FDC Nominal Cathode Charge Calculation – v4.0

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In this document we are interested in computing the total charge induced on the cathode planes in the FDC prototype chamber. This can then be used to understand the cathode charges on the final full-scale FDC system cathodes. An expression for the charge induced on a single cathode plane can be written as [1]:

$$\mathcal{Q} = N_{ion} \cdot F_{att} \cdot F_{ind} \cdot F_{sh} \cdot \mathcal{G}_{amp} \cdot \mathcal{G}_{gas} \cdot 1.60 \times 10^{-19} \text{ C/e}. \quad (1)$$

where:

- N_{ion} = total number of ion pairs generated by the traversing particle.
- F_{att} = fraction of drift electrons lost due to re-attachment to chamber gas molecules.
- F_{ind} = fraction of anode charge induced on either cathode.
- F_{sh} = fraction of avalanche charge collected by the anode for a given preamp shaping time.
- $\mathcal{G}_{amp}$ = gain of preamplifier.
- $\mathcal{G}_{gas}$ = gas multiplication gain.

Determination of each of the above factors is necessary to compute the total induced charge on either of the cathode planes. For this calculation we will assume factors related to the current FDC prototype geometry, readout, and setup. Thus the path length through the chamber is considered to be 1 cm, the gas mixture is 90% Argon - 10% CO_2, and the readout time window is 350 ns.

- ***N_{ion}***

The number total number of ion pairs (n_T) to consider includes both the primary ion pairs created along the trajectory of the incident charged particles, plus the number of secondary ion pairs created by the primaries drifting to the anode wire. This number can be taken from tabulations by Sauli [2] for an Argon 90% - CO_2 10% gas mixture. The total number of ion pairs created per cm of gas for Argon is given as 94 and for CO_2 as 91. For a gas mixture, we can use the mixing ratio to determine the resulting n_T as:

$$n_T = 94 \cdot 0.9 + 91 \cdot 0.1 = 93.7 \text{ ion pairs/cm}. \quad (2)$$

Given the 1-cm thickness of the chamber active region, we compute N_{ion}=93.7. We have also studied N_{ion} based on fits to our measured FDC prototype data. Using the form of the gas multiplication factor given by Sauli below (see Eq.(4)), we have fit our data and determined N_{ion}=82. This number is reasonably consistent with the value tabulated by Sauli, and certainly within the uncertainties of the quantity that we are fitting. The fit to our measured FDC data is contained in Fig. 1. This figure shows the total charge summed from the U and V cathode layers plotted vs. chamber high voltage. The line is from the fit.

- $\boldsymbol{F_{att}}$

F_{att} represents the fraction of drift electrons lost due to re-attachment to chamber gas molecules after they are created. The probability of re-attachment h is essentially zero for all noble gases (like Argon) and is very small for CO_2 (h=6.2$\times 10^{-9}$) [2]. However the value is quite sensitive to the levels of oxygen and water in the chamber gas. The addition of these or other electro-negative gases, even at the few parts-per-million level can have noticeable affects. It should also be noted that the re-attachment coefficient is a strong function of electric field. Using the same value as for the CMS endcap chambers, we assume F_{att} is assumed to be 0.5 for these calculations.

In reality, this factor is not crucial to pin down to high accuracy. Certainly we should expect that F_{att} is very close to unity within our Argon-CO_2 atmosphere. However it is relevant to point out that we have a measure of the gain from the FDC prototype chamber based on a fit from theory to our prototype data. This fit actually gives us the product of $F_{att} \cdot \mathcal{G}_{gas}$.

- $\boldsymbol{F_{ind}}$

F_{ind} represents the fraction of the anode charge induced on either cathode. This fraction is given by $F_{ind} = 0.5$. This statement is true for the chamber configuration with no field wires. If we configure a chamber with alternating sense and field wires, F_{ind} goes down to 0.41 [3].

- $\boldsymbol{F_{sh}}$

The factor F_{sh} represents the fraction of the avalanche charge collected by the anode for a given preamplifier shaping time. However given the current readout window employed of 350 ns, the factor of F_{sh}=1.0 is reasonable to employ for these calculations. Ultimately we will want to reduce this gate duration in order to reduce possible noise levels in the system. In this case the factor F_{sh} will have to be reduced. If the gate duration is reduced to 100 ns, F_{sh} falls to about 0.2. This value is consistent with that used for the CMS endcap chambers and what Gerard Visser thinks is reasonable.

- $\boldsymbol{\mathcal{G}_{amp}}$

The amplifiers used on the FDC prototype are the SIP transimpedance amplifiers used on the Hall B chambers. These amplifiers have an intrinsic gain given by 2.2 mV/μA. In order to compute $\mathcal{G}_{amp}$, we need to know the load impedance that these amplifiers see looking into

the ADC (which are connected through 110 Ω cables and a VPI postamplifier). The VPI postamplifier is set to unity gain. Its purpose is to allow impedance matching to the signals from the chamber to the ADC (with 50 Ω input impedance). Here we use a load impedance value of 50 Ω. Therefore we can compute the necessary preamplifier gain factor for Eq.(1) using:

$$\mathcal{G}_{amp} = 2.2 \text{ mV}/\mu\text{A} \cdot \frac{1}{50\ \Omega} = 44 \tag{3}$$

