Alkali-antimonide Photocathodes for Gas-Avalanche Photomultipliers

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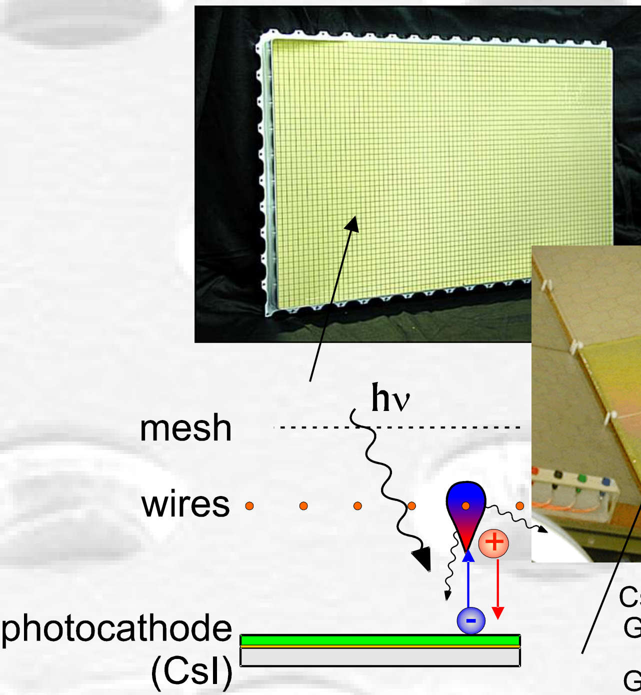
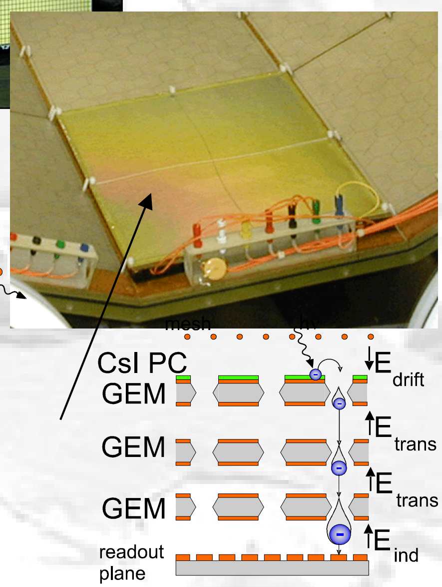
Recent review on GPMs: Chechik & Breskin NIM A595 (2008) 116
Summary article visible-light GPM: Lyashenko et al. JINST 4 (2009) P07005

Gaseous Photo-Multipliers (GPM)

UV-exist:
ALICE, HADES, COMPASS, J-LAB, PHENIX



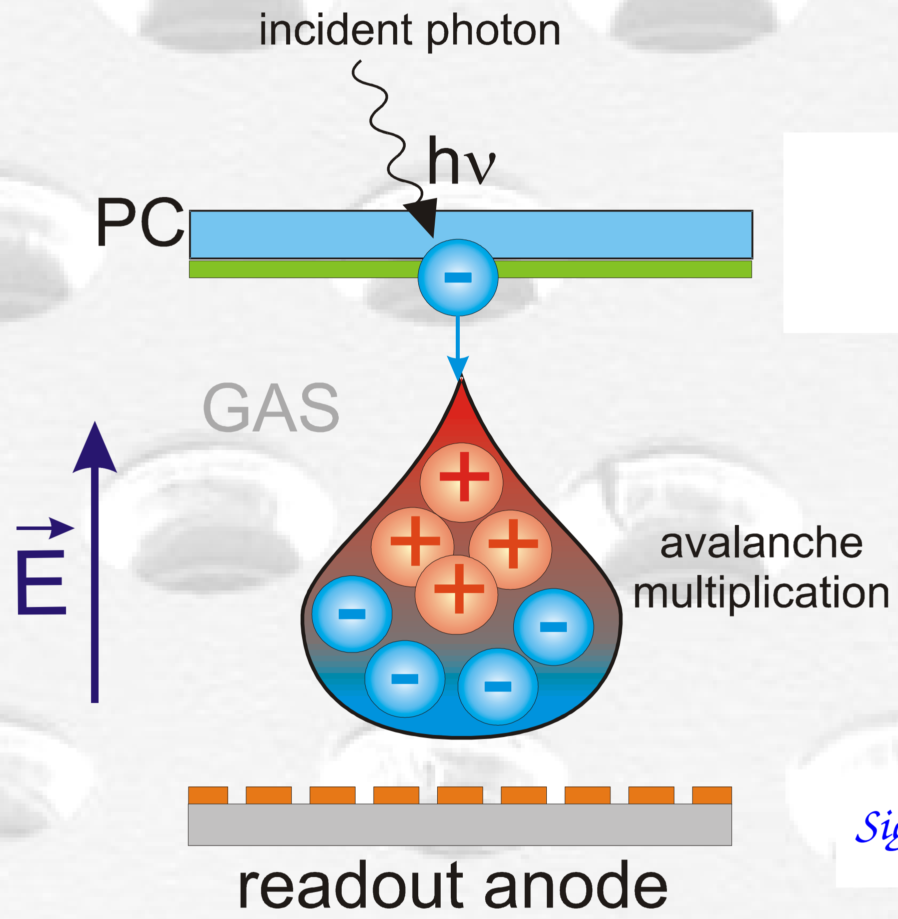


Visible-in course

Motivation:

- **large areas**, *flat geometry*
- *operation in magnetic fields*
- *sensitivity to single photons*
- **visible spectral range**
- *fast (ns range)*
- *high localization accuracy (sub-mm range)*

Principles of GPM operation

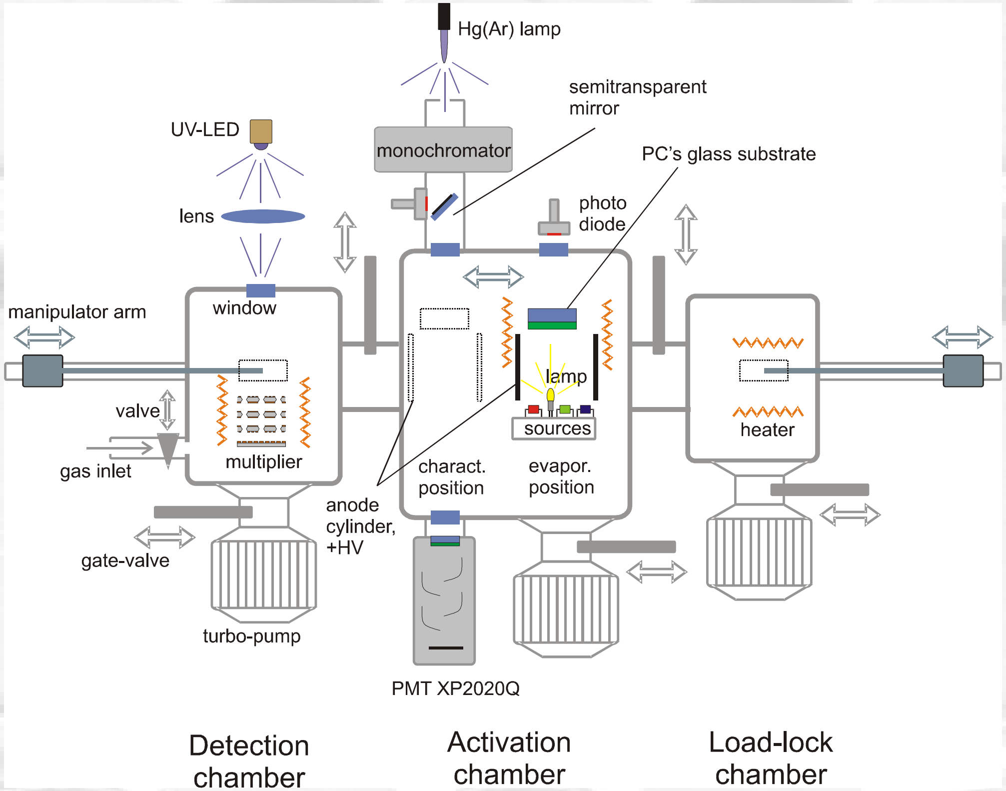


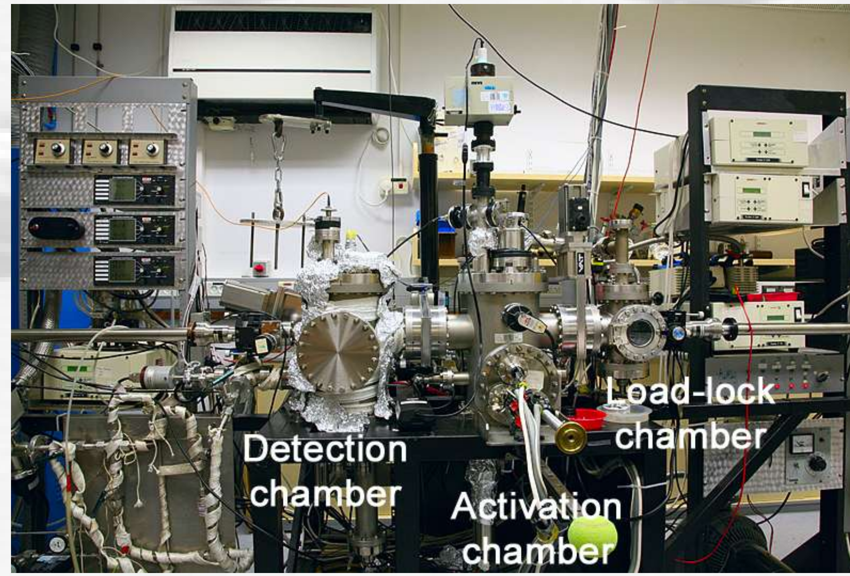
Photoelectron emission from photocathode

