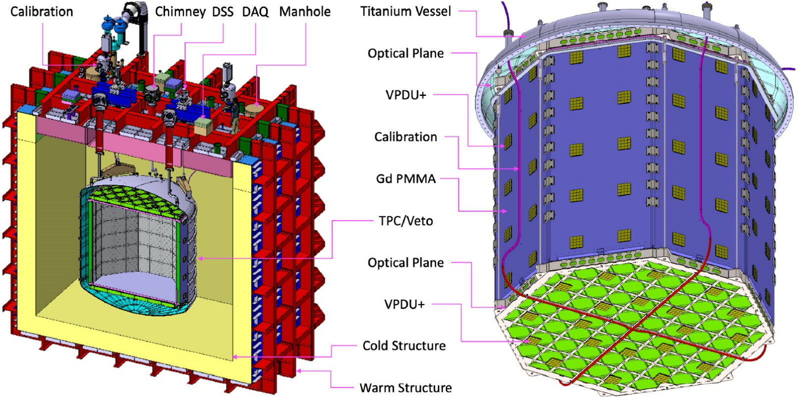
From Photoelectrons to Bytes in DarkSide-20k

Andrea Capra
On behalf of the Darkside-20k Collaboration

UCLA Dark Matter 2023, March 31



- Dual-phase liquid argon TPC @ Laboratori Nazionali del Gran Sasso (Italy)
- Integrated neutron veto
- Active volume: 50 t of underground argon see talk by F. Gabriele today at 18
- For Darkside-20k overview see talk by T. Thorpe this morning

1. Photosensors
   - SiPM
   - PhotoDetecion Unit - PDU

2. Data AQuisition System
   - System Overview
   - Implementation and Prototype

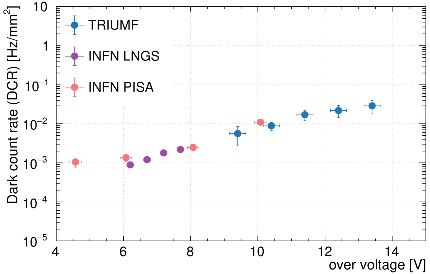
From PMT to SiPM

Light detection with PMTs: DarkSide-50, DEAP3600, XENON1T, XENONnT, LZ, ...
Light detection with SiPMs: DarkSide-20k, ARGO, nEXO, DUNE, ...

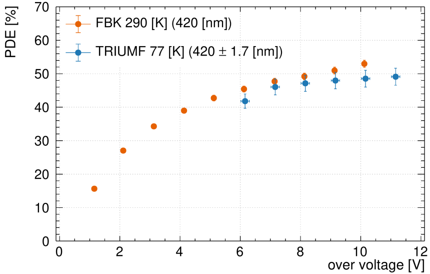
- ✓ Lower radioactivity
- ✓ Higher photon-detection efficiency
- ✓ Higher active area (”fill factor”)
- ✓ Lower bias voltage

- ✗ Higher dark and correlated noise (afterpulsing, cross-talk)
- ✗ Smaller size (many individual channels)
- ✗ Higher capacitance (reduced signal-to-noise ratio)

The development of the photosensors for DarkSide-20k overcomes those issues.



- SiPM must operate at cryogenic temperatures and
  - ✓ DN rate < 0.1 Hz/mm^2
  - ✓ PDE $\geq$ 40% at 420 nm[a]
  - ✓ DiCT probability < 50 %



- NUV-HD-Cryo - by Fondazione Bruno Kessler (Trento, Italy) - exceeds DS-20k specifications.
- SiPMs manufacturing by LFoundry s.r.l. (Avezzano, AQ, Italy)

[a] wavelength shifter main emission peak

PhotoDetection Unit Design

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- Photo Detection Unit or PDU is designed at LNGS to have a ”PMT-comparable” area

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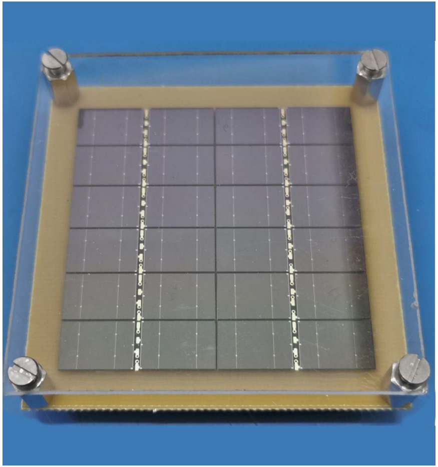

