PDMs). Electronics read-out and DAQ of 50 PDMs ready for cryogenics test.

- **Proto II.** Assembly and commissioning of full system (cryogenics and TPC with 400 first production PDMs). Full readout and DAQ operational. Evolution towards final configuration.

A full test plan and use of the prototype will be developed during the Proto II construction phase.

The details of the 3 phases are described in Tab. XVIII.

X. VETO DETECTORS: LSV AND WCV

A. Introduction

Nuclear recoils induced by single neutron scatters are indistinguishable from WIMP interactions. Even the large size of the LAr TPC of DarkSide-20k does not allow a fiducial volume completely shielded from neutron-induced backgrounds. External passive shielding provides protection against neutrons from outside the TPC (cosmogenic or radiogenic from Hall C), but not from neutrons from the components of the TPC itself. Neutron induced recoils will be suppressed in DarkSide-20k using a liquid-scintillator neutron veto [126], the LSV, a separate detector surrounding the TPC in which the neutrons from both internal and external sources are detected with very high efficiency, and the corresponding recoil events in the LAr TPC are identified and rejected. In addition to removing neutron backgrounds, the LSV also provides in situ measurements of the neutron backgrounds, allowing reliable predictions of the number of neutron-induced recoils expected in the data sample. It also has a substantial efficiency for detecting γ-rays from the TPC and cryostat.

? ~

Shielding is still needed, notably to lower the rate in the LSV to allow a low neutron-detection threshold. In DarkSide-20k the LSV will be surrounded by a large tank of ultra-pure water, instrumented as a Cherenkov detector to veto cosmic rays, the Water Cherenkov Veto, or WCV. This layered veto concept has been used very successfully in DarkSide-50 [62, 63, 127]. ~~at as additional shielding~~

dead-time

Neutrons that enter the LAr TPC of DarkSide-20k come primarily from four sources:

1. Radioactivity in the environment outside the detector;
2. Cosmogenic interactions due to cosmic ray muons.
3. Spontaneous fission reactions in the detector materials;
4. (α,n) reactions in the detector materials.

Neutrons from the first two sources are suppressed by the shielding and signals from the two layers of veto. Fission reactions that produce neutrons often generate multiple neutrons and high energy gamma-rays, significantly increasing the probability of multiple coincident interactions in either the LAr TPC or in the neutron veto. This leaves (α,n) neutrons as the most challenging type of neutron to veto, and much of the design is targeted around vetoing this class of neutrons with high efficiency.

(α,n) neutrons are produced by the alpha decays of radioisotopes in the detector materials, in particular by the ^{238}U, ^{235}U, and ^{232}Th decay chains. Cross sections for (α,n) reactions result in a neutron yield usually between 10^5 to 10^7 neutrons per equilibrium decay of the entire chain, with light elements giving the highest yields. (α,n) yield is strongly dependent on the α energy, making the lower sections of the ^{238}U and ^{232}Th particularly important. This has serious implications for the DarkSide-20k materials assay campaign, discussed in Sec. ??.

decay chain ?

For DarkSide-20k we plan to use the same boron-loaded scintillator, a solution of 1,2,4-TriMethylBenzene (PseudoCumene or PC), TriMethylBorate (TMB), and 2,5-DiPhenylOxazole (PPO), used for DarkSide-50 [62, 63, 127]. With this scintillator neutrons can be detected by exploiting two signals, usually defined as prompt and delayed signals. The prompt signal is produced during the thermalization of the neutrons. Neutrons lose their energy by scattering off the nuclei of the scintillator, in particular hydrogen and carbon nuclei. Protons that are scattered by neutrons produce scintillation light. The scintillation light of the protons, although heavily quenched, can be detected by the PMTs. The thermalization of the neutrons is a fast process, usually contained in a narrow time window of few hundred ns with respect to the scattering on argon, therefore a very low threshold can be used in a narrow prompt window.

