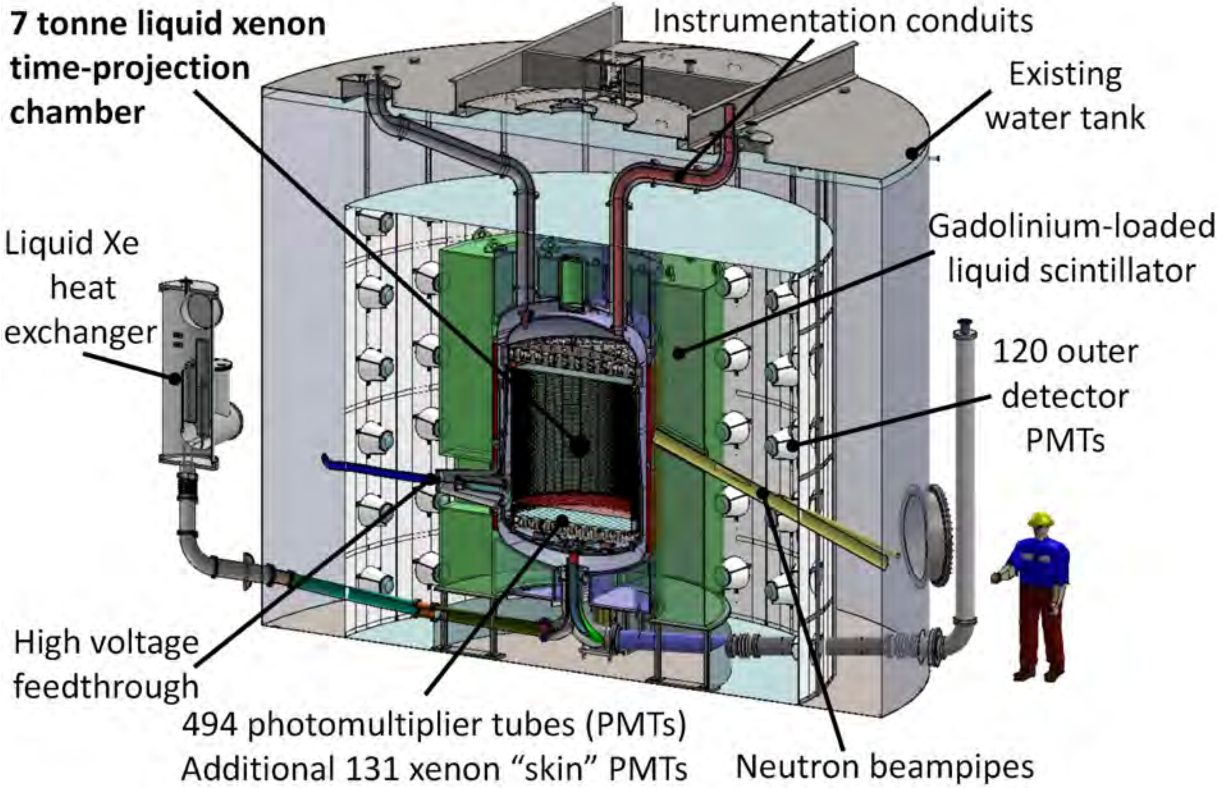
Noble liquid detector R&D with the LZ System Test platform at SLAC

Kelly Stifter
On behalf of the LZ collaboration

Stanford University
Kavli Institute for Particle Astrophysics and Cosmology
SLAC National Laboratory

The LZ Dark Matter Detector

LZ TDR: 1703.09144

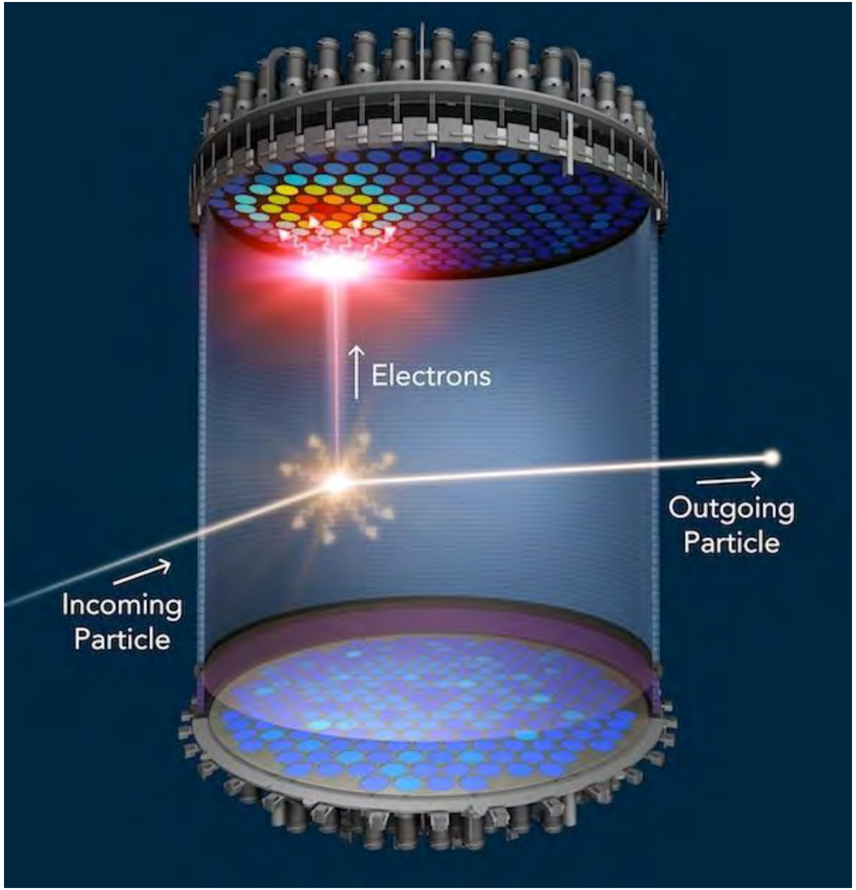


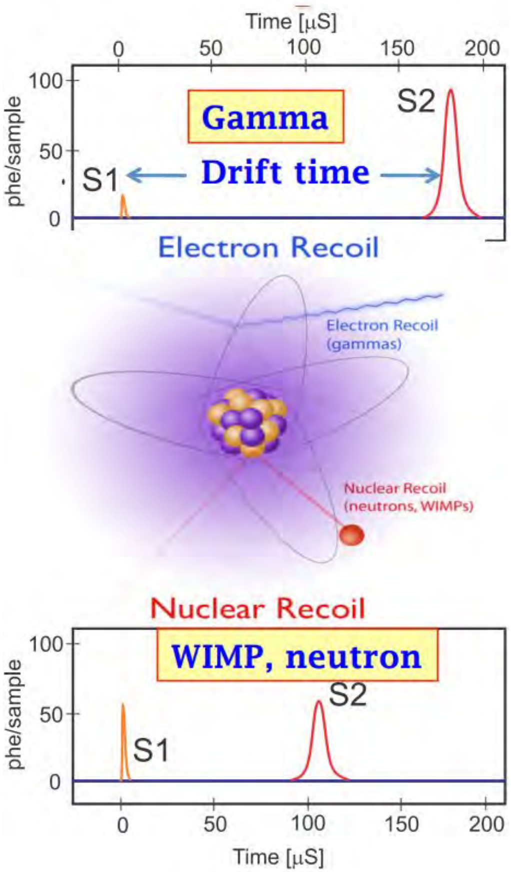
Goals of rare event search:

- **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)





