Micro-Pattern Gaseous Detector: Technologies, Developments and Perspectives

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Content

MicroPattern Gaseous Detectors

MPGD technologies and developments

GEMs, Micromegas, µRWELL, RPWELL, …
Resistive detectors
Precise timing detectors
Additive manufacturing

Readout approaches

Electronic readout
Optical readout
Hybrid readout and readout ASICs

Applications

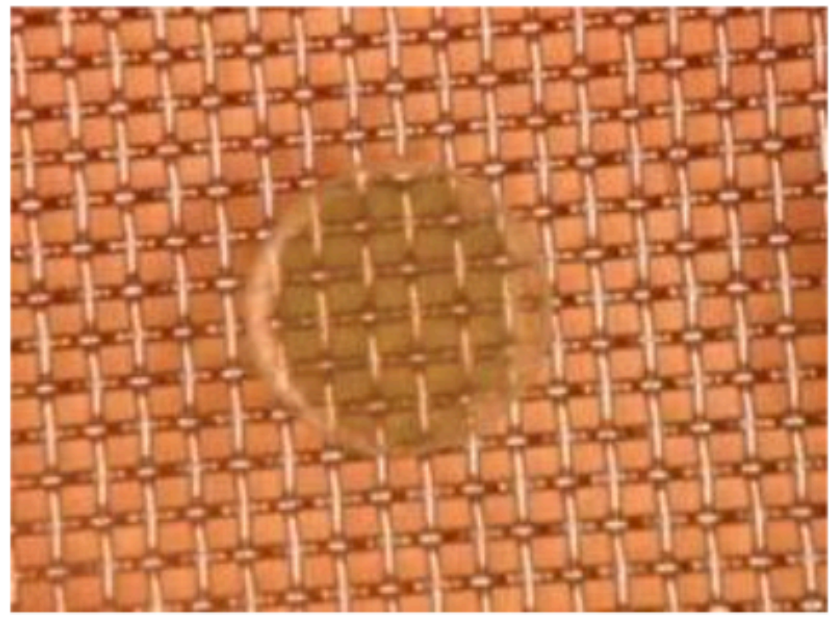
High energy physics
Dark matter searches
Medical applications
Beyond fundamental research

Micro Pattern Gaseous Detectors

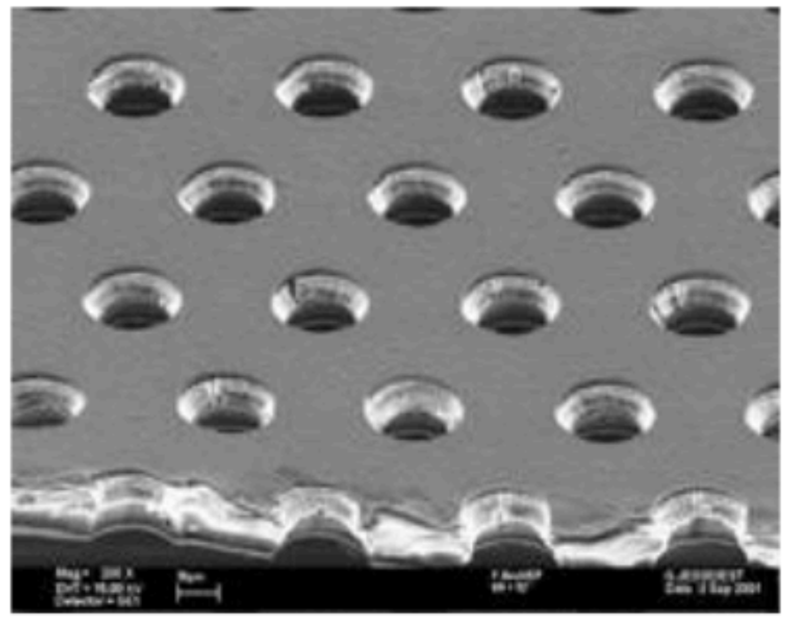
Exploit photolithography techniques to accurate structure insulators and electrodes with structures on the scale of tens of micrometers.

Allows for higher spatial resolution and concentration of high electric field regions on µm-scale structures.

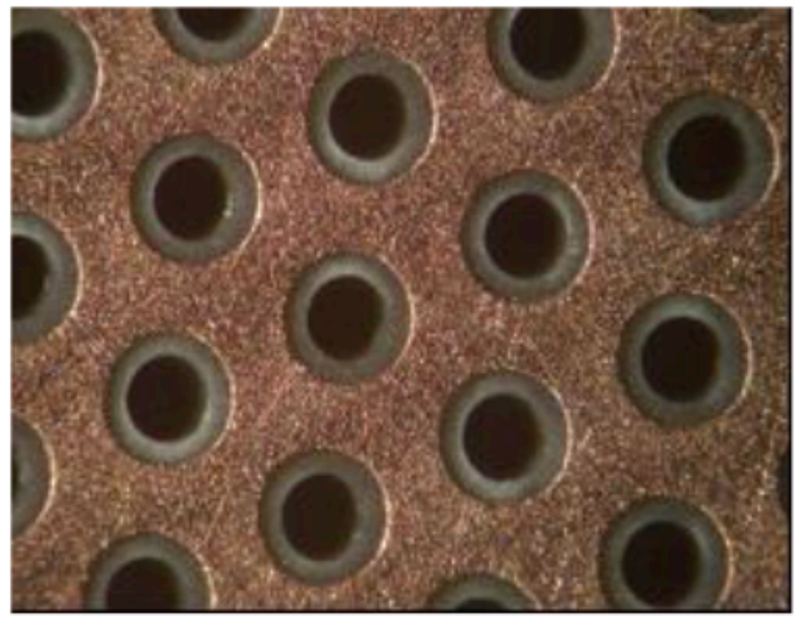
Integration of detector on planar substrates (rigid or foils).



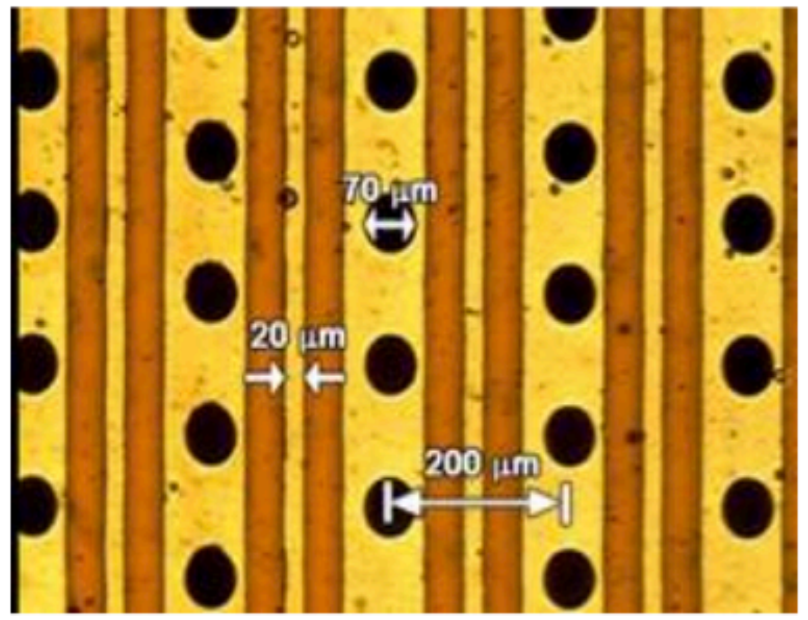
MicroMegas



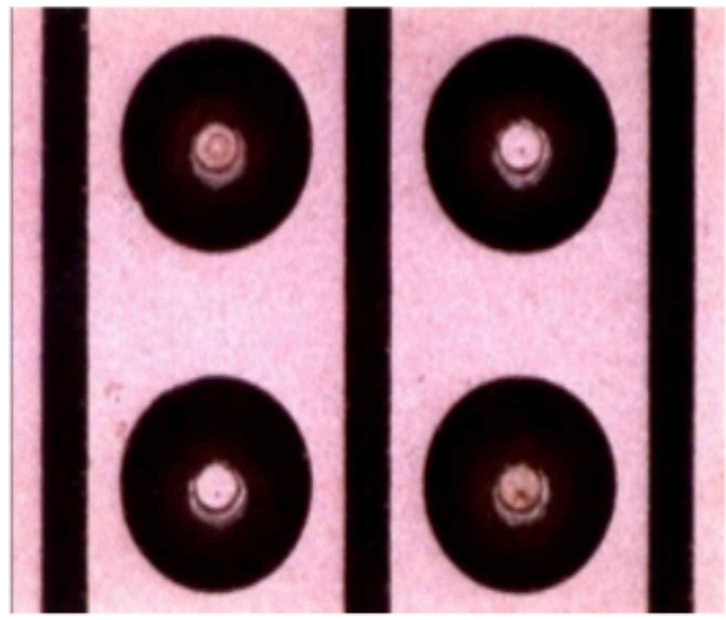
GEM



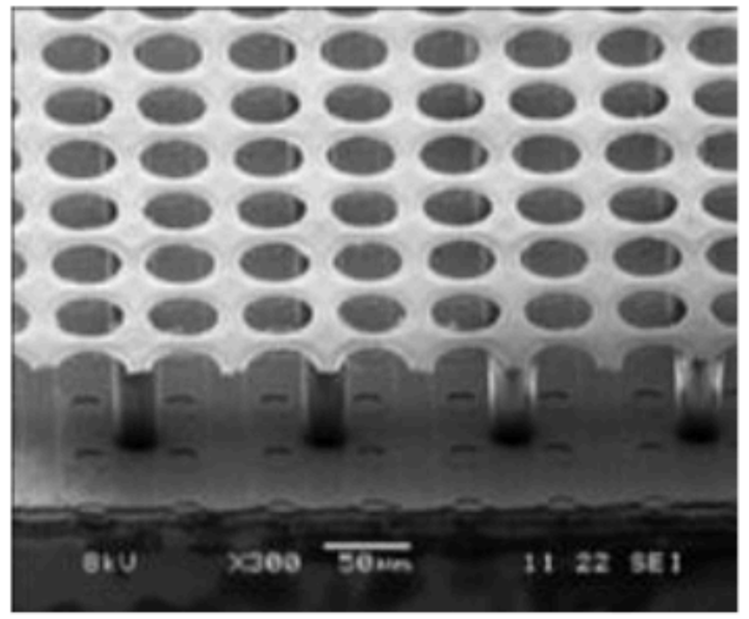
THGEM



MHSP



microPIC



Ingrid

Gaseous Electron Multipliers

Fine-pitch holes in **conductor-insulator-conductor** structures
E.g. 70μm diameter holes at 140μm pitch in 50μm thick polyimide with Cu electrode on both sides

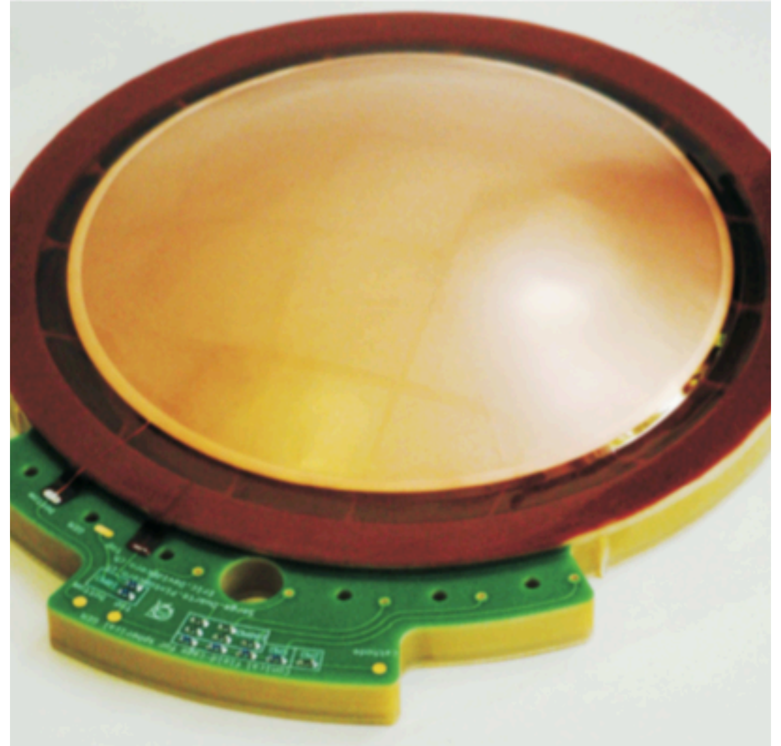
Open structure allowing for **multi-stage amplification** multi-GEM stacks

Varying geometries and materials for specific experimental requirements

GEM tracker

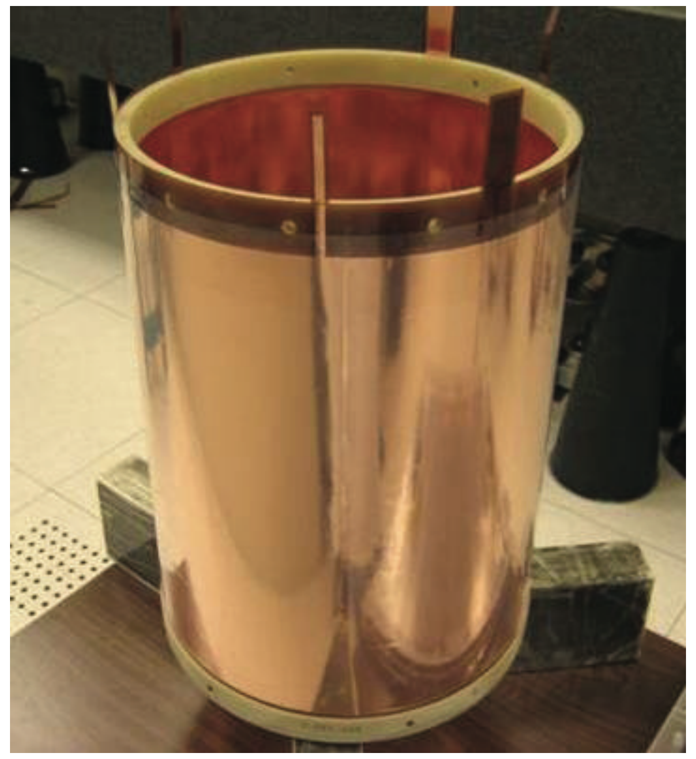
C. Altumbas et al, Nucl. Instr. and Meth. A490(2002)177

Spherical GEM



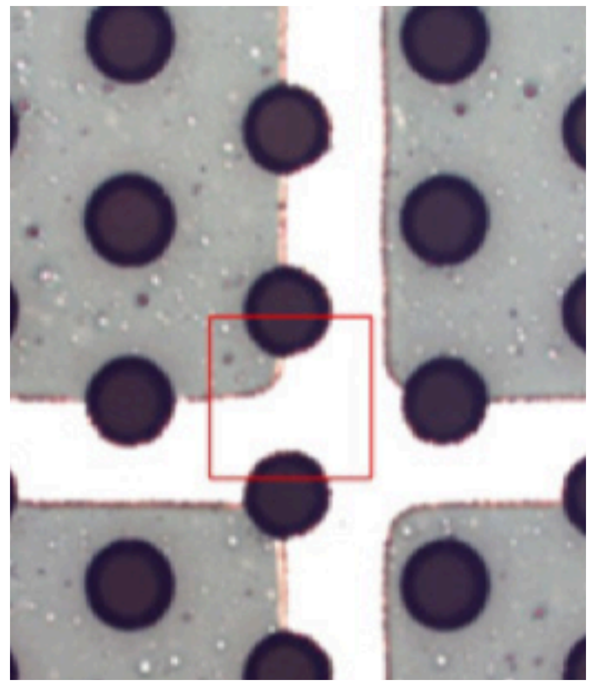
S. Duarte Pinto et al., 10.1109/NSSMIC.2010.5874100

Cylindrical GEM



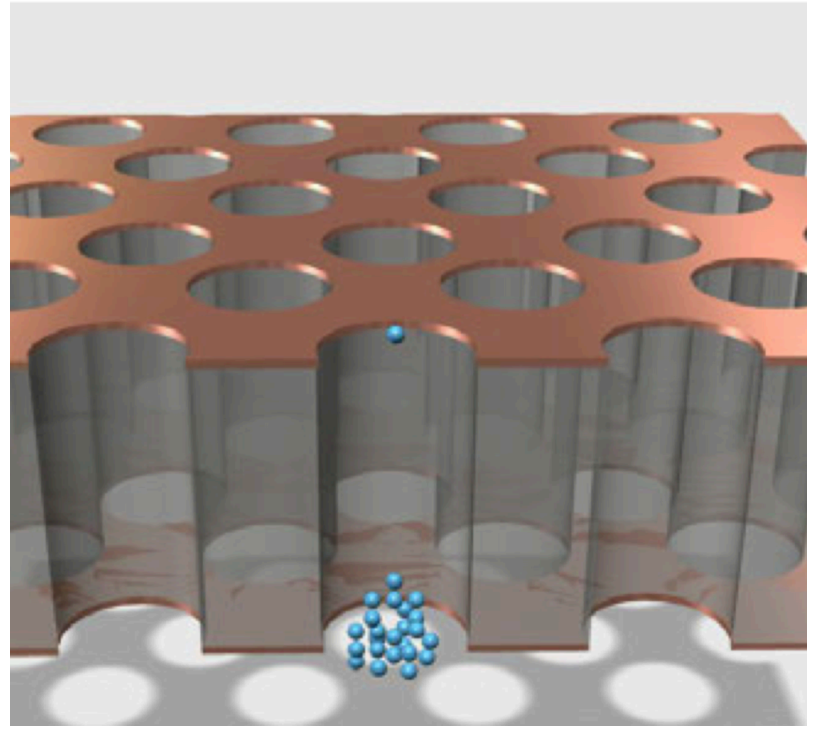
A. Balla et al., Physics Procedia 37 (2012) 522 – 529

Cr GEM



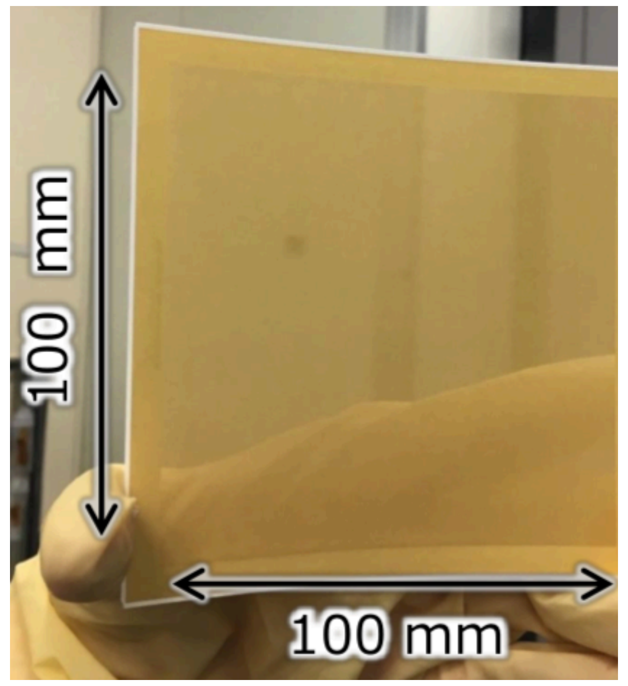
W. Dąbrowski et al 2016 JINST 11 C12025 doi:10.1088/1748-0221/11/12/C12025

Glass GEM



T. Fujiwara, MPGD2017

LTCC GEM



Y. Takeuchi et al 2020 J. Phys.: Conf. Ser. 1498 012011

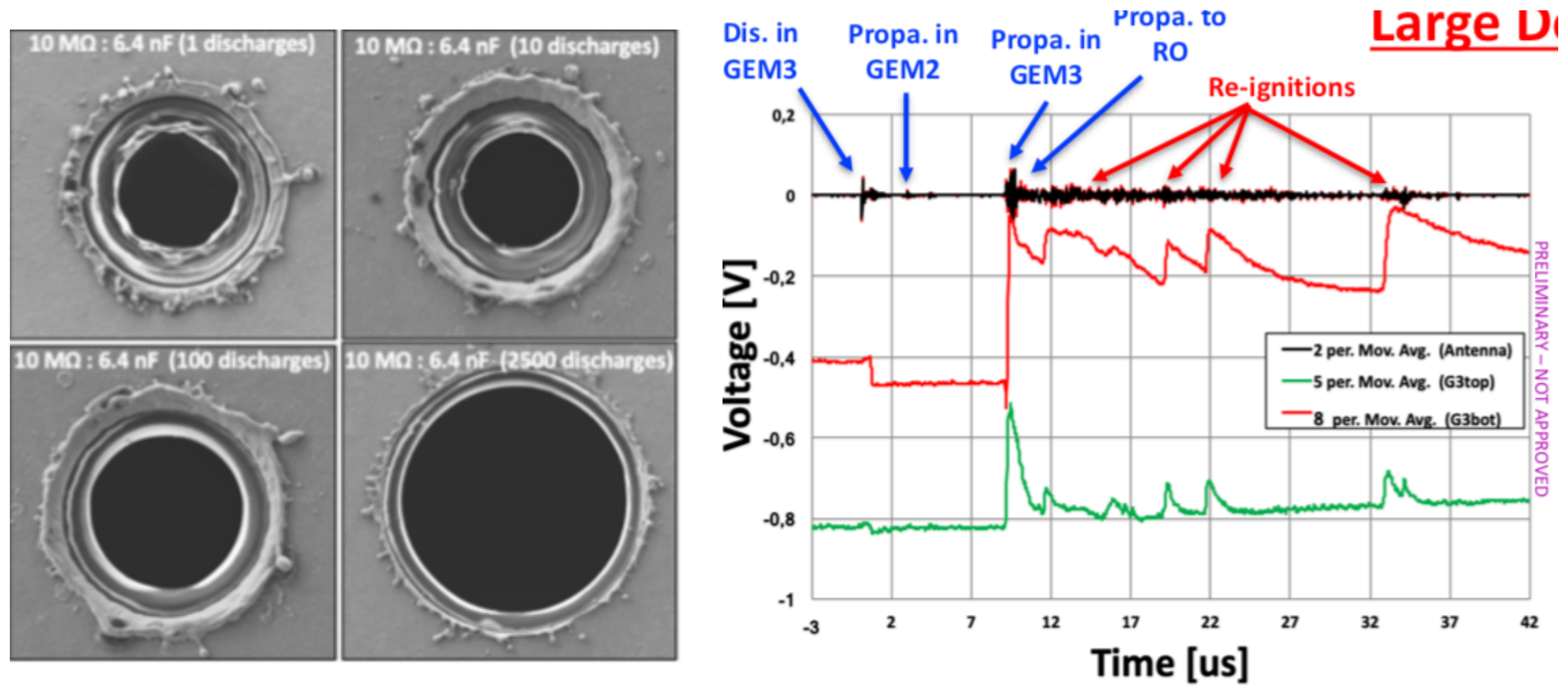
DLC GEM

M. Lisowska, RD51 CM May 2019

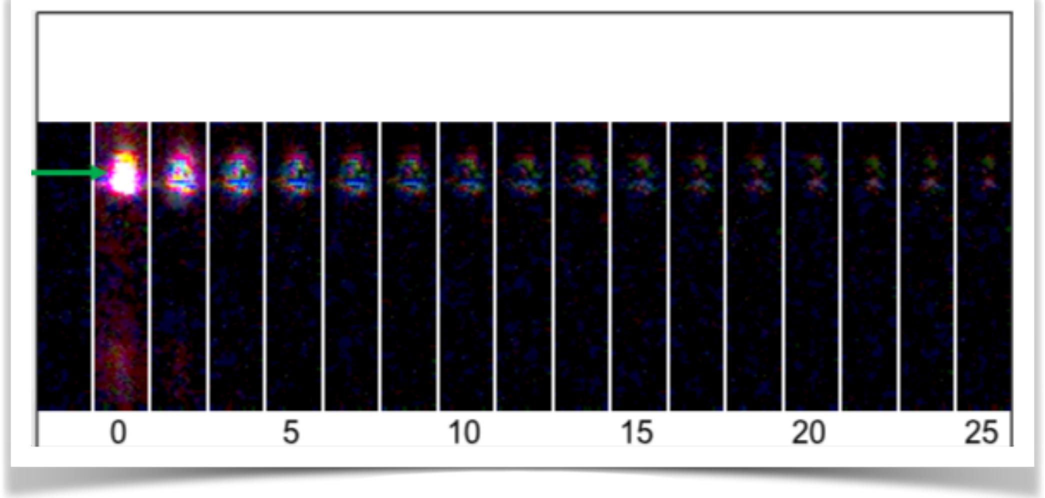
Gaseous Electron Multipliers

Discharge studies and mitigation

Understanding discharge formation and propagation and suppressing damaging processes



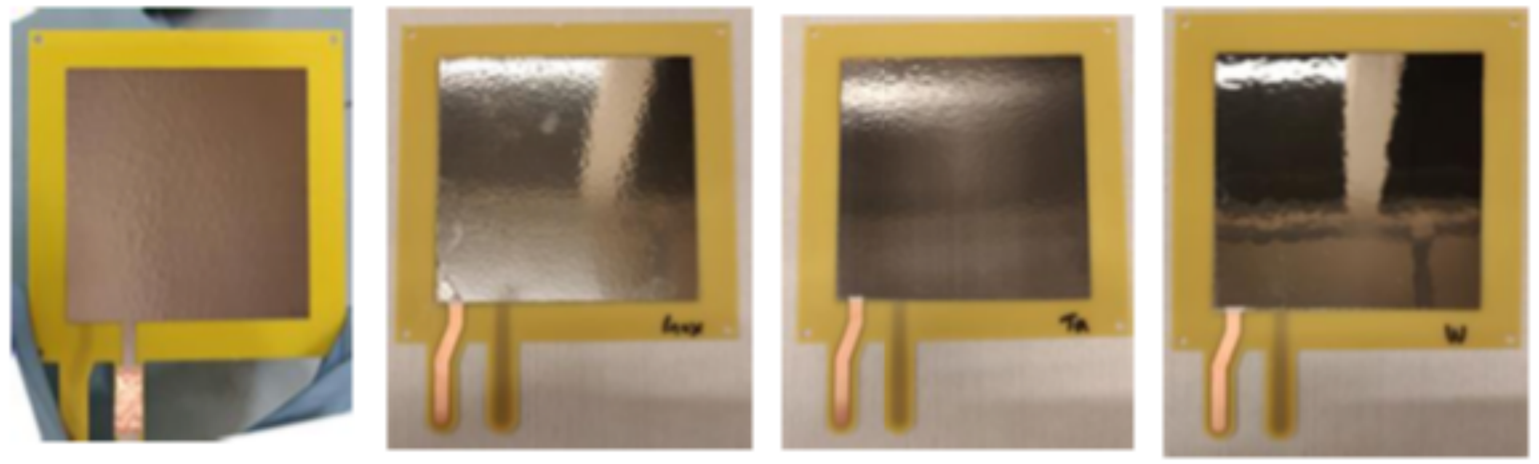
J. Merlin, IEEE-NSS, Sydney, 2018 & MPGD 2019



Antonija Utrobičić et al. MPGD 2019

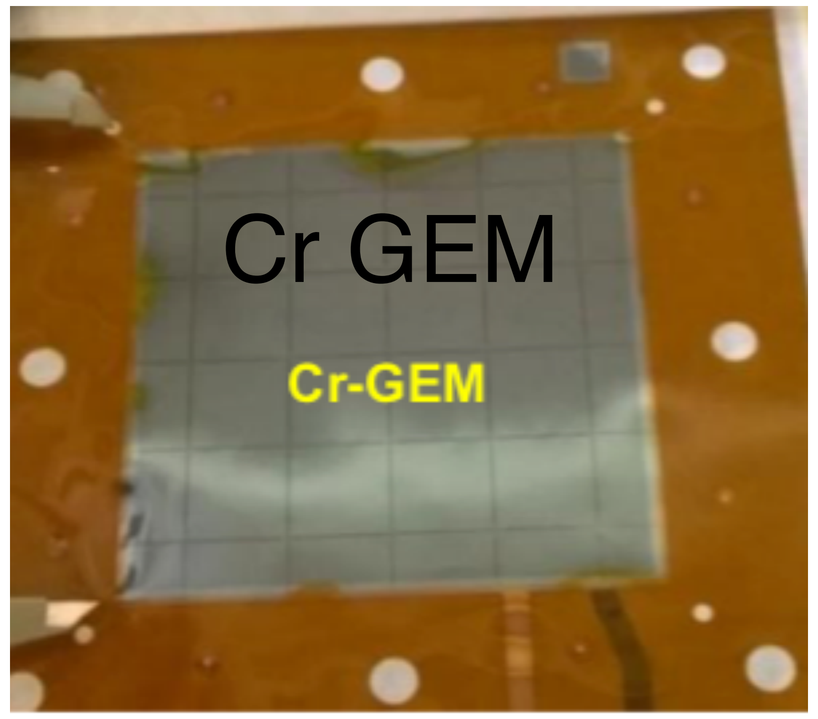
Alternative electrode materials

Lower material budget or increased spark resistance.



Mo THGEM Inox THGEM Ta THGEM W THGEM

Berkin Ulukutlu et al. RD51 CM 2020



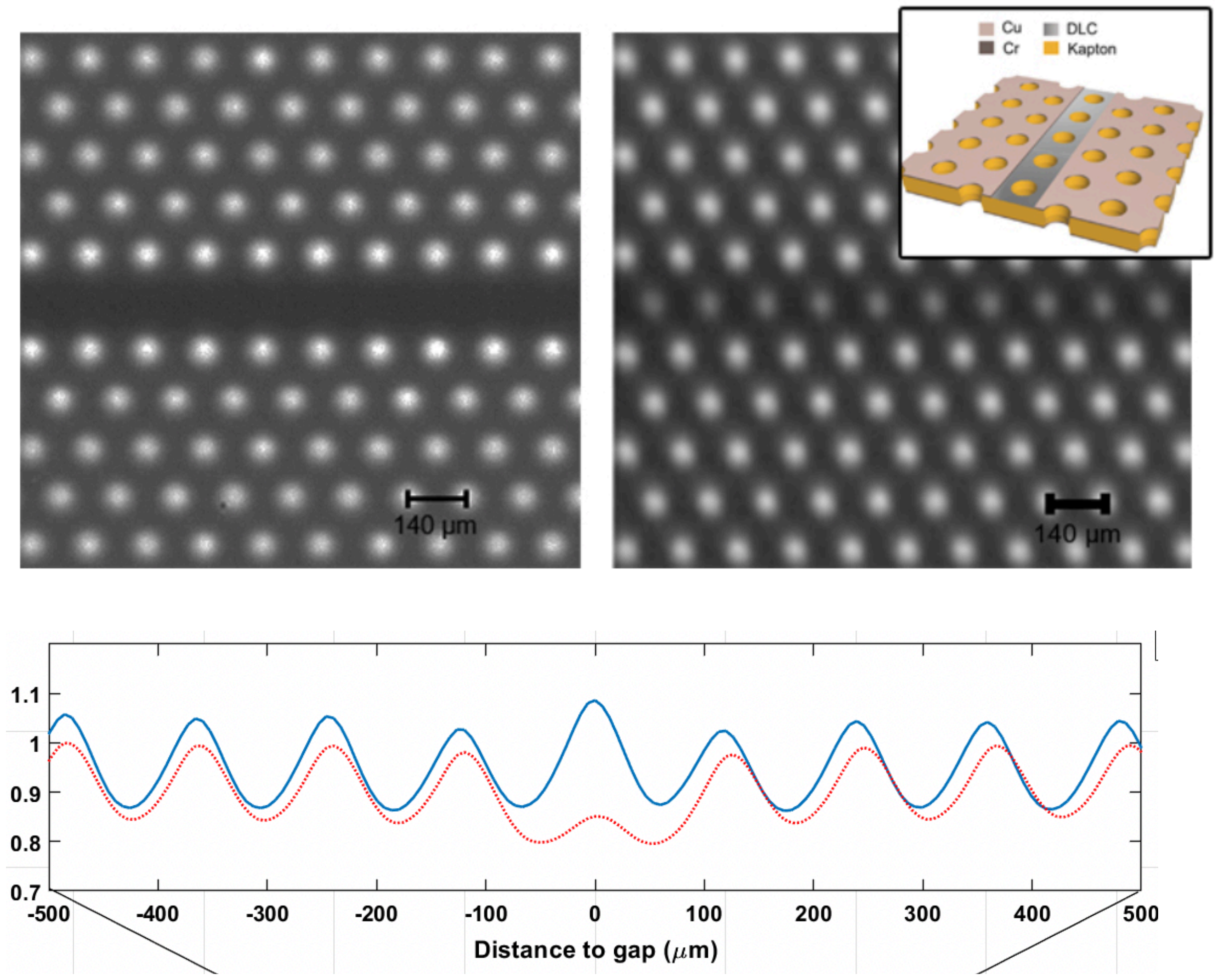
Kondo Gnanvo, RD51 Mini Week 2017

M. Lisowska, RD51 CM May 2019

Minimising distortions with DLC-based segmentation

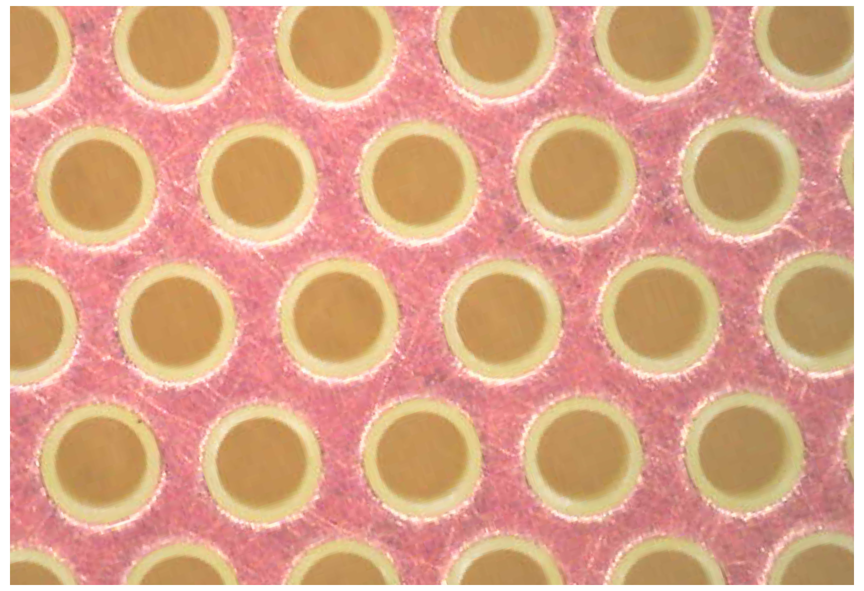
Electrode segmentation limits capacitance for spark protection

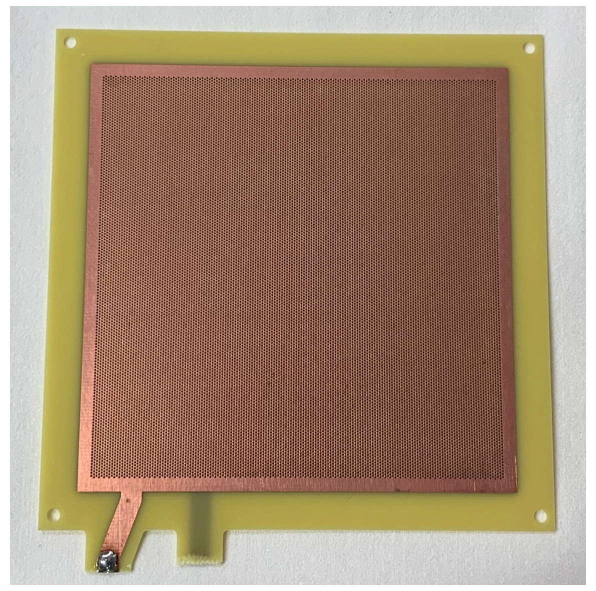
Holes in sector gaps can be used to minimise distortions



A.P. Marques et al. Minimizing distortions with sectored GEM electrodes, NIM A, 2020

THGEM



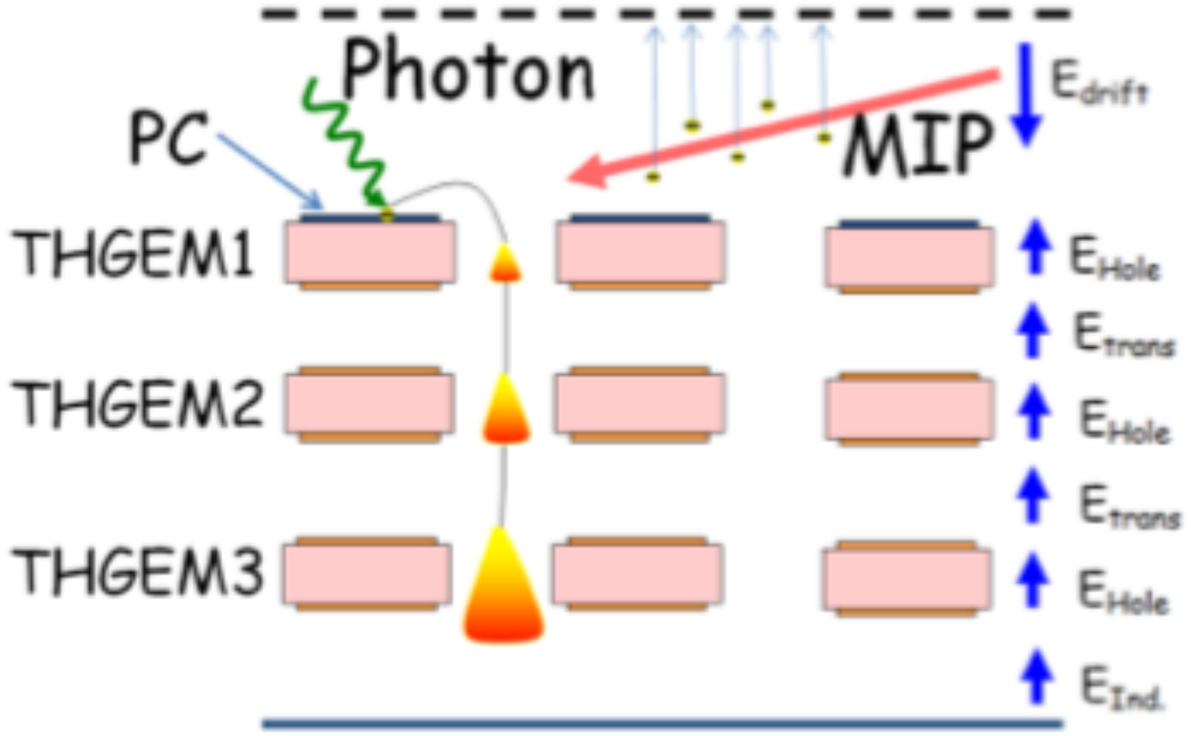


Mechanically drilled Cu-FR4-Cu structures with thickness ranging from hundreds of μm to millimetres

Open structure allowing for **multi-stage amplification** multi-GEM stacks

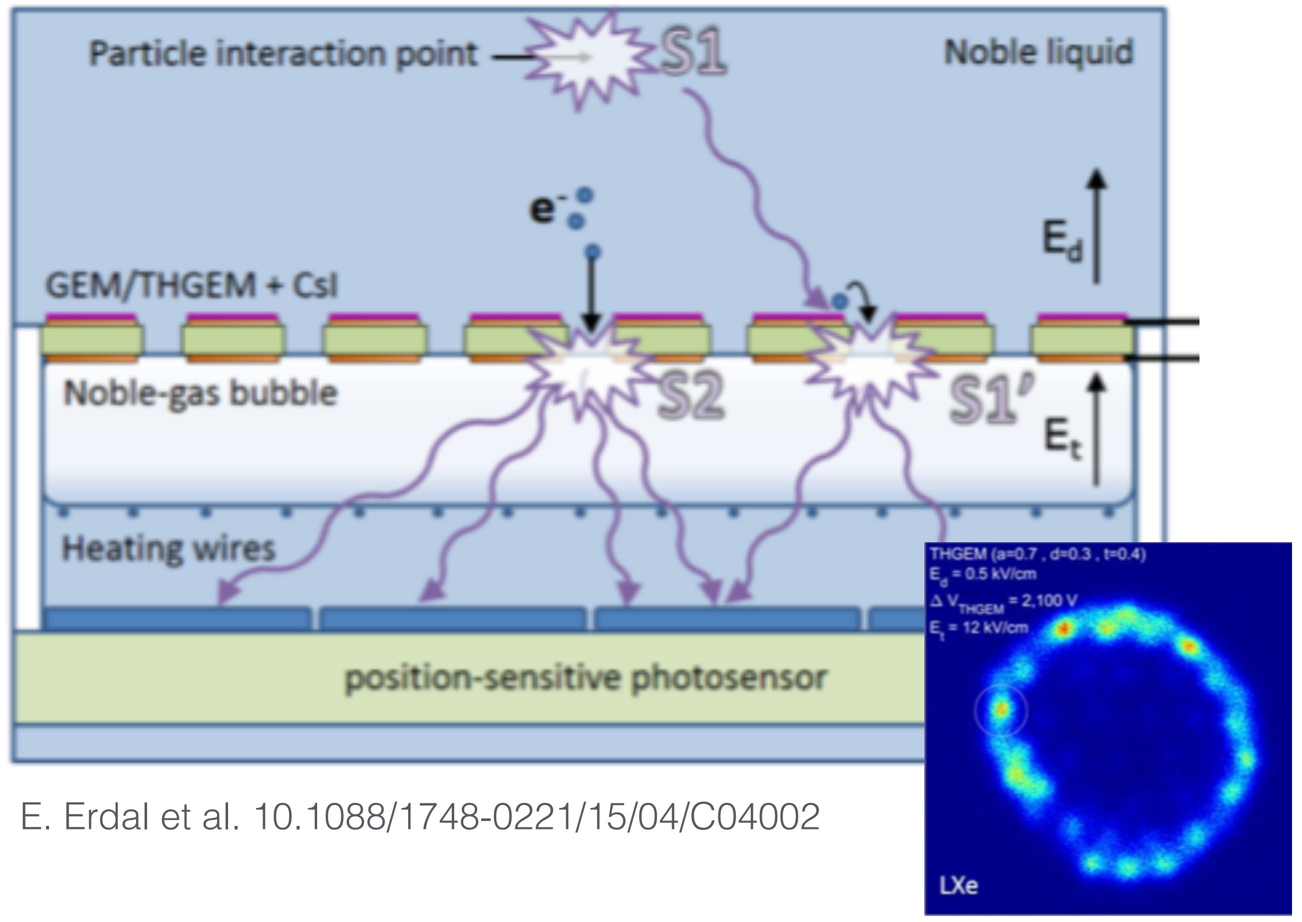
Long-amplification paths advantageous for low pressure operation

CsI-coated THGEM



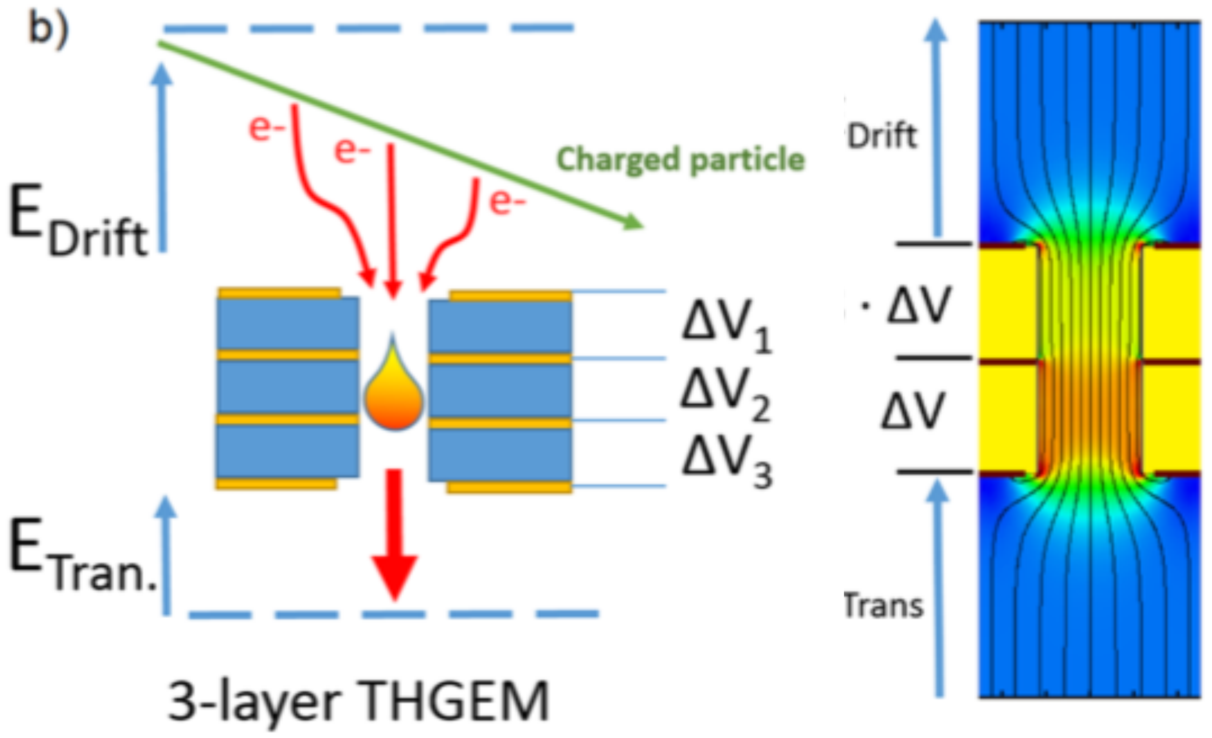
A. Breskin et al. 10.1016/j.nima.2010.10.034

Bubble-assisted Liquid Hole Multiplier



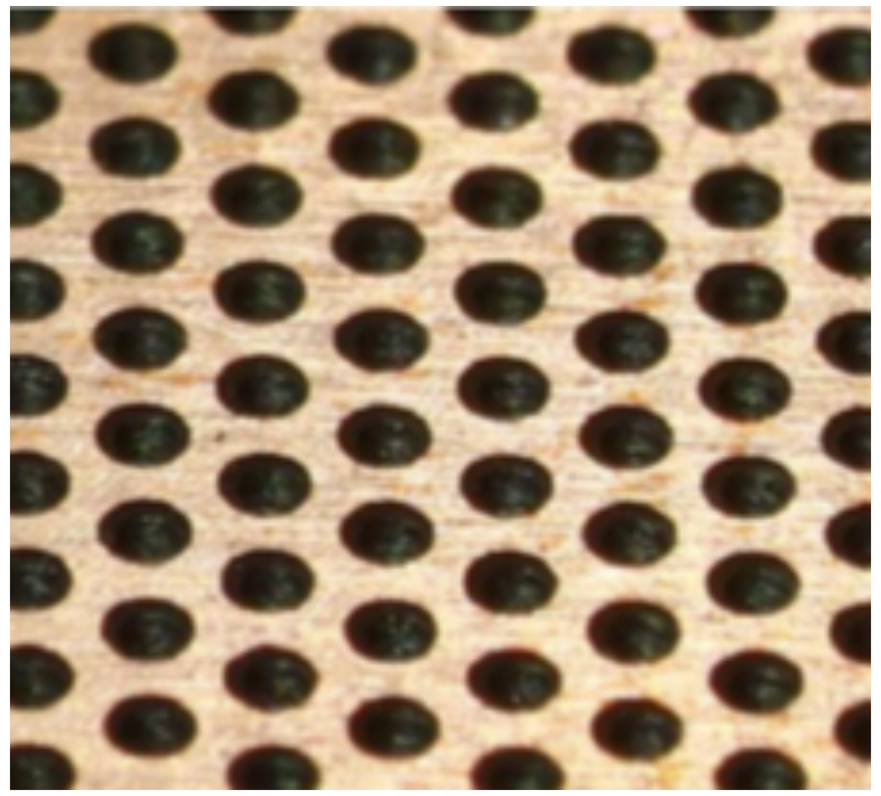
E. Erdal et al. 10.1088/1748-0221/15/04/C04002

Multi-layer THGEM



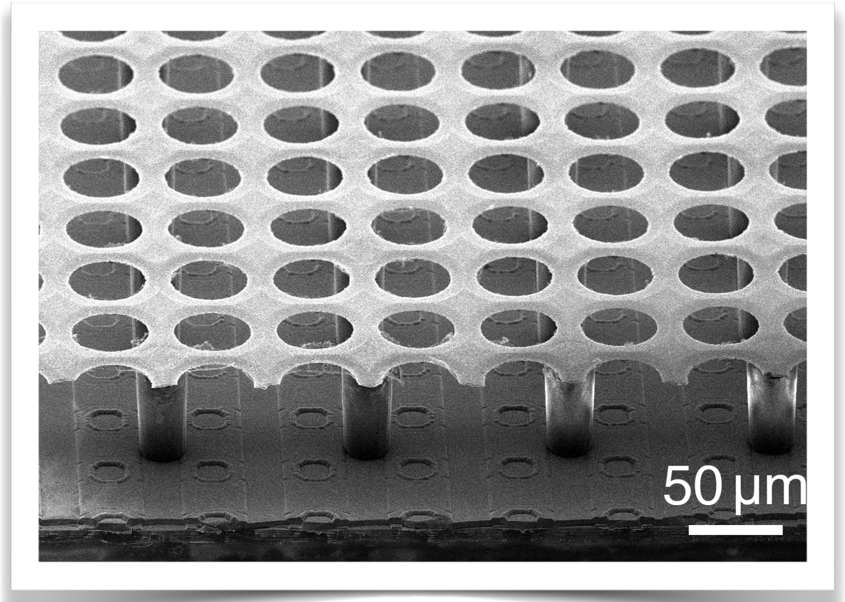
M. Cortesi et al. Rev. Sci. Instrum. 88, 013303 (2017); https://doi.org/10.1063/1.4974333

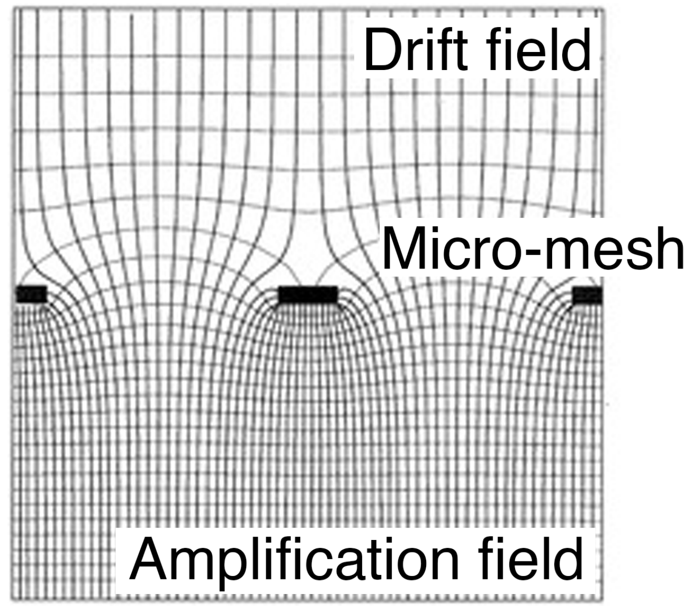
DLC-coated THGEM



Guofeng Song et al. /10.1016/j.nima.2020.163868

Micromegas



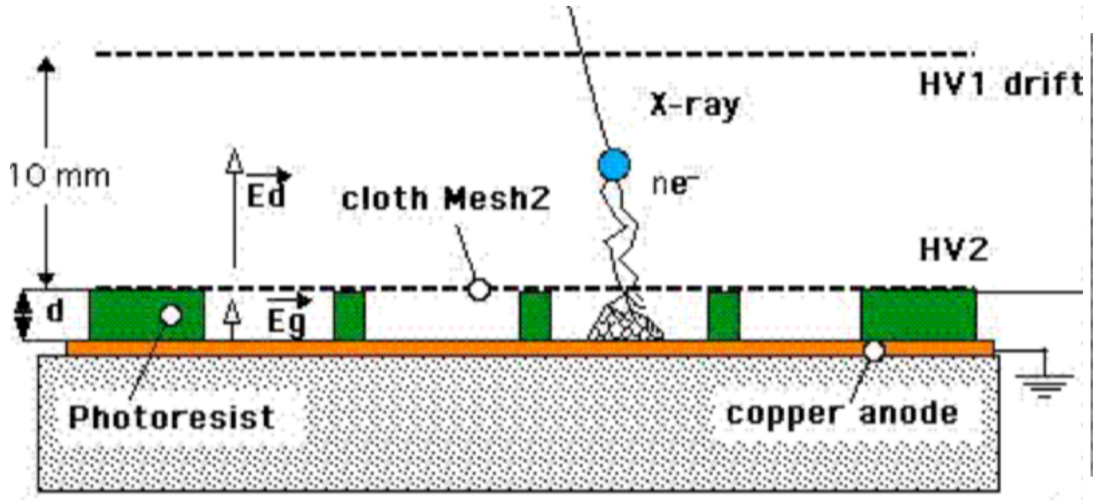


InGrid Micromegas

Micro-mesh suspended by pillars above anode.
Single-stage amplification with high gain and energy resolution realised in bulk or microbulk varieties.

