Developing high-bandwidth digital data transmission for next-generation $0\upsilon\beta\beta$ detections

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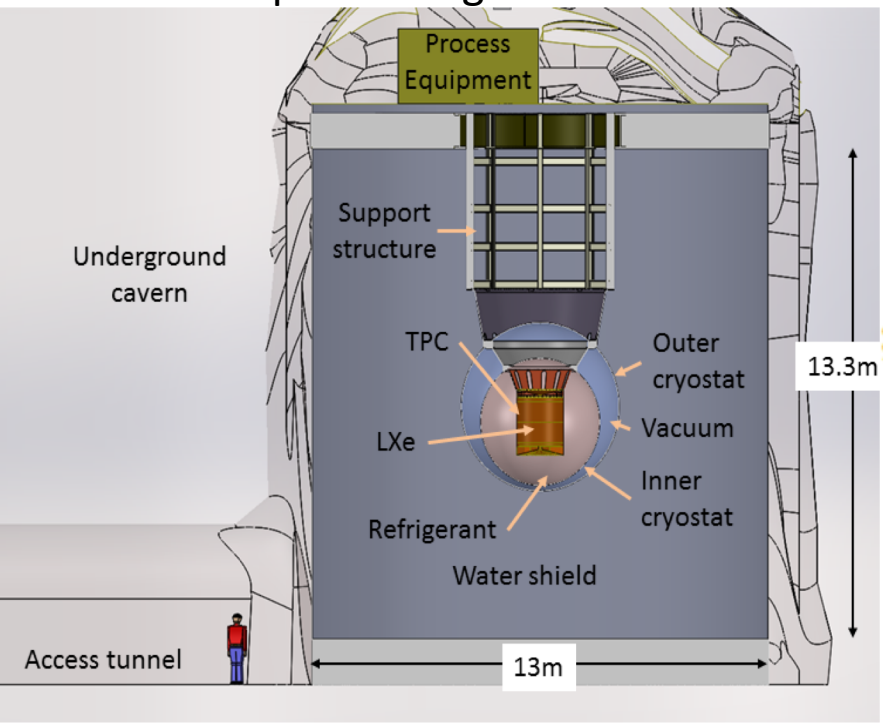
nEXO – the next generation tonne-scale LXe detector

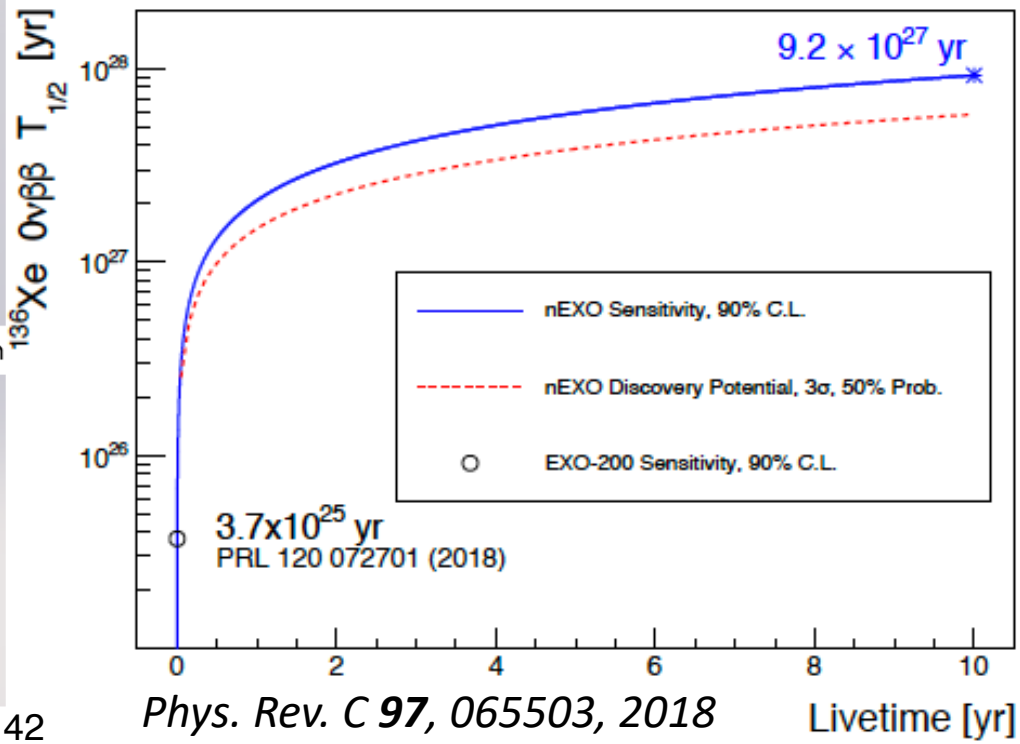
- nEXO is a next generation neutrinoless double beta decay ($0\upsilon\beta\beta$) experiment aimed at reaching half-life sensitivity of 10^{28} yr
- Electronics in the detector will transmit high-speed digital signals from ~10k sensors
- Aim to develop ultra-low radioactivity, high-bandwidth interconnections, with **broad applications to next-generation rare event searches.**

Conceptual design of nEXO



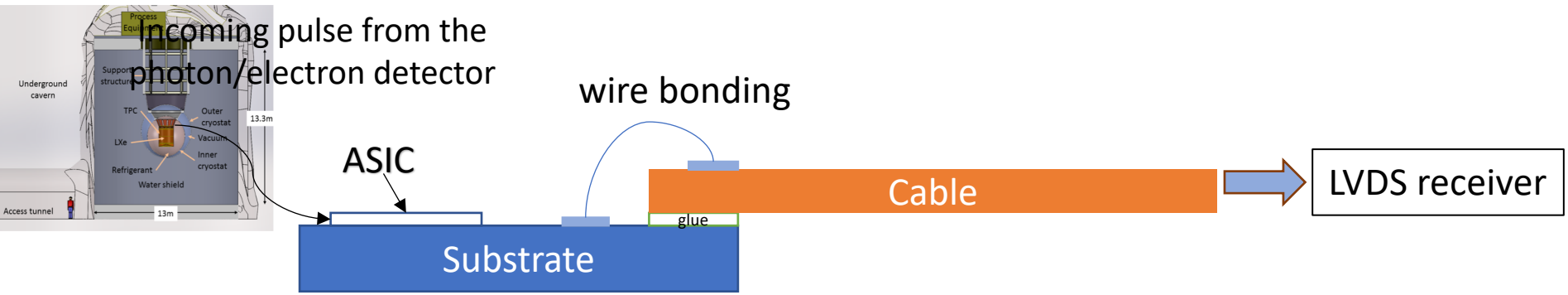
nEXO Pre-Conceptual Design Report, arxiv:1805.11142

Sensitivity of nEXO detector



*Phys. Rev. C **97**, 065503, 2018*

nEXO interconnection design

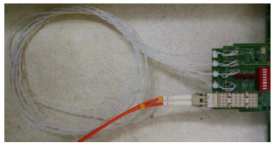


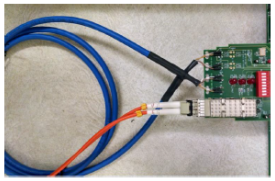
So far there has been no commercial high bandwidth digital cable which has low enough radioactivity for use.

