The Dynamic Range of LZ

Jun Yin
For the LZ Collaboration

Department of Physics and Astronomy
University of Rochester, Rochester, NY 14627

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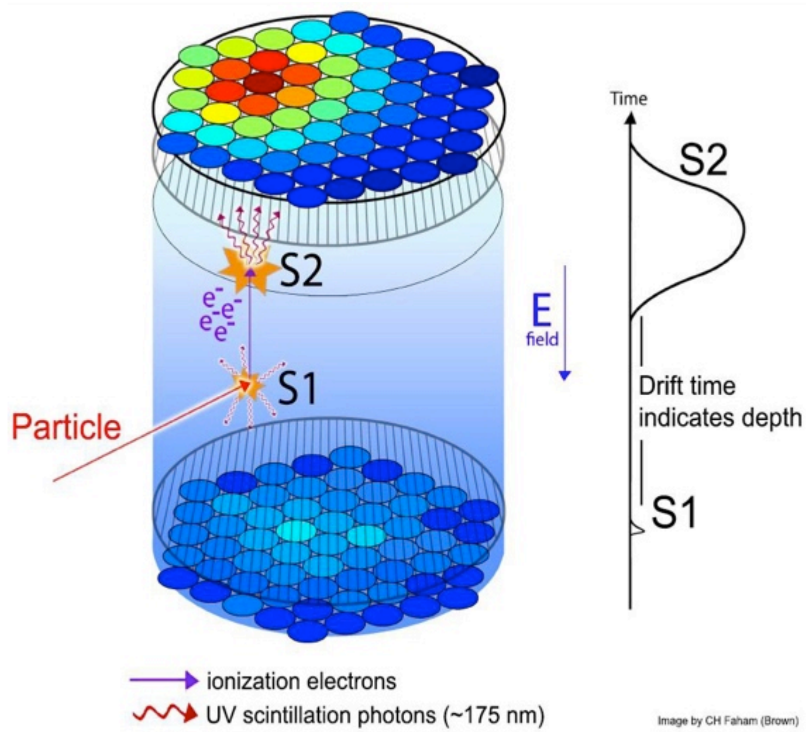
Outline

- Energy and position reconstruction in LZ.
- Factors that limit the dynamic range:
  - PMTs
  - Amplifiers
  - Digitizers
- Assumptions made to estimate the dynamic range:
  - Light yields
  - Ionization yields
  - Light collection efficiency
- Results
- Summary

Energy and position reconstruction in LZ.

- S1 pulse area:
  - Most light is detected with the bottom PMT array.
  - Uniform light distribution.
- S2 pulse area:
  - Most light is detected with the top array.
  - A large fraction of the total light is detected in a single PMT.
  - S2 signals produce a uniform light distribution across the bottom PMT array.
- Position:
  - (x,y) position: center of the S2 light distribution on the top array.
  - z position: drift time between S1 and S2 signals.

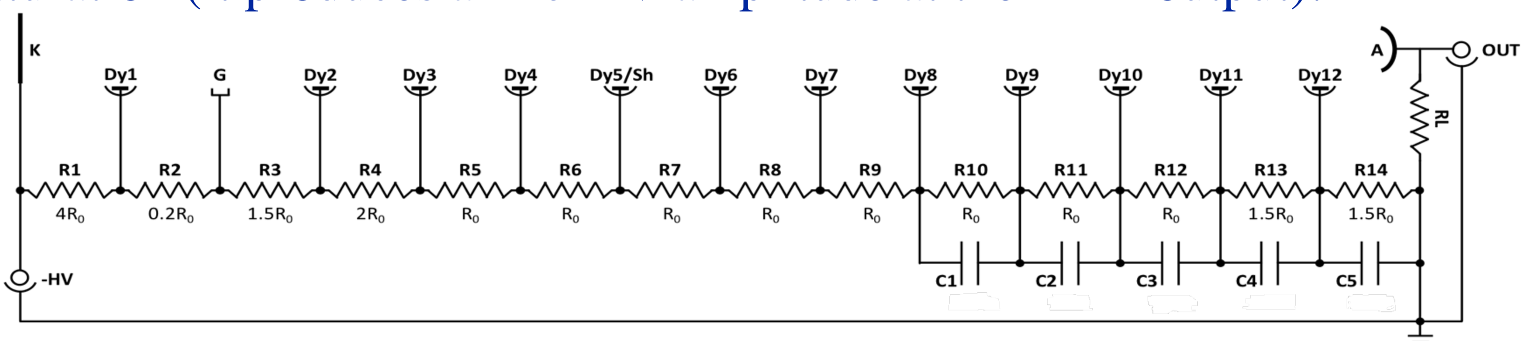


Dynamic range requirements

- Requirements:
  - Provide a 95% detection efficiency for single photoelectrons (SPHEs).
  - Provide the ability to calibrate LZ with a variety of sources:
    - CH_3T: 18.6 keV endpoint (electron-recoil calibration).
    - ^{83m}Kr: 41.6 keV (purity measurements).
    - Neutrons from DD: 74 keV endpoint (nuclear-recoil calibrations).
    - ^{129m}Xe activation line: 236 keV.
  - Good energy and position reconstruction for other possible physics goals and background studies:
    - High energy depositions for decays in the U and Th chains.
    - $0\nu\beta\beta$: 2457.8 keV.