Avalanche charge multiplication in gas

Signal recording

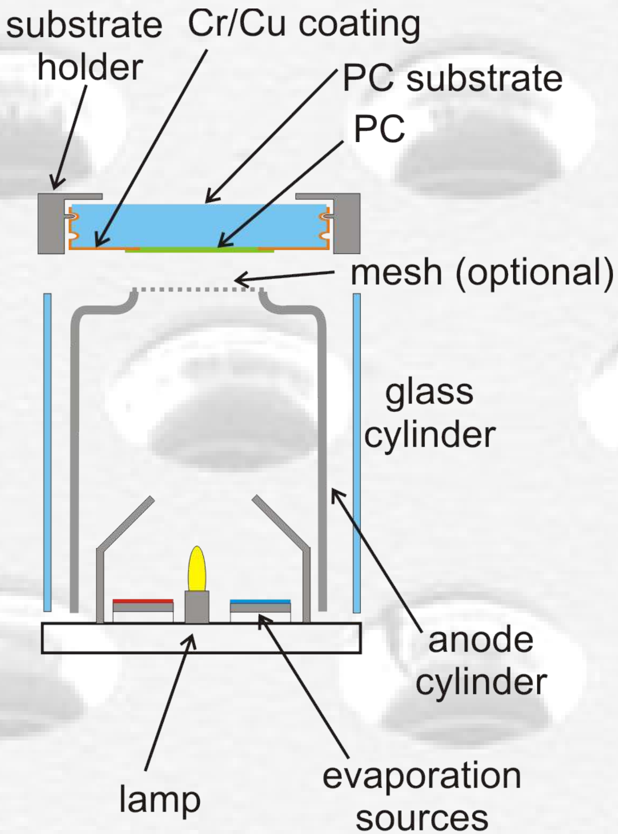
Multi-chamber UHV setup

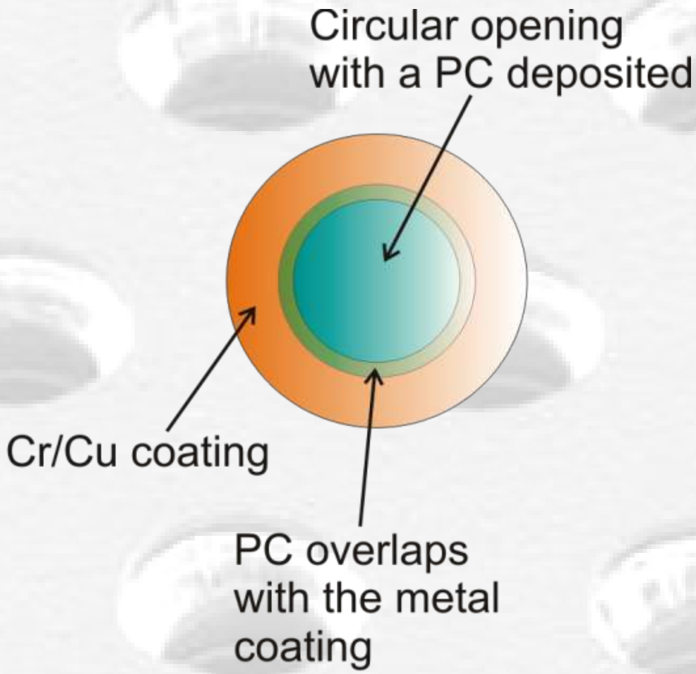




- **Alkali-antimonide pc production** *(QE 20-50% @ 350-400nm in vacuum for semi-transparent PC)*
- **Hot Indium sealing** *to package @130-150ºC => critical for pc*

PC fabrication process:





- *PC substrate treatment in air*
- *PC substrate treatment in vacuum (usually baking at 270-300^{0}C)*
- *Evaporation of alkali-metals*

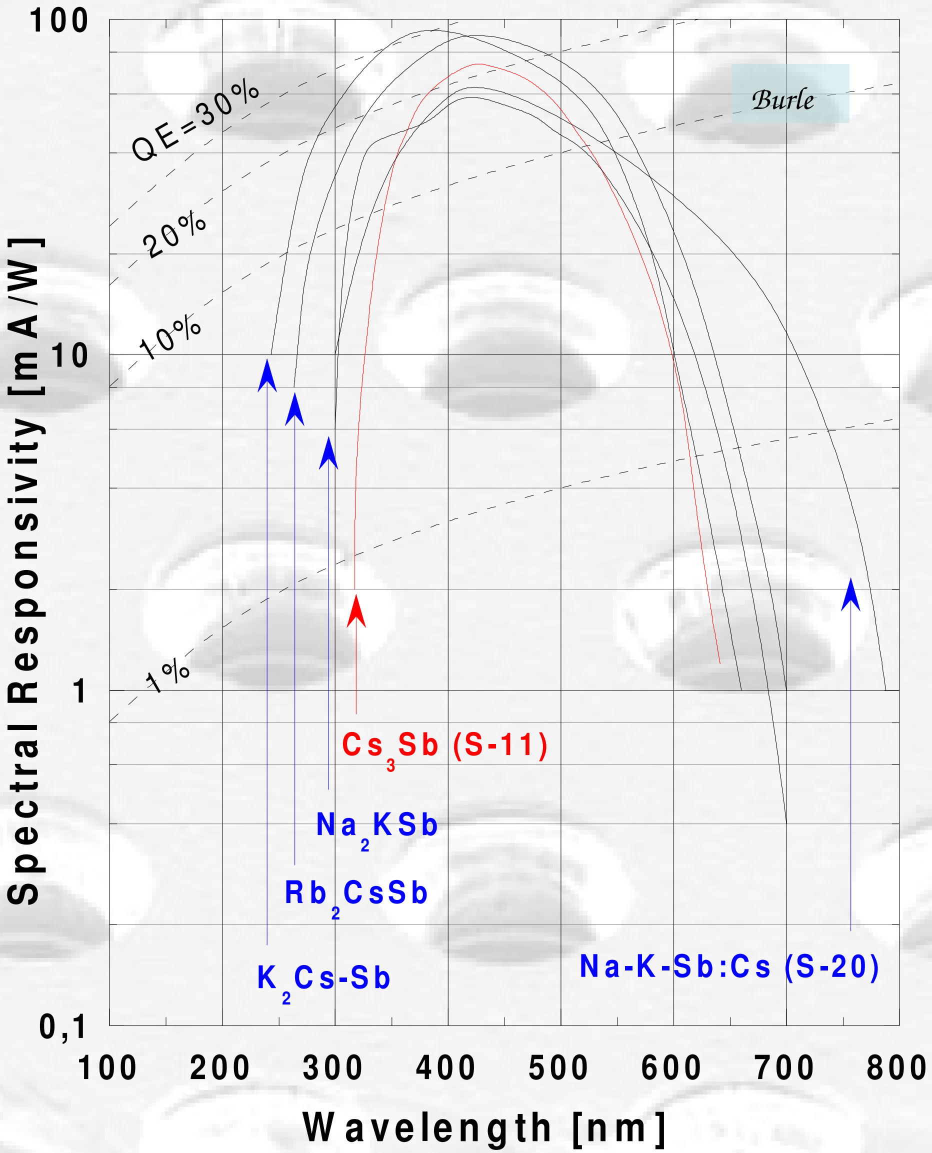
PC sensitivity

Long term stability

Designation: S-11

Activation steps:

1. Evaporation of **Sb** at 180-200^{0}C onto a substrate until it looses ~20% of its transparency
2. Exposure to **Cs** at 150-180^{0}C until the maximum of photocurrent is reached.
3. Post-treatment if needed (removing of excess of **Cs** by baking at ~200^{0}C)



Activation time: 30-60 min

PC characteristics (typical):

- Wavelength of max response: λ_{max}=370-400nm
- Luminous sensitivity: 100-120μA/lm
- Responsivity at λ_{max}: 65-75mA/W
- QE at λ_{max}: 20-25%
- Dark emission current at 25^{0}C: ≤0.1fA/cm^2
- Surface resistance at 25^{0}C: 3*10^7 Ohm/square

Large area: YES

Photocathodes: K_2CsSb

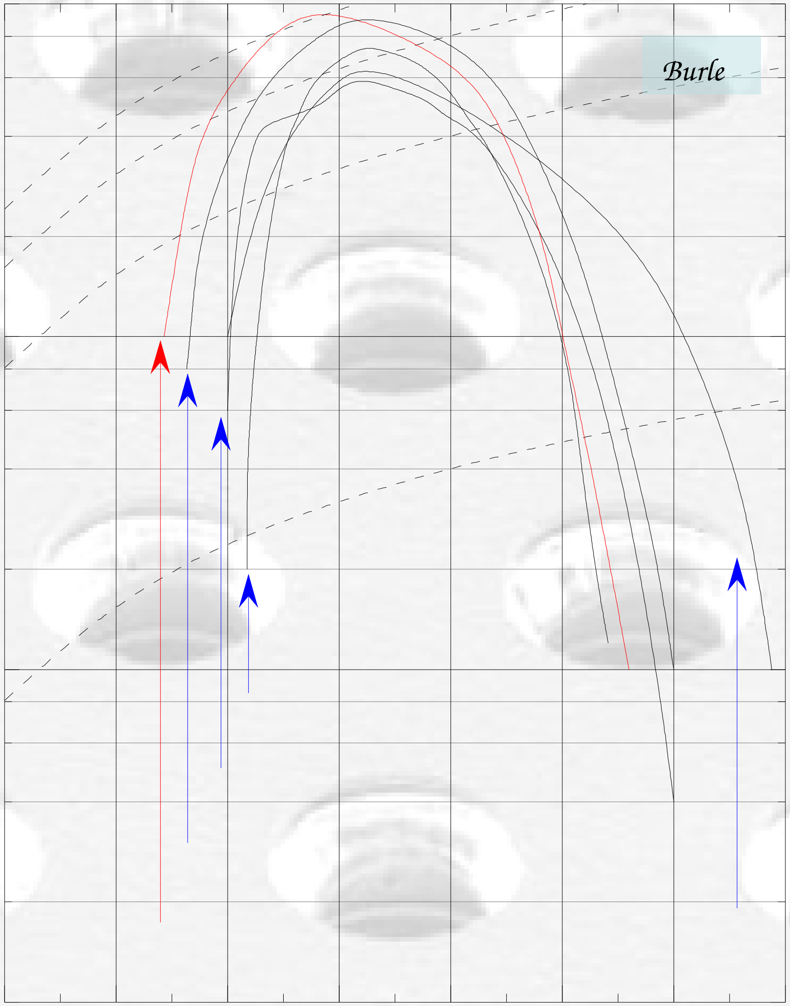
Activation steps:

One possibility:

1. Evaporation of **Sb** at 180-200^{0}C onto a substrate until 20% of transparency is lost
2. Exposure to **K** at 160-200^{0}C until the maximum of photocurrent is reached (formation of K_3Sb PC).
3. Repetitive (yo-yo) exposure to **Cs** & **Sb** at 180-225^{0}C until the maximum of photocurrent is reached.

Another possibility:

So called co evaporation



PC characteristics (typical):

- Wavelength of max response: λ_{max}=380-420nm
- Luminous sensitivity: 70-100 μA/lm
- Responsivity at λ_{max}: 100mA/W
- QE at λ_{max}: >30%
- Dark emission current at 25^{0}C: ≤0.01fA/cm^2
- Surface resistance at 25^{0}C: 6*10^{9}Ohm/square

