The OptoTracker project

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**Project goal**

Investigate a new approach to charged particle tracking: **use the optical signal from a scintillating material**, exploiting the light as information carrier.

**Proposed technology:**

- Collect the scintillation light emitted by organic or inorganic scintillators along the primary particle path with pixelized photo-detectors.
- Measure the hit charge and time for each pixel.
- Perform 3D-tracking by using a sophisticated reconstruction algorithm implementing the time-reversal imaging.

**Main deliverable:** design, construct, and test a working small-scale demonstrator.
Charged particles tracking

Traditional approach to charged particles tracking (TPC detectors)

The “traditional” approach exploits the ionization process:
- The primary particle produces ionization along the path.
- Secondary $e^-$ and ions drift in an external $\vec{E}$ field toward the collecting region.

Track reconstruction:
- Transverse coordinates measured using a pixelized readout.
- Drift coordinate determined by measuring the drift time.

Critical aspects of this approach:

1. Position resolution is limited by the diffusion of charge carriers:
   \[
   \sigma_x^2 \geq \frac{2kT}{e} \frac{L_d}{E} \rightarrow \text{ALICE TPC}^1: \sigma_x \approx 1 \text{ mm} @ L_d = 2.5 \text{ m}
   \]

2. Slow signal formation time limits the maximum operation rate to $O(1-10 \text{ kHz})$

\(^1\)arXiv:1001.1950
A new approach to the problem

A tracking detector exploiting the light signal does not suffer these limitations

- Light is the fastest information carrier within a material: an OptoTracker is intrinsically capable of sustaining a very high rate.
- The diffusion length of the carriers (photons) in a scintillator is $O(m)$: it does not affect the position resolution in a detector with comparable dimensions.

This technology would permit to construct large-scale active-targets with enhanced particle ID and background rejection capabilities.

The design of an OptoTracker requires state-of-the-art technologies, with superior performances.

- Fast, high light yield, highly transparent scintillators.
- Highly pixelized, fast photo-detectors, sensitive to single photoelectrons: MA-PMTs, SiPMs, LA-PPDs.
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These technologies are available today!
Reconstruction algorithms: numerical approach

**Approach:** investigate the solutions developed in other fields, sharing similar issues, and adapt them to the specific problem.

**Optical Tomography**

Starting point: methods used in Optical Tomography, based on the Expectation-Maximization approach. Specificity of this problem: the use of the time information in the reconstruction algorithm.

Reconstruction approach: discretize the system, in terms of voxels.

- Measured pixels response (including noise)
- System transfer matrix
- Unknown voxels excitation
- Noise

\[
g = H \cdot x + n
\]
Reconstruction algorithms: numerical approach

- **Direct problem**: use MonteCarlo simulations to characterize the system matrix $H_{ij}$. “Switch on” one voxel $x_i$ at time and evaluate the corresponding pixels response $g_j$.

- **Inverse problem**: reconstruct the “image” $x_i$ from pixels response using the Moore-Penrose pseudoinverse matrix.

First results look promising:

**Setup:**

- Plastic scintillator cube, $L=6$ cm, $5 \times 5 \times 5$ voxels
- 4 detectors on side faces, $2.4 \times 4.8$ cm$^2$, $8 \times 16$ pixels

**Results for a central vertical trace:**

- Data: pixels response for a single event
- Reconstruction: voxels excitation
Reconstruction algorithms: numerical approach

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Reconstruction algorithms: analytic approach

Second reconstruction step: use an analytic reconstruction algorithm, where the event topology is imposed a-priori (track-like or point-like), using results from the numerical approach.

