

# Space charge effects in the LAr-TPC

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# Space charge effects in Lar-TPC's

- In the ICARUS LAr-TPC, a faithful 3D imaging of the ionizing events is ensured by the uniformity of the electric field applied in the drift region, because the drift co-ordinate is proportional to the drift time through the electron velocity, which depends on the electric field.
- A possible source of field non-uniformity could be the presence in the liquid of positive ions ( $\text{Ar}^+$ ) produced by ionizing tracks, which flow very slowly toward the cathode.
- Being the positive ion mobility in LAr,  $\mu_i \sim 1.6 \cdot 10^{-3} \text{ cm}^2\text{s}^{-1}\text{V}^{-1}$ , more than  $10^5$  smaller than that of free electrons ( $500 \text{ cm}^2\text{s}^{-1}\text{V}^{-1}$ ), ions survive in the drift region for a very long time (typically minutes/meter of drift).
- As a consequence, non-negligible distortions of the drift field could arise because of the space charge due to the ionizing event rate in the detectors. This effect could be particularly relevant in case of running large LAr-TPC's (with several meters of drift) at surface or shallow depth where the event rate is dominated by the cosmic rays flux.

# Electric field calculation with space charge

- To appreciate the effect of space charge, one has to solve the electric field equation in the drift volume under the combined action of electrodes potentials and ion charge:

$$\operatorname{div}(\vec{E}) = \frac{\rho(x, y, z)}{\epsilon_o \epsilon_r}; \quad \epsilon_o = 8.854 \times 10^{-12} \text{ F m}^{-1}; \quad \epsilon_r = 1.5 \text{ for LAr}$$

- Under stationary conditions, the charge density,  $\rho$ , is related to the ionization density rate,  $R_i$ , and the ion drift velocity in the LAr-TPC volume,  $\vec{v}_i = \alpha \vec{E}$ .

➤ f.i., in the approximation of parallel plates electrodes and with  $R_i$  uniformly produced by ionizing radiation:

$$\frac{dj(x)}{dx} = \frac{d(\rho(x)v(x))}{dx} = R_i \quad \longrightarrow \quad \rho(x) = \frac{R_i}{v(x)} x \approx \frac{R_i}{\mu_i E(x)} x$$

where  $j(x)$  is the current density.

## Electric field calculation (cont.)

- Combining previous equations, an approximate differential equation can be obtained, which is easily integrated:

$$\frac{dE(x)}{dx} \approx \frac{R_i}{\epsilon_0 \epsilon_r \mu_i} \frac{x}{E(x)}$$

$$\int_{E_0}^E E dE \approx \frac{R_i}{\epsilon_0 \epsilon_r \mu_i} \int_0^x x dx$$

$$E^2(x) - E^2(0) \approx \frac{R_i}{\epsilon_0 \epsilon_r \mu_i} x^2$$

$$E(x) \approx \sqrt{E^2(0) + \frac{R_i}{\epsilon_0 \epsilon_r \mu_i} x^2}$$

where  $E(0)$  is the field at the electrode at anode ( $x=0$ ).

- Without ionization rate, e.g.  $R_i=0$ , the field is defined by the potentials on the electrodes and it is constant.
- The presence of a small ionization rate introduces a distortion of the field which increases rapidly with the drift path length.

# Space charge in LAr-TPCs on surface

- The case of a LAr-TPC running at a nominal drift field  $E = 500 \text{ V/cm}$  and operated on surface has been investigated.
  - The dominant ionizing radiation are high energy muons, about  $220 \text{ m}^{-2}\text{s}^{-1}$ . Assuming  $dE/dx \sim 2 \text{ MeV/cm}$  (m.i.p.) and a ionization yield of  $\sim 4 \text{ fC/MeV}$  (including recombination in LAr), the ion density rate is about  $R_i \sim 0.18 \text{ fC cm}^{-3}\text{s}^{-1}$  and:

