Summary of Beaune 2005

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Outline

Focus on big picture:
- New trend on scientific applications
- Demands, specs on detectors
- Major new technology
- Fair comparison of detectors

My apologies for not including:
- UV, X and direct Gamma detection
- Readout electronics, systems
- Friday’s talks
Why are we here?

F. Rocard
Are we alone?

F. Rocard
Science of 21st Century

Why are we here?

- Origin of Ourselves
- Origin of Life
- Origin of the Solar System
- ...
- Origin of the Universe

What is the most fundamental law in nature?

We rely on weak, fast photon signals.
Scientifics
Applications

- High Energy
- Particle Astrophysics
- Bio and Medical Imaging
High Energy

- LHC
- B-Factory etc.
- ILC
Large Hadron Collider (LHC)

Expected to start in 2008.
CMS Detector under 4 Tesla

Select:
- Muon
- Electron
- Neutral Hadron
- Charged Hadron
- Photon

Electron Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers

4 Tesla
Today’s APD is a result of about 10 years R&D with (EG&G and) Hamamatsu Photonics KK.

Delivery from Hamamatsu started last year: ~37 000 APD`s delivered so far.
CMS HCAL Multi pixel HPD (DEP) (Beaune 2002)

Photocathode (-10 kV)  Fiber-Optic Window

Ceramic feedthrough  PIN Diode array

3.4 mm

19 channel pixel layout

pixel size: 5.4 mm flat-flat
gap between pixels: 0.04 mm
LHCb experiment
Advantages of this hybrid, pixel structure:

- low noise: excellent resolution of single photoelectrons
- high channel number/density
Belle Spectrometer - PID

Particle identification:
- TOF
- dE/dx
- ACC: threshold aerogel Cherenkov counter

Large solid angle detector at the KEKB e^+ e^- collider
Dedicated to nucleon structure and spectroscopy studies
On CERN-SPS 160 GeV $\mu$ and $h$ beam (Prévessin site)
Need to identify hadron particles ($\pi$, $K$, $p$)
International Linear Collider

- Electron/Positron collider.
- Expandable, energies 0.5TeV to 1.5TeV.
- 10X larger than the Stanford Linear Accelerator.
- Two detectors.
ILC Detector Concepts

5Tesla

“SiD”

“LDC”

“GLD”

Main Tracker
EM Calorimeter
Had Calorimeter
Cryostat / Solenoid
Iron Yoke / Muon System

SiD: Silicon Detector
- Small, ‘all’ silicon
- TPC based

LDC: Large Detector Concept

GLD: Global Large Detector

SiD: B R²
LDC: B R²
GLD: B R²
Particle Astrophysics

(Eckart Lorenz)
Multi-Messenger Exploration of Energy Frontiers

- **Energy Frontier of Particle Physics, Cosmology and Astronomy**
  - Earliest Universe: Inflation, Planck Scale ...
  - Extreme Universe: AGN, GRB, SN ...

- **Need for Multi-Messenger Approach**
  - Gamma ray: Hess, MAGIC, GLAST ...
  - Charged Particle: Auger, EUSO ...
  - Neutrino: Super-K, Icecube...
  - Gravitational Wave: LIGO, VIRGO, LISA ...
  - Anti-Matter: AMS, BESS...
  - Dark-Matter: CDMS, Edelweiss ...
Super-Kamiokande

• 11,200 of 20” PMTs
Hyper Kamiokande, UNO

Photocathode coverage
~40% of surface

~200,000 PMTs => prohibitive cost
(~10,000 PMTs for SK)
ICECUBE

Ice Top

Snow Layer

IceCube

Photomultiplier

60 PMTs/string x 80 strings
= 4,800 PMTs
AMS - Anti-Matter Search

0.3 TeV

<table>
<thead>
<tr>
<th></th>
<th>$e^-$</th>
<th>$e^+$</th>
<th>P</th>
<th>$\bar{\text{He}}$</th>
<th>$\gamma$</th>
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<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
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<td>Calorimeter</td>
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<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
</tbody>
</table>
EUSO on International Space Station

