Status and perspectives of gaseous photon detectors

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Outline

• Principle of gaseous photomultipliers – GPM

• Generations of GPMs, from MWPC to MPGDs

• Visible sensitivity

• Applications
GPM principle

1 - Photo-conversion (solid/gas)
2 - Photoelectron multiplication (gas)

solid (CsI, Bialkali...)

gas (TEA, TMAE...)

window

e⁻ multiplication

Moscow 31/07/2018 - 10th International Workshop on Ring Imaging Cherenkov Detectors - João Veloso
• Photo-conversion – **solid** photocathodes

**GPM principle**

![Diagram](image)
• Photo-conversion - **solid** photocathodes

1- absorption of the incident photon→ **transfer of energy to an electron** within the photoemissive material.
2- electron migration do the pc surface – energy losses (**e-e scattering**)
3 – escape from the surface of the pc – energy losses (angle of emission)- only e with $K_E$ above the potencial barrier

*Dowell and Schmerge, Phys. Rev. ST Accel. Beams 12, 074201 (2009)*
• Backscattering of photoelectrons in the gas medium → QE degradation

vibrational excitation of molecules → threshold at low electron impact energy
⇒ electron cooling effect

Escada et al., J. of Physics D 43(2010)65502
Extraction to a gaseous medium

- Backscattering of photoelectrons in the gas medium – CsI PC

Covita et al., PLB 701(2011)151

vibrational excitation of molecules → threshold at low electron impact energy
=> electron cooling effect

Di Mauro et al., MIMA 371(2010)137
Extraction to a gaseous medium

- Extraction from $pc$ to noble gases with molecular additives

**CsI**  
*Azevedo et al., JINST 5(2010) P01002*

![Graph showing extraction efficiency vs. electric field strength](image1)

**Bialcali**  
*Tokanai et al., NIMA 766(2014)176*

![Graph showing normalized photoelectron collection efficiency vs. electric field strength](image2)

*Alexeev et al., NIMA 623(2010) 129*
MWPC based GPM

- First implementation with MWPC
- TMAE vs CsI

TMAE drawbacks:
- strong anode ageing
- operation at high temperatures (complex)

CsI (strongly studied within RD26):
- easy production
- much simpler operation
- allow for higher time resolution

E. Nappi, NIMA 471(2001) 18

Thin CsI coating on cathode pads
MWPC based GPM

• CsI-based MWPC photosensors used in RICH detectors
  – ALICE HMPID, COMPASS RICH1, STAR...

• Tens of square meters of sensitive areas were produced, tested, commissioned and operated

• Some of them still in operation
• **Drawbacks**
  – Long term degradation of the CsI
    • *ion feedback* (Ion bombardment $\sim$ 50-60%)
    • some contribution from photon feedback ($2\pi \rightarrow 50\%$)

  – **Gain limitations**
    • *signal disruption* due to photon feedback
      feedback factor $> 1 \rightarrow G_f \gamma_f = 1$

    • breakdown
      – feedback effects and discharges
• Long term degradation of CsI pc

Breskin et al., NIMA 371(1996)116
• Long term degradation of CsI $pc$
accelerated tests – ALICE/HMPID (Ion bombardment)

CsI-MWPC

![Graph showing decrease in normalized current](image1)

- Clear degradation in the irradiated areas
- Degradation not well understood - physical and chemical mechanisms competing? Evaporation? Cesiation?..
- No degradation observed for accumulated charge $< 0.2$ mC/cm$^2$

*Hoedlmoser et al., NIMA 574(2007)28*
• New generation of gaseous detectors combined with solid photocathodes overcome some of the limitations

• **Micro Pattern Gaseous Detectors (MPGDs)**
  – Triggered new possibilities for GPM performance
    • *Intrinsic mitigation of the photon feedback*
    • *Strategies for ion backflow reduction*
    • High gain
    • High position resolution
    • Fast signals
    • Visible sensitivity
    • *Nano/Pico second resolution*
The main objective is to advance MPIGD technological development and associated electronic-readout systems, for applications in basic and applied research.

