LAr Charge and Light in presence of Electric Field

PD Analysis Mtg - June 4, 2020

FLC

Solid Argon is characterized by the existence of an electron band structure and it is usually assumed that the same band structure also exists in the liquid state, characterized by an energy gap of E_{gap}=14.3 eV

In LAr ionization process besides electron-hole (Ar^+) pairs formation, also Ar^* excited atoms are produced in the $\frac{N_{ex}}{N_i} = 0.21$ ratio

with:

- N_i n. of Ionizations per unit of dep. energy
- N_{ex} n. of Excitations per unit of dep. energy

W_{ion}, the average energy expended per ion pair separation:

$$W_{ion} = E_i + \epsilon_{kin} + \frac{N_{ex}}{N_i} E_{ex}$$

- E_i average energy loss per ionizing collision corresponds to the mean value of the gap energy (E_{gap}=14.3 eV)
- E_{ex} average energy release per excited atom of 12.7 eV
- ϵ_{kin} average kinetic energy carried by the subionization electron 6.3 eV

Good agreement with the experimental result

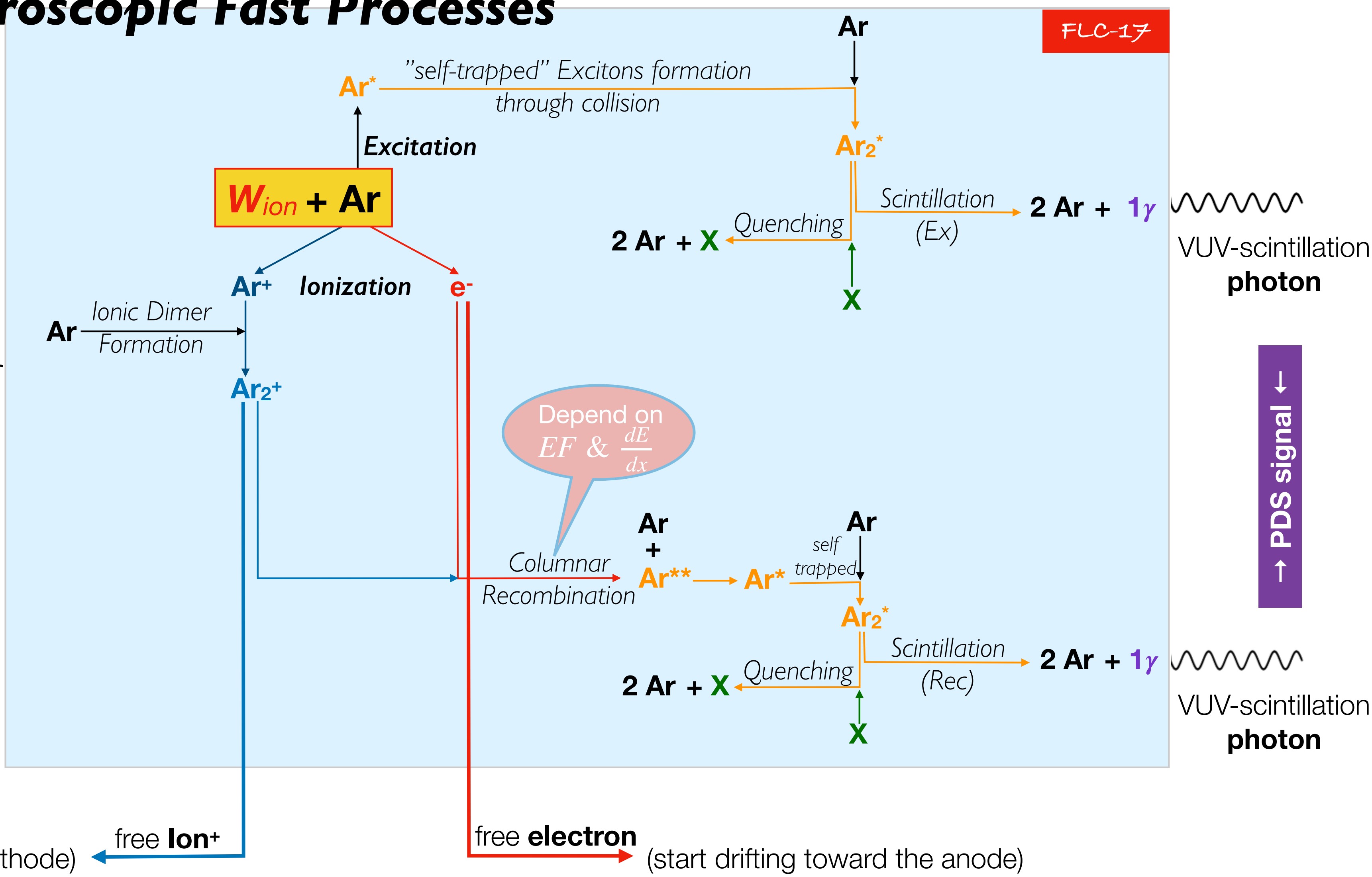
$$W_{ion} = 23.6 \pm 0.3 \; eV \text{ in LAr}$$

T. Doke, Fundamental properties of liquid Argon, Krypton and Xenon as Radiation detector media, Portgal Phys. 12 (1981), 9.

