Novel sensors for Cherenkov counters

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Ring Imaging CHERenkov counters
Novel photon sensors: HAPD, MCP PMT, G-APD
Summary and outlook
Why particle ID?

Example 1: B factory

Particle identification reduces the fraction of wrong $K\pi$ combinations (combinatorial background) by ~6x

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Why particle ID?

Example 2: HERA-B

K⁺K⁻ invariant mass.

The inclusive $\phi \rightarrow K^+K^-$ decay only becomes visible after particle identification is taken into account.
Why particle ID?

Example 3: LHCb
(MC prediction)

Need to distinguish $B_d \rightarrow \pi\pi$ from other similar topology
2-body decays

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Particle identification at B factories (Belle and BaBar): was essential for the observation of CP violation in the B meson system.

\[ B^0 \rightarrow J/\psi K^0 \]

\[ \bar{B}^0 \]

\( B^0 \) and its anti-particle decay differently to the same final state \( J/\psi K^0 \)

Flavour of the B: from decay products of the other B: charge of the kaon, electron, muon

→particle ID is compulsory
Why particle ID?

PID is also needed in:

• Spectroscopy of charmonium and charmonium like states
• Spectroscopy of charmed hadrons
• Searches for exotic hadronic states
• Searches for exotic states of matter (quark-gluon plasma)
Example: Belle

- **μ and K_L detection system** (14/15 layers RPC+Fe)
- **Aerogel Cherenkov Counter** (n=1.015-1.030)
- **Silicon Vertex Detector** (4 layers DSSD)
- **Central Drift Chamber** (small cells, He/C_2H_6)
- **Electromag. Cal.** (CsI crystals, 16X_0)
- **ToF counter**
- **1.5T SC solenoid**

3.5 GeV e^+

8 GeV e^−

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Particle identification systems in Belle

- **Silicon Vertex Detector** (4 layers DSSD)
- **Aerogel Cherenkov Counter** (n=1.015-1.030)
- **3.5 GeV e^+**
- **Electromag. Cal.** (CsI crystals, 16X₀)
- **Central Drift Chamber** (small cells, He/ C₂H₆)
- **ToF counter**
- **μ and K_L detection system** (14/15 layers RPC+Fe)
- **8 GeV e^-**
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Identification of charged particles

Particles are identified by their mass or by the way they interact.

Determination of mass: from the relation between momentum and velocity, \( p=\gamma mv \). Momentum known (radius of curvature in magnetic field)

→ Measure velocity:
  - time of flight
  - ionisation losses \( dE/dx \)
  - Cherenkov photon angle (and/or rate)
  - transition radiation

Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons
Cherenkov radiation

A charged track with velocity $v = \beta c$ exceeding the speed of light $c/n$ in a medium with refractive index $n$ emits polarized light at a characteristic (Cherenkov) angle,

$$\cos \theta = \frac{c}{nv} = \frac{1}{\beta n}$$

Two cases:

1. $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.
2. $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy $E = h\nu$ in a radiator of length $L$:

$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2 \theta = 370 (cm)^{-1} (eV)^{-1} L \sin^2 \theta$$

$\rightarrow$ Few detected photons
Measuring Cherenkov angle

Idea: transform the direction into a coordinate → ring on the detection plane → Ring Imaging CHerenkov

Proximity focusing RICH

RICH with a focusing mirror
Measuring Cherenkov angle

ring radius on the detection plane
→ Cherenkov angle
Photon detection in RICH counters

RICH counter: measure photon impact point on the photon detector surface

→ detection of single photons with

- sufficient spatial resolution
- high efficiency and good signal-to-noise ratio
- over a large area (square meters)

Special requirements:

- Operation in magnetic field
- High rate capability
- Excellent timing (time-of-arrival information)
Belle upgrade $\rightarrow$ Belle-II

- SC solenoid 1.5T
- CsI(Tl) $16X_0$ $\rightarrow$ pure CsI (endcap)
- $\mu$ / $K_L$ detection 14/15 lyr. RPC+Fe $\rightarrow$ tile scintillator
- $\mu$ / $K_L$ detection 14/15 lyr. RPC+Fe $\rightarrow$ tile scintillator
- Aerogel Cherenkov counter + TOF counter $\rightarrow$ “TOP” or DIRC + Aerogel RICH
- Tracking + $dE/dx$ small cell + He/C$_2$H$_5$ $\rightarrow$ remove inner lyr. fast gas+Si r<20 cm
- Si vtx. det. 4 lyr. DSSD $\rightarrow$ 2 pixel/stripet lyr. + 4 lyr. DSSD
- New readout and computing systems
Present Belle: threshold Cherenkov counter
ACC (aerogel Cherenkov counter)

