Simulation studies of the electroluminescence signal in the LXe TPC of the LUX-ZEPLIN (LZ) detector

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for LZ collaboration

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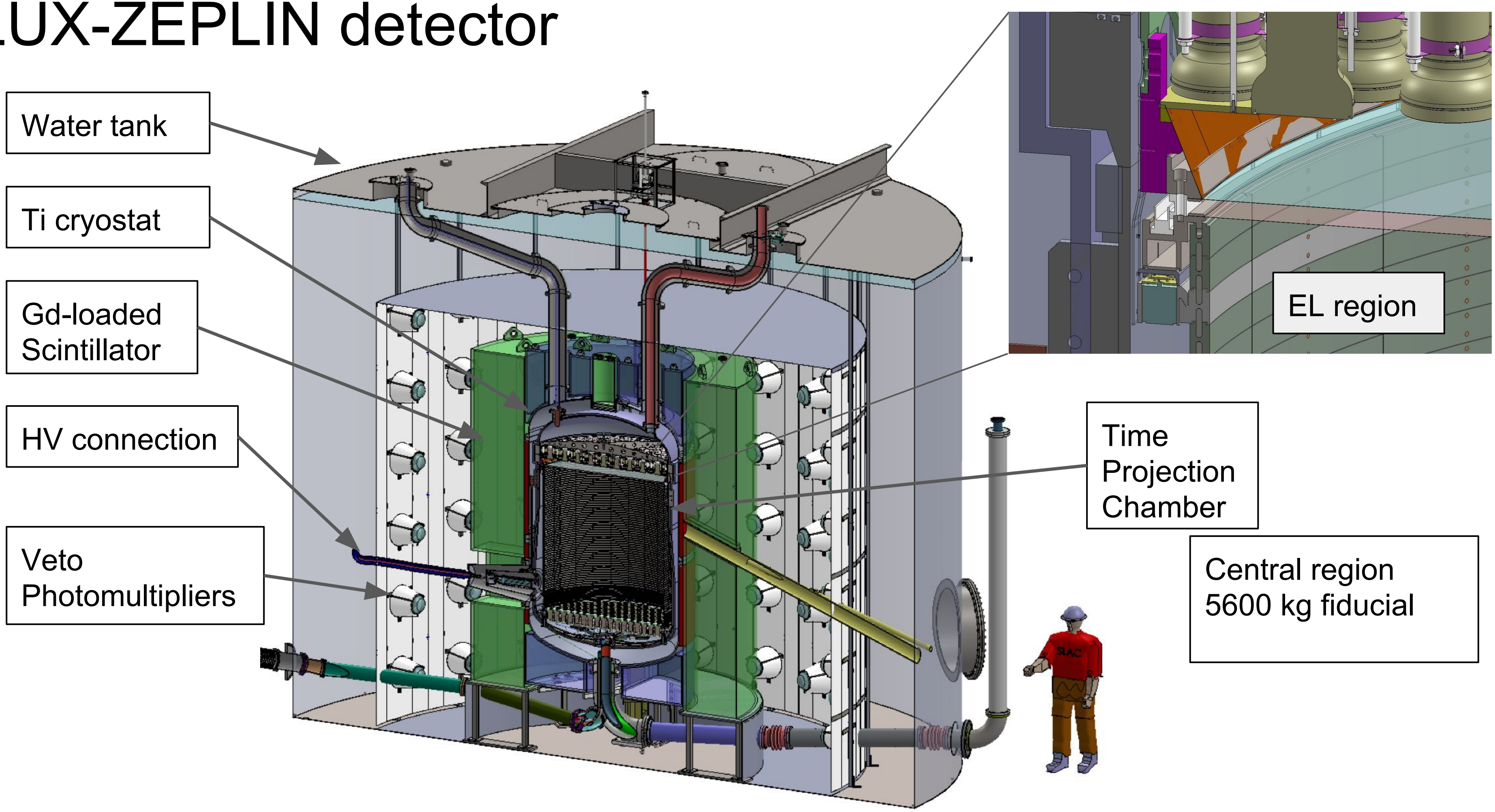
Presentation Outline

1. The LUX-ZEPLIN (LZ) detector
2. Scintillation in xenon, S1 and S2 signals in double-phase detector
3. Simulation of electroluminescence using GMSH, ELMER and Garfield++
4. Electric field simulation in ZEPLIN-III, LUX and XENON100
5. Design of the LZ electroluminescence region
6. Conclusions

LUX-ZEPLIN detector

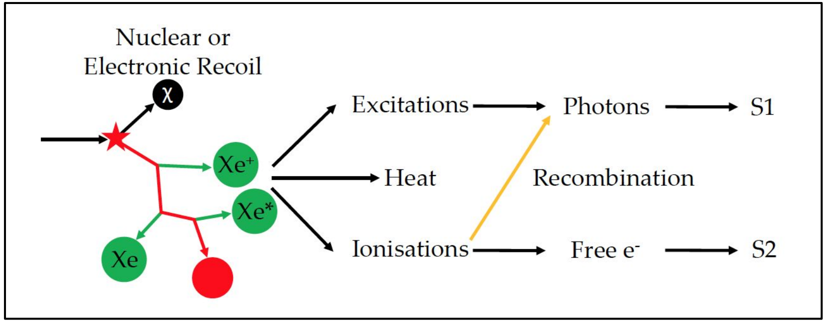


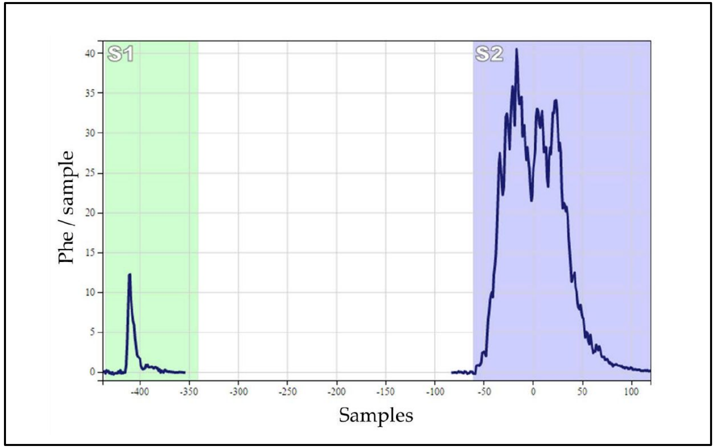
Why liquid xenon ?

Advantageous properties of liquid xenon for direct dark matter searches :

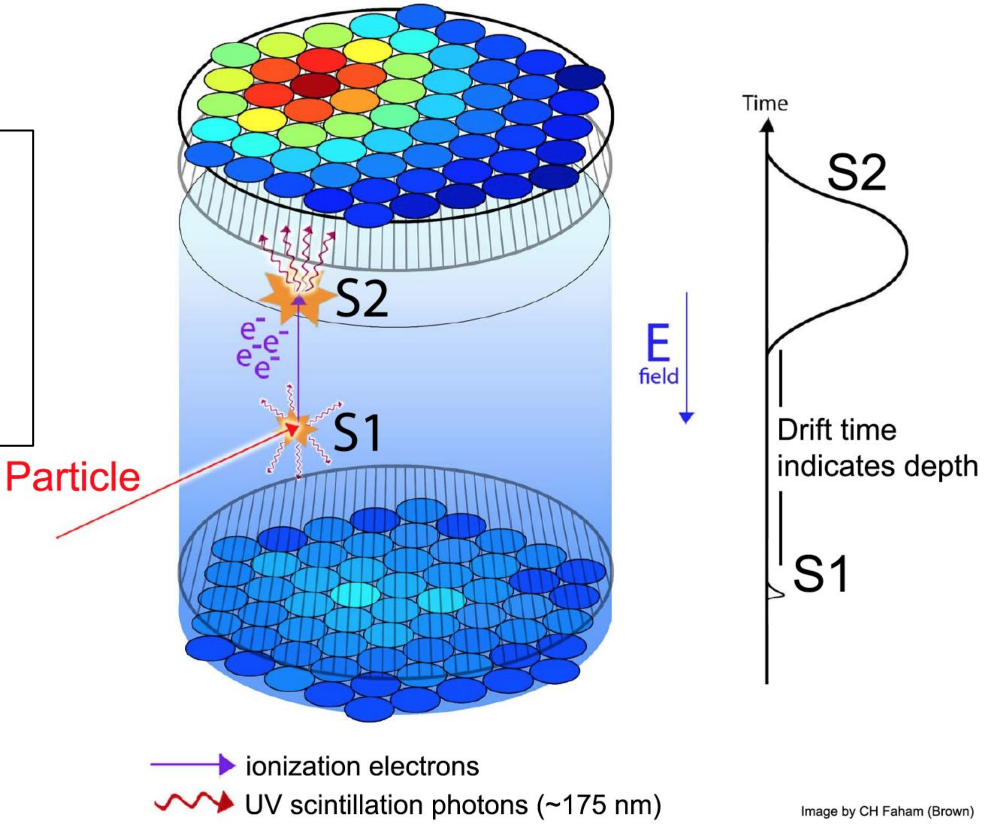
1. Scintillation and ionisation yield high - low energy detection threshold
2. High density - interaction length of radiation short - excellent self shielding
3. Spin-independent WIMP-nucleus scattering - A^2 enhancement of the rate due to coherent nature of the interaction
4. Easy to scale up (filling larger vessel) comparing to solid media
5. No long lived isotopes (exc. ^{136}Xe 2NBB, which is not problematic)
6. Dispersed impurities can be removed prior/during operation

