Prototyping progression and lessons learned

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PDR - 04/05/2022

Timeline and main benchmarks

February 2021 start of investigations

- analog circuit component selection
- decision to use lasers (over LED) with connectors
- definition of basic circuit characteristics

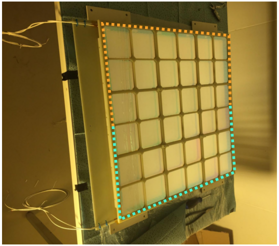
June 2021 First working analog transmitter

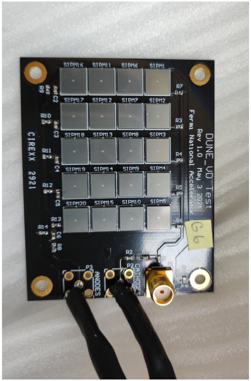
- laboratory tests with SiPMs in LN2 → SPE transmission

September - December 2021 Coldbox A_1 → successful proof of principle
March 2021 - Ariadne parasitic run (A_2) → additional statistics for linearity measurement
May 2022 Coldbox A_3 → GaAs PoF and new shielding
July 2022 Coldbox B→ Optimized full test
November 2022 Preliminary Module 0 test
March 2023 Module 0

2021 - R&D towards functional prototypes
2022 - Optimization, performance, mechanics and installation

Coldbox A prototypes

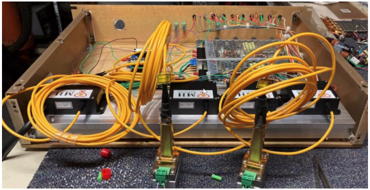




xARAPUCA tile:
20 SiPMs/flex circuit
2 channels (80 SiPMs)
Single-sided

ARGON2x2(2 channels/board)
5.1V, $<$ 35 mA ($<$ 100 mW/ch)
FP 1310nm lasers FC connector
Voltage gain $\sim$20
Optical power $\lesssim$ 1 mW @receiver
MiniArapuca:
20 ganged SiPMs + custom filter

PoF: Si modules in custom unit
Fibers: MM silica core, 5m to connector box, 10m through feed through to racks.



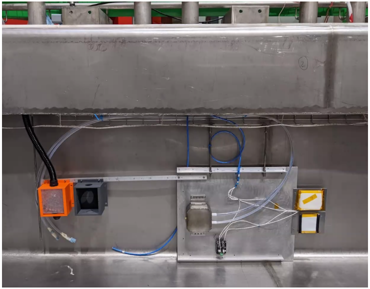
September-December 2021 ColdBox A Installation

CERN Neutrino Platform coldbox:
$3 \times 3 \times 1\ m^3$ cryostat for LAr tests
Cathode placed on feet ∼10cm from the floor, TPC is mounted on the coldbox cover.

Target: proof of principle
PD with signal and power transmission through fiber, operating on an HV surface

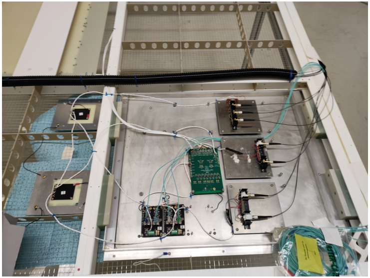
On the wall:
Various tests, copper powered

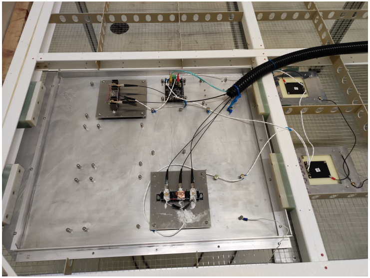
- Two boxes for fiber connectors
- Two miniArapucas (35V and 48V)
- LED (275 nm) setup



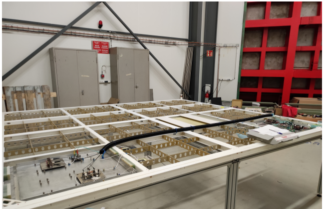
September-December 2021 ColdBox A Installation