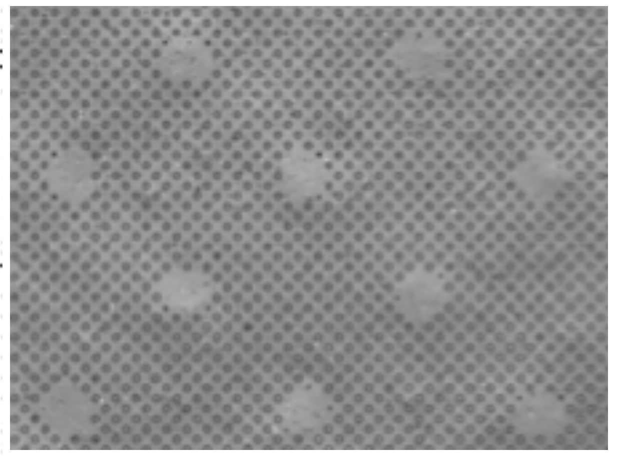
Resistive anode for spark protection and signal spreading

Bulk Micromegas



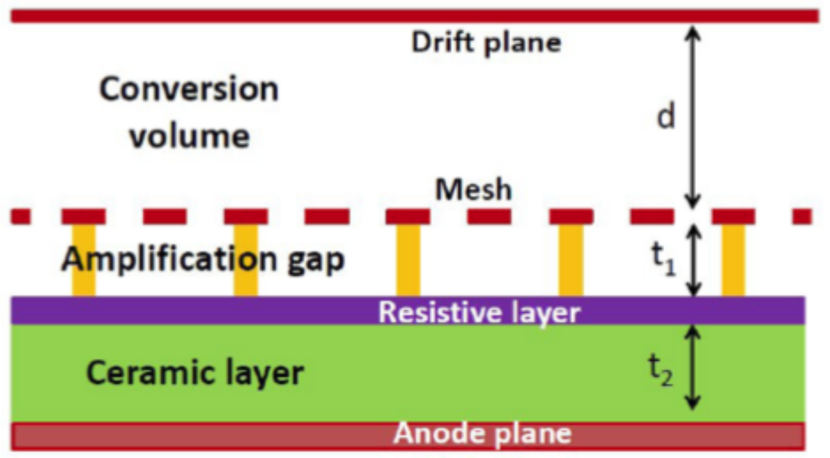
I. Giomataris et al. https://doi.org/10.1016/j.nima.2005.12.222

Microbulk MM



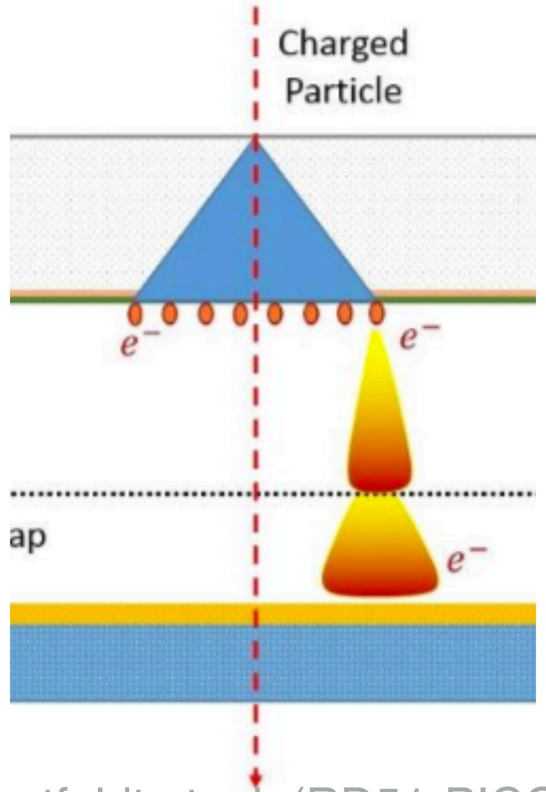
S Andriamonje et al 2010 JINST 5 P02001

Piggyback resistive Micromegas



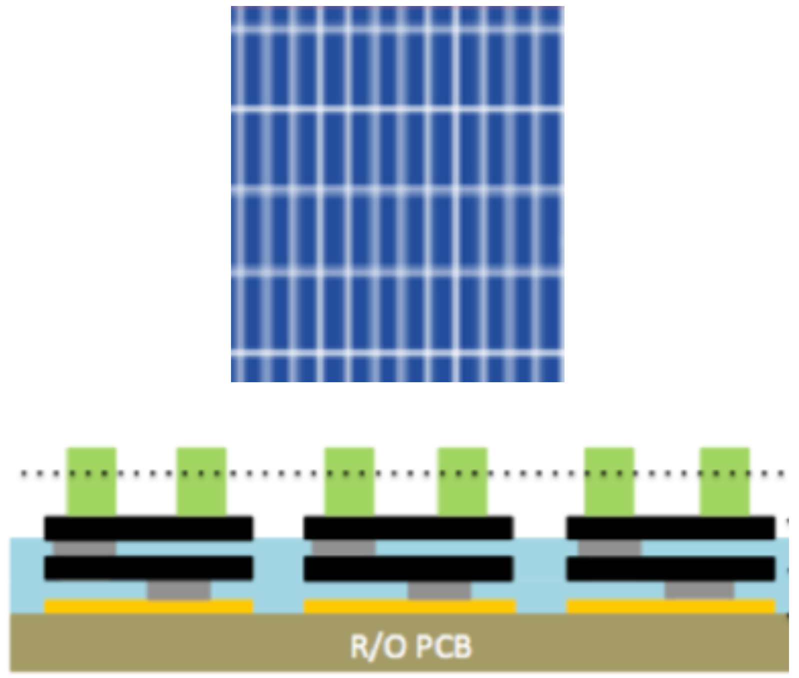
D. Attié et al. 10.1088/1748-0221/8/05/P05019,

Precise-timing Micromegas



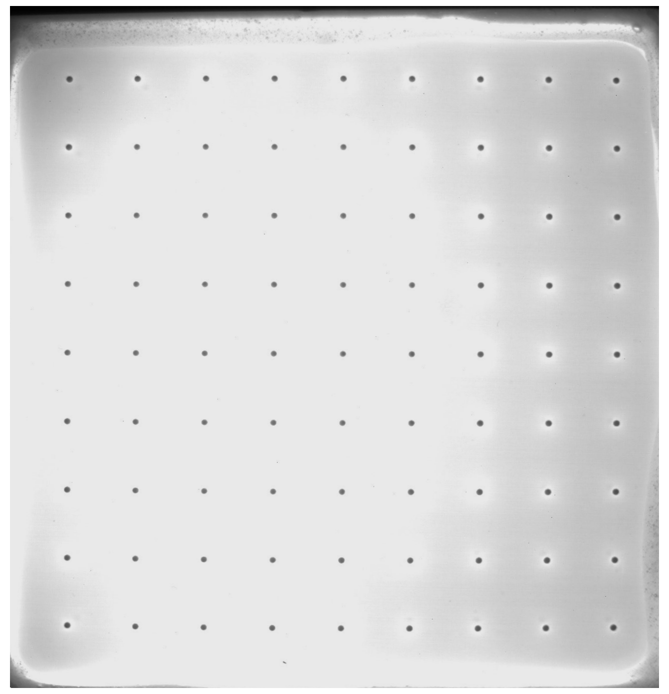
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), Nuclear. Inst. & Methods A 903 (2018) 317-325

Small Pad Micromegas



Mauro Iodice et al. MPGD 2019

Glass Micromegas



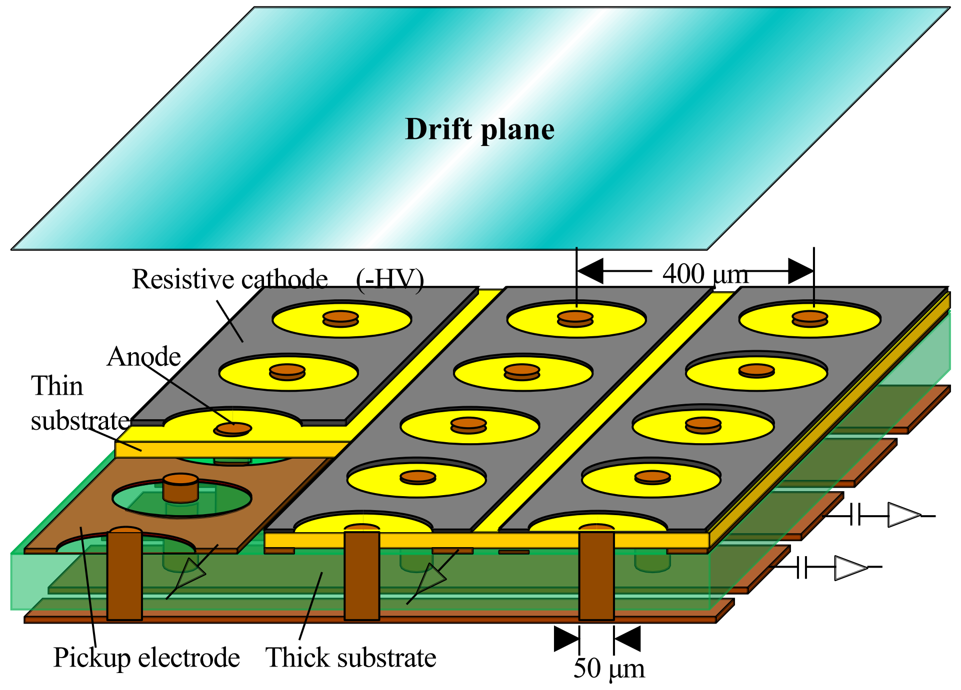
F. Brunbauer et al. https://doi.org/10.1016/j.nima.2019.163320

μPIC & well-type MPGDs

Single-stage amplification devices with resistive anodes for spark protection

Micro Pixel Chamber *μ*PIC

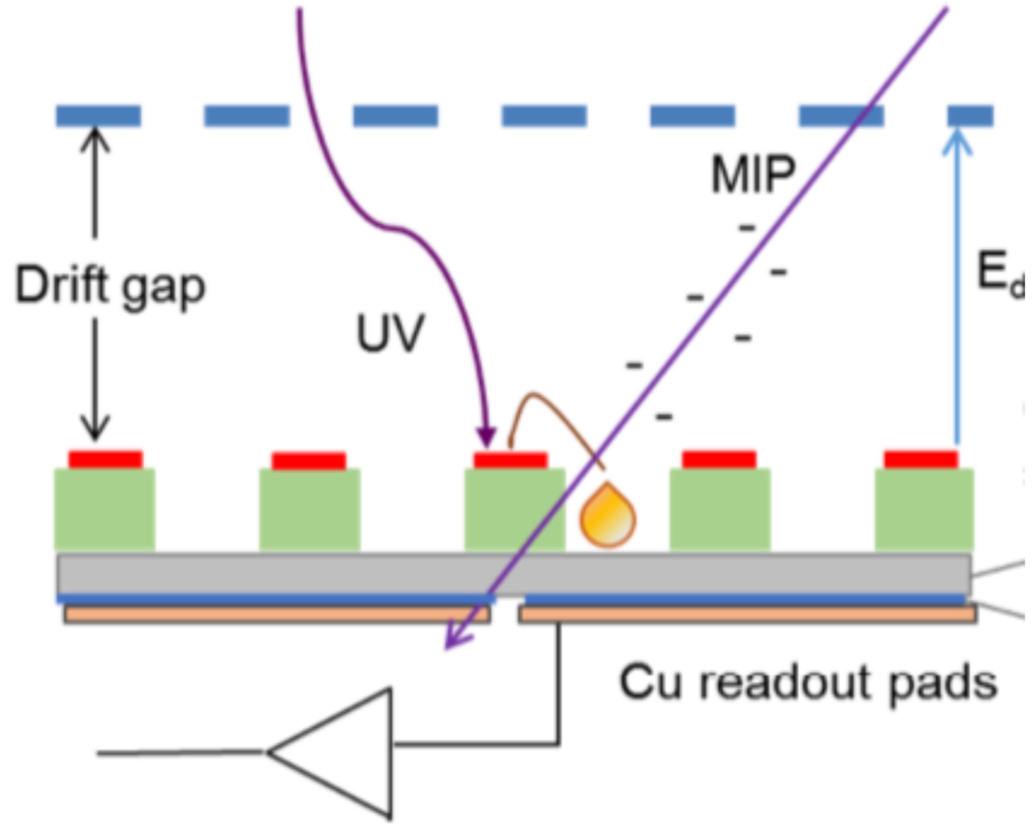
Pixellated anode structure for robustness, capable of high-rate operation and good spatial resolution



A. Ochi, RCGD2019@Bari

RPWELL

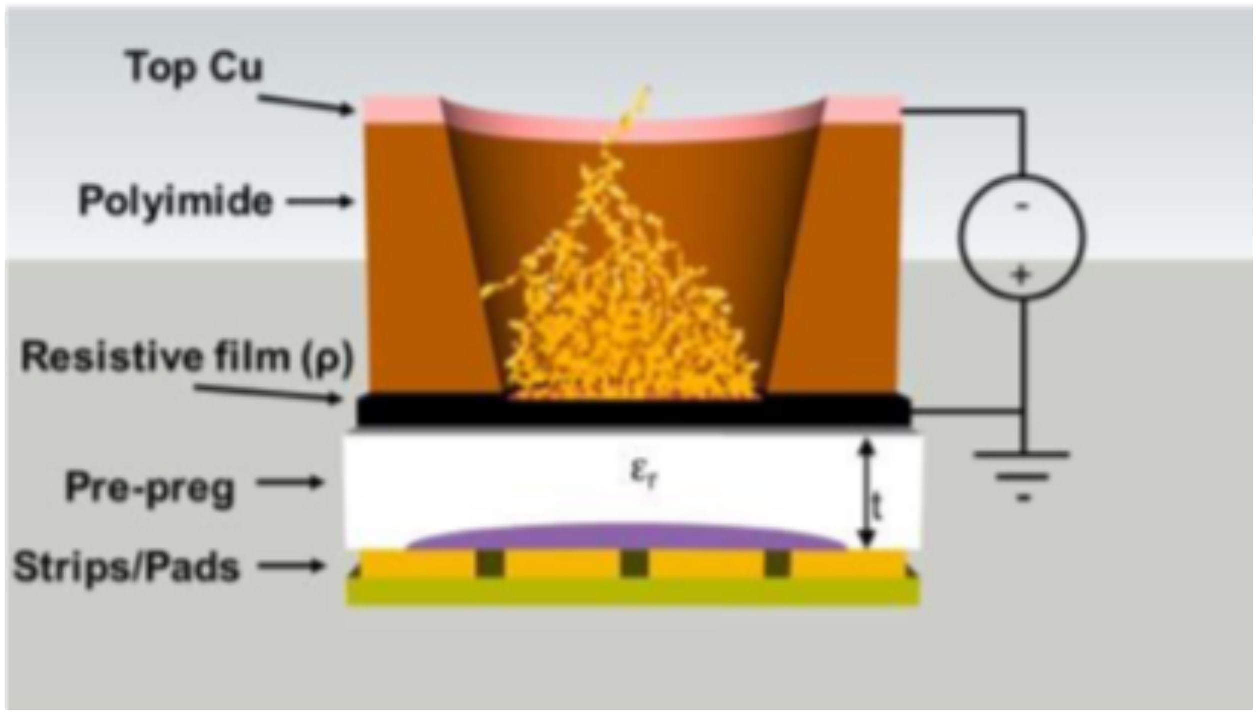
Single-sided Thick Gaseous Electron Multiplier coupled to resistive anode

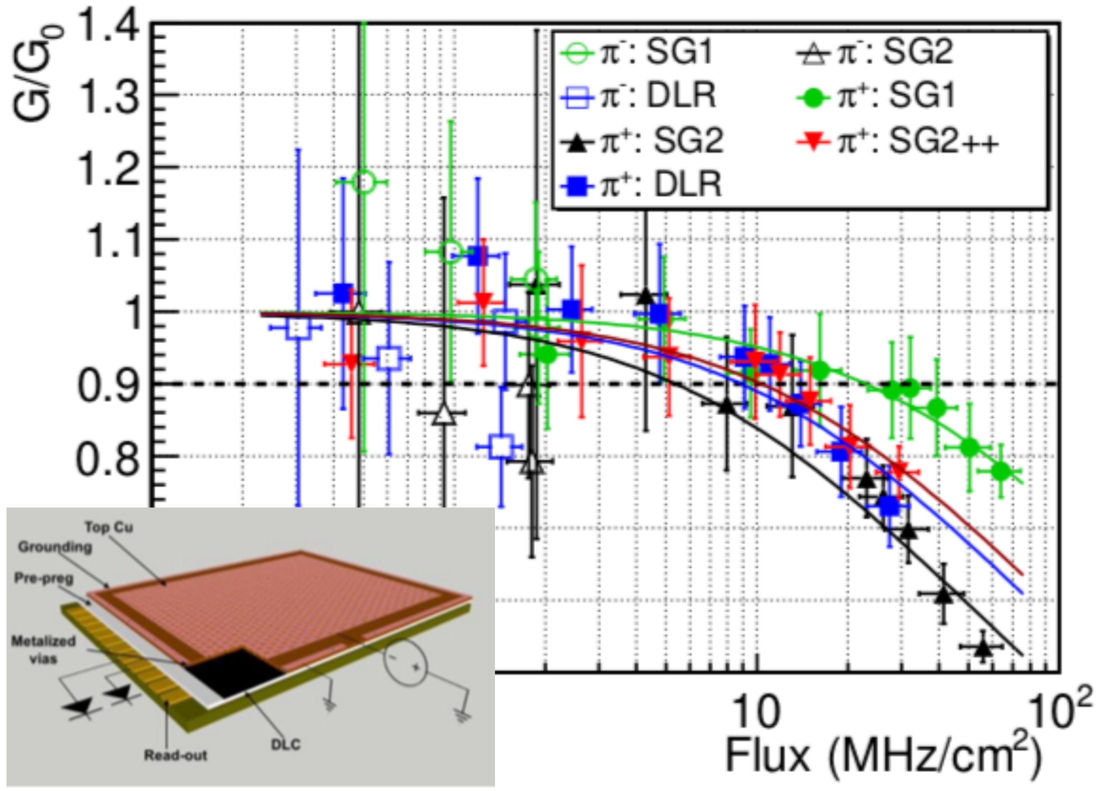


A. Roy et al 2019 JINST 14 P10014

*μ*RWELL

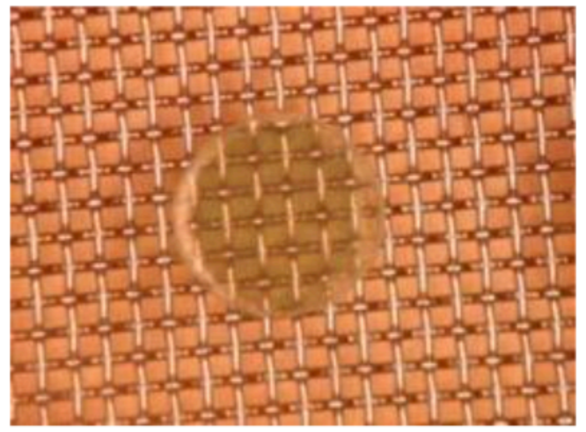
DLC based resistive layers with charge evacuation schemes compatible with high-rate operation



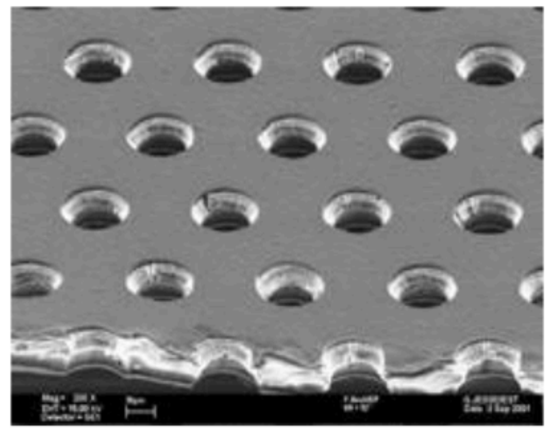


G. Bencivenni et al 2019 JINST 14 P05014

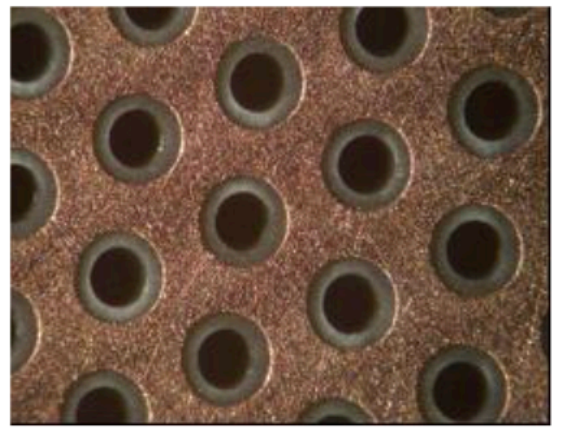
MPGD timeline



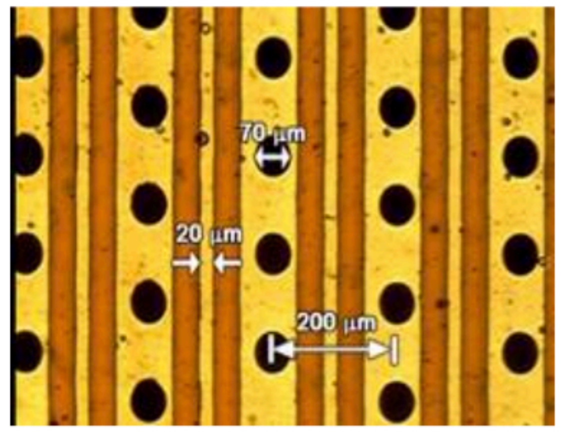
MicroMegas



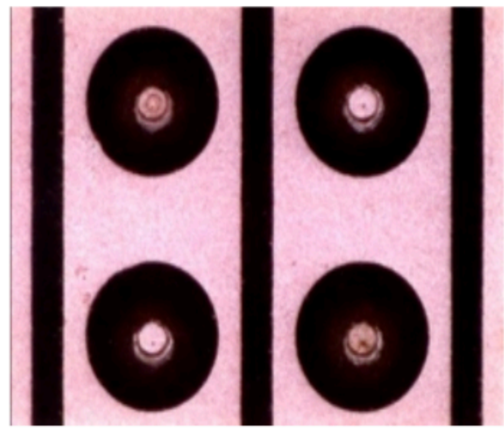
GEM



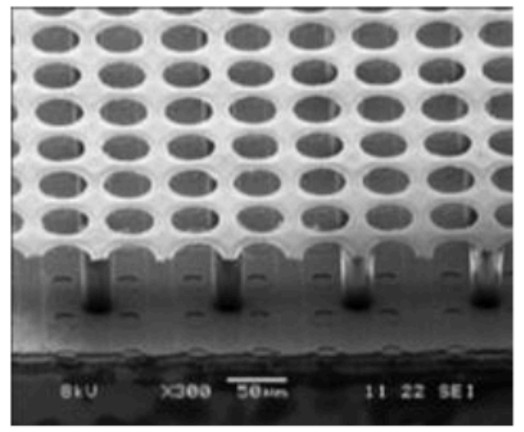
THGEM



MHSP



microPIC

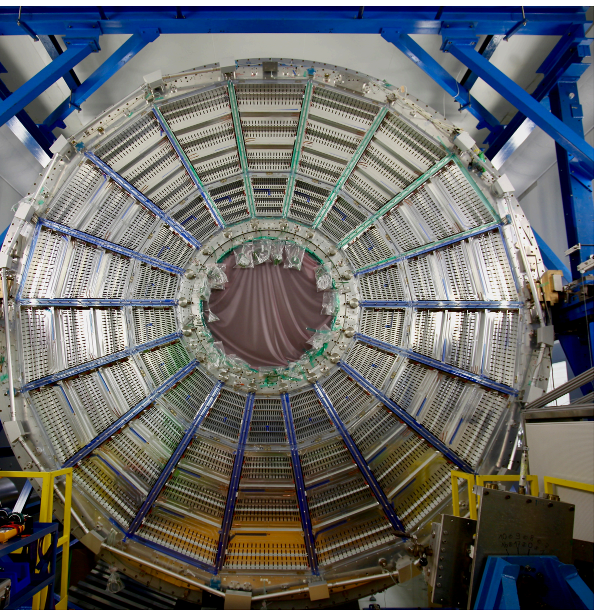


Ingrid

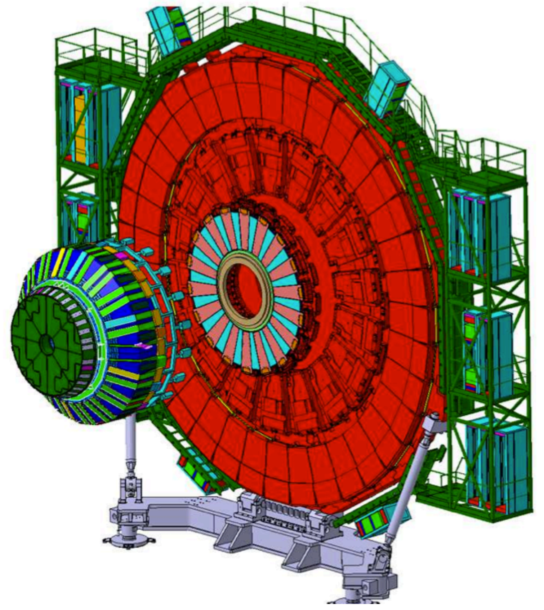
RD51

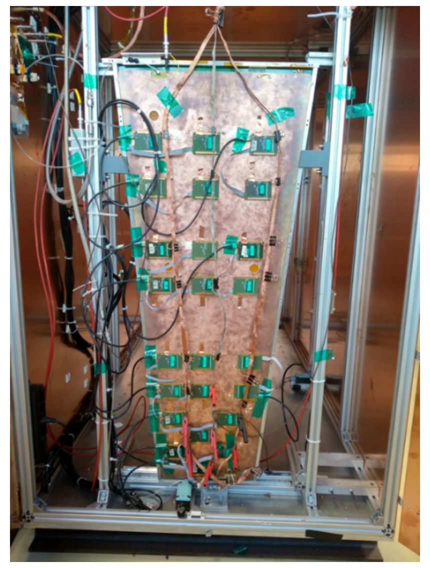
- 1988 — MSGC
- 1996 — Micromegas
- 1997 — GEM
- 2000 — μPIC
- 2002 — THGEM
- 2009
- 2014
- 2019

Adoption of MPGD technologies:
ATLAS NSW (Micromegas)
CMS forward tracking update (GEM)
COMPASS RICH upgrade (hybrid MPGD)
ALICE TPC upgrade (GEM)
KLOE2 & BESIII (GEM)
LBNO-DEMO (THGEM)
n-detection at ESS (GEM)
Muon radiography (Micromegas)
…

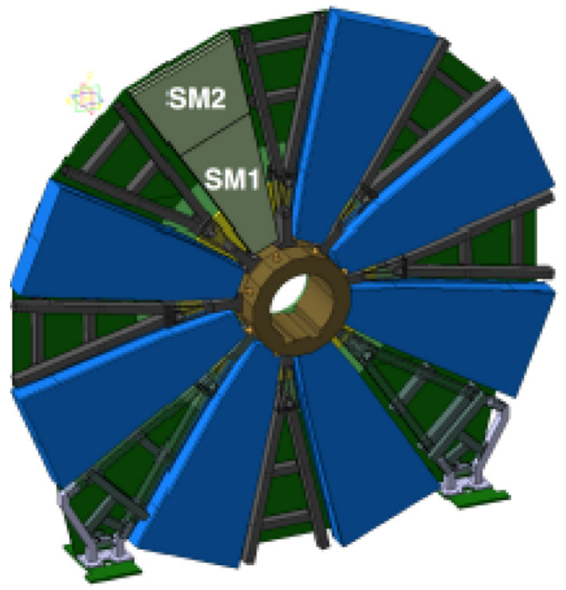


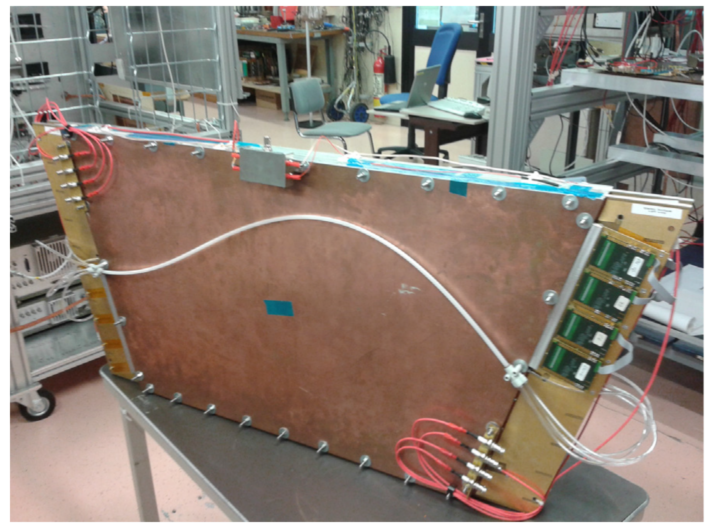
Alice GEM TPC



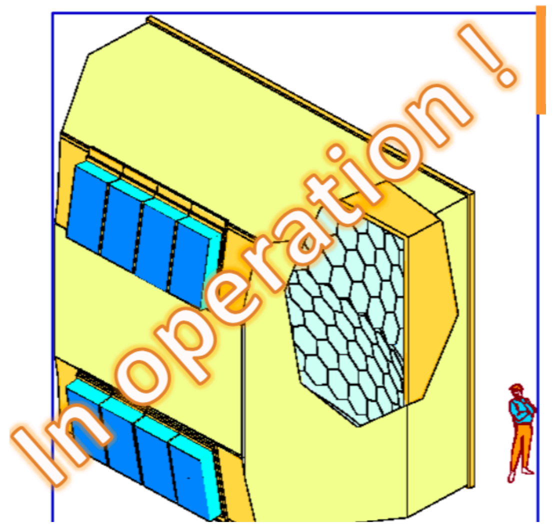


CMS Muon GEM upgrade

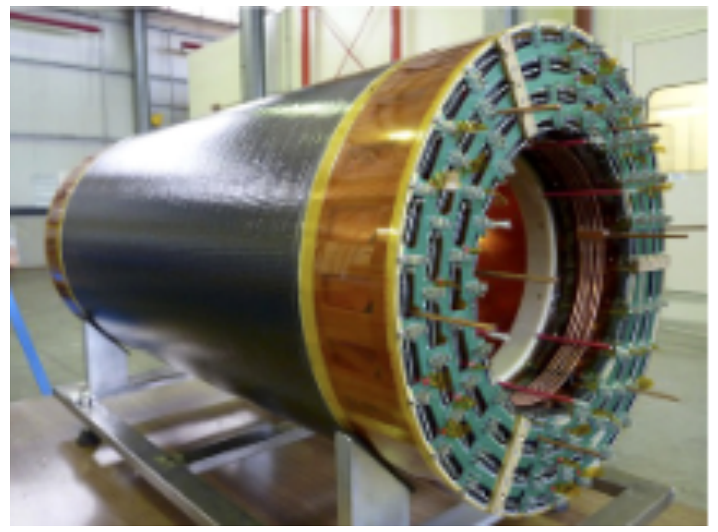




ATLAS NSW Micromegas upgrade



COMPASS RICH



KLOE-2 GEM tracker

Muography with Micromegas

RD51 collaboration

Development of Micro-Pattern Gas Detectors Technologies

Advance the technological development and application of MicroPattern Gas Detectors (MPGDs) and contribute to the dissemination of these technologies.

Development

Exploit existing technologies
Large size single-mask GEMs
Resistive Micromegas

Develop novel technologies
µPIC, µR-WELL, GRIDPIX

Dissemination

High-Energy Physics
ALICE, ATLAS, CMS, Compass, KLOE, BESIII

Fundamental research beyond HEP
LBNO-DEMO, active-target TPCs

Beyond fundamental research
Muon radiography, n-detection, X-ray radiographies

Production techniques and industrialisation

Common infrastructures
(GDD lab, common test beam)

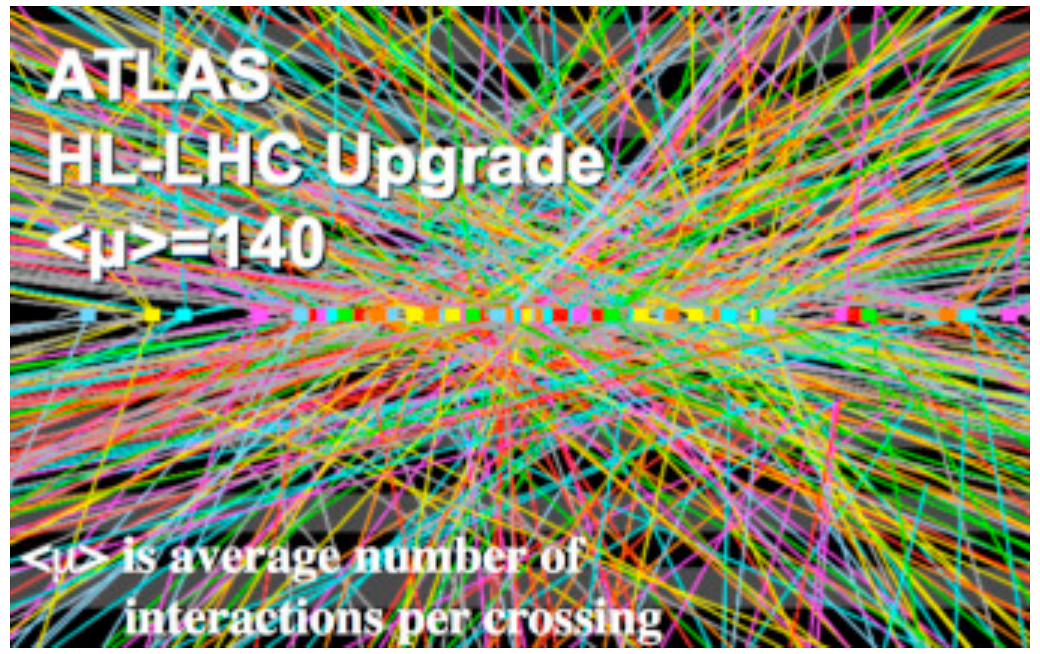
Electronics
(Scalable Readout System SRS, instrumentation)

Simulation
(Garfield, Magboltz, Degrad, neBEM)

rd51-public.web.cern.ch

Precise timing with Micromegas

PICOSEC detection concept



PID techniques: Alternatives to RICH methods, J. Va'vra, NIMA **876** (2017) 185-193, https://dx.doi.org/10.1016/j.nima.2017.02.075

To mitigate pile-up and separate particles coming from different vertices:

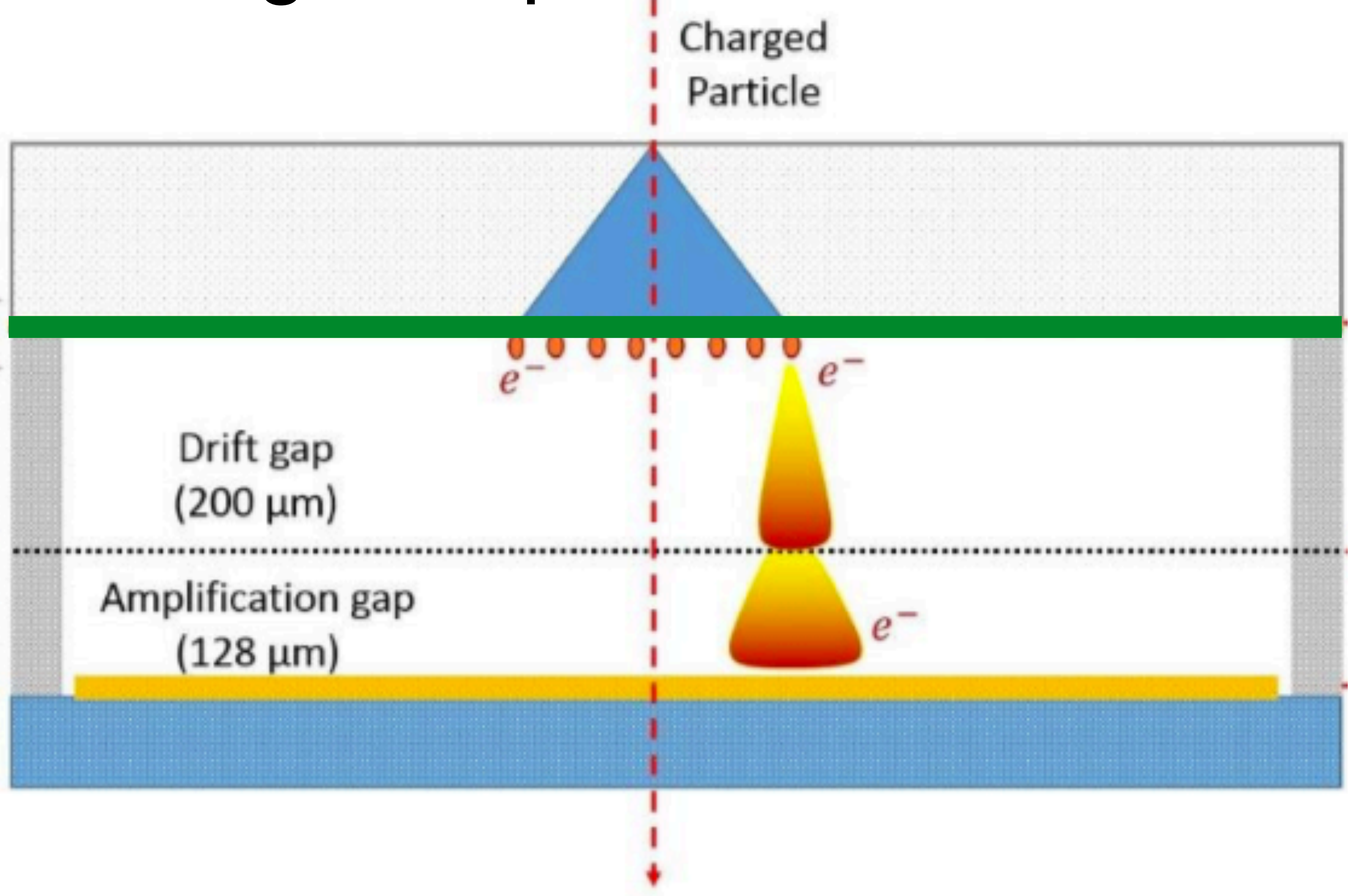
- Exploit precise timing to separate tracks

Cherenkov radiator
(3 mm MgF_2)

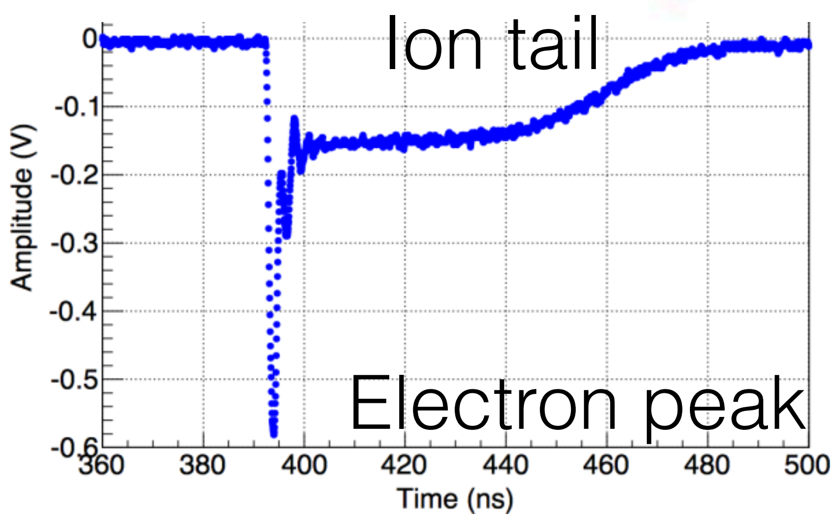
Photocathode
(3 nm Cr + 18 nm CsI)

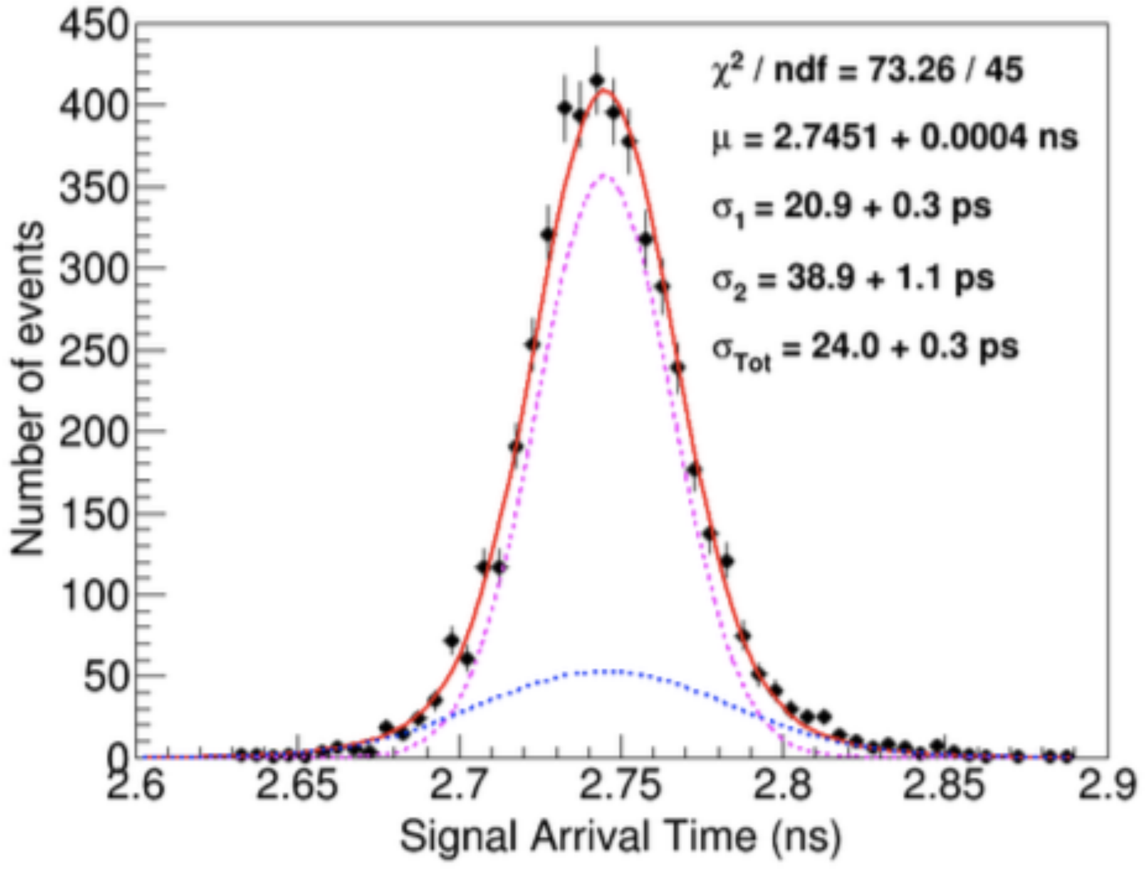
Drift gap
(Pre-amplification)

Micromegas
(Amplification)

