Utilization of a remotely controlled DC-DC Boost Converter: for the biasing of Silicon Photomultipliers for DUNE

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Summary. — The Deep Underground Neutrino Experiment (DUNE), dedicated to studying neutrino oscillation physics, is currently under construction in the United States in collaboration with Fermilab, where the neutrino beam will be generated, and the Sanford Underground Research Facility (SURF) in South Dakota, which will host the Far Detector (FD) modules for future data collection. The FD will mostly employ Liquid Argon Time Projection Chamber (LAr-TPC) technology with an innovative system for collecting scintillation photons using Silicon Photomultipliers (SiPMs). In this paper, it is introduced the concept of FD, with a focus on the Vertical Drift module, and the results on the characterization of a remotely controlled DC-DC Converter designed for cryogenic applications in high voltage environments. Additionally, the advantages of its possible implementation in future Far Detector modules of DUNE are discussed.

1. – DUNE

The Deep Underground Neutrino Experiment [1] is a next-generation long baseline experiment focused on neutrino oscillation studies. Construction is ongoing in the United States, where the beam is produced at Fermilab and the Far Detector modules will be located at the Sanford Underground Research Facility (SURF) in South Dakota. A proton beam, with an energy spectrum peaked at 60-120 GeV, impacts with a high power production target, producing an intense neutrino flux. A Near Detector (ND) is placed 500 m from the source, consisting of multiple detectors designed to characterise the composition of the generated neutrino beam and minimize systematic uncertainties. Located at a distance of 1300 km from the accelerator, and 1500 m underground in order to be shielded by cosmic rays, the Far Detector (FD) will study neutrino oscillation

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parameters with high sensitivity, while at the same time acting as target for solar and diffuse supernova neutrino [2]. The DUNE program includes also the investigation of physics Beyond the Standard Model and charge-parity (CP) symmetry violation [3].

To cover this extremely complex physics program, DUNE will employ Liquid Argon Time-Projection Chamber (LAr-TPC) [4] as main detector technology, since it will allow to read with sub-centimeter granularity the patterns of ionization in 10 kt volumes of liquid argon, generated by neutrinos from the main beam as well as from additional sources. The large volume of LAr will be subject to a strong electric field, i.e. 500 V/cm, in order to drift the ionization electrons to be collected towards a charge read-out system. The information resulting from the monopolar signal will give crucial information on the interaction between neutrinos and Liquid Argon. Since LAr is known for its powerful scintillation qualities, emitting VUV light at 127 nm wavelength [5], the TPCs of DUNE will also host what is called Photon Detection System (PDS). Scintillation light will be collected by silicon photomultipliers (SiPMs) arranged in an innovative system called X-ARAPUCA [6], which main purpose is to trap photons inside a wavelength shifting slab in a reflecting box, thus increasing the collection area and enhancing light collection efficiency. The PDS will register the arrival time of photons which is in the order of ns for each event, and by comparison with charge read-out timing information, it will enable reconstruction in the direction of the ionizations charges drift.

2. – Far Detector Vertical Drift

The Far Detector, with its modular design, will be composed up to 4 modules positioned in the cavern at SURF. The first two modules (FD1 and FD2) are based on LAr-TPC technology, as presented in the previous Section, and now under construction. New approaches and proposals are rising for the next modules (FD3 and FD4), which FD3 consists in a further optimized LAr-TPC and FD4 is still under investigation.

In particular, the FD Vertical Drift (VD) [7] contains 17 kton of Liquid Argon and it takes its name from the internal design of the TPC. Inside the detector, there are two drift modules divided by an horizontal cathode plane that is biased up to -300 kV and placed in the middle of the volume: due to its configuration, the ionization charges have a vertical drift distance of 6 m inside the detectors. The anode planes take the name of Charge Readout Plane (CRP) and they consist of copper strips printed on perforated PCBs with biased strip electrodes on the other faces. The three planes, as defined, are oriented at different angles to one another, enabling charge read-out from multiple projections. Due to the CRP opacity to scintillation light and to ensure proper light detection, the solution proposed by DUNE is to install the PDS on both on the walls of the cryostat hosting the TPC (outside the sensitive volume and at ground), and on the cathode, employing a completely new technology to overcome the limitations introduced by the high voltage (HV) environment. To enable the installation of PDS modules on the cathode, dedicated systems have been developed to transmit both power and signals. Power Over Fiber (PoF) delivers optical power from an external laser source, which is converted into electrical power via an Optical Power Converter (OPC). The signals generated by the PDS modules are instead transmitted using the Signal over Fiber (SoF) system.

