Rivelazione di fotoni e PID

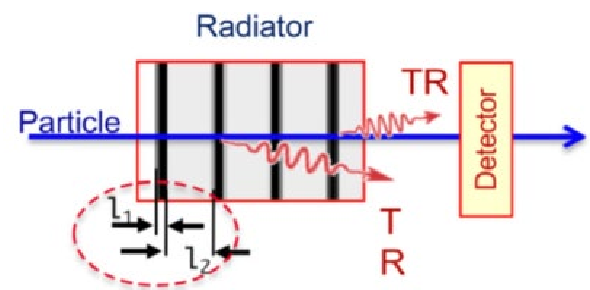
Il campo è vastissimo ed eterogeneo. Scopi, tecniche ed applicazioni diverse.

Sia la PID che la rivelazione di fotoni sono aree di ricerca in vivace sviluppo.

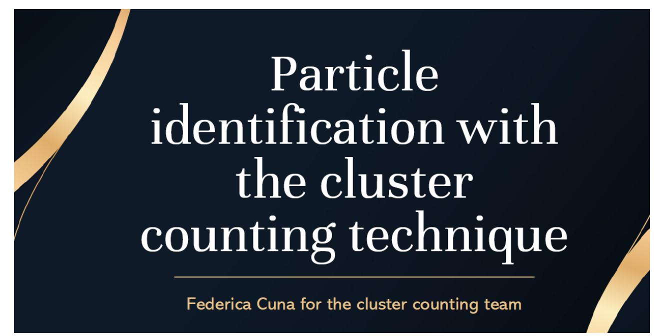
Overlap importanti con altri settori di R&D:
- **PID con componenti solide, liquide, gassose; tecniche comuni ad altri ambiti**
- **i fotosensori sono elementi di altri sistemi di rivelazione.**

Overlap con rivelatori a gas:

Non discutiamo TRD (ATLAS, ALICE, AMS, CBM, EIC, …), tecnologia matura, con alcuni limiti (→GEMs?) Progetto SAS



PID con dE/dx e dN_{cl}/dx molto efficace e molto promettente:
→ Federica Cuna cluster counting technique



Altri overlap:
LGAD,
scintillatori veloci, nuovi materiali ottici,
readout veloce, a basso consumo, …

ECFA roadmap preparation

A symposium for TF4 was held on 6 May 2021 for community consultation and discussion

09:00 → 09:25	Intoduction and overview	Speaker: Neville Harnew (University of Oxford (GB))
09:30 → 10:00	RICH technology requirements & optical elements	Speaker: Carmelo D'Ambrosio (CERN)
10:10 → 10:35	Radiator materials	Speaker: Ichiro Adachi (KEK)
10:45 → 11:00		
11:00 → 11:25	DIRC technology requirements	Speakers: Joachim Schwiening (GSI Helmholtzzentrum für Sc GmbH (DE))
11:35 → 12:00	Time of flight technologies	Speaker: Roger Forty (CERN)
12:10 → 12:35	Gaseous detectors with photocathodes/ MPGDs	Speaker: Fulvio Tessarotto (INFN Trieste)
12:45 → 13:30		
13:30 → 13:55	MCP-PMT technologies	Speaker: Kenji Inami (Nagoya university)
14:05 → 14:30	SiPMs technologies and timing	Speaker: Samo Korpar (Jozef Stefan Institute (SI))
14:40 → 15:05	SiPMs - radiation hardness, low-temperature opera	Speaker: Yuri Musienko (University of Notre Dame (US))
15:15 → 15:30		
15:30 → 15:55	Photomultiplier technologies	Speaker: Razmik Mirzoyan (Max-Planck-Institute for Physics)
16:05 → 16:30	Superconducting devices overview	Speaker: SaeWoo Nam (NIST)
16:40 → 17:05	Overlapping technologies and summary	Speaker: Peter Križan (Jožef Stefan Institute, Ljubljana)
17:15 → 17:45	Discussion session	

TF4 Panel Members

- Ichiro Adachi (KEK)
- Neville Harnew (Oxford) Co-convener
- Christian Joram (CERN)
- Peter Krizan (Ljubljana) Co-convener
- Eugenio Nappi (INFN Bari)
- Hans-Christian Schultz-Coulon (KIP Heidelberg)

PID and Photon

DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2	Develop photosensors for extreme environments
DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4	Develop compact high performance time-of-flight detectors

Fotorivelatori gassosi

Sono la soluzione più economica per coprire con fotorivelatori grandi superfici.

Sensibili nel VUV. Hanno poco materiale. Tollerano il campo magnetico,

Non sono acquistabili sul mercato.

R&D INFN (2007-2015): sviluppo di fotorivelatori gassosi per applicazioni RICH.

1.5 m^2 di rivelatori (tecnologia ibrida THGEM+CsI e Micromegas) installati su COMPASS (CERN SPS) nel 2016.

Tecnologia in corso di ulteriore sviluppo:

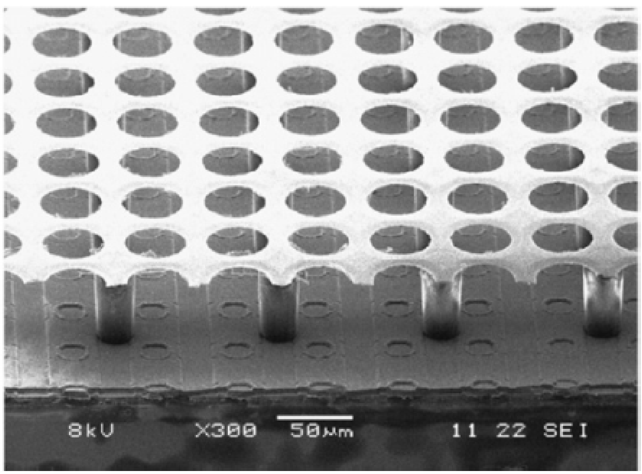
- **migliore risoluzione spaziale**
- **fotoconvertitore alternativo al CsI**

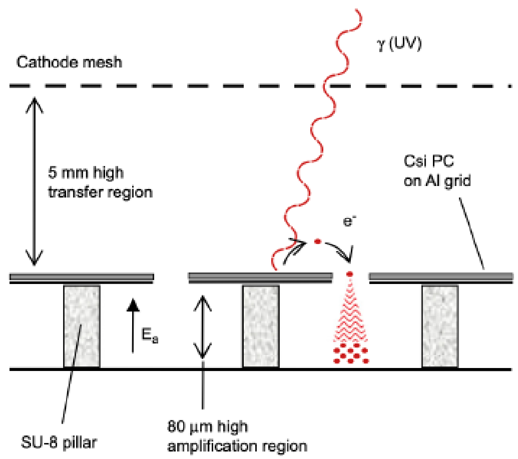
→ Daniele D'Ago: single photon detection with MPGDs