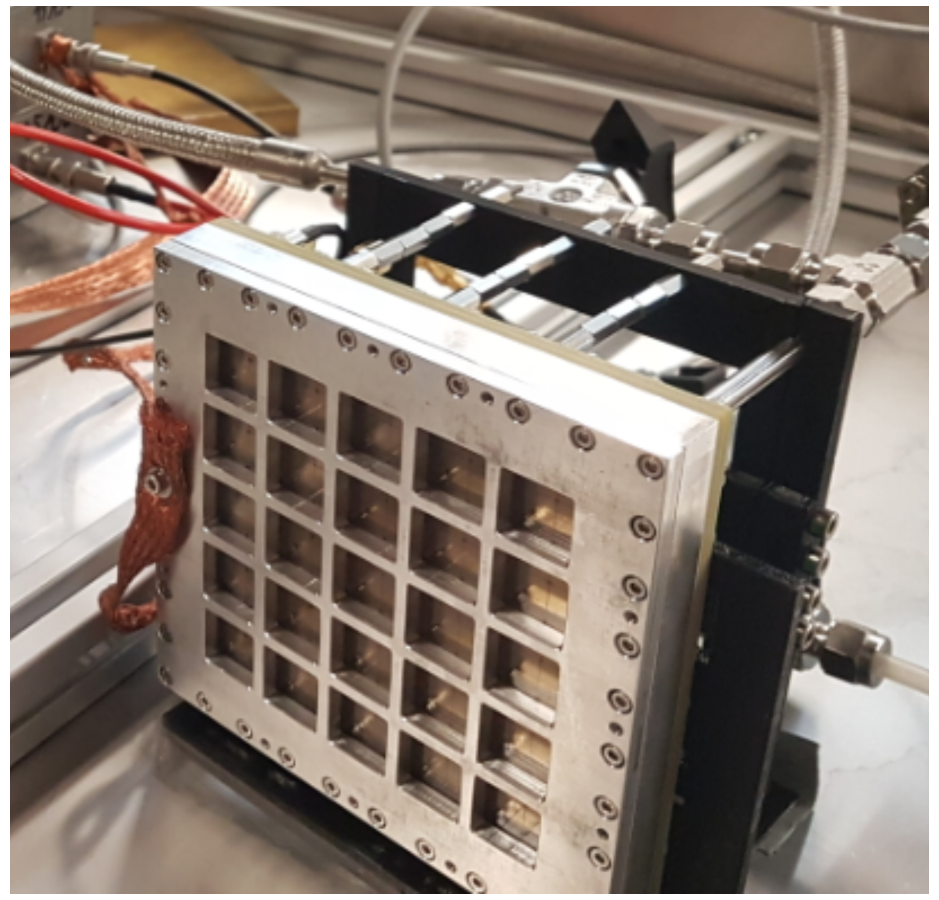


Typical signal shape





24 ps MIP timing resolution



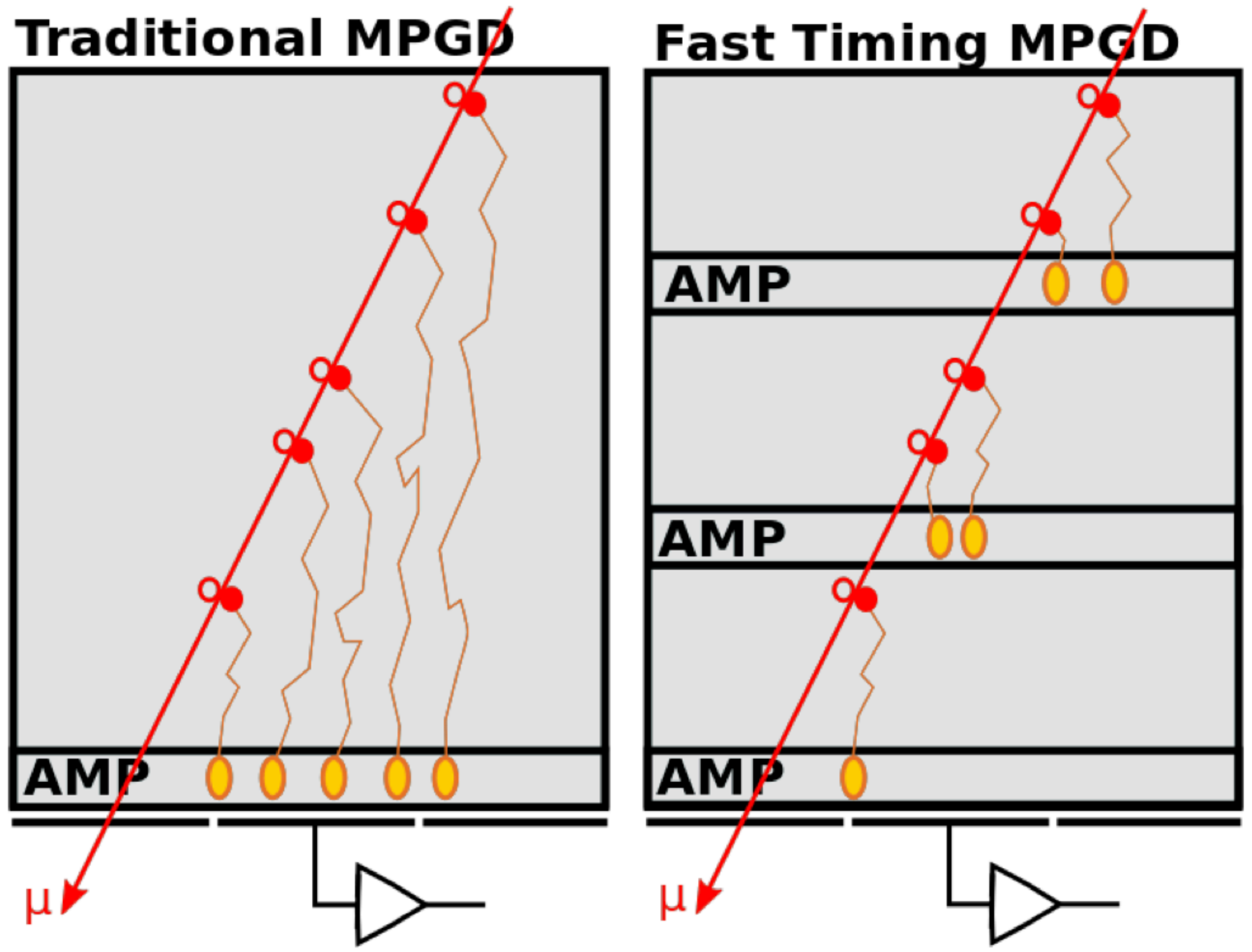
10x10 module

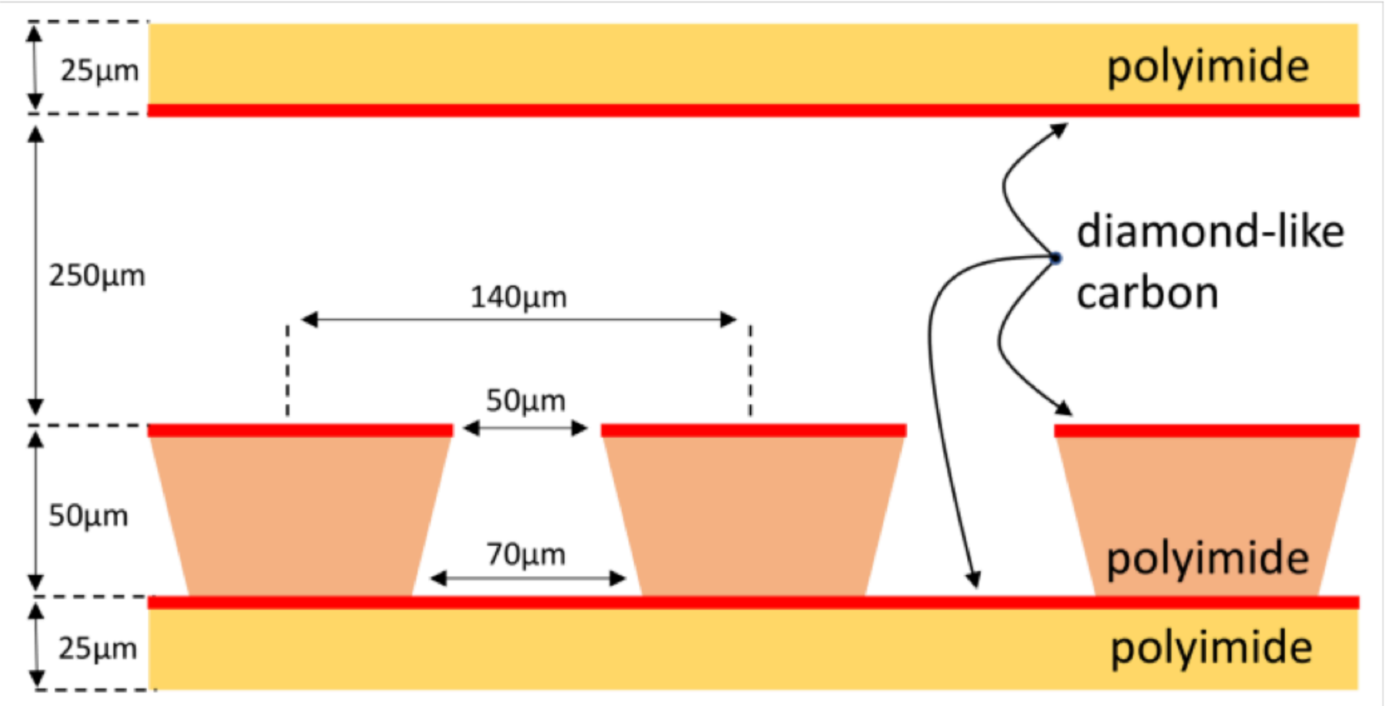
▫ 1 cm

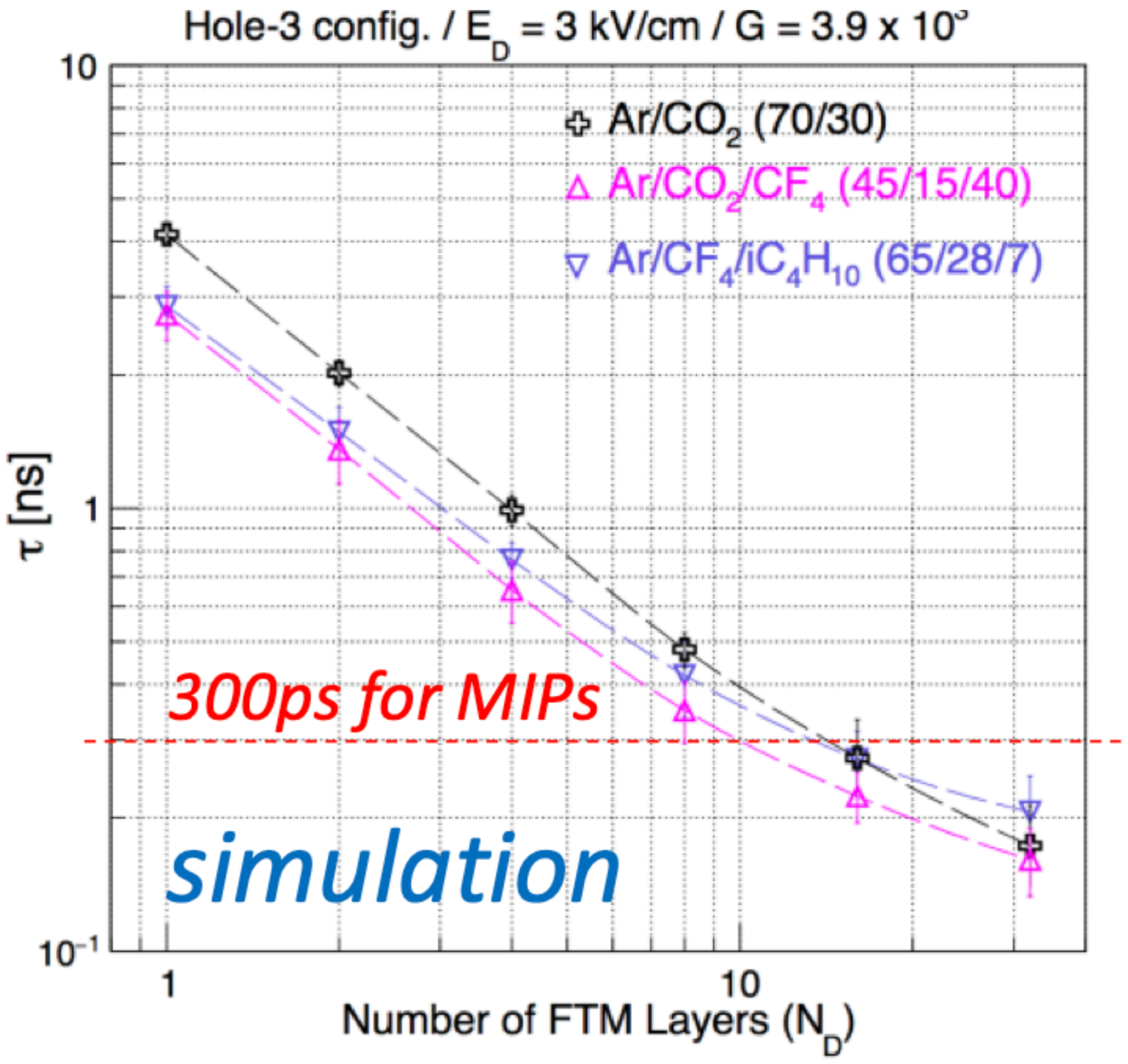
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), Nuclear. Inst. & Methods A 903 (2018) 317-325

Fast Timing with MPGDs: FTM

- Drift region divided in multiple layers, each with its own amplification stage
- Resistive electrodes to allow signal induction from all layers in readout plane
- Time Resolution $\sigma t = 1/(\lambda \cdot v_{drift} \cdot N)$, where N = layers





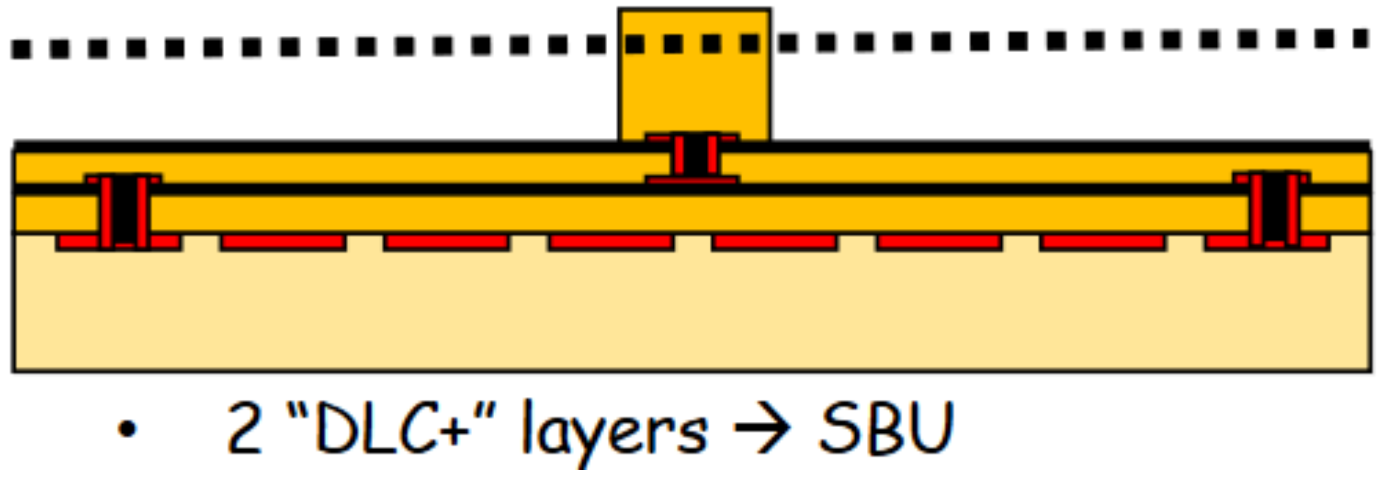


Piet Verwilligen, Ilenges and New developments Precision timing detectors, ECFA TF1 symposium
https://indico.cern.ch/event/999799/contributions/4257078/attachments/2236046/3790401/20210429_ECFA_TF1_FastTiming.pdf

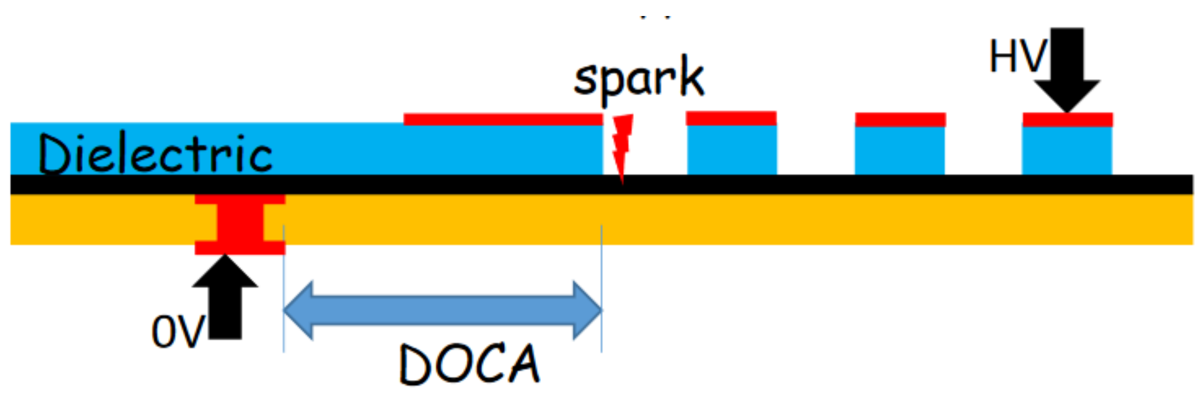
Resistive detectors

- Protection again destructive discharges and charge sharing for improved spatial reconstruction
- R&D on resistive materials with DLC being employed for various technologies including μRWELL and GEMs

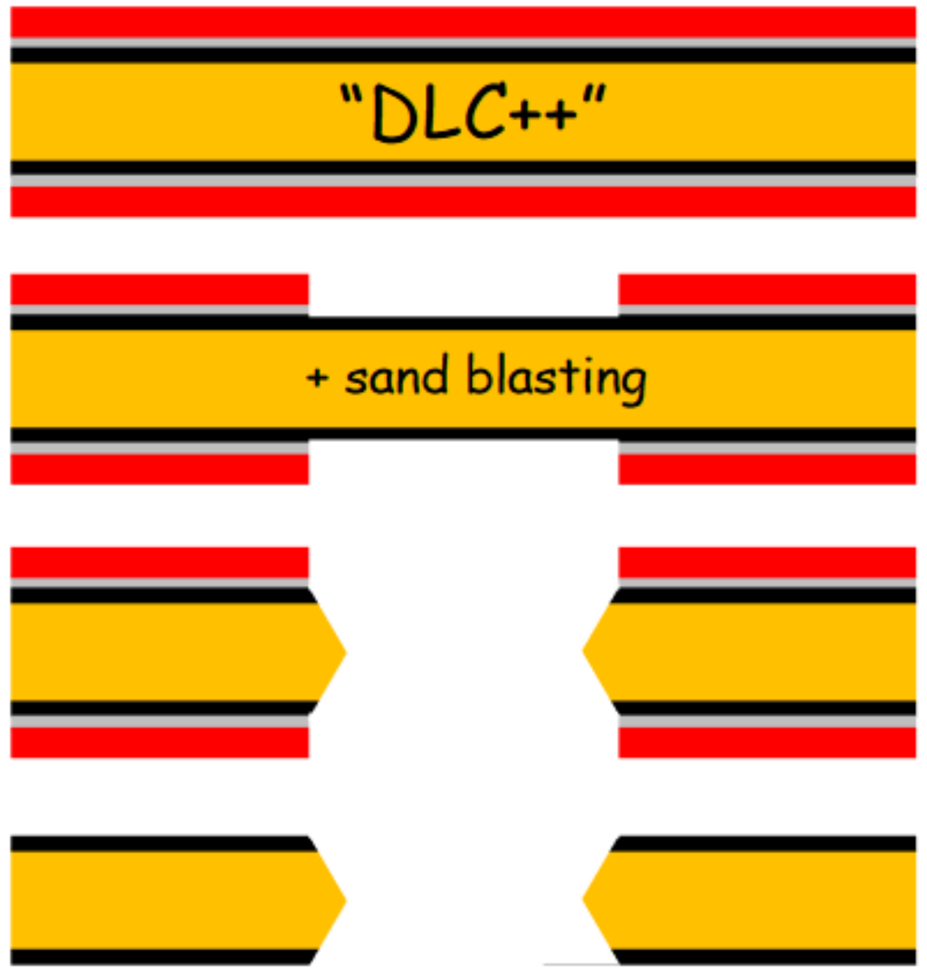
Sequential build'up technique



Distance of closest approach in resistive detectors

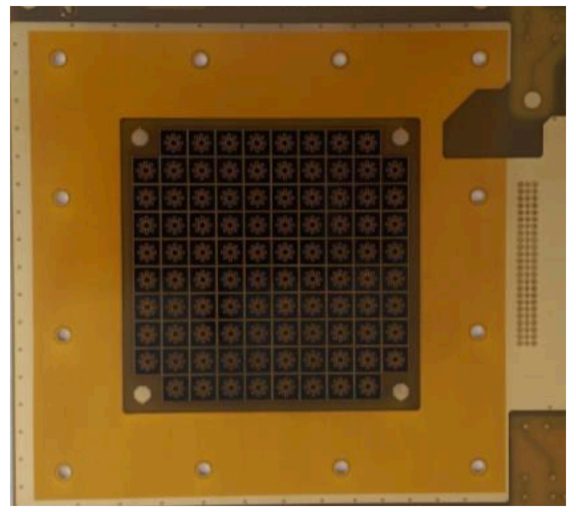


DLC GEM



https://ep-dep-dt.web.cern.ch/micro-pattern-technologies

Embedded printed resistors

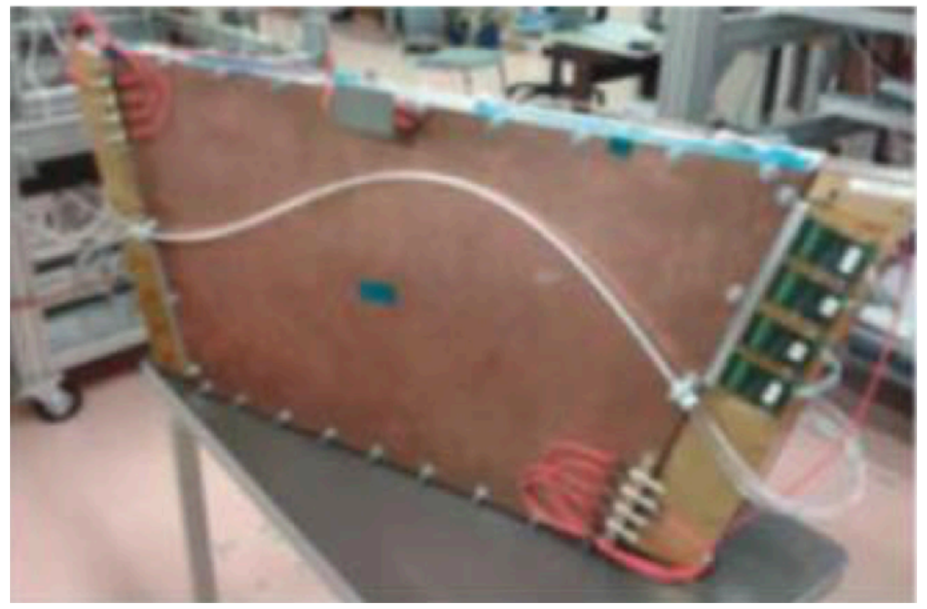


https://indico.cern.ch/event/613107/contributions/2494876/attachments/1430109/2196412/T2K_-Rui-presentation.pdf

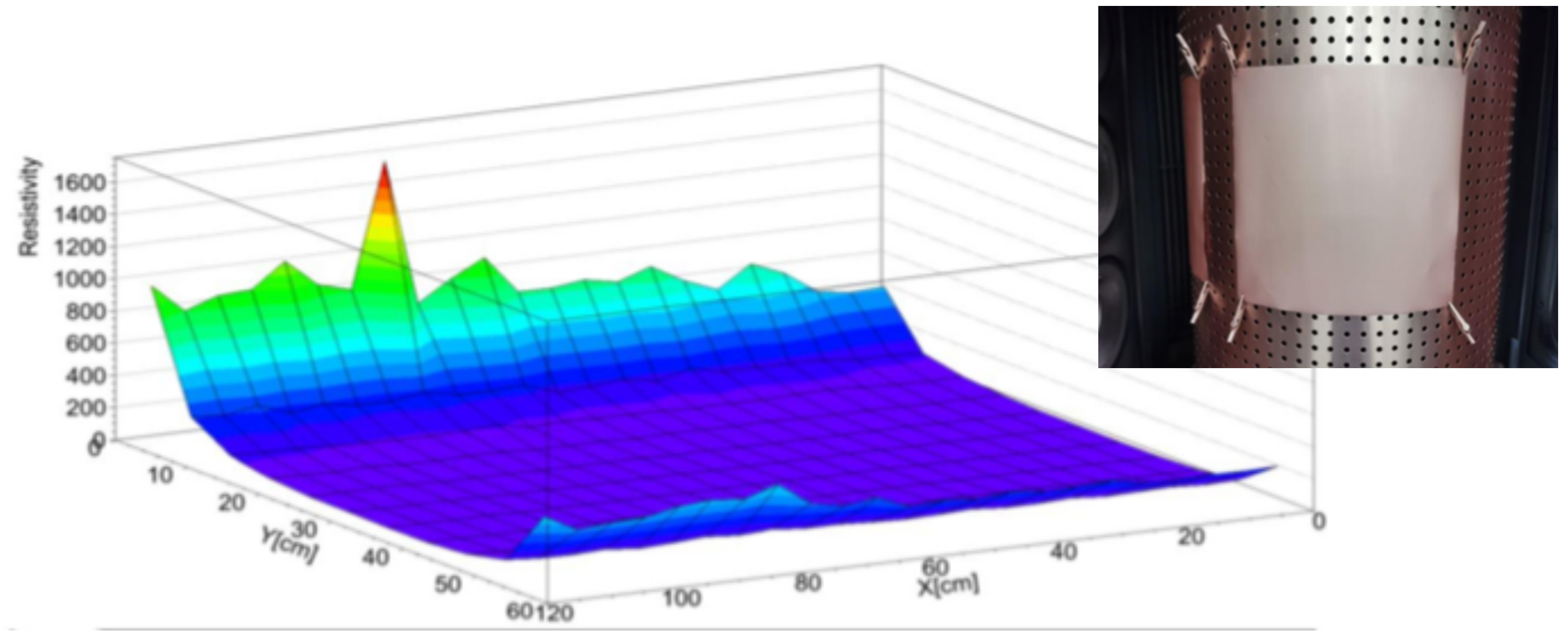
High-rate µRWELL prototype

https://indico.cern.ch/event/889369/contributions/4020066/attachments/2115302/3560690/RD51_collabration_meeting_YouLv.pptx

ATLAS resistive Micromegas



R&D progress on resistive DLC

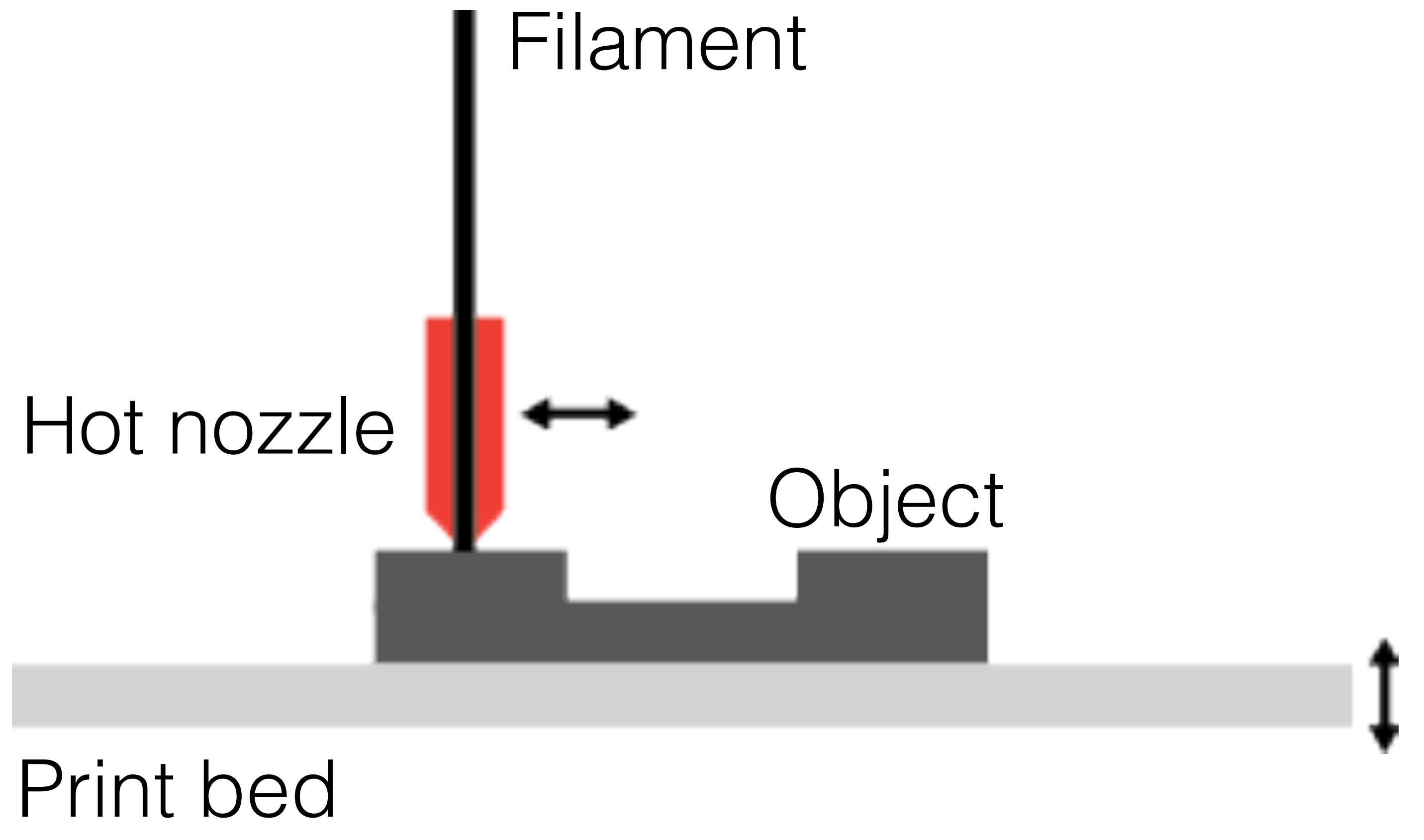


https://indico.cern.ch/event/889369/contributions/4042718/attachments/2119630/3567203/RD51-Collaboration-Meeting-WG6-ZhouYi_2020-10-09.pdf

Additive manufacturing techniques

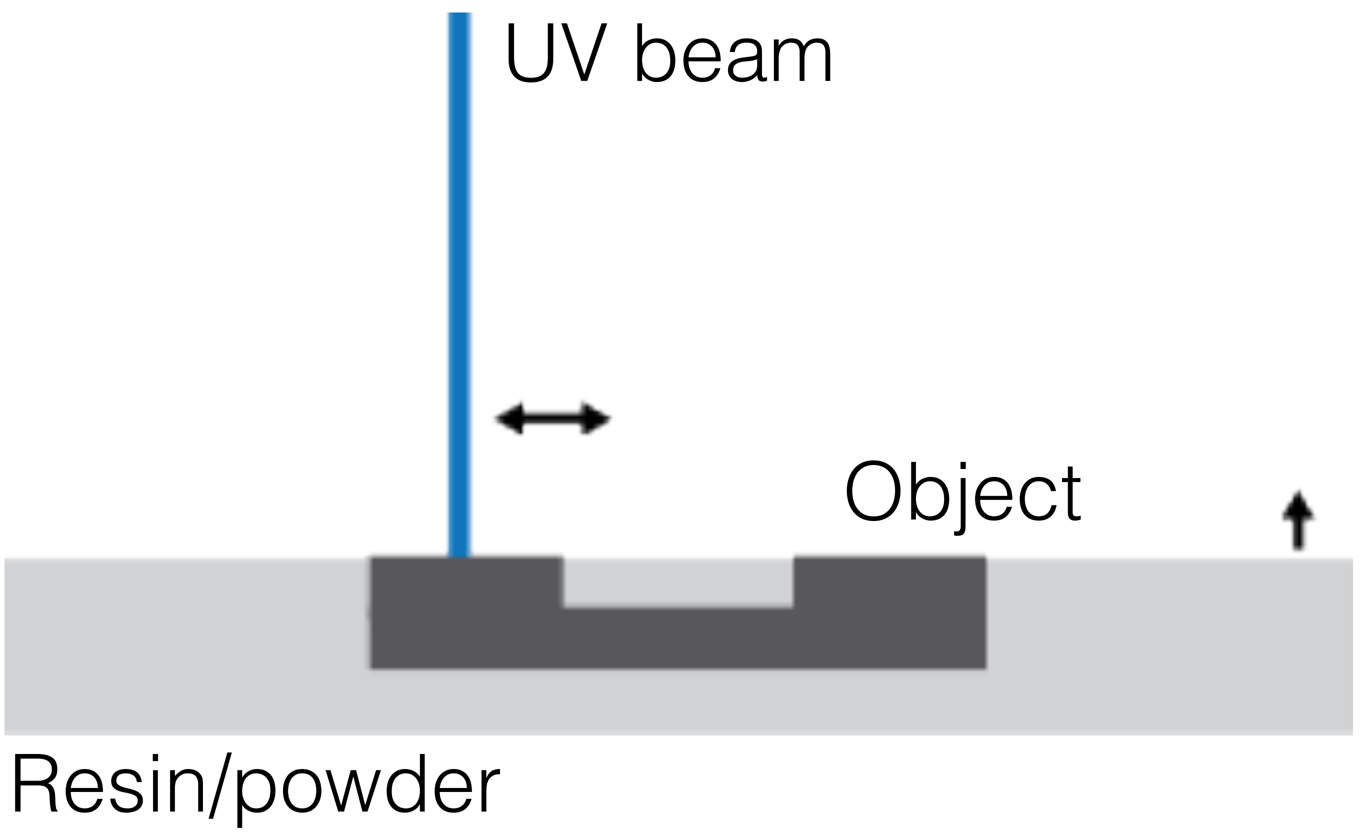
Available 3D printing techniques offer a wide range of spatial resolution and material capabilities. Multi-material fabrication including electrically conductive and insulating materials is crucial for fabricating functional structures.

Fused deposition modeling (FDM)



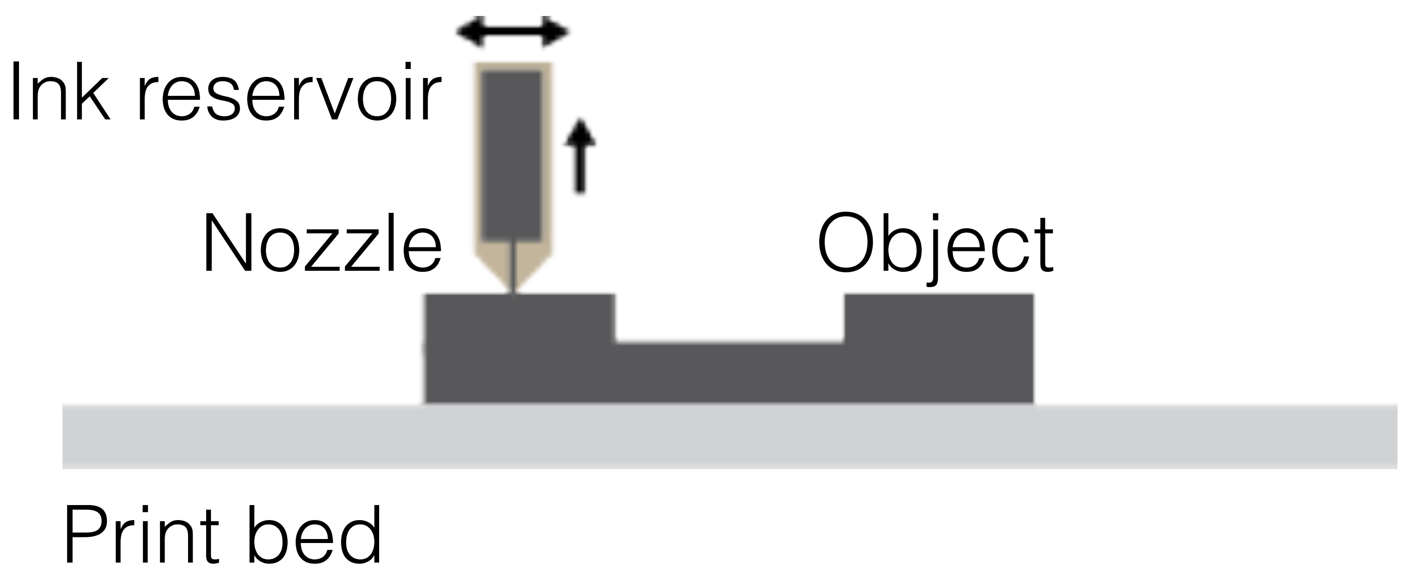
- Hundreds of micrometer resolution
- Conductive and insulating material available

Stereolithography



- Tens of micrometer resolution
- Insulating material only

Inkjet printing

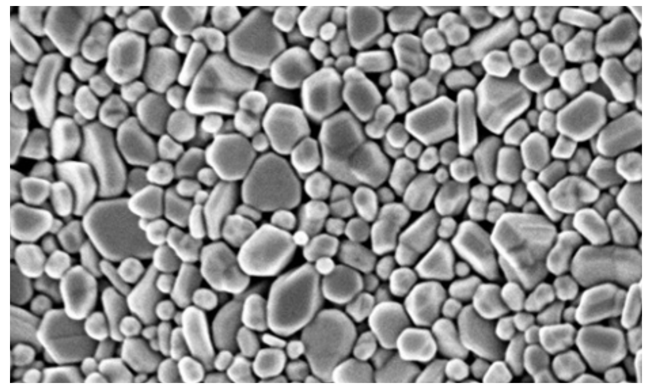


- Tens of micrometer resolution
- Conductive and insulating material available

Schematics not drawn to scale

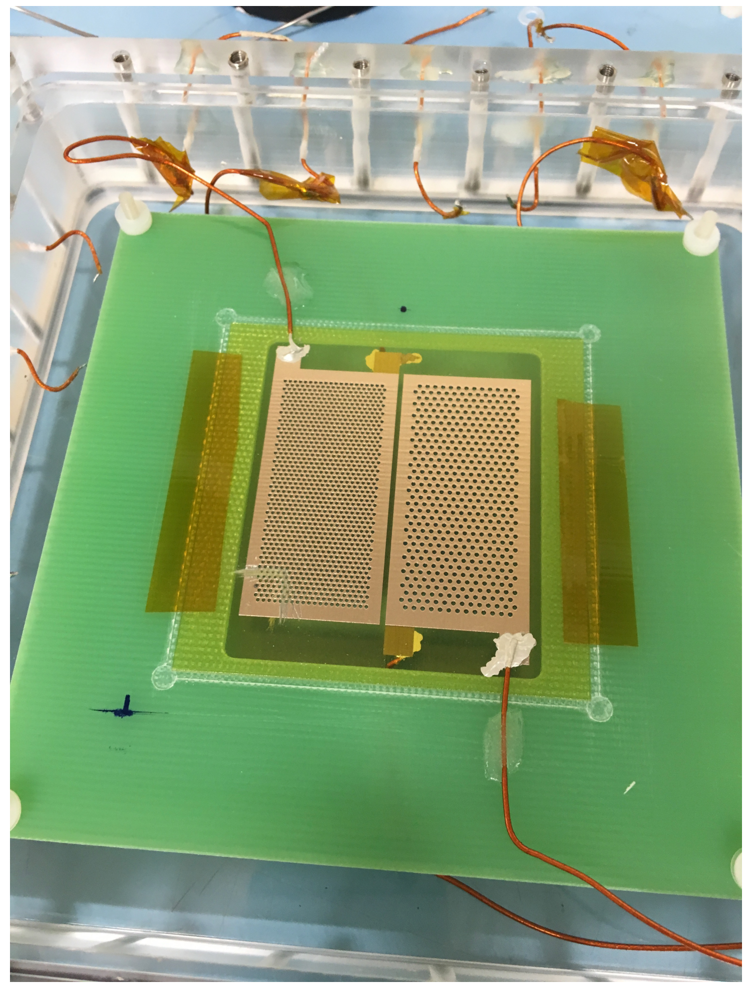
Additive manufacturing

Printing with inkjet technology offers unprecedented resolution for 3D printing. Conductive inks based on silver nanoparticles permit printing of conductive structures in combination with dielectric ones.



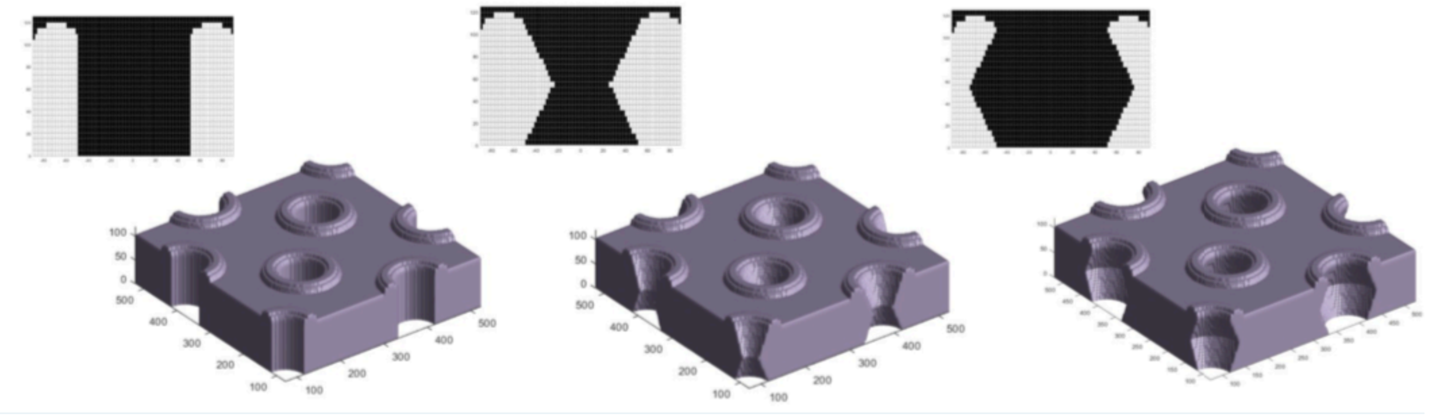
Nanoparticle silver ink

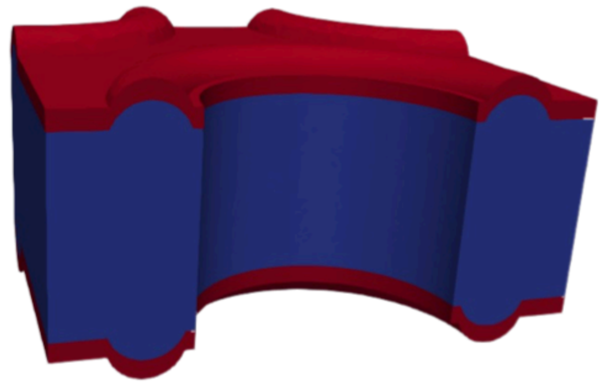
https://www.nano-di.com

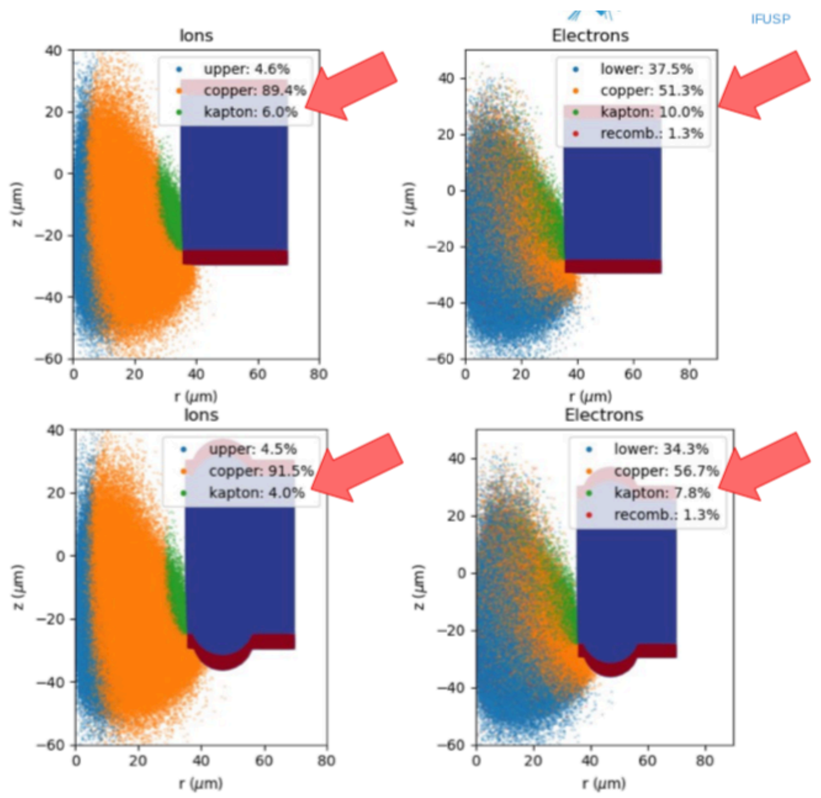


3D printed THGEM

Simulation of micro-structures for GEM optimization

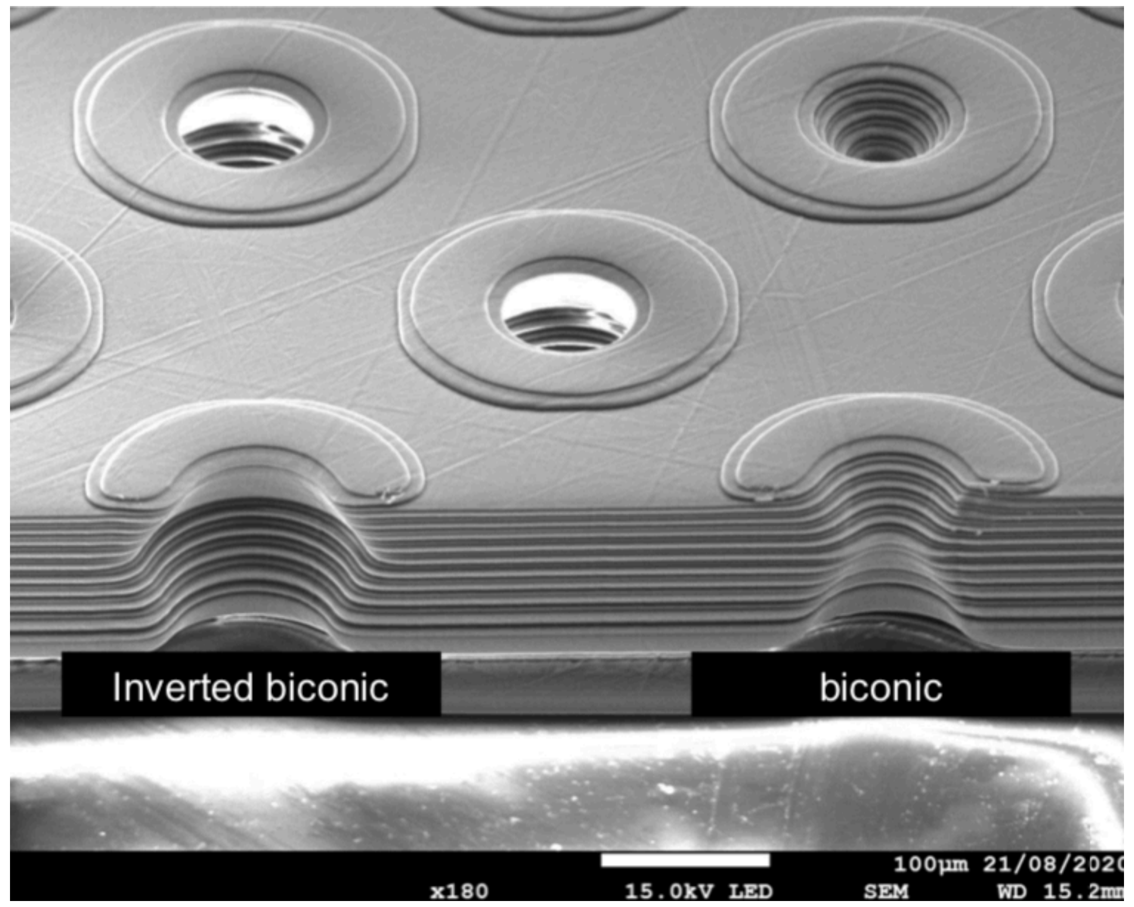






https://indico.cern.ch/event/889369/contributions/4041558/attachments/2115142/3558763/RD51_TBS.pdf

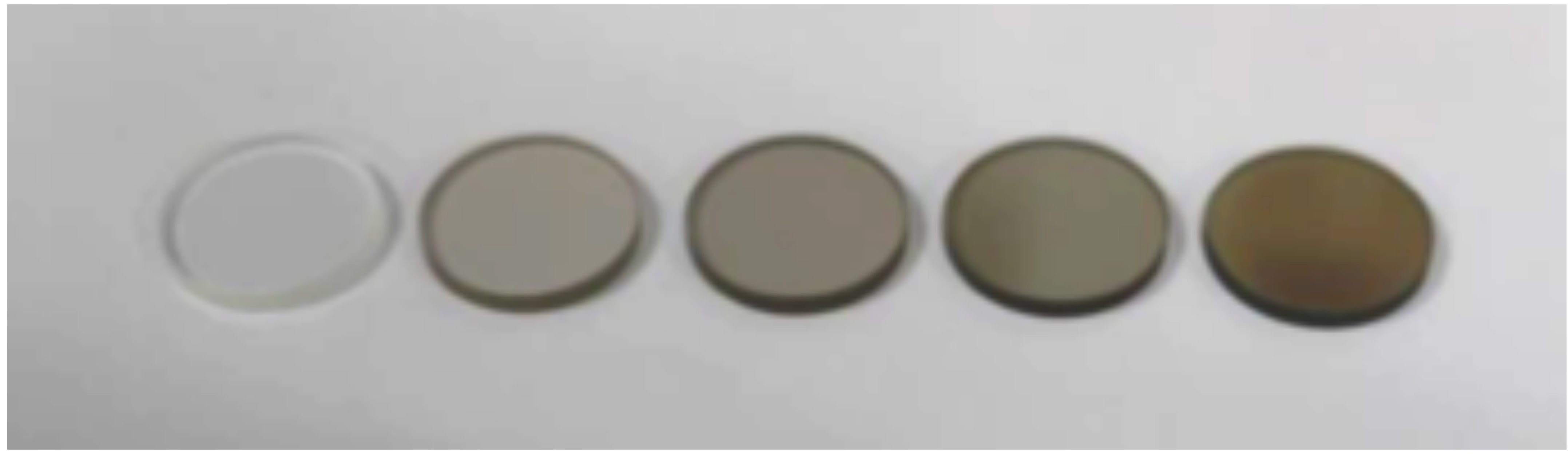
50μm diameter printed holes in HDDA based polymer



Advanced materials

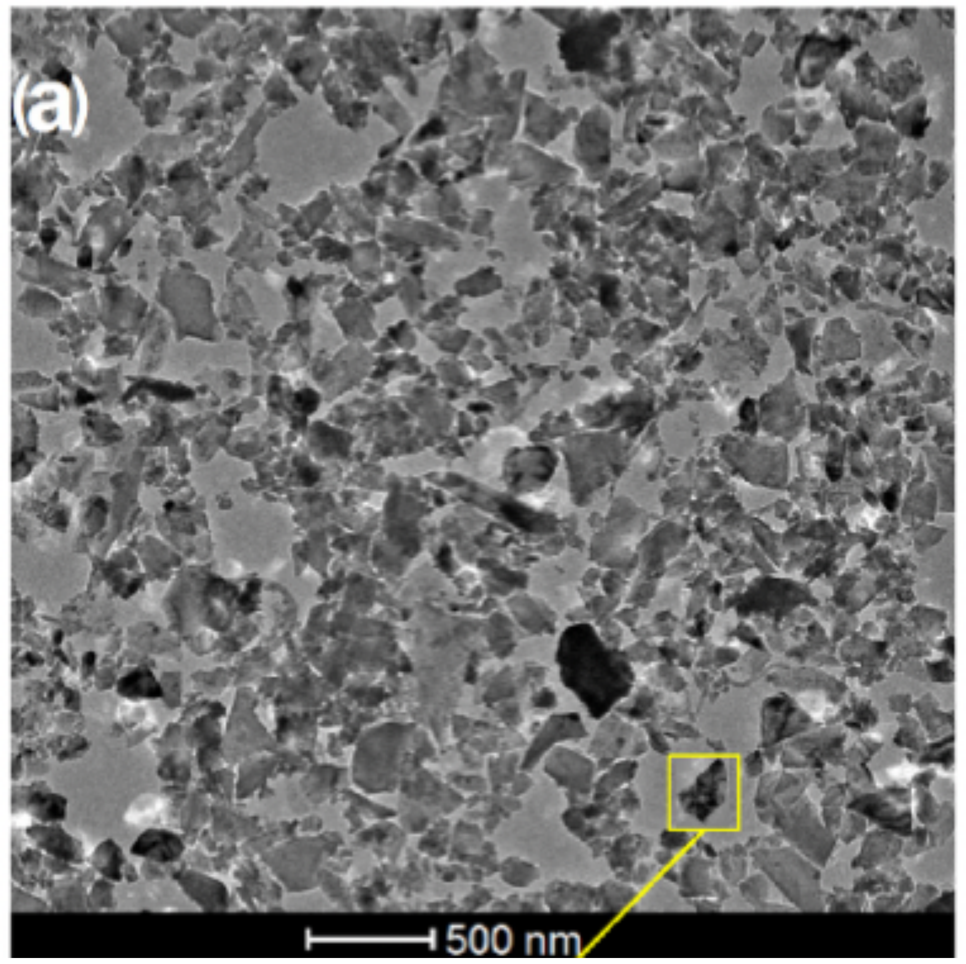
Advanced materials can boost detector performance and applicability. Solid converters and photocathodes enable new detector concepts and resistive materials with well-controlled parameters can be used to develop robust and performant MPGDs.

