Chapter 1

Detector components

1.1 Overview of detector components

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The elements composing the detector, listed in Section intro:detector **??**, include the time projection chamber (TPC), the cold electronics (CE), and the photon detection system (PDS). The TPC components, e.g., anode planes, a cathode plane and a field cage, are designed in a modular way. The six APAs are arranged into two APA planes, each consisting of three side-by-side APAs. Between them, a central cathode plane, composed of 18 CPA modules, splits the TPC volume into two electron-drift regions, one on each side of the central cathode plane. A field cage (FC) completely surrounds the four open sides of the two drift regions to ensure that the electric field within is uniform and unaffected by the presence of the cryostat walls and other nearby conductive structures. The sections in this chapter describe the components individually.

Figure fig:tpc-overview 1.1

get a figure

illustrates how these components fit together. The FC is shown in Figure fig:fc-overview 1.2.

Figure 1.1: NEED A FIGURE fig:tpc-

Table tab:tpc-components 1.1 lists the principal detection elements of ProtoDUNE-SP along with their approximate dimensions and their quantities.

Table 1.1: TPC detection components, dimensions and quantities

Detection Element	Approx Dimensions	Quantity
APA	6 m H by 2.4 m W	3 per anode plane, 6 total
CPA module	2 m H by 1.2 m W	3 per CPA column, 18 total in cathode plane
Top FC module	2.4 m W by 3.6 m along drift	3 per top FC assembly, 6 total
Bottom FC module	2.4 m W by 3.6 m along drift	3 per bottom FC assembly, 6 total
End-wall FC module	1.5 m H by 3.6 m along drift	4 per end-wall assembly (vertical drift volume edge), 16 total
PD module	2.2 m × 86 mm × 6 mm	10 per APA, 60 total

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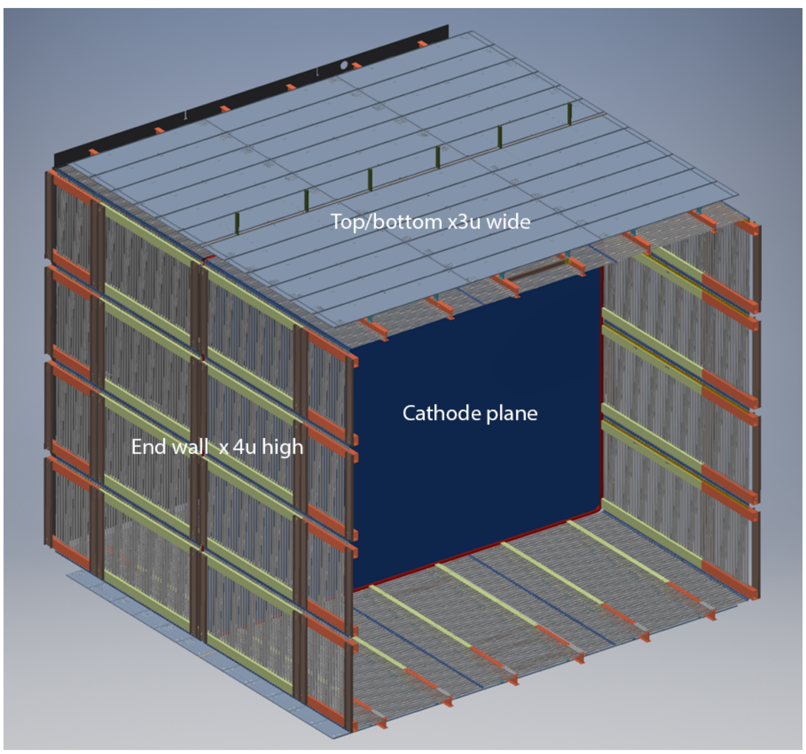

Figure 1.2: A view of the TPC field cage and the central cathode plane (CPA). fig:fc-c

1.2 Data Acquisition (DAQ)

1.2.1 Scope and requirements

The data acquisition (DAQ) system is shown in Figure 1.3 along with its interfaces to the cold electronics, beam instrumentation, and online computing systems.

Figure 1.3 requires significant zooming to read. Need a simpler diagram initially to show the major pieces, and only the DAQ pieces. Also some descriptive text; relate the physical components to data rates and such.

List components: timing, trigger, throttle systems, FPGA-based master, etc.

The physics requirements of ProtoDUNE-SP are the primary drivers of the DAQ system requirements. The front-end electronics and assumed bandwidth and storage requirements from the online and offline computing systems impose additional constraints.

