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Scintillation imaging in GRAIN Liquid Argon detector of DUNE experiment

A. Montanari on behalf of the DUNE collaboration

Istituto Nazionale di Fisica Nucleare, Sezione di Bologna,
Viale Berti-Pichat 6/2, Bologna, Italy

E-mail: alessandro.montanari@bo.infn.it

Abstract: GRAIN (GRanular Argon for Interaction of Neutrinos) is a Liquid Argon detector which is part of the Near Detector complex of DUNE experiment. Most conventional noble liquid detectors employ scintillation light as either a timing signal for a TPC or as a calorimetric measurement, or both. The signal's relative amplitude and timing on multiple detectors can also be used to approximately locate an interaction. In GRAIN we go a step further, by using scintillation light to reconstruct images of tracks associated to charge particles in Liquid Argon volume. In fact, by developing a suitable optical system, coupled with finely segmented SiPM arrays, it is possible to build photographic cameras that capture images of the primary scintillation light. In absence of a TPC, scintillation imaging alone can provide vertexing and tracking information, while combined it can enhance resolution and rate capability (which is a concern for near detectors located on powerful neutrino beams). Argon scintillates in the VUV range, imposing stringent requirements on the optical system and SiPMs. By replacing a traditional set of lenses with lenses built with materials specifically designed to operate in cryogenic conditions or with coded aperture masks, a compact camera can be created. The latest results from simulation and reconstruction of charged tracks in GRAIN LAr detector equipped with these cameras will be presented. In particular, the development of key enabling technologies, such as a large, low power cryogenic ASIC and VUV-enhanced Backside Illuminated SiPMs will be emphasized.

Keywords: Neutrino detectors; Photon detectors for UV, visible and IR photons (solid-state); Electronic detector readout concepts (solid-state); Data processing methods

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1 Introduction

The state of the art for Liquid Argon readout is the Time Projection Chamber (TPC), pioneered by ICARUS detector, where both ionization signals and scintillation light induced by charged particles are used. Ionization electrons are drifted in a uniform electric field to a segmented (wires or pads) anode, allowing the 2D reconstruction of the track. The drift time, calculated from the reference time of scintillation light, allows to reconstruct the third coordinate, given a known drift velocity. We will exploit a completely new technique for the readout of GRAIN (GRanular Argon for Interaction of Neutrinos) that is a 1-ton Liquid Argon detector which is part of the Near Detector complex of the DUNE experiment. In particular we will use only the scintillation light to reconstruct the tracks of charged particles in Liquid Argon. In order to accomplish this task, we developed imaging cameras based on matrices of Silicon PhotoMultipliers coupled to dedicated optical systems. The main advantages of this approach are related to the high rate capability, the insensitivity to magnetic fields, the simplicity and robustness.

2 The DUNE experiment

The DUNE experiment (see figure 1) aims to address key open questions in neutrino physics, including the mass hierarchy, the CP-violating phase δ_{CP}, and precise measurements of mixing angles. It will also search for nucleon decay, dark matter signatures, and Beyond Standard Model (BSM) physics, while studying supernova neutrino fluxes.

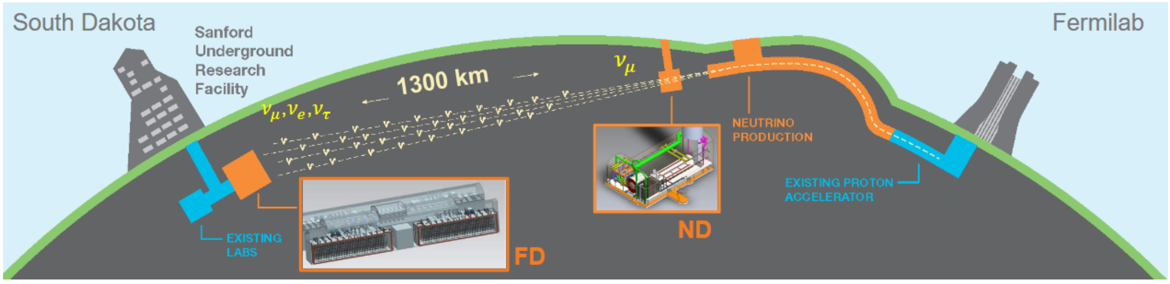

Figure 1. The DUNE Long Baseline experiment.