DLC photocathodes



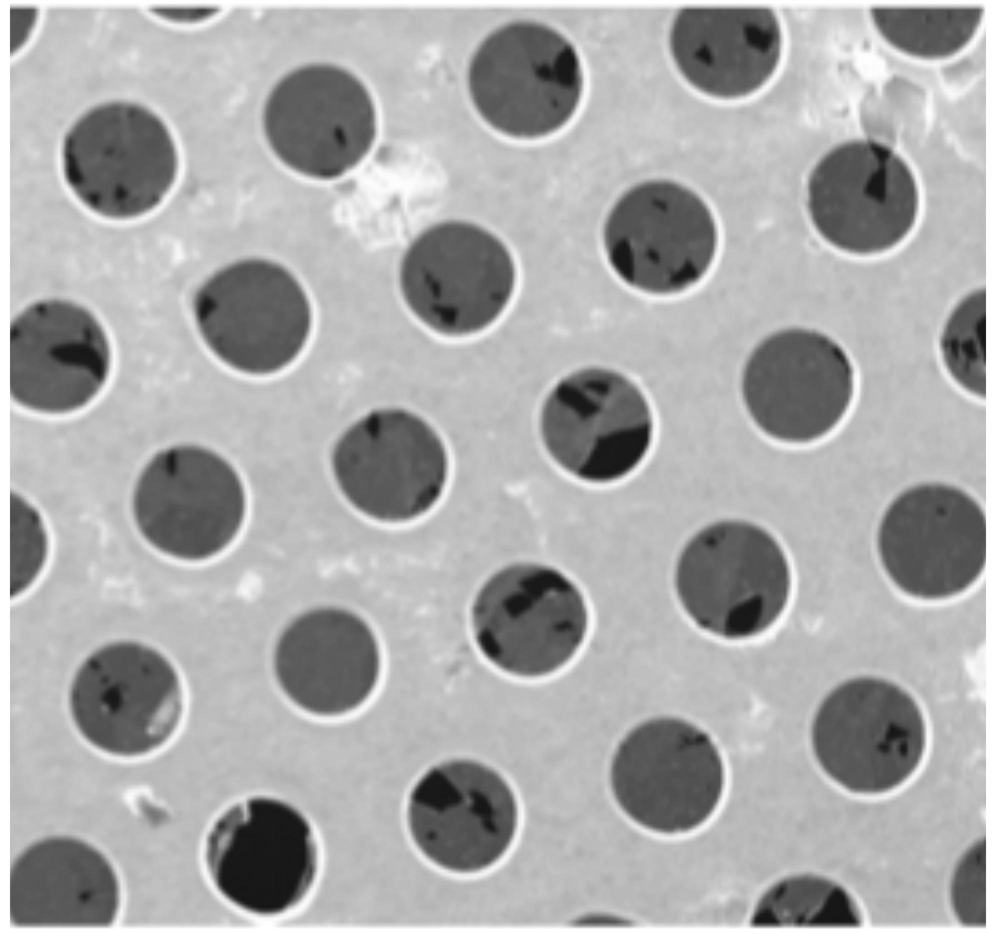
https://indico.cern.ch/event/709670/contributions/3020862/attachments/1672921/2684467/

Nanodiamond photocathodes



Highly efficient and stable ultraviolet photocathode based on nanodiamond particles L.Velardi, A.Valentini, and G.Cicala, Appl. Phys. Lett. 108, 083503 (2016)

Graphene layers



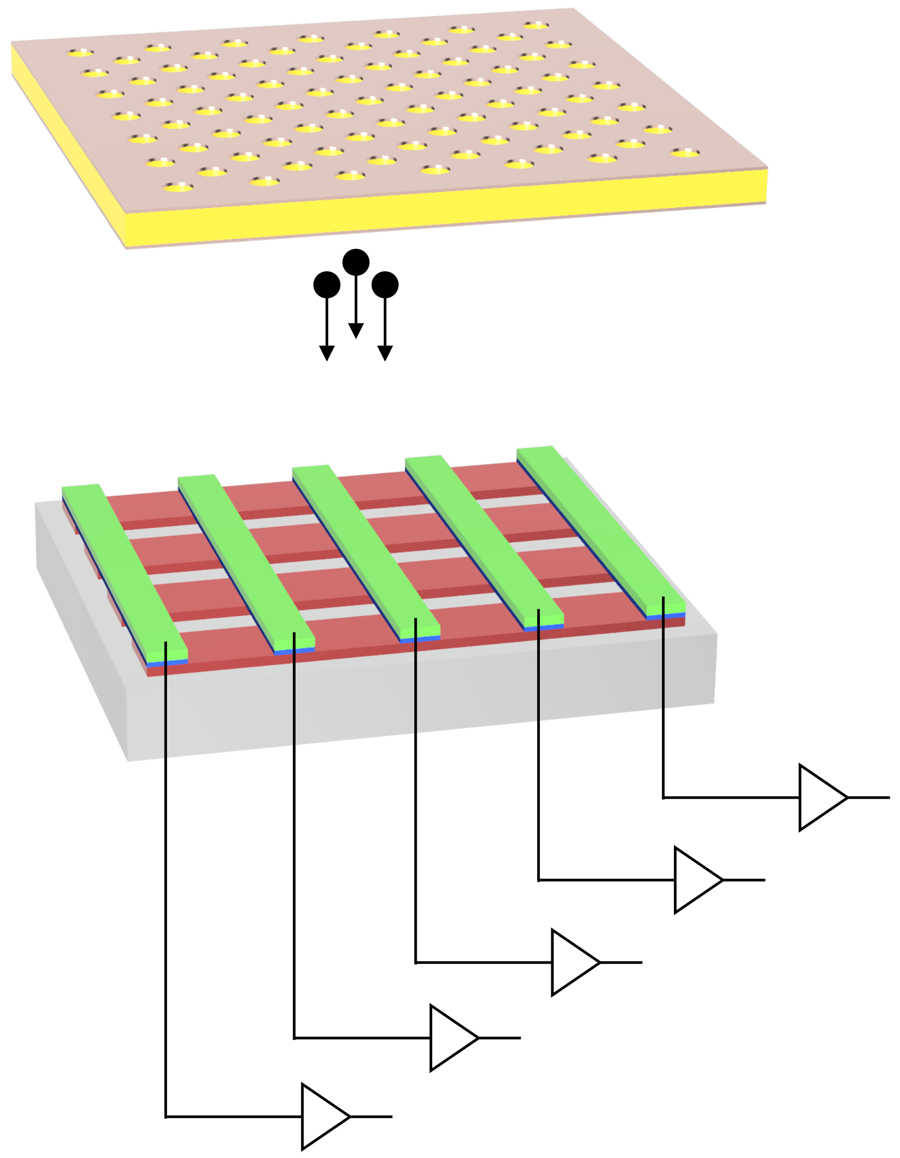
http://cds.cern.ch/record/2238855/files/CERN-THESIS-2016-199.pdf?version=1

Readout approaches

Readout of MPGDs

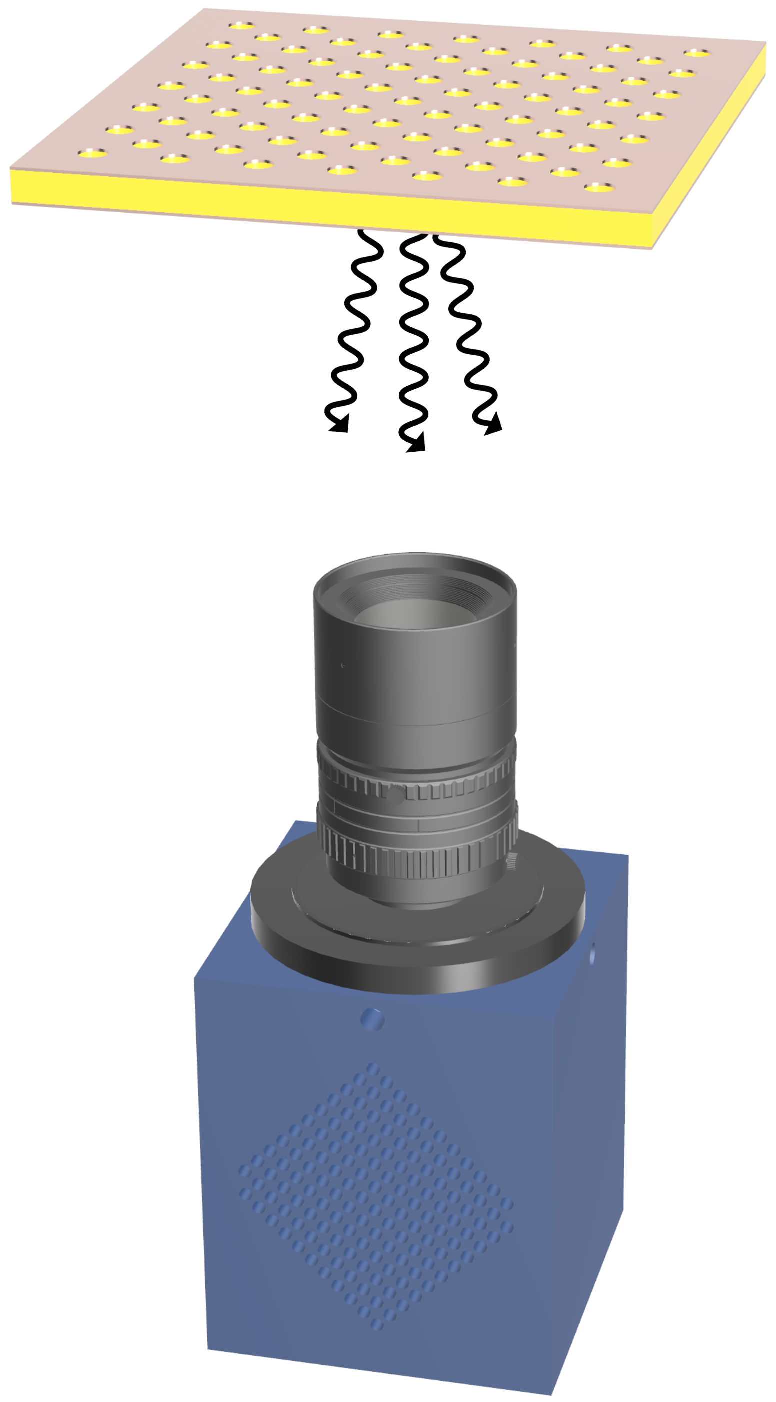
Electronic readout

Recording induced electronic signals with readout electronics



Optical readout

Recording scintillation light with imaging sensors



Schematics not drawn to scale

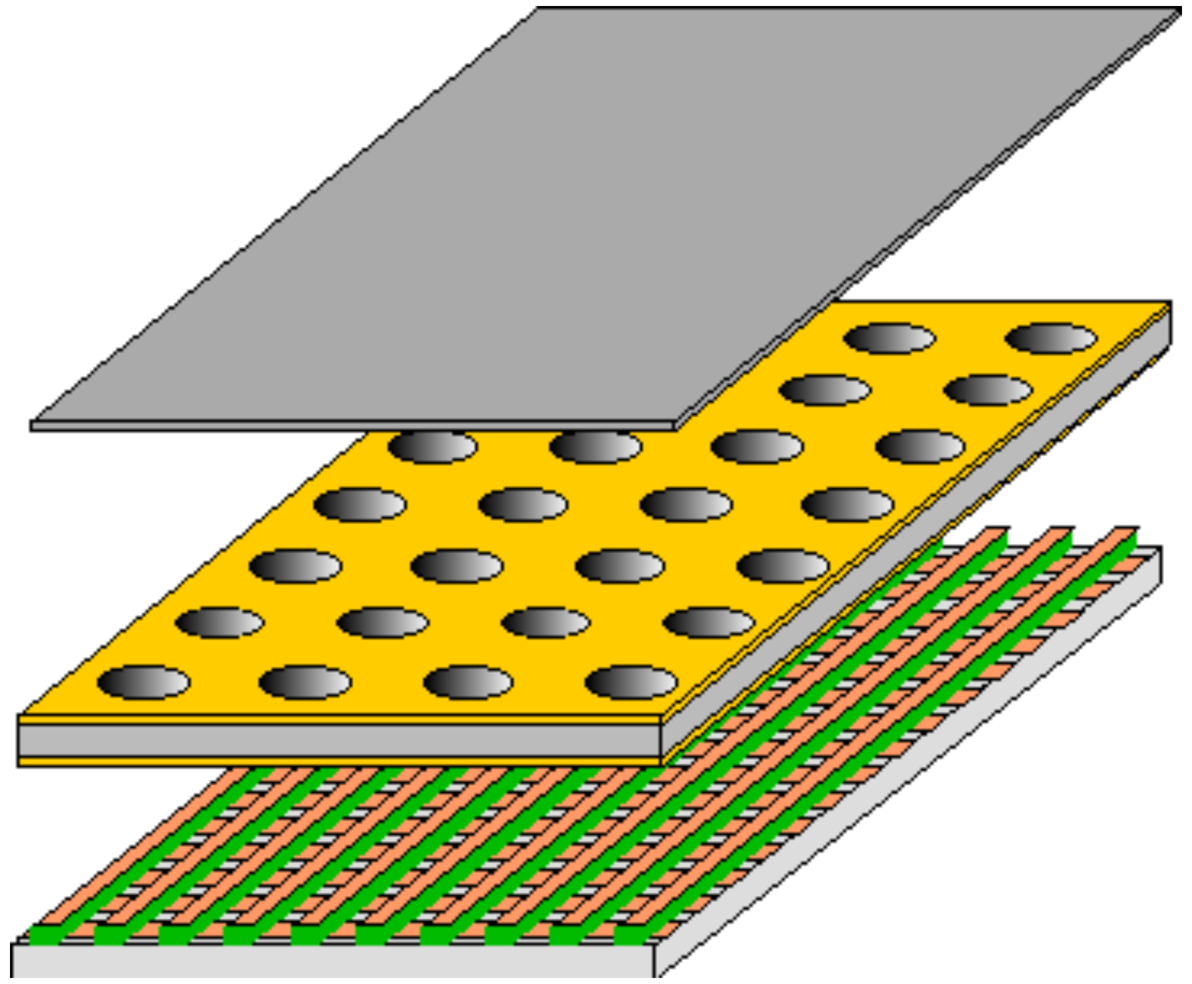
Readout approaches

Electronic readout

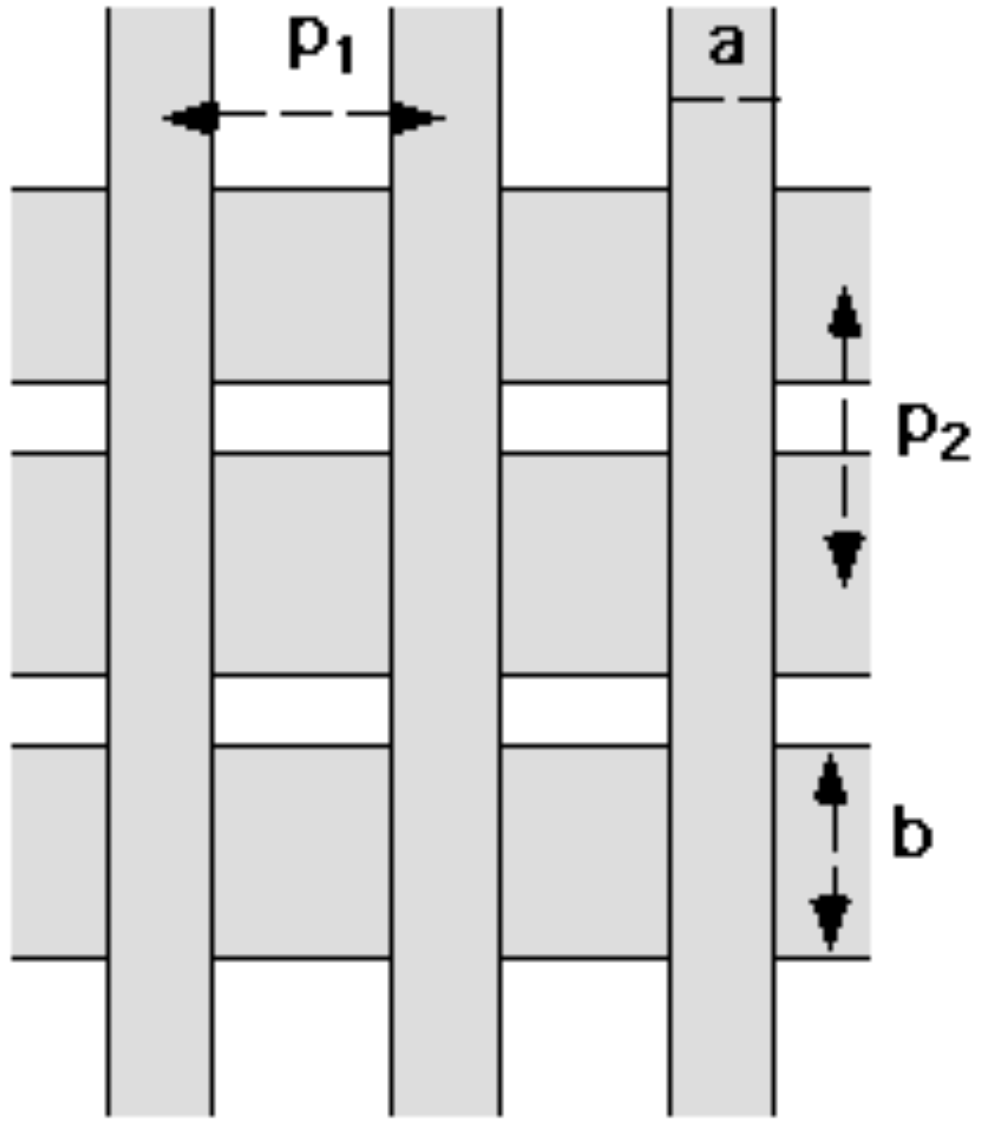
Electronic readout

Movement of electrons below amplification structure induces signals in readout anode. Structured readout anodes (strips, pads, pixels) can be used to obtain spatial information and reconstruct particle hit locations.

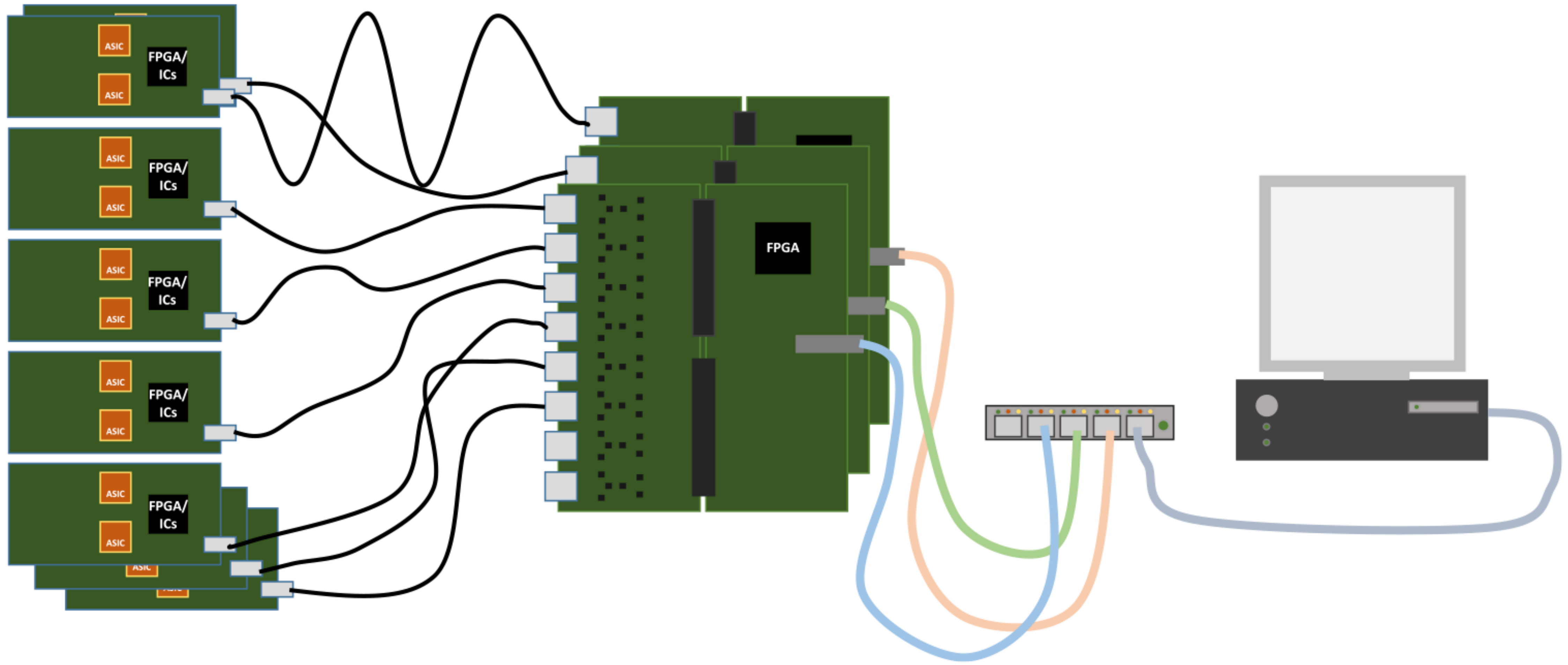
Detector buildup with readout anode



XY strips for 2D readout



Readout system with front end chips, concentrator cards, acquisition computer



Schematics not drawn to scale

MPGD electronics

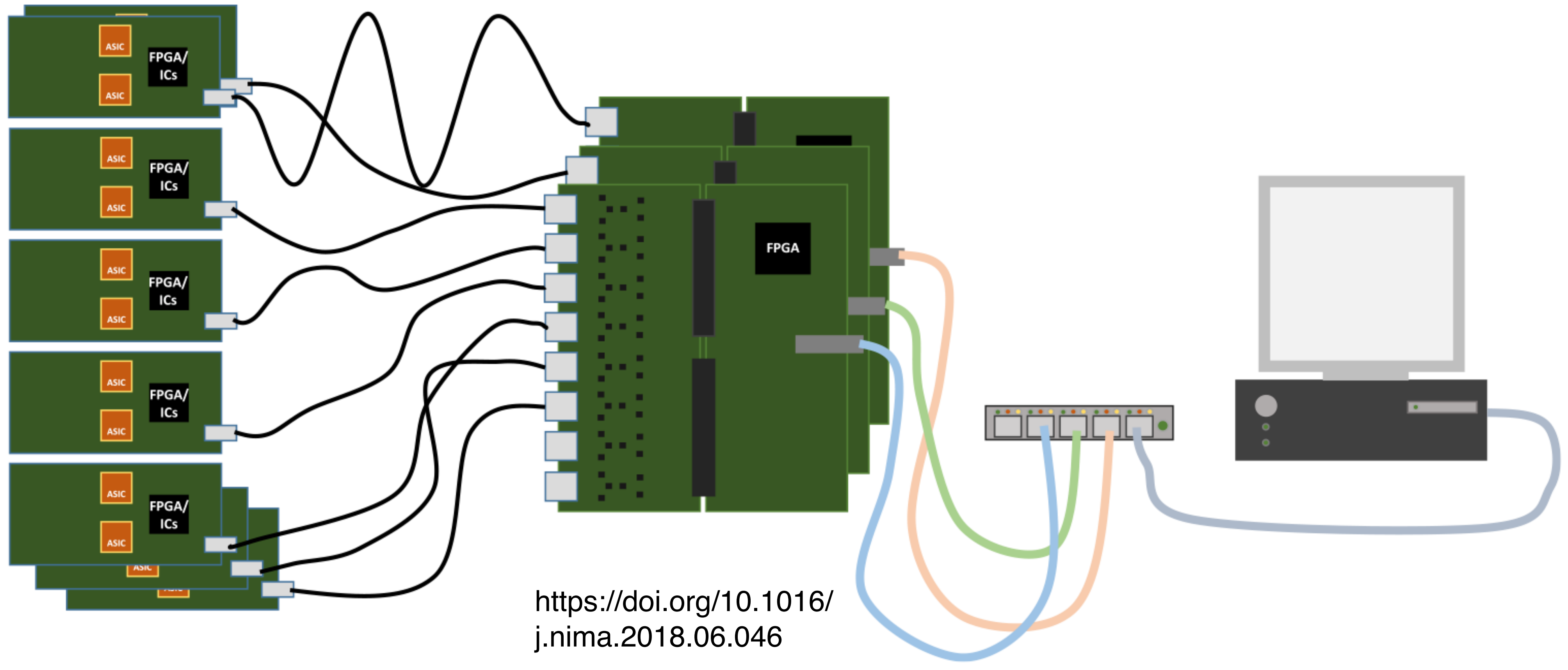
The RD51 Scalable Readout System

A **multi-purpose Scalable Readout System** with different front-end chips is developed and maintained in the RD51 collaboration. This simplifies detector R&D and can be scaled from small prototypes to operational experiments.

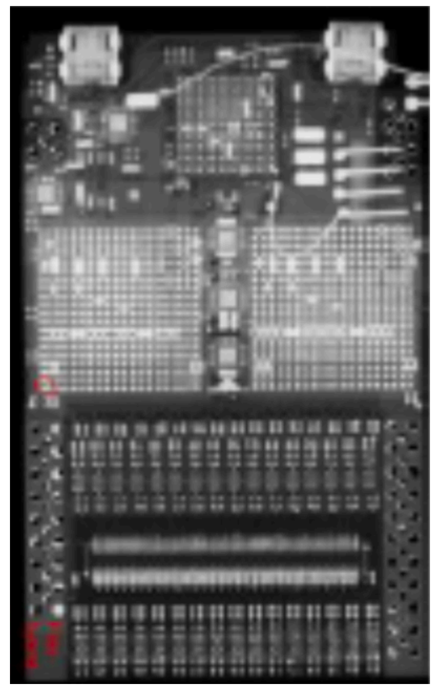
Highly successful with worldwide users and applications
Generic detector R&D, DAQ for TOTEM, CMS GEM upgrade development

APV25 chip (from CMS) implemented in SRS and **>2000 hybrids** used in the RD51 community

New FE ASIC: **VMM3a hybrids** produced and delivered to first users. Extensive developments, performance studies and test beam campaigns ongoing in collaborative effort.



https://doi.org/10.1016/j.nima.2018.06.046

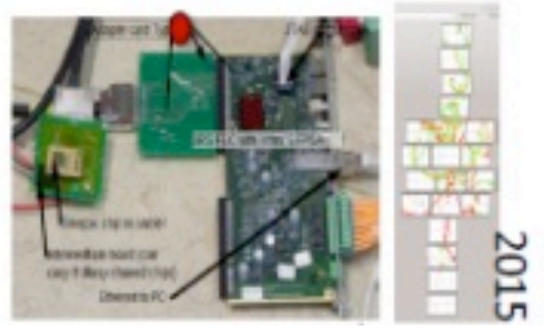


SRS + different front-ends

SRS+SiPM (NEXT TPC)

SRS-FEC+TOTEM DAQ

SRS+Timepix (LC-TPC) – Bonn/Desy

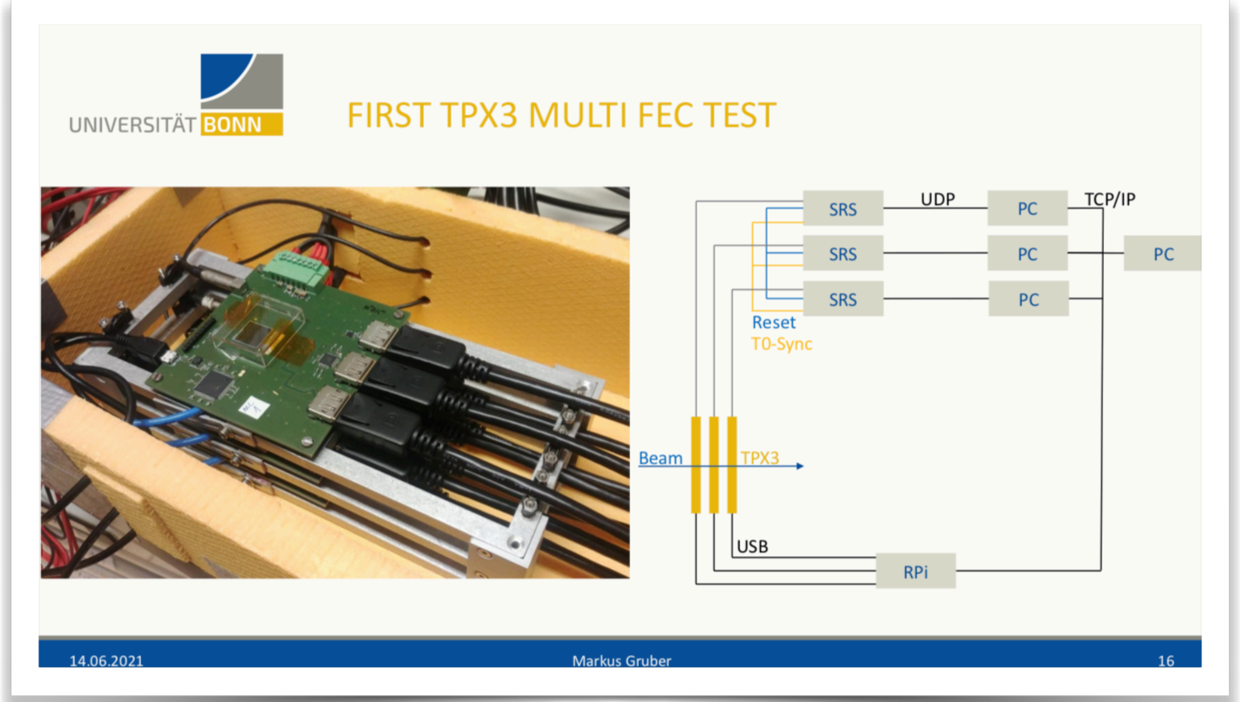


H. Müller, Development of multi-channel readout system optimised for gaseous detectors
https://indico.desy.de/indico/event/7435/material/1/4.pdf

Readout electronics

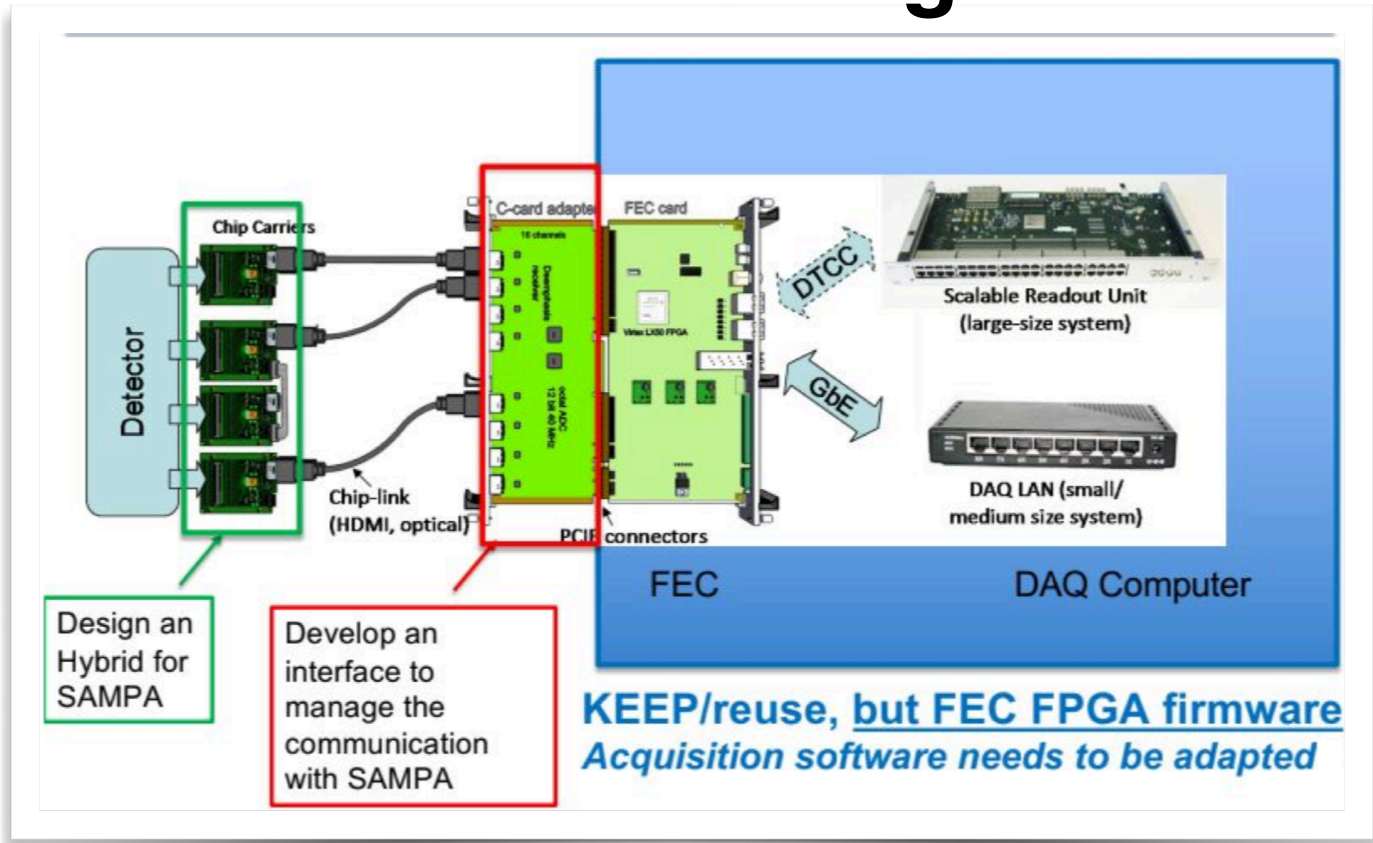
See dedicated **RD51 workshop on Front End Electronics for gas detectors** for more developments and details: https://indico.cern.ch/event/1040996/timetable/

SRS-based Timepix3 Readout



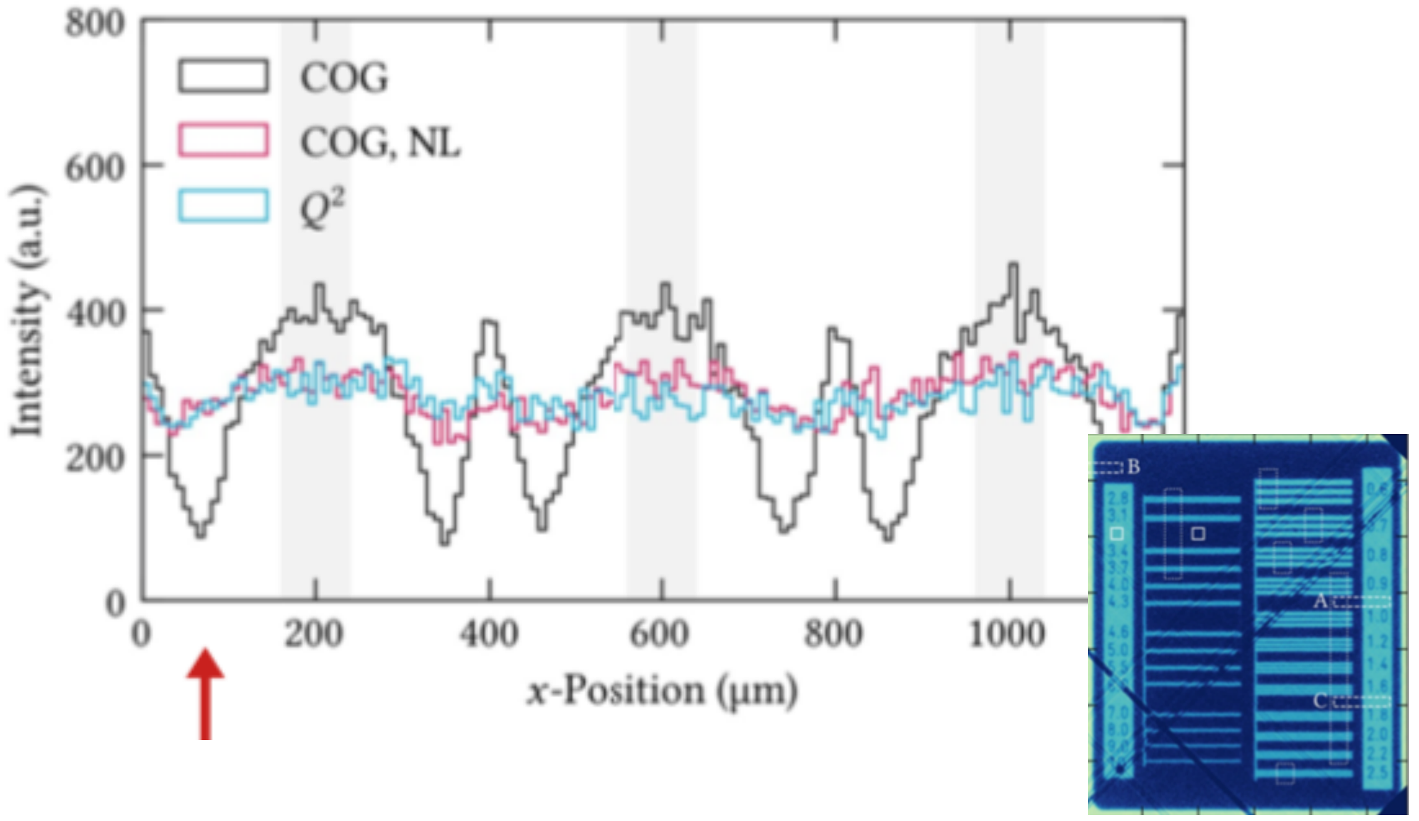
https://indico.cern.ch/event/1040996/contributions/4406959/attachments/2263612/3842696/RD51_Timepix3.pdf

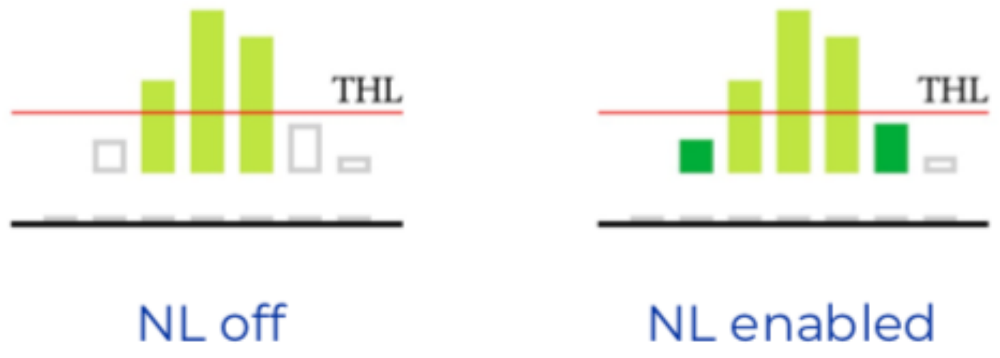
SAMPA SRS Integration



https://indico.cern.ch/event/889369/contributions/4049207/attachments/2117046/3562475/SAMPA_SRS_Integration_Report.pdf

VMM3a neighboring logic to improve position response of MPGDs



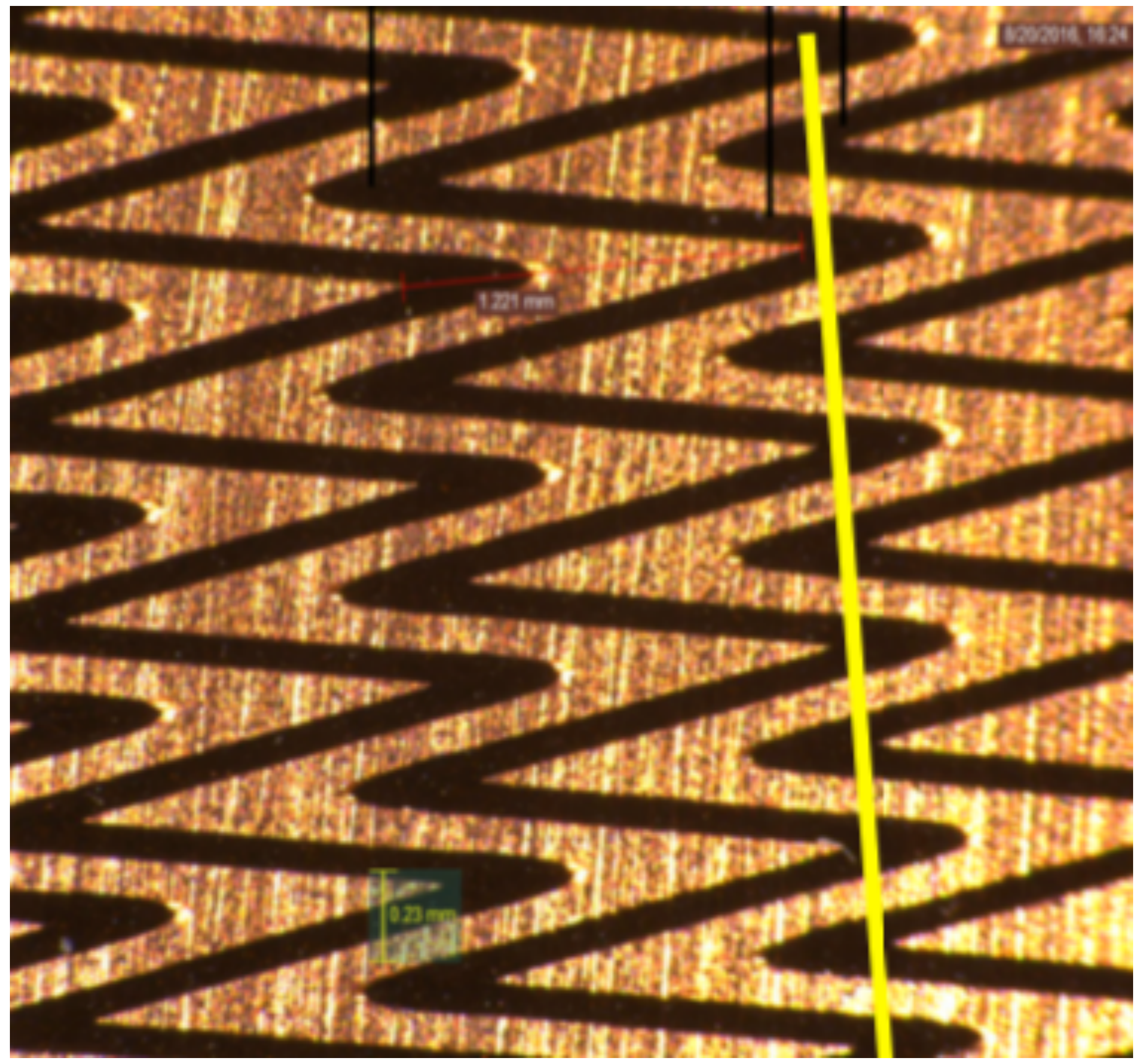


https://indico.cern.ch/event/889369/contributions/4044539/attachments/2118842/3565481/rd51-2020-10-08-position-and-resolution.pdf

Electronic readout

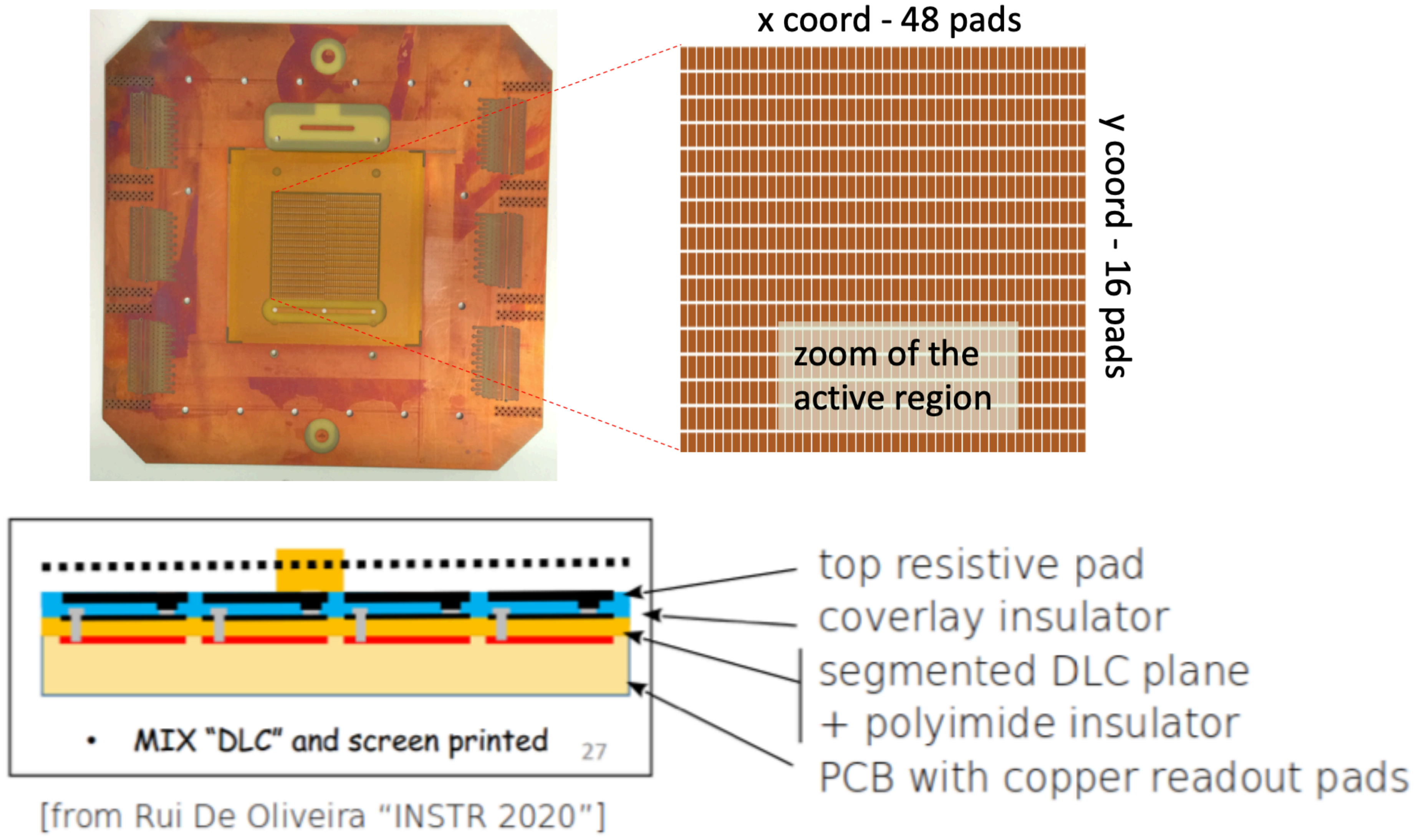
Intricate readout anode geometries are developed to optimise charge sharing, achieve high spatial information and mitigate pileup in high-rate environments.

