The NOvA Power Distribution System

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Abstract

We describe the power distribution systems and grounding schemes built for the near and far detectors of the NOvA long-baseline neutrino experiment. They are used to power the avalanche photodiodes and their thermoelectric coolers, the front-end boards that read out, digitize and time stamp the signals from the avalanche photodiodes, and the data concentrator modules used to receive and format the data from the front-end boards before sending them to a farm of computers used to build the events. The system powers 344,064 readout channels in the far detector and 20,192 channels in the near detector.

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1 Introduction

NOvA is a long-baseline neutrino experiment employing a 14 kilotonne far detector (FD) near Ash River, MN, USA and a smaller 290 tonne near detector (ND) at Fermilab (Fig. 1). Both detectors are centered at an angle of 14.6 mrad from the axis of the Fermilab NuMI neutrino beam [1] and are located 1 km and 810 km from the NuMI target. The two detectors are essentially finely grained, low-Z, sampling calorimeters, with a high ratio of active to passive material. They are functionally equivalent with the exception of the muon catcher placed at the rear of the near detector.

The far detector is composed of 28 blocks, each consisting of 32 planes, for a total of 896 planes. Each plane contains 12 modules, the fundamental mechanical element of the detector. Each module has 32 cells, the fundamental detector element, giving a total of 384 cells per plane. The orientation of the cells in each plane alternates between horizontal and vertical. Each plane is offset from those of the same orientation adjacent to it by half a cell width. The near detector has 6 blocks, each with 32 planes, giving a total of 192 planes.¹ Each near detector plane consists of 3 modules, or 96 cells. In addition, there is a muon catcher at the rear of the near detector that consists of 22 planes interspersed with 101.6-mm-thick (4 in) iron plates. The muon catcher horizontal (vertical) oriented planes

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 $^{^{1}}$ The physical and electrical definitions of a block differs for the near detector: we use the latter definition throughout this paper.

are 2 (3) modules wide for a total of 62 (96) cells per plane. There are a total of 344,064 (20,192) cells in the far (near) detector.

Each cell is 39 mm wide by 66 mm deep (internal dimension) polyvinyl chloride (PVC) [2] filled with liquid scintillator, pseudocumene being the main dopant [3]. Cell lengths are $15.5 \,\mathrm{m}$ in the far detector; $3.9 \,\mathrm{m}$ (2.6 m in the vertical cells of muon catcher) in the near detector. Each cell has a 0.7 mm diameter wavelength-shifting fiber which is looped at the far end of the cell. The fiber transports light to an avalanche photodiode (APD) at the other end of the cell. The 32 fibers of a module are read out by a single 32-pixel APD; both ends of a fiber are coupled to a single (rectangular) pixel. They are cooled to -15° C by thermoelectric coolers (TEC). The signals from each APD pixel are continuously digitized by a custom front-end board (FEB) at 500 ns intervals for the far detector and 125 ns for the near detector. The FEBs also feed down-regulated high voltage to the APDs from a 425 V input, and 24 V to the thermoelectric cooler controller daughter board on the FEB that controls the temperature of the APD in a feedback loop. The FEBs themselves are powered by 3.5 V. There are 10,752 (631) FEBs in the far (near) detector. Zero-suppressed digitized signal snippets from the APDs are sent to data concentrator modules (DCM). The DCMs, powered by 24 V, accumulate $50 \,\mu s$ data fragments into 5 ms blocks from the 2048 cells served by 64 APDs/FEBs. The DCMs then send their data via high-speed switches to a computer farm where the full events are built and, if satisfying trigger criteria, sent to permanent storage [4].



Figure 1: The NOvA far and near detectors. The detectors have alternating vertical and horizontal PVC cells filled with liquid scintillator. Each plane is composed of twelve modules, each module with 32 cells.

The NOvA power distribution system supplies power to four different electronic components used in the readout: 3.5 V to the front-end boards, 425 V to the avalanche photodiodes, 24 V to the thermoelectric coolers, and 24 V to the data concentrator modules. It does *not* provide power to the timing distribution units used to provide an absolute time to the data, which have an on-board AC-to-DC adapter that runs off of 120 VAC. The power distribution system consists of: (1) the power supplies and their relay racks, (2) the power distribution boxes that fan out the power to the FEBs, APDs, TECs, and DCMs, (3) the power cables and their cable trays, and (4) the detector grounding system. The numbers of each component are given in Table 1. A detailed description of the system is found in Ref. [5].

 Table 1: NOvA electronics channel counts.

Item	Near Detector	Far Detector
Channels (cells)	20,192	344,064
Front-end boards (FEB)	631	10,752
Thermoelectric coolers (TEC)	631	10,752
Avalanche photodiodes (APD)	631	10,752
Data concentrator modules (DCM)	14	168
Power distribution boxes	14	168
Wiener MPOD high voltage mainframes	1	2
Wiener ISEG high voltage cards	1	11
Wiener PL506 low voltage mainframes	5	56
Wiener PL506 $2.0-5.8\mathrm{V}$ pods	14	168
Wiener PL506 $12-30 V$ pods	14	168
Relay racks	3	16
Total wall power	6 kW	$71 \mathrm{~kW}$

The NOvA power distribution system was largely designed by physicists, with help from several electrical engineers in key areas, as electrical engineering resources were both scarce and costly. The system was designed to have very low noise levels, to be easily scalable, simple to operate, reliable, safe, and to have a lifetime in excess of ten years. The large number of channels, extent of the detectors, and their remote locations demanded that the power distribution system be remotely controllable.² The very low light levels and low gain of the APDs demanded low-noise power supplies and that great care be taken in the design of the grounding system. Estimates of the currents needed for the FEB, TEC, DCM, and APDs, based on early prototypes, were 0.5 A, 0.15 A, 1.25 A, and 40 μ A, respectively. The system was designed to handle twice those currents in most cases, and indeed, the requirements increased to the final values given in Table 2.