2˙1. *The Power over Fiber Technology.* – PoF technology transmits laser power through a non-conductive optical fiber to a remote photovoltaic receiver known as an OPC, and enabling the operation of remote sensors or electronic devices. Existing PoF technologies are widely used to provide voltage isolation between the power source and receiver, and to supply embedded electronics in high-voltage or high-noise environments. However, none of the commercially available solutions are qualified for operation in cryogenic conditions such as liquid argon [8]. Electrical power for the electronics is supplied by two gallium arsenide (GaAs) OPCs and they convert optical power into electrical power with an efficiency primarily dependent on load matching to the laser power, and to a lesser extent on temperature. This innovative Power over Fiber approach offers three key advantages: voltage isolation, immunity to noise, and spark-free operation.

3. – DC-DC Boost Converter

The photon detection system, as introduced previously, is based on SiPMs, which require a bias voltage in the range of 30 V to 50 V at LAr temperature (87 K) to correctly fuction in detecting scintillation light inside the TPC. The innovative approach of the PoF technology introduces one main limit: OPCs tested output is between 5 V and 7 V, which is insufficient to bias the SiPMs. In this paper, the design and implementation of a cryogenic DC-DC Boost Converter, along with its control system which is able to bias the SiPMs at the desired voltage, are presented, as well as its possible application in the future FD modules. The DC-DC converter steps up the voltage from the PoF receiver to the appropriate level, with key design goals including low noise, high stability, reliability, and low power consumption. Given that the system will be inaccessible for the entire duration of the experiment (approximately 30 years), the output voltage should also be adjustable without requiring significant hardware redesigns, ensuring adaptability to future experimental requirements. For this reason, the Milano Statale group proposes a remotely controlled DC-DC Boost Converter with the implementation of an external optical set-point to adjust to different output voltages at cryogenic temperature. The laser source remains at room temperature, outside the detector, and via optical fiber and the appropriate OPC, the external signal reaches the DC-DC Boost Converter, enabling the possibility of obtaining different output voltages. This feature covers also a key role when choosing the correct SiPMs bias, since different configurations are still possible after installing all the cold electronics boards.

3·1. *Circuit design.* – After selecting the circuit design of the DC-DC Boost Converter, the different circuit components are chosen in order to work at cryogenic temperatures [9]. The topology used in this work is shown in Fig. 1.

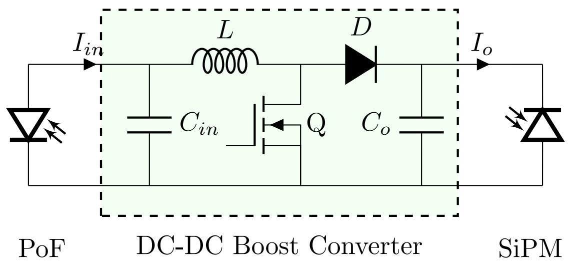

Fig. 1. – Schematic of the DC-DC Boost Converter circuit.

The circuit is used for a voltage step-up, starting from the PoF output, to the desired SiPM bias voltage. The inductor (L) and capacitor (C_o) are selected and sized in order to minimize voltage ripple. The voltage transfer function is governed by the duty cycle (ρ) of the Pulse Width Modulation (PWM) control signal, which drives the circuit only active element, the MOSFET Q [10]. For this reason, the control circuitry plays a crucial role in maintaining a stable output voltage, preventing the control loop from drifting and causing an unintended voltage drop. The DC-DC converter circuit also allows external output voltage adjustments, thanks to the introduction of an external signal whose duty cycle regulates the DC-DC output. The board, hosting a Broadcom HFBR-2506AFZ photodiode receiver (HFBR), is plugged in the DC-DC board and it permits to set the output voltage given via optical fiber. A picture of the device is presented in Fig.2. In the absence of the remote control signal or in case of failure, the Converter automatically reverts to operating correctly with the default output value. The ability to select a specific output voltage, using the Over-Fiber technology, enhance the flexibility of the Converter to be introduced in a hostile environment such as the one presented in the FD VD.

