Development of Photon Detectors at UC Davis

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Future particle astrophysics projects to study very rare phenomena

- Proton Decay
- Neutrino Physics
- Neutrino Astrophysics
- Gamma-ray Astronomy
  (low detection threshold & wide acceptance angle)
- Ultra-high energy cosmic rays (>10^{19} eV)
- Neutrinoless Double Beta Decay
- WIMP Searches
SEARCHING FOR RARE AND/OR WEAK RADIATION SOURCES

- PARTICLE ASTROPHYSICS (new generation of experiments)
- NUCLEAR SECURITY (nonproliferation)
- MEDICAL IMAGING
  WIDELY ACCESSIBLE
  MEDICAL DIAGNOSTICS
  Industrial Mass-Production of Very-large-area cameras
A new Technology for
Industrial Mass-Production
of large photosensor areas,

based on modified existing technologies

(e.g. the assembly of modern, plasma and field-emission flat-panel TV screens; low production cost ~$1000 per sq. meter)

+ ‘REAL’ (non-physics) MARKETS,
Several Unconventional Photosensors

- Flat-Panel *Reference* Camera Concept (Patented)

- *Light Amplifier* - general concept
  - *Reference* panels $\rightarrow$ scintillator (fiber) readout
  - QUASAR or SMART PMT in a modified configuration
    + Geiger-mode APDs

- “SIMPLE” Space Imaging Camera Concept for EUSO, OWL, but also ground-based applications (Patented)
Cherenkov angle in water
\[ \sim 40 \text{ degrees} \]

Full angular coverage

⇒ “Camera” surrounds the detector volume
Cherenkov angle in air < 1 degree, also well defined observational direction, and small angular spread in the EM shower

- Liouville’s theorem allows significant beam area reduction
- Camera can have a small area
Irreducibly Large Illuminated Area

strong internal signal concentration

Vacuum

( photon $\rightarrow$ photoelectron $\rightarrow$ ‘no more Liouville’ )
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)
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WHY NOT ACCOMPLISHED ALREADY???
Semiconductor Photosensors

→ developed very successfully

(but pixel sizes and areas - 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

Production Cost: < $1,000 per m²
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
Flat Panel Camera – wishful thinking:

“Continuous” Hybrid Photon Detector (HPD)

PiN, APD, something else

window

electrons

vacuum

Reflection-Mode Photocathode
Problem #1 – Electron Optics

This doesn’t work!
Problem #2  – Mechanical Stability
 (flat plates need supports)
Flat-Panel Pixelized Camera Configuration

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

Photon

PIN, APD, or SCINTILLATOR

Optimal Electron Lens

Photoelectrons

Photocathode
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)

SEALED with In/Au

SEALED with SOLDER GLASS

Equipment (Candescent, Litton Night Vision) ~$2M
7-pixel 5-inch ReFerence Flat-Panel Prototype

UHV Transfer System:
- Photocathode deposition
- Indium/Au/Cr deposition
- Vacuum sealing
Reflection Mode Hybrid Photomultiplier Tube (ReFerence Tube)

Program: ITT funded development of a small prototype reflection mode Hybrid PMT using a Compound Parabolic Concentrator (CPC) for light concentration and electron focusing. The use of CPCs instead of lenses greatly improves light gathering and allows for a very precise cut-off on the acceptance angle.

The intent of this program is to produce a high-efficiency, low-jitter photodetector with high QE from UV to red for use in various applications, including imaging atmospheric Cherenkov telescopes.

The use of a reflection mode cathode in this application will improve QE, particularly in the UV. Dr. Daniel Ference of UC Davis developed this design concept and collaborates with ITT on this development program.

Timeline:
- Program start: Nov/Dec 2001
- First prototypes sealed: April 2002
- Present emerging results at New Developments in Photodetection, Beaulieu, France: June 2002

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Approved for unlimited Public Release per 02-5-1463.
Reference Tube Design

- Reflection mode GaAs cathode (12.5mm used)
- Sapphire input window 25mm aperture
- High voltage APD (API)
- Segmented Kovar CPCs for concentration and timing
- Size chosen to use standard parts and tooling
- Prototype device to test design concept with short time and internal funding
- Anticipate improved external QE 300-400nm and good QE out to 900nm
3rd Reference Prototype

3” diameter, single pixel

(successfully tested – see below)
Ideal Light Concentrator = OK!

Optimal Electron Lens

Photocathode

Phosphor Screen

Photon

verify

Photoelectrons

Optimal Electron Lens
XYZ Motion Stage
Strong signal concentration, factor $\sim 1500$

(one of our goals)
Strong signal concentration, factor $\sim 1500$
(one of our goals)

Replaces the entire Dynode Column!
Provides $\sim 100\%$ Collection Efficiency!