K (below threshold) vs. $\pi$ (above) by properly choosing $n$ for a given kinematic region (more energetic particles fly in the ‘forward region’)

Detector unit: a block of aerogel and two fine-mesh PMTs

Fine-mesh PMT: works in high B fields
Belle ACC: threshold Cherenkov counter

expected yield vs $p$

yield for $2\,\text{GeV} < p < 3.5\,\text{GeV}$: expected and measured number of hits

NIM A453 (2000) 321
Belle upgrade – side view

Two new particle ID devices, both RICHes:

Barrel: TOP or focusing DIRC

Endcap: proximity focusing RICH
K/π separation at 4 GeV/c:
\[ \theta_c(\pi) \sim 308 \text{ mrad (} n = 1.05) \]
\[ \theta_c(\pi) - \theta_c(K) \sim 23 \text{ mrad} \]

For single photons:
\[ \delta\theta_c(\text{meas.}) = \sigma_0 \sim 14 \text{ mrad}, \]
typical value for a 20mm thick radiator and 6mm PMT pad size

Per track:
\[ \sigma_{\text{track}} = \frac{\sigma_0}{\sqrt{N_{pe}}} \]

Separation: \[ [\theta_c(\pi) - \theta_c(K)]/\sigma_{\text{track}} \]

\[ \rightarrow 5\sigma \text{ separation with } N_{pe} \sim 10 \]
Beam tests

pion beam ($\pi^2$) at KEK

Photon detector: array of 16 H8500 PMTs

Clear rings, little background

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Beam test: Cherenkov angle resolution and number of photons

Beam test results with 2cm thick aerogel tiles:

$>4\sigma K/\pi$ separation

$\sigma_0 \sim 15\text{mrad}$

$N_{pe} \sim 6$

$\rightarrow$ Number of photons has to be increased.
Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: “focusing” configuration

normal

$\begin{align*}
n_1 &= n_2 \\
\end{align*}$

→ focusing radiator
Focusing configuration – data

4cm aerogel single index

2+2cm aerogel

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→ NIM A548 (2005) 383
Radiator with multiple refractive indices

Such a configuration is only possible with aerogel (a form of $\text{Si}_x\text{O}_y$) – material with a tunable refractive index between 1.01 and 1.13.
Photon detectors for the aerogel RICH requirements and candidates

Need: Operation in a high magnetic field (1.5 T)
Pad size ~5-6mm

One of the candidates: large active area HAPD of the proximity focusing type

Multialkali photocathode

-10kV
15~25mm

Pixel APD

Long development time

→ Finally enough working samples for a beam test at KEK last spring

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→ NIM A595 (2008) 180
Photon detector candidate: HAPD beam test

- test with 2 GeV/c electrons @ KEK
- detected number of photons: \( \sim 6 \)
- Cherenkov angle resolution: \( \sim 13 \text{mrad} \)
- large background due to the Cherenkov photons produced in the HAPD window
- second ring due to reflection on APD

Better than \( 4\sigma \pi/K \) separation @ 4 GeV/c

Open issues: long term stability and neutron irradiation damage – both under study

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Photon detector candidate: BURLE/Photonis MCP-PMT

BURLE 85011 microchannel plate (MCP) PMT: multi-anode PMT with two MCP steps

- good performance in beam and bench tests, NIMA567 (2006) 124
- very fast
- open issue: ageing
BURLE/Photonis MCP-PMT

BURLE 85011 microchannel plate (MCP) PMT: excellent time resolution after time walk correction

σ = 40ps

σ = 37ps

σ = 39ps

σ = 38ps

Tails can be significantly reduced by:

- increased cathode-MCP voltage difference
- decreased photocathode-MCP distance

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Geiger-APDs as photon detector?

Can we use SiPMs (Geiger mode APDs) as the photon detector in a RICH counter?

+ immune to magnetic field
+ high photon detection efficiency, single photon sensitivity
+ easy to handle (thin, can be mounted on a PCB)
+ potentially cheap (not yet...) silicon technology
+ no high voltage

- very high dark count rate (100kHz – 1MHz) with single photon pulse height
- radiation hardness
SiPMs as photon detectors?