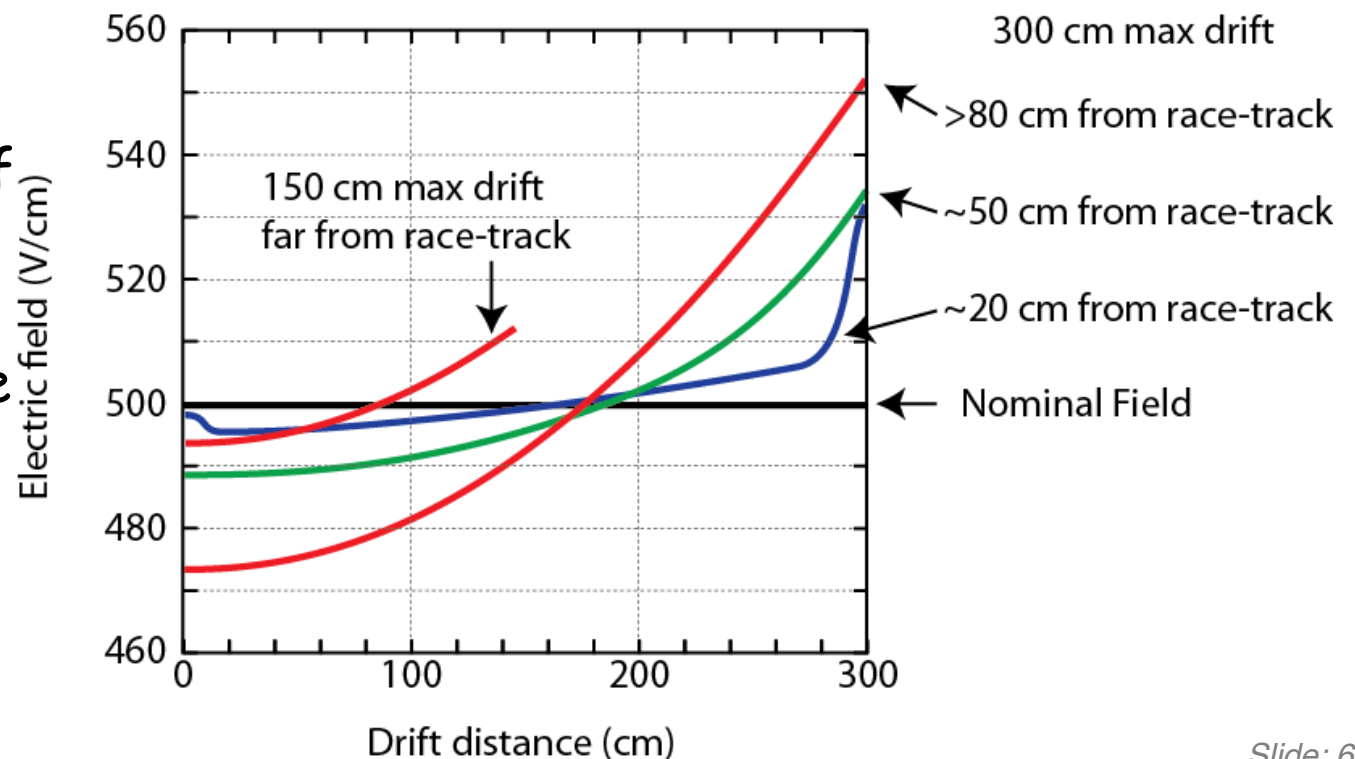
$$E(x) \approx E(0) \sqrt{1 + \left( \frac{1.8x / \text{cm}}{1000} \right)^2}$$

- The approximate field distortions,  $(E(x)-E(0))/E(0)$ , for various drift distances are:

Drift path length	El. Field distortion
50 cm	0.4%
100 cm	1.6%
150 cm	3.6%
225 cm	7.9%
300 cm	13.6%