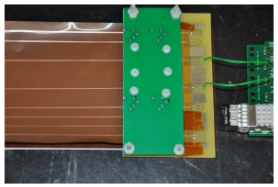
The instrument we are going to develop consists of:

- *An Application-specific integrated circuit (ASIC) developed for nEXO*
- *2m Copper microstrip transmission lines on a Kapton substrate*
- *Warm and cold feedthroughs for the cables transitioning from the liquid xenon volume to the cryostat*

nEXO cable choice



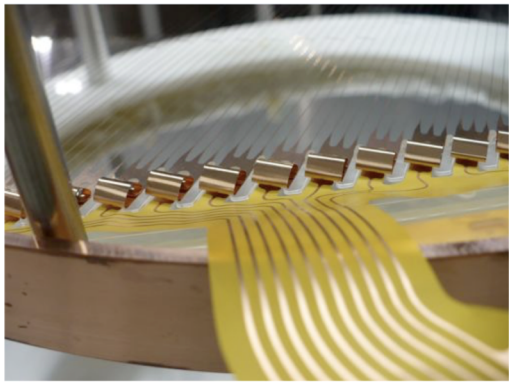




Wire	U-238	Th-232	K-40	Background contribution to ROI
Cat 5 Ethernet	-400+/- 400 ppt	1750+/- 1000ppt	-5000+/-2500 ppb	100%
Gore (Germany)	-10+/- 30ppt	-108+/- 80 ppt	-90/+ 140 ppb	~75%
Flex cable (Cu/Kapton)	161+/- 3 ppt	25+/- 1.5	<210	~10%

The choice fell on flat cables for the following reasons:

- **They have largest bandwidth per unit radioactivity compared to twisted pairs of wires used in Ethernet, etc.**
- **Minimize space behind the charge collection planes required for routing**
- **Low background vacuum feedthrough for flex cables was demonstrated in EXO-200**



Flexible cables of EXO-200

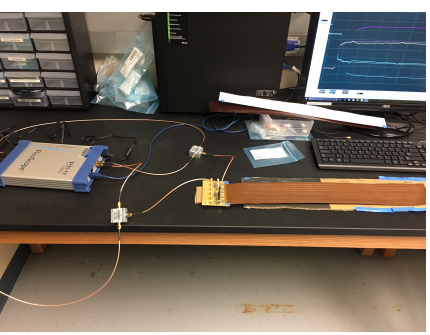
JINST 7 (2012) P05010

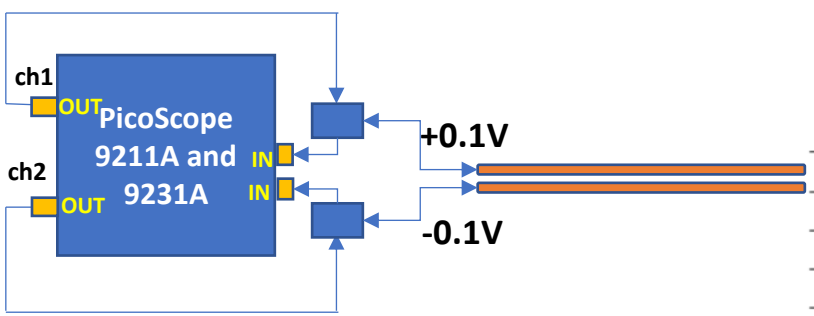
Cable impedance measurement

❖Geometry of the microstrip line cables under test:

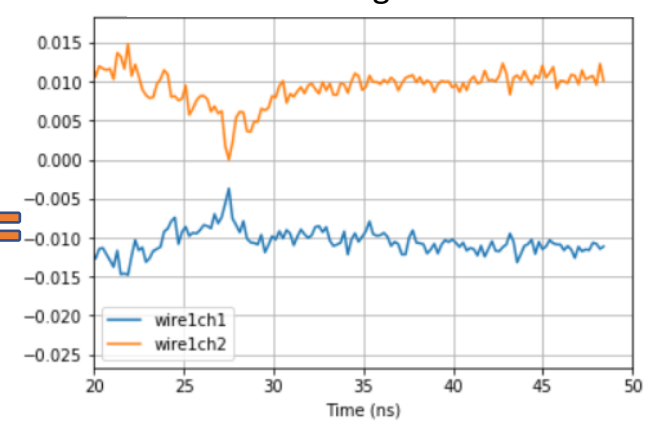
Cable Index	Trace length	Trace width	Trace thickness	Trace spacing	Kapton thickness
Wire 1	1023 mm	0.165 mm	0.025 mm	0.277 mm	0.05 mm
Wire 2	1543 mm	0.165 mm	0.025 mm	0.277 mm	0.05 mm
Wire 3	2049 mm	0.165 mm	0.025 mm	0.277 mm	0.05 mm

❖TDR (Time Domain Reflectometry) measurement setup:



