Recent results from the LZ System Test platform at SLAC

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On behalf of the LZ collaboration

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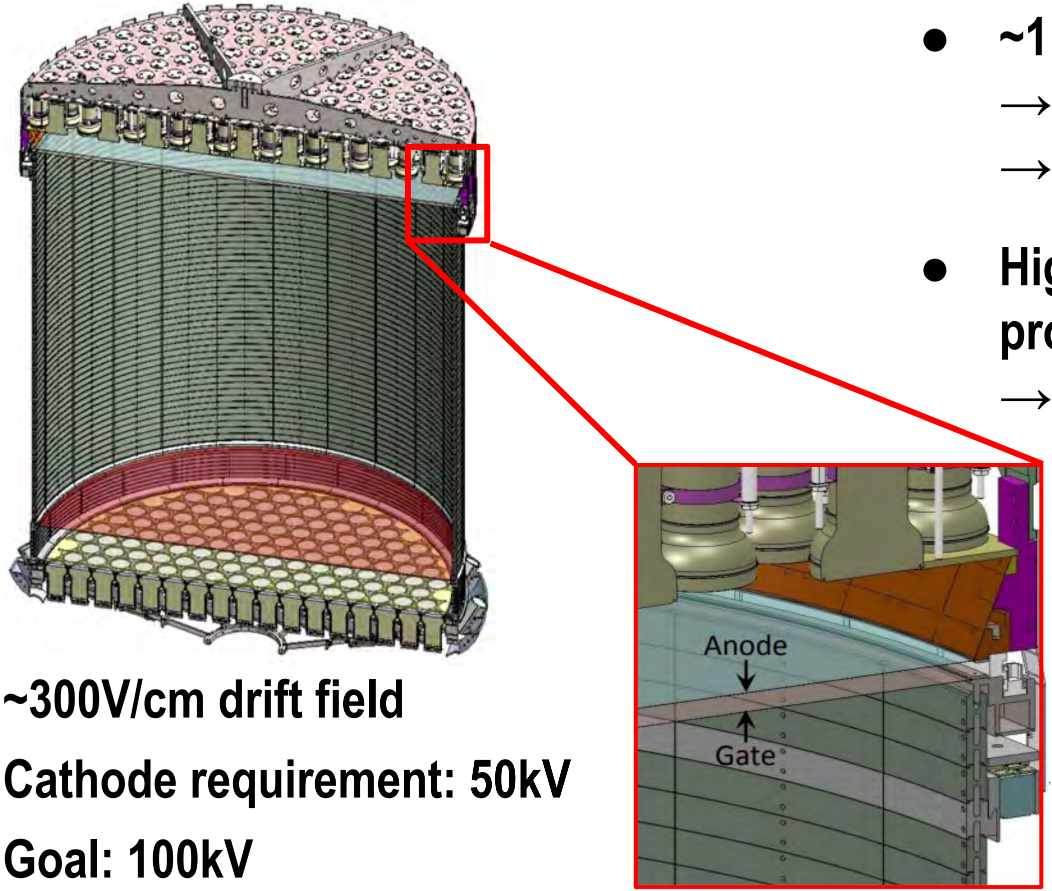
SLAC National Laboratory

Meeting the needs of LZ



- ~1.5m height, ~1.5m diameter
  → Want high fields
  → Scale up from LUX is a challenge
- High voltages and fields historically problematic
  → Undertake extensive R&D campaign

~300V/cm drift field

Cathode requirement: 50kV

Goal: 100kV

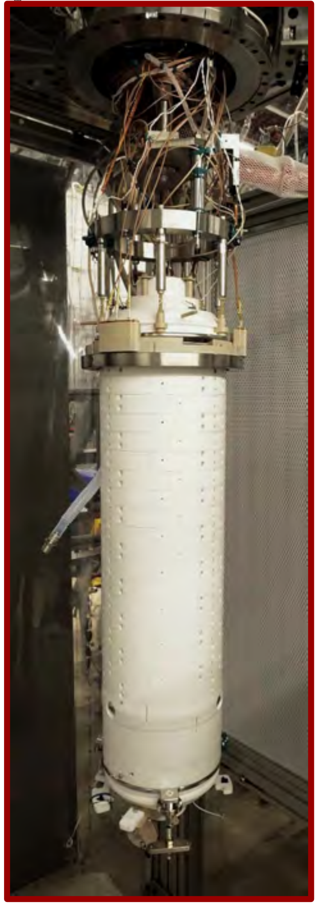
~10 kV/cm "extraction" field

Anode-gate requirement: 11.5kV

Goal: 14kV

LZ TDR: 1703.09144

The LZ System Test at SLAC



Suite of tools to enable more than order of magnitude scale-up (from LUX to LZ):

Phase 1 (SUE)

Test detector subsystems at scales approaching LZ:

- Cryogenics
- Circulation (see D. Temple's talk)
- Detector condition sensors
  - Level sensors (see D. Temple's talk)
  - Position sensor
  - Loop antenna
- Slow control and PLC
- High voltage grid performance
  - Stability
  - Spurious electron emission
- Radioactive source injection

Allows for correlation between gas result from Phase 2 and liquid performance

Phase 2

Validation of full-scale LZ grids

Study of electron emission from grid wires

Small gas tests

Rapid turnaround testing of grids, HV cables, etc.

Phase 1 (SUE)

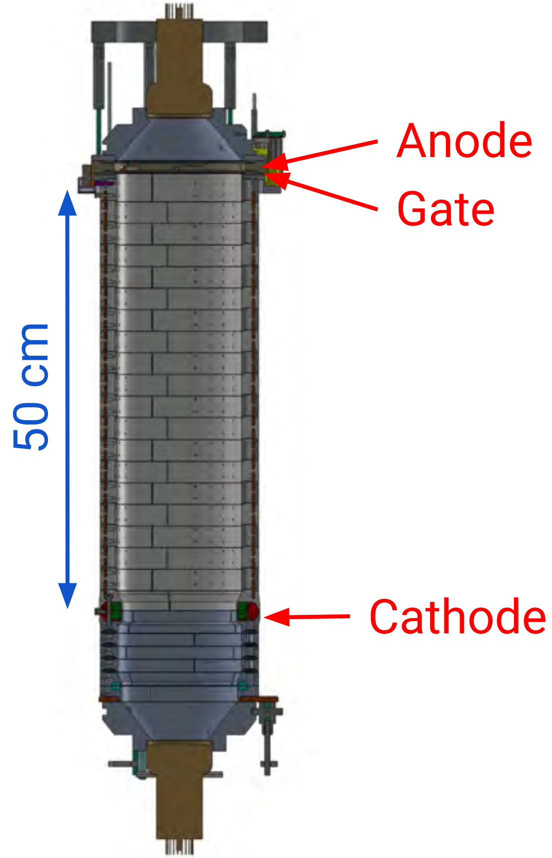
~30kg active volume, liquid xenon dual-phase TPC

Designed to match LZ drift field and extraction field

Anode-gate region architecture, xenon circulation path, cryogenics → SLAC scaling up these technologies for LZ

Limitations:

- At sea level = high rates
- 2 PMTs
  - ➔ Low light collection efficiency (1-2%)
  - ➔ No 3D position reconstruction



Recent SUE Extraction Region Upgrades

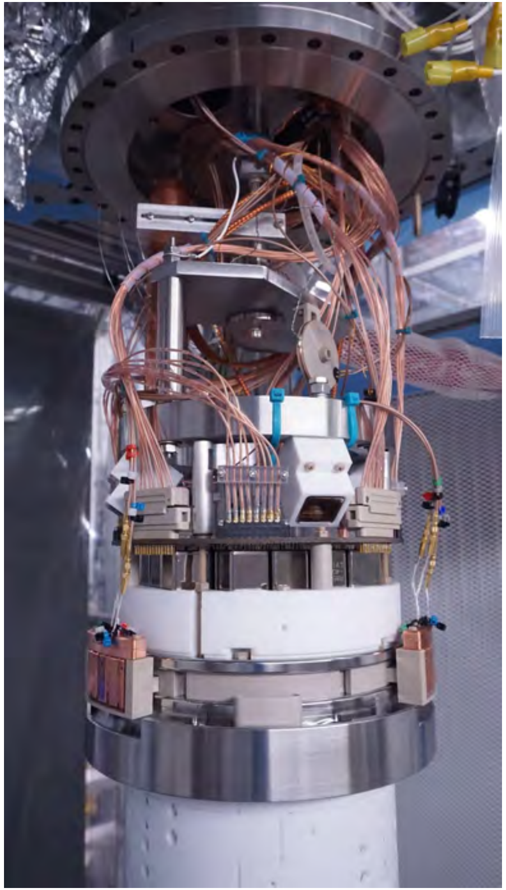
Clone of LZ extraction region

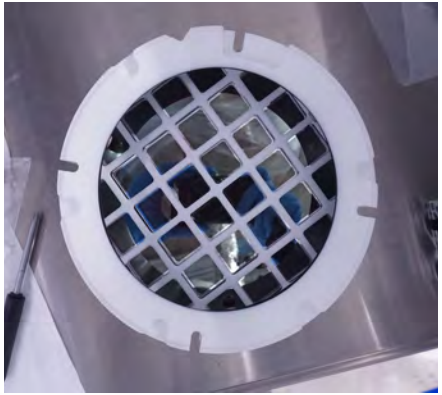
Single top PMT → 32 PMT array

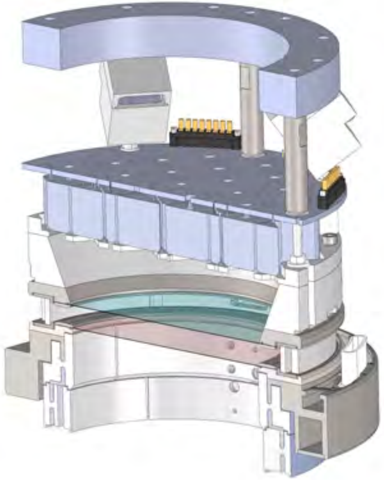
- Enhanced light collection efficiency (~x5)
- 3D position reconstruction
- Individually tunable gains

