FOURIER TRANSFORMATION ON WAVEFORMS OF LIGHT EVENTS.

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dedicated to Davide Porzio.

Neutrino physics in recent times has been going through a revolutionary period. Measurements of neutrinos coming from the sun or produced by cosmic rays in the Earth's atmosphere have revealed that neutrinos "oscillate" [1], which means that they change their flavor periodically with time and for this reason additional experiments are being designed in order to address questions coming from this discovery.

1. ARGONCUBE

The experiment Argoncube [2], shown in *fig.1*, is a new designed tool for building advanced Liquid Argon Time Projection Chambers (LarTPCs) [3], based on detector modularization, enabling the scalability to large active detector masses.
One of the main purposes of ArgonCube is to be a model for the construction of DUNE [4], a future experiment on neutrinos and proton decay studies.

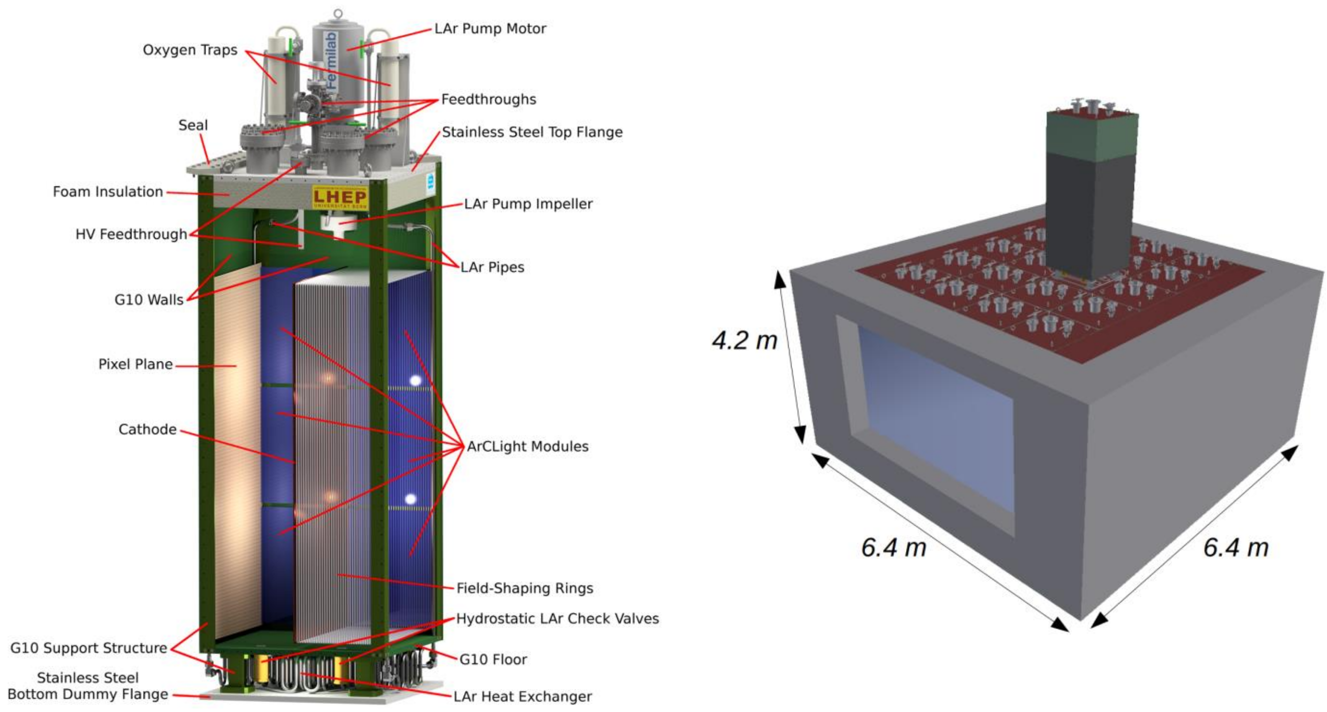

Fig 1: the figure shows how ArgonCube is built, including new technologies such as ArClight modules. Additionally some measurement of the dimensions of the experiment are shown.

