# Aerogel Cherenkov counters of the KEDR detector

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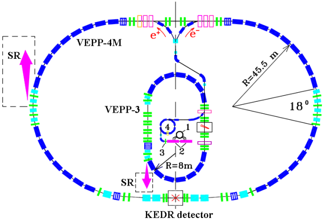
# VEPP-4M collider and KEDR detector

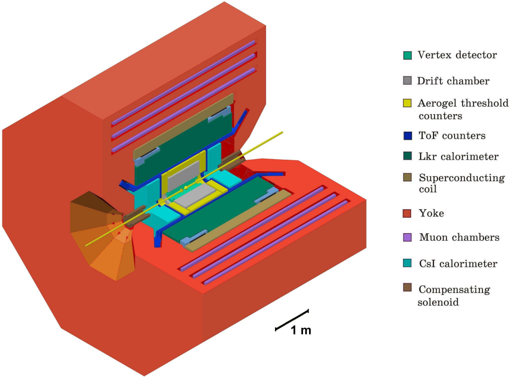
- Beam energy 1÷5.5 GeV
- Number of bunches 2×2
- Luminosity $10^{30}$ cm$^{-2}\cdot$c$^{-1}$ for $E_{beam}$=1.5 GeV

Beam energy measurement:

- Resonant depolarization technique:
  Instant measurement accuracy $\simeq 1\times10^{-6}$
  Energy interpolation accuracy $(5\div15)\times10^{-6}$(10÷30 keV)
- Infra-red light Compton backscattering:
  Statistical accuracy $\simeq 5\times10^{-5}$ / 30 minutes
  Systematic uncertainty $3\times10^{-5}$(50÷70 keV)



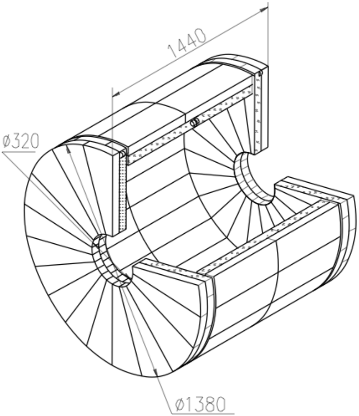

Injector:
1 - Girokon (430 MHz)
2 - Linac (50 MeV)
3 - Electron to positron converter
4 - Synchrotron B-4 (350 MeV)

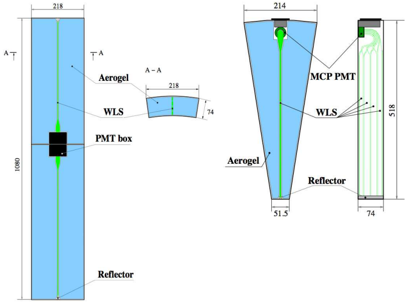


# ASHIPH method

- In 1988 the first project of aerogel Cherenkov threshold counters for the KEDR detector with direct light collection was suggested (A. Onuchin et al., World Scientific, 1990, 208-213)
- ASHIPH (Aerogel, SHifter, PHotomultiplier) method of light collection was suggested in 1992. Cherenkov light from aerogel is collected by the wavelength shifter (WLS) placed in the middle of the counter and transported by WLS like a lightguide to photomultiplier (PMT) (A. Onuchin et al. NIM A315, 1992, 517-520)
  - This method helped us significantly to decrease the PMT photocathode area (cost of the system)
- The fully installed particle identification system of ASHIPH counters began its operation at the KEDR detector in 2014

# The ASHIPH system of the KEDR detector




- 160 counters arranged in 2 layers;
- 1000 liters of aerogel with n=1.05;
- $\pi/K$-separation in the momentum range 0.6-1.5 GeV/$c$;
- 160 MCP PMT with multialkali photocathode ⊘18 mm able to work in the magnetic field up to 2 T.