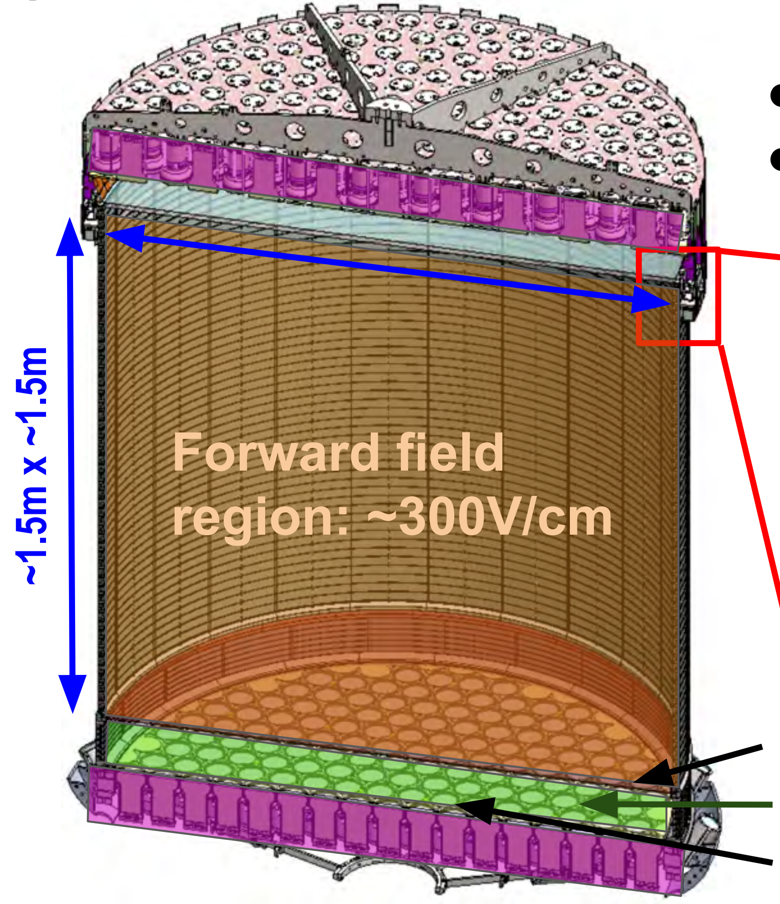
S1 = prompt scintillation signal from liquid bulk

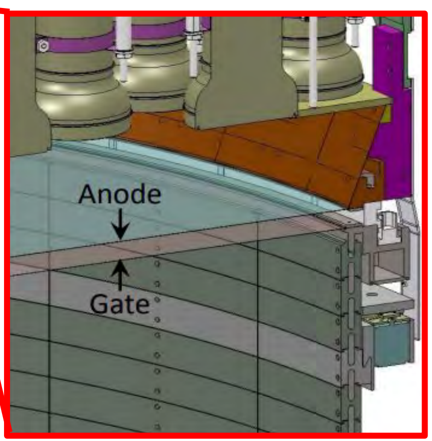
S2 = signal from electrons extracted into gas phase

3D position: x,y from pattern on photosenors, z from drift time

The LZ TPC

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





"Extraction Region" - between anode and gate grids (slide 6)

Cathode grid = 50-100kV

Reverse Field Region: 3.5kV/cm

Bottom grid = -1.5kV

LZ TDR: 1703.09144

LZ wire grid production

(https://www.youtube.com/watch?v=yNycDcMQkss)

LZ Loom at SLAC

Size & cleanliness requirements not commercially available

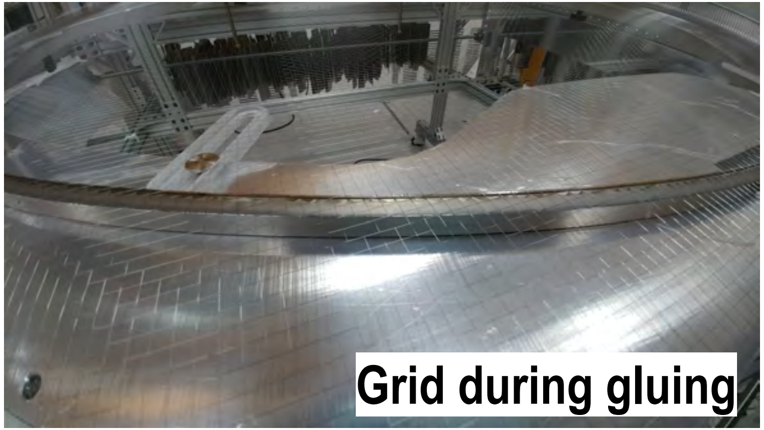
Production process and automated loom developed at SLAC

Uniformity a major challenge

Production process:

- Weave grid on the loom (2-5 days/grid)
- Glue between SS rings
- Clean and passivate commercially

Glue-dispensing robot



Grid during gluing

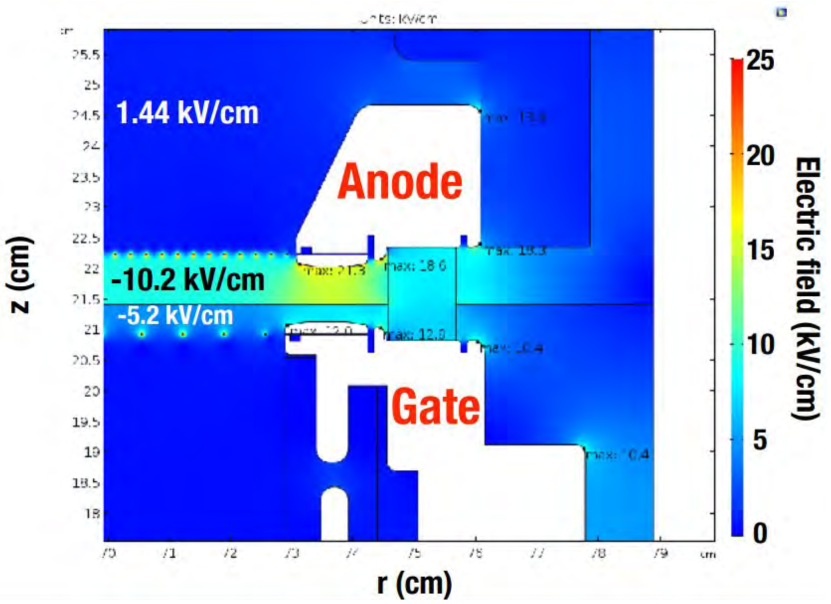
Empty grid ring (staff scientist for scale)

Extraction region

Responsible for S2 production - performance critical to LZ

Need:

1. High extraction field → 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 → 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

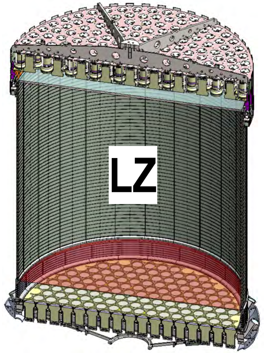
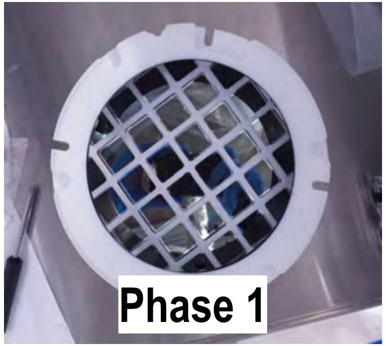
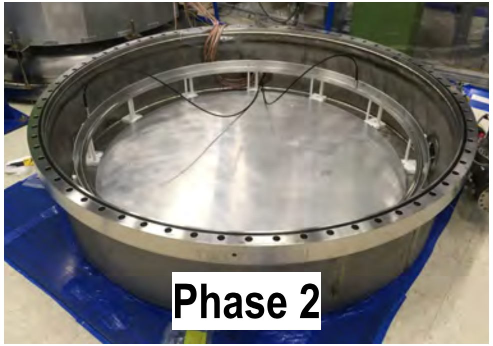
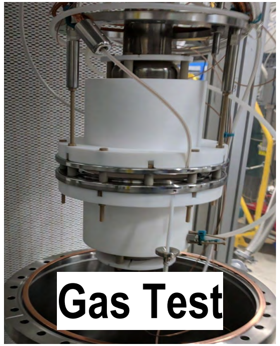
Anode-gate voltage differential requirement (goal): 11.5kV (14.0kV)