On the cathode: Signal and Power over Fiber





- Six channels:
  - Four miniArapucas (20 SiPMs + filter)
  - One xArapuca (2×80 SiPMs)
- Three Argon2x2 boards with varying configurations
- Si PoF modules: 36V for SiPMs, 5.6V and 35mA for transmitters
- Signal and power fibers reaching the edge of the cathode and connected in LAr to feed through fibers

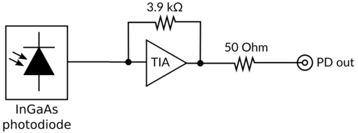


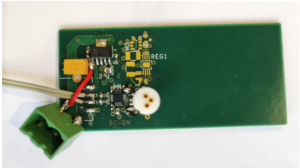
Warm Electronics

Analog optical receiver - Lecroy WaveRunner 1GHz oscilloscope
CAEN DT5725B 14 bit 250 MHz

Koheron PD100 low noise pd

- single channel commercial solution found early 2021
- DC-coupled
- 0.9A/W - 3.9 kV/A amplification
- 600 μW maximum input at 100 MHz
- $\pm$ 6V bias, $\sim$40mA





In-house designed solution (not tested yet)

- First prototype of single-channel receiver April 2022
- Based on same functioning principle
- Possibility to adjust input/output to PDS specific needs
- Future: 16-channel board or modified DAPHNE input stage

Achievement of first Milestones

- Successful proof of principle: first operation of photodetection system powered and read only through optical fibers

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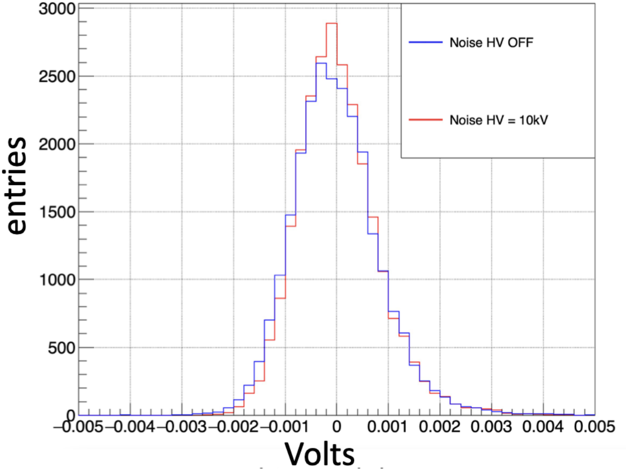
- Operation with cathode HV ON (10 kV - $\sim$500 V/cm)
  - no effect on PD performance, noise and signal characteristics conserved
  - no interference with TPC functioning



HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

HV = 10 kV
Mean =-0.02 mV
Sigma=0.71 mV

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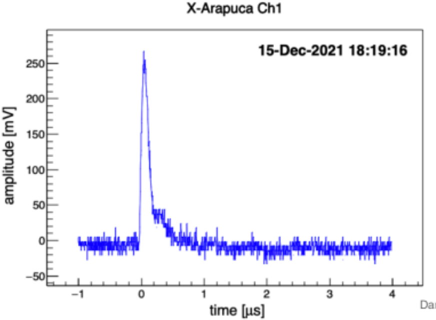
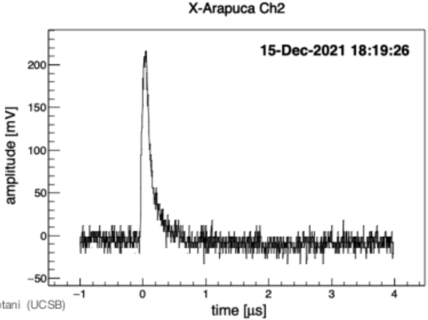
- Signals triggered through cosmic-ray taggers on top of roof