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- TILE front-end amplification based on commercial low-noise high-speed Trans-Impedance Amplifier (TIA)

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- Veto TILE front-end amplification based on with custom ASIC

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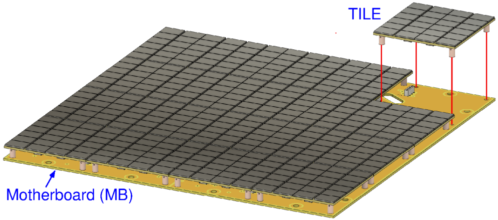
- The Motherboard (MB) is a 200×200 mm^2 board that hosts 16 TILEs.



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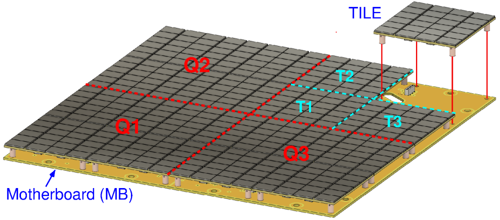
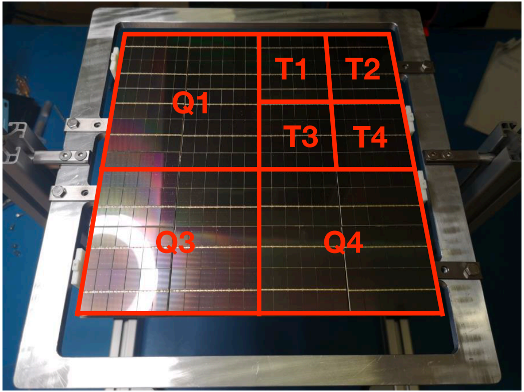
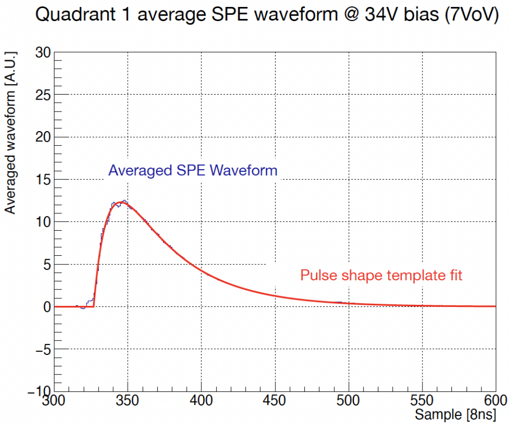


Each PDU has 4 outputs: active sum of 4 TILEs reducing the number of TPC channels to 2112

Each quadrant is an individual channel

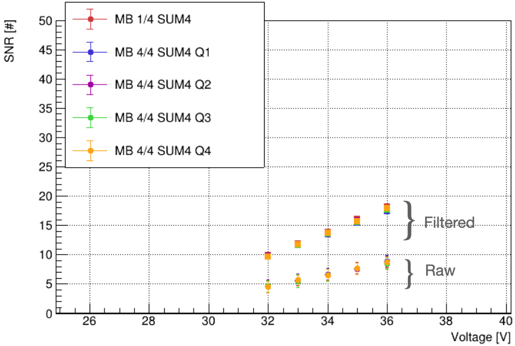


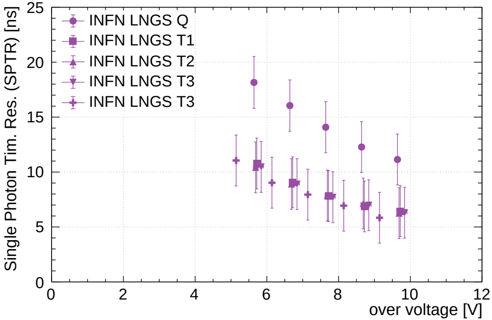


Pulse shape: $V(t) = \left(e^{\frac{t_0 - t}{\tau_1}} - e^{\frac{t_0 - t}{\tau_2}} \right),$