The run plan (see Section **??**) calls for about 25 M analyzable beam events to be collected in the first run of ProtoDUNE-SP. Data sets may be enhanced in desirable particle types and energies with dedicated triggers (such as PID) from the beam instrumentation. The latter is described in Section **??**.

Parameters of the data collection plan are listed in Table 1.2. The lossless compression factor cited in the table is based on the assumption that the signal-to-noise level is similar to or better than that achieved by MicroBooNE.

needs citation

Table 1.2: Parameters defining data rate and volume in the "most likely" scenario v5 [?]. The buffer depth includes both the in-spill and out-of-spill data.

Parameter	Value
Trigger rate	25 Hz
Spill duration	4.8 s
SPS Cycle	22.5 s
Readout time window	5 ms
# of APAs to be read out	6
Single readout size (per trigger)	230.4 MB
Lossless compression factor	4
Instantaneous data rate (in-spill)	1440 MB s^{-1}
Average data rate	576 MB s^{-1}
3-Day buffer depth	300 TB

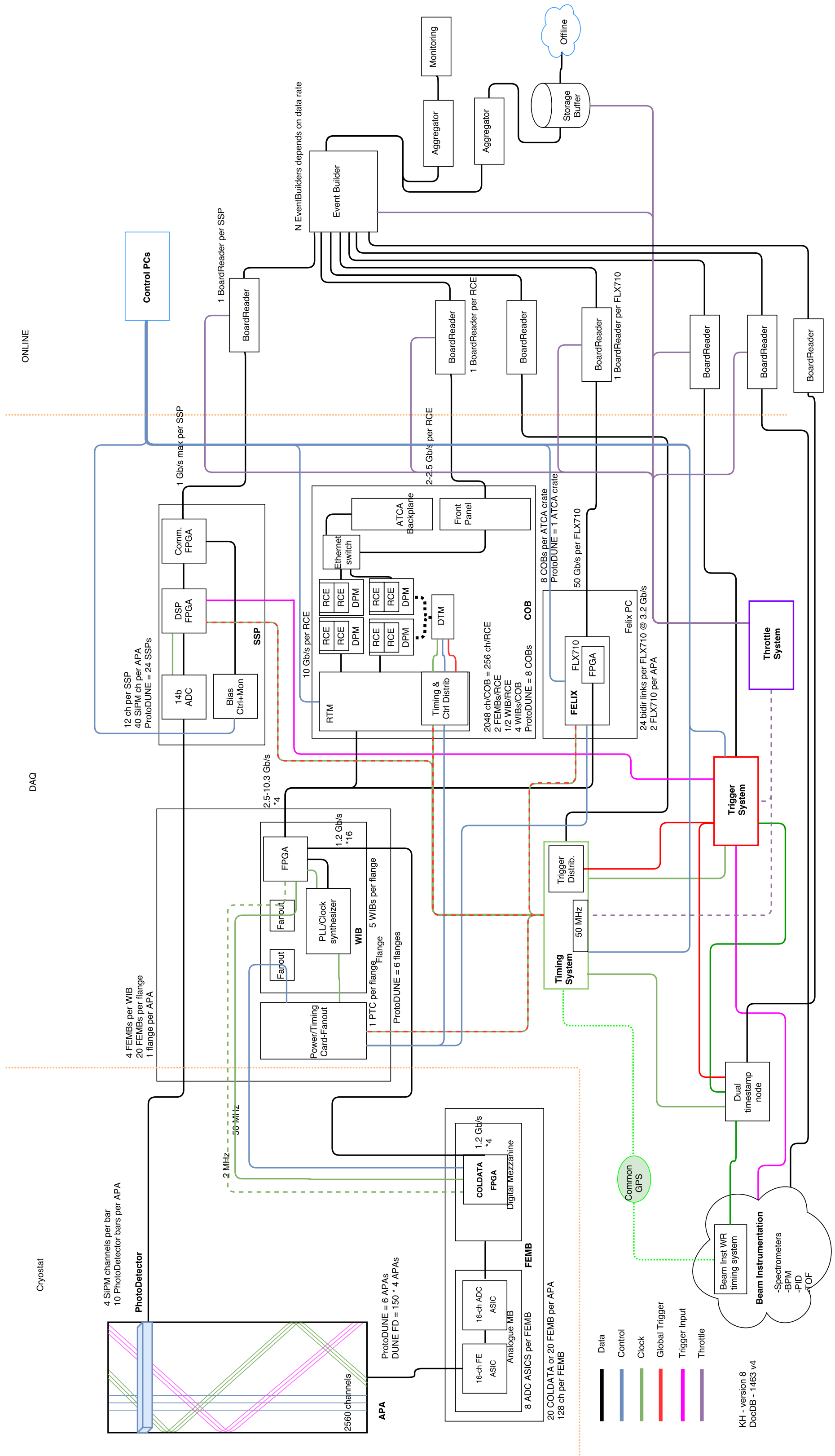

Figure 1.3: Detailed overview of the DAQ system, its interconnections, data flow, timing and control signals, and the interfaces to the electronics and online computing systems fig:daq-

