DP-FE electronics and DAQ interface aspects (V1.0 25/10/2017)

a) General description of the DP-FE electronics

The Dual-Phase Front-End Electronics Consortium deals with the analog front-end cryogenic electronics for the charge readout (based on dedicated large dynamics dual-slope cryogenic ASIC chips) and the warm FE digitization system (for both charge and light readout) which is hosted in uTCA crates. These crates are located close to the signal feedthrough chimneys, for the charge readout, and near the PMTs signal feedthroughs for the light readout.

The components foreseen for a 10 kton DP modules are based on those already produced for ProtoDUNE-DP. A subset of this system is operative since the fall 2016 on the 3x1x1 detector.

The charge readout system is designed in order to provide **continuous, non-zero-suppressed, zero-loss-compressed** readout of 3m long charge readout strips, arranged in two collection views of 3 mm pitch on the anode PCBs of the Charge Readout Planes (CRPs).

Dedicated signal feedthrough chimneys allow operating the analog charge readout FE electronics at a temperature around 100 K, while keeping the possibility of replacing the FE cards without contaminating the pure liquid argon volume.

The analog FE cards, hosting the cryogenic ASIC chips, are plugged on a cold flange at the bottom of each chimney. The cold flange ensures the UHV tightness with respect to the pure liquid argon volume. The other side of the cold flange, inside the cryostat, is connected to the CRPs with flat cables. The FE cards are mounted on 2m long blades, which support the connection cables for signals and LV and allow for the insertion or extraction of the FE cards in/from the cold flange connectors. The access to the electronics at cold was tested on the 3x1x1 detector. It has been quite straightforward with no additional complications compared to the situation when the chimneys were at warm.

The SFT chimneys are closed at the top by a warm flange. This flange is used for dispatching differential analog signals to the AMC cards in the uTCA crates and it allows as well for the connections of the low voltage lines and of the calibration and control signals. The uTCA AMC cards include also a last stage of analog shaping before the input to the ADCs. The AMC cards host ADC chips (eight AD9257 per card) dual port memories (IDT70T3339) and an FGA (ALTERA Cyclone V) with a virtual processor (NIOS) which takes care of the readout and of the data transmission over the 10 Gbit/s network. See Fig. 0 for a general synoptic of the card.

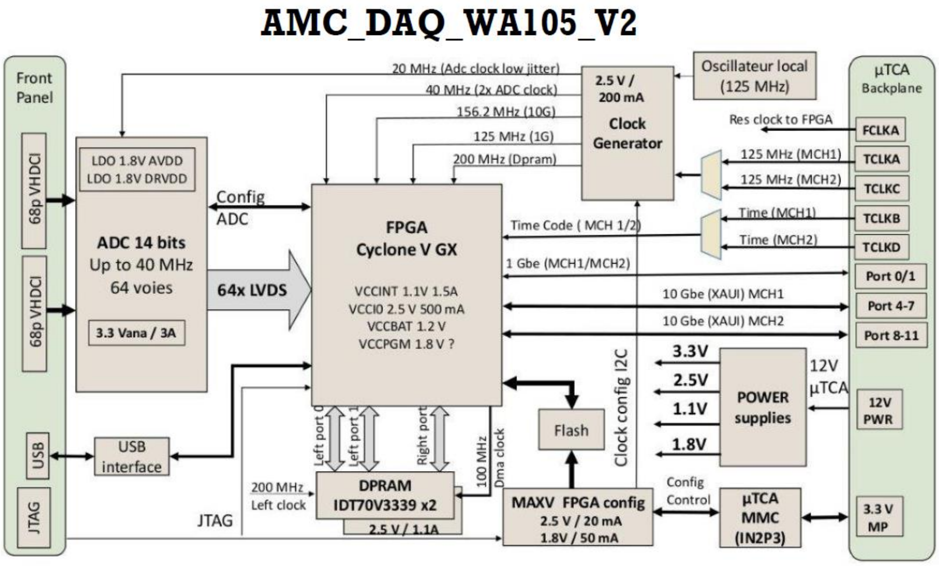


Fig.0: Synoptic of the ProtoDUNE-DP AMC digitization cards

Data sampling is performed at 2.5 MHz. The ADCs have 14 bits however; the final data transmitted take only the 12 most significant bits. Lossless data compression based on an optimized version of the Huffman algorithm is performed on the AMCs and then data are organized in data frames to be transmitted over the links, these frames contain also the absolute timing information of the first data sample.

Digitized data are collected from the cards by the MCH switch present the each crate and transmitted from the uTCA crates to the DAQ back-end via optical fiber links at 10 or 40 Gbit/s, depending on the version of the MHC. The present layout in ProtoDUNE-DP uses MCH at 10 Gbit/s but it should be considered for the 10 kton implementation to move to 40 Gbit/s links in case the channel density per AMC will be increased for costs reductions or simply because of the evolution of the technology and its market.

The uTCA crates host the digitization AMC cards for the charge and light readout with a high channel density. For the charge readout the minimal figure, corresponding to the present channel density already achieved in ProtoDUNE-DP, consists in 640 channels per crate, 64 channels/card, 10 AMCs per crate.

The timing and trigger distribution is based on an independent White Rabbit network operating at 1 Gbit/s. The trigger distribution relies on the transmission of timestamp trigger data over the White-Rabbit network. A White-Rabbit slave node card is also present in each uTCA crate allowing for timing/trigger distribution on the backplane of the crate to the AMCs by using dedicated lines and a customized protocol.

The detection of the direct scintillation light is the main purpose of the light readout electronics in order to provide the absolute time of the events. The system will also be capable to detect the so-called proportional scintillation light produced by the electrons extracted and amplified in the gaseous phase. The actual photon detectors are assumed to be TPB coated 8-

inch photomultipliers (Hamamtsu R5912-02-mod) located under the cathode. The number of photomultipliers assumed in the DUNE CDR was 180. This number of channels is likely to be increased by a factor 4 in order to have a similar or better surface coverage as in ProtoDUNE-DP. The system will group up to 16 PMTs to be read by a single AMC card in uTCA standard which architecture is derived from an adaptation of the charge readout cards. The different cards are inserted in uTCA crates and the events are time stamped using the White-Rabbit system of the charge readout by including in each uTCA crate a White-Rabbit slave node card.

The use of the uTCA standard allows a cost-effective integration of the light read-out electronics together with the charge readout electronics into the global DAQ system. As for the charge readout, each crate is connected to the back-end via an optical fiber links for the data and White-Rabbit.

Figures 1-4 provide a general description of the FE electronics and DAQ design implemented in ProtoDUNE-DP. Fig.1 shows the physical implementation of the analog and digital charge readout electronics on the cryostat. Fig. 2 shows the architecture of the digitization and timing system in ProtoDUNE-DP. Fig. 3 provides the description of the charge readout data corresponding to a drift window in ProtoDUNE-DP. ProtoDUNE-DP will operate during the beam spills by acquiring drift windows triggered by scintillation counters on the beam line.
The drift windows last 4 ms and the system will operate at a rate of 100 Hz, which is not far from a continuous operation mode. Fig. 4 shows the working principle of the AMC cards for the light readout, which in ProtoDUNE-DP, during beam spills, will sample the light signals producing a final sampling at 2.5 MHz in the 4 ms before and after beam triggers. These cards can also have a continuous streaming mode and generate local light triggers.