M. Miyajima et al., Average energy expended per Ion pair in liquid Argon, Ph. Rev. A 9 (1974), 1438

Initial Microscopic Fast Processes

(ps-µs)
induced by Energy release from charged particles in LAr



Conventional Notation and nomenclature

Energy density $\frac{dE}{dx}\left[\frac{MeV}{cm}\right]$ $\frac{dE}{dx}\Big|_{mip} = 2.1\ \frac{MeV}{cm}$ $W_{ion} = 23.6\ \frac{\mathrm{eV}}{e} = 23.6 \times 10^{-6}\ \frac{\mathrm{MeV}}{e}$

Charge density $\left(\frac{dQ}{dx}\right)^{free}\left[\frac{e}{\mathrm{cm}}\right]$ $\left(\frac{dQ}{dx}\right)_{\infty} = \frac{dE/dx}{W_{ion}}\left[\frac{e}{\mathrm{cm}}\right]$

Charge Yield $QY = \left(\frac{dQ}{dE}\right)^{free} = \frac{\frac{dQ}{dx}^{free}}{\frac{dE}{dx}}\left[\frac{e}{\mathrm{MeV}}\right]$ $QY_{\infty} = \frac{1}{W_{ion}}\left[\frac{e}{\mathrm{MeV}}\right]$

A similarly for Light: Light Density $\left(\frac{dL}{dx}\right)\left[\frac{ph}{\mathrm{cm}}\right]$ and Light Yield $LY\ [\frac{ph}{MeV}]$

$$\frac{dE}{dx} \rightarrow (\frac{dQ}{dx})_\infty$$ Tot Ion Charge (as collectable at infinite EF - no Recombination)

$W_{ion} = 23.6\ \mathrm{eV}/e = 23.6 \times 10^{-6}\ \mathrm{MeV}/e, \qquad \rho_{LAr} = 1.39\ g/cm^3$

<u>Recombination</u>

Mod Box Model:
$\alpha_{MBM} = 0.93, \quad \beta'_{MBM} = 0.212$

$$\frac{dE}{dx} \rightarrow$$ Mod Box Mod or Birks Mod $\rightarrow (\frac{dQ}{dx})^{free}_{EF}$

Birks Model
$A_B = 0.800 \pm 0.003, \ \ k_B = 0.0486 \pm 0.0006\ \frac{\mathrm{kV}}{\mathrm{cm}} \frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$

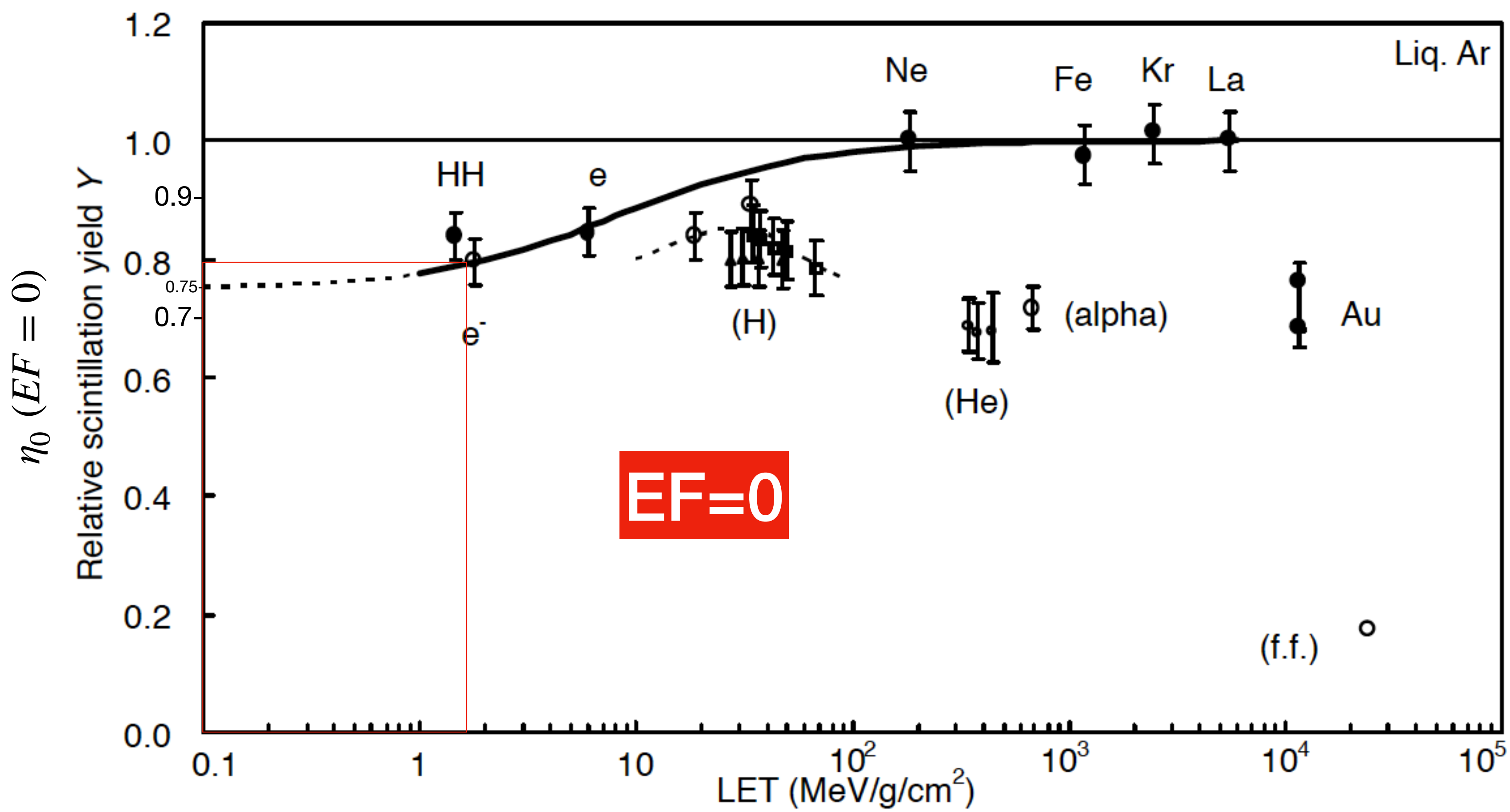
$$\rightarrow \frac{(\frac{dQ}{dx})^{free}_{EF}}{(\frac{dQ}{dx})_\infty} = R(EF, \frac{dE}{dx}) = \text{Charge Recombination Factor}$$

(Relative IonCharge Density)

(Relative ScintLight Density)

$$R(EF, dE/dx) \rightarrow \text{Doke} \rightarrow S(EF, dE/dx) = \text{Light Recombination Factor} = \frac{(\frac{dL}{dx})^{EF}}{(\frac{dL}{dx})_0}$$