DUNE's Far Detector (FD) employs Liquid Argon Time Projection Chamber (LArTPC) technology for precise tracking and calorimetry. It consists of four modules, each with a 10 kt fiducial mass, enabling high sensitivity to neutrino interactions. The experiment benefits from a 1300 km baseline, which enhances sensitivity to matter effects and mass ordering. Fermilab provides a wideband neutrino beam, allowing the study of oscillation patterns. The Near Detector (ND), illustrated in figure 2, measures the neutrino beam before oscillations occur, reducing systematic uncertainties [1]. It includes ND-LAr, the Muon Spectrometer (TMS), and later ND-Gar, a high-pressure gaseous argon TPC for improved particle tracking. The PRISM technique allows shifting the detector off-axis to study different neutrino energy spectra, refining predictions for the FD.

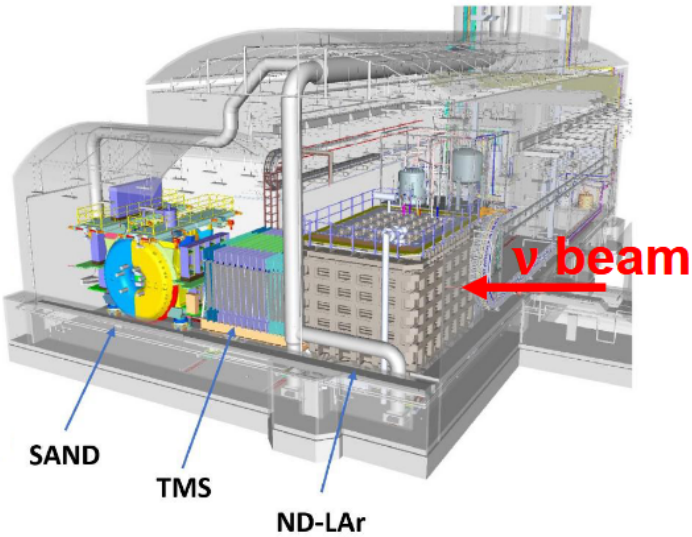

Figure 2. The Near Detector complex, including a multipurpose neutrino detector (SAND), a muon spectrometer (TMS) and a liquid argon TPC (ND-LAr). A high-pressure gaseous argon TPC (ND-GAr) will be added later.

DUNE is being deployed in phases, with the first FD module installation starting in 2024. Initial data-taking will begin with two modules and a 1.2 MW beam, followed by additional modules and a beam upgrade to 2.4 MW.

SAND is a multipurpose neutrino detector, part of the Near Detector complex, designed to study neutrino interactions on various target materials, including Argon, Carbon, and CH_2. It will be permanently centered on beam and it will provide precise tracking and calorimetry measurements.

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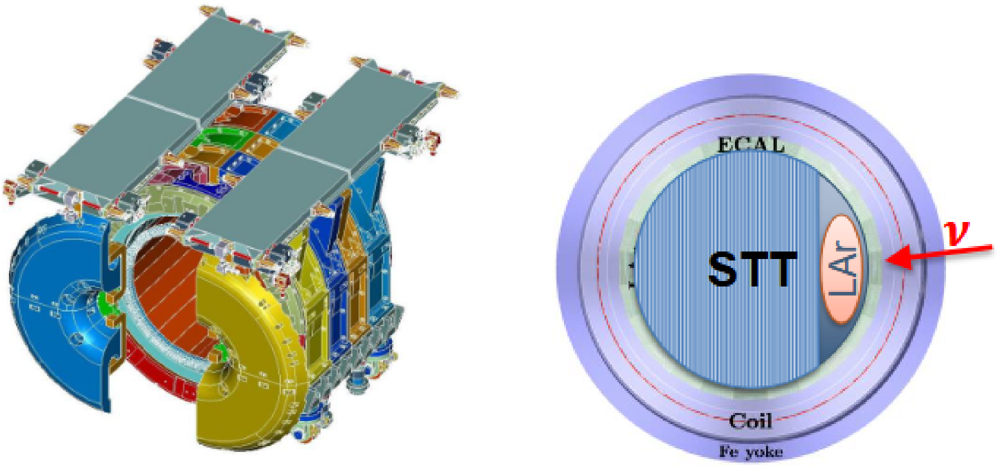