## More precise numerical evaluation

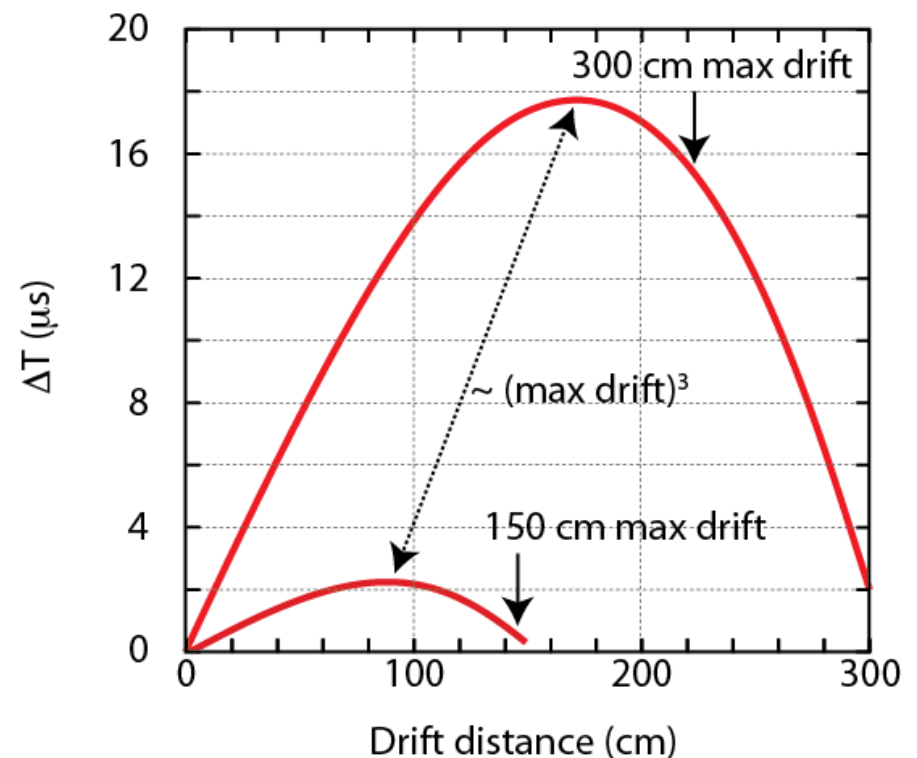
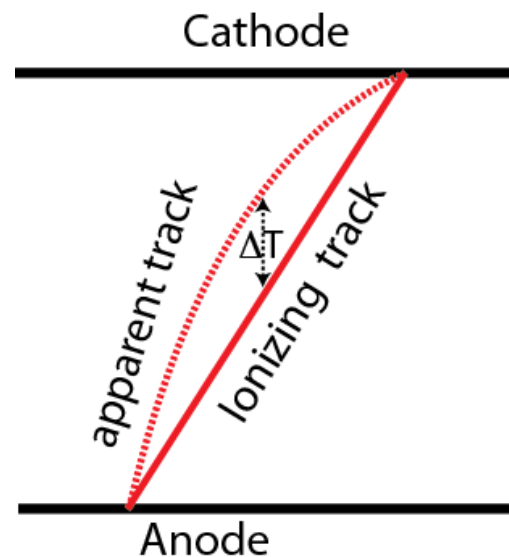
- A better estimation of the space charge effect on E-field can be obtained numerically in 2D/3D including the actual detector geometry (anode, cathode, field shaping rings, ...) with finite element programs.
- Preliminary 2D calculations (horizontal cut at half-height) for the standard T600 *LAr-TPC* (1.5 m drift) and the expanded version (3.0 m drift) show that the distortion strength is not very different from that predicted by the simple analytical solution (~15% for 3m drift, ~4% for 1,5 m drift)
- Field distortions are larger at the center of the detector because, close to the active volume boundaries, the field is forced to be uniform by the presence of the field shaping rings.



# Track bending due to space charge

- Given the dependence of the electron drift velocity on the electric field,  $v_d \sim \text{sqrt}(E)$ , the ionization electron arrival time on the anode in the presence of space charge,  $T_{\text{spch}}$ , will be delayed with respect to that in case of uniform electric field,  $T_{\text{unif}}$ , depending on the starting position along the drift path,  $\Delta T = T_{\text{spch}} - T_{\text{unif}}$