$\frac{N_{ex}}{N_i} = 0.21$ (fraction of excitations), $\qquad \frac{N_0}{N_i} = \chi_0 = 0.26$ (fraction of escape electrons) for mip



Measure η_0

$[(1-\eta_0) = \text{fraction of missing photons}] \quad \Longrightarrow \quad \chi_0 \quad \left(= \frac{N_0}{N_i}\ \text{fraction of escape electrons}\right)$

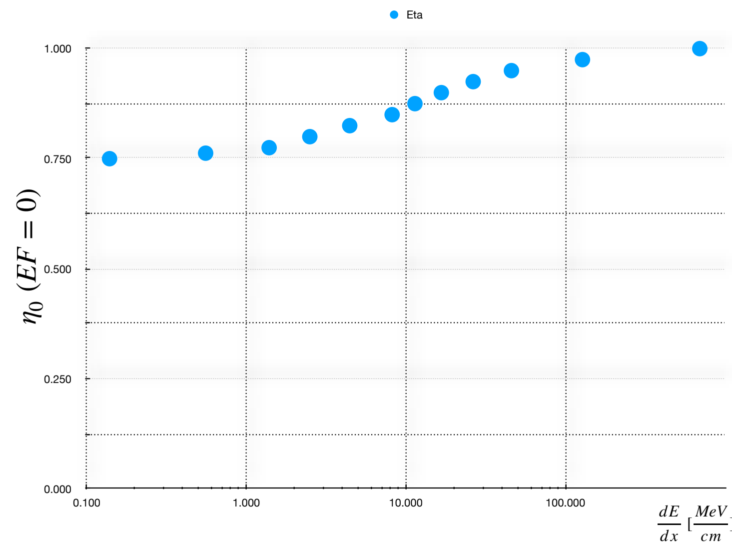
$(Doke'02)$

dE/dx-> eta —> chi(dE/dx) at EF=0 [i.e. chi0(dE/dx)]

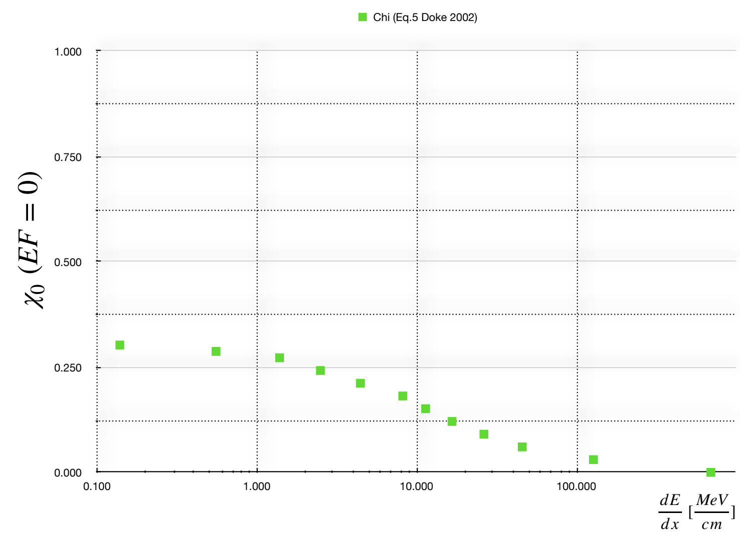
dE/dx [MeV/g/cm2]	dE/dx [MeV/cm]	Eta_0	Chi_0 (Doke 2002)
0.100	0.139	0.750	0.303
0.400	0.556	0.763	0.287
1.000	1.390	0.775	0.272
1.799	2.501	0.800	0.242
3.200	4.448	0.825	0.212
5.900	8.201	0.850	0.182
8.200	11.398	0.875	0.151
12.000	16.680	0.900	0.121
19.000	26.410	0.925	0.091
33.000	45.870	0.950	0.061
92.000	127.880	0.975	0.030
500.000	695.000	1.000	0.000

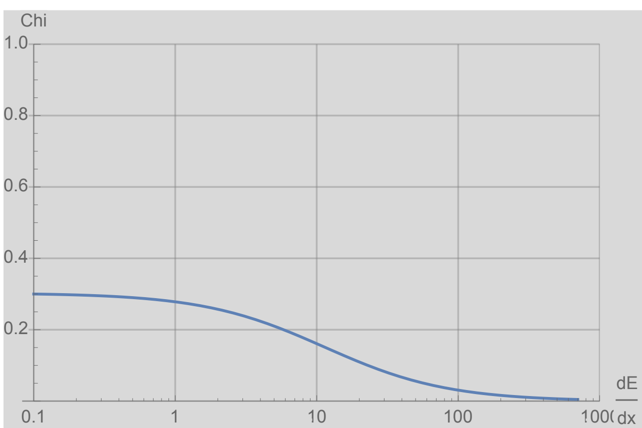
$$\eta_0 = \frac{(1 - \chi_0 + \frac{N_{ex}}{N_i})}{(1 + \frac{N_{ex}}{N_i})}$$

$$\eta_0 = \eta_0(\frac{dE}{dx})$$



$$\chi_0 = (1 + \frac{N_{ex}}{N_i}) - (1 + \frac{N_{ex}}{N_i}) \cdot \eta_0$$





Fit w/ Sigmoid fcn

$$sig(x) = \frac{p1}{p2 + exp[p3 + p4\ x]}$$

$$\chi_0\left(\frac{dE}{dx}\right) = \frac{0.00365337}{-5.46204 + exp\left[1.70003 + 0.000194084\ \frac{dE}{dx}\right]}$$

