Raytracing studies of ECAL prototype modules

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Part I:

Light Extraction from Crystal Fibers

Main Aim

Main objective of the work:

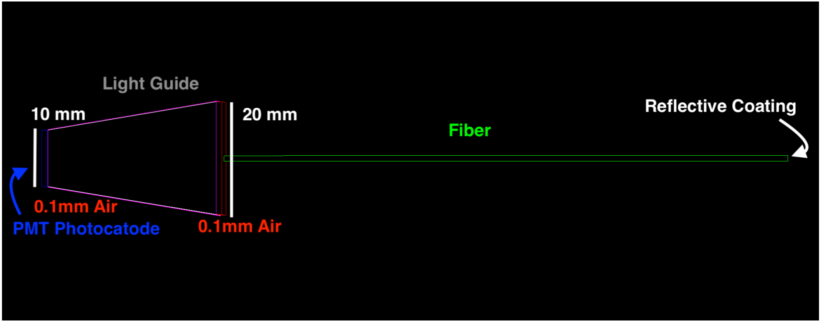
Calculating Crystal Fibers Light Yield

To do so, 3 quantities are needed:

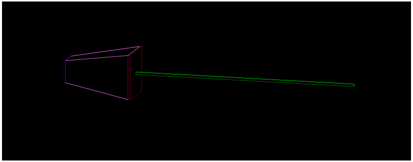
- PMTs' Quantum Efficiency;
- Geometrical Light Extraction Efficiency;
- Sampling Fraction (provided by Shmanin Evgenii).

Simulations and/or direct measurements required.

Setup

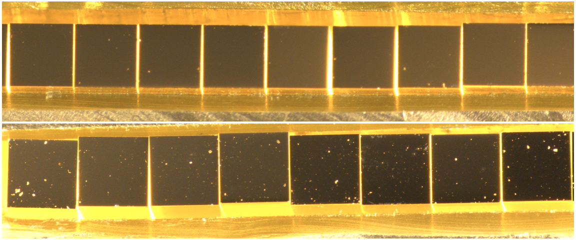


- Crystal Fiber: 10 cm;
- Air coupling → Thin air layers: 0.1 mm;
- Light Guide: 30 mm long, 20×20 mm^2 and 10×10 mm^2 surfaces. Material: PMMA;
- Reflective Aluminium coating on the back of the fiber;
- Scintillation events in multiple positions along the fiber axis.

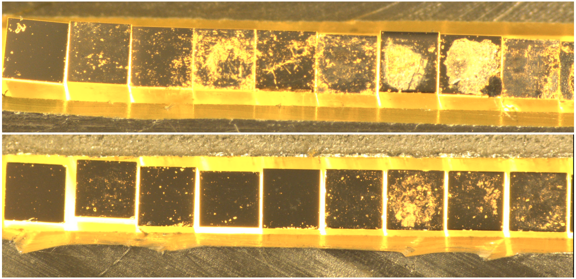


Aluminization

With some fibers Al deposition worked fine...



...With others not that much.



Light Extraction Efficiency

Averaging over different positions of the fiber on the light guide surface the following results are obtained:

- Perfectly reflective Al coating

Material	Mean Detected Light [%]	$\pm$
GAGG	2.01	0.01
YAG	2.41	0.01

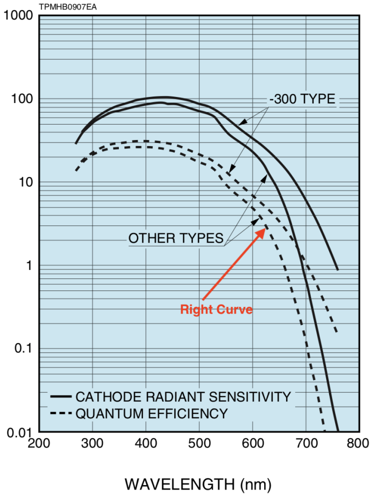
- No Al coating

Material	Mean Detected Light [%]	$\pm$
GAGG	1.25	0.01
YAG	1.41	0.01

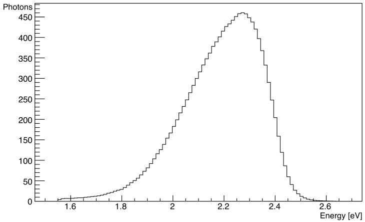
The true value will be an in-between the two!