The baseline trigger rate during the SPS spill is taken to be 25 Hz. Cosmic data are also acquired at an appropriate rate such that bandwidth and processing priority are given to beam data. The data rate from the electronics is dominated by the TPC data. However, the photon detection system (PDS) can produce a signifcant amount of calibration data (where full waveforms are extracted), during commissioning and special runs (up to 24 Gb/s maximum).

The TPC data are sent via the Warm Interface Boards (WIB) on the cryostat flanges for the six APAs, un-triggered at a total rate of 480 Gb/s. The PDS is estimated to send data at a total rate of 1.2 Gb/s from the 24 SSPs (detailed further in Section 1.2.6). The maximum bandwidth from the ProtoDUNE-SP online system to CERN IT (and hence, the offline world), is 20 Gb/s at a maximum. Therefore, the DAQ system must reduce the data by a significant fraction before they are sent offline. This is achieved by a combination of data compression and triggering.

1.2.2 Timing, trigger and beam interface

daq_time

The timing and trigger are two distinct subsystems. The timing system provides the distribution for the trigger signals over the same fabric as the clock and calibration signals.

Timing

The timing system is required to provide a stable and phase-aligned master clock to all DAQ components; synchronize external signals into the ProtoDUNE-SP clock domain and time-stamp them; distribute synchronization, trigger and calibration commands to the DAQ system; and conduct continuous checks of its own function. In addition, the timing system acts as a data source, providing a record of triggers received, distributed, or throttled. The system is designed to meet the full eventual requirements of the DUNE experiment, but needs only a subset of that functionality for ProtoDUNE-SP. For instance, absolute time-stamping with respect to an external GPS reference is not required.

An FPGA-based master unit

is this part of the DAQ?

receives a high-quality clock signal (from a quartz crystal oscillator or external source) and external signals from the trigger system and SPS accelerator. It interfaces to the ProtoDUNE-SP control and DAQ via a gigabit Ethernet interface. The master unit multiplexes synchronization and trigger commands, along with arbitrary command sequences requested by software, into a single encoded data stream, which is broadcast to all timing endpoints, and decoded into separate clock and data signals. A uniform phase-aligned cycle counter, updating at the ProtoDUNE-SP system frequency of 50 MHz, is maintained at all endpoints, allowing commands to take effect simultaneously at all endpoints regardless of cable lengths or other phase delays.

The timing signal is broadcast via multi-mode optical fiber (for medium-distance connection to the

WIB crates on the detector) and LVDS signals are sent over twisted-pair cable (for short-distance connection to RCEs, SSPs and FELIX modules). Optical signals are fanned out and recombined using commercial 32:1 passive splitters, and active optical–LVDS converter boards further split the signals for local distribution to endpoints.

Endpoints decode the timing signal into separate clock and data signals using a commercial clock-data recovery ASIC siliconlabs:Si5344 [?], which in turn feeds a low-bandwidth PLL

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in order to remove any remaining jitter in the clock and provide phase adjustment. The data stream employs 8b/10b encoding, ensuring sufficient transitions in the timing signal for clock recovery and correct operation of optical links, and uses scrambling of idle patterns to minimize electromagnetic interference (EMI). A common firmware block is used to decode the timing protocol, which is incorporated into the overall firmware design for the receiving FPGA in each DAQ component. This block provides a cycle counter, several independent trigger, calibration and synchronization signals, and a general-purpose packet data output

packet of data output?

to each endpoint. The cycle counter is used to generate low-frequency timing signals for further propagation, e.g., the 2-MHz sampling signal for the cold ADCs.