if originated in TPC

The delayed signal is due to the neutron capture. The thermalized neutron can capture on various isotopes in the scintillator. ^{10}B, with a natural abundance of 20 %, is one of the isotopes with the highest thermal neutron capture cross section, 3840 b. The time scale and the relative probability of capture in boron, hydrogen, or carbon nuclei depends on the amount on boron in the scintillator, with ^{10}B dominant at all but the smallest concentrations. The capture on ^{10}B has two branches:

barn

$$
\begin{aligned}
{}^{10}\mathrm{B} + n &\to\ {}^{7}\mathrm{Li} + \alpha\ (1775\,\mathrm{keV})\ [6.4\,\%] \\
{}^{10}\mathrm{B} + n &\to\ {}^{7}\mathrm{Li}^{*} + \alpha\ (1471\,\mathrm{keV})\ [93.6\,\%] \\
&\qquad \hookrightarrow {}^{7}\mathrm{Li}^{*} \to {}^{7}\mathrm{Li} + \gamma\ (478\,\mathrm{keV})
\end{aligned}
$$

The advantage of ^{10}B final products is that the alpha and ^{7}Li have very short range. Therefore if a neutron is captured on ^{10}B in the LSV, the reaction always produces some scintillation light. An important feature of this signal is that it is independent of the energy of the neutron, meaning that a neutron that has too low an energy to produce a detectable prompt signal may still produce a detectable delayed signal. However, the light yield of alpha and ^{7}Li nuclei is highly suppressed due to ionization quenching, causing them to scintillate equivalent to a 50 to 60 keV electron. Detecting these reaction products therefore requires a high light collection efficiency. The time scale of the delayed ~~signal~~ depends on the TMB concentration. With a 50 % volume concentration, the neutron capture time is 2.2 µs, and ~99.2 % of neutron captures happens on ^{10}B (the rest of the captures happens mostly on H), while with a 5 % concentration, the neutron capture time is 22 µs and ~92 % of neutron captures happens on ^{10}B.

The delayed neutron tagging works in this way: a delayed veto window is opened in the LSV after each event in the TPC. If a scintillation signal above a certain threshold is detected in the LSV during the delayed veto window, the TPC event is discarded. The threshold must be low enough to reliably detect the signal due to the alpha plus ^{7}Li signal from the ground-state capture. The concentration of TMB drives the width of the delayed veto window needed to reach the required veto neutron efficiency. The window width then determines the fraction of the TPC events that will be accidentally discarded, due primarily to scintillation from radioactivity in the LSV components. The requirements on the radioactive contamination in the LSV are derived requiring an acceptable level of TPC event loss due to accidental background in the veto delayed window.

Sec. X B will describe the baseline design of the veto detectors. Sec. X C will focus on the detectors equipping the LSV and WCV, the PMTs. Sec. X D will describe the front end electronics for the DarkSide-20k veto detectors. The overall performance of the detector will be discussed in Chapter XVI.

?

B. Baseline Design

The geometry of the new WCV water tank has been optimized to provide the required amount of shielding for the LSV and LAr TPC, but still fit within the confines of Hall C. The new stainless steel water tank will have a cylindrical shape 15 m in diameter and 8.5 m tall, with a dome-shaped ceiling having a radius of 7.5 m. The total height of the water tank is 16 m. The new LSV will be 8.0 m in diameter, lined with Lumirror reflective foil to increase light collection, and equipped with PMTs as was done in DarkSide-50. However, the DarkSide-20k LSV will use 20″ diameter PMTs, as described in the next section. The LSV will be filled with the same boron-loaded liquid scintillator as was used in DarkSide-50, but with the TMB concentration optimized for the new detector. The water tank will also be instrumented with 20″ PMTs (same type as the LSV) and lined with Tyvek to provide ample light collection. It will provide at least 3.5 m of active shielding to the LSV in all directions.

constrains

To achieve at least the same light yield per unit of quenched energy inside the new LSV, the surface area covered by PMTs will be increased with respect to what was used in DarkSide-50. This will compensate for the increase in surface area and for the loss of light due to the moderate attenuation length (a few to ten meters) of the scintillator cocktail. 130 20″ PMTs will be used in the new LSV, leading to ~13 % photocathode coverage, more than sufficient to see the α following a neutron capture on ^{10}B to the ^{7}Li ground state. 70 20″ PMTs are sufficient to instrument the WCV. In total, the DarkSide-20k veto system will require 200 20″ PMTs.