The LZ System Test at SLAC

<u>Solution:</u> 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

	Large	Small
Dual-Phase TPC		
Single-Phase TPC		

Gas Test

<u>Goal:</u> rapidly turn around tests on prototype LZ grid designs

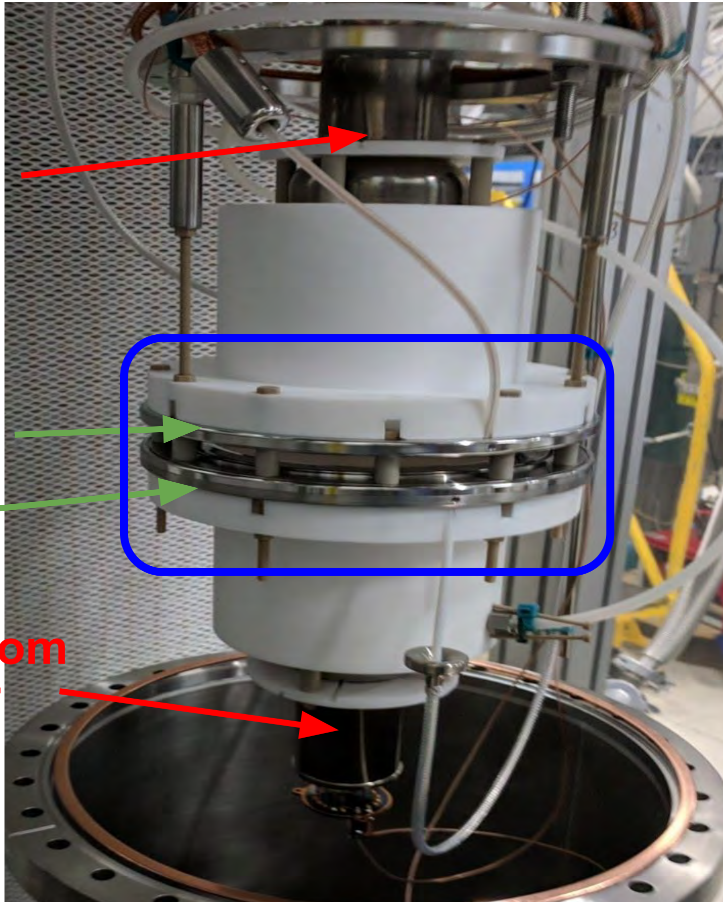
20cm diameter grids

Extraction region only

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

2 PMTs, top and bottom - single electron efficiency

Viewports, cameras for spark localization



Phase 1

<u>Goal:</u> test suite of hardware in conditions closest to LZ

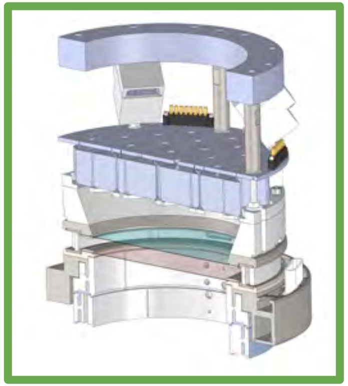
~30kg active volume, liquid xenon dual-phase TPC

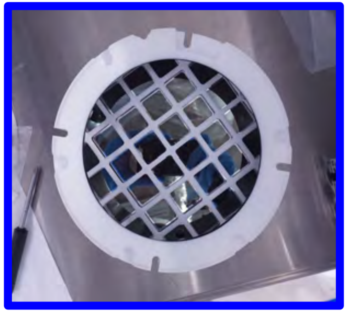
Clone of LZ extraction region, designed to match LZ drift field and extraction field

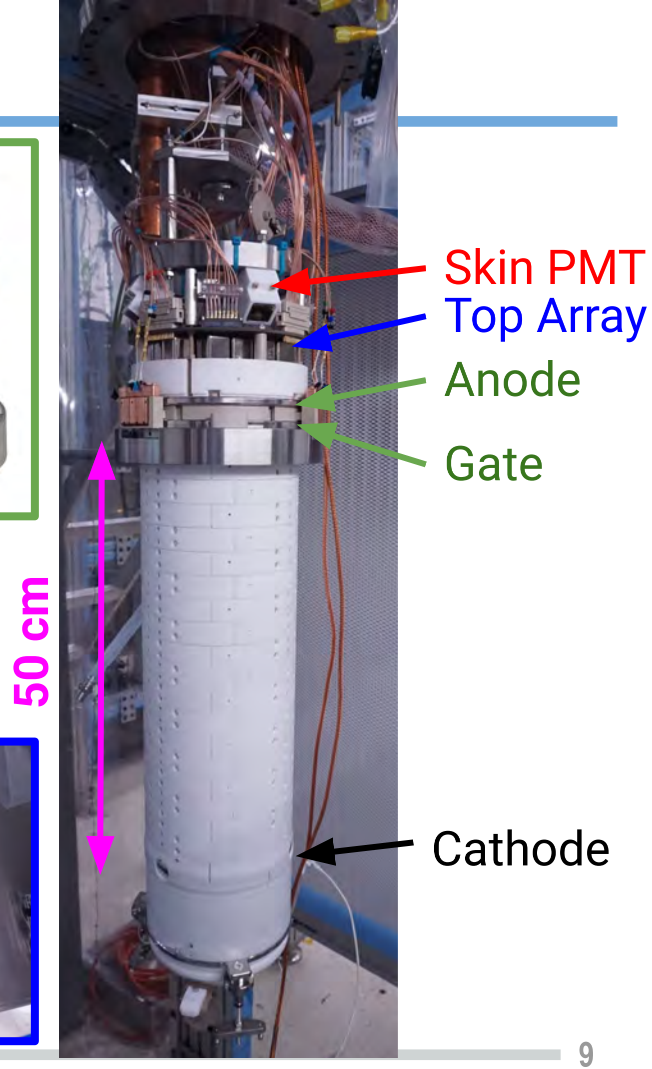
Xenon circulation path, cryogenics → SLAC scaling up these technologies for LZ

3D position reconstruction

- 32 PMT top array + 6 skin PMTs + 1 bottom PMT
- Localize sparking w/ skin PMTs





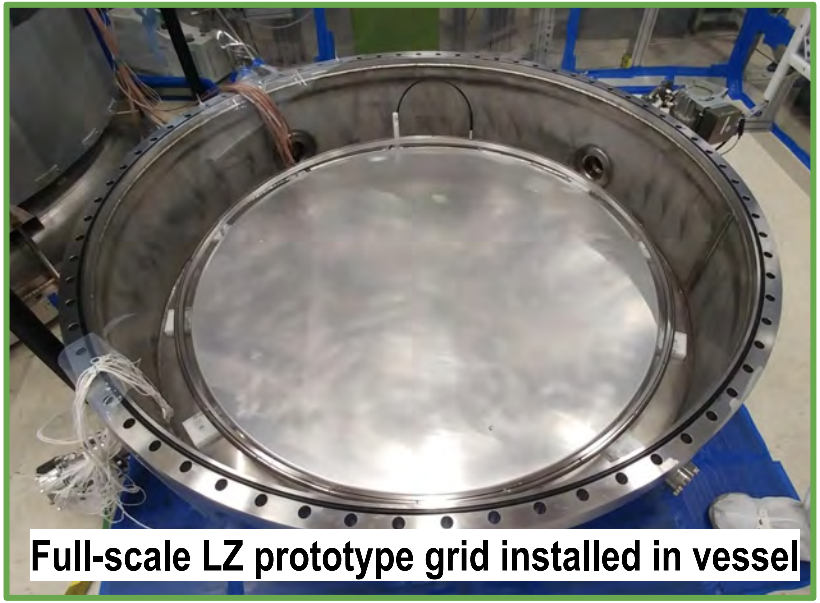


Phase 2

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

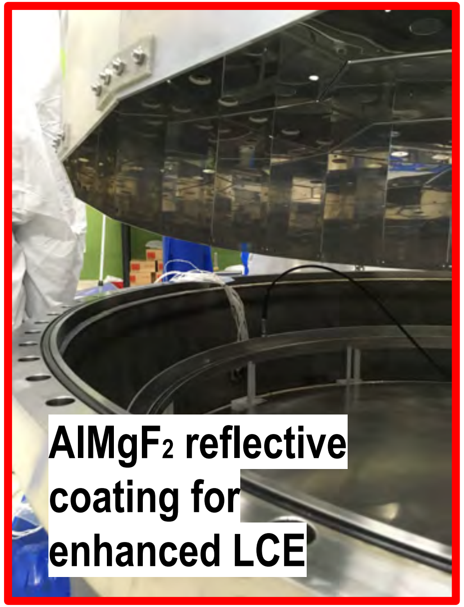
Sparse 32 PMT array provides 2D position reconstruction in warm xenon gas

Single electron sensitivity for electron emission testing



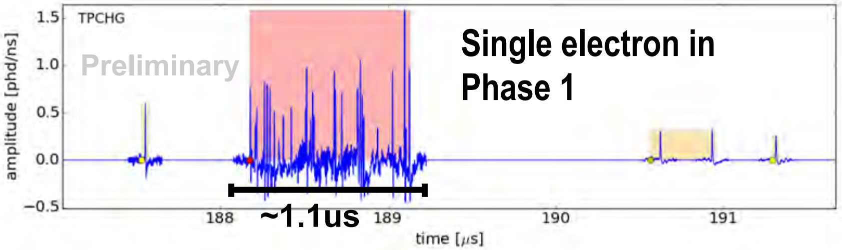
Full-scale LZ prototype grid installed in vessel

