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Project X Physics Study
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KOPIO
Preradiator and Calorimeter

KOPIO $K_L \rightarrow \pi^0 \nu\nu$ Experiment

$K_L \rightarrow \pi^0 \nu\nu$ is dominated by direct CP-violation

Standard model prediction

$$Br(K_L \rightarrow \pi^0 \nu\nu) \sim 4A^4\eta^2\, 10^{-10}$$

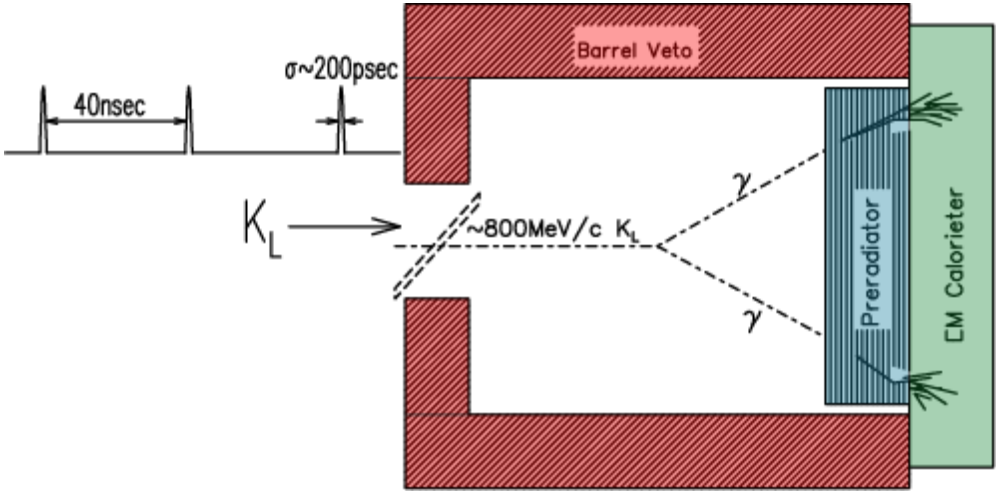
$$= (2.6 \pm 1.6)\, 10^{-11}$$

Backgrounds:

$$Br(K_L \rightarrow \pi^0\pi^0) = 0.0009$$

$$Br(K_L \rightarrow \pi^- e^+ \nu\gamma) = 0.0036$$

$$Br(K_L \rightarrow \pi^+\pi^-\pi^0) = 0.1255$$



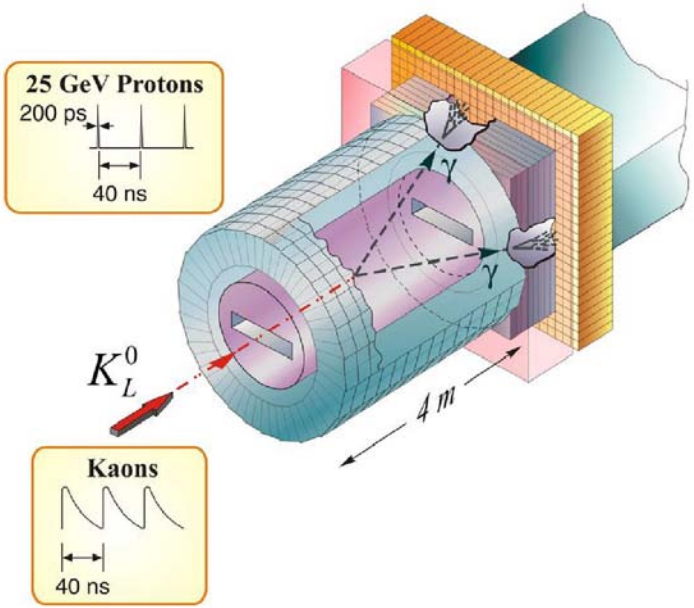
Experimental challenge:

- "Nothing to nothing" decay
- Low branching ratio
- High background
- Only one of three emitted particles may be observed

Event Reconstruction

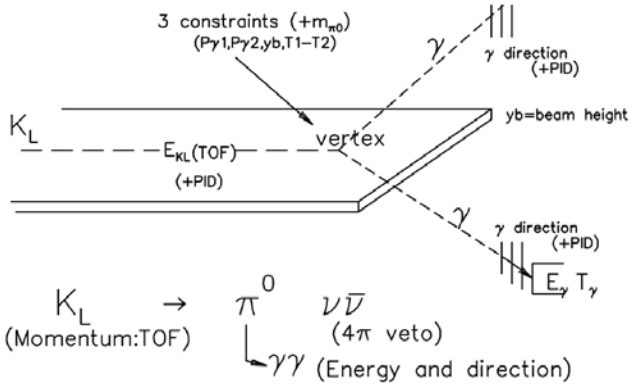
Measuring of photon directions, energies and times allows us to make a full event reconstruction:

- find decay vertex
- calculate kaon momentum
- determine effective mass of two photons (π^0 mass)
- determine c.m. energy of the pion



<u>Requirements for preradiator and calorimeter:</u>

- Photon angular resolution ~ 25 mrad @ 250 MeV
- Photon energy resolution ~ 3% / √E(GeV)
- Time resolution ~ (90 ps / √E(GeV)
- Photon detection inefficiency < 10^{-4}



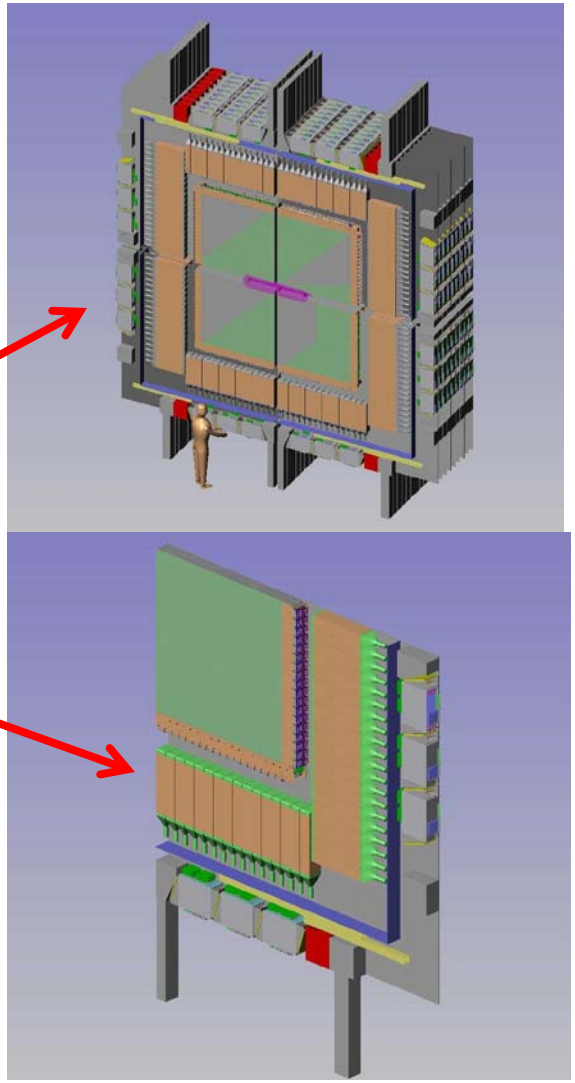
Preradiator

Requirements:

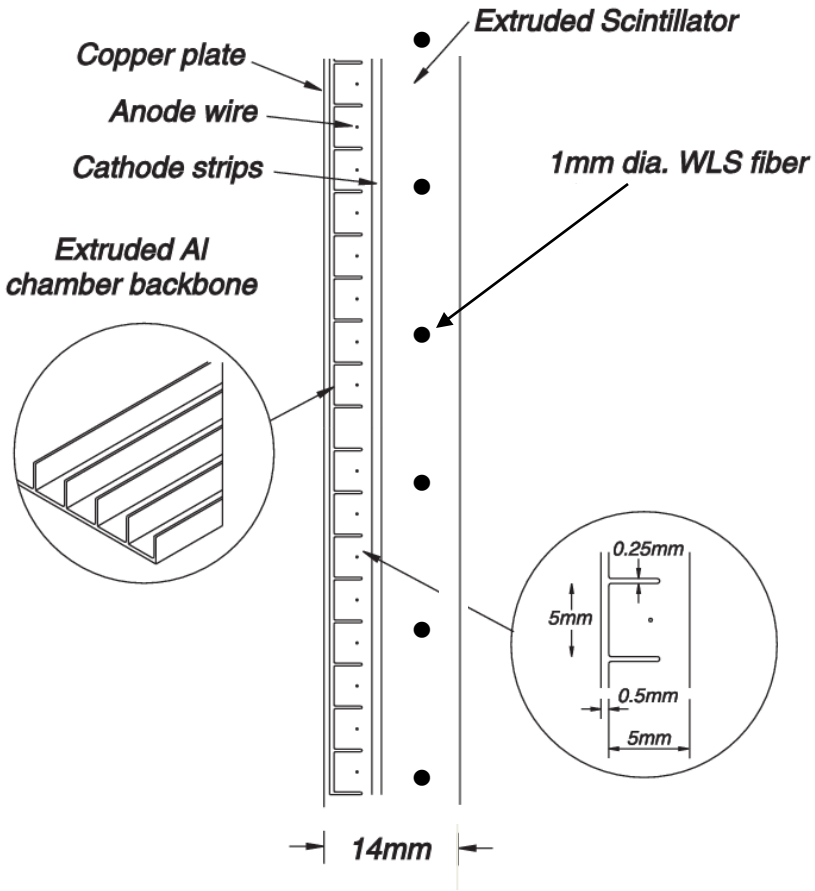
- Active area ~ 3x3 m^2
- Total thickness ~ 1.4 m
- Photon angular resolution ~ 25 mrad (E_γ=250 MeV)
- Total radiation length 2.7 X0
- Single photon detection efficiency ~ 85%
- Energy resolution ~ 2.7%/sqrt(E)

