Considerations for an ion gate for LCTPC

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Introduction

LCTPC, the Time Projection Chamber (TPC) for the International Linear Collider (ILC), aims at an unprecedented performance in momentum resolution for this type of detector. This high performance relies strongly on the quality of the electric field in the drift volume. All the different technologies considered for the electron readout in LCTPC will release positive ions into the drift volume during the amplification process. Even though the amount of back drift ions is much smaller for MicroPattern Gas Detector (MPGD) amplification than with the traditional MultiWire Proportional Chamber (MWPC), they will create significant distortions of the electric field in the drift volume. Simulations by K. Fujii [1] have shown that a gating system will be required to reach the tight momentum resolution requirements in the nominal running conditions of ILC.

During the readout period (1ms of train crossing), the readout amplification will produce a cloud of positive ions extending about 10mm from the readout plane. These ions have to be neutralised during the 200ms period between the crossings. There are several possibilities to make a gating system to block the ions: a traditional wire grid, a GEM gate, or other MPGD based systems.

In a first section, we will discuss the challenges of using a wire gate in the context of LCTPC. In a second part, we will show the GEM gate concept and the performance achieved with prototypes for LCTPC.

1 Wire grid

Wire grids have always been used successfully as gating system in past TPCs using MWPC readout. Although the technology is well known, the high magnetic field and fine spatial resolution of LCTPC require a careful analysis of the effect of the wires on the electron position resolution.

1.1 Possible configurations within LCTPC

Building a wire gate independently from the MPGD readout modules would require extra structure, and would be very difficult to achieve without introducing problematic dead areas. Besides, it would be difficult to devise a system compatible with installation procedure for the LCTPC module concept. A wire gate should therefore be included within the modules. There are two different configurations that can be considered:

Transverse wires It is the traditional configuration for a wire gate, with wire transverse to the track direction. In the case of LCTPC, it has several disadvantages. The fan shaped modules do not allow to easily integrate this kind of gate (see Fig. 1a). It would also require support structures on the sides of the modules, which would increase the dead regions between the modules. Finally, the electron displacements along the wire (i.e. transverse to the track) will directly worsen the position resolution. As will be detailed in section 1.2.1, this effect dominates in a high magnetic field, but remains small.
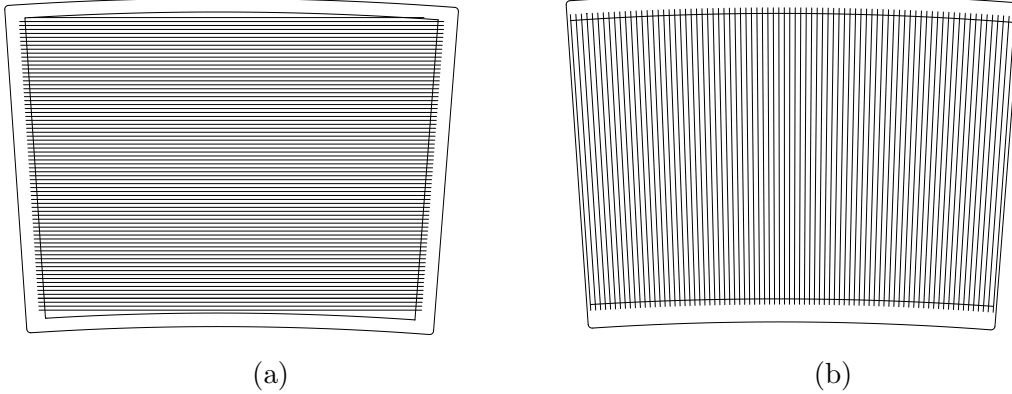

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<tr><td>(a)</td><td>(b)</td></tr>
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Figure 1: Wire gate configurations for LCTPC modules. (a) Transverse wires. The support structure creates dead regions on the sides. (b) Radial wires. No dead region.

Radial wires In the small sized modules of LCTPC, an interesting solution would be to string the wires radially (see Fig. 1b). In that case, the support structure would be mainly transverse to the tracks, so that the dead areas would not harm the tracking coverage. It is also much easier to integrate in the module, with a simple frame (for example a ceramic frame).

On the other hand, this configuration has never been tested and presents two main challenges. The wires along the track direction could create local angular effects on high momentum tracks. The radial configuration of the wires would induce a radial component to the electric field.

