Monte-Carlo simulation of light collection efficiency of scintillation detectors using ZEMAX

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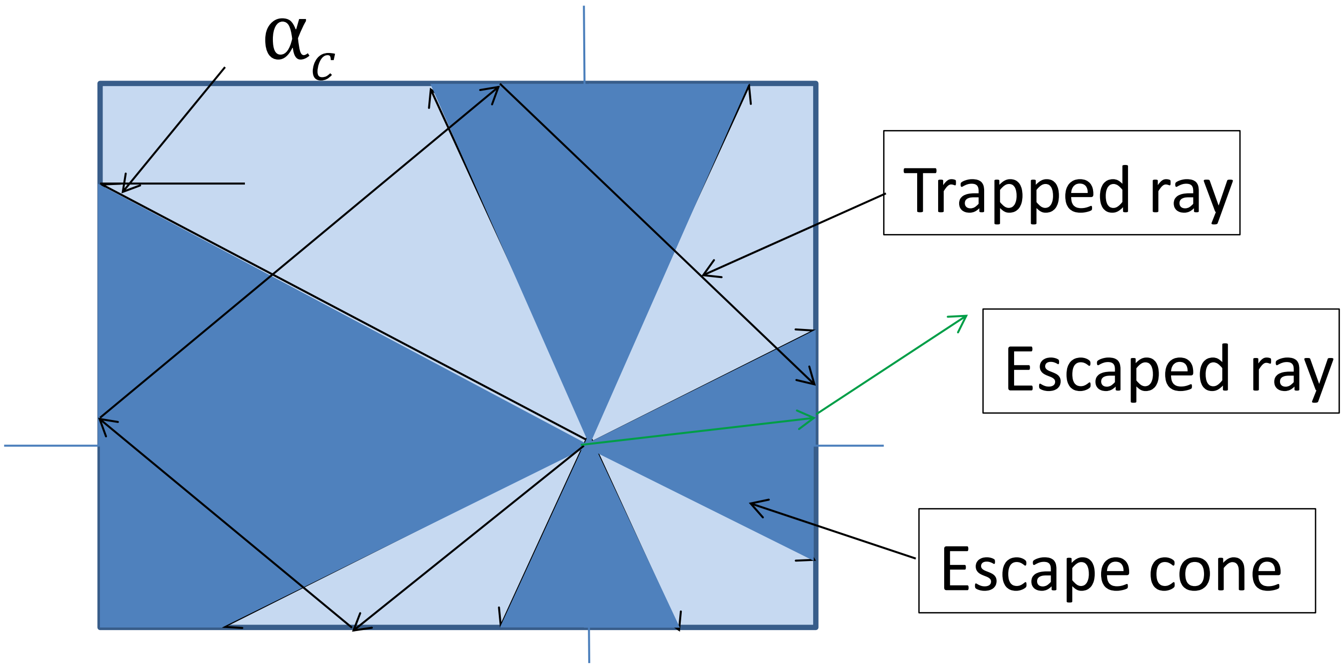
Outlook

- Light collection in crystal: trapping vs scattering
- ZEMAX toolkit for simulation of light collection
- Validation of ZEMAX modelling: determination of absolute light output of $CaMoO_4$
- Shape and light collection: optimization of geometry of scintillation detectors