Constraints on dynamic range. PMTs.

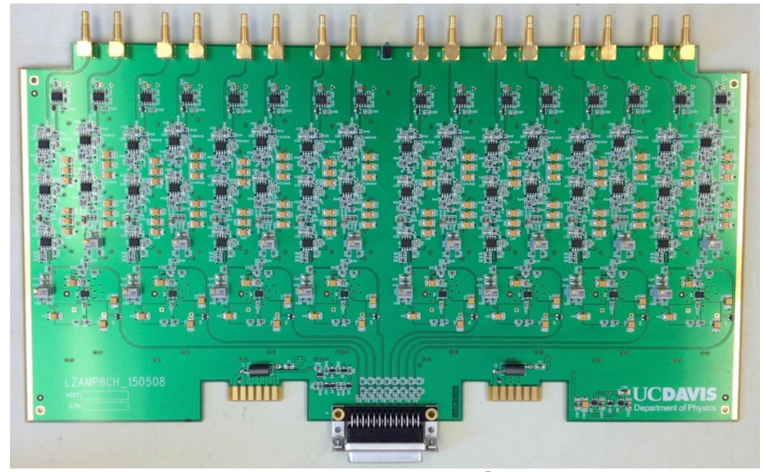
- The LZ PMTs operate with a gain of 3.5×10^6.
- The pulse area of 1 phe equals 28 mV ns.
- Due to attenuation in the internal signal cables, the LZ amplifiers see a pulse area of 23 mV ns for 1 phe.
- By adding capacitors to the last dynode stages on the PMT base, we can assume a linear PMT response except for the very large S2 signals associated with $0\nu\beta\beta$. For these events the response of up to 19 PMTs located above the interaction point will be non-linear.
- A 1 μs square S2 pulse with 15,000 phes can be handled without PMT saturation (it produces a 440 mV amplitude at the PMT output).



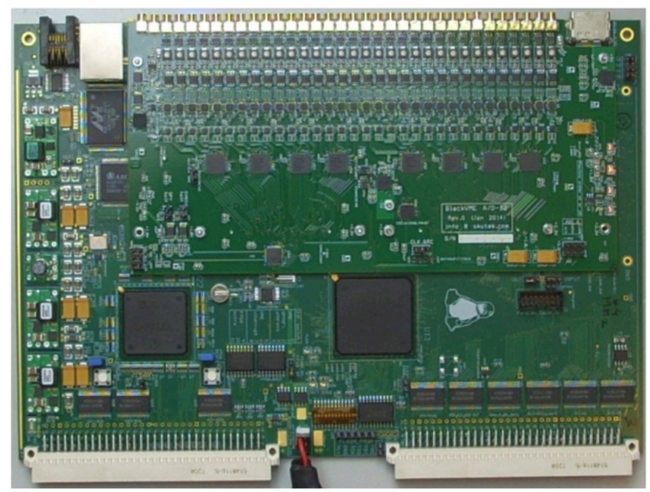
Constraints on dynamic range. Amplifier and Digitizers.

- The LZ amplifiers for the TPC PMTs are dual gain amplifiers.
  - Low-energy channel: 60 ns shaping (FWTM) and area gain of 40.
  - High-energy channel: 30 ns shaping (FWTM) and area gain of 4.
- The amplifier outputs saturate at 2.6 V.

- The ADC in the LZ DAQ system has a 2 V dynamic range.
- Allowing for a 0.2 V undershoot, the effective dynamic range is 1.8 V.
- The digitizers limit the dynamic range of the electronics.



Amplifier developed at UC Davis.



DDC 32 developed in collaboration with skutek.com.

Scintillation and ionization yields.
Noble Element Simulation Technique (NEST).