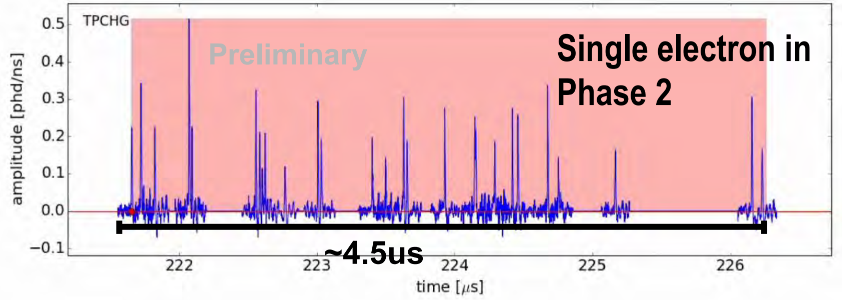
PMT Array

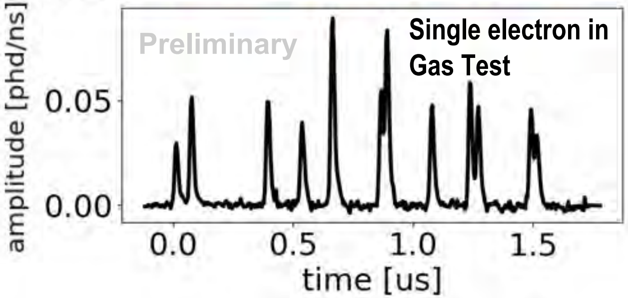


$AlMgF_2$ reflective coating for enhanced LCE

Investigation of electron emission







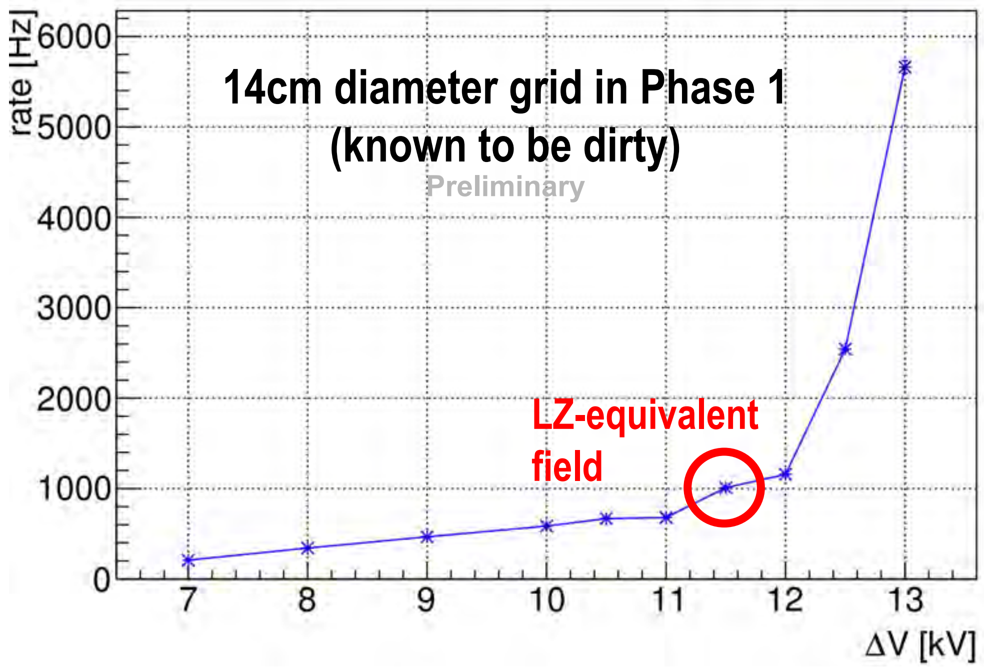
<u>All three detectors sensitive to single electrons</u> - signal properties vary by detector (drift length, LCE), voltage, pressure, etc.

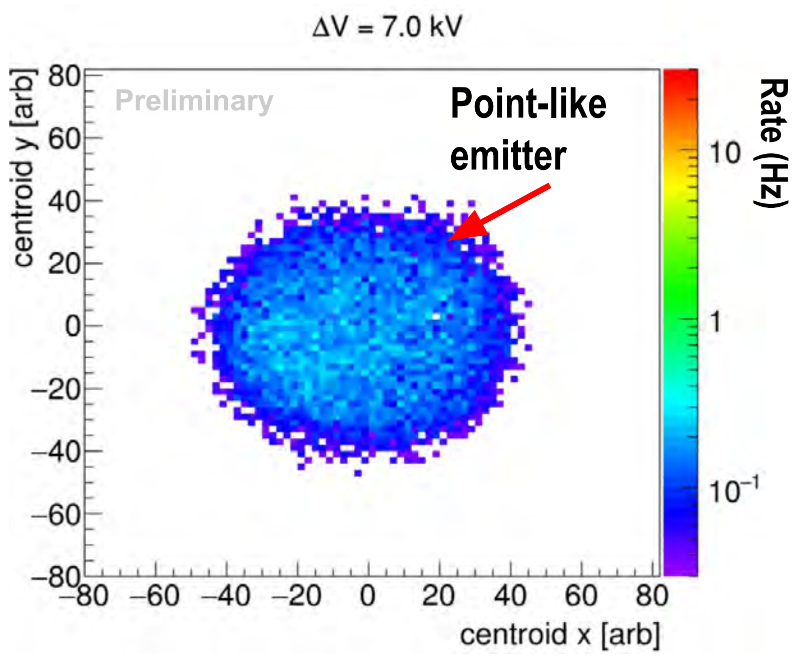
All electron emission datasets shown as increasing anode-gate voltage differential (ΔV) - LZ-equivalent fields marked where appropriate