A. Petrolini
EUSO Detector

- 2.5m Diameter
- 60° FOV
- f/1.25

Electronic system

Focal surface detector

Hamamatsu R7600-M36 250k Pixel

Optics system

Support structure
Detection of Cosmic Radiation

- Larger Volume
- Lower Threshold

- CDMS
- Super-K
- AMANDA
- Pierre-Auger
- Hyper-K
- ICECUBE
- OWL
- EUSO
- Cosmic Ray
- Zeplin
- Dark Matter
- Neutrino
- Super-K
- CDMS
Photon Detector

More Pixels
Better Sensitivity

No. of Pixels

Pixel Size (mm)

Photon Detector devices shown:
- LSST
- SDSS
- CCD
- PMT
- EUSO
- OWL
- γ Wide FOV
- Hyper-K
- Super-K
- Auger-FD
- AMS
- VERITAS
- Auger-SD
Bio/Medical Imaging

- SPECT & PET
- Molecular Imaging
γ-Camera Today

Workhorse of nuclear medicine

Improvements:
- Large imaging area (up to 91 PMTs)
- Square & rectangular imaging FOV
- Variety of configurations for specific needs
- Digital signal processing \(\rightarrow\) improved \(\Delta E\) & \(\Delta x\)
- Multiple heads
- Rotating gantry for tomography (SPECT)

Bone scan
- 512 x 512 HRLE Collimator
- (190 cpm/µCi)

Cardiac SPECT imaging
- \(^{99m}\)Tc Sestamibi
- 64 x 64 matrix
- 48 45-sec steps
- Gated 8 frames/R-R
- HRGP Collimator
- (250 cpm/µCi)

http://www.is2research.com/

R. Lecomte
Anger Camera

N. Inexpensive

N. Isotropic spatial resolution
   \rightarrow \sim 5 \text{ mm FWHM}

N. High energy resolution
   \rightarrow \text{ Efficient scatter rejection}

N. Poor stopping power

N. Limited count rate / high dead time

\Rightarrow \text{ Excellent spatial resolution possible by reducing crystal thickness at the expense of sensitivity (Green et al)}

\Rightarrow \text{ Count rate performance can be improved by:}
   - Local triggering
   - Slotted surface / Detector granularity
   - Faster scintillator


Large continuous NaI(Tl) bars

C-PET Module


\text{R. Lecomte}
## Crystals

<table>
<thead>
<tr>
<th>Crystals</th>
<th>Density (g/cm³)</th>
<th>Light yield (ph/MeV)</th>
<th>Decay time (ns)</th>
<th>Maximum Emission length (nm)</th>
<th>ΔE/E (FWHM) PMT read-out</th>
<th>PMT read-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI:Ti</td>
<td>3.67</td>
<td>41000</td>
<td>230</td>
<td>410</td>
<td>5.6 %</td>
<td>662 keV **</td>
</tr>
<tr>
<td>CsI:Na</td>
<td>4.51</td>
<td>40000</td>
<td>630</td>
<td>420</td>
<td>7.4 %</td>
<td>140 keV</td>
</tr>
<tr>
<td>CsI:Tl</td>
<td>4.51</td>
<td>66000</td>
<td>800+6×10³</td>
<td>550</td>
<td>6.6 (PMT)/4.3 (SDD)</td>
<td>14 %</td>
</tr>
<tr>
<td>LaCl₃ :Ce</td>
<td>3.79</td>
<td>49000</td>
<td>28</td>
<td>350</td>
<td>3.8 %</td>
<td>6.6 (PMT)/4.3 (SDD)</td>
</tr>
<tr>
<td>LaBr₃ :Ce</td>
<td>5.3</td>
<td>63000</td>
<td>26</td>
<td>380</td>
<td>2.8 %</td>
<td>14 %</td>
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<tr>
<td>Bi₄Ge₃O₁₂ (BGO)</td>
<td>7.1</td>
<td>9000</td>
<td>300</td>
<td>480</td>
<td>9.0 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Lu₂SiO₅:Ce (LSO)</td>
<td>7.4</td>
<td>26000</td>
<td>40</td>
<td>420</td>
<td>7.9 %</td>
<td>18 %</td>
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<tr>
<td>Gd₂SiO₅:Ce (GSO)</td>
<td>6.7</td>
<td>8000</td>
<td>60</td>
<td>440</td>
<td>7.8 %</td>
<td>22 %</td>
</tr>
<tr>
<td>YAI O₃:Ce (YAP)</td>
<td>5.5</td>
<td>21000</td>
<td>30</td>
<td>350</td>
<td>4.3 % (APD)</td>
<td>20 %</td>
</tr>
</tbody>
</table>