1.2 Distortions of the electrons trajectories

With the high precision requirements of LCTPC, the displacements of drift electrons should be minimised. For that purpose, the open gate should be run as close as possible to a uniform electric field. This means that the electric potential of wires should match the field cage, so that the charge induced in the wires is near null.

1.2.1 $E \times B$ effect close to the wires

Even in the ideal case where the wire potential matches perfectly the drift field, the surface charge distribution on the wires will create a dipole electric field transverse to the wire (xz-plane). In the high magnetic field of LCTPC, this will create a displacement of the drift electrons along the wire (y direction), according to the Langevin equations, with large $\omega\tau$ (of the order of 10 to 15 in LCTPC), and no field along the wires:

$$
\begin{array}{rcll}
\frac{dx}{dz} & = & \frac{1}{1+\omega^2\tau^2}(E_x + \omega\tau E_y) & \sim \quad E_x/\omega^2\tau^2 \\
\frac{dy}{dz} & = & \frac{1}{1+\omega^2\tau^2}(E_y - \omega\tau E_x) & \sim \quad -E_x/\omega\tau
\end{array}
\tag{1}
$$

We see that the amplitude of the displacement along the wire should be a factor $\omega\tau$ larger than the transverse displacement (x direction). This displacement should still be about a factor $\omega\tau$ smaller than the displacement without magnetic field (following the electric field lines). In an open gate configuration, as shown on Fig. 2a, the dipole field from the wire extends only a few times its radius. With a very thin wire ($r \sim 20\mu$m), this means that the displacements from $E \times B$ effect around the wire should be of the order of a few microns along the wire, and smaller than a micron transverse to the wire. In an ideal where the drift field is identical on both sides of the gate, the system is symmetric around the gate plane and the $E \times B$ effect cancels itself. More realistically, due to fluctuations of the wire voltage and position, a charge can appear on the wires which will increase this effect. This is shown on Fig. 2b and 2c.
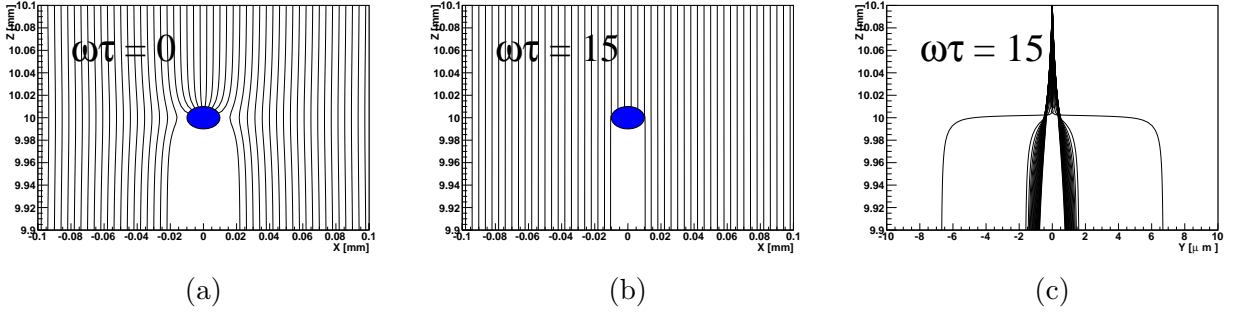

(a) (b) (c)

Figure 2: Drift lines around the wires, without diffusion. The wire voltage is 10V below nominal. The field distortions appear only very close to the wires. (a) without magnetic field (electric field lines). (b) with magnetic field, transverse to the wire. (c) with magnetic field, along the wire.

We see that this effect can produce distortions of the drift electron position of the order of a few microns in the wire direction. In a radial configuration, this would be in the track direction, and have only a negligible effect on space point resolution.

1.2.2 Radial electric field

In the case of radial wires, the symmetry present in a parallel configuration is not valid, and a radial component to the electric field induced by the wires appears. The amplitude of this radial field can be estimated in a first approximation by calculating the electric field created by a circular array of finite wires with uniform charge distribution. This is a strong approximation but should give an upper limit to the value of the radial field. In reality, the charge distribution cannot be uniform with a fixed potential, which should reduce the field produced by the wires. Besides, the field cage and the module frames will contribute to make the field more uniform.