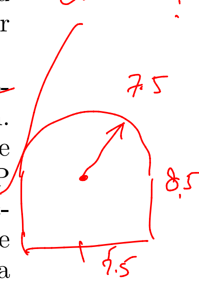
C. PMTs

G4DS studies demonstrated that the choice of the PMTs diameter does not affect the physics performance of the LSV and WCV if the total photocathode coverage remains fixed. We opted to instrument the LSV and WCV with the same 20″ MCP-PMTs developed by the IHEP group for the JUNO neutrino detector [128]. The MCP-PMTs will be provided by the DarkSide IHEP group. The choice of 20″ MCP-PMTs allows to reduce the number of cables, connectors, and electronics channels, containing the cost and simplifying the design and construction of the experiment. The expected performance of the MCP-PMTs is summarized in Table VIII. The LSV will be equipped with 130 20″ PMTs mounted on the stainless steel sphere; the WCVwill be equipped with 70 20″ MCP-PMTs mounted on the water tank. (where exactly ??)

is ?

The MCP-PMTs of choice a double stage microchannel plates (MCP) instead of a dynode chain. A voltage divider is still necessary to provide the proper voltage to the front and back side of the MCP and to the anode which collects the multiplied electrons. The socket with the voltage divider will be mounted on the back side of the MCP-PMT and a single cable will run from this socket to the front end board located outside the water tank. In the front end board the MCP-PMT signal will be decoupled from the HV bias. The cables from both

Cathod V ?



mark on figure to point out the seal location.

TABLE VIII. Expected performances of the MCP-PMTs in construction for JUNO and to be used in DarkSide-20k.

Item	Value
Type	MCP-PMT
Gain	10^7
QE at 420 nm	>25 %
Peak/Valley	>3
TTS (top point)	<15 ns
Rise time	2 ns
Fall time	12 ns
Anode Dark Rate at 300 K	<30 kHz
After-Pulse Time	4.3 µs
After-Pulse Rate	<3 %

the LSV and WCV MCP-PMTs will be immersed in deionized water for many years. Based on the Borexino and DarkSide-50 experience, we will use cables and connectors designed for submarine operation that demonstrated proven success and ensure reliable working conditions.

With this choice of PMTs, the signal from a single photoelectron (SPE) is expected to be a pulse of ∼10 mV in amplitude and 10 ns FWHM. Very preliminary simulations suggest that scintillation events with energy higher than a few hundred keV are no longer in the SPE regime. Simulations also suggest that most of the scintillation light is collected in 100 ns to 200 ns, with tails extending to 300 ns to 500 ns. The dark rate of the LSV MCP-PMTs is expected at 30 kHz at 300 K. Muons in the LSV produce a huge scintillation signal that can last for several microseconds, blinding the LSV MCP-PMTs for this time. After-pulses occur in a time window of 4.5 µs, with a probability which is <3 % per SPE of signal.

The MCP-PMTs must be encapsulated using low radioactivity materials and with long-term chemical compatibility both with deionized water and with the organic liquid scintillator. We are planning to adapt to these large MCP-PMTs the sealing solution already used in Borexino water Cherenkov muon veto [129] that showed high performance over many years. To be specific, we plan to use this style of encapsulation for both the LSV and WCV. PMT.