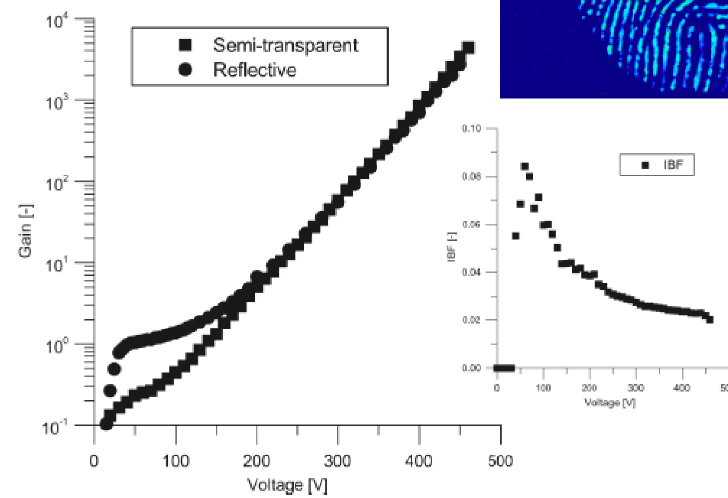
Micromegas/Ingrid photon detector

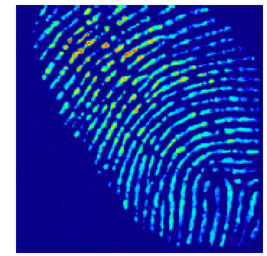
Micromegas amplifications stage directly integrated on **Timepix ASIC**
Added photosensitivity by either semi-transparent photocathode or reflective photocathode direction coated on Al grid

Very good position resolution (≈25μm) and good IBF suppression
Very well coupled to (integrated) readout electronics
Limited by size of pixels and integration procedure





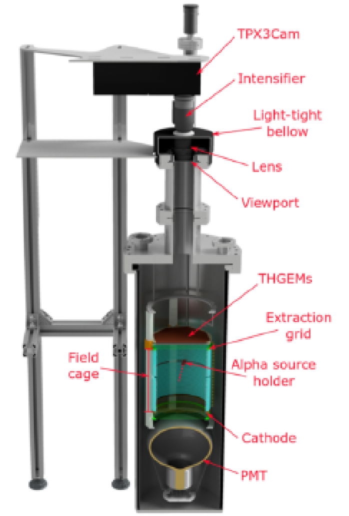




J. Melai et al. / Nuclear Instruments and Methods in Physics Research A 633 (2011) S194–S197

3D track reconstruction

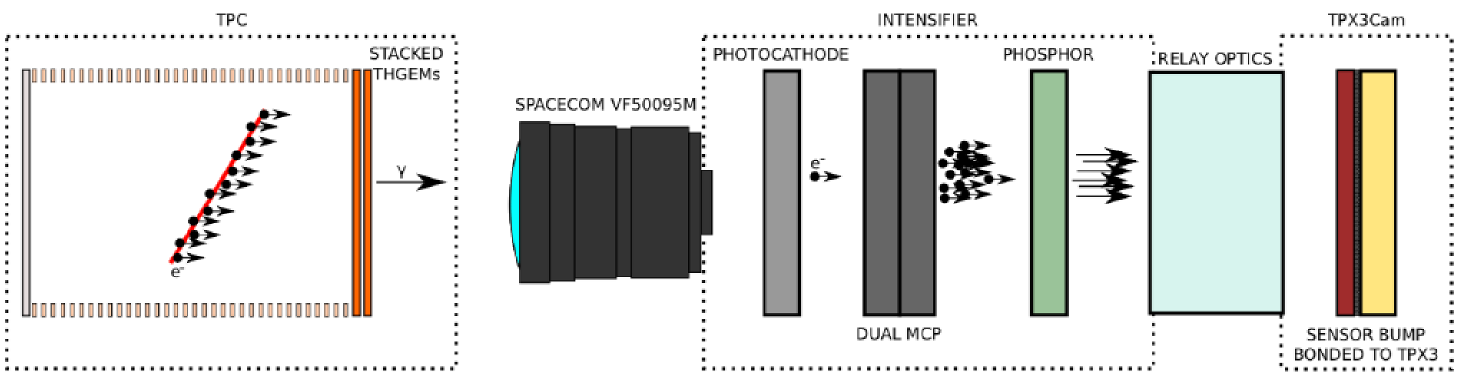
Intensified TPX3Cam

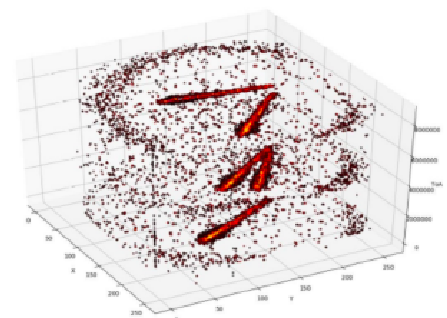


Readout of S2 scintillation in **dual phase TPC**

Light production with THGEM / GlassGEM in avalanche mode, operated at low amplification due to inherent signal amplification in image intensifier of readout system

TPB wavelength shifter and VIS **photocathode** or **direct VUV imaging** with UV photocathode on intensifier



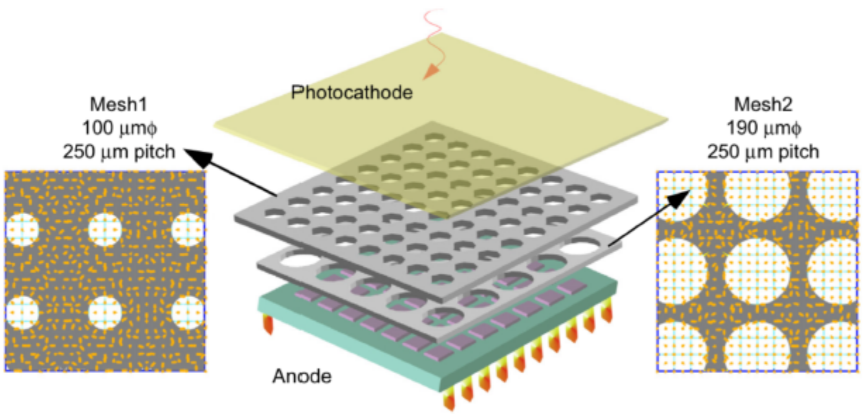


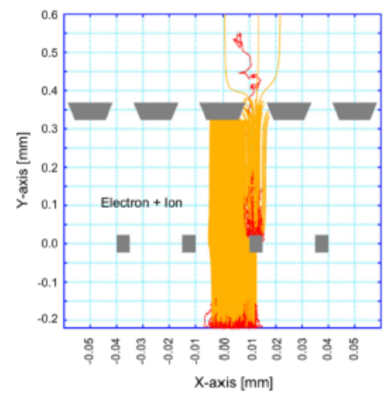
A. Roberts, ARIADNE, arXiv:1810.09955v3
https://indico.cern.ch/event/989298/contributions/4217751/attachments/2190565/3702236/RD51%20Optical%20readout.pdf

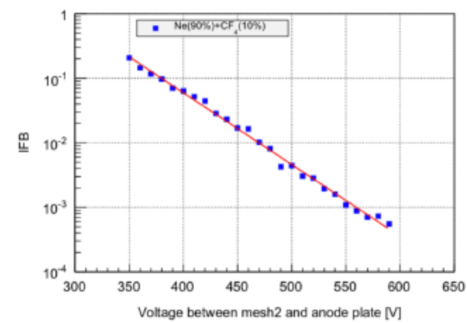
Fotorivelatori gassosi nel visible?

To be able to use bialkali photocathode for visible light sensitivity, a Micromegas-based photon detector was developed for reduced ion back flow fraction. Two micromeshes with different openings were used to minimise the ion back flow and IBF < 6x10^-4 was achieved.