SiPM is an array of individual APDs operating in Geiger mode; a resistor is used to quench the pulse. Characteristics:

- low operation voltage ~ 10-100 V
- gain ~ $10^6$
- peak PDE up to 65% (@400nm)
  
  \[
  \text{PDE} = \text{QE} \times \varepsilon_{\text{geiger}} \times \varepsilon_{\text{geo}}
  \]
- $\varepsilon_{\text{geo}}$ – dead space between the cells
- time resolution ~ 100 ps
- work in high magnetic field
- dark counts ~ few 100 kHz/mm²
- radiation damage (p,n)
Surface sensitivity for single photons

- 2d scan in the focal plane of the laser beam ($\sigma \approx 5 \, \mu m$)
- intensity: on average $<< 1$ photon
- Selection: single pixel pulse height, in a 10 ns window

5 $\mu m$ step size

Close-up: 1 $\mu m$ step size
Time resolution after time walk correction

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- $\sigma_{\text{red}} (\text{ps})$: 127, 182, 145, 212, 154
- $\sigma_{\text{blue}} (\text{ps})$: 97, 151, 136, 358, 135

$\sigma \approx 100-200 \text{ ps}$

$\sigma_{\text{red}} > \sigma_{\text{blue}}$
Can such a detector work?

Improve the signal to noise ratio:

- **Reduce the noise by a narrow (<10ns) time window**
- **Increase the number of signal hits per single sensor** by using light collectors and by adjusting the pad size to the ring thickness

E.g. light collector with reflective walls

or combine a lens and mirror walls
Expected number of photons for aerogel RICH with multianode PMTs or SiPMs(100U), and aerogel radiator: thickness 2.5 cm, $n = 1.045$ and transmission length (@400nm) 4 cm.

$N_{\text{SiPM}} / N_{\text{PMT}} \sim 5$

Assuming 100% detector active area

Never before tested in a RICH where we have to detect single photons. Dark counts have single photon pulse heights (rate 0.1-1 MHz)
Cosmic test setup

- 6 Hamamatsu SiPMs used:
  - 2x 100U; background ~400kHz
  - 2x 050U; background ~200kHz
  - 2x 025U; background ~100kHz
- signals amplified (ORTEC FTA820), discriminated (EG&G CF8000) and read by multihit TDC (CAEN V673A) with 1 ns / channel

scintillation counter

MWPC telescope

2.5cm aerogel, n=1.045

multianode PMTs array 2x6

SiPMs x6

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Cherenkov photons appear in the expected time windows → First Cherenkov photons observed with SiPMs!
SiPM Cherenkov angle distribution

scintillation counter

MWPC telescope

2.5cm aerogel n=1.045

multianode PMTs array 2x6

SiPMs x6

→ SiPMs give 4 x more photons than PMTs per photon detector area – in ~ agreement with expectations

N.B. Signal/noise should improve by x3 with better tracking!
Detector module design

SiPM array with light guides

A multi-channel module prepared for a beam test at CERN
Light guide geometry optimisation

Light Guide Acceptance / (d and out)

rays in = random isotropic 0-30°
N = 10^5

2.54mm

10°
d

0.3mm
(n=1.5)

SiPM (1x1mm)

out = 2.54mm - 2 * d * tan(10°)

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Light guide geometry optimisation

Light guide length optimisation

Light guide – SiPM gap

d=3.0mm  d=4.0mm  d=5.0mm

Gap (mm)
Detector module for beam tests at KEK

SiPMs: array of 8x8 SMD mount
Hamamatsu S10362-11-100P
with 0.3mm protective layer

Light guides

SiPMs

2cm

SiPMs + light guides

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Photon detector for the beam test

SiPMs: array of 8x8 SMD mount Hamamatsu S10362-11-100P with 0.3 mm protective layer

64 SiPMs

20mm
Fully assembled detector module
**MPPC module 2**

- pad size 5.08 mm, 4 mm² active
SiPM beam test: TDC distributions

- Total noise rate $\sim$35 MHz ($\sim$600 kHz/MPPC)
- Hits in the time window of 5ns around the peak are selected for the Cherenkov angle analysis

\[\text{without light guides}\]

\[\text{with light guides}\]
**Ring images**

- module was moved to 9 positions to cover the ring area
- these plots show only superposition of 8 positions (central position is not included)

**w/o light guides**

**w/ light guides**
SiPM beam test: Cherenkov angle distributions

without light guides
Cherenkov angle distributions

- background subtracted distributions
- ratio of detected photons w/ and w/o: ~ 2.3
- resolution within expectations (14.5 mrad)

Background-subtracted distributions
Number of photons

Expected number of photons is ~3/full ring, this includes:
- Hamamatsu PDE
- aerogel: 1cm thickness, n=1.03, 25mm attenuation length
- dead time and double hit loss ~10%

Measured (extrapolated to full ring - acceptance corrected):
- w/o LG ~ 1.6
- w/ LG ~ 3.7

Estimated numbers for aerogel with n=1.05 and thickness of 4cm (~5x) and better quality of light guides (surface polishing: ~2x) are
- w/o LG ~ 8
- w/ LG ~ 37
Can such a detector work?