The potential created by a charged wire of length L and linear charge λ centred at the origin is written:

$$V(x,y,z) = -\frac{\lambda}{4\pi\epsilon_0}\ln\frac{L/2-y+\sqrt{x^2+(y-L)^2+z^2}}{-L/2-y+\sqrt{x^2+(y+L)^2+z^2}} \tag{2}$$

Through symmetrisation, we can introduce the ground plane (MPGD plate). By summing the contribution of all the wire in the circle, we can get a numerical solution.

$$V(r,\theta,z) = -\frac{\lambda}{4\pi\epsilon_0}\sum_{k=-N/2}^{N/2-1}\ln\left(\frac{L/2-y_k+\sqrt{x_k^2+(y_k-L)^2+(z-z_0)^2}}{-L/2-y_k+\sqrt{x_k^2+(y_k+L)^2+(z-z_0)^2}}\frac{-L/2-y_k+\sqrt{x_k^2+(y_k+L)^2+(z+z_0)^2}}{-L/2-y_k+\sqrt{x_k^2+(y_k-L)^2+(z+z_0)^2}}\right) \tag{3}$$

3

Where x_k and y_k are the coordinate relative to the wire k ($\delta\theta = 2\pi/N \approx 10^{-3}$ is the angle between two wires):

$$\begin{aligned} x_k &= r\sin(\theta - k\delta\theta) \\ y_k &= r\cos(\theta - k\delta\theta) \end{aligned} \qquad (4)$$

This formula can be again symmetrised to take into account the anode plane. The charge λ is calculated from the voltage set in the middle of the wire and is proportional to the voltage difference between the gate and the field cage. In an ideal case, this difference would be zero, but the imprecision of the high voltage and the sagging of the wires will change this value by a few volts. Figure 3 shows the results of the computations for 10V difference.
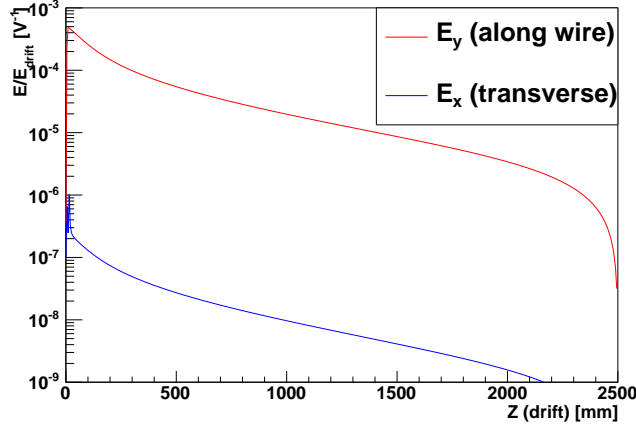

Figure 3: Strength of the electric field parallel and perpendicular to the wires, compared to the drift field. Numerical calculation for a ring of finite wires with uniform charge. The value shown is the maximum over the xy-plane.

We can see that the radial field decreases quite slowly with the drift distance. It reaches $10^{-4}E_{drift}$, which is the level expected for fluctuations of the electric field in the drift chamber, after about 30cm. This result depends very little on the wire spacing, or the wire diameter. This shows that the effect of the non parallel wire on the electric field, when the gate in open, should be small. As it was pointed out, more realistic model would show that this effect is much smaller and well within the accepted fluctuations of the drift field.

1.3 Closed gate configuration

There are to different regimes that can be used to close the gate:

Single potential By applying a large positive voltage on all the wires, we can reverse the electric field below the gate. In that case, the positive ions will drift back and be neutralised on the MPGD plane. As shown on Fig. 4a, it requires a very large voltage to reverse the field at the level of the gate. The gate should therefore be a couple of millimetres beyond the limit of the ion cloud. Fig. 4b shows that in that case the voltage required is much smaller, but field below the gate is much weaker than the drift field. In the ILC running scheme, the period between the trains (closed gate) is 100 times longer than the trains themselves, so that a weaker field would be enough to allow the ions to drift back to the MPGD plane.