S1 and S2 signal





Example of waveform from LUX



- Single photon and electron sensitivity
- Z position from S1-S2 timing
- X-Y position from S2 signal pattern
- ER/NR discrimination by charge to light ratio (S2/S1)

Design of the Electroluminescence Region

1. Photon yields

   Number of photons emitted per electron extracted from the liquid - large enough for single e^- detection with high s/n.
   The LZ photon detection efficiency of 7.5% requires 1,190 photons per electron

2. Extraction efficiency

   Depends on the electric field in the liquid - high efficiency gives larger S2 signal, remove a source of variance and also possible charge accumulation at the liquid surface. LZ extraction is 95% with field 5.6 kV/cm

3. Resolution of S2 signal

   The variance should be limited (ideally) by statistical fluctuations and the impact of EL region by design should be minimal - S2 variance affected by: xenon purity, extraction efficiency, E-field uniformity in the gas gap and statistical fluctuation on the number collisions/created excitons

4. Maximum electric fields on the anode wire surface

   High electric field can lead to end-of-track ionisation and hence additional electroluminescence.

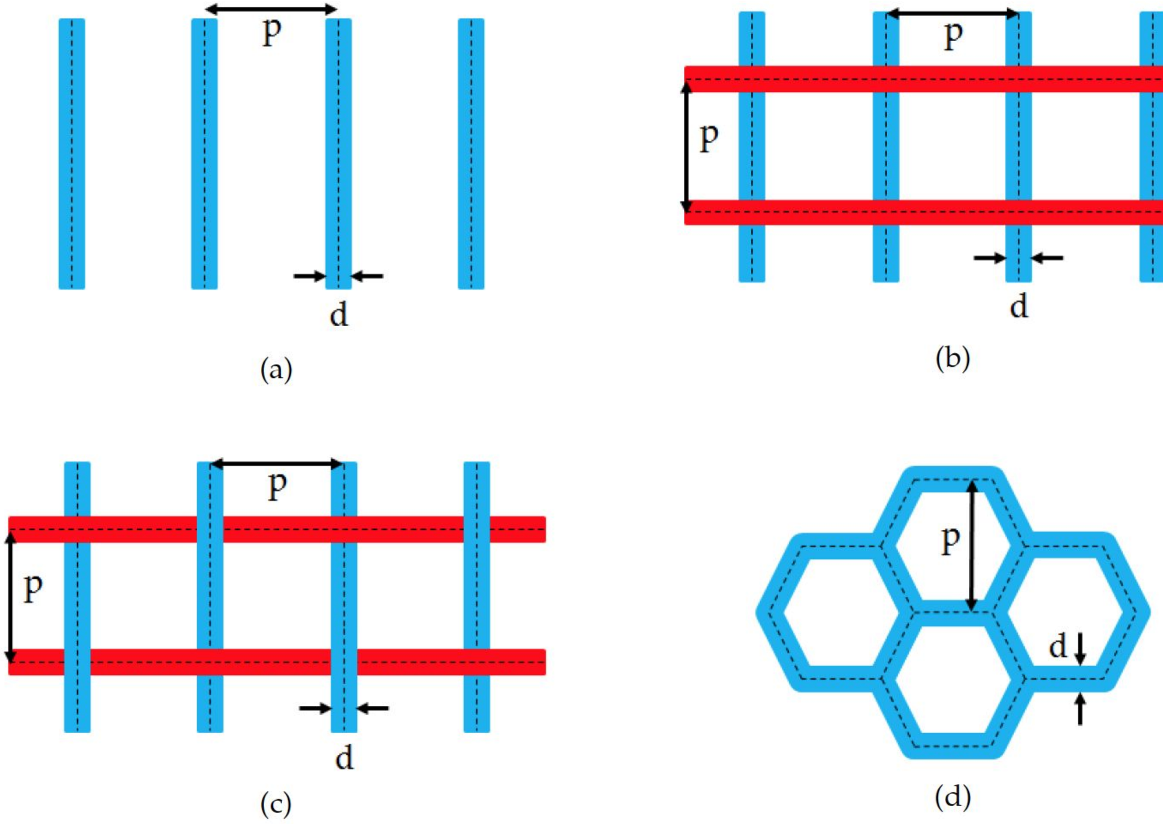
5. Optical transparency

   High photon detection efficiency requires minimal obscuration. In LZ the transparency of all grids is >80%.

6. Mechanical requirements

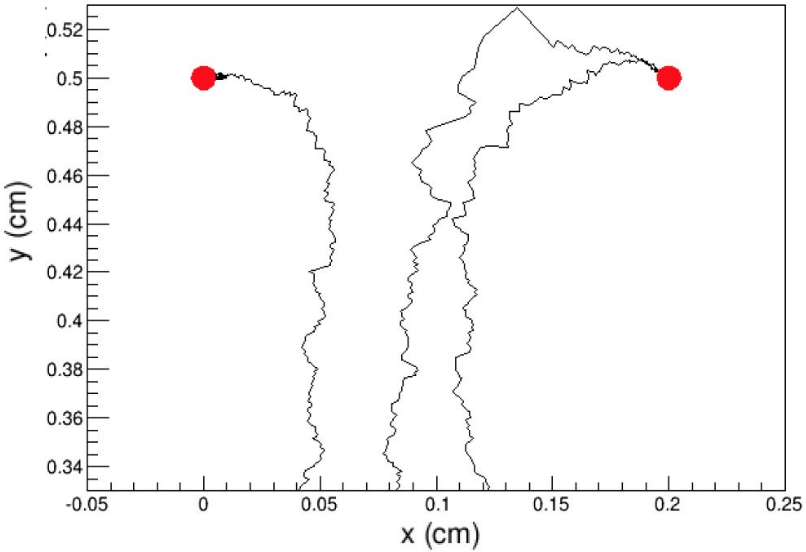
   Wire tension must be large enough to resist electrostatic forces. This has impact on uniformity of the field.
   In LZ a sagging of 2 mm at the centre can be tolerated.

Common wire grid geometries



a) Parallel wire grid, b) crossed wire grid, c) woven wire mesh, d) hexagonal mesh

S2 signal - secondary scintillation light



Example of three electron drifts
from the liquid surface to anode wires

- Acceleration in the gas phase
  (lower xenon density and higher electric field)
- Collisions exite xenon atoms and produce electroluminescence

Excimer creations through three body interaction:

$$R^{*} + 2R \rightarrow R^{**}_{2} + R$$

Decay via:

$$R^{**}_{2} \rightarrow 2R + hv_{1}$$

Or collision:

$$R^{**}_{2} + R \rightarrow R^{*}_{2} + R$$

With resulting light emission:

$$R^{*}_{2} \rightarrow 2R + hv_{2}$$

Where:

$2R$ - two atoms at ground state

R^{*} - excited atom

R^{**}_{2} - eximer (high vibrational state)

S2 signal yield (parametrised)

Number of emitted photons per cm depends on the electric field E and gas pressure P:

$$dN_{ph}/d_x = \alpha * E - \beta * P - \gamma$$

Where α=0.137/V; β=177/bar/cm and γ=45.7/cm (V.Chepel and H. Araujo)

The minimum electric field required to produce electroluminescence in xenon vapour at ~ 1.6 bar is 2.5 kV/cm

Typically hundreds of photons are emitted per electron in 1 cm gas gap.

With drift velocity 4-12 mm/μs S2 pulse width ~ 1 μs giving much larger pulse than S1.

Electroluminescence light simulation flow

Gmsh → (Geometry + mesh) → ElmerGrid → (Format trans.) → Elmer → (Field map) → Garfield++

Gmsh

Meshing of arbitrary 2D/3D geometry

Geometry coding:

Points,
Lines,
Surfaces,
Volumes,

CAD file input

No adaptive mesh;
Local mesh density controlled manually by element size, smaller=finer