2. ARGON

ArgonCube uses the strategy of liquid argon in order to detect particles [5], because with forty protons and neutrons, this element is denser than water or oil (which were – and are - used for other kind of detectors in the past), so liquid-argon detectors see more neutrino collisions per unit volume than their oil- or water-based predecessors which translates into higher statistics and precision that can be obtained in shorter run times.
Due to the particular stable state, given by the fact that argon is a noble gas, argon hardly interacts with matter, meaning that there is not the risk for a particle to affect the atom or vice versa; additionally it is transparent so it cannot absorb photons.
Another advantage of liquid argon is that, when a particle interacts with it and subsequently generates other charged particles, it produces two separate kinds of signals; oil- or water-based detectors produce only one.
One type of signal, unique to liquid argon, results from its ability to record the charged particles' trajectories.
The second signal type is one shared with oil- and water-based detection: a flash of light.

The flash of light happens when two atoms of argon join together or when a charged particle collides with an argon atom's electron, in this case the electron would transit to a state of higher energy and to come back to the original state it would need to release the excess of energy by emitting a photon.

While the ability of detect charged particles occurs because when charged particles are created in the liquid argon, after a neutrino arrives and collides with an argon nucleus, they travel through argon and easily displace electrons from the neighboring atoms along their path.
The ionisation electrons in the liquid argon drift toward an array of wires on the side of the detector, thanks to the action of an applied electric field. The wires collect data on the particle trajectories, resulting in a signal.

These detection methods combined with relatively high density, resulting in higher rates, properties such as being transparent and a noble gas, make argon the perfect candidate for experiments in the fields of neutrino physics and particle decay.
Furthermore Argon is not expensive and its usage allows the development of research in the cryogenic field, since it is used at the temperature of 80K.

3. LIGHT READOUT TECHNOLOGIES

For ArgonCube, new technologies have been developed for the development of a modular design, including a pixelated charge readout and light detectors with a precise time resolution. [6]
The pixelated charge readout provides an event topology reconstruction, vital to prevent pile up in high multiplicity environments and it allows to study interactions and decays in a very accurate way. [7]
The scintillation light produced by particle interactions within each module is used to provide precise timing information for neutrino event in order to determine t0 (starting moment). [8]

Two complementary light readout technologies for collecting the scintillation light (ArCLights and LCM, Light Collection Modules) , shown in *fig. 2*, have been produced by the University of Bern and by JINR in Dubna.

The working principle of these large-area detectors is based on the trapping of wavelength-shifted photons with the aid of dichroic mirrors (Bern prototype) or wavelenght-shifting light guiding fibres (Dubna prototype).
Silicon photo-multipliers that detect the trapped photons (SiPMs) are located at one edge of the unit. The whole sensor is made of dielectric material and can operate in regions of high electric field.

Fig 2: prototype (left) and Bern prototype (right) used for light detection in Argon cube. They use two different working principle in order to accomplish the detection: the trapping of wavelength-shifted photons with the aid of dichroic mirrors for the Bern prototype) and the wavelenght-shifting light guiding fibres for the Dubna prototype.

4. FOURIER TRANSFORMATION

The Fourier transform (FT) is a mathematical transform that decomposes functions depending on space or time into functions depending on spatial or temporal frequency [9]. The Fourier transform and the inverse of it,

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt$$

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} d\omega \tag{1}$$

where ω is the frequency domain, t the time domain and the power of the exponential is a basis function, reveal a signal's elemental periodicity by decomposing the signal into its constituent sinusoidal frequencies and identifying the magnitudes and phases of these constituent frequencies.

The term *Fourier transform* can refer to both the frequency domain representation and the mathematical operation that associates the frequency domain representation to a function of space or time.

The Fourier transform of a function of time is a complex-valued transformation of frequency, meaning that the transform itself is neither the magnitude of the frequency components in *f(t)* nor the phase of these components and its argument is the phase offset of the basic sinusoid in that frequency.
The transformation is not limited to functions of time, but the domain of the original function is usually called 'time domain'.
Linear operations performed in one domain (time or frequency) have corresponding operations in the other domain, which are sometimes easier to perform. After performing the desired operations, transformation of the result can be made back to the time domain.
Harmonic analysis is the systematic study of the relationship between the frequency and time domains, including the kinds of functions or operations that are simpler in one or the other and can be related to many areas of modern mathematics. Functions that are localized in the time domain have Fourier transforms that are spread out across the frequency domain and vice versa.