where $\tau_1 = 330$ ns and $\tau_2 = 77$ ns

PhotoDetection Unit Characterization



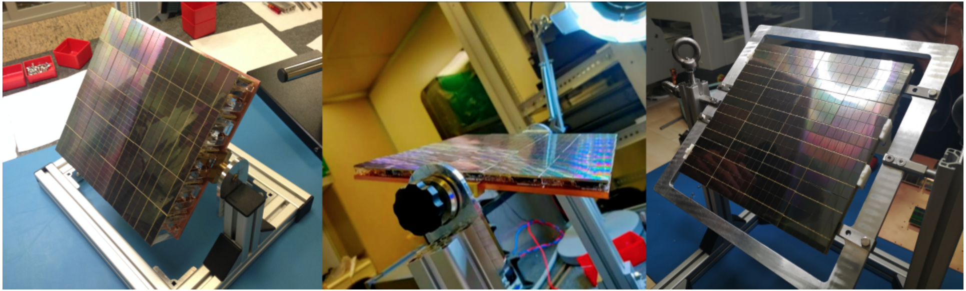


✓ Signal-to-Noise-Ratio (after pulse processing) must be $>$ 8

✓ Single PhotoElectron Time Resolution must be $<$ 30 ns

PhotoDetection Unit Status

- Several PDU prototypes have been built and tested in liquid nitrogen and argon
- All the specs have been met!
- Mass production (soon) to start in a dedicated facility in Assergi (AQ) Italy - NOA
  see talk by R. Tartaglia, tomorrow at 8



DAQ Requirements

- **Single photoelectron detection**
- Detection of very low energy scintillation signal O(10 keV)
- Detection of ionisation signals equivalent to few electrons
- Sensitive to O(10 MeV) signals in the Outer Veto and O(100 keV) in the Inner Veto
- Time alignment of different detectors element at O(1 ns) level

DAQ Design

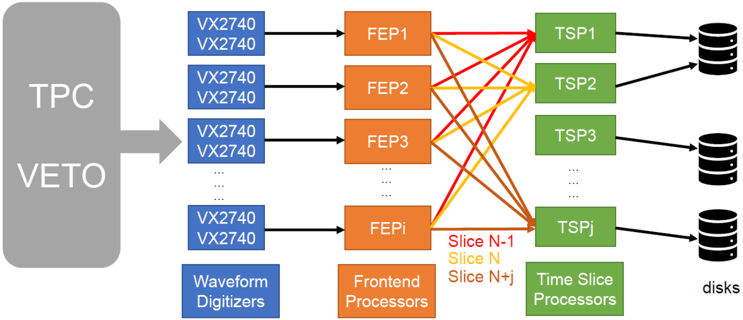
- Detectors are readout without global (hardware) trigger - *Trigger-less*
  - Each channel generates a data flow independent from the others
- Digitized waveform are processed in real time - FPGA+CPU processing
- Flexible selection of events from full state of the detectors - *Time Slice*
- Additional requirement: On-the-fly *data reduction* before writing to disk

DAQ Relevant Parameters

- Typical S1 (light signal) duration $\sim 5\mu s$
- Typical S2 (charge signal) duration $\sim 20\mu s$
- Maximal drift time $\sim$ 5 ms

- 2112 readout channels TPC
- 480 readout channels Veto (inner)
- 128 readout channels Veto (outer)
- Expected event rate:
  88 interactions/s in the TPC active volume

DAQ Overview



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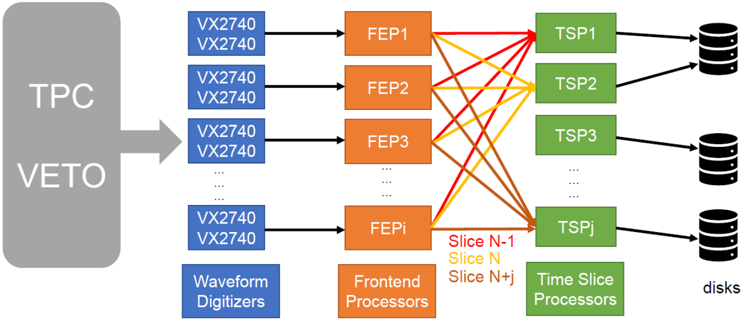
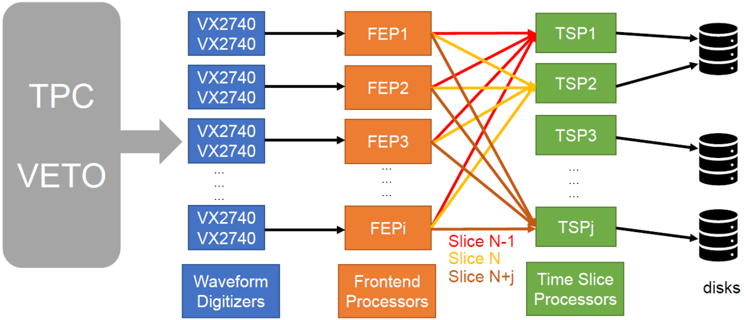