Light trapping and escape

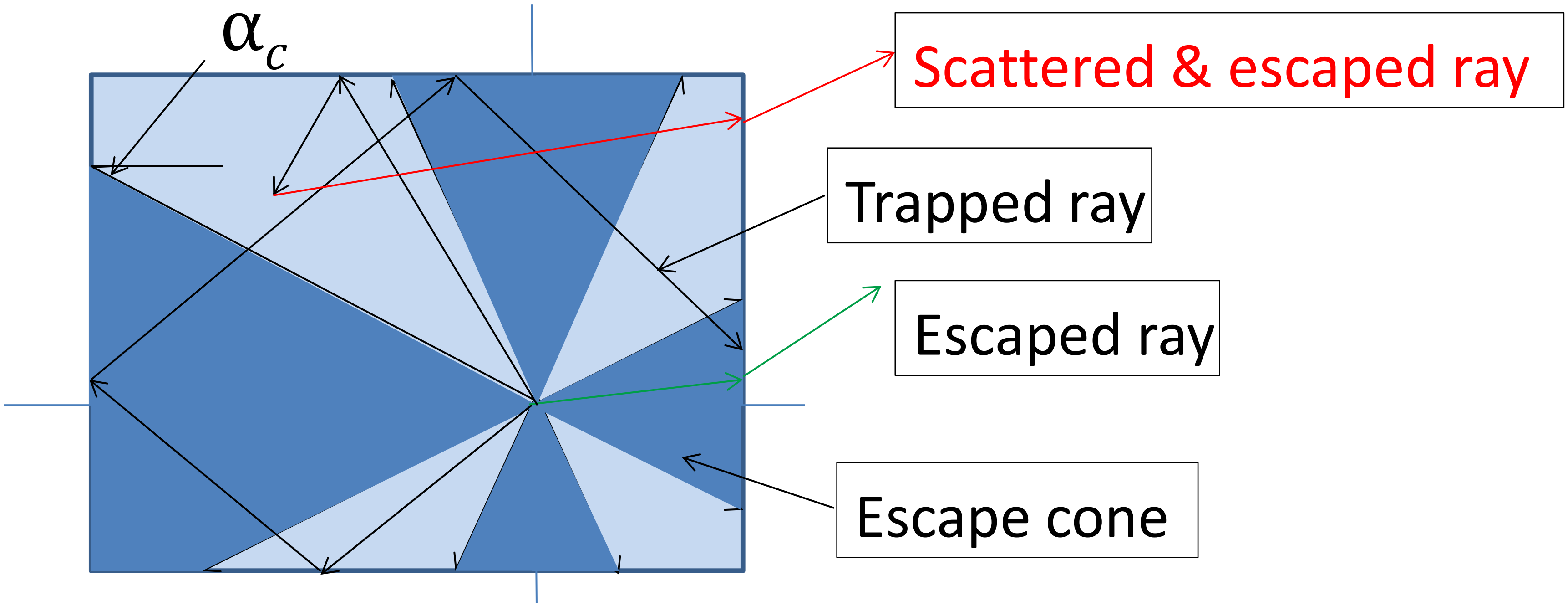


Snell's law: $\alpha_c = \mathrm{asin}(1/n)$

Light collection fraction: $\eta = \frac{Number\ of\ detector\ hits}{Total\ number\ of\ rays}$

$\eta = \frac{1}{2}\left(1 - \frac{\sqrt{n^2-1}}{n}\right)$ - light collection from a rectng. plane

Effect of light scattering



Scattering brakes symmetry of permanent reflections modes allowing light escape crystal

+ effect of surface (diffuse reflection and scattering)

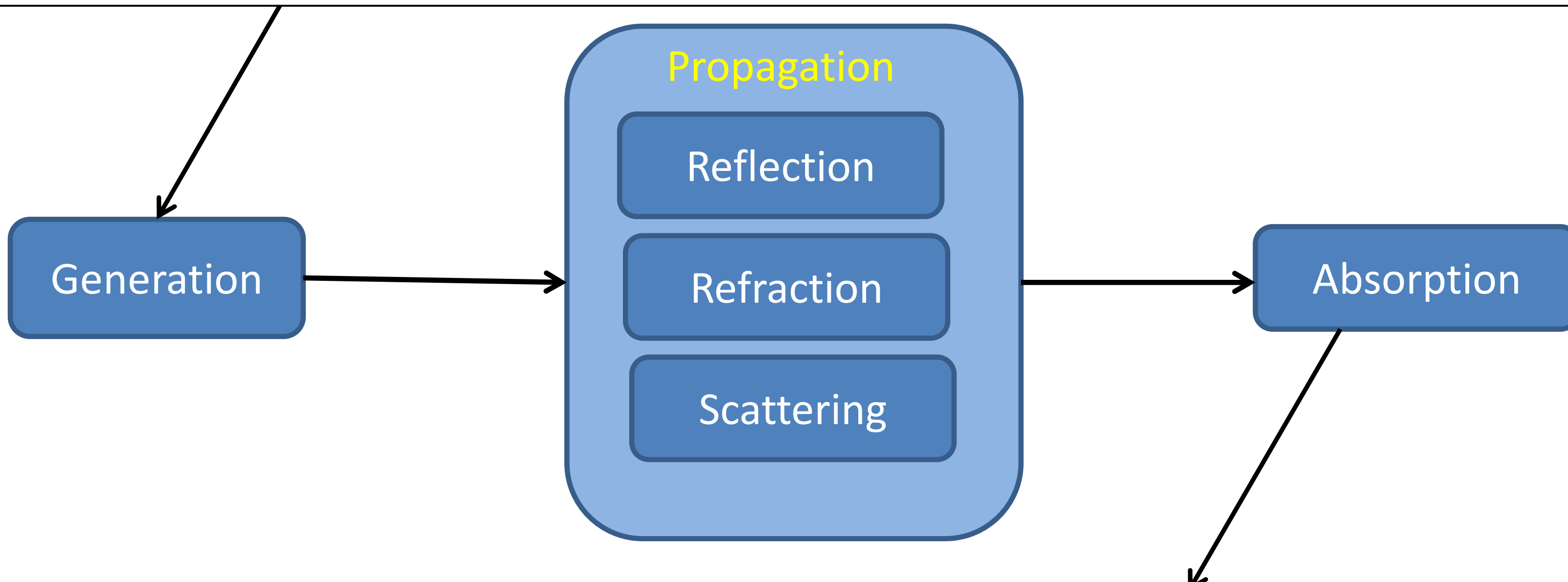
No analytical solution for light collection η →