- The scintillation and ionization yields used to determine the dynamic range were obtained from NEST.
- Numbers used (700 V/cm):

Source	Scintillation Yield (S1)	Ionization Yield (S2)
CH_3T	43 ph/keV	30 e-/keV
^{83m}Kr	39 ph/keV	34 e-/keV
DD	12 ph/keV	3 e-/keV
^{129m}Xe	30 ph/keV	43 e-/keV
0νββ	20 ph/keV	53 e-/keV

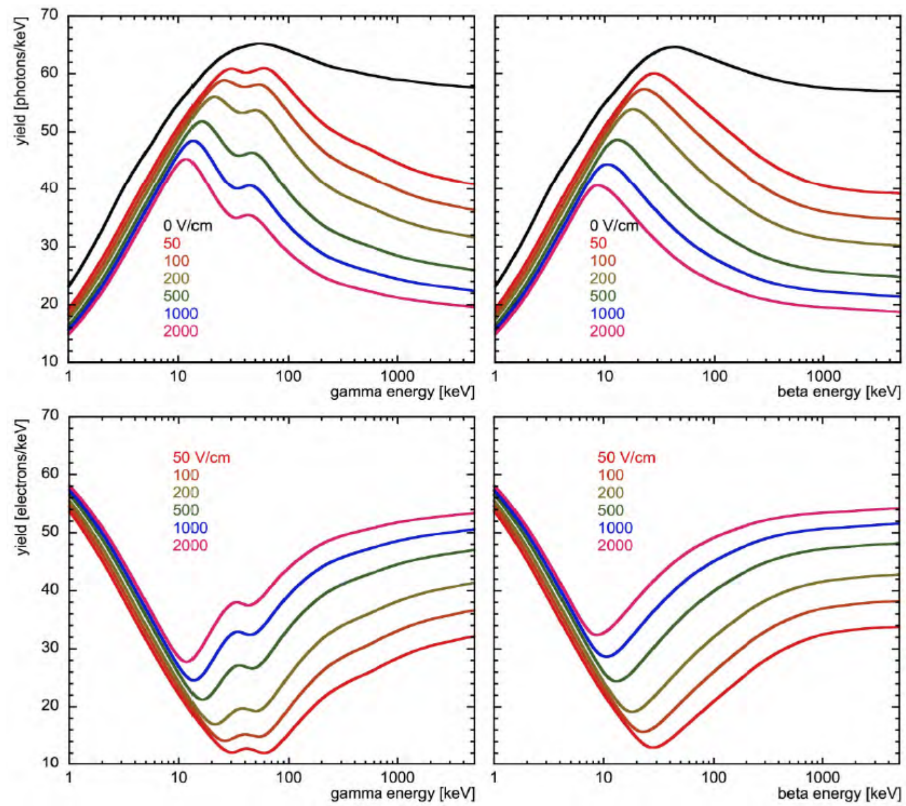


Figure 3.3.1. NEST predictions of light (top) and ionization yields for ERs in LXe, for incident gamma rays (left), and primary electrons (β-particles, δ-rays) (right) [30]. Increasing the electric-field strength reduces recombination, raising the charge yield at the expense of light. The dip in the gamma-ray curves is due to the Xe K-shell X-ray that creates a second interaction site, displaced from the initial energy deposition.

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S1 dynamic range. Assumptions made

- The average photon detection efficiency (fraction of UV photons that produce photoelectrons in any of the LZ PMTs) is 7.5%.
- Two different calculations are carried out to determine the pmt with the maximum number of phes:
  - Assume that 80% of S1 light is detected with the bottom PMTs and assume a uniform light distribution across that array. Fraction of photoelectrons in one bottom PMT = 0.075*0.8/241 = 0.025%
  - Assume the interaction happens 1 cm above the cathode: Largest fraction of photoelectrons in one bottom PMT = 0.4%.

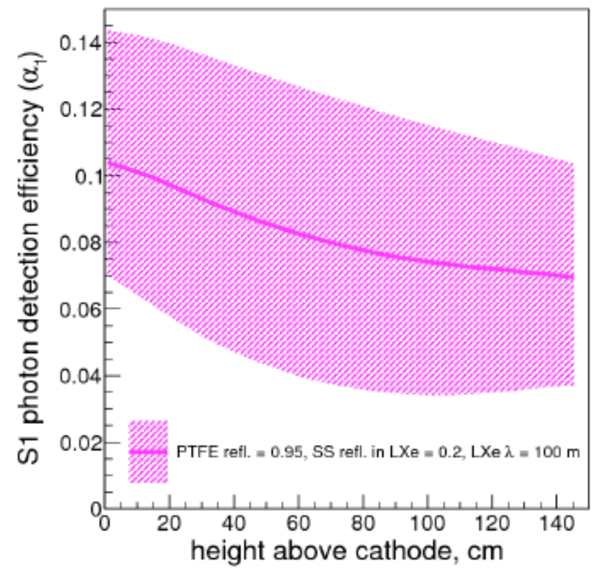

Figure 3.4.3.1. Simulated S1 photon-detection efficiency as a function of distance from the cathode for three light-collection scenarios, averaging 4.4% (lower bound), 8.3% (line), and 12.5% (upper bound). Varied parameters are the PTFE and grid reflectivities and the photon absorption length; the number of PMTs (488) and their QE at 178 nm (25%) is the same in all cases. The baseline assumed for sensitivity calculations is α_1=7.5%, with 5.0% and 10% also assessed to represent pessimistic and optimistic scenarios.