- Use an analytic model to describe the light emission and propagation in the scintillator.
- Construct the Likelihood function for the pixel $p_i$ to measure $N_i$ photo-electrons at times $t_i$: $L_i(N_i, t_i; \vec{x})$
- Maximize the overall Likelihood function to determine the trajectory: $\mathcal{L} = \prod_i L_i$

The likelihood approach permits to exploit both the hit charge and the hit time information in the reconstruction algorithm.
Reconstruction algorithms: analytic approach. First results

Reconstruction algorithm has been tested on MonteCarlo data, to validate it (only hit-charge information included in the Likelihood so far). First results look promising.

Detector configuration: $6 \times 6 \times 6$ cm$^3$ plastic scintillator cube, 4 detectors on the lateral faces.

Point-like event: $\alpha$ particle in (0.5, 2.1, -1.6) cm
Reconstruction algorithms: analytic approach. First results

Reconstruction algorithm has been tested on MonteCarlo data, to validate it (only hit-charge information included in the Likelihood so far). First results look promising.

Detector configuration: $6 \times 6 \times 6$ cm$^3$ plastic scintillator cube, 4 detectors on the lateral faces

Track event: $\mu$ entering in $(3,0.51,0.02)$ cm with $\theta = 12.6^\circ$, $\phi = 26.6^\circ$
First prototype

A first prototype, optimized for charge measurements only, has been designed and constructed. The response to radioactive sources has been measured.

Goals

- Validate MC (charge part)
- Study the reconstruction direct problem

Setup

- EJ-230 scintillator cube, $6 \times 6 \times 6 \text{ cm}^3$
- $2 \times$ H8500 MA-PMTs coupled to orthogonal faces
- Anti-reflection black coating
- MAROC3-based readout system, optimized for internal trigger only: OR of all channels, threshold $\approx 1$ phe
First measurements

The prototype response to a point-like $\alpha$ radioactive source ($^{241}$Am, $E = 5.49$ MeV) placed on the top face in different positions has been measured.

1. For each channel, the charge spectrum with and without the source has been measured.
2. To obtain the “true” source spectrum: pedestal subtraction + background subtraction.

The H8500 single phe response function is too broad to perform a charge-based event-by-event reconstruction. Instead: perform a whole-spectrum analysis.

$$< N(Q_i) > = < E > \cdot LY \cdot G_i \cdot \varepsilon_i \cdot k_i$$

Normalize to the sum of the pixel averages:

$$\frac{< N(Q_i) >}{\sum_i < N(Q_i) >} = \frac{G_i \varepsilon_i k_i}{\sum_i G_i \varepsilon_i k_i} \Rightarrow \text{This can be compared with MC results for } k_i$$
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Experimental results

\( \alpha \) source at the center of the TOP face

Data

Analytical model

MonteCarlo
α source in the opposite corner with respect to PMTs
Future activity

The obtained results will be used to design and construct a new prototype version, optimized for both photon count and hit-time measurements.

- Photo-detector: MPPC array, S12642-008PB-50 or S13361-3050AE-08 (low-cross talk version)
- Readout: TOFPET$^3$ ASIC-based

The prototype response to radioactive sources, cosmic rays, and possibly $e^-$ beams (Frascati BTF) will be measured.

\[^3\] JINST 8 C02050, 2013
Backup slides
Project outline

Participants:
- A. Celentano (PI) - INFN Genova
- P. Boccacci - Unige DIBRIS
- D. Comoretto, M. Castellano - Unige DCCI

External collaboration:
- P. Musico, M. Turisini (FEE and DAQ)

Project details:
- INFN-Gruppo V project, call for young researchers
- Time frame: 2 years (Jan 2015 - Dec 2016)
- Budget: \(\sim 75+75\) k€
Reconstruction algorithms: alternative approach. Charge

**Point-like case**

Isotropic emission of photons in the full solid angle (Poisson statistics) \( \otimes \) Photons detection probability (Binomial statistics):

\[
\log(L_i) \propto N_i \log(\mu_i) - \mu_i
\]

\[
\mu_i = N_{tot} \cdot k_i (\vec{x}_P - \vec{x}_i) \cdot \varepsilon_i
\]