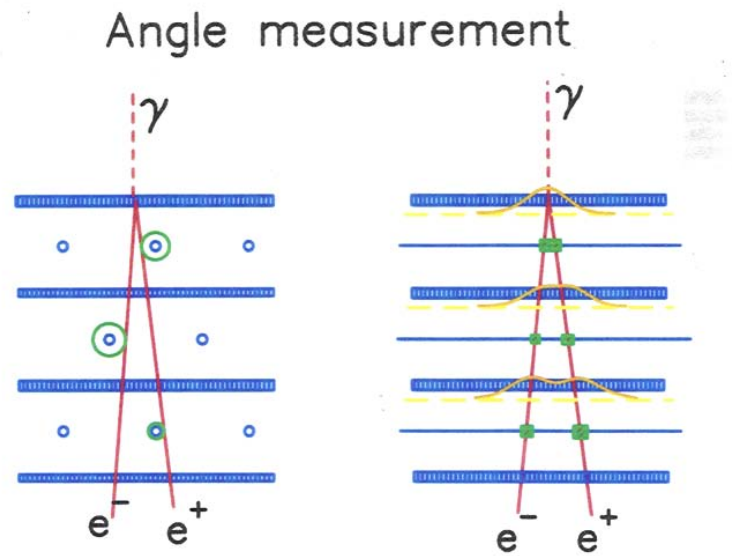
Mechanical Construction:

- The preradiator is divided into 4 quadrants
- Each quadrant consists of 8 identical modules
- Each module consists of 9 scintillator and 8 drift chamber planes
- Each drift chamber includes 288 anode wires and 288 cathode strips. Totally 75,000 readout channels for the anode wires and the same for the cathode strips.
- The scintillator plane consists of 27 scintillator planks readout by WLS fibers. Totally 1252 readout channels (PMT)



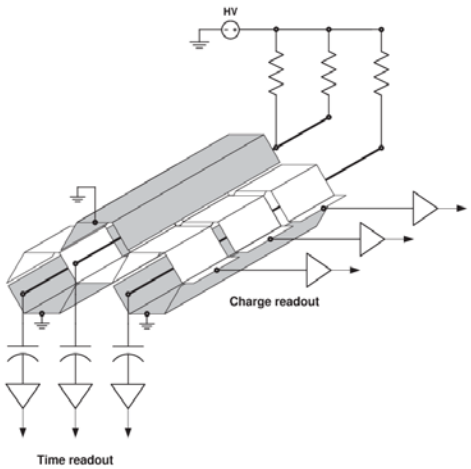
Thin-gap, dual-coordinate drift chamber with cathode strips

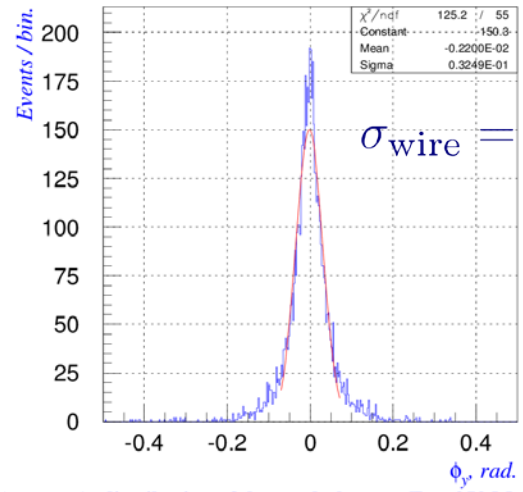




Angular resolution

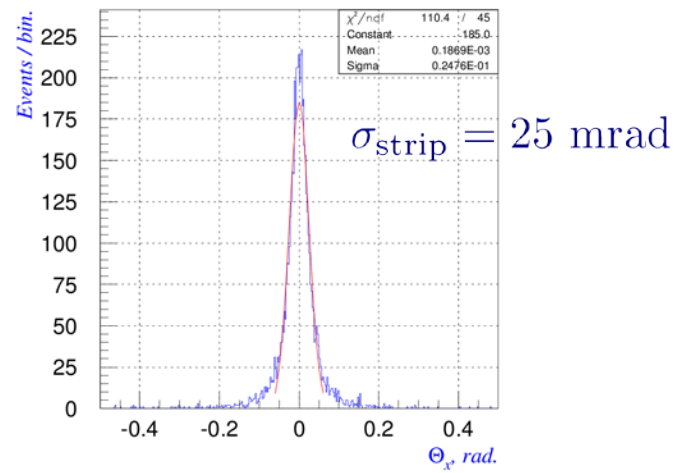
Experimental tests of the first prototype at NSLS photon beam.





ϕ_y distribution of detected photons. E_γ = 250 MeV.

	Photon beam $\theta = 0^\circ$ $\phi = 0^\circ$	Photon beam $\theta = 15^\circ$ $\phi = 0^\circ$	Photon beam $\theta = 30^\circ$ $\phi = 0^\circ$
Strip readout			
$100 - 200$ MeV	$\sigma_\theta = 31$ mrad	$\sigma_\theta = 35$ mrad	$\sigma_\theta = 44$ mrad
$200 - 300$ MeV	$\sigma_\theta = 25$ mrad	$\sigma_\theta = 31$ mrad	$\sigma_\theta = 41$ mrad
Wire readout			
$100 - 200$ MeV	$\sigma_\phi = 37$ mrad	$\sigma_\phi = 37$ mrad	$\sigma_\phi = 37$ mrad
$200 - 300$ MeV	$\sigma_\phi = 32$ mrad	$\sigma_\phi = 33$ mrad	$\sigma_\phi = 34$ mrad



Θ_x distribution of detected photons. E_γ = 250 MeV.

Experimental results are in a good agreement with simulations.

Scintillator plane

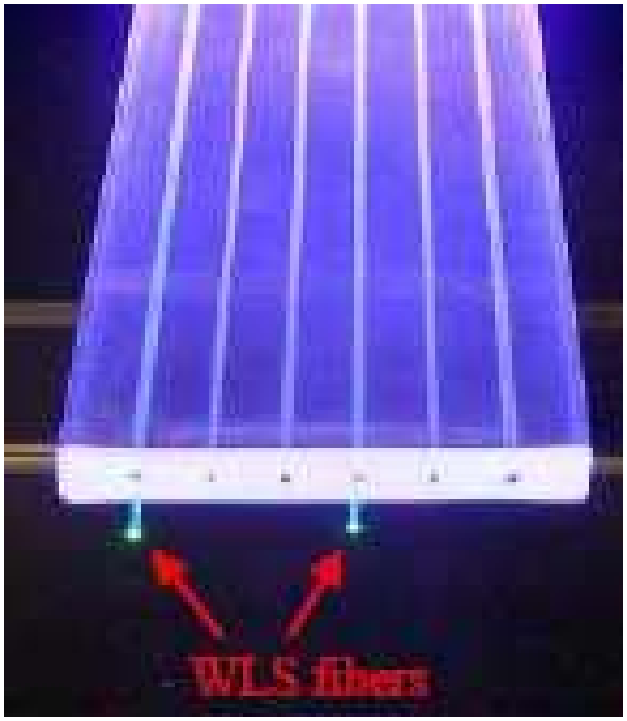
Made of polysterene scintillator planks that were were extruded with six 1.4 mm diameter holes for WLS fibers.

1-mm diameter KURARAY Y-11 WLS fibers were employed for readout.

<u>Test based estimates:</u>

Photostatistics contribution to the energy resolution: $\sim 1.1\%/\sqrt{E\ (\mathrm{GeV})}$

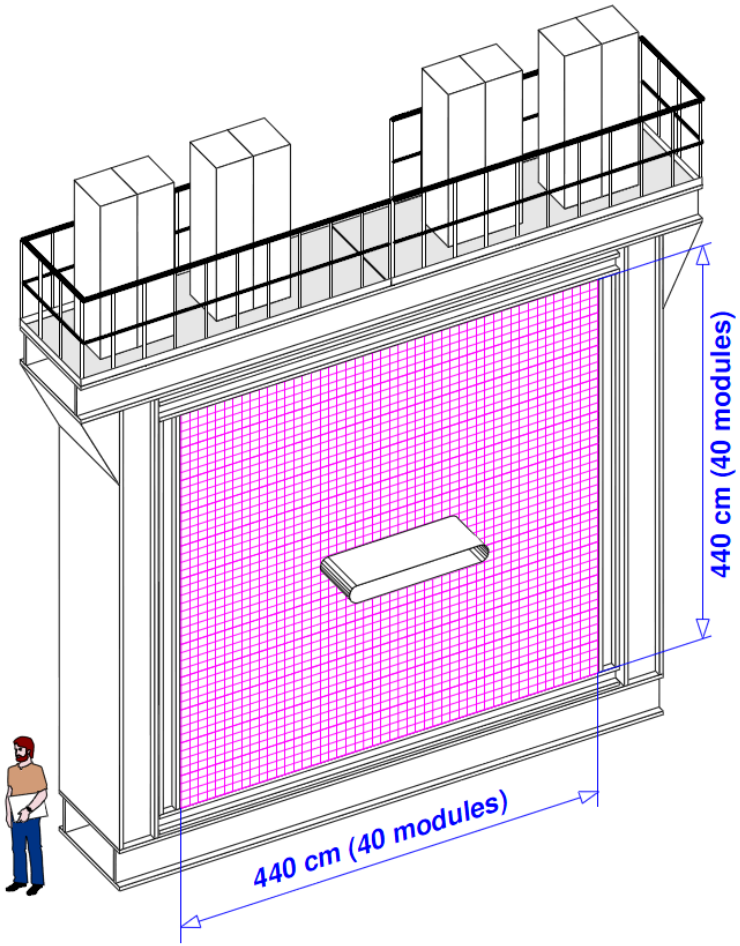
Time resolution: $\sim (90\ \mathrm{ps})/\sqrt{E\ (\mathrm{GeV})}$