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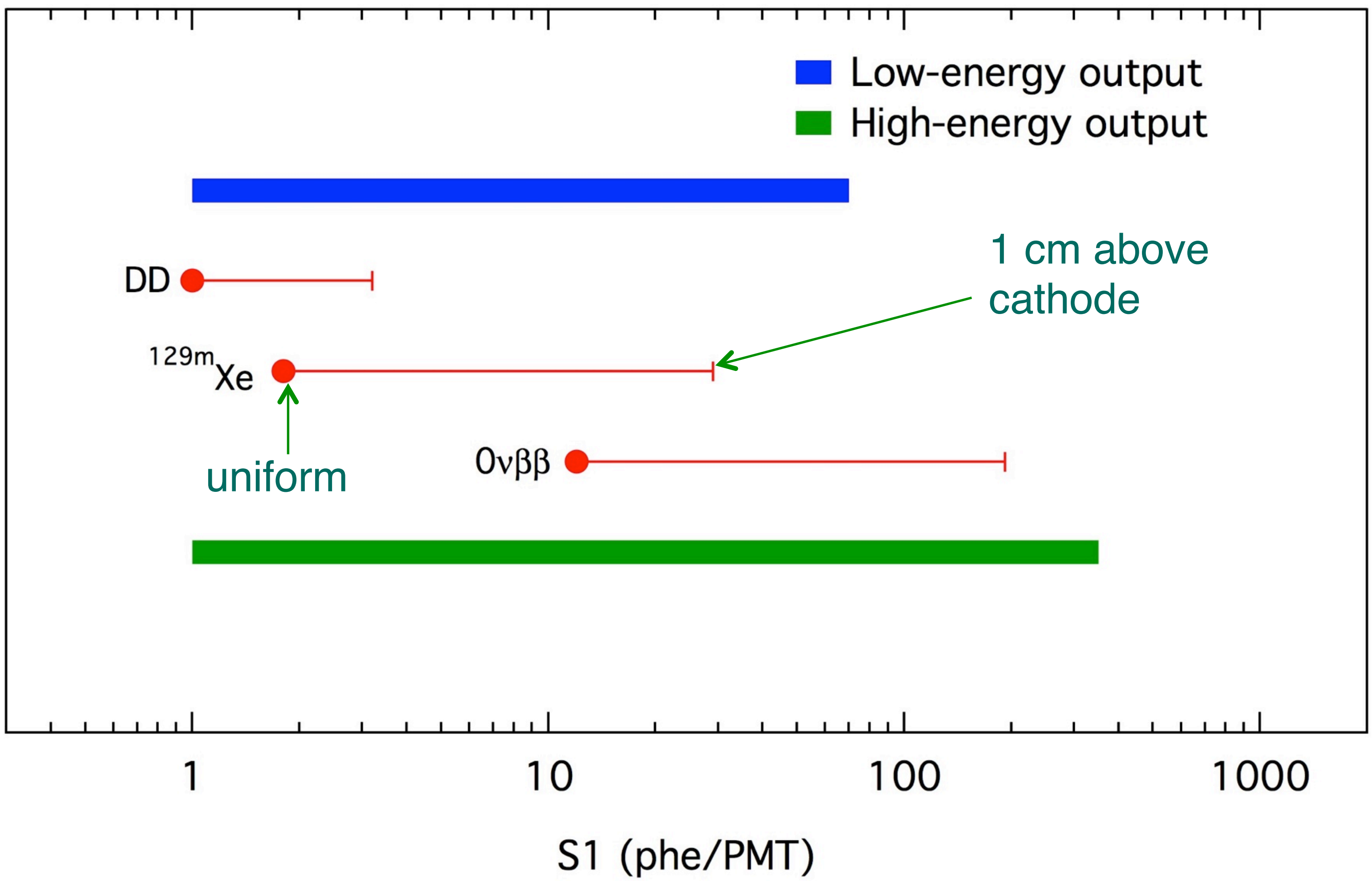
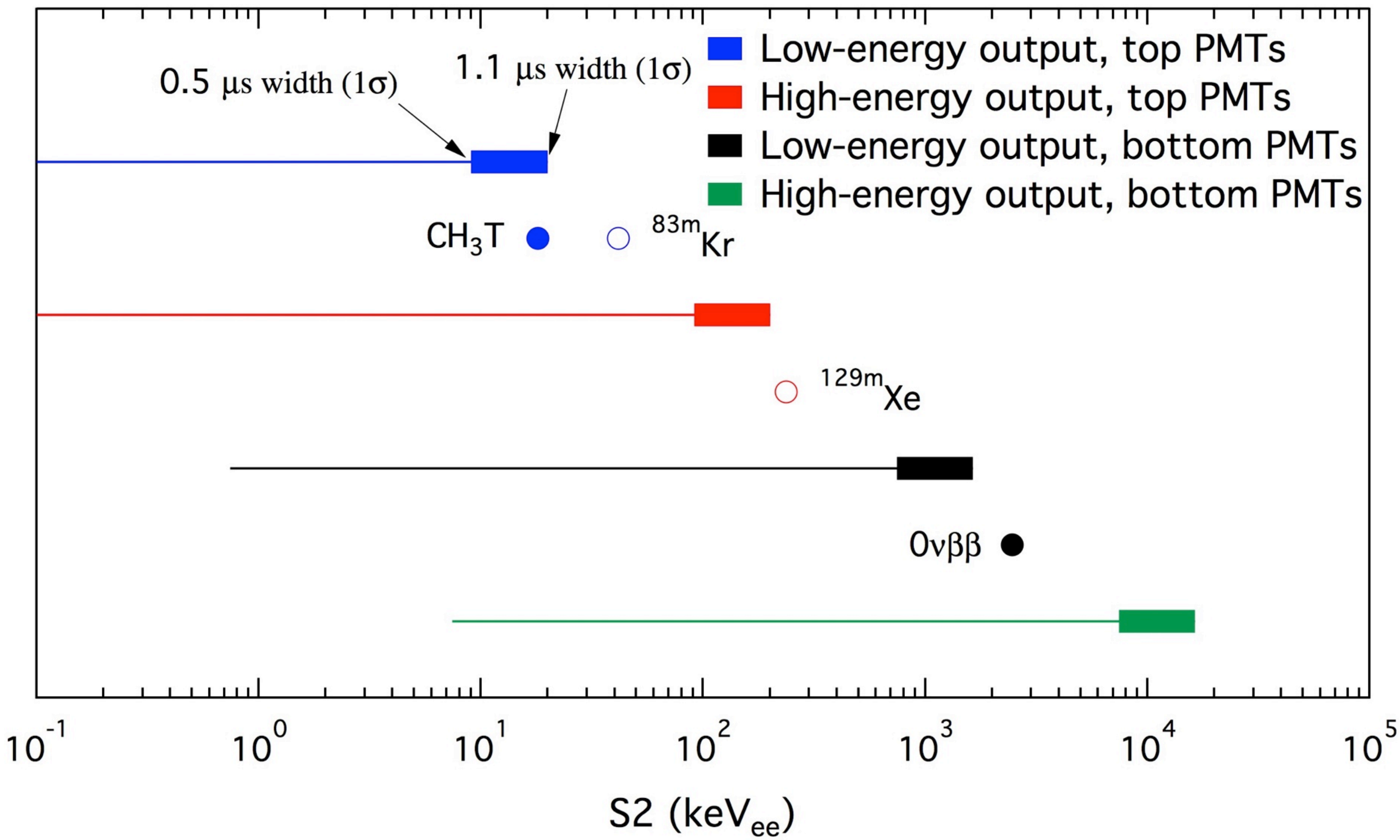
S1 dynamic range at 700 V/cm.