At any dE/dx in the range of interest (from 2.1 to ~40 MeV/cm),

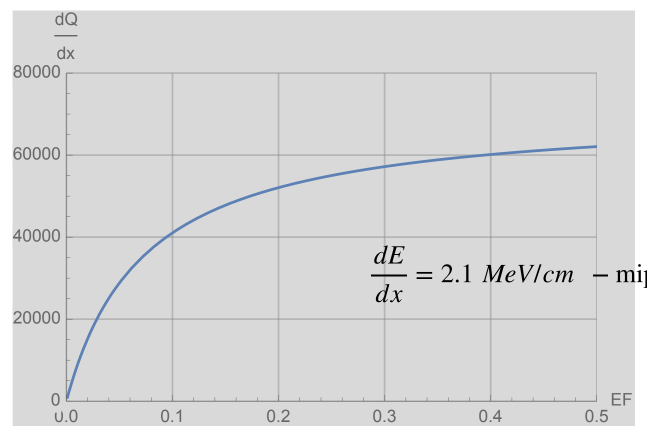
@EF=0 ⇒ $(\frac{dQ}{dx})_0^{free} = \chi_0 \cdot (\frac{dQ}{dx})_\infty \neq 0$ due to escape electrons

$$\rightarrow \chi_0 \cdot (\frac{dQ}{dx})_\infty \leq (\frac{dQ}{dx})_{EF}^{free} \leq (\frac{dQ}{dx})_\infty$$

However in standard Charge parameterizations (e.g. Birks Model)

$(\frac{dQ}{dx})_{Birks}^{free}(dE/dx,\ EF \rightarrow 0) \rightarrow 0$, in friction with escape electron evidence

From Birks Model: $$\left(\frac{dQ}{dx}\right)_{Birks}^{free} = \frac{\frac{A_B}{W_{ion}} \frac{dE}{dx}}{1 + \frac{k_B}{\rho_{LAr}} \frac{1}{EF} \frac{dE}{dx}}$$



$$A_B = 0.800 \pm 0.003,\quad k_B = 0.0486 \pm 0.0006\ \frac{\text{kV}}{\text{cm}} \frac{\text{g/cm}^2}{\text{MeV}}$$

Modified Birks Model (FLC proposal)
to include escape electrons at 0-EF and correction for charge freed at low EF

Introduce charge protection for escape el:

(i) at EF=0, require $(\frac{dQ}{dx})_0^{free} = \chi_0 \cdot (\frac{dQ}{dx})_\infty$,

(ii) at low EF (above/near EF=0), add EF-extracted electrons in addition to escape electrons,

(iii) at higher EF, additional electrons must decrease to 0, restoring standard behavior from Birks Model (valid for EF > ~200 V/cm)

$$\chi_0 = \chi_0\left(\frac{dE}{dx}\right) \quad \rightarrow \quad \chi = \chi\left(\frac{dE}{dx}, EF\right) = \chi_0\left(\frac{dE}{dx}\right) \cdot f_{corr}(EF)$$

$$(\frac{dQ}{dx})_{ee}\left(\frac{dE}{dx}, EF\right) = \chi \cdot \left(\frac{dQ}{dx}\right)_\infty$$

$$\left(\frac{dQ}{dx}\right)^{free}_{ModBirks} = \left(\frac{dQ}{dx}\right)^{free}_{Birks} + \left(\frac{dQ}{dx}\right)_{ee} = \frac{\frac{A_B}{W_{ion}}\frac{dE}{dx}}{1+\frac{k_B}{\rho_{LAr}}\frac{1}{EF}\frac{dE}{dx}} + \chi_0\left(\frac{dE}{dx}\right)\cdot f_{corr}(EF)\cdot\left(\frac{dQ}{dx}\right)_\infty$$

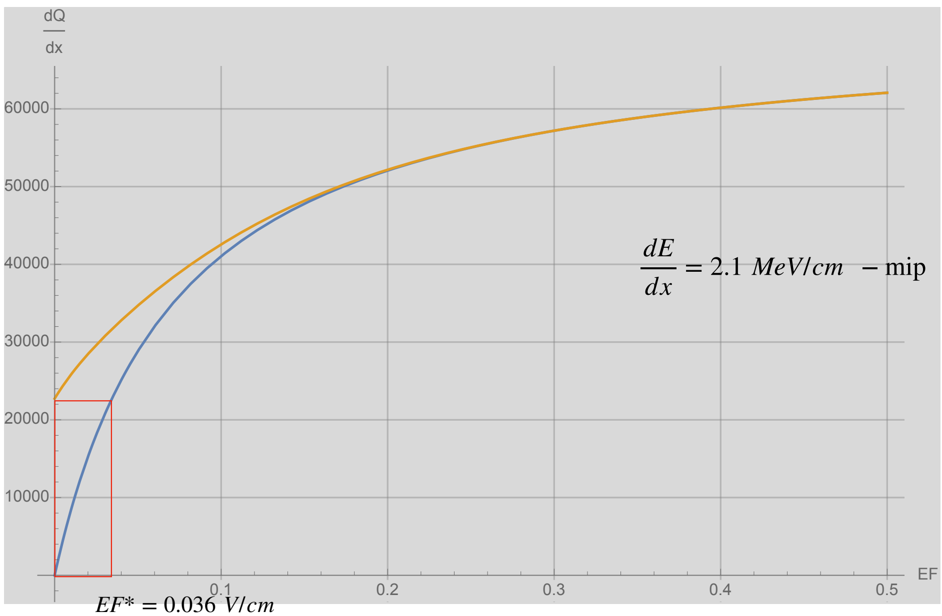
Modified Birks Model
(to include escape electrons at 0-EF and correction for charge freed at low EF)

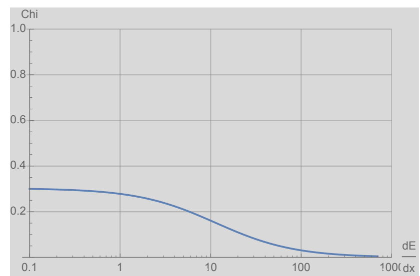
$$\left(\frac{dQ}{dx}\right)^{free}_{ModBirks} = \frac{\frac{A_B}{W_{ion}}\frac{dE}{dx}}{1+\frac{k_B}{\rho_{LAr}}\frac{1}{EF}\frac{dE}{dx}} + \chi_0\left(\frac{dE}{dx}\right)\cdot f_{corr}(EF)\cdot\left(\frac{dQ}{dx}\right)_{\infty}$$

