1. Optical elements

2. Simulation software and sequence of operations

3. Light collection efficiency

4. Analysis of different optical configurations

5. Conclusion
Geant4 files generated by T.J. Roberts

$\mu^+$ and $e^+$ tracks generated 1 mm ahead of CKOV2.

Configuration: TRD, Stage VI, Case 1
- RF off
- Empty absorbers

1. Muons generated in front of Tracker 1 with a wider (Gaussian) distribution
   Distributions becoming close to perfect at Tracker 2, and tracked down to CKOV2

2. Muons forced to decay at Tracker 1, Absorber 2 and Tracker 2

3. Samples

<table>
<thead>
<tr>
<th>Count</th>
<th>Particle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1084</td>
<td>electrons</td>
<td>Muon decay in Absorber 2</td>
</tr>
<tr>
<td>604</td>
<td>electrons</td>
<td>Muon decay in Tracker 1</td>
</tr>
<tr>
<td>3312</td>
<td>electrons</td>
<td>Muon decay in Tracker 2</td>
</tr>
<tr>
<td>5527</td>
<td>muons</td>
<td>from a simulation of the cooling channel</td>
</tr>
</tbody>
</table>
Spatial distributions

Beam spots at CKOV2

Projections

Aperture of CKOV2
• Muons are more focused than electrons

• For electrons the divergence is larger if the parent $\mu$ decays farther upstream
New files (T. Roberts)

- Lower $\mu$ momentum allows to increase the index of refraction of the radiator!

- The very low energy electrons have disappeared (all electrons are now fully relativistic).

Proposal and present TRD (P. Janot)
Electrons only!

No light generated by muons!

Threshold index for muons = 1.06
Optical elements

- Aerogel
- Windows
- Mirrors: substrates and reflecting layers
- Winston cones
- Photomultipliers
Pictorial view of optical elements

- Particle entrance window
- Aerogel box
- Front mirror
- Optical windows, Winston cones, PM's
- Reflecting pyramid
- Back mirror
- Particle exit window
- + various small elements (clamping pieces for windows)
Aerogel and its container

Aerogel tiles made by Matsushita

130 mm x 130 mm x 10 mm
Index of refraction = 1.02 (attn. CKOV1: n could be as large as 1.13 ...)
Density = 1.01 kg m\(^{-3}\)
Hydrophobic aerogel (i.e. chemically modified)

Less sensitive to atmospheric moisture, easier to cut and machine)

Number of tiles \(\cong\) 320

Cost \(\cong\) 260 € /tile

Aerogel box  Polygonal honeycomb box

Inside walls assumed optically absorbing (black)
Transmission of optical windows

Schott optical glasses

For 10 mm thickness

B270 choosen
90% transmission
Cost!
Mirrors

- Substrate: polycarbonate (Lexan) 3 mm sheets supported by Honeycomb panels
  
  Very stiff at room T (but thermally deformable)
  
  Good surface properties of raw material and experience as a mirror support (HARP)

- Reflecting layer: multilayer [Aluminium + SiO$_2$ + Hf O$_2$]

  Very good reflectivity (A. Braem/CERN)
Manufacturing of mirrors

Assembly on honeycomb structure

Bending by hot forming
Winston cones

Raw material:
- transparent PMMA (lucite)
  milled on a CNC lathe
  polishing

Reflecting surface:
- same as for mirrors

Measurements from HARP at different points on the surface
  (Reflecting layer Al + SiO₂)
Profile of Winston cones

Acceptance angle = 30 degrees

Profile: see table

<table>
<thead>
<tr>
<th>Nr</th>
<th>Radius R (mm)</th>
<th>Height h (mm)</th>
<th>Radius of curvature (mm)</th>
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Manufacturing of Winston cones
EMI 9356 KA low background selected tubes (from Chooz and HARP)

8-inch diameter hemispherical borosilicate window / High QE 30%
Bialkali photocathode / 14 stages / High gain $6.7 \times 10^7$ (at 2300 V)
Positive HV supply ! (i.e. photocathode at ground and anode at HV !)