Trigger

The baseline trigger solution for ProtoDUNE-SP is the Central Trigger Board (CTB). The CTB is designed to receive triggers from various subsystems (Photon Detection System, Beam Instrumentation, SPS spill signal, veto signals, etc.). Up to 100 input channels are provided. It combines these into a global trigger based on a configurable input mask (or more sophisticated algorithm, if desired). It provides functionality to globally time-stamp triggers, keep event counts, and provide artDAQ-compatible (see Section sec:daq-ev-build 1.2.7) header information with trigger type and error conditions. Internally generated triggers and calibration pulses allow for testing the board itself and the endpoints receiving the trigger signals.

The CTB is based on the MicroZed development board avnet:microzed [?], which comprises a Xilinx Zynq-7000 System-on-Chip (SoC), 1-GB DDR3 RAM, Gigabit Ethernet, and 115 I/O ports. The Programmable Logic of the Zynq-7000 is used to perform fast triggering operations, whilst the Processing System is used to interface to the readout and controls systems.

Configuration and operation is performed using an XML file which is sent to the CTB. This allows for fast reconfiguration of the CTB without the need for new firmwares. The file is used to both configure the board and send start/stop/reset, etc., commands from the run control. The trigger output format consists of a trigger type (physics/calibration/random), a time-stamp, the trigger word, counter information and the values of the inputs causing the triggers. The trigger system uses the timing system clock and global triggers are distributed via the timing system.

Beam Interface

The beam instrumentation is described in Section sec:beaminstruments **??**. The beam instrumentation DAQ and the DAQ for ProtoDUNE-SP have separate timing systems. A common GPS clock is used to keep both systems synchronized relative to each other. A common endpoint receives time stamps from both WhiteRabbit (for the beam instrumentation) and the ProtoDUNE-SP timing system are used to create a matching table from the two systems.

what does the 'both' refer to?

Data from the beam instrumentation are acquired continuously via a separate DAQ path.

separate from the actual data?

Triggered data for ProtoDUNE-SP have both the TPC, PDS, and beam instrumentation data and the timestamps and trigger information of both.

here 'both' seems to refer to 3 things

1.2.3 TPC data readout

The readout of the TPC wires, prior to being received by PCs in the back-end DAQ, consists of CE on the APAs inside the cryostat and electronics outside the cryostat, both directly on the cryostat flange and in a rack (the warm electronics). This section addresses the warm part of the TPC readout and describes how it receives data from the CE (the Front-End Boards), manipulates the data, and delivers them to the back-end DAQ.

From an electronics point-of-view, the flange (one per APA) consists of a 5-slot "crate," where the connectors on the warm side of the feedthrough form the "back-plane" into which the boards plug when inserted into the crate assembly.

crate vs crate assembly?

These connectors and the boards that plug into them (warm interface boards, WIBs) serve to send the power, timing, and configuration down to the FEBs

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and receive the high-speed signals from the FEBs. From a data standpoint, each WIB receives the data from four FEBs over sixteen 1.25-Gbps data lines, and multiplexes these data to four 5-Gbps (or two 10 Gbps) lines that are sent over optical fiber to the DAQ.

Two systems are used to receive data from the WIBs. The baseline solution is based on Reconfigurable Computing Elements (RCE) and read out data from five APAs. An alternative exploratory prototype based on the Front-End-Link-EXchange (FELIX) system is used to readout the sixth APA.

1.2.4 RCE-based readout

The data from the WIB are received by processing units called RCEs (Reconfigurable Cluster Element), [?] which are housed in industry-standard ATCA shelves on COB (cluster-on-board) motherboards that are designed at SLAC for a wide range of applications. The RCE is a SoC from the Xilinx Zynq family and contains a full Linux processor system on the chip accompanied by 1 GByte of DRAM. The primary processing functions of the RCEs are compression (and/or zero-suppression) and buffering of the raw data and then sending data to the back-end upon the receipt of an external trigger. Each COB carries eight RCEs, all connected to each other via an on-board 10-Gbps Ethernet switch, which also sends data out of the COB to the back-end DAQ PCs.

The interface with the WIB is provided via the ATCA compliant rear-board, the RTM (Rear Transition Module). This application-specific board uses a set of QSFP transceivers to receive the data from the WIB and an SFP+ (small form-factor pluggable) optical interface for communication with the timing and trigger distribution system.

As the multiplexed data from the WIB come into the RCE FPGA fabric, it is de-multiplexed and buffered into per-channel, fixed-time-length chunks (for instance 512- or 1024-ticks). These chunks are compressed and written to the DRAM where the RCE processor waits for a trigger (also handled by the FPGA) to arrive. Upon a trigger, the processor sends data for a fixed window in time, including pre- and post-trigger time chunks for all channels, to the back-end PCs.