Goto Simulation

Simulation of light collection in ZEMAX

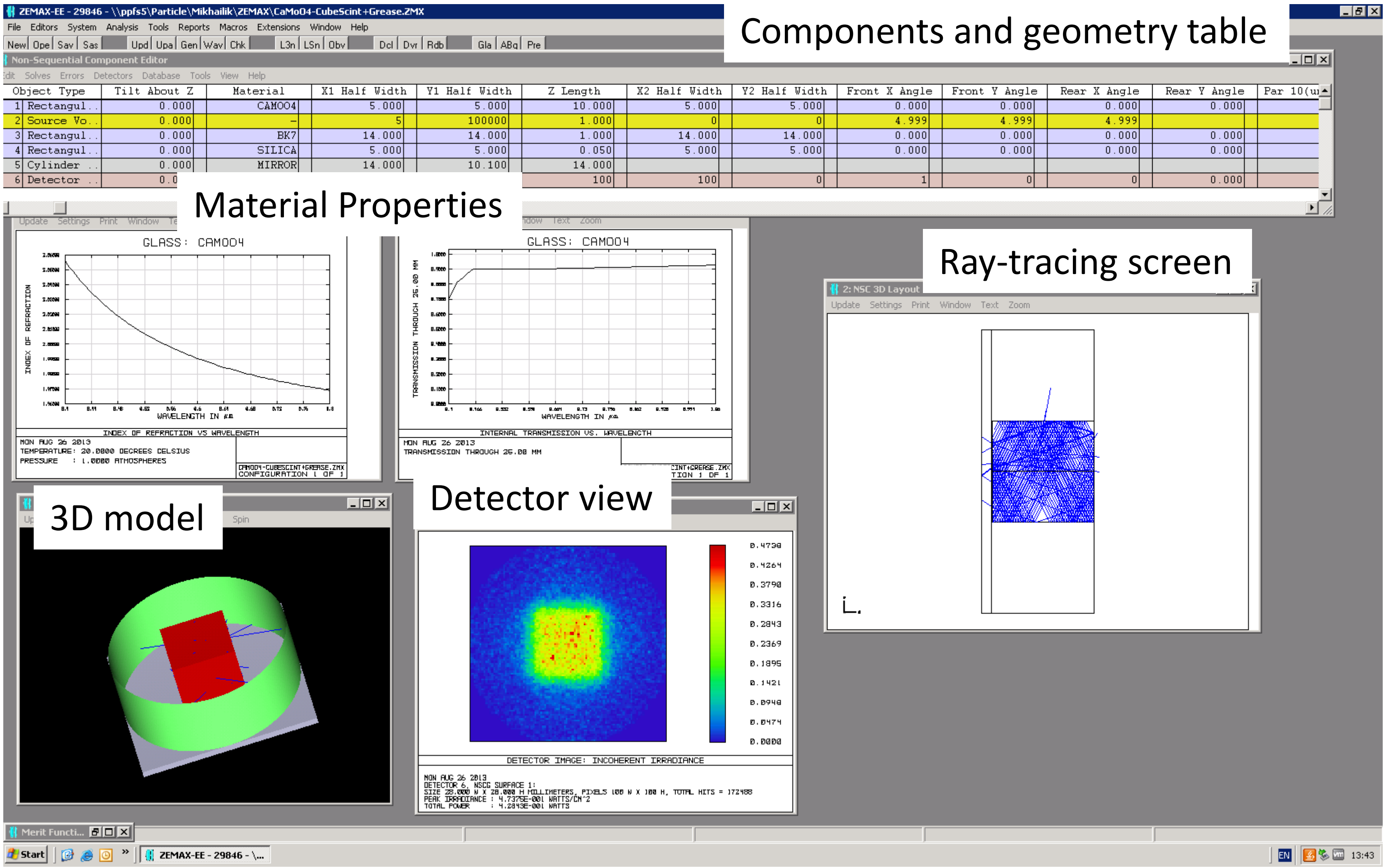
Simulates photon propagation in *non-sequential* mode *(after* energy deposition stage):

Input : i)wavelength, ii) material's characteristics, (refraction, absorption and scattering), iii) experiment geometry



Output : i) fraction of detected energy = light collection efficiency ii) energy distribution in detector plane(s)

User interface of ZEMAX

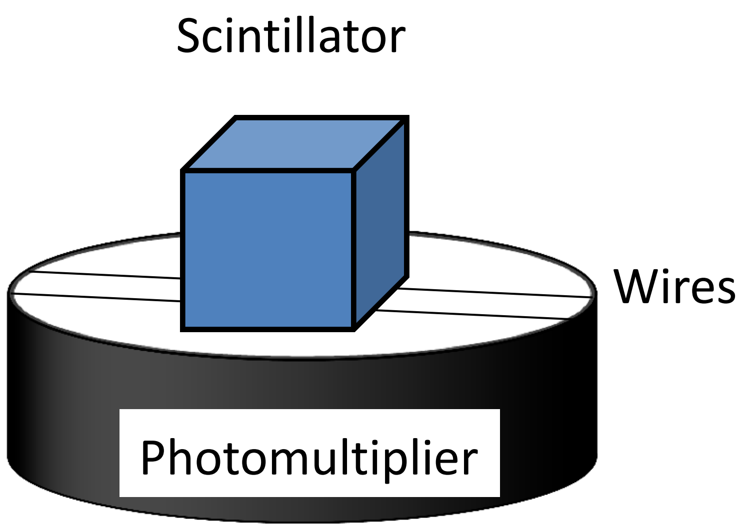


Validation: Light collection of $CaMoO_4$

$$R_{1/2} = \frac{N_1}{N_2} = \frac{N_0 \eta_1 \varepsilon_\lambda}{N_0 \eta_2 \varepsilon_\lambda} = \frac{\eta_1}{\eta_2}$$