Table 2: Design power requirements for the detector electronics.

		Max.	Power Distribution Box		
Device	Voltage	Current	Channels	Total current	Power
FEB	$3.5 \mathrm{V}$	1.0 A	64	64 A	$211 \mathrm{W}$
TEC	24 V	$0.30 {\rm A}$	64	20 A	$480 \mathrm{W}$
APD	$425 \mathrm{V}$	$40\mu\mathrm{A}$	64	2.6 mA	$2 \mathrm{W}$
DCM	$24 \mathrm{V}$	$1.5 \mathrm{A}$	1	1.5 A	$30 \mathrm{W}$

²The far and near detectors are operated remotely, usually without anyone on site.

2 System Layout

The layout for a far detector diblock is shown in Fig. 2 and for the entire near detector in Fig. 3. A system schematic of the power distribution system is shown in Fig. 4 with a more detailed electrical schematic given in Fig. 5.



Figure 2: Layout of the power distribution system for one of the 14 far detector diblocks. Each of the 12 power distribution boxes powers all of the front-end boards (FEB) and data concentrator modules (DCM) in a two block deep by two module wide area. The total for an entire diblock is 768 FEBs, 12 DCMs, and 24,576 channels (cells). A relay rack on the upper catwalk hosts the low-voltage power supplies needed for the diblock. Two relay racks host the high-voltage power supplies needed for all of the power distribution boxes for the entire detector.

The repeatable unit served by the power distribution system is two blocks, called a diblock, composed of 64 detector planes. All power to the front-end electronics is supplied by low voltage and high voltage power supplies in relay racks on the top catwalk of the far detector hall and in an alcove hewn into the rock for the near detector. The power is distributed by power distribution boxes which are placed on the detector. Each far detector power distribution box feeds (via 16 four-channel cards) a 32 plane by two module



Figure 3: Layout of the power distribution system for the near detector. Each top/beam-left (bottom/beam-right) power distribution box feeds power to front-end boards in a two block by two (one) module wide portion of the detector. Two power distribution boxes feed the muon catcher.

wide segment of the detector: 64 FEBs, or 2048 APDs (see Fig. 2). Each near detector power distribution box feeds a 32 plane by either a one or two module wide segment of the detector: 64 or 32 FEBs (see Fig. 3). The near detector muon catcher has a single power distribution box feeding the 33 FEBs that serve the vertical oriented modules and another power distribution box that serves the 22 horizontal FEBs. A total of 64 single 6-conductor, 18 AWG cables from each power distribution box to 64 front-end boards carry the high voltage needed by the APDs, the 24 V needed by the TECs, and the 3.5 V needed by the FEBs, as well as their return currents. All the electronic components and the power supplies float: ground reference is at the power distribution boxes.³ Note that having the ground reference at the front-end boards would have required equal-length PDB-to-FEB cables as well as ground cables to all 10,752 front-end boards.

There is an associated data concentrator module (DCM) for each power distribution box, whose power is also supplied through the power distribution box.

A far detector diblock requires 12 power distribution boxes, each feeding power to 64 FEBs of the 32 vertical or horizontal planes they serve. The low-power supplies are mounted on relay racks on the upper catwalk: one supply serves three power distribution boxes for a total of four for each diblock. Two high-voltage mainframes are needed for the entire detector: they are situated at the upper catwalk midpoint. Since each high-voltage channel supplies power to one power distribution box, 12 high voltage channels are needed to supply the 12 power distribution boxes in a diblock.

A drawing of part of the far detector vertical modules serviced by a single power distri-

³The high-voltage supply chassis for safety reasons are connected via a $1 \text{ k}\Omega$ resistor to the power distribution box ground through the high-voltage cable shield, as shown in Fig. 5.



Figure 4: Layout of the power distribution system serviced by a single power distribution box. Each power distribution box feeds 3.5 V, 24 V, and 425 V via 6-conductor cables to 64 front-end boards, and 24 V via a 2-conductor cable to the nearby data concentrator module. The 425 V to the power distribution boxes is provided by a Wiener MPOD mainframe. The 3.5 V and 24 V power are provided by a Wiener PL506 power supply. The channel counts shown are for the far detector only.

bution box is shown in Fig. 6. The power distribution boxes and data concentrator modules were required to have a low profile (limited to 3U or 133.35 mm) in order to allow the rolling access bridge used to install and service the electronics mounted on top of the detector to be as close as possible to the detector. The power distribution boxes and data concentrator modules that serve the vertical modules are mounted on a custom-built tray [6] whose feet rest on the horizontal modules (see Fig. 7). The power distribution boxes (and data concentrator modules) serving the horizontal modules are mounted sideways on the catwalk side of the detector using a commercial framing system (see Fig. 8).

The layout for the power distribution system for the near detector is shown in Fig. 3. The power distribution boxes are on the top and on one side of the detector. A total of 10 power distribution boxes, 4 low-voltage supplies, and one high-voltage mainframe with one high voltage card serve the entire near detector.