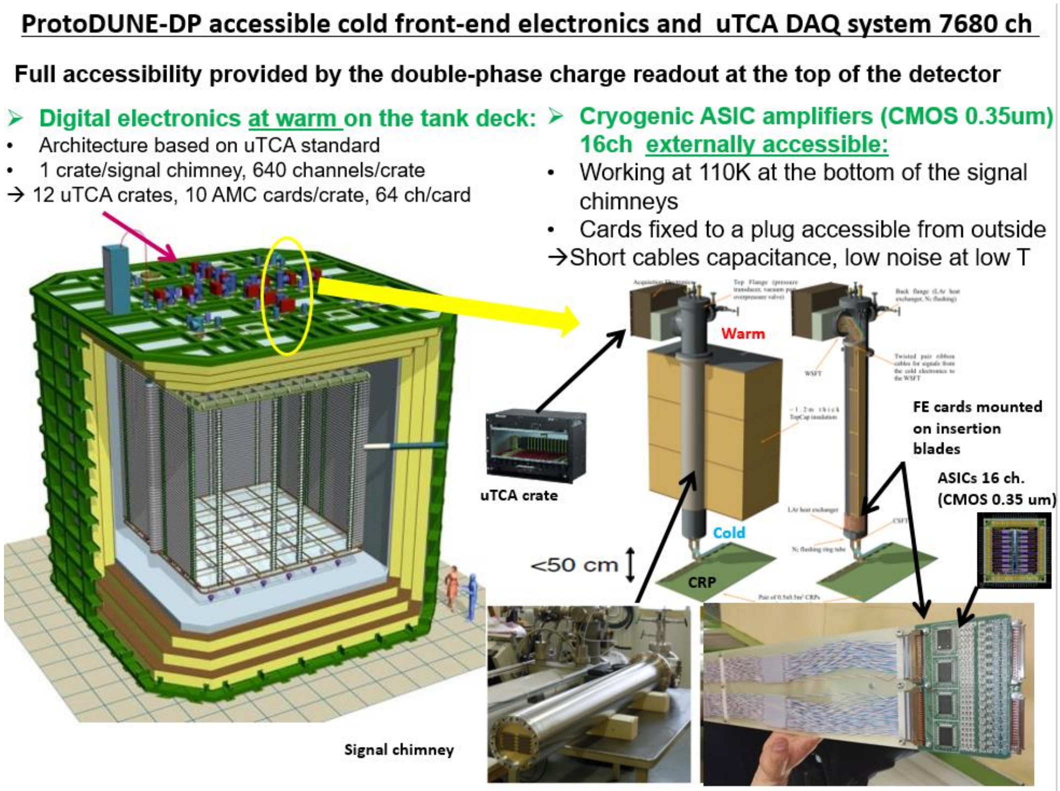


Fig.1: Physical layout of the components of the charge readout FE electronics in ProtoDUNE-DP (analog FE cards in the chimneys and digitization cards in the uTCA crates)