Photon Calorimeter

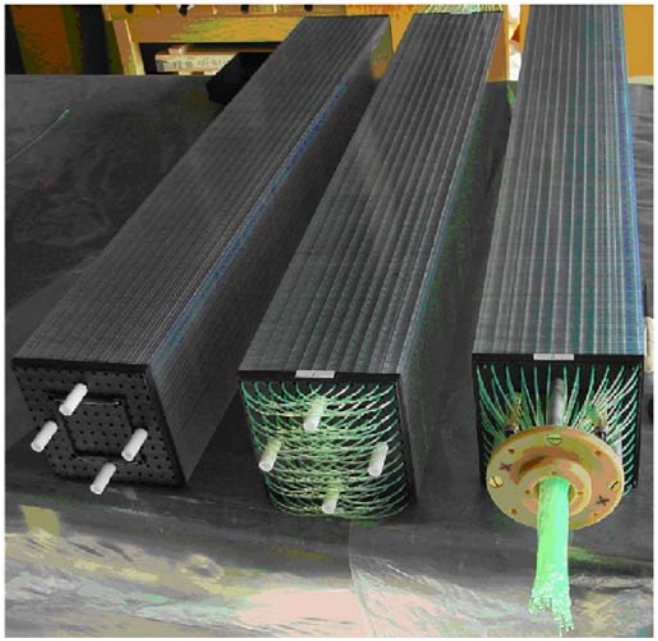
The requirements

- Energy Range 50 – 1000 MeV
- Energy resolution $\leq 3\% / \sqrt{E}$.
- Time resolution ≤ 100 psec / $\sqrt{E}$
- Effective noise per channel ≤ 0.5 MeV
- Photon detection inefficiency $\leq 10^{-4}$
- Operation in a magnetic field of up to 500 G
- Active area - 4.4×4.4 m^2
- Granularity - 10×10 cm^2.
- Radiation length - $16X^0$ ($18X^0$ including Preradiator).
- Physical length - ≤ 60 cm.



Using Shahslyk, the performance level can be achieved economically with well understood and reliable technique.

Shashlyk Calorimeter



A lead scintillator sandwich read out by means of Wavelength-Shifting (WLS) fibers passing through holes

The first Shashlyk calorimeter was built in 1993 for the BNL E865

$60 \times (1.4\ \text{mm lead} + 4\ \text{mm scint.})$ $\quad \sigma_E/E \approx 8\%/\sqrt{E\ (\text{GeV})}$

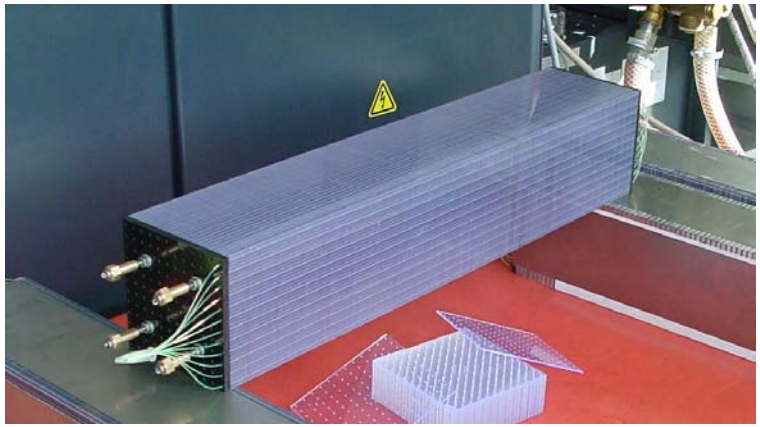
The first prototype for KOPIO (2000):

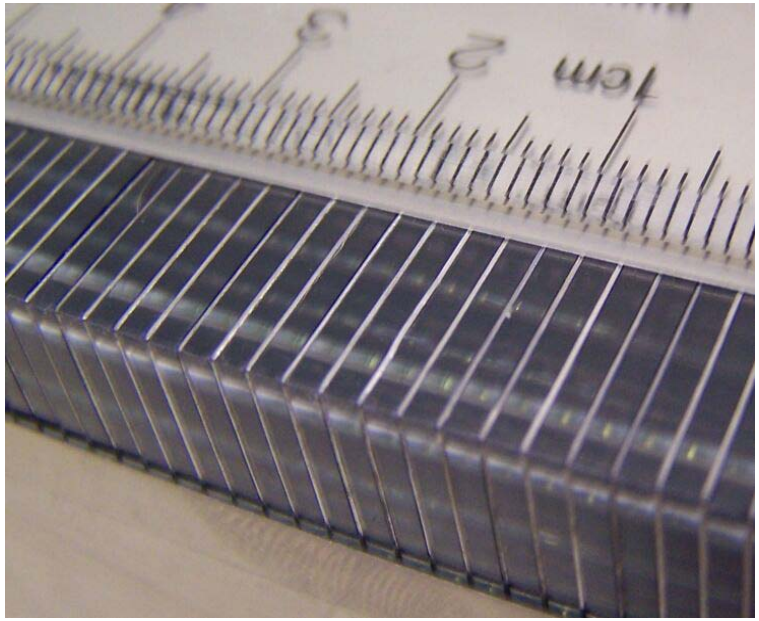
$240 \times (0.35\ \text{mm lead} + 1.5\ \text{mm scint.})$ $\quad \sigma_E/E \approx 4\%/\sqrt{E\ (\text{GeV})}$

Based on our experience with Shashlyk, we had a good understanding how to achieve the KOPIO requirements for KOPIO: $3\%/\sqrt{E\ (\text{GeV})}$

The 3% / √E(GeV) module

Transverse size	110×110 mm^2
Scintillator thickness	1.5 mm
Spacing between scintillator tiles	0.350 mm
Lead absorber thickness	0.275 mm
Number of the layers (Lead / Scint)	300
WLS fibers per module	72 × 1.5 m = 108 m
Fiber spacing	9.3 mm
Holes diameter in Scintillator / Lead	1.3 mm
Diameter of WLS fiber (Y11-200MS)	1.0 mm
Fiber bundle diameter	14.0 mm
External wrapping (TYVEK paper)	150 μm
Effective X_o	34.9 mm
Effective R_M	59.8 mm
Effective density	2.75 g/cm^3
Active depth	555 mm (15.9 X_o)
Total depth (without photo-detector)	650 mm
Total weight	21.0 kG



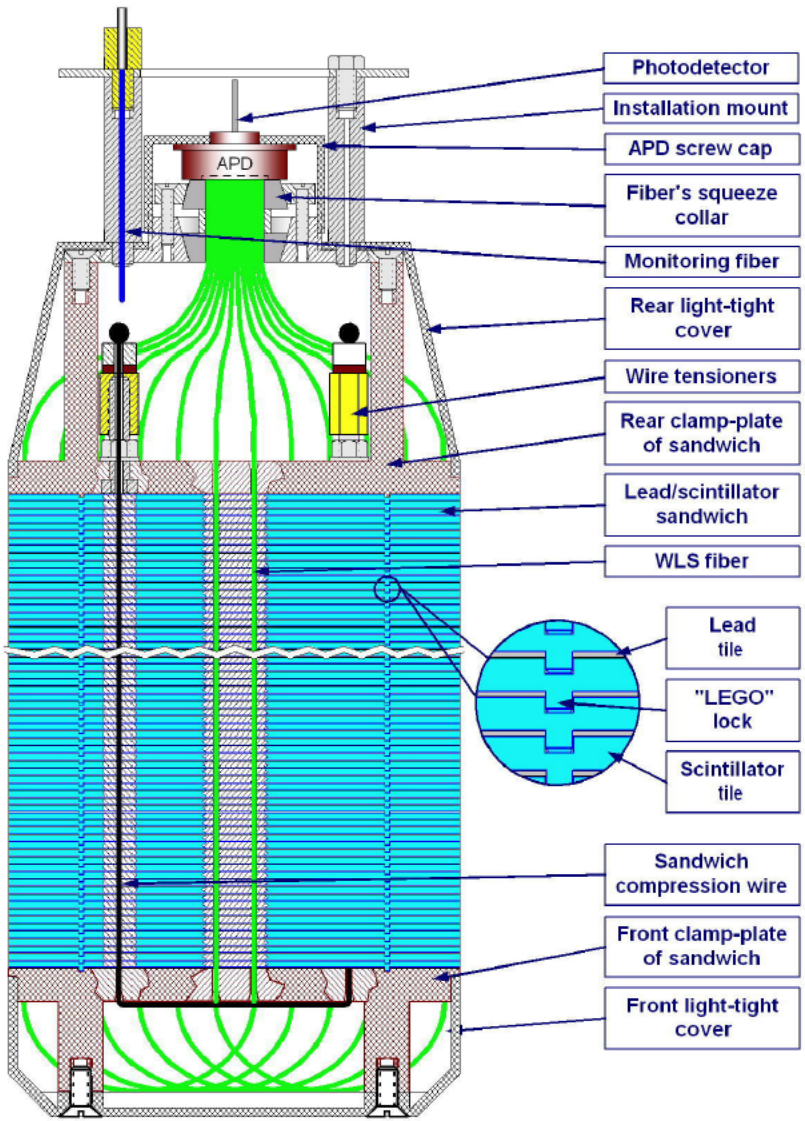


Main improvements

•***New mechanical design*** of a module has four special "LEGO type" locks for scintillator's tiles. These locks fix the position of the scintillator tiles with the 350-μm gaps, providing a sufficient room for the 275 μm lead tiles without optical contact between lead and scintillator. The new mechanical structure permits removing of 600 paper tiles between scintillator and lead, reduces the diameter of fiber's hole to 1.3 mm, and removes the compressing steel tape. The effective radiation length X_0 was decreased from 3.9 cm to 3.4 cm The insensitive areas were reduced from 2.5 % up to 1.6 %. The module's mechanical properties such as dimensional tolerances and constructive stiffness were significantly improved.