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

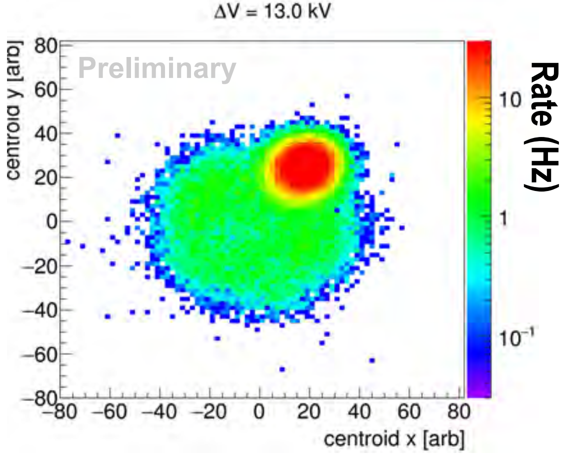




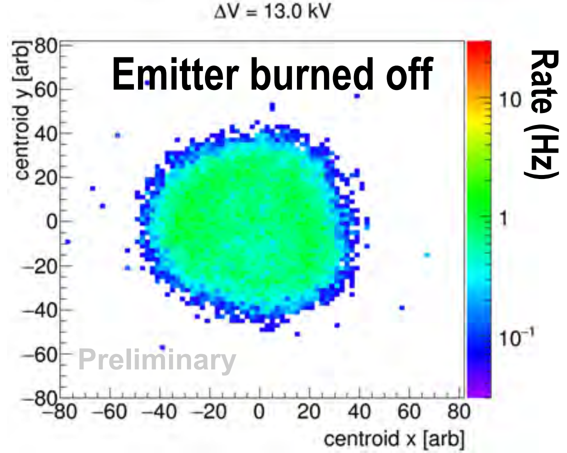
Emitter appears around 10.5kV ΔV

Electron emission from point-like sources

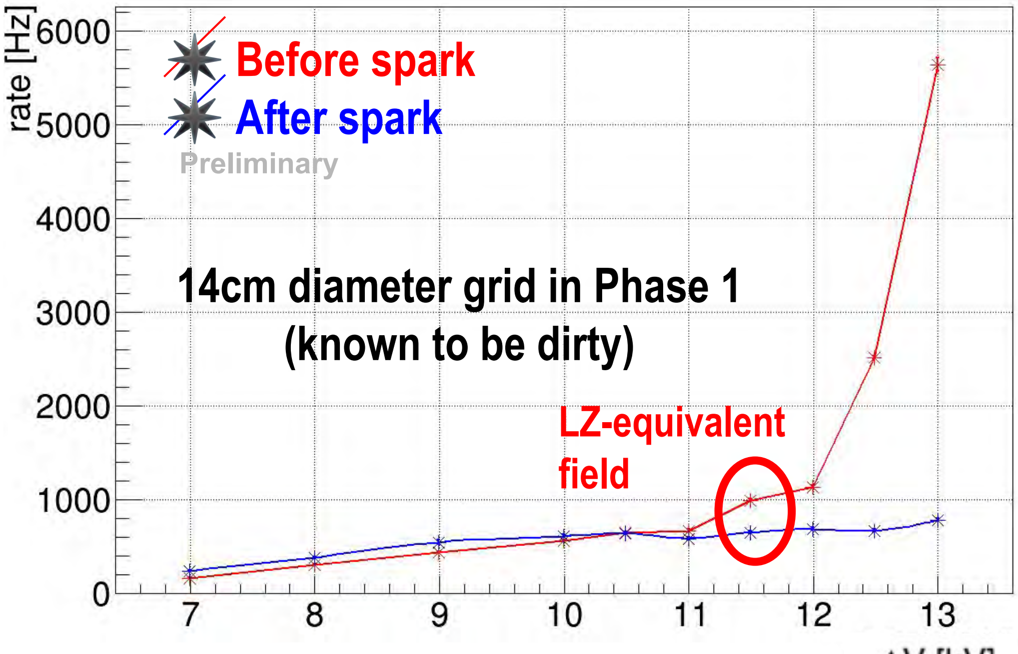
Before spark:



After spark, same voltage:



Single electron rate vs. voltage



See R. Mannino's Thesis

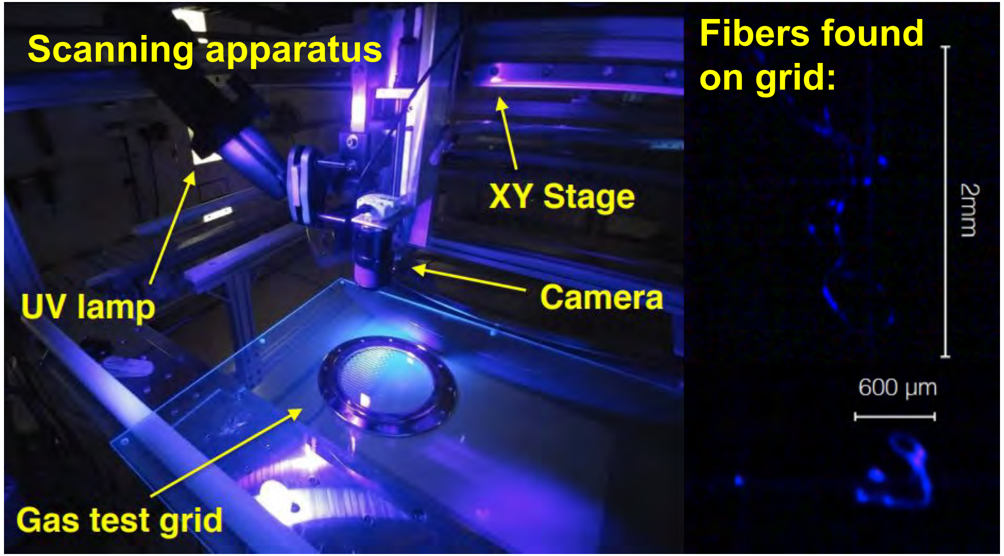
Electron emission from point-like sources

Work done by
R. Linehan

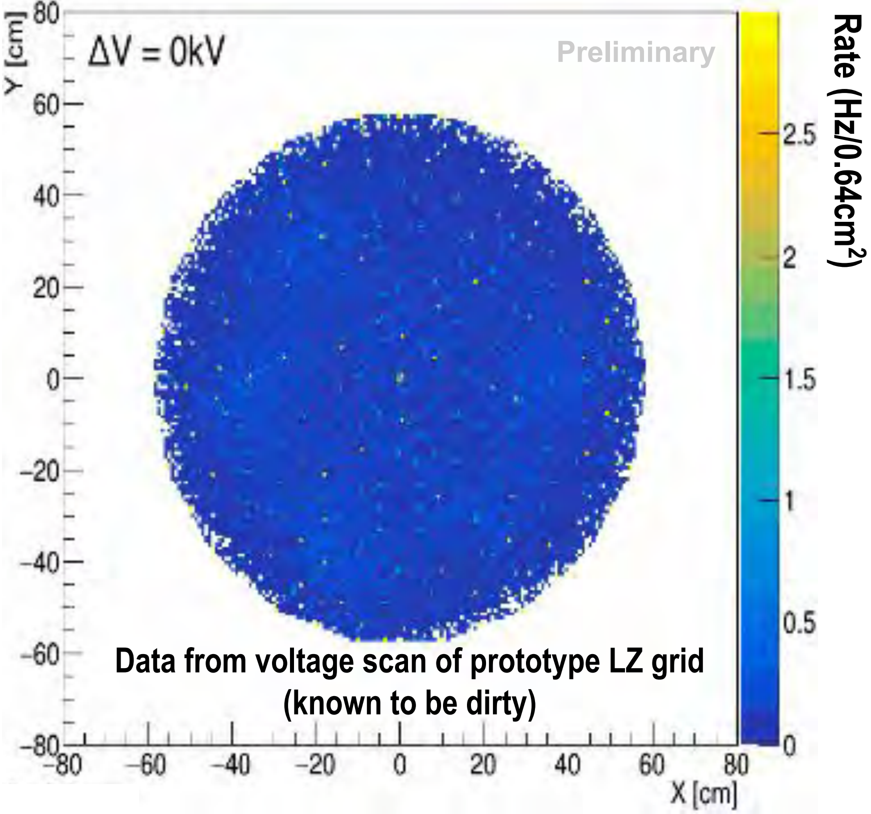
Similar emission points seen in Phase 2 on full-scale LZ grid

Can do automated visual scans

Correlation to fibers on grid preliminary

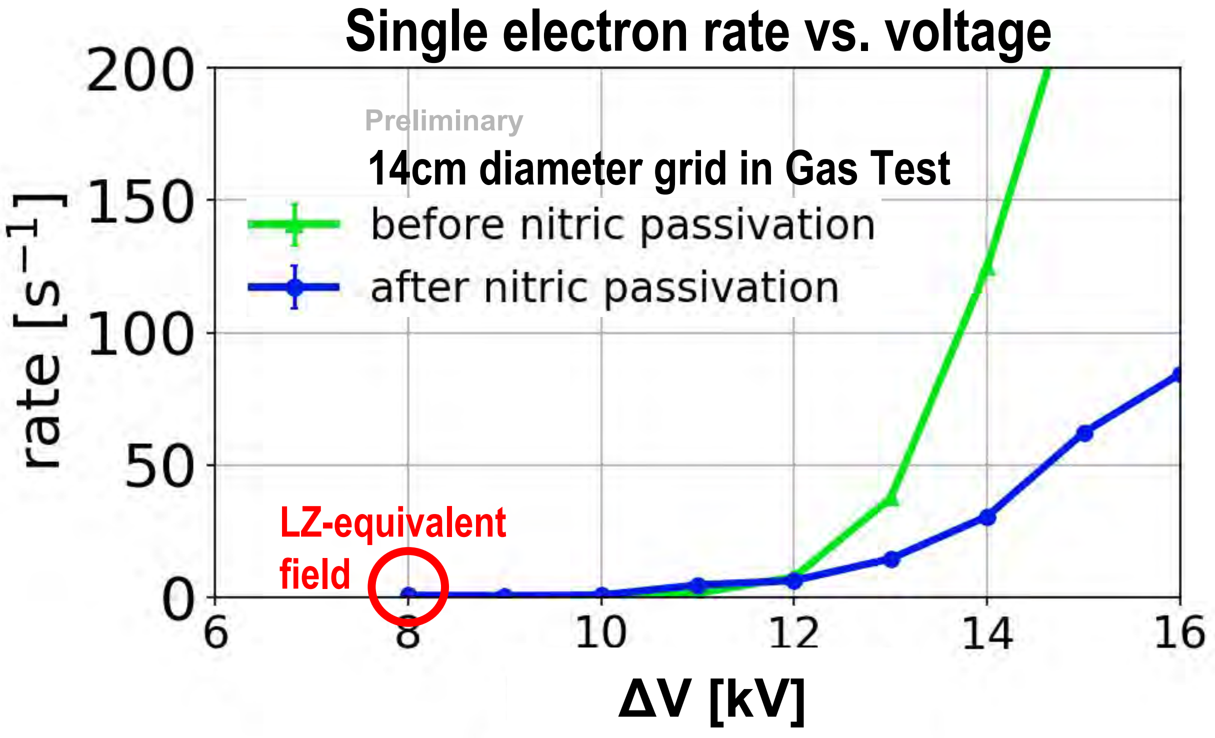


Rate of pulses with centroid at (X,Y)