http://rd51-public.web.cern.ch/rd51-public

RD51 Collaboration

- Large Scale R&D program to advance MPIGD Technologies
- Access to the MPIGD “know-how”
- Foster Industrial Production

- ~ 90 institutions
- ~ 500 members
- National and International Laboratories
- National Institutes and Universities
Micropattern gaseous detectors

- High Rate Capability
- High Gain
- High Space Resolution
- Good Time Resolution
- Good Energy Resolution
- Excellent Radiation Hardness
- Good Ageing Properties
- Ion Backflow Reduction
- Photon Feedback Reduction
- Large Size
- Low Cost

Micromegas

Bulk

Micro bulk

InGrid

Triple-GEM

Gain

~20

~20

~20

~8000

50μm GEM

THGEM

GLASS GEM

MHSP

THCOBRA

μPIC
• MPGD based photomultipliers
  – GEM
  – THGEM
  – Micromegas
  – Hybrids
• GEM based GPMs

- triple gem with CsI pc
- semitransparent vs reflective pc
- typical stable gains $\sim 10^5$
- large area $> 1 \text{ m}^2$ can be produced

Bachman et al. NIMA 438(1999)376
Breskin et al. NIMA 478(2002)225
Bondar et al. NIMA 496(2003)325
Chechik and Breskin NIMA 595(2008) 116

$3\% \text{ IBF @ 0.5 kV/cm}$
Gain $\sim 10^5$
Hadron-Blind detector (HBD) at RHIC-PHENIX

- Triple GEM
- CsI reflective pc
- $G \sim 10^4$
- In operation

Anderson et al., NIMA 546 (2005) 466.
• **THGEM based GPM**

- typical dimensions: hole:pitch:thickness $\approx 0.5:1:0.8$ mm
- Rim $< 0.1$ mm
- Csi reflective pc
- Gains $> 10^5$ (triple configuration)
- Large size production (60x30 cm$^2$)
- Fair IBF $\sim 10\%$

Breskin et al. NIMA 598 (2009) 107-111
Alexeev et al. JINST 7(2012) C02014
MPGD based GPM

- THGEM based GPM

No significant gain variation when adding CsI pc

Peskov et al. JINST 5(2010) P11004

Alexeev et al. JINST 7(2012) C02014
MPGD based GPMs

- Micromegas based GPMs

InGrid – Micromegas integrated in a Timepix

- Very interesting performance for imaging (high granularity)
- Compact system with integrated electronics
- Limited to small detection areas – timePix limitation

Melai et al., NIMA 628 (2011)133
MPGD based GPMs

- Micromegas based GPMs

InGrid – Micromegas integrated in a Timepix

- Gain $\sim< 10^5$
- Good IBF reduction $\sim 10^{-2}$
- Very high position resolution $\sim 25 \, \mu m \, \sigma$
- Good $pe^-$ collection

(low noise and position provided by TimePix)

Melai et al., NIMA 628 (2011)133
THGEMs+Resitive Micromegas combination

THGEM 1- provide support for the CsI $p_c$, gain and partial block of ions and photons

THGEM 2 - extra gain and extra ion blocking

Resistive Micromegas - efficient for ion trap and provide extra gain and spark mitigation

Gain > $10^4$
IBF ~ 3%
Effective $pe$ detection > 80%
(MWPC+CsI ~50-60%)

60 x 60 cm$^2$ detectors formed by 30 x 60 cm$^2$ active elements

77% surface for CsI coating

THGEM, detail

Micromesh support pillars (diam. 0.4 mm, pitch 2 mm → 8% dead area)
Detailed technological aspects were given by Fulvio’s talk, yesterday