* Expected values
Individual Coupling & Independent Processing

Munich APD PET (MADPET II)

4 × 8 APD Array (Hamamatsu Photonics)

2 × 2 × 6 mm³ LSO individually coupled

b ~ 0 mm → Intrinsic FWHM ~ 1.2 mm

Pichler et al, IEEE MIC 2000

R. Lecomte

√ Good packing fraction
• Poor light collection

PTFE

LSO

3M foil
Dual APD Readout

PS-APD Module

1.65 × 1.65 × 22 mm³ MLS crystals
8 × 8 array on dual 14 × 14 mm² PS-APDs
~ 3 mm FWHM DOI resolution

Burr et al, IEEE NSS/MIC 2003

R. Lecomte
Intrinsic Spatial Resolution of PET Scanners

Crystal Size (mm)

FWHM Resolution (mm)

SHR-2000 (Hamamatsu)
A-PET (Philips)
TierPET (Julich)
ATLAS (NIH)
microPET (UCLA)
YAPPET (Ferrara)
GeV eXplore (Suinsa)
HIDAC
microPET II
Focus
ClearPET
LabPET

Hammersmith
Exact HR (CTI)
BaF$_2$/TMAE (VUB)
Donner 600 (Berkeley)
APD-BGO (Sherbrooke)
MADPET (Munich)

Light Sharing (b~2.1 mm)
Electronic Coding (b~1.1 mm)
Individual Coupling (b~0 mm)
Crystal Resolution (d/2)

R. Lecomte
Nutts’ Law

The Number of Detector Elements Per PET Tomograph Double Every 24 Months

Number of Detector Elements

Year

Nutt’s Law

PET III  ECAT II  ECAT III  931  951  EXACT  HR++  HRRT

The H33D capabilities will allow protein-protein interaction, protein trafficking at the single-molecule level to be followed with nanometer resolution and arbitrary time-resolution.
Emission of Quantum Dot

![Diagram of Quantum Dot with chemical bonds and wavelengths](image)

**Chemical Compositions:**
- CdSe
- InP
- InAs

- Wavelengths:
  - CdSe: 4.6 nm
  - InP: 2.1 nm
  - InAs: 

**Normalized Fluorescence vs. Wavelength (nm):**
- Wavelengths range from 460 nm to 471 nm.
Schematic of the H33D detector

Sample excitation (Laser)

Sample emission (dye, quantum dot)

Photocathode

MCP 1
MCP n

XDL or XS Anode

e^-

hν
e^-

e^+ cloud

X + Y + T = 3D

~ ns

~ ps

X

Y

High spatial resolution: 100 um
High temporal res.: 100 ps
High throughput: 50 MHz

= H^3

H33D = Heed = Attention, Notice

24 June 2005

X. Michalet
General Requirements

- **Various Sizes**
  - Large Area > 30 cm
    - Neutrino, Proton decay…
  - Coarse Pixel 1-5 mm
    - RICH, Tile Calorimeter, EUSO, PET…
  - Imaging < 100 µm
    - Astronomy, Single Molecule…

- **High Speed**
  - TTS < 1 nsec
  - Rate > 1 MHz

- **Single Photon Counting**

- **(Insensitive to Magnetic Field)**

- **Los Cost !**
New Developments on Detectors

- Gaseous
- PMT
- Hybrid
- Solid State
Gaseous Detector

(Amos Breskin)
CERN-ALICE CsI-RICH

RICH: Ring Imaging Cherenkov UV-detectors for particle identification

1 element: 400 x 600 mm$^2$

~2m$^2$

- Single arm detector, radial distance of 4.9 m
- $|\eta| < 0.9$, 5% of barrel acceptance
- Proximity focusing (80 mm gap), 15 mm $C_6F_{14}$ radiator, 7 modules each with 6 CsI PC
- Total active area $\sim 12$ m$^2$
- FEE: Gassiplex 0.7 $\mu$, noise 1000 e$^-$