→ experiment with AIR gap

→ experiment with GEL gap



Refraction: Crystal n=2.01,

Gel n_{gel}=1.46

Absorption: α=0.039 cm^{-1}

Emis.-wgt. detector efficiency : 0.127

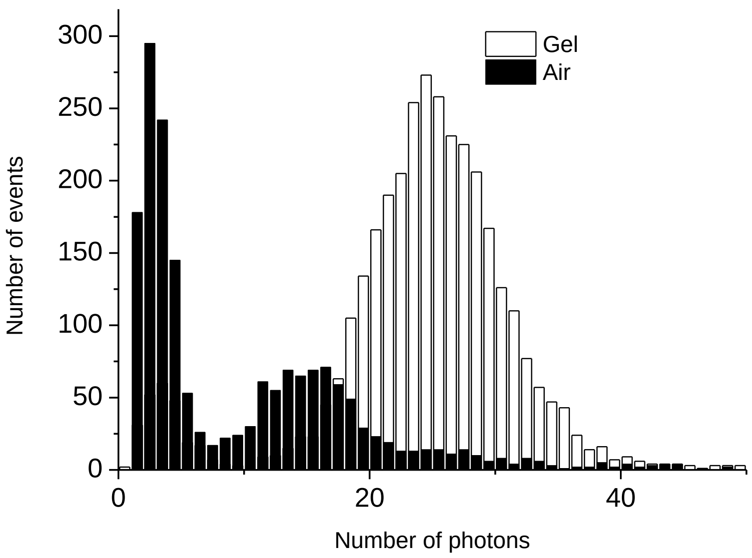
Measured light yield

@59.5 keV ^{241}Am:

N_{air}=14.3±0.2

N_{gel}=24.5±0.4

$R_{air/gel}$= 0.58±0.01



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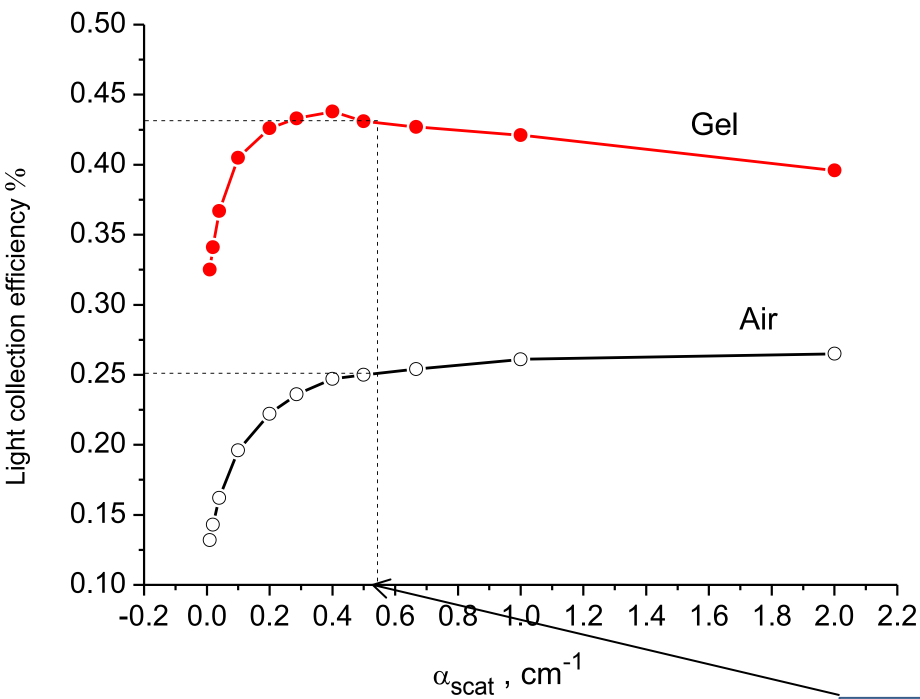
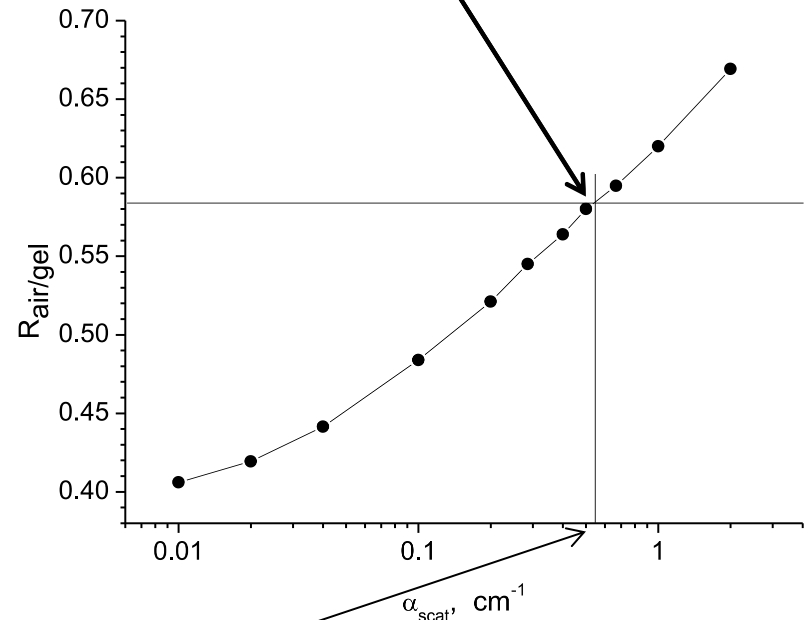