3 Power Supplies

3.1 High Voltage Power Supplies

The high voltage to the power distribution boxes is provided by two Wiener [7] MPOD HV-EX high voltage power supplies outfitted with 15 ISEG EHS F6 05xi_156-F floating 16-channel cards. (See Table 3 for the power supply parameters.) Each of the 16 channels of the ISEG card is individually programmable from 0–500 V and provides a maximum of 15 mA of current. Input power to the supplies is single-phase, 120 V, 20 A. A custom-made cable harness [8] takes the 16 high voltage channels from each ISEG card to a nearby breakout box [6] (see Fig. 9). The breakout box has a jumper that if interrupted cuts the high-voltage power off at the supply. Shielded triaxial RG-58A/U cables with triaxial 3-lug BNC connectors go from the high-voltage breakout box to the power distribution







Figure 6: Front, side, and top views of a far detector top two-module wide sector served by a single power distribution box. The power distribution box, data concentrator module, support table, cable trays and their supports are shown; cables are not.



Figure 7: Photograph of a power distribution box (foreground) and data concentrator module (background) on top of the far detector. Black 6-conductor power cables run from the power distribution box to the front-end boards (copper). Violet CAT5e cables run from the data concentrator module to the font-end boards. The ground braid, sense cable (gray), high voltage cable (yellow), 3.5 V cable, and 24 V cable can be seen connected to the back of the power distribution box. The front-end boards and APDs are inside the copper enclosures.



Figure 8: Photograph of a power distribution box and data concentrator module mounted on the side of the far detector. The power cables in the vertical cable tray at left come down from the power supplies located in relay racks situated on the top catwalk.

boxes. Each Wiener high voltage channel feeds a single power distribution box or up to 64 avalanche photodiodes.



Figure 9: Photograph of a high-voltage breakout box with the top cover off. The triaxial connectors at top are mounted on an insulated circuit board and connected through $1 k\Omega$ resistors to ground, a safety requirement in case the cables were disconnected at the power distributions boxes or perhaps accidentally cut. The REDEL connector can be seen at bottom.

3.2 Low Voltage Power Supplies

The required power for a far detector diblock, including cable losses, is given in Fig. 11. The low voltages (3.5 V and 24 V) needed by the FEBs, DCMs, and TECs, are provided by the Wiener PL506 LX Power Supply System [7]). This power supply was chosen for its low noise, high current capability, and high power density. No specific noise requirements were given by the designers of the NOvA front-end electronics; however, the supplies were tested to insure that they added nothing to the noise budget. The high power density is particularly important as the relay racks into which the power supplies are mounted are full, and adding additional relay racks in the limited catwalk space was not possible. Each Wiener PL506 chassis has six floating individually programmable power supply pods: three 2.0-5.8 V pods, each rated to 115 A and 550 W, and three 12-30 V pods, each rated to 23 A and 550 W. (Note: the standard PL506 LX low voltage module has a range of 2–7 V. Because the front-end boards have a voltage regulator that is rated only to 6.0 V, the pods procured from Wiener were modified to only go to 5.8 V.) The power supplies have a remote sense feature which was used as the voltage drops between the power supplies and the power distribution boxes are large and vary. The remote sense feature can be run in fast, moderate, and slow modes: the moderate setting is used due to the lengths of the cables.⁴ Input power to the supplies is single-phase, 240 V, 15 A. The 240 V input was chosen early in the system design in order to allow the 3.5 V and 24 V pods to be run at their maximum power.

Each PL506 crate feeds power to three power distribution boxes: the 3.5 V via 2 AWG cables and the 24 V via 6 AWG cables. The cables are rated to safely carry the maximum current of the Wiener supplies without the need for fuses; nevertheless they were fused

⁴Note that when the remote sense setting was inadvertently set to a different mode the power supply tripped.

using a special box affixed to the rear of the power supply mainframe [6] (see Fig. 10). The remote sensing feature allows the voltages at the power distribution boxes to be set to their desired values. This feature is needed because the different cable lengths from the low-voltage power supplies to the power distribution boxes produce non-negligible differences in the voltage drops. The longest (shortest) cable runs are 21 m (6 m), corresponding to one-way voltage drops of 0.32 V (0.07 V) and 0.23 V (0.05 V), respectively for the 3.5 V and 24 V lines. Voltage drops on the 18 AWG cables running from the power distribution boxes to the FEBs are smaller, resulting in a voltage range at the FEBs between 3.45-3.40 V, well within the allowed range of the FEB voltage regulator. For each diblock the input wall power is 5084 W of which 3866 W (76%) is delived to the front-end boards and data concentrator modules, 187 W (4%) is lost in cables, and 12 W (0.2%) lost in the power distribution boxes. The APDs consume no appreciable power. A total of 71 kW of power is used by the entire far detector system.



Figure 10: Photograph of the back of a low-voltage power supply showing the attached breaker box with the cover removed. The 3.5 V (24 V) connectors can be seen in blue (gray) at the back. Just inside are the 6 black breakers. The sense cables are gray, the power cables are black, and the 3.5 V (24 V) cable lugs are red (yellow).

Both the low- and high-voltage Wiener power supplies are remotely controllable with Ethernet interfaces. They have programmable trip levels.

3.3 Power Supply Testing

The high- and low-voltage power supplies underwent extensive testing at the University of Virginia upon reception from the vendor to insure they met requirements. A separate test jig was used for each type of supply. A technician and two undergraduate students performed the tests, documented in Ref. [9] and Ref. [10].

