Development and performance of high voltage electrodes for the LZ experiment

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On behalf of the LZ collaboration
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The LZ Dark Matter Detector

- 7 tonne liquid xenon time-projection chamber
- Instrumentation conduits
- Existing water tank
- Gadolinium-loaded liquid scintillator
- 120 outer detector PMTs
- High voltage feedthrough
- 494 photomultiplier tubes (PMTs)
- Additional 131 xenon “skin” PMTs
- Neutron beampipes
The LZ Dark Matter Detector

7 tonne liquid xenon time-projection chamber

Instrumentation conduits

Existing water tank

Gadolinium-loaded liquid scintillator

120 outer detector PMTs

Liquid Xe heat exchanger

High voltage feedthrough

494 photomultiplier tubes (PMTs)
Additional 131 xenon “skin” PMTs

Neutron beampipes
Time projection chamber (TPC)

Sensitive to single quanta of light and charge

S1 = prompt scintillation signal from liquid bulk

S2 = signal from electrons extracted into gas phase

XY from light pattern, Z from drift time
Sensitive to single quanta of light and charge

\[ S_1 = \text{prompt scintillation signal from liquid bulk} \]
\[ S_2 = \text{signal from electrons extracted into gas phase} \]

XY from light pattern, Z from drift time

**“Extraction Region”**

S2 = signal from electrons extracted into gas phase
Extraction region design drivers

1. High electroluminescence (EL) field for high extraction efficiency and S2 yield

2. Optical (S1) and electron (S2) transparency of electrodes

= Mesh electrodes (grids)

- Anode electrode in gas
- S2 light production
- Liquid level
- “Gate” electrode in liquid
- Electron bunch from scatter in LXe
Extraction region design drivers

1. **High electroluminescence (EL) field** for high extraction efficiency and S2 yield

2. **Optical (S1) and electron (S2) transparency of electrodes**

   + **= Mesh electrodes (grids)**

3. **S2 resolution** - optimize gate-anode alignment for electron drift

4. **Mechanical constraints** - load on rings, thermal properties, minimize dead material, etc.

5. **Uniformity of EL field** - limit electrostatic deflection of grids, minimize high field points
LZ extraction region and grid design

- Four woven meshes of SS wires glued between SS rings
- Ring geometry designed to limit material and surface fields

Full LZ extraction region - anode + gate grids

<table>
<thead>
<tr>
<th>Grid</th>
<th>Pitch (mm)</th>
<th>Gauge (um)</th>
<th>Optical transparency</th>
<th>Nominal voltage (max surface field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>2.5</td>
<td>100</td>
<td>92%</td>
<td>+5.75kV (46.2kV/cm)</td>
</tr>
<tr>
<td>Gate</td>
<td>5</td>
<td>75</td>
<td>97%</td>
<td>-5.75kV (-51.8kV/cm)</td>
</tr>
<tr>
<td>Cathode</td>
<td>5</td>
<td>100</td>
<td>96%</td>
<td>-50kV (-30.1kV/cm)</td>
</tr>
<tr>
<td>Bottom</td>
<td>5</td>
<td>75</td>
<td>97%</td>
<td>-1.5kV (-33.8kV/cm)</td>
</tr>
</tbody>
</table>
LZ wire grid production at SLAC

Custom-built LZ Loom at SLAC

Wires pre-tensioned with weights

Semi-automated weaving

Glue-dispensing robot

Grid during gluing

(Link to grid production youtube video)
LZ wire grid production at SLAC

Electrostatic grid deflection
- Optical measurement at voltage in air using camera's changing plane of focus
- Results mapped to field in liquid, meets requirement of <2mm total deflection

Gate in focus, anode out of focus

Gate/anode wire alignment mapped for entire extraction region
Electron emission from grids

Problematic:
- LUX extraction voltage limited by emission from grids
- High rate = DAQ deadtime
- Low energy signal - bad for key physics searches (WIMP search, S2-only, etc.)
  - Fiducialization doesn’t help: appears in bulk in XY, no S1 → no Z reconstruction
  - Compounded by gain in liquid - evidence seen in LUX data [A. Bailey thesis]
Measuring electron emission in SLAC System Test