# Operation in the KEDR detector

## HV system::

- High voltage source (HVS) – 6 HV converters H40N (EMCO: 4000 V, 3.75 mA, 15 W) in one standard CAMAC 4M module was developed at BINP.
- High voltage module (HVM, PNPI, St. Petersburg) – 10 modules of 16-ch active HV dividers provide tuning of voltage for each counter from 2500 to 4000 V.

## DAQ system:

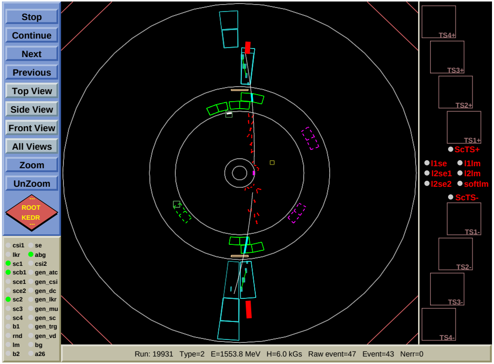
- The counters are read out by 28 A6 boards.
- A6 board supported in special the KLUKVA standard developed at the BINP.
- A6 has 6 channels with 10-bits flash ADC which makes measurements each 55 ns and save them in a pipe-line register.
- The register is blocked when the detector trigger system generate positive decision.
- Five amplitude values are read out for each channel.

## Slow control system:

- The system monitors the dark count rates of the PMTs and provides HV power control.
- In case of emergency each counter is switched off by active HV divider individually.
- Monitoring of the gain stability and the counters efficiency is performed twice per week during calibration runs with LED and cosmic particles.

# Event reconstruction

KrAtc (C++/C) package has been developed for the event reconstruction in the ASHIPH counters.




## Event reconstruction:

1. Fit of 5 hit amplitudes by a predefined pulse shape to determine amplitude and time of the hit.
2. Extrapolate a track into the ASHIPH system and determine its intersections with different parts of the counters.

# Alignment of the ASHIPH system

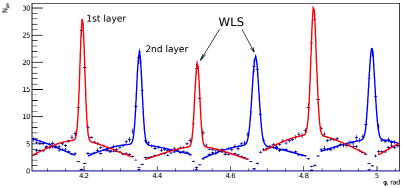
What is displacement the axis coordinate the system of ASHIPH relative to the tracking system?

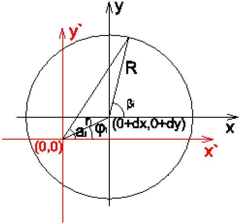
**Alignment with cosmic muons:**

- single track with P>1 GeV/c;
- central events from the sphere of radius 30 cm;
- $\geqslant$1 cluster in the calorimeter;
- energy of cluster >20 MeV;
- $\geq$1 hits in the muon system;
- 4 hits in TOF system for barrels counters.

**Alignment with BhaBha events:**

- 2 collinear tracks of opposite charge from the interaction point IP;
- $\geq$2 clusters in the EMC;
- energy of clusters in the calorimeter $\geq$450 MeV;
- sum energy of clusters $\geq$2 GeV;
- momentum track P>1300 MeV/c;



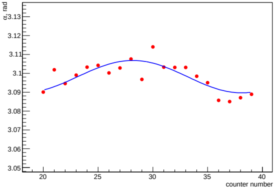




$$\alpha_i = \arctan\left(\frac{R \cdot \sin(\beta_i - i \cdot \pi/10) + r_i \cdot \sin(\varphi_i)}{R \cdot \cos(\beta_i - i \cdot \pi/10) + r_i \cdot \cos(\varphi_i)}\right) + (\pi/10) \cdot i$$

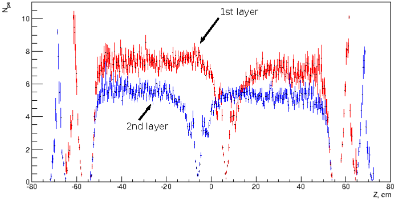
Parameters – $\beta_i$, $\varphi_i$, $r_i$ are determined in the fit to the experimental data $\rightarrow \triangle x, \triangle y$