Quantum Efficiency

PMTs' Quantum Efficiency.



Detected photons spectrum.



Averaging:

Material	Quantum Efficiency [%]
GAGG	8.6
YAG	8.9

Light Yield

It is eventually possible to calculate the Light Yield starting from the number of photoelectrons measured:

Material	Light Yield [Ph/MeV]	$\pm$
GAGG	30 000	7 500
YAG	24 000	3 700

In agreement with the expected values.

What's Next?

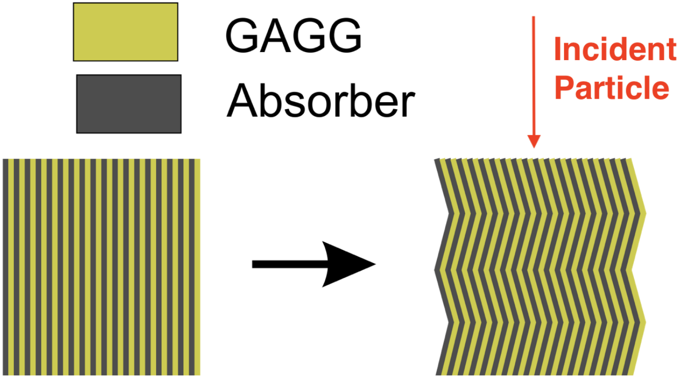
- Results heavily depending on energy calibration $\rightarrow$ fine tuning work;
- Uncertainty on Aluminization effectiveness $\rightarrow$ direct measurements;
- Plastic fibers simulation work is in progress.

Part II:

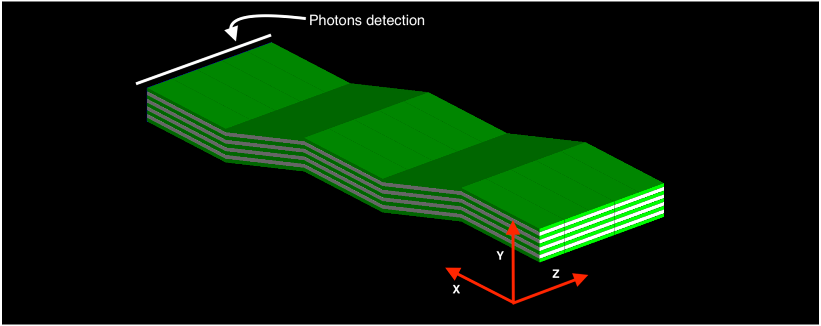
Accordion SPACAL

The Idea

In order to improve the calorimeter performances at incident particle angles orthogonal to the surface the front section could be built as an Accordion-like structure.



Simulation Program



Colours and Materials:

Green Scintillator: GAGG;

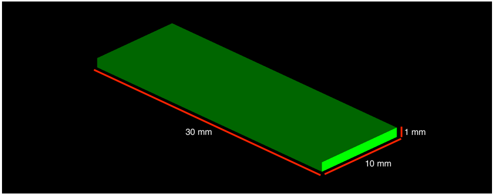
White Absorber: Lead.

- Incident particle along X axis;
- Perfectly polished surfaces;
- Thin layer of air between absorber and scintillator ($\sim$0.1 mm);
- Optical photons collected at the end of the detector.

Simulation Configuration

Dimensions of a single tile:

- X: 30 mm;
- Y: 1 mm;
- Z: 10 mm.