Alternate potential Another scheme consists in applying alternate potentials $V_g - \Delta V_g/2$ and $V_g + \Delta V_g/2$ to every other wire. In that case, at large distance from the wires, the electric field is unaffected. The resulting field lines are shown on Fig. 4c. The ions will drift towards the wires

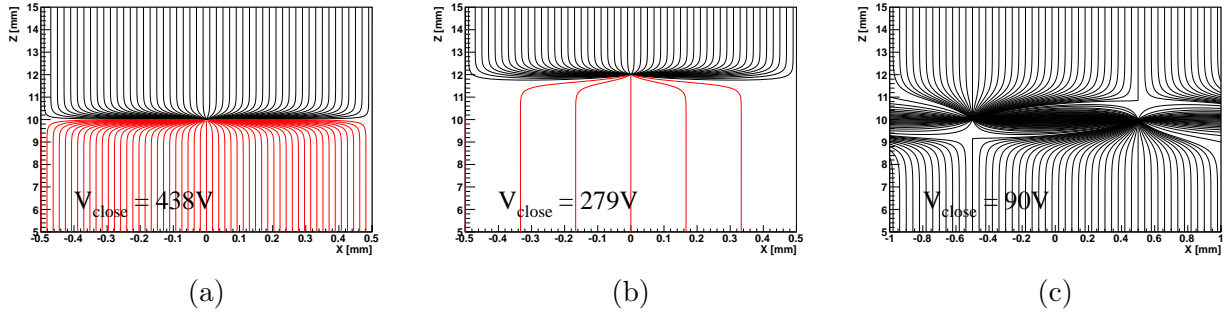(a)   (b)   (c)

Figure 4: electric field lines for closed gate configurations. (a) Single potential closed at the level of the gate. The red lines represent the different orientation of the electric field. (b) Single potential closed 2mm below the gate. The field s much weaker below the gate. (c) Alternate potential. The field below the gate is the same as the drift field.

with lower potential. This solution is a bit more difficult to implement than the previous one, but it requires lower voltages, and will not affect the drift field inside the field cage.

The voltage required to close the gate will depend on the space between the wire. To reduce the strain on the support structure, the number of wires should be minimised, and therefore the wire spacing should be maximised. The voltage required to close the gate can easily be calculated analytically for parallel wires. The required voltage in the case of radial wires is found numerically to be very similar. Figure 5 shows the dependence of the closed gate voltage with the wire spacing.
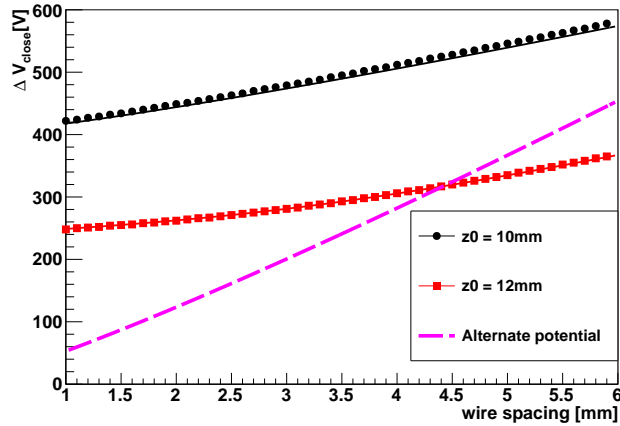

Figure 5: Voltage required to close the gate 10mm from the amplification plane. For the single potential solution, the voltage has to be slightly increased to allow the ions to drift back quickly enough.

2 GEM gate

GEM has been initially proposed as a gating device by F.Sauli [3] without a function of gas amplification. Such a gate would be most adapted for the module structure of LCTPC. However, a good electron transmission is difficult to achieve with such a gate.

2.1 principle of GEM gate

In order to keep the maximum information about the track, as many ionisation electrons as possible must be transferred from the drift volume, through the gate, to the amplification region of the MPGD. Sauli pointed out the existence of higher electron transmission region at very low voltage operation of the GEM for certain gas mixtures.

This would allow to use the GEM as a gate without affecting the space resolution too much. The GEM can easily be used as a closed gate by reversing the electric field in GEM hole. This can be achieved by changing only the potential of lower electrode of GEM, without affecting the field in drift region.

2.2 transmission measurements

Electron transmission under LCTPC conditions has been measured by two different methods. One consisted in comparing signal charge passing through the gate to the signal without gate using a small test chamber irradiated with an ^{55}Fe source. The other method is based on the effective number of electrons, N_{eff}, which can be extracted from the behaviour of the spatial resolution as a function of drift distances. The transmission can then be evaluated as the ratio of N_{eff} with and without gate.