ALICE-RICH: 12m$^2$

CsI-RICH: ALICE, HADES, COMPASS, J-LAB....
8 chambers with 2 photocathodes each, methane gas

photocathode: 72x72 pads of 8x8 mm²
γ detection range 160-200 nm
gas gain ~ 3.10⁴ at 2000V
Gated GPM for visible light

GAIN: 100-1000 in DC mode (ion feedback limit)

~$10^6$ in ion-gating mode

A breakthrough!

A. Breskin et al. Physics/0502132
Ion Back-flow Reduction: Reversed-MHSP

MHSP: 2-step gain & some ion blocking

R-MHSP: hole-gain & ion defocusing from successive multiplier*

* R-MHSP: Roth, Vienna 04

Ion blocking:
Breskin et al. physics/0502132
Veloso et al. physics/0503237

Simulations: Oleg Bouianov
A Very Flat Gaseous Imaging PM

- THGEM
- ~10mm
- 100x100mm² THGEM
- With 2D delay-line readout
- φ 0.3mm holes
- 20x525 photocathode
Photomultiplier

- High QE Alkali
- Multi Pixel, Flat PMT
Hamamatsu High QE Photocathode

New Process

Standard

Bialkali Photocathode

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>new process BEST</td>
<td>37 %</td>
</tr>
<tr>
<td>new process TYPICAL</td>
<td>34 %</td>
</tr>
<tr>
<td>standard typical</td>
<td>27.5 %</td>
</tr>
</tbody>
</table>

(at 360 nm)

24 June 2005

Hamamatsu / Y Yoshizaawa
Improved QE of Photonis 9 inch PMT

- **Quantum efficiency (400 nm)**
  - Standard: ~26%
  - Improved: ~32% \(+19\%\)

- **Quantum efficiency (600 nm)**
  - Standard: ~1.6%
  - Improved: ~6.3% \(+75\%\)

- Extension of the spectral sensitivity in the red region

\[
QE(\%) = 124 \frac{S_{k,\lambda}(\mu A/W)}{\lambda(nm)}
\]
Hamamatsu Flat Panel PMT

H8500 (2 inch square)

Pixel Size: 6 x 6 mm

3 x 3 array

500 tubes were delivered since 2002 for Medical, Radiation monitor and HEP.
BURLE 85011 MCP-PMT:

- multi-anode PMT with 2 MCPs
- 25 mm pores
- bialkali photocathode
- gain ~ $0.6 \times 10^6$
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- 64(8x8) anode pads
- pitch ~ 6.45mm, gap ~ 0.5mm
- active area fraction ~ 52%
Hybrid Detector

- GaAsP HAPD
- Multi Pixel
- Large Area
HPD with 18-mm GaAsP Photocathode by Hamamatsu

Designed for MAGIC-II camera

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td>Photocathode</td>
<td>GaAsP (for high QE)</td>
</tr>
<tr>
<td>Cathode Size</td>
<td>18 mm [old &lt; 8 mm]</td>
</tr>
<tr>
<td>Avalanche Diode</td>
<td>3 mm Silicon</td>
</tr>
<tr>
<td>Sensor shape</td>
<td>hexagonal 28 mm</td>
</tr>
<tr>
<td></td>
<td>39 mm height</td>
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</tbody>
</table>
QE of GaAsP + WLS

- HPD with WLS
- HPD without WLS
- PMT with lacquer (MAGIC-I)

QE enhancement with WLS

QE [%] vs Wavelength [nm]

QE ratio [a.u.] vs Wavelength [nm]
Hybrid Photon Detectors (HPD)

Gain:

\[ G \approx \frac{e \cdot U_c}{3.6 \text{ eV}} \]

Gain is achieved in a single dissipative step!

\[ U_c = 20 \text{ kV} \rightarrow G \sim 5000 \]
DEP Hybrid Photodiode (HPD)
(Beaune 2002)

• Baseline design for LHC-b RICH
• 8cm diameter
• 61 Pixel, (5mm view)
### HPD pre-series (9 tubes): performance results