1st stage SiPM (4 tiles) WaveForm Digitizer (WFD) with CAEN VX274x



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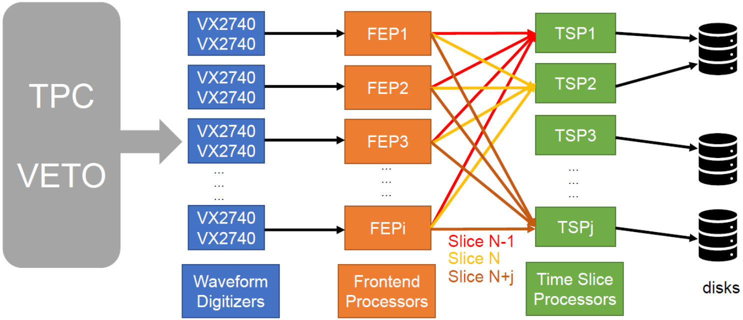

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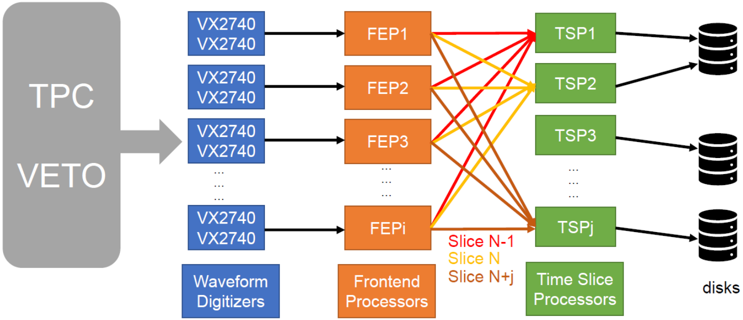
3rd stage **T**ime-**S**lice **P**rocessor acquires data from all FEPs



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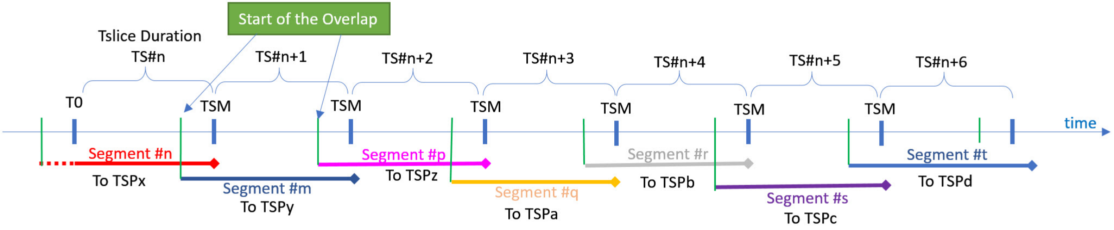
Pool Manager coordinates data transfer from FEP to TSP

Time Slice Concept



- Data acquisition is divided into ***time slices***
- A ***time slice*** is the complete collection of detector data over a fixed amount of time (with overlap with previous slice)
- ***Time slices*** are submitted individually to a dedicated processor - TSP
- *Time Slice Marker* is injected at the digitizer level to keep track