Elmer

Finite element electric field solver

Boundary conditions : voltages and symmetries

Material dielectric constant

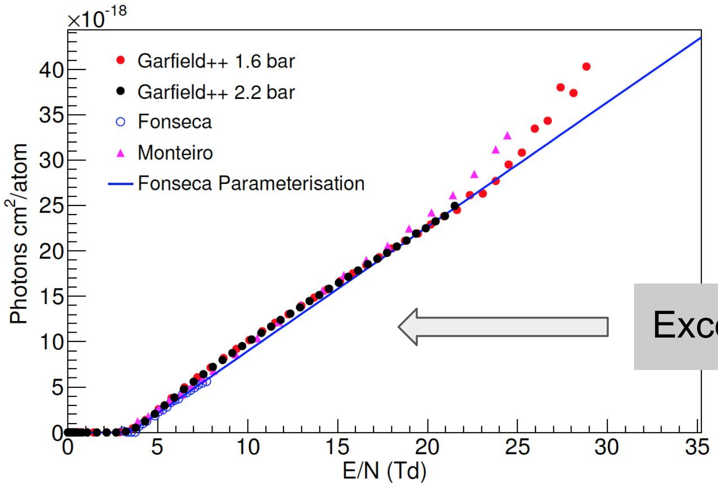
Garfield++

Electric field map import
Electron drifting in the gas
Interfaced with ROOT

Gas properties by Magboltz

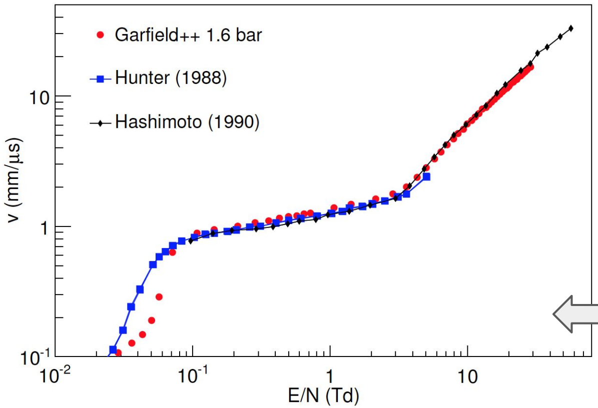
Xenon - 50 excitation levels

Validation of the simulation model



Electroluminescence yield: measured, parameterised and simulated with Garf++ at both P=1.6 and 2.2 bar. Deviation at higher reduced field (approx above 17 kV/cm) due to onset of charge multiplication process.

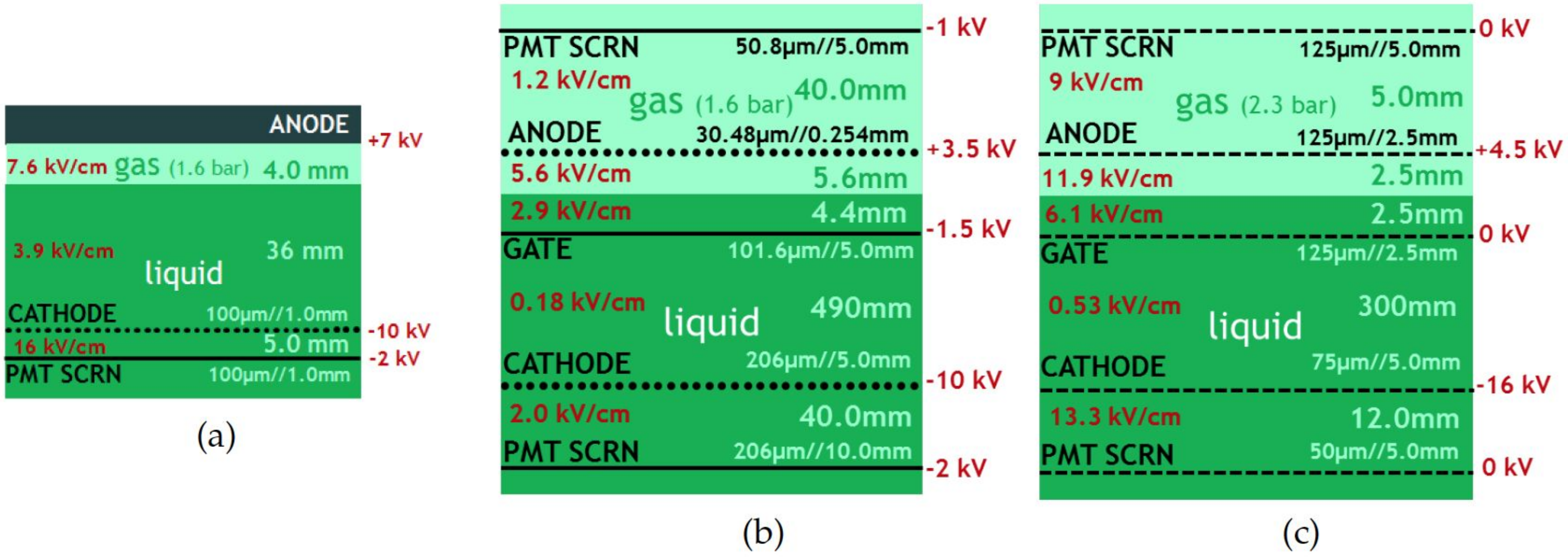
Excellent agreement with data



Validation of the electron drift velocity against two measurements.

Excellent agreement for fields >100 kV/cm relevant in this simulation.

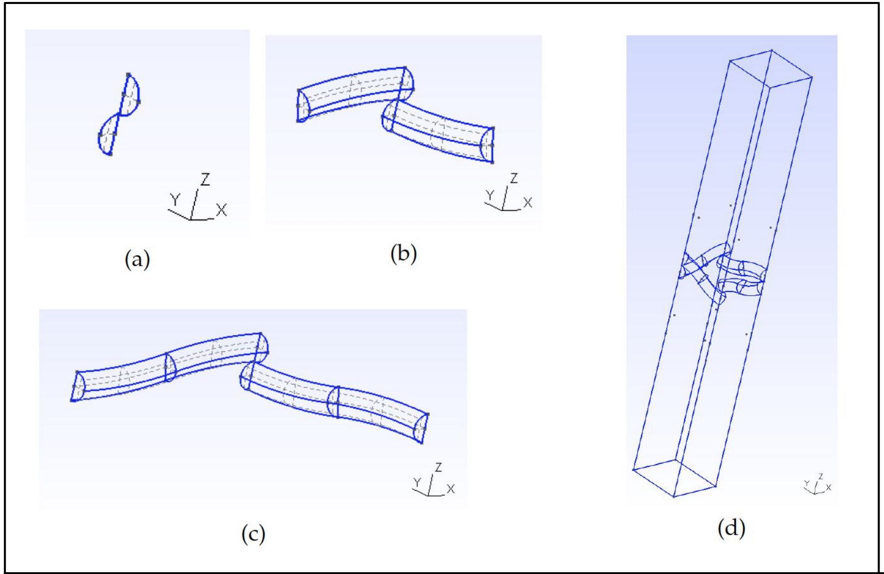
Validation of the simulation model



Geometry and parameters used in the simulations:

a) ZEPLIN-III : Anode - solid plate, cathode and PMT screen wires are parallel
b) LUX : Anode - woven mesh, other - parallel wire grids
c) XENON100 : All grids are hexagonal etched meshes

Modelling of the woven wire mesh in Gmsh

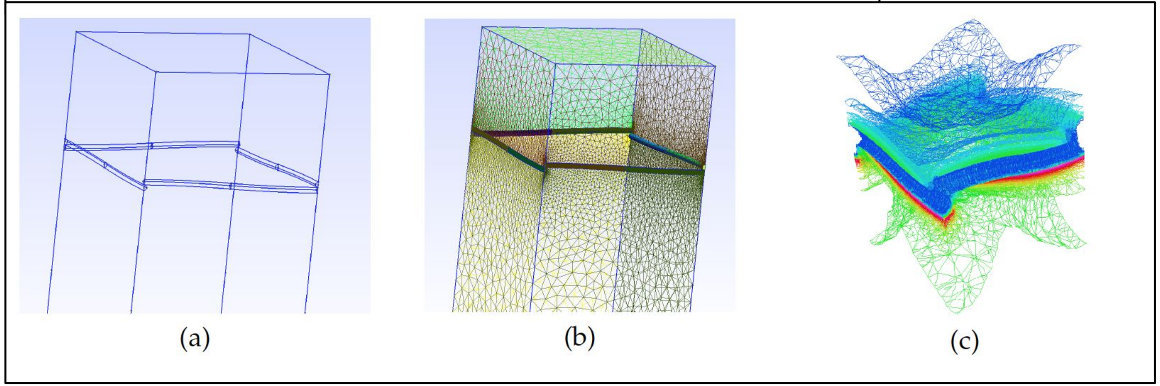


a) Initial semi-circles for creating wires
b) First extrusion of the wires along arc:

   Radius = $(p^2 + r^2_w)/2r^2_w$

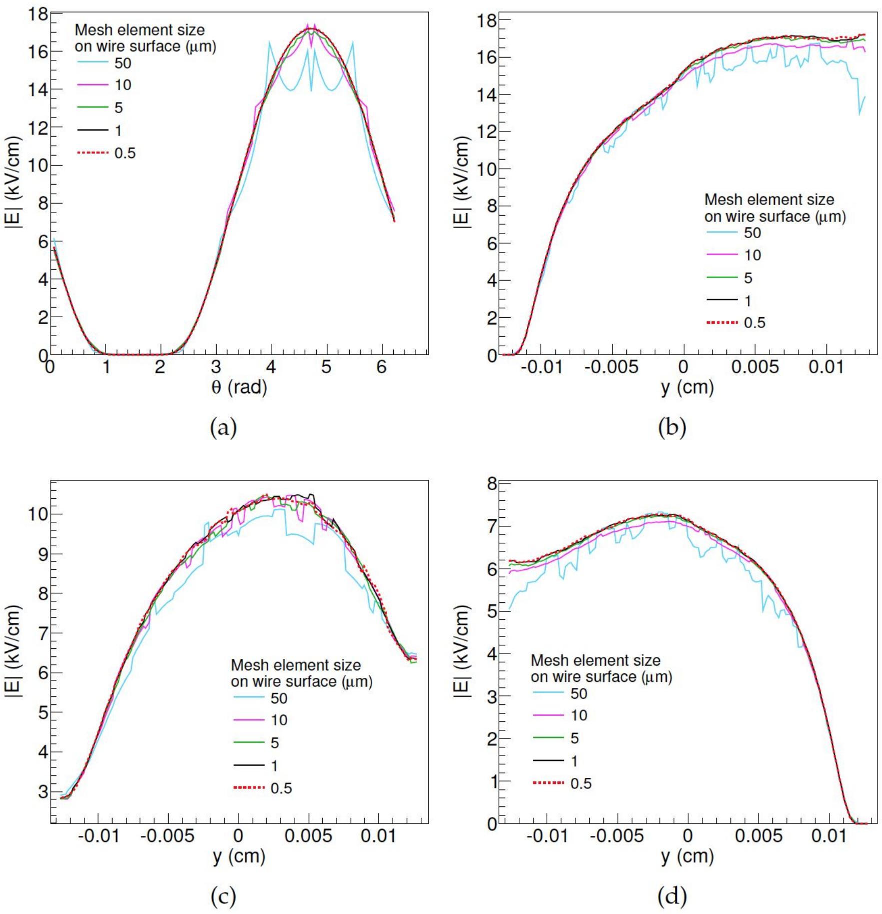
   Angle = $\sin^{-1}(p/R)$

   Where: p - wire pitch, r_w - wire radius
a) Second extrusion of the wires
b) Adding cell filled with gas



a) Woven wire single cell in Gmsh
b) 2D triangular meshing in Gmsh
c) Elmer electric field contours

Electric field strength on the wire surface in LUX



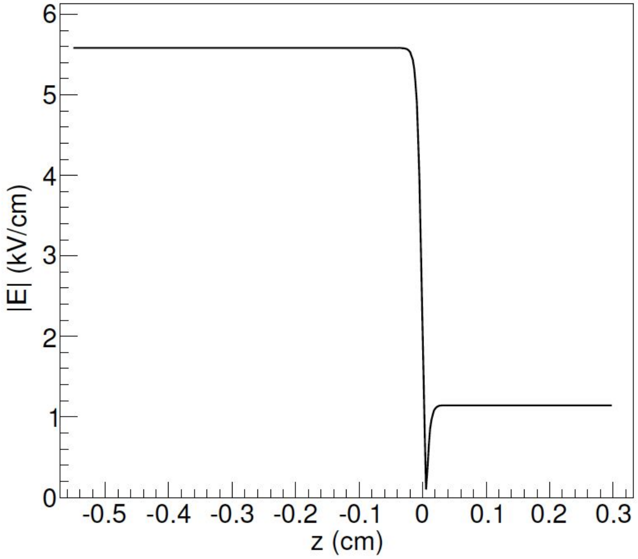
a) Around the bottom wire

b) Along the bottom wire

c) Along the side of the wire

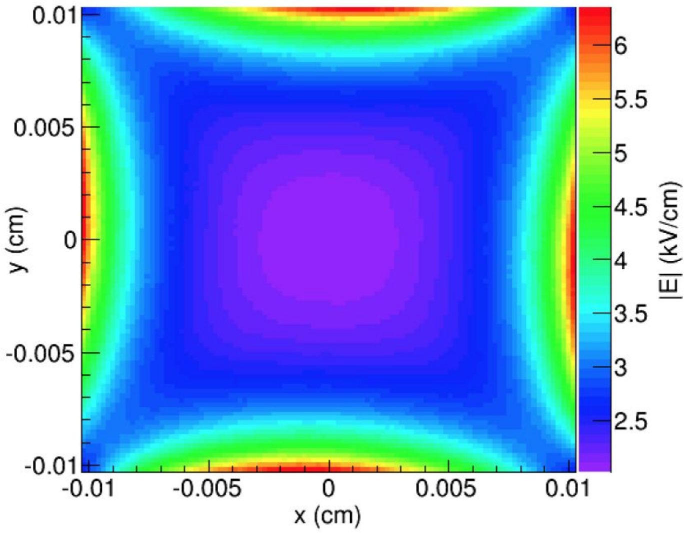
d) Along the top of the wire

Electric field along the cell axis and at anode's plane



(a)

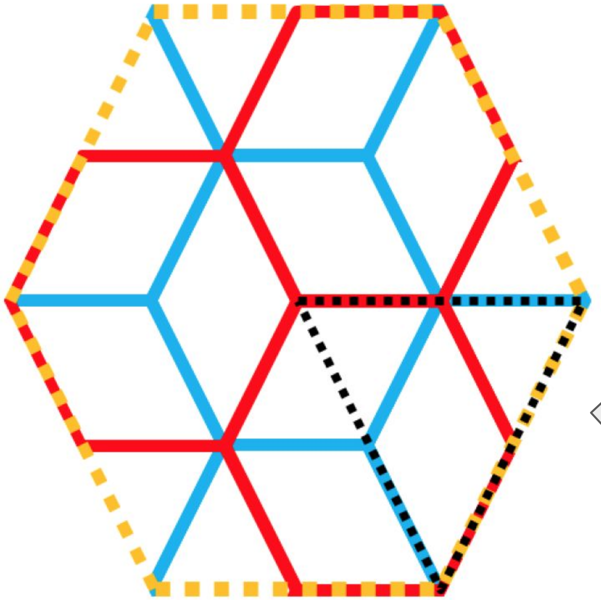
Liquid level at z=-0.56 cm and anode at z=0



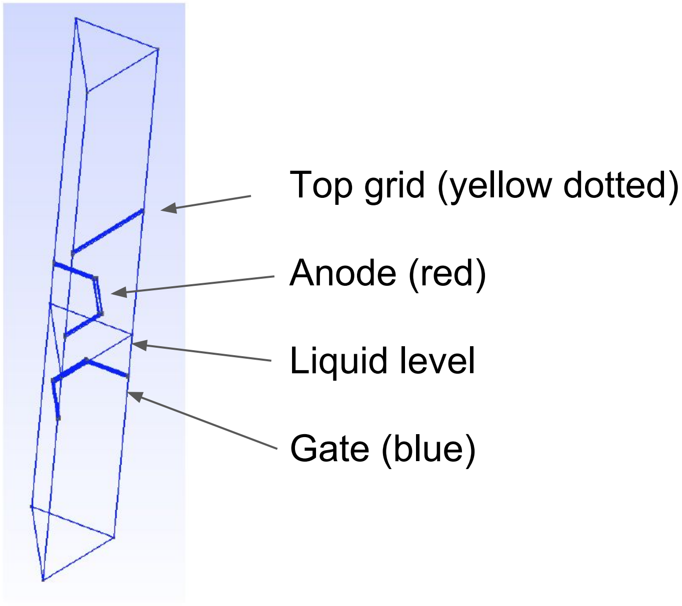
(b)

X-Y electric field at z=0

Calculation of the electric field in XENON100



(a)

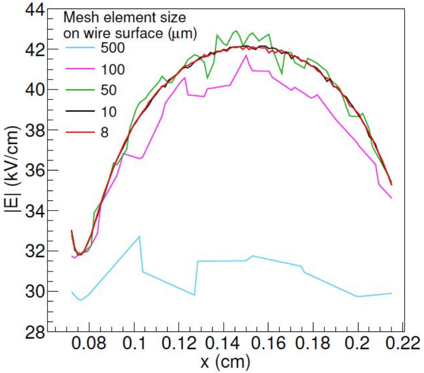


(b)

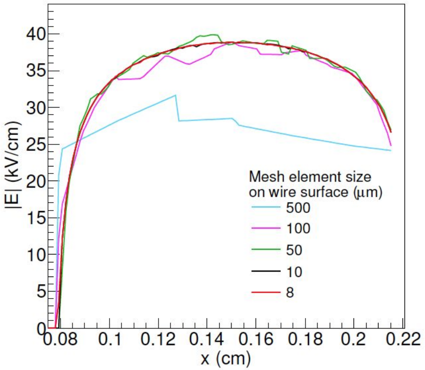
Layout of hexagonal grids in XENON100
(unit cell - black dotted)

Unit cell created in Gmsh

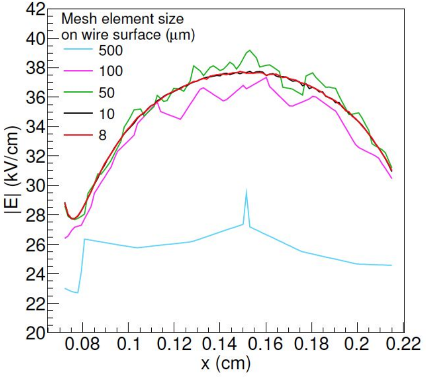
Calculation of the electric field in XENON100



(a)



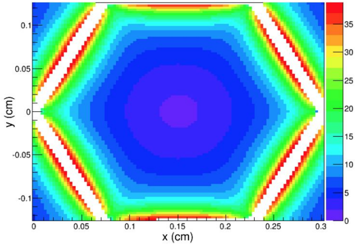
(b)