Instrumented skin region

- Anti-coincidence







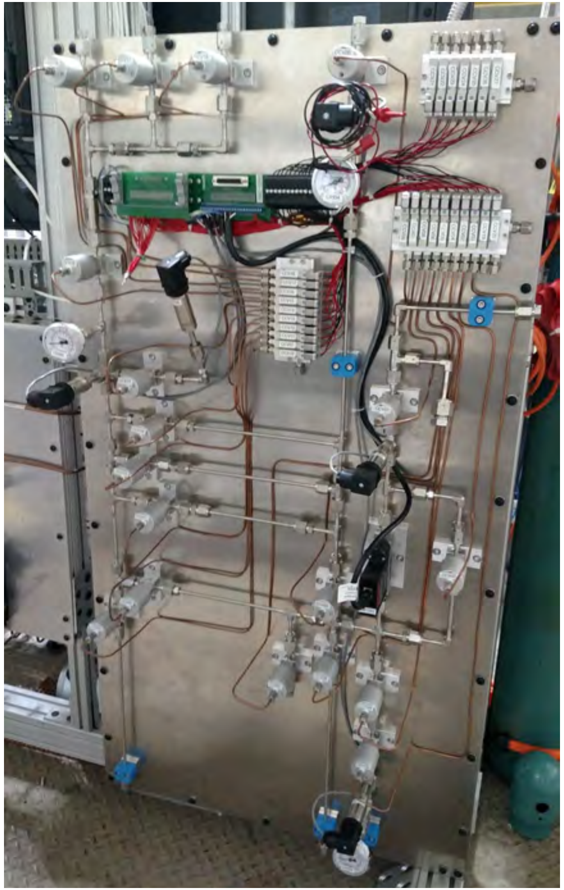
Recent SUE Upgrades

Radioactive source injection system

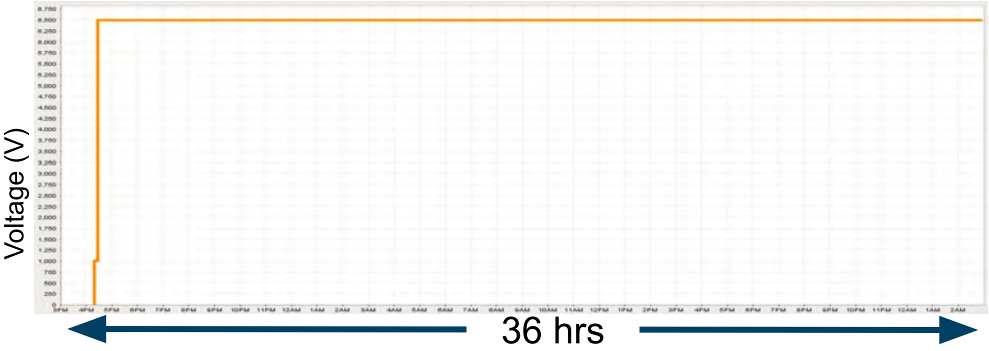
- Delivers trace amounts of radioactive sources to detector through Xe circulation path
- Mixes in liquid → get position calibration in addition to energy calibration
- First iteration of design for LZ

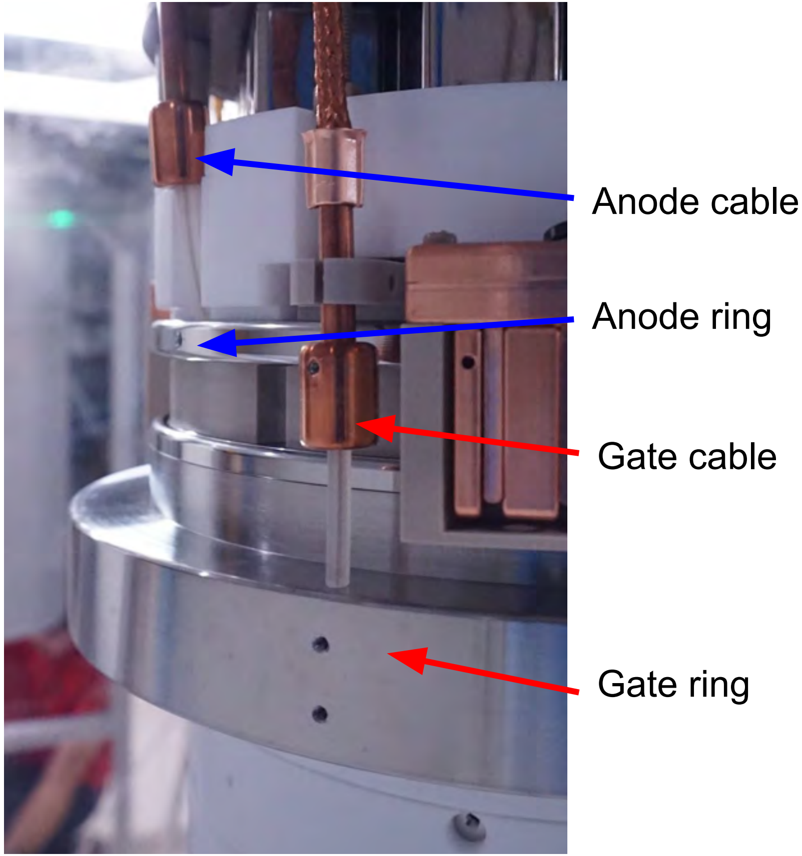
New DAQ built by SLAC

- Low gain samples at 250MHz (4ns/sample)
- High gain samples at 1GHz (1ns/sample)
  - Excellent SPE resolution



High Voltage Performance of Grids





Extraction region performance:

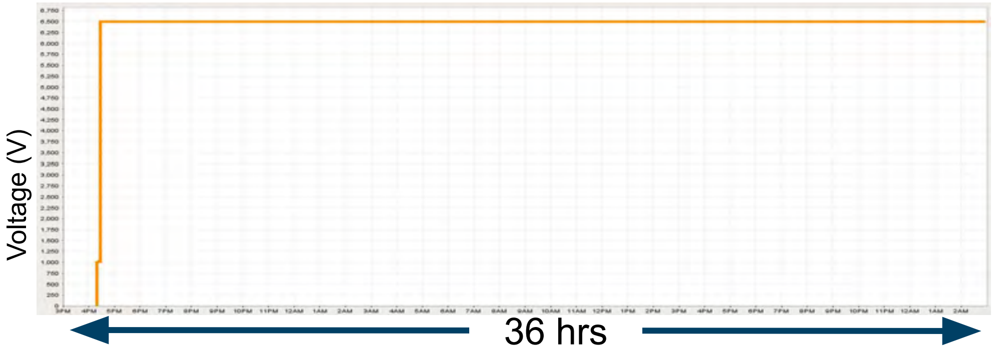
Held LZ goal field for over 5 hours

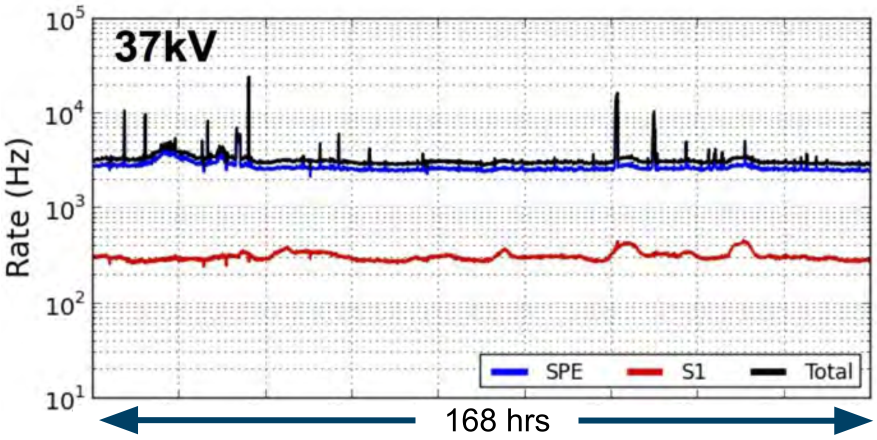
Exceeded LZ requirement for over 36 hours

Suspected culprit: termination of cables

- ➔ **Further studies ongoing**
- ➔ **Solving for SUE = solving for LZ**

High Voltage Performance of Grids





Extraction region performance:

Held LZ goal field for over 5 hours

Exceeded LZ requirement for over 36 hours

Suspected culprit: termination of cables

➔ Further studies ongoing

➔ Solving for SUE = solving for LZ

Cathode performance:

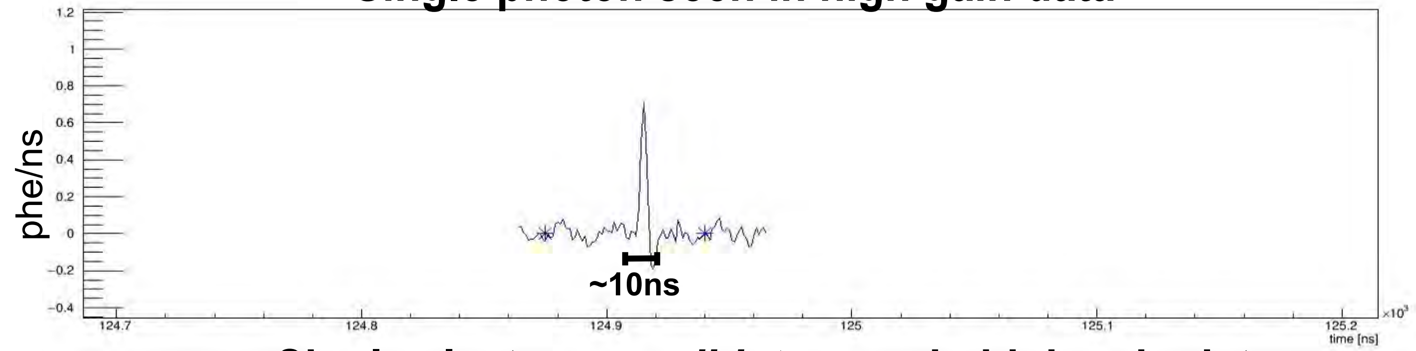
Stable operation at 37 kV = 740V/cm drift

- RFR: meets LZ requirement
- FFR: exceeds LZ goal

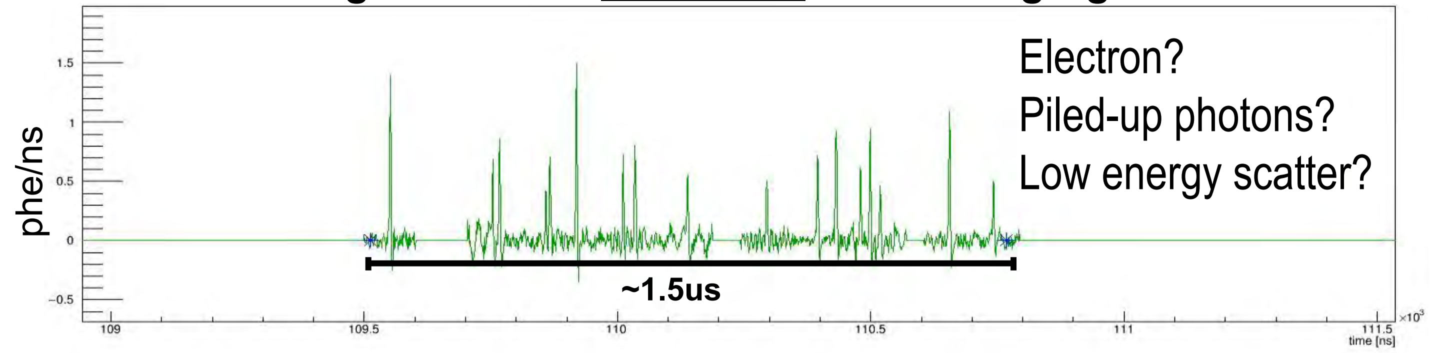
First quality data since upgrades

- Took data focused on the extraction region and electron emission

Single photon seen in high gain data



Single electron *candidate* seen in high gain data



Path to understanding electron emission

Have data to reproduce previous SE rate results

- Better sensitivity and more handles to turn

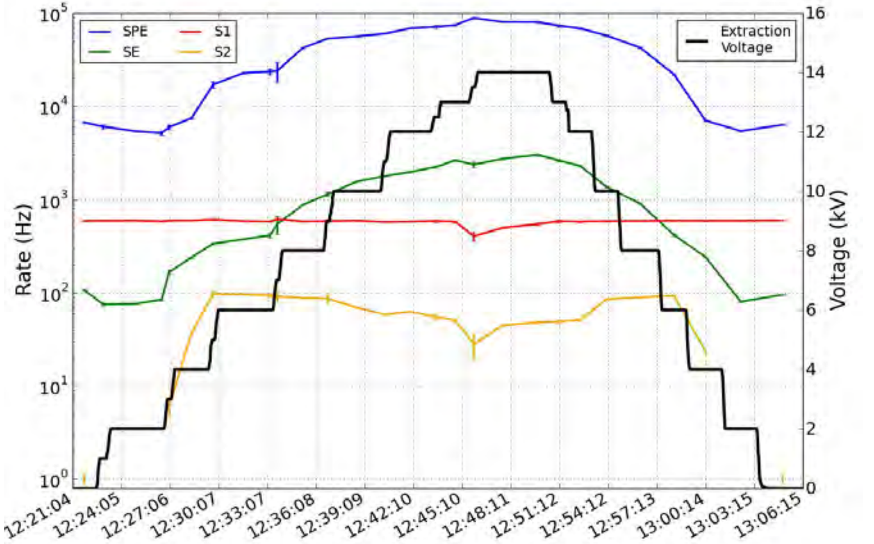
Still needed:

- Robust single photon efficiency and calibration
- Single electron detection efficiency
- Disentangle real emission electrons from low energy recoils, S2 tails, etc.
- More data!

All currently in progress for Phase 1

➔ Correlate results to gas tests and Phase 2

Data rates prior to upgrades

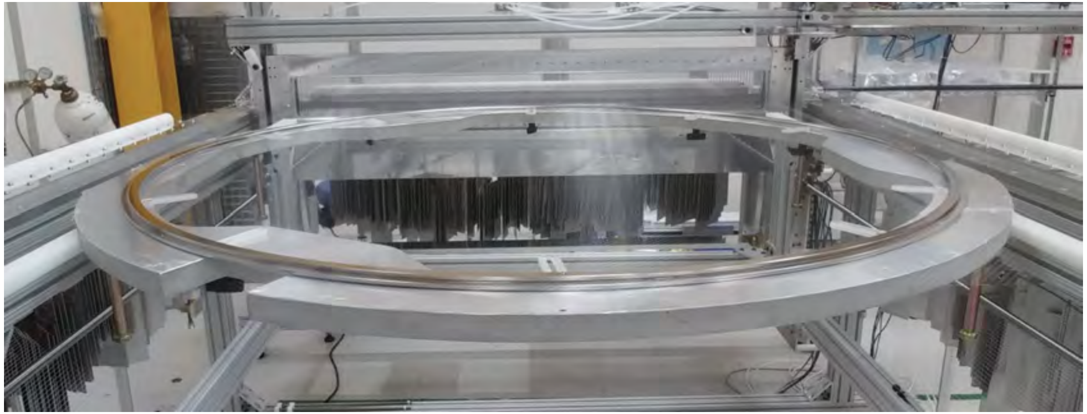


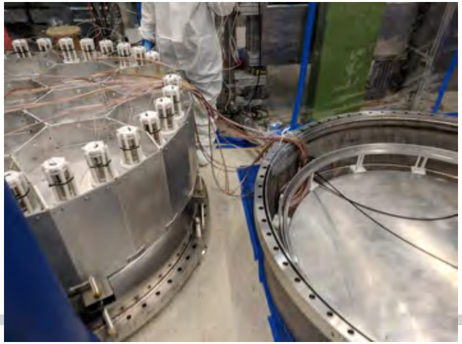
Phase 2 System Test

Test all full-scale grids before they are shipped to SURF, ensure they reach LZ requirements (and goals)

Further understand electron emission from grids

Two grids woven, first one ready to be put in vessel (see R. Linehan's talk)

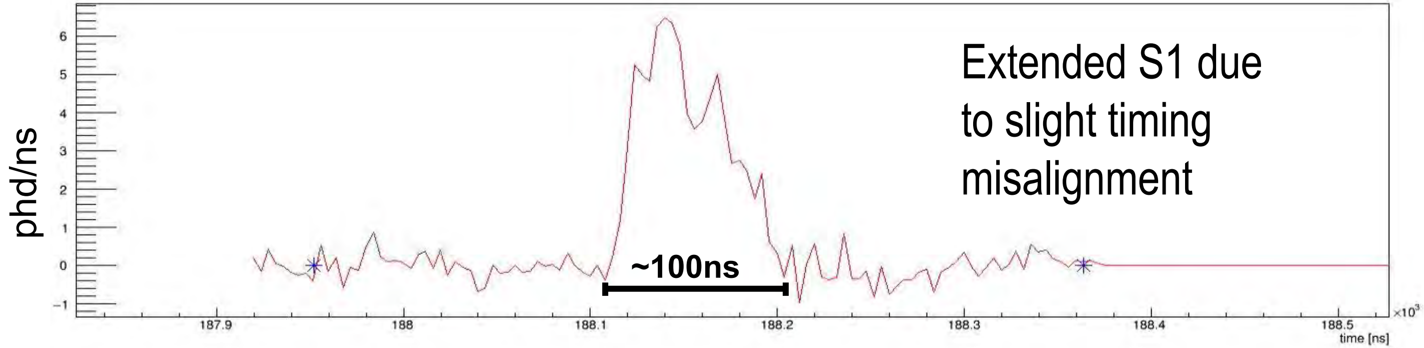




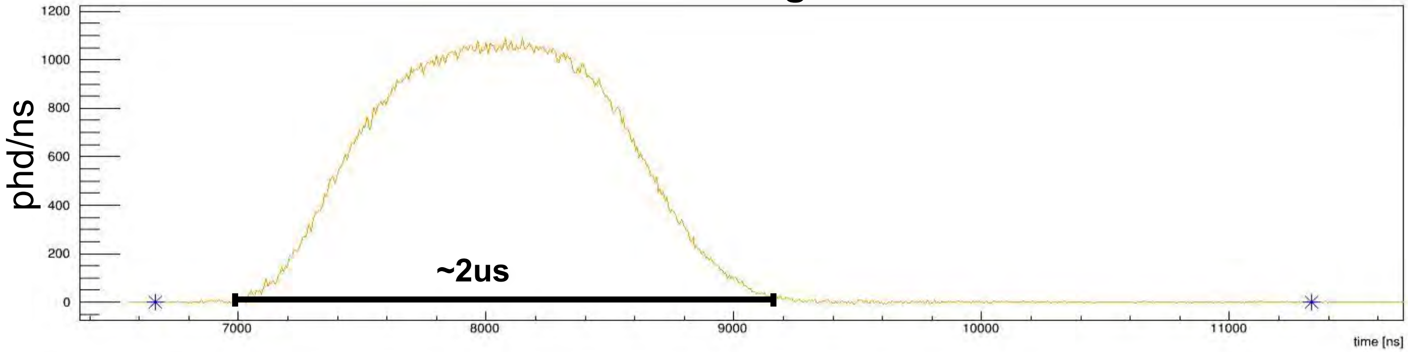
First quality data since upgrades

- Took data focused on drift region, including with radioactive source for calibration