Features: Very high surface resistance

Large area: YES, needs a conductive layer

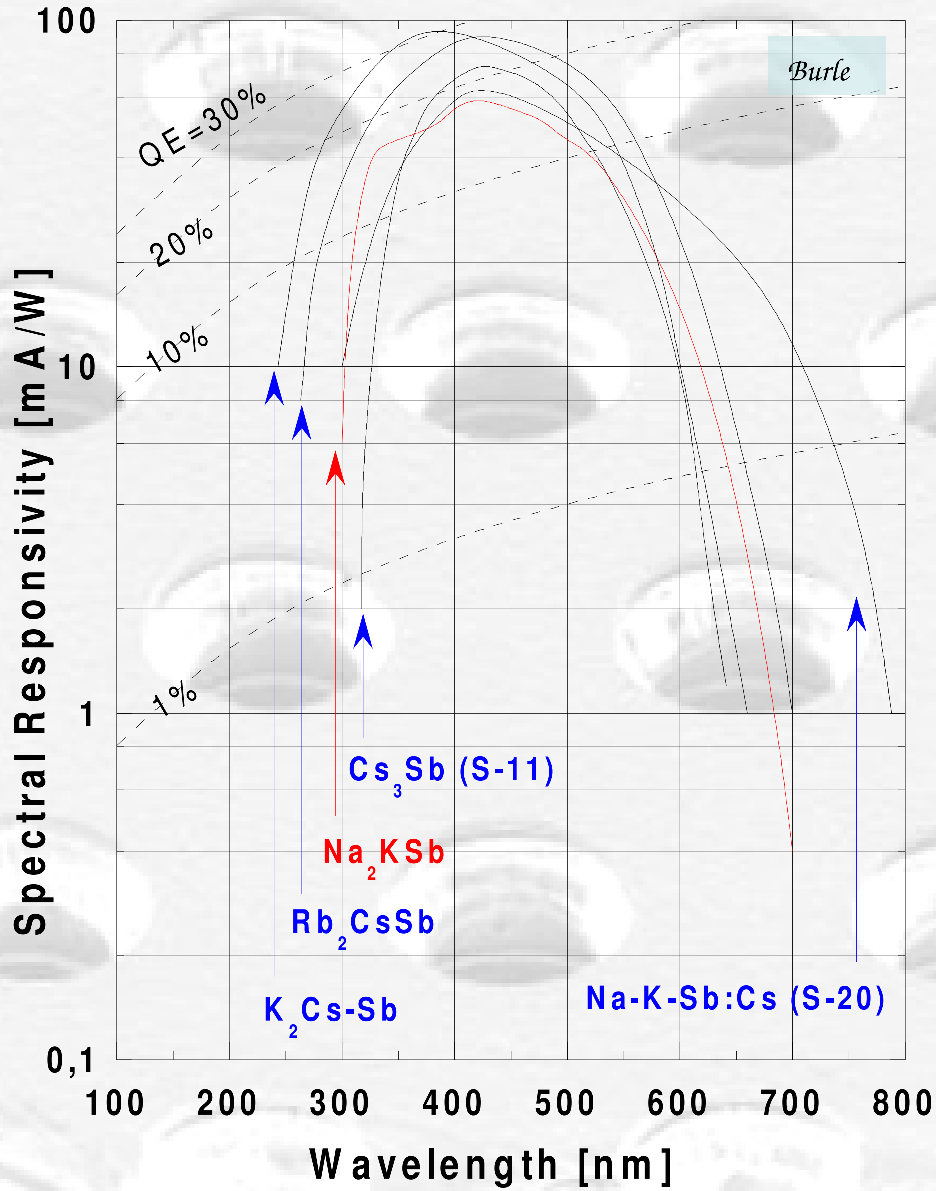
Activation steps:

1. *Evaporation of* **Sb** *at 180-200°C on substrate until it looses 20% of its transparency*
2. *Exposure to* **K** *at 160-200°C until maximum photocurrent reached* (**K_3Sb**).
3. *Exposure to* **Na** *at ~220°C until the raise of PC current start slowing down*.*
4. *Alternating addition of* **Sb** *and* **K** *at ~160-180°C until maximum photocurrent reached.*

* *Simultaneous evaporation of K and Na is possible*

PC characteristics (typical):

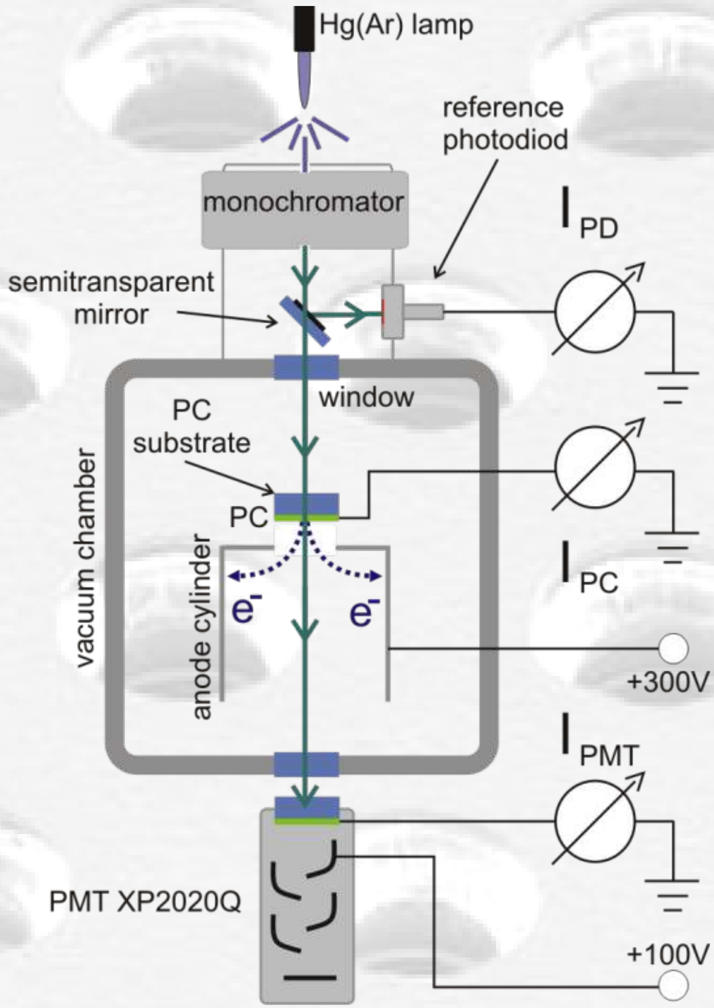
- *Wavelength of max response:* λ_{max}=380-410nm
- *Luminous sensitivity:* 65-80μA/lm
- *Responsivity at* λ_{max}: 64mA/W
- *QE at* λ_{max}: 19-21%
- *Dark emission current at 25°C:* **≤0.0001fA/cm²**
- *Surface resistance at 25°C:* $2*10^6$ Ohm/square



Features: *Outstanding temperature stability (up to 200°C),* **lowest dark current**

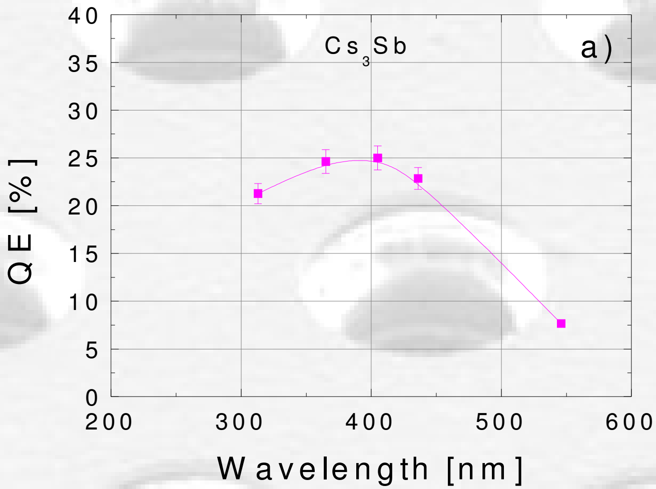
Large area: *YES, but production is rather complicated, QE< other Bi-alkali.*

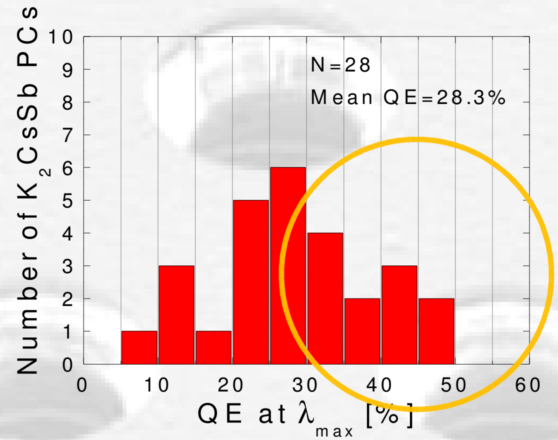
PC characterization

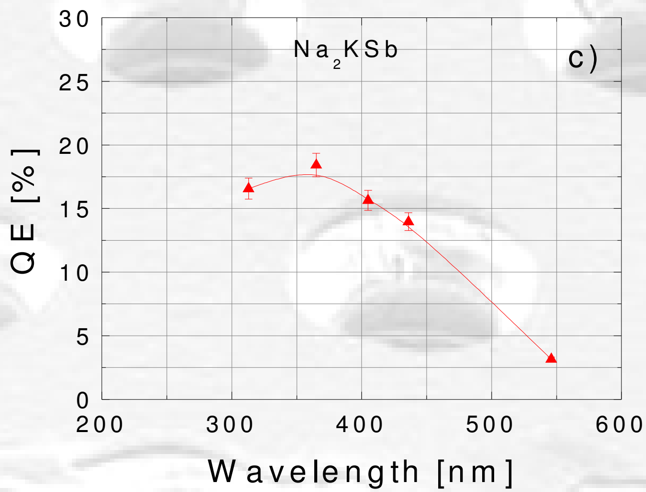


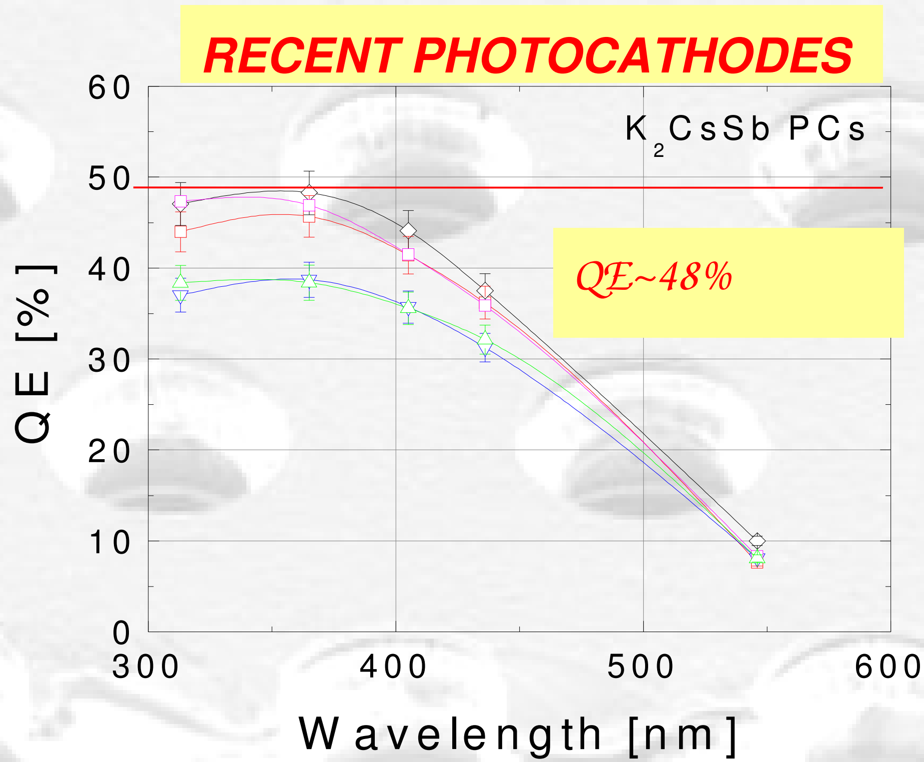
$$QE(\lambda) = \frac{I_{PC}(\lambda) - I_{PC}^{dark}(\lambda)}{I_{PMTtrans}(\lambda) - I_{PMTtrans}^{dark}(\lambda)} \cdot \frac{I_{PDtrans}(\lambda) - I_{PDtrans}^{dark}(\lambda)}{I_{PD}(\lambda) - I_{PD}^{dark}(\lambda)} \cdot T_W(\lambda) \cdot QE_{PMT}(\lambda)$$