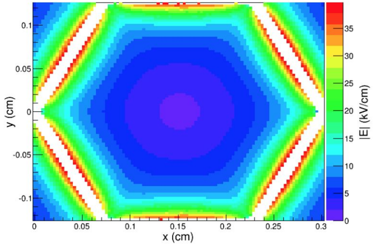
(c)

Electric field along anode segment a) bottom; b) side; c) top

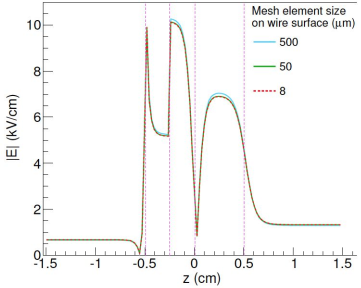
a) and b) X-Y field at the anode plane
(different mesh size)



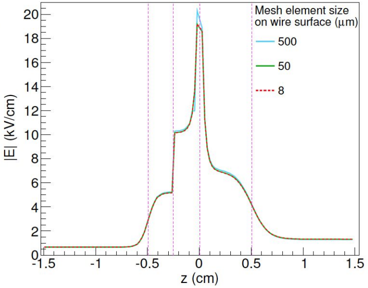
(a)



(b)



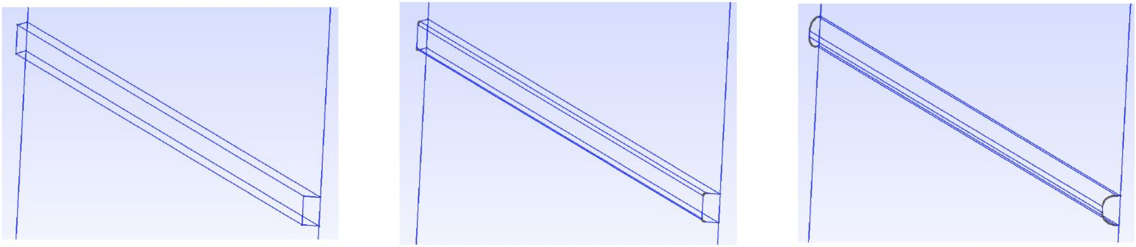
(c)



(d)

E- field along z axis : c) centre of the anode;
d) centre of the gate

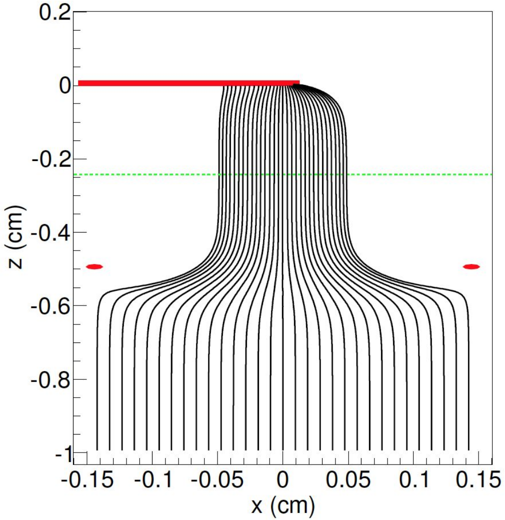
Calculation of the electric field in XENON100



(a) (b) (c)

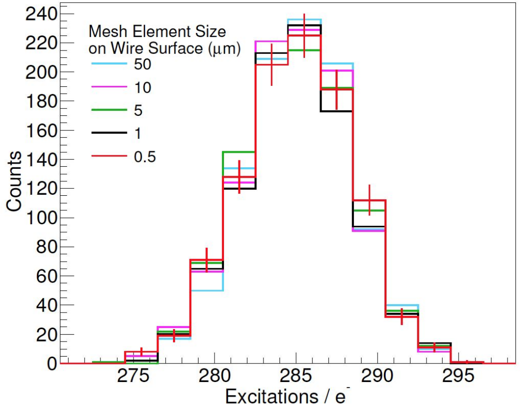
Different wire roundings:
0, 20 and 80%

With higher rounding lower field at the wire hence less ionisation is expected.



Drift lines in XENON100
Red - electrodes
Green - liquid level

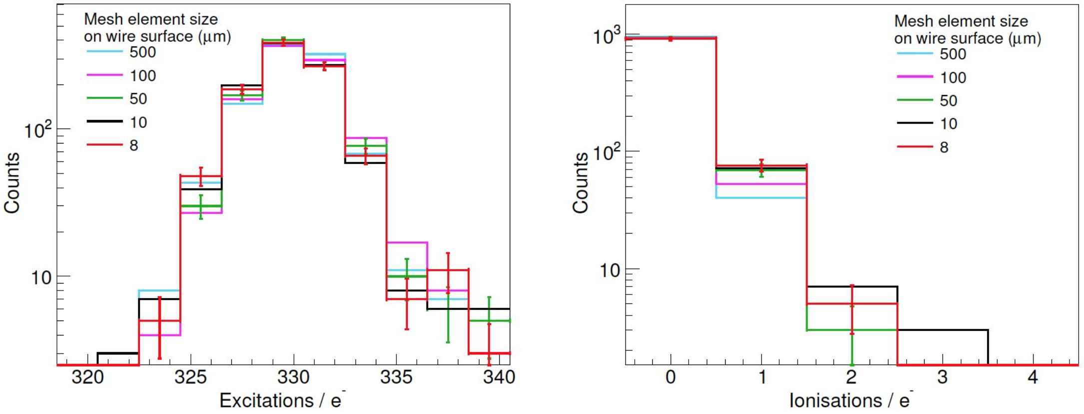
Mesh density effect on photon and ionisation yields



Number of excitations (electroluminescence photons) emitted per drifting electron in LUX

Mesh element size at wire surface (μm)	γ/e^-	σ/μ (%)
50	285.2 ± 0.1	1.13 ± 0.02
10	284.9 ± 0.1	1.15 ± 0.02
5	285.1 ± 0.1	1.18 ± 0.02
1	285.0 ± 0.1	1.16 ± 0.02
0.5	285.0 ± 0.1	1.18 ± 0.02

50 μm taken as optimum and used in further calculations

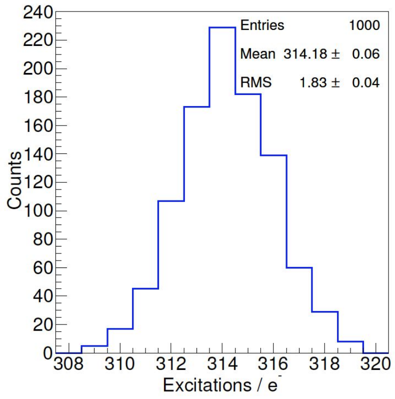


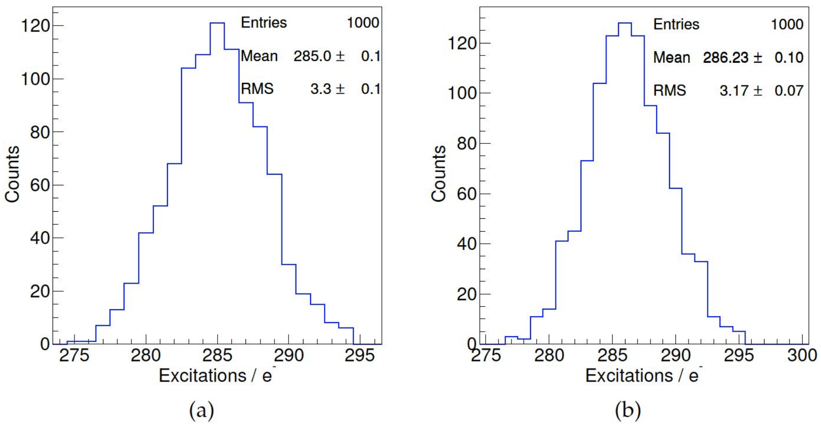
(a) (b)

Number of excitations (a) and ionisation (b) per drifting electron in XENON100 with different size of the mesh

Mesh element size at wire surface (μm)	γ/e^-	σ/μ (%)	ions$/e^-$
500	330.4 ± 0.1	1.00 ± 0.02	0.05 ± 0.01
100	330.9 ± 0.2	1.45 ± 0.03	0.07 ± 0.019
50	330.5 ± 0.1	1.15 ± 0.02	0.08 ± 0.01
10	330.3 ± 0.1	1.31 ± 0.03	0.10 ± 0.01
8	330.3 ± 0.1	1.13 ± 0.02	0.09 ± 0.01

