \frac{e^{-\frac{t}{\tau_N(z_j)}}}{\tau_N(z_j)} \right) + \left( I_h(t, z_j) \circledast \frac{e^{-\frac{t}{\tau_P(z_j)}}}{\tau_P(z_j)} \right) \quad (0.17)$$

The total current would have to be calculated making  $2k$  convolutions for every track, where  $k$  is the number of slices with which we divided the height of the columns:



**Figure 6.** Model for 3D detector with highly resistive columns with arbitrary directory and shape of the tracks.

$$\begin{aligned}
 I_{TOT}(t) = & \left( I_e(t, z_1) \otimes \frac{e^{-\frac{t}{\tau_N(z_1)}}}{\tau_N(z_1)} \right) + \dots + \left( I_e(t, l) \otimes \frac{e^{-\frac{t}{\tau_N(l)}}}{\tau_N(l)} \right) \\
 & \left( I_h(t, z_1) \otimes \frac{e^{-\frac{t}{\tau_P(z_1)}}}{\tau_P(z_1)} \right) + \dots + \left( I_h(t, l) \otimes \frac{e^{-\frac{t}{\tau_P(l)}}}{\tau_P(l)} \right) \quad (0.18)
 \end{aligned}$$

A fast convolution algorithm is needed to produces reasonable statistics. Considering  $k = 100$  as the number of slices ( $dz = 5\mu m$  for a detector with  $l = 500\mu m$ ) if we want a set of  $10k$  waveforms to characterize the hole detector we would have to make about two millions convolutions.