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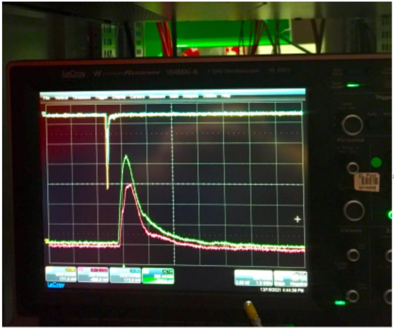
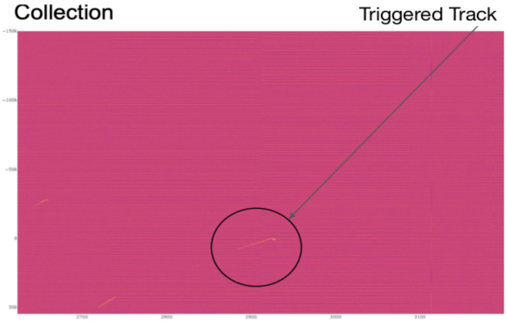
- Signals triggered through cosmic-ray taggers on top of roof
- PDS-triggered TPC signals





Ariadne parasitic run - March 2022

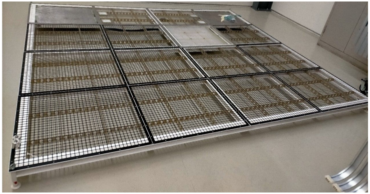
- Data-taking in December 2021 was very short (few hours over few days)
- Use of oscilloscope: no DAQ system, intrinsic few mV noise

ARIADNE: dual-phase PD based TPC

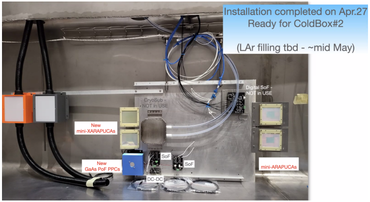
- Using the VD-PD of December (no modifications) for S1 signal collection
- Opportunity to take enough statistics to improve the analyses and conduct further investigations
- However, light interference from Ariadne operation
- Using a CAEN digitizer (14 bits, 250 MHz) for data taking (larger buffer, lower noise)
- First test of data taking using DAPHNE with analog readout devices

Coldbox A May 2022

- Starting in a few days (2-week delay)
- Same cathode configuration, resistive mesh added
- new wall setup to test GaAs PoF and
- revisited grounding scheme



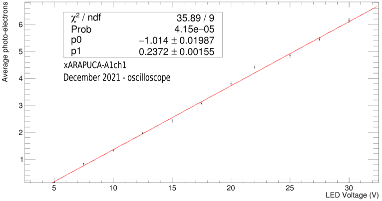
- Coldbox noise conditions possibly improved by new shielding and grounding
- On-going evaluation of vibrations
- Data acquisition with digitizer as during Ariadne test
  - study of noise levels and sources
  - compare performance of wall and cathode setup

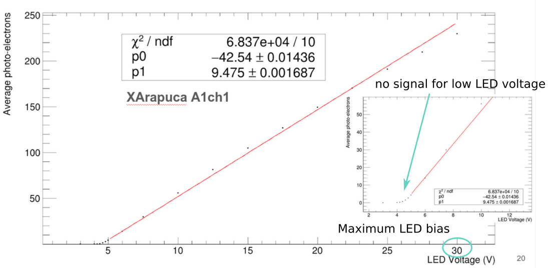


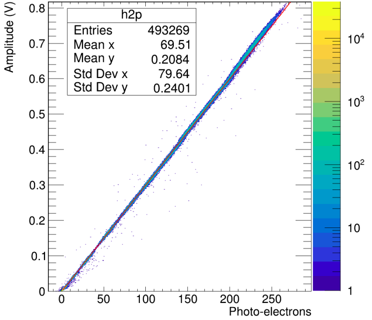
The GaAs modules would considerably reduce the number of modules needed to power the devices.