Simulation validation: ZEPLIN-III and LUX





Excitations per electron in ZEPLIN-III
P=1.6 bar,
Eg=7.6 kV/cm
Hg=0.4 cm

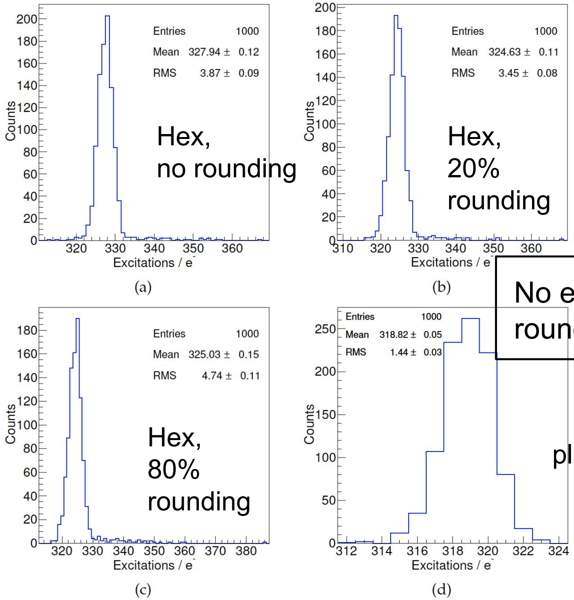
Excitations per electron in LUX
P=1.6 bar,
Eg=7.6 kV/cm
Hg=0.4 cm

a) Woven mesh
b) Planar geometry

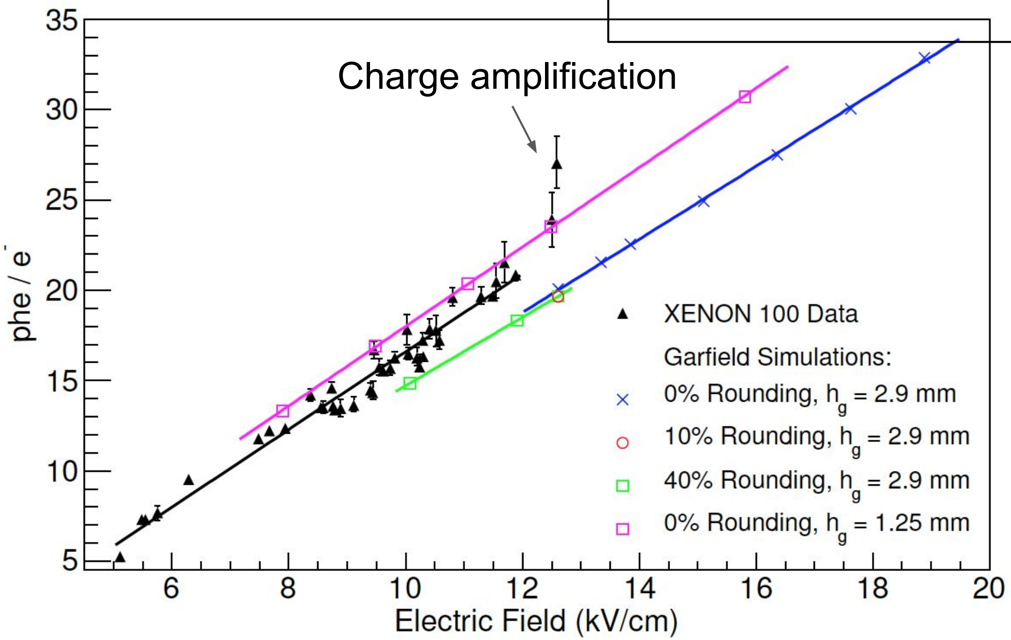
ZIII and LUX difference - higher yield due to higher field

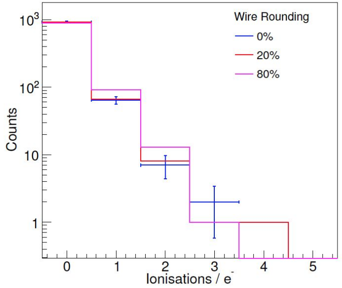
Simulation validation: XENON100

Systematic 10% difference attributed to scaling and assumption on photon detection and quantum efficiencies



No effect from rounding





Excitations and ionisation per electron in XENON100
P=2.3 bar,
Eg=11.9 kV/cm
Hg=2.5 mm

Single electron data from XENON100 and simulations of that geometry

Data taken at different gas gaps and scaled to 2.9 mm

Results from the simulations

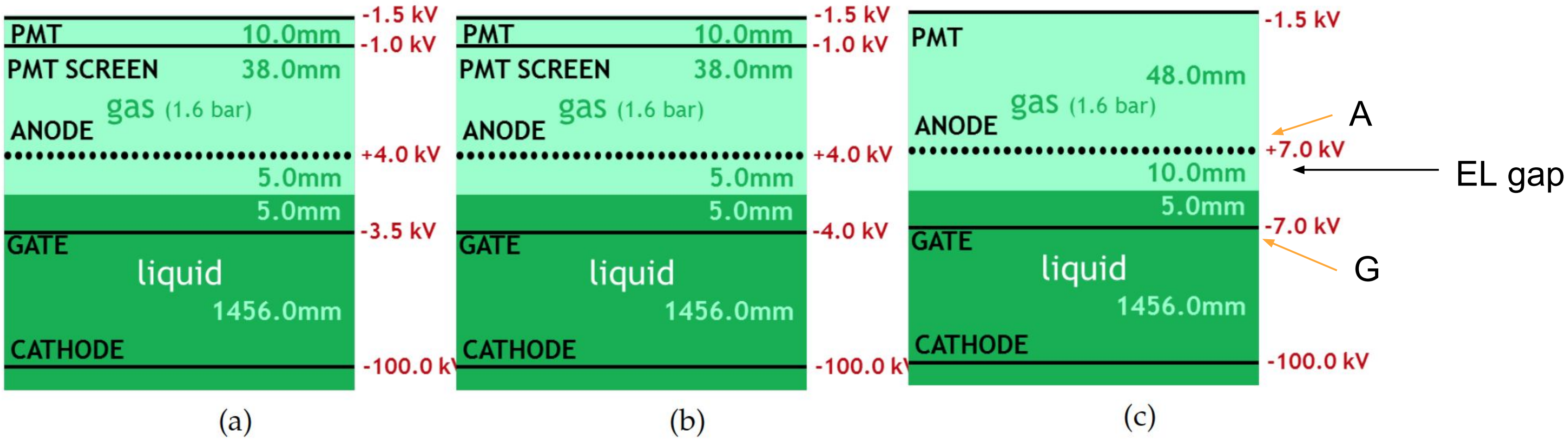
	h_g (cm)	P_g (bar)	E_g (kV/cm)	γ/e^-	σ/μ (%)	Max Field on Wire (kV/cm)			Optical Transmission (%)		e^- Emission Probability
						A	G	C	A	G	
ZEPLIN-III	0.40	1.6	7.6	314.2 ± 0.06	0.58 ± 0.01	-	-	75	-	-	82
LUX Run03	0.56	1.6	5.6	285.0 ± 0.1	1.16 ± 0.02	17*	46	19	77.4	98.0	49
XENON100	0.25	2.3	11.9	328.0 ± 0.1	1.15 ± 0.02	120*	22*	-	90.3	90.3	≈ 100
ZEPLIN-III LUX-like	0.56	1.6	5.6	286.2 ± 0.1	1.11 ± 0.02	-	-	-	-	-	-
ZEPLIN-III XENON-like	0.25	2.3	11.9	318.8 ± 0.05	0.45 ± 0.01	-	-	-	-	-	-

Planar geometry with LUX and
XENON
EL gap properties

No rounding (upper limit)

- ZEPLIN-III anode (planar) geometry - lowest variance in photon production

LUX-ZEPLIN grids



<u>Three sets of possible anode-gate configuration:</u>

a) 1 cm distance A-G and liquid level in the middle

b) Same as a) with -4 kV on the G

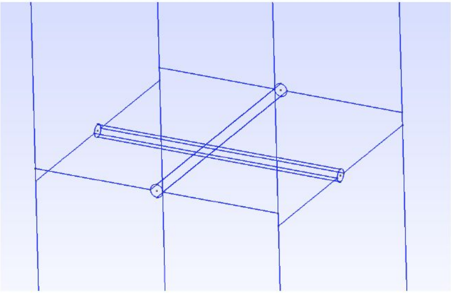
c) Large A-G distance, large EL gap and higher voltages on A and G to get similar field to (a) and (b) Large gap = large S2 signal, variance reduced, effect of grids deflection reduced

LUX-ZEPLIN grids (details of simulated geometries)

a) Ranges of wire pitches 1 - 3 mm and diameters (50 -200 μm) for parallel and crossed-wire grids, only gas gap considered between liquid level and anode grid. Potential at the liquid level calculated using multiple grid calculations. Top of the main kept at fixed potential.

