IMPERIAL

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Flex-cable readout for XLZD Skin Detector and beyond

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Introduction

XLZD will instrument the TPC and the Skin with photosensors requiring large channel count.

Cabling/interconnect solutions must comply with extremely low radioactivity budget, minimal radon outgassing, and low signal loss.

Coaxial cables have very low attenuation (~0.5 dB/m @ 100 MHz) [1] —
potential for higher radioactive backgrounds and installation challenge within the Xenon detector

Copper–Kapton flex-cable transmission lines are a viable alternative:

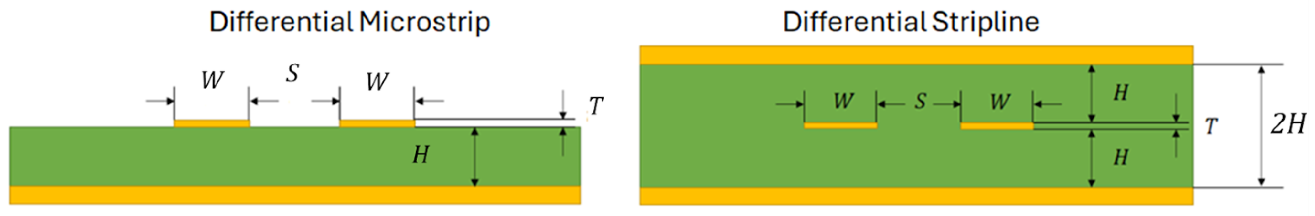
- high trace density
- potential for ultra-low radioactivity

Flex cables are more lossy —

- careful geometry optimization to minimize attenuation
- prototyping to test signal integrity over ~15–20m runs

Flex-cable design

Pulse shape modifications in transmission lines →
Loss – attenuates amplitude via conductor/dielectric dissipation
Dispersion – broadens pulses via frequency-dependent speed (negligible for XLZD)



Differential microstrip and stripline modes – *can be an option for transmission line study*

Differential topologies – tight line coupling for common-mode noise rejection and precise impedance control via trace width/spacing.

Do we need differential readout? Can microstrip/stripline design work?

Stripline mode – embedded between reference planes

- confines fields in a homogeneous dielectric
- ~4× thicker substrate vs. microstrip mode to achieve similar attenuation – higher radioactivity and manufacturing challenge

Path forward → microstrip design with adhesiveless-coverlay (asymmetric stripline) could be the optimal compromise.

Radioactivity & manufacturing

nEXO collaboration have developed an extremely low-background flex-cable with a US-based supplier → path to achieve low radioactivity cables is clear

Radioactivity comparison of custom cables used in low background rare event experiments [2].

Cable	Copper layers [μm]	Polyimide layers [μm]	Coverlay	Surface finish	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
nEXO SiPM	**18 (x2)**	**50.8 (x1)**	**No**	**No**	**20 ± 2**	**<12.3**	**40 ± 12**
nEXO SiPM [Com.]	18 (x2)	50.8 (x1)	No	No	1300-6200	16-63	
DAMIC-M CCD	**18 (x2)**	**50.8 (x1)**	**x2**	**ENIG**	**31 ± 2**	**13 ± 3**	**550 ± 20**
DAMIC-M CCD [Com.]	18 (x2)	50.8 (x1)	x2	ENIG	2600 ± 40	261 ± 12	170 ± 50
EXO-200 [3, 12]	18 (x1)	25.4 (x1)	No	No	412 ± 47	<117	
EDELWEISS III [7, 14]	18 (x4)	25/125 (x3/x4)	No	No	650 ± 490	3700 ± 2500	2100 ± 840
DAMIC at SNOLAB [4]	18 (x5)	25.4 (x4)	x2	ENIG	4700 ± 400	790 ± 120	940 ± 60

QFlex are the frontrunners for flex cables due to low-radioactivity capability.

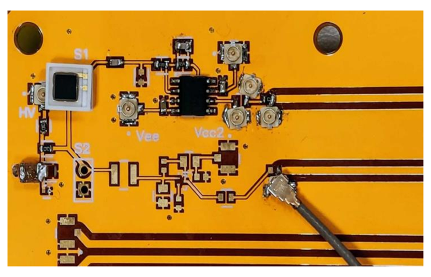
Fralock (US) and Amphenol (UK) are potential suppliers for long flex-cables.