The PMTs will be fully encapsulated within a leak-tight case made of two pieces: 1. A truncated stainless steel cone, shown in Fig. 79, that surrounds the PMT and the socket; 2. A thin, transparent, PET window, conforming to the shape of the photocathode and covering it. The stainless steel truncated cone has a flange as shown in Fig. 79 with a diameter slightly above the maximum PMT diameter. This flange has a first sealing surface on the side facing the MCP-PMT photocathode, allowing the transparent window to make a leak-tight seal with the truncated cone. The stainless steel truncated cone extends to host a second sealing surface, on the side opposite to the MCP-PMT photocathode, which anchors the encapsulated MCP-PMT to the stainless steel sphere and makes a leak-tight seal with the sphere itself. For the mounting of the MCP-PMTs in the WCV, the first sealing surface is still in use to ensure a leak-tight seal between the stainless steel truncated and the thin transparent photocathode window; the second sealing surface is not in use, and its bolt holes are instead in use to mount the encapsulated MCP-PMT to proper mechanical supports.

define

larger than

The stainless steel truncated cone is equipped, at the end opposite to the MCP-PMT photocathode, with a submarine connector, mating to the submarine connector of the cable. As for the PMTs of the Borexino water Cherenkov muon veto [129], the volume delimited by the stainless steel truncated cone and by the thin transparent photocathode window will be filled by transparent mineral oil. Extensive tests on prototypes and screening of materials to ensure both the chemical compatibility and the needed low radioactivity will be performed: we have already a baseline solution which consists of a replica of the materials in use for the PMTs of the Borexino water Cherenkov muon veto [129].

Following the lead of Ref. [129], we will mount optical fibers such as to illuminate each MCP-PMT, thus allowing seamlessly to perform precise, periodic calibrations and monitoring of the MCP-PMTs gain. Fibers serving the WCV MCP-PMTs will be spliced inside the water tank, and fibers serving the MCP-PMTs of the LSV will be spliced inside the stainless steel sphere, also following the lead of Ref. [129], such as to miminize the number of fibers feedthroughs. All fibers will be connected to a pulsed laser source with adjustable power, eventually tuned to provide an illumination level equivalent to a fraction of PE per MCP-PMT per pulse.

The terrestrial magnetic field (TMF) causes the degradation of the characteristics of the large area PMTs because of the deflection in the trajectories of the photoelectrons drifting from the photocathode to the first dynode. Trajectories of secondary electrons in the dynode chain can also be affected, depending on the orientation of the PMT relative to the TMF. The TMF effects are increased with increased photoelectron path length inside the PMT (longer path from the photocathode to the first dynode). Photoelectrons are defocused causing losses in collection efficiency on the first dynode and degradation of gain at the first dynode, resulting in worse SPE resolution transit time spread. The TMF effects increase with the increasing size of the PMTs [130]. These effect can be compensated by shielding the TMF in the entire detector, such as

TABLE IX. Relative PDE for various applied magnetic fields, without and with μ-metal cage, and with only half (hemisphere) of the μ-metal cage. See text for details.

Field Strength and Orientation	No Cage	Full Cage	Half Cage Only
Null	1.00	0.96 ± 0.04	1.02 ± 0.04
20 µT, Dynodes Axis $\parallel B$	0.74 ± 0.04	0.92 ± 0.04	0.89 ± 0.04
40 µT, Dynodes Axis $\parallel B$	0.17 ± 0.04	0.71 ± 0.04	0.38 ± 0.04
TMF (55 µT in Dubna), Avg. of Random Orientations	0.53 ± 0.04	0.85 ± 0.04	0.62 ± 0.04