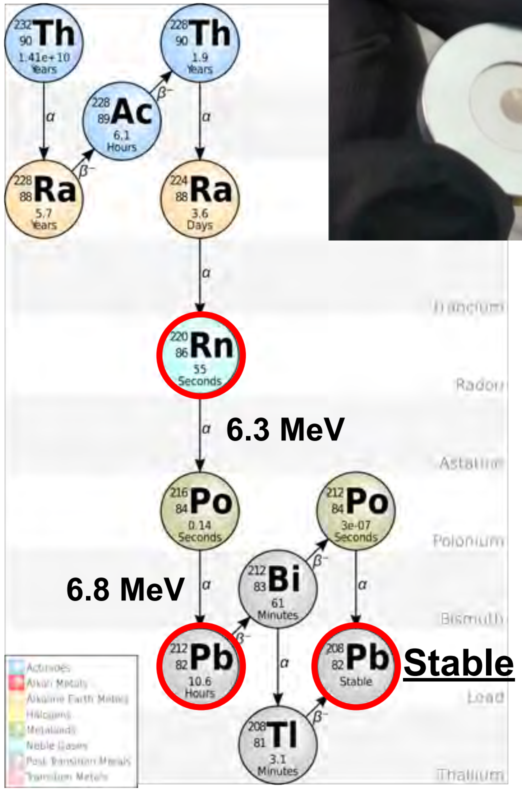
S1 seen in low gain data

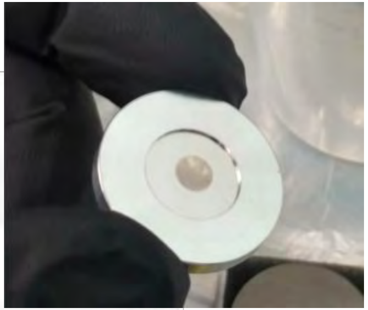


S2 seen in low gain data

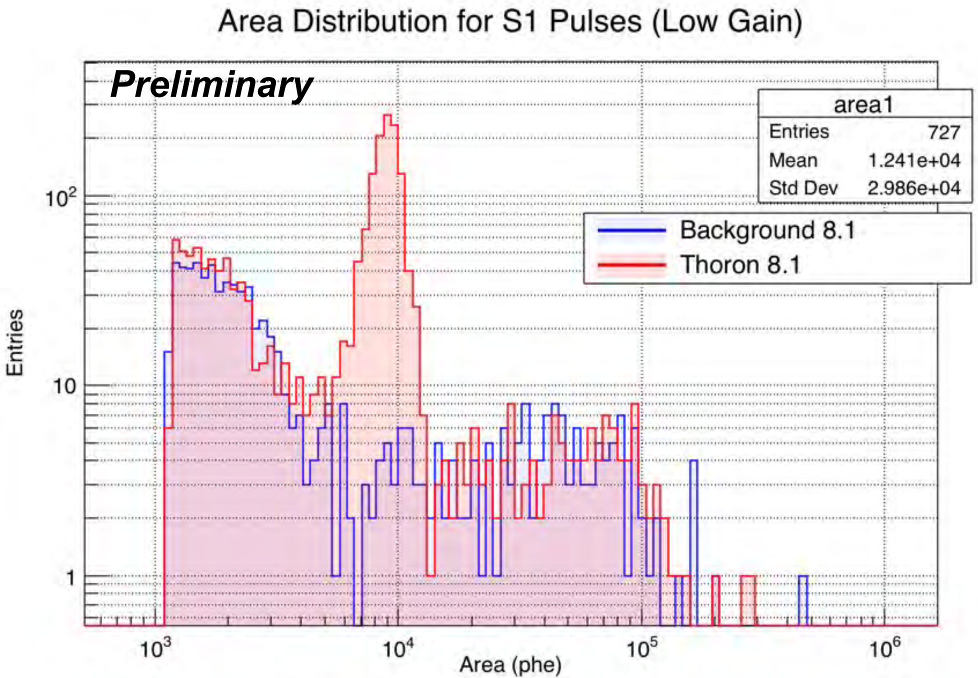


Source Injection: Rn220





- Can clearly see the source compared to background data
- Will allow us to perform energy and position calibrations



Conclusion & Future Work

Phase I of SLAC LZ System Test is ideal platform for studying designs of a broad range of subsystems for LZ

Grid HV performance critical to LZ → Phase 1 tests key link in chain

Results have already impacted the LZ design

Future of Phase 1:

- **More physics to inform LZ (PTFE fluorescence, SE backgrounds, etc.)**
- **Turn into R&D platform for xenon measurements (Cherenkov light, impurities, etc.)**

Acknowledgments

Previous SUE team: Tomasz Biesiadzinski, TJ Whitis, Wei Ji, et al.

We stand on the shoulders of giants.

Current SUE team: Alden Fan, Jacob Cutter

Dylan Temples for rebuild of cryo tower

Steffen Luitz & Christina Ignarra for Ignition

FengTing Liao, Theresa Fruth, and Cees Carels for capacitive sensors

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

Supportive advisors: Dan Akerib, Tom Shutt, and Maria Elena Monzani

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

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

Gas test team: Wei Ji, Christina Ignarra, Aude Glaenzer

Rest of the LZ collaboration (see next slide) for all their contributions

LZ collaboration, September 2017

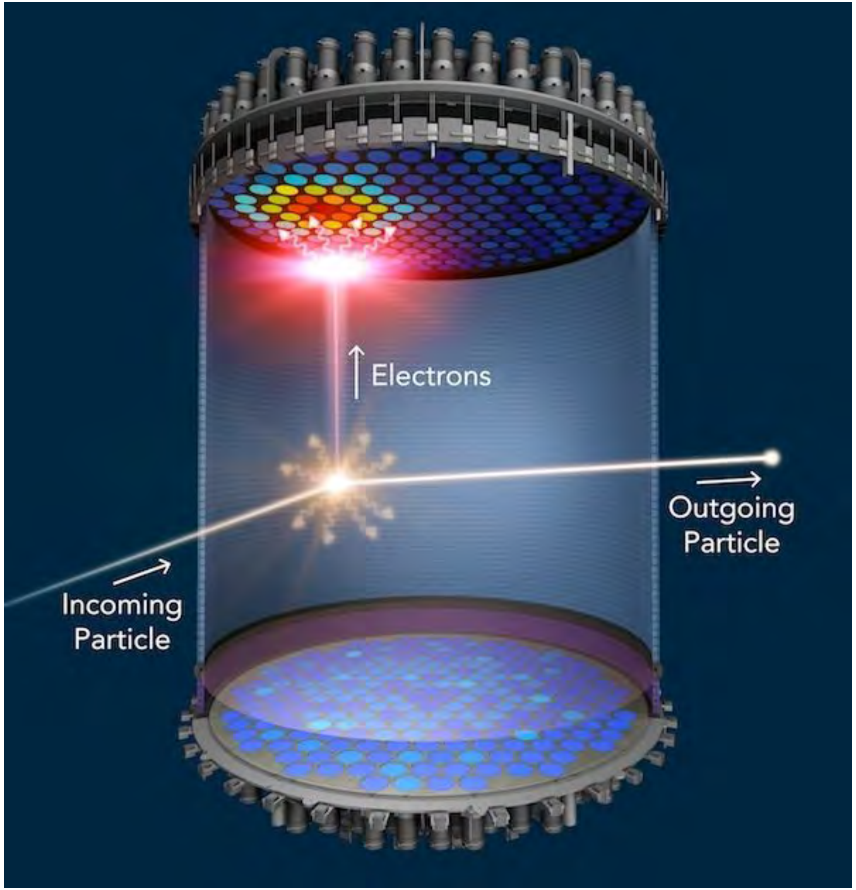
38 institutions

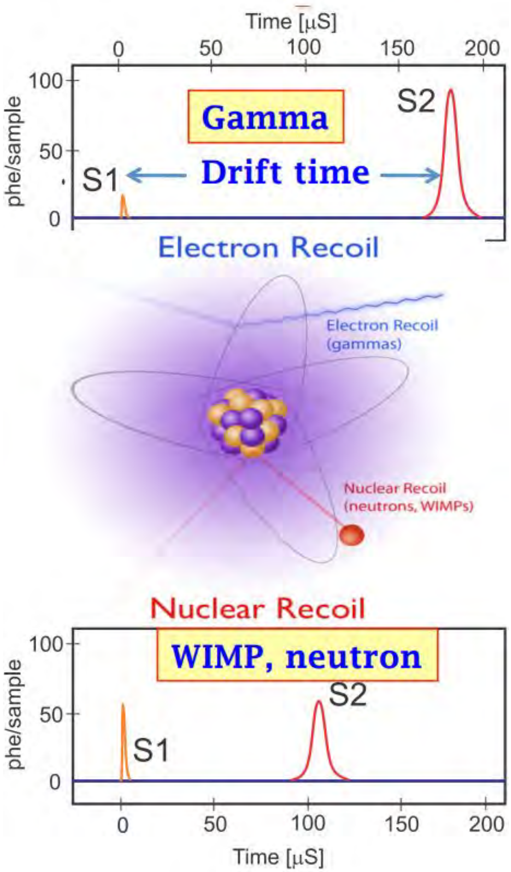
250 scientists, engineers, and technicians

