Space Charge

“Space charge” refers to the underlying distribution of charge in the detector volume.

Non-zero space charge can be induced by ionizing radiation.

The ionized electrons are highly mobile and quickly drift to the anode.

This leaves the slower-moving positive ions to produce a net charge density in the medium.

Space charge produces distortions in the electric field, which can interfere with signal readout.

E-field near the anode is reduced, near the cathode is increased.

In FLArE, a space charge will be induced by the ~1 hz/cm^2 muon flux.

Space Charge: 1D model

Palestini* presents a one-dimensional model for space charge effects.

Can be parametrized with dimensionless parameter α: $\alpha = \frac{L}{E_o}\sqrt{\frac{K}{\epsilon\mu^+}}$

L = drift length

E_0 = electric field in absence of space charge

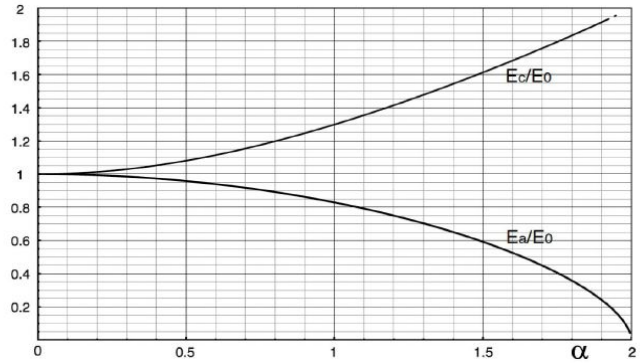
ε = permittivity of LAr

μ^+ = ion mobility in LAr

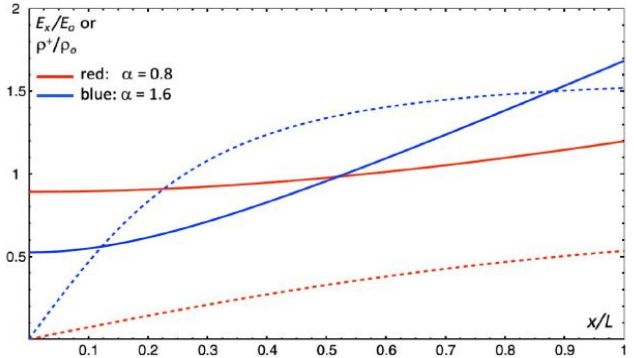
K = charge density injection rate

Note:

- α is linear w.r.t. L and $1/E_0$
- Effect on field is roughly quadratic in α
- Above $\alpha \approx 2$, field at anode is zero and field at cathode increases ~linearly



Electric field at anode and cathode as function of α



Electric field (solid) and charge density (dotted) vs. position for two values of α

*S. Palestini and F. Resnati. Space charge in liquid argon time-projection chambers: a review of analytical and numerical models, and mitigation methods. JINST, 16:P01028, 2021, 2008.10472

What are these numbers for FLArE?

L = 30 cm. for horizontal drift, 180 cm. for vertical drift
E_0 is to be determined, but we've been thinking ~0.5 to 2.0 kV/cm.
ε for LAr = $1.504\varepsilon_0$
μ^+ for LAr has large experimental uncertainties; best fit value about 1.6E-7 m^2/Vs

K is the product of:

- Flux of muons, about 1 hz./cm^2
- Average dE/dx for muons in LAr, about 2.1 MeV/cm.
- Dimensionless recombination factor R in LAr, roughly 0.7±0.1 for E in range of 0.5 to 2 kV/cm.
- Elementary charge e
- Average ionization energy of an electron in argon, 23.6 eV

Some caveats:

- Our muon flux is not constant over the detector cross-section. This is a 1D model that ignores any effects from that variance.
- Uncertainties on μ^+ and R mean that there should actually be sizeable error bars on these numbers, but for now I'm ignoring those.

What are these numbers for FLArE?

Plugging everything in, with a field of 1 kV/cm, we get α **= 0.21** for horizontal drift and α **= 1.2** for vertical drift. These correspond to a ~1% effect and a 25-40% effect on the field.

But remember, it scales linearly with the field, so just by going to 2 kV/cm, we reduce it to **0.6** for vertical drift, corresponding to a 5-10% effect on the field.

For comparison, Palestini calculates α = 0.4 in ICARUS and 0.81 in MicroBooNE.