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Results</th>
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<tbody>
<tr>
<td>Pixel response</td>
<td>&gt;95%</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Min. threshold Noise</td>
<td>&lt;2000e-</td>
<td>Typ. 1200e-</td>
</tr>
<tr>
<td></td>
<td>&lt;250e-</td>
<td>Typ. 160e-</td>
</tr>
<tr>
<td>Leakage current</td>
<td>Typ. 1uA @ 80V bias</td>
<td>&lt; 1uA</td>
</tr>
<tr>
<td>Dark count rate</td>
<td>Max. 5kHz/cm²</td>
<td>0.03–3kHz/cm²</td>
</tr>
<tr>
<td>Ion feedback rate</td>
<td>Max. 10-2 rel. to signal</td>
<td>&lt;10-3</td>
</tr>
<tr>
<td>P.e. detection efficiency</td>
<td>Typ. 85%</td>
<td>79-89%</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>See next picture</td>
<td>Generally well above specs</td>
</tr>
</tbody>
</table>
Multi-pixel HAPD (8x8 matrix)

8x8 Matrix (64 Pixels)
2x2 mm / Pixel

FOP with Multialkali

R9503U-04-M064

Effective Area

APD Format

43mm in diameter

15 mm

16mm

16mm
RMD Position Sensitive HAPD

- Proximity design
- 14 x 14 mm² PSAPD
- High gain $10^6$ to $10^7$
- 320 µm with ~5 photons/pulse

8 x 8 CsI:Tl, 1 mm pixel
CsI:Tl imaged at 23 °C with $^{241}$Am (60 keV).

# 13inch HAPD by Hamamatsu

<table>
<thead>
<tr>
<th></th>
<th>13inch</th>
<th>5inch</th>
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<tbody>
<tr>
<td>Diameter</td>
<td>332mm</td>
<td>128mm</td>
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<tr>
<td>Effective area</td>
<td>240mmφ</td>
<td>-</td>
</tr>
<tr>
<td>APD size</td>
<td>5mmφ</td>
<td>3mmφ</td>
</tr>
<tr>
<td>APD type</td>
<td>Low capacitance (~70pF)</td>
<td>Low capacitance (~30pF)</td>
</tr>
<tr>
<td>Bias max</td>
<td>370V</td>
<td>350V</td>
</tr>
<tr>
<td>HV max</td>
<td>+12kV</td>
<td>-8.5kV</td>
</tr>
</tbody>
</table>
HPD developed and built at CERN

5-inch → 10-inch

127 mm Ø, D ~ 2.5, 2048 channels 1mm² bialkali photocathode
NIM A 442 (2000) 128-135
NIM A 478 (2002) 400-403
www.cern.ch/ssd/HPD

254 mm Ø, D ~ 4, 2048 channels 1mm² bialkali photocathode
NIM A 504 (2003) 19
NIM A 518 (2004) 574-578
C2GT Optical Module (38cmφ)

Al coating
2 rings
Development of Other Vacuum Devices

~1960

Production Cost: < $1,000 per m²

~2000

D. Ferenc
Scintillators + fiber optics

NO electronics in the vacuum

Resolution determined outside !!

READOUT ➔ APD array
Solid State Detector

- APD
- SiPM
Planar Process for APD Fabrication

Standard Wafer

Deep Diffusion into Si wafer, p-n-p

Si Removal

Bevel Formed

Grooved Wafer

HV

Wafer Diced

HV

Position Sensitive and Discrete APDs

Figure 15. Photographs of an octagonal 45 cm$^2$ (left) and a square 40 cm$^2$ (right) planar APDs fabricated at RMD.

8 x 8 mm$^2$ PSAPD

45 cm$^2$ Planar APD
Fabrication for Position Sensitivity

28 x 28 mm² PSAPD coupled to 7 x 7 LSO array with 3 mm pixels at –20 °C. Average energy resolution = 15.5% at 511 keV.

8 x 8 mm² PSAPD coupled to 6 x 6 LSO array with 1 mm pixels at 23 °C. Average energy resolution = 16% at 511 keV.
Silicon Photomultiplier
(from Beaune 2002)

Gain ~ $10^6$
ENF = 1.0
DQE ~ 10%
At present many people consider that the new APDs with inner microstructures are very easy devices. To my mind, the way to micro-pixel APDs was not easy. This development took about 20 years.