Newbury (UK) have fabricated 1.5m long prototypes → tests ongoing at Imperial.

Prototype testing at Imperial

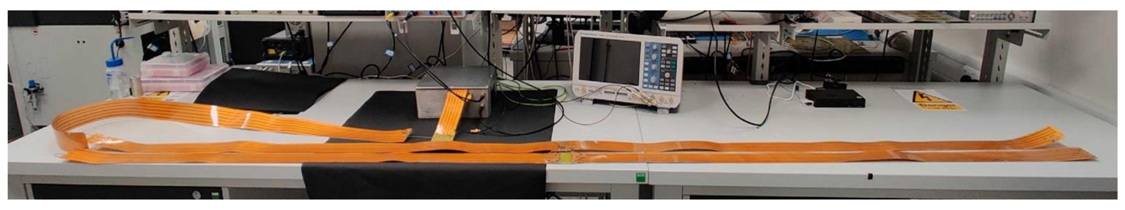
Newbury prototype designed as microstrip, with Kapton coverlay:

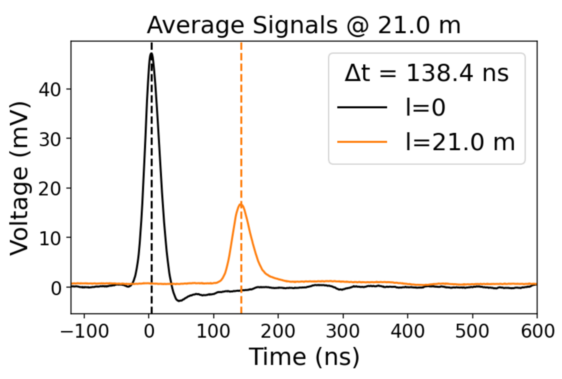
- 50 μm substrate thickness
- 1.5m long; 1mm trace width (W) and spacing (S)
- evaluated component assembly challenges on thin flex, signal loss, and high-voltage performance

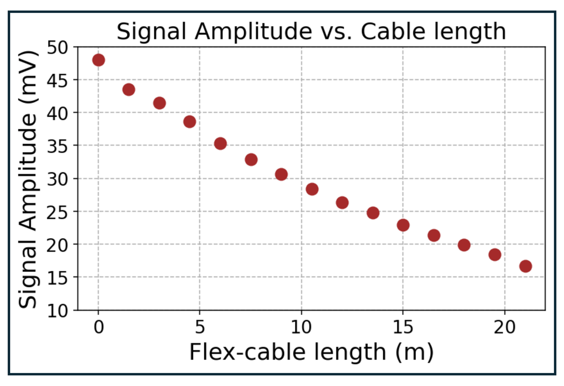


SiPM amplifier component assembly on 50μm flex

Prototype 21m test cable setup – 1.5 m segments joined together with surface-mount coaxial connectors