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

Dual-Phase Time Projection Chamber (TPC)



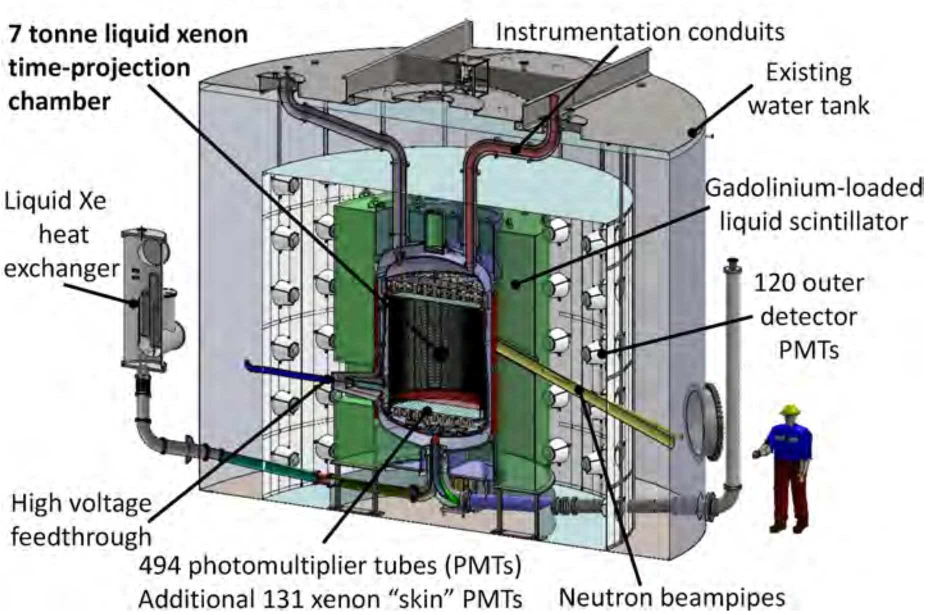


S1 = prompt scintillation signal

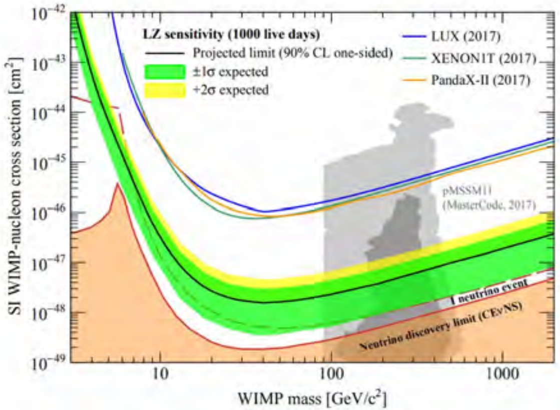
S2 = signal from extracted electrons

3D position reconstruction: xy from array, z from drift time

The LZ Detector

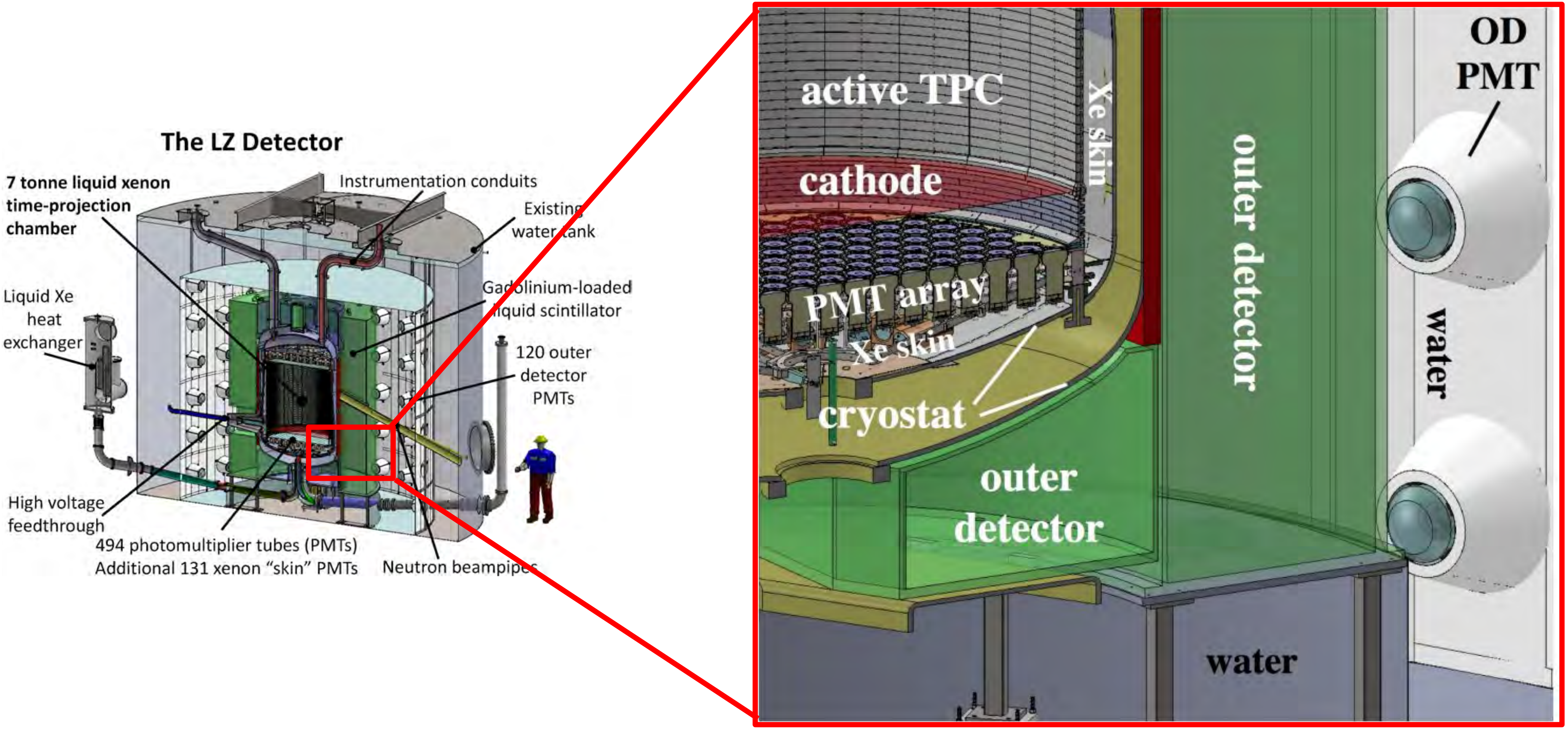


- Located on the 4850ft level at SURF
- 10 tons of xenon, 7 active and ~5.6 fiducial
- Ultra low backgrounds
- Will come online in 2020



LZ TDR: 1703.09144

The LZ detector: a closer look



LZ TDR: 1703.09144

Scaling up for LZ

Experiment	Drift height [cm]	Anode-gate height [cm]	Cathode HV [kV]	Anode-gate ΔV [kV]
LUX	48	1.0	~10	5-7
PandaX-II	60	1.1	29	5
XENON1T	97	0.5	12	4
LZ	145	1.3	50	10

LZ Backgrounds

Background Source	Mass	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER	NR
	(kg)	mBq/kg							(cts)	(cts)
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
								subtotal	**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 µBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
								subtotal	**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.81 µBq/kg)									681	-
^{220}Rn (0.09 µBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
								subtotal	**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
								subtotal	**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N									255	-
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
								subtotal	**322**	**0.51**
Total									1195	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.97	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									6.49	