Gaseous photomultiplier with Micromegas and bialkali photocathode







F. Tokanai et al. / Nuclear Instruments and Methods in Physics Research A 766 (2014) 176–179

20

Vacuum-based Photon Detectors

INFN
Istituto Nazionale di Fisica Nucleare

90 anni dopo la loro invenzione sono ancora importantissi e in dinamico sviluppo.

Gli ultimi PMTs hanno QE > 30%, CE ~ 95% → PDE ~ 30%

Single anode PMT usati ampiamente (ν and astropartilce physics).

- MCP-PMTs with <10 μm pores can be operated up to ~2 T magnetic fields
- ALD-coating of MCP pores increased lifetime to ~35 C/cm² integrated anode charge
- Rate capability is not yet enough for very high rate experiments
- No irradiation tests for MCP-PMTs available

- Currently there are several types of 1- and 2-inch high-quality MCP-PMTs commercially available (Hamamatsu, Photek, Photonis), also in highly segmented anode designs
- LAPPDs (up to 8-inch) are promising candidates for low-cost photon sensors in HEP (and other) experiments
- **Despite the success of SiPMs, vacuum PMTs will probably remain important devices** for many neutrino and astroparticle experiments and for detecting single photons (RICH, DIRC, etc.) in high radiation environments

→ Federica Borgato:
The LHCb RICH Upgrade

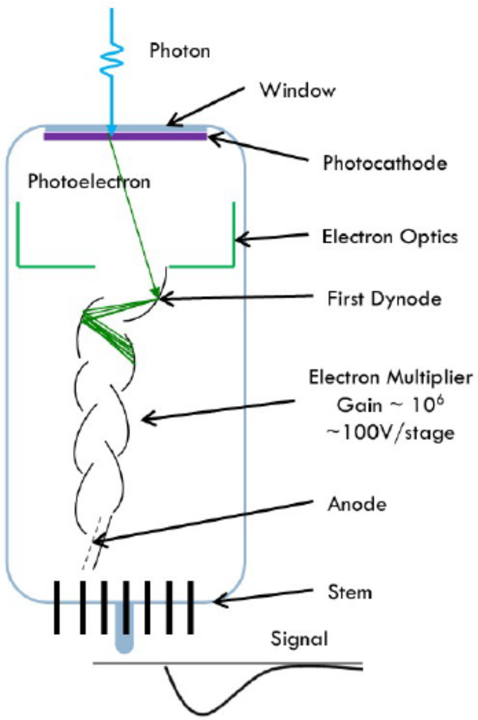
The LHCb RICH Upgrade

Federica Borgato on behalf of the Italian RICH groups
INFN Workshop on Future Detectors, 18th October 2022

Structure of Vacuum-Based Photo Detectors

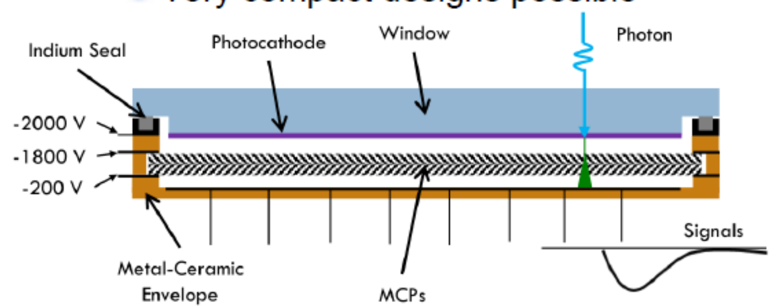
Dynode Photomultiplier

- **Discrete** electron multiplication stages (→ 7 – 14 dynodes)
- Often bulky glass/ceramic housings



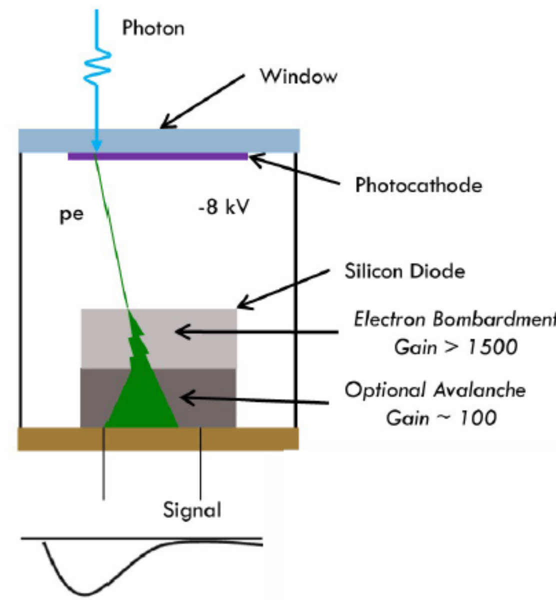
Microchannel-Plate PMT

- **Continuous** electron multiplication in thin (Ø 3-25 µm) glass capillaries of a few hundred µm thickness → typically **2 microchannel-plates** (MCPs) in Chevron configuration
- Very compact designs possible



Hybrid Photo Detector

- **Direct** electron acceleration in static electric field (8 to 25 kV) and electron detection with
  - Segmented PIN diode (HPD)
  - Avalanche photo diode (HAPD)
  - Silicon photomultiplier (VSiPMT)



Common to all these photon detectors:

- **Photo cathode**
- **Electron multiplication stage**
- **Single or segmented anode**

All schematics from P. Hink, Talk at RICH2016

RICH 2022 -- Edinburgh, Scotland -- September 15, 2022

RICHs with Vacuum-based Photon Detectors

Gruppi I e III

Application	#PMTs	Photo detector	Pixel size (mm²)	Readout
COMPASS RICH	576	4x4 ch. R7600-03-M16 MaPMT	4.5 x 4.5	CMAD FE + DREISAM F1 TDCs
CLAS12 RICH	2344	8x8 ch. H8500/H12700 MaPMTs	6 x 6	MAROC3 FE + digital FPGA board
GLUEX DIRC	180	8x8 ch. H12700 MaPMT	6 x 6	MAROC3 FE + digital FPGA board
LHCb RICH Upgrade	3072	8x8 ch. R13742/R13743 MaPMTs	2.8x2.8 / 5.6x5.6	CLARO ASIC chip + further FE boards
CBM RICH	1100	8x8 ch. H12700 MaPMT	6 x 6	DiRICH: FPGA-TDC board
Belle2 iTOP	512	4x4 ch. Hamamatsu MCP-PMT	5.3 x 5.3	IRSX waveform sampling ASIC
Belle2 ARICH	420	12x12 ch. Hamamatsu HAPD	4.9 x 4.9	4 ASICs + Spartan6 FPGA
Proto-TORCH	11	8x128 or 64x64 ch. MCP-PMT	6x0.4 or 0.8x0.8	Customised: NINO + HPTDC + FPGA
PANDA Barrel DIRC	128	8x8 ch. Photonis MCP-PMT	~ 6 x 6	DiRICH: FPGA-TDC board
PANDA Endcap DIRC	96	3x100 or 6x128 ch. MCP-PMT	0.4-0.5 x 16	TOFPET ASIC
EIC mRICH	open	LAPPD or SiPM	open	Still open, with waveform sampling ASICs being considered
EIC hpDIRC		Commercial MCP-PMTs / HRPPD		
EIC dRICH		LAPPD of SiPM		

