The Emulsion Scanning System of the OPERA experiment

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Abstract
The OPERA experiment has for goal the direct detection of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation, using an hybrid apparatus composed of electronic detectors and nuclear photographic emulsions. A charged particle crossing an emulsion layer ionizes the medium along its path leaving a latent image which leads, after development, to a sequence of aligned grains. Nuclear emulsions are analyzed by means of optical microscopes to reconstruct the 3D particle tracks. The OPERA collaboration has developed a dedicated system to scan a large number of emulsions (surface of about 1000 m^2). The achieved resolution is $\sim$1 μm and $\sim$1 $mrad$ allowing to observe directly the short-lived τ particles produced in $\nu_\tau CC$ interactions.

1 The OPERA experiment

OPERA is a long-baseline neutrino oscillation appearance experiment designed to obtain an unambiguous signature of $\nu_\mu \rightarrow \nu_\tau$ oscillations in the parameter region indicated by atmospheric neutrino experiments. The detector, located in the underground Gran Sasso Laboratories, plans to detect ν_τ's in the CERN to Gran Sasso (CNGS) ν_μ beam, which is optimised for ν_τ appearance observation. It may also explore the $\nu_\mu \rightarrow \nu_e$ oscillation channel, improving the current $\sin^2 2\theta_{13}$ limit. OPERA is an hybrid experiment with electronic detectors, iron magnets and Emulsion Cloud Chambers.

2 The main detector unit: The Emulsion Cloud Chamber

The Emulsion Cloud Chamber (ECC) combines the high tracking precision of nuclear emulsions ($\sim$1 μm) and the large target mass of many lead plates (Fig. 1). The basic element, the "brick", has dimensions of 12.7$\times$10.2$\times$7.5 cm^3; it is a sequence of 56 lead (1 mm thick) and 57 emulsion plates. Each emulsion layer is composed of a pair of 44 μm thick emulsion films on either side of a 205 μm plastic base [1]. The bricks are arranged in "walls" separated by electronic detectors. The lead target has a total weight of $\sim$1.25 kton, corresponding to $\sim$150000 bricks. Charged particles give a track segment in each emulsion film. The $\sim$1 μm granularity of the emulsions [2] ensures redundancy in the measurement of particle trajectories. If a τ is produced, its decay is detected by measuring the angle (kink) between the τ direction and the charged decay daughter or by identifying the τ decay secondary vertex.

3 The emulsion scanning system

The emulsion scanning system has been developed in the framework of an R&D project for the OPERA experiment. It is able to scan nuclear emulsion films at a speed up to 75 cm^2 emulsion surface per hour, one order of magnitude higher than past systems. Nuclear emulsions are analyzed by means of optical microscopes: adjusting the focal plane of the objective lens through the whole thickness of the emulsion allows to obtain an optical tomography of each field of view, and therefore to reconstruct 3D particle tracks. Two different systems have been developed, one in Japan and one in Europe. The first one uses a dedicated hardware approach and the second one is a a software approach using commercial hardware.

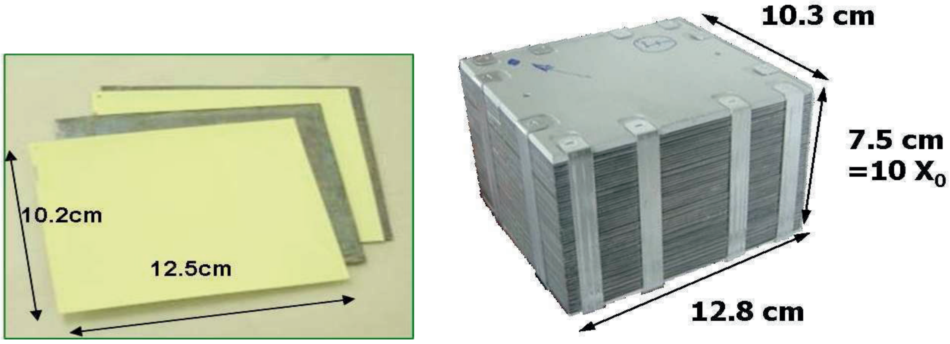

Fig. 1: The OPERA Emulsion Cloud Chamber.

3.1 The Japanese Scanning system

The Japanese scanning system, which is called "S-UTS", has been developed based on the track recognition algorithm mentioned in ref. [3]. The S-UTS is equipped with a CMOS camera capturing images up to 3000 frames per second and 512 by 508 pixel. The objective lens, whose field of view is 230 by 230 μm^2, is driven by piezo actuators not only in vertical axis but also in horizontal. The horizontal actuator synchronizes the motion of the lens with the the nuclear emulsion film mounted on the stage. The S-UTS therefore enables capturing tomographic images through the whole thickness without stopping the stage. The time interval between a view and the subsequent view is 20 otherwise millisecond. In order to achieve a processing speed up to 75 cm^2 per hour, the main part of the track recognition process is performed by a custom FPGA board, which consists of 10 Xilinx XC2VP70 and a Xilinx XC2VP100 FPGA. Since two track recognition engines described in HDL are implemented in an XC2VP70 FPGA, in total 20 engines are provided per system and work simultaneously.