LZ sensitivity: 1802.06039

Cryogenics - Thermosyphon System

Xenon liquid at ~170K

➔ **Can use LN (77K) to cool**

Developed at SLAC for use by LZ @ SURF

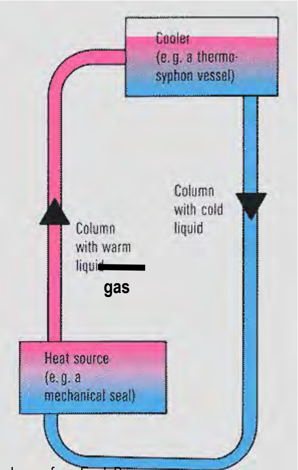


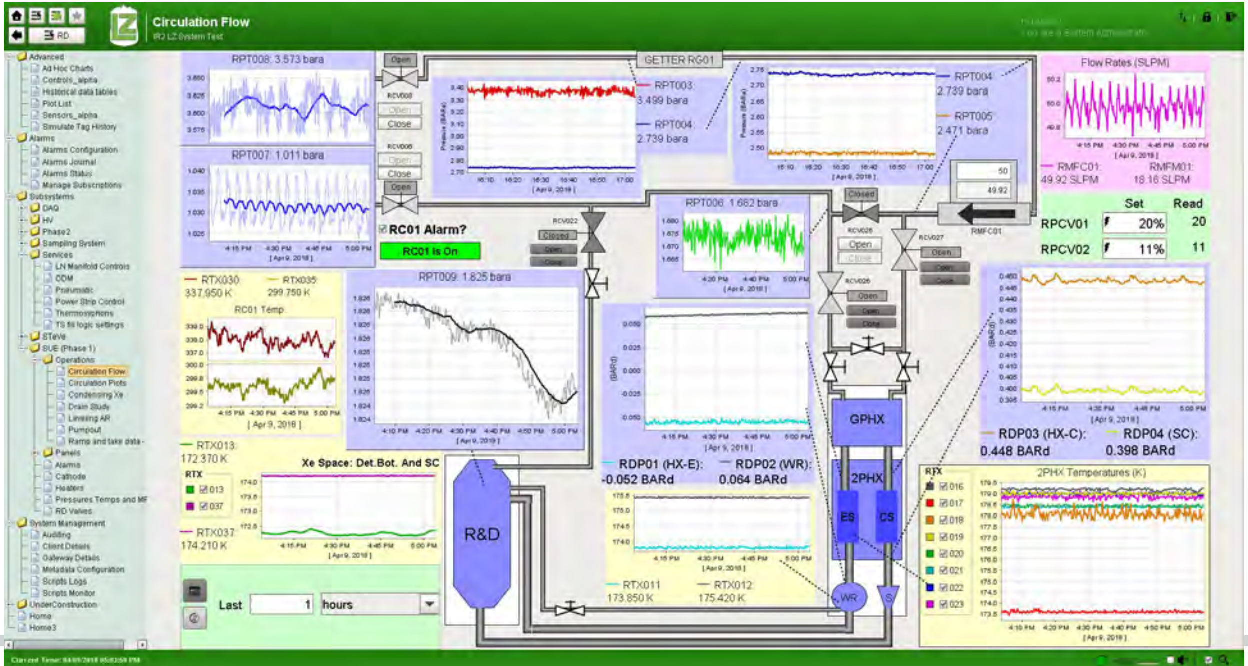
Image from EagleBurgmann

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



SUE (and LZ) circulation path

Xenon circulated due to need for high purity levels

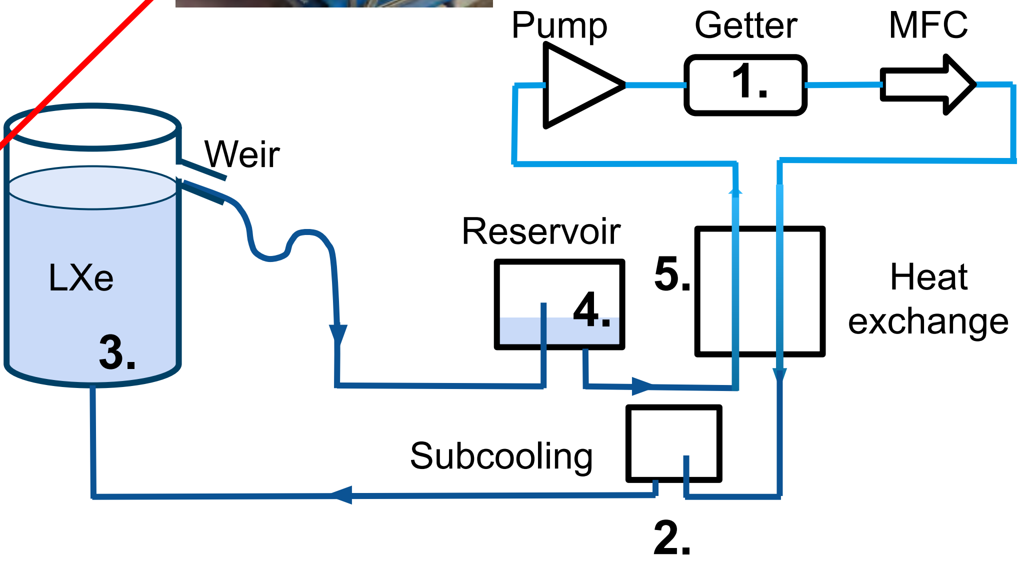
➔ Electronegatives limit free electron lifetime

Developed by Akerib & Shutt's group

➔ Path for LZ will largely be a clone

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



Previous SUE Results

Trapped liquid volumes can be trouble

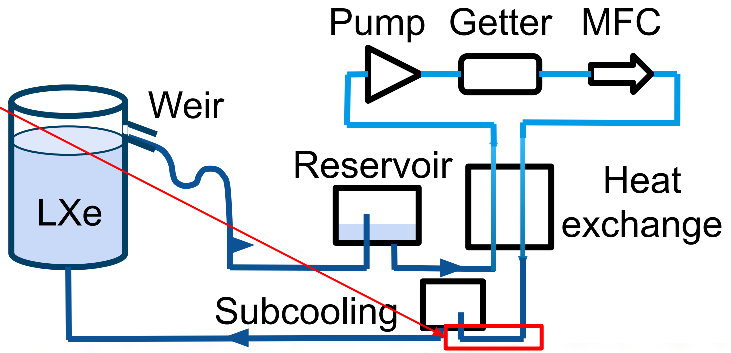
➔ Oscillations caused by pressure buildup and release

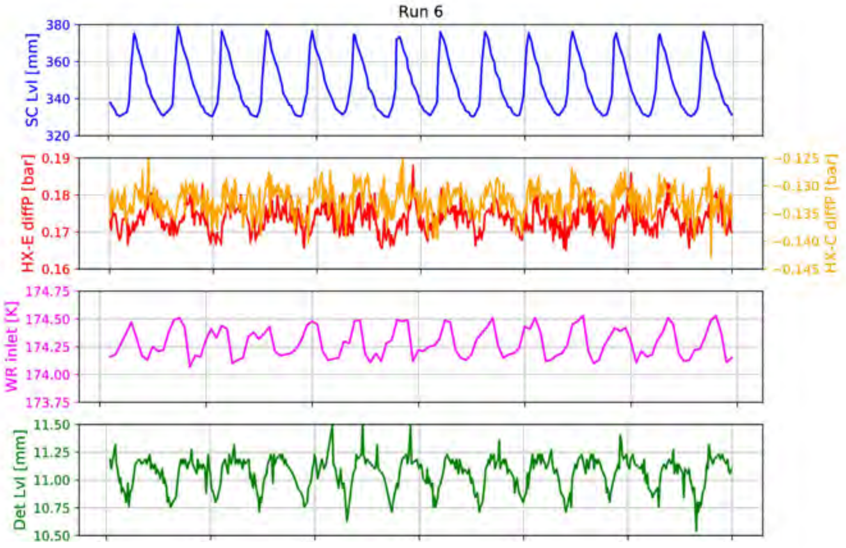
Oscillations seen w/ varying periods

Leads to changes in liquid level

➔ Affects data rates, S2 shape, etc.

Suspect trapped liquid volumes in U-bends





45 minutes

Recent SUE Upgrades

Rebuilt almost all cryo components of the detector in Summer 2017

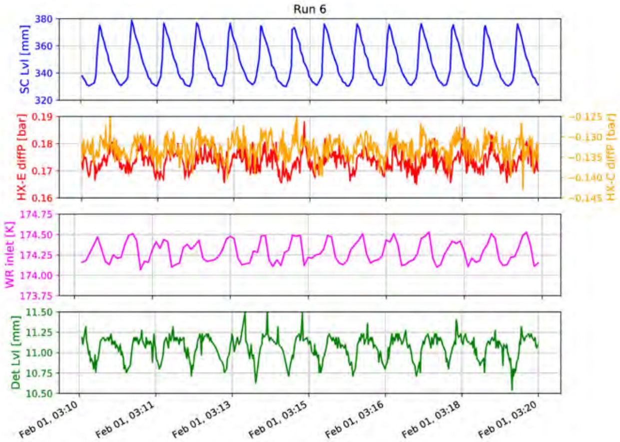
Solutions:

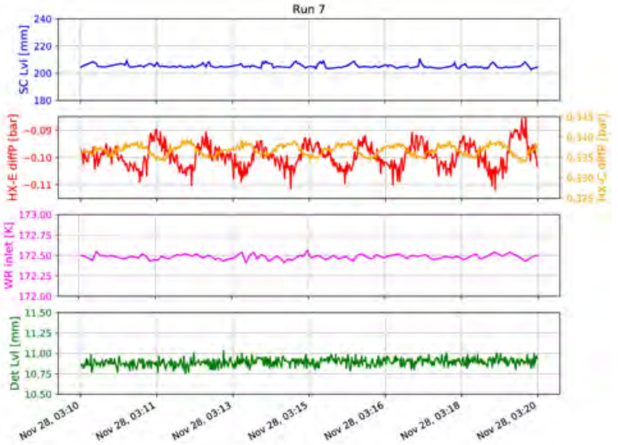
- Eliminated a U-bend by lowering subcooler
- Increased cooling power
- New subcooler and weir reservoir

Oscillations eliminated!