Figure 3. The SAND detector 3D (left) and side view (right).

The detector features a superconducting solenoidal magnet, which generates an axial magnetic field, housing an electromagnetic calorimeter (ECAL), a tracking system, and a liquid Argon detector. SAND repurposes the magnet and ECAL from the former KLOE detector [3], previously used at the INFN LNF laboratory in Italy to study CP violation in neutral Kaon decays. The original drift chamber of KLOE, instead will be replaced by a inner tracker consisting of Straw Tube Target (STT) modules and an active 1-ton LAr target named GRAIN (Granular Argon for Interactions of Neutrinos), both within the magnetized volume (see figure 3).

3 The GRAIN detector

GRAIN will provide inclusive Argon interactions to reduce systematic uncertainties from nuclear effects and will remain permanently on-axis for continuous monitoring of neutrino beam flux.

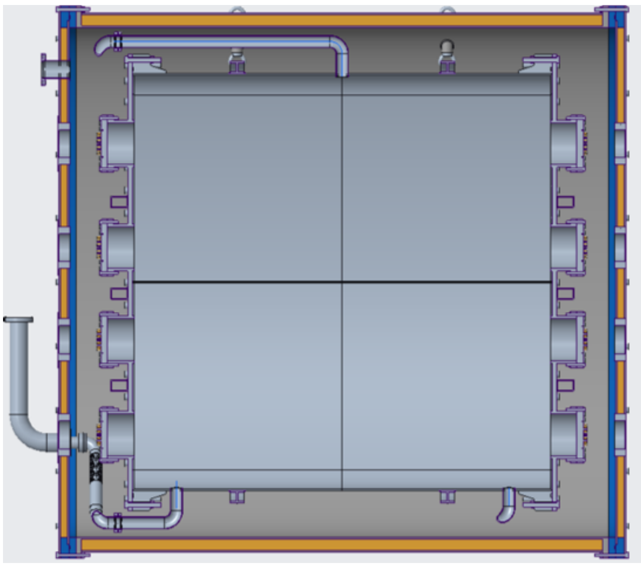

Figure 4. GRAIN cryostat.

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The cryostat design consists of two coaxial cylindrical vessels with an elliptical base, thermally insulated by a vacuum between the inner and outer layers. The inner vessel (see figure 4), made of stainless steel, maintains liquid Argon at 1.5 bar pressure, while the outer vessel is reinforced with carbon fiber and aluminum. The design minimizes material thickness to reduce energy loss, showering, and multiple scattering.

Instead of a traditional LAr TPC, which faces challenges due to high event rates and long ionization drift times, GRAIN explores an alternative tracking and calorimetry system based on scintillation light imaging. Charged particles, produced by the interaction of neutrino, excite and ionize argon atoms, producing scintillation light. Pixellated photon detectors inside the cryostat will capture these emissions, forming a "picture" of particle interactions.

Two imaging technologies are under evaluation: one using lenses and another using coded aperture imaging. Research is ongoing to develop optics for Argon scintillation light (128 nm) and suitable light sensors for cryogenic conditions, marking a novel approach in neutrino detection.