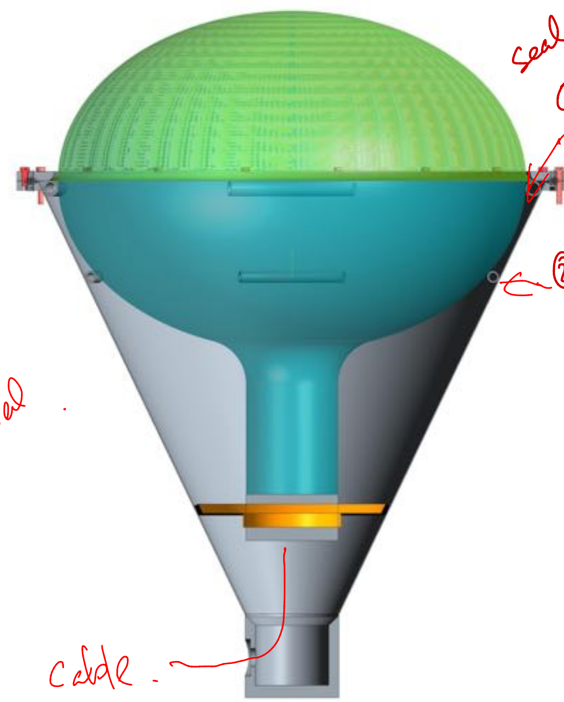


FIG. 79. Design principle of the encapsulation of a DarkSide-20k MCP-PMT.

by covering the entire detector with large Helmoltz coils, or by shielding the TMF locally, for example by the use of μ-metal screens or cages. For PMTs with a classic dynode system, the effects can also be reduced by properly orienting the dynodes axis in a direction orthogonal to the TMF. The preferred option DarkSide-20k is the use of μ-metal cages, in form of a hemispherical mesh of μ-metal wires placed in front of the MCP-PMT photocathode. These hemispherical cages were already successfully applied to compensate the TMF for the smaller (8″) PMTs in the DarkSide-50 experiment, and are being developed for use in JUNO by the same JINR Dubna group that will develop them for DarkSide-20k.

in

We performed initial tests at Dubna using a Hamamatsu 20″ PMT with a classic dynode system, covered by a spherical cage composed by two hemispheres made by μ-metal mesh. Results are presented in the Table IX. We focus on the relative PDE, normalized to the first run performed in near absence of magnetic field (TMF almost completely compensated). Data at 20 µT and 40 µT were collected with the dynodes axis oriented in the direction parallel to the field, which maximizes the magnetic field disturbance. Data for TMF represent the average for random orientations of the PMT dynodes axis. Blank runs with an ideal compensation of the TMF were performed throughout the experiment, to provide a first order assessment of possible statistical errors. As one can see from the table, the cage options provides a satisfactory path towards the goal of containing the loss in PDE due to the TMF within 10 %. Studies will proceed in the next few months, this time directly with the MCP-PMT chosen for DarkSide-20k, with the goal of finalized the design in next few months.

While the baseline solution for shielding the veto PMTs from external magnetic fields is to used a μ-metal cage, as was done for DarkSide-50 and is currently being developed for the 20″ PMTs intended for JUNO and now DarkSide-20k, another option is currently being investigated by the JINR Dubna group. This second option consists in the use of μ-metal foil, which would rolled into a cone and wrapped around the bottom portion of the MCP-PMT. This solution would have the advantage of eliminating the cage in front of the photocathode and the associated loss of light due to the blockage by the mash. Also, initial tests have shown that this solution can provide better shielding of the external fields without the need for annealing the material, as is instead necessary for the μ-metal cages. This option will also be studied in details. A final decision on the best solution will be made plenty in advance of the time required for production and delivery of the components. The total cost of the two alternatives is similar, so we do not expect any funding issues triggered by the choice of particular technology.

be

1. PMTs Backup Solution

A back-up solution would be necessary if the JUNO PMTs were not able to be delivered on time pulses for 4 channels

or they did not meet the DarkSide-20k requirements. The alternative option is that the IHEP group would instead provide the same number of 20″ Hamamatsu PMTs, which have been used in past experiments and will also be used inside the JUNO detector to provide improved timing resolution. (The performance of the PMTs being developed for JUNO is set to match that of the Hamamatsu PMTs in all but timing.) The encapsulation developed for the 20″ MCP-PMTs would still be compatible for use with the 20″ Hamamatsu PMTs, modulo the necessary mechanical adaptations.

D. LSV and WCV Front-End Electronics

The vetoes front-end electronic system must be able to handle the LSV and WCV PMTs signals, extracting charge and time information. The design baseline follows the DarkSide-50 front-end system [131], successfully adopted in a prototype, implementing different modularity and a better mechanical arrangement. R&D is currently underway to provide a prototype of the system.