- CCD and MW type APDs. 2002- present
Various SiPM

<table>
<thead>
<tr>
<th>MPGM name</th>
<th>Area (mm²)</th>
<th>Number of pixels</th>
<th>Geometric factor [%]</th>
<th>Si substrate type</th>
<th>MPGM source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSPM (or MRS APD)</td>
<td>1</td>
<td>576</td>
<td>70</td>
<td>p</td>
<td>&quot;Photonique SA&quot; and V. Golovin (CPTA, Moscow)</td>
</tr>
<tr>
<td>SIPM</td>
<td>1</td>
<td>556</td>
<td>25</td>
<td>p</td>
<td>B. Dolgoshein and &quot;PULSAR&quot; (Moscow)</td>
</tr>
<tr>
<td>R8-type AMPD</td>
<td>0.5</td>
<td>10 000</td>
<td>?</td>
<td>n</td>
<td>Z. Sadygov (JINR, Dubna)</td>
</tr>
</tbody>
</table>

The table above lists various types of SiPMs along with their characteristics such as area, number of pixels, geometric factor, and substrate type, along with the sources of these MPGMs.
SiPM Layout

- General view 1x1 mm,
- Common Electrode Layout,
- Microcells with Quenching Mechanism,

CPTA SiPM

Pulsar SiPM

(LCWS2004, M. Danilov ITEP, Moscow)
PE Distribution of Various SiPM
SiPM Performance

Detection Efficiency – Wavelength Dependent:

- QE of Hamamatsu Photonic APD
- Efficiency of Si-PM

UV region of SiPM
- is limited by dead layers on the top of structure

IR region of SiPM
- is limited by the thickness of sensitive layer of SiPM

Absolute value scaling
- is limited by geometry factor

The Si-PM has green light sensitivity
- and total Detection Efficiency for green range of light is ~25%

24 June 2005
V. Saveliev
QE of Various SiPM

Dubna APD (U=101.5 V, T=2 C)

MEPhI/PULSAR APD, T=22C, U=59 V

CPTA APD, U=40.6 V, T=22 C

Reference PMT  XP2020

Wavelength [nm]

PDE [%]

Wavelength [nm]

PDE [%]
Optical Cross Talk of 1mm$^2$ SiPM

![Graph showing Optical Cross Talk vs Gain for different sizes of SiPMs (32 µm, 64 µm, 96 µm, 128 µm).]
Dark Rate of 1mm$^2$ SiPM

1 MHz / mm$^2$

Overvoltage $\Delta U$, V

Gain, $10^6$

- $T=+20,7^0\,C$ ($U_{bd}=60,27$)
- $T=+9,9^0\,C$ ($U_{bd}=59,81$)
- $T=-6,4^0\,C$ ($U_{bd}=58,82$)
- $T=-21,6^0\,C$ ($U_{bd}=58,02$)
- $T=-36,5^0\,C$ ($U_{bd}=57,15$)
- $T=-50^0\,C$ ($U_{bd}=56,23$)
Future of SiPM

- Combination of the Sensors and FE Electronics in the same technology Process.

Larger area (up to 10x10 mm$^2$) is required for a number of applications:

- astroparticle physics
- PET
- Particle physics
- . . .
SiPMs in ILC Tile HCAL Prototype

SiPMs
1156 pixels
1x1 mm²

Precise ceramic plate
5±0.03

Tile with milled groove for WLS and precise hole for SiPM installation

The first HCAL prototype cassette

40 Cassettes will be required
Production for ALICE CRF

Akindinov et al., High-efficiency and low noise scintillation detector for ionizing particles START (Scintillation Tile with MRS APD Light Readout)
Space experiment “LAZIO” (MEPHI-INFN Collaboration)

Scientific goal: The measurement of low energy particle fluxes and radiation monitoring by apparatus, including scint tile+WLS fiber+SiPM hodoscope system