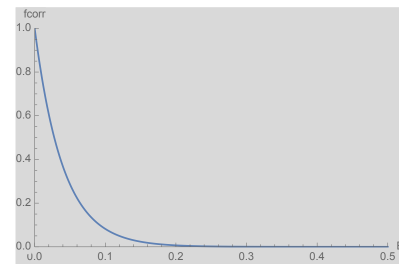
Where:

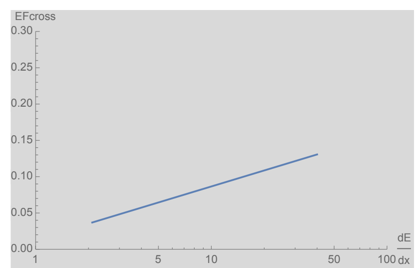
$$\chi_0\left(\frac{dE}{dx}\right) = \frac{0.00365337}{-5.46204 + exp\left[1.70003 + 0.000194084\ \frac{dE}{dx}\right]}$$

$$f_{corr} = exp\left[-\frac{EF}{EF^*}\right]$$







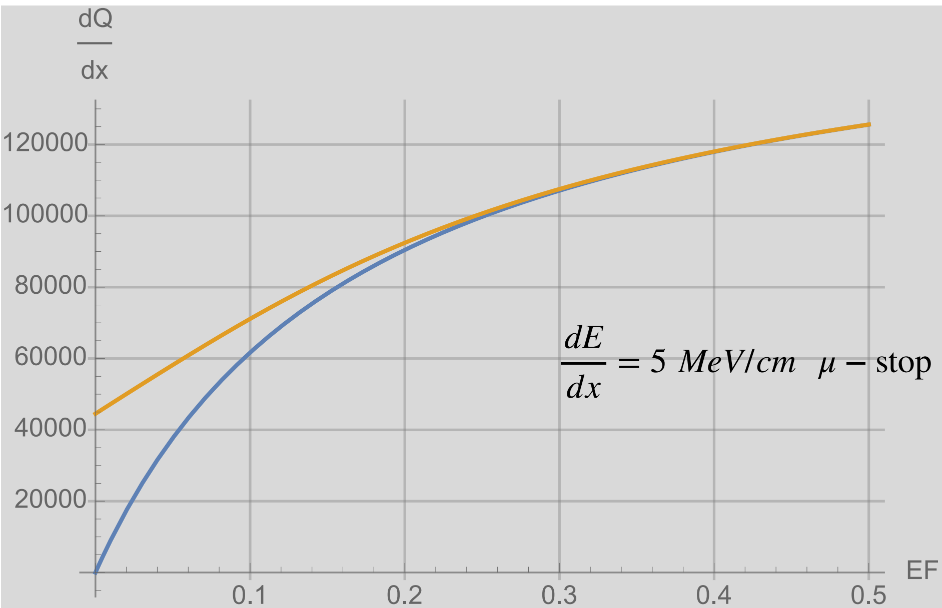


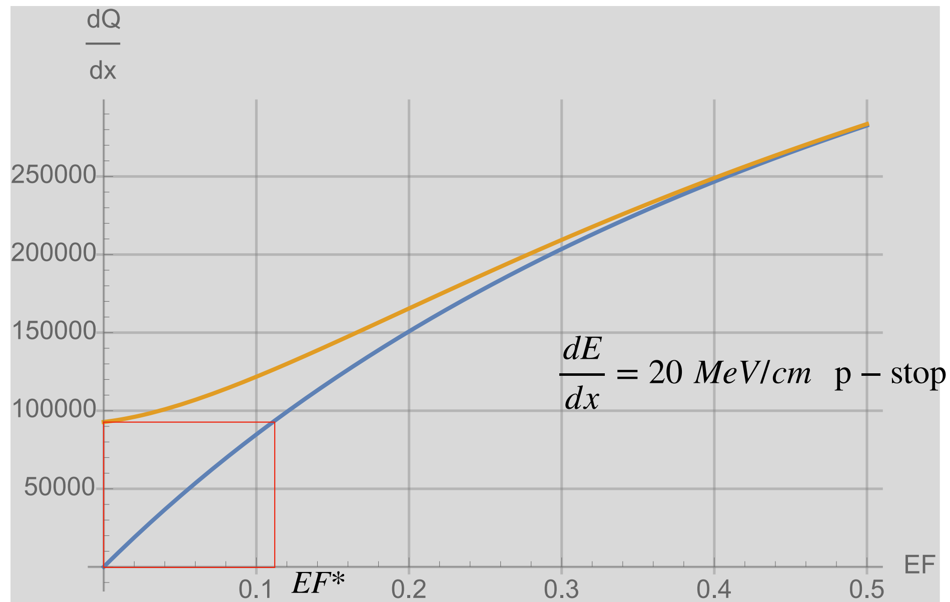
EF^* is the EF where $QY_{Birks}(EF = EF^*) = \chi_0\ QY_{\infty}$

Note: EF^* depends on $\frac{dE}{dx}$

$$EF^*\left(\frac{dE}{dx}\right) = 0.0318\ \ln\left[\frac{dE}{dx}\right] + 0.0133$$

Fit with Log fcn



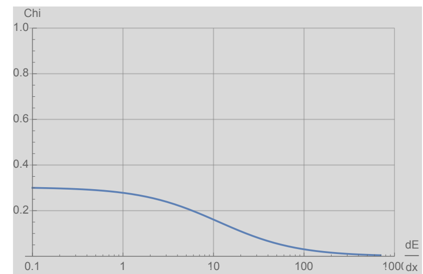


$$QY_{Birks}(EF = EF^*) = \chi_0 \cdot QY_\infty \; at \; EF^* = 0.127 \;\; V/cm$$