The Hybrid MPGD-based photon detectors of COMPASS RICH-1

Monday 30 of July form 11h25m-11H50m - RICH2018
Hybrid GPMs

MM-TGHEM – Multi-Mesh

UV-light

Top M-THGEM

Top Mesh

Bottom Mesh

Bottom M-THGEM

Pre-amplification gap

Amplification gap

0.5 mm

0.2 mm

0.5 mm

Post-amplification gap

Oliveira and Cortesi., JINST 13 (2018) P06019
Hybrid GPMs

MM-TGHEM

\[ \alpha = \frac{\Delta V_{\text{MM}}}{\Delta V_{\text{THGEM}}} \]

\( \alpha = 0.25 \)
\( \alpha = 0.5 \)
\( \alpha = 0.75 \)
\( \alpha = 1.00 \)

Circle: He/(10\%)CO\(_2\)

Circle: Ar/(10\%)CH\(_4\)
Hybrid GPMs

MM-TGHEM + WELL-THGEM (for extra gain)

- Gain $\sim 10^6$
- Fair IBF for CsI pcs

Oliveira and Cortesi., JINST 13 (2018) P06019
• MHSP – very successful but limited in area
  – difficult to produce with large areas

• THCOBRA
Hybrid solution for IBF reduction

- Reversed MHSP
- Ions are trapped by negatively biased cathode strips

**Can trap its own ions**

**IBF: 3% @ Gain > 10^5**

**IBF = 3*10^-4 @ Gain = 10^5**

Veloso et al., RSI 71(2000)2371

Maia et al. NIM A504(2003)364

Lyashenko et al., JINST (2007) 2 P08004
Hybrid solution for IBF reduction

- PACEM-photon-assisted cascaded electrom multiplier

  - need of scintillation gases
  - any type of hole type multipliers

L. Arazi et al., JINST 8 (2013) C12004

Veloso, et al., 2006 JINST 1 P08003

Effective IBF reduction

Veloso, et al., NIMA581(2007) 261
THCOBRA: Ion back flow reduction in patterned THGEM cascades

A patterned THGEM

Fig. 4. Plot of Ion Back Flow (IBF) as a function of $V_{AC}$ for the detector of Fig. 2.
• Visible sensitivity

GPM Solutions

more challenging!

Nakamura et al., NIMA 623 (2010) 276
Visible sensitive GPMs

**Electron avalanches in gases produce an equal number of ions**

- **Critical factor** – very high Ion induced secondary electron emission from alcali pcs

- Ion induced secondary emission in CsI is negligible, due to a very wide band gap of about 6 eV
- **Critical for alcali based pcs**
- **For a standard D-GEM +alcali pc → Max Gain = 100**

Lyashenko et al., JAP 106(2009)044902

So, at maximum IBF ~ $10^2/G$
Visible sensitive GPMs

• **First successful operation** (no voltage gating)

Lyashenko et al., JINTS 4(2009)P07005
Visible sensitive GPMs

Ion back flow $\sim 10^{-4}$ $\rightarrow$ high stable gains

Lyashenko et al., JINTS 4(2009)P07005

- Ageing observed
  - some QE degradation with time
- Outgassing from materials
  $\rightarrow$ Kapton is the must probable cause
Visible sensitive GPMs

- New micromesh gas (micromegas)

- Clean materials $\rightarrow$ low outgassing
- Sealed detector
- Was not able to reach single photon
- IBF is the limited factor
- Measured the $pe$ extraction eff.

Tokanai et al., NIMA 766 (2014)176
Visible sensitive GPMs

- Improved version for further IBF reduction

Tokanai et al., NIMA 766 (2014)176
Visible sensitivity - **problems to be solved**

**Alcali based pcs are highly reactive to gases** (e.g. O₂, H₂O ...)

- **Gas purity**
  - Use of low outgassing materials
    - GEM based → glass or ceramic
    - Micromegas → eliminating “plastic” pillars and mesh supports
  - Gas purifiers
  - Sealed detectors - everybody wants!