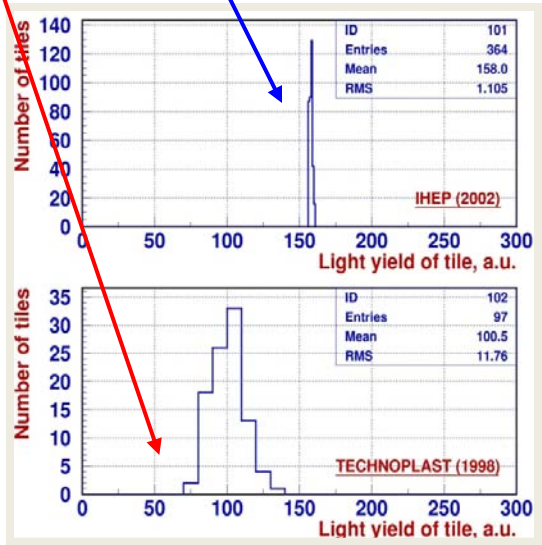
• ***New scintillator tile*** *(BASF143E + 1.5%pTP + 0.04%POPOP produced by IHEP) with improved optical transparency and improved surface quality. The light yield ~ 60 photons per 1 MeV of incident photon energy. Nonuniformity of light response across the module is <2.3% for a point-like light source, and < 0.5% if averaged over the photon shower.*

•***New photodetector*** Avalanche Photo Diode (630-70-74-510 produced by *Advanced Photonix Inc.*) with high quantum efficiency (~93%), good photo cathode uniformity (nonuniformity ≤ 3%) and good short- and long-term stability. A typical APD gain is 200, an excess noise factor is ~ 2.4. The effective light yield of a module became ~24 photoelectrons per 1 MeV of the incident photon energy resulting in negligible photo statistic contribution to the energy resolution of the calorimeter.



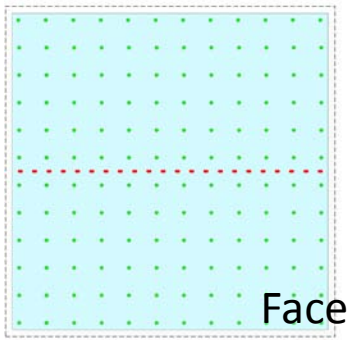
Scintillator

Scintillator: PS+Fluor1+Fluor2, Manufacturer	Light yield (%)	Attenuation Length (cm)	MIP signal, photoelectrons per tile	Simulated light collection efficiency
PSM115+1.5%pTP+0.04%POPOP, TECHNOPLAST, 1998	53 ± 6	4.0 ± 0.3	4.4 ± 0.3, 100%	0.134 ± 0.013, 100%
BASF158K+1.5%pTP+0.04%POPOP, IHEP, 2001	56 ± 6	4.9 ± 0.4	5.6 ± 0.3, (127 ± 10)%	0.170 ± 0.017, (127 ± 13)%
BASF165H+1.5%pTP+0.04%POPOP, IHEP, 2001	56 ± 6	6.1 ± 0.5	6.4 ± 0.3 (145 ± 10)%	0.191 ± 0.019, (143 ± 14)%
BASF143E+1.5%pTP+0.04%POPOP, IHEP, 2002	54 ± 6	6.8 ± 0.5	7.1 ± 0.3, (161 ± 10)%	0.215 ± 0.021, (160 ± 16)%

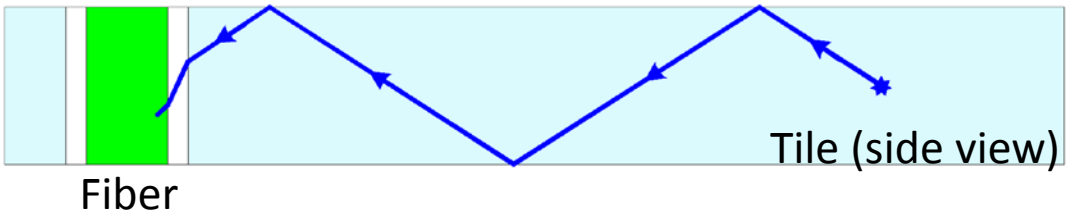


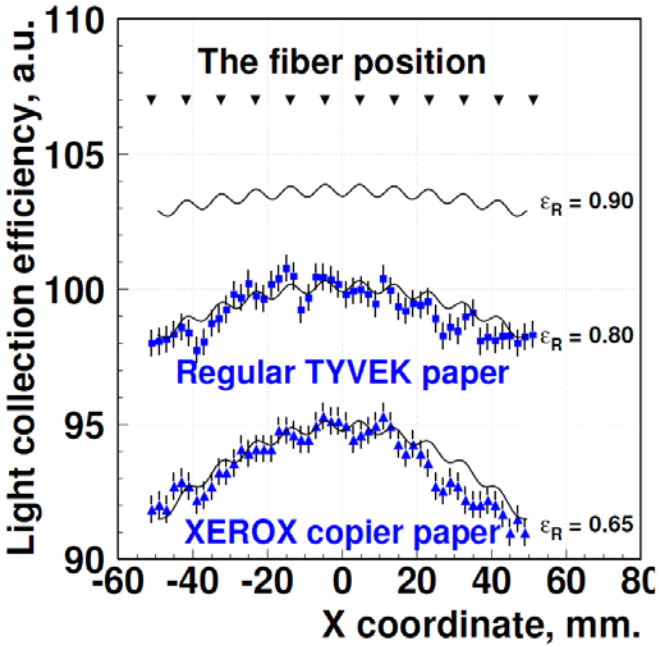
MIP signal variation over tile's samples

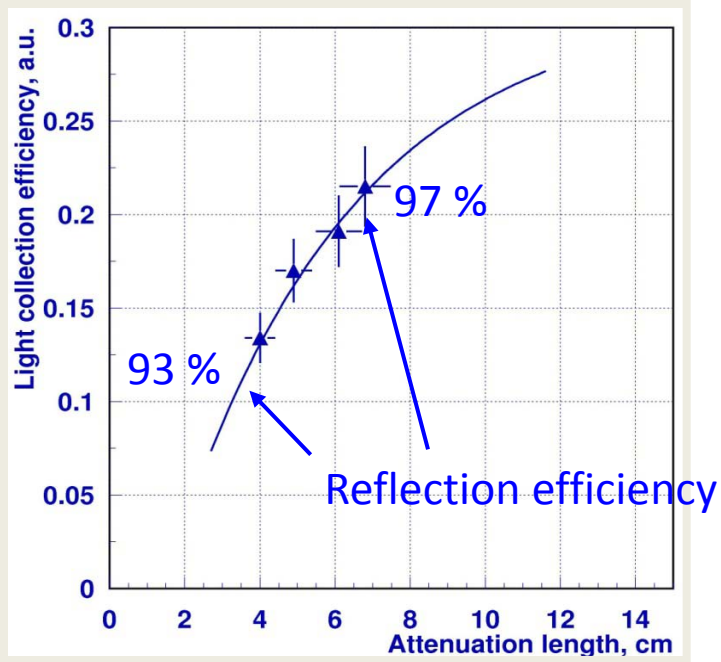
Light collection in the scintillator tile



Efficiency of the total internal reflection is crucial for the Shashlyk performance. ***93% ⇒ 97% !***