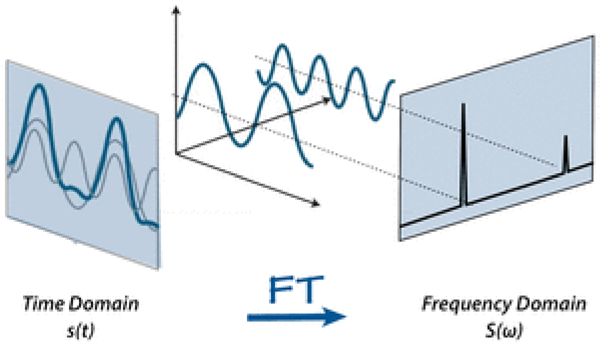

Fig 3: the figure above shows the difference between the time domain and the frequency domain once the FT has been applied. The same wave has two different shapes in the domain.

5. NOISE

Electrical noise is the lower boundary for a communications signal, and forms the noise floor. It is an intrinsic component because an electrical current consists of many single electrons. The lower the signal, the fewer electrons are involved. For example the motion of the electrons is not only determined by the force which is given by the electrical field, supplied by the voltage of the external signal source, but also by collisions of the electrons with the atoms of the conductors. With these collisions the temperature of the material will also be transfered to the electrons. This is a matter of thermal noise.
The terms error and noise are somehow closely related. Noise is a fluctuation on the input signal which can come from different sources and can have different spectral components. It can cover desired information and needs to be suppressed with advanced techniques, nut some noise components can be intrinsic and cannot be eliminated by any technique.

6. FT ON LIGHT EVENTS

After data taking, the analysed signal can have excess of noise, coming from the detector itself.
It is shown that some small peaks always appear as background interferences and to understand what is the event on the display and if it is the one needed for research, it is needed to look at the event without those noise components. Since the light signal has a higher amplitude, using the FT for deleting what is useless is possible in the frequency domain.
Background noise appears smaller, instead the flash of light has a high peak that can be easily distinguished from the others, as well as some smaller peaks which could represent the second phase of a decay or the appearance of photons producted by interactions between particles.

For example when a muon decays[10], two neutrinos and one electron, or a positron based on the charge of the muon, appear and in this case the electron is called 'Michel electron'.
This decay, and particularly the michel electron, has a specific light-event shape: as it takes place it is possible to notice a deep peak followed by others.