Coldbox A analysis results

- Full chain linearity up to $\sim 250 - 300$ PE using LED calibration light
  - Light output regulated through voltage (up to 30V) or pulse width
  - SPE charge 0.3Vns (measured)
  - few PE characterization also done in the lab (see backup)

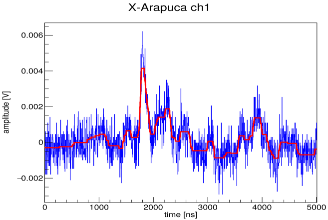


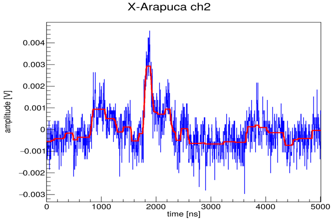


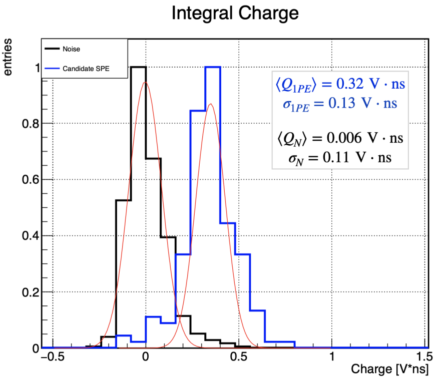


Coldbox A analysis results

- Full chain linearity up to $\sim 250 - 300$ PE using LED calibration light
- Small signal sensitivity: SPE detection
  - SPE signal visible 'by eye', but due to noise fluctuations they have to be selected manually to estimate the S/N (shown by Flavio)
  - in some channels it was possible to implement a first automatic selection
  - possible improvements in May's data

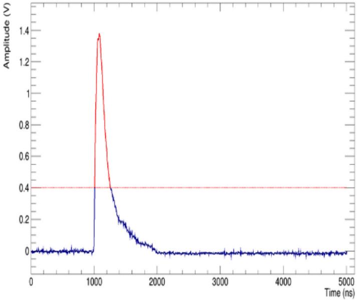


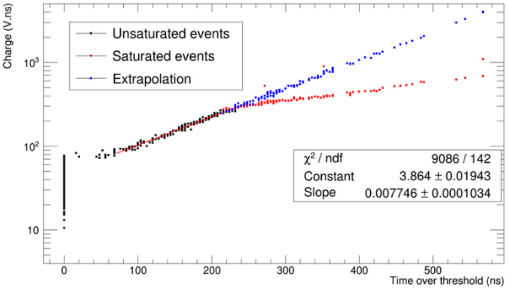




Coldbox A analysis results

- Full chain linearity up to $\sim 250 - 300$ PE using LED calibration light
- Small signal sensitivity: SPE detection
- Large signals (currently) affected by saturation
  - range: ~5 mV minimum signal in oscilloscope - commercial receiver saturation
  - Time-over-Threshold is a good probe to amplitude/charge and can be used as a correction





Coldbox A (many) lessons

A dedicated document summarizes what we've learned:

- Fibers:

  PoF Multi-mode, large core, shielded to avoid light leakage

  - Need to secure the connection to laser (used silicon)
  - Dirt deposits on fiber tips must be avoided

  SoF Multi-mode 60 μm silica core

  - looking into better cladding and jacket material options (tefzel..)
  - investigating possible modal noise (comparing SM and MM in the lab)
  - comparing FC connector vs pigtails (tbd with vendor)
  - will verify possible channel-to-channel variations with May data
- Laser-fiber coupling: efficiency loss when under $>$ 30 cm of LAr
  - Possibly due to LAr infiltration into connector
  - Potting options under investigation (lab test showed it solves the issue, and seems to be possible considering installation constrains)
- Noise sources: conditions at CB worse than in the lab tests
  - use of oscilloscope: few mV noise level, use of long cables
    $\rightarrow$ improved when using CAEN digitizer and should be OK with ADC
  - upcoming new data with improved shielding and grounding scheme