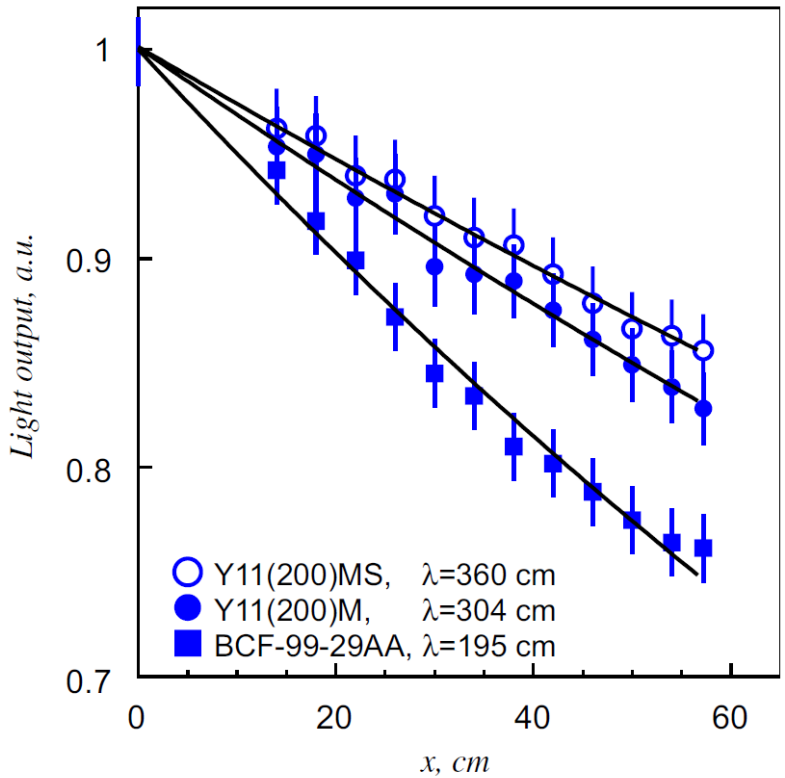


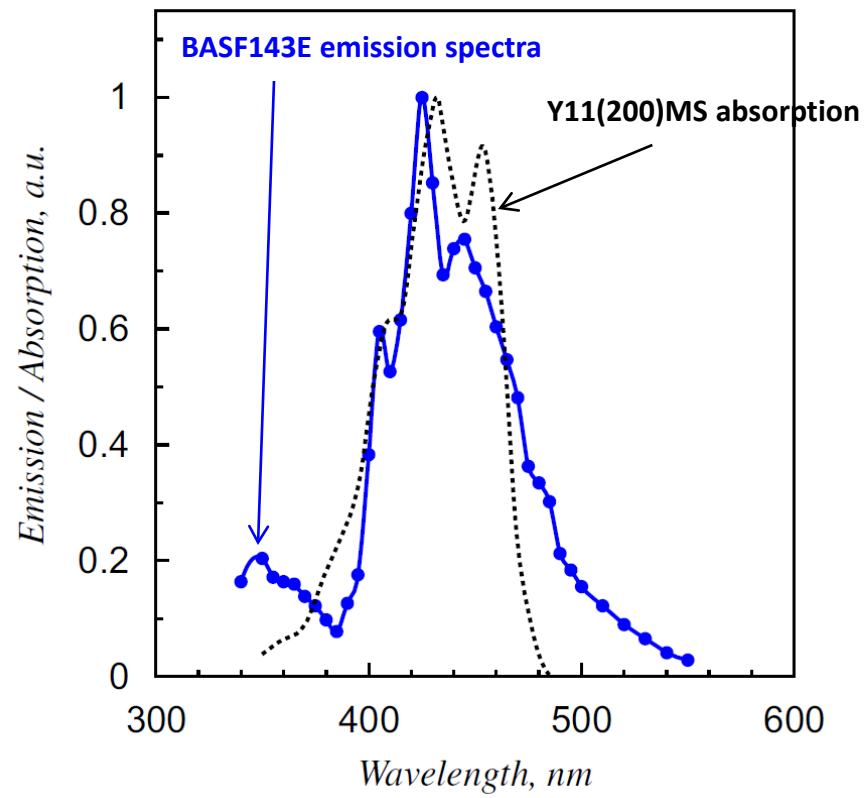




WLS fibers

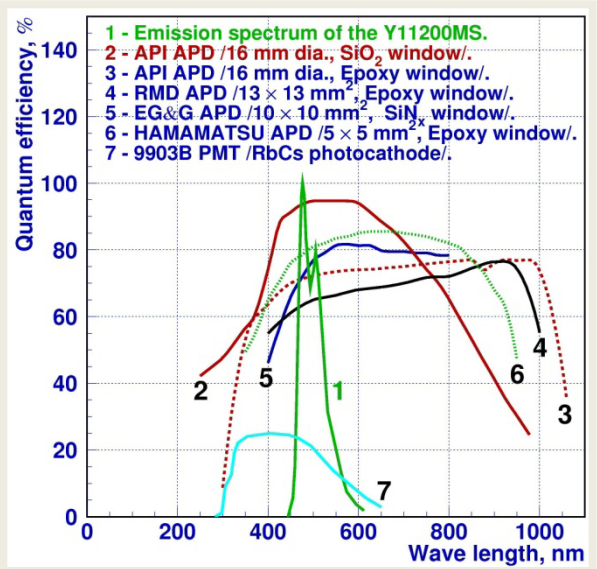
Attenuation length in WLS fibers

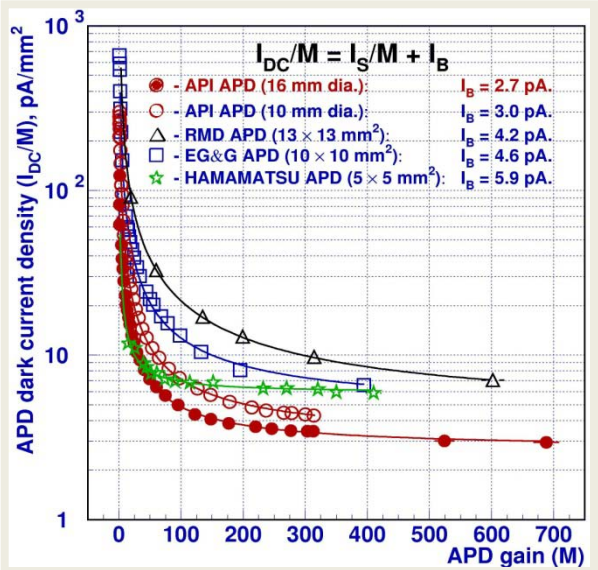


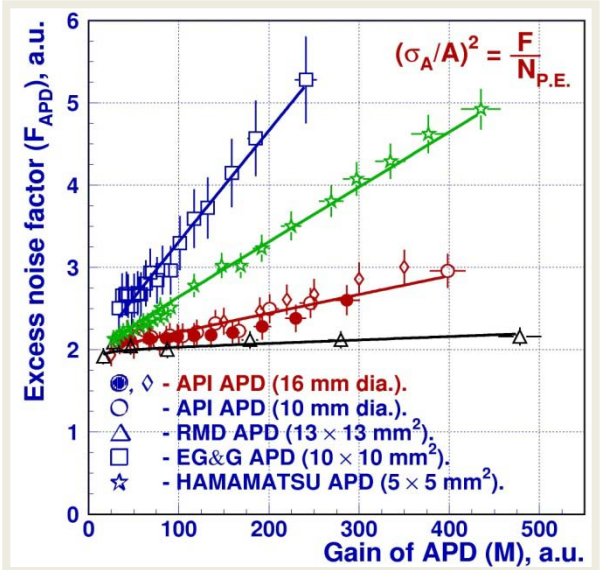


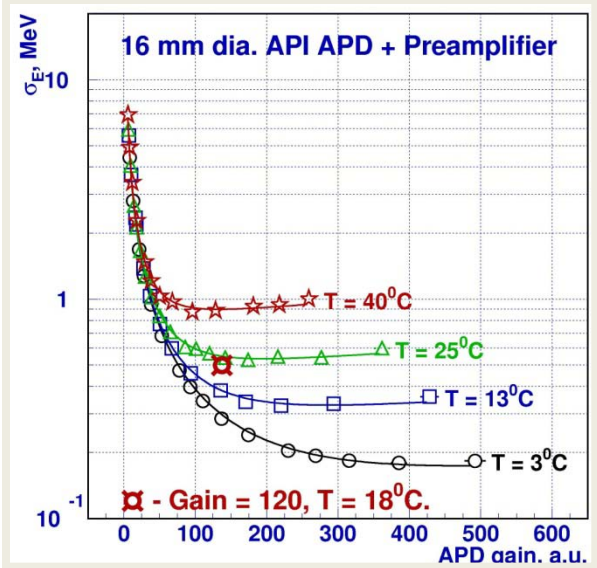
KURARAY Y11(200)MS fiber was chosen for KOPIO calorimeter.

Photodetector: APD









Advance Photonics Inc. APD 630-70-74-810 was chosen

APD Readout

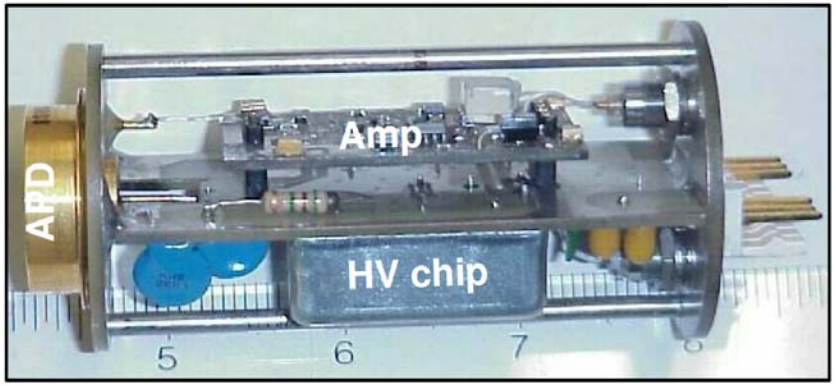
Performance:

- High quantum efficiency ~94%
- Excess noise Factor 2.2-2.5
- Effective photostatistics 24 ph.e/MeV

$$(\sigma_E/E)_{\mathrm{ph.stat}} = 0.7\%/\sqrt{E}$$

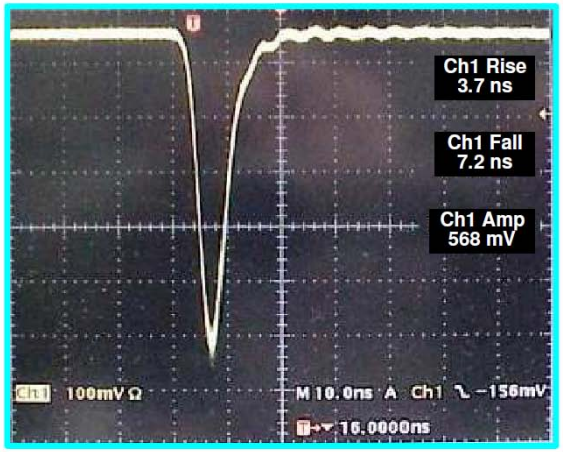
- Low effective noise ~ 0.4 MeV
- Can operate in magnetic field
- No gain dependence on rate
- Gain depends on the temperature (1/M)dM/dT = -4%
- Gain depends on High Voltage (1/M)dM/d V = (2-3)%

APD Unit

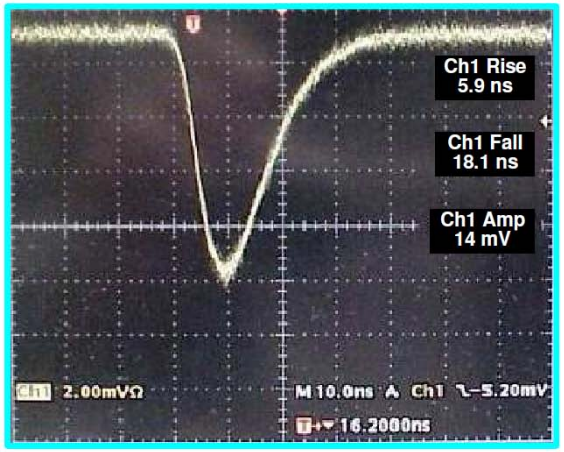


Cooling and gain monitoring is needed

Response to a short (3 ns) light pulse. Light intensity corresponds to the 700 MeV photon signal.