Zigzag readout to minimise number of strips and maintain spatial resolution



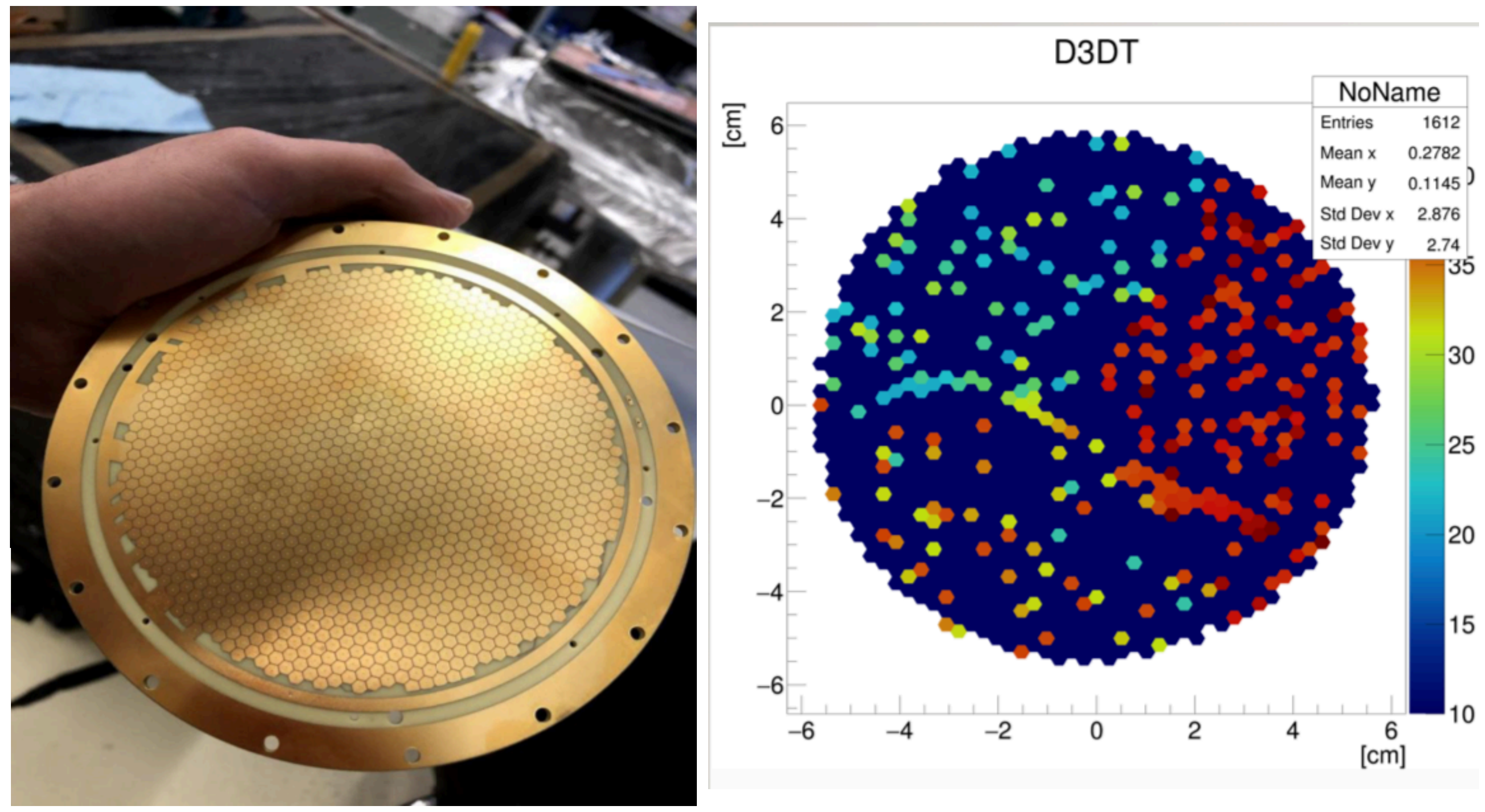
M. Hohlmann, et al. MPGD 2017

Resistive High granUlarity Micromegas



https://indico.cern.ch/event/989298/contributions/4225233/attachments/2191432/3704013/SmallPadMicromegas_RD51_miniweek_Feb2021_v1.pdf

Multiplexed readouts for lower readout channel count



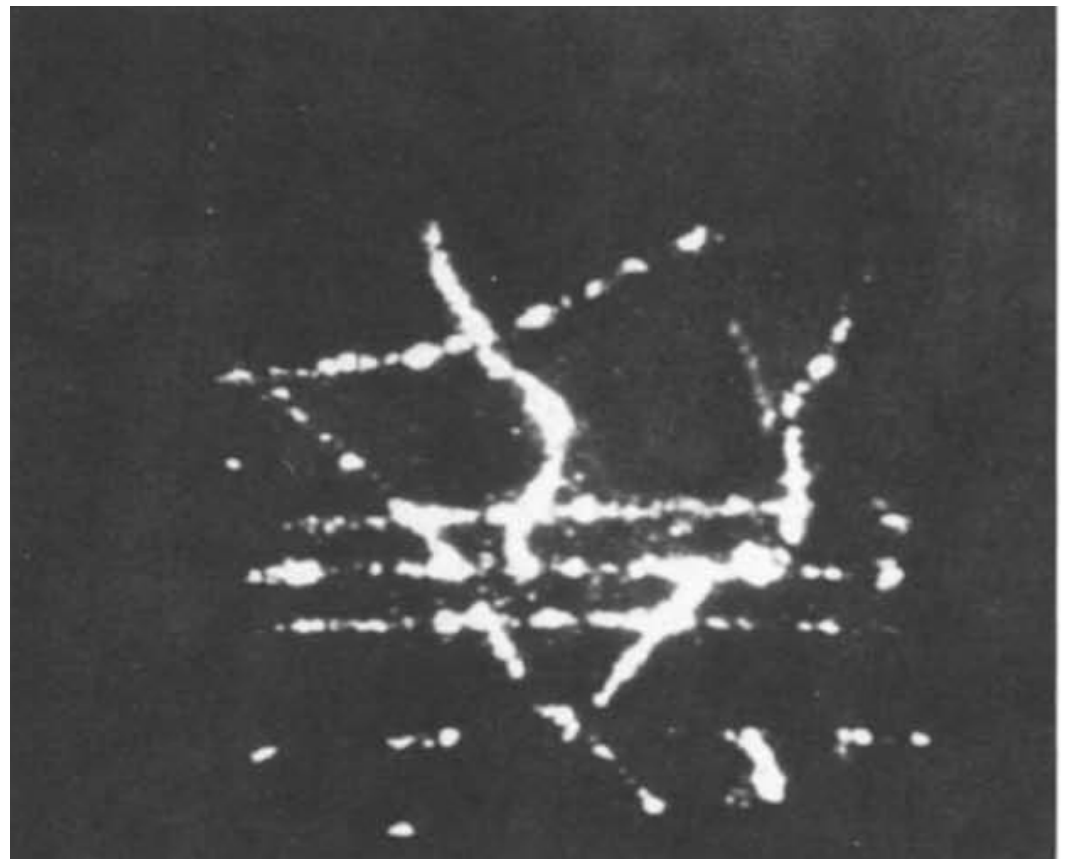
M. VANDENBROUCKE, TPC workshop, RD51 October 2020

Readout approaches

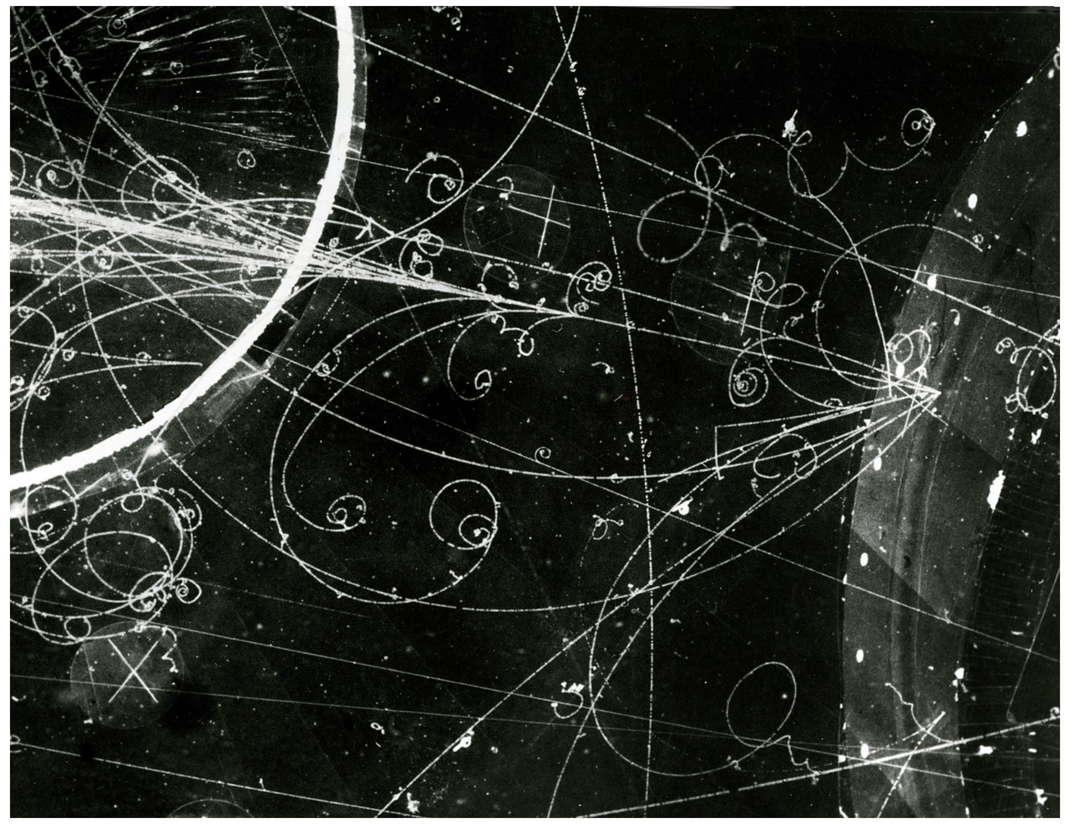
Optical readout

Optical readout

- Readout of detectors with imaging sensors or fast photon detectors
- Modern CCD and CMOS sensors allow high resolution and low readout noise
- Inherent stability to electronic readout noise
- Wide range of optical elements (mirrors, lenses, fibers) available



G. Charpak et al., NIM A258 (1987) 177

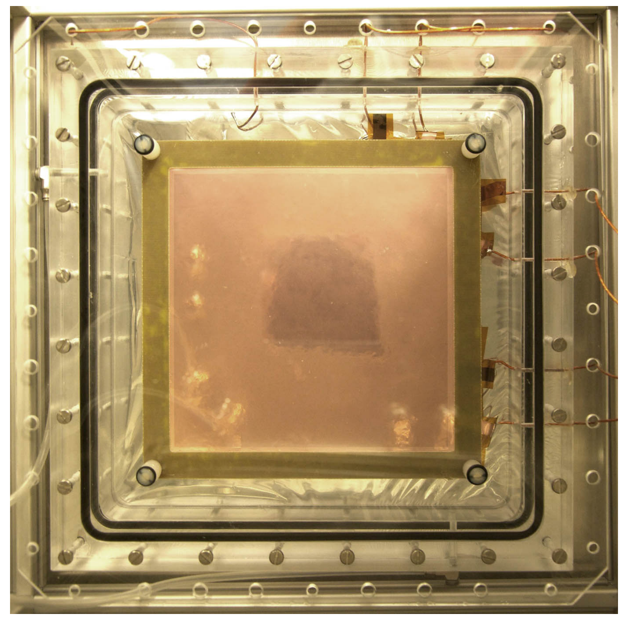


Courtesy of Brookhaven National Laboratory

0.25MP EMCCD

4MP CMOS

6MP CCD



Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

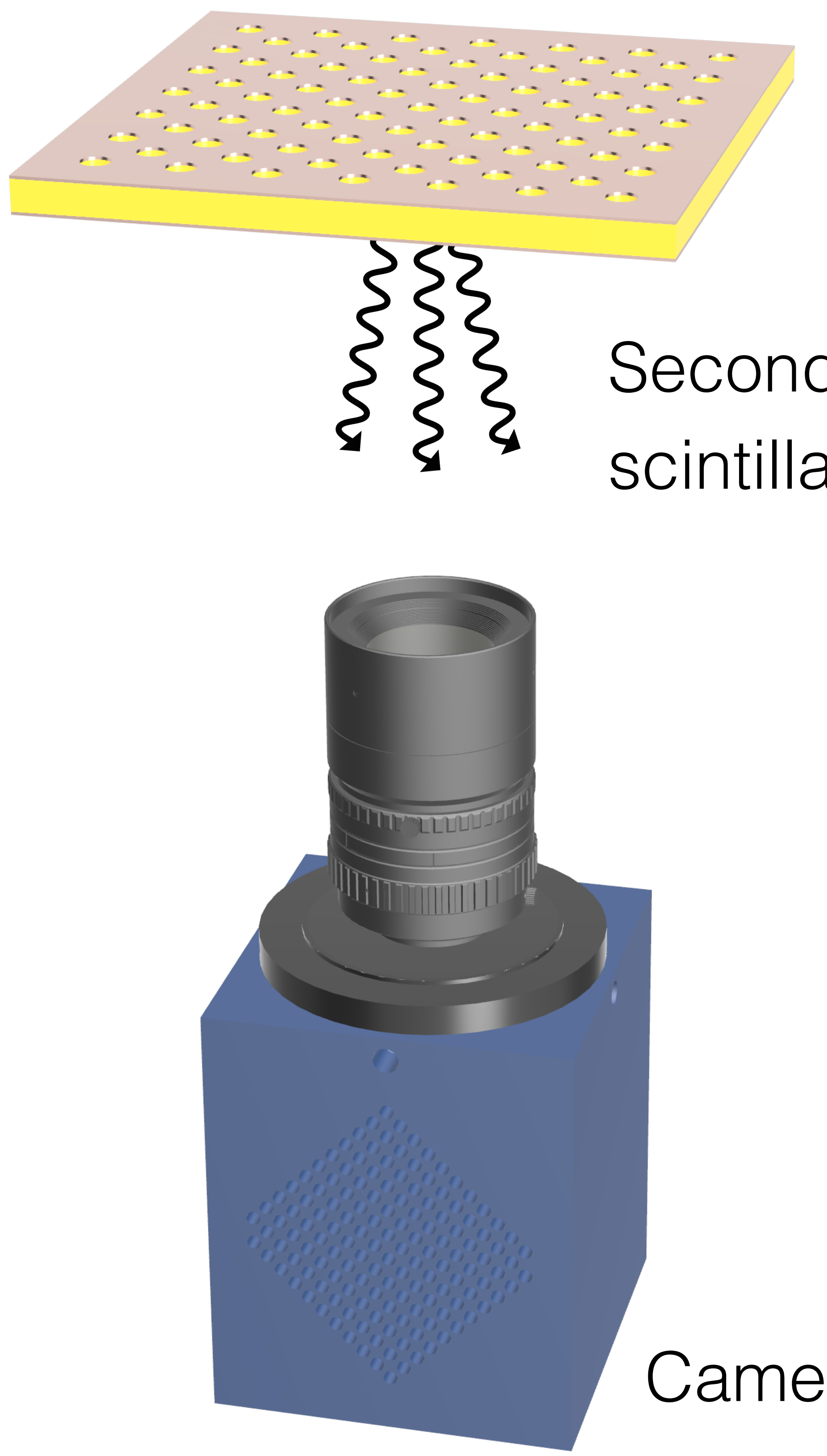
High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

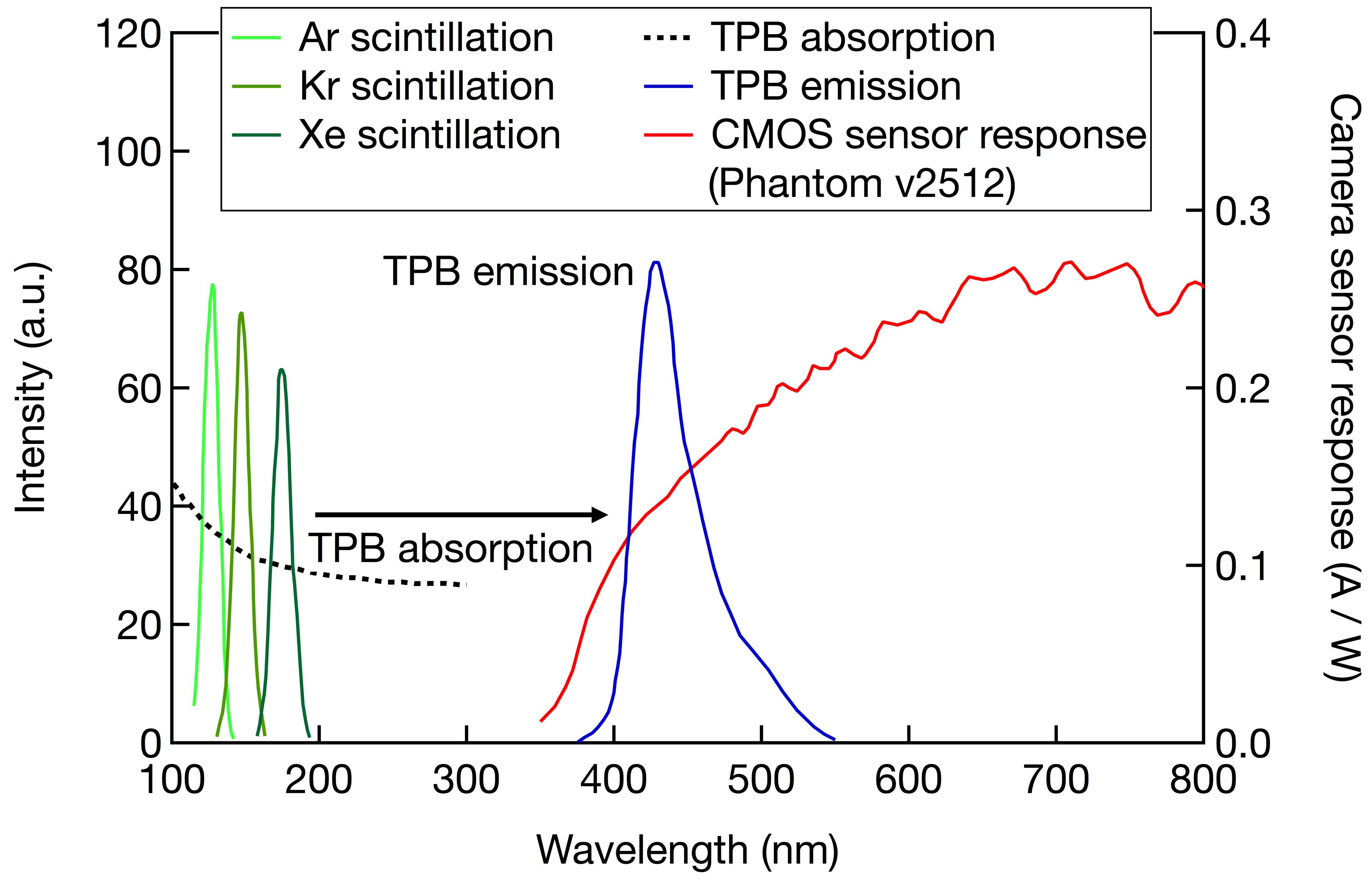
Need of **CF_4**-based gas mixtures
or wavelength shifters



Schematics not drawn to scale

Optical readout **scintillation spectra**

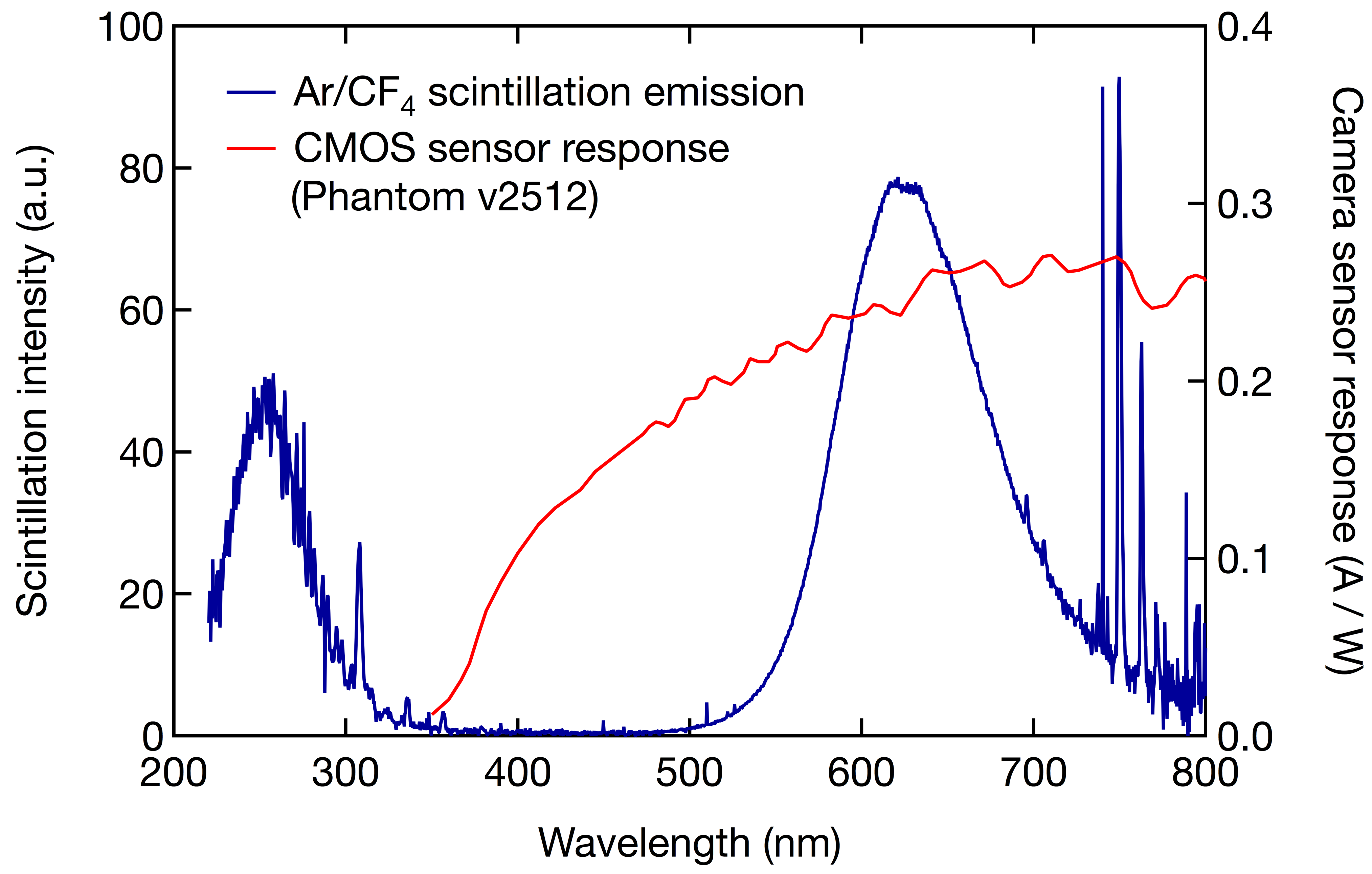
Using wavelength shifters



Data from: Ignarra, C.M. Physics Procedia 37 (2012): 1217–1222.
Scintillation data from: V. M. Gehman et al. NIM A 654 (2011) 1.

Wavelength shifters such as tetraphenyl butadiene (**TPB**) can be used to shift scintillation light spectrum to visible range with peak around **425 nm**

Using CF_4-based gas mixtures

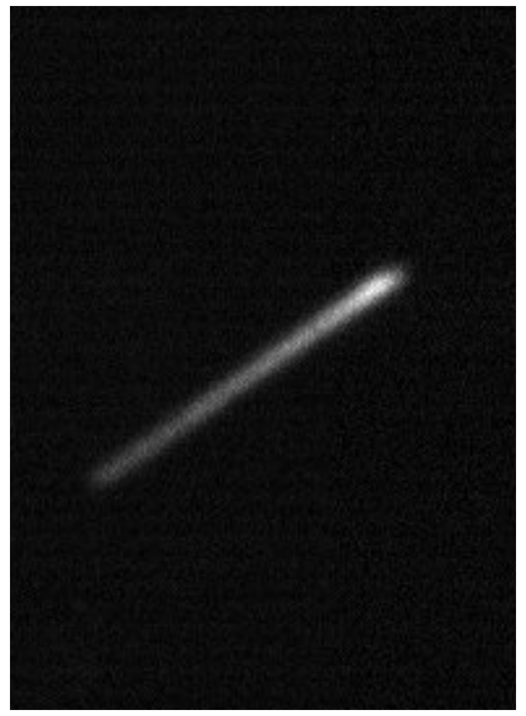


Ar/CF_4 gas mixtures feature ample visible scintillation light emission with a peak around **630 nm**

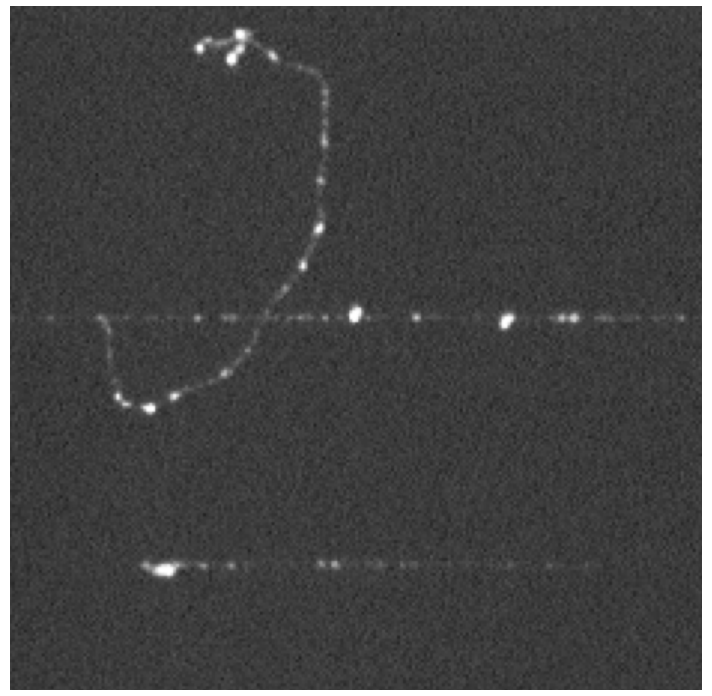
Gaseous radiation detectors optical readout