3.3.1 Low Voltage Power Supply Testing

The tests included verifying the proper operation of: (1) the SNMP communication, (2) the configuration settings, (3) the voltage stability during a long burn-in period, (4) the

Item	Low Voltage	High Voltage
Manufacturer	Wiener	Wiener
Mainframe type	PL506	MPOD HV-EX
Size	$3\mathrm{U}$	$8\mathrm{U}$
Weight	$27.3 \mathrm{~kg}$	24 kg
Power	3840 W (240 VAC, 16 A)	$1200 \mathrm{W}$
	550 W per pod	
Input Power	92 - 265 VAC, $16 A$	95 - 220 VAC, $50/60$ Hz, 16 A
Power factor	0.997	
Efficiency	$77\% (4.2 \mathrm{V})$	$88\% (24.8 \mathrm{V})$
Pods (cards) per mainframe	6	10
Pod (card) type	MEH	ISEG EHS F6 $05x_{156}$ -F
Channels per pod (card)	1	16
Voltage range	$2-5.8\mathrm{V}^a$	$0-500\mathrm{V}$
	$12-30\mathrm{V}$	
Maximum current	115 A (3.5 V) 23 A (24 V)	$15 \mathrm{mA}$
Voltage resolution		$100\mathrm{mV}$
Ripple	$< 3 \mathrm{mV}$ pp	$< 30 \mathrm{mV}$ pp
Regulation	$<25\mathrm{mV}$ @ $\pm100\%$ load	
Remote sense	Fast: $< 1 \mathrm{m}$ run	NA
	Moderate: $> 1 \mathrm{m} < 30 \mathrm{m}$ run	NA
	Slow: $> 30 \mathrm{m} \mathrm{run}$	NA
Float range	$\pm 10 V$	$200\mathrm{V}$

Table 3: Power supplies parameters.

^{*a*}Modified from standard 2 - 7 V.





voltage accuracy and precision, (5) temperature monitoring, (6) the 5.8 V limit for the 3.5 V channels, and (7) the remote sense operation. Ripple was also measured and was required to be less than 10 mV (25 mV) for the 3.3 V (24 V) channels. The low-voltage power supply tests were run using a National Instruments PXIe-1062Q chassis running LabVIEW 2009 on Windows XP [11]. Data were recorded and stored. Each of the 6 pods in a Wiener PL506 low-voltage mainframe was connected to a BK Precision 8510 600 W programmable DC electronic load [12] via 15.2 m-long (50 ft) 2 and 6 AWG cables. It was found that the source and return cables had to be wound around each other at one twist per 0.3 m (1 ft) to eliminate a loud audible sound caused the cable inductance effect on the remote sense system. For the voltage stability tests the channels were burned in for three hours at 90% capacity and the output voltage drift was recorded.

Of the 70 power supply mainframes and 420 pods that were tested, 8 pods failed the due to voltages deviating by more than 25 mV from their set point values. Two of these were new pods, and six were older pods used for prototype tests. After recalibration all supplies passed all tests. In general the Wiener power supplies were found to work extremely well.

3.3.2 High Voltage Power Supply Testing

The high-voltage power supply tests included tests of the: voltage stability, voltage accuracy and precision, and general functionality. The tests were run using a National Instruments PXIe-1062Q chassis running LabVIEW 2009 on Windows XP. Data were recorded and stored. GwInstek PEL-2041 high-voltage programmable loads [13], as well as a custommade fixed load for burn-in tests, were used.

Of the 15 high-voltage cards tested, 13 passed all tests. One had two channels that fell outside of the set value by more than the 145 mV specified by the manufacturer. The other had a channel that would not ramp up to the proper value. The cards were replaced by the manufacturer. The five mainframes all passed the tests as well as the 13 custom-made, high-voltage breakout boxes.

4 Power Distribution Boxes

4.1 Overview

There are a total of 168 (14) far (near) detector power distribution boxes. Figures 12 and 13 show front and rear views of a power distribution box. To fit within the tight space constraints of both detectors the power distribution boxes employ a standard DIN 3U subrack [14]. A custom backplane feeds 3.5 V, 24 V, and 425 V to 18 cards: 16 FEB cards that feed 3.5 V, 24 V, and 425 V power each to four front-end boards, one DCM card that feeds 24 V power to a data concentrator module, and one Indicator card that has LED lamps that indicate of the on/off status of the power distribution box. Schematics of circuit boards used in the power distribution box can be found in Ref. [15]. Figure 14 and Fig. 15 show the front-panel layout of the FEB and DCM cards; Fig. 16, Fig. 17, and Fig. 18 show photographs of the front and back of the FEB, DCM and Indicator cards described below.

The low-voltage power is fed to the power distribution boxes through quick connect receptacles at the back [16]. Internal cables go to front-panel circuit breakers rated at 100 A



Figure 12: CAD drawing of the front of the power distribution box. The top is removed to show the inside. Internal cables are not shown.



Figure 13: CAD drawing of the back of the power distribution box. The top is removed to show the inside. Internal cables are not shown.

and 60 A respectively for the 3.5 V and 24 V lines [17]. These breakers serve as fuses, but can also be used to locally power off the power distribution box, although the operating procedure is to always power off the crate at the supply. The high-voltage power goes to a front-panel switch rather than a breaker.

The power distribution box was designed to provide the currents given in Table 4, all of which are roughly a factor of two greater than the original design currents. The individual cards, described below, are fused at 1/0.75 = 1.33 of the maximum rating. The card trace widths are set to handle currents 1.4 times the fused value. The power distribution boxes and their cards were fabricated by a local electronics manufacturing firm near the University of Virginia [18]. They were tested at the University of Virginia using a custom test stand described below.

Table 4: Power distribution box current design capacity.