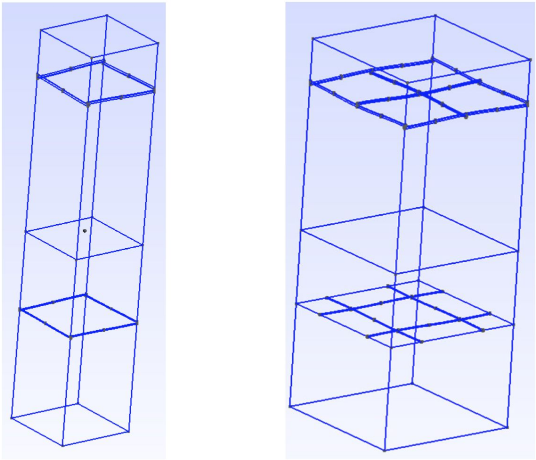
b) and c) Pitches and wire diameters - both simulation include gate and the anode grids (large pitch = significant field leakage)
Grid alignment taken into account -> e^- starting point depends on the focusing

Parallel wires - field fromGarf++
Crossed wires from Gmsh:

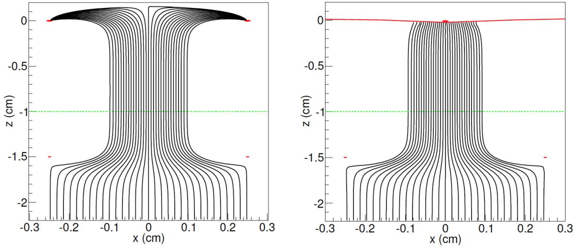


Anode		Gate	
Pitch (mm)	Wire Diameter (μm)	Pitch (mm)	Wire Diameter (μm)
5	150	5	75
2.5	150	5	75
7.5	150	7.5	75

Grid and woven mesh modelling in Gmsh

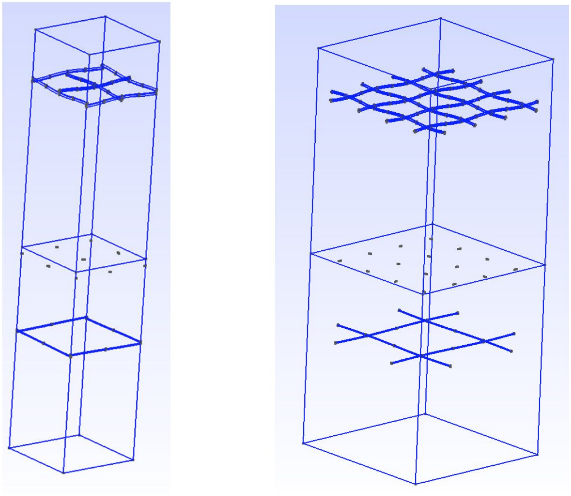


(a) (b)

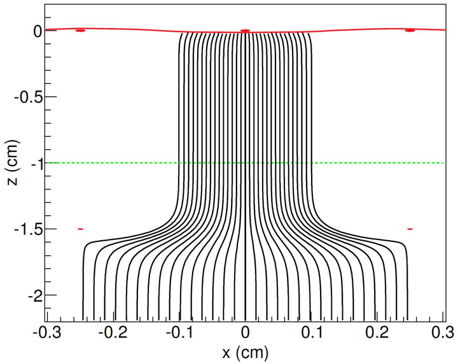


(a) (b)

Woven mesh A-G unit cell with equal A and G pitches.
(a) aligned and (b) with half pitch offset



(a) (b)



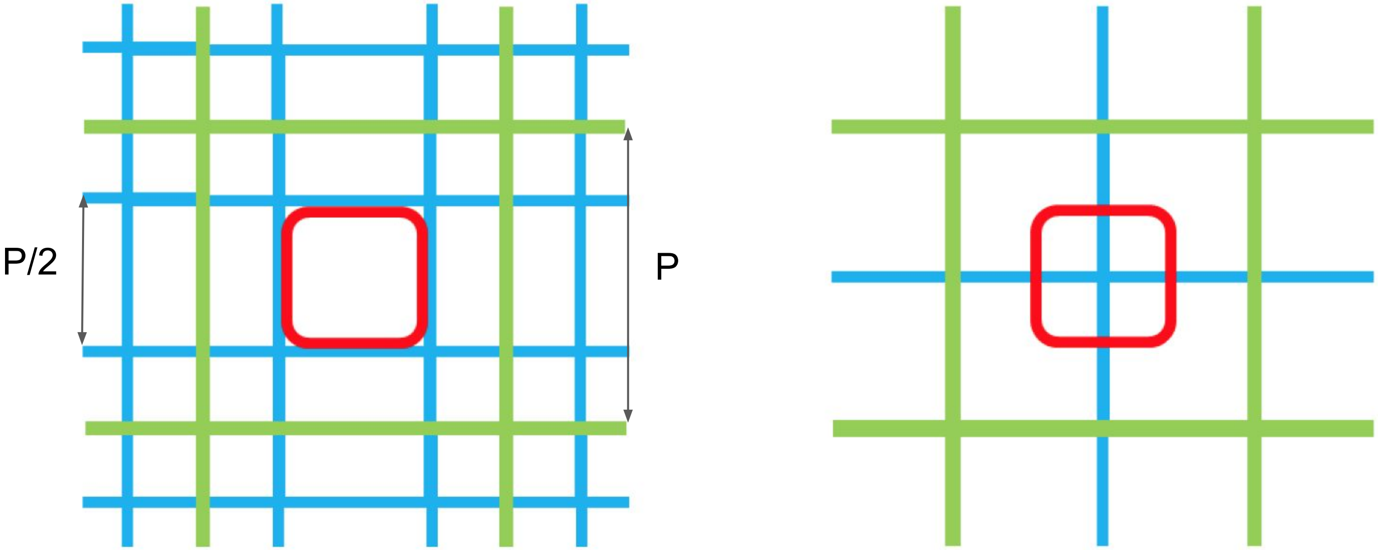
Woven mesh A-G unit cell with equal G pitch twice large as for A.

(a) aligned and (b) with half pitch offset

Charge focusing effect

Grids offset by half the gate pitch

Grids aligned



(a) (b)

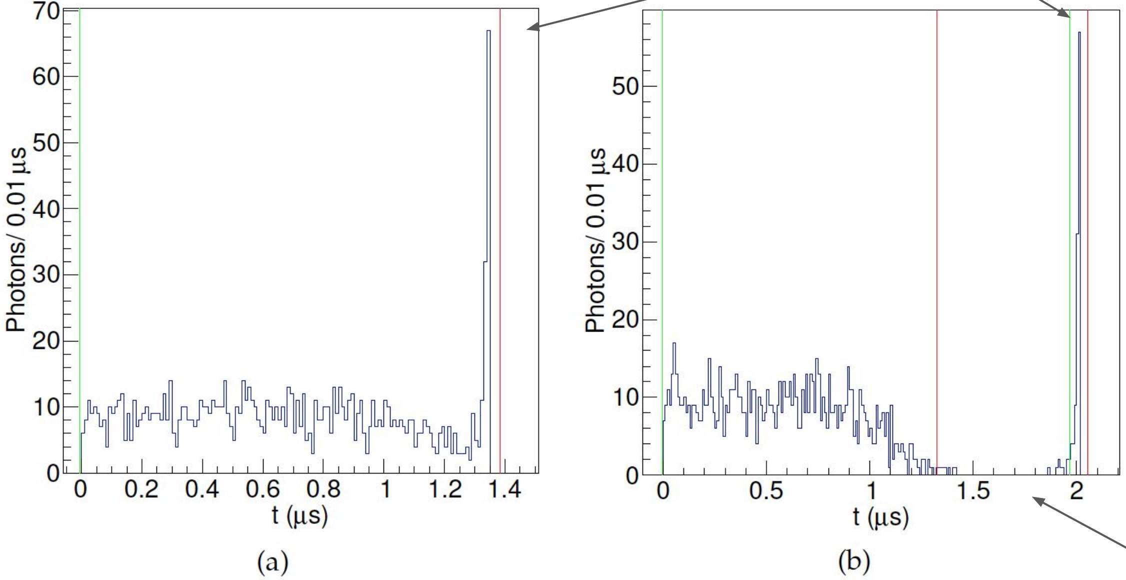
Here blue lines are underneath green lines

Anode - blue , Gate - green (from below)