QE of alkali-antimonide photocathodes

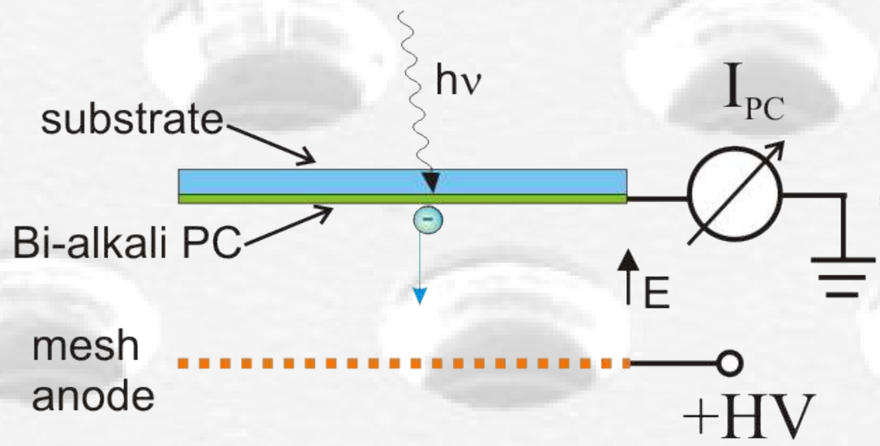


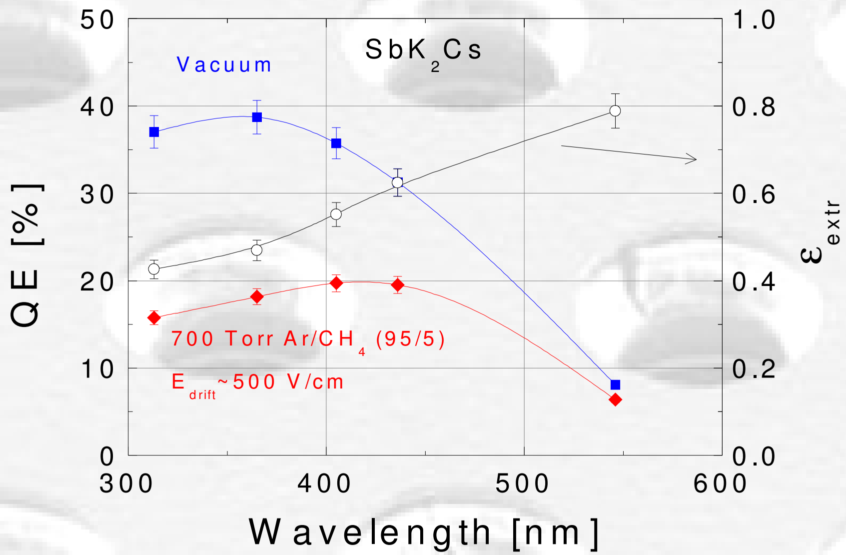


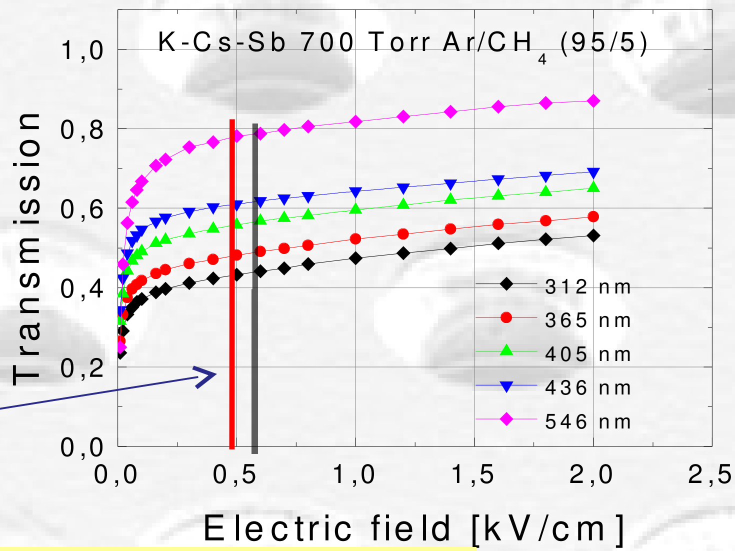




Photoelectron extraction from bi-alkali PC into gas



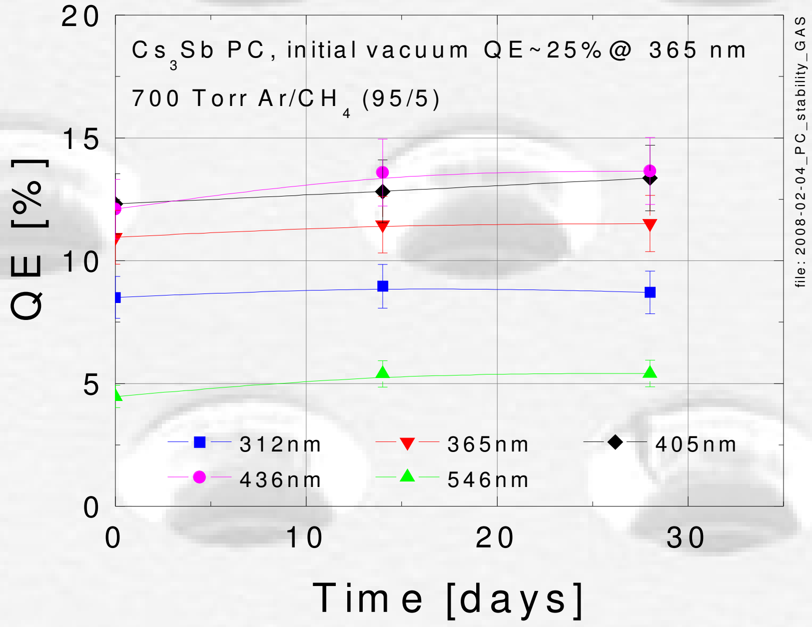


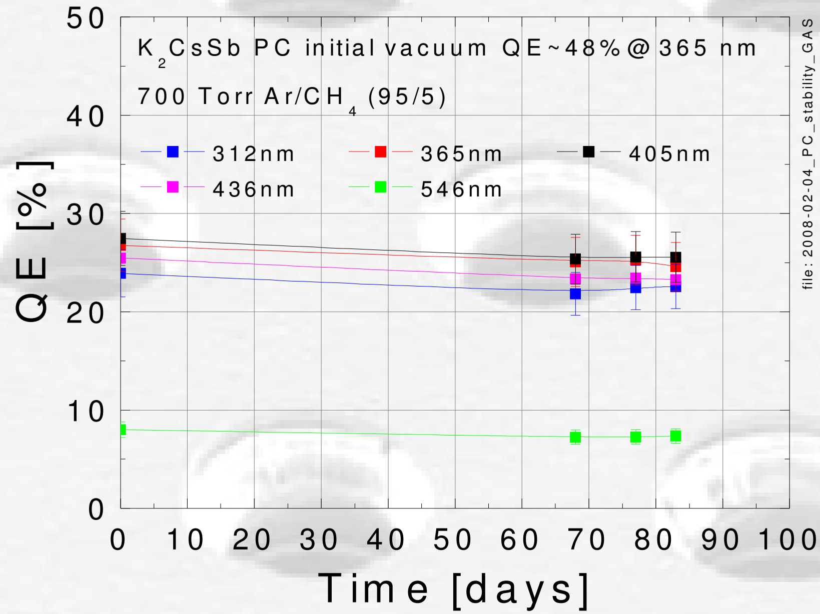


Optimal field for GPM

Higher transmission in other gases, e.g. CH4

Long-term photocathode stability in gas



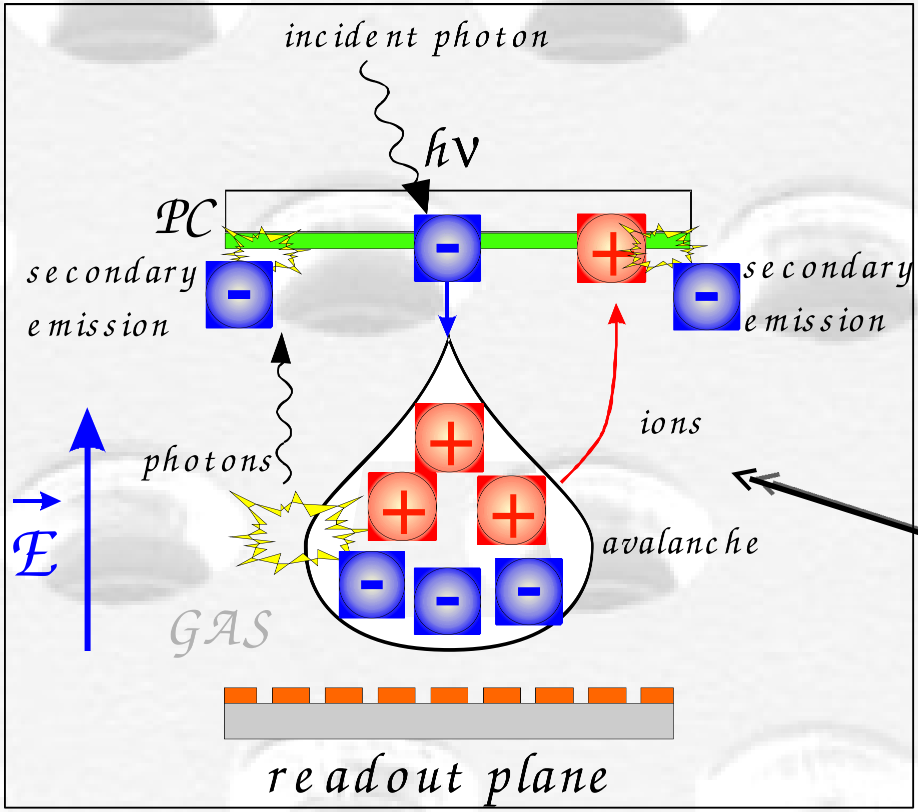


PC is stable in gas in the large vacuum chamber

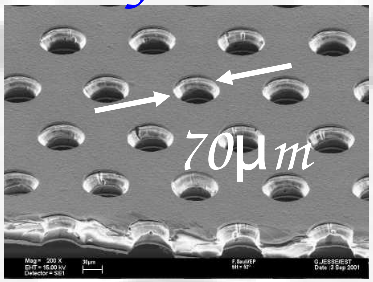
Expected even better stability for sealed devices

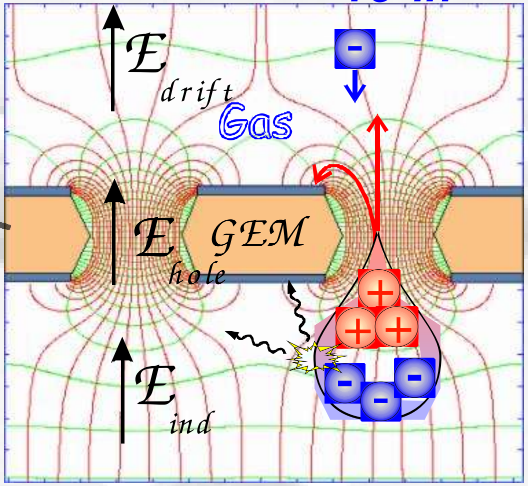
Secondary effects in visible-sensitive GPMs

Gaseous Photo-Multiplier (GPM)



GEM*





Main problem: Ions & photons →
- → **secondary e emission**
- → **ion/photon feedback pulses**
- → **gain & performance limitations**

Photon feedback is largely reduced
PC masked by electrode

*GEM: Gas Electron Multiplier - Sauli, NIM A 386, (1997) 531.