- $\boldsymbol{\mathcal{G}_{gas}}$

The form of the gas gain $\mathcal{G}_{gas}$ is given by Sauli [2] as:

$$\mathcal{G}_{gas} = \exp\left[2\sqrt{\frac{kNCV_0a}{2\pi\epsilon_0}}\left(\sqrt{\frac{V_0}{V_T}} - 1\right)\right], \tag{4}$$

where,

- k = gas constant proportional to the first Townsend coefficient. In this calculation we use k=1.81$\times 10^{-17}$ cm^2/V which is the value for Argon [2]. Sauli does not report a value of k for CO_2. From our fits to the FDC prototype data, if we fix N_{ion}=94 and let k be a free parameter (along with the threshold voltage V_T), we find k=1.86$\times 10^{-17}$ cm^2/V. Thus our value of k from argon seems reasonably to employ.
- N = number of gas molecules per unit volume. At the temperature T and pressure P, N is given by:

$$N = 2.69 \times 10^{19} \frac{P}{760} \cdot \frac{273}{T} \text{ molecules/cm}^3 \tag{5}$$

  If we assume P=1 atm (760 Torr) and T=30°C (303 K), then we compute the molecular density as N=2.42$\times 10^{19}$ molecules/cm^3.
- V_0 = operating high voltage. The operating voltage of the FDC prototype is V_0=1800 V.
- V_T = threshold voltage. The threshold voltage has been determined from fits to the measured FDC charge to the above gas multiplication form in Eq.(4) from Sauli. We find V_T=703.5 V as shown in Fig. 1.
- a = radius of anode wires. The radius of the anode wires in the FDC prototype is 0.001 cm.
- ϵ_0 = 8.85 pF/m for gases.
- C = capacitance per unit length of anode wires. The capacitance per unit length has been computed in Ref. [3] to be 8.34 pF/m.

Plugging in these terms, we find $\mathcal{G}_{gas}$=4.7$\times 10^5$ for the multiplication gas gain.

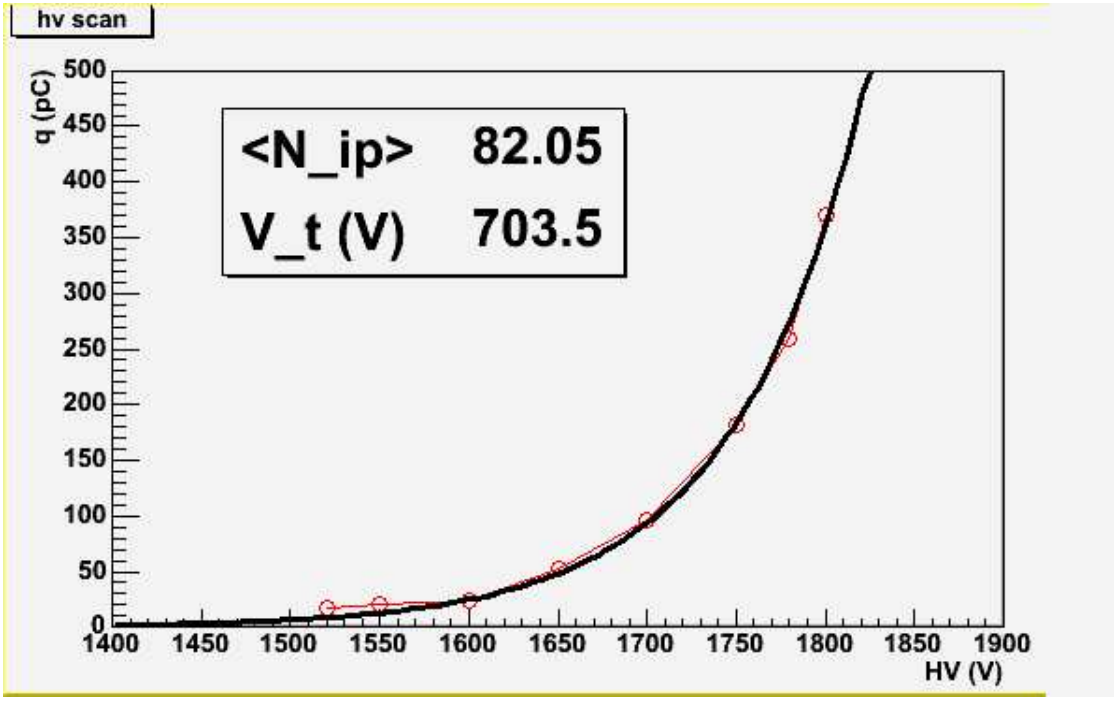

Figure 1: Fit of gain curve from Sauli [2] with respect to the FDC data (summed over both cathode planes) to determine the total number of ion pairs and the threshold voltage.

Now in the calculation of the cathode charge from Eq.(1), we use the following values:

- $N_{ion} = 94$
- $F_{att} = 0.5$
- $F_{ind} = 0.50$
- $F_{sh} = 0.2$
- $\mathcal{G}_{amp} = 44$
- $\mathcal{G}_{gas} = 4.7 \times 10^5$

$$\Rightarrow \quad \boxed{\mathcal{Q} = 15.5 \text{ pC}}$$

References

[1] CMS write-up: http://www.physics.ohio-state.edu/ cms/elec/preamp.html

[2] F. Sauli, "Principles of Operation of Multiwire Proportional and Drift Chambers", CERN internal note 77-09, (1977).

[3] D.S. Carman, "FDC Capacitance Calculations", http://www.jlab.org/Hall-D/detector/fdc/design/capacitance.ps