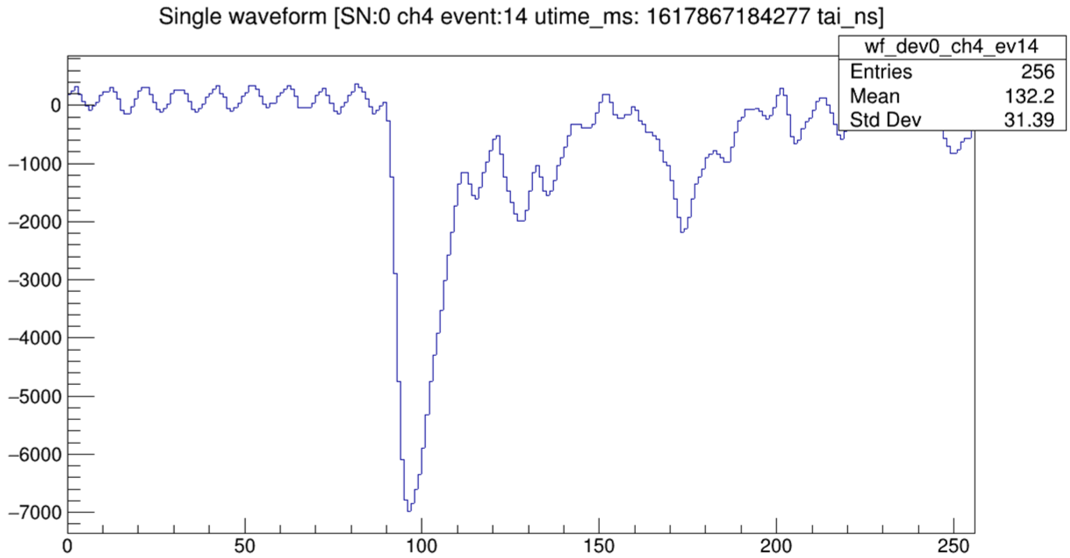

Fig 4: possible light event candidate for a muon decay. The first and deepest peaks is the decay of the muon itself, the second peak shows the light emitted by the Michel electron.

as shown in the figure, in the first part from the left to the right the graph is distorted by various noise components which are smaller in amplitude, so they must be removed in order to look at the figure in the proper way and extract correct quantities.

Applying the Fourier Transformation is a simple and fast way, but it would require too much time and it would not be practical and efficient for real purposes for long data sets where *N* (data size) may be in the thousands or millions. The process can be accelerated by using the algorithm of the Fast Fourier Transformation, which computes the discrete Fourier Transformation of a sequence or the inverse of it (IFFT) but faster.

In fact periodic signatures appear in the graph of the Fourier Transformation as centered around their frequency so they can be removed by manually setting them to zero and then using the inverse Fourier Transformation to recover the original signal.

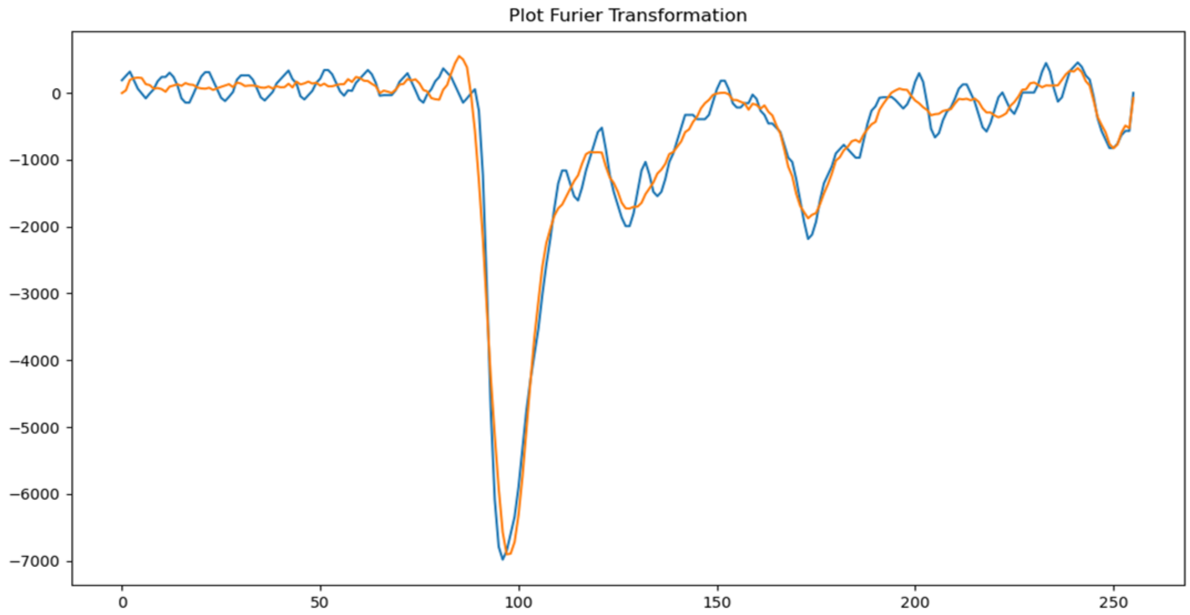

Fig 5: The figure above shows a comparison between the normal light event (blue wave) and the inverse of the Fourier Transformation (orange wave) with noise components set to zero..

The plot clearly shows that the first part was affected by noise, while the right side of the wave was composed by other events, interactions or decays that happened after the main one (deepest peak in the middle of the figure).

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