IBF: Ion Back-Flow Fraction

IBF: The average fraction of avalanche-generated ions back-flowing to the photocathode

➔ **Major efforts to limit ion backflow**

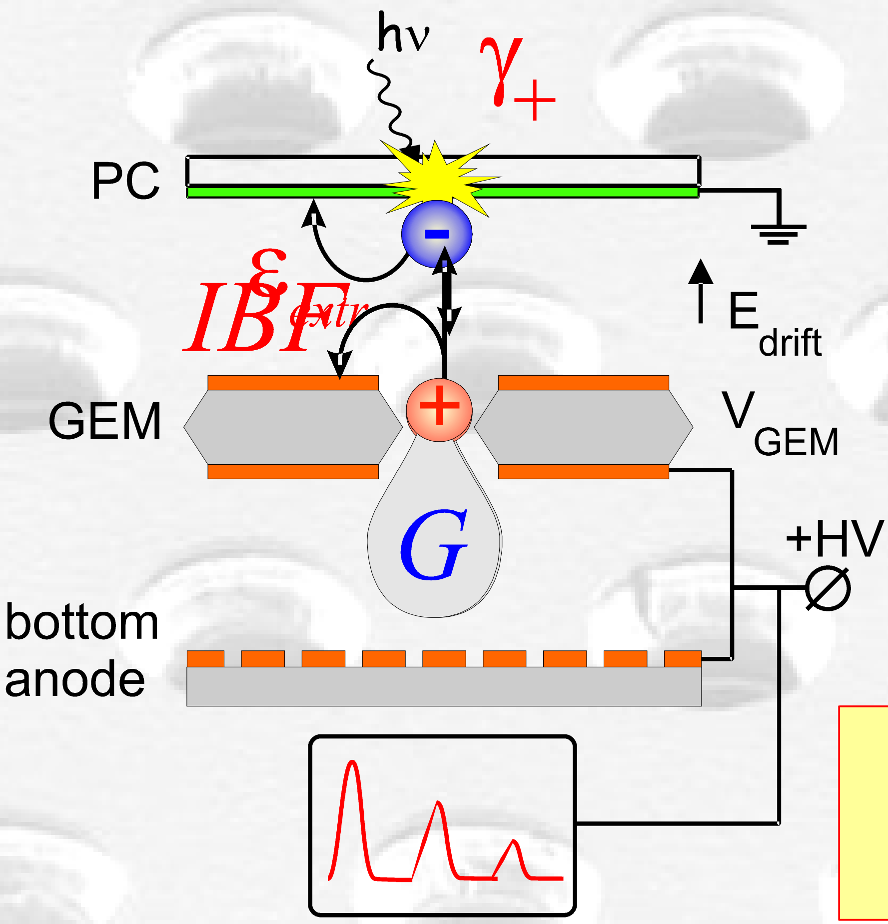
GATING .1➔ operation in “gated-mode”➔ deadtime, trigger

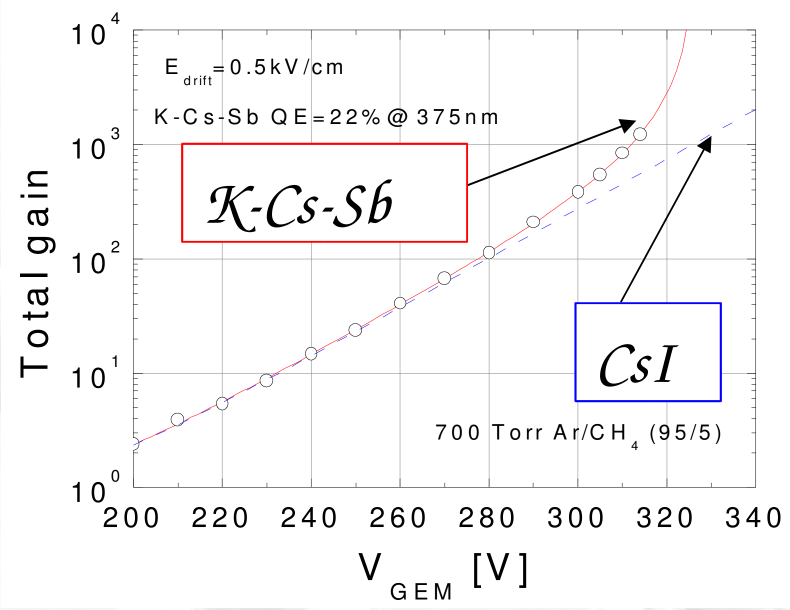
NEW e .2$^-$ - MULTIPLIERS➔ operation in continuous mode

) OTHERScascaded-GEM, MICROMEGAS…&:(

➔ **Challenge: BLOCK IONS WITHOUT AFFECTING ELECTRON COLLECTION**

Visible-sensitive GPM: Ion-feedback development





K-Cs-Sb, Na-K-Sb, Cs-Sb : Current deviates from exponential
Max Gain ~ few 100, IBF~10%

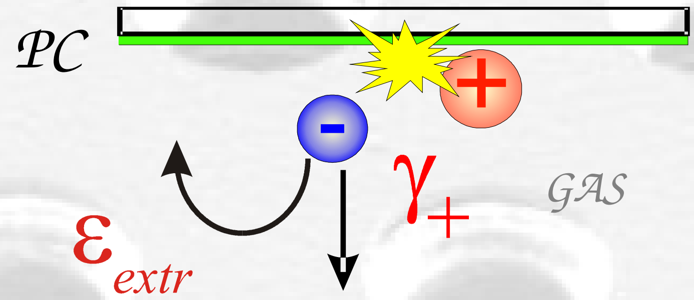
if $\gamma_+^{eff} \cdot IBF \cdot G < 1$ ➔ *stable operation of visible sensitive GPM*

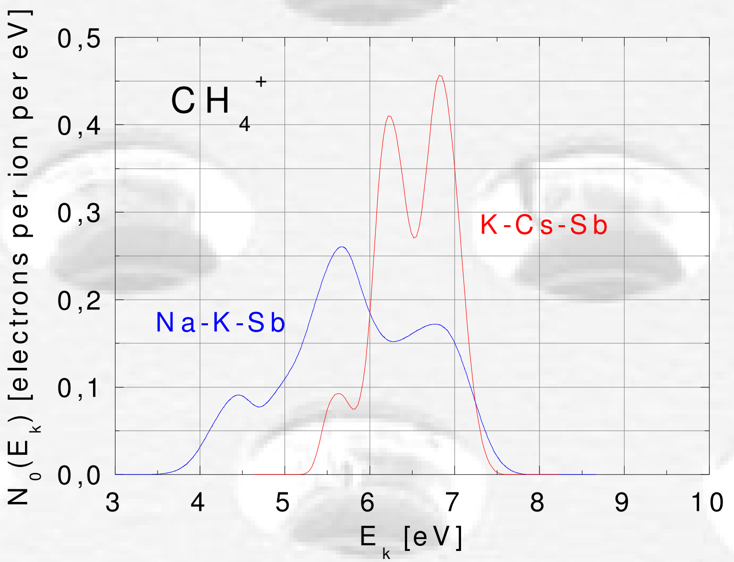
$G \sim 10^5$, γ_+^{eff} - ?, IBF - ?

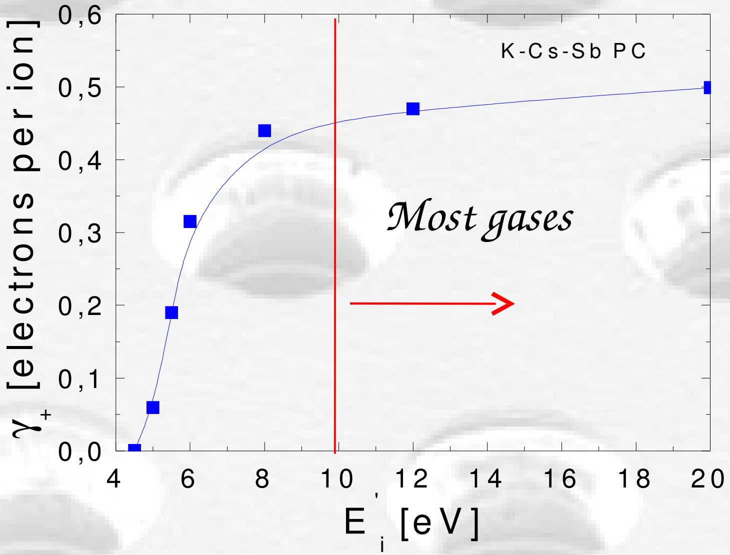
Visible-sensitive gas photomultiplier review:
M. Balcerzyk et al., IEEE Trans. Nucl. Sci. Vol. 50 no. 4 (2003) 847

Calculation of ion induced secondary emission probability from bi-alkali PCs $\gamma_+^{eff} = \gamma_+ \cdot \epsilon_{extr}$

Auger neutralization + Backscattering



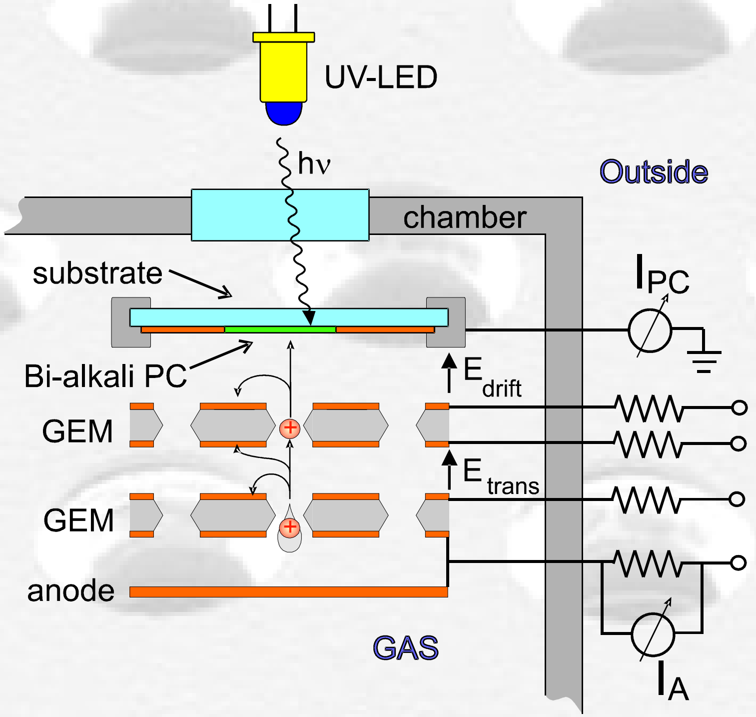




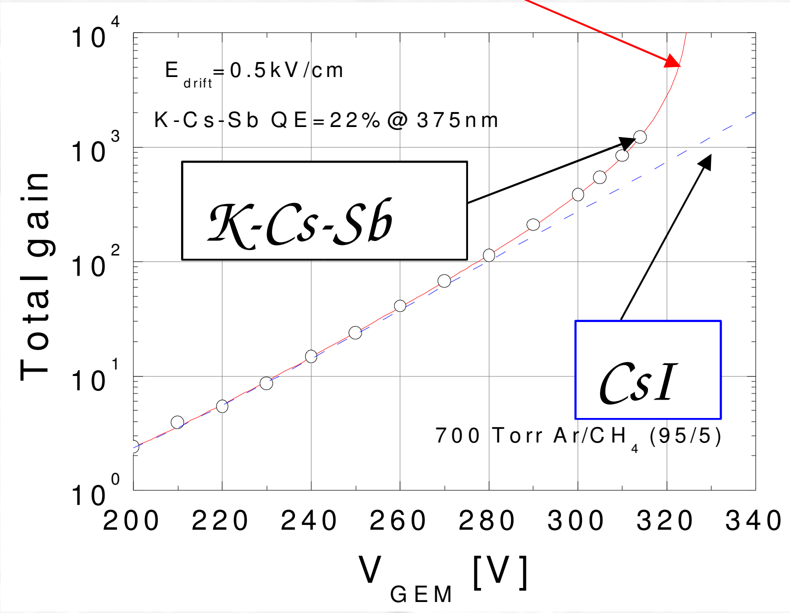
PC	K-Cs-Sb	Na-K-Sb
γ_+^{eff}	0.027	0.029