Gruppo II

Various PMTs	≤1.5-inch	HESS, MAGIC, MAGIC-II, VERITAS, etc.	(super-)bialkali,	20% – 35%	
R12992, R11920	1.5-inch	CTA	super-bialkali	>35%	Linear-focused (LF)
R14374, R12199-02	3-inch	KM3NeT multi-PMT Optical Module (OM)	bialkali		Circular & LF
R15458-02	3-inch	IceCube Upgrade mDOM	bialkali		
XP72B22, XP82B20	3-inch	JUNO, Hyper-Kamiokande		~25%	
R1408	8-inch	IMB, IMB-3, MACRO, SNO, SNO+	bialkai		
R5912	8-inch	MILAGRO, Daya Bay, HAWC,	bialkali K_2CsSb	28 – 30%	Box & Line
R5912-100		Super-Kamiokande, TAIGA, LHAASO	super-bialkali	35 – 40%	
ETL9350	8-inch	MACRO, SNO, Borexino, GERDA, Tunka-133, Neutrino-4, etc.	bialkali K_2CsSb or Rb_2CsSb (green)	<25 – 28%	
R14688-100	8-inch	New development	super-bialkali	~35%	Box & Line
R7081	10-inch	Ice-TOP, TAIGA-HiSCORE, etc.	bialkali	25 – 30%	Box & Line
R7081-100		Double-Chooz, RENO, STEREO, etc. IceCube, ANTARES, GVD, etc. + LBNT	super-bialkali	35 – 40%	
R7250	17-inch	KamLAND, KamLAND-Zen	bialkali		Box & Line
R1449, R3600	20-inch	Kamiokande, Super-Kamiokande	bialkali		Venetian blind
R12860	20-inch	Hyper-Kamiokande, JUNO	bialkali	25 – 30%	Box & Line
MCP-PMT	20-inch	JUNO	bialkali	33 – 35%	MCP

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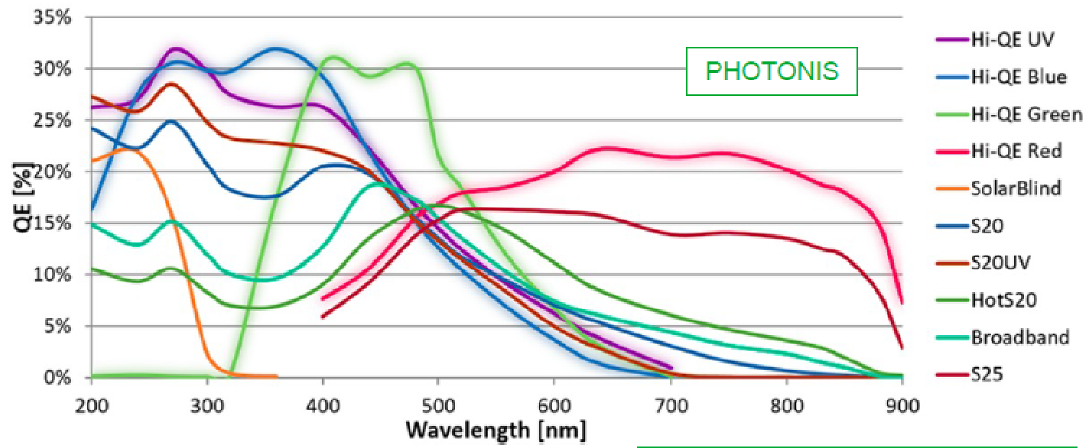
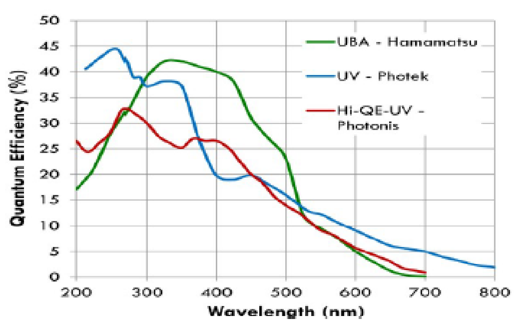
Photo Cathode (PC) and QE

- QE of latest PCs
  - Photonis
    - **HiQE** (>30%) **in different wavelength bands**
    - Originally developed for image intensifiers, now also available for MCP-PMTs
  - Hamamatsu
    - Bialkali: **SBA/UBA (35%/45%)** for MaPMTs and HAPD, reached by better PC quality (not yet in MCP-PMTs)
    - III-V: GaAs (30%) and **GaAsP (>60% in visible range)** → reached by better crystallinity → improved absorption, diffusion, and emission
  - Photek
    - **>40% in UV** region with bialkali PC

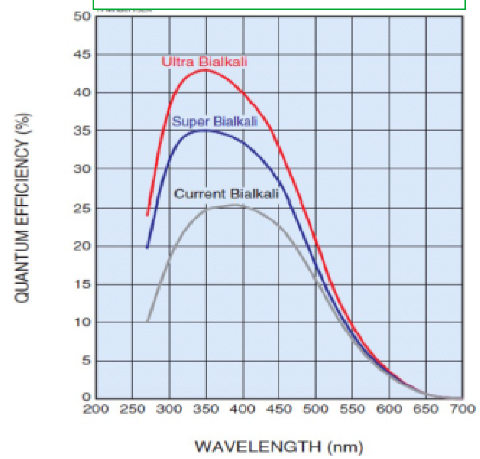


comparison of **recent UV/blue** alkali-antimonide photo cathodes

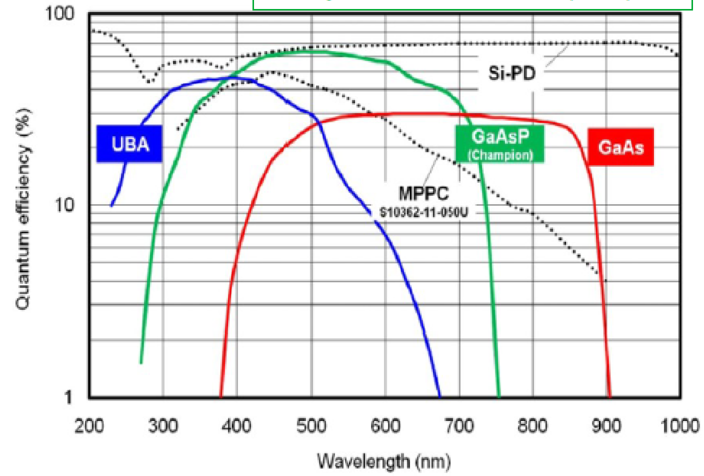
P. Hink, RICH2016



S. Nishida, Talk at NDIP 2014



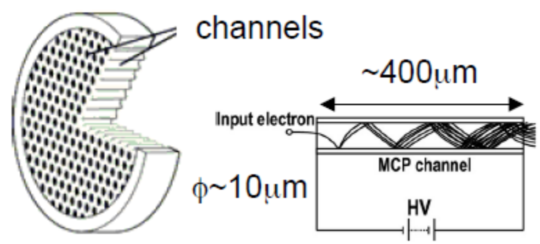
M. Suyama, K. Nakamura, PoS (PD09) 013

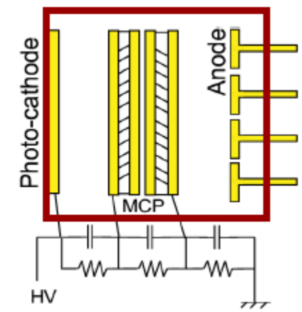


Continuous Electron Multiplication

- Electron multiplication in thin glass capillaries
  - Standard microchannel-plates (→ **MCP-PMTs**)
    - Array of many such capillaries (MCP) with 3 – 25 mm diameter each
    - Hydrogen-fired lead glass capillaries to produce resistive surface
    - Exponential dep. of gain on aspect ratio L/D (pore length / diameter)
  - **High gain** (>10^6) **even in strong magnetic fields** (>1 T)
  - **Very fast** (<50 ps TTS ; <100 ps RMS)
  - Limits: **PC aging** (feedback ions) and **rate capability** (τ = RC)