at the Gaseous Detector Development lab at CERN

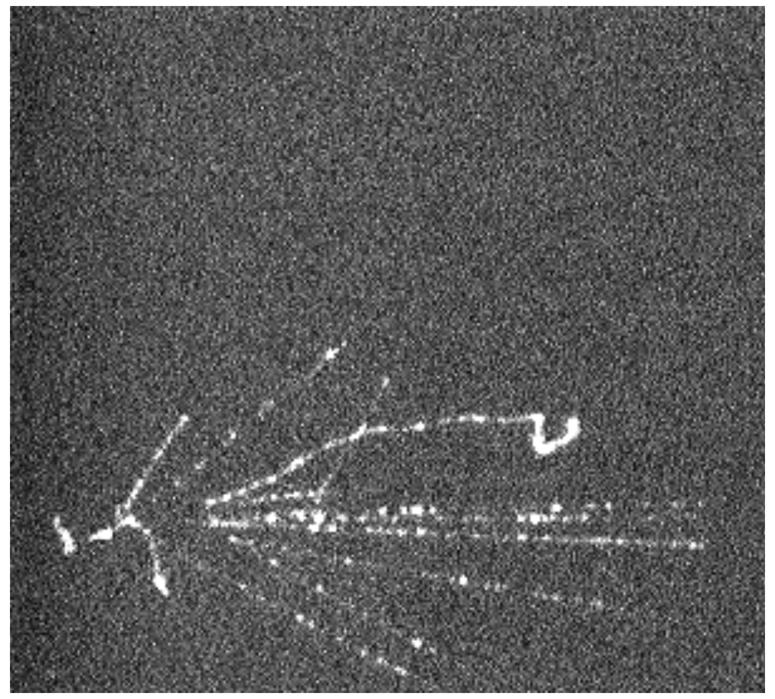
X-ray photons



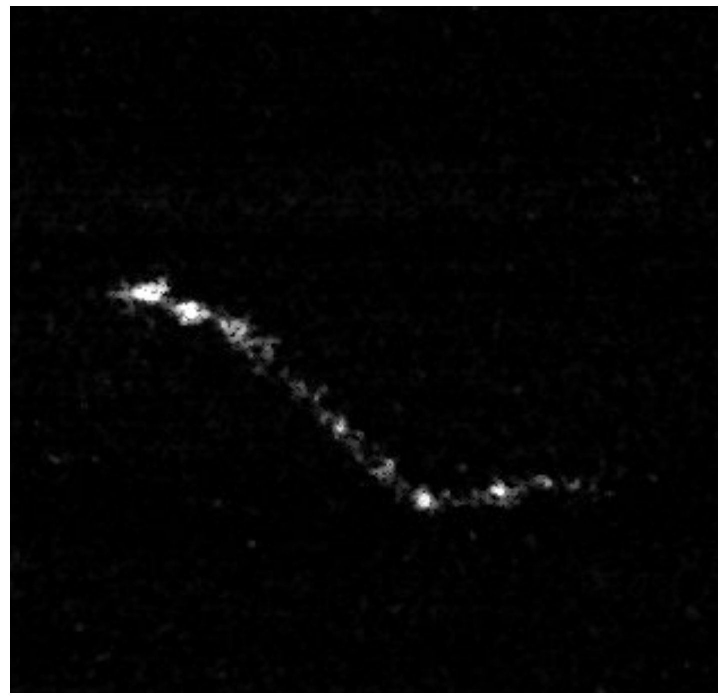
Alpha track



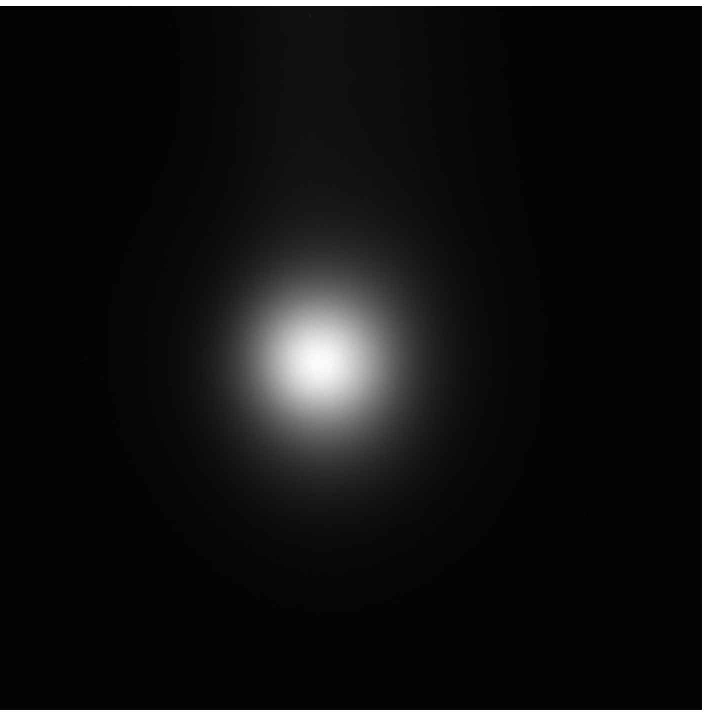
Muon tracks with δ-ray



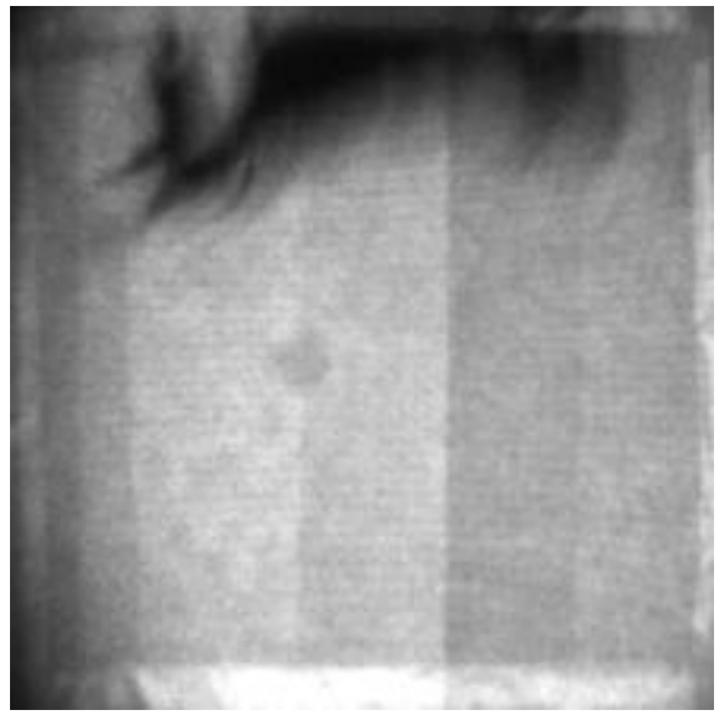
Hadronic shower



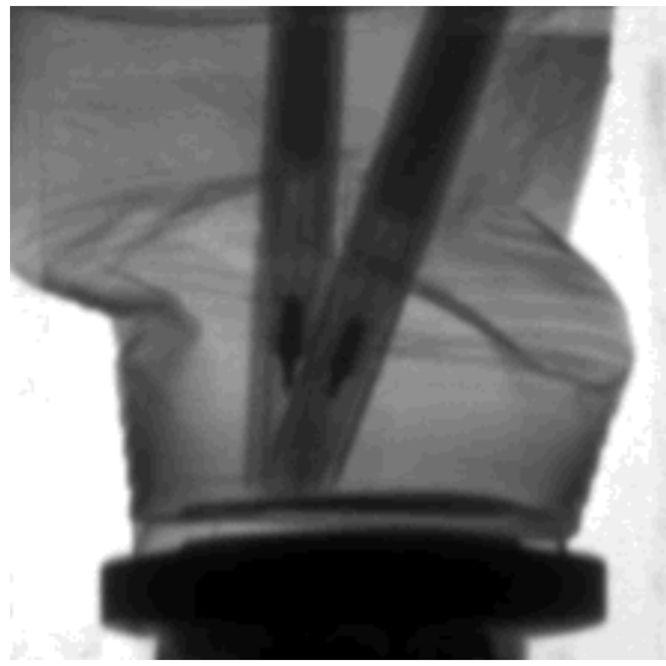
Cosmic event



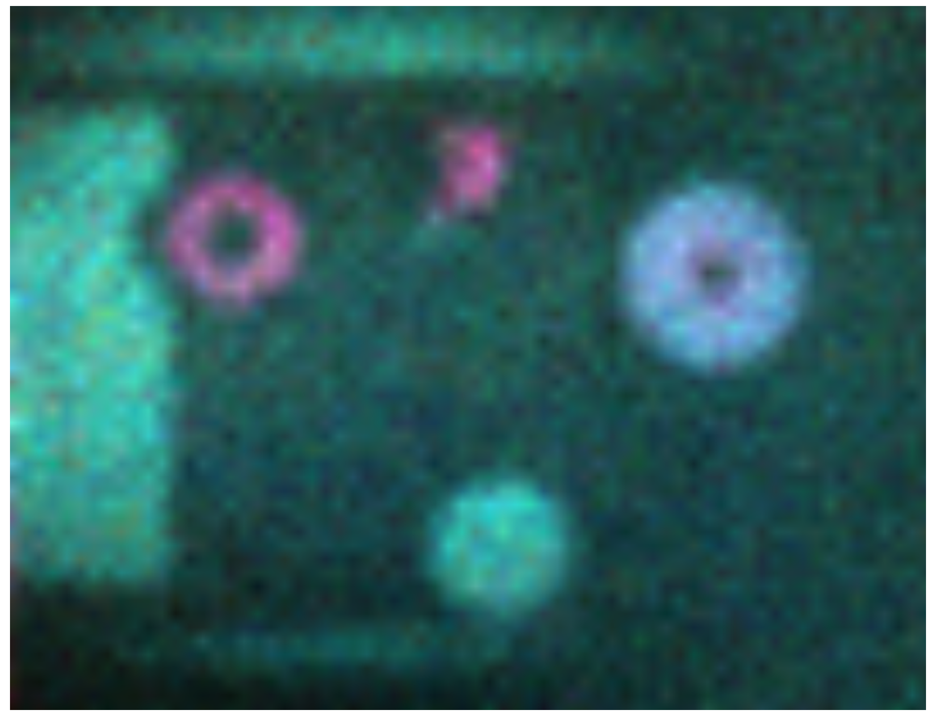
Proton beam profile



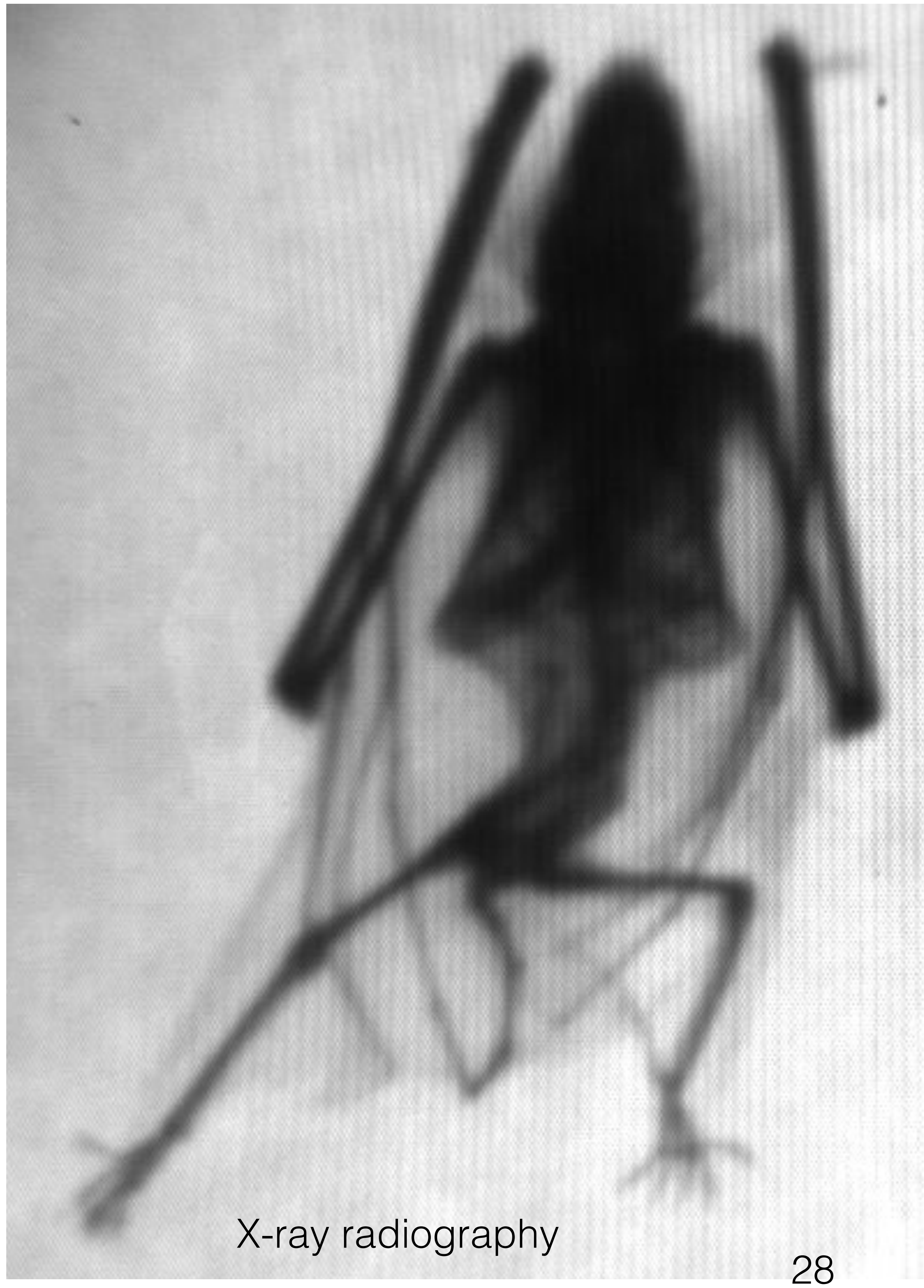
X-ray fluoroscopy



X-ray tomography

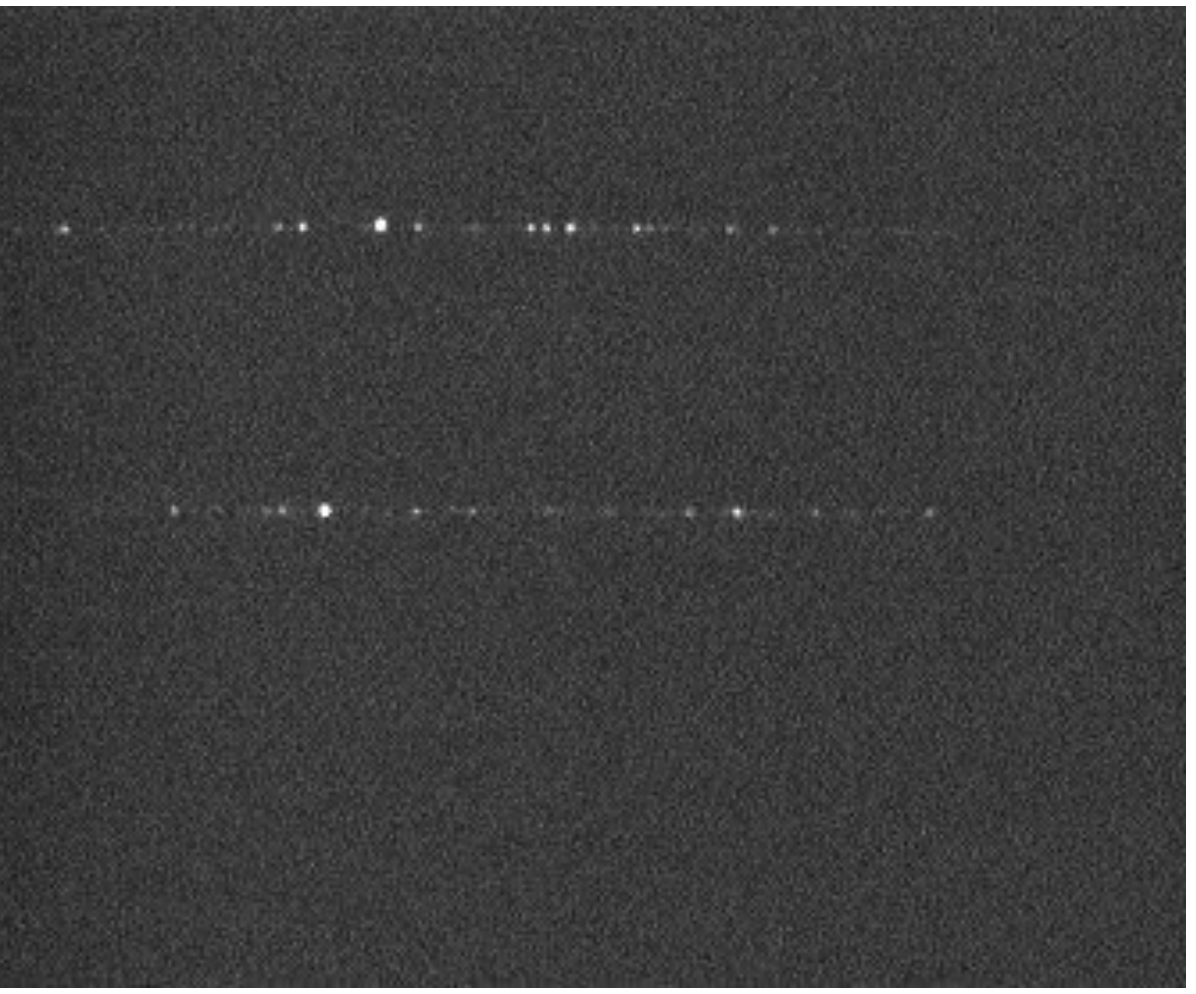


X-ray fluorescence

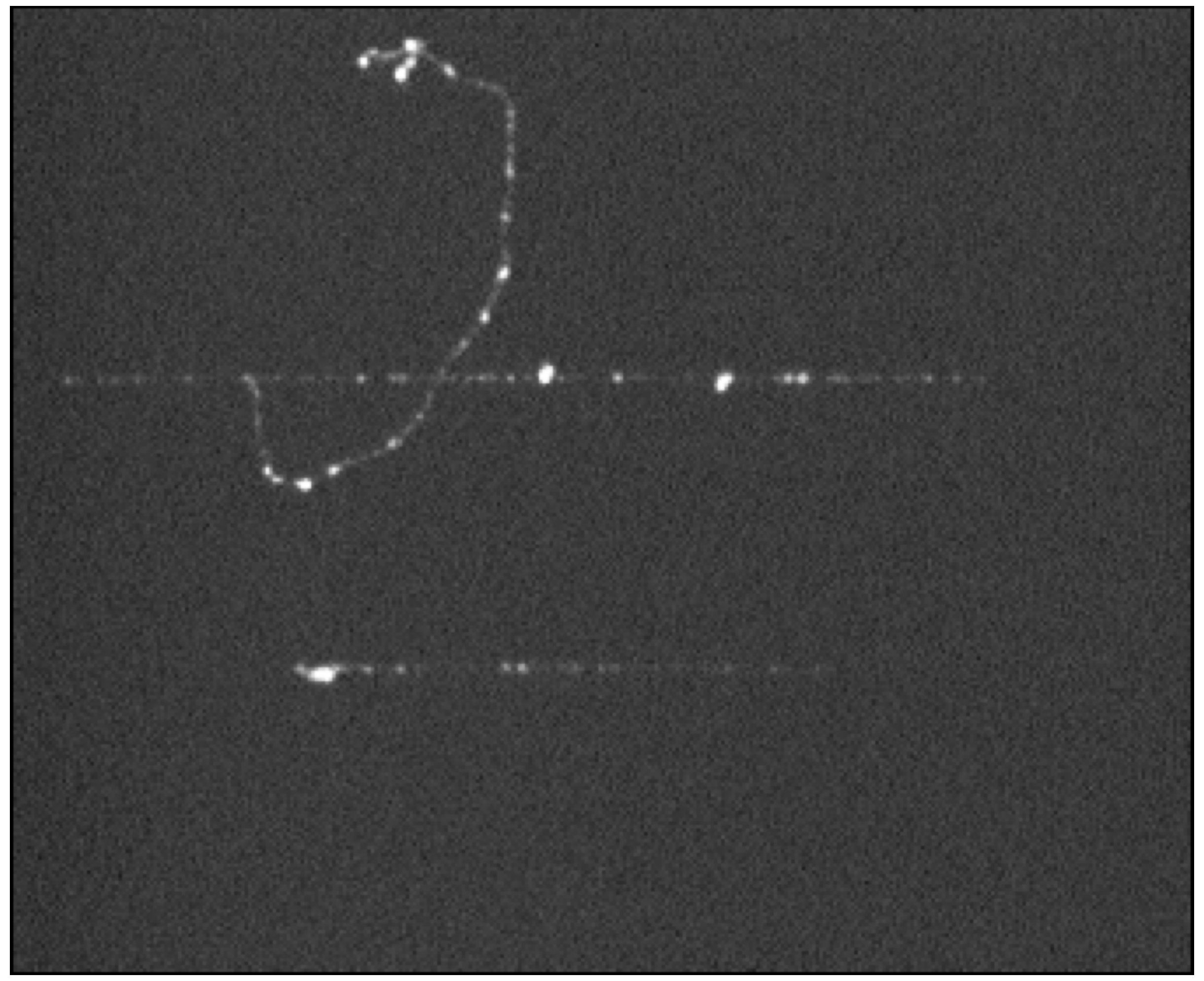


X-ray radiography

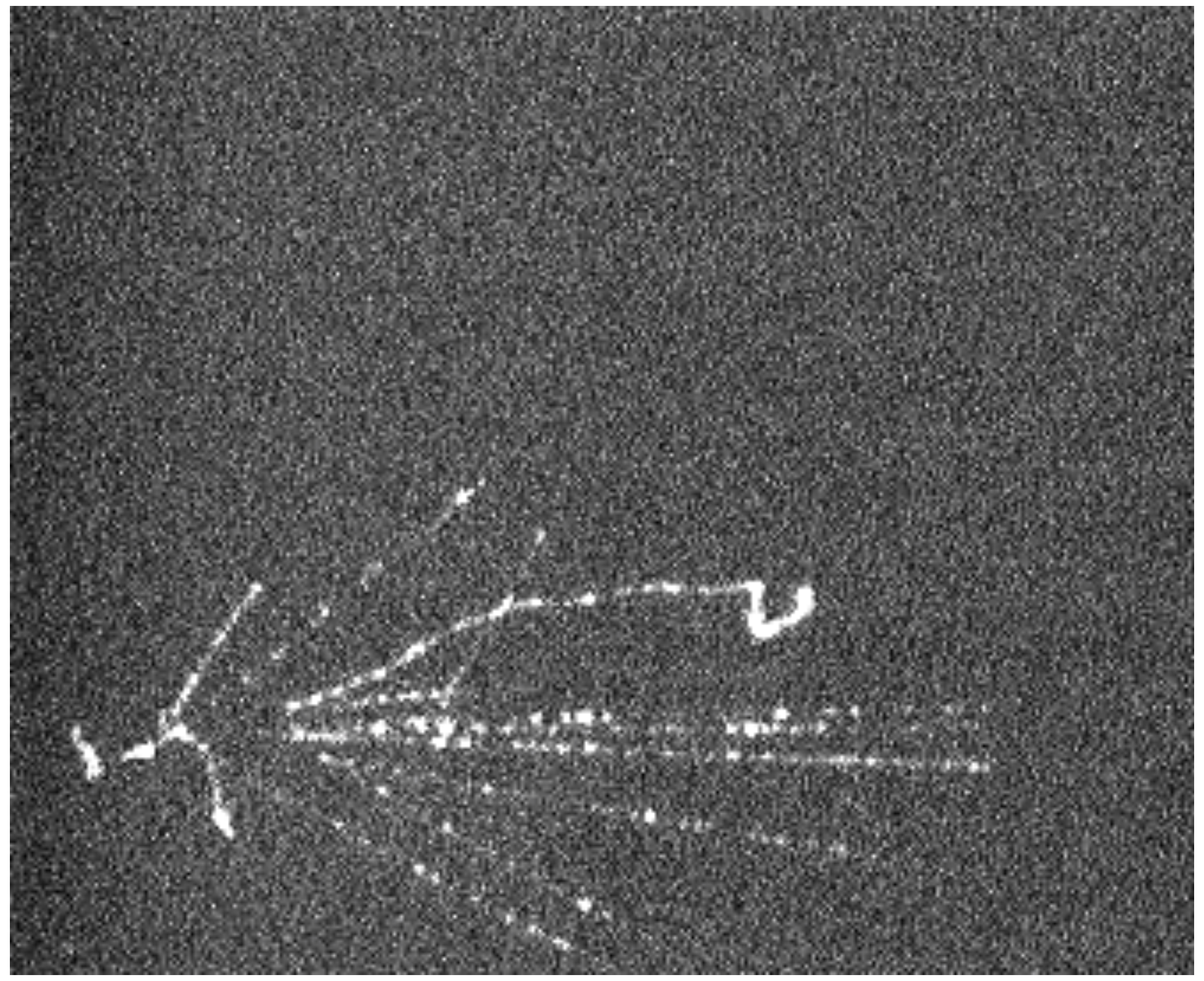
Particle track images



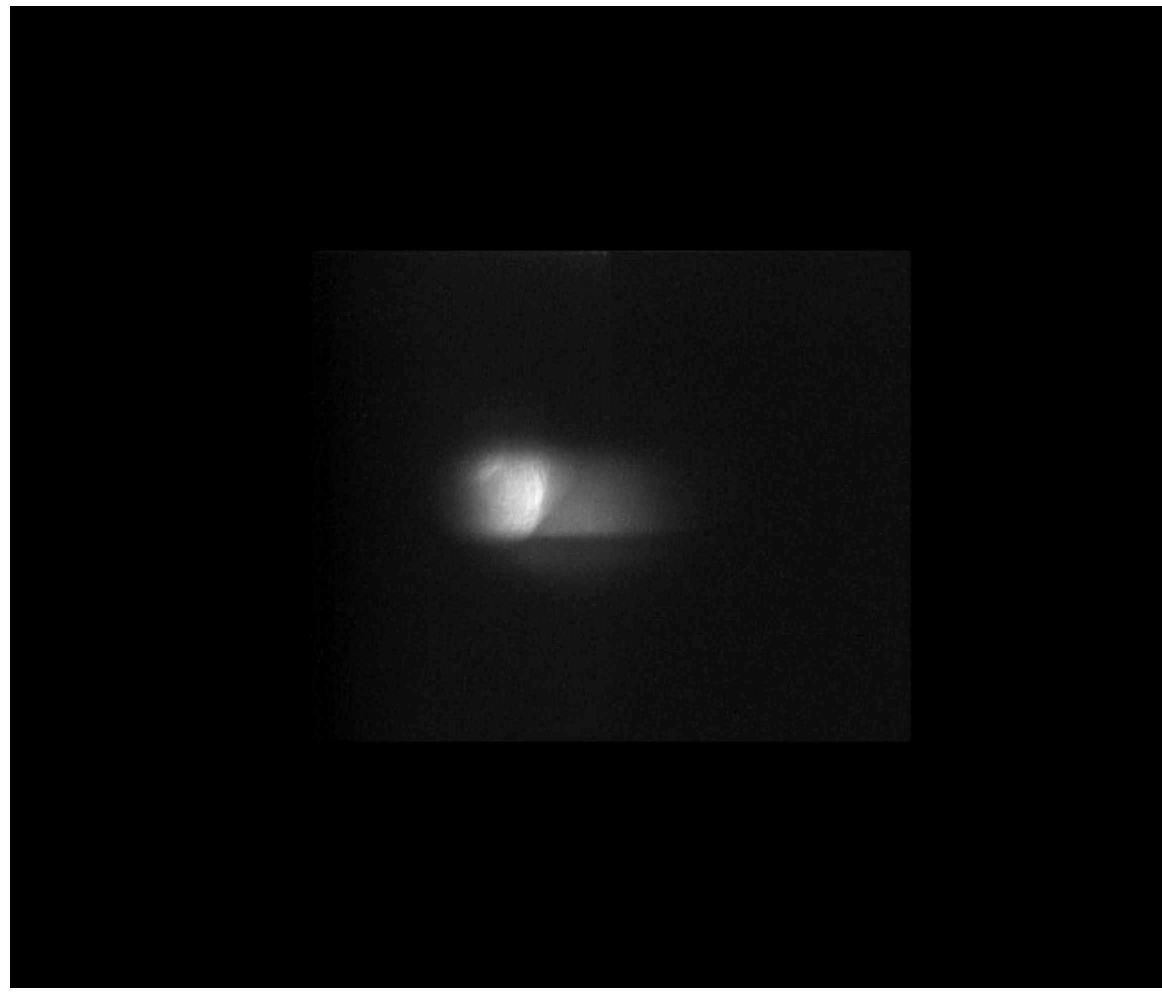
Muon tracks



Muon tracks with δ-ray



Hadronic shower

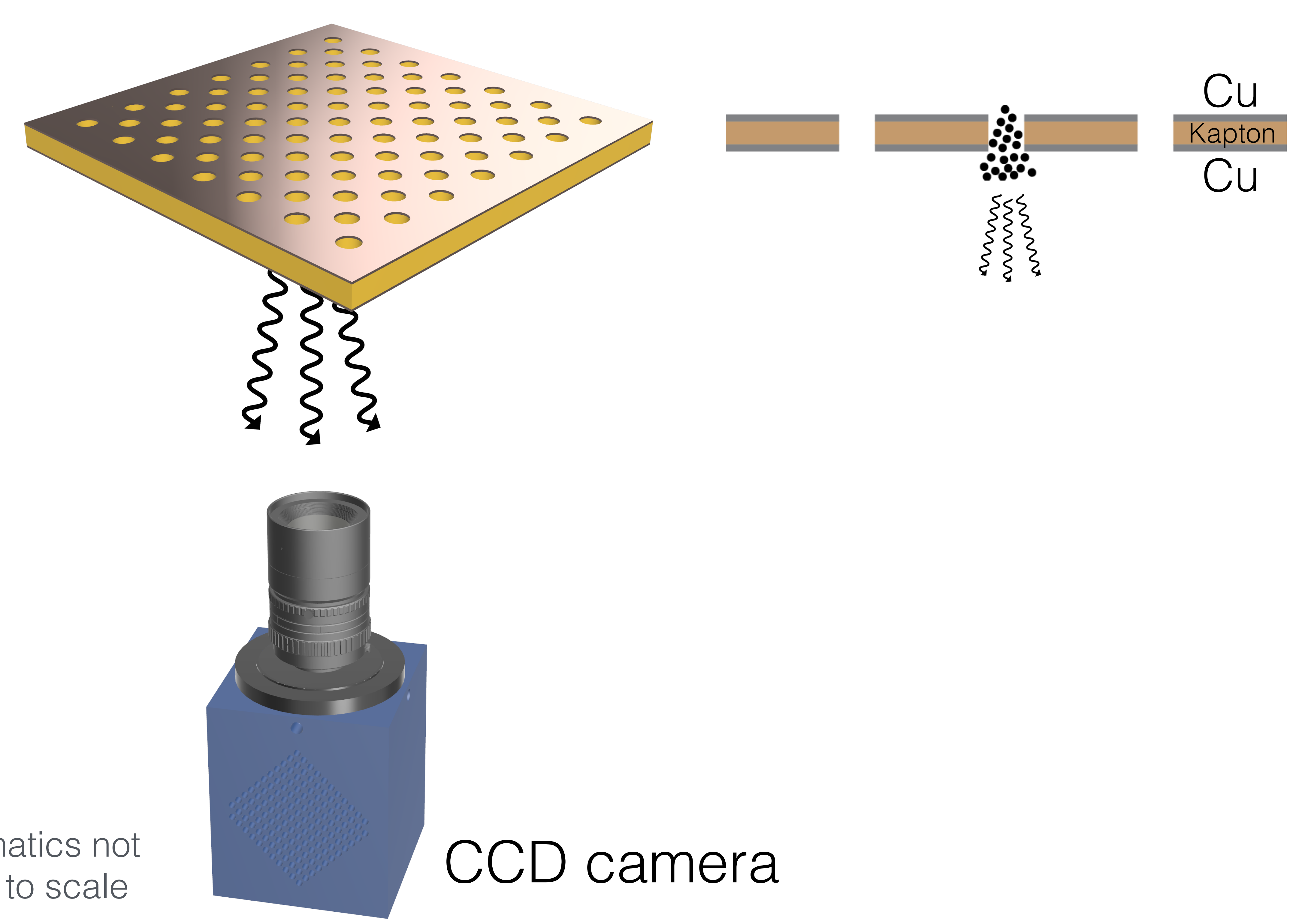


Pion beam profile

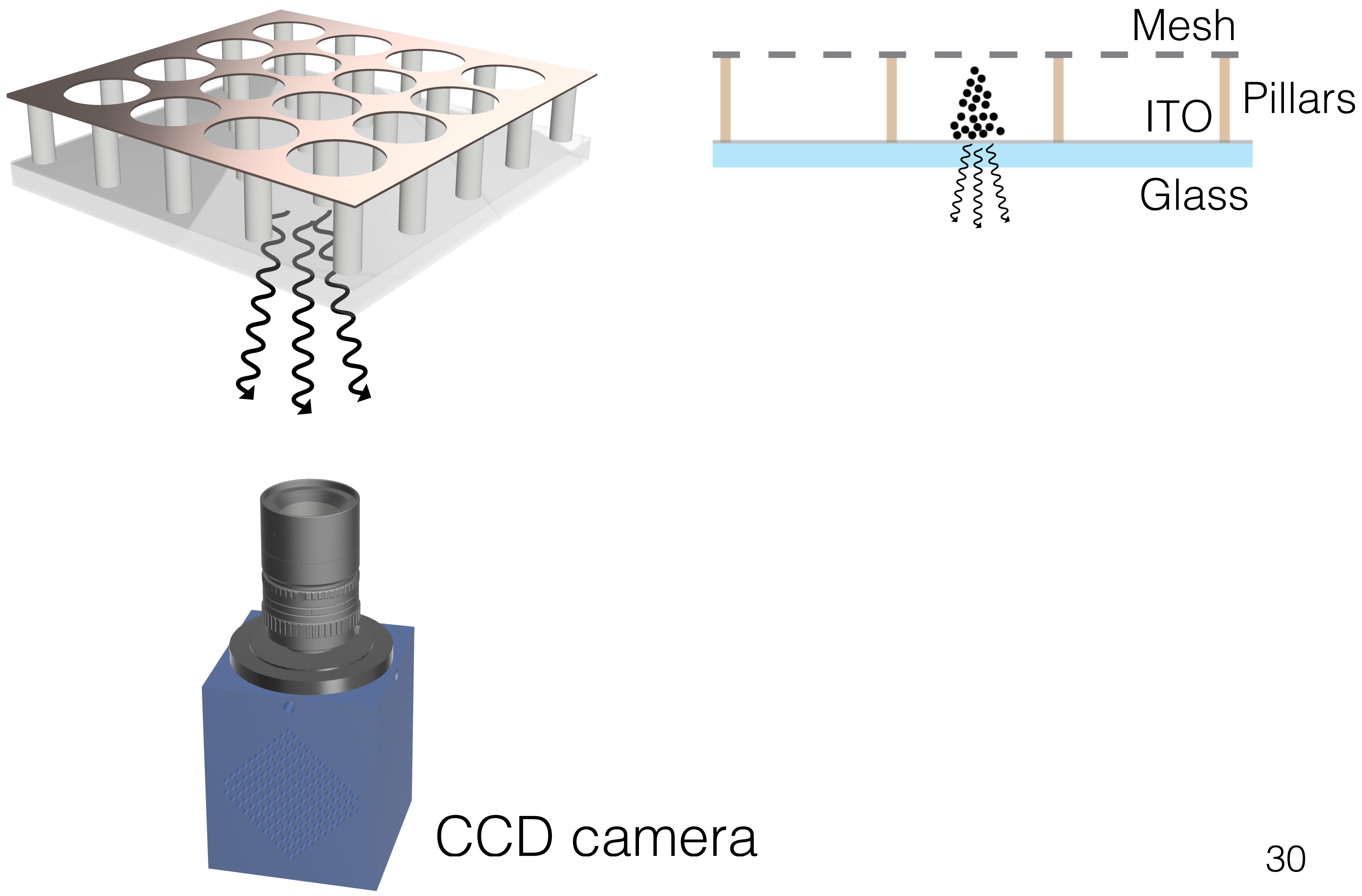
Optical readout of Micromegas

Exploiting uniform amplification region of MicroMegas detectors

Gaseous Electron Multiplier (**GEM**)



Micro-Mesh Gaseous Structure (**MicroMegas**)



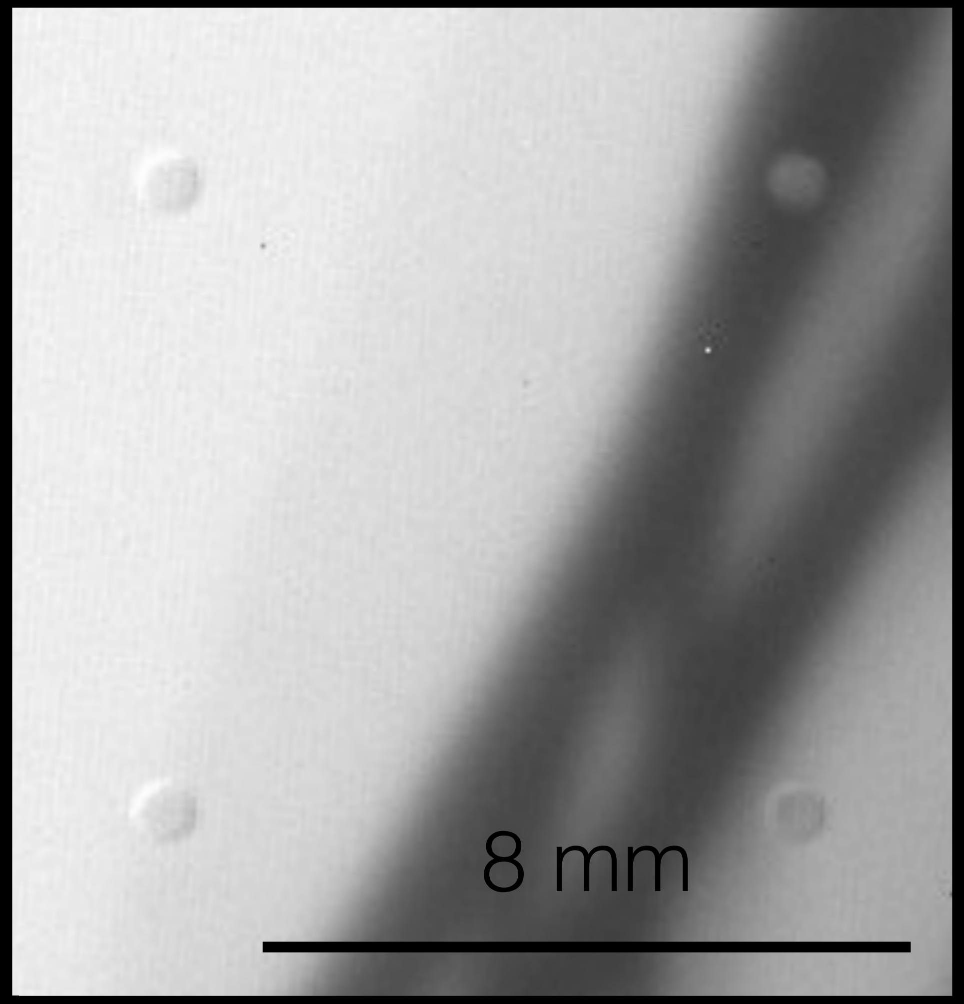
Schematics not drawn to scale

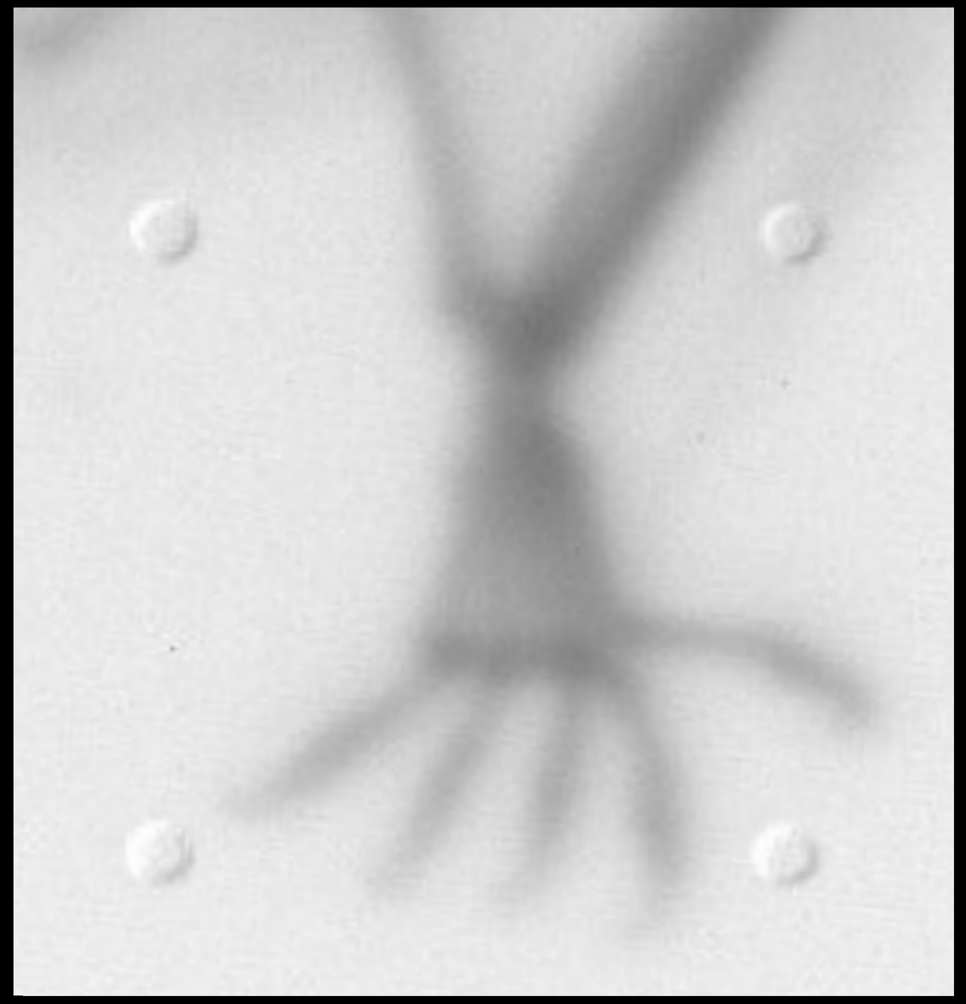
X-ray radiography imaging with glass Micromegas

Optically read out **glass Micromegas** detectors are well suited for X-ray radiography.

They appear to permit higher spatial resolution than optically read out GEMs.

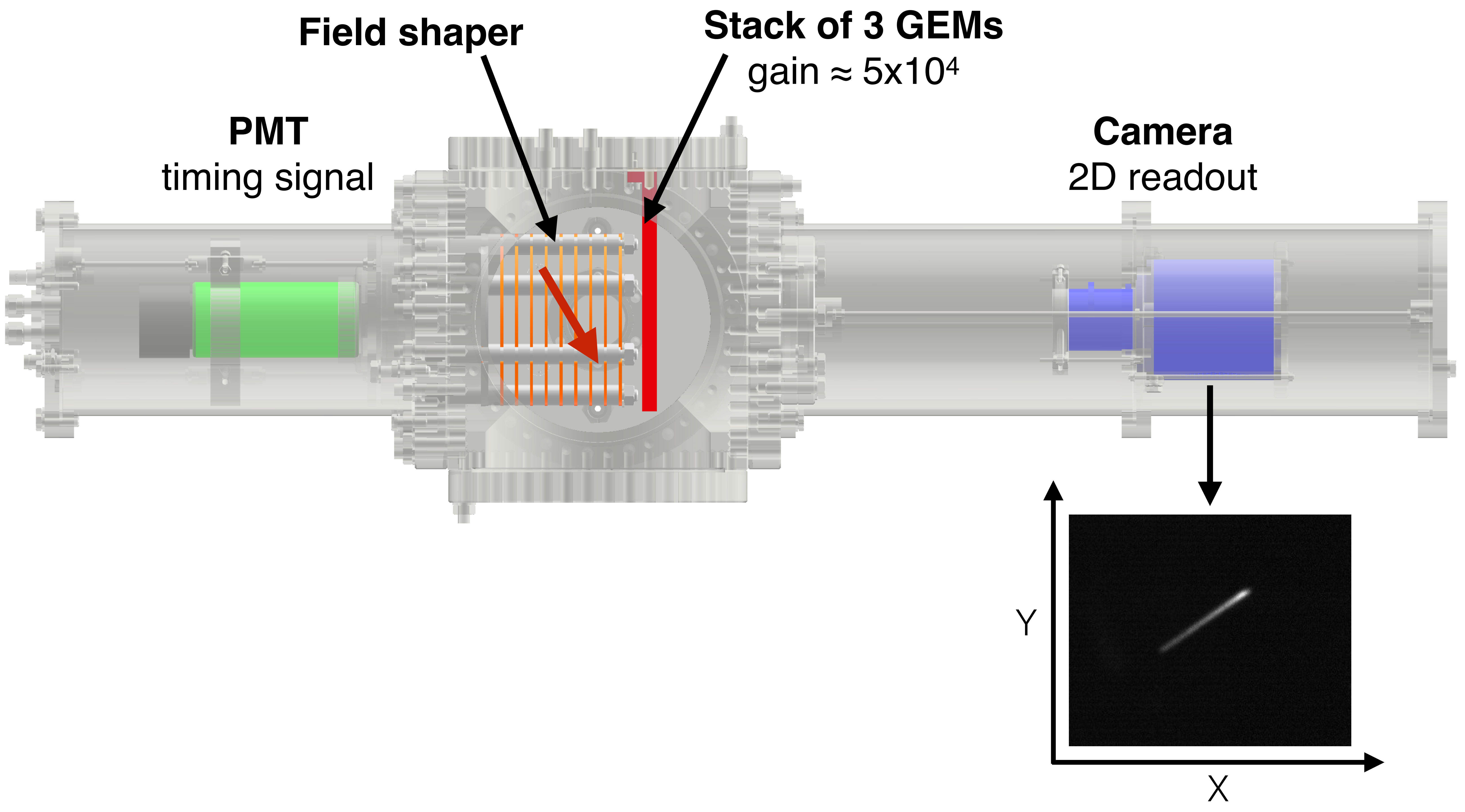
Pillars are visible as inefficient areas in background subtracted, beam-shape corrected images.





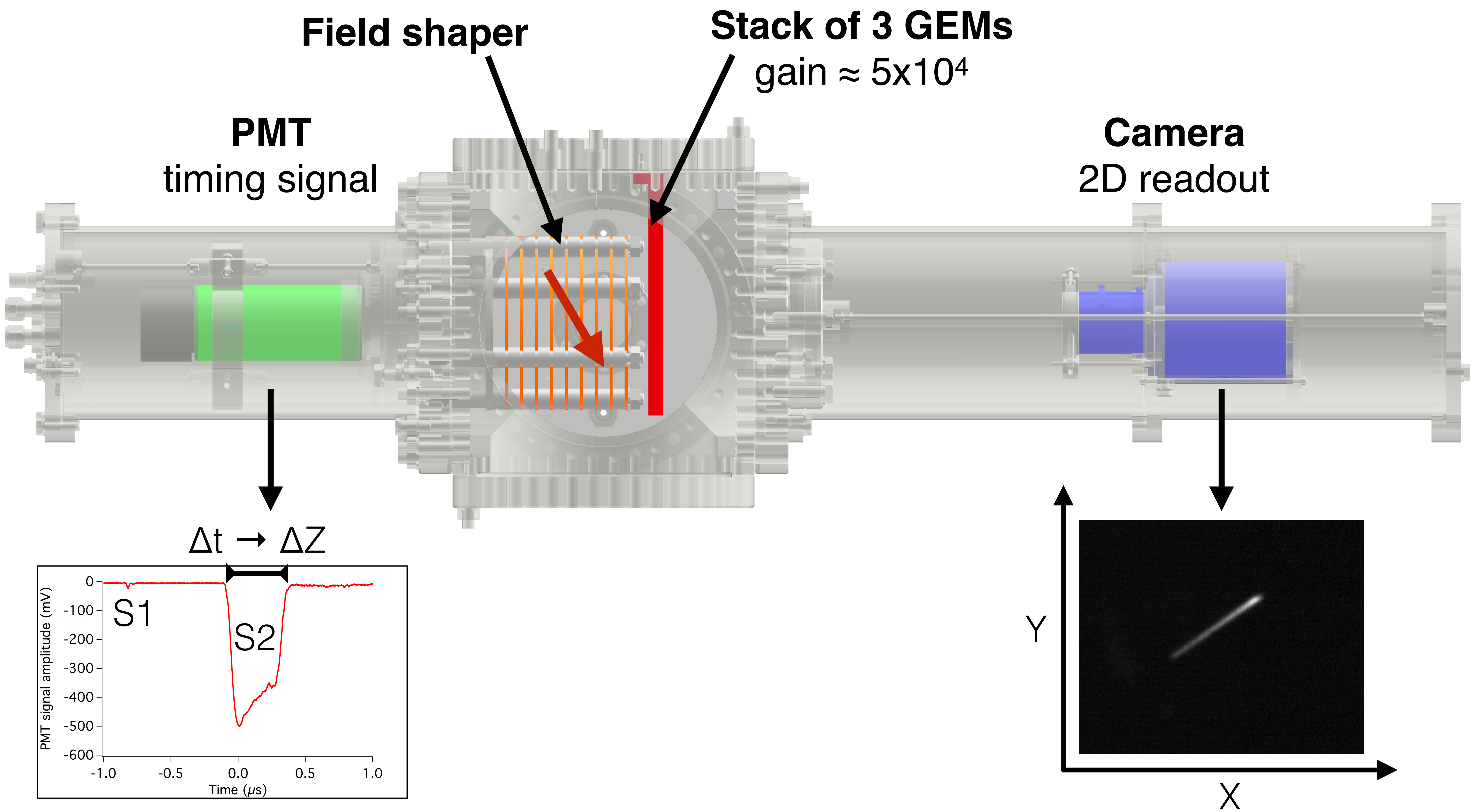
3D track reconstruction with optically read out TPC

Optically read out TPC PMT + CCD



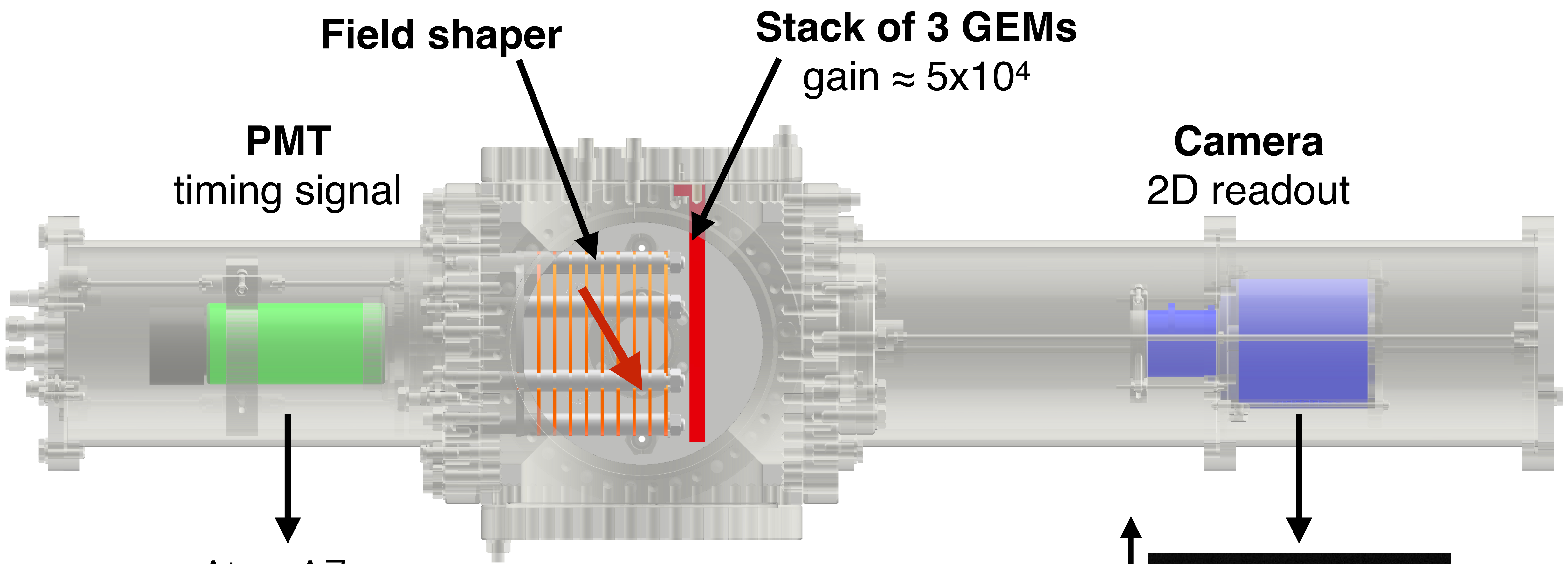
Schematics not drawn to scale

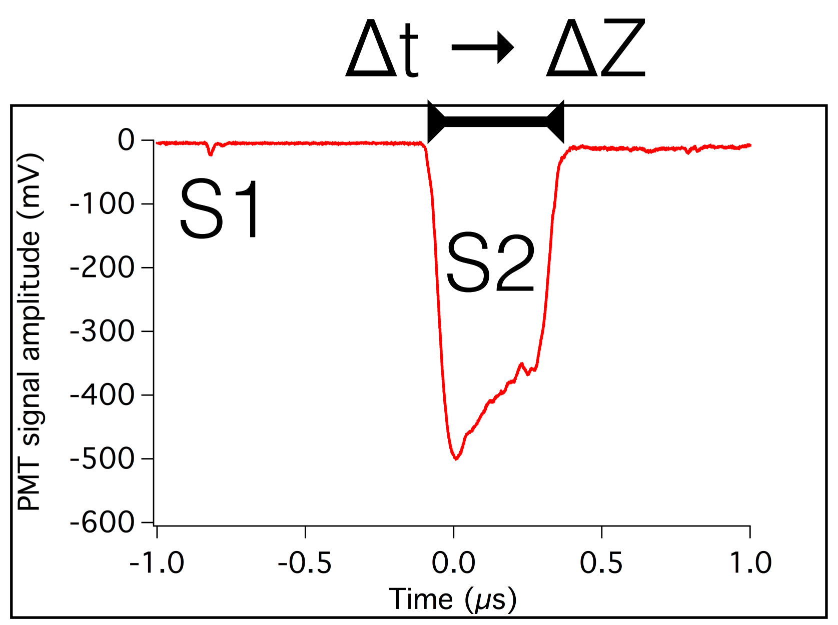
Optically read out TPC PMT + CCD

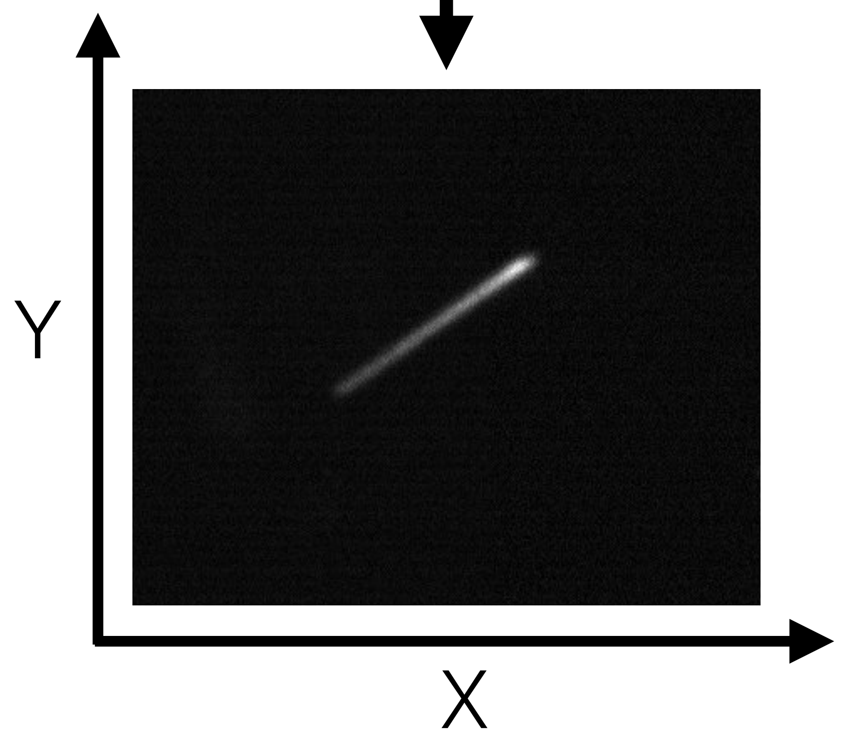


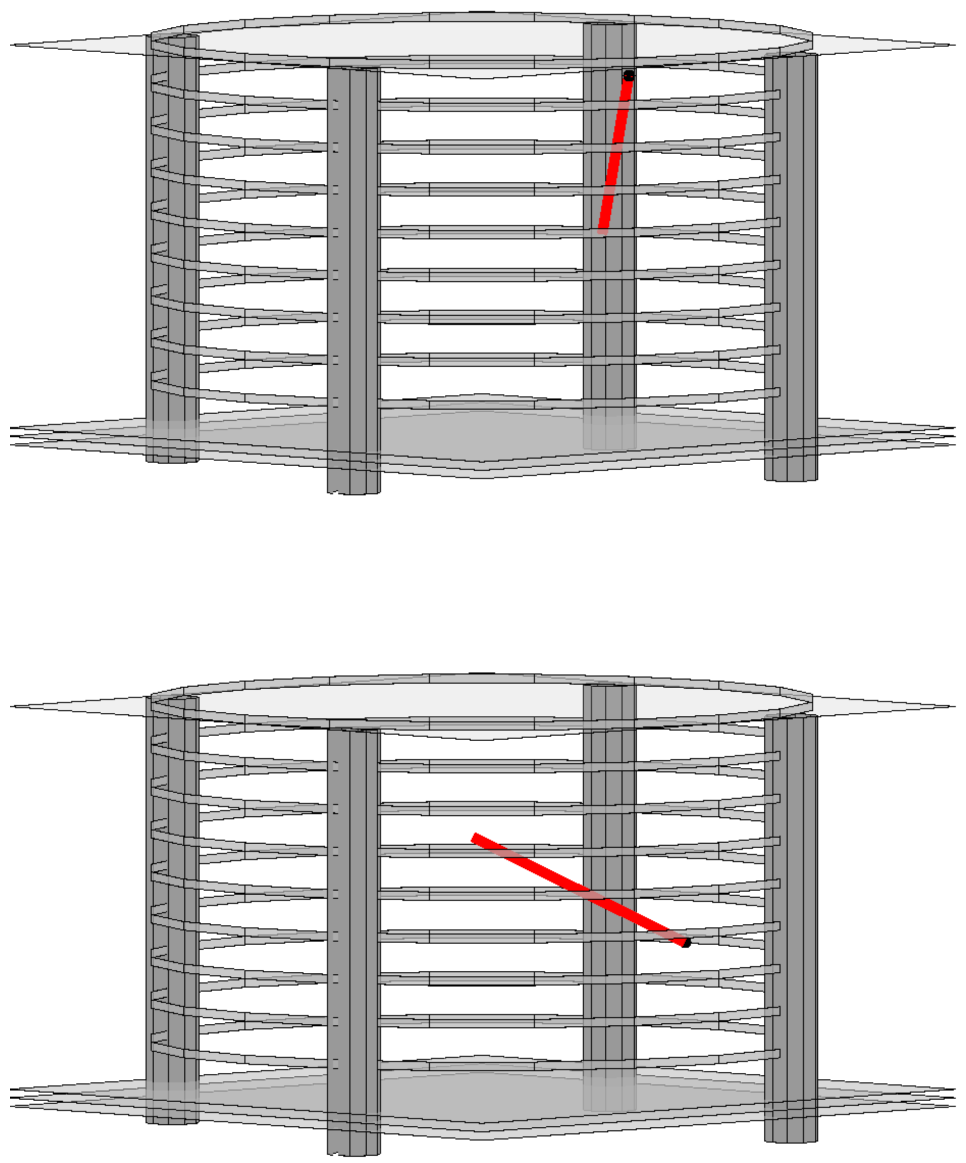
Schematics not drawn to scale

Optically read out TPC PMT + CCD



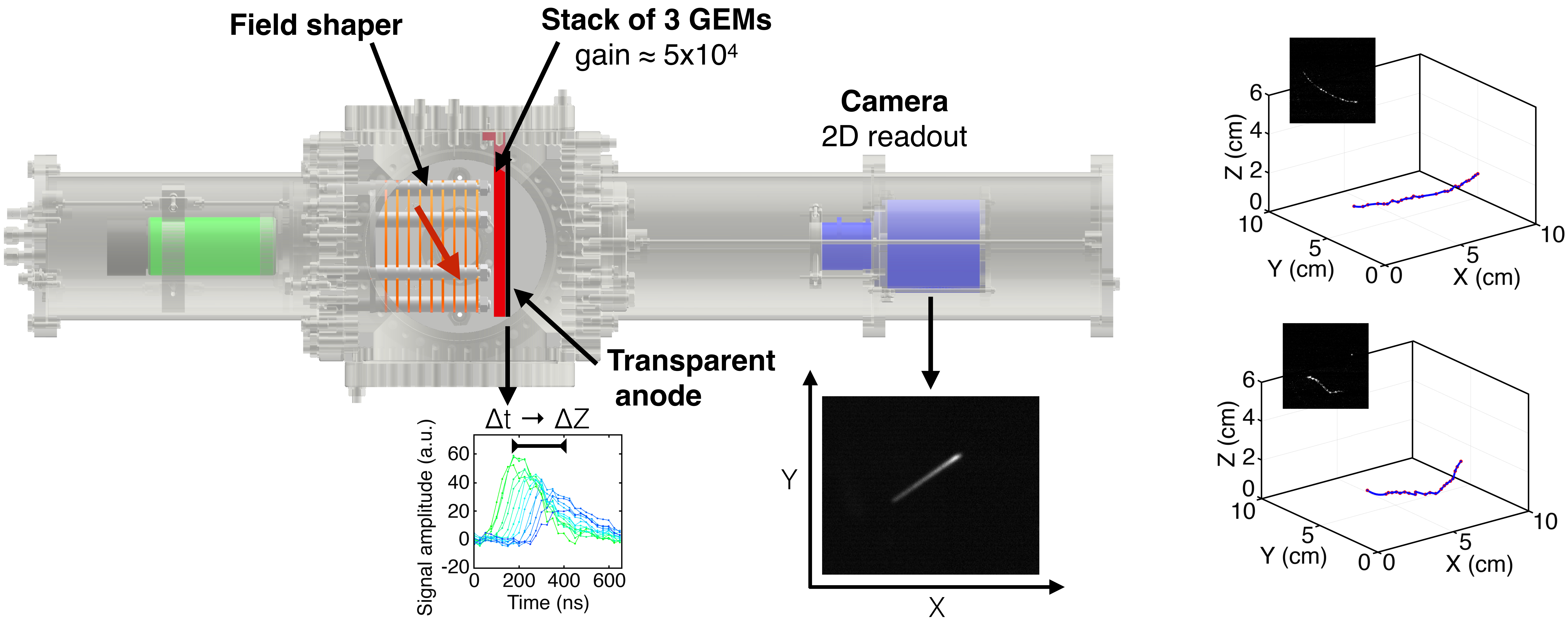






Schematics not drawn to scale

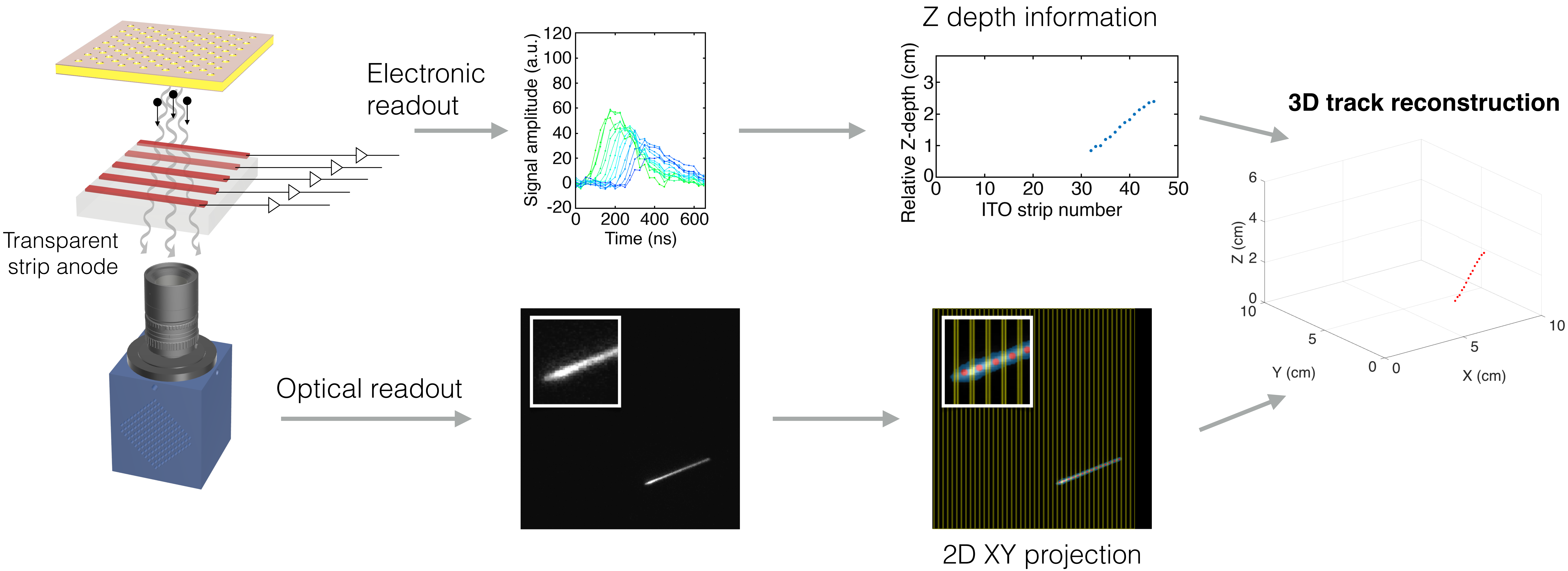
Optically read out TPC Electronic + CCD



F. M. Brunbauer et al., IEEE NSS 2017

Schematics not drawn to scale

Combined optical and electronic readout

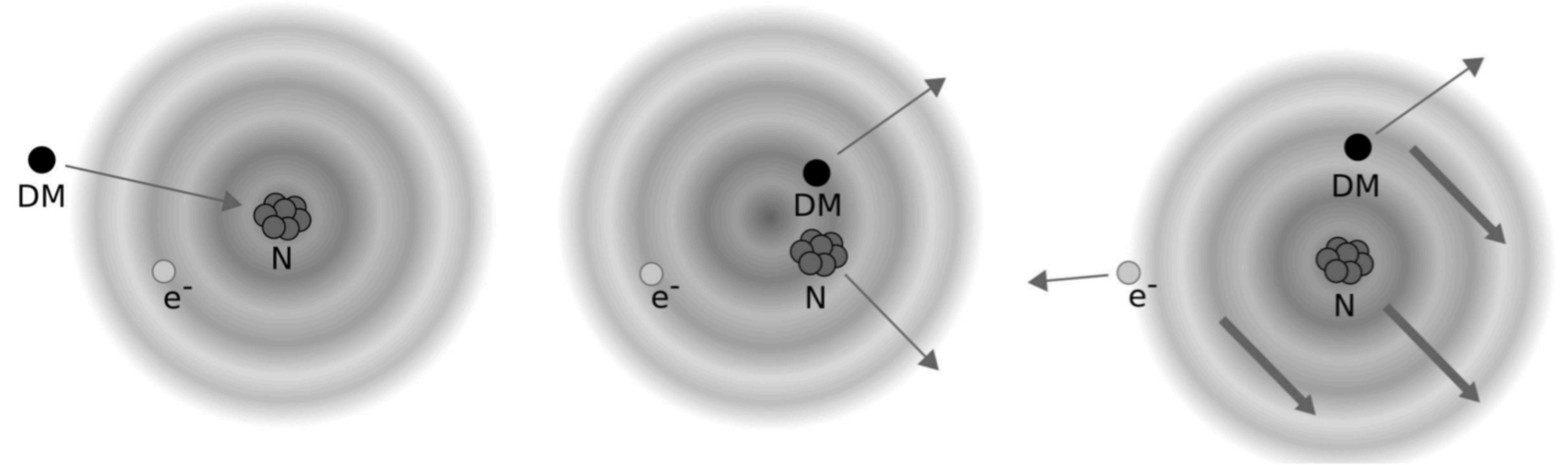


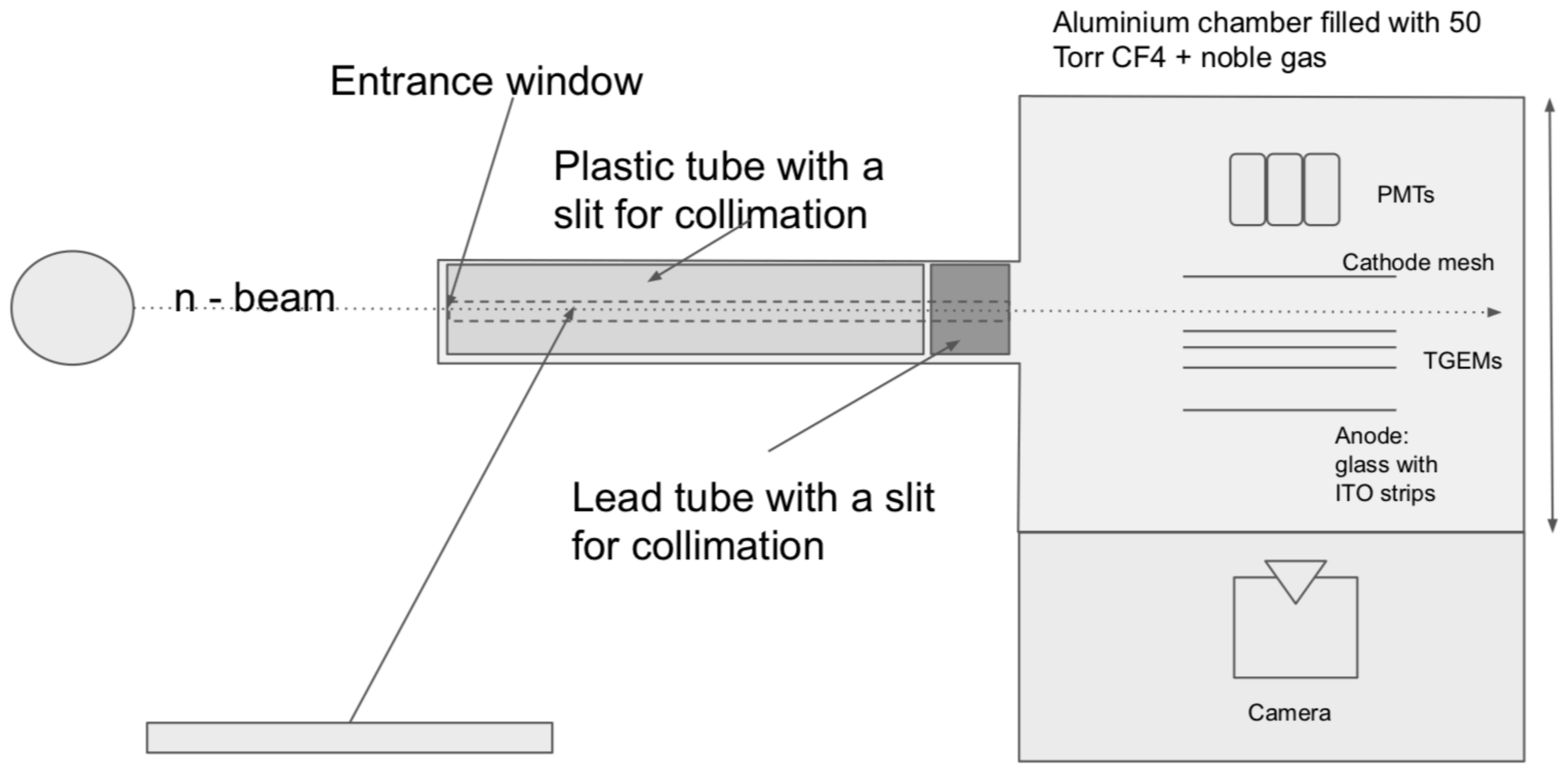
Schematics not drawn to scale

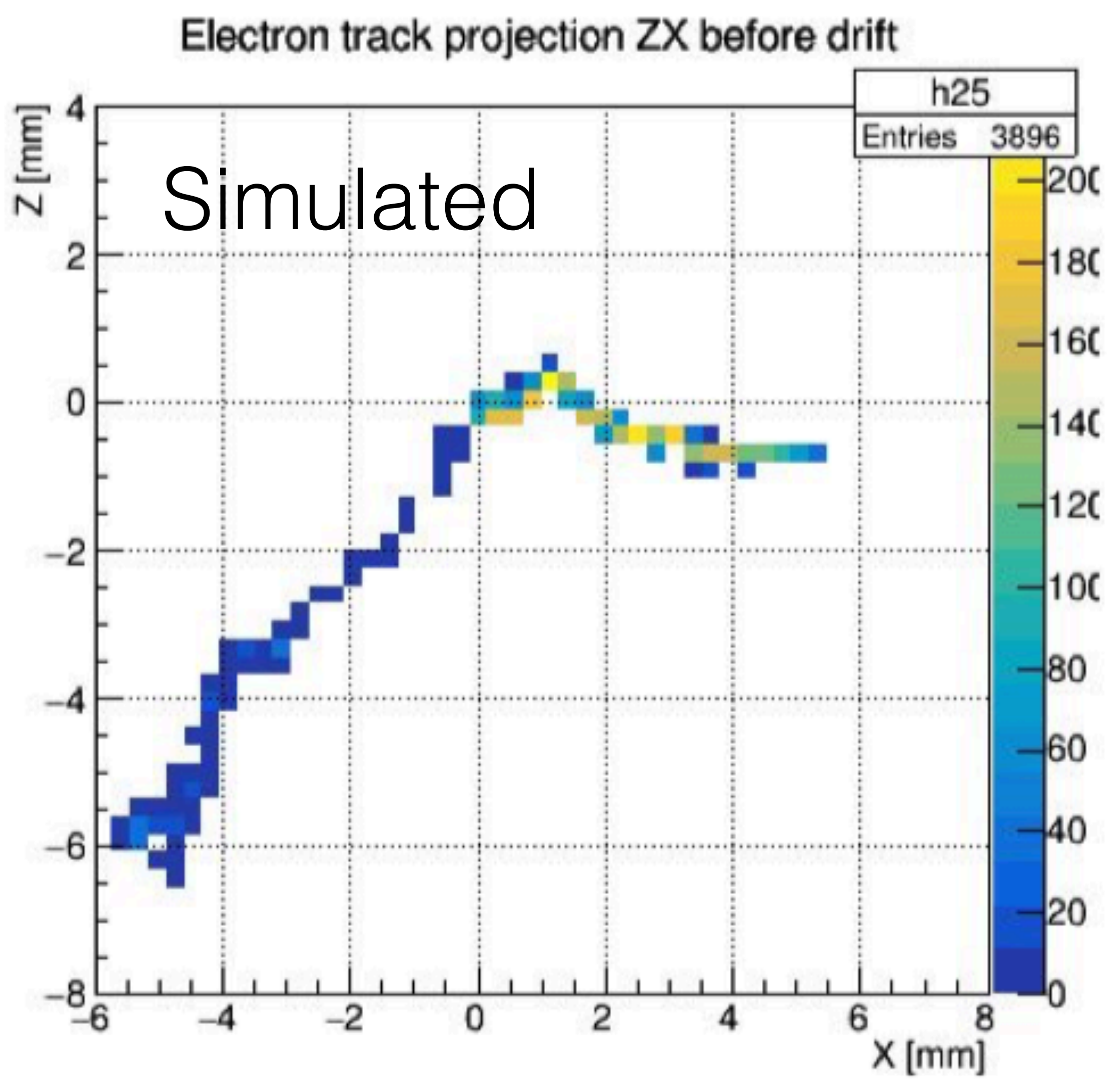
Migdal TPC: Combined optical and electronic readout

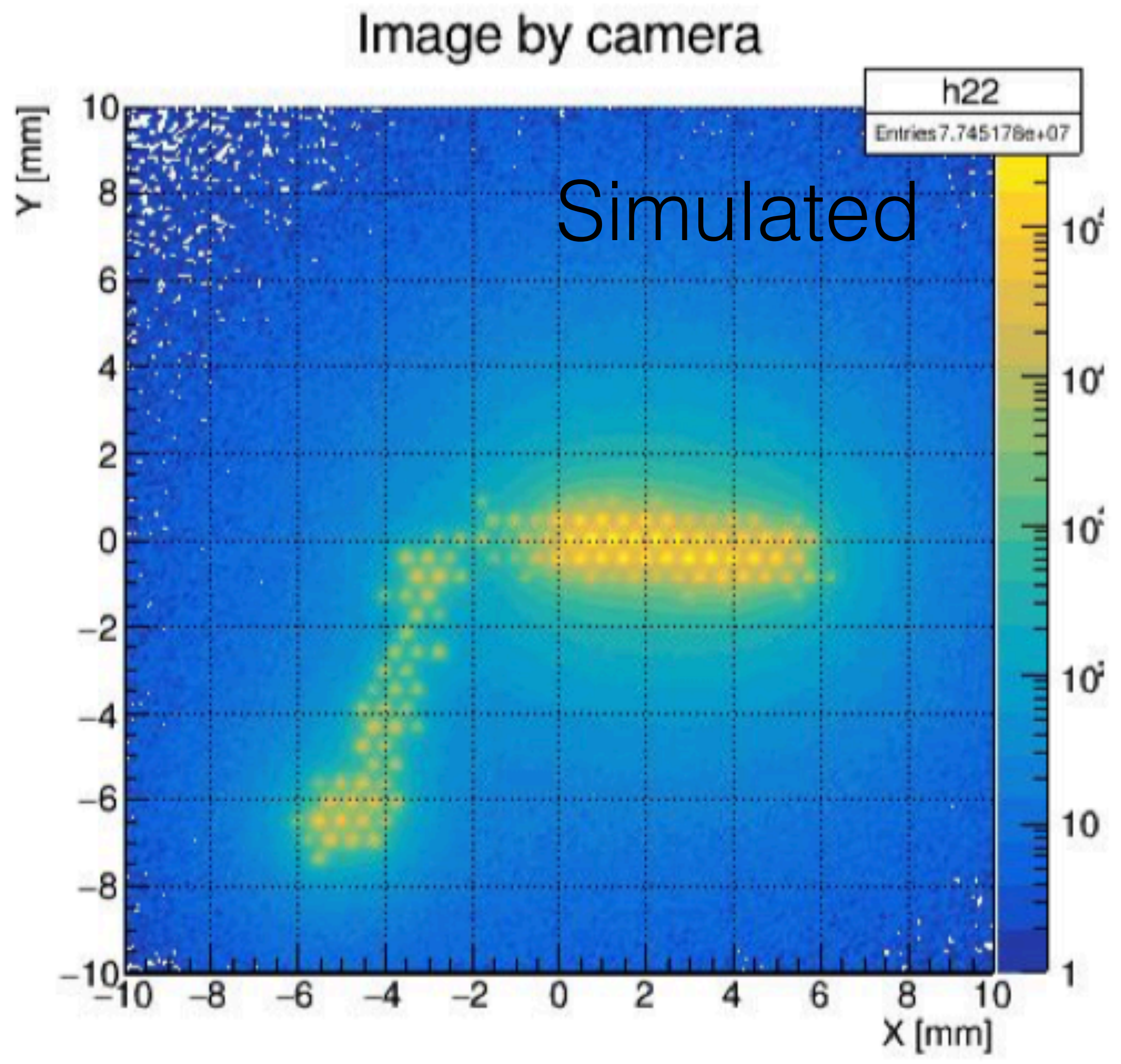
Low pressure optical TPC for Migdal effect observation

Observing nuclear recoil and low energy electron track at same time requires wide dynamic range detector.