# Alignment of the ASHIPH system

Fit of the experimental data




$\triangle z$ – determination

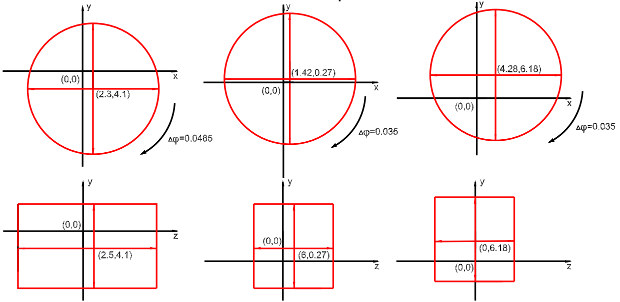



Results – $\triangle x, \triangle y, \triangle z, \triangle \varphi$

Barrel

Left endcap

Right endcap




* dimensions in mm and radians

# Geometric efficiency on $e^+e^- \to e^+e^-$ events

$$\varepsilon = \frac{N_{\mathrm{atc\_tracks}}}{N_{\mathrm{tracks}}},$$

$N_{\mathrm{tracks}}$ - number of charged particle tracks, $N_{\mathrm{atc\_tracks}}$ - number of charged particle tracks hits in the system ASHIPH.

Events were selected by the calorimeter in polar angle $20^\circ < \theta^\circ < 160^\circ$ (94% from $4\pi$).

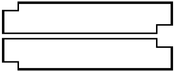
11377 $e^+e^- \to e^+e^-$ events (22754 tracks) were selected from runs collected in May 2014 ($\sim$40 mln. events).

**Selection Bhabha events:**

- 2 collinear tracks of opposite charge from the interaction point IP;
- $\geq$2 clusters in the EMC;
- energy of clusters in the calorimeter $\geq$450 MeV;
- sum energy of clusters $\geq$2 GeV;
- momentum track P>1300 MeV/$c$.

# Geometric efficiency on $e^+e^- \to e^+e^-$ events

«Aerogel» – area of the aerogel with electronics and shifter cut and indented from the walls.



«All counter» – aerogel+shifter with electronics cut and indented from the walls.

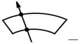
 – intersection of the bottom surface of the counter

Two layers by «OR»

| Area counter indented | Geometric efficiency |
|---|---|
| 1) «Aerogel»–0 mm | 95.7±0.6% |
| 2) «Aerogel»–5 mm | 86.1±0.6% |
| 3) «Aerogel»–10 mm | 76.2±0.6% |
| 4) «All counter»–0 mm | 99.5±0.5% |
| 5) «All counter»–5 mm | 99.1±0.6% |
| 6) «All counter»–10 mm | 98.4±0.6% |

Two layers by «AND»

| Area counter indented | Geometric efficiency |
|---|---|
| 1) «Aerogel»–0 mm | 84.6±0.6% |
| 2) «Aerogel»–5 mm | 74.4±0.6% |
| 3) «Aerogel»–10 mm | 64.5±0.5% |
| 4) «All counter»–0 mm | 86.4±0.6% |
| 5) «All counter»–5 mm | 76.5±0.6% |
| 6) «All counter»–10 mm | 66.5±0.5% |

 – intersection of the bottom and top surfaces of the counter

Two layers by «OR»

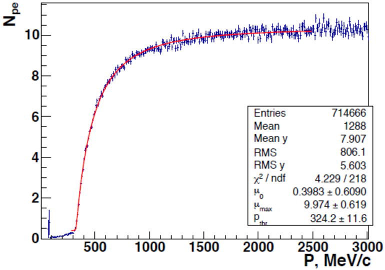
| Area counter indented | Geometric efficiency |
|---|---|
| 1) «Aerogel»–0 mm | 89.0±0.6% |
| 2) «Aerogel»–5 mm | 77.1±0.6% |
| 3) «Aerogel»–10 mm | 67.4±0.5% |
| 4) «All counter»–0 mm | 98.3±0.6% |
| 5) «All counter»–5 mm | 94.9±0.6% |
| 6) «All counter»–10 mm | 93.4±0.6% |