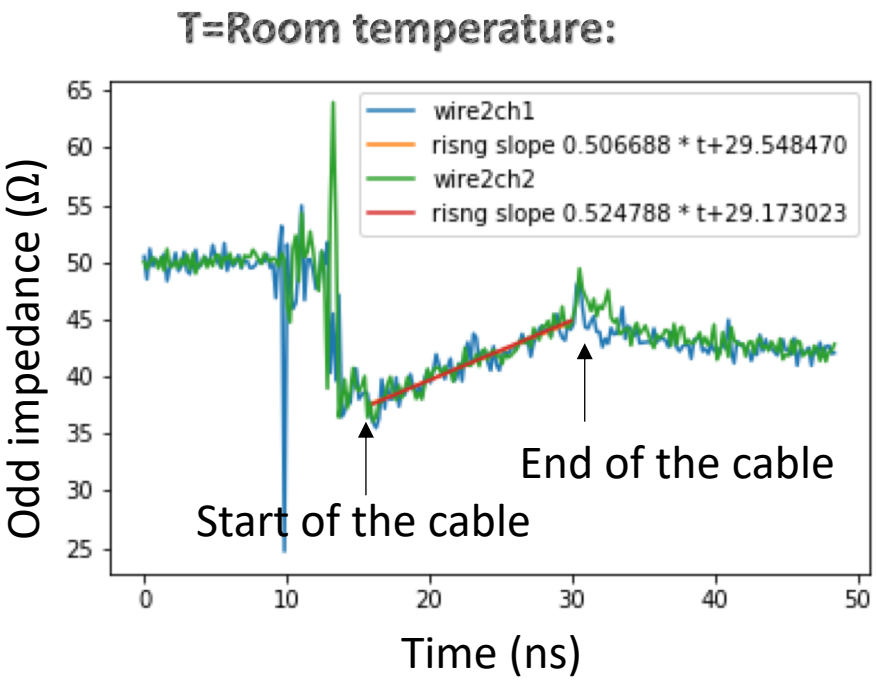


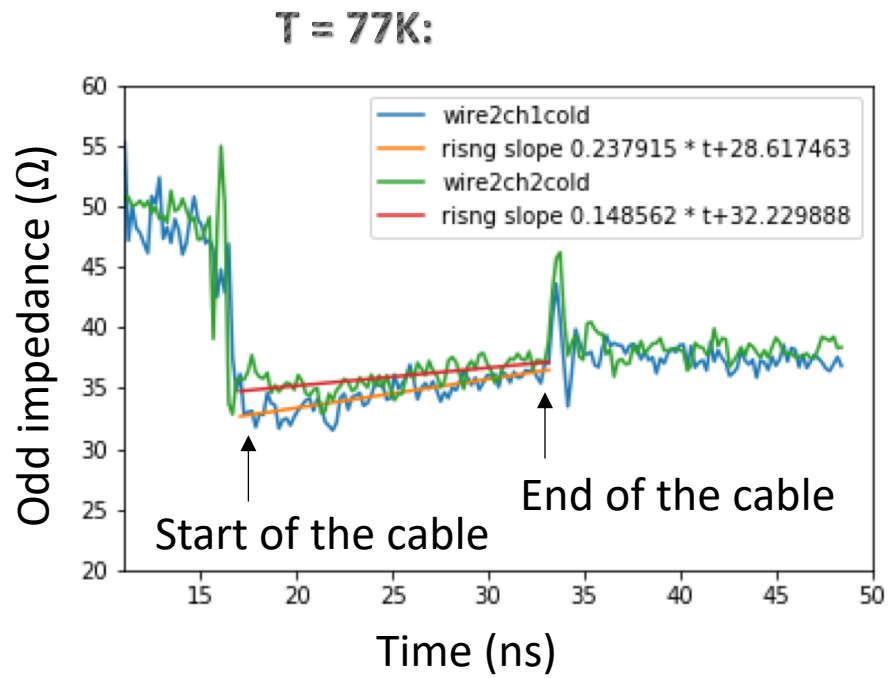
Reflected voltage vs. time



$Z = Z_0 \frac{1+\rho}{1-\rho}$ (Z is impedance under test, Z_0 =50Ω), $\rho = \frac{V_r}{V_o}$ $\left(\frac{reflected\ voltage}{input\ voltage}\right)$

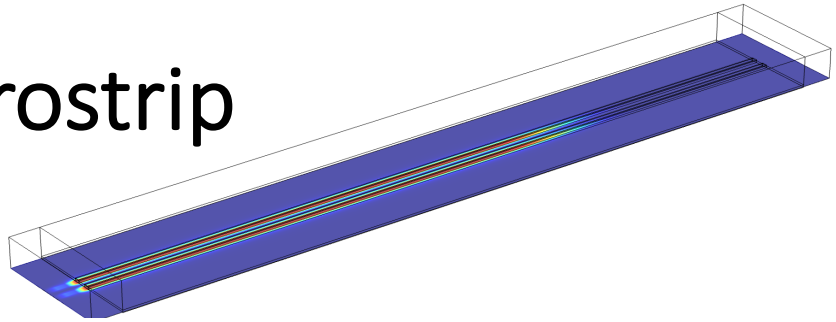
TDR measurement of prototype cables





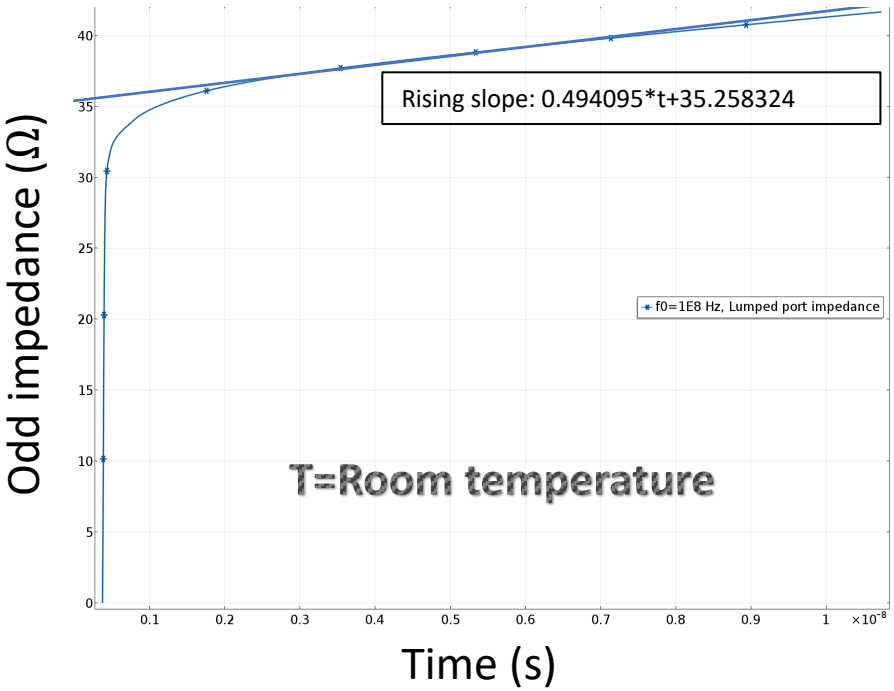
- The measured impedance agrees with the theoretical calculation of coupled microstrip lines of this geometry
- Calculation shows the slope observed in the TDR measurement is mainly caused by resistive loss

COMSOL simulation of microstrip line impedance

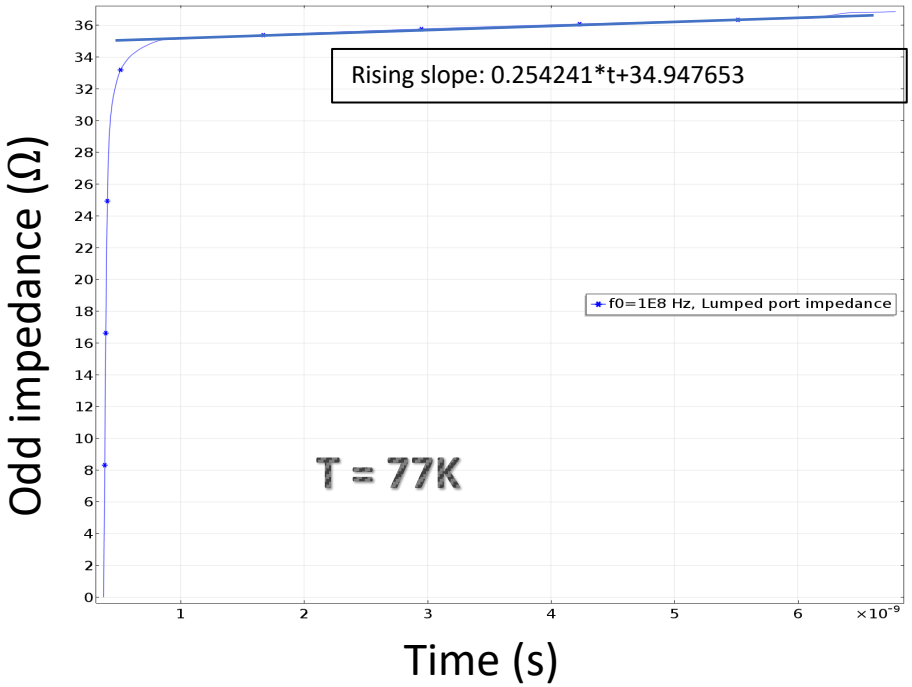


- **Input: differential signal, 1V in amplitude, step function**

Impedance vs. distance for one copper trace



Impedance vs distance for one copper trace

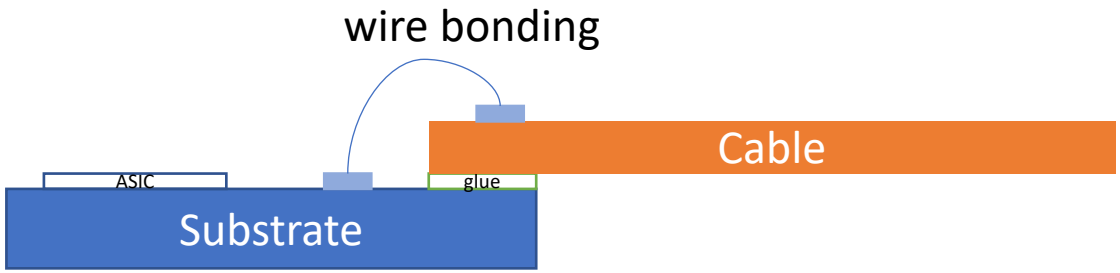


	Measurement	Simulation
TDR slope under room temperature	$0.50 \pm 0.01\ \Omega/ns$	$0.49\ \Omega/ns$
TDR slope under liquid N_2 temperature (~77K)	$0.18 \pm 0.01\ \Omega/ns$	$0.25\ \Omega/ns$