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

Effect of nitric passivation on electron emission



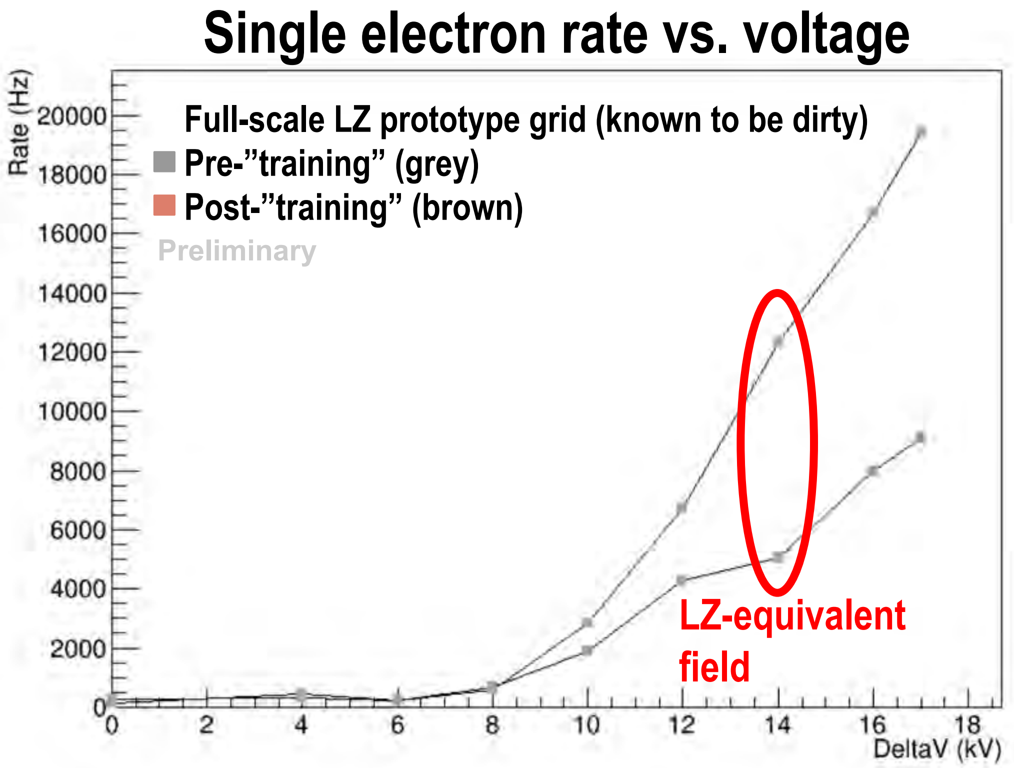
Tested several iterations of grid treatment in Gas Test

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

Work done by W. Ji

Effect of "training" on electron emission

Work done by R. Linehan



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

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

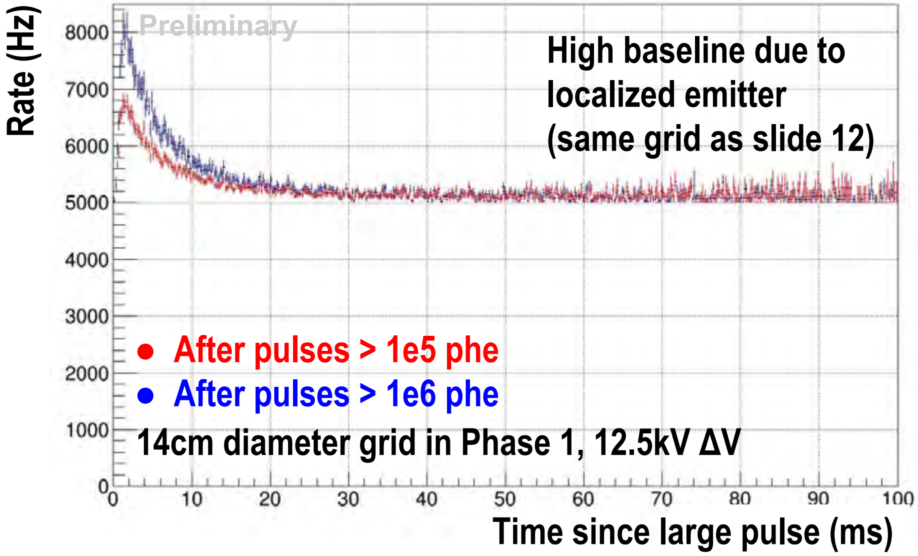
Data from same grid on slide 14 - much of rate from localized emitters likely from dust/debris

Correlated electrons in Phase 1

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

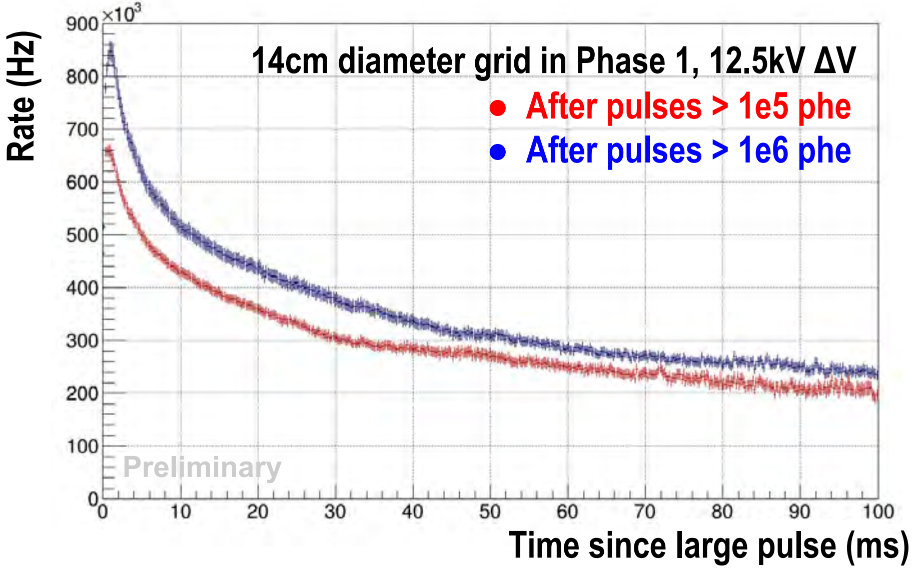
Both effects seen previously (arXiv:1711.07025, doi:10.1088/0954-3899/41/3/035201), vary with extraction field & S2 size

Single electron rate after large S2s



Hypothesized to be due to <100% prompt electron extraction efficiency and photoionization of impurities

Single photoelectron rate after large S2s



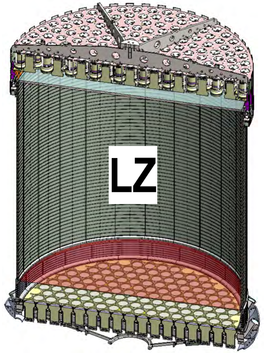
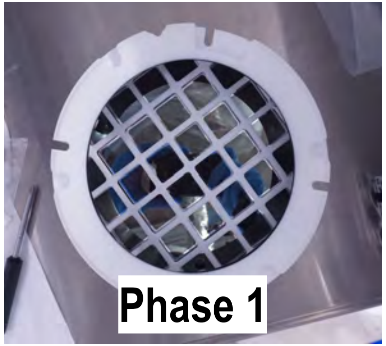
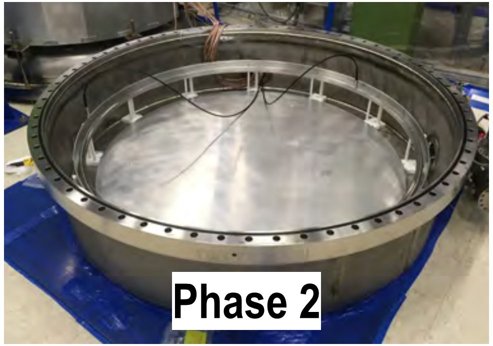
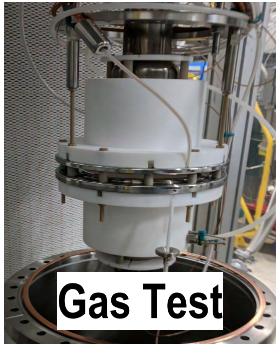
Hypothesized to be due to Teflon fluorescence