A.Lyashenko et al., J. Appl. Phys. (2009) accepted, **arXiv:0904.4881**

Measurements of $\gamma_+^{eff}=\gamma_+\cdot\epsilon_{extr}$

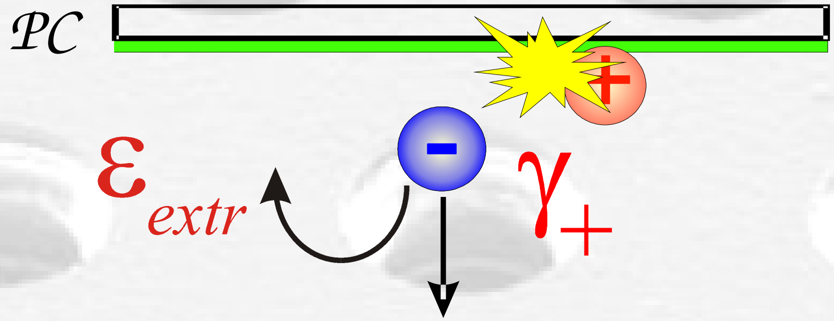


$$G_{meas}=\frac{G}{1-G\cdot IBF\cdot\gamma_+^{eff}}$$



PC	K-Cs-Sb	Na-K-Sb
γ_+^{eff} (experiment)	0.03±0.01	0.02±0.006

Effective IISEE from K-Cs-Sb and Na-K-Sb PCs



$$\gamma_{+}^{eff} = \gamma_{+} \cdot \epsilon_{extr}$$

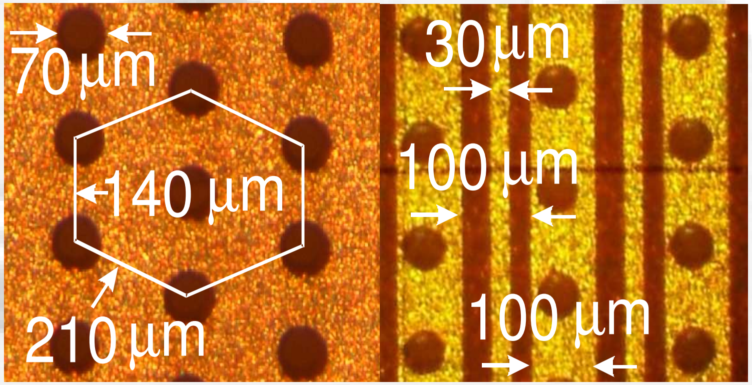
PC	*K-Cs-Sb*	*Na-K-Sb*
Ion	CH_4^+	CH_4^+
γ_+^{eff} (exp)	*0.03±0.01*	*0.02±0.006*
γ_+^{eff}(theory)	*~0.03*	*~0. 03*

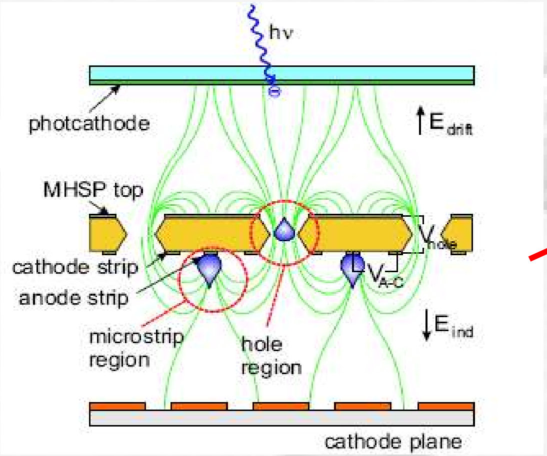
if $\gamma_{+}^{eff} \cdot IBF \cdot G < 1$ ➔ *stable operation of visible sensitive GPM*

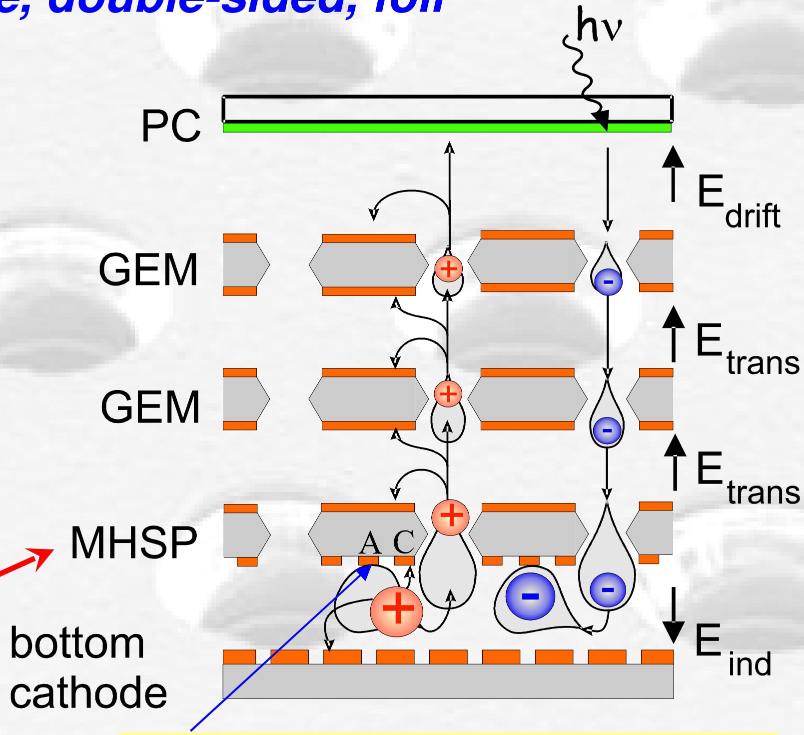
Ar/CH_4 (95/5), γ^{eff}_+ ~0.03, Gain ~ 10^5 => IBF < 3.3*10^{-4}

The Microhole & Strip plate (MHSP)

Two multiplication stages on a single, double-sided, foil







Strips: multiply charges

7 times lower IBF than with cascaded GEMs

R&D: Weizmann/Coimbra

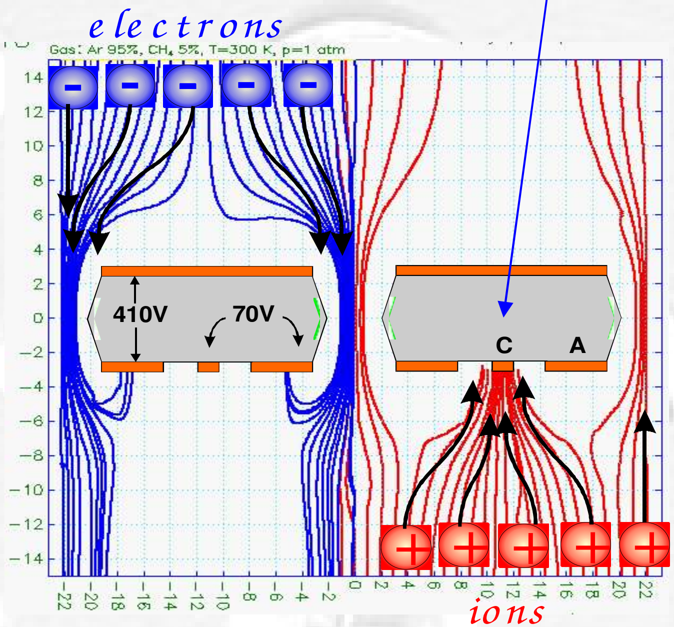
Veloso et al. Rev. Sci. Inst. A 71 (2000) 237.

Reverse-biased MHSP (R-MHSP) concept

Ions are trapped by negatively biased cathode strips

Strips: collect ions

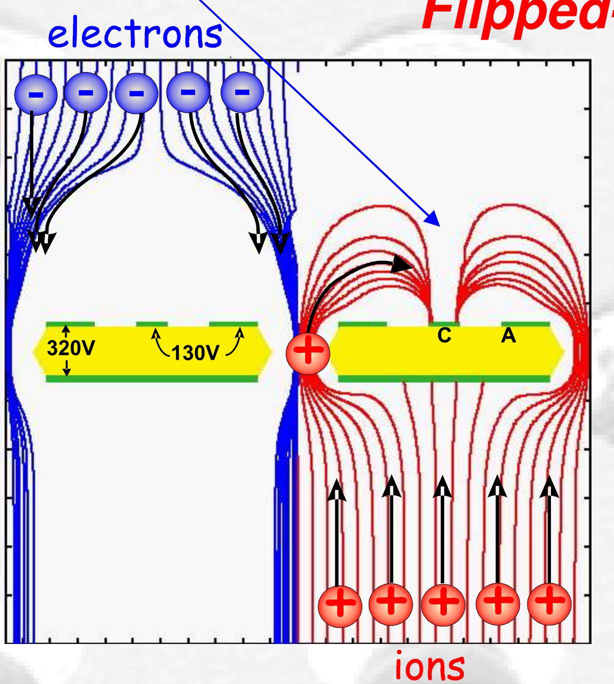
R-MHSP



Can trap only ions from successive stages

Roth, NIM A535 (2004) 330
Breskin et al.NIM A553 (2005) 46
Veloso et al. NIM A548 (2005) 375