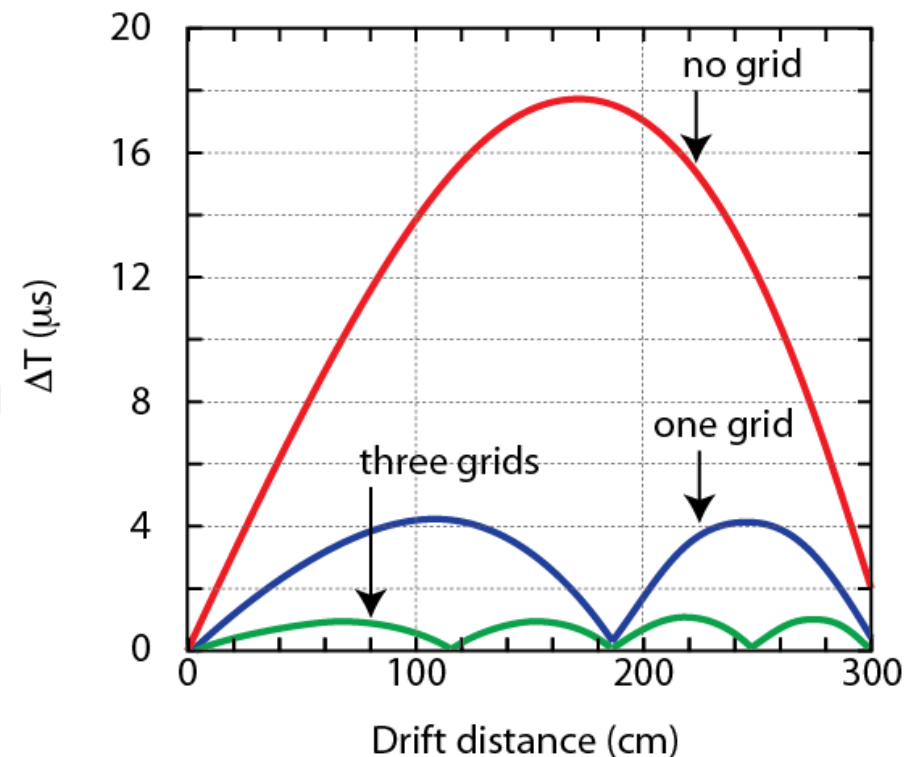
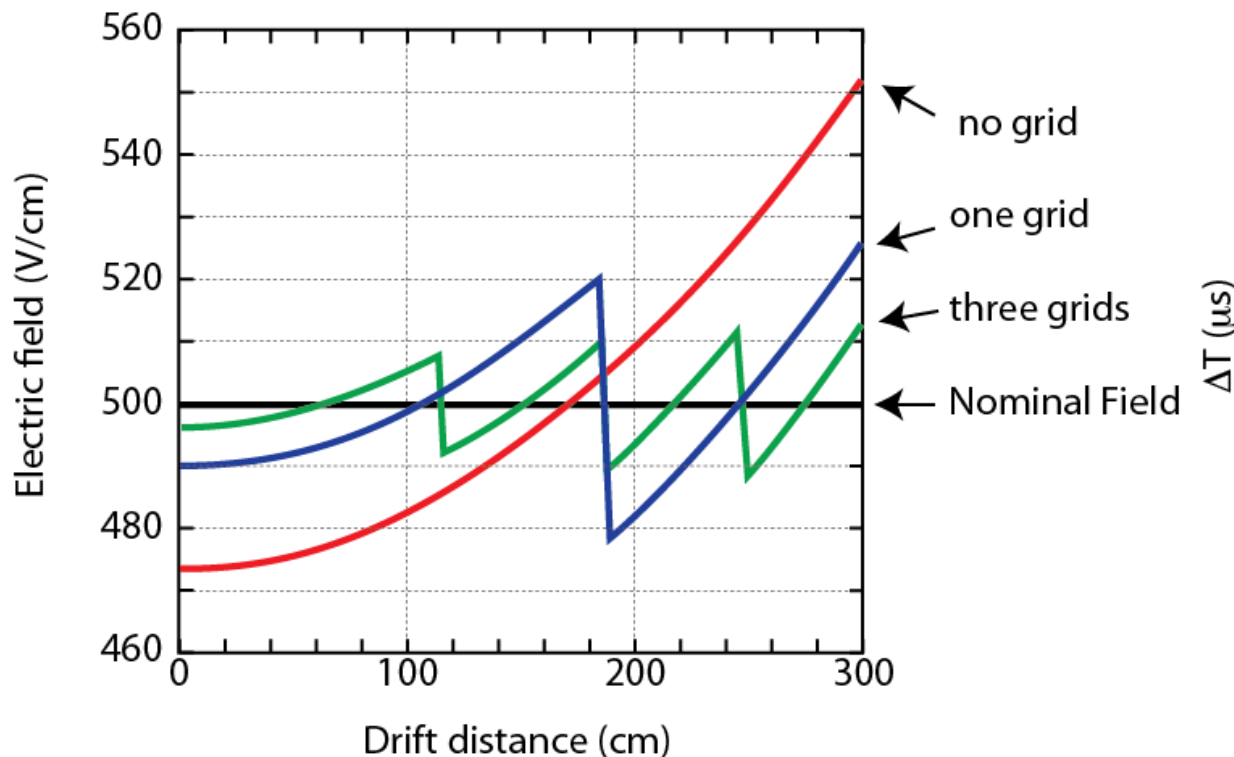
- This can introduce apparent track bending, depending on the track inclination with respect to the wire plane.



- Electron-ion recombination can also be slightly affected by the non uniformity of the electric field.

# Electric field stabilization

- A possible solution to minimize the effect of the space charge would be to stretch transparent metallic grids at given positions along the drift path, to fix the potential over the whole detector surface. This will reduce the gap length over which the space charge affect the field.



- Grids of vertical wires (< 1 mm diameter) with few cm pitch appears adequate (pitch  $\ll$  drift length) to ensure potential fixing.