Using all the tricks, the background occupancy will still be high.

Experience from HERA-B RICH: successfully operated in a high occupancy environment (up to 10%).

→ Need >20 photons per ring (had ~30) for a reliable PID.

HERA-B RICH event

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K identification efficiency at 1% π misid. probability for different number of photons per ring vs background level

→ Again OK if the number of photons >20
Summary of tests

We have proven that SiPMs can be used as single photon sensors in Ring Imaging Cherenkov (RICH) counters.

Light guides improved signal/noise.

The sensor is easy to operate, robust.

The number of photons is high enough to allow for sufficient kaon/pion separation even at high dark count rates.

Can we use it in Belle-II?

• Cost
• Radiation damage
Radiation damage

Becomes very hard to operate above the neutron fluence of $10^{11}$ n cm$^{-2}$

Expected fluence in at Belle-II at 50/ab: 2-20 $10^{11}$ n cm$^{-2}$

→ Worst than the lowest line

→ Very hard to use the presently available SiPMs as single photon detectors for the whole lifetime of a Super B factories because of radiation damage by neutrons

→ Also: could only be used with a sophisticated electronics – wave-form sampling
Read out: Buffered LABRADOR (BLAB1) ASIC

Gary Varner, Larry Ruckman (Hawaii)

Successfully flew on ANITA in Dec 06/Jan 07 (<= 50ps timing)

Being used in the focusing DIRC tests at SLAC

3mm x 2.8mm, TSMC 0.25um

- 64k samples deep
- Multi-MSa/s to Multi-GSa/s

Typical single p.e. signal [Burle]

Overshoot/ringing

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Summary

Particle identification is an essential part of several experiments, and has contributed substantially to our present understanding of elementary particles and their interactions. Techniques based on Cherenkov radiation have become indispensable for PID.

Novel photo-detectors are being developed for operation in high magnetic fields. They will play an essential role in the next generation of B physics experiments at Super B factories, as well as at hadron structure experiments.

Geiger mode APDs (SiPMs) have been demonstrated to work well as single photon detectors in spite of the high dark count rates.

Radiation damage of the available devices is at present limiting their use in Super B factories.

A very interesting application of SiPMs as scintillation light sensors for PET imaging is opening a new field of research.
Beta+ emitters (e.g. radioactive fluor) produce two collinear gamma rays. These gamma rays are detected by a combination of a scintillation crystal and a photo-sensor. From the lines given by the hit pairs, the source distribution is reconstructed.
Traditionally, PMTs are used as light sensors for PET scanners.

SiPMs: much smaller, no high voltage needed, works in high magnetic fields (several T).
The use SiPMs could allow for a dual modality imaging – at the same time perform magnetic resonance (MRI) and PET imaging – an important improvement for a faster and better diagnostics!
PET with SiPMs: tests

Test PET modules with:

4x4 arrays of LYSO crystals (4.5 x 4.5 x 20(30) mm³)
16 SiPMs (Photonique 2.1x2.1 mm²)
16 SiPMs (Hamamatsu 3x3 mm²)

Also interesting: SiPMs have a fast response (~100ps rms) → important for TOF-PET
Photon detectors for the aerogel RICH

Needs:

- Operation in high magnetic field (1.5T)
- High efficiency at $\lambda>350\text{nm}$
- Pad size $\sim 5$-6mm

Candidates:

- Large area H(A)PD of the proximity focusing type
- MCP PMT (Burle 85011)
- SiPMs
Tails can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference

- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution
MCP PMT: Gain in magnetic field

Gain as a function of magnetic field for different operation voltages and as a function of applied voltage for different magnetic fields.

More talks on MCP PMTs during this workshop – W. Plass and A. Lehmann
MCP PMT: sensitivity

Number of detected hits on individual channels as a function of light spot position.

B = 0 T,
HV = 2400 V

B = 1.5 T,
HV = 2500 V

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.
Tests in magnetic field: charge sharing 2

Number of detected hits on all channels as a function of light spot position.

- HV = 2400 V
- B = 0 T

- HV = 2500 V
- B = 1.5 T
TOF capability of a RICH

With a fast photon detector (MCP PMT), a proximity focusing RICH counter can be used also as a time-of-flight counter.

