Photodetector R&D in Japan

Hiroaki Aihara
University of Tokyo

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Hyper-Kamiokande
Ring-imaging water Cherenkov detector

Hyper-K (current baseline)
1Mton total vol.
540kton fiducial vol.
Inner Detector \(\{D43m \times L(5x50m)\} \times 2\)
PMT \(\sim 100,000\) (20inch)
(Photo-coverage 20%)
MEMPHYS : MEgaton Mass PHYSics

- water Cherenkov ("cheap and stable")

- total fiducial mass: 440 kt

- 3 cylindrical modules 65 x 65 m
  - size limited by light attenuation length ($\lambda \approx 80$ m) and pressure on PMTs
  - readout: $\sim 3 \times 81k$ 12” PMTs, 30% geom. cover
  - PMT R&D + detailed study on excavation @Fréjus existing & ongoing

4800m water equivalent

physics goals:
- proton decay searches
- superNovae core collapse and diffuse neutrinos
- precision measurement of neutrino oscillations with beams and solar neutrinos
Why R&D of photodetectors?

- Photodetectors and electronics are cost and schedule drivers.
- Take Hyper-K baseline as an example: $350M (20inch PMT+ protective case) + $30M (electronics) for 100,000 PMTs for the photo cathode coverage of 20%.
- To reduce the cost
  - Fewer detectors with high QE
  - Cheaper/better detectors
Ultra bialkali (UBA)

Higher Quantum Efficiency

UBA: R7600-200
SBA: R7600-100
STD: R7600

Hamamatsu Photonics

Higher Dark Rate?
Fewer components leading to cost reduction (1/2 - 1/4)
Photon

PMT

Photon

Photo Electron

Dynode

1st Dynode Gain: x5

Ne/s_{Ne} = 2.2

Total Gain: ~10^7

HAPD

Bombardment: x4500@20kV

Ne/s_{Ne} = 67

Avalanche Gain: X30

Total Gain: ~10^5

Operation Principle
Front- vs Back-illuminated AD

Front-illuminated AD

- Radiation Damage
- Blocking electrode

Back-illuminated AD

- EB gain
- Avalanche gain
Back-illuminated AD has advantages

**Back-illuminated AD**
(5mm-diameter)

**EB-Gain:** 4500 at -20kV
**AD-Gain:** 50 at 390V
No increase in dark current after 1000h operation at 4mA.
Radiation hard.

Si substrate to extract a front-side electrode
Stem

HPK
Clear single p.e. signals can be seen.
PMT

HAPD

HAPD gives excellent signal to noise separation.

Pulse Height Resolution at 1P.E.
Resolution ~190ps (s)

Time resolution at 1P.E.
>95% at operation HV (70% for PMT)

P.E. collection efficiency

Simulation
Digital HPD

Compact detector with Network + Power supply

Capacitor array

→ Sampling intervals are determined by delay buffer. (No fast clock)

1. Simple control and fast waveform sampling (1GHz)

2. Low power consumption

Analog Memory Cell (AMC) operation concept
One FPGA

HAPD signals

Ethernet (1Gbps)

(Q, T)

All functions in one board

13cm X 24cm

New AMC and its readout system
Clear P.E. peaks up to 5.

Time resolution=200ps@1P.E.

**Pulse Height distribution**
**HPD vs PMT**

<table>
<thead>
<tr>
<th></th>
<th>13inch HPD</th>
<th>13inch PMT (R8055)</th>
<th>20inch PMT (for SK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Photon Time Resolution</td>
<td>190ps</td>
<td>1400ps</td>
<td>2300ps</td>
</tr>
<tr>
<td>Single Photon Energy Resolution</td>
<td>24%</td>
<td>70%</td>
<td>150%</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>97%</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;&lt;700mW</td>
<td>~700mW</td>
<td>~700mW</td>
</tr>
<tr>
<td>Gain</td>
<td>10^5</td>
<td>10^7</td>
<td>10^7</td>
</tr>
</tbody>
</table>

Hamamatsu/ Tokyo/ KEK
With 5mm diameter back-illuminated avalanche diode

<table>
<thead>
<tr>
<th></th>
<th>8-inch HPD</th>
<th>13-inch HPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>动作电压</td>
<td>10kV</td>
<td>18kV</td>
</tr>
<tr>
<td>ターゲット</td>
<td>裏面電子照射型5mmφ</td>
<td>アバランジェダイオード</td>
</tr>
<tr>
<td>光電面</td>
<td>パイアルカリ</td>
<td></td>
</tr>
</tbody>
</table>

Large format HAPDs will be available from HPK in 2012
8 inch HAPD

Readout system & HV power supply (Cockcroft-Walton generator) contained in the base
開発の達成目標（3年間）
8インチHPD開発: 電圧を定格10kVとして、金属フランジを用いない安価な構造
8インチHPDモジュールの開発: ユーザーの使い易さを考慮した次の2つのモジュールを開発
・アナログタイプモジュール（プリアンプと高圧電源回路内蔵）
・デジタルタイプモジュール（プリアンプ、高圧電源回路と信号処理回路内蔵）

アナログタイプモジュール
高圧電源回路及び、プリアンプを付加
汎用化

デジタルタイプモジュール
信号処理回路を付加
使い勝手向上、商品価値向上
ガラスだけでできたHPD試作品の製作
We have developed 13inch HAPD and its readout system with a wave form sampler.