Flipped-R-MHSP

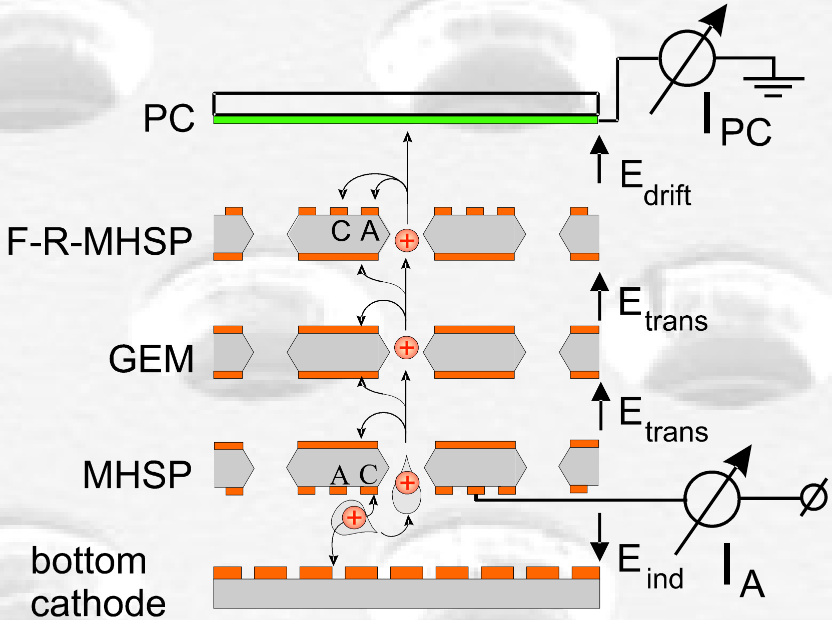


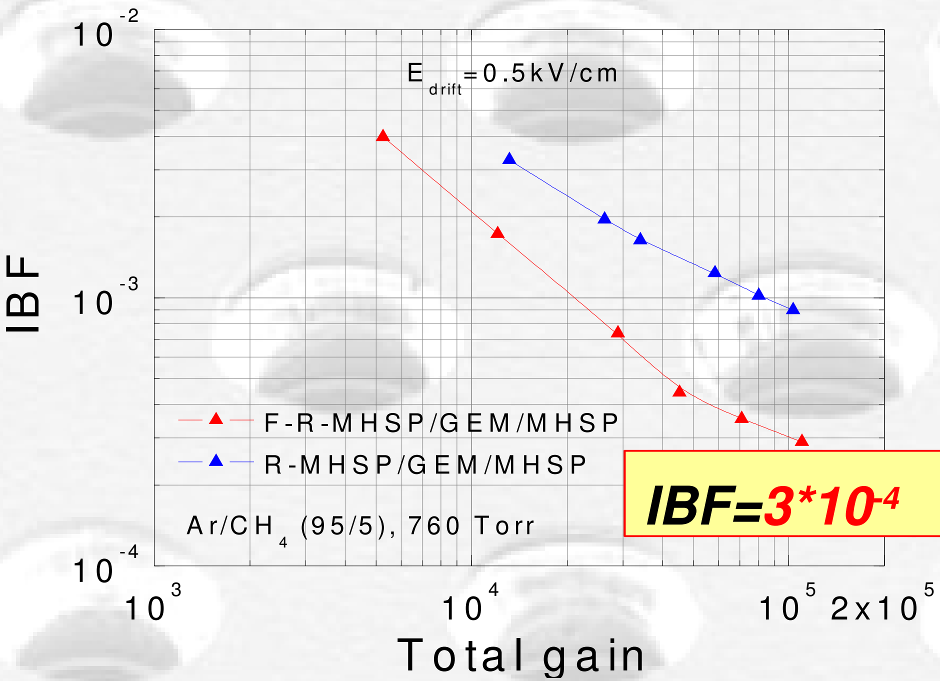
Can trap its own ions

Lyashenko et al., JINST (2006) 1 P10004
Lyashenko et al., JINST (2007) 2 P08004

BEST ION BLOCKING: :COMPOSITE" CASCADED MULTIPLIERS"

1st R-MHSP or F-R-MHSP: ion defocusing (no gain!)
Mid GEMs: gain
Last MHSP: extra gain & ion blocking





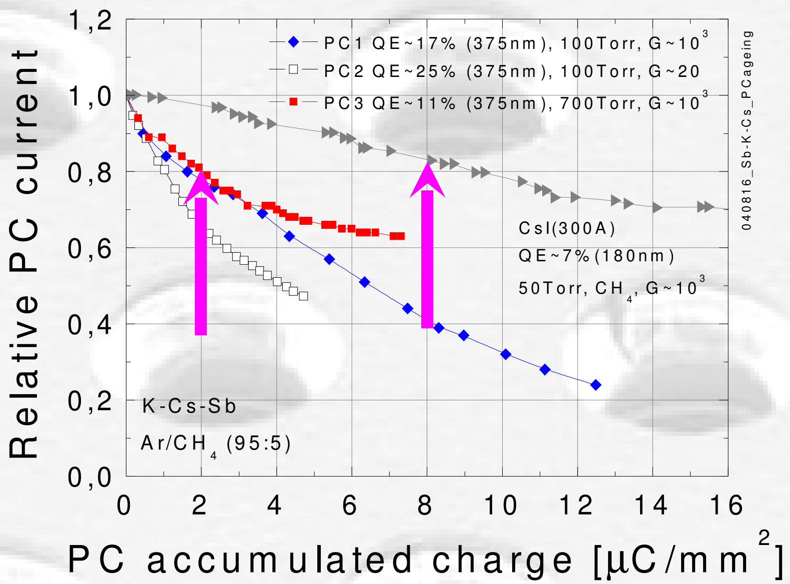
IBF=3*10^{-4}

IBF measured with 100% e-collection efficiency

IBF=3*10^{-4} @ Gain=10^5 is 100 times lower than with 3GEMs

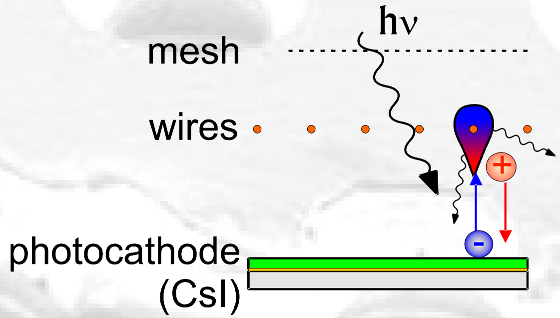
Lyashenko et al., JINST (2007) 2 P08004

K-Sb-Cs PC ageing in avalanche mode



- *20% QE drop @ 2 μC/mm² ion charge on photocathode:*
- *only ~ 4 x faster drop compared to thin ST CsI (~8 μC/mm²)*

Real conditions: *gain=10⁵*; **IBF=3*10⁻⁴**.
•20% QE drop **46 years** *@ 5kHz/mm² ph.*
same conditions with a MWPC (**IBF~0.5**)
→ *3000 times shorter lifetime:* **~5 days!**