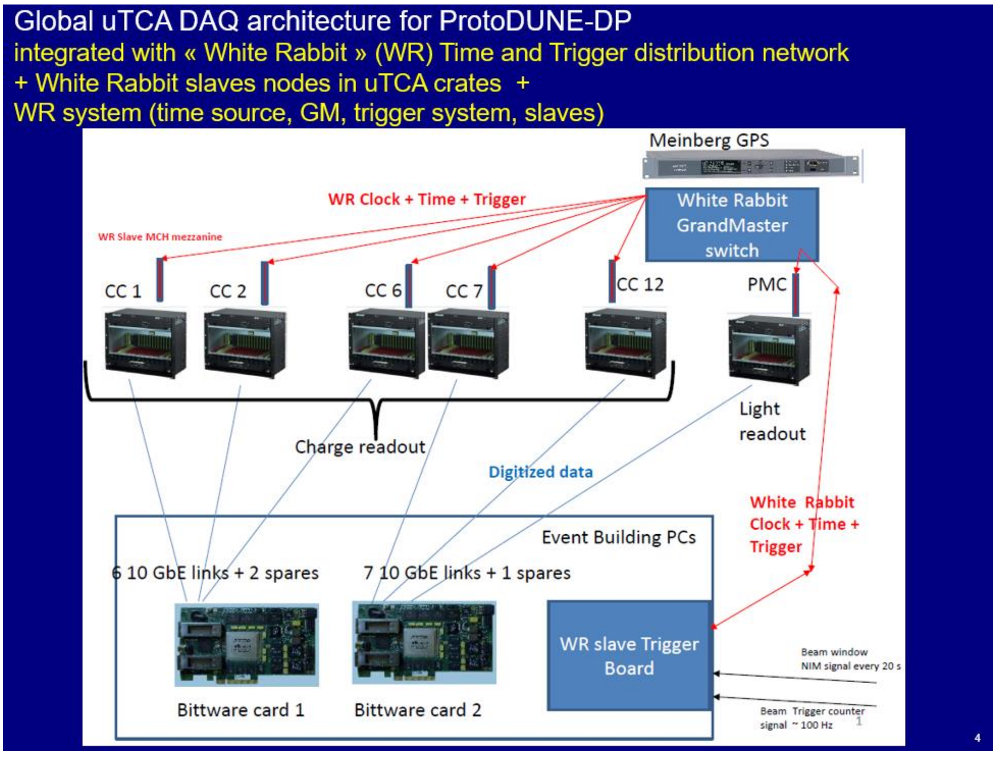


Fig.2 Architecture of the DAQ and timing system in ProtoDUNE-DP

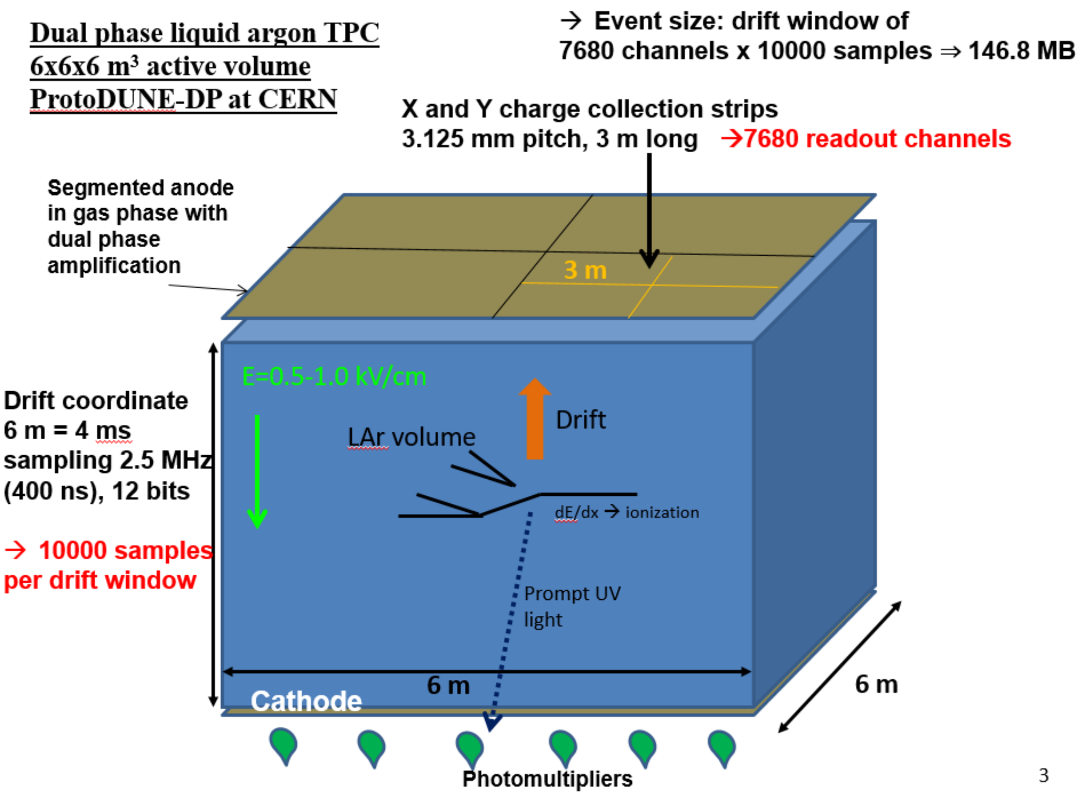


Fig.3: Charge readout digitization scheme corresponding to a drift window in ProtoDUNE-DP

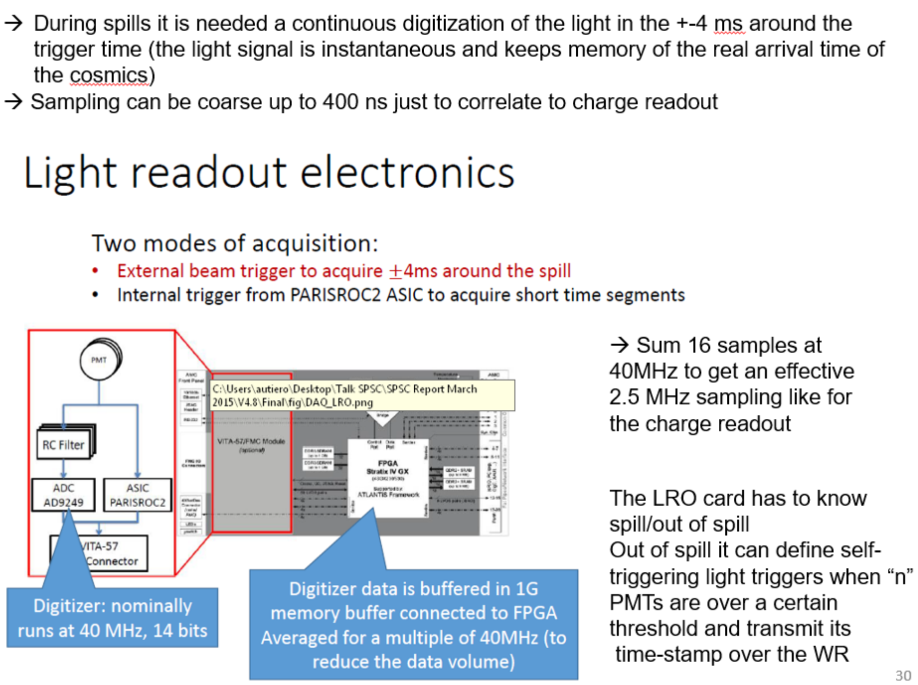


Fig.4: Light readout AMC cards designed for ProtoDUNE-DP and their sampling mode for beam events

b) Details on the ProtoDUNE-DP timing/trigger system

The timing/trigger system in ProtoDUNE-DP is based on a White-Rabbit network. A GPS unit feeds the 10 MHz and 1 PPS signals to a White-Rabbit commercial Grand Master switch. This switch is connected via 1 Gbit/s optical links to the uTCA crates for timing and trigger distribution.

In each uTCA crate it is present a dedicated White-Rabbit end-node slave card. Triggers (beam counters, cosmic ray counters, photomultipliers reading the UV light, starts of beam spills) are time stamped in a dedicated White Rabbit slave node: a FMC-DIO card commercial card + SPEC, with customized firmware, hosted in a PC. The FMC-DIO is connected to the Grand-Master for synchronization and in order to transmit back the trigger information. The time stamps data produced on the FMC-DIO are then transmitted over the White Rabbit network as Ethernet packets by using a customized protocol.

A White Rabbit slave node card (WR MCH) is present in each uTCA crate allowing for clock/timing/trigger distribution on the backplane of the crate to the AMCs by using dedicated lines and a customized frames protocol. This White-Rabbit MCH is another development performed by ProtoDUNE-DP. It includes as mezzanine a commercial WRLEN White-Rabbit slave node card with customized firmware.

This timing/trigger system was already completed and installed in the fall 2016 for the operation of the 3x1x1 detector. The same system will be used for ProtoDUNE-DP and it is a system completely scalable to the 10 kton detector. White-Rabbit is suitable for transmission and synchronization with optical fibers over tens of kilometers, as currently used in the CERN accelerators chain. In case of DUNE the GPS unit and Grand Master can be installed on surface and then connected with 1 Gbit/s optical fibers to the other White-Rabbit switches located underground on the detector.

c) ProtoDUNE-DP FE electronics and DAQ installation for the 3x1x1 detector in hall 182

A subsample of the charge readout electronics produced for ProtoDUNE-DP (for 1280 readout channels) and of the other components of the timing and DAQ system is operative since the fall 2016 on the 3x1x1 pilot detector, which allowed as well validating the noise conditions which are relevant for the compression performance. The DAQ system of the 3x1x1 detector included also a reduced version of the online storage and processing facility foreseen for ProtoDUNE-DP. Figures 5-8 show various details of the system implemented on the 3x1x1.