4 A VUV imaging camera

A Minimum Ionizing Particle produces, through the scintillation of Liquid Argon [2], about 1000 photons per 100 µm. Despite the abundance of photons from scintillation, the development of an imaging camera for the detection of scintillation light implies several challenges. Since the wavelength of scintillation light in LAr is in VUV regime (about 128 nm), the optics based on lenses normally used for visible light does not work. For the same reason, also the common light sensors are completely inefficient. Finally the camera and its electronics should be able to operate at Liquid Argon temperature, that is 87 K.

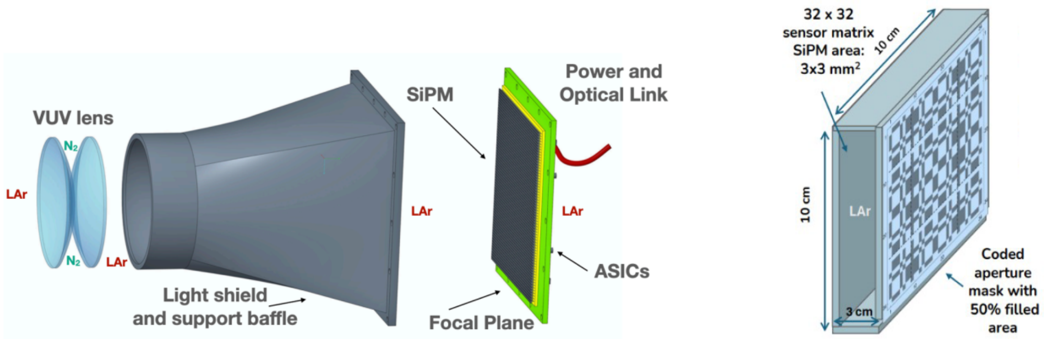

Figure 5. Layout of camera based on Lens (left) and Mask(right).

Currently two technologies for the camera optics are being evaluated for their use in GRAIN (see figure 5), based either on UV Lenses or on Coded Apertures Masks: lenses are traditional imaging systems, but their use for LAr scintillation light (Vacuum UltraViolet) poses some challenges related to material properties (transmittance in VUV regime, matching of index of refraction of lens and liquid argon) and to the choice of the main optical parameters. Currently different materials are under test, some of these have high transmittance only at wavelength higher than 180 nm. In this case the usage of Xenon doping for shifting the 128 nm wavelength Argon scintillation light is necessary.

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The Coded Apertures technique [5] is the direct evolution of the pinhole camera, the simplest imaging device. A perforated mask is placed in front of the photo-detector. This optical system will form an image on the sensor plane from which one can extract the track parameters through iterative numerical algorithms. This is independent on the light wavelength, but it requires a large amount of collected light for a good reconstruction.

In both the technologies the impinging photons are detected by matrices of 32×32 SiPMs. A coating of Wave Length Shifter is necessary to shift the wave length to better match with the photon detection efficiency spectrum of presently available SiPMs. The size of the SiPM range from 3×3 mm^2 devices in the case of masks to 1×1 mm^2 for lenses. The size of the SiPMs is smaller for the lenses because they focus the light while the masks filter about 50 % of impinging photons and need larger SiPMs to collect enough statistics.