Suite of three detectors built to enable comprehensive testing of critical LZ systems

To study physics of electron emission: single electron sensitivity through S2 process, position reconstruction from PMT arrays

- Dual-phase TPC, near-clone of LZ extraction region profile with 20cm grids
- Single-phase detector, full LZ extraction region (160cm) installed in vessel
Passivation reduces electron emission

Untreated 20cm grid shows two reproducible electron emission hotspots:

Electron emission rate, by centroid position:

- Max surface field: 117kV/cm
- Preliminary

Not localized field emission - due to position reconstruction artifact

20cm grids
Passivation reduces electron emission

Untreated 20cm grid shows two reproducible electron emission hotspots:

Electron emission rate, by centroid position:

Max surface field: 117kV/cm
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- Not localized field emission - due to position reconstruction artifact

Passivation previously shown to reduce electron emission
[arXiv:1801.07231]

Process:

1. Heated acid bath preferentially etches away surface iron, leaves chromium rich surface
2. Thickness of outer chromium oxide increases (30Å → ~70Å, measured by Auger electron spectroscopy)

Prototype grid in passivation fluid
Passivation reduces electron emission

Untreated 20cm grid shows two reproducible electron emission hotspots:

Post-passivation, both hotspots have been removed:

Electron emission rate, by centroid position:

Max surface field: 117kV/cm
Preliminary

Not localized field emission - due to position reconstruction artifact

20cm grids
Dust/cleanliness contributes to emission

“Transient” electron emission hot spots seen in full-scale LZ extraction region test, moved after dust exposure/removal:

Electron emission rate, by centroid position:

Between tests:
1. Exposure to dust
LZ grid treatment and cleaning

- LW grid being passivated in citric acid
- Citric acid passivation of LZ gate grid
- LW grid being spray-washed with DI water

Wash grids with DI water spray prior to installation
Installation of grids into LZ

1. Bottom grid above bottom PMT array
2. Bottom and cathode grids installed above bottom PMT array
3. Assembled extraction region
4. Attachment of top PMT array
5. Installation on TPC
Summary

Extraction region performance key to success of LZ

LZ grids designed, fabricated, and tested with single electron sensitivity at SLAC

In order to mitigate the risk of electron emission, we:
1. Passivated the gate grid
2. Recleaned all grids after shipping and prior to installation

The grids were safely installed in LZ TPC, expecting first science in 2021
Thanks to the LZ Grids/System Test teams

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The whole LZ collaboration (see next slide) for all their contributions, help, and advice.

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LZ collaboration, July 2019

5 countries, 36 institutions, ~250 scientists/engineers

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Royal Holloway University of London (UK)
STFC Rutherford Appleton Lab (UK)
University College London (UK)
University of Bristol (UK)
University of Edinburgh (UK)
University of Liverpool (UK)
University of Oxford (UK)
University of Sheffield (UK)
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Brandeis University (US)
Brookhaven National Lab (US)
Brown University (US)
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Lawrence Berkeley National Lab (US)
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University of Massachusetts (US)
University of Michigan (US)
University of Rochester (US)
University of South Dakota (US)
University of Wisconsin – Madison (US)
Backup slides
Effect of gate-anode $\Delta V$ on S2 response

**Parameter** | **value**
--- | ---
Gate-Anode separation (and tolerance) | 13.0 mm ($\pm$0.2 mm)
Gas gap (and tolerance) | 8.0 mm ($\pm$0.2 mm)
Field in LXe (GXE) | 5.2 kV/cm (10.2 kV/cm)
Electron emission probability | 97.6 %
S2 photon yield | 820 ph/e
S2 width FWHM | 1.2 $\mu$s

Detailed modeling:

- S2 photon yield | 910 ph/e
- S2 photon rms | 2.0 %
- S2 width FWHM | 1.0 $\mu$s to 2.0 $\mu$s$^a$

$^a$ The larger value is for diffusion-broadened S2 pulses from interactions near the cathode (see Figure 3.6.4).