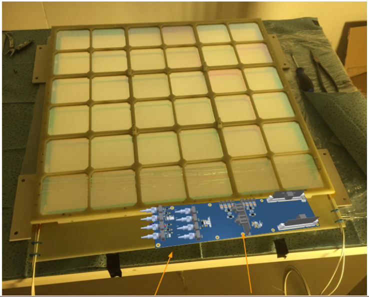
Coldbox A (many) lessons

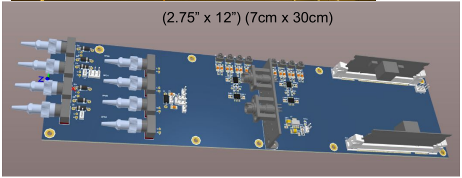
- Analog transmitter board:
  - board was too thin and hard to connect/disconnect
    $\rightarrow$ improved thicker PCB material and connectors
  - laser-fiber connection should be horizontal to avoid fiber hard bend and fit well within cathode width
  - warm 'alive' testing capability using NTC resistors (laser threshold current is 9 mA in warm and 2 mA in cold)
  - pre-installation characterization, defined list of parameters to check
- Installation: important exercise to understand constrains and improve procedures
  - improvement of fiber routing and protection
  - larger boxes for FC connector
  - definition of tooling and technical skills needed

All to be implemented in the next installation!

Coldbox B: June-July 2022

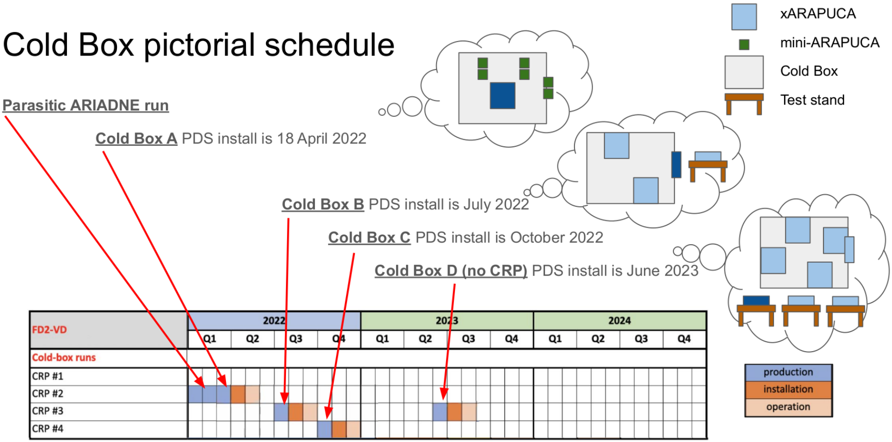
- PoF and SoF combined in single optimized board
  - possible to populate with either Si or GaAs receivers
  - PoF: 4 LV, 4 bias
  - DC/DC converters test option
  - Optimized gain and warm alive test in SoF transmitter
  - boards produced, population and testing started
- Double-sided xARAPUCA with 8 flex circuit v2, each with 20 SiPMs
- Digitization with DAPHNE, integrated to DAQ





- Minimum requirement:
  one full xArapuca-SoF-PoF module working on cathode
- Target 1: 1 xArapucas on cathode (PoF-ds) and 1 on wall (copper-ss)
- Targer 2: 2 xArapucas on cathode (PoF-ds) and 1 on wall (copper-ss)

Coldbox schedule



- September 2022: extra Coldbox B possible → 4 cathode xARAPUCAS
- November 2022 : preliminary Module 0 installation possible
- July 2023: final SoF and PoF configuration

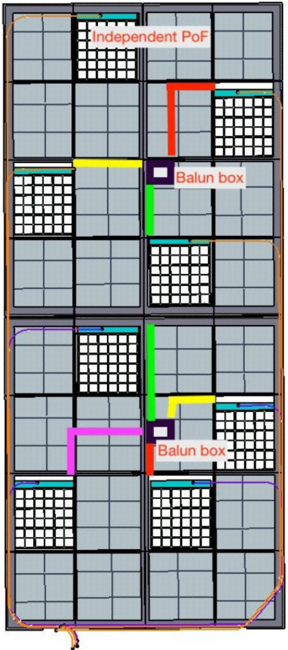
Towards Module 0

Configuration nominally 1/20th scale:
4 xARAPUCAS per CRP
→ 16 ds modules, 32 channels
Wall: 6 ss xARAPUCAS
At least 2 DAPHNE boards
(SiPM procurement most urgent item)

HV Discharge survival tests:

- Testbench to emulate discharge situation
- 1-3-4 interconnection scheme
- discharges induced at the end of the run
- work on-going to define lists of measurements to be done, discharge control strategies, etc...