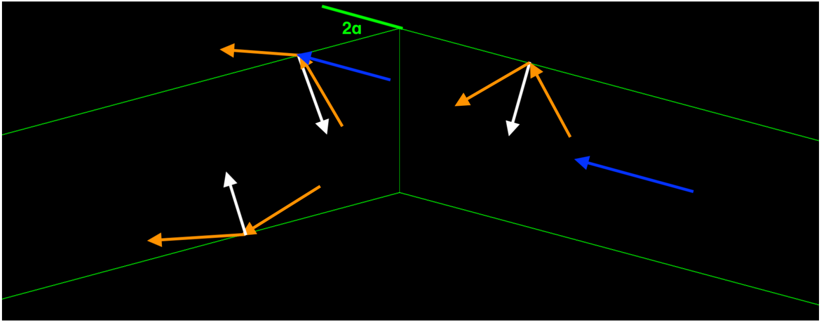
Two series of simulations:

1. Low energies for optical physics study;
2. High energy charged particles for energy resolution.

Parameters:

- Number of tiles along the x axis $\in$ [5, 25];
- Bending angle (α) with respect to the x axis $\in$ [0, 26];

What to expect?



An optical photon travelling parallel (blue) to the 1st tile ($\theta_{inc} = 90^\circ$) will be mapped by the rotation α into a photon with $\theta_{inc} = 90^\circ - 2\alpha$ in the 2nd tile.

- $\theta_{critical}$ GAGG-Air interface: $\sim 32^\circ$;
- Half of the light is mapped on to higher angles, half on to lower ones;
- No photon is scattered backwards if $2\alpha < \theta_{crit} < \theta_{inc}$.

The Model

1^{st} Assumption

If $\theta_{inc} < \theta_{crit}$ the photon is lost.

Lost light angles:

$$\underbrace{\int_0^{\theta_{crit}} d\theta}_{1^{st}\ \text{tile}} + \underbrace{\int_{2\alpha}^{2\alpha+\theta_{crit}} d\theta}_{2^{nd}\ \text{tile}} - \underbrace{\int_{2\alpha}^{\theta_{crit}} d\theta}_{\text{overlap}} = 2\alpha + \theta_c$$

2^{nd} Assumption

Exponential loss of light due to material absorption.

Assuming $x = Ln_x$ with n_x the number of tiles along the x axis. Then:

$$I(n_x, \alpha) = (I_0 - m\alpha)\, e^{-\frac{L}{\lambda} n_x} \tag{1}$$

At a Closer Look

However, having a closer look at the physics with a discontinuous approach, the produced light can be divided into 3 groups.

- I_c: photons with $\theta_{inc} < \theta_{crit}$;
- $m\alpha$: photons with $\theta_{crit} + 2\alpha > \theta_{inc} > \theta_{crit}$;
- I_r: photons with $\theta_{inc} > \theta_{crit} + 2\alpha$;

$\Longrightarrow$

$$I_c + I_r + m\alpha = I_0$$

I_0 = Total produced light.

Two possible behaviours:

$$dI_c = -\left(\frac{I_c}{\lambda} + TI_c\right) dx \qquad \text{(Absorption and Transmission)}$$

$$dI_r = -\frac{I_r}{\lambda} dx \qquad \text{(Absorption)}$$

$m\alpha$ light bounces back and forth between the two behaviours.

$I_0 = I_c + I_r + m\alpha$ is the total light produced.
Then at each tile:

1. $I(n_x = 1) = \left[I_r + m\alpha + I_c e^{-T}\right] e^{-\frac{L}{\lambda}}$
2. $I(n_x = 2) = \left[I_r + m\alpha e^{-T} + I_c e^{-2T}\right] e^{-2\frac{L}{\lambda}}$
3. $I(n_x = 3) = \left[I_r + m\alpha e^{-T} + I_c e^{-3T}\right] e^{-3\frac{L}{\lambda}}$

...

n-th. $I(n_x) = \left[I_r + m\alpha e^{-T\frac{n_x}{2}} + I_c e^{-Tn_x}\right] e^{-\frac{L}{\lambda}n_x}$