Set relation between Free Charge Density $\left(\frac{dQ}{dx}\right)^{free}$ $\left[\frac{e}{\text{cm}}\right]$ and Scintillation Light Density $\left(\frac{dL}{dx}\right)$ $\left[\frac{ph}{\text{cm}}\right]$

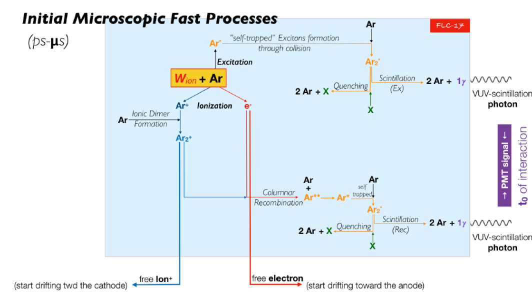
based on 3 parameters (experimentally measured):

- $N_i = \frac{1}{W_{ion}}$
- $\frac{N_{ex}}{N_i}$
- $\chi_0 \quad \left(= \frac{N_0}{N_i} \right)$ with $\chi_0 (\frac{dE}{dx})$ - This accounts for escape electron charge



on the initial Ionization Energy partition:

- $W_{ion} \;=\; E_i \;+\; \epsilon_{kin} \;+\; (\frac{N_{ex}}{N_i})\; E_{ex}$



and on the Charge to Light relation:

- $LY = N_i - QY\left(\frac{dE}{dx}, EF\right) + N_{ex}$ where $N_i - QY =$ n. el. recombined = n. Ph. Emitted

Implementation in MC simulation (starting from energy deposited in G4 step):

$$\frac{dE}{dx} \rightarrow \text{(STD) Birks Mod} \rightarrow \left(\frac{dQ}{dx}\right)^{free}_{Birks} \rightarrow \text{Mod Birks Mod} \rightarrow \left(\frac{dQ}{dx}\right)^{free}_{ModBirks} \rightarrow \frac{dL}{dx}$$

$$\left(\frac{dQ}{dx}\right)_{\infty} \left(1 + \frac{N_{ex}}{N_i}\right) - \left(\frac{dQ}{dx}\right)^{free}_{ModBirks} = \frac{dL}{dx}$$

$$\left(\frac{dQ}{dx}\right)_{ModBirks} = \left(\frac{dQ}{dx}\right)_{Birks} + \chi\left(\frac{dE}{dx}, EF\right)$$

$$\left(\frac{dQ}{dx}\right)_{\infty} \left(1 + \frac{N_{ex}}{N_i} - \chi\right) - \left(\frac{dQ}{dx}\right)^{free}_{Birks} = \frac{dL}{dx}$$

- N. of escape *e* *(due to kin. energy)*

N. of *e* of primary Ionization + N. of γ from direct excitation

N. of free *e* *(not recombined) due to EF pull)*

N. of γ emitted

$$\left(\frac{dQ}{dx}\right)_{\infty} = \frac{1}{W_{ion}}\frac{dE}{dx}$$

$$\frac{1}{W_{ion}}\frac{dE}{dx}\left[1 + \frac{N_{ex}}{N_i} - \chi_0\left(\frac{dE}{dx}\right) f_{corr}(EF) - \frac{A_B}{1 + \frac{k_B}{\rho_{LAr}}\frac{1}{EF}\frac{dE}{dx}}\right] = \frac{dL}{dx}$$