Item	$24\mathrm{V}$	$3.5\mathrm{V}$	$425\mathrm{V}$
Backplane	$72\mathrm{A}$	$132\mathrm{A}$	NA
FEB card 1 channel	$1.0\mathrm{A}$	$2.0\mathrm{A}$	$300\mu\mathrm{A}$
FEB card 4 channels	$4.0\mathrm{A}$	$8.0\mathrm{A}$	$1.2\mathrm{mA}$
DCM card output to DCM	$6.3\mathrm{A}$	NA	NA

Providing higher voltage DC power to the power distribution boxes and then stepping it down using DC-to-DC converters for the 3.5 V and 24 V lines was considered. Although such a system would have been in principle less expensive, sparse engineering design resources would have had to been used, and the cost, including design, would have been essentially the same. Note that there are no space constraints limiting the size of the power cables to the power distribution boxes. Producing clean, noise-free power was also important; DC-to-DC converters would have added noise to the system.

The power distribution boxes were designed from the outset to be simple distribution boxes that fan out power to the FEB boards, with no means by which the outputs could be switched remotely on or off. To do so the appropriate cable to the front-end board must be unplugged. Operationally, there has been no need for such a feature.

4.2 Backplane

The backplane feeds power to the all of the cards. The 3.5 V, 24 V, and ground feeds are copper busbars [19] that are soldered to the backplane circuit board. They range in size from $3.2 \times 28.6 \text{ mm}^2 (1/8'' \times 1.125'')$ for the 3.5 V source and return; $3.2 \times 15.9 \text{ mm}^2 (1/8'' \times 0.625'')$ for the 24 V source and return; and $3.2 \times 41.3 \text{ mm}^2 (1/8'' \times 1.625'')$ for the ground. The 3.5 V return and 24 V return lines are connected to the ground busbar, although if it were decided to float the power distribution box rather than the power supplies, those connections can be easily disconnected. To reduce the possibility of a short, the return busbars are on the outside. The busbar cross sectional area was set to limit the current to be below the $1.55 \text{ A/mm}^2 (1000 \text{ A/in}^2)$ requirement given in Ref. [20]. Note that the busbar current capacities exceed the maximum output capacities of the power supplies.



Figure 14: Front panel layout of power distribution box FEB card. It feeds 3.5 V, 24 V and 425 V to four FEBs.



Figure 15: Front panel layout of power dis-



Figure 16: Production version (V3.3) of the power distribution box card (FEB card) that powers four FEBs.



Figure 17: Production version (V3.3) of the power distribution box card (DCM card) that powers a data concentrator module (as well as has two FEBs.)



Figure 18: Production version (V3.3) of the power distribution box card (Indicator card) with indicator lamps.

4.3 FEB Card

Each FEB card provides power to 4 front-end boards, allowing a maximum of 64 frontend boards to be powered through one power distribution box by the 16 FEB cards. The outputs are connected to the front-end boards via 6-conductor 18 AWG cables using 6-pin receptacles [21]. The receptacles are keyed to prevent incorrect insertions. Note that these receptacles are only rated for 20 insertions over their lifetime: receptacles of the same size but rated to more insertions could not be found. This has not been a problem as to date none have failed. Two more FEBs can be powered by extra channels in the DCM card described below, allowing a maximum of 66 FEB channels to be served by a single power distribution box. Each 3.5 V and 24 V output is individually fused and has LED indicators. There is no LED indicator for the high-voltage outputs.⁵ Transient voltage suppressors on the 3.5 V lines protect the FEBs from over voltage due to an out of regulation power supply.

A current limiter for the high voltage lines limits the current to below 1.0 mA for safety reasons. It has the added feature that a short in one front-end board, rather than tripping the high-voltage power supply and disabling all of the high voltage channels served by the power distribution box, only disables the shorted channel. However, the limiter does produce a current-dependent drop in the output voltage. Because of this, and because we wanted channel-by-channel bias control for individual APDs, a shunt regulator voltage control circuit was added to the front-end board design [22].

4.4 DCM Card

A special card, called the DCM card, feeds 24 V power to the associated data concentrator module and has two spare FEB power outlets. The power to the DCM card is tapped off before the 24 V breaker, allowing the data concentrator module to be powered on while the 24 V to the TECs has been switched off using the front-panel breaker.⁶ An LED lamp indicates that the power is on. The power distribution box crate and DCM card are keyed

 $^{^5\}mathrm{A}$ self-powered high voltage LED indicator would require more power than the high-voltage supply provides.

 $^{^{6}\}mathrm{A}$ front-panel switch for the 24 V on the DCM card was desired, but a small enough one could not be found.

so that it can only fit in a special slot and no other.

4.5 Indicator Card

A third card, called the Indicator card, has LEDs that show which power supply voltages are being supplied to the power distribution box: 3.5 V, 24 V, and 425 V.

4.6 Testing

A detailed description of the power distribution box tests is given in Ref. [23]. The tests were done using a jig designed and fabricated at the University of Virginia. The testing was carried out using LabVIEW 2009 running on Windows XP on a National Instruments PXIe-1062Q chassis [11]. Two power supplies provided three different voltages (6 V, 30 V, and 445 V) to the power distribution boxes and three programmable electronic loads were used to put the DCM and FEB cards under load. The testing was split into two parts: one LabVIEW program tested the power distribution box backplanes and a second LabVIEW program tested the FEB, DCM, and Indicator cards. Relays allowed each channel and each slot to be tested under load, with the current and voltage data written to a database. The backplane test was performed using special load boards plugged into the power distribution box backplane. A standard power distribution box was used to perform this test. Another test checked the correct functioning of the high voltage current limiter circuit. Cards that failed these tests were sent back to the manufacturer to be repaired.

5 Cabling

The power distribution system cables are listed in Table 5. There are three power cables that run from the power supplies to the power distribution boxes on the detector: 3.5 V, 24 V, and 425 V. As mentioned above, the 3.5 V and 24 V hot and return cables were twisted to reduce self induction using a jig designed to fabricate rope [24]. This eliminated a loud noise when using the power supply remote sense function. The 3.5 V, 24 V, and 425 V power from the power distribution boxes to the front-end boards is carried by a single six-conductor cable and a single two-conductor cable carries the 24 V power to the data concentrator modules.