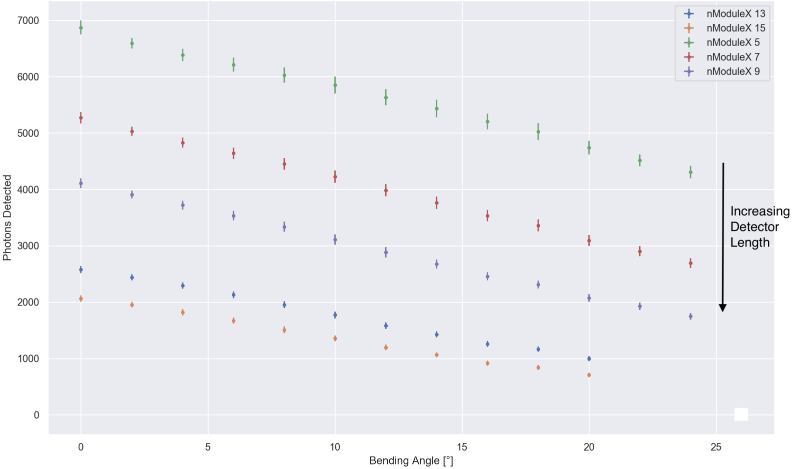
Eventually:

$$I(n_x) = \left[I_0 - I_c[1 - e^{-Tn_x}] - m\alpha[1 - e^{-T\frac{n_x}{2}}]\right] e^{-\frac{L}{\lambda}n_x} \quad (2)$$

- $\lim_{T\to\infty} = [I_0^* - m\alpha]e^{-\frac{L}{\lambda}n_x}$ as the previous model;
- Line slope increases $\propto 1 - e^{-T\frac{n_x}{2}}$;
- Coefficient $\frac{n_x}{2}$ or $\frac{n_x}{4}$? (Only half of the light is mapped on to lower θ_{inc}).

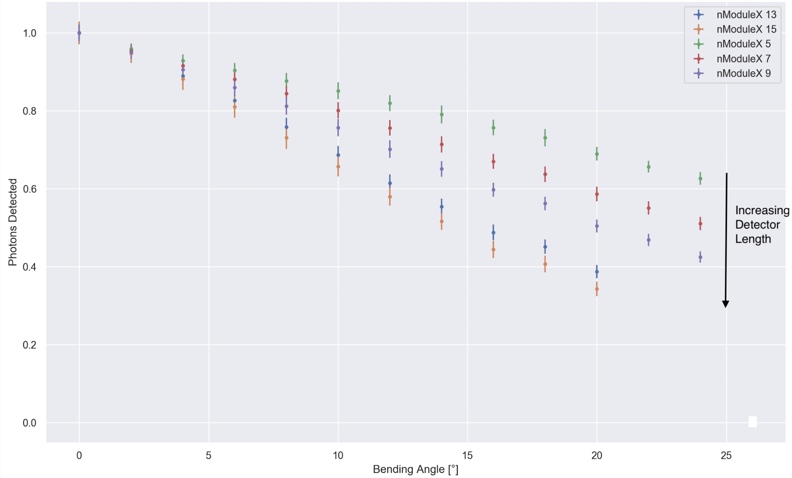
Results

$$I = I(\alpha)$$



$$I \propto \alpha$$

$$\frac{I(n_x, \alpha)}{I(n_x, 0)}$$



The line slope is increasing.

Mean Path Length L

In order to quantitatively understand the data the mean path length travelled by a photon in a tile *and* the absorption length are needed.