Dynamic range S2. Assumptions made.

- The photon yield is 500 photons/ionization electron (e-).
- The ionization electron yield is 27 e-/keV (at low energies) – 55 e-/keV (at high energies).
- Assume 100% extraction efficiency.
- The light detected on the top array is concentrated in a single PMT. The photon detection efficiency in this PMT is 2%.
- The total S2 pulse area can be reconstructed on the basis of the bottom light only (this provides the largest dynamic range).
- The position reconstruction requires the distribution of S2 light on the top array (this constrains the dynamic range).
- The dynamic range also depends on S2 width (depth dependent).

S2 dynamic range at 700 V/cm.



Conclusions

- The dual-gain design of the LZ electronics allows us to optimize the dynamic range for the smallest energy depositions and at the same time be sensitive to large energy depositions (e.g. $0\nu\beta\beta$).
- Saturation:
  - For the low-energy channels: the digitizers saturate before the PMTs saturate.
  - For the high-energy channels: the PMTs saturate before the digitizers saturate.
- The dynamic range for S1 signals accommodates energy depositions up to the endpoint of $0\nu\beta\beta$.
- The dynamic range for S2 signals, based on the response of the bottom PMTs , accommodates energy depositions up to $0\nu\beta\beta$.
- The dynamic range for S2 signals observed with the top PMTs is limited by saturation in the PMTs. This impacts position reconstruction for large energy depositions.