The LZ System Test at SLAC

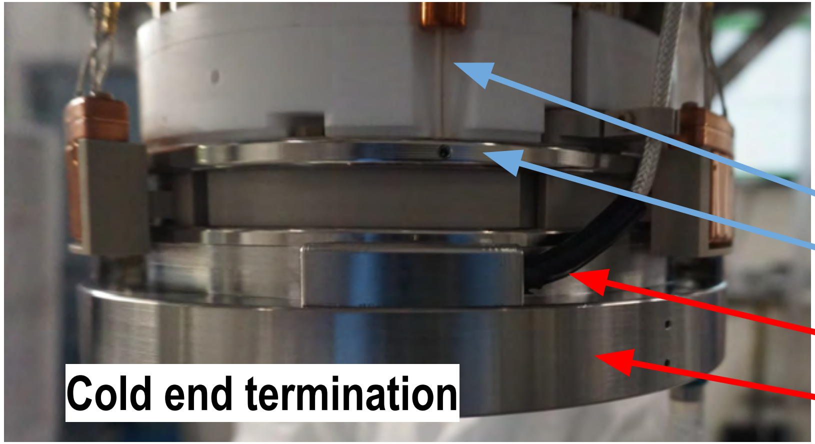
Proven ability to quantify electron emission (final results forthcoming)

Still developing paths to reducing emission for LZ

What else?

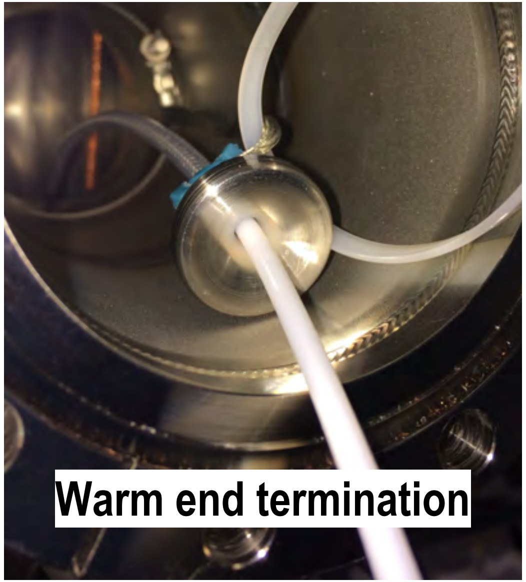
	Large	Small
Dual-Phase TPC		
Single-Phase TPC		

High Voltage Termination



Anode cable
Anode ring

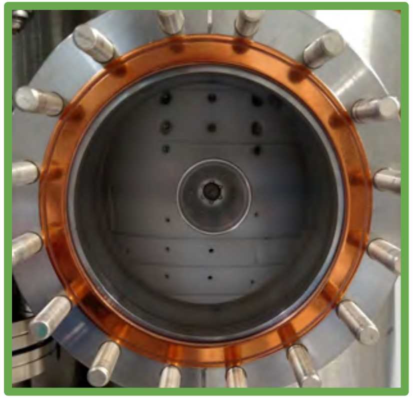
Gate cable
Gate ring



New termination technologies and geometries tested in <u>Gas Test</u> and <u>Phase 1</u>

Inform and validate final LZ design

Cathode HV connection - not final LZ design



Xenon circulation path & liquid level stability

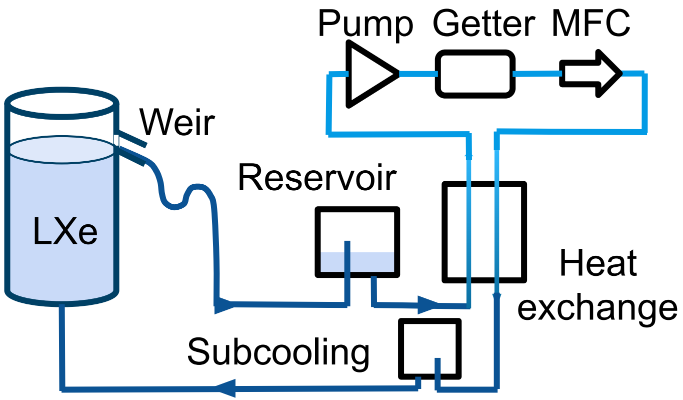
Xenon constantly circulated for purity: Electronegatives limit free electron lifetime

Detailed design done by SLAC group, several iterations built for <u>Phase 1</u>

➔ **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



Liquid level oscillations eliminated

See T. Whitis's thesis

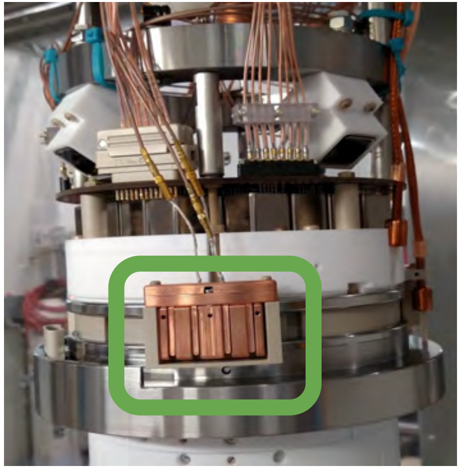
Leveling & weir height studies in Phase 1

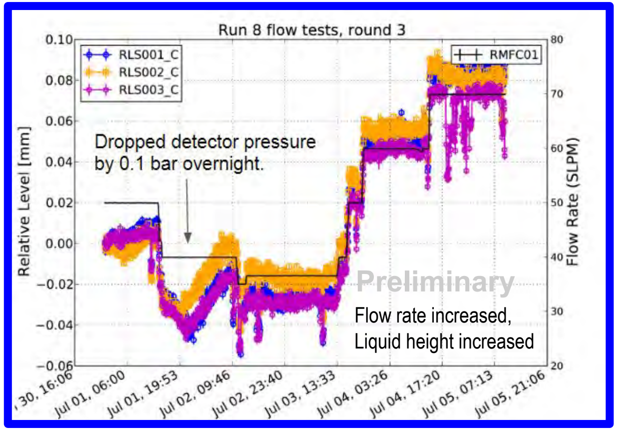
LZ-like level sensors give resolution of ~7μm

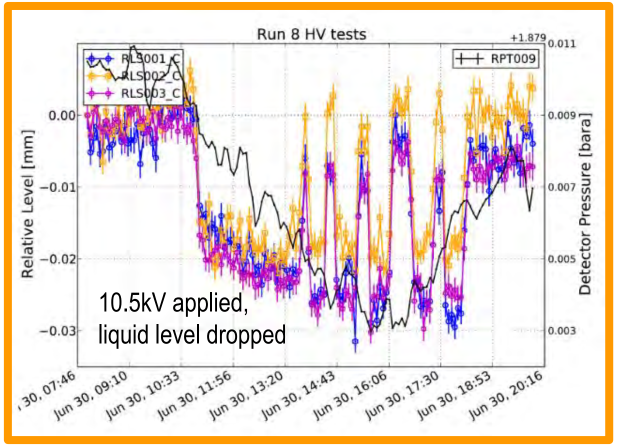
Studying liquid head height above weir vs. flow rate

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:

- Energy response of low-energy nuclear recoils (arXiv:1608.05381)
- Pulse shape discrimination in liquid xenon (arXiv:1802.06162)

Conclusions

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)

Advisors: Dan Akerib, Maria Elena Monzani, Tom Shutt

Phase 1 team: Maris Arthurs, Tomasz Biesiadzinski, Alden Fan, TJ Whitis

Dylan Temples for rebuild of cryo tower

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 Mizrachi

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.