MCP operation

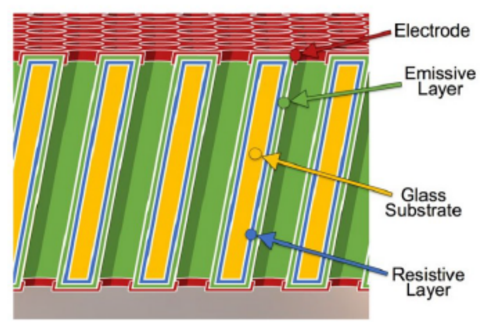




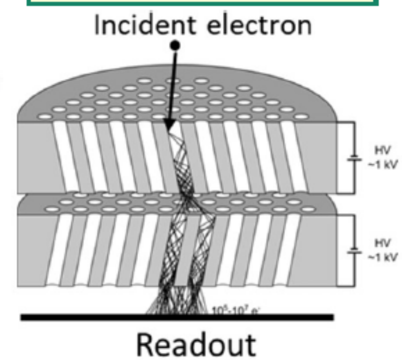
- Atomic Layer Deposition (ALD) coated MCPs
  - **Ultra-thin films of resistive and emissive layers** (MgO, Al_2O_3) applied to (borosilicate) glass capillary arrays (MCPs)
    - Technique originally developed by **Arradiance Inc.**
    - **No PC aging up to >10 C/cm² IAC** (integrated anode charge)
    - Higher gain due to higher secondary electron yield → **lower HV**
    - Rate capability still marginal (1 - 10 MHz/cm^2 dep. on PMT size)
  - PMT sizes range from **1x1/2x2 inch²** (Hamamatsu, Photonis, Photek) **to 20x20 cm²** (LAPPD, ANL, Incom)
  - ALD-coated MCP-PMTs are considered for several future Cherenkov and non-Cherenkov applications

Cremer et al., DOI: 10.1109/NSS/MIC42677.2020.9507831

Different layers of ALD coated pores



Electron trajectories with 2 MCP stages

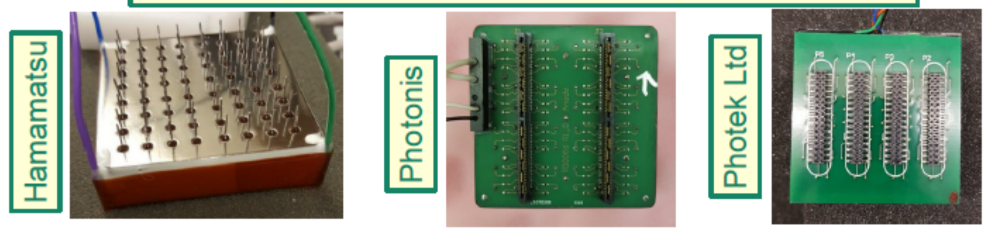


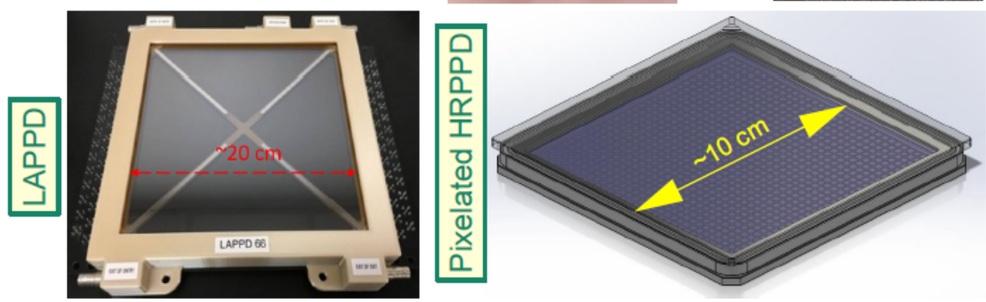
Currently Available MCP-PMTs

Talk of J. Milnes on Thursday

- Photonis, Hamamatsu, Photek
  - **1- and 2-inch PMT types in various configurations**
  - Segmented anode (4x4, 8x8, 16x16, 3x100, 8x128, etc.)
- Fast MCP-PMTs (China) Talk of S. Qian on Thursday
  - R&D for 8x8 pixel 2-inch PMT (prototypes produced)
- **LAPPD**, ANL and Incom
  - MCP-PMTs designed for **large area coverage**
    - LAPPD Collaboration formed in 2009
    - Commercialization process transferred to Incom Inc. in 2013
    - ongoing R&D in collaboration with ANL and Univ. of Chicago
    - Now available: sizes of 6x6 (ANL), 10x10 or **20x20 cm²**
  - Anode and readout options
    - Gen-I: strip line (delay line) anode with ~1.5 mm resolution
    - Gen-II: **anode capacitively coupled to highly segmented external readout board** provides <<1 mm² 2D-resolution
    - Gen-III: **pixel anode design** studied for EIC applications
  - Working on Gen-III HRPPD (10x10 cm²)
    - Design **optimized for high rates** and B-field tolerance

Backplane design of some commercial 2-inch MCP-PMTs





Gen-I Direct Read-out Strip Line Anode

Gen-II Resistive Interior Anode with Capacitive Coupled Patterned Signal Board

M.J. Minot, Incom Inc., 2020

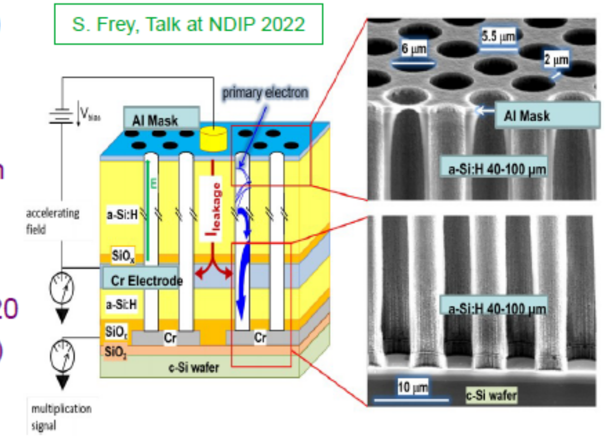
Sviluppi di MCP per il futuro

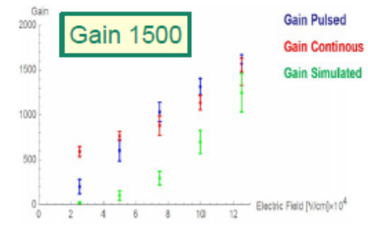
Possible Future MCP-PMTs

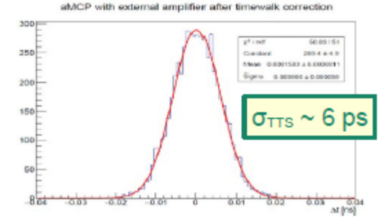
- **Monolithic MCP** from amorphous Si (a-Si:H)
  - Goal: overcome complicated fabrication process and long channel dead time of conventional glass MCPs
    - Possibility of much **higher rate capability** and spatial resolution
  - Fabricated by chemical vapor deposition of a-Si:H layer (80 µm) on any substrate and deep reactive-ion etching
    - Reactive-ion etching process → pores with aspect ratio (L/D) >20
    - **Aspect ratio ~25 led to gain of 1500** (~8000 with ALD coating)
    - Readout electronics can be embedded into Si-wafer
    - Funnel-shaped AMCPs with ~95% open area being tested