For ProtoDUNE-SP, 256 wires worth of data (2 FEBs) are sent to each RCE. Given that there are 120 FEBs in ProtoDUNE-SP, 60 RCEs are needed to readout the full detector. These fit into eight COBs which in turn reside in a single 14-slot ATCA shelf.

1.2.5 FELIX-based readout

The FELIX is a PCIe card receiving data on point-to-point links from the detector electronics and routing those through a switched network to computers. The aim is to reduce to a minimum any specific hardware developments and to fully rely on commercial networks and servers to perform the DAQ tasks. For ProtoDUNE-SP, data from five WIBs (20 FEBs) are read out over ten 9.6-Gbps links into two FELIX cards. Grouping time slices around a trigger signal, as well as data compression, is dealt with in software. Similar to the RCE-based readout, the FELIX generates artDAQ fragments to be sent to the event builder.

1.2.6 PDS and beam instrumentation data readout

A combination of externally triggered events and self-triggered events make up the PDS data. The external triggers come from the beam instrumentation via the trigger system at 25 Hz. This amounts to 118 Mb/s. The self-triggered data are induced by cosmic rays. A cosmic rate of 10 kHz is assumed, totalling 1106 Mb/s. The combined rate comes to ≈1.2 Gb/s. An alternative scheme with just self-triggered header-only data with a resultant rate of ≈1.1 Gb/s is considered for implementation if the former proves difficult.

1.2.7 Event-building software

Developed within the Fermilab Scientific Computing Division and already used for the 35-t prototype, *artDAQ* provides data transfer, event building, and event analysis functionality. This latter feature includes built-in support for the *art* event analysis framework, also developed at Fermilab [**?**], allowing experiments to run art modules for real-time filtering, compression, disk-writing and online monitoring. As art is also used for offline analysis, a major advantage of artDAQ is that it allows developers to easily switch between developing online and offline software.

ArtDAQ provides three types of processes, each of which fulfills a specific role. In the order of upstream-to-downstream, these are boardreader processes, eventbuilder processes, and aggregator processes. A given boardreader process is intended to be associated with a particular geographical region of the detector, and provides hooks (in the form of C++ base classes) for an experiment's developers to embed experiment-specific code (called "fragment generators"), designed both to upload configuration values to hardware and to read out the hardware. For ProtoDUNE-SP, the full DAQ consists of 87+ boardreaders, in charge of the 60 RCEs, 24 SSPs, the timing system, the Penn Trigger Board, and at least one for the beam instrumentation. For testing purposes, fragment generators can perform useful functions such as providing a "playback" mechanism," and modeling sudden or unexpected data flow events.

Downstream of the boardreader processes are the eventbuilder processes. An eventbuilder receives data from every boardreader (a chunk of data from one boardreader corresponding to an event is referred to as a "fragment"), and assembles the fragments for a given event into a raw, complete data event. Optionally, filtering via art modules can be performed at this stage.

The most downstream process type is the aggregator. Traditionally in artDAQ-based DAQ systems, there are two aggregators, one in charge of writing data to disk and reporting aggregate statistics (e.g., MB/sec), and one in which experiments can run art analysis modules for real-time online monitoring. For ProtoDUNE-SP this model will change as artDAQ becomes more flexible and throughput capability increases. The functionality of aggregators may be replicated in eventbuilders. While this solution reduces the number of interprocess connections in the DAQ software, the number of processes assembling raw events is the same as the number of processes writing to disk.

For the 35-t prototype, artDAQ processes were controlled by a program called *DAQInterface*. DAQInterface takes charge of launching the artDAQ processes, checking for error states, and shutting down processes in an orderly fashion as needed, to avoid improperly closed output files, zombie processes, etc. For ProtoDUNE-SP, some of the functionality of DAQInterface (e.g., querying status) is shifting to JCOP (Joint Controls Project); DAQInterface code is reused as appropriate/possible, to minimize duplication of effort.

1.2.8 Control, configuration and operational monitoring

The artDAQ software used for all applications dealing with the movement, processing and storage of data is interfaced with software of the Joint Controls Project (JCOP) for the purpose of control, configuration and operational monitoring. JCOP provides a toolkit to implement run control (finite state machine (FSM), distribution of commands, error propagation and handling) as well as graphics tools that allow for the implementation of user interfaces and monitoring dashboards.

