Development of Novel Photosensors at UC Davis

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MOTIVATION:
Unique importance of Photosensors for Next-Generation Projects in HE Physics and Astrophysics

Similar importance for Homeland Security
An Medical Imaging
1. Motivation(s) for Photosensor Development → ‘MARKETS’

2. The Problem

3. Proposed Solution

4. Reference Prototypes:
   - 3-inch 1-pixel UCDavis (2001-2003)
   - 18 mm 1-pixel ITT-NV (2002)
   - 5-inch 7-pixel panel (end of 2004)
   - Industrial prototyping – defense grant (2004→)

5. Status
Future projects are aiming to study very rare phenomena

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

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

- Ultra-high energy cosmic rays (>10^{19} eV)
  P. Auger, EUSO, OWL,…

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

PARTICLE ASTROPHYSICS
(new generation of experiments)

HOMELAND SECURITY
Work supported by the:

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

(2) National Nuclear Security Administration
(NNSA), Office of Nonproliferation Research
and Engineering, DOE
Proposal for a Super-large Radiation Detector
Based on ReFerence Flat-Panel Photosensor Concept
SEARCHING FOR EXTREMELY RARE AND WEAK RADIATION SOURCES, IN LARGE DETECTORS

PARTICLE ASTROPHYSICS
(new generation of experiments)

NATIONAL SECURITY
(non-proliferation)
Got funding!!!
NNSA

NEW INITIATIVE:
MEDICAL IMAGING:
WIDELY ACCESSIBLE
MEDICAL DIAGNOSTICS
Industrial Mass-Production of Very-large-area cameras
• Collaboration with bio-medical research groups at UC Davis
• Proposed for significant private, philanthropic funding, offered to UCD
• Industry likely to be involved
New Experiments need sensitivity for very rare phenomena

Very Large Volumes/Areas

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

PHOTOSENSORS
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, (Patent Pending)

- A New Concept – currently secret (patentable?)
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
- The Camera can have a small area
SuperKamiokande

Cherenkov angle in water
\( \sim 40 \) degrees

\( \Rightarrow \) Liouville’s theorem still allows slight beam-area reduction (see AQUARICH)

\( \Rightarrow \) Camera must be large
Irreducibly Large Illuminated Area

Photosensors with
- Very strong *internal information concentration*
- Vacuum
- More efficient photocathodes
- *Industrial Mass-Production at a very low cost*
  \(< 5\% \text{ of PMTs per square meter}\)
Why the old PMT technology is not satisfactory?

- PMTs are ~hand-made:
  - Glass bulbs (glass-blown)
  - Dynode chains are hand-assembled
  - Wire connections spot welded
  - Installation and handling is complex and risky

- Intrinsically very expensive technology

- Large-Scale production is virtually impossible
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)
OBJECTIVES

1. Large Photosensor Area
   • High Quantity
   • High Quality
   • Low Price
   Industrial Mass Production

2. High Detection Efficiency and S/N

WHY NOT ACCOMPLISHED ALREADY???
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
Flat Panel Camera – wishful thinking:

“Continuous” Hybrid Photon Detector (HPD)

PiN, APD, something else

electrons

window

vacuum

Reflection-Mode Photocathode
Problem #1 – Electron Optics

This doesn’t work!
Problem #2 – Mechanical Stability

(flat plates need supports)
Flat-Panel Camera Configuration

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

Photoelectrons

Photon

PIN, APD, or “Something Else”

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,
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, Besançon, France: June 2002

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Approved for unlimited Public Release per 02-S-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 (tested)

3” diameter, single pixel

(successfully tested – see below)
“Photocathode”
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)
Aluminum but should be GLASS
Reflection Mode vs. Transmission Mode

Extension into "blue & UV"

~35-40% QE bialkali

Quantum Efficiency vs. Wavelength
Photocathode Cooling - Diminished Dark Current

![Graph showing Thermionic emission vs. angle with cooling (Peltier) and cooling at Carlsbad NM.]

- Thermionic emission [e/sec/cm²]
- Cooling (Peltier)
- Carlsbad NM

The graph illustrates the reduction in thermionic emission with cooling at Carlsbad NM, showing a decrease in emission as the angle increases with cooling applied.
VERY EFFICIENT MAGNETIC SHIELDING

Slow electrons

e.g. UNO with Magnetic Field (???)
Single-Photon Resolution

Number of Detected Photons

- APD
- PMT
- HPD

TransReference
Reference
Resources @ UC Davis

• Ideas, enthusiasm, physicists
• Running Projects
• Equipment (>$2M value)

For Photocathode development:
Surface Science laboratory: AES, XPE, SIMS, ...

For Flat Panel manufacturing:
2 Flat Panel Sealing Devices (IR Laser Sealing)
Several Transfer UHV Systems !!!
Night Vision production machine
WHAT WE NEED:

NEW PHYSICS
STATUS

NEW INITIATIVE:
MEDICAL IMAGING:
WIDELY ACCESSIBLE MEDICAL DIAGNOSTICS
Industrial Mass-production of Very-large-area cameras

DEFENSE

UNO
Finding the Optimal
• Configuration,
• Photosensor parameters
• E.g. AQUARICH
• IMAGING →
Tom Ypsilantis: “AQUARICH - Super Kamiokande with Spectacles”
Tom Ypsilantis:
“AQUARICH - Super Kamiokande with Spectacles”

“AQUARICH with Fresnel Lenses

“SIMPLE” camera

MIRROR ➔ Fresnel Lens
Photon Absorption (Electron Creation)

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

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