MCPs based on hydrogenated amorphous Si

S. Frey, Talk at NDIP 2022





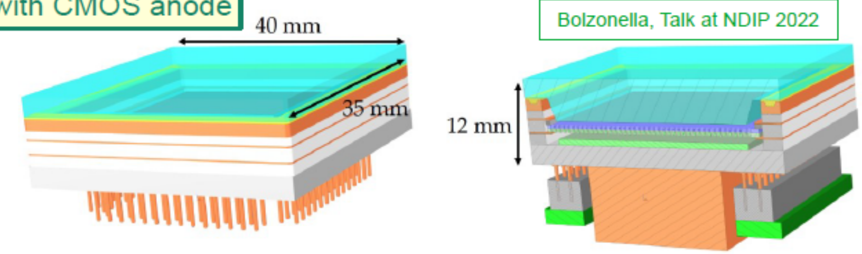


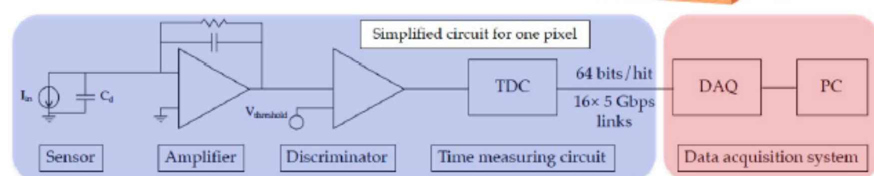
- MCP-PMT with CMOS anode
  - Conceptual design for 4D detection of single photons
    - Hybrid concept: **MCP-PMT** where the **pixelated anode** is an **ASIC** (CMOS) embedded **inside the vacuum**
    - **Prototype** with Timepix4 ASIC as anode (array of 23k pixels)
  - Envisaged performance

    Talk of M. Fiorini on Friday
    - <100 ps time resolution and 5-10 µm spatial resolution
    - **Rate capability** of **>100 MHz/cm²** (<2.5 Ghits/s @ 7 cm² area)
    - Low gain (~10⁴) operation possible → x100 **lifetime increase**

MCP-PMT with CMOS anode

Bolzonella, Talk at NDIP 2022





Albert Lehmann RICH 2022 -- Edinburgh, Scotland -- September 15, 2022 20

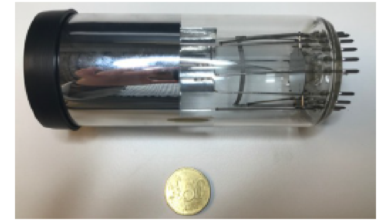
New Hybrid Vacuum-based Photon Detectors

INFN Istituto Nazionale di Fisica Nucleare

New HPDs with SiPMs

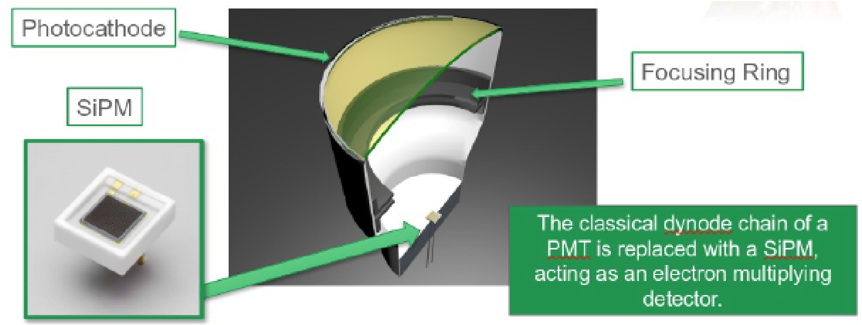
- **Vacuum Silicon PhotoMultiplier Tube (VSiPMT)**
  - Hybrid PD with SiPM as electron multiplier
    - Goal: increase SiPM surface
    - R&D was started in 2007 for future astroparticle experiments
    - **One amplification stage:** photo electron is accelerated to **~2 keV** to trigger a Geiger avalanche in the **SiPM** (for **electron multiplication**)
  - Performance
    - **Higher gain** (>10^6) **than other HPDs** and faster than dynode PMTs
    - Compact and simple
    - Weak point: **high DCR** → single photon sensitivity questionable
- **ABALONE photo detector**
  - Hybrid PD read out by scintillating window and outside SiPM
    - **Goal:** build **photon detector with few components** → radio purity
    - **Two amplification stages:** electron accelerated to scintillator layer → creates N(ph) proportional to ~25 keV electron energy → SiPM
  - Performance
    - Very high **gain of up to 10^8** [10^6 from SiPM and 10^2 from N(ph)]
    - **Excellent single photon sensitivity**
    - **Very low afterpulse rate** (~$5x10^{-3}$) and **low DCR** (~1 Hz/cm^2)

VSiPMT 2-inch prototype



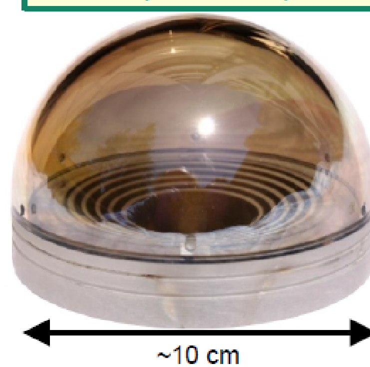
VSiPMT concept

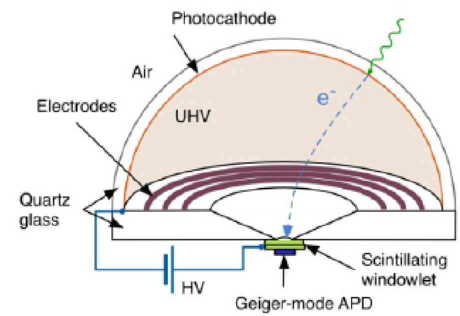
F.C.T. Barbato et al., NIMA 958 (2020) 162144



ABALONE photo detector for astroparticle experiments

V. D'Andrea et al., JINST 17 (2022) C01038





Idee per futuri amplificatori di elettroni

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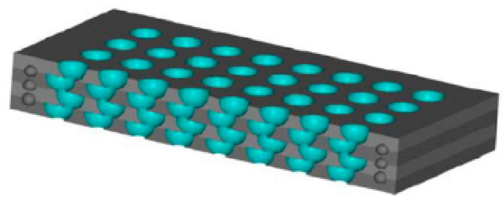
Possible Future of Electron Multiplication