6x6x6: 12 uTCA crates (120 AMCs, 7680 readout channels)

→ 3x1x1: 4 uTCA crates (20 AMCs, 1280 readout channels) Operational since fall 2016

Event builder, network, GPS/White Rabbit GM, WR Trigger PC

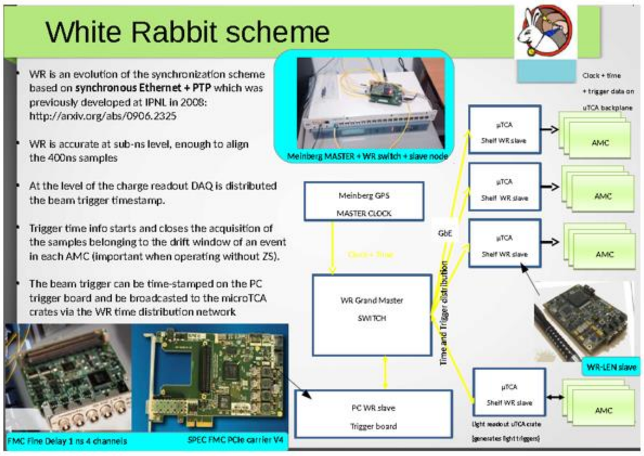
Signal Chimneys and uTCA crates

Fig.5: Subsystem of the ProtoDUNE-DP charge readout system operating on the 3x1x1 detector since the fall 2016

White Rabbit trigger time-stamping PC (SPEC + FMC-DIO)

White Rabbit Grand-Master

GPS unit



White Rabbit uTCA slave node based on WRLEN developed and produced for entire 6x6x6

Other components of the chain (GPS receiver, WR grandmaster, SPEC+ FMC-DIO + 13 WRLEN) available commercially

7

Fig.6: Details of the White-Rabbit timing-trigger system already implemented on the 3x1x1 detector

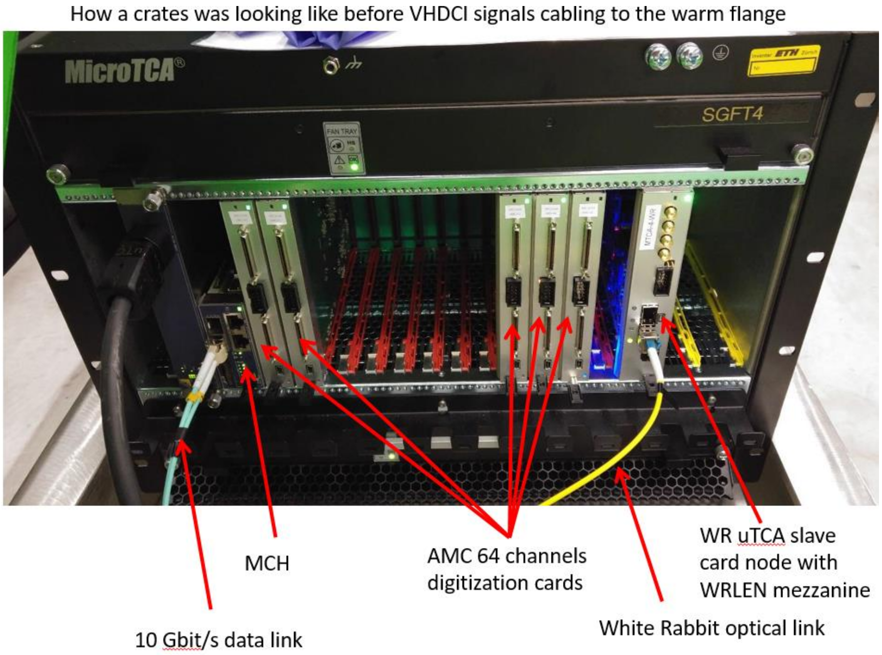


Fig.7: Picture of a uTCA crate installed on the 3x1x1 detector charge readout system. The crate contains five AMC cards corresponding to the chimney modularity of the 3x1x1. The crates of ProtoDUNE-DP contain 10 AMC cards.

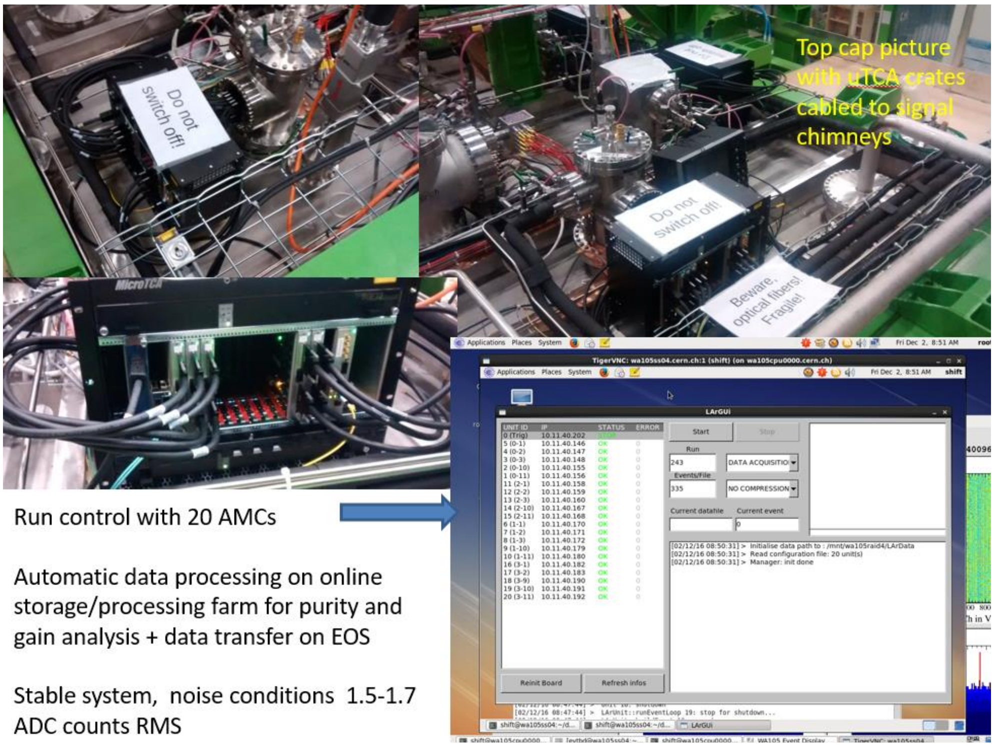


Fig.8: Charge readout system and DAQ operating on the 3x1x1 detector.

d) ProtoDUNE-DP FE electronics scaled to a 10 kton DP module

Figures 9-12 show the architecture of the system foreseen for a 10 kton DP module, on the basis of a scaling by a factor 20 of the electronics developed for ProtoDUNE-DP and the number of associated components.