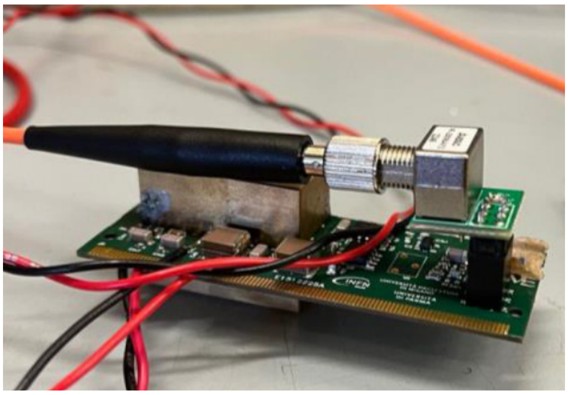

Fig. 2. – Ad-hoc board with optical to electrical receiver for the external optical set-point reading, connected to the DC-DC Boost Converter board.

3˙2. *Experimental results*. – After characterizing the DC-DC Boost Converter at room temperature, the same procedure is followed at cryogenic temperature (i.e. liquid nitrogen, 77 K) [10]. Liquid nitrogen has a temperature similar to that of LAr, but is more readily available. For this reason, characterization of electronic circuits in liquid nitrogen (LN2) is generally accepted by the scientific community when the circuits are intended for use in LAr environments. The output voltage used for the characterization in LN2 is set to the nominal value of 48 V, which corresponds to the bias voltage expected by Hamamatsu SiPMs, based on the over-voltage selected by the DUNE Collaboration. The comparison of the experimental tests are presented in Fig. 3. Analysing the graph of the output voltage V_{out} as a function of the external optical PWM duty cycle ρ reveals a key feature: the output voltage exhibits good linearity at cryogenic temperature. Moreover, under cryogenic conditions, the response curve is steeper, resulting in faster and more responsive control. At 77 K, the output voltage can reach up to approximately 54 V, while remaining linear down to values as low as 24 V.

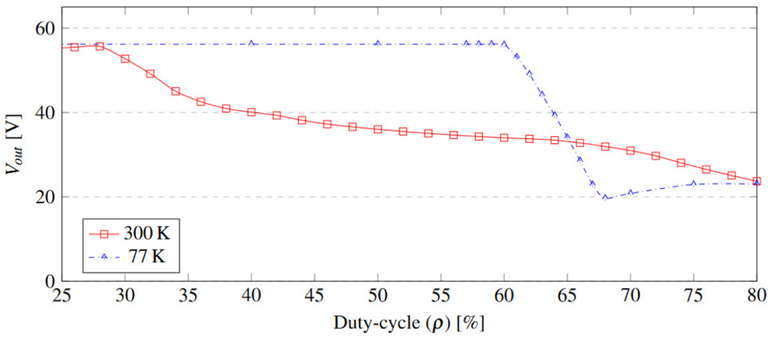

Fig. 3. – Results of the room and LN2 temperature tests for the DC-DC Boost Converter: output voltage as a function of the duty cycle of the optical PWM signal.

4. – Conclusions

In this paper, a brief description of the DUNE experiment is introduced with a specific focus on the Vertical Drift module and its advanced technology in powering and reading signals in a high tension environment at cryogenic temperature. The design and characterization of a working, remotely-controlled DC-DC Boost Converter, specifically designed for DUNE Far Detector Vertical Drift modules, are presented. The experimental results show the circuit to perform successfully at cryogenic temperatures while employing an external control via optical fiber. The control linearity and fast response, particularly at 77 K, demonstrate the suitability of the solution for operation in hostile environments. These design choices enhance the flexibility of the DC-DC Converter for future DUNE modules compared to the configuration currently installed in the FD VD detector module.

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