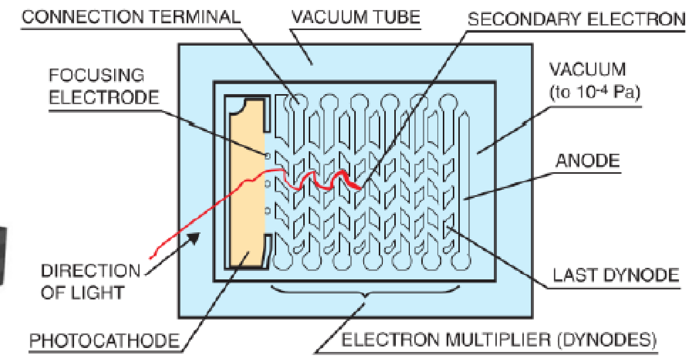
- Micromachined PMTs (→ μPMTs)
  - First developed by Hamamatsu ~2010
    - Pro: easy mass production and customization
    - Con: poor active area ratio and B-field tolerance
  - Improved MEMS/NEMS PMTs (R&D)
    - MEMS: micro-electro-mechanical systems
    - Compact: dynode stage thickness 100 – 500 μm → **PMT thickness of <3 mm** with 8 – 10 dynodes
    - High time/spatial resolution and minor crosstalk
    - High rate capability and B-field tolerance
- Tynodes (→ Time Photon Counter)
  - Transmission mode dynode → tynode
  - Fabrication of tynodes (MgO ALD, diamond) using MEMS technology
  - "Anode" is a CMOS chip (e.g., TimePix)
  - Very promising properties
    - Very compact; high B-field tolerance; very fast
    - Very low DCR; very good 2D spatial resolution

MEMS/NEMS PMT

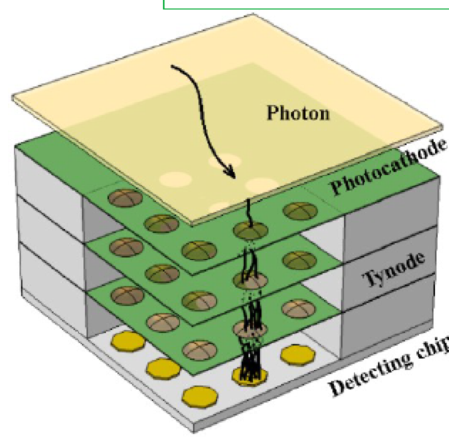
D. Winn, Talk at CPAD 2021



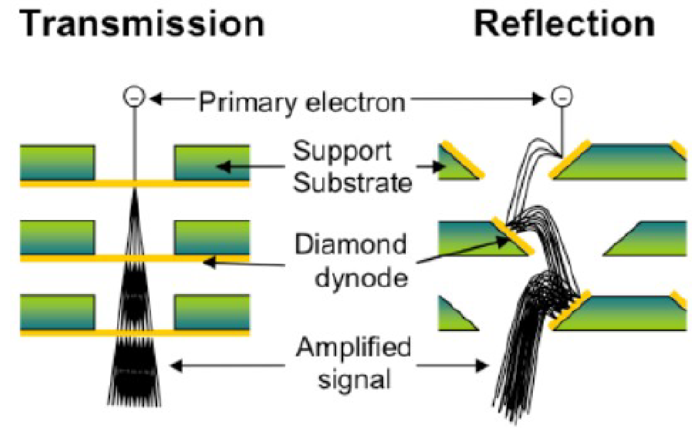
μPMT



H. van der Graaf et al., NIM A847 (2017) 148



TiPC operation



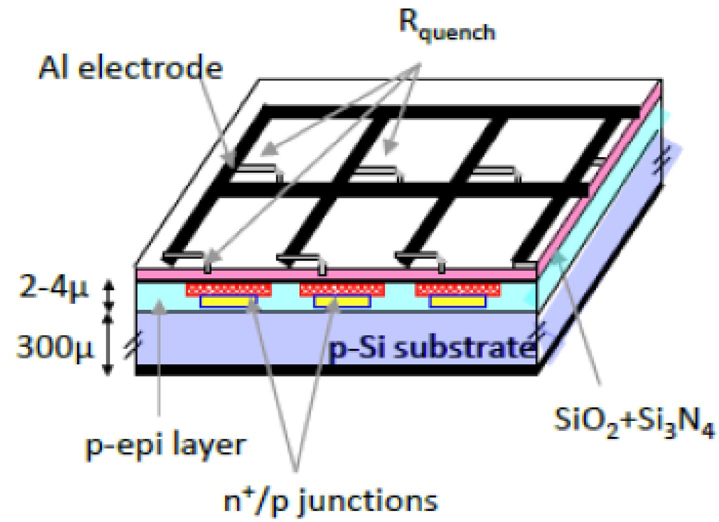
SiPM

An array of APDs operated in Geiger mode – above APD breakdown voltage (microcells or SPADs – single photon avalanche diodes)

• each triggered microcell contributes equal amount of charge to the signal with a gain

$$G = C_{m.c.} \cdot (V_{bias} - V_{bd})/e_0$$

• large gain $\approx 10^5 - 10^7$
• fast rise time $\approx 100\ ps$
• relatively short signals, order of $10\ ns$



• SiPMs have some very nice properties: low operation voltage, high PDE, high gain, excellent timing, insensitive to magnetic field, easy to operate, not damaged by operation at ambient light ...,
• and some drawbacks : high dark count rate, gain variation with temperature, sensitive to neutron irradiation ...

ECFA roadmap table

equirements

		DRDT	SPS fixed target	FAIR (hep)	PIP-II/LBNF/DUNE	Dark matter, noble liquids	ALICE 3	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	Belle II Upgrade	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030				2030-2035						2035-2040	2040-2045		>2045		
RICH and DIRC technologies	Rad-hard	4.2	Orange	Green			Yellow	Red		Red		Red		Yellow				
	Rate capability	4.2	Orange	Green			Yellow	Red		Red		Red		Orange				
	Fast timing	4.3	Orange	Green			Orange	Red		Orange		Orange		Orange				
	Spectral range and PDE	4.1	Yellow	Green			Orange	Orange		Orange		Orange		Orange				
	Radiator materials	4.3	Orange	Green			Orange	Orange		Orange		Yellow		Orange				
	Compactness, low X_0	4.3	Yellow	Green			Orange	Orange		Red		Orange		Orange				
Time of flight	Rad-hard	4.2	Yellow	Green			Orange	Orange		Orange		Yellow		Yellow				
	Low X	4.3	Yellow	Green			Orange	Orange		Orange		Yellow		Yellow				
	Fast timing to <10ps level & clock distribution	4.3	Orange		Orange		Orange	Orange		Orange		Yellow		Yellow				
Other	TRD	4.3		Green						Orange								
	dE/dx	4.3			Orange					Orange			Yellow	Orange	Yellow			
	Scintillating fibres (light yield, rad-hard & timing)	-						Orange					Yellow		Yellow			
Silicon photomultipliers	Rad-hard	4.2	Orange	Green			Yellow	Red	Yellow	Orange	Red	Orange	Red	Red	Red	Red	Red	Red
	Low noise	4.1	Orange	Green	Orange	Red	Orange	Red	Yellow	Orange	Red	Orange	Red	Red	Red	Red	Red	Red
	Fast timing	4.1	Orange	Green	Orange		Orange	Red	Yellow	Orange	Red	Orange	Red	Red	Red	Red	Red	Red
	Radio purity	4.2				Red												
	VUV / cryogenic det op	4.2			Red	Red												
Vacuum photon detectors	Photocathode ageing & rate capability	4.2	Orange	Green				Orange		Orange		Orange		Yellow				
	Fast timing	4.1	Orange	Green				Red		Red		Red		Yellow				
	Fine granularity / large area	4.1	Yellow	Green	Orange	Orange		Orange		Orange		Orange		Yellow				
	Spectral range and PDE	4.1	Yellow	Green	Orange	Orange		Orange		Orange		Orange		Yellow				
	Magnetic field immunity	4.2		Green				Yellow		Red		Red		Yellow				
Gaseous photon detectors	Photocathode ageing & rate capability	4.2	Orange							Yellow								
	Fine granularity / large area	4.1	Yellow							Yellow								
	Spectral range, PDE and fast timing	4.1	Orange							Yellow								

PDE stands for photon detector efficiency.