The transmission measurement based on iron source has been carried out using a test chamber which contain a standard $10 \times 10 cm^2$ $100 \mu m$ thick GEM readout and a $14 \mu m$ thick gate GEM placed $10mm$ above. Figure 6 shows a sketch of the experiment. X-rays from the Fe source can penetrate the thin window and the cathode and are converted in the gas volume. In case A, the conversion happens in the drift region, so that the produced electrons have to pass the gate and the signal is affected by the gate transmission. A small portion of the X-rays are converted in the region between gate and amplification GEM (case B), which produce signal without any effect of the gate. The electron transmission is calculated as the ratio of the two signals in the same measurement, without any systematic changes.
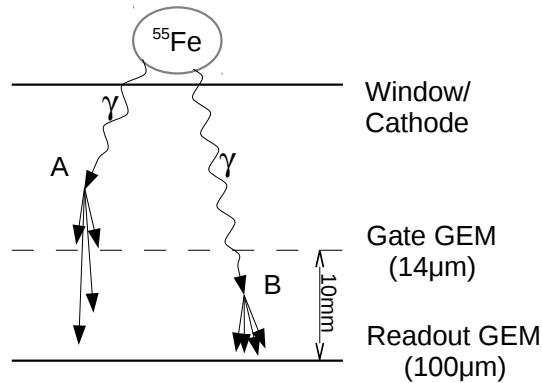

Figure 6: Sketch of the gate transmission test. We measure at the same time signals produced above the gate (A) and below (B). The ratio give the electron transmission.

Figure 7 shows the measured transmission as a function of the voltage applied to gate GEM. Measurement is done under typical LCTPC conditions: T2K gas, 230V/cm for drift E field and 1T magnetic field. The transmission is maximal for a 10V voltage applied to the GEM. In that case, the transmission is still only about 40%, which is too low for the resolution requirement of LCTPC.

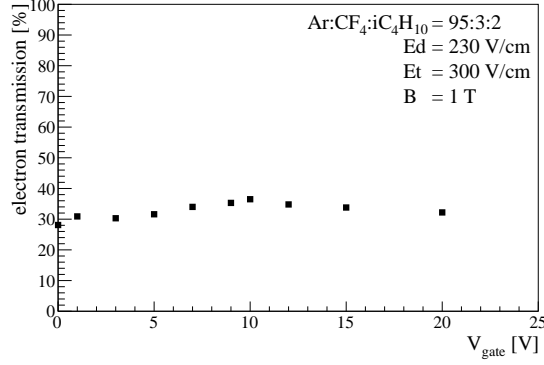Figure 7: Measured electron transmission as a function of the voltage applied to the GEM gate. A maximum is observed at 10V.

The $14\mu m$ GEM gate was also equipped into MPTPC (a small prototype TPC for LCTPC study [2]) and cosmic ray tracks were measured under a 1T magnetic field. The spatial resolution was measured for different drift distances. The effective number of electrons N_{eff} can be extracted from these measurements, with and without gate. The obtained ratio $\dfrac{N_{eff}^{wGate}}{N_{eff}^{w/oGate}} \simeq 0.5$ shows a electron transmission of about 50% at 1T, $E_{drift} = 230V/cm$ and $V_{GATE} = 5V$. This result is roughly consistent with the previous direct measurement with ^{55}Fe source.
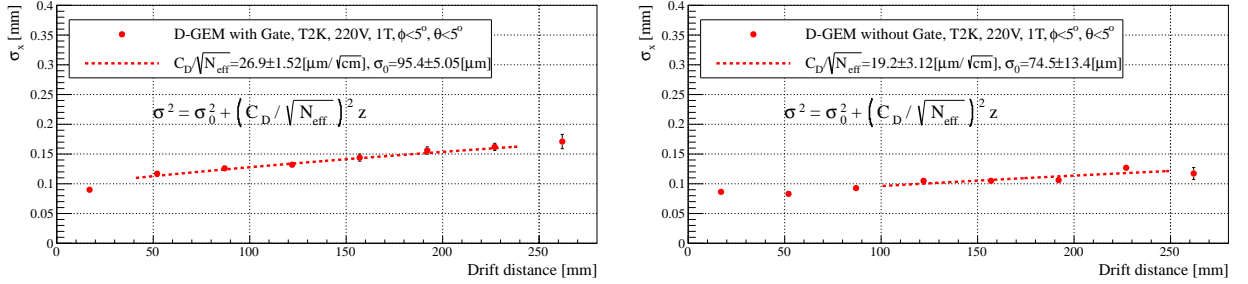

Figure 8: Space resolution measurements with and without gate. From the slope of the fits, we find a value for N_{eff} of 18 ± 2 without gate and 9 ± 1 with gate. The resolution is clearly worse with gate.