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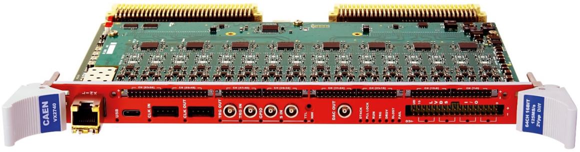
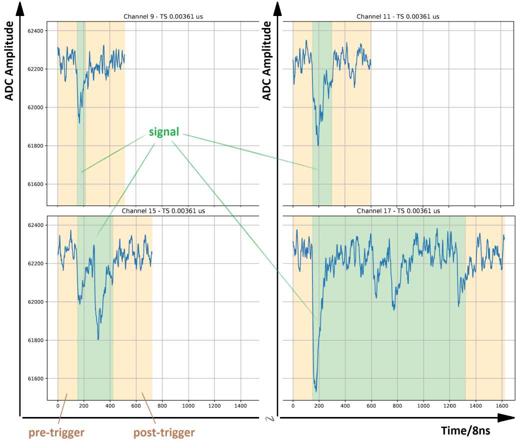
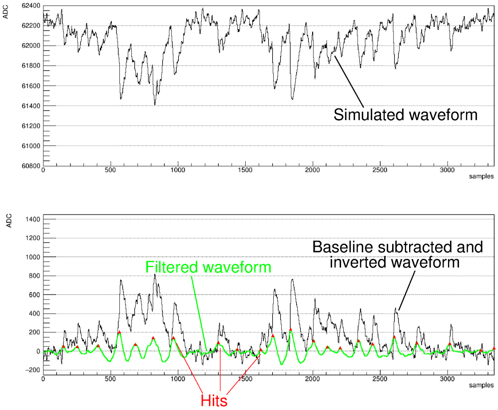
Dynamic Acquisition Window in the Digitizers





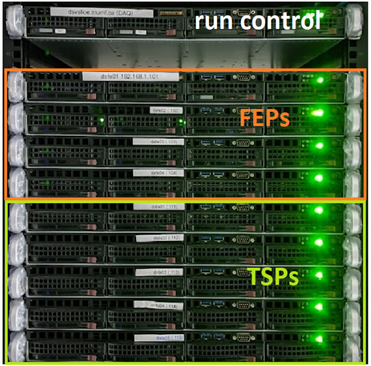
- CAEN waveform digitizers provide ”OpenFPGA” service that allows a user to customize the digital pulse processing.
- Firmware developed at TRIUMF is designed to identify only those waveform segments that contain a signal and transfer those to the next processing stage

✓ DAW applied to MC data shows that data rate is $\sim$ 40 MB/s/digitizer during normal data taking

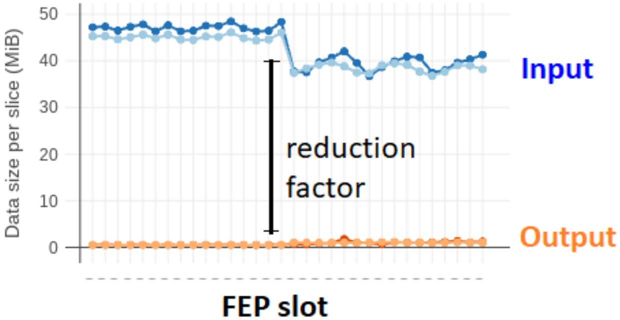


- Waveform segments are reduced to *hits*
- A *hit* represents one or more photoelectrons by its prominence
- The hit finding algorithm must be efficient to process real time data
- The FrontEnds ship to the next processing stage time ordered collection of hits, plus ancillary observable, like integral of the segment

Vertical Slice (Prototype) at TRIUMF

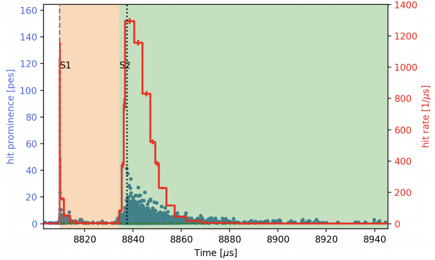


Simulated waveform segments fed into FrontEnds at realistic rate



✓ Live monitor shows data reduction by a factor of ~ 40 between FEPs and TSP

- Assembles the payload received from all the FEPs
- Performs detector analysis over a time period corresponding to a time slice duration
- Operates a selection of the hits reconstructed in the previous stage of processing in order
- Writes to disk the detector data



Example detector analysis: clustering and *pulse shape discrimination* (Credit: T. Hessel, APC)

header: Start time [int], channel [short int], charge integral [float]

Hit info: Sample [short int] (relative to segment start time), Prominence [float]	Hit info	...	Hit info