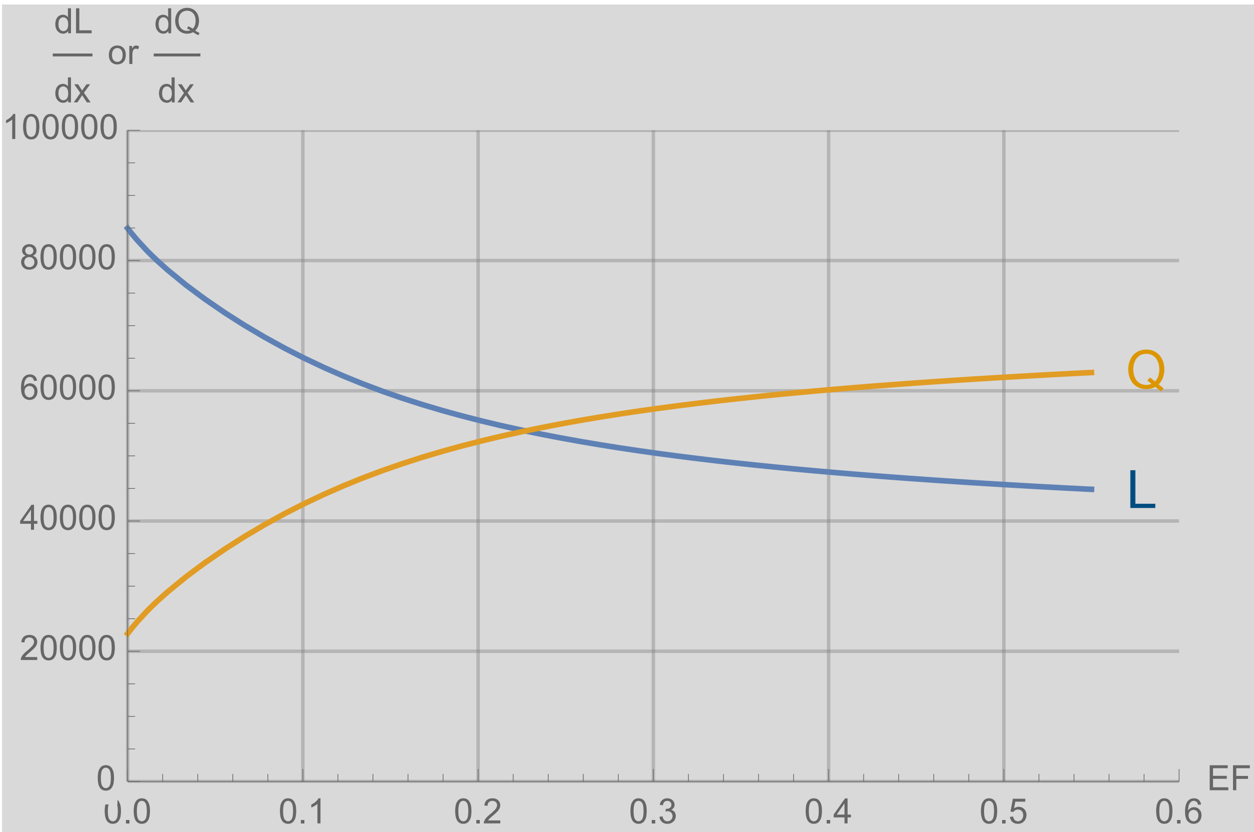
Where

$$\chi_0\left(\frac{dE}{dx}\right) = \frac{0.00365337}{-5.46204 + exp\left[1.70003 + 0.000194084\ \frac{dE}{dx}\right]}$$

$$f_{corr} = exp\left[-\frac{EF}{EF*}\right]$$

$$EF*\left(\frac{dE}{dx}\right) = 0.0318\ \ln\left[\frac{dE}{dx}\right] + 0.0133$$

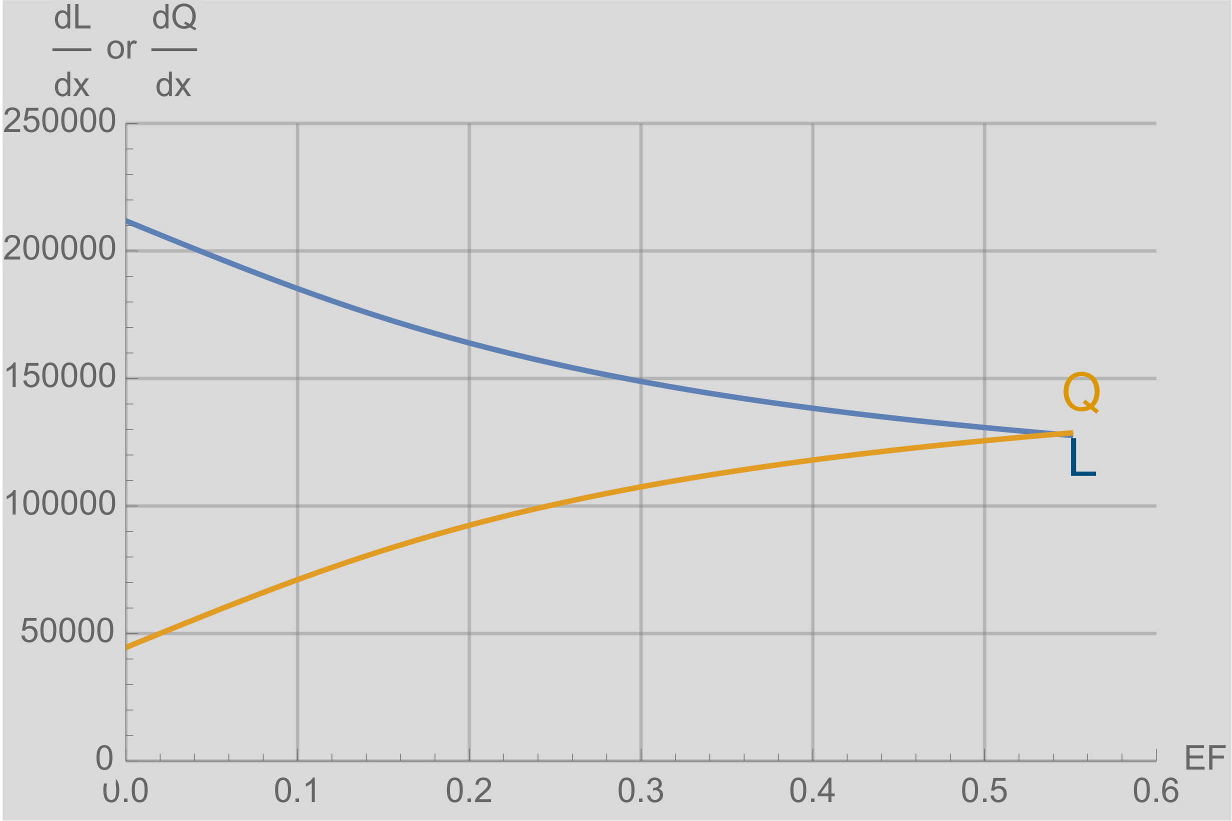
$$\frac{dE}{dx} = 2.1\ MeV/cm \quad - \text{mip}$$