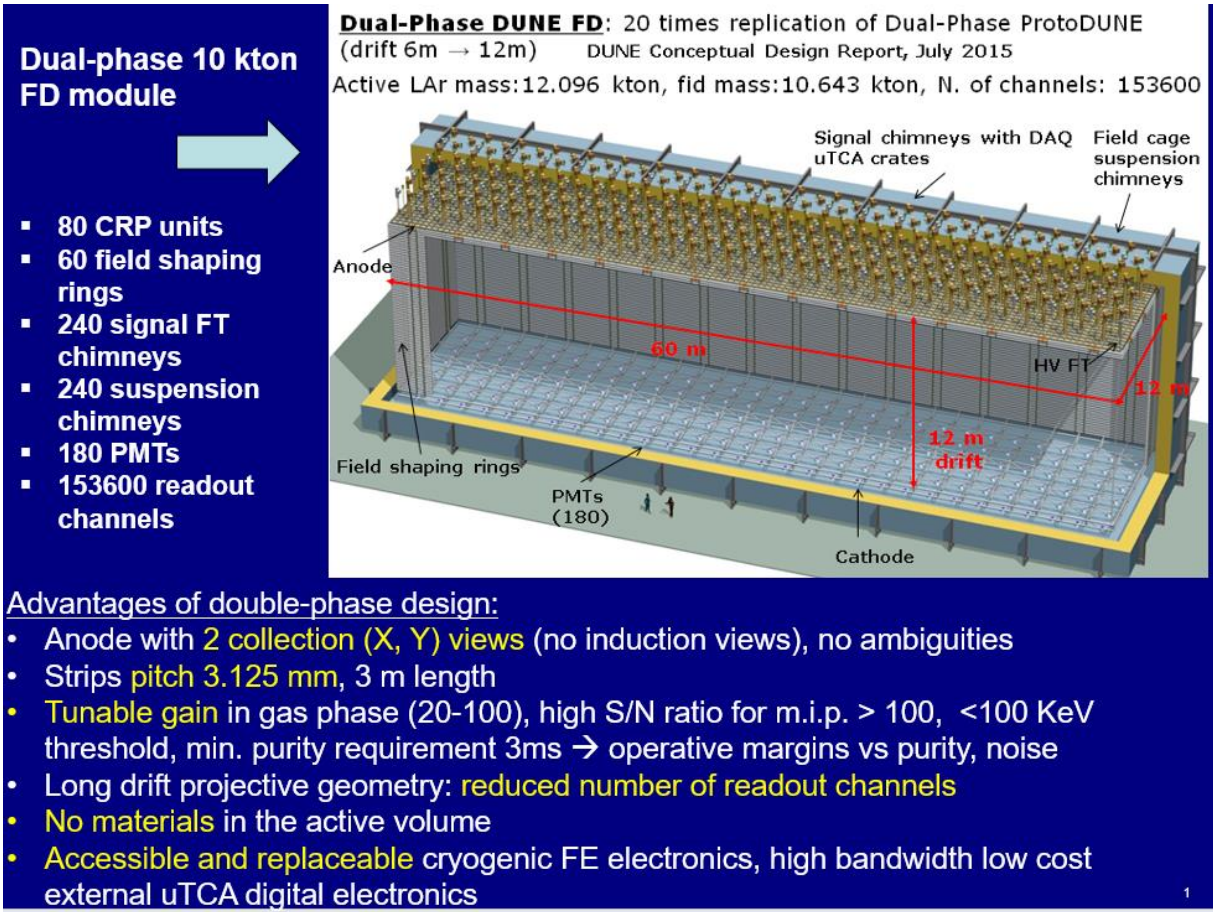


Fig.9: General description of a 10 kton DP module

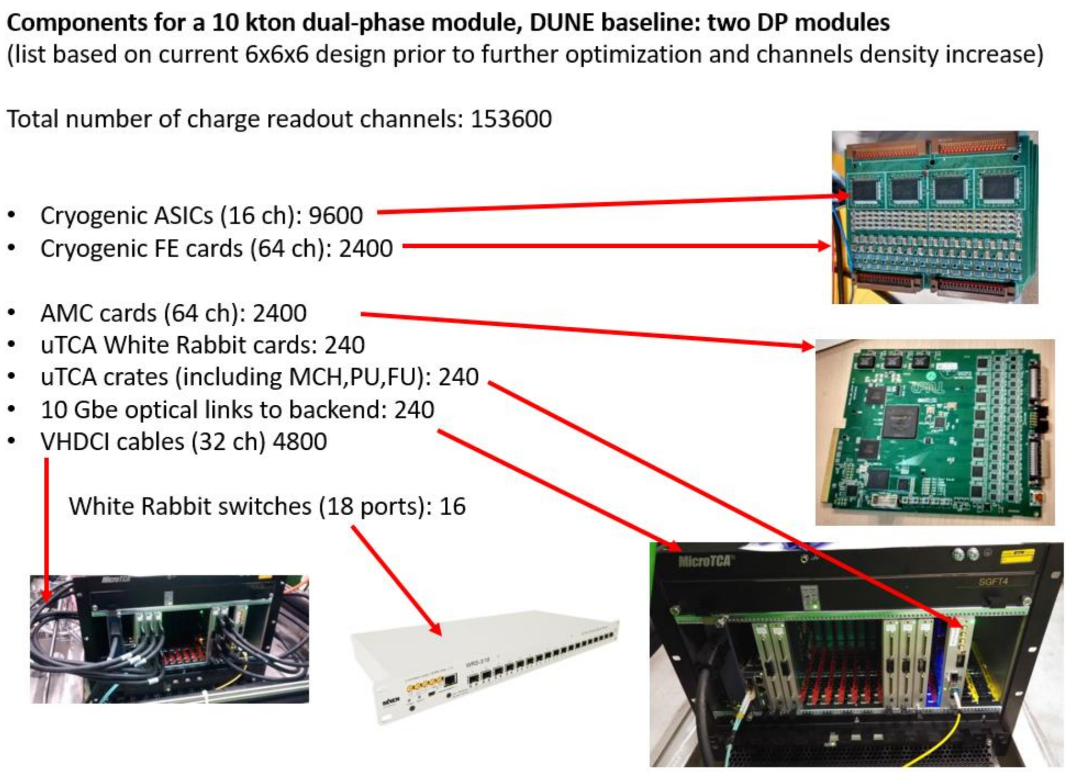


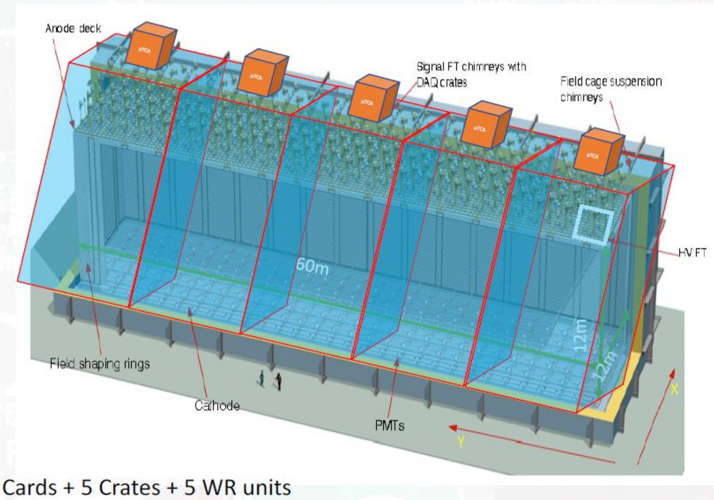
Fig. 10: Different components of the DP charge readout FE electronics foreseen for a 10 kton module