Response and Quantum efficiency (from Electron Tubes Ltd catalog)
Photomultiplier windows

Spectral transmission through window material

Transmission (shown here for rays parallel to PM axis)

Losses due to reflection

Distance to PM axis

Radius

Transmission / Reflection

UV

Mg F₂

Spectrosil

Borosilicate

Transmission (%)

Wavelength (nm)
Sequence of operations

**Mechanical constraints**

**Optical/material constraints**

**Physical constraints**

**Mechanical design** -> **Optical performances** -> **Analysis of ray data base** -> **Detection performances**

- **Autocad 2000**
- **Zemax Engineering**
- **Mathematica 3.0**

**MC files (T.J. Roberts)**

**Generation of Cherenkov photons**

**This presentation**

**Iteration**
ZEMAX v. Feb 02, 2005 (Engineering Edition)

• Non sequential configuration
  (i.e. the optical elements are not necessarily hit sequentially)

• Source file: Cherenkov photons generated from T. Roberts’ electron files
  (via an independent Mathematica program)

• Measured reflectivity of mirrors taken into account

• Measured transmission of windows taken into account
### Zemax configuration editor

<table>
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<tr>
<th>U.S.</th>
<th>Ellipses</th>
<th>X Position</th>
<th>Y Position</th>
<th>Z Position</th>
<th>Tilt About X</th>
<th>Tilt About Y</th>
</tr>
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<td>0.00000</td>
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</tbody>
</table>

### Diagram

[Image of Zemax configuration editor interface]

---

20
Typical output display
Theoretical efficiency $\varepsilon$

For a single particle losing an energy $\Delta E$ in the radiator,

$$N_{p.e.} = L \ K \int \varepsilon(E) \ \sin^2 \theta_c(E) \ dE$$

with

$K = 370 \ \text{cm}^{-1} \ \text{eV}^{-1}$

$L = \text{thickness of radiator (cm)}$

$E = \text{photon energy}$

where $\varepsilon(E) = \text{efficiency for collecting light and converting it in photoelectrons}$

Threshold:

$$\sin \theta_c = \frac{1}{\beta n(\lambda)} = 1 \quad \text{or} \quad p > \frac{m}{\sqrt{n^2 - 1}}$$

Since $(\sin \theta_c)$ is slowly dependent on $E$ (above threshold)

$$N_{p.e.} \approx L \ N_0 \left\langle \sin^2 \theta_c \right\rangle$$

with

$$N_0 = K \int \varepsilon(E) \ dE$$

For a typical PMT working in the visible and near UV

$N_0 = 90-100 \ \text{cm}^{-1}$

$N_0$ already “contains” the Q.E. of a (typical) PMT and assumes all photons are collected!
Realistic efficiency $\varepsilon$

Since the geometrical photon collection probability substantially varies for different tracks, we use

$$N_{p.e.} \approx \varepsilon L N_0 \langle \sin^2 \theta_c \rangle$$

where

$$\varepsilon = \varepsilon_{geom} \times \varepsilon_{phys}$$

$\varepsilon_{geom}$ is the geometric light collection probability

( probability that a given light ray reaches a photodetector detector)

$\varepsilon_{phys}$ is the physical attenuation of light in the device

( due to reflections, transmissions, absorptions)
Tested: three optical configurations

- externally identical (with the same external envelope!) with the same optical elements except the reflecting pyramid

# 1 12-sided pyramid with flat faces and back mirror

# 2 12-sided pyramid with cylindrical faces (no back mirror needed)

# 3 12-sided pyramid with spherical faces (no back mirror needed)

Examples of several optical tracks (pathological !)
Geometries

# 1

- 12 flat faces
  - at 45°

# 2

- 12 cylindrical faces
  - (R = 843 mm)

# 3

- 12 spherical faces
  - (R = 843 mm)
Goals

1. Best light collection probability $\varepsilon_{\text{geom}}$ among different geometries!

$$\varepsilon_{\text{geom}} \overset{\text{def}}{=} \frac{\text{Nr of rays detected}}{\text{Nr of rays emitted}}$$

2. Minimal attenuation

Minimize number of reflections

(or ray path length or nr of detectors hit !)

i.e. maximize $\varepsilon_{\text{phys}}$

Expected

a) 1 or 2 reflections (on the pyramid and on a Winston cone)

b) Ray path length $\cong \text{« vessel width »} + \text{« vessel radius »}$

i.e. $360 + 650 = 1010$ mm

Analysis of many pathological tracks ...
Typical event (config. #1)

35 photons from a single electron

Lots of rays
- bouncing back and forth between front and back mirrors
- trapped and/or absorbed inside aerogel box, ...