- **Photocathode protection**
  - Minimize contamination
  - Reduces ion induced secondary emission ?? (needs to be study)
Low outgassing materials

• Glass MPGD

Glass CP
hole type MPGD
25 and 50 μm Ø

Optical readout (CCD)

Sugiyama et al., NIMA 845 (2017) 304
Low outgassing materials

• Large size **Glass GEM** (30 x 30 cm$^2$)

<table>
<thead>
<tr>
<th>Past reported G-GEM[10, 12]</th>
<th>Large size G-GEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective area</td>
<td>100 mm square</td>
</tr>
<tr>
<td>Substrate size</td>
<td>145 mm square</td>
</tr>
<tr>
<td>Hole size</td>
<td>180 $\mu$m</td>
</tr>
<tr>
<td>Hole pitch</td>
<td>280 $\mu$m</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>680 $\mu$m</td>
</tr>
<tr>
<td>Number of holes</td>
<td>141,417</td>
</tr>
</tbody>
</table>

Fujiwara et al., EPJ Web Conf., 174(2018)02003
Photochatode protection

• New strategy to protect bialcali pc based on coating layers

- *ab initio* density functional calculations

- reduces the work function of alcali based pc

*Wang et al., npj 2D Materials and Applications 17(2018)*
• New strategy to protect bialcali pc based on **BN**

- Boron Nitrite (BN) reduces the work function of alcali based *pc*
- Very low electron affinity
- Same QE as uncoated *pc*

*Wang et al., npj 2D Materials and Applications 17(2018)*
• New carbon based promising Photocathodes
Carbon based photocathodes

- Very promising photocatode for VUV
  - very interesting QE
  - high radiation hardness
  - spray technique – hydrogenated ND powder

- Still presenting some ageing →
- Ion bombardment resistance !
- Compatible with MPGD operation !

Velardi et al., Diamond & RM 76(2017)1 ; Valentini et al. Patented
Carbon based photocathodes

Advances in DLC films triggered the possibility of producing photocathodes to operate in gas medium for MPGDs

- **DLC - Diamond-like carbon**
  - Widely used in industry as a solid lubricant
  - Recently introduced to the MPGD field as excellent resistive electrodes
  - First samples were produced in a 3 mm thick MgF$_2$
    - Tested with success in the PICOSEC Collaboration

- A breakthrough in **carbon based photocathodes** would favour:
  - GPMs performance in general
  - RICH detectors for PID for future NP/HEP experiments

*Yi Zhou et al., presented in RD51 collaboration meeting, Munich, June 2018*
Extreme time resolution

- PICOSEC Collaboration aims for the development of a Micromegas based detector coupled to a photocathode for time resolution in the **ten pico second** time scale.

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**CsI photocathode**

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Lukas Sohl et al. For the PICOSEC Collab., presented in RD51 collaboration meeting, Munich, June 2018
**Extreme time resolution**

- **Strong deterioration due to ion bombardment**
  - Ion back flow damages CsI photocathode under higher particle flux
  - IBF > 60% at high detector gain
  - Robust photocathodes needed

Preliminary results:
- **DLC photocathode**
- **Resistance to ion bombardment? needs to be proved!**

<table>
<thead>
<tr>
<th>$V_{anode}$ [V]</th>
<th>$V_{drift}$ [V]</th>
<th>$I_{anode}$ [mA]</th>
<th>$I_{drift}$ [mA]</th>
<th>IBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>+450</td>
<td>-350</td>
<td>98.00</td>
<td>23.40</td>
<td>24</td>
</tr>
<tr>
<td>+450</td>
<td>-375</td>
<td>193.85</td>
<td>53.00</td>
<td>28</td>
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<tr>
<td>+450</td>
<td>-325</td>
<td>45.47</td>
<td>10.65</td>
<td>23</td>
</tr>
<tr>
<td>+425</td>
<td>-400</td>
<td>193.50</td>
<td>53.10</td>
<td>28</td>
</tr>
<tr>
<td>+425</td>
<td>-375</td>
<td>87.30</td>
<td>23.95</td>
<td>27</td>
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<tr>
<td>+425</td>
<td>-350</td>
<td>44.48</td>
<td>10.99</td>
<td>25</td>
</tr>
<tr>
<td>+400</td>
<td>-425</td>
<td>178.84</td>
<td>112.39</td>
<td>63</td>
</tr>
</tbody>
</table>