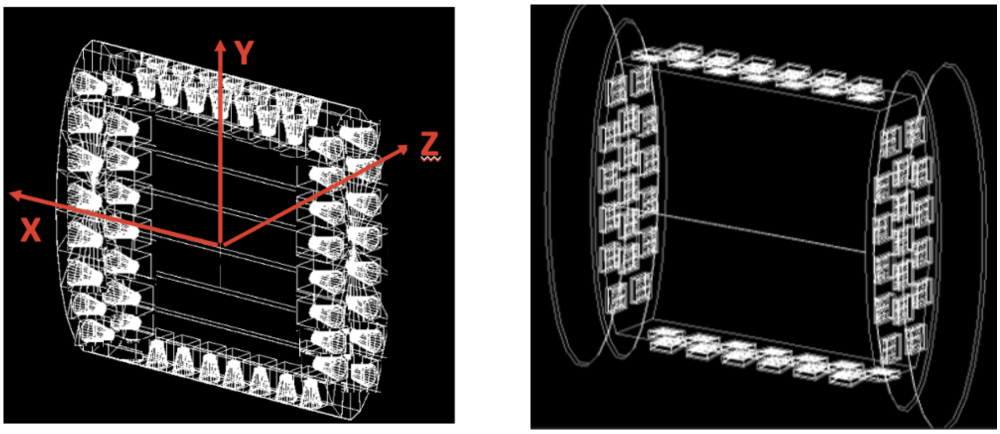

Figure 6. Layout of camera based on lens (left) or masks (right).

As depicted in figure 6, in order to allow the 3D reconstruction of tracks inside the fiducial volume of GRAIN, about 60 cameras (based on lens or mask) are placed on the two sides and on the top and the bottom.

5 Track reconstruction

Track reconstruction with Coded Aperture mask is based on a iterative process of Maximum Likelihood Expectation Maximization [4]. The measured data are considered samples from a set of random variables whose probability density functions are related to the photon source distribution according to the model of the data acquisition process. It is possible to calculate the probability that any initial distribution density in the object under study could have produced the observed data. In the set of all possible measured data, the one having the highest of such probability is the Maximum Like lihood Estimate of the original photon source distribution (see figure 7). The algorithm can be directly applied to a three-dimensional reconstruction, with the segmentation of the fiducial detector in volume units, called voxels. The reconstruction algorithm has been implemented in Python with OpenCL for acceleration on GPU devices, with the possibility of running on multiple GPUs.

In the case of the lenses, the pattern formed on the SiPM matrix is the 2D projection of a track of the event. By combining the projections on different cameras it is possible to reconstruct the track in 3D.

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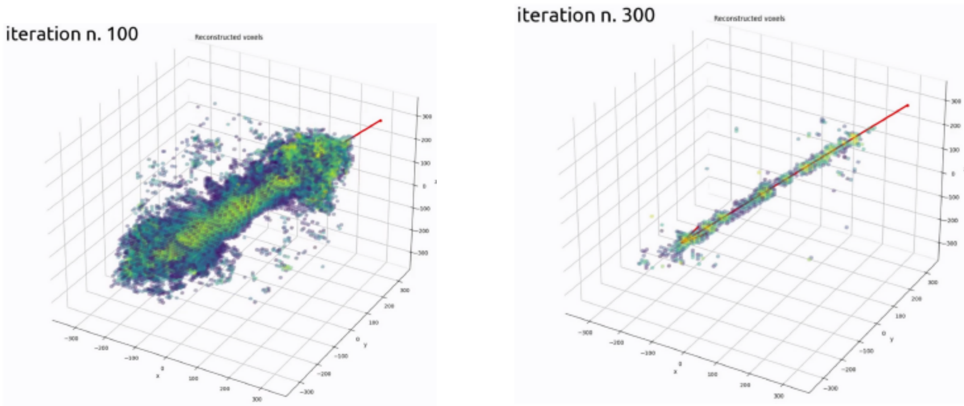

Figure 7. Track reconstruction with mask recursive alghorithm after 100 (left) and 300 (right) iterations.