BACKUP SLIDES

Nuclear Recoils

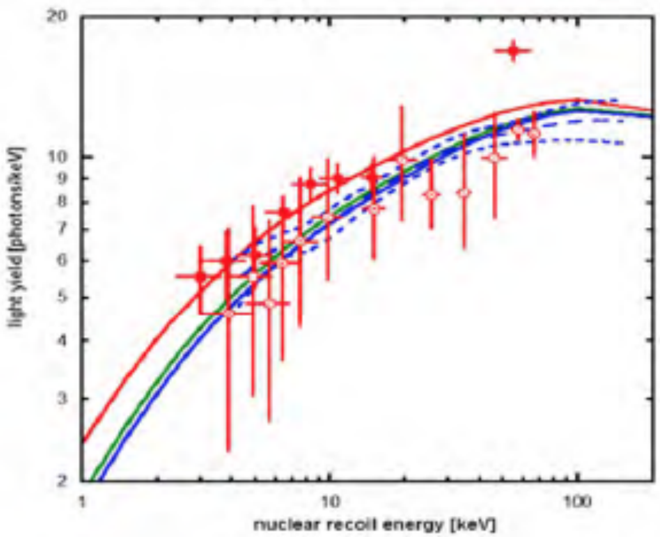


Figure 3.3.2. Absolute NR scintillation yield in LXe. Hollow red markers are from neutron-beam measurements at Yale [35] and filled markers from [36] — both at zero field. Blue dashed lines are the combined mean and 1-σ curves from two in situ measurements with Am-Be neutron sources via fitting to MC simulation from ZEPLIN-III [37] (3,650 V/cm). The NEST model [32] is shown in red, green, and blue for zero field, 700 V/cm (LZ baseline), and 3,650 V/cm, respectively. The green curve conservatively zeroed below 3 keV is used for LZ sensitivity calculations.

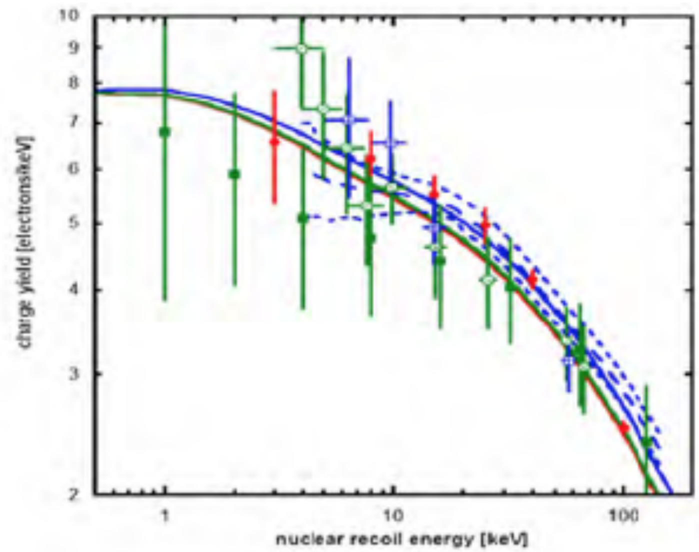


Figure 3.3.3. NR ionization yield in LXe. Data are as follows: blue and green hollow squares from neutron beam data from Yale at 4 kV/cm and 1 kV/cm, respectively [35]; dashed blue curves from Monte Carlo matching from ZEPLIN-III [37] at 3,650 V/cm; solid green squares from XENON10 at 730 V/cm [38]; red markers from XENON100 [39] at 530 V/cm. The NEST prediction [32] is shown in red, green and blue for 530 V/cm, 700 V/cm (LZ baseline) and 3,650 V/cm, respectively. The green curve is used for LZ sensitivity calculations.

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S2 Width and Gain.
Different operating conditions.