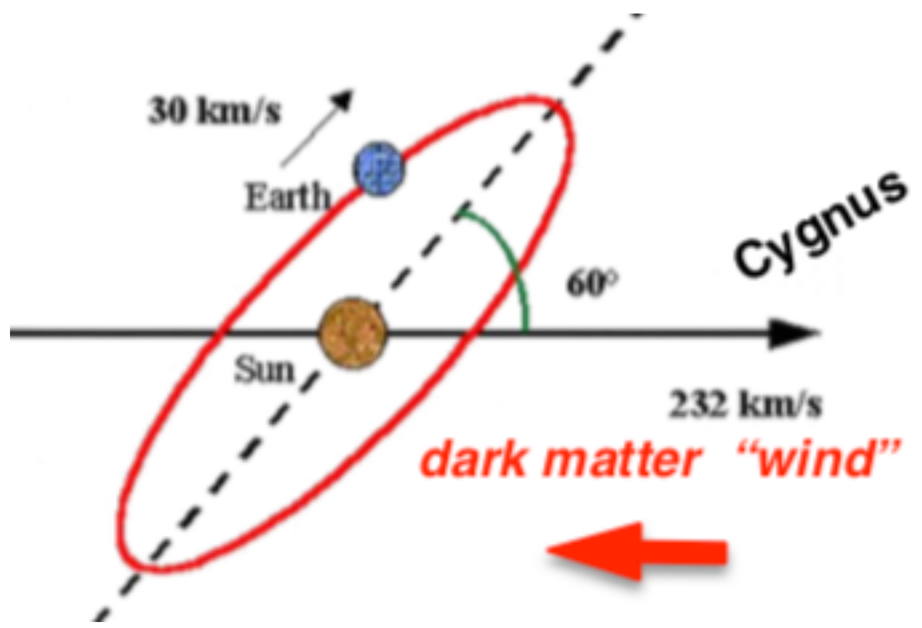


10 keV electron and 200 keV F ion in pure CF4

P. Majewski, RD51 mini-week Feb 2020

https://indico.cern.ch/event/872501/contributions/3730586/attachments/1985262/3307758/RD51_mini_week_Pawel_Majewski_ver2.pdf

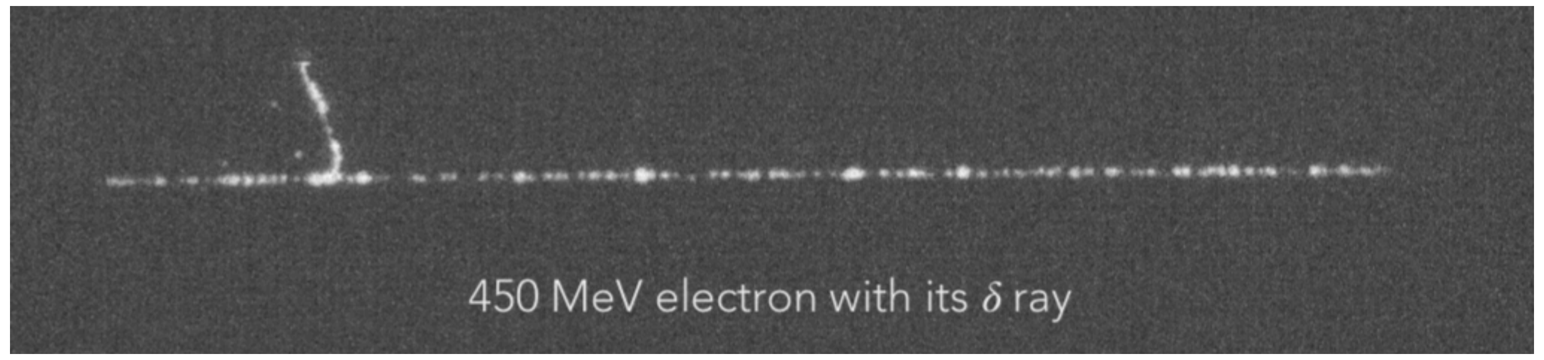
Directional dark matter search

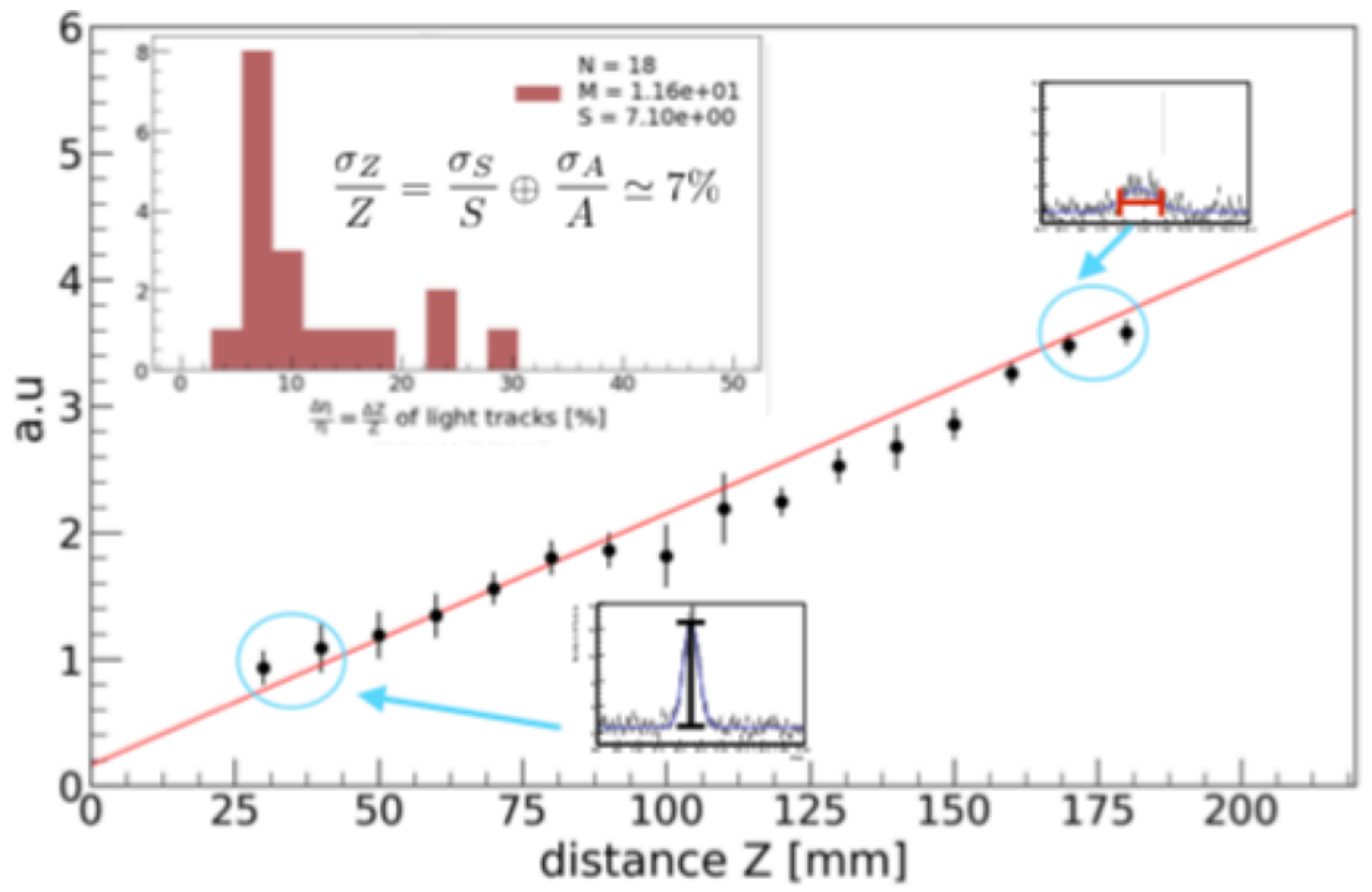


G. Cavoto (CYGNO, INFN)

Directional dark matter search requires **high granularity 3D track reconstruction** to measure shape and direction of recoil

Low event rate expected (few events / kg / yr), low background rate required



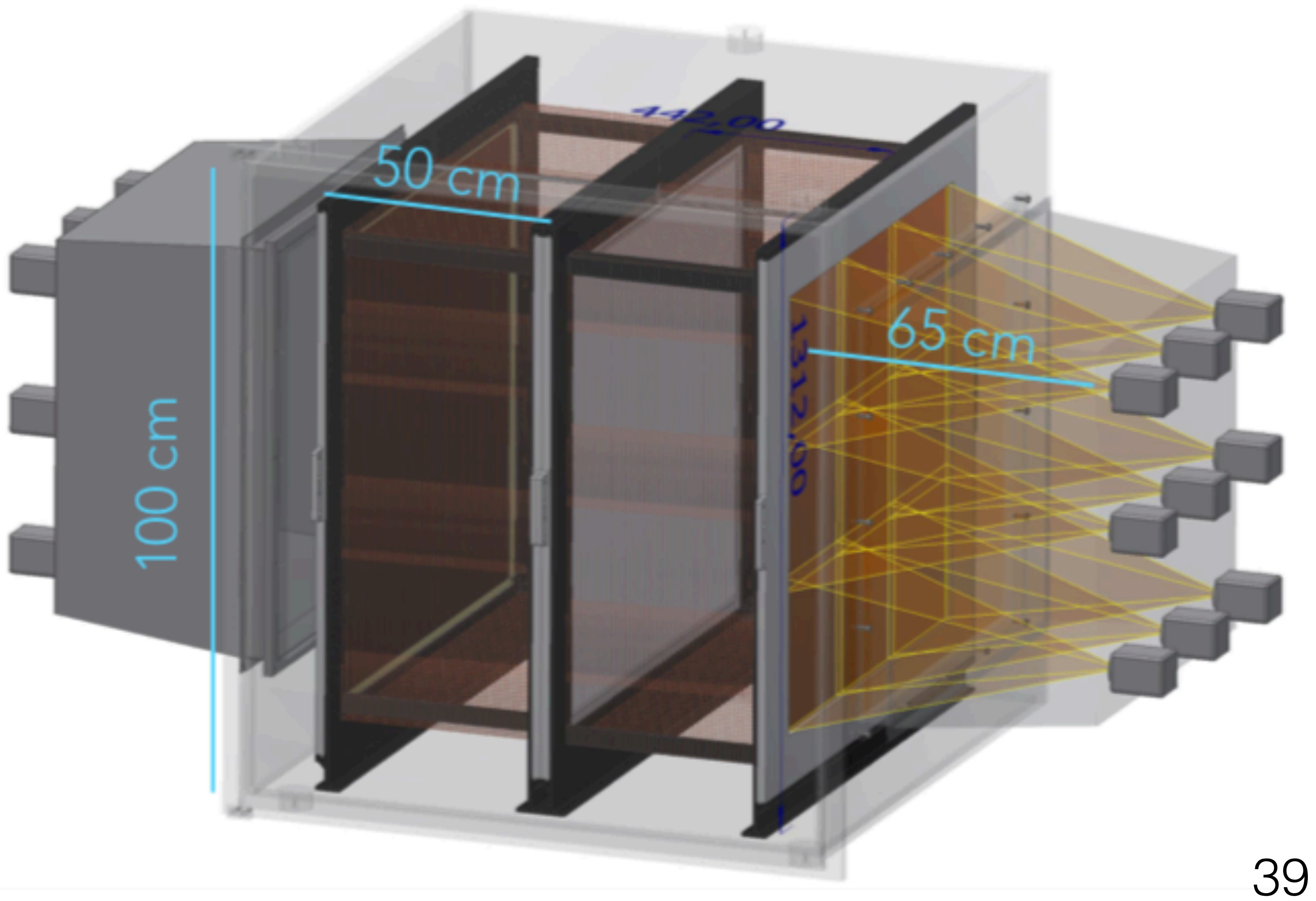


Optical TPCs based on GEMs well suited to provide high granularity 2D images

Camera (CMOS) used for 2D image, PMT used for Z-information

Light profile from camera can be compared with PMT waveform for Z-coordinate extraction
Alternatively: amplitude/width ratio of PMT signals used

Planned CYGNO apparatus: $1 m^3$ of He/CF4 60/40 (1.6kg) with $72 x 10^6$ pixels



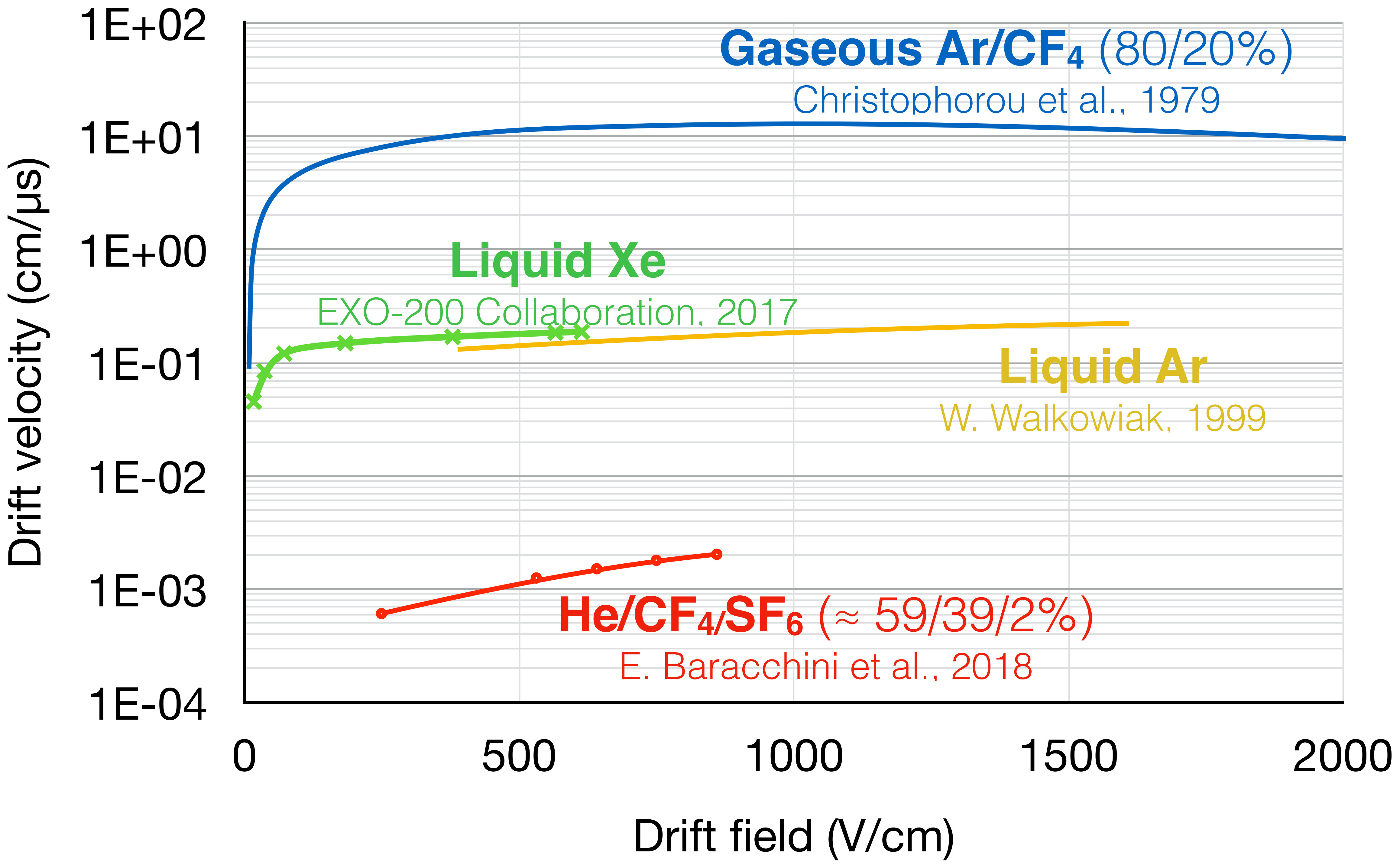
D. Pinci, CYGNO project, RD51 MiniWeek, Feb 2019
https://indico.cern.ch/event/782786/contributions/3283435/

Negative ion drift for optical TPCs

Low drift velocities

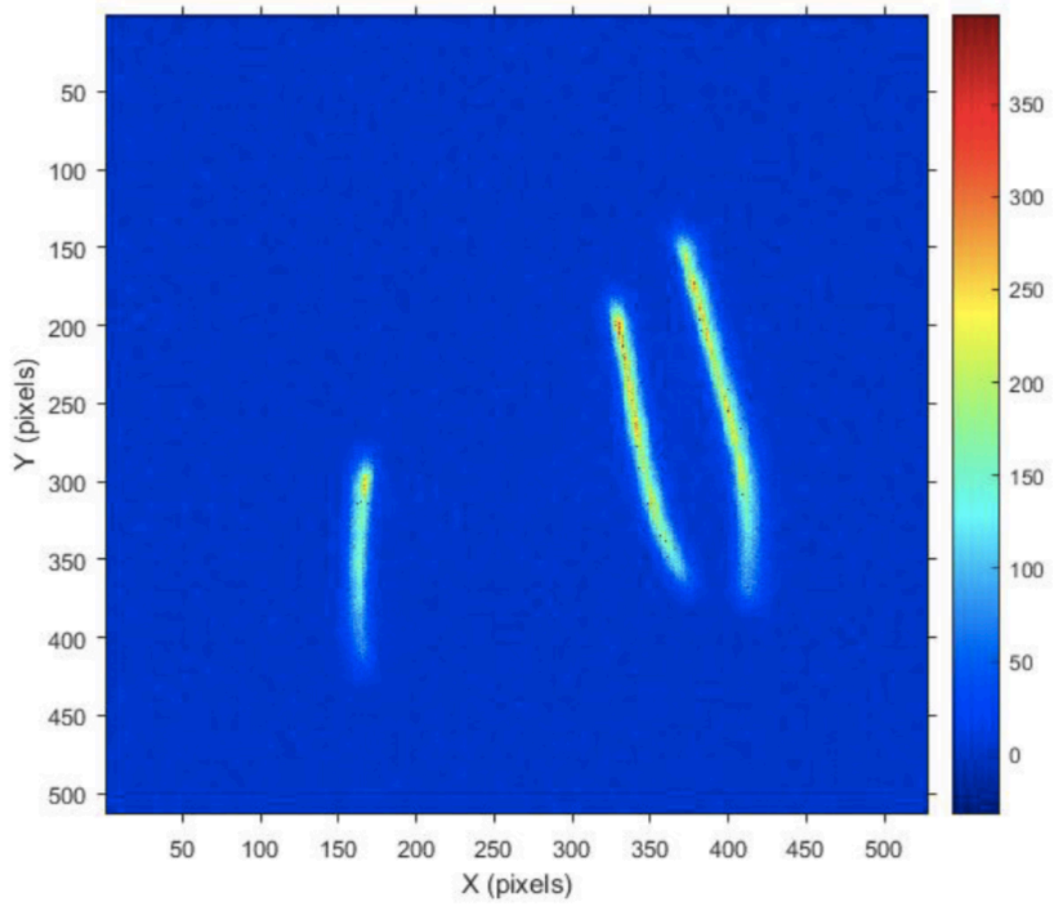
Negative ion drift can provide significantly slower drift velocities, which are ≈3 orders of magnitude slower than electron drift velocitites.

This may permit the recording of multiple frames at high resolution during negative ion drift time.

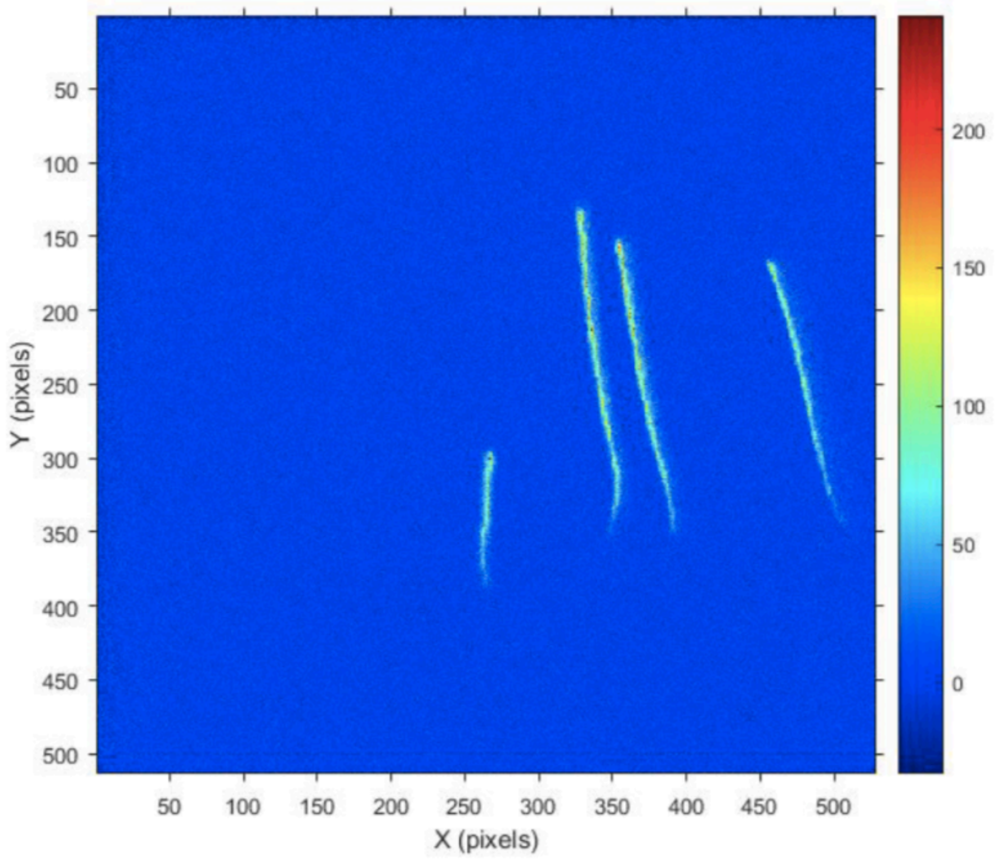


Low diffusion

Drift of ions strongly suppresses diffusion and can provide significant improvement in achieving well-defined images which profit from high-granularity image sensors.



150 Torr CF_4, **σ ~ 450 um**



150 Torr CF_4 + 5.9 Torr CS_2, **σ ~ 150 um**

D. Loomba, UNM

Ultra-fast optical readout

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

High spatial **resolution**

Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

Need of **CF_4**-based gas mixtures
or wavelength shifters

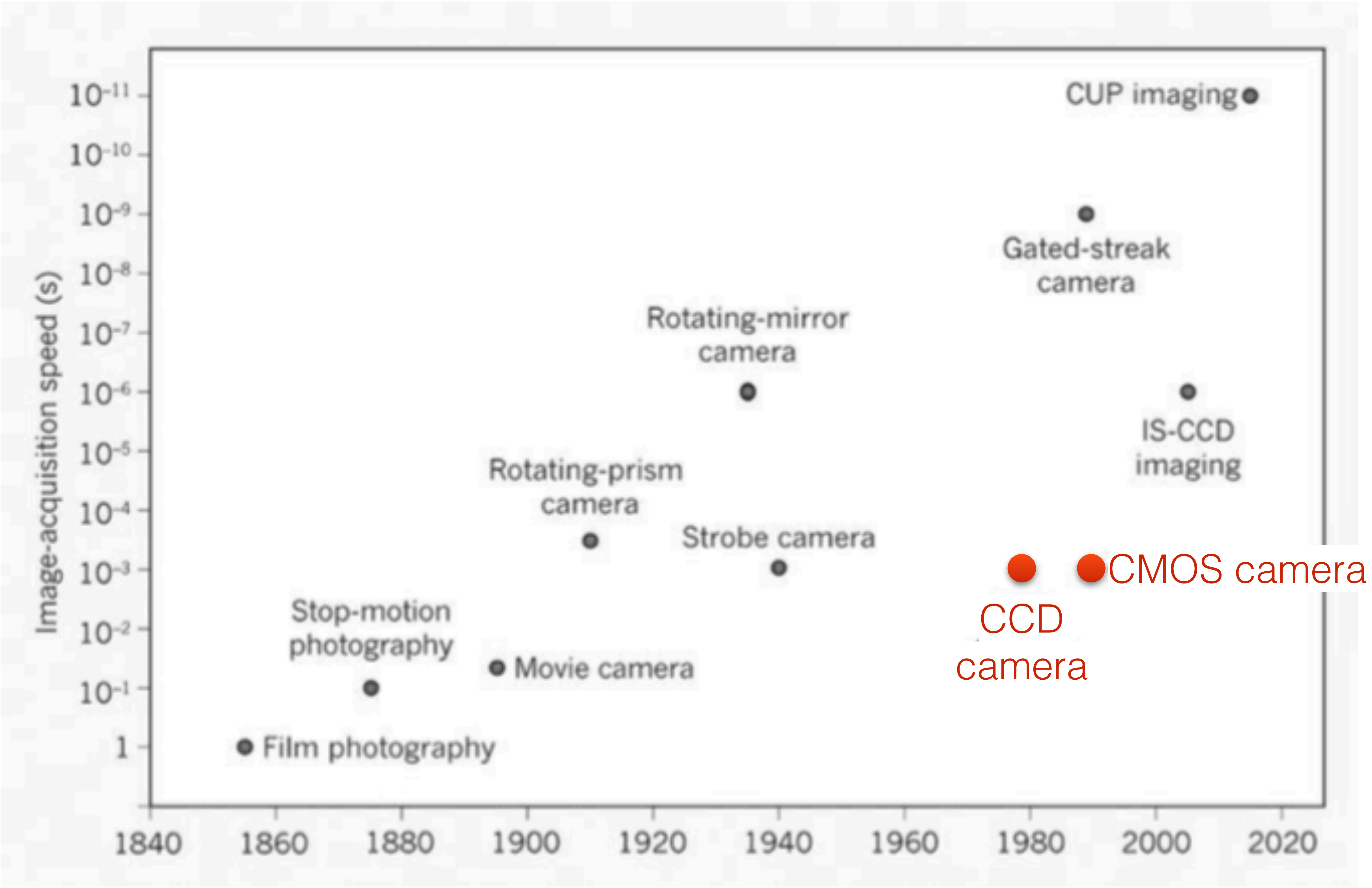


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Optical readout

Integrated imaging approach

Intuitive pixelated readout with **megapixel imaging sensors**

High spatial **resolution**

Lenses and mirrors to enable **adjustable magnification** and camera location

Frame rate

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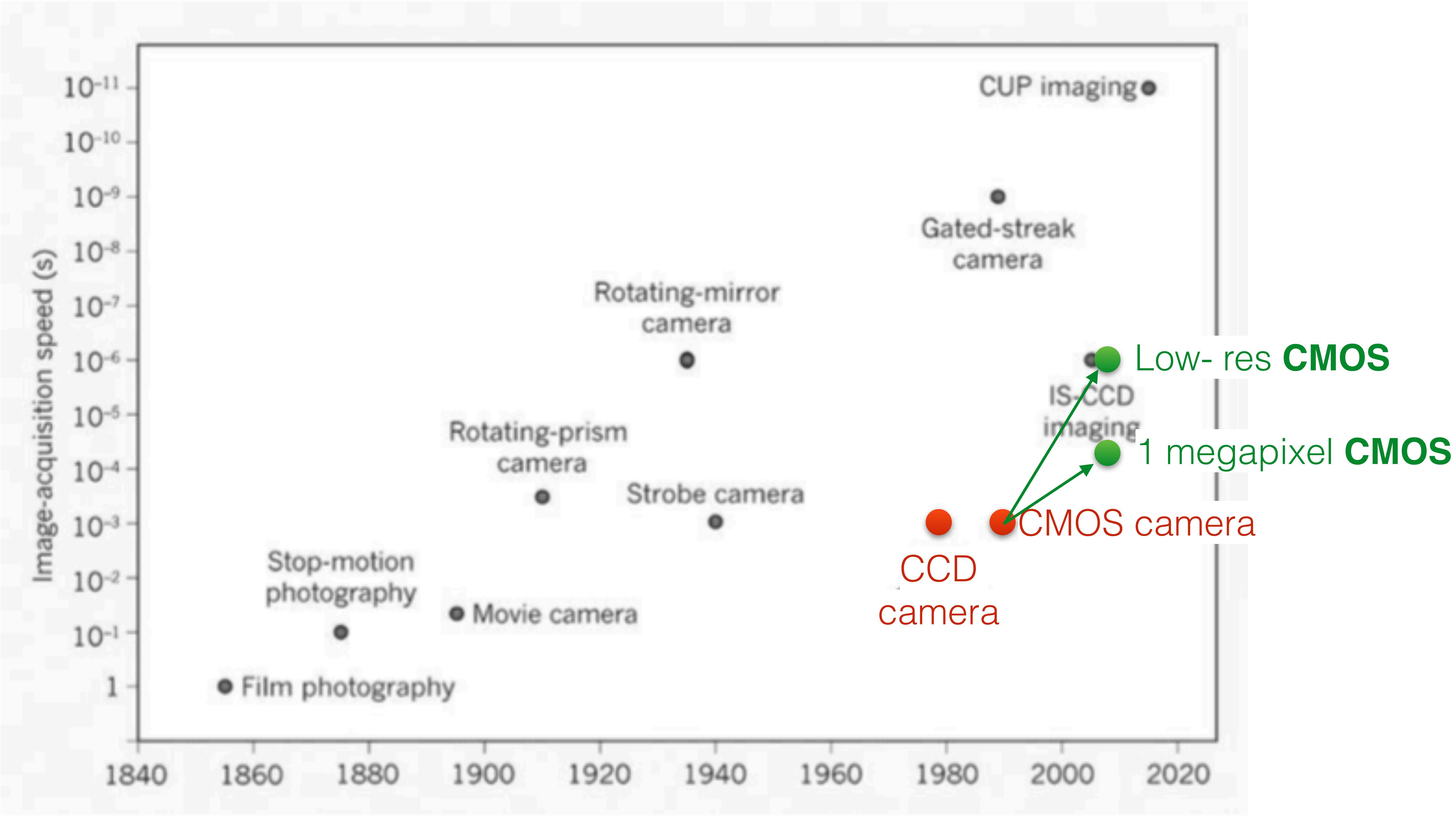

Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Optical readout

Integrated imaging approach

Intuitive pixelated readout with
megapixel imaging sensors

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Lenses and mirrors to enable
adjustable magnification and camera location

Frame rate

Radiation hardness of imaging sensors

Need of **CF_4**-based gas mixtures
or wavelength shifters

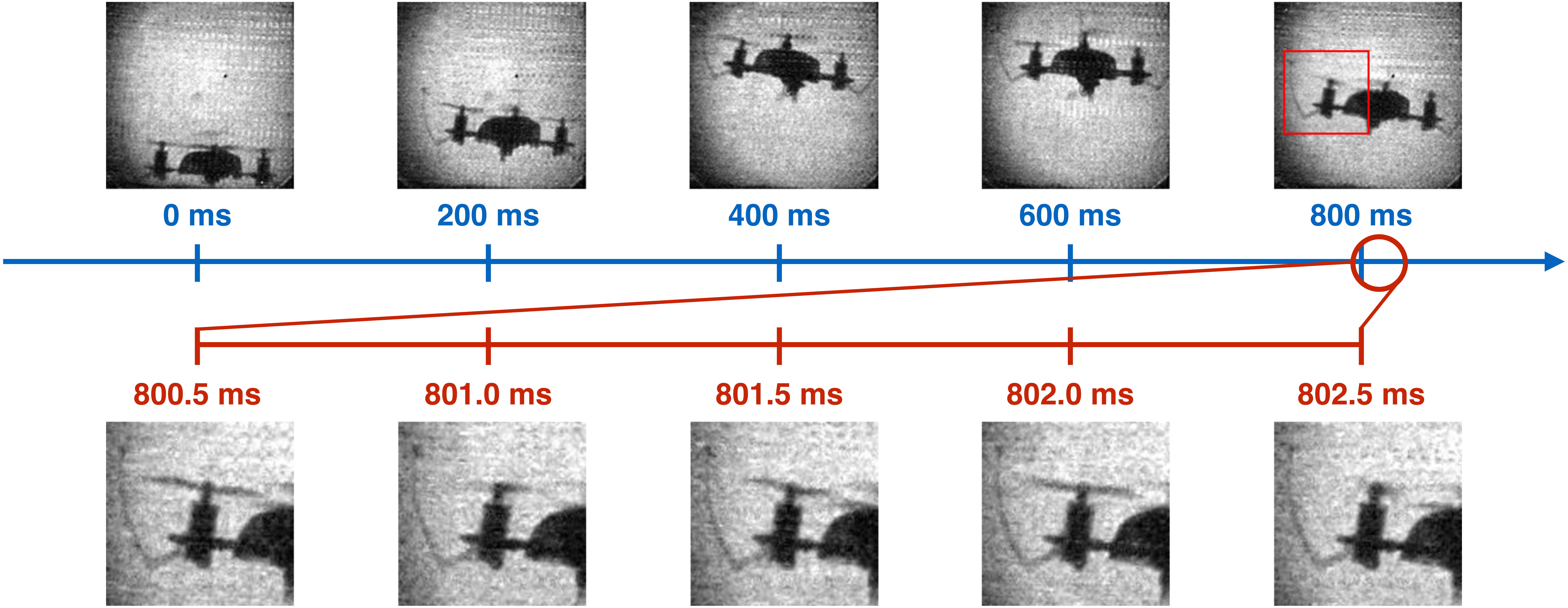
Photron FASTCAM SA-Z

- 1 megapixel CMOS sensor
- 12 bit depth
- **20 kfps** at 1024x1024
- **2.1 Mfps** at 128x8
- ISO 50,000 sensitivity

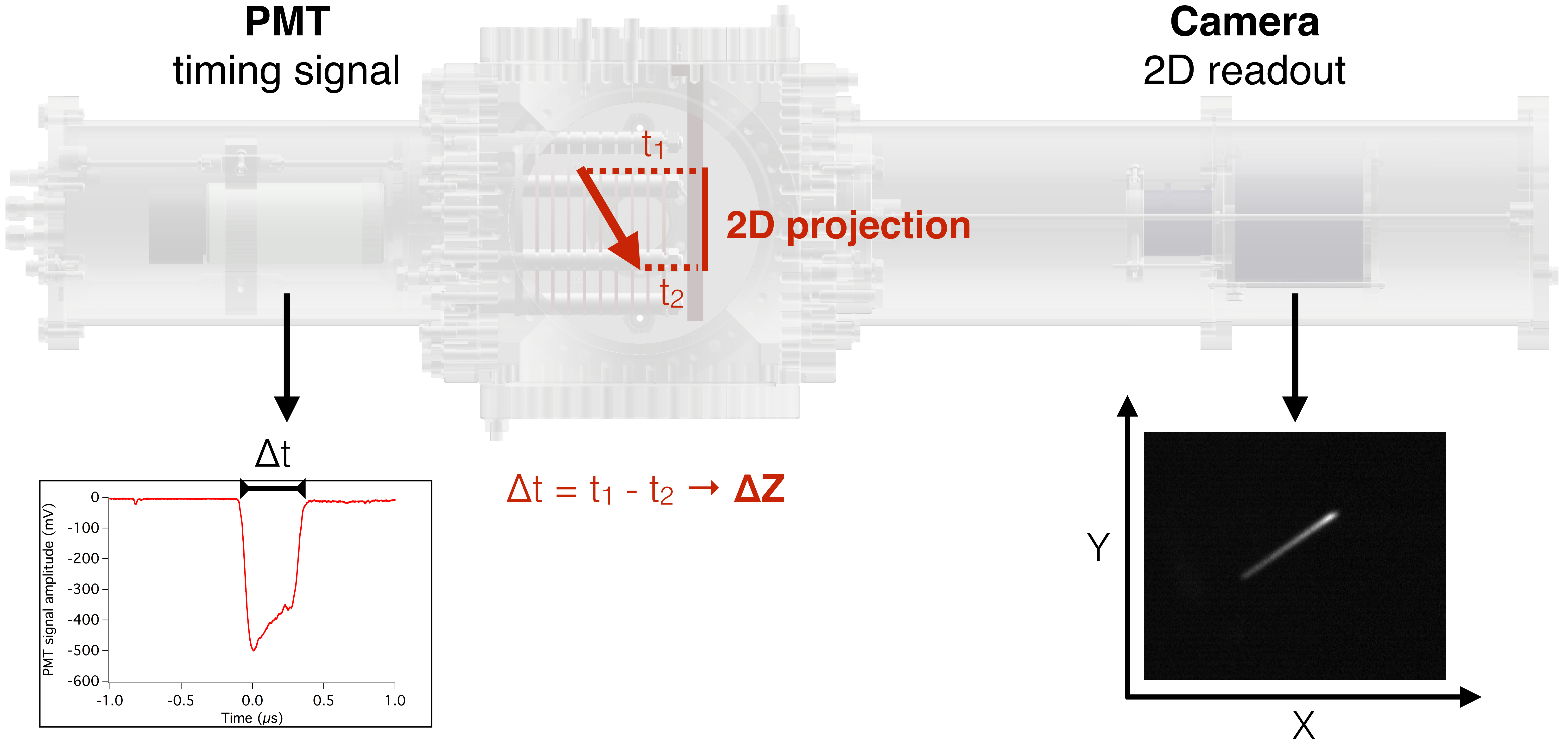
Phantom v2512

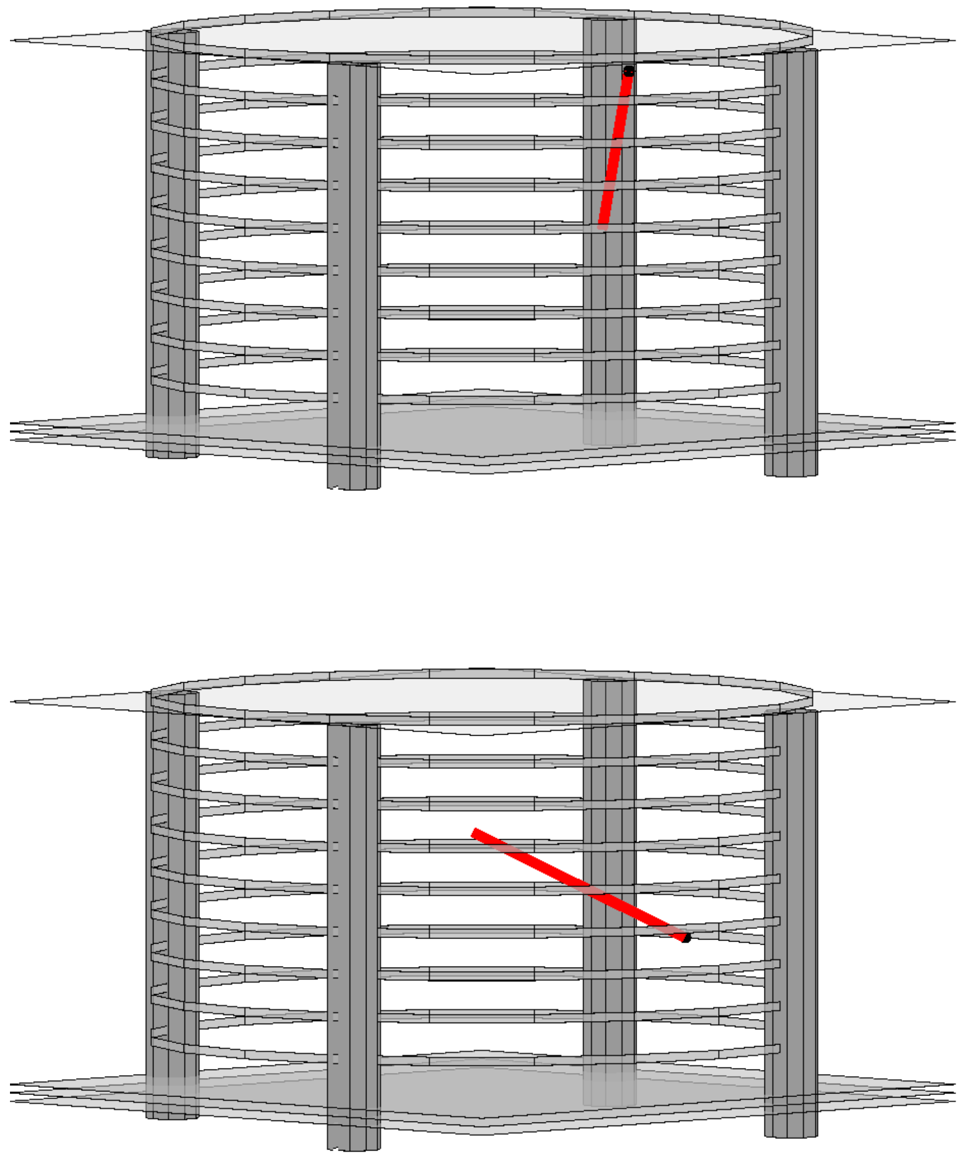
- 1 megapixel CMOS sensor
- 12 bit depth
- **25 kfps** at 1280 x 800
- **1 Mfps** at 128x32
- ISO 100,000 sensitivity

