Development of Novel Photosensors

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1. Motivation for Photosensor Development

2. The Problem – Liouville

3. Proposed Solutions

4. ReFerence Flat-Panel Prototypes:
   - 3-inch 1-pixel, unsealed
   - 5-inch 7-pixel panel, sealed
   - Industrial prototyping – defense grant (2004→)

5. THE LIGHT AMPLIFIER CONCEPT, flat and spherical

6. Geiger-mode APDs
Future projects to study very rare phenomena

- **Proton decay, Neutrino Physics and Astrophysics**
  UNO, MEMPHIS, HYPER-K, Kilometer-Cube, also deep-sea Nestor, Nemo, Antares, etc.

- **Gamma-ray Astronomy** – a study of faint and/or variable sources requires telescopes with
  low detection threshold & wide acceptance angle (huge photosensor area)

- **Ultra-high energy cosmic rays** (>10^{19} eV)

- **Double beta decay**
SEARCHING FOR EXTREMELY RARE AND WEAK RADIATION SOURCES

PARTICLE ASTROPHYSICS
(new generation of experiments)

PREVENTION OF NUCLEAR TERROR
Work supported by:

(1) *Advanced Detector Research Award*  
DOE/HEP  
“Novel Highly Sensitive Photosensor Technology for Inexpensive Large Area Cherenkov Detectors”

and now by

(2) National Nuclear Security Administration (NNSA), Office of Nonproliferation Research and Engineering, DOE  
Proposal for a Super-large Radiation Detector Based on Industrially mass-produced ReFerence Flat-Panels ($750,000)
New Experiments need sensitivity for very rare phenomena

Very Large Volumes/Areas

‘Natural’ Transparent Media (Water, Atmosphere, Ice)

PHOTOSENSORS

No other choice than
Several unconventional photosensor concepts

- Flat-Panel “ReFerence” Camera Concept (Patented)

- “Light Amplifier” concept, development just started
  - SMART PMT (Phillips) → modified configuration
  - ReFerence panels → scintillator (fiber) readout

- “SIMPLE” Imaging Camera Concept, project idling, for EUSO, OWL, but also ground-based applications Patent Pending, project pending
Cherenkov angle in water
~40 degrees

- Liouville’s theorem still allows slight beam-area reduction (AQUARICH)
- Camera must be large
Irreducibly Large Illuminated Area

Photosensors with very strong internal information concentration (photoelectrons)

Vacuum
OBJECTIVES

1. Large Photosensor Area Coverage
   • High Quantity
   • High Quality
   • Low Price

   ➔ Industrial Mass Production

2. High Detection Efficiency and S/N
   (collection and quantum efficiency)
Semiconductor Photosensors
→ developed very successfully
(but pixel sizes and areas far too small)

Vacuum Photosensors
(suitable for large-area applications, strong area reduction) did not develop significantly since mid-1960s

Why?
Because of the Vacuum?
Development of Other Vacuum Devices

~1960

~2000
1. Dielectric
2. Patterned Resister Layer
3. Cathode Glass
4. Row Metal
5. Emitter Array
6. Single Emitter Cone & Gate Hole
7. Column Metal
8. Focusing Grid
9. Wall
10. Phosphor
11. Black Matrix
12. Aluminum Layer
13. Pixel On
14. Faceplate Glass

Candescent
Flat-Panel Pixelized Camera Configuration

provided by the ReFerence Photosensor Concept
Ideal Light Concentrator
(takes the maximum of Liouville!)

Optimal Electron Lens

Photon

Photoelectrons

PIN, APD, or “Something Else”

Photocathode

Optimal Electron Lens
Very Important: Hexagonal Packing

Entrance Aperture

Photocathode
Flat-Panel Honeycomb Sandwich Camera Construction

Industrial Production (no glass blowing etc.)
Intrinsic Mechanical Stability, Low Buoyancy...
PROTOTYPE DEVELOPMENT

UNSEALED 1-PIXEL

CYLINDRIC
2001-2002

HEXAGONAL
2003

SEALED PANELS
(7 pixels, 5 inch)

Equipment (Candescent, Litton Night Vision) ~$2M Purchased and installed

SEALED with In/Au

SEALED with SOLDER GLASS
3rd Reference Prototype

3” diameter, single pixel

(successfully tested – see below)
XYZ Motion Stage
Strong signal concentration, factor ~ 1500
(one of our goals)

Replaces the entire Dynode Column!
Provides ~100% Collection Efficiency!

- APD
- Scintillator + Fiber (both of small and comparable diameter – transmission efficiency)
From Tubes to Large Flat Panels
Reference Panel Prototype (under construction)
Currently Aluminum – ultimately GLASS
Evaporation Chamber
Sealing Chamber
Load-lock Chamber
TRANSFER SYSTEM
For 5” prototypes
Base pressure ~6x10^{-11} Torr
Cs, Na, K dispensers
Reflection Mode vs. Transmission Mode

~30-43 % QE bialkali
~190-450 nm
(Hamamatsu side-on PMT R7517)

Quantum Efficiency

Wavelength

Extension into “blue & UV”
High Q.E., Bialkali Photocathode
28mm (1-1/8 Inch) Diameter, 9-Stage, Side-On Type

FEATURES
- Spectral Response: 185 to 760 nm
- High Cathode Sensitivity
  - Luminous: 160 μA/Im Typ.
  - Radiant at 420nm: 105 mA/W Typ.
  - Quantum Efficiency at 220nm: 40% Typ.
- High Anode Sensitivity (at 1000V)
  - Luminous: 1600A/Im Typ.
  - Radiant at 420nm: 10.5 × 10^5 A/W Typ.

APPLICATIONS
- Fluorescence Spectrophotometers
- Fluorescence Immuno Assay
- SO₂ Monitor (UV Fluorescence)
Photocathode Cooling - Diminished Dark Current

Thermionic emission $[e/\text{sec/cm}^2]$

- InGaAs
- S20

Carlsbad NM

Cooling (Peltier)
VERY EFFICIENT MAGNETIC SHIELDING

Slow electrons

e.g. UNO with Magnetic Field (???)

Slow electrons
“Light Amplifier” Concept

Scintillators + fiber optics

NO electronics inside!!

Resolution determined outside!!

READOUT ➔

APD array
Tuby or not Tuby?
That is the question!
Spherical LIGHT AMPLIFIER STUDIES

SMART PMT, QUASAR

1 photoelectron $\rightarrow$ >15 photons in APD

Geiger-mode APD array

scintillator

Al (10µm)

photocathode

photomultiplier

phosphor scintillating layer

R = 170 mm

Benthos sphere 16" i.d.
Silicon photomultiplier (SiPM)

SiPM main features:
- Sensitive size 1x1mm² on chip 1.5x1.5 mm²
- Gain $2 \times 10^6$
- $U_{bias}$ ~ 50V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 576
- Nuclear counter effect: negligible (due to Geiger mode)
-Insensitive to magnetic field
- Dynamic range ~ $10^3$/mm²

For further details see:
«Advanced study of SiPM»
http://www.slac.stanford.edu/pubs/icfa/fall01.html

Single photoelectron (single pixel) spectra

SiPM:
- excellent single photoelectron resolution
- low ENF expected

More about pixel signal resolution: tens of photoelectrons

$\langle N_{ph.e} \rangle \sim 46$