- A similar quantum efficiency as the metallic photocathodes has been reached
- Time resolution correlates with photoelectrons
- Efficiency of ~85%
• Applications

a few examples ...
Forest fire detection
• Fire detection

The highest sensitivity Class 1, the Hamamatsu UVtron: 
~ 30 x 30 x 30 cm³ flame at ~20 m for 20 sec

Not suitable for outdoor applications

Flame sensors UVTRON

UVTRONs are ultraviolet ON/OFF detectors that can quickly detect a flame’s weak UV emission from a distance, making them suitable for flame detectors and fire alarms. They have a narrow spectral sensitivity from 185 nm to 300 nm and are completely insensitive to visible light. They make it possible to design a high-sensitivity, quick-response UV detection system with simple circuitry.
Fire detection

- MPGDs based fire detectors with CsI pcs
  - Single photon detection - high sensitivity
  - Solar blind (no visible background)
  - Good image capabilities - localization

Can trigger efficient forest fire detection!
Fire detection

- Flame spectrum


CsI sensitive region
Fire detection

• Why **CsI**?

- simple to produce
- can be produce in high areas (hundred of cm²)
- solar blind
- high sensitive to the UV flame emission

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*Carrithers, Appl. Opt. 14(1975)1667*

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*Figure 1. The spectral irradiance of terrestrial ultraviolet radiation at solar noon on an unshaded, horizontal surface at Durham (55°N) (Difffey 1987a). ——, 2nd October 1986 (uniform light cloud); - - -, 1st July 1986 (clear sky).*

*Frederick J E, Snell H E and Haywood E K 1989
Solar ultraviolet radiation at the earth's surface
Photochem. Photobiol. 50 443-50*
Fire detection

- Strip Resistive TGEMS - ethylferrocene (EF) vapours

Detector | Price (Euro) | Sensitivity (Ham. units)
----------|-------------|-----------------------
*Hamamatsul* | 80 [21] | 1
Sealed single wire (TMAE vapors) | 120–150 | 1000
Sealed S-RETGEM (Ne+EF) | 100 [22] | 100
Sealed S-RETGEM, pos-sens, Ne+EF | 150 | 100
S-RETGEM, pos. Sens Ne+ air | 80 [22] | 25
S-W filled with air (see appendix) | 40–70 [21] | 10

**Sensitivity increases:**
- sensitive area
  40 → 120 mm Ø → **10 X**
- position resolution

*Charpak et al., JINST4(2009)12007*
Fire detection

• Forfire project - MM with preamplification

Pc: CsI
Gas: 90% Ne + 10% Ethane
144 pixels

Peyaud et al., NIMA787(2015)102; NDIP2014
Fire detection

- **Outdoor tests** - deuterium lamp with 193, 200 and 214 filters

  - Possible detection at 0.5 km
  - Sensitivity increases quadratically with detection area

*Peyaud et al., NIMA787(2015)102; NDIP2014*
Fire detection

- THGEM+THCOBRA CsI position sensitive GPM

- Built for cryogenic environment
- MgF window - (LAr light – 110 nm)
- Filling gas – Ne5%CH4

Paredes et al., JINST 10(2015) P07017
Fire detection

- single photon - 185 nm
- polya

- $G > 10^6$
- collection efficiency $\sim 100\%$
- $R_{p(\text{anode})} = 60 \, \mu\text{m}$
- $R_{p(\text{top})} = 90 \, \mu\text{m}$
- only a few discharges for several months even for high photon flux