Item	Cond.	AWG	Туре
Power supply to PDB 3.5 V	2	2	Tray cable
Power supply to PDB $24 \mathrm{V}$	2	6	Tray cable
Power supply to breakout box $425\mathrm{V}$	37	26/7	Multiwire HV cable
Breakout box to PDB 425 V	2	22	RG-58A/U triaxial cable
Sense	4	22	2 pairs with shield and drain
PDB to FEB	6	18	Tray cable
PDB to DCM	2	18	Tray cable
ground strip to PDB	896	$16\mathrm{mm}^2$	$15 \times 1.5 \mathrm{mm^2}$ braid
ground strip	1	NA	$51 \times 0.4 \mathrm{mm^2}$

Table 5: NOvA cable types.

All cables were required to be rated either CMR (can be used in risers for commercial buildings) or CMP (can be used in plenums) and all cables were flame-tested at Fermilab to insure they met internal safety requirements. The cables used in the near detector had 38.1 mm (1.5'') flame retardant shrink tubing placed over each termination end for additional fire protection.

The power cables from the Wiener low voltage power supplies to the power distribution boxes range in lengths from 6 m to 21 m. Sense cables that run from the Wiener low voltage power supplies to the power distribution boxes consist of two individually shielded twisted pairs. The sense lines are terminated on the power supply end to the manufacturer's pluggable terminal strips. At the power distribution box they are terminated in a D-sub style DB-9 connector with an insulated housing. The sense lines are attached to the back of the power distribution box in a corresponding DB-9 receptacle. The sense lines employ 0.50 A inline fuses inside the power distribution box to prevent damage to the lines.

The power cables from the Wiener high-voltage power supplies are routed to a breakout box mounted on the same relay rack. The cables running from the breakout box to the power distribution boxes are triaxial cable. They range in lengths from 8 m to 39 m.

The power cables going from the power distribution boxes (PDB) to the FEBs are 6conductor, 18 AWG, non-paired, unshielded, tray cable, with a PVC jacket (Belden 27600A [25]). They are placed in wire basket cable trays of $152.4 \times 50.8 \text{ mm}^2$ ($6 \times 2 \text{ in}^2$) size. The PDB-FEB cables are grouped into four cable harnesses, each with 16 cables, and of four different bundle types. They range in lengths from 1.2 m to 3.8 m. A total of 672 (30) cable harnesses are used for the far (near) detector (where we have excluded the near detector muon catcher from the total). An amount of 10,752 (631) 6-conductor, 18 AWG, cables carry the power from the power distribution boxes to the FEBs for the far (near) detector. The power supply to power distribution box cables and power distribution box to FEB cables were fabricated in Charlottesville, VA, USA and shipped out to Fermilab and far detector site [26].

6 Relay Racks

The power supplies are mounted in deep 44U high relay racks situated on the upper catwalk at the far detector and in an alcove at the near detector. There is one relay rack per diblock for the far detector low voltage supplies and two relay racks for the high voltage supplies that serve the entire far detector. For the near detector there are three relay racks, one with three and one with two low voltage power supplies. The remaining near detector relay rack mounts the sole high-voltage power supply. Figure 19 shows a front view of the rack population for the far detector low-voltage and high-voltage relay racks.

The relay racks have a custom-made power interruption system [27] required for safety purposes. It disables AC power to the equipment in the rack when smoke is detected, with the exception of the rack monitor itself and the field point system used to monitor the integrity of the detector structure. Test results of the system are found in Ref. [28].

The proper functioning of the rack protection system imposes limitations for the airflow within the rack. Specifically, the rack must form a chimney to funnel smoke to the sensors on the top. The Wiener PL506 low voltage supplies consume quite a bit of power. Their air intakes are located below the units, with exhaust above. A set of internal fans cool the

Position	Equipment	Voltage	Power	Position	Equipment	Voltage	Power
U-44	Pack Protection Monitor	120	12 W	U-44	Rack Protection Monitor	120	12 W
U-43				U-43			
U-42	Patch Panels			U-42			
0-41	Cable Management Panel			U-41	Blank Panel		
0-40	Patch Panels	400	0.14/	0-40		120	720 14/
0-39	TDU	120	8 VV	0-39		120	720 VV
0-36		400	0.14/	0-38			
U-37	TDU	120	8 11	U-37	Wiener MPOD HV mainframe		
U-35	Cable Management Panel			U-35	6 ISEG HV cards		
11-34				U-34			
U-33	Block Structure Sensor Crate	120	160 W	U-33			
U-32				U-32			
U-31	Blank Panel			U-31			
U-30	Fan Tray	120	135 W	U-30			
U-29				U-29			
U-28	Wiener PL506 #4	240	3.840 W	U-28			
U-27			-,	U-27	Blank Panel		
U-26	Power Interrupt panel			U-26		120	250 W
U-25	serving PL506 #4			U-25			
U-24	Fan Tray	120	135 W	U-24			
U-23				U-23			
U-22	Wiener PL506 #3	240	3,840 W	U-22	RMR	120	250 W
U-21				U-21	DCS Rack Monitor Readout		
U-20	Power Interrupt panel			U-20	Crate: DCS-01		
U-19	serving PL506 #3			U-19			
U-18	Fan Tray	120	135 W	U-18		120	450 W
U-17				U-17	Blank Panel		
U-16	Air Plenum			U-16			
U-15				U-15			
U-14	Fan Tray	120	135 W	U-14		120	450 W
U-13				U-13	Block Structure Sensor Crate #1		
U-12	Wiener PL506 #2	240	3,840 W	U-12			
U-11				U-11	Blank Panel		
U-10	Power Interrupt panel			U-10	Power Interrupt panel		
U-9	serving PL506 #2			U-9	for 120V		
U-8	Fan Tray	120	135 W	U-8	HV Patch Pannel (16 Channel)		
U-7				U-7	HV Patch Pannel (16 Channel)		
U-6	Wiener PL506 #1	240	3,840 W	U-6	HV Patch Pannel (16 Channel)		
U-5				U-5	HV Patch Pannel (16 Channel)		
U-4	Power Interrupt panel			U-4	HV Patch Pannel (16 Channel)		
U-3	serving PL506 #1	400	405.141	U-3	HV Patch Pannel (16 Channel)		
0-2	Fan Iray	120	135 W	U-2	Empty		
U-1	Empty			U-1	Empty		
		Total:	16,357 W			Total:	2,132 W