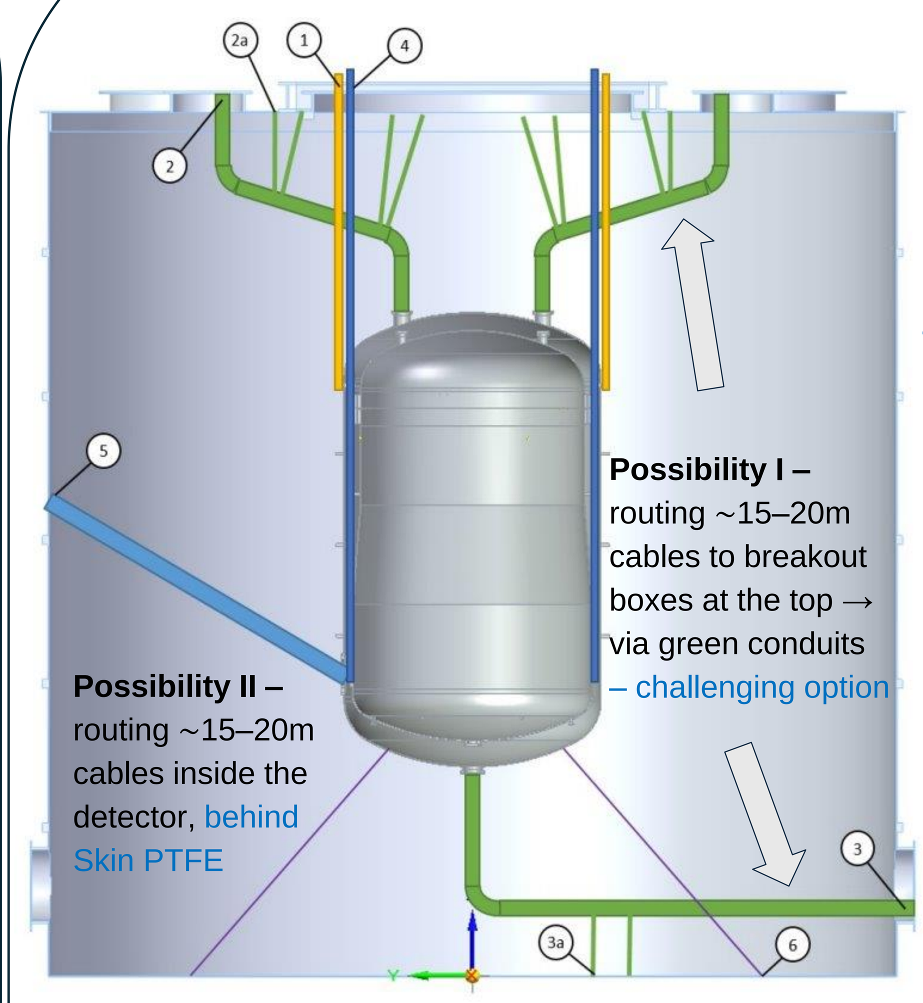






Signal amplitude vs. distance tested with an amplified SiPM signal → ~x3 voltage loss over ~20m at our limited bandwidth (<100 MHz) – better than expected!

Cabling challenges



Requirements:

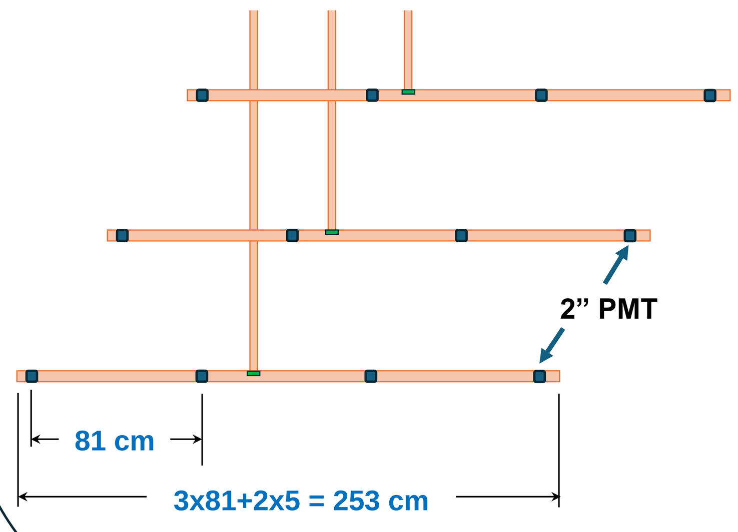
~15–20m cable lengths
Low-loss photosensor signal transmission

- requirements assuming LZ front-end performance
- prototyping w/21.5m flex

Ease of integration
Ultra low-radioactivity

Recent XLZD integrated CAD model. Tank dimensions – 12m dia; 12m tall.

36 2" PMTs split across three rows along Skin height



For details on Skin PMT geometry: see poster on optical simulations by Tim Marley

Possible Skin flex-cable routing option

- 4-PMT flex-cables → 9x ~2.5-m long cables + 9x long cables to breakout boxes
- All 9 cables with same design
- Group of 3 tapes emerge at the top; spanning 81 cm, at three ICV locations