Paredes et al., JINST 10(2015) P07017
Fire detection

- $R_{p\text{(top)}} = 90\, \mu m$
- $R_{p\text{(anode)}} = 60\, \mu m$

*Paredes et al., JINST 10(2015) P07017*
Fire detection
• Applications in EXOTIC ideas
  – High pressure and Liquid →
  electroluminescent UV and VUV emission
Most complete analysis of photon emission processes in gaseous and liquid Ar doped with Xe and N2

A. Buzulutskov, EPL 117 (2017) 39002
Revealing new electroluminescence mechanism in two-phase Ar: bremsstrahlung of electrons scattered on neutral atoms - neutral bremsstrahlung (NBrS)

A. Buzulutskov et al., Astropart. Phys. 103 (2018) 29]

First quantitative theory of NBrS electroluminescence

NBrS theory vs experiment in proportional electroluminescence: good agreement below excitation threshold and chances to have that above the threshold
Compton camera

Azevedo et al., NIMA 732(2013) 551
Compton camera

PEEK with Aluminium Layer (cathode)
Shaping ring electrode
Meshes
CsI-THCOBRA
Quartz Window
EL chamber
Photosensor

Azevedo et al., NIMA 732(2013) 551
Compton camera

Position sensitive GPM

- Position sensitive UV GPM (Ar10%CH$_4$)
  → **good energy resolution & localization**

Essential for the reconstruction of the cone of emission
Combined detection of ionization electrons and UV photons in noble liquids

Eran Erdal, Lior Arazi & Amos Breskin - Weizmann Institute

- Resistive heating wires generate a bubble in Lxe, under a hole-electrode (here GEM).
- CsI photocathode is deposited on top of the GEM.
- Ionization electrons & UV-scintillation photoelectrons from CsI are focused into the hole and drift into the gas bubble.
- Electroluminescence in the bubble generates light → imaged by a photosensor (here PMT), e.g. SiPMs.

Electroluminescence distributions:
Ionization $S_2$ (by $\sim 10^4$ ionization electrons) & UV-induced $S_1'$ (by $\sim 5 \times 10^3$ photoelectrons).

- **A “local dual-phase” TPC for $e^-$ & $h
$
- **Main potential application: future 50 ton LXe DARWIN Dark-Matter Observatory** Aalbers, JCAP11(2016)017
- **Current R&D: localization, LAr etc.**

Electroluminescence-photon yield from different LHM hole-electrodes.
Best: $\sim 420$ photons/e/$4\pi$ from a single-conical GEM
FAT-GEM - electroluminescence

novel scintillating structures developed at Santiago

Diego Diaz et al. (IGFAE)

FAT-GEM: a ‘super-thick’ (5mm) acrylic-based GEM with semitransparent ‘gate’ plane

several geometries procured at the RD51 workshop for optimization

main characteristics of FAT-GEM
(Field-Assisted Transparent Gaseous Electroluminescent Multiplier)

- Transparent.
- Homogeneous (advantageous for CNC-drilling).
- Inexpensive.
- Customizable (e.g., allows resistive or wavelength-shifting coatings)
- Robust against discharges (and very low capacitance).
- Easy to scale.
- Versatile: spectrum of emission can be easily tuned.
- Compatible with high-pressure operation.
- Ultimate energy resolution close to Fano factor, position resolution: mm-scale.

preliminary results in Ar/Xe at ~90/10 (10 bar)
• Two CERN R&D collaborations (RD26 & RD51) have provided the main tools for the breakthrough in the development of CsI based gaseous photomultipliers for RICH detectors in the view of the new challenges for high luminosity:
  – **RD26** for the understanding and the development of CsI based photocathodes
  – **RD51** for the development of structures for high electron amplification and strong mitigation of the limiting effects: photon feedback & ion back flow

• These developments also lead to unique applications in the detection of UV and VUV photons with an outstanding performance

• There is a strong competition in the visible region, however, when considering large area and the need of a good position resolution, GPM may be considered as the right choice
Thank you

Acknowledgements:
for all authors who have contributed for this talk