- Liquid level stable to w/in ~200μm

Informed final design of LZ circulation path





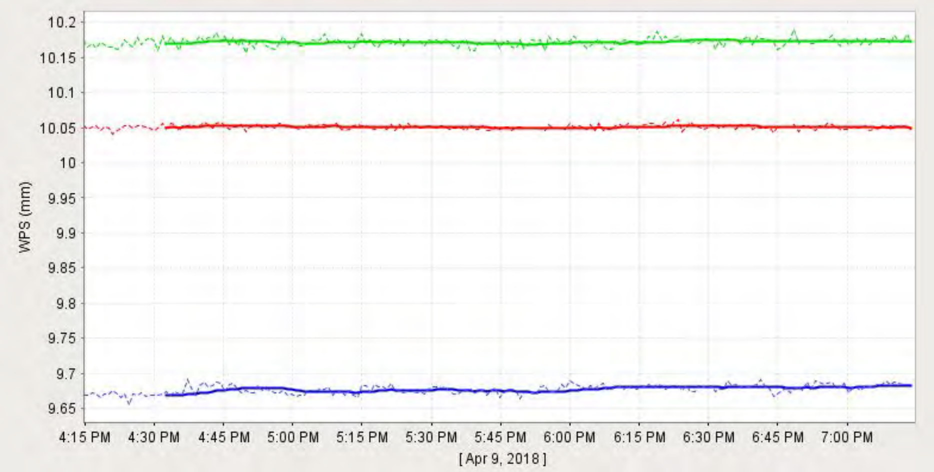
Recent SUE Upgrades - Sensors

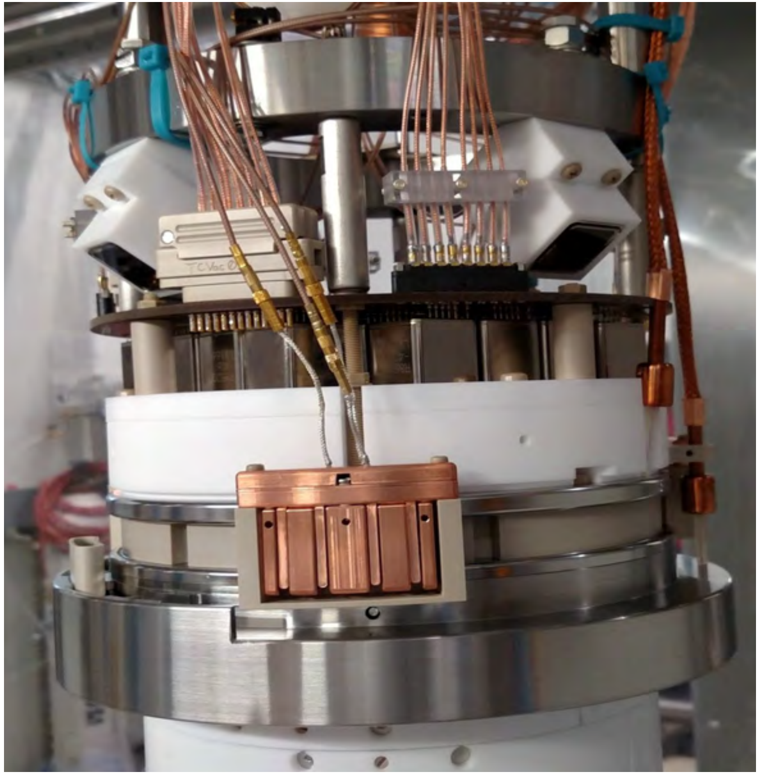
Improved level sensors - less noise

- Resolution of ~7μm

Functional position sensor, loop antenna, and acoustic sensors

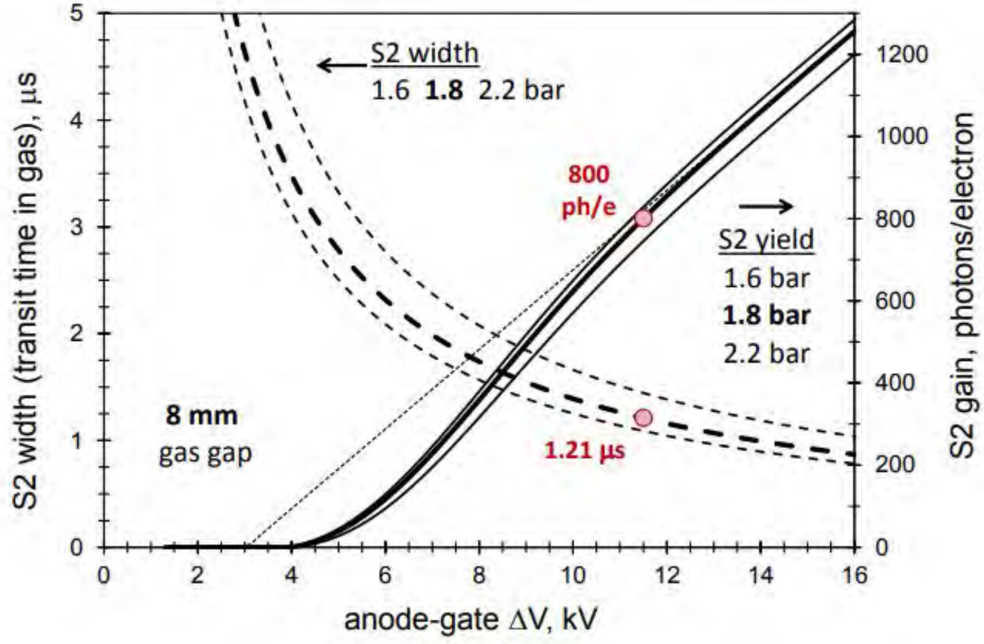
All of which will be used in LZ





https://slack-files.com/T04R0FSH2-F7ZEYN19D-5b7b35ae43

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)

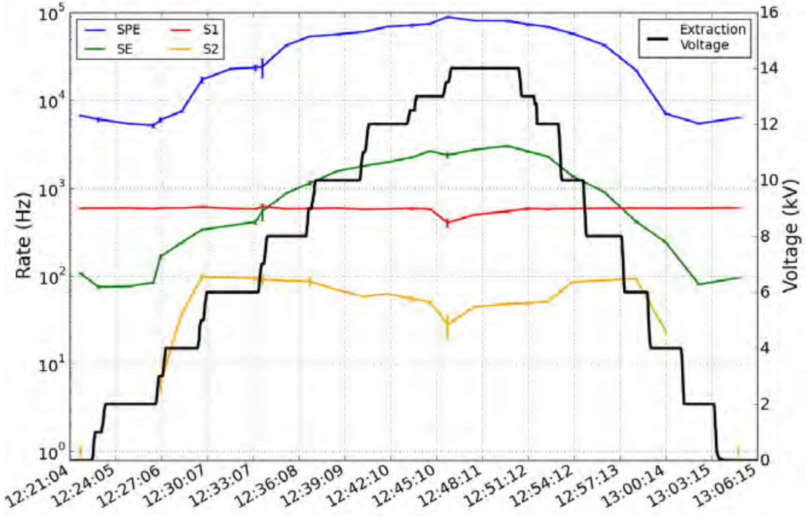
LZ TDR: 1703.09144

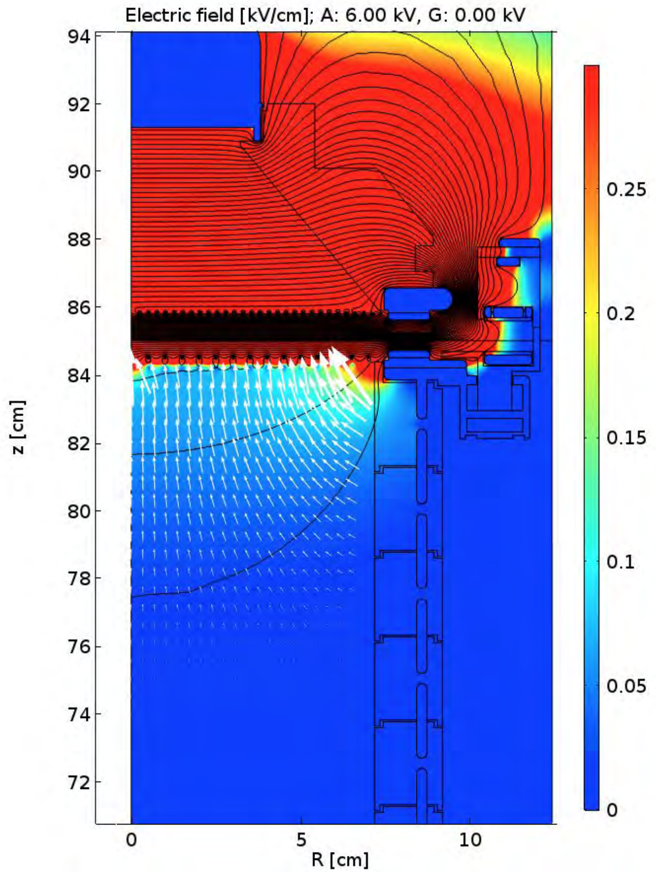
Dependence of TPC parameters on Cathode HV

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

Previous SUE results





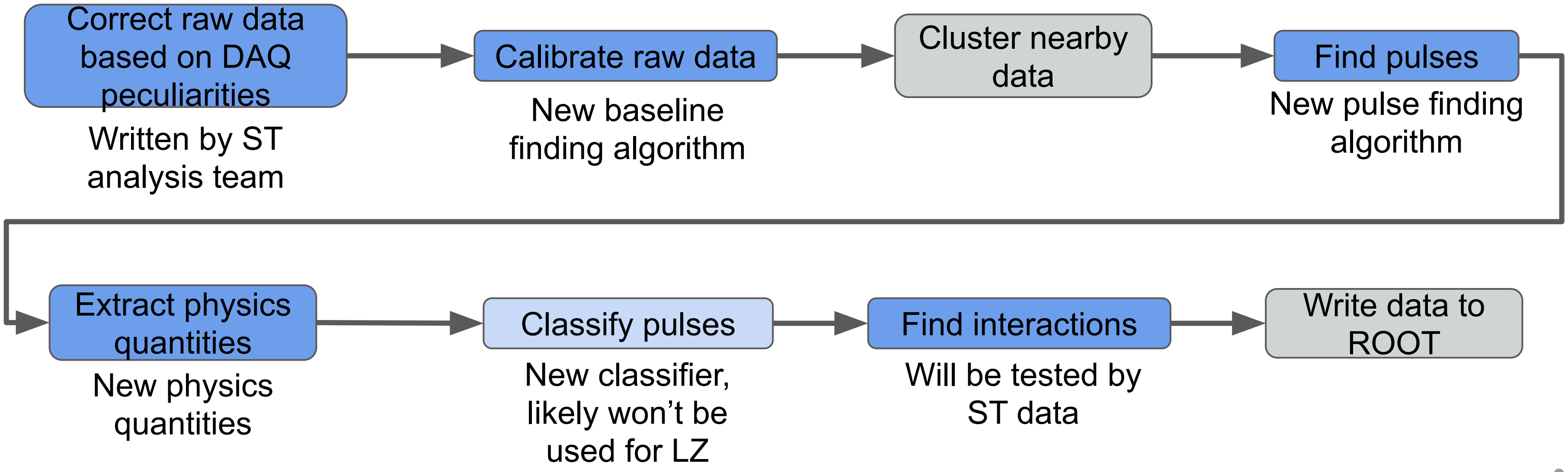
Up to 100kHz of single photons!