- \( k_i = \delta \Omega (\vec{x}_1 - \vec{x}_i)/4\pi \): fraction of solid angle seen from the point \( \vec{x}_1 \) by the pixel at \( \vec{x}_P \)
- \( \varepsilon_i \): pixel quantum efficiency

**Trajectory case**

Derived from the previous case, assuming uniform energy deposition along the trajectory:

\[
\mu_i = \int_{\vec{x}_1}^{\vec{x}_2} d\vec{x} \mu_i(\vec{x}, N_{tot}/L)
\]

Comparison between the analytic model and the MC prediction (point-like case):

---

\[\text{I derived the formula for the general case of a rectangular surface arbitrary oriented.}\]
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Reconstruction algorithms: alternative approach. Time

Involved functions:

- $p_s(t)$: Intrinsic scintillator photon-emission time PDF (exponential)
- $p_d(t)$: Detector intrinsic time-response function (gaussian)

**Point-like case:** spherical light source at $\vec{x}_0$

$$p_i(t) = p_s(t - t_0 - t_i) \otimes p_d(t - t_0 - t_i) \Rightarrow t_i = \frac{c}{n} |\vec{x}_i - \vec{x}_0|$$

**Trajectory case:** linear superposition of spherical light source between $\vec{x}_0$ and $\vec{x}_1$

$$p_i(t) \propto \int_{\vec{x}_1}^{\vec{x}_2} d\vec{x} n_i(t - t_0 - t_i^i) k_i(\vec{x}_p - \vec{x}_i) \Rightarrow t_i^i = \frac{1}{\beta c} |\vec{x}_i - \vec{x}_0| + \frac{n}{c} |\vec{x}_2 - \vec{x}|$$

**Geometrical interpretation:**

- “Top” detectors: first photon comes from $\vec{x}_1$
- “Bottom” detectors: first photon comes from $\vec{x}_2$
- “Middle” detectors: first photon comes from the Čerenkov cone
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**Trajectory case**: linear superposition of spherical light source between $\vec{x}_0$ and $\vec{x}_1$

$$p_i(t) \propto \int_{\vec{x}_1}^{\vec{x}_2} d\vec{x}_2 n_i(t - t_0 - t_i^i) k_i(\vec{x}_p - \vec{x}_i) \Rightarrow t_{i_\vec{x}}^i = \frac{1}{\beta c} |\vec{x} - \vec{x}_0| + \frac{n}{c} |\vec{x}_i - \vec{x}|$$

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MAROC3 readout system

MAROC3: 64-channel ASIC for MA-PMT readout

Features:
- Preamplifier, configurable (8 bit, 0...4)
- Fast line: 25 ns shaper + discriminator
- Slow line: 100 ns shaper + mem. cell
- Internal ADC (12 bit)

Outputs:
- 64x digital trigger signal
- Multiplexed analog charge
- Internal ADC digitized charge

Readout system:
- Original system developed for Medical Imaging with radionuclides
- 4096 channels, USB2.0 readout
- Internal trigger only (OR of all channels)
- No hit-time measurement
Components R&D

The last part of the project (≈ last 6 months) will be devoted to a specific R&D program on the detector components.

Develop a custom scintillator with optimized properties

• Dope organic scintillators with a quencher, such as benzophenone (Ph$_2$CO), to lower the scintillation decay time$^5$.
• Develop wave-length shifting optical interfaces with organic molecules (for example, PVK).

Use LA-PPD as photo-detectors

State-of-the-art photo-detectors, MCP-based, with micron-sized glass capillary arrays and ALD coating for functionalization. Performances:

• High gain: $G > 10^7$
• Extreme time resolution ($\sigma_t < 20$ ps single-phe)
• Very fine pixelization (20 $\mu$m)

The project is currently in R&D phase: first samples (36 cm$^2$) available for tests in 2015.

$^5$IEEE Transactions on Nuclear Science 24.1 250-254 (1977)