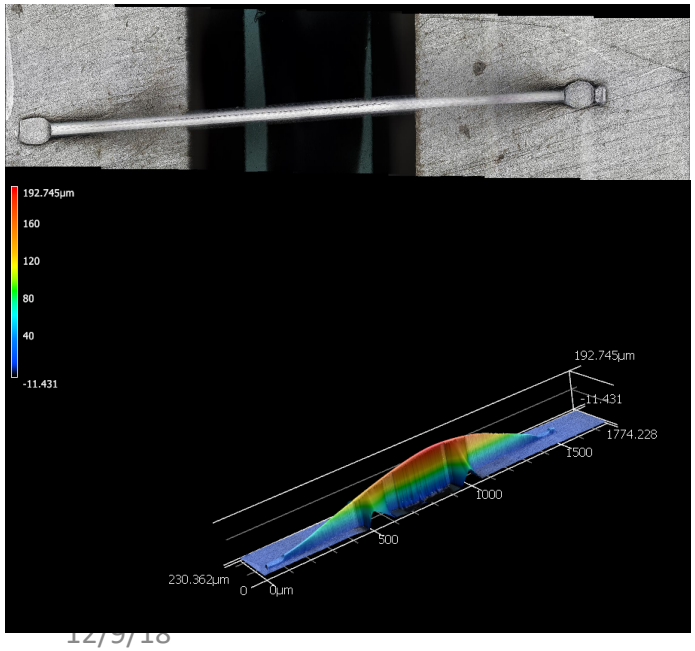
- Low-temperature resistive loss allows cable lengths up to 5m with <5% loss of signal amplitude

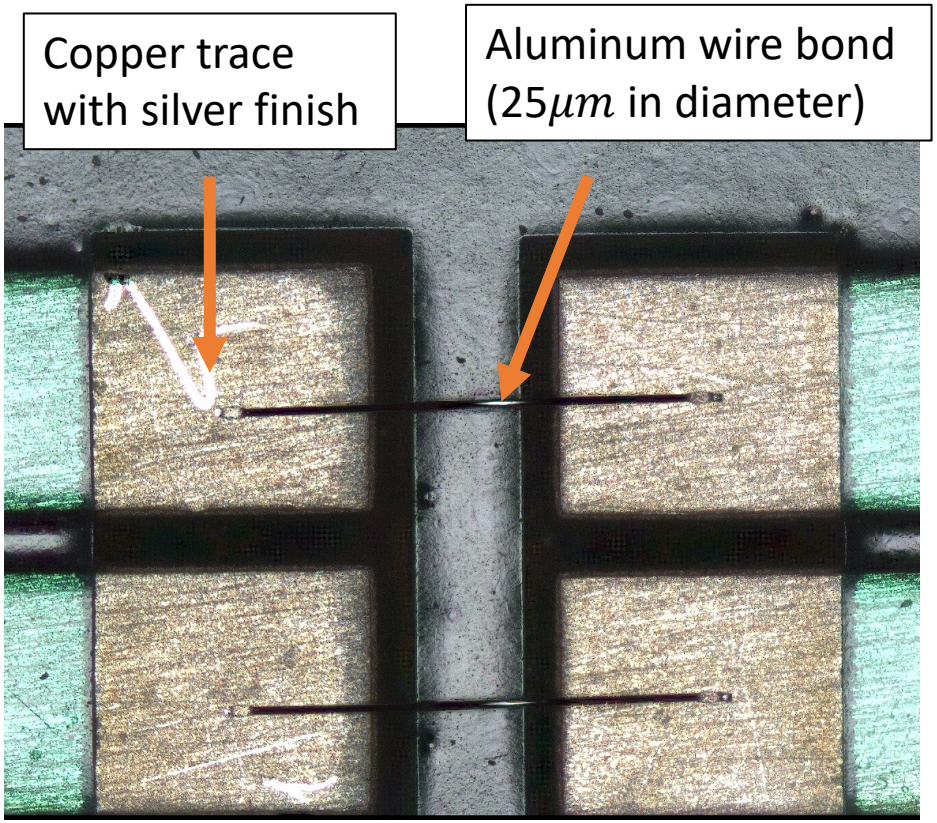
Wire bond impedance matching

- Wire bonds are required to electrically connect the cable to the ASIC substrate
- Want to characterize digital signal transmission through wire-bonded connections

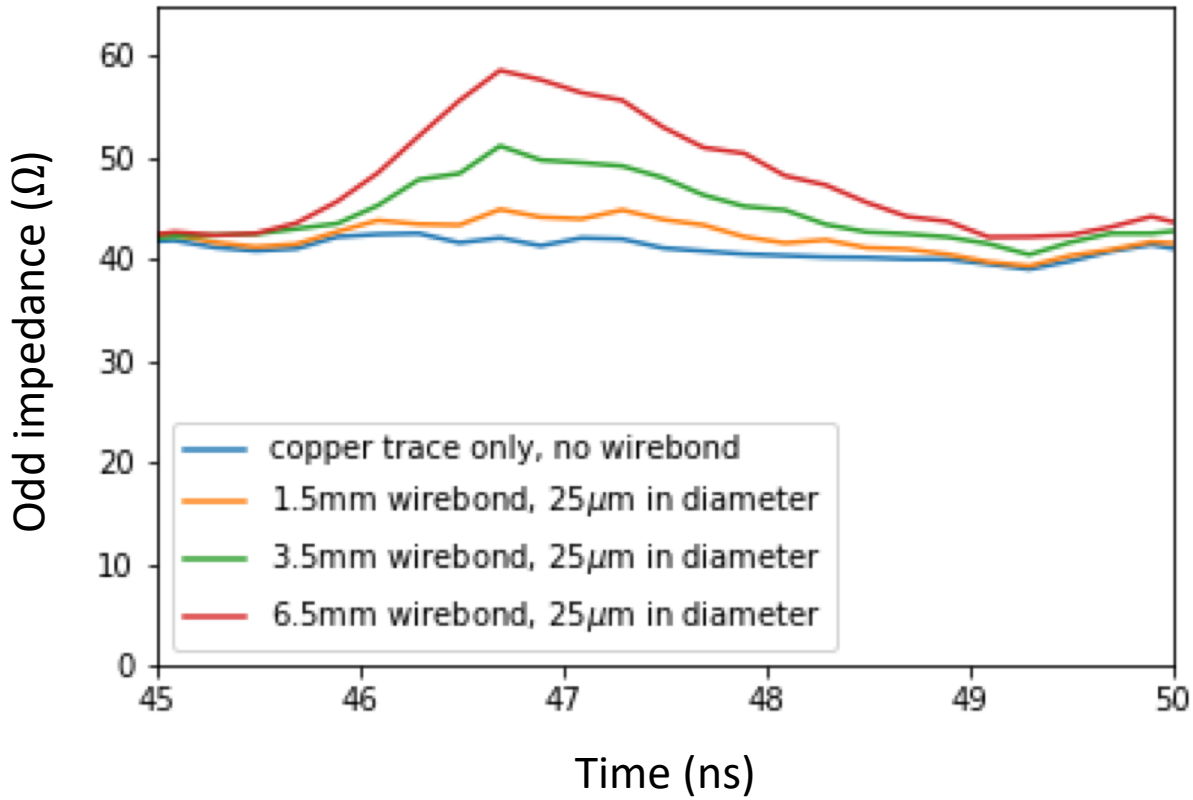


A test wire bond between two copper traces under the laser microscope at BNL:





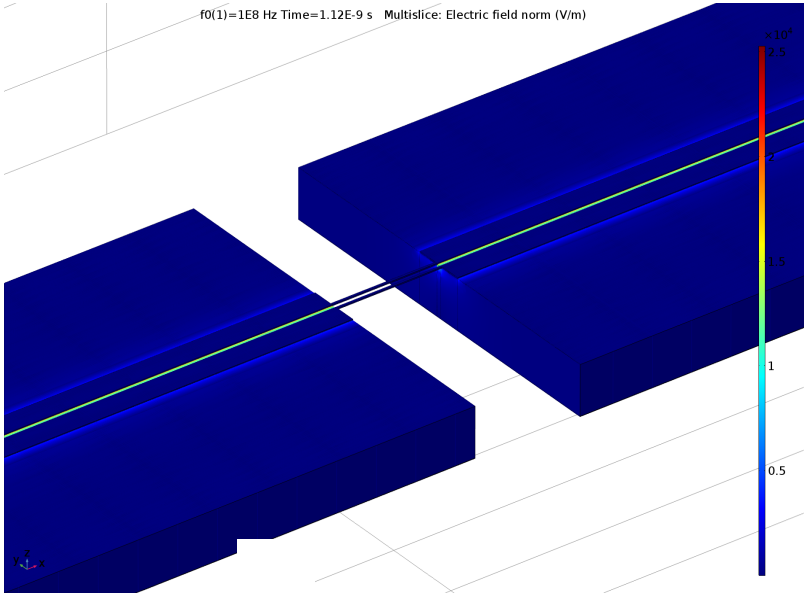
Wire bond impedance vs. length



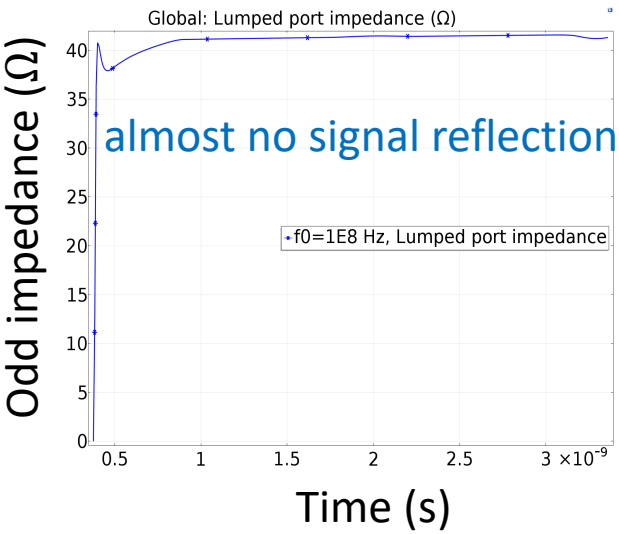
- Wire bond impedance increases with its length
- Measurement shows a ~1 mm wire bond is good enough to enable relatively smooth signal transmission
- Require multiple wire bonds to ensure interconnection robustness

COMSOL simulation of wire bond impedance

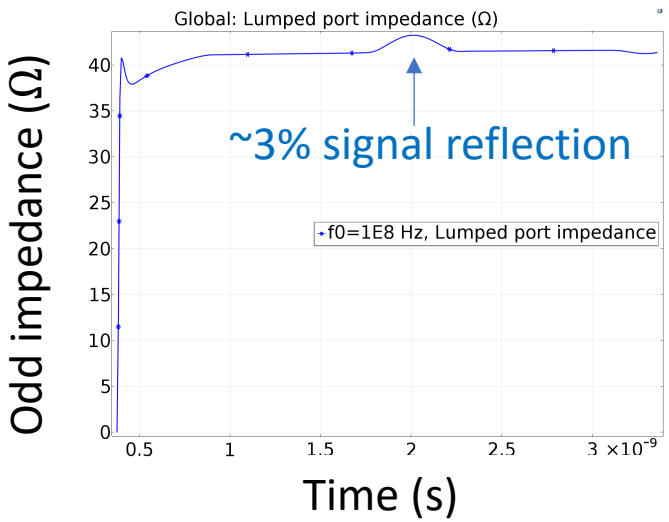
- Input: differential signal, 1V in amplitude, step function



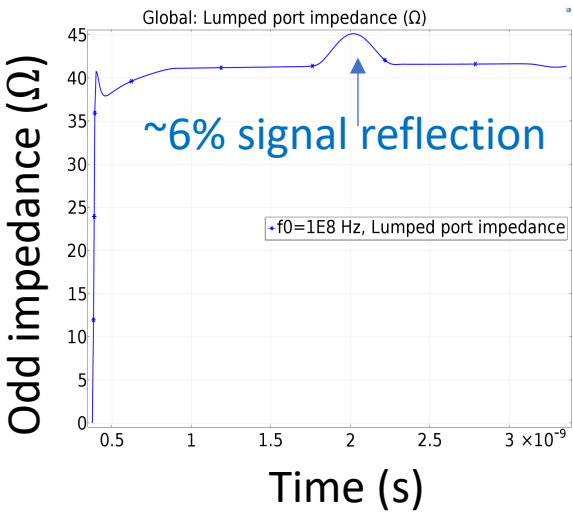
0.1mm long wire bond:



1.5 mm long wire bond:

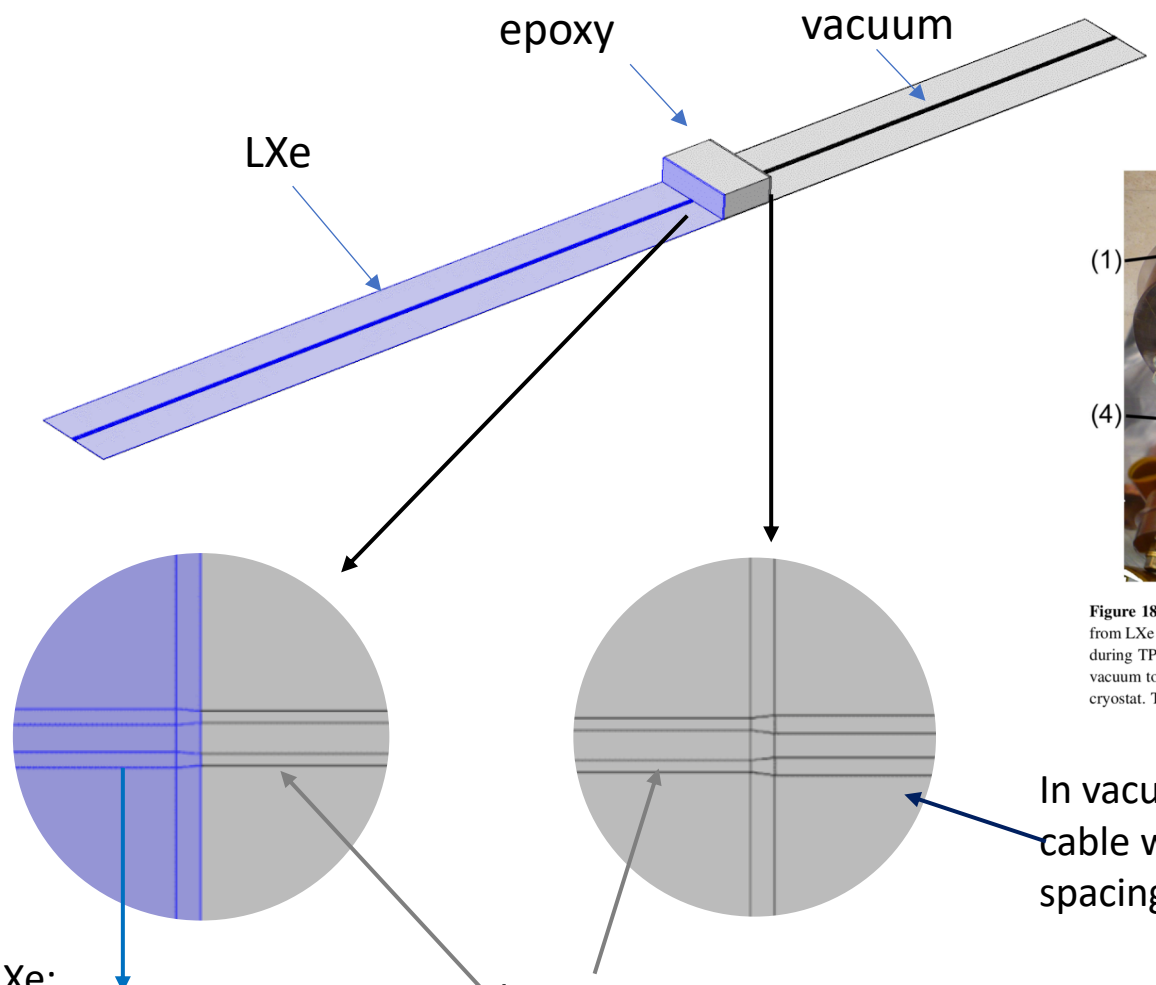


3mm long wire bond:



- Simulation shows the wire bond impedance increases with length, consistent with measurements

Impedance matching at the epoxy feedthrough



In LXe:
cable width = 0.165mm
spacing btw cables = 0.277mm

In epoxy:
cable width = 0.125mm
spacing btw cables = 0.317mm

In vacuum:
cable width = 0.185mm
spacing btw cables = 0.257mm

E.g. feedthrough of EXO-200

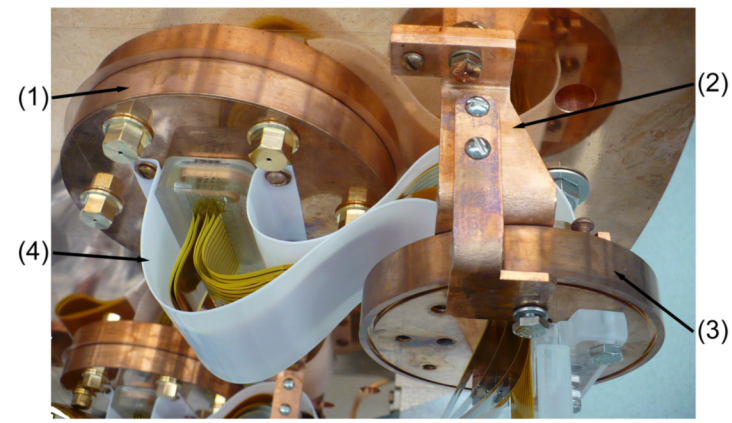


Figure 18. View of warm and cold cable feedthroughs, as installed. (1) Cold flange that makes the seal from LXe to vacuum, showing acrylic cup filled with epoxy. (2) Temporary bracket holding the warm flange during TPC transportation and installation. (3) Warm flange making the seal from the cryostat insulation vacuum to atmosphere. (4) PTFE strain relief. The service loop shown is in the insulation vacuum of the cryostat. The warm flanges are sealed against the inside face of the warm cryostat hatch.

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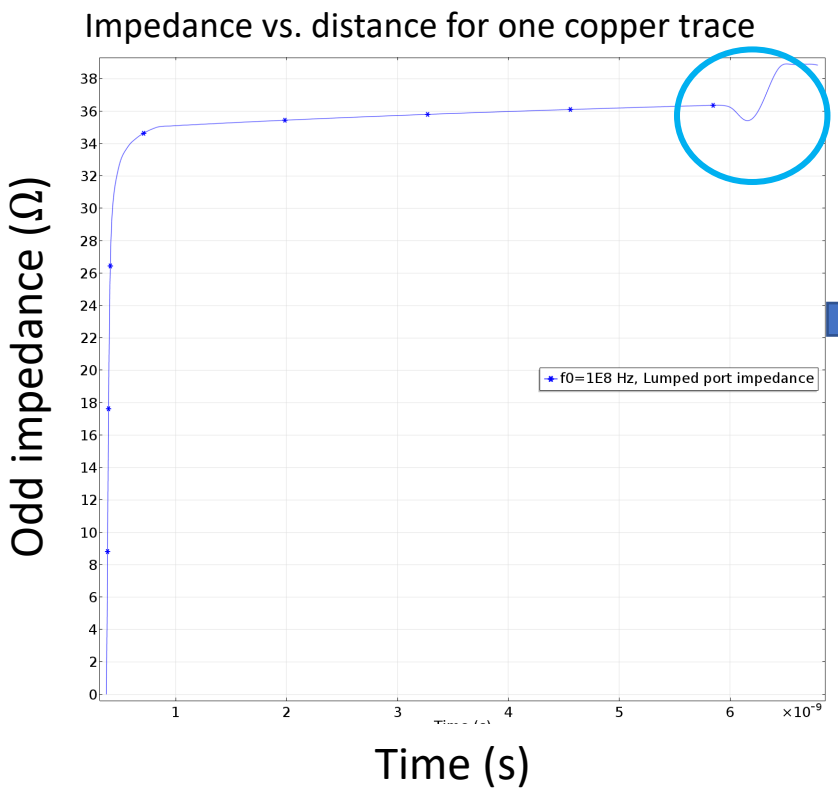
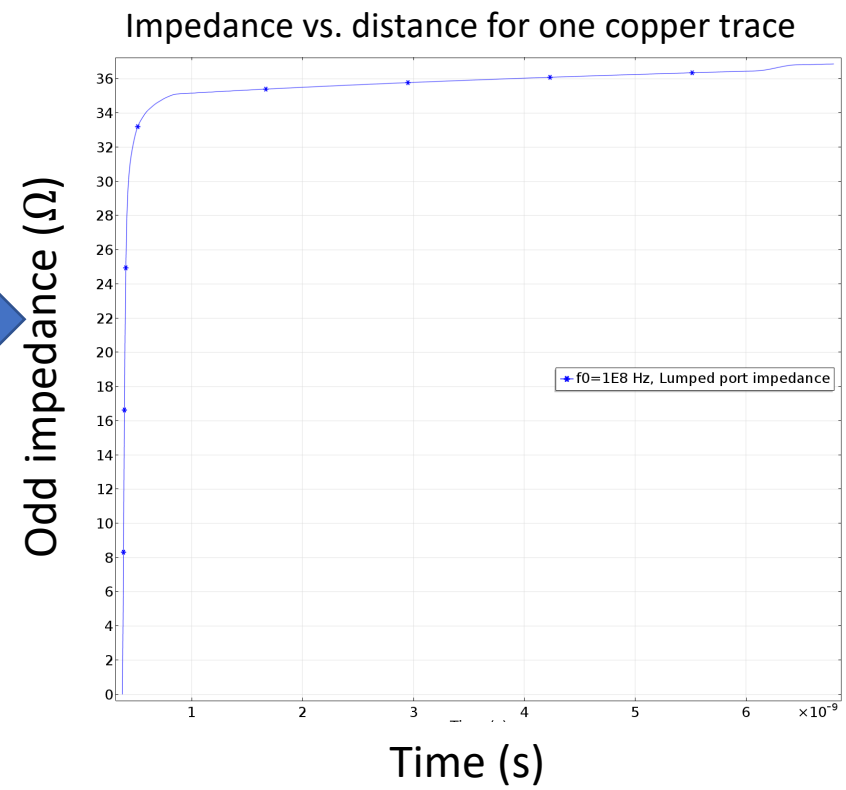
Impedance match at the epoxy feedthrough (COMSOL)

- The impedance mismatch between cable in LXe and feedthrough is small (<2Ω), can be fixed by tapering the cables.