High-speed X-ray fluoroscopy



Optically read out TPC CCD + PMT

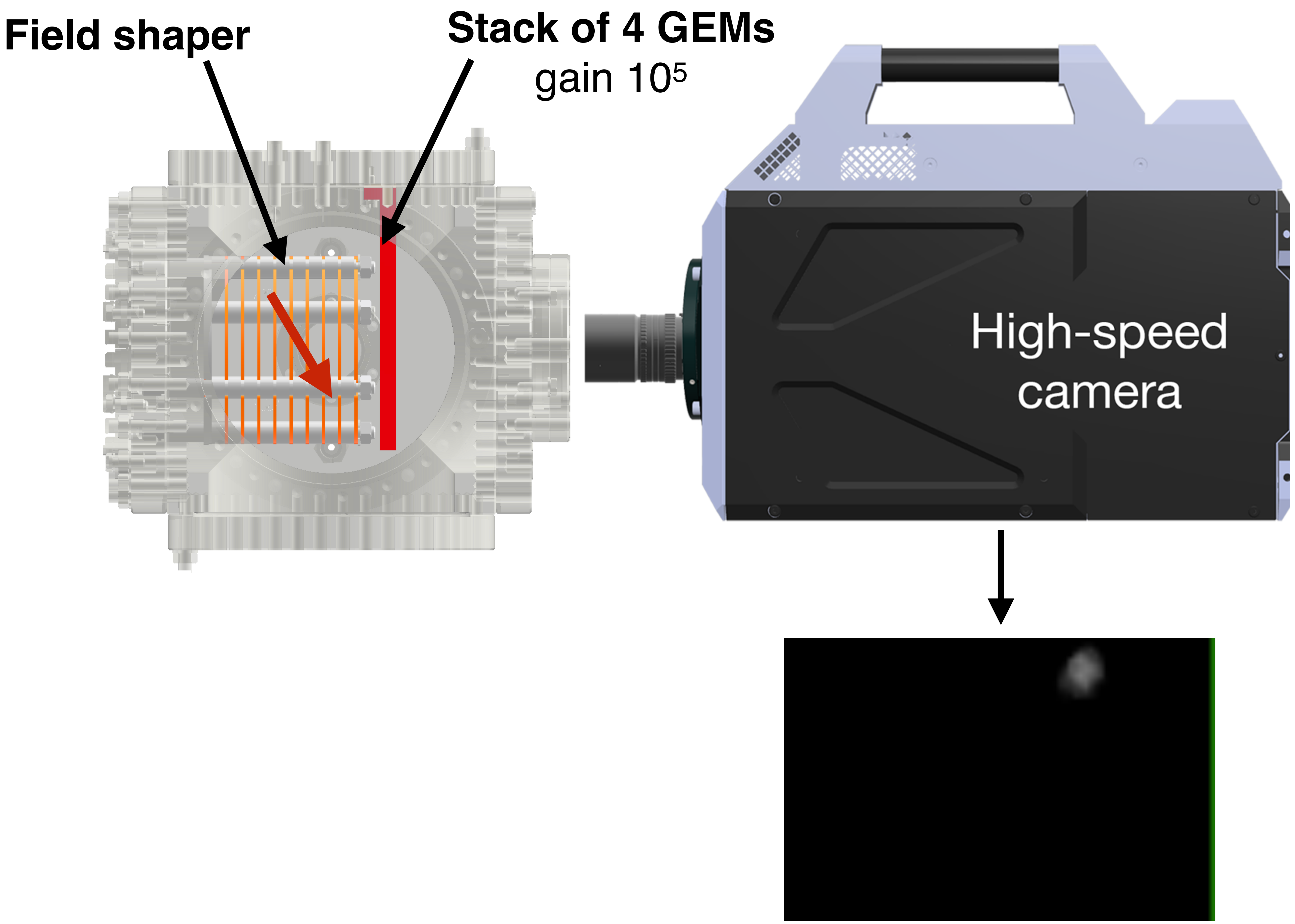




F. M. Brunbauer et al., IEEE NSS 2016

Schematics not drawn to scale

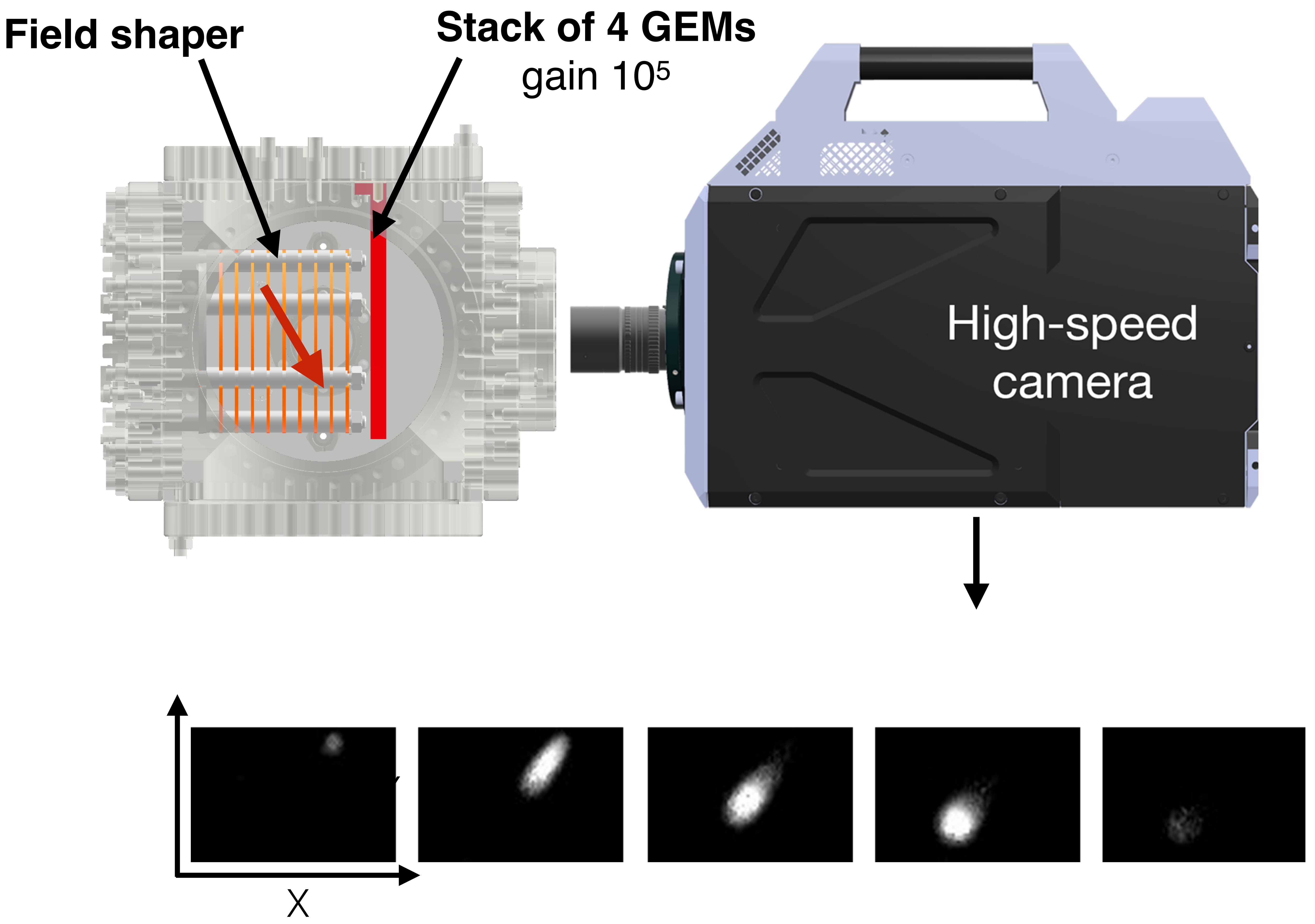
Optically read out TPC Ultra-fast CMOS



F. M. Brunbauer et al., IEEE NSS 2018

Schematics not drawn to scale

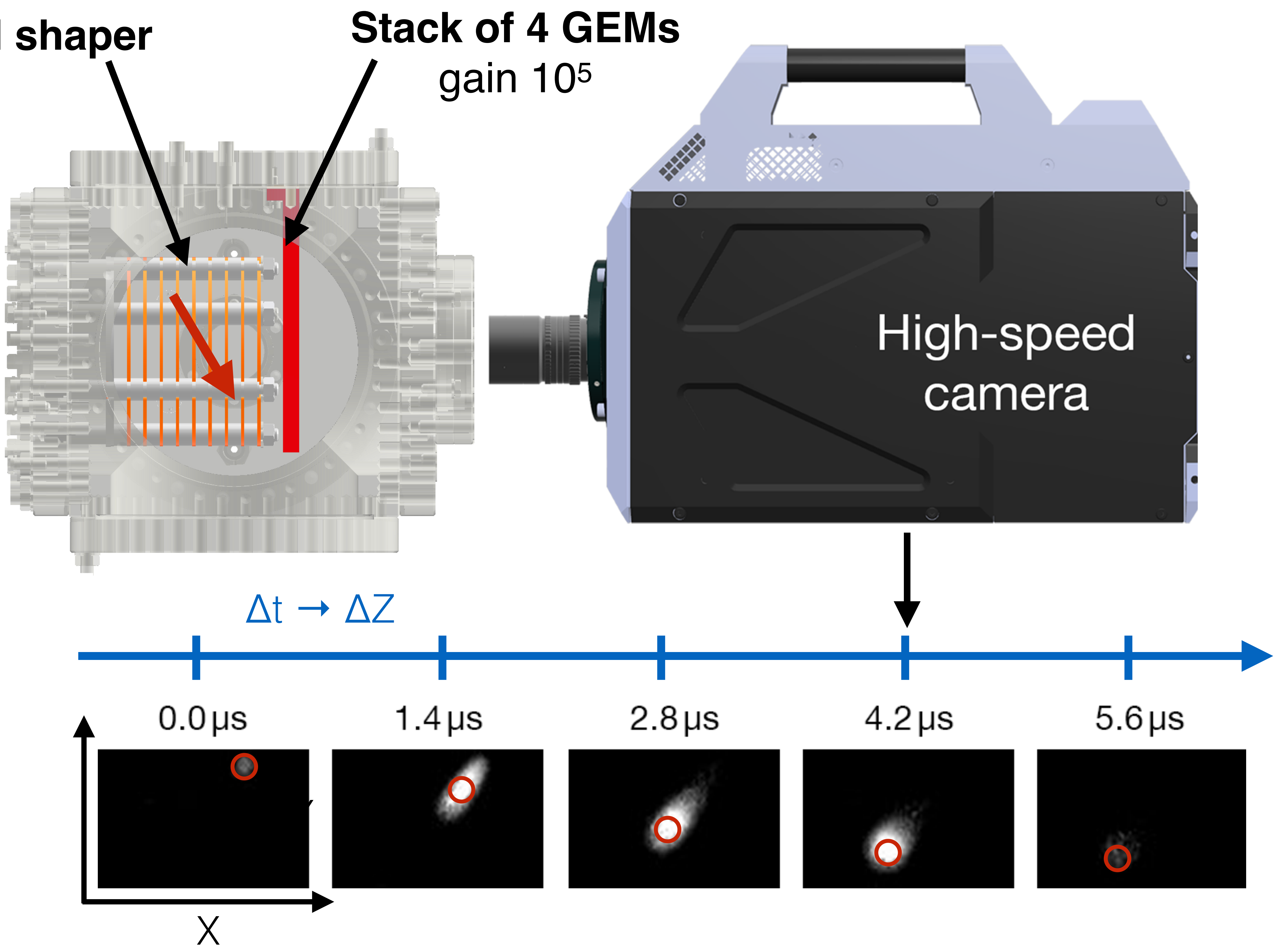
Optically read out TPC Ultra-fast CMOS



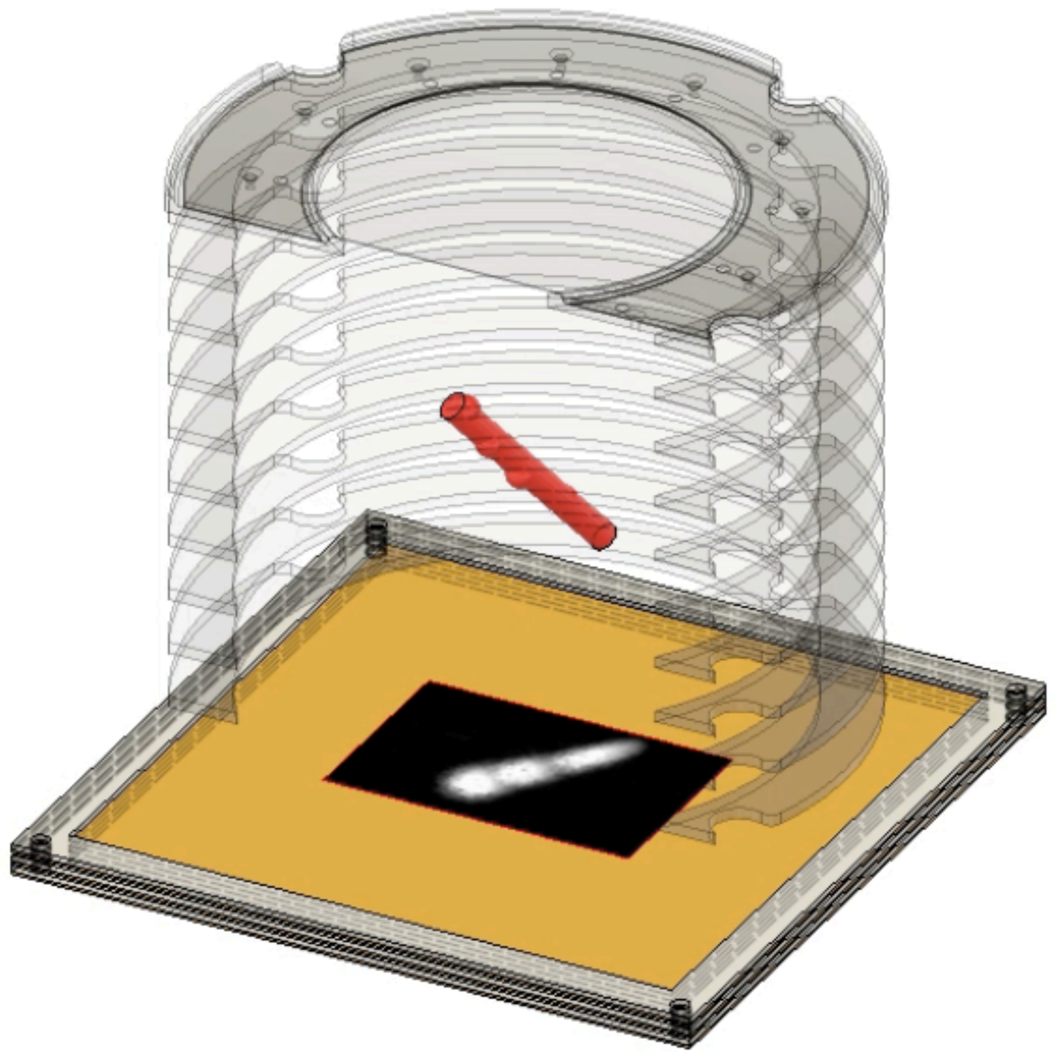
F. M. Brunbauer et al., IEEE NSS 2018

Schematics not drawn to scale

Optically read out TPC Ultra-fast CMOS



Recorded with 10 V/cm drift field corresponding to ≈0.5 cm/μs in Ar/CF_4



3D alpha track reconstruction (schematic)

Schematics not drawn to scale

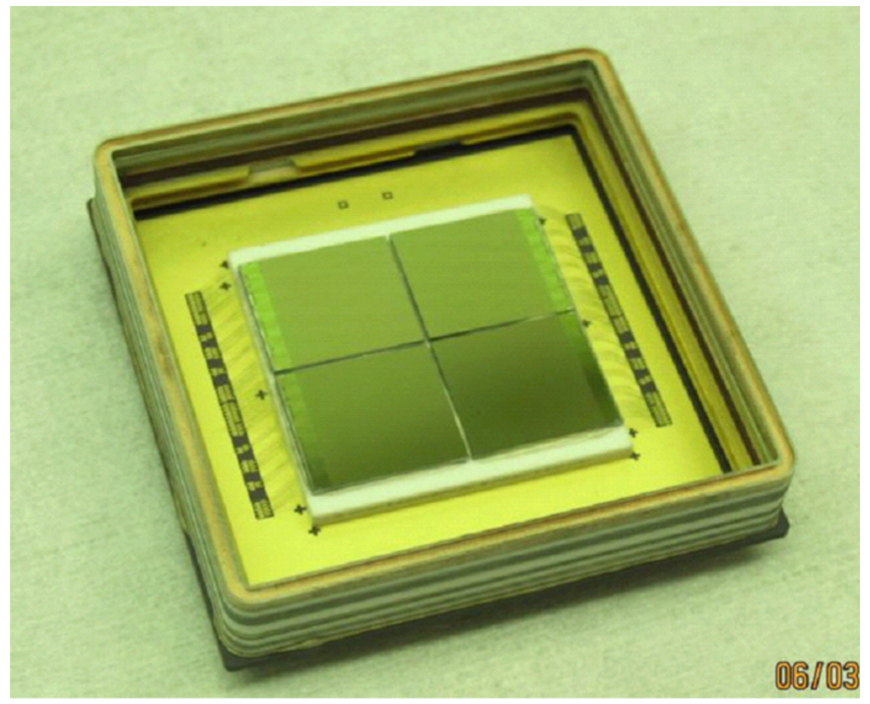
Readout approaches

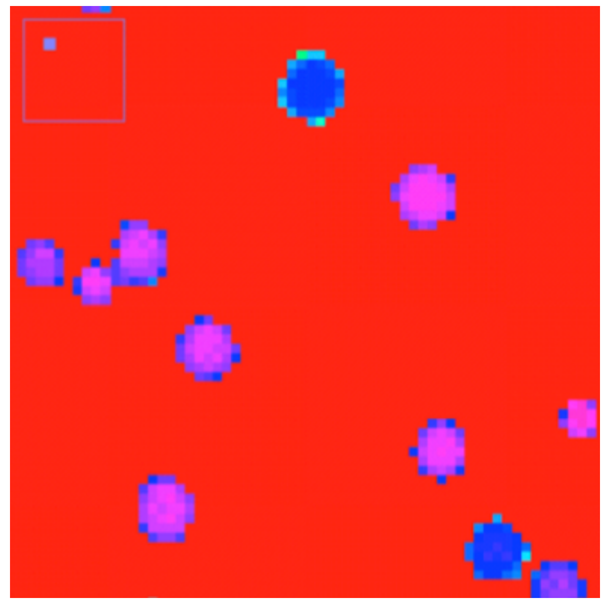
Hybrid readout and readout ASICs

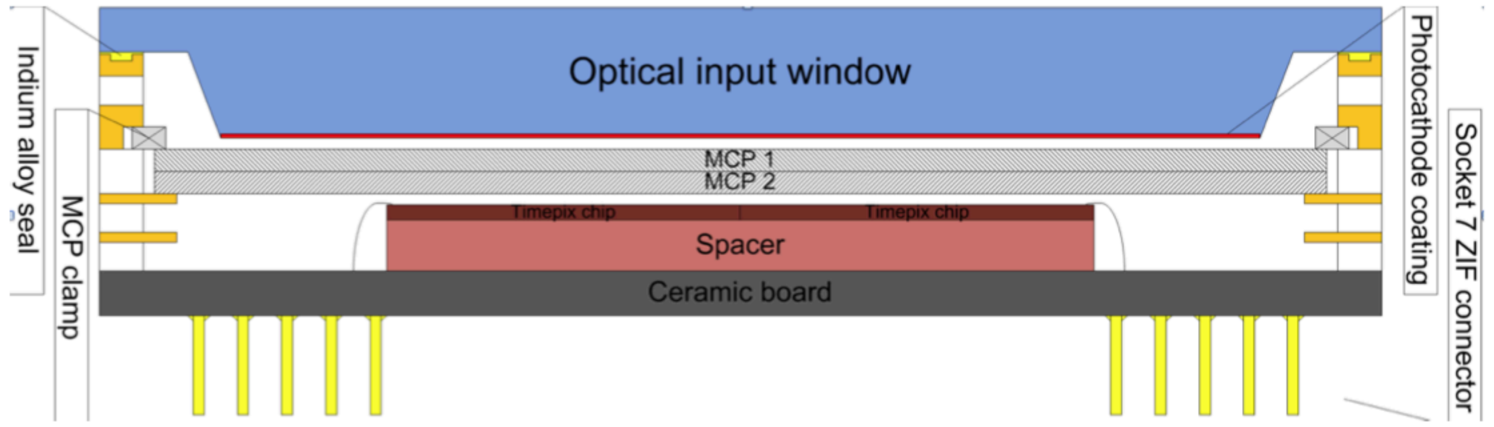
Timepix cameras

Timepix array with MCP and bi-alkali photocathode

Event counting with threshold or time of arrival recording





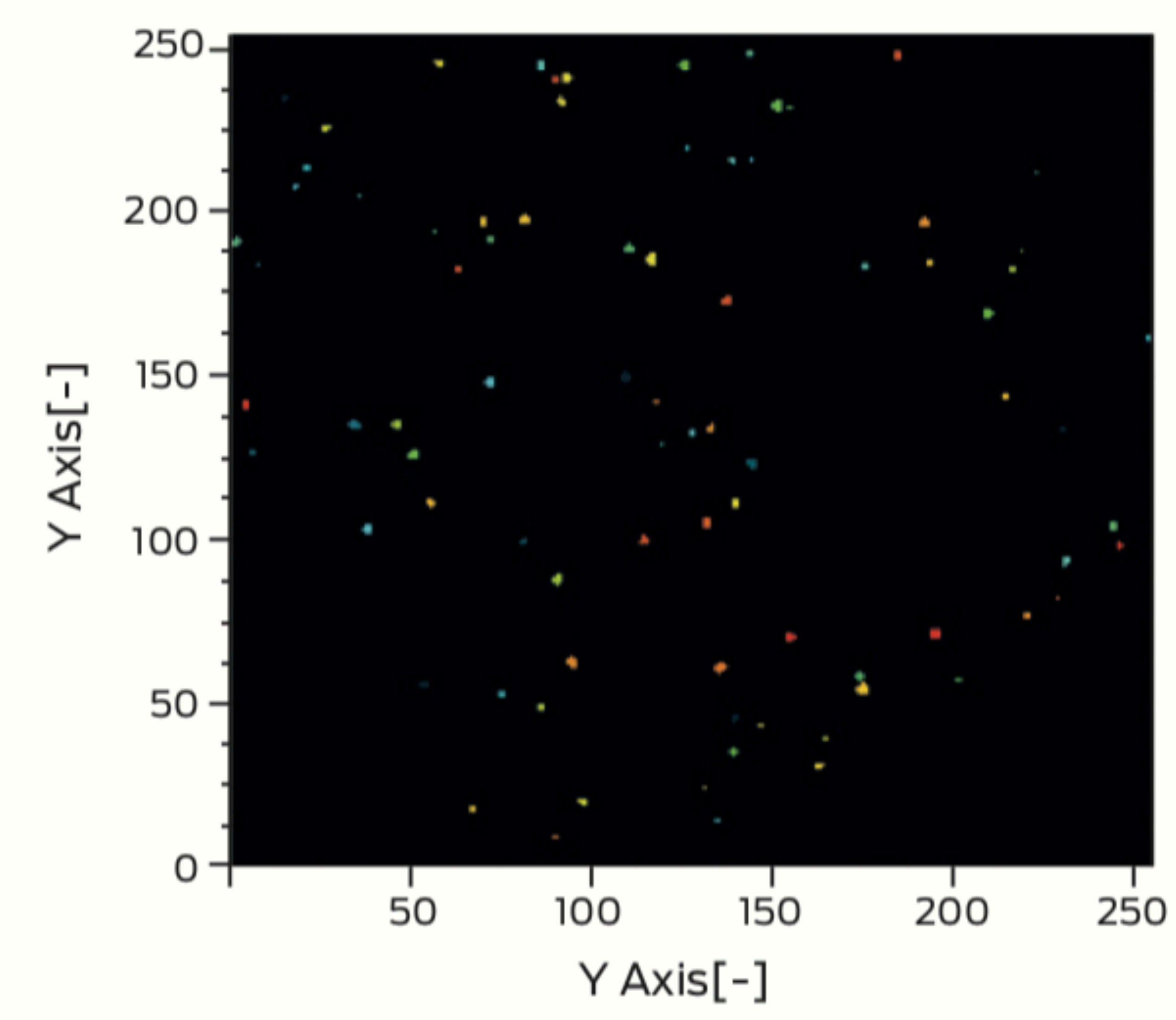


J Vallerga et al 2014 JINST 9 C05055

Timepix3 based optical camera with image intensifier

1.6ns timestamp resolution of single photon hits
Up to 80 Mhits/s rate

Commercially available

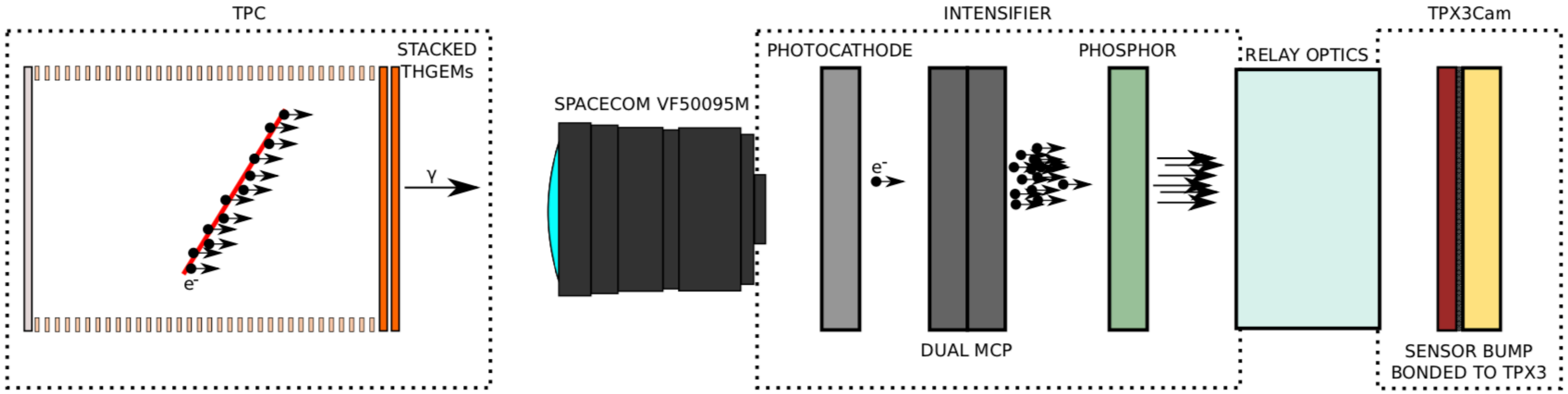


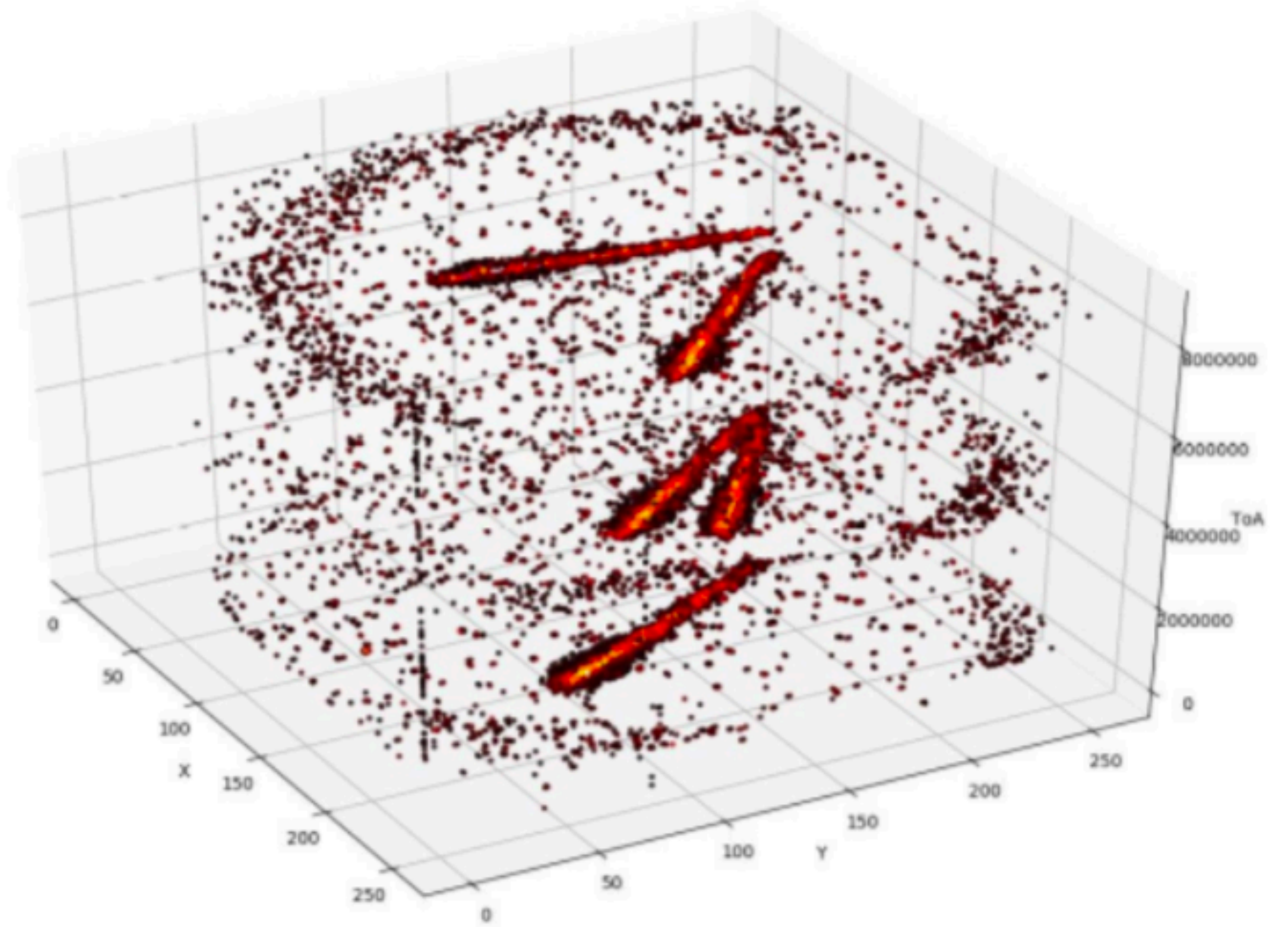
https://www.photonis.com/products/mantis3

Timepix cameras

Image-intensified single-photon sensitive **Timepix3** camera provides time information with 1.6ns timestamp resolution at a resolution of 256 x 256 pixels.

3D track reconstruction for alpha particles and cosmics has been demonstrated in low pressure CF_4 with a double THGEM as amplification structure.



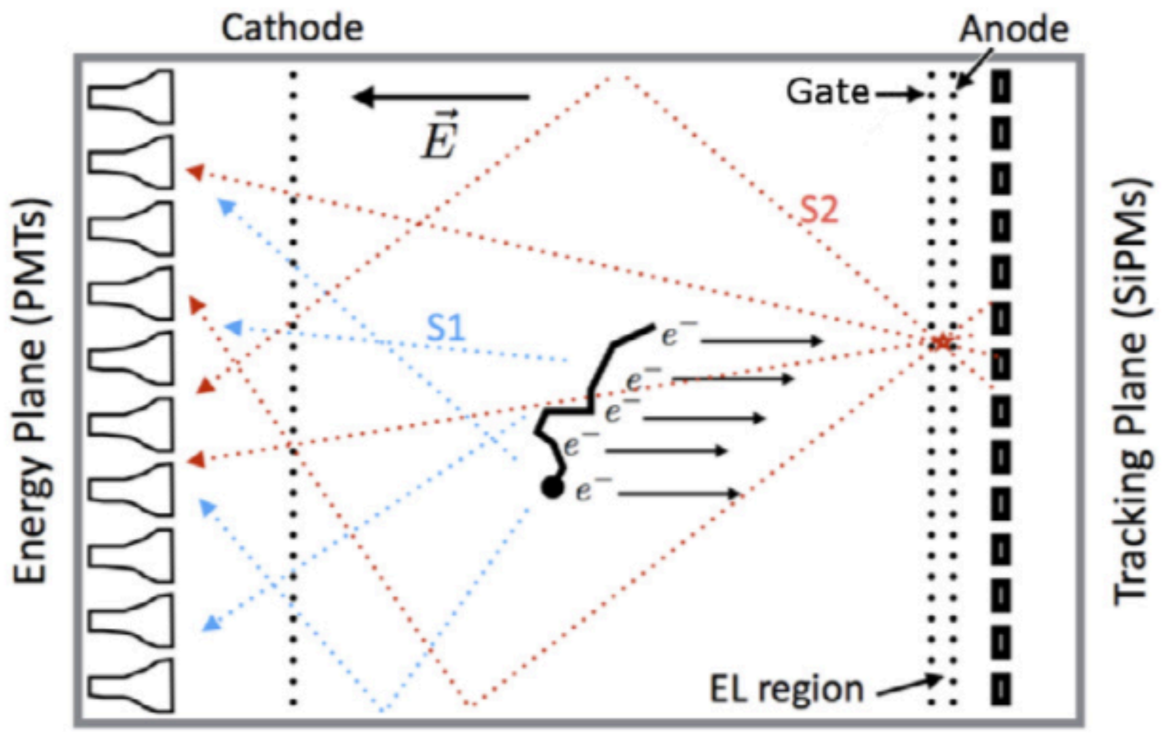


A. Roberts, ARIADNE, arXiv:1810.09955v3

SiPMs, LG-SiPMs

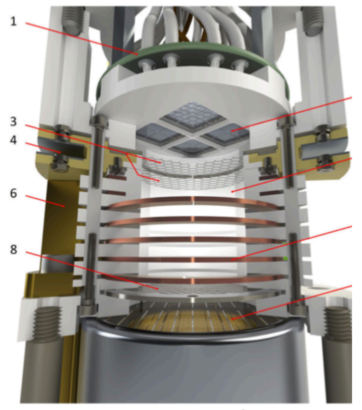
SiPMs

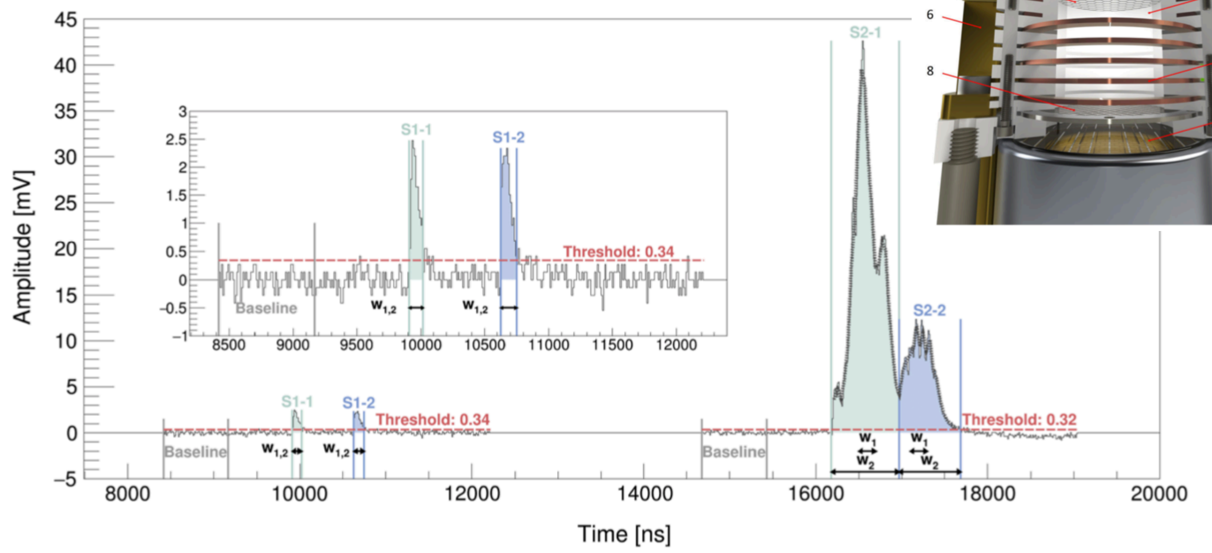
Time-slices of SiPM signals used to reconstruct hit locations as function of time



NEXT TPC concept
SiPMs for tracking plane

Dual-phase xenon
Xurich II TPC



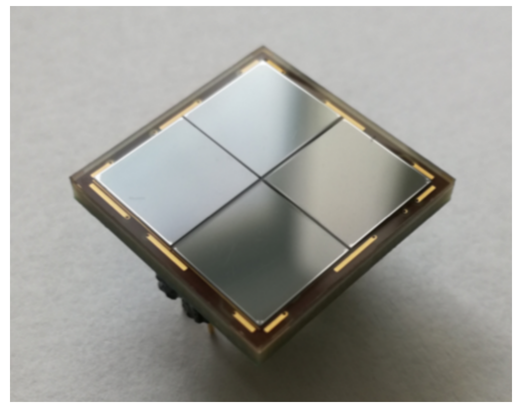


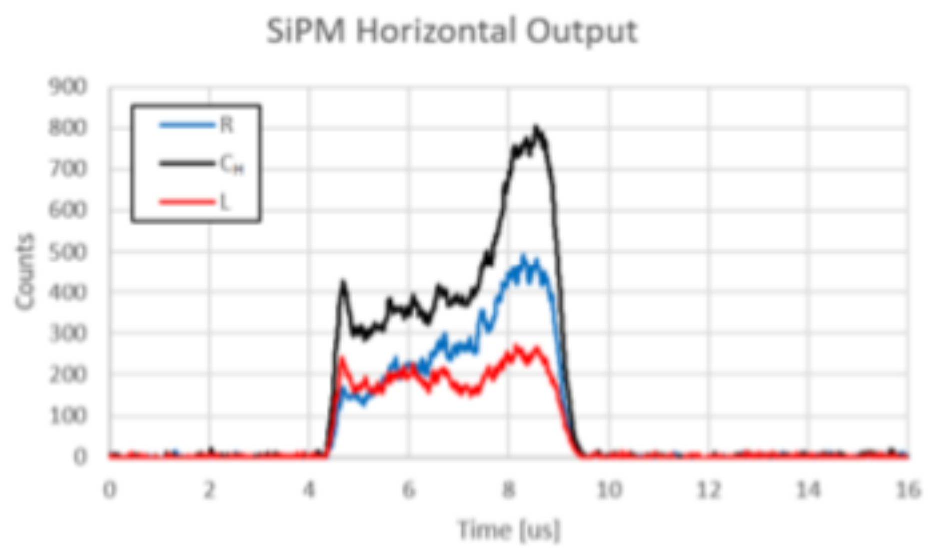
L. Arazi and NEXT collaboration, collaboration, NIM A 958 (2020) 162126

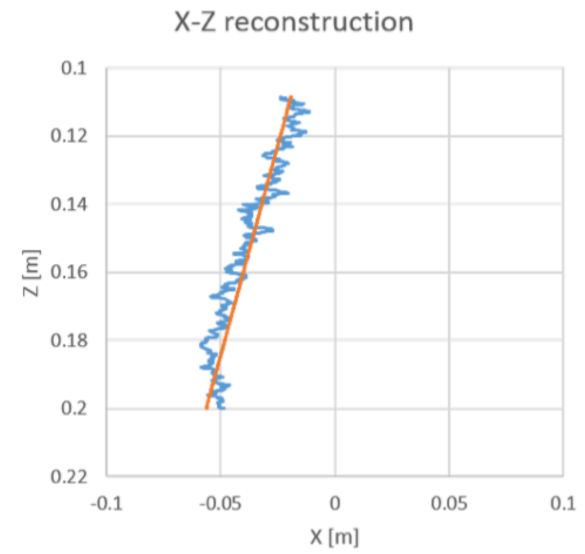
L. Baudis et al, https://doi.org/10.1140/epjc/s10052-020-8031-6

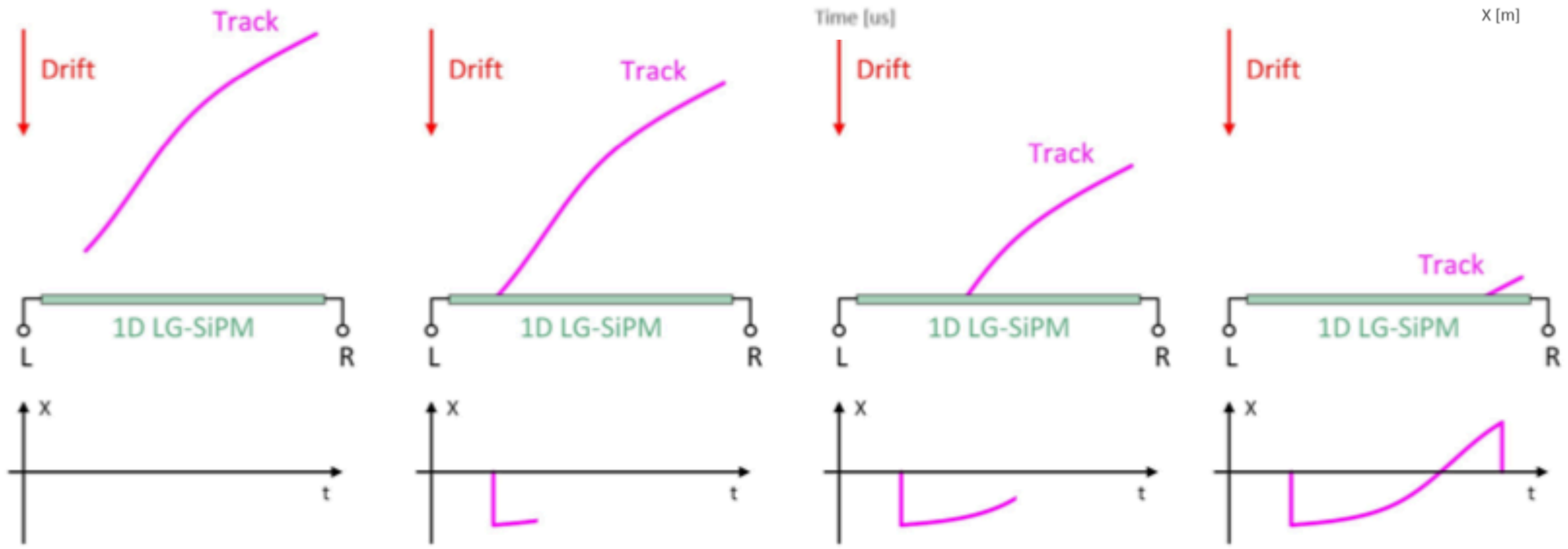
Linearly-graded SiPMs

Time-varying voltage signals are read out by multiple readout channels and ratios are used to determine position at a given time.







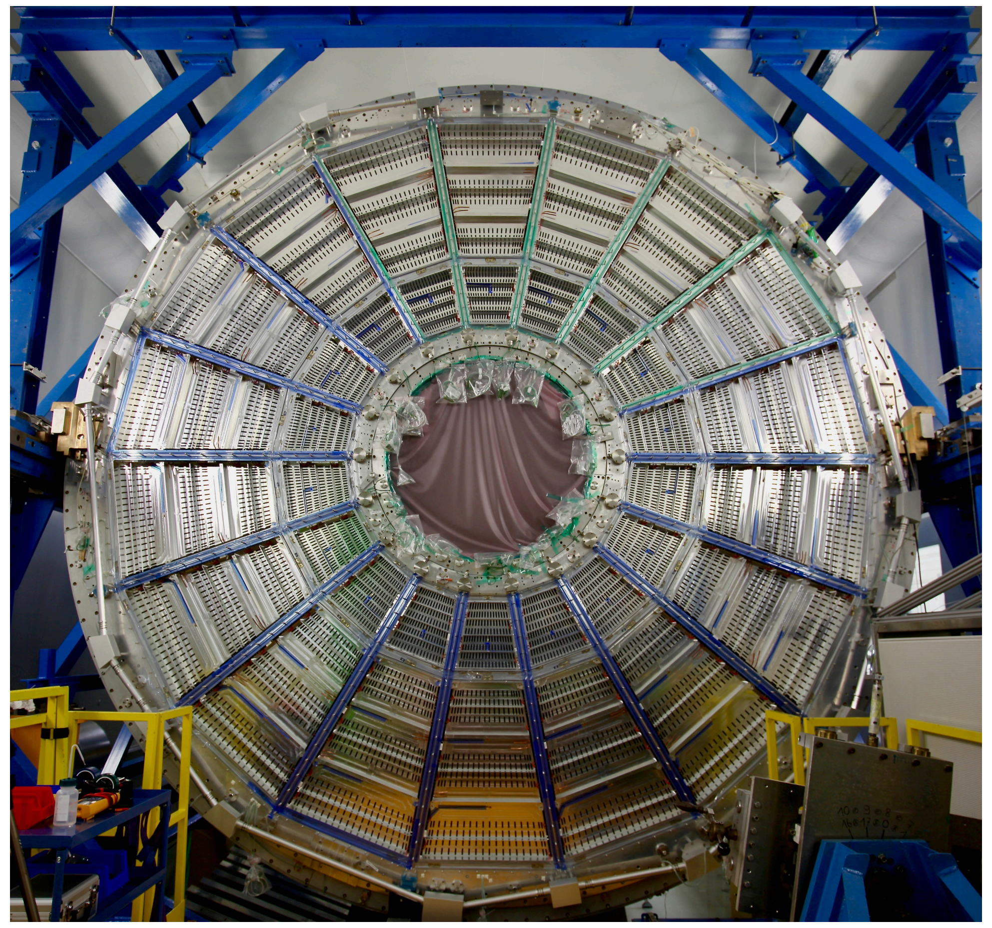


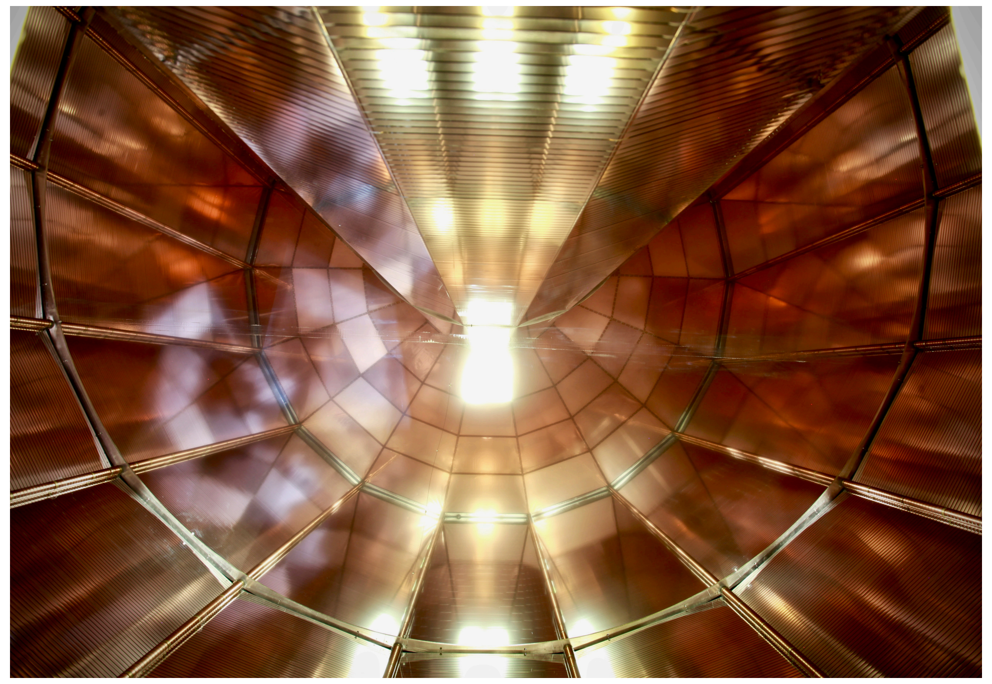
A. Gola et al, arXiv:2009.05086 [physics.ins-det]

Applications

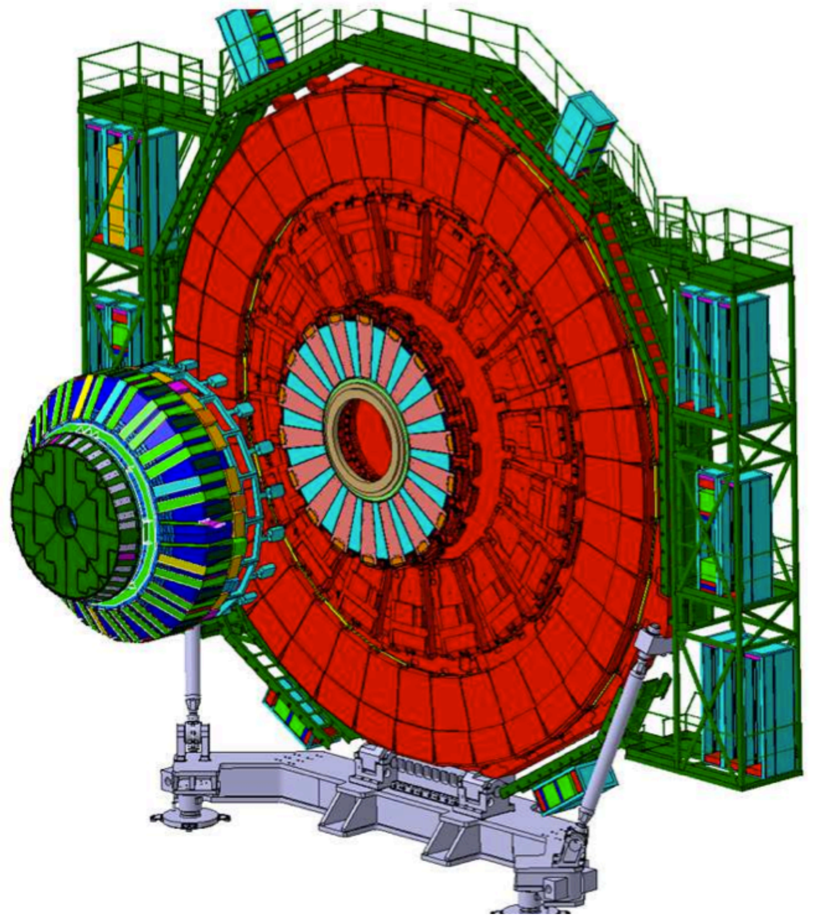
High-energy physics applications at LHC

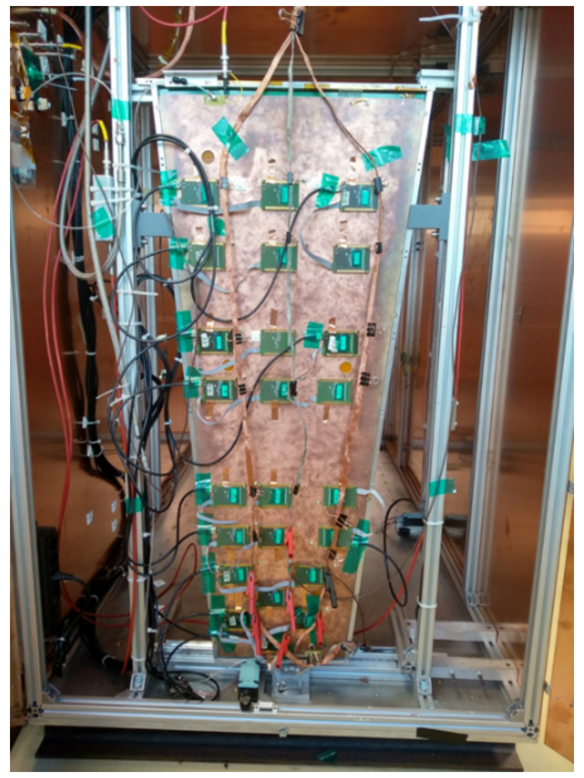
ALICE TPC
GEM upgrade



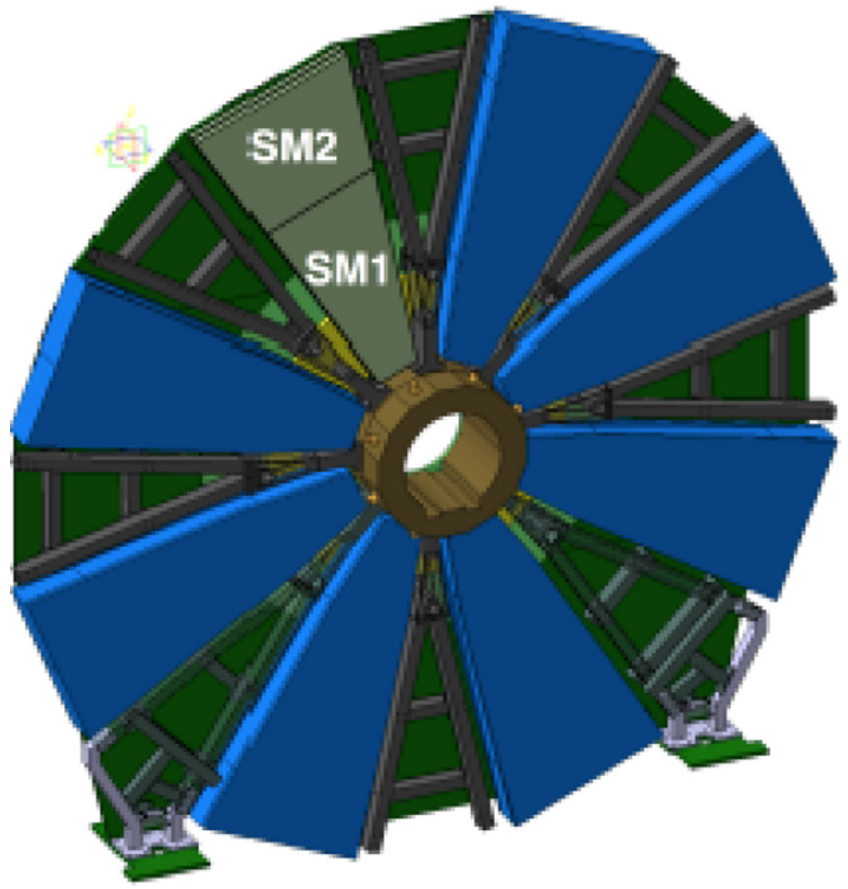


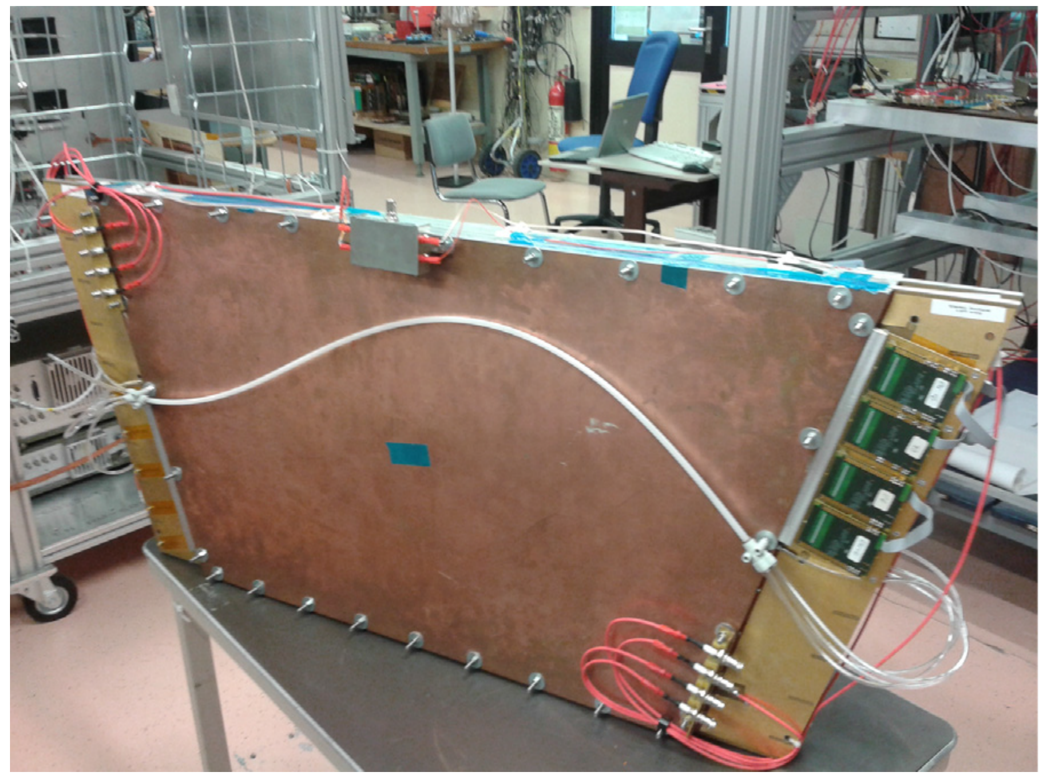
CMS Muon system
GEM upgrade