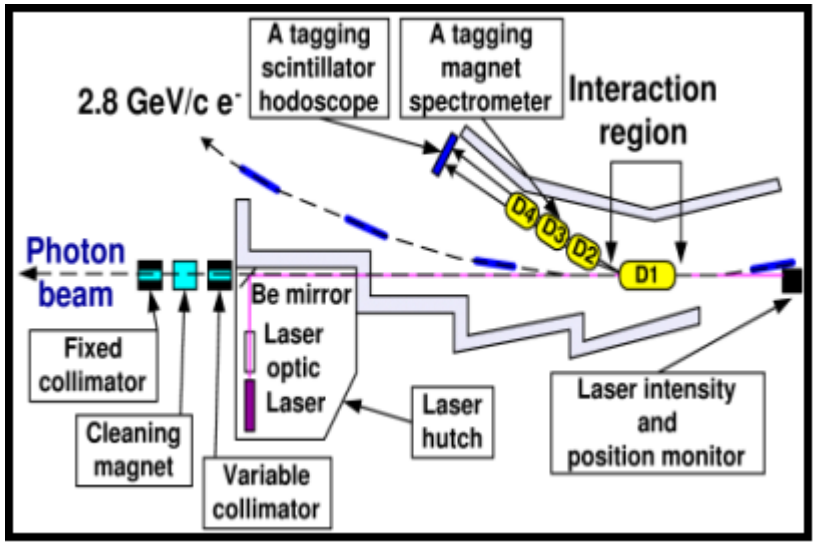
PMT-9903B

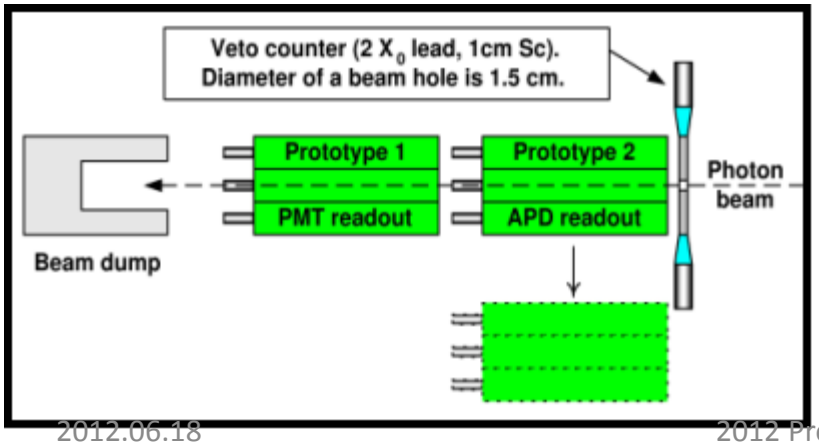


API APD

Beam test of Calorimeter prototypes

Two KOPIO calorimeter prototypes were tested at the Laser Electron Gamma Source (LEGS) facility at BNL NSLS.





Studied prototypes

1st prototype of 3×3 modules:

- The conventional design of modules (with paper between lead and scintillator);
- A 30 mm diameter 9903B PMT *(Electron Tube Inc.)*;
- The conventional 12-bits ADC digitizing of the PMT signal.

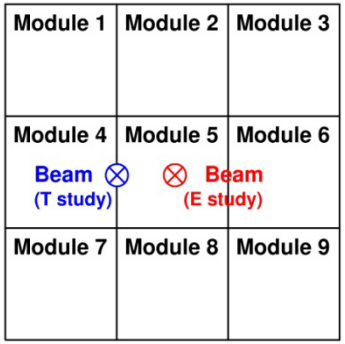
2nd prototype of 3×3 modules:

- New design of modules (no paper between lead and scintillator);
- A 16 mm diameter 630-70-74-510 APD *(Advanced Photonix Inc.);*
- *An 8-bits 140 MHz WFD and 12-bits ADC digitizing of the APD signal.*

Measurements

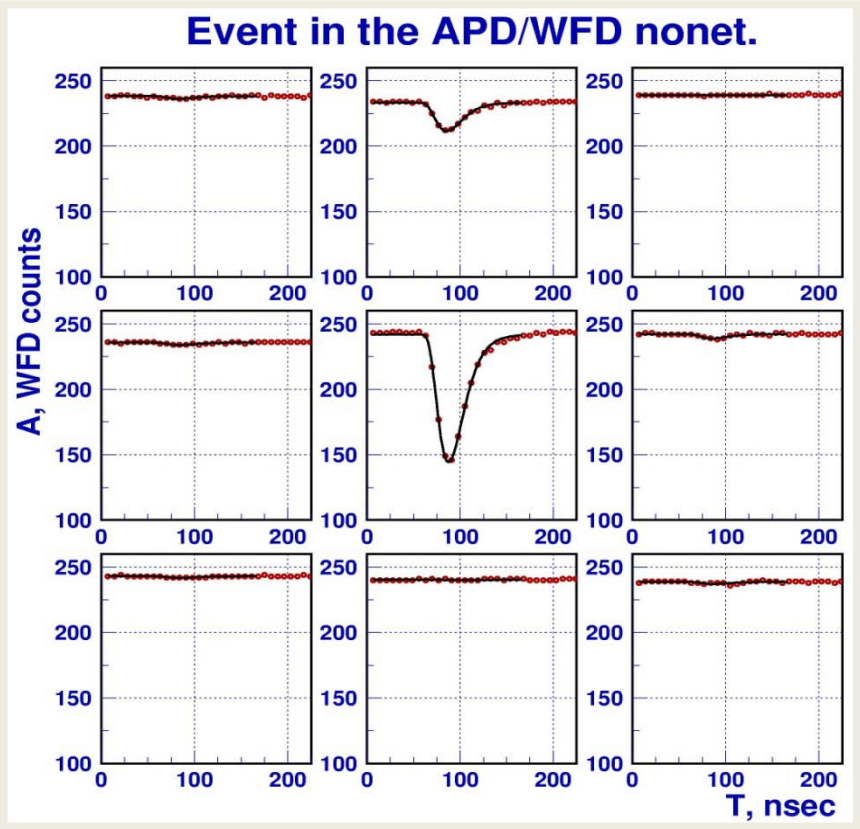
- Beam intensity was ~ 3×10^5 Hz.
- Triggered and tagged photon energy was in the range 220 - 370 MeV.
- Beam angle spread was ~ 2 mrad.
- Diameter of the beam spot at the prototype was ~ 1.5 cm.
- Photon energy spread was $\Delta E/E \approx 1.5\%$ (for the triggered and tagged monochromatic photon energy line).

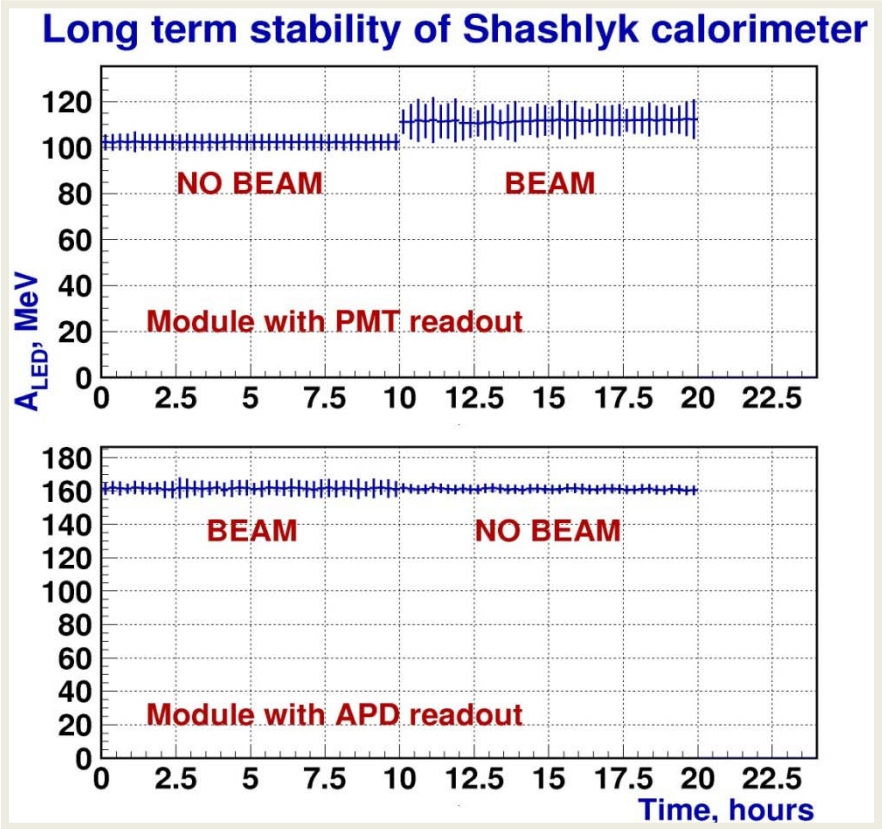
- The energy resolution was measured for both prototypes with the beam in the center of nonet.
- The time resolution was studied for the 2nd prototype (with WFD only), comparing timing in two modules when the beam is between the two.
- The photon detection inefficiency was measured by the detecting photons in Prototype 1 located behind Prototype 2.