Number of CRPs	80				
Number of strips/CRP X	960				
Number of strips/CRP Y	960				
Number of RO channels/CRP	1920	Total number of channels/10 kton module	153600		
Number of channels/chimney	640	Number of chimneys/10 kton module	240	Number of warm flanges/10 kton module	240
Number of channels/ASIC	16	Number of chimneys/CRP	3	Number of cold flanges/10 kton module	240
Number of ASIC/FE card	4	Number of uTCA crates/10 kton module	240	Number of 10Gbe optical links/10 kton	240
Number of channels/FE card	64	Number of FE cards/10 kton module	2400	Number of 1Gbe WR links/10 kton	240
Number of FE cards/chimney	10	Number of ASIC/10 kton module	9600		
Number of channels/AMC	64			Number of 68 pins flat cables/chimney	10
Number of AMC/uTCA crate	10	Number of AMC cards/10 kton module	2400	Number of 80 pints flat cables/chimney	10
Number of channels/crate	640			Number of 68p flat cables/10 kton	2400
Number of uTCA crates/chimney	1			Number of 80p flat cables/10 kton	2400
Number of MCH/crate	1	Number of MCH/10 kton module	240		
Number of WR slave/crate	1	Number of WR slaves/10 kton module	240	Number of output ports per WR switch (WR	17
Number of uTCA power units/crate	1	Number of power units/10 kton module	240	Number of switches layer 2	15
Number of fan units/crate	1	Number of uTCA fan units/10 kton module	240	Number of GM switches/layer 1	1
Number of channels/VHDCI cable	32			Number of WR switches total	16
Number of VHDCI cables/AMC	2	Number of VHDCI cables/10 kton module	4800		

Fig. 11: Table of the different components of the DP charge readout electronics foreseen for a 10 kton module

Optimized version 1: 720 PMTs (1 PMT/ m^2)

Item	Details	Quantity
PMTs		720
FE-Cards	16 channels	45
	Components	
	printed cirquid	45
	PCB masques	1
	Mounting of components	
	Cabels SMA	720
	Catyroc	45
	ADC	45
micro-TCA crate		5
	MCH	5
	Power Module	5
	XAUI (x4)	5
	Uplink SFP+	5
	Uplink SFP+850	5
White Rabbit		5
	SPEC Card	5
	FMC DIO	5
	SFP (x2)	5



45 FE Cards + 5 Crates + 5 WR units

The distribution of the cards and number of crates to be optimized wrt to cable length and signal attenuation

First idea: cut detector in 5 12 m long segments

(5 x 12 m) long x 12 m wide -> 5 crates on top of the detector

Fig. 12: Different components of the DP light readout FE electronics for a 10 kton module, example corresponding to a similar surface coverage as in ProtoDUNE-DP.

e) ProtoDUNE-DP back-end system and possible evolution at the 10 kton scale

It will be possible to extract some valuable experience for the design of the DUNE DAQ system from the design and operation experience of the ProtoDUNE-DP back-end system. This will be another contribution provided by the groups of the DP FE electronics Consortium, which are involved in ProtoDUNE-DP as well as in the DAQ consortium.

The FE system of ProtoDUNE-DP consists of 12 uTCA crates for the charge readout and 1 crate for the light readout. All these crates are connected to the back-end system with Ethernet optical links operating at 10 Gbit/s.

The backend consists of two levels of event builder machines. The L1 event building is provided by two machines DELL R730 (256GB RAM). Each of these machines has network cards receiving up to eight 10 Gbit/s links and a card providing two 40 Gbit/s links in output to the LV2. The two L1 machines put together the data flow from the crates in two halves of the detector and the light readout data.

A scalable architecture including 4 LV2 machines (DELL R630, 128 GB RAM) performs the last step needed to format the events in files to be written on disk by putting together the two event halves in the complete event, by buffering several events in memory, and by writing the data on disk. In order to have an efficient files throughput data are grouped in files of a few GB size. Each file including hundreds of events. The LV2 machines work in parallel in

ProtoDUNE-DP in order to provide the maximal data writing bandwidth to the storage system and each one of them assembles and writes its own data file once having put together enough events to fill the desirable data file size.

The network architecture interconnecting the machines is based on 40 Gbit/s links handled by a switch (40 Gbps DAQ switch with 26 ports, expandable to 32, Brocade ICX 7750-26Q). This switch is interconnected via 4 links at 40 gbit/s with a router (10 Gbps Router 48 ports with 6 uplinks at 40 Gbps Brocade ICX7750-48F). The router connects the DAQ system to the storage servers and the processing farm.

The system of storage servers includes 20 machines DELL R510 (72 TB per machine, up to 1.44 PB total disk space for 20 machines) each one of them has 10 Gbit/s connectivity. The storage system operates under a distributed file-system based on EOS. This file system was accurately choses after a long tests campaign, since it was found to provide the best data flow performance. The distributed file-system allows for a fast data access by making a parallel use of the disks installed on the storage servers thanks to a metadata server. The storage system is capable of handling a data bandwidth of 20 Gbytes/s, which guarantees a margin of a factor 10 with respect to the data flow of ProtoDUNE-DP operating at a trigger rate of 100 Hz.

The processing farm includes about 1000 cores arranged in 12 racks with 10 Gbit/s connectivity per rack. The farm operates a system of batch queues for the submission of the online processing jobs. An automatic software provide the submission of the analysis jobs as soon as the files are created on disk. A subset of this online storage and processing farm has been already operating for the 3x1x1 detector, including the local EOS distributed file-system.

This DAQ architecture was designed for the particular operation mode of protoDUNE-DP based on:

1) external triggers not generated by the charge readout itself (triggers from: beam counters, large area cosmic ray counters or light readout system) defining events corresponding to a drift window
2) very large data volume to be written continuously on disk (all drift windows at 100 Hz rate during the spills without zero suppression and using lossless compression)
3) data quality online-analysis (aimed at measuring the LAr purity and the detector gain) performed with batch jobs on the processing farm, each job corresponding to a multi-event file written on disk.

The system for the 10 kton module may have several similarities in the architecture and some differences related to new aspects related to the specific operation mode of the 10 kton detector also for proton decay an SN neutrino searches:

a) Continuous triggerless data taking flow from the AMC cards to the event builders situated in the DAQ system. The AMC cards operating in ProtoDUNE-DP function by dumping from their internal dual-port memories the drift windows corresponding to the time-stamps of the external triggers but they are already capable of working in a continuous sampling mode, as foreseen for the 10 kton operation.
b) Charge triggers to be generated by the data analysis on the events builders, this is a main difference with respect to the ProtoDUNE-DP working mode and it will require to implement the proper algorithms at the level of the event building farm.

c) Smaller data volume to be written on disk, just for the selected events (beam events, cosmic rays and proton decay candidates, SN burst candidates)
d) Necessity of keeping a 10s window on the event builders for SN events searches
e) Different requirements on the online analysis, smaller rate of events, mainly cosmics

The general architecture for the 10kton could be designed as a scalable version of the existing ProtoDUNE-DP architecture. The number of event building machines and the RAM memories should be properly scaled in order to guarantee the 10 s window events buffering. The network architecture may have several similarities with the already existing one, once properly scaled to the 10 kton detector needs. Figures 13-15 document the back-end infrastructure designed for ProtoDUNE-DP at EHN1.