3.2 The European Scanning system

This system uses a software-based approach which has proven extremely flexible and effective, since new algorithms can be easily tested and the integration of commercial components has been possible. It consists of a microscope equipped with a computer-controlled motorized stage, movable in the horizontal X-Y and in the vertical Z direction. The stage is equipped with nano-step motors and optical encoders with a resolution of 0.1 μm. An X-Y displacement takes about 125 ms for a 300 μm-step with a positioning reproducibility of 0.3 μm. A dedicated optical system and a CMOS camera are movable along the Z axis. For each field of view, several images of the emulsion are taken at equally spaced levels (2-3 μm). They are grabbed and processed using a dedicated commercial acquisition card. The CMOS camera is used at 376 frames per seconde with a sensor of 1280 $\times$ 1024 pixels. The size of the field of view is 390 $\times$ 310 μm^2. The features and performances of the European Scanning System hardware used for the emulsion scanning are reported in Ref. [4–8].
The basic idea of the track reconstruction in an emulsion layer is that a track is a straight sequence of grains lying in different levels. If two grains belonging to a real track are measured in two adjacent levels, the pair is used as a track hint. Then the algorithm collects other grains along the line between the two (Fig. 2). With an emulsion sensitivity for m.i.p tracks of 33 grains/100 μm, the number of grains of a track in each of the two 44 μm-thick emulsion layers of the film is distributed according to the Poisson's law with an average of $\sim$ 13 grains (Fig. 2). The resulting base-track finding efficiency is around 90% with a slight angular dependence over the range [0,700] mrad.

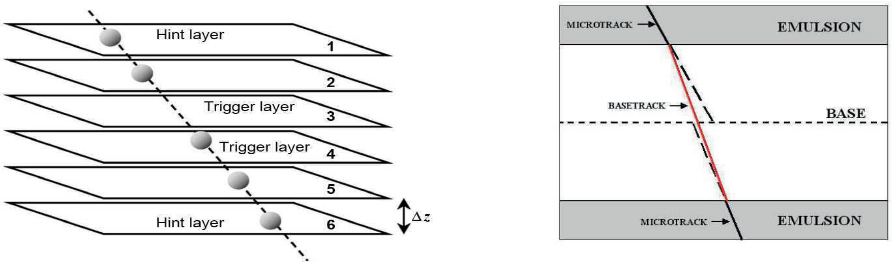

Fig. 2: Left: two grains in level 1 and 6 are used has hint to collect grains along the path of the track in emulsion layers. Right: two "microtracks" reconstructed in the top and bottom layers and connected through the plasic base to form a single track: the "base-track".

3.3 Track reconstruction in the Emulsion Cloud Chamber

The track reconstruction algorithm is based on finding and fitting a sequence of base-tracks through the lead plates. The principle consists of building base-track pairs and trying to extend the pairs in both directions. The chain is stopped when 3 consecutive holes (missing base-tracks) is found. The track fitting is based on the Kalman filtering algorithm. The position misalignment between base-tracks is about 0.3 μm showing the good estimate of the track reconstruction quality.

4 The neutrino interaction reconstructed in the ECC

Figure 3 shows a ν_μCC interaction reconstructed in an OPERA brick. The colored dashes represent base-tracks found in one emulsion film and attached to other base-tracks to form the particle track reconstructed in the brick. In this event, the primary vertex and one secondary vertex (hadron interaction) are reconstructed. Several gammas can be linked either to the primary or to the secondary vertex without ambiguity using their impact Parameters.

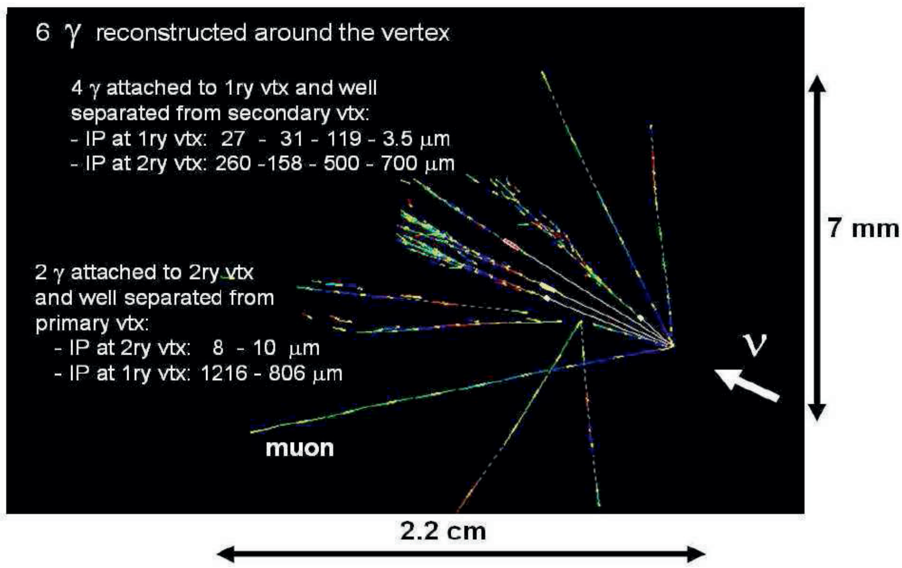

Fig. 3: A ν_μCC interaction where several gammas are well separated from primary and secondary vertices using their impact parameters.

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