- **Field leakage induces drift field even with cathode at 0 V → High rate of SPEs**

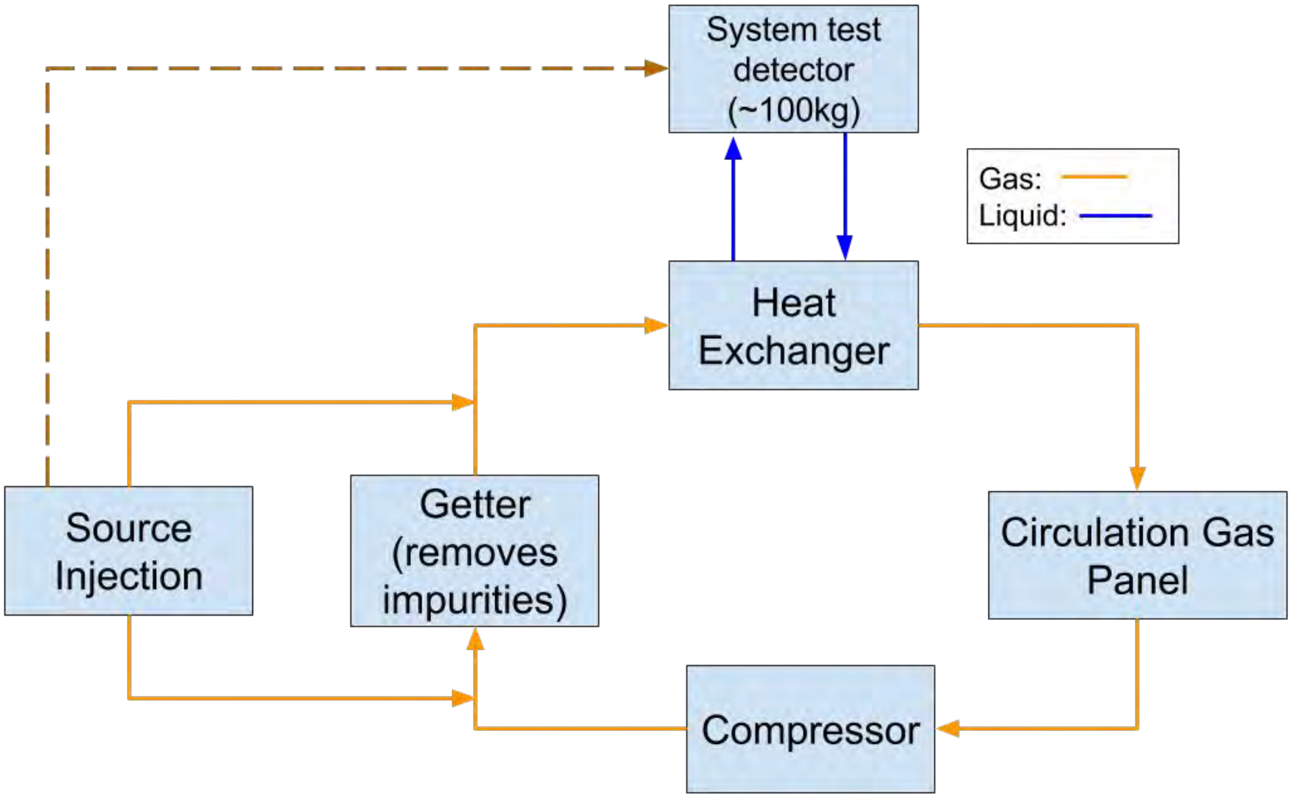
Solution: bias cathode positive

Event Reconstruction - LZap

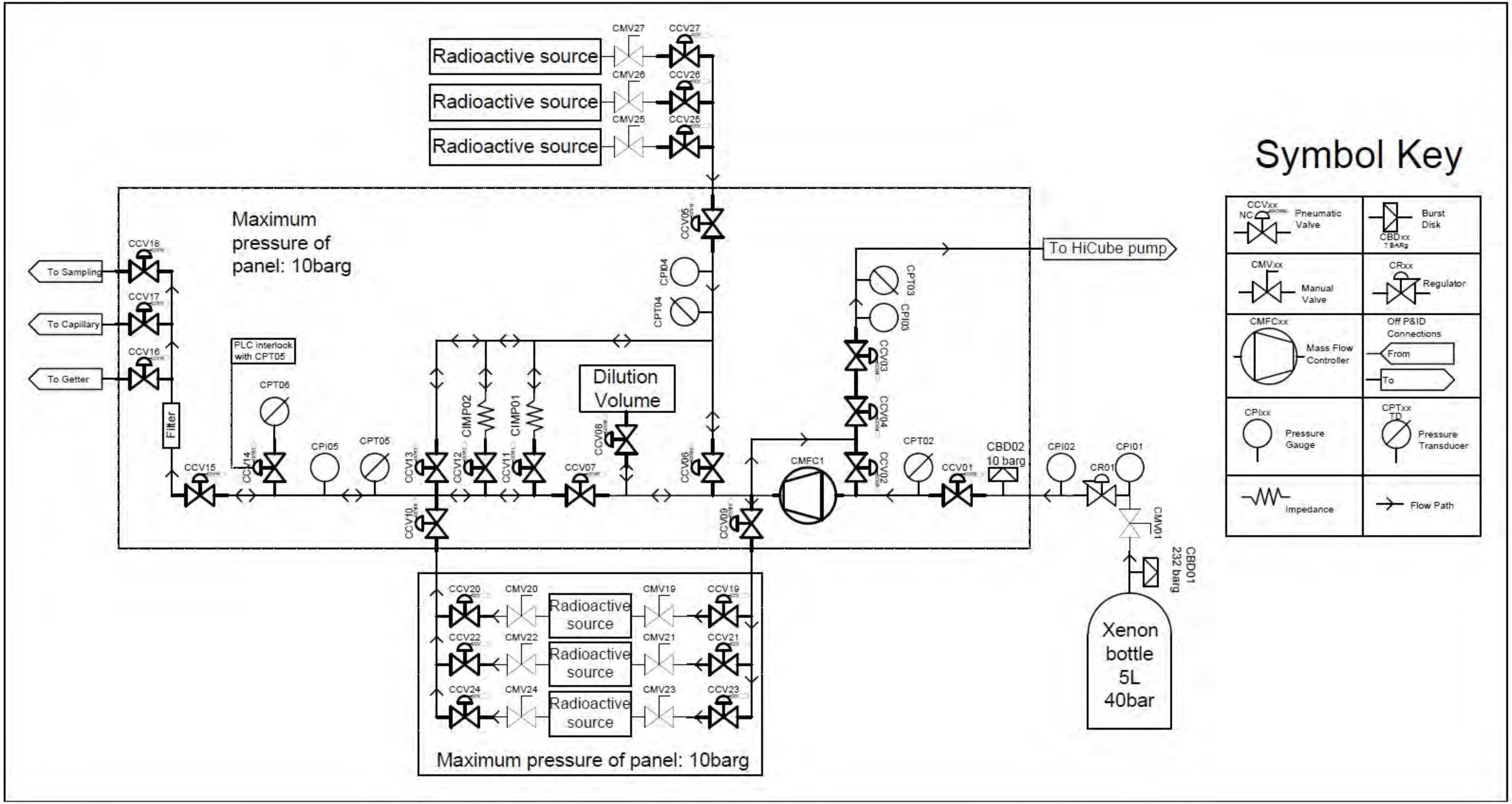
- **LZap = LZ's event reconstruction software**
- **New SUE data necessitates a functional reconstruction chain, many parts created/updated by ST analysis team**
- **First time real data pushed through entire chain**
- **Doing physics with real data before LZ comes online**



Source injection flow path



Source Injection P&ID



Other physics to help inform LZ

Circulation:
Weir height vs. flow rate
Data rates vs. liquid level

High voltage:
Liquid level vs. ΔV, effect on S2 width
Try to reduce single photon emission to below the combined dark rate
Single photon rate vs. ΔV, xy

Physics:
PTFE fluorescence
Calibration sources, energy calibration
Single electron background estimates for LZ (for S2 only search, etc.)

Looking forward...

Grid emission platform coming together to provide test criteria for qualifying grids

What about after LZ deliverable is completed?

➔ Built a robust, complex system

➔ Will be more than just an engineering testbed for LZ

Turn SUE into an R&D platform for LXe measurements

R&D goals may include:

ER/NR discrimination measurements

Effect of impurities

Measurement of Cherenkov light in xenon

And more...