Time difference between $\pi$ and $K$ →

For time of flight: use Cherenkov photons emitted in the PMT window.
TOF capability: window photons

Expected number of detected Cherenkov photons emitted in the PMT window (2mm) is \( \sim 15 \)

→ Expected resolution \( \sim 35 \) ps

TOF test with pions and protons at 2 GeV/c.
Distance between start counter and MCP-PMT is 65cm

→ In the real detector \( \sim 2m \)
→ 3x better separation
Time-of-flight with photons from the PMT window

Benefits: Čerenkov threshold in glass (or quartz) is much lower than in aerogel.

Aerogel: kaons (protons) have no signal below 1.6 GeV (3.1 GeV): identification in the veto mode.

Threshold in the window: $\pi$  $K$  $p$

Window: threshold for kaons (protons) is at $\sim0.5$ GeV ($\sim0.9$ GeV): → positive identification possible.
Timing with a signal from the second MCP stage

If a charged particle passes the PMT window, ~10 Cherenkov photons are detected in the MCP PMT; they are distributed over several anode channels.

Idea: read timing for the whole device from a single channel (second MCP stage), while 64 anode channels are used for position measurement.

MCP second stage output

Timing resolution as a function of light intensity
BURLE MCP-PMT mounted together with an array of 12 (6x2) Hamamatsu R5900-M16 PMTs at 30mm pitch (reference counter)
Photon detector candidate: MCP-PMT

BURLE 85011 MCP-PMT:
- multi-anode PMT with two MCP steps
- 25 μm pores
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- 64(8x8) anode pads
- pitch ~ 6.45mm, gap ~ 0.5mm
- active area fraction ~ 52%

- Tested in combination with multi-anode PMTs
  - σ₉ ~ 13 mrad (single cluster)
  - number of clusters per track N ~ 4.5
  - σ₉ ~ 6 mrad (per track)
  - → ~ 4 σ π/K separation at 4 GeV/c

- 10 μm pores required for 1.5T
- collection eff. and active area fraction should be improved
- aging study should be carried out
Cherenkov angle resolution

- charge sharing at the edges of the pads and backscattering affects the resolution
- in magnetic field this effects will be minimized and resolution will improve

$\sigma_\theta : 17.6 \text{ mrad} \rightarrow <15 \text{ mrad}$
Can such a detector work?

MC simulation of the counter response: assume 1mm$^2$ active area SiPMs with 0.8 MHz (1.6 MHz, 3.2 MHz) dark count rate, 10ns time window

$K$ identification efficiency at 1% $\pi$ missid. probability

For different background levels

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SiPM Photon Detection Efficiency (PDE)

Photons with short wavelengths will be absorbed in the very first layer of Si and create there an electron-hole pair.

In a structure with a n-type substrate (right) the electrons drift towards the high field of the p-n junction and trigger with high probability a breakdown. A G-APD made on a n-type substrate will be preferential sensitive for blue light.

A G-APD made on a p-type substrate (left) needs long wavelengths for the creation of electrons in the p-layer behind the junction and will have the peak sensitivity in the green/red.

D. Renker, RICH Workshop, Giessen, May 2009
Surface sensitivity for single photons

- 2d scan in the focal plane of the laser beam ($\sigma \approx 5 \, \mu m$)
- intensity: on average $<< 1$ photon
- Selection: single pixel pulse height, in TDC 10 ns window

5 $\mu m$ step size

S137

Close up: 1 $\mu m$ step size
Surface sensitivity for single photons

E407
Surface sensitivity for single photons 3

H050C

H025C
**MPPC module**

- main board with dividers, bias and signal connectors
- piggy back board with MPPCs (8x8 array of HC100 in SMD package; background ~ 400kHz/MPPC)
- light guides
- 16 electronics channels (4x4) - 4 MPPCs connected to single channel
Multilayer extensions

Cherenkov angle resolution per track: around 4.3 mrad
→ π/K separation at 4 GeV: >5σ

Several optimisation studies:
Križan et al NIMA 565 (2006) 457
Barnyakov et al NIMA 553 (2005) 70
Aerogel production

Two production centers: Boreskov Institute of Catalysis, Novisibirsk, and KEK+Matsushita

Considerable improvement in aerogel production methods:
- Better transmission (>4cm for hydrophobic and ~8cm for hydrophylic)
- Larger tiles (LHCb: 20cmx20cmx5cm)
- Tiles with multiple refractive index

n1=1.046
n2=1.041
n3=1.037

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