Noble liquid detector R&D with the LZ System Test platform at SLAC

Kelly Stifter
On behalf of the LZ collaboration
The LZ Dark Matter Detector

Goals of rare event search:

- **Increase exposure:**
  - 10t xenon, 7t active, ~5.6t fiducial
  - 1000 live days

- **Lower backgrounds:**
  - Located on the 4850ft level at SURF
  - Nested detectors for background suppression
  - Etc...

- **Lower threshold:**
  - Dual-phase TPC
  - Etc...

First data in 2020
Dual-Phase Time Projection Chambers (TPC)

S1 = prompt scintillation signal from liquid bulk

S2 = signal from electrons extracted into gas phase

3D position: x,y from pattern on photosensors, z from drift time
The LZ TPC

- Top and bottom arrays, 494 PMTs total
- 4 wire grids to create very uniform electric fields

Cathode grid = 50-100kV
Reverse Field Region: 3.5kV/cm
Bottom grid = -1.5kV

“Extraction Region” - between anode and gate grids (slide 6)
LZ wire grid production

Size & cleanliness requirements not commercially available
Production process and automated loom developed at SLAC
Uniformity a major challenge
Production process:
- Weave grid on the loom (2-5 days/grid)
- Glue between SS rings
- Clean and passivate commercially

LZ Loom at SLAC

Glue-dispensing robot

Grid during gluing

Empty grid ring (staff scientist for scale)

(https://www.youtube.com/watch?v=yNycDcMQkss)
Responsible for S2 production - performance critical to LZ

Need:
1. High extraction field $\rightarrow$ high anode/gate voltages
   a. High yield
   b. High electron extraction probability
   c. Large electron drift velocity
2. Liquid level stability
   a. Stable S2 characteristics $\rightarrow$ energy resolution
3. Low/no electron emission from cathodic surfaces
   a. Geometry, surface fields
   b. Creates background for low-energy searches

10.2 kV/cm “extraction” field
Anode-gate voltage differential requirement (goal): 11.5kV (14.0kV)
The LZ System Test at SLAC

**Solution:** undertake extensive R&D campaign

Suite of three detectors at SLAC provide comprehensive testing abilities at scale

Key link in whole LZ R&D effort

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<td><strong>Dual-Phase</strong></td>
<td><strong>Phase 1</strong></td>
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<td><strong>TPC</strong></td>
<td><strong>LZ</strong></td>
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<td><strong>Single-Phase</strong></td>
<td><strong>Phase 2</strong></td>
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<td><strong>TPC</strong></td>
<td><strong>Phase 2</strong></td>
<td><strong>Gas Test</strong></td>
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**Phase 2**

**Gas Test**
Gas Test

**Goal:** rapidly turn around tests on prototype LZ grid designs

20cm diameter grids

**Extraction region only**

Warm xenon gas pressure chosen to match cold gas density in LZ

2 PMTs, top and bottom - single electron efficiency

Viewport, cameras for spark localization
Phase 1

**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
Phase 2

**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

PMT Array

AlMgF$_2$ reflective coating for enhanced LCE
Investigation of electron emission

All three detectors sensitive to single electrons - signal properties vary by detector (drift length, LCE), voltage, pressure, etc.

All electron emission datasets shown as increasing anode-gate voltage differential (ΔV) - LZ-equivalent fields marked where appropriate

Disclaimer: All following plots are PRELIMINARY. Error bars are statistical - systematic errors are unquantized and likely large. Final results forthcoming.
Electron emission from point-like sources

Single electron rate vs. voltage

14cm diameter grid in Phase 1 (known to be dirty)

\[ \Delta V = 7.0 \text{ kV} \]

Emitter appears around 10.5kV $\Delta V$
Electron emission from point-like sources

Before spark:

After spark, same voltage:

Single electron rate vs. voltage

14cm diameter grid in Phase 1
(known to be dirty)

LZ-equivalent field

See R. Mannino’s Thesis
Electron emission from point-like sources

Similar emission points seen in Phase 2 on full-scale LZ grid
Can do automated visual scans
Correlation to fibers on grid preliminary

Rate of pulses with centroid at (X,Y)

Data from voltage scan of prototype LZ grid (known to be dirty)

Scanning apparatus
UV lamp
XY Stage
Camera
Gas test grid
Fibers found on grid:

Rate (Hz/0.64cm²)

Preliminary
Effect of nitric passivation on electron emission

Tested several iterations of grid treatment in Gas Test

Confirmed that nitric passivation of grid reduces electron emission (arXiv: 1801.07231)

Single electron rate vs. voltage

Rate [s⁻¹] vs. ΔV [kV]

LZ-equivalent field

14cm diameter grid in Gas Test

Before nitric passivation

After nitric passivation

Work done by W. Ji
Effect of “training” on electron emission

Electron emission further reduced by factor of ~2 through “training” without sparking

“Training” = holding grid at voltage for several hours before taking data

Data from same grid on slide 14 - much of rate from localized emitters likely from dust/debris
Correlated electrons in Phase 1

Rate of single photoelectrons and single electrons after large S2s: high, and then decay over 10s of ms

Single electron rate after large S2s

- High baseline due to localized emitter (same grid as slide 12)

Single photoelectron rate after large S2s

- 14cm diameter grid in Phase 1, 12.5kV ΔV
  - After pulses > 1e5 phe
  - After pulses > 1e6 phe

Hypothesized to be due to <100% prompt electron extraction efficiency and photoionization of impurities
Hypothesized to be due to Teflon fluorescence
### The LZ System Test at SLAC

<table>
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<tbody>
<tr>
<td><strong>Proven ability to quantify electron emission</strong> (final results forthcoming)</td>
<td></td>
</tr>
<tr>
<td>Still developing paths to reducing emission for LZ</td>
<td></td>
</tr>
</tbody>
</table>