Two layers by «AND»

| Area counter indented | Geometric efficiency |
|---|---|
| 1) «Aerogel»–0 mm | 74.7±0.6% |
| 2) «Aerogel»–5 mm | 64.3±0.5% |
| 3) «Aerogel»–10 mm | 54.2±0.5% |
| 4) «All counter»–0 mm | 76.6±0.6% |
| 5) «All counter»–5 mm | 65.7±0.5% |
| 6) «All counter»–10 mm | 55.9±0.5% |

# Efficiency of charged particles detection

The amplitude dependence of barrel counters on momentum of cosmic muons which crossed two layers of aerogel in the KEDR ASHIPH system




$$\mu = \mu_0 + \mu_{max} \cdot \frac{p^2 - p_{thr}^2}{p^2}$$

$$\varepsilon = 1 - e^{-\mu}$$

The sources of under threshold signal:

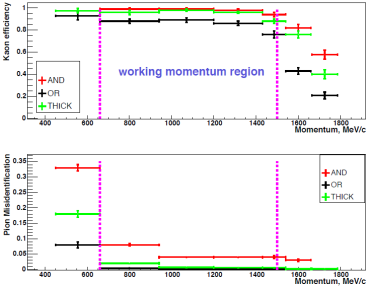
- Cherenkov light from $\delta$-electrons in aerogel;
- Scintillation in PTFE wrapping;
- Cherenkov light in PTFE wrapping.

- $P_{thr}(\mu)$=324±11 MeV/$c$ $\rightarrow$ n=1.051±0.004
- $N_{pe}$ from relativistic muons (P>1 GeV/$c$):
  - $1^{st}$ layer 4.9 ph.e.
  - $2^{st}$ layer 4.7 ph.e.
  - 2 layers 9.6 ph.e.
- Efficiency of relativistic particles detection at the threshold 0.5 ph.e. (P>1 GeV/$c$):
  - $1^{st}$ layer 1-(1.10±0.07)$\cdot 10^{-2}$
  - $2^{st}$ layer 1-(1.55±0.09)$\cdot 10^{-2}$
  - 2 layers 1-(2±1)$\cdot 10^{-4}$

# Investigation the efficiency

- To evaluate registration efficiency for kaons and pions with some momenta muons with corresponding momentum were chosen ($P_\mu = P_{K,\pi} * [m_\mu / m_{K,\pi}]$)
  - $950 < P_K < 1450\ MeV/c :\rightarrow 200 < P_\mu < 300\ MeV/c \rightarrow 0.885 < \beta < 0.944$
  - $950 < P_\pi < 1450\ MeV/c :\rightarrow 700 < P_\mu < 1100\ MeV/c \rightarrow 0.989 < \beta < 0.995$
- The several approaches of efficiency measurement of double layer system were studied:
  - AND $\rightarrow$ a relativistic particle gives a signal in both layers of the system
  - OR $\rightarrow$ a relativistic particle gives a signal at least in one layer of the system
  - THICK $\rightarrow$ sum of the amplitudes in both layers exceeds threshold

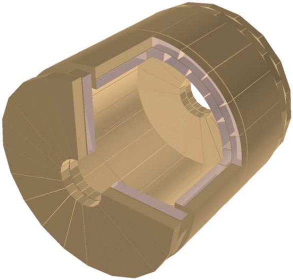
Two layer system efficiency (approach comparison)




$\pi/K$–separation better than 4 sigma in the momentum range from 0.95 to 1.45 GeV/c.

# Simulation of ASHIPH counters

KedrSim – KEDR detector simulation package based on GEANT 3.21.



Simulation includes:

1. Realistic geometry description of all 160 counters:
   - three active media – aerogel, shifter, teflon
   - electronics boxes and HV outputs.
2. For all counters a real aerogel refractive index was put and inhomogeneity of light collection was taken into account.
3. Digitized amplitudes are generated from calibrated single-photon spectra and pulse shapes.
4. Simulation produces the same event data as in the experiment.