In order to minimize the software development needs, the same FSM as defined by artDAQ is implemented and commands are sent to the applications using the already supported XML-RPC protocol. Monitoring data are pushed into the JCOP framework by implementing the appropriate artDAQ monitoring plugin. Log and error messages will be most probably collected and processed using an implementation of the ELK (elastic search, logstash, kibana [?]) stack. The internal configuration of DAQ applications are carried out using the mechanisms provided by artDAQ. The overall system is modeled and configured using the JCOP paradigm (data points).

1.2.9 Interface of the DAQ to the online storage

This could use a bit of introduction, so I'm moving things around a bit, e.g., start with

The software framework for interfacing with the electronics, building events, writing data files, and providing an interface to online monitoring of data as they are acquired is *artdaq* [?].

Computers running BoardReader processes read out the RCEs and SSPs and transmit data to a set of computers running EventBuilder processes. These computers and a pair of 10 Gbit/sec NIC provide the CPU and networking needed to build events, collect basic metadata, and send the data to storage and online monitoring. The Event Builders assemble data fragments into self-consistent events and perform basic data integrity checks before writing records out.

end Anne's intro

Table 1.2 indicates a nominal trigger rate of 25 Hz for the mid-range scenario. Data are assumed to be collected based on prompt trigger signals generated by the beamline instrumentation in order to purify samples of desired particles.

Current estimates put the PDS data at approximately 10% of the TPC data rate. Beam instrumentation data are expected to be lower still. Although adding to the total data rate only slightly, adequate resources must be provisioned in order to acquire and store the data from these systems.

The network speed of all computers in the DAQ chain is anticipated to be 20 Gbits/sec. Computers running nearline processing of subsets of the data, which are generally CPU-bound, may be connected with 1 GBit/sec links.

Given that each RCE reads out 256 channels of the TPC, 60 RCEs need to be active. For the PDS, 24 SSPs are used. At least two computers running BoardReader processes are therefore used to read out the RCEs and transmit the data to the EventBuilder processes.

The online buffer layer consists of ∼300 TB of storage, which is connected directly to the Event Builders. The baseline storage option consists of two SAS arrays DAS with > 40Gbit/s bandwidth, redundant paths, controllers, and power supplies. A backup option for storage is an XRootD cluster [?] taking data directly from the Event Builders over the network.

After the data are written to disk by artDAQ, the data handling system creates metadata files, optionally runs nearline monitoring jobs, and transfers the data from EHN1 to the CERN Computing Center [?]. The *Fermi File Transfer Service* (F-FTS) software developed and maintained at Fermilab is the central element of the data flow management at this level.

1.2.10 Data-quality monitoring

In addition to the monitoring of the operations of the DAQ system, the quality of the data taken by the detectors has to be constantly monitored. This assurance is provided by the online and nearline monitoring systems. This subsection describes the baseline monitoring frameworks for ProtoDUNE-SP. The final implementation is subject to change, but will likely be similarly linked to artDAQ and LArSoft as described here.

Online monitoring

The online monitoring framework runs as a DAQ process and therefore is able to provide data quality assurance in real-time. ArtDAQ splits the data into distinct physics and monitoring streams via its aggregator processes. The data rate to the monitoring is tunable such that the monitoring can digest the data in a timely fashion. The software framework used for online monitoring consists of an `art::Analyzer` module which interfaces with the artDAQ framework and owns instances of further classes, each designed to handle different aspects of the monitoring.

The DataReformatters restructure the data to allow for efficient subsequent analysis and provide a standard interface to the methods, which look through the events. These reformatted objects are passed to MonitoringData, which owns all of the data products (`TTree`s, `TH1`s, `TGraph`s, etc.) output from the monitoring software and provides methods for filling them when required. Finally, the online event displays are written as part of the monitoring framework, so the EventDisplay class was responsible for this.

prev sentence is awkward

The output is then saved in a common area for offline access and for syncing with a web server. This is hosted at CERN and allows for remote monitoring of the experiment.

Nearline monitoring

The nearline monitoring is designed to provide complimentary information to that given by the online system. It runs separately as a series of automated shell scripts and provides feedback on a slower timescale than the online monitoring, thus allowing for a broader view of the quality of data over time. It also utilizes offline software (LArSoft) to provide, for example, reconstruction, facilitating a more complete monitoring of much more complex information.

Once an output data file has been closed by the DAQ, it can be processed by the nearline system. A LArSoft job is initially run over the events to perform reconstruction and extract information from the data. The output of this, along with the output of other runs, is then analyzed by a separate automated job, to form the high-level view of the data for monitoring.
Similarly to the online framework, an interface for this system with the web allows for remote access of the information.