6 A new ASIC

In order to readout individually all the SiPMs of a matrix, a 1024 channels ASIC called Dune Itegrated Electronics for NEutrino Beams (DENEB) is presently under development. The ASIC must be able to function at both cryogenic and room temperature. In order to ensure this versatility it is possible to rely on externally controlled parameters. The ASICs will have 1024 channels and it will be mounted in close proximity to the sensors, most likely on the opposite side of the same PCB. A 1024 channels ASIC is optimal for a sensor of 32×32 SiPMs. The requirements on power consumption and data throughput assumes that about 60 cameras, each of one with 1024 channels, will equip the detector. It is important to note that the beam structure is characterized by an extremely low duty cycle (10 µs spill, nearly 1 s interspill). While one may want to also occasionally collect off-beam data for acquiring cosmic events for calibration and background studies, a duty cycle limitation can be accepted if it is necessary to meet the other requirements related to power consumption and data throughput. As a reference for the design, a limit on the power consumption of 5 mW for channel was defined. The architecture is designed in such a way that for each channel for each spill a few integration windows can be acquired and each integration window starts when the first photon is detected (since a 0.5 photoelectrons (PE) threshold is considered) and close when the waveform signal is lower than the threshold for more than 40 ns (hold-on time). For each integration window we can record the time with O(100 ps) resolution for rising edge on a 0.5 PE threshold, the time over threshold with O(2 ns) resolution and the integrated charge. In this way many photons arriving close in time are detected in the same integration window since they probably comes from the same neutrino interaction, while photons separated by more than 100–200 ns are usually detected in different windows so the time of the first photon is well acquired.

7 The demonstrator prototype

While the construction of a full scale prototype of one camera with 1024 channels will require the new ASIC, a readout system for testing prototypes with matrices of 16×16 (256 channels) has been built (see figure 8). The readout chain consists of a SiPM matrix (16×16), connected to a custom PCB hosting eight ALCORs (A Low-power Circuit for Optical sensor Readout) a 32 channels integrated circuit suitable in cryogenic environment developed by INFN-Torino [6]. This board is connected via an FMC extension cable with a Virtex-7 VC707 FPGA with a custom firmware based

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on the IPbus protocol. This readout system was designed to accommodate SiPM matrices with different pitch. A matrix of 1×1 mm^2 SiPMs is directly available in a monolithic 16×16 array by Hamamatsu (S13615-1050N-16), while for the configuration with 3×3 mm^2 SiPM size, four 8×8 arrays (S14161-3050HS-08 and S13361-2050NE-08) have been mounted on the same board as close as possible to form a 16×16 matrix. The gap between the four arrays results in being only slightly bigger than the dead space between the other SiPMs. All these SiPMs are designed for the visible range and they will require TPB deposition to be sensitive to UV wavelengths.