Figure 19: Left (right): far detector low-voltage (high-voltage) relay rack population.

units. A test was made with a single supply run at full power and outfitted with temperature sensors [29]. The maximum temperature was found to be 48°C, which is within the specified operational range of 0–70°C for the supply. However, to increase the time between failures for the power supplies we specified a temperature limit of 30°C for each of the low-voltage power supply pods. Additional cooling is provided by nine-fan, 1-U rack packs at the bottom of the relay racks and above each power supply, giving a total of five (three) fan packs for the far (near) detector relay racks. In addition a custom-designed plenum [30] was installed between the second and third power supplies. It brings in air from the front of the relay racks and deflects to the rear the warm air that is blown upwards from the bottom two power supplies. Typical average far detector low-voltage pod temperatures are 24°C, 27°C, 26°C, and 28°C, going from bottom to top of the relay rack. Typical average pod temperatures for the near detector low-voltage power supplies are 24°C, 28°C, and 24°C going from bottom to top in relay rack 2, and 24°C for relay rack 1. Far (near) detector average high-voltage power supply temperatures at 27°C (32°C).

7 Ground Scheme

Great care was taken in the design of the far and near detector grounding schemes. In particular, from the outset the design of the far detector building incorporated elements to insure a robust ground, not only from a safety viewpoint, but to minimize high-frequency noise. All transformers are single Faraday shielded units. All detector electronics have their own transformers and these transformers are not shared with any other equipment.

7.1 Far Detector Grounding Scheme

The large size of the far detector, wide distribution of the electronics, and lack of large metallic surfaces demand a good instrument ground. Hence the building itself was designed to facilitate a high quality ground with little additional cost. This method was pioneered by H.G. Ufer for ammunition storage facilities for the US military during World War II [31]. Rebar is used rather than Ufer's copper wire, which has been shown to have resistances to earth ground as low as a fraction of an ohm [32].

The NOvA far detector building is large $(100.8 \text{ m} [350 \text{ ft}] \log, 20.16 \text{ m} [70 \text{ ft}] \text{ wide}$ and 20.16 m [70 ft] high), has ample rebar (#6 rebar on 177.8 mm [7 in] centers) and is semi-underground. The catwalks are made of steel that is tied to the rebar every meter and is welded together to provide a continuous conducting structure. This large structure combined with multiple connections to the rebar provides the low inductance necessary for a good instrument ground. In addition, the spread out structure of the catwalk provides multiple current paths so magnetic coupling from ground current flows are minimized. Ground attachment points are placed on the catwalk next to the electronics racks.

The far detector grounding scheme is shown for a top and side power distribution box station in Fig. 20. Thick copper cables (2 AWG) connect to thin (0.53 mm [0.021 in]) wide (50.8 mm [2 in]) copper ground strips that are placed on the top of the detector, spaced apart by approximately 1.2 m (4 ft). The large aspect ratio of the strips keeps their self inductance as low as possible. The power distribution box enclosures and backplane ground busbars are connected to the ground strips by short ground braid strips [33]. The shield of

the high voltage triaxial cable, as well as the return, is connected to the ground braid, as are the 3.5 V and 24 V return lines and sense cable shield, as shown in Fig. 5.

The data concentrator module chassis sits on the same aluminum tray as the power distribution box; however the data concentrator module ground, unlike the power distribution box ground, is not directly connected to the data concentrator module chassis.

Cable trays on the top of the detector are connected by 6 AWG cables to the ground strips. On the side of the detector they are attached to Unistrut supports which are fixed to the catwalk.





Figure 20: Far detector grounding scheme for one diblock.

7.2 Near Detector Grounding Scheme

The NOvA near detector ground scheme, shown in Fig. 21, is similar to that of the far detector. Noise issues are mitigated by the small size of the detector and its location over 100 m underground. Also, on average the signals are larger due to the shorter fiber length.



Figure 21: Near detector grounding scheme.

8 Operation

The power distribution system has worked extremely well in the four years of detector operation with very little loss of detector livetime due to any failures. No high-voltage power supply channels have failed. There have been eight low-voltage power supply failures. They include: a tripping power supply pod, an unresponsive power supply, non-functioning temperature sensors, and pods which reported inaccurate sense channels. Failed power supplies have been immediately replaced by spares. The only other failures to the system have been several power distribution boxes that were damaged by water leaks in the avalanche photodiode cooling system at the beginning of the data taking. They were replaced.

Typical operating voltages (at the power distribution boxes) and currents for the frontend boards and thermoelectric coolers are given in Table 6. Note the higher maximum front-end board currents in the near detector due to the higher digitization rates.

Table 6: Range of near and far detector power distribution box voltages and currents.

	Near Dete	ector	Far Detector		
Component	Terminal Voltage	Current	Terminal Voltage	Current	
FEB (3.5 V) TEC (24 V) APD (425 V)	4.1–5.2 V 24.2–24.7 V 425 V	23.0–66.6 A 4.4–12.1 A 2.2–3.9 mA	3.9–4.4 V 24.2–24.6 V 425 V	30.3–30.6 A 8.2–9.7 A 3.2–4.2 mA	

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References

- P. Adamson *et al.*, Nucl. Instrum. Meth. A 806, 279 (2016); NuMI Technical Design Report, FERMILAB-DESIGN-1998-01.
- [2] R.L. Talaga *et al.*, Nucl. Instrum. Meth. A **861**, 77 (2017).
- [3] S. Mufson *et al.*, Nucl. Instrum. Meth. A **799**, 1 (2015).
- [4] A. Norman *et al.*, J. Phys. Conf. Ser. 664, 082041 (2015).
- [5] "NOvA Power Distribution System," E.C. Dukes, R. Ehrlich, B. Mason, and S. Goadhouse, NOvA internal document, Docdb-9670.
- [6] Automated Production Machining, Inc., PO Box 1687, 300 Taylor Ave., Gordonsville, VA 22942, USA.
- [7] Wiener, Power Electronics GmbH, Linde 18, D-51399 Burscheid, Germany.
- [8] SL-v2YCEH cable by LEONI Kerpen GmbH, Zweifaller Straße 275-287, 52224 Stolberg, Germany, with REDEL SAG.H51 and SRG.H51 connectors, assembled by Wiener, Power Electronics GmbH, Linde 18, D-51399 Burscheid, Germany, and cataloged as HV_cable_REDEL_2m.
- [9] "NOvA PDS Low Voltage Power Supply Testing Procedure," S. Hasselquist, K. Tran, and B. Mason, NOvA internal document, Docdb-7185.
- [10] "PDS High Voltage Power Supply Testing Procedure," S. Hasselquist, K. Tran, and B. Mason, NOvA internal document, Docdb-7507.
- [11] National Instruments Corporation, 11500 Mopac Expwy, Austin, TX 78759-3504, USA.
- [12] BK Precision Corp., 22820 Savi Ranch Parkway, Yorba Linda, CA 92887-4610, USA.
- [13] INSTEK America Corp., 5198 Brooks St., Montclair, CA 91763, USA.
- [14] Schroff, 170 Commerce Dr., Warwick, RI 02866, USA.
- [15] "Power Distribution Box Schematics," S. Goadhouse, NOvA internal document, Docdb-1967.
- [16] SB175 connector for the 3.5 V 2 AWG cables and SB120 connector for the 24 V 6 AWG cables. Anderson Power Products, 13 Pratts Junction Rd., Sterling, MA 01564-2305, USA.
- [17] BS-7547 breaker for the 3.5 V and BS-7549 breaker for the 24 V lines. Blue Sea Systems, 425 Sequoia Dr., Bellingham, WA 98226, USA.
- [18] WWW Electronics, Inc., 3670 Dobleann Drive, Charlottesville, VA 22911, USA.
- [19] Storm Power Components, 240 Industrial Park Lane, Decatur, TN 37322, USA.

- [20] "Electrical Design Standards for Electronics to be used in Experiment Apparatus at Fermilab," April 15, 1999 (unpublished).
- [21] TYCO MINI MATE-N-LOK, Tyco Electronics Corp., 1050 Westlakes Dr., Berwyn, PA 19312, USA.
- [22] "NOvA Power Distribution Box High Voltage Current Limiter Evaluation," H. Tammaro, E.C. Dukes, and L. St. John, NOvA internal document, Docdb-4154; "Fault Analysis: Single Point Failures for the 3-Transistor Current Limiter," J. Oliver, NOvA internal document, Docdb-4526.
- [23] "Nova PDB Hardware Tests for v3.3 Far Detector Hardware", S. Goadhouse, NOvA internal document, Docdb-5979, and "NOvA Power Distribution Box Testing," J. Gran and E. Ho, NOvA internal document, Docdb-7509.
- [24] Rope Master Rope Machine, F. Mueller, 5947 Coffeen Ave., Sheridan, WY 82801, USA.
- [25] Beldon, 401 Pennsylvania Parkway, #200, Indianapolis, IN 46280, USA.
- [26] ECLINC, 702 Charlton Ave., Charlottesville, VA 22903, USA.
- [27] "Smoke Detection and AC Power Distribution/Interruption for NOvA Near Detector Surface Building Electronics Racks," M. Matulik, Technical Note: IG_20100001.
- [28] "Test of the Smoke Detection and AC Power Interruption System for NOvA Near Detector Surface Building Electronics Racks," M. Matulik, Technical Note: IG_20100002.
- [29] "Wiener PL506 Heat Rise Tests," A. Norman, NOvA internal document, Docdb-4532.
- [30] Suter Machine & Tool, Inc., P.O. Box 4530, Harrisonburg, VA 22801, USA.
- [31] H.G. Ufer, IEEE Trans. Power Apparatus and Systems, vol. 83, pp. 1042–1048, October 1964.
- [32] E.J. Fagan and R.H. Lee, *IEEE Trans. Industry and General Applications*, vol. IGS-6, No. 4, pp. 337–348, July/August 1970.
- [33] Eriflex 557240 tinned copper braid with 557180 lugs. Pentair Corp., 5500 Wayzata Blvd. Ste. 800, Minneapolis, MN 55416, USA.