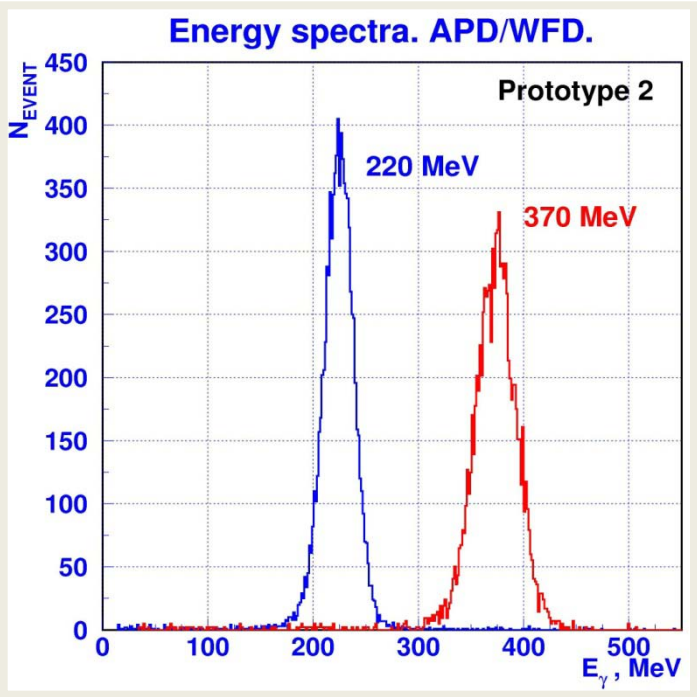
- The stability of the Calorimeter signals was tested by a LED monitoring system during the 24-hours measurements

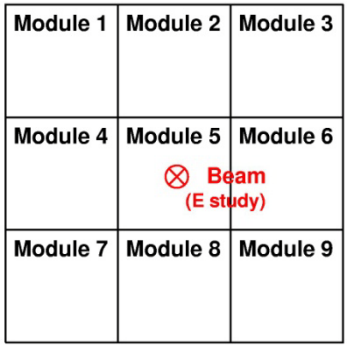
Beam test of Calorimeter prototypes

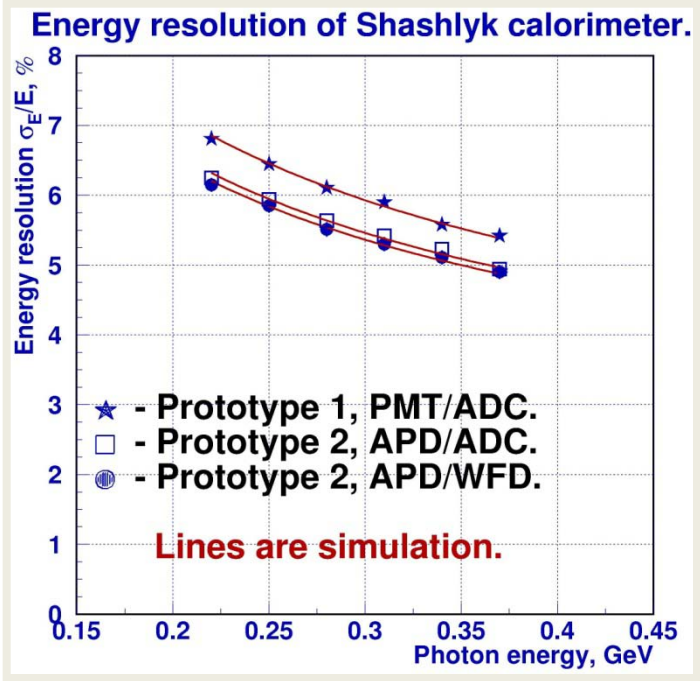




Energy resolution







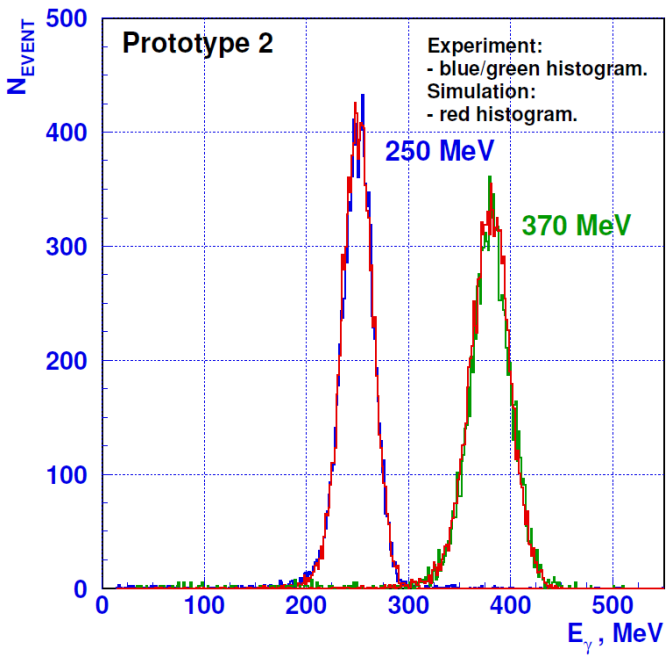
Energy resolution for 220-370 MeV photons:

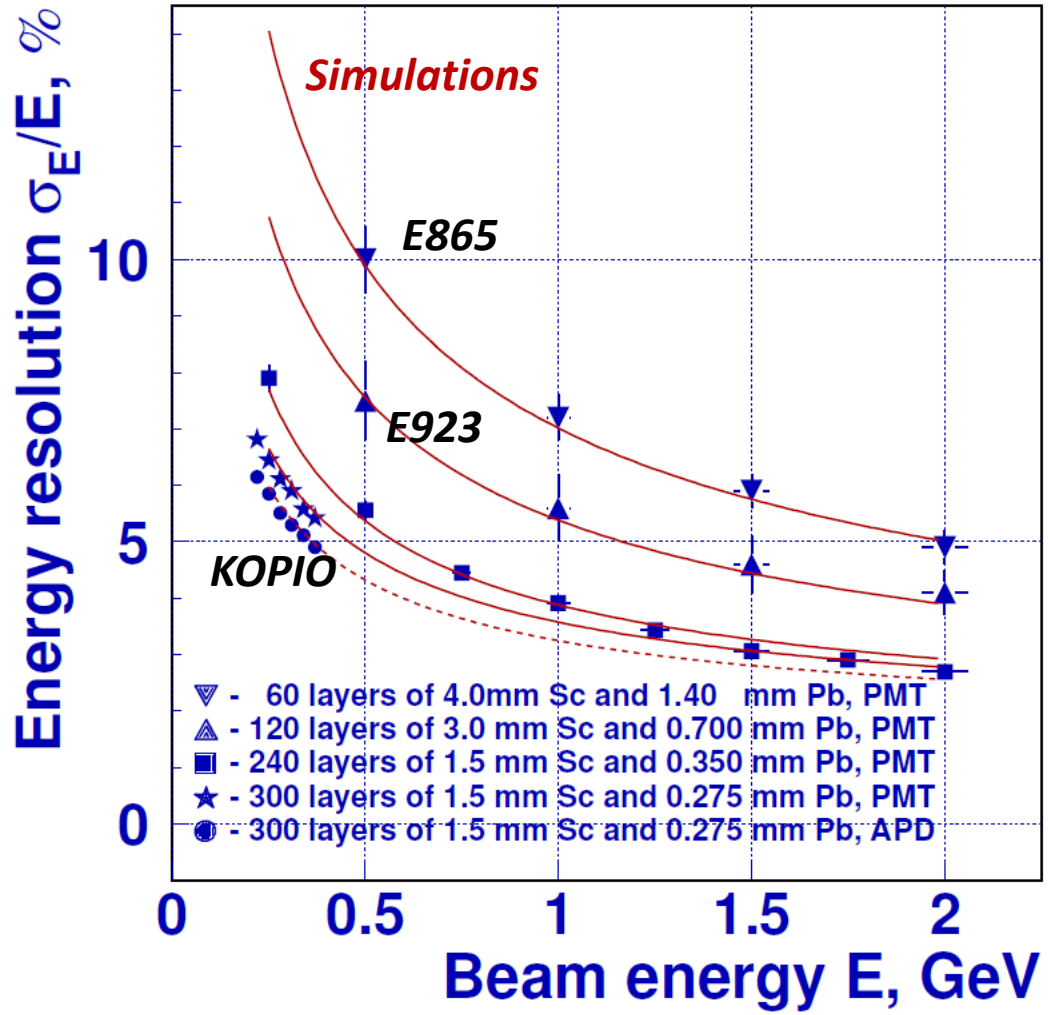
$$\sigma_{\mathrm{PMT}}/E = (2.03 \pm 0.1)\% \oplus (3.06 \pm 0.05)\%/\sqrt{E\ (\mathrm{GeV})}$$

$$\sigma_{\mathrm{APD}}^{\mathrm{QDC}}/E = (1.98 \pm 0.1)\% \oplus (2.79 \pm 0.05)\%/\sqrt{E\ (\mathrm{GeV})}$$

$$\sigma_{\mathrm{APD}}^{\mathrm{WFD}}/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)\%/\sqrt{E\ (\mathrm{GeV})}$$

Shashlyk energy resolution: experiment vs simulation





Simulation:

Geant 3 + Optical model

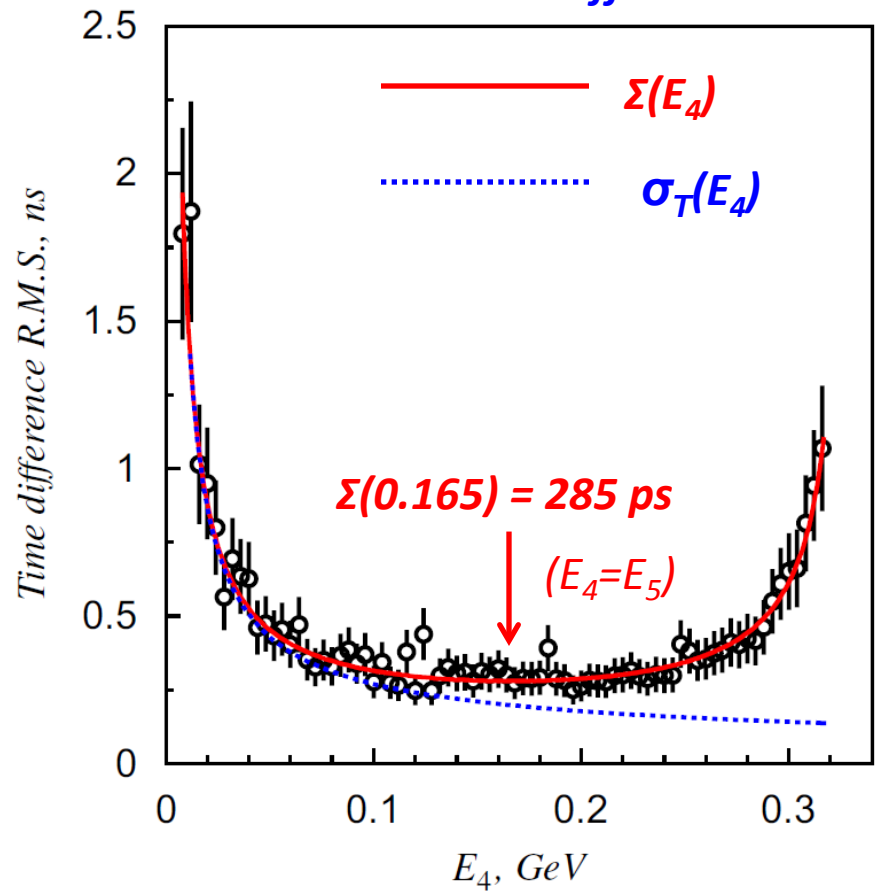
(G.S.Atoian et al, NIM A531 (2006) 467-480)