Fig. 80 shows the block diagram of the front-end. Each PMT will be connected to the electronic system with a single coaxial cable (RG213-like) used for both HV supply and analog signal (see green box in Fig. 80). The HV bias will be provided by an external power supply (gray box, CAEN-SY127-like) and will be decoupled from the signal with a simple RC network. Then the analog signal pulse will be amplified and discriminated (see cyan box in Fig. 80).

The specifications for the preamplifier are:

1. Bandwidth greater than 300 MHz;
2. Gain of 10 V/V;
3. $Z_{\text{in}} = 50\,\Omega$;
4. SNR > 10.

The preamplifier output signal is output directly and also feeds a leading-edge discriminator with a programmable threshold. Multiple discriminator feed a local veto digital control board (VDCB) and the overall DarkSide-20k DAQ system, described in Sec. XII.

~~We propose~~ a highly modular design is proposed. 8 preamplifier-discriminator channels ~~will be put on~~ a single printed circuit board (PCB) called the veto front end board (VFEB), shown in Fig. 81. The VFEB PCB dimensions will be $233 \times 160\,\text{mm}^2$, a standard double Eurocard module. On this card, the input PMT signals come from the crate backplane connectors (right side in the picture); the analog output signals will be put on the board front panel to be easily connected to the external digitizers. The discriminator digital signals will be sent to the backplane connectors to be handled by the VDCB. Moreover four channels pulses are summed together giving ~~ad~~ additional information that can be used to have a coarse information on energy. In total two summed outputs will be available on the front panel. Up to 8 VFEBs will be housed into a standard 19″ 6-U crate having a modular unit of 64 channels.

The HV decoupling circuits will be implemented in a separate board, handling 8 channels, placed in the rear part of the crate. There will be 8 HV decoupling circuits per crate. This will help a lot during system setup and cabling: the PMTs RG213 cables (heavy and rigid) will be connected once to the system and never touched again. Analog signals will be distributed to the VFEB via a dedicated backplane using tiny UFL coax cables (state of the art in the mobile phone era).

define UFL

The low voltage power supply and the VDCB will also be housed in the crate. The VDCBs functions will include:

1. VFEB parameter settings (On/Off, thresholds, etc.);
2. Slow control (measure of voltages, currents, temperatures, etc.);
3. Event counters (scalers);
4. Time-to-digital conversion (TDC) of discriminator signals;
5. Trigger logic.

The VDCB will be implemented using state-of-the-art FPGA components: all logic functions are in a single chip, giving the flexibility to change the operational code at any time during the development process and also during the lifetime of the apparatus. The firmware upgrade can be also done remotely, thus avoiding the access of the board. TDCs with ns resolution, which is adequate for veto PMT signals, can easily be implemented in the FPGA. Current R&D work is focusing on a ALTERA Cyclone IV device as possible FPGA candidate for the VDCB implementation. The VDCB will communicate to the control and DAQ systems using a high-speed serial standard interface like Fast Ethernet or Gigabit Ethernet, connected using CAT-6 copper cable or standard optical fiber.

define FPGA?

define ALTERA

The system can be run triggered or trigger-less. To implement the first option some coincidence functions will be implemented in the FPGA. This function requires information from other crates, and would also provide coincidence results to the external world.

In the current design of the vetoes, the LSV and WCV together have 200 PMTs, so the electronic front-end system will have only 4 crates.

a.

Small scale single-channel prototypes have been developed to test the performance of the preamplifier-discriminator channels and also the