HAPD is fast and has good single photon resolution.

HPK plans to make HAPDs (13inch and 8inch) commercially available in 2012. (Unit price still not settled.)

If we employ new photodetectors, we better have an intermediate step with a reasonably large number of detectors before get to full scale.

Summary
Geomagnetic level

With geomagnetic filed canceller

<2% degradation with canceller

Collection efficiency vs. magnetic field
Readout system performance is good enough for HAPD. 
→ possible to mount readout system on HAPD and obtain (Q,T) of signals via network.

Timing resolution @ 1P.E.
We employ fast waveform sampling + digital signal processing.

HAPD measurement under VERY HIGH EXTERNAL NOISE ENVIRONMENT

Waveform after preamplifier

Signal peak

5GS/s 4096pts
800ns
Complicated system but clear signal to noise separation.

Technology choice for readout system
FINENET (VME6U)

HAPD signals

Ethernet(<1Gbps)
(Q,T)

AMC: Fast waveform sampling
64 cells ΔT=0.8ns

ADC

AMC is a key device

Digital Signal Processing

Readout module
We employ digital signal processing technique.
AMC gives smaller power consumption and better resolution.

<table>
<thead>
<tr>
<th></th>
<th>AMC (+slow FADC)</th>
<th>FADC (ADC081000 N.S.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling rate</strong></td>
<td>~1GHz</td>
<td>1GHz</td>
</tr>
<tr>
<td><strong>Supply voltage</strong></td>
<td>+5V</td>
<td>+1.9V</td>
</tr>
<tr>
<td><strong>Power/channel</strong></td>
<td>72mW(*) (+160mW FADC)</td>
<td>1.45W</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>≥10bit</td>
<td>~8bit</td>
</tr>
</tbody>
</table>

(*) readout clock=200kHz
New AMC:
To improve AC performance
• $C(\text{New}) = \frac{1}{5} C(\text{OLD})$
→ Widen analog band width (~500MHz)
• Keep same AC performance in each cells
HAPD’s small power consumption enables to make small HV supplier.

HV supply
Motivation:
Demands for the experiments other than Hyper K

Advantages WRT 13inch HAPD
1. Lower operational high voltage
   Collection efficiency = 99% @ 8kV
2. Improvements of TTS based on light incident point on photo-cathode
   210ps (8inch) vs. 500ps (13inch)
Gain uniformity: ~2% for photons < 5

Gain uniformity
HAPD works stably for 1000 hours.

Long term stability test
- **Preamplifier**
  - ENC=3400 (S/N~30 at 1P.E.)

- **Waveform sampler (AMC)**
  - Sampling rate=\(~1GHz\)
  - Power consumption=70mW/ch
  - Dynamic range=11bit (2V/0.7mV)
  - # of sampling points=512\textasciitilde1024

- **Digital part**
  - Online DSP (matched optimal filter in FPGA)
  - Ethernet interface

**Readout system characteristics**
• We can make dead timeless readout system with AMC.
• AMC can speed its readout time up because:
  ◦ Multiple outputs ([0-15] [16-31]...).
  ◦ Tandem AMC system
• It is a trade off business between fast readout and power consumption.
New HV system can give 20kV under HAPD load.
Current status of Digital HAPD
AMC operation and readout system

Sample trigger

Signal

Gate to delay

~1ns

Analog switch

Cell capacitor
AMC operation and readout system

Sample trigger

Gate to delay

Signal $v_1$

Analog switch

Cell capacitor

$\sim 1\text{ns}$  $\sim 1\text{ns}$  $\sim 1\text{ns}$  $\sim 1\text{ns}$
AMC operation and readout system

Sample trigger

Gate to delay

Signal

Analog switch

Cell capacitor
AMC operation and readout system

Sample trigger

Gate to delay

Signal

Analog switch

Cell capacitor

\[ v_1 \sim 1\text{ns} \]

\[ v_2 \sim 1\text{ns} \]

\[ v_3 \sim 1\text{ns} \]
AMC operation and readout system

Sample trigger

Gate to delay

~1ns ~1ns ~1ns ~1ns

Signal

$V_1$ $V_2$ $V_3$ $V_4$

Analog switch

Cell capacitor
AMC operation and readout system

Gate to delay

~1ns ~1ns ~1ns ~1ns

Readout trigger + readout clock

~250kHz

Signal

\( v_1 \) \( v_2 \) \( v_3 \) \( v_4 \)

Analog switch

Cell capacitor

\( \sim 1\text{ns} \)
AMC operation and readout system

- Gate to delay
- Analog switch
- Cell capacitor
- Signal

Readout by slow ADC ~250kHz
AMC operation and readout system

**Fast sampling → Slow readout**

- Gate to delay
- Low power consumption
- Analog switch
- Cell capacitor
- Readout by slow ADC

Signals: $v_1$, $v_2$, $v_3$, $v_4$

Frequency: $\sim 250$ kHz