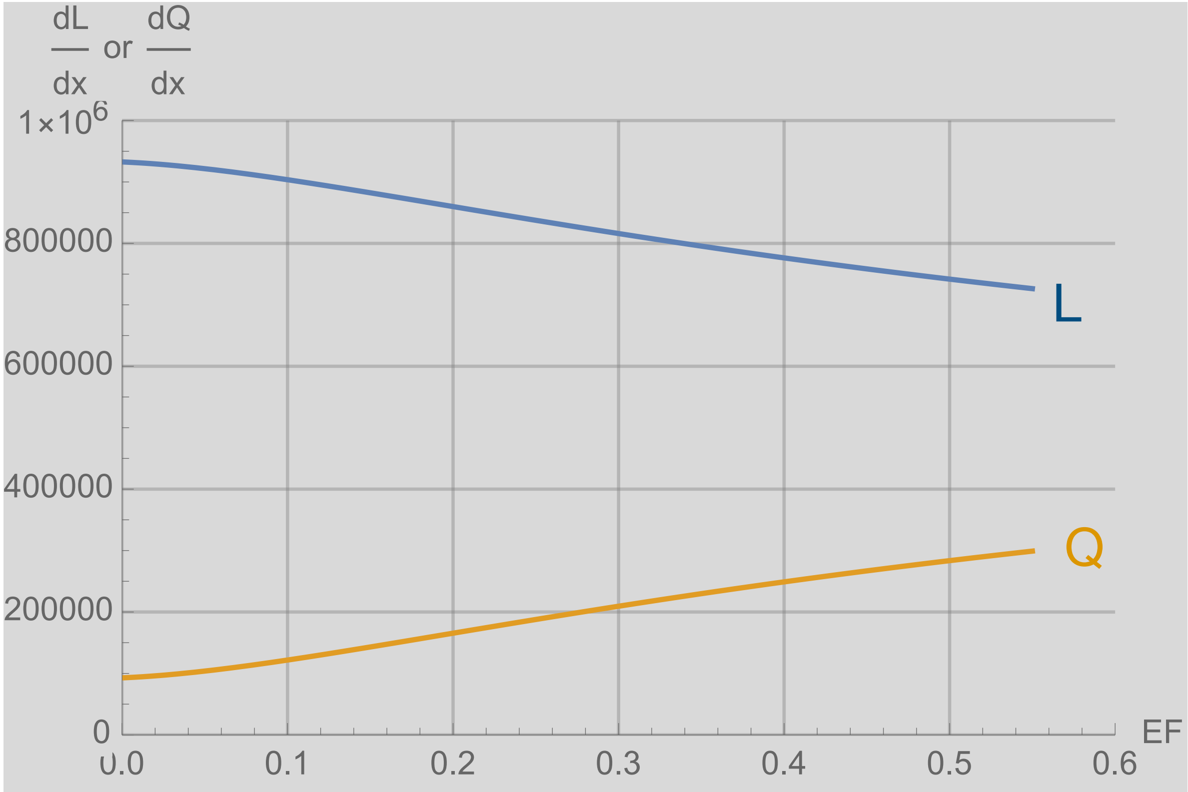
Q+L = const

$$= \frac{1}{W_{ion}}\left(1+\frac{N_{ex}}{N_i}\right)\cdot\frac{dE}{dx}$$

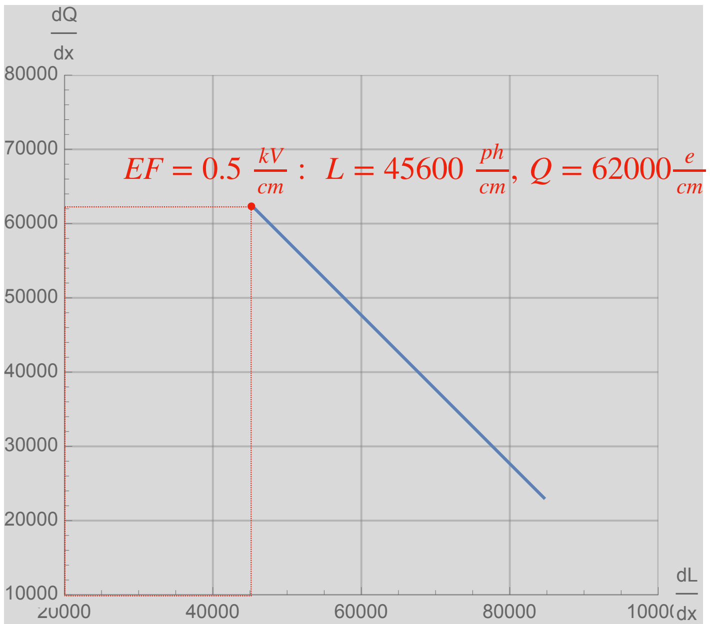
$$\frac{dE}{dx} = 5\ MeV/cm \quad \mu - \text{stop}$$



$$\frac{dE}{dx} = 20\ MeV/cm \qquad \text{p} - \text{stop}$$



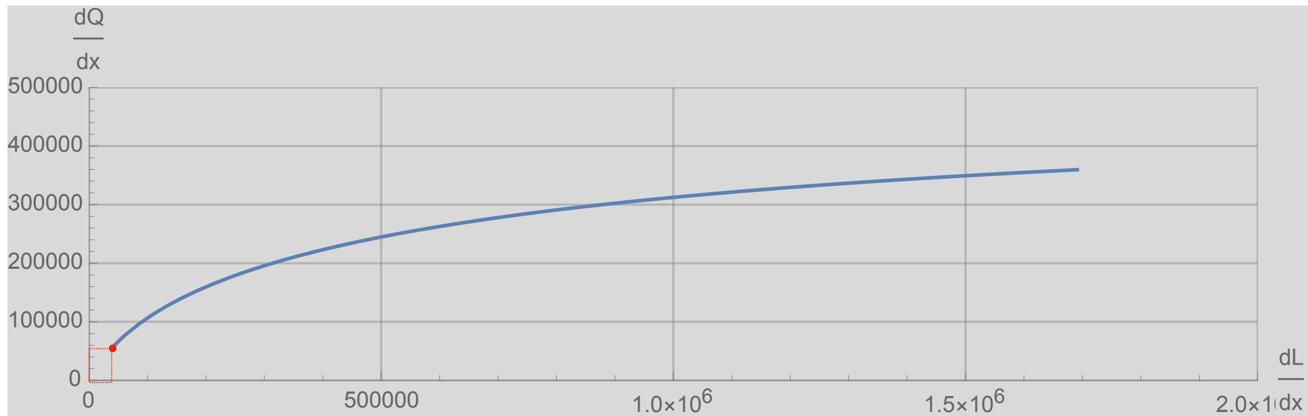
$$\frac{dL}{dx} \text{ vs. } \frac{dQ^{free}}{dx}$$



Varying EF: $0 \leq EF \leq 0.5\ \frac{kV}{cm}$

at $\frac{dE}{dx} = 2.1\ \frac{MeV}{cm}$ (mip)

$$\frac{dL}{dx} \text{ vs. } \frac{dQ^{free}}{dx}$$



Varying $\frac{dE}{dx}$: $2.1 \leq \frac{dE}{dx} \leq 40\ \frac{MeV}{cm}$

at $EF = 0.5\ \frac{kV}{cm}$ $(LArTPC\ nominal)$