Red: Must happen or main physics goals cannot be met · Orange: Important to meet several physics goals · Yellow: Desirable to enhance physics reach · Green: R&D needs being met

SiPM: R&D technology requirements

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- A non-exhaustive list – different applications, different requirements:
  - LH-LHC, FCC, ILC, muon collider
    - Improved rad hardness and lower dark count rates (2-3x10^{12} n MeV cm^2 eq @ CMS, 10^{17}-10^{18} @ FCC-hh !)
    - Improved timing characteristics (aspire to 5 ps time resolution!)
    - Increasing photon yield (quantum efficiency) for single-photon detection
    - Spectral range, for example to become more sensitive to Cerenkov light into the UV
    - Cryogenic operation of SiPMs : improved cooling systems (to reduce dark noise), -50 °C
    - Optimised SiPM integration with cooling
    - Optimised optical couplings. Development of micro-lenses/filters.
    - New materials for SiPMTs (eg SiC, GaN, InGaN, AlGaN)
    - Improved dynamic range for calorimetry
    - Cheaper solutions for SiPMs (eg CMOS) for large area applications and high pixel density
  - Neutrinos and non-accelerator
    - Improving pulse shape discrimination; development of corresponding r/o electronics
    - High radioactive-purity for underground experiments, better than a few Bq/kg depending on material

TF4 Symposium 6th May 2021 P. Allport & N. Harnew

Fondazione Bruno Kessler

Fondazione Bruno Kessler
Custom Silicon Photomultipliers

Detector-grade clean-room, 6 inches, class 10 and 100

Silicon Photomultipliers account for a significant portion of the detectors fabricated here.

Private Research Foundation

- ~400 researchers in different fields, ranging from Microelectronics to Information Technology
- 50% funding from local government
- 50% self-funding rate
  - 25% from publicly funded research
  - 25% from collaboration with companies

FBK is typically interested in R&D activities and collaborations to improve and customize SiPM technology for specific applications.

Large area productions can be carried out in FBK (up to ~5 sqm) or relying on external partners (low cost): success stories of technology transfers.

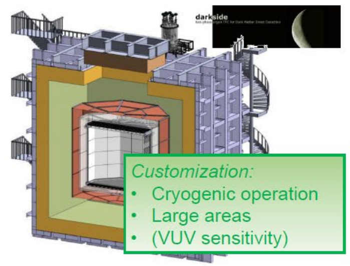
LFOUNDRY Solutions for great visions

BROADCOM

FBK SiPM technologies
Use in Big Physics Experiments

Thanks to constant *performance improvement,* SiPM technologies are now used in several upgrades of Big Physics Experiments: *deep customization is often required.*

Cryogenic TPCs



Customization:
- Cryogenic operation
- Large areas
- (VUV sensitivity)

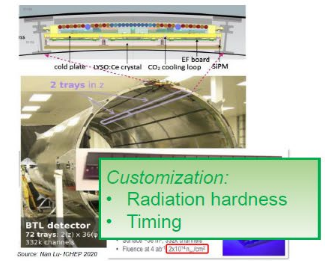
Cryogenic SiPMs will be employed in experiments such as DarkSide-20k

CTA

Customization:
- Low CT
- Maximum PDE

Prototype pSCT installed in the VERITAS, equipped with FBK SiPMs.

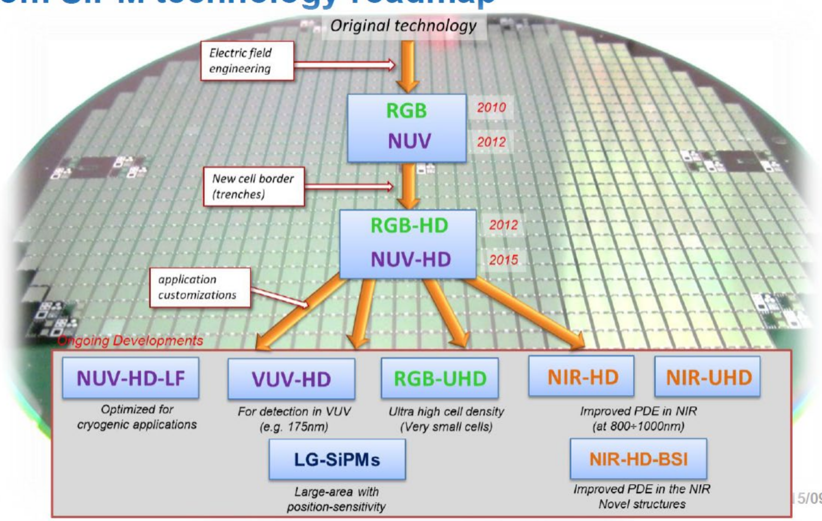
HEP



Customization:
- Radiation hardness
- Timing

NUV-HD SiPMs are being evaluated for the MIP timing detector of CMS (LYSO scintillator readout).

Fondazione Bruno Kessler
Custom SiPM technology roadmap



FBK SiPM technologies
Current R&D activities and Roadmap

Outline:

- **Timing performance**
- **Reduction of Optical Crosstalk**
- **Cryogenic operation**
- **Radiation Hardness**
- **Light concentration**
- **Future developments: 2.5 and 3D integration**

SiPM

La maggioranza delle presentazioni e delle discussioni riguardano i SiPM.

→ **Giacomo Volpe:** *SiPM studies for the ALICE 3 Aerogel RICH detector*

A. R. Altamura[a], D. Di Bari[b], A. Di Mauro[c], E. Nappi[a], N. Nicassio[b], G. Volpe[b]

[a]INFN, Bari, Italy
[b]University and INFN, Bari, Italy
[b]CERN, Geneva, Switzerland

→ **Luigi Riganese:** **A SiPM-based optical readout system for the EIC dual-radiator RICH**

→ **Ezio Torassa:** **SiPM development for the TOP detector upgrade of the Belle II experiment**

Flavio Dal Corso[(a)], Roberto Stroili[(a,b)], Ezio Torassa[(a)]
INFN Padova[(a)], Univ. Padova[(b)]

SiPM

INFN Istituto Nazionale di Fisica Nucleare

→ **Lucia Consiglio:**

Nuova Officina Assergi — INFN LNGS

a new reality for novel SiPM-based detector production

→ **Felicia Barbato:**

Particle Identification in Space Experiments with Scintillator Detectors

→ **Leonardo Di Venere:**

INFN Istituto Nazionale di Fisica Nucleare

Gamma-ray identification with Imaging Atmospheric Cherenkov Telescopes

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