![Dual-Phase TPC](image1)

**What else?**

![Single-Phase TPC](image2)
High Voltage Termination

New termination technologies and geometries tested in Gas Test and Phase 1 Inform and validate final LZ design

Warm-end feedthrough

Warm end termination

Cold end termination

Anode cable
Anode ring

Gate cable
Gate ring

Cathode HV connection - not final LZ design

19
Xenon constantly circulated for purity: Electronegatives limit free electron lifetime

Detailed design done by SLAC group, several iterations built for Phase 1

Path for LZ will largely be a clone

Problems: no liquid flow, oscillations in detector liquid level

Solutions and best practices informed final design of LZ circulation path

See T. Whitis’s thesis
Leveling & weir height studies in Phase 1

LZ-like level sensors give resolution of ~7μm

Studying liquid head height above weir vs. flow rate

Observe liquid level changes with applied electric field

Informs LZ weir design
**Future work: general R&D**

Physics to inform LZ science using current hardware:

- Measurement of teflon reflectivity in liquid - analysis appearing in T. Whitis’s thesis
- Performance of LZ internal sources, complementary to S1-only setup at UMass (see C. Nedlik’s talk)
- Contribution of single electron rate to backgrounds for WIMP, B8, etc. at lowest energy thresholds (S2 only)

Probing limits of noble element TPC technology using detector upgrades w/in existing infrastructure:

- Pulse shape discrimination in liquid xenon ([arXiv:1802.06162](http://arXiv.org/))
LZ System Test at SLAC is ideal platform for studying designs and performance of a broad range of subsystems for LZ and other noble element detectors

Extraction region performance critical to LZ → SLAC delivering finished grids, System Test responsible for full validation

System Test results have already impacted many aspects of LZ design

Well-suited to transition to R&D to further impact LZ physics and probe limits of noble element TPC technology
Acknowledgments (all alphabetical)

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  Christina Ignarra, Steffen Luitz for Ignition
  Cees Carels, Theresa Fruth, FengTing Liao for capacitive sensors

Phase 2 team: Shaun Alsum, Christina Ignarra, Ryan Linehan, Rachel Mannino

Gas test team: Alden Fan, Christina Ignarra, Wei Ji, Randy White

Previous System Test contributors: Jacob Cutter, Aude Glaenzer, Wolfgang Lorenzon, Eli Mizrahi

System test reconstruction software developers: Tomasz Biesiadzinski, Jacob Cutter, Alden Fan, Theresa Fruth, Aude Glaenzer, FengTing Liao, Ryan Linehan, Rachel Mannino, Jonathan Nikoleyczik, TJ Whitis (among others)

Grids team: Ryan Linehan, Steffen Luitz, Rachel Mannino, Randy White

The rest of the SLAC team: Tyler Anderson, Tomie Gonda, Eric Miller

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

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LZ collaboration, September 2017
38 institutions
250 scientists, engineers, and technicians

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MPEI (Russia)
4) Imperial College London (UK)
5) Royal Holloway University of London (UK)
6) STFC Rutherford Appleton Lab (UK)
7) University College London (UK)
8) University of Bristol (UK)
9) University of Edinburgh (UK)
10) University of Liverpool (UK)
11) University of Oxford (UK)
12) University of Sheffield (UK)
13) Black Hill State University (US)
14) Brandeis University (US)
15) Brookhaven National Lab (US)
16) Brown University (US)
17) Fermi National Accelerator Lab (US)
18) Lawrence Berkeley National Lab (US)
19) Lawrence Livermore National Lab (US)
20) Northwestern University (US)
21) Pennsylvania State University (US)
22) SLAC National Accelerator Lab (US)
23) South Dakota School of Mines and Technology (US)
24) South Dakota Science and Technology Authority (US)
25) Texas A&M University (US)
26) University at Albany (US)
27) University of Alabama (US)
28) University of California, Berkeley (US)
29) University of California, Davis (US)
30) University of California, Santa Barbara (US)
31) University of Maryland (US)
32) University of Massachusetts (US)
33) University of Michigan (US)
34) University of Rochester (US)
35) University of South Dakota (US)
36) University of Wisconsin - Madison (US)
37) Washington University in St. Louis (US)
38) Yale University (US)
Backup slides
Effect of gate-anode $\Delta V$ on S2 response

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)  

S2 photon detection efficiency (photoelectron yield)

LZ TDR: 1703.09144
# 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></td>
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</tbody>
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LZ TDR: 1703.09144
Xenon liquid at ~170K

Can use LN (77K) to cool

Developed at SLAC for use by LZ @ SURF
System Test Slow Control: PLCs + Ignition

Same system as being used by LZ

Provides control, automation, and fail-safes for xenon & LN handling systems (and more)

SLAC System Test implemented and testing all elements before LZ comes online
Closed loop, driven by compressor:
1. Pumped through Getter
2. Gas cooled/liquified by TS heads
3. Pumped into TPC
4. Flows over weir into reservoir
5. Evaporates in heat exchanger
Radioactive source calibrations with Phase 1

Source injection system:
- Delivers trace amounts of radioactive sources to detector liquid through Xe circulation path
- First iteration of design for LZ (see C. Nedlik’s talk for update)
- Complementary to S1-only UMass test stand

External gamma source calibration (Cs137, Na22, etc.)

Beginning to pursue neutrons sources

Current source injection capabilities:

- Rn220: Th228 electroplated to platinum disk from E&Z
- Kr83m: Rb83-soaked charcoal from Yale/UMass
Waveforms

From Phase 1
$\Delta V = 12 \text{ kV}$