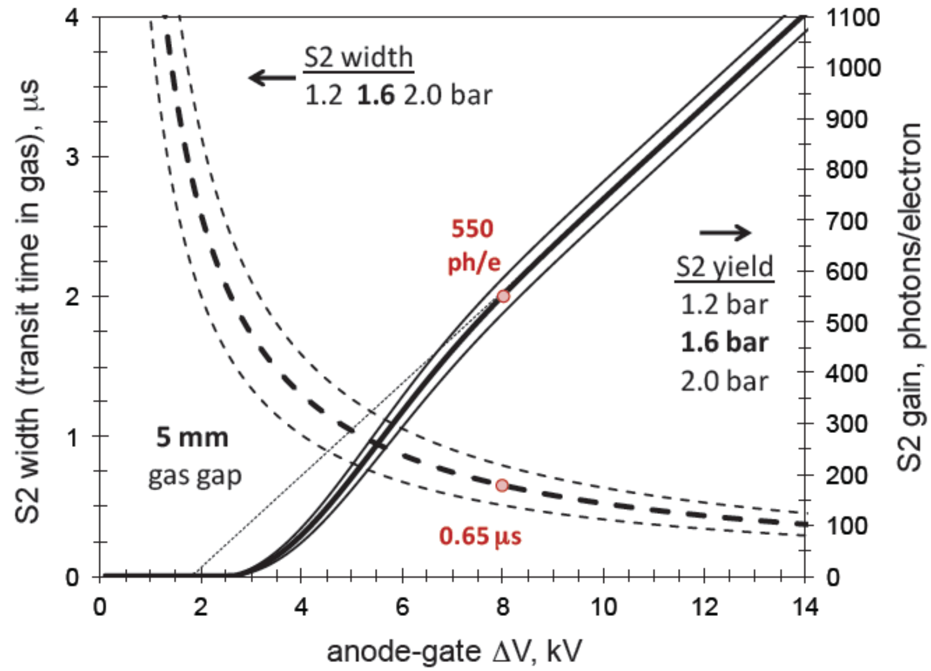

Figure 6.6.1. Dependence of the S2 photon yield and S2 pulse width (for emitted electrons, i.e., ignoring longitudinal diffusion in the liquid) on the voltage between anode and gate electrodes. At the nominal ΔV=8 kV, the photon yield [18], including the electron emission probability [19] and the electron transit time in the gas phase (S2 pulse width) [20] (for operating pressures around the 1,6 bar nominal and a gas gap of 5 mm) are shown.

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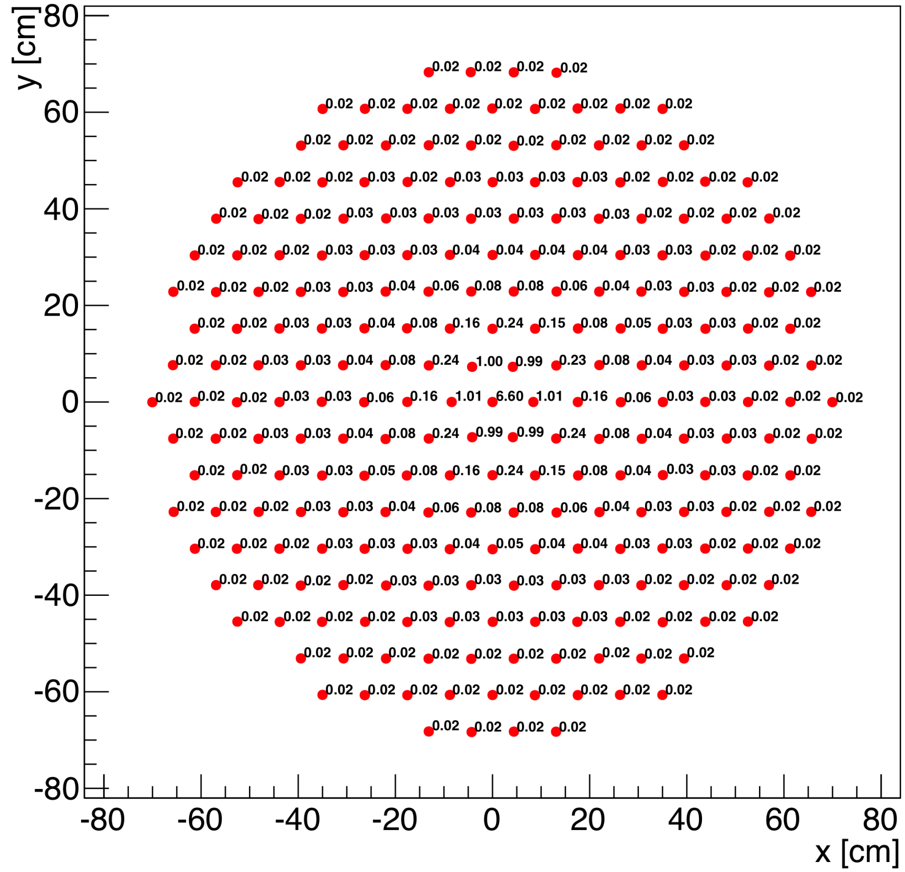
S2 Top Array