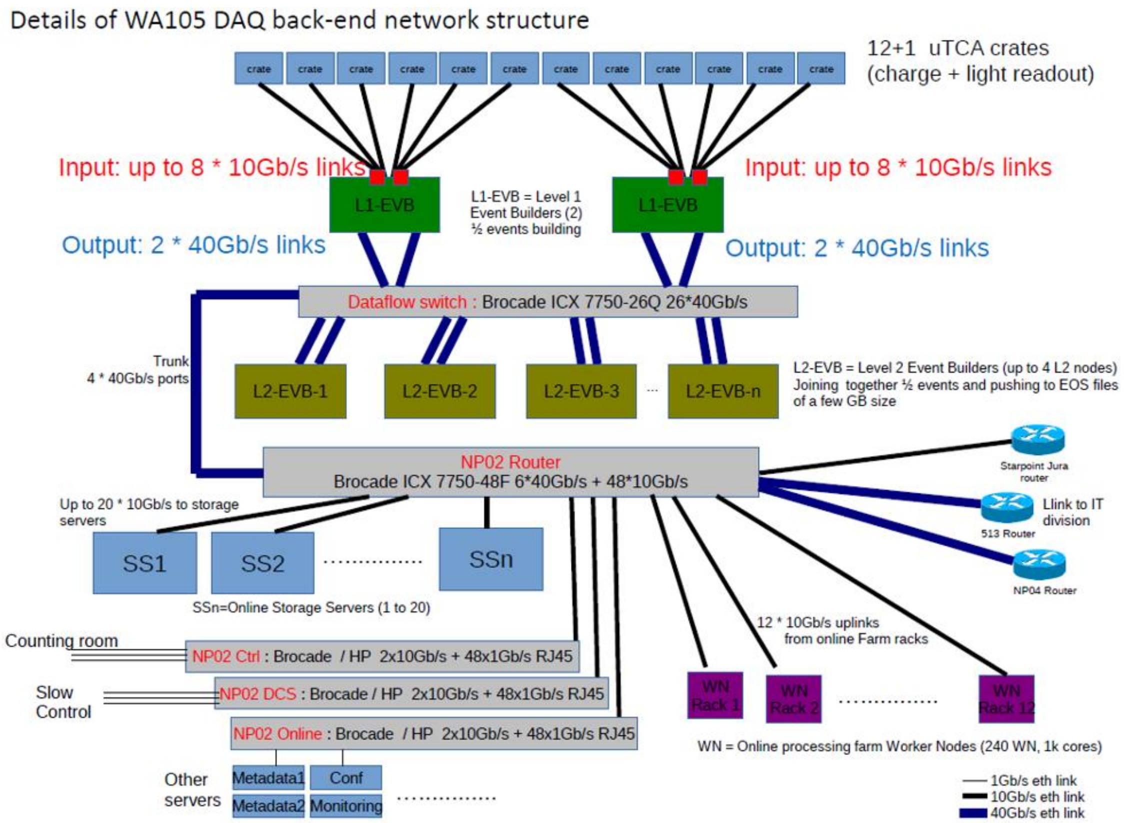


Fig. 13: Layout of the ProtoDUNE-DP back-end DAQ architecture and of the online storage/processing facility

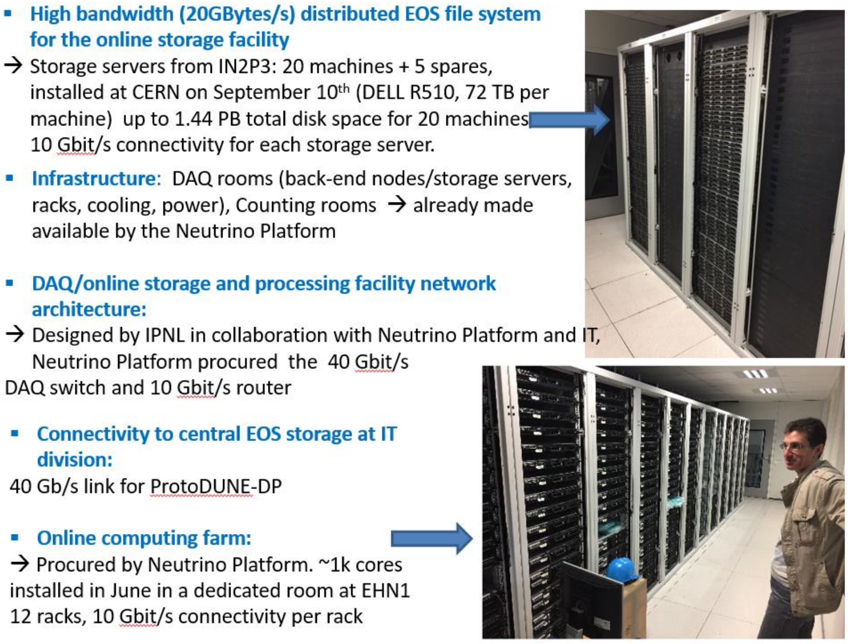


Fig. 14: Some pictures of the ProtoDUNE-DP online storage/processing facility at EHN1

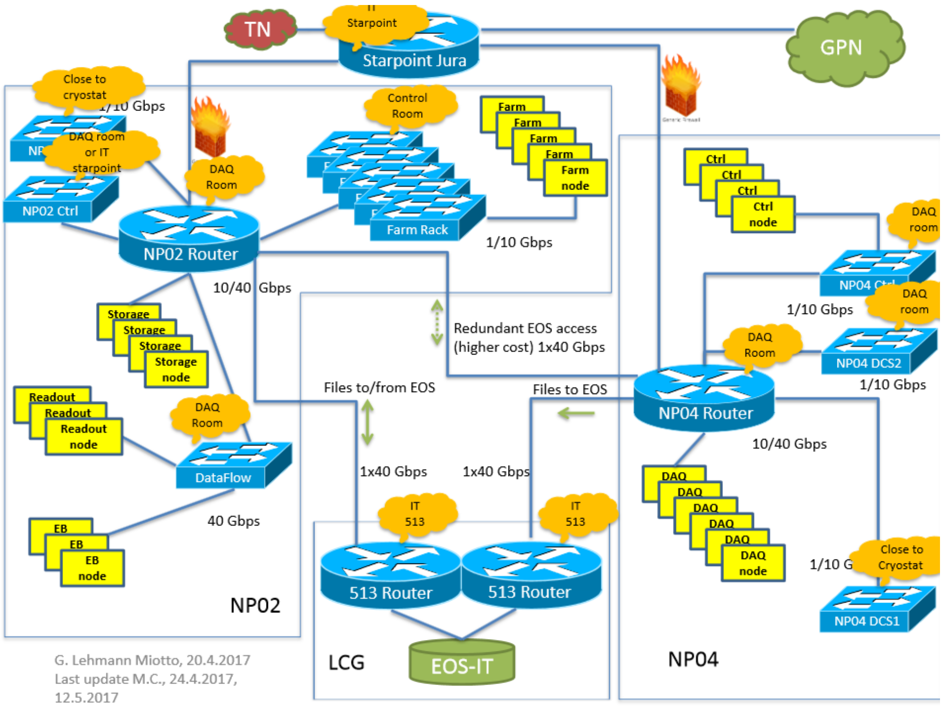


Fig. 15: General network infrastructure at EHN1

f) General assumptions on the DAQ back-end for the 10 kton detector

The DP digital FE electronics deals with the digitization of both charge and light signals. The digitization is performed in high channels density AMC cards hosted in uTCA crates.