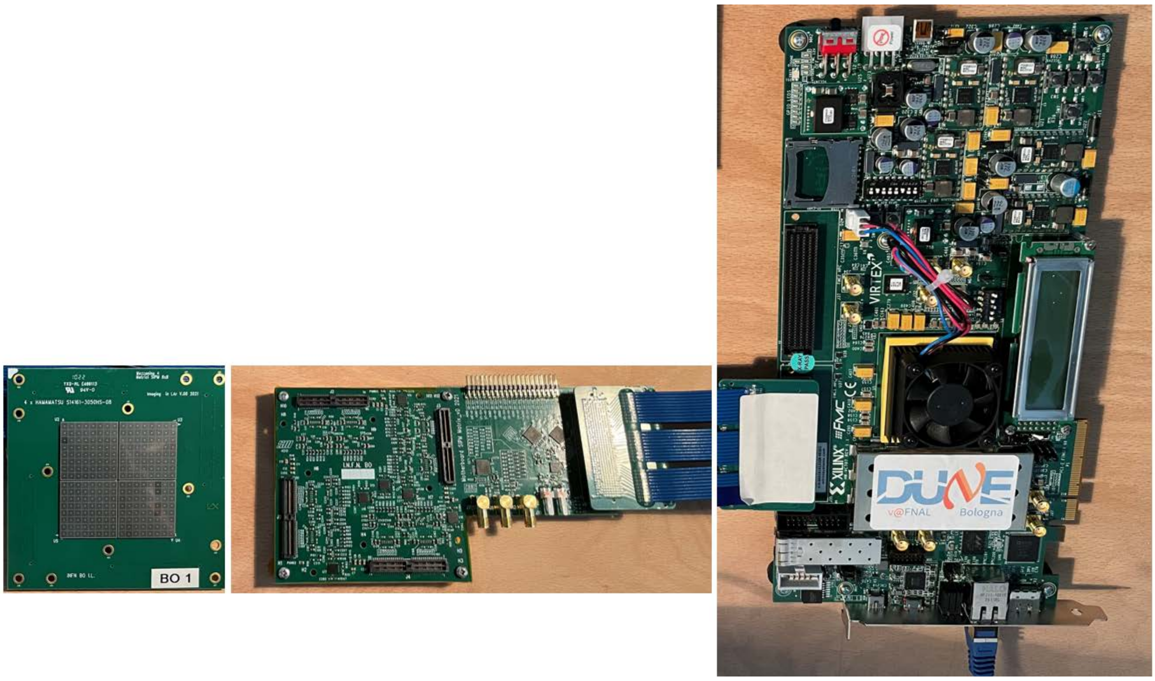

Figure 8. From left to right: mezzanine board with SiPMs matrix, mother board with 8 Alcor ASICs, readout board with FPGA.

For each channel, together with the timing information of the first detected photon, which is measured with a global time resolution of 50 ps, the time-over-threshold is acquired in order to estimate the number of detected photons in each acquisition window.

8 Future perspectives

One of the most important limitation to the imaging technique presented in this work, especially in the case of mask optics, is represented by the small number of detected photons.In fact roughly 50 % of photons are lost due to the optics and further 50 % are lost by the wave length shifter that is necessary to shift the scintillation light from 128 nm to longer wavelength, where the SiPM is more sensitive.

In order to improve SiPM sensitivity in the Vacuum Ultra Violet (VUV), an R&D program for the development of BackSide Illuminated (BSI) SiPMs was started. As illustrated in figure 9, in the BSI SiPMs the entrance window is on the back of the wafer, after having removed most of the Silicon bulk. All the metallic network and the quenching resistors remains on the original front side, so that the entrance window is completely free with the benefit of enhancing the fill factor and enabling the possibility to apply surface treatment to reduce reflectivity. As a further benefit, a readout chip will be more easily integrated by bonding on the front contacts.

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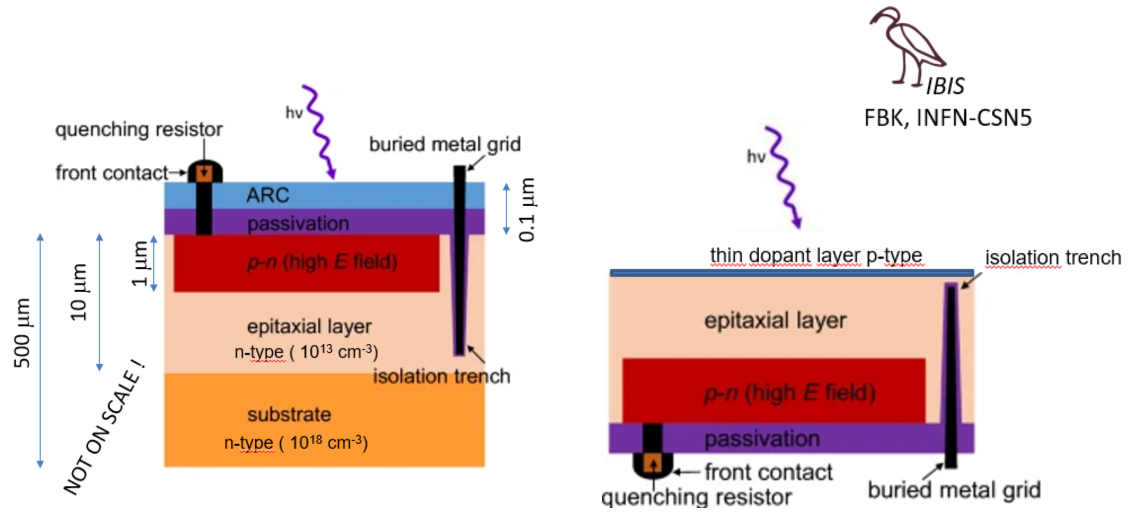

Figure 9. Layout of the standard SiPM (left) and the Backside Illuminated (right).

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