Definition of installation procedure



2022 and Beyond

Parasitic ARIADNE run run complete!

Cold Box A PDS install is 18 April 2022

Preliminary Design Review (PDR) is 1st week of May 2022

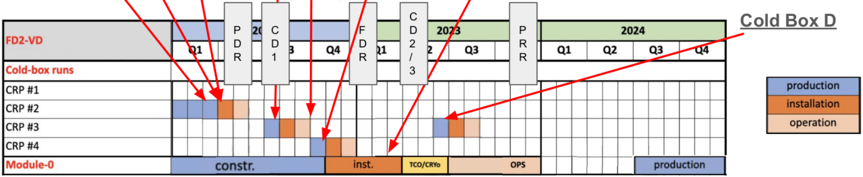
Cold Box B PDS install is July 2022

Cold Box C PDS install is October 2022

Cold Box B+ (No CRP)

FD2 PDS Module-0 install thru March 2023

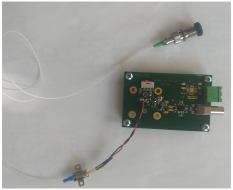
Cold Box D



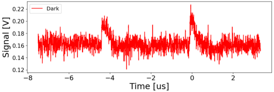
Back Up

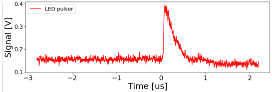
Preliminary laboratory tests - March-July 2021

- Investigations and tests to find fast, low noise components that work in cold
- Laser characterizations, optical coupling solution
- Optical receiver solution
- Convergence towards main circuit specifications:
  bias voltage, DC offset for laser $\sim$ 2-3 mA, bandwidth $>$ 20 MHz, gain

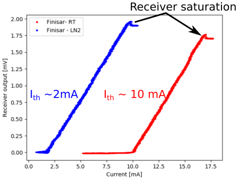


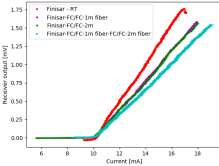
Tests with SiPMs in LN2





Laser and receiver linearity
Threshold current much smaller in LN2/LAr temperatures





Lasers

Lasers:

- LEDs discarded: less efficient, reported non linearities
- VCSELs 850 nm large amount of options, some worked, but within SiPM sensitivity range
- FabryPerot 1310 nm is outside of SiPM sensitivy and showed good results

Connectors:

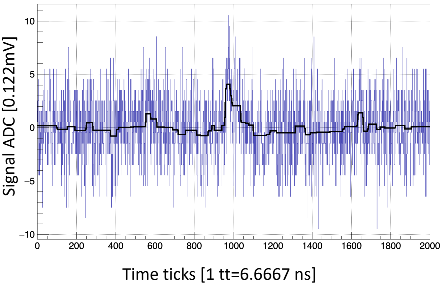
- Reported as main issue in laser-fiber coupling in cryo/not air
- Choise of FC connector for rigidity and convenience

SiPM lab tests - Fermilab

- Measurements on 20 SiPM board, S14160
- Tested different bias voltages (36V shown here)
- Data acquisition with ”SSP” (dedicated system used in ProtoDUNE-SP)

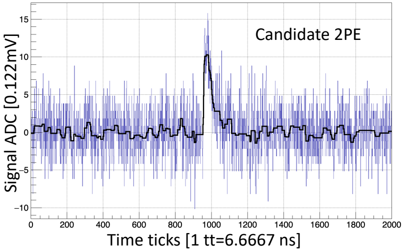
36 V studies:

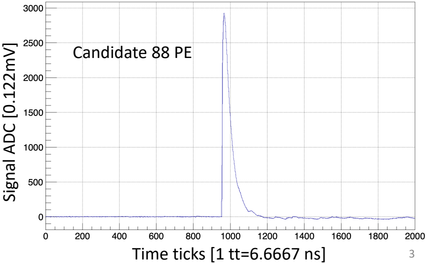
Candidate SPE



Black line represent denoised signal using
1D total variation filter

There is a small undershoot for large signal:



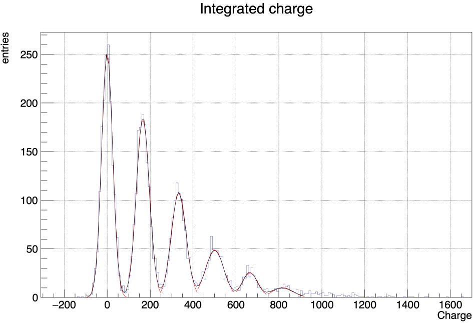


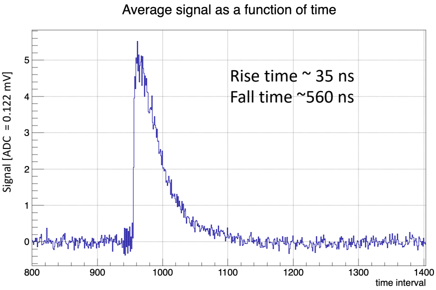
Charge integral (36V):

Signal to noise ratio:

= mean of SPE/sigma of noise
=165.8/25.8 = 6.42

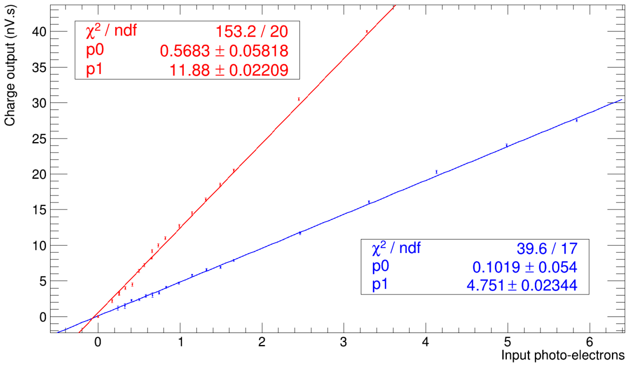
Sigma of SPE = 29.98





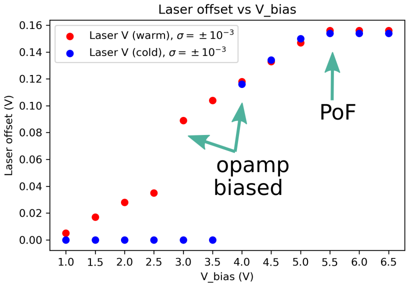
Linearity Argon board

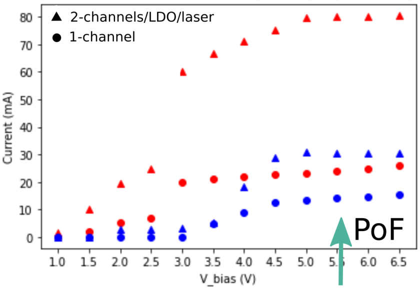
- Input pulses from pulse generator (20ns rise time, 80ns fall time)
- Using x100 attenuators for small signals
- Considering SPE at 75μV amplitude for x-axis
- Difficulties from noise pick-up on long cables, specially in cold



Power consumption

- Supply ranges THS4131 5-±5 V; OPA354 2.5-5.5 V; LDO 2.5-7 V
- Laser constant DC offset same in warm/cold
  → no changes in circuit DC behavior
- Circuit consumption ∼ 50% lower in cold (∼ 14 mA)
  - laser current 3mA - 15mA (hardware setting)
- LDO working correctly in cold (LP3964, and testing others)





SPE analysis

Analysis in miniARAPUCA on cathode (A4-ch1) using LED calibration light from March 2022 (Ariadne)

- Signal found using LED trigger
- Not sure whether Ariadne was running (possible noise addition)
- Difference 2 phe - 1 phe= 0.184 V*ns