S2 photon detection efficiency (photoelectron yield)

**PMT array** | **Center** | **Edge**
--- | --- | ---
Top | 6.6% (52 phe/e) | 5.4% (43 phe)
Bottom | 2.2% (18 phe/e) | 1.5% (12 phe)
Top+Bottom | 8.8% (70 phe/e) | 6.9% (55 phe)
## Dependence of TPC parameters on Cathode HV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>-30 kV (LUX)</th>
<th>-50 kV (Base)</th>
<th>-100 kV (Goal)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC drift field, kV/cm</td>
<td>0.17</td>
<td>0.31</td>
<td>0.65</td>
<td>Gate $-5.5$ kV</td>
</tr>
<tr>
<td>ER/NR discrimination</td>
<td>99.6%</td>
<td>99.7%</td>
<td>99.7%</td>
<td>NEST LZ04</td>
</tr>
<tr>
<td>Electron drift velocity, mm/µs</td>
<td>1.5</td>
<td>1.8</td>
<td>2.2</td>
<td>[11]</td>
</tr>
<tr>
<td>Maximum drift time, µs</td>
<td>970</td>
<td>806</td>
<td>665</td>
<td>Interactions at cathode</td>
</tr>
<tr>
<td>Longitudinal diffusion, µs</td>
<td>2.4</td>
<td>2.2</td>
<td>2.0</td>
<td>FWHM, cathode events</td>
</tr>
<tr>
<td>Transverse diffusion, mm</td>
<td>2.4</td>
<td>1.8</td>
<td>1.4</td>
<td>FWHM, cathode events</td>
</tr>
<tr>
<td>Gate wire field, kV/cm</td>
<td>-64</td>
<td>-62</td>
<td>-58</td>
<td></td>
</tr>
<tr>
<td>Cathode wire field, kV/cm</td>
<td>-18</td>
<td>-31</td>
<td>-63</td>
<td>TPC drift field, kV/cm</td>
</tr>
</tbody>
</table>

LZ TDR: 1703.09144
Deflection tests

**Un-deflected Grid**
- Camera
- Wire

When undeflected, the wire is near the POF of the camera at its original height.

We can focus the camera on the wire and use this to set the initial position of the camera (to some uncertainty).

**Deflected Grid**
- Old camera pos
- Old wire pos
- New camera pos
- New wire pos

When deflected, the wire causes the POF of the camera to move downward.

We can move the camera downward to re-find the POF. We can use this to find the final position of the camera.

Deflection = (initial position) - (final position)

DOF = depth of field of camera focus
POF = plane of focus
Alignment of gate-anode grids

Study from A. Bailey’s thesis shows more uniform drift length for electrons through the extraction region for anode pitch equal to half the gate pitch and both grids aligned.
Mid-scale dual-phase TPC at SLAC

Goal: test suite of hardware in conditions closest to LZ

~30kg active volume, liquid xenon dual-phase TPC

Clone of LZ extraction region, designed to match LZ drift field and extraction field

Xenon circulation path, cryogenics → SLAC scaling up these technologies for LZ

3D position reconstruction
- 32 PMT top array + 6 skin PMTs + 1 bottom PMT
- Localize sparking w/ skin PMTs
Waveforms

From liquid run of mid-scale detector, $\Delta V = 12$ kV
LZ-scale single-phase detector at SLAC

**Goal:** validate all full-scale grids before shipping to SURF

Sparse 32 PMT array provides 2D position reconstruction in warm xenon gas

Single electron sensitivity for electron emission testing

*Full-scale LZ prototype grid installed in vessel*

*Sparse 32 PMT array*

*AlMgF2 reflective coating for enhanced LCE*
Electron emission reduced via passivation

Electron emission sites were reduced after acid bath, but only eliminated after oxide layer growth:

Untreated grid:
- Voltage-dependent hotspots present

Post-acid bath:
- Hotspots reduced

Post-oxidation:
- Hotspots eliminated
Gate/anode HV terminations

LZ gate grid termination

LZ anode grid termination

PMT

Anode

Gate

LZ extraction region and top PMT array installed on top of TPC field cage