Financial support: DOE, SLAC LDRD, NSFGFP

LZ collaboration, September 2017

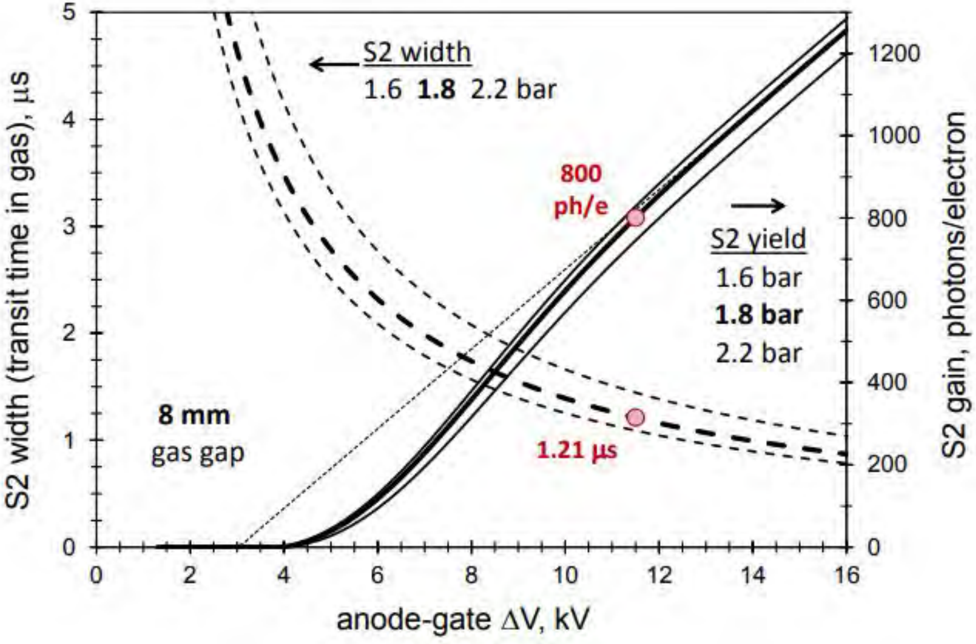
38 institutions

250 scientists, engineers, and technicians

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (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 ΔV on S2 response



Parameter	value
Gate-Anode separation (and tolerance)	13.0 mm (±0.2 mm)
Gas gap (and tolerance)	8.0 mm (±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 μs
Detailed modeling	
S2 photon yield	910 ph/e
S2 photon *rms*	2.0 %
S2 width FWHM	1.0 μs to 2.0 μs[a]

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

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

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

LZ TDR: 1703.09144

System Test Cryogenics - Thermosyphons

Xenon liquid at ~170K

➔ **Can use LN (77K) to cool**

Developed at SLAC for use by LZ @ SURF

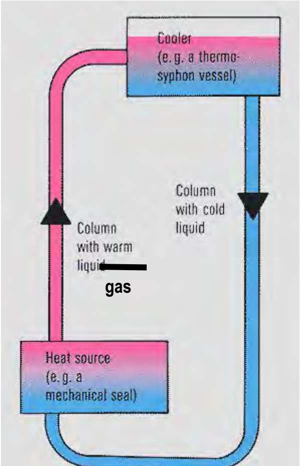


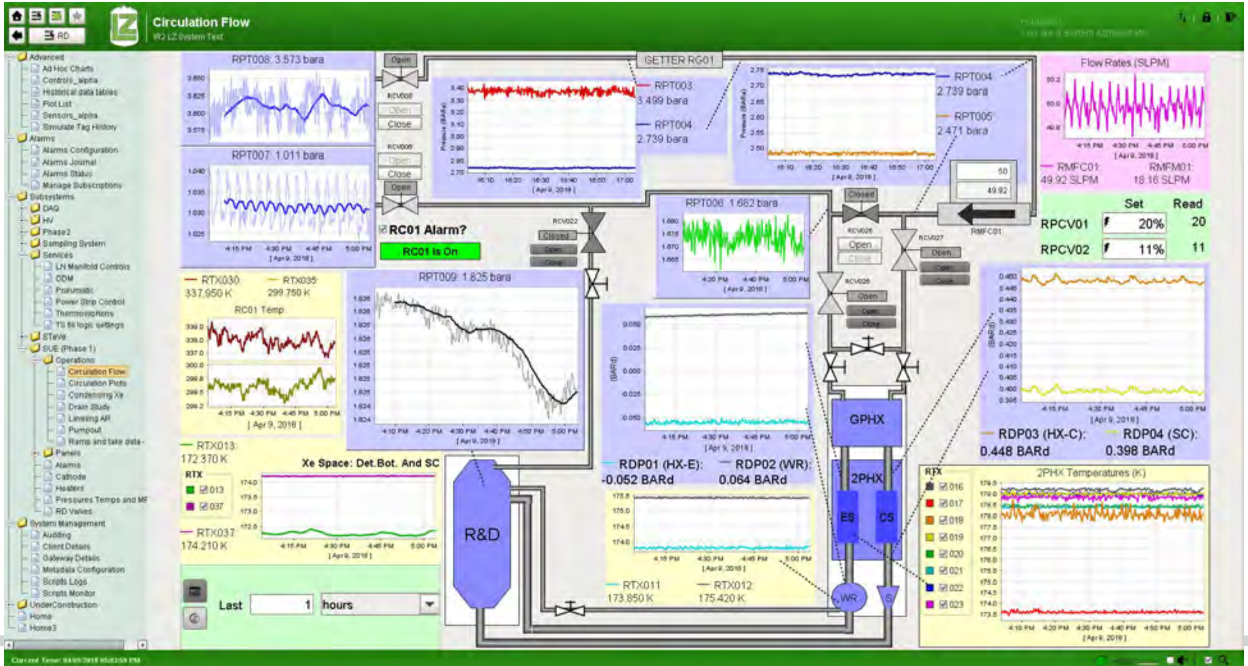
Image from EagleBurgmann

System Test Slow Control: PLCs + Ignition

Same system as being used by LZ

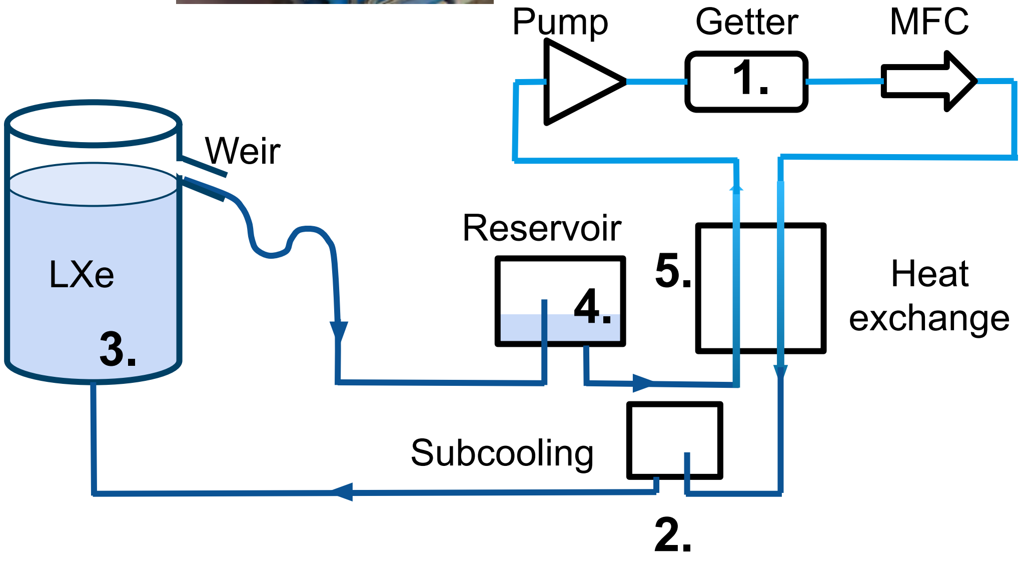
Provides control, automation, and fail-safes for xenon & LN handling systems (and more)

SLAC System Test implemented and testing all elements before LZ comes online



Phase 1 (and LZ) circulation path

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

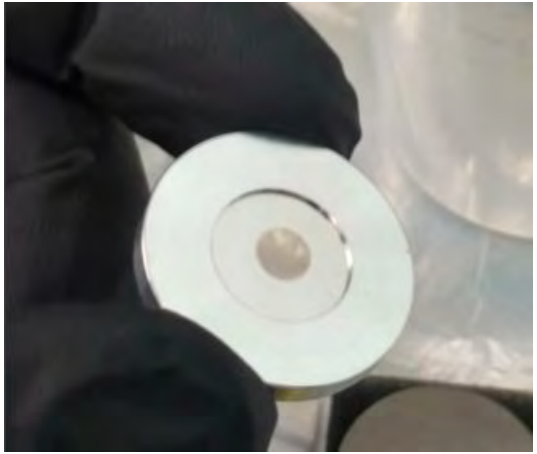
Source injection system:

- **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
ΔV = 12 kV