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y [cm]
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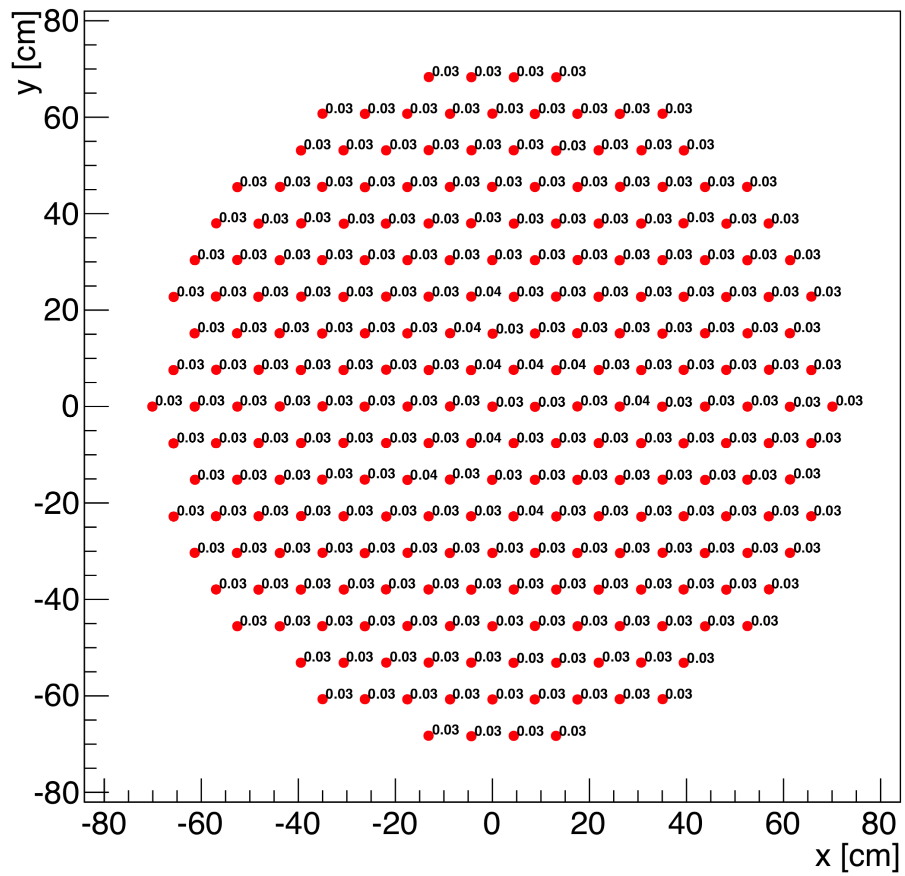
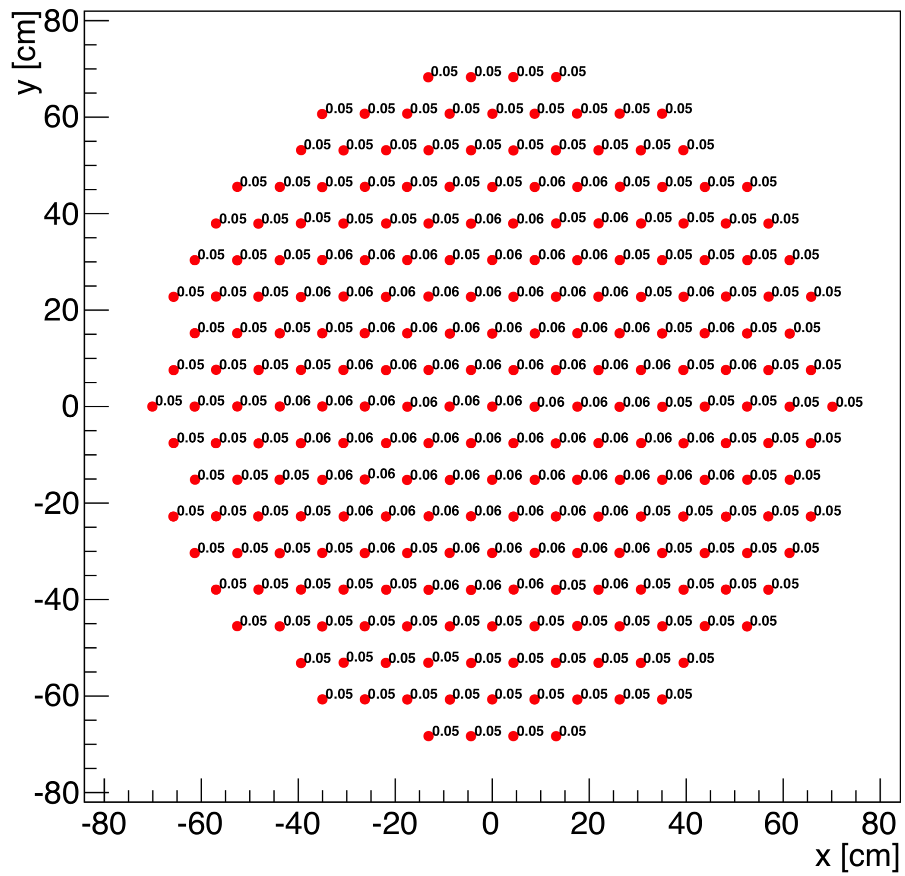
x [cm]

S2 Bottom Array



S1 Bottom Array
(1 cm below gate)



S1 Bottom Array
(1 cm above cathode)