α=0.54 cm^{-1}

η_{air}=25%

η_{gel}=43%

→ $CaMoO_4$ absolute light yield= 7.5 ph/keV

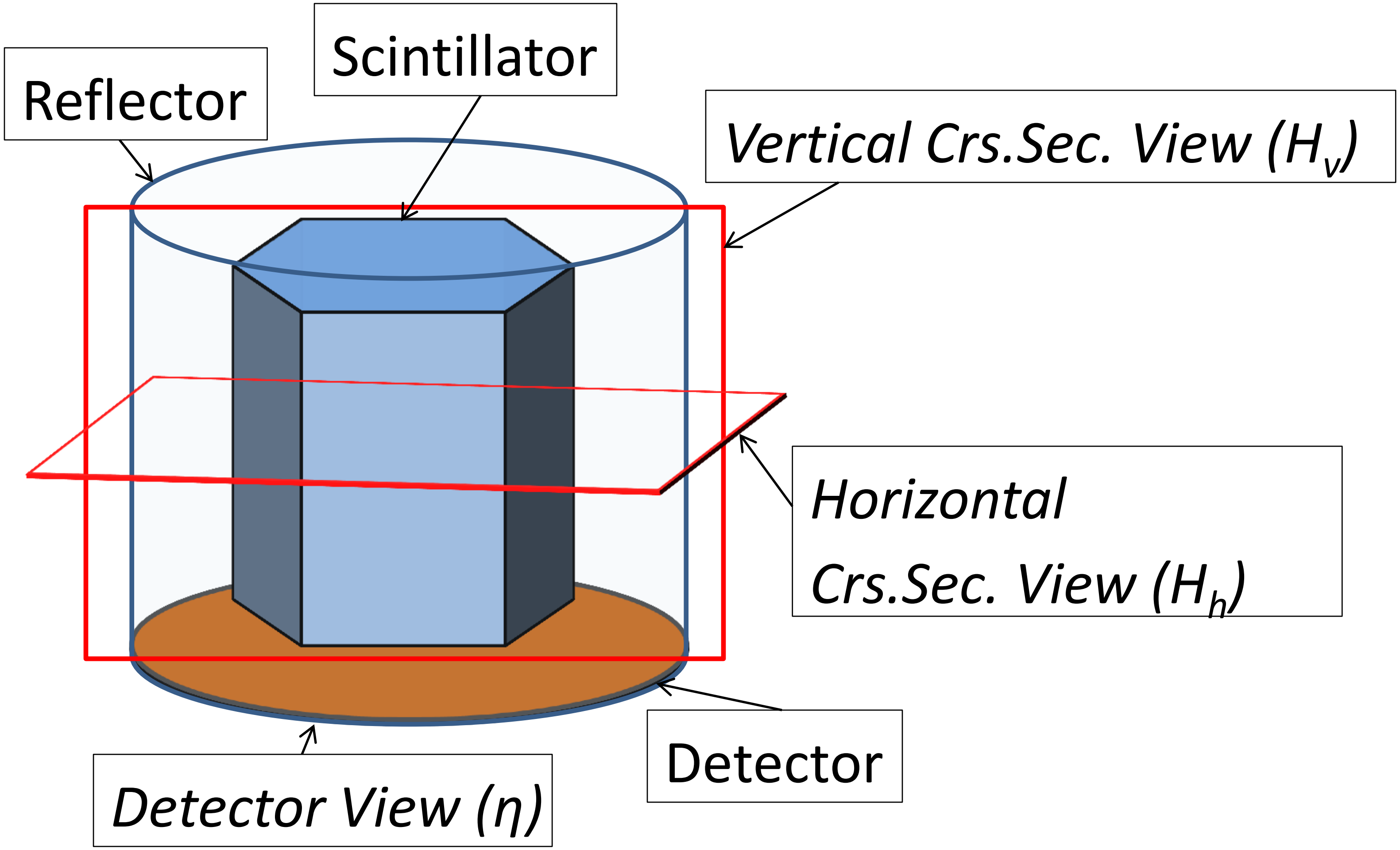
Optimization of cryogenic scintillation detector

Features of cryogenic experiment:

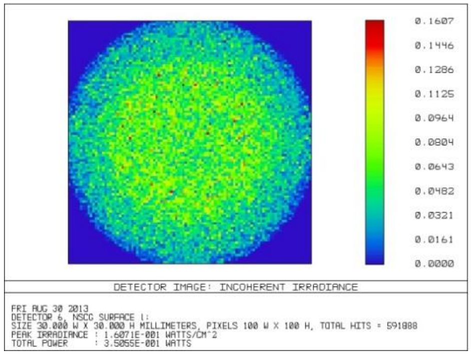
- space limited experiment (maximise "scientific payload")
- no touching, no coupling
- large crystal volume and aspect ratio H/S
- enhanced light trapping and self absorption
- manufacturability and maintainability

Q. Can light collection be improved through optimisation of experiment geometry?

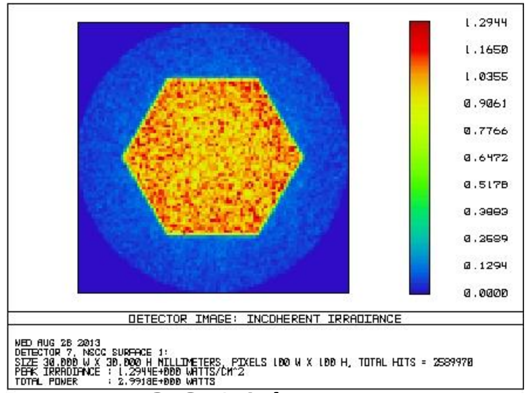
Model geometry



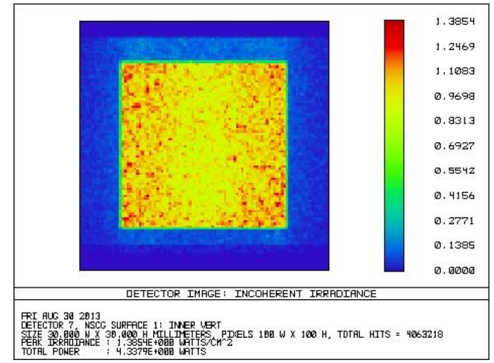
Light hit fraction: $H = \frac{Number\ of\ hits}{Total\ number\ of\ rays}$