The uTCA crates are then connected to the DAQ system with 10 or 40 Gbit/s Ethernet optical fiber links (depending on the MCH version and the channels density per crate (640 channels/crate current density or possibly doubled density).

A White-Rabbit slave node card is also inserted in each uTCA crate for timing/trigger distribution on the backplane of the crate to the AMCs.

The charge readout FE digital system is designed in order to support **continuous, non-zero-suppressed, zero-loss-compressed readout** of 3m long charge readout strips, arranged in two collection views of 3 mm pitch on the anode PCBs of the Charge Readout Planes (CRPs).

Similarly, the light readout FE system can produce high bandwidth data and also issue light triggers transmitted via the White-Rabbit network. The baseline readout granularity corresponds, per 10 kton module, to 153600 charge readout channels and a few hundred light readout channels. This corresponds to 240 10 Gbit/s Ethernet optical links for the charge readout and The DAQ system common to SP and DP should be capable of supporting this high data bandwidth from the FE electronics.

The DAQ system, common to both single and dual phase, is expected to be a network based DAQ system capable of:

a) Collecting this high bandwidth data volume coming from the data links of the FE crates
b) Putting together the data streams from different crates in Regions Of Interest (ROIs) or over the entire detector volume
c) Processing this data flow by an online trigger farm in order to select relevant events to be recorded on disk: neutrino beam, and off-beam events.
d) Producing charge readout triggers independently on the light readout triggers and beam spill information. In particular, triggers over a sliding timing window of about 10 seconds may be issued by the trigger farm for the search of SN neutrinos based on the presence of low energy depositions, in order to dump on disk the entire content of the SN trigger sliding time window.

It is assumed that the DAQ system will be constituted by a set of event building/trigger machines, high performance network elements, an online computing farm and a high bandwidth distributed storage system based on an array of storage servers operating in parallel.

As discussed before, an example of such architecture, which can be inspirational to the one developed for the DUNE FD SP and DP DAQ system, can be obtained from the DAQ backend architecture actually foreseen at EHN1 for ProtoDUNE-DP. That system was already designed to be capable of supporting a data bandwidth of 20 GBytes/s.

The institutes involved in the DP Electronics consortium are also part of the DAQ consortium in order to support the correct interfacing of the FE electronics to the DAQ and to provide the experience coming from the design and operation of the ProtoDUNE-DP DAQ system.

g) Interfaces between the DP-FE electronics and the DAQ and data rates

We expect that the FE-electronics for the 10 kton detectors will be very similar to the one presently produced for ProtoDUNE-DP. The only evolution which is foreseen at the moment could consist in increasing the channels density per card (doubling the channel density). This will also imply moving from the current MCH with optical links at 10 Gbit/s to MCH at 40 Gbit/s.

It is also assumed that the 10 kton detector will have a White-Rabbit network scaled from the currently existing one. The number of foreseen components is provided in the first paragraph of this note.

With the current baseline design the interface to the DAQ system will consist of 240 (10 Gbit/s) optical ethernet links for the charge readout + 5 (10 Gbit/s) optical ethernet links for the light readout. In case of increase of the channels density for the charge readout this figure will become 120 (40 Gbit/s) optical Ethernet links. Ethernet cards operating at 40 Gbit/s are already used in ProtoDUNE-DP event builders and it is expected that they will become even cheaper and more commonly used at the time of the construction of the 10 kton module. The possibility of the uTCA system of evolving with the general trend of the networking industry for better performance and costs reduction is a plus in the design of the system. Also the scalability of the event bulding computing will allow to follow the market trend and benefit from the technology and performance evolution and costs reductions.

It is assumed that the DAQ will consist in a cluster of PCs allowing for the search of charge triggers and event building. The architecture could be quite similar to the one studied for ProtoDUNE-DP after proper dimensioning

In the baseline layout each 10 Gbit/s optical link for the charge readout corresponds to a single uTCA crate (640 channels distributed in 10 AMC cards all connected to the MCH at 10 Gbit/s). The AMC cards will work in continuous sampling mode at 2.5 MHz, 12 bits producing a continuous stream of non-zero suppressed, zero-loss compressed data formatted in Ethernet frames to be transmitted over the 10 Gbit/s optical link. The compression factor achievable for the DP charge readout data is 10. The frames contain also the absolute time information from the White-Rabbit system. Each link will produce a continuous data volume of 1.79 Gbit/s with about a factor 5 margin with respect to its bandwidth. In the current ProtoDUNE-DP back-end the L1 machines have a RAM memory of 256 Gbytes and look at up to 8 links per machine. The current RAM memory looks already sufficient in order to handle a 10 s buffer sliding memory which would go to 180 Gbytes per machine uncompressed format. The compressed format would be kept anyway in memory for transmission to the LV2 and events writing on disk.

The light readout data flow can be formatted by the LRO FE cards in samples corresponding to the charge readout sampling (2.5 MHz) at 14 bits. A finer sampling (40 MHz, 16 times faster) is possible as well for special studies (for instance to measure LAr purity in the initial stage of the experiment). The LRO FE cards can also produce local triggers to be transmitted over the data network or White-Rabbit network. A continuous streaming of the LRO data would correspond to 4.7 Gbit/s per optical link (assuming 9 cards per crate).

We can imagine the 10 kton detector seen as operating as 20 ProtoDUNE-DP detectors running in parallel as possible ROIs.

The search for charge triggers can be performed by the L1 event builders. These machines will also select the events (drift windows) corresponding to the beam spills or to light readout triggers which can be issued by dedicated L1 machines which will be looking at the light readout data flow or by the FE LRO cards. For the cosmic rays flow the events selection can be performed by selecting a drift window corresponding to the T0 from the light information. The search for SN events over the 10 s sliding window buffer can be performed as well by the L1 machines. The LV1 machines can exchange the trigger information over the network in order to decide to dump drift windows (cosmics/beam) or the entire 10s windows (SN bursts candidate) to the LV2 machines which will then assemble the parts of the events on disk files.

The charge readout data size for a drift window (event size) by reading the entire 10 kton detector corresponds to 0.43 Gbytes compressed, this data size could fit several events, of the order of 15, in a single EOS file. This is a pessimistic figure since one could think just to dump on disk (for beam or cosmic events) the interested ROI(s). The size for one ROI of the size of ProtoDUNE-DP would be 22 MB compressed. In this case, one could think to assemble of the order of 300 events per file for the standard cosmics/beam flows in the L2 machines.

For the SN triggers one could think to dump up all the ROIs in the 10s window. In this very pessimistic case the total size would correspond to 536 GB compressed, to be assembled by the L2 machines in 100 separate files of about 6 Gbytes size.