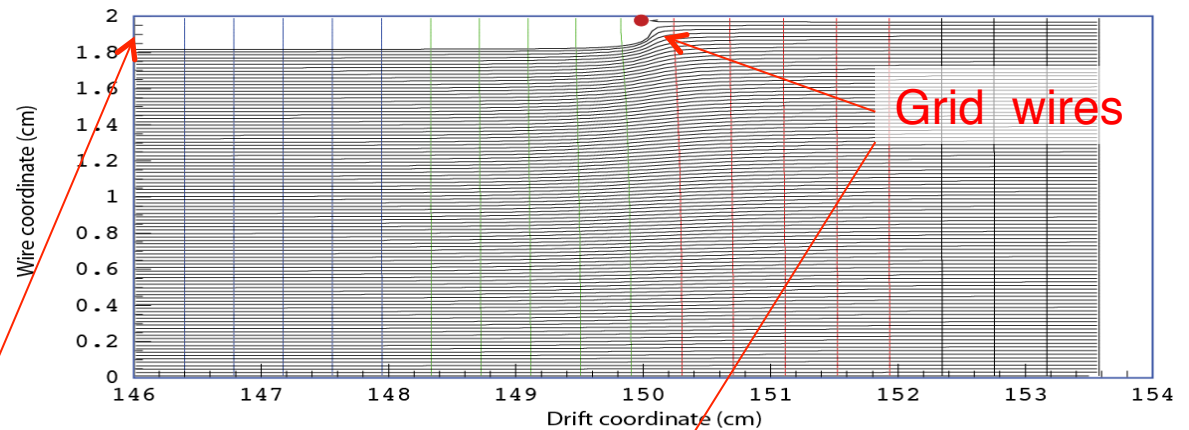


# Additional track distortion due to grids

- Electric field increase across the grid produce a "squeezing" of the free electron trajectories along the drift coordinate:

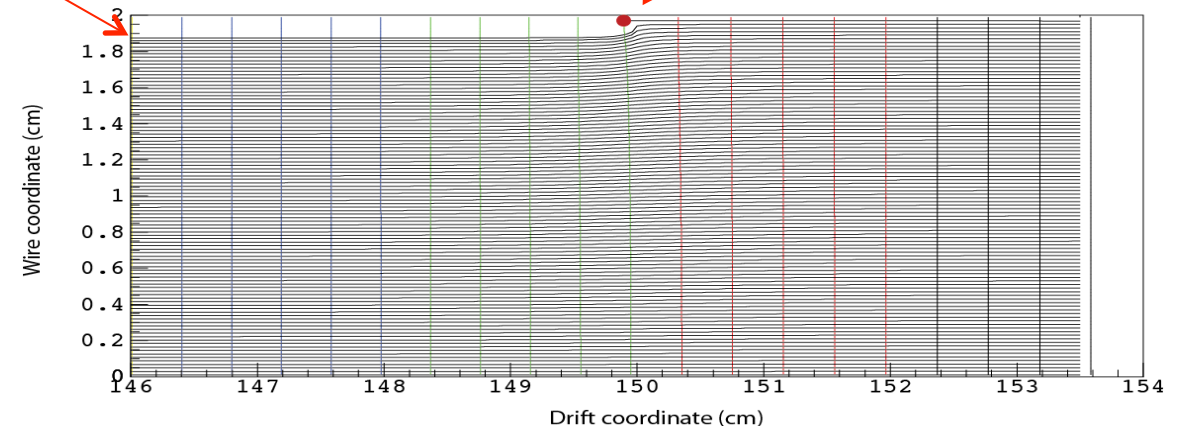
- A single grid in a 3m drift,  $\Delta E/E$  is  $\sim 8\%$  corresponding to max lateral displacement of  $\sim 2\text{mm}$ .

Lateral displacements



Free electron drift direction

- In case of 3 grids,  $\Delta E/E \sim 4\%$  at each step produces a lower lateral displacement ( $\sim 1.3\text{ mm}$ ).



- Lateral diffusion ( $\sigma \sim \text{mm}$  after 1 m drift) could partially compensate the "shadowing" effect of the grid wires.

# Follow-up

- 3D calculation of whole volume including field shaping rings
- Evaluation of effects of convective motions that could reshuffle the space charge distribution within the LAr volume and/or speed up the ion collection at the electrodes depending on their direction and speed.
- Track bending (predicted sagitta  $\sim 2$   $\mu\text{s}$ ) due to space charge could be evaluated from Pavia muon data
- Design proper grid integration with the existing field shaping rings.