Losses! Low light collection efficiency
Track #01

Ray absorbed inside aerogel box

Incidence angle on the pyramid is too small and the initial ray gets reflected away from the PM
bouncing back and forth between front and back mirrors

Incidence angle on the pyramid is too small and the initial ray gets reflected away from the PM
Performances of configuration #1

Pyramid with flat faces

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average nr of reflections</strong></td>
<td>4.68</td>
</tr>
<tr>
<td><strong>Most probable nr of reflections</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Average path length</strong></td>
<td>2065 mm</td>
</tr>
<tr>
<td><strong>Most probable path length</strong></td>
<td>1100 mm</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rays emitted</strong></td>
<td>2000</td>
</tr>
<tr>
<td><strong>Rays detected</strong></td>
<td>1210</td>
</tr>
</tbody>
</table>

ε_{geom} = 0.61
Typical event (config. #2)

35 photons from a single electron (same event as for config. #1)

Only one ray is lost!
Same event (config.#2)

Only 3 detectors hit! Some ring imaging clearly visible on the screen display.
Performances of configuration #2

Pyramid with curved cylindrical faces

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average nr of reflections</td>
<td>3.31</td>
</tr>
<tr>
<td>Most probable nr of reflections</td>
<td>2</td>
</tr>
<tr>
<td>Average path length</td>
<td>1647 mm</td>
</tr>
<tr>
<td>Most probable path length</td>
<td>1100 mm</td>
</tr>
</tbody>
</table>

Rays emitted       | 2000    |
Rays detected      | 1347    |

$\varepsilon_{\text{geom}} = 0.67$
Tracking 2000 rays

<table>
<thead>
<tr>
<th>Configuration</th>
<th># 1</th>
<th># 2</th>
<th># 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Flat faces</td>
<td>Cylindrical faces</td>
<td>Spherical faces</td>
</tr>
<tr>
<td>Average nr of reflections</td>
<td>4.68</td>
<td><strong>3.31</strong></td>
<td>3.69</td>
</tr>
<tr>
<td>Most probable nr of reflections</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Average path length</td>
<td>2065 mm</td>
<td><strong>1647</strong> mm</td>
<td>1774 mm</td>
</tr>
<tr>
<td>Most probable path length</td>
<td>1100 mm</td>
<td>1100 mm</td>
<td>1100 mm</td>
</tr>
<tr>
<td>Geometrical light collection efficiency $\varepsilon_{geom}$</td>
<td>0.61</td>
<td><strong>0.67</strong></td>
<td>0.67</td>
</tr>
</tbody>
</table>

*best!*
Physical attenuation

for $\lambda = 400$ nm

- Cylindrical faces
- Flat faces
- Spherical faces

Frequency vs. Physical attenuation factor for different face types.
<table>
<thead>
<tr>
<th>Configuration</th>
<th># 1</th>
<th># 2</th>
<th># 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Flat faces</td>
<td>Cylindrical faces</td>
<td>Spherical faces</td>
</tr>
<tr>
<td>Average attenuation factor</td>
<td>0.685</td>
<td>0.711</td>
<td>0.689</td>
</tr>
<tr>
<td>Most probable attenuation factor</td>
<td>0.750</td>
<td>0.750</td>
<td>0.750</td>
</tr>
</tbody>
</table>

*best!*
The configuration with cylindrical faces for the reflecting pyramid is better

\[ \langle \varepsilon_{\text{geom}} \rangle = 0.67 \quad \langle \varepsilon_{\text{phys}} \rangle = 0.75 \quad \text{(most probable values)} \]

so that

\[ \langle \varepsilon \rangle = \langle \varepsilon_{\text{geom}} \rangle \times \langle \varepsilon_{\text{phys}} \rangle = 0.50 \]

We thus expect about 18-20 photoelectrons for \( n_{\text{aerogel}} = 1.02 \)

( I had no time yet to compute \( \varepsilon \) particle by particle ! )
About CKOV2 To be studied further (… to come soon !)

For a given PMT threshold and a given index of aerogel,

determine detection efficiency per particle

- as a function of momentum

- as a function of position and direction of particle on the entrance window