Signal propagation and front-end electronics

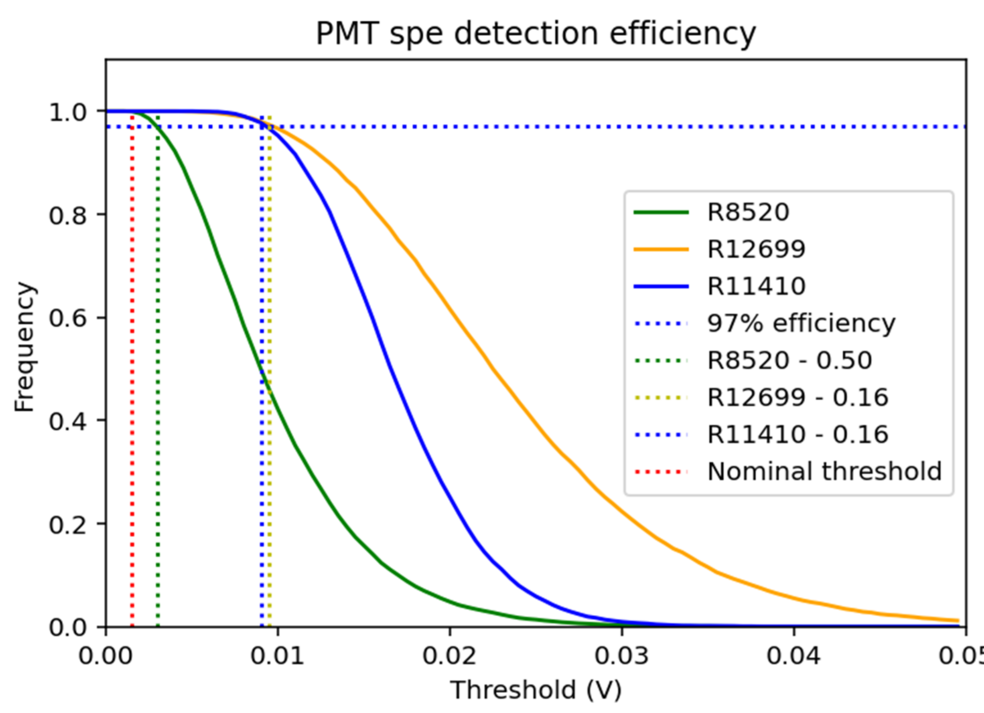
PMT signals travel ~15–20m to FE electronics.
FE modules perform amplification and shaping
Shaping (LZ [3]): gaussian amplifier, 60 ns FWTM, ×40 area gain
Digitization: 100 MHz sampling rate
Noise floor: ~0.3mV (1σ) at DAQ input

These specs define maximum tolerable cable attenuation to check if cold pre-amplification is needed.

Simulation & optimization pipeline

- PMT signal generation: realistic time-domain pulses (shape, transit time & spread, gain, load, SPE resolution)
- FFT: convert to frequency domain
- Attenuation: apply frequency-dependent losses
- IFFT: attenuated waveform in time domain
- Shaping amplifier [3]: gaussian filter (60 ns FWTM, ×40 gain) to maximize S/N.
- Noise injection: add gaussian noise (0.3 mV; 1σ) to simulate the real LZ performance.
- ADC sampling: 100 MS/s after sample & hold
- Statistical analysis: histogram signal and noise over many trials to evaluate baseline and resolution
- POD threshold: 1.5mV to limit false SPE rate

Simulation results



Fraction of individual spe signals above threshold for each of the PMTs, as a function of 'effective' threshold

Attenuation assessment: the 97% efficiency line marks the "effective threshold" where the detection efficiency falls below the target efficiency requirement.

Allowed loss budget: comparing this point to the nominal threshold yields → ×2 voltage reduction for the R8520 (1") PMT and up to ×6 for R12699 (2") / R11410 (3") PMTs.

Flex-cable requirement: these limits define the flex-cable attenuation budget over ~20 m w/o needing cold pre-amplification.

Conclusions & next steps

- ~20m flex-cable prototype tested with representative pulse signals, demonstrating low loss at our limited bandwidth (<100 MHz). Based on performance, flex cables look usable with R12699 (2") and R11410 (3") PMTs, without the requirement of cold pre-amplification. 1" PMT performance is borderline.
- Design an optimized prototype for the proposed Skin cable-routing configuration, including connectors and PMT bases for testing at low-temperature.
- These conclusions naturally apply to the TPC readout. A technical note will be available soon.

References
1. Waldron, W, PMT Cable Evaluation, 10/10/2016 - LZ PPT presentation.
2. Arnquist et al (nEXO), Ultra-low radioactivity flexible printed cables, EPJ Techniques & Instrumentation 10, 17, 2023 [2303.10862].
3. Aalbers, J. et al., The data acquisition system of the LZ dark matter detector: FADR, *Nucl. Instrum. Meths*. 1068 (2024) 169712.