• APD

• Scintillator + Fiber (both of small and comparable diameter $\rightarrow$ good coupling efficiency)
From Tubes to Large Flat Panels
Reference Panel Prototype (under construction)
Reference Panel Prototype (under construction)
Reference Panel Prototype (under construction)
Currently Aluminum – ultimately GLASS
Evaporation Chamber
Sealing Chamber
Load-lock Chamber
TRANSFER SYSTEM
For 5” prototypes

Base pressure
$\sim 6 \times 10^{-11}$ Torr
Cs, Na, K dispensers
Vacuum

Photocathode

Glass Window

Photo-Electron

Probability for an Electron to Reach the Vacuum Surface (Random Walk)

Photon Absorption (Electron Creation)

Therefore: QE ~ 10-20%
Photon Absorption (Electron Creation)

Probability for an Electron to Reach the Vacuum Surface (Random Walk)

(e.g. Substrate, Reflector, ...)

LOW PRODUCTION COST!
UV Photon Absorption (Electron Creation) Mostly @ Surface

Probability for an Electron to Reach the Vacuum Surface (Random Walk)

Thin Photocathode on a Reflector, Interference Multi-layer Systems

Westinghouse, RCA, ITT ~1963-1975
Reflection Mode vs. Transmission Mode

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

Quantum Efficiency

Wavelength

Extension into “blue & UV”
PHOTOMULTIPLIER TUBE
R7517

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 x 10^5 A/W Typ.

APPLICATIONS
● Fluorescence Spectrophotometers
● Fluorescence Immuno Assay
● SO₂ Monitor (UV Fluorescence)
TransReFerence

Single-Photon Color Sensitivity

Spectral Coverage

Classical PMT
Transmission-Reflection
(and also light trap)
Single-Photon Resolution

Number of Detected Photons

APD

PMT

HPD

TransReference

Reference

Single-Photon Resolution
Photocathode Cooling - Diminished Dark Current

Thermionic emission [e/sec/cm²]

\begin{align*}
\text{InGaAs} & \quad 10^4 \\
\text{S20} & \quad 10^5
\end{align*}

Carlsbad NM

Cooling (Peltier)

WATER
VERY EFFICIENT MAGNETIC SHIELDING

e.g. UNO with Magnetic Field (???)
Light Amplifier Concept

Scintillators + fiber optics

NO electronics in the vacuum

Resolution determined outside !!

READOUT ➔ APD array
Light Amplifier Concept

Scintillators + fiber optics

NO electronics in the vacuum

Resolution determined outside!!
SMART PMT, QUASAR

photocathode

Benthos sphere
16" i.d.

R = 170 mm

phosphor
scintillating layer

power supply
photomultiplier
Hemispherical LIGHT AMPLIFIER

Al (100 nm) Scintillator Y2SiO5(Ce)

Geiger-mode APD array

Fiber Plate

1 photoelectron $\rightarrow$ >15 photons in APD

SMART PMT, QUASAR
CURRENT SETUP

SMART PMT, QUASAR

SINGLE Geiger-mode APD, 1x1 mm²

No face-plate → low light Collection Efficiency ~1:150

Pulsed LED+fiber
57.4 V power

Coax signal

Pulsed LED+fiber

Geiger-mode APD
ZS-2 from Sadygov, MICRON

EXTREMELY SIMPLE!
Silicon photomultiplier (SiPM)

SiPM main features:
- Sensitive size 1x1mm² on chip 1.5x1.5 mm²
- Gain 2x10⁶
- U_bias ~ 50 V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 576
- Nuclear counter effect: negligible (due to Geiger mode)
- Insensitive to magnetic field
- Dynamic range ~ 10⁵/mm²

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

B. Dolgoshein  "SiPM possible applications"

Single photoelectron (single pixel) spectra

SiPM:
- excellent single photoelectron resolution
- low ENF expected

More about pixel signal resolution: tens of photoelectrons

SiPM consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device
- signal uniformity from pixel to pixel is quite good

B. Dolgoshein  "SiPM possible applications"
Very Simple Electronics

57.4 mV

20 kΩ

1 kΩ

20 kΩ

ZS-2 from Sadygov, MICRON

1 photo-electron → 200 mV

g = 25

1 pe → 200 mV

50 Ω
A Typical Single-Photon Signal in the Geiger-mode APD

Amplitude

Time

1 photo-electron $\rightarrow$ 200 mV
Superposition of many light pulses in the Geiger-mode APD (signal integrated)

~5 photo-electrons $\rightarrow$ 1 V
Superposition of many light pulses in the Geiger-mode APD (full bandwidth)

Note the individual photon structure and decay spectrum of the scintillator
Rotating Light Source (LED) → Image @ Scintillator

30 cm → 1 cm

➔ IMAGING (even without fiber coupling)
CONCLUSIONS

Light Amplifier:

*LIGHT IN-(VACUUM)-LIGHT OUT*

- CONCENTRATION (photoelectron focusing)
- AMPLIFICATION (photoelectron acceleration)

ADVANTAGES:

• No electronic components in the vacuum
• Extreme Simplicity & Robustness
  → Low cost, mass production

Tested - a QUASAR tube + a Geiger-mode APD
“Light Amplifier” Concept

Scintillators + fiber optics

NO electronics inside!!

Resolution determined outside!!

READOUT ➔ APD array
Spherical LIGHT AMPLIFIER

1 photoelectron $\rightarrow >15$ photons in APD

SMART PMT, QUASAR
Silicon photomultiplier (SiPM)

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\[ <N_{phe}> \approx 46 \]