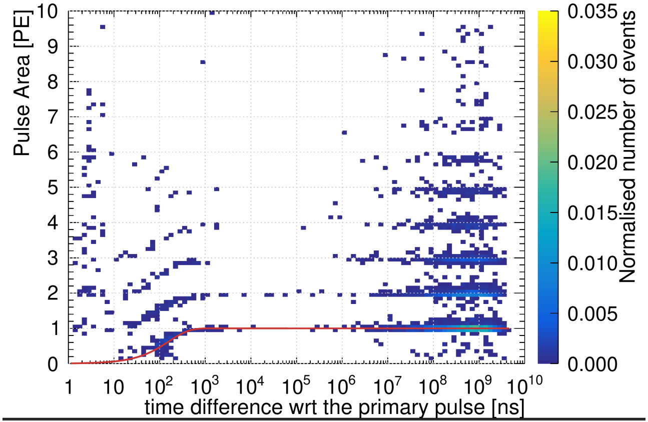
✓ Preliminary MC estimates showed that the data rate to disk $\sim$ 35 MB/s (TPC only)

Summary

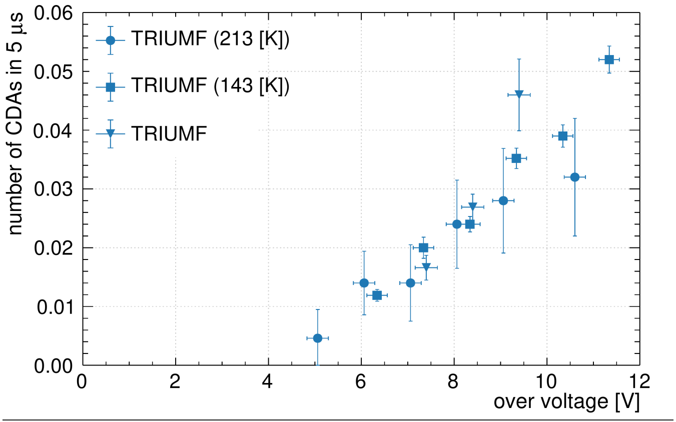
- Light detection in DarkSide-20k with SiPM
  - R&D at LNGS, FBK and LFoundy lead to large area devices, with acceptable noise and high efficiency
- Signals from photosensors are acquired independently from one another: trigger-less DAQ
- Online computing farm will process the data stream
  - Vertical Slice at TRIUMF testing the ”mechanics” of Time Slice
  - Upcoming ”data challenge” (1/4 of readout) to test network and data flow
- DarkSide-20k can transform photons into bytes!

Additional Material

FBK NUV HD LF Cryo

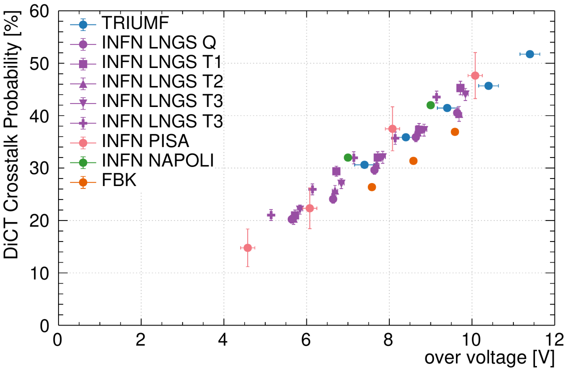


Charge distribution of first pulses following single PE dark noise driven trigger pulses as a function of the time difference with respect to their primary pulse for a temperature of 77 K and for an over voltage of 10.4 ± 0.2 V.

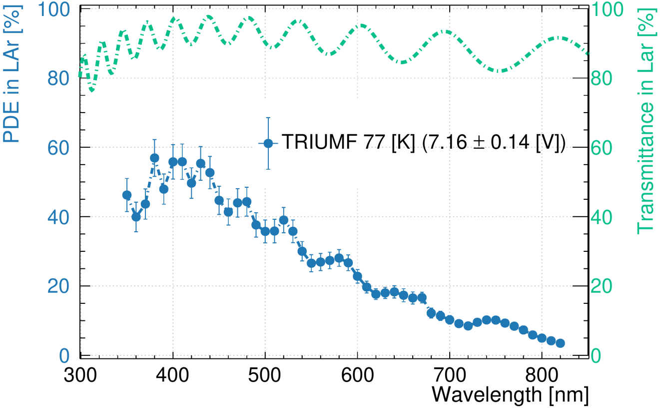


Correlated Delayed Avalanches (CDAs) in FBK NUV HD LF Cryo are negligible therefore Direct crosstalk as the main source of correlated avalanches for these SiPMs.