Red - region where electrons are focused by the gate at the liquid surface

S2 pulse shape

Electron experiences higher field at the wire surface

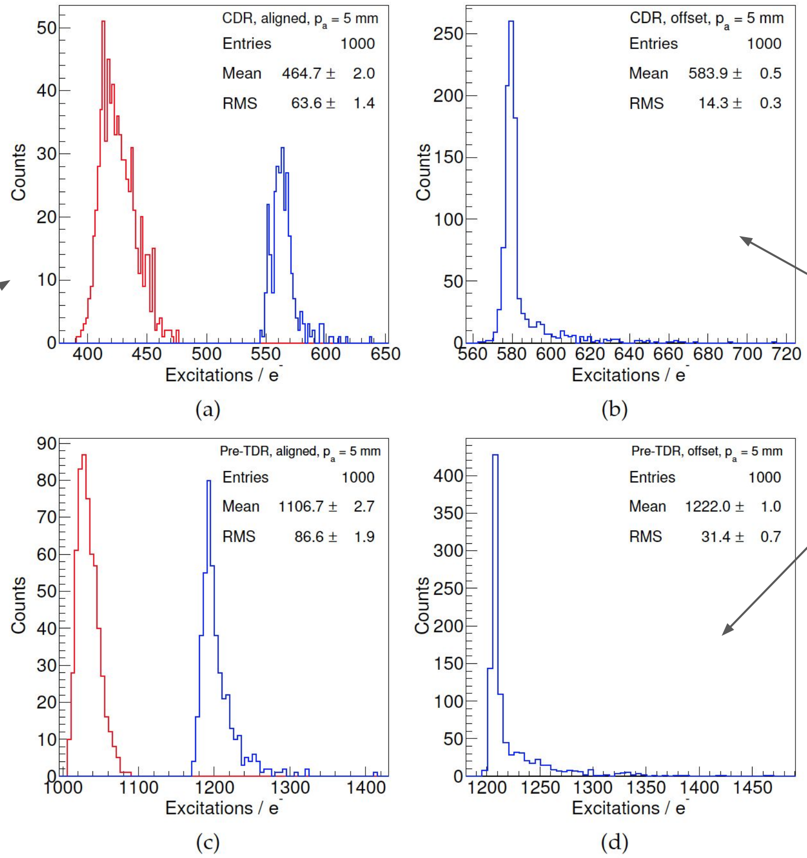


Single electron pulse from 5 mm gap with aligned grids

No EL at low field above anode plane
Δt can be up to 3.5 µs

Difference between grids aligned and with offset

Grids aligned



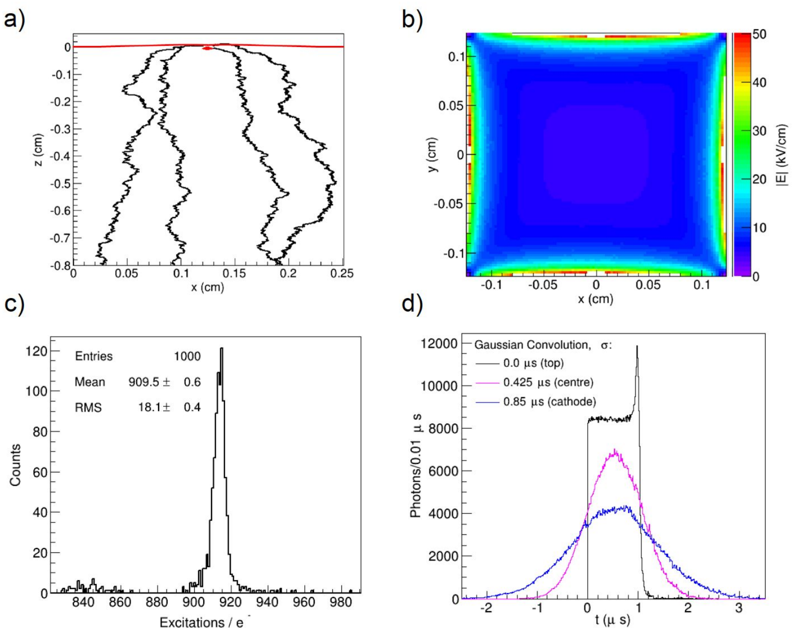
Grids with offset

Results

h_g (mm)	P_G (mm)	P_A (mm)	G-A Voltage (kV)	Align-ment	γ/e^-	σ/μ (%)	Max Field on Wire (kV/cm)		T_a (%)	
							A	G	A	G
5	5	5	± 4	Aligned	464.7 ± 0.2	13.7 ± 0.31	52	20	94	97
5	5	5	± 4	Offset	583.9 ± 0.5	2.45 ± 0.05	52	20	94	97
5	5	2.5	± 4	Aligned	553.1 ± 0.3	$\boxed{1.61 \pm 0.04}$	39	22	88	97
5	5	2.5	± 4	Offset	540.6 ± 0.7	4.38 ± 0.09	39	22	88	97
10	5	5	± 7	Aligned	1106 ± 2.7	7.83 ± 0.17	59	24	94	97
10	5	5	± 7	Offset	1222 ± 1.0	2.57 ± 0.06	59	24	94	97
10	5	2.5	± 7	Aligned	1190 ± 0.5	$\boxed{1.25 \pm 0.03}$	43	24	88	97
10	5	2.5	± 7	Offset	1182 ± 0.5	2.04 ± 0.04	43	24	88	97
10	7.5	7.5	± 7	Offset	1235 ± 2.3	5.82 ± 0.13	64	30	96	98

- The variance improves with anode pitch of 2.5 mm
- Configuration with anode grid half pitch of the gate grid the aligned grids are better

Final TPC grid parameters



Simulated S2 electroluminescence in LZ:

a) Examples of electron drifts from the liquid surface

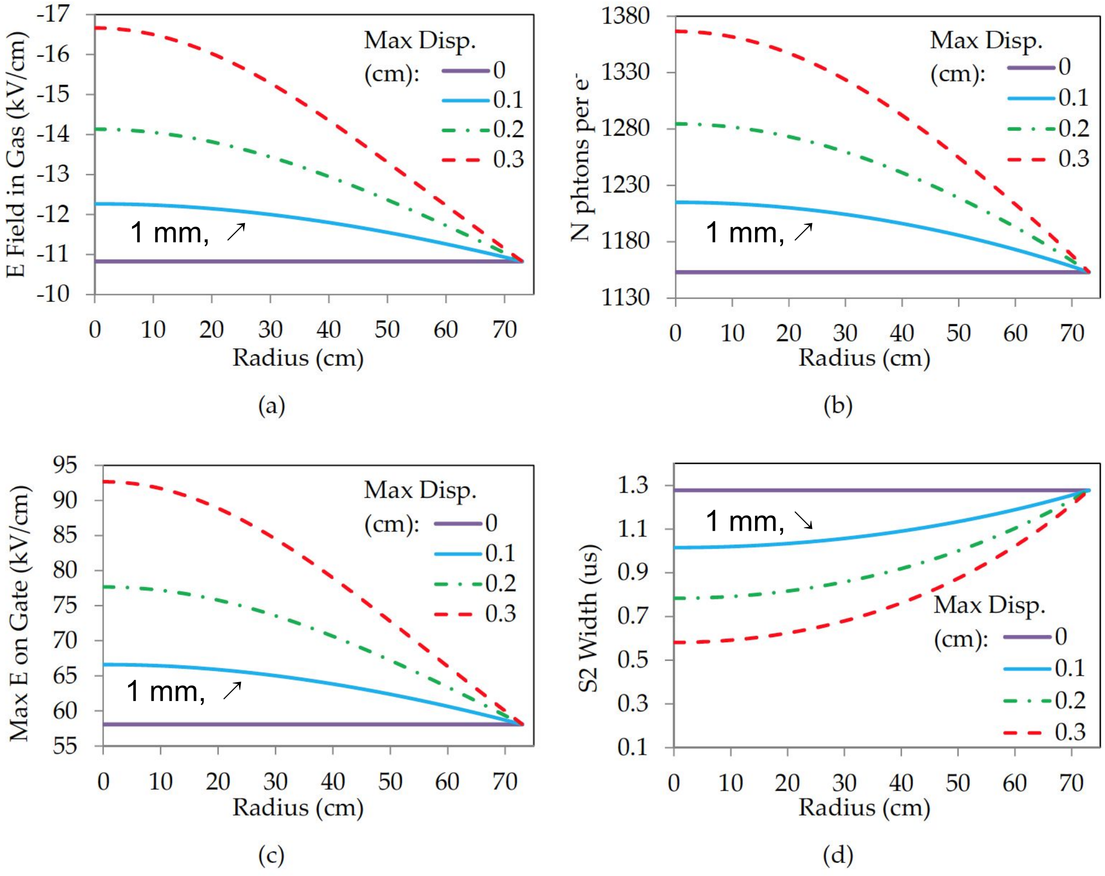
b) Electrostatic field strength through the anode plane;
c) Photon yield (number of excitations),

d) S2 simulated pulse shape of the electron signal, without longitudinal electron diffusion in the liquid (black), and the same distribution convolved with the amount diffusion expected for drift from center (magenta) bottom (blue) of the detector

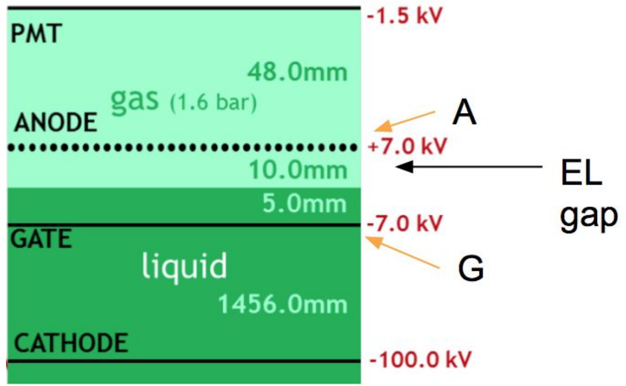
S2 size smaller for linearity reason
Lower voltages (± 7kV - too aggressive): ±5 kV
Gas gap reduced from 10 to 8 mm

Electrode	Voltage	Wire diameter/pitch	Number	Wire field	Opacity
Anode	+5.5 kV	100 µm / 2.5 mm	1,184	+55 kV/cm	8.0 %
Gate	−5.5 kV	75 µm / 5.0 mm	592	−62 kV/cm	3.0 %
Cathode	−50 kV	100 µm / 5.0 mm	592	−31 kV/cm	4.0 %
Bottom	−1.5 kV	75 µm / 5.0 mm	592	+34 kV/cm	3.0 %

Wire deflection (parametric calculations)



Effect of maximum grids deflection (at the center) on electroluminescence in :



A (2.5 mm pitch, 150 μm)
G (5 mm pitch, 75 μm)

a) Field in the gas
b) EL yield
c) Max E on the gate wire surface
d) S2 width

Conclusions

1. S2 signal in double-phase LXe detector can be fully simulated in arbitrary geometry using Gmsh for mesh generation, Elmer for field calculation and Garf++ with Magboltz for electron drifting in the gas.
2. The whole chain has been successfully validated and used in LZ grid design optimisation.

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