Before cable tapering:

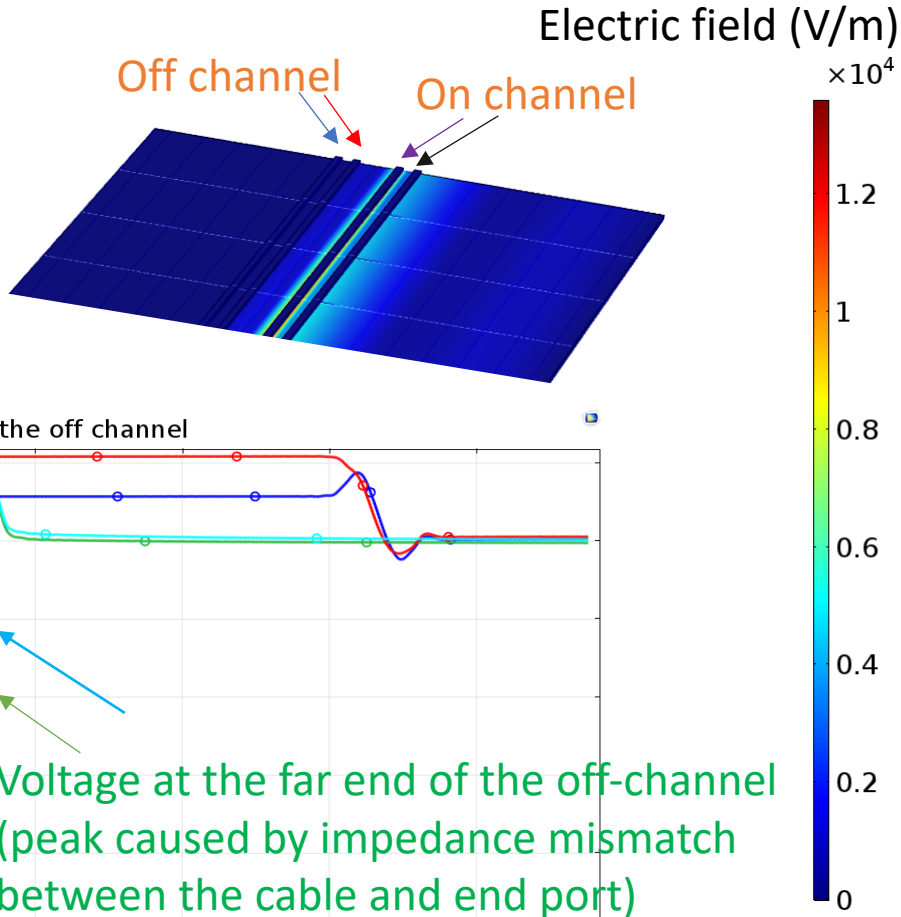


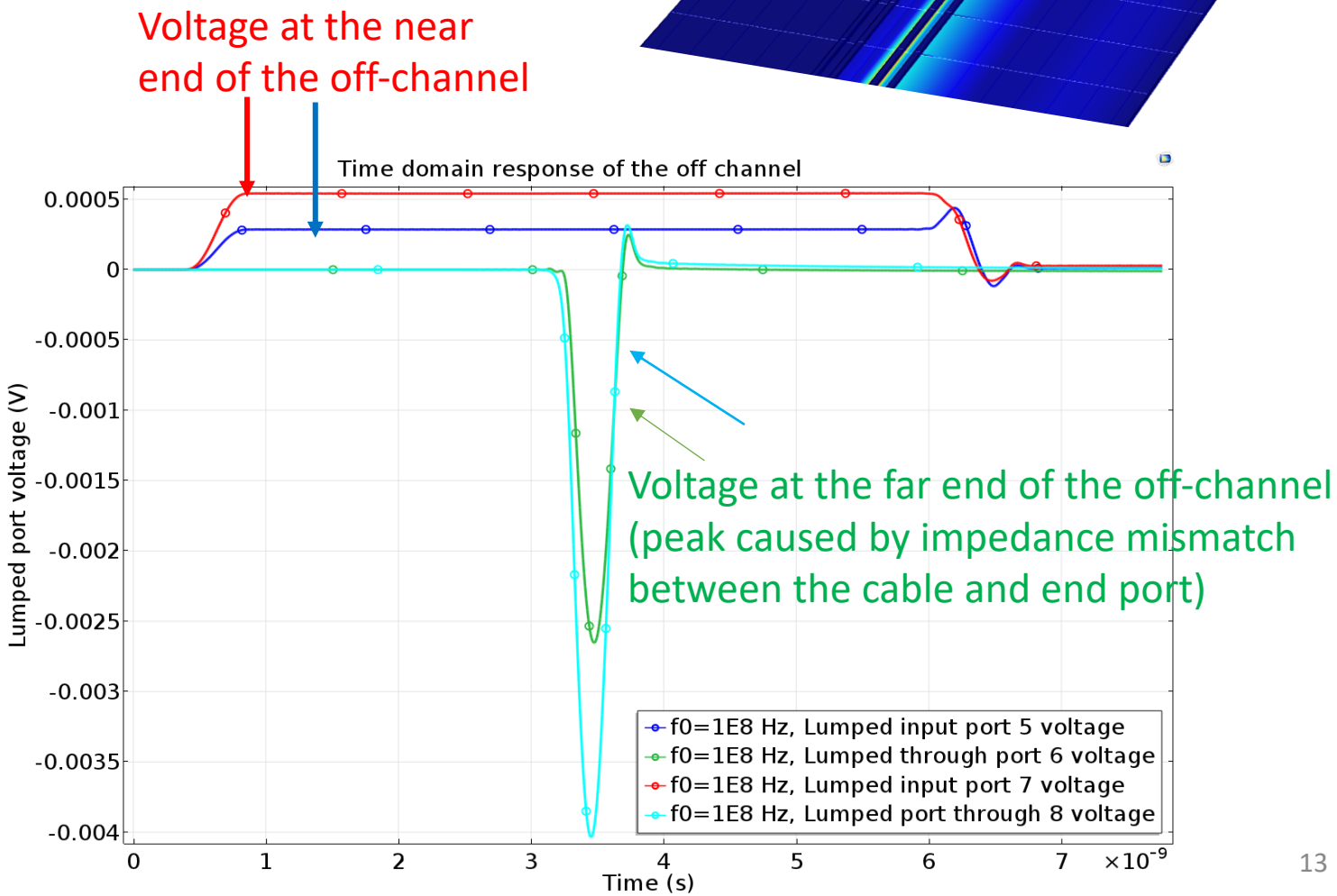
After cable tapering:



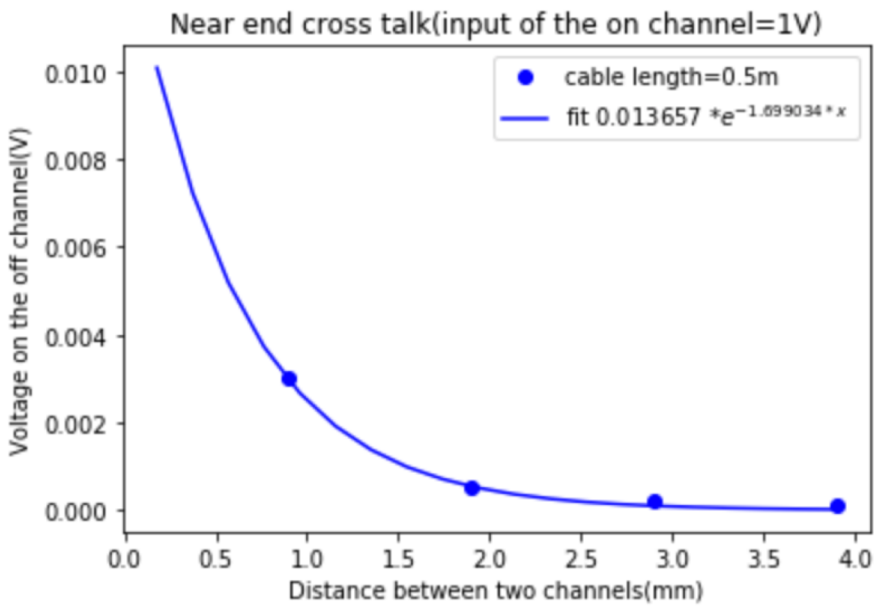
Cross talk between channels (COMSOL)

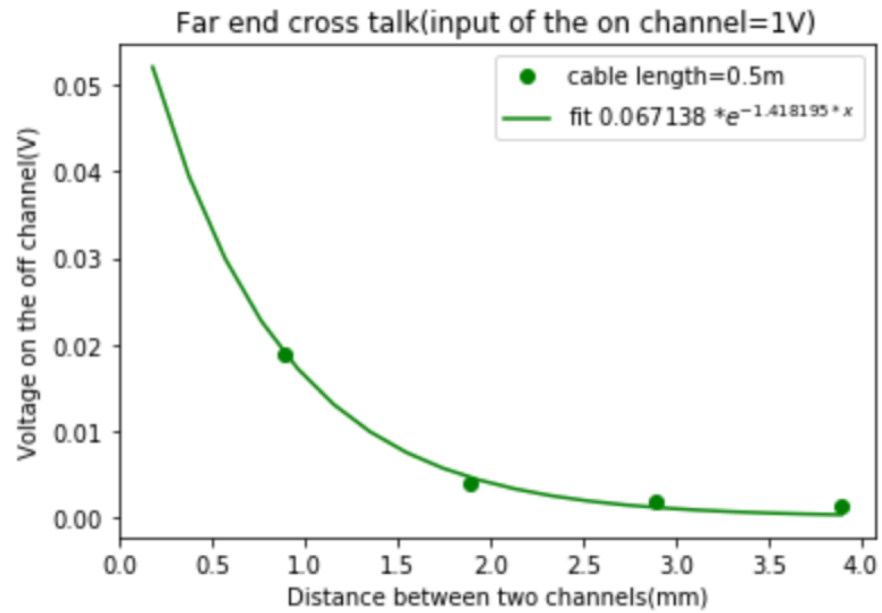
- Input voltage of the on-channel: differential signal, 1V in amplitude, step function
- Gap between two channels = 1.9mm





Cross talk vs. channel gap (COMSOL)





- Cross talk between channels decreases rapidly with their distance.
- There is 0.3% cross talk at the near end and 2% cross talk due to reflection at the far end when the gap is ~1mm
- Allows ~50 channels on a 5cm wide substrate.

Summary and Prospects

- We are developing prototype high-speed cables with low radio-activity for signal transmission in the nEXO detector
- Progress has been made on validating basic design of flat cables in loss, impedance matching, cross-talk, etc.
- Current work aims to demonstrate full readout chain including cable, connections to substrate, and feedthrough
- Development of radiopure, high-bandwidth cabling and interconnection techniques is relevant for many next-generation rare- event searches with large channel counts and high-speed digital electronics.

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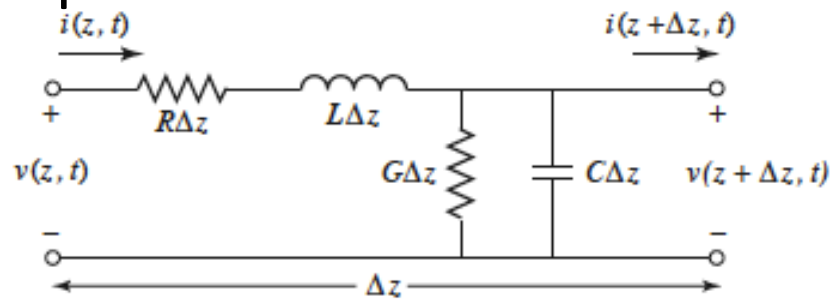
Backup slides

Explanation for the slope in the TDR waveform

The Lumped-Element Circuit Model for a transmission line:



- The characteristic impedance Z_0 is defined as $Zc = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$

In the limit G→0, Z_c can be written as $Z_c = Z_0\left(1+\frac{1}{j\omega\tau}\right)$ using a first-order Taylor-series approximation, where $Z_0 = \sqrt{\frac{L}{C}}$, $\tau = \frac{2L}{R}$. In the time domain, it indicates that the characteristic impedance in response to a step input has a gradual rising slope:

$$Z_c(t) = Z_0(1+\frac{t}{\tau}) \text{ when } t \ll \tau \text{ (in our case, } \tau \sim 100\text{ns})$$

(Reference: High-Speed Signal Propagation: Advanced Black Magic by H.Johnson and M.Graham)

- By similar reasoning, the shunt conductance G creates a negative slope with a time constant $\tau = \frac{2C}{G}$
- COMSOL calculation shows L=2*10^{-7} H/m, C=1.5*10^{-10}F/m (for a single line) for signal frequency between 100MHz and 200GHz. G is 6*10^{-4}S/m derived from the measured kapton loss tangent tanδ =0.003 at room temperature at 1GHz. It drops by a factor of ~2 under 77K.
  (http://www.dupont.com/content/dam/dupont/products-and-services/electronic-and-electrical-materials/flexible-rigid-flex-circuit-materials/documents/DEC-Using-Flex-in-High-Speed-Applications.pdf; arXiv:1206.1461v1)
- Thus R(4Ω/m) under room temperature generates a slope of ~0.5Ω/ns, and R(0.8Ω/m) under 77K generates a slope of ~0.1 Ω/ns.
- G generates a slope of -0.072 Ω/ns under room temperature, and -0.036 Ω/ns under 77K.

Implications for nEXO cables

- Using $\mathrm{Z}(t) \approx Z_0\left(1+\frac{t}{\tau}\right)$ and $\mathrm{Z}(t) = Z_0\frac{1+\rho}{1-\rho}$, where $\rho = V_r/V_o$

Assuming the slope due to loss is $s = \frac{Z_0}{\tau}$ =0.3 Ω/ns under LXe temperature (170K), the loss of voltage w.r.t time is then ρ(t)=$\frac{t}{\frac{2Zo}{s}+t}$.

- Writing ρ in terms of cable length: ρ(l)=$\frac{l/c}{\frac{2Zo}{s}+l/c}$, where c is the speed of the signal.
- Given good impedance match at the interfaces, we can use cables with length <5m to ensure >95% voltage passing.