Direct CrossTalk



Secondary photons that that are absorbed in the same SiPM produce avalanches nearly simultaneous to the primary one Direct CrossTalk (DiCT)



To model correctly the FBK NUV HD LF Cryo PDE for DS-20k simulations, it is necessary to know it not only at 420 nm but also in a broader wavelength range due to the not monochromatic TPB emission that is expected to be between [350-600] nm at LAr

Optical Plane Map

DarkSide-20k Optical plane SiPM Map

Tile x **8448**

PDM x **2112**

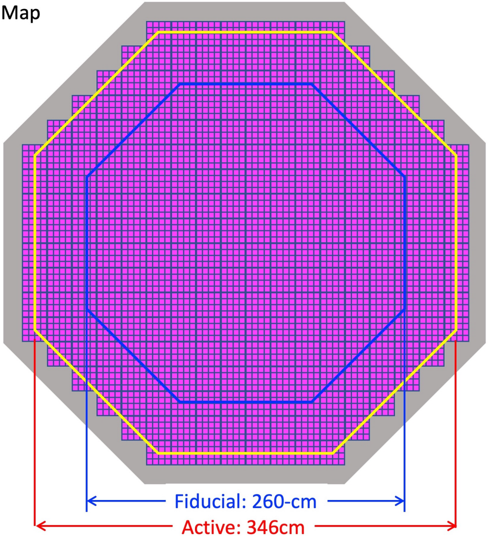
PDU x **528**

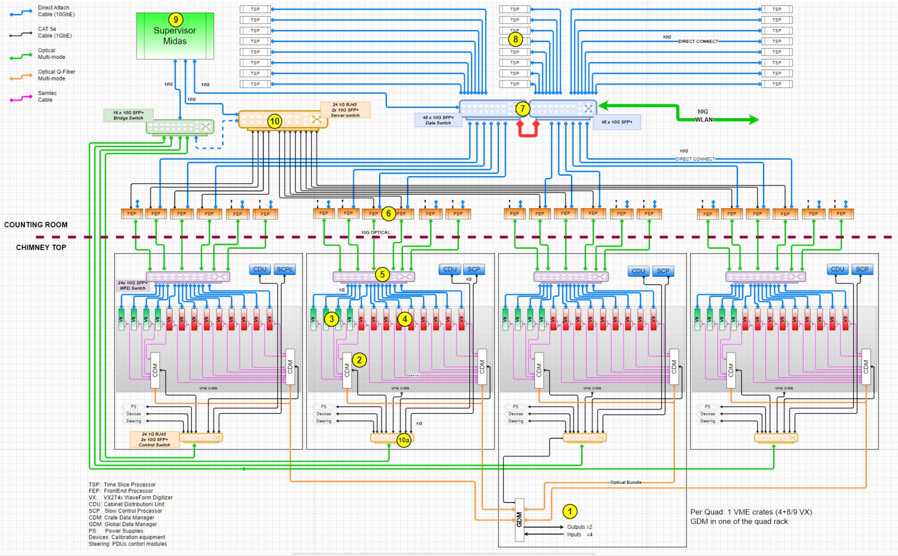
Optical Plane:

4224 tiles;
1056 Ch
264 PDU x **4** PDM x **4** Tile

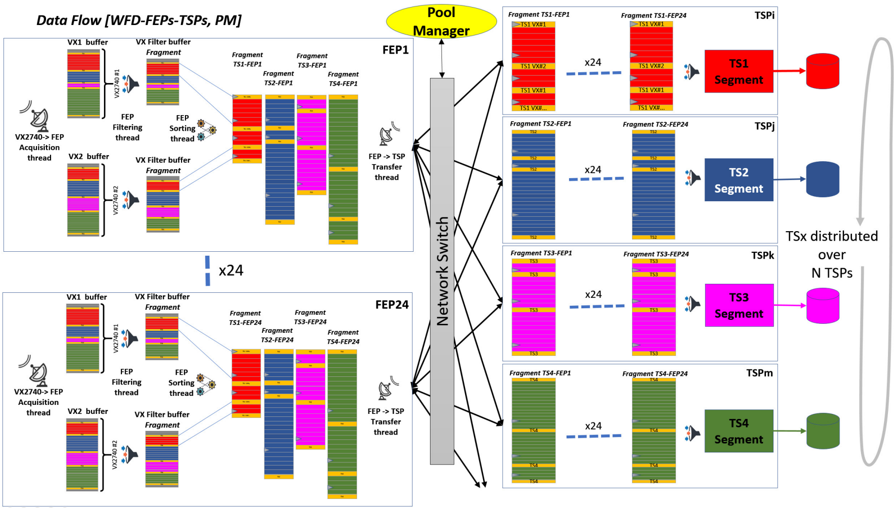
Total: **8448** Tiles,
2112 channels,
528 PDUs
Total: **33** 64-ch-DAQ-boards