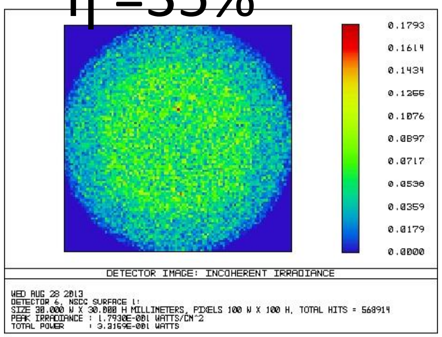
η =35%



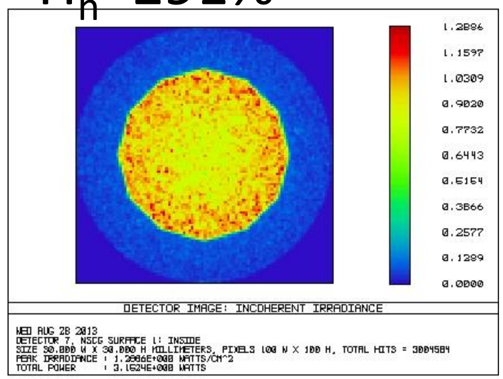
H_h=291%



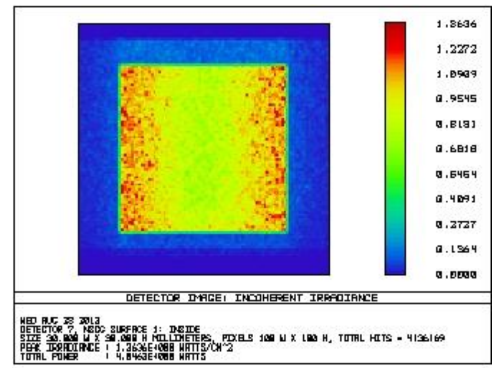
H_v=372%



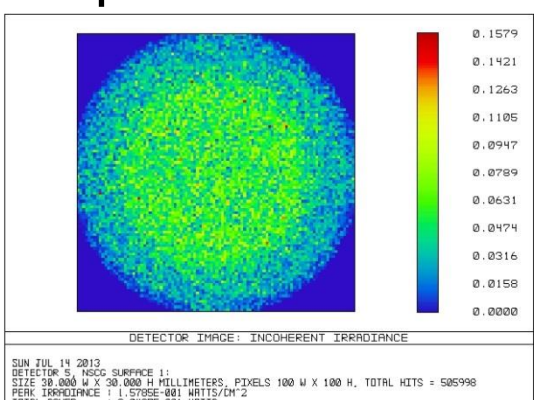
η =33.1%



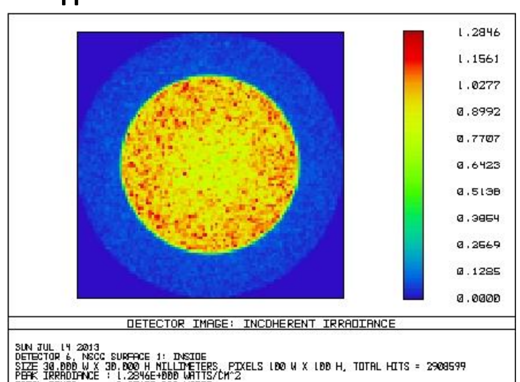
H_h=308%



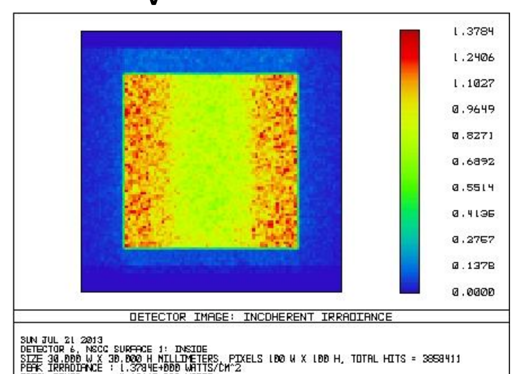
H_v=397%



η =31.3%

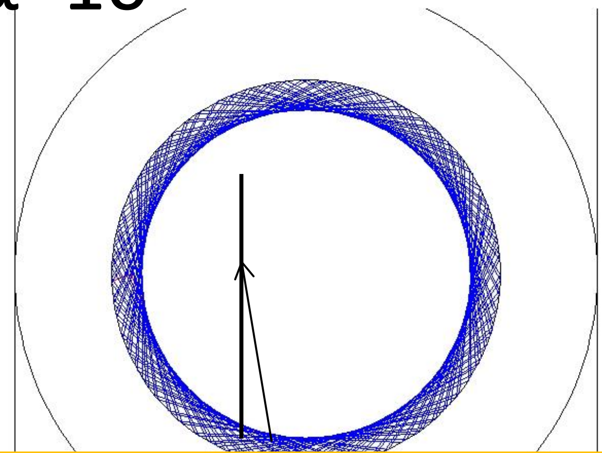


H_h=326%

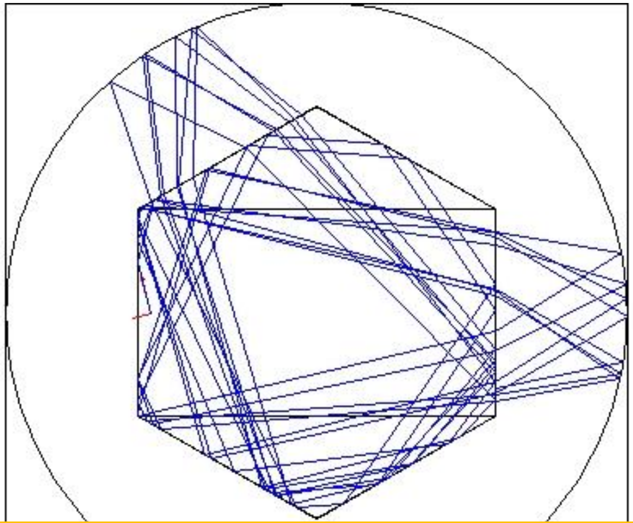


H_v=407%

α=10°

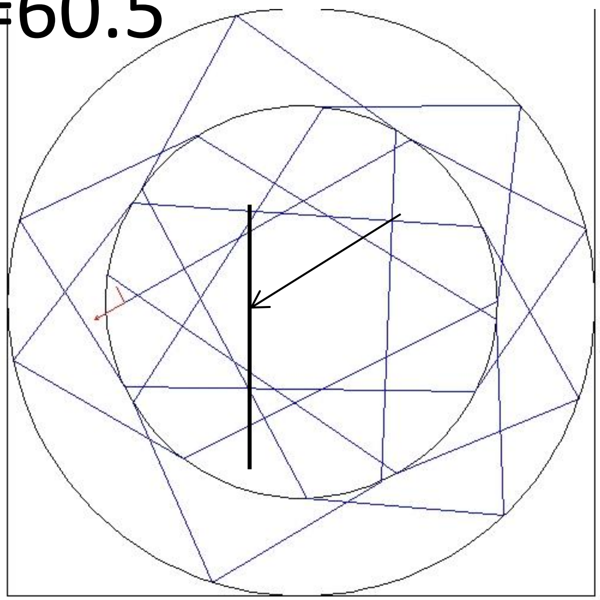