Experimental estimate of time resolution

Photon beam energy 0.33±0.02 GeV

Module 1	Module 2	Module 3
Module 4 Beam ⊗ (T study)	Module 5	Module 6
Module 7	Module 8	Module 9

Time difference RMS



Parametrization: $\sigma_T(E) = a/\sqrt{E} + b/E$

$$\sigma(t_4 - t_5) = \Sigma(E_4) = \sigma_T(E_4) \oplus \sigma_T(0.33 - E_4)$$

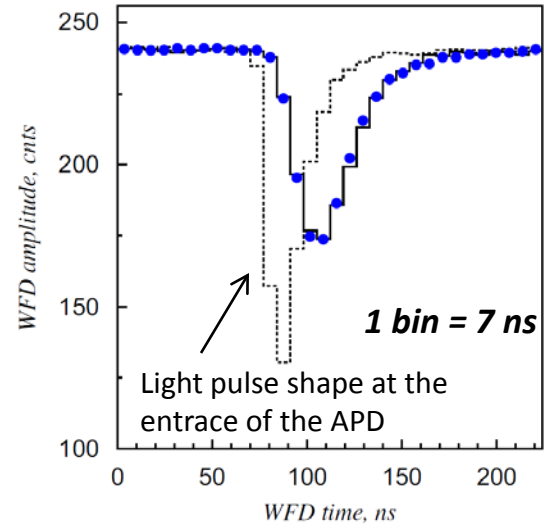
Fit: ***a = 72 ± 4 ps***
b = 14 ± 2 ps

Simulation of the time response and time resolution

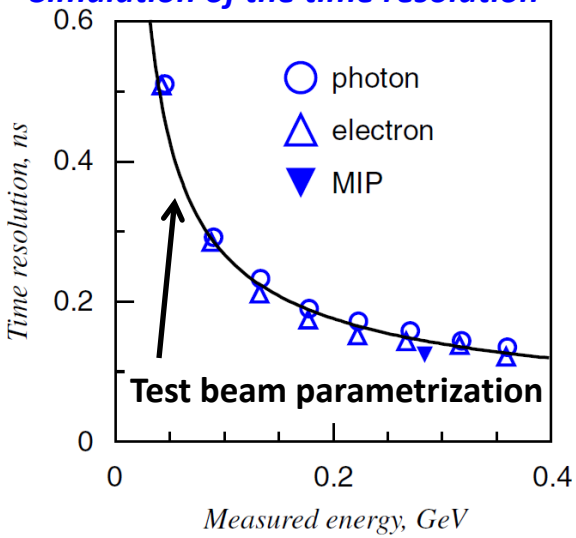
Simulation includes: space time distribution of hits, decay time in scintillator and WLS fiber, photon propagation in scintillator and fiber, response function of the detector chain.
No parameters of the simulation were derived from the test beam measurements.

$\Sigma_{sim}(0.165) = 280$ ps ***$\Sigma_{exp}(0.165) = 285$ ps***

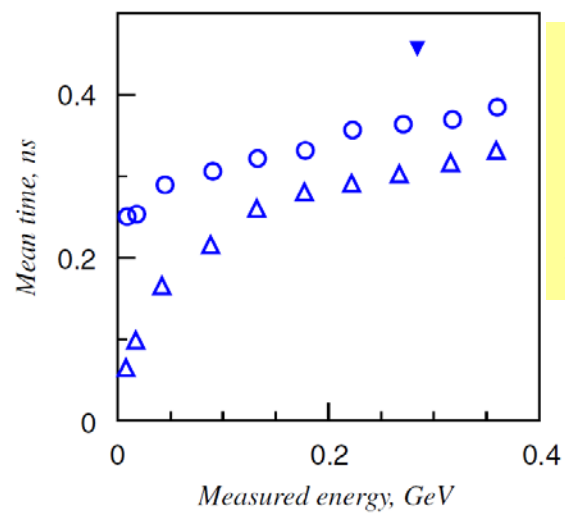
Simulated vs mesured waveforms



Simulation of the time resolution

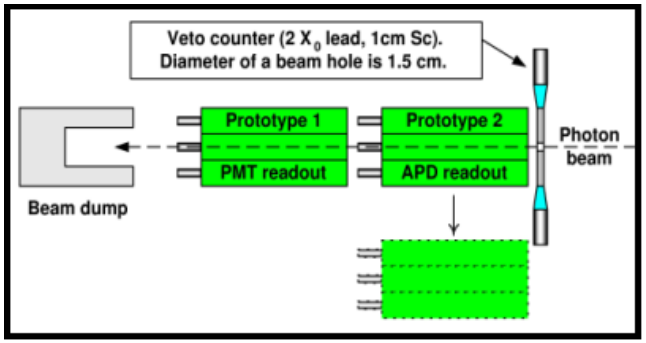


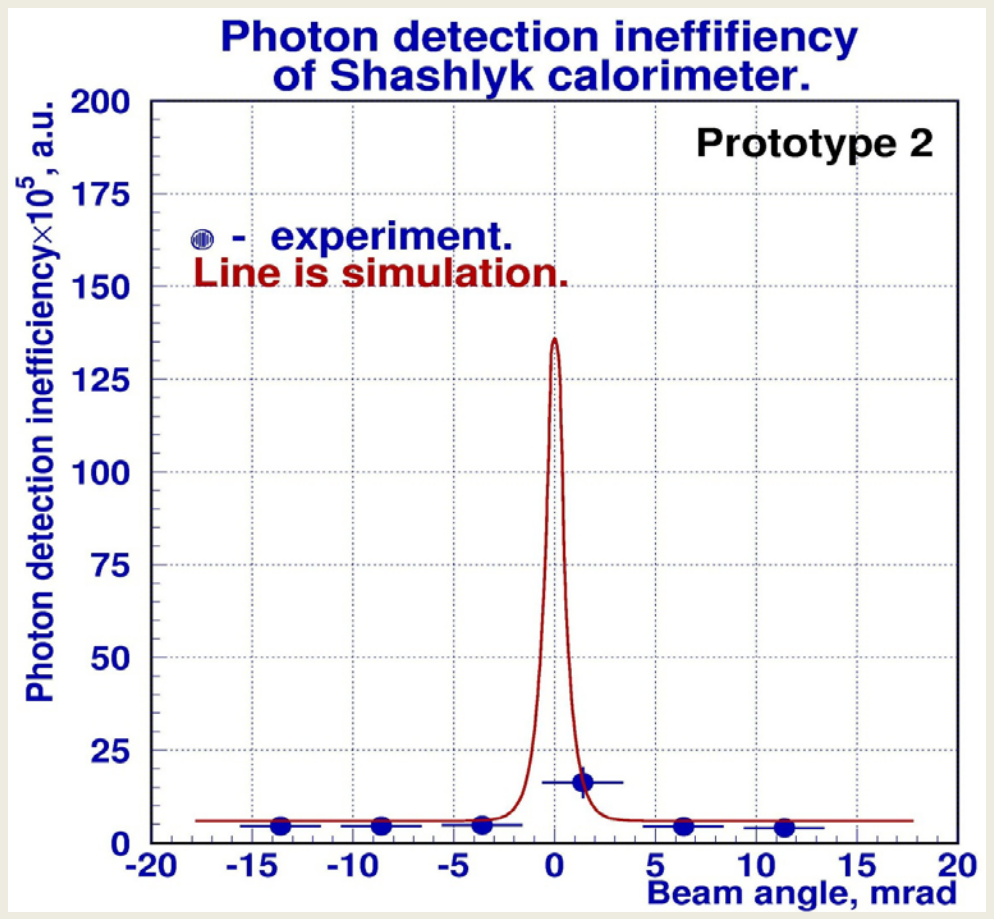
Simulation of the mean meas. time



In shashlyk, the deeper shower penetrate to the module, the larger time is measured !

Photon detection inefficiency





Simple estimate of Inefficiency (due to holes):

$$\sim N_f \frac{\pi r_h^2}{a^2} \frac{r_h^2}{L^2 \sigma_\theta^2}$$

$$\approx 0.02/\sigma_\theta^2 \ (\mathrm{mrad}^2)$$

Effect of holes is negligable if incident angle > 5 mrad

Summary

In 2005

- ***we had a good progress in developing of the preradiator***
- ***we had working and tested Shashlyk modules satisfying the KOPIO requirements:***

  - ***Energy resolution*** $\sigma_E/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)/\sqrt{E\,(\mathrm{GeV})}$
  - ***Time resolution*** $\sigma_T = (72 \pm 4\ \mathrm{ps})/\sqrt{E\,(\mathrm{GeV})} \oplus (14 \pm 2)/(E\,(\mathrm{GeV}))$
  - ***Inefficiency in photon detection*** $\varepsilon \approx 5 \times 10^{-5}\ (\theta_{\mathrm{beam}} > 5\ \mathrm{mrad})$

- ***we had reliable simulation tool for the Shashlyk module***
- ***IHEP (Protvino) was ready to start the production of all 1600 modules for KOPIO calorimeter***
- ***We planned to start the calorimeter construction in 2006***

but KOPIO was not continued

Shaslyk properties may be easily changed depending on experiment requirevents.