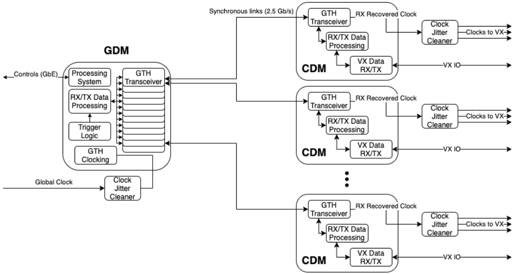
Only 1 type of PDU





Direct Attach Cable (10GbE)
CAT 5e Cable (1GbE)
Optical Multi-mode
Optical Q-Fiber Multi-mode
Samtec Cable
9 Supervisor Midas
16 x 10G SFP+ Bridge Switch
10 24 1G RJ45 2x 10G SFP+ Server switch
7 48 x 10G SFP+ Data Switch
48 x 10G SFP+
8 TSP
10G DIRECT CONNECT
10G WLAN
6 FEP
10G OPTICAL
COUNTING ROOM
CHIMNEY TOP
CDU SCPc
CDU SCP
5 24x 10G SFP+ WFD Switch
3 4 VX
2 CDM
vme crate
PS
Devices
Steering
24 1G RJ45 2x 10G SFP+ Control Switch
10a
1G
Optical Bundle
1 GDM
Outputs x2
Inputs x4
TSP: Time Slice Processor
FEP: FrontEnd Processor
VX: VX274x WaveForm Digitizer
CDU: Cabinet Distributioni Unit
SCP: Slow Control Processor
CDM: Crate Data Manager
GDM: Global Data Manager
PS: Power Supplies
Devices: Calibration equipment
Steering: PDUs contorl modules
Per Quad: 1 VME crates (4+8/9 VX)
GDM in one of the quad rack


Data Flow [WFD-FEPs-TSPs, PM]
Pool Manager
FEP1
VX1 buffer
VX Filter buffer
Fragment
VX2740 #1
FEP Filtering thread
FEP Sorting thread
VX2740-> FEP Acquisition thread
VX2 buffer
VX2740 #2
Fragment TS1-FEP1
Fragment TS2-FEP1
Fragment TS3-FEP1
Fragment TS4-FEP1
FEP -> TSP Transfer thread
x24
FEP24
Fragment TS1-FEP24
Fragment TS2-FEP24
Fragment TS3-FEP24
Fragment TS4-FEP24
Network Switch
TSPi
TS1 VX#1
TS1 VX#2
TS1 VX#...
TS1 Segment
TSPj
TS2 Segment
TSPk
TS3 Segment
TSPm
TS4 Segment
TSx distributed over N TSPs



- The DAQ system can run in *trigger'ed mode* thanks to a custom board developed at TRIUMF, called Global Data Manager, or GDM.
- This unit receives bit patterns from all the digitizer crates.
- Local crate Data Managers, or CDMs, collect the bit pattern of the discriminated output of the waveforms digitizers (WFDs) before transferring them to the GDM.
- GDM and CDMs
  - distribute a global clock (GPS),
  - (can) issue a global readout trigger based on a *hit map*.

Data Reduction

- Input per digitizers (WFD): $\sim$ 16 GB/s
- Max. digitizer output: 125 MB/s (1Gbps)
- Reduction factor per digitizer: 120
- Max. rate into TSP: 1.25 GB/s (10Gbps)
- Reduction factor to TSP: 5
- Required reduction factor to disk: 19

- Number of digitizer for TPC: 36
- Number of digitizer for Veto: 12
- With 2 WFD per FEP, 24 FEP are required
- Input per FEP: $\sim$ 250 MB/s
- Total FEP output: 250 MB/s $\times$ 24 $=$ 6 GB/s
- *Desired* maximum data logging rate: 60 MB/s = 2 PB/y