# Simulation of ASHIPH counters

The signal from particle in counter:

$$\boxed{I = I_{\mathrm{ch\_aer}} + I_{\mathrm{ch\_sh}} + I_{\mathrm{ch\_tef}} + I_{\mathrm{sc\_aer}} + I_{\mathrm{sc\_sh}} + I_{\mathrm{sc\_tef}}.}$$

The magnitude of scintillation is proportional to the energy loss in matter:

$$I_{\mathrm{sc_i}} = \alpha_{\mathrm{i}} \Delta E_{\mathrm{i}},$$

where $\alpha_{\mathrm{i}}$ – coefficient of proportionality.

The number of Cherenkov photoelectrons from relativistic particles above threshold:

$$I_{\mathrm{ch_i}} = \frac{dN_{\mathrm{i}}}{dx_{\mathrm{i}}} = K_{\mathrm{i}} \cdot z^2 (1 - \frac{1}{(n_{\mathrm{i}}\beta)^2}),$$

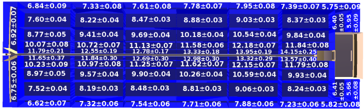
where $n_{\mathrm{i}}$ – refraction index, $K_{\mathrm{i}}$ – coefficient of proportionality taking into account inhomogeneity of light collection, $\beta = v/c$.

The coefficient of proportionality is determined from experimental data as:

$$\boxed{K_{\mathrm{i}} = \frac{\frac{N_{\mathrm{ph.e.}}}{L_{\mathrm{track}}}}{z^2 (1 - \frac{1}{(n_{\mathrm{i}}\beta)^2})},}$$

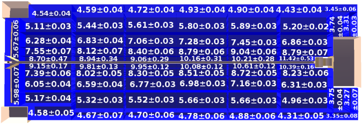
where $N_{\mathrm{ph.e.}}$ – number of photoelectrons, $L_{\mathrm{track}}$ – track length in counter.

### Long counter of the first layer



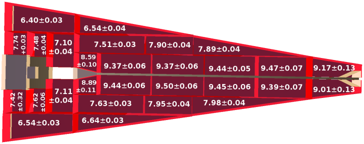

### Short counter of the first layer


### Long counter of the second layer.




### Short counter of the second layer.


### Endcap counter




| Type of counter | Inhomogeneity of light collection |
|---|---|
| Short counter of the first layer | ±26% |
| Short counter of the first layer | ±25% |
| Short counter of the second layer | ±32% |
| Long counter of the second layer | ±36% |
| Endcap counter | ±19% |

# Simulation of ASHIPH counters

The number of photoelectrons is described by the Poisson distribution:

$$P_n = \frac{\mu^n e^{-\mu}}{n!},$$

where n – number of photoelectrons, $\mu$ – average number of photoelectrons in the counter.

The amplitude distribution is a convolution of single-electron spectrum with a Poisson distribution with mean $\mu$:

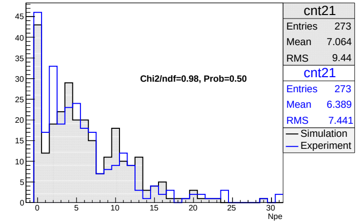
$$F(x) = \sum_{n=0}^{n=25} P_n f_n(x).$$

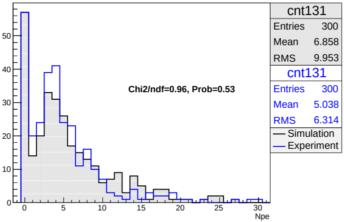
$$f_n(x) = \int f_1(y) f_{n-1}(x-y) dy,$$

here $f_1(x)$ - single-photoelectron spectrum.