α=10°

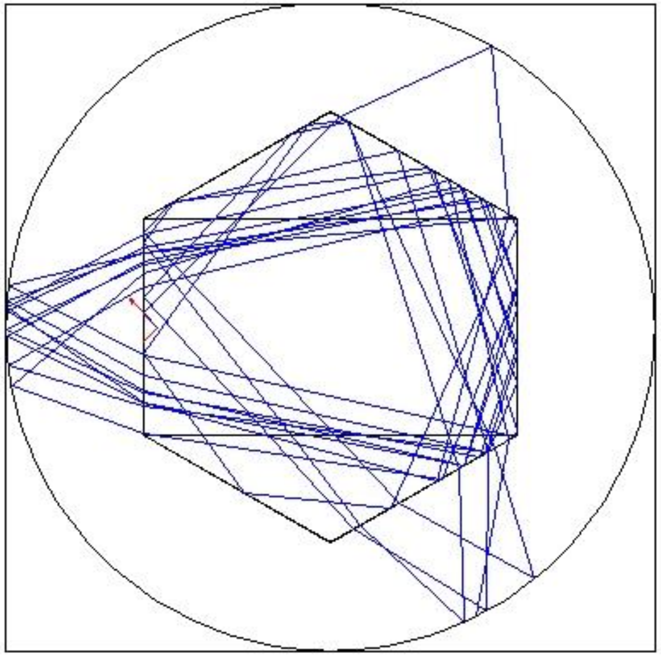


Hexagonal shape = escape

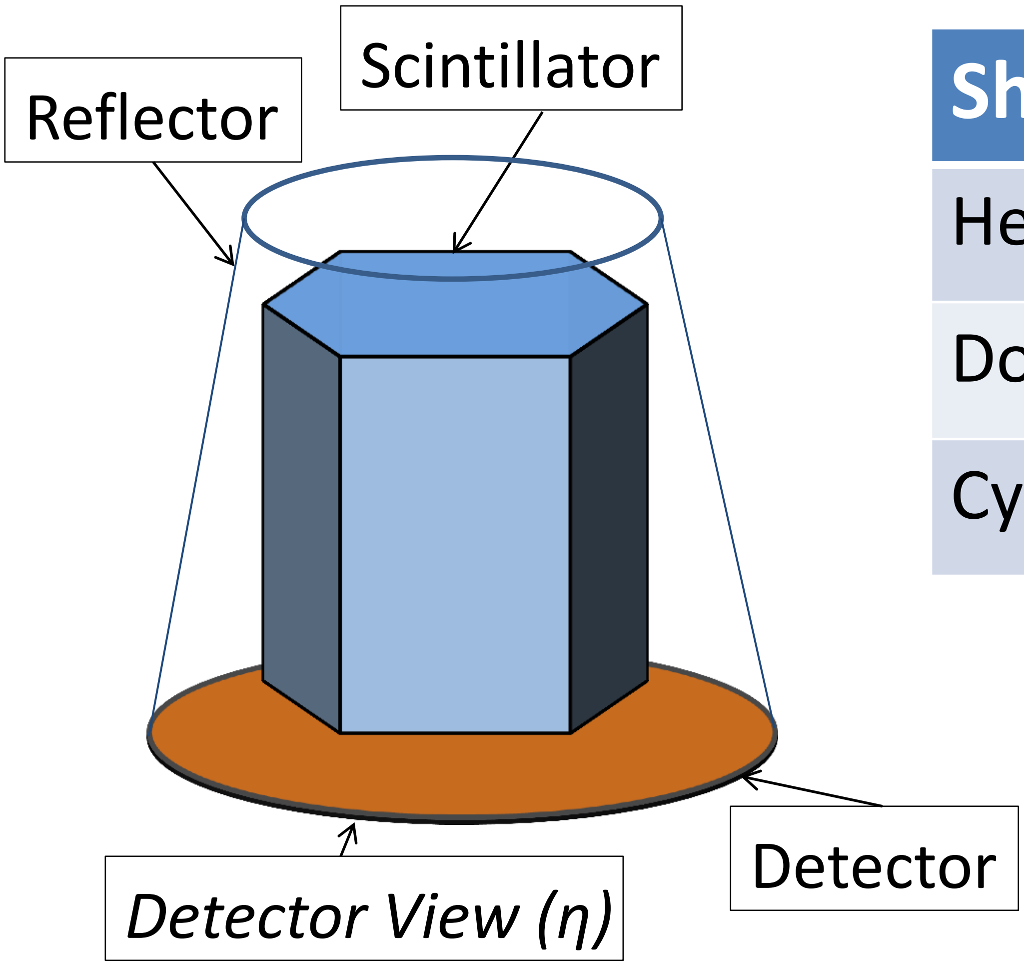
α=60.5°



α=45°

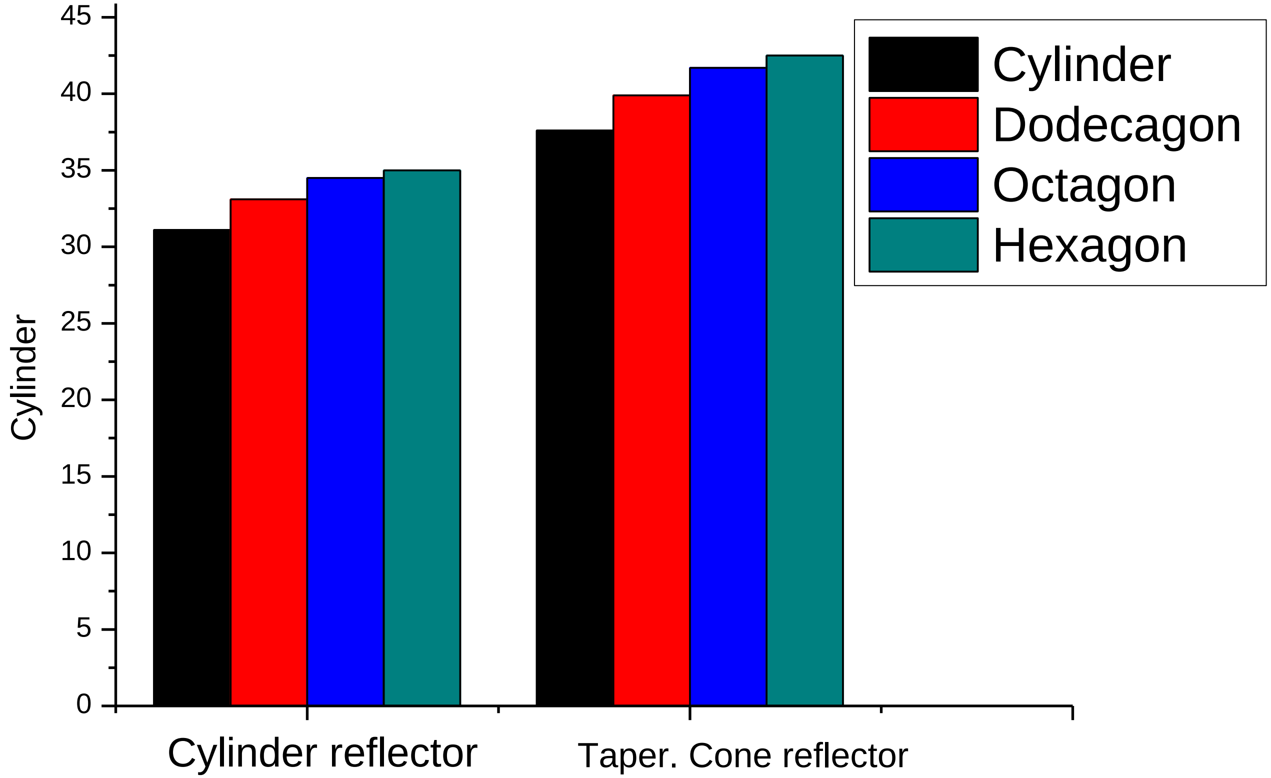


Effect of reflector shape (tapered conical reflector 1:1.5)



Shape	η, %
Hexagon	42.5
Dodecahedron	39.9
Cylinder	37.6

Effect of shape on light collection



Scintillator:

$ZnWO_4$

H=20 mm,

D=20 mm

Refl.

R=15 mm

H=25 mm

T=84%

α_{scat}=0.2 cm^{-1}

Summary

- ZEMAX proves to be efficient and competitive tool for reliable simulation of light collection of scintillation detectors.
- Absolute light yield of $CaMoO_4$ scintillator is determined to be 7.5 ph/keV
- Improvement in light collection of is possible by a) changing cylindrical geometry of scintillator crystal for multifaceted prism b) changing reflector from cylindrical to truncated cone
- Envisaged improvement of light collection is from 31.3% to 42.5% (*or one third*)