$14\mu m$ thick GEM gates for LP1 module were also produced and tested at the LPTPC test facility. However the stretched thin gates exceeded the nominal size due to higher elasticity and touched to neighbouring module, resulting in discharge between module. This problem could be solved in a new production, but the transmission must be improved before new tests at LP1.

2.3 Simulation

The software for simulation of electrons and ions in gas, Garfield [4], has been used to try to understand quantitatively the data from the electron transmission measurements. The old version of Garfield contains an artificial parameter, so called step size, which needs to be tuned for each condition in order to reproduce measurement data. We this version of Garfield, we could see that the thickness of the gate was an important parameter, but the tuning of that parameter made the results less reliable, and prevented the use of the simulation for developing an improved new gate. In the newer Garfield version, Garfield++ [5], the software has been improved, including automated step-size selection according to physics process, photo-emission processes in gas amplification, etc... We have used this updated

simulation tool for our gate operation conditions. Figure 9 shows how Garfield++ reproduces our data for Ar/iso-butane(90/10) gas mixture. The very thin 14 micron thick GEM with 90 micron diameter hole in 140 micron pitch is operated under 50V/cm of drift field and 150V/cm field below gate.
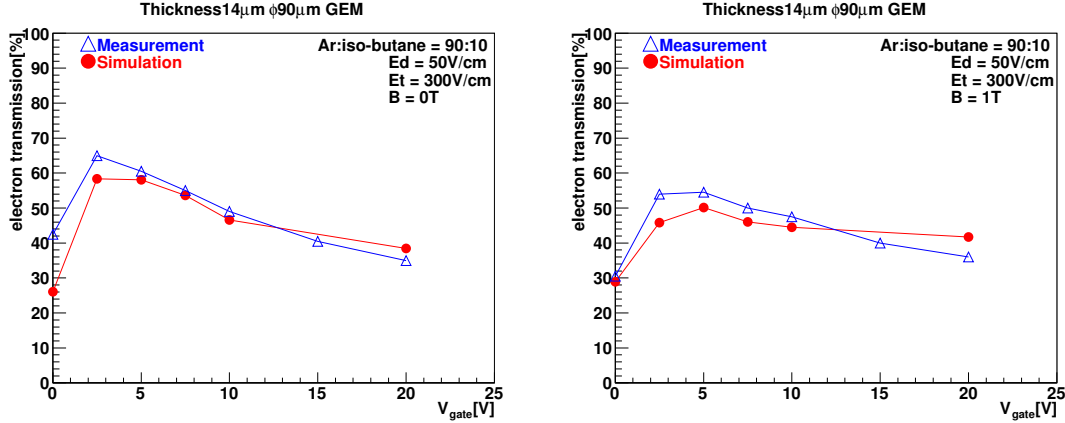

Figure 9: Simulation of the electron transmission for a 14 μm thick GEM gate. The Garfield++ simulation gives a good description of the data both with and without magnetic field.

The simulation could reproduce the measurement data well, both with and without magnetic field, without specific tuning. This implies that we can use Garfield++ to design new gate devices which can provide enough electron transmission.

A major problem to make GEM with the currently used method is controlling a passive etching process with an accuracy of O(10μm).

R&D on hardware work is also ongoing. In order to keep hole aperture larger than 80%, the thickness of the rib (wall around the hole) must be at most $10\mu m$ for a $100\mu m$ pitch structure. This requires an etching accuracy below O(10μm), which is difficult to achieve with the methods currently used. The possibility to use MEMS techniques instead is now being investigated.

Conclusion

It has been shown by simulation that the back drift ions in LCTPC will create significant distortions on the drift field. To prevent this, several gating systems are being investigated.

A wire gate is a good candidate. The effect of an open wire gate on the electron trajectories should be negligible, even in a high magnetic field. A radial configuration would be most adapted to the LCTPC module concept and would minimise dead regions. The effect of the induced radial electric field should be negligible, but has to be better understood experimentally. A prototype will be tested at LP1, with 1T magnetic field. Further studies and engineering considerations should be taken into account to choose the most appropriate voltage scheme for the closed gate as well as the gate position.

A gating system with thin GEMs has been tested experimentally, but has shown lower transparency than expected. Work in ongoing to better understand this effect in simulations. Until then, it is impossible to guarantee that such a gate can provide the performance required by LCTPC.

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