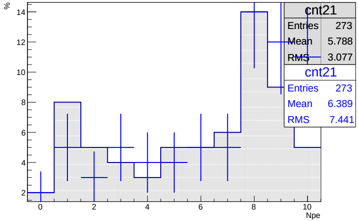
# Simulation vs experiment

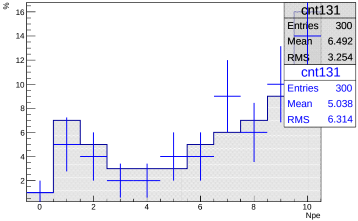
Amplitude spectra




Integral efficiency




$\varepsilon \approx 98\%$, at threshold 0.5 ph.e.

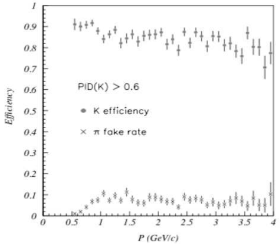
# Summary

- The ASHIPH technique of Cherenkov light collection was developed at BINP. It allowed us to decrease significantly the sum of all photocathodes area and production cost.
- Alignment of the ASHIPH counters was performed with an accuracy of 1 mm.
- The first results on the full system efficiency for particles of different momenta has been obtained.
  - Average number of photoelectrons for relativistic cosmic muons (>1GeV/c) that cross both counter layers 9.6±0.4
  - Detection efficiency for muons with $(700 < P_{\mu} < 1100\ MeV/c)$ is $(1-(7\pm1)\cdot10^{-3})$ for threshold on the amplitude sum equal to 2.0 photoelectron.
  - Detection efficiency for under-threshold muons $(200 < P_{\mu} < 300\ MeV/c)$ in the same approach is 0.03±0.01.
  - These data correspond to $\pi/K$–separation better than 4 sigma in the momentum range from 0.95 to 1.45 GeV/c.
- The geometric efficiency on $e^+e^- \to e^+e^-$ events measured. In case «OR» geometric efficiency is 96% and in case «AND» is 89%.
- Inhomogeneity of the ASHIPH counters was measured with cosmic muons. Inhomogeneity in barrel and endcap counters is ±30% and ±19% respectively.
- Simulation program of the ASHIPH counters has been being developed.

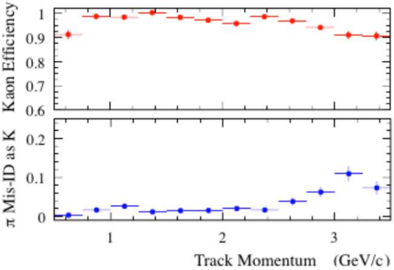
# BACKUP

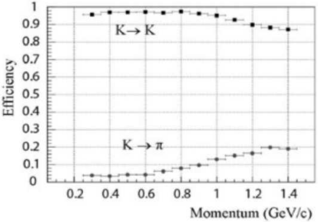
# Comparison different PID systems

Belle: ACC




BaBar:DIRC




BES-III:TOF

- BaBar:DIRC – at P=1.2GeV/c -- separation ~4σ [D0 → K+π− ]
- Belle:ACC – при P=1.2GeV/c – separation ~2.6σ [D*+ → D0(Kπ)π+]
- BESIII:TOF – at P<0.9GeV/c – separation ~3σ [calculation and simulation]
- KEDR: ASHIPH – at P=1.2GeV/c –separation ~4.3σ [cosmic muons]

# Some perspective to use in the KEDR experiment

- $\mathrm{Br}(\mathrm{J}/\Psi \to \mathrm{p}\overline{\mathrm{p}}, \mathrm{K}^+\mathrm{K}^-, \pi^+\pi^-, \gamma\mathrm{p}\overline{\mathrm{p}}, \gamma\mathrm{K}^+\mathrm{K}^-, \gamma\pi^+\pi^-)$
- $\mathrm{Br}(\Psi^{`} \to \mathrm{p}\overline{\mathrm{p}}, \mathrm{K}^+\mathrm{K}^-, \pi^+\pi^-, \gamma\mathrm{p}\overline{\mathrm{p}}, \gamma\mathrm{K}^+\mathrm{K}^-, \gamma\pi^+\pi^-)$
- $\Psi(3770)$ – D-meson mass measurement.