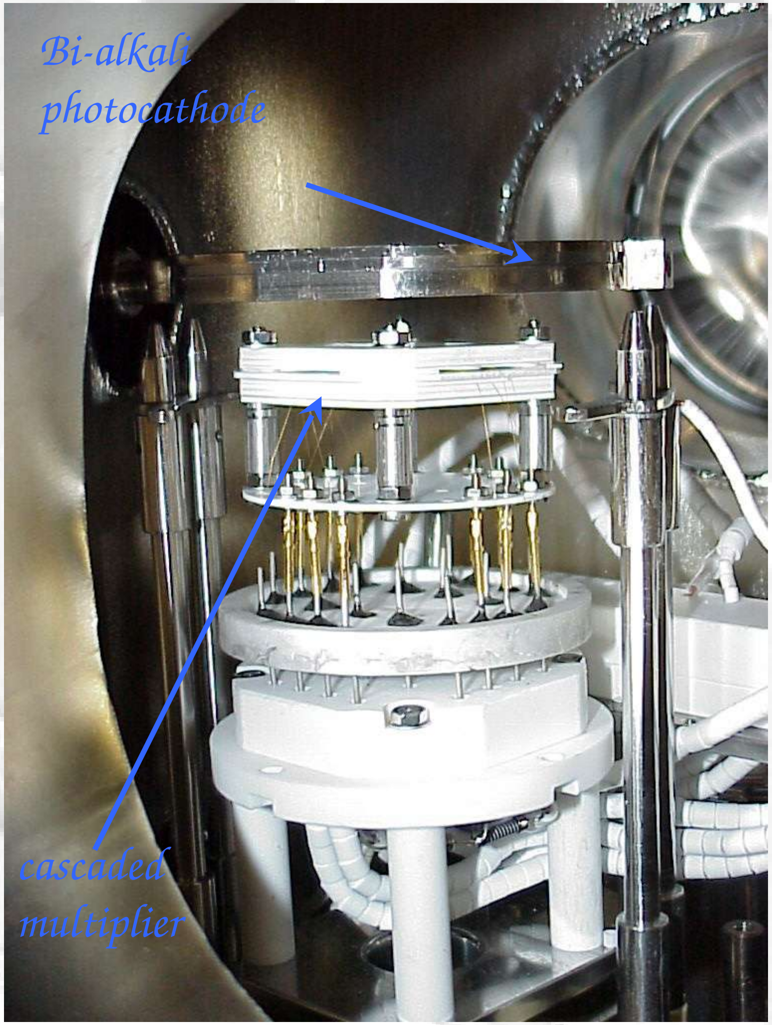


A. Breskin al. NIM A553 (2005) 46

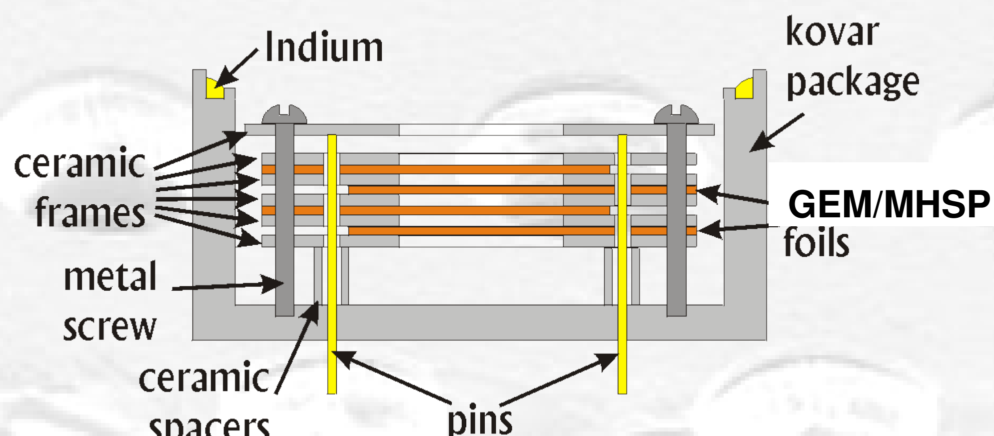
Visible-sensitive GPM

UHV compatible materials

Test detector setup

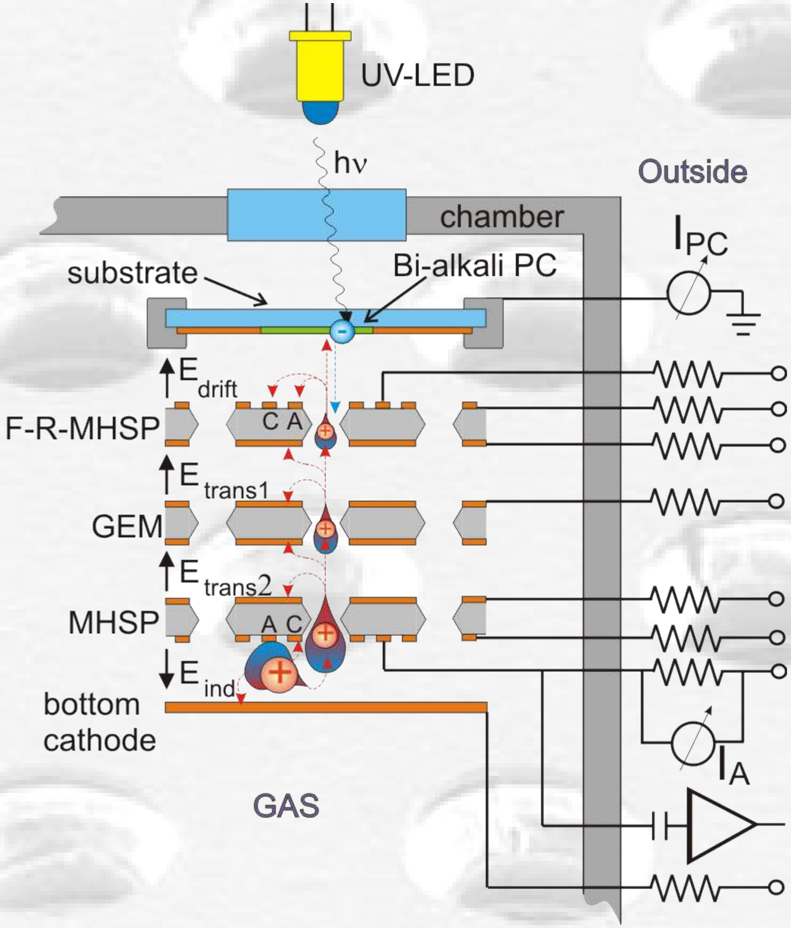


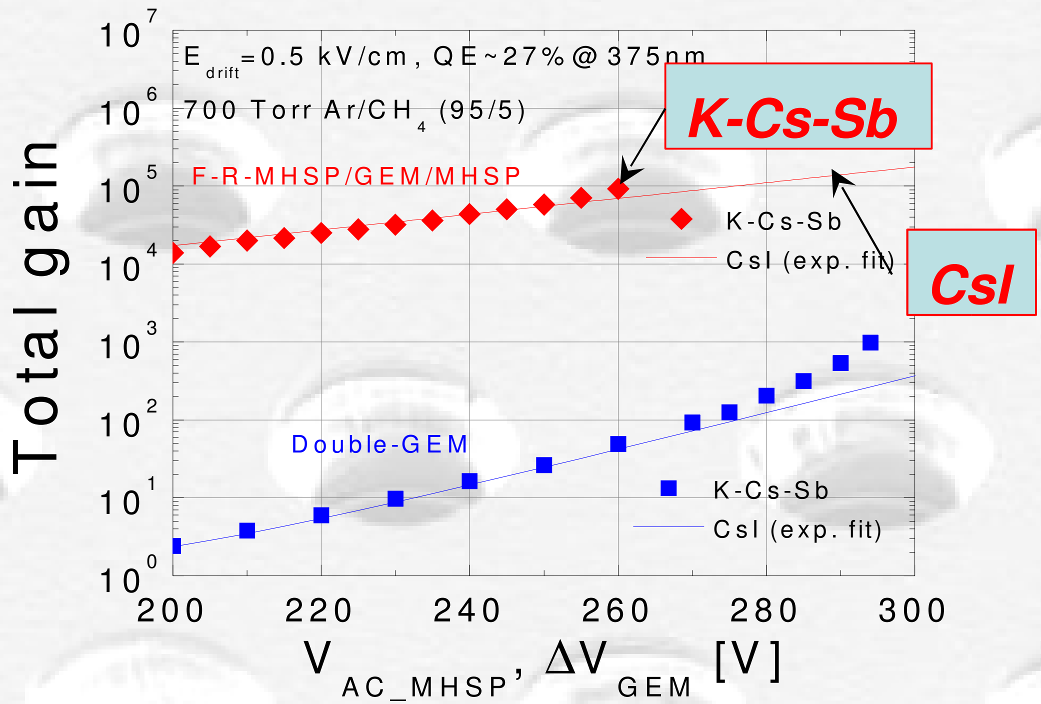
Sealed detector



M. Balcerzyk et al., IEEE Trans. Nucl. Sci. Vol. 50 no. 4 (2003) 847

Continuous operation of F-R-MHSP/GEM/MHSP with K-Cs-Sb photocathode



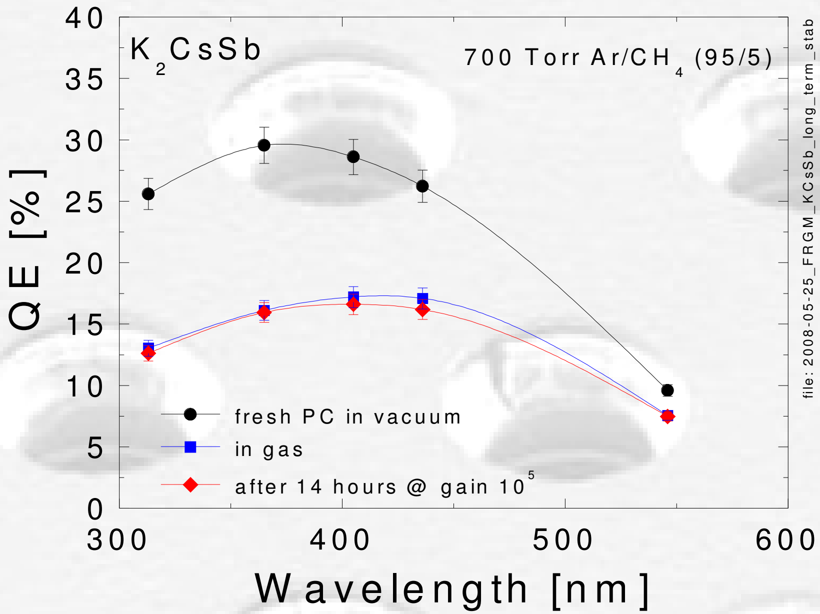


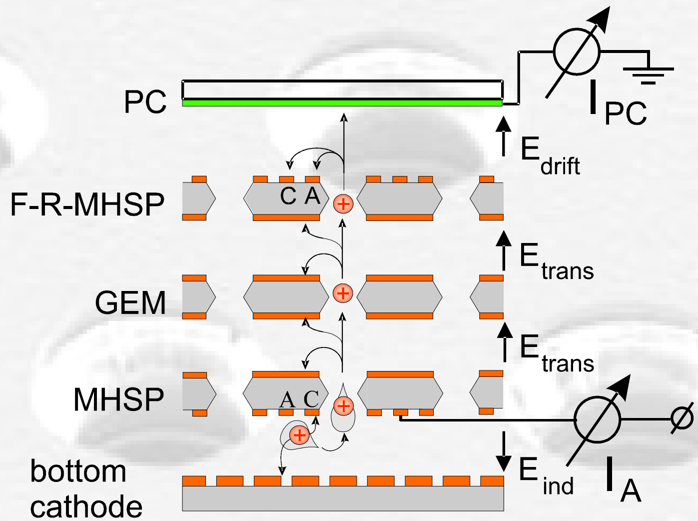
Gain ~10^5 at full photoelectron collection efficiency

First evidence of continuous high gain operation of visible-sensitive GPM

Lyashenko et al., JINST (2009) 4 P07005

Short-term GPM stability



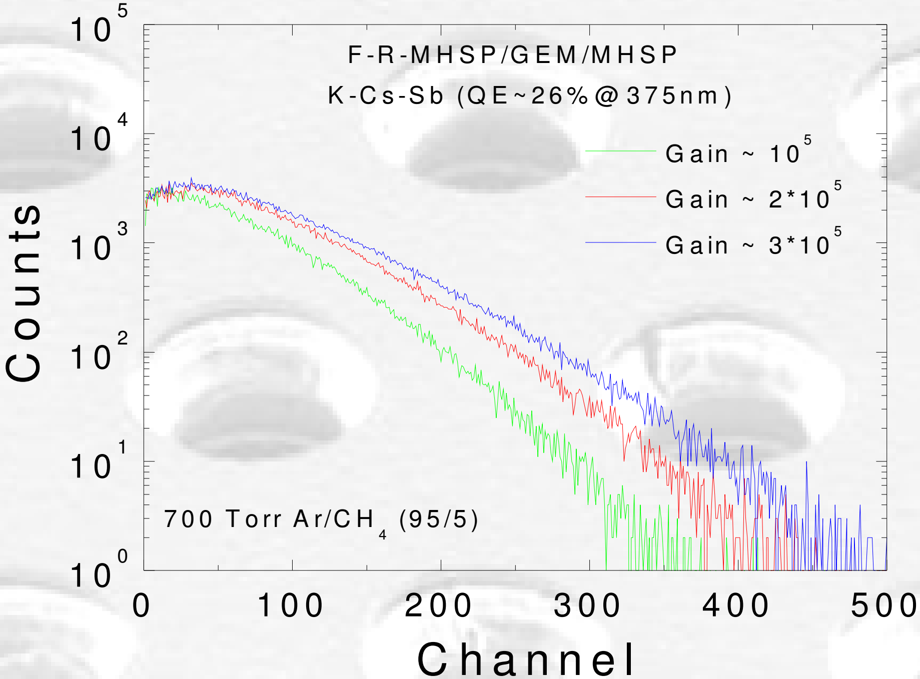


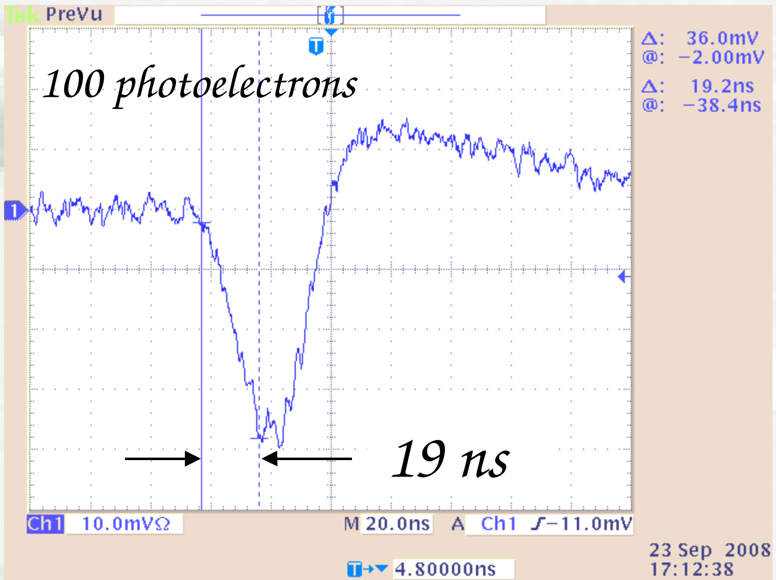
Rate: 12kHz/mm² photons

Gain: 10^5

Total anode charge ~125μC

Visible-sensitive GPM features





Single photon sensitivity
No ion-feedback

Fast ns pulses

Summary

Alkali-antimonide PCs for GPMs

High (>40%) QE values reached

Stability in gas verified

Probability of IISEE evaluated → Required IBF estimated

MHSP/GEM-based CASCADED MULTIPLIERS

- 100 times lower IBF than with cascaded GEMs with full efficiency for collecting primary electrons!
- Gain ~10^5 reached with visible-sensitive K-Cs-Sb PC
- Demonstrated stable GPM operation at a gain 10^5
- Atmospheric pressure operation → Many potential applications in large-area photon detectors: Particle Physics, Medical Imaging, Astroparticle, Military, Bio

First evidence of high-gain continuous operation of visible-sensitive GPM