Being $X = 30$ mm, $Y = 1$ mm, $Z = 10$ mm a photon bounces on the surface of the tiles perpendicular to the y direction N times:

$$N = \frac{X}{Y}\cot(\theta)$$

Being $\theta_{crit} \sim 32^\circ \simeq \frac{\pi}{6}$ the possible angles of incidence for a totally internal reflected particle are $\theta \in [\frac{\pi}{6}, \frac{\pi}{2}]$.

$$\Downarrow$$

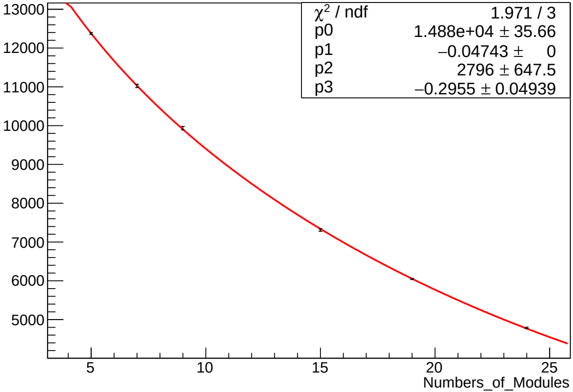
$$\langle N \rangle = \frac{1}{\int_{N_{min}}^{N_{max}} dN} \int_{N_{min}}^{N_{max}} NdN = \frac{1}{\int_{\frac{\pi}{6}}^{\frac{\pi}{2}} \frac{X}{Y} \frac{-1}{\sin^2\theta} d\theta} \int_{\frac{\pi}{6}}^{\frac{\pi}{2}} \left(\frac{X}{Y}\right)^2 \frac{-\cot\theta}{\sin^2\theta} d\theta = \frac{\sqrt{3}}{2}\frac{X}{Y}$$

Therefore the Mean Path Length of a photon whilst moving of X is:

$$L = \sqrt{X^2 + \left(\frac{\sqrt{3}}{2}\frac{X}{Y}Y\right)^2 + \left(\frac{\sqrt{3}}{2}\frac{X}{Z}Z\right)^2} = \sqrt{\frac{5}{2}}X \simeq 47.4 \text{ mm}$$

Exponential Decrease

$$I = I(n_x, \alpha = 0)$$



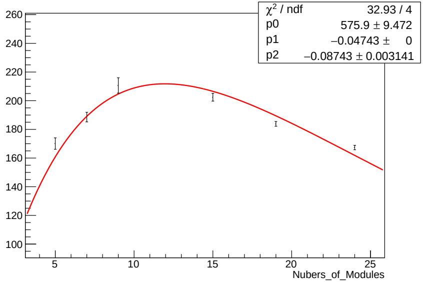
Fit function: $I(x) = p_0 e^{p_1 x} + p_2 e^{p_3 x}$

- Monochromatic emission spectrum used!
  $\rightarrow$ Well-defined absorption length.
- p_1 fixed at known value $\frac{L}{\lambda} = \frac{47.43}{1000}$.
- $p_2 = I_c$
- $p_3 = -(T + \frac{L}{\lambda})$

Line Slope

Line Slope Vs. n_x

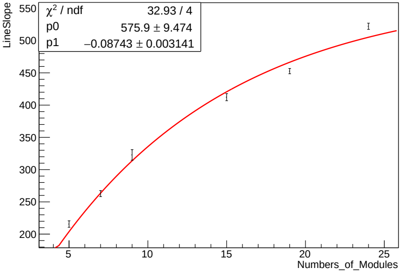
$$\text{Slope} = m\left(1 - e^{-T\frac{n_x}{2}}\right) e^{-\frac{L}{\lambda} n_x}$$



$$p_0(1 - e^{p_2 n_x})e^{p_1 n_x}$$

Correcting for the absorption decrease.

$$\text{Slope} = m\left(1 - e^{-T\frac{n_x}{2}}\right)$$



$$p_0(1 - e^{p_1 n_x})$$

Line slope is *asymptotically* constant!

Furthermore, on the right, p_1 is $\frac{1}{4}$ of the value of the exponential $I = I(n_x, 0)$ fit! $\Rightarrow$ n_x must be divided by 4.

What's next?

- Careful analysis of the light transport by moving arbitrarily the scintillation origin point, gathering timing, and wavelength of the photons;
- High Energy Simulations data analysis and finding of an optimum angle;
- Simulating glue layers.

Thank you for your attention.