Latitude particle flux dependence
Final Comparisons

- QE
- TTS
- Energy Resolution
- Cost
Time Resolution vs. Sensitive Area
(Beaune 1999 → 2005)

- Photo Diode
- Metal Channel
- Fine mesh
- MCP PMT
- Conventional PMT
- HPD
- SiPM
- Streak Tube
Effect of Magnetic Fields
(Beaune 1999 → 2005)

Magnetic Field (Gauss)

Relative Gain

Linear Focus
Metal Channel
Fine Mesh
MCP PMT
Solid State
HPD
APD
SiPM
CMS
Equivalent Noise Charge (ENC) after CRRC^n

- **A useful formula**: ENC (e- rms) after a CRRC$^2$ shaper:

\[
\text{ENC} = 174 \, e_n C_{\text{tot}} / \sqrt{t_p (\delta)} + 166 \, i_n \sqrt{t_p (\delta)}
\]

- $e_n$ in nV/√Hz, $i_n$ in pA/√Hz are the preamp noise spectral densities
- $C_{\text{tot}}$ (in pF) is dominated by the detector ($C_d$) + input preamp capacitance ($C_{PA}$)
- $t_p$ (in ns) is the shaper peaking time (5-100%)

**Noise minimization**

- Minimize source capacitance
- Operate at optimum shaping time
- Preamp series noise ($e_n$) best with high trans-conductance ($g_m$) in input transistor
  => large current, optimal size

---

C. De La Taille
Energy Resolution ($\sigma/E$)

- **In ideal case:**
  \[
  \frac{\sigma}{E} = \sqrt{\frac{N_\gamma}{N_\gamma}} = \sqrt{\frac{1}{N_\gamma}}
  \]

- **In reality:**
  \[
  \frac{\sigma}{E} = \sqrt{\frac{ENF}{N_\gamma \cdot QE \cdot CE}} + \left( \frac{ENC}{N_\gamma \cdot QE \cdot CE \cdot G} \right)^2
  \]

- $N_\gamma$: Number of incident photons
- $QE$: Quantum Efficiency
- $CE$: Collection Efficiency:
- $ENF$: Excess Noise Factor (from Dynodes)
- $ENC$: Equivalent Noise Charge (Readout Noise)
- $G$: Gain

K. Arisaka
## Summary Table
(Beaune 1999)

<table>
<thead>
<tr>
<th></th>
<th>QE</th>
<th>CE</th>
<th>$\delta_i$</th>
<th>ENF</th>
<th>G</th>
<th>ENC</th>
<th>$\sigma/E$</th>
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## Summary Table (Beaune 2005)

<table>
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Resolution (over Poisson Limit) (Beaune 1999)

Resolution / Poisson

HPD  APD

PMT

TOF  RICH

Hardon Calorimeter

EM Calorimeter

#Photon
Resolution (over Poisson Limit) (Beaune 1999)

K. Arisaka
Resolution (over Poisson Limit) (Beaune 2005)

- APD
- PD
- SiPM
- PMT (35% QE)
- G-APD
- HPD (50% QE)
- HAPD
- VLPC

Resolution / Poisson vs. #Photon
Market Price
(Beaune 1999 → 2005)
Katsushi’s Dream Detector
(at Beaune 1999, 2002)

Glass Window (1mm)

Solid State Photo Cathode

Ceramic Case

APD Array (32 x 32 = 1024 Pixel)

Readout Electronics

Optical Fiber for Signal Readout

- 1.4mm Pixel Size
- 32 x 32 = 1,024 Pixels
- QE ~ 50% at 350 ~ 500nm
- Gain ~10^5
Katsushi’s Dream Detector
(at Beaune 2005)

- Glass Window (1mm)
- Solid State Photo Cathode
- APD Array (1024 x 1024 = 1M Pixel)
- Readout Electronics
- Ceramic Case
- Optical Fiber for Signal Readout

• 50 µm Pixel Size
• 1024 x 1024 = 1M Pixels
• QE ~ 80% at 300 ~ 800 nm
• Gain ~10^5
Concluding Remarks

Areas of interests at Beaune 2005:
- SiPM
- Large area HPD
- Integrated front-end electronics

Future direction will be driven by
- Broader markets (outside of Physics)
- Low Costs