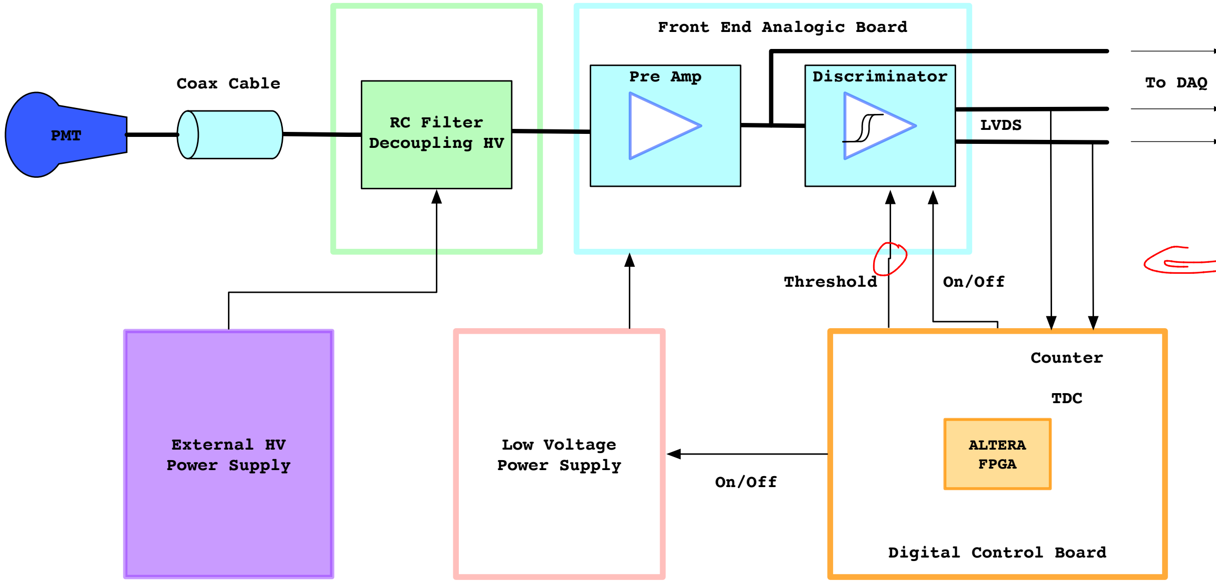


FIG. 80. Vetoes front end block diagram.

FIG. 81. Vetoes front end board drawing.

HV decoupling. In Fig. 82 a prototype of the preamplifier-discriminator is shown.

The baseline design described above follows the implementation of the existing veto system of DarkSide-50. All the functions are implemented using off-the-shelf components.

1. *Front-End Electronics Alternative*

As a possible evolution path we can consider a multichannel VLSI chip. In particular a 16 channel preamplifier-discriminator chip has been developed in the recent past and is now available to the experimental physics community. This chip has been developed by Omega (a CNRS-IN2P3-Ecole Polytechnique microelectronics design center located in Palaiseau, France) and it is called CATIROC. CATIROC implements 16 independent channels to

define VLSI ?

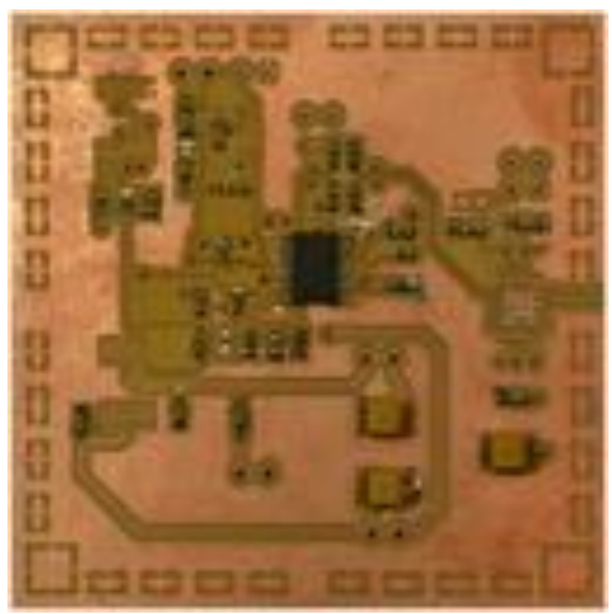


FIG. 82. Preamplifier prototype card (single channel).

measure charge and timing information from PMT signals. A dedicated evaluation board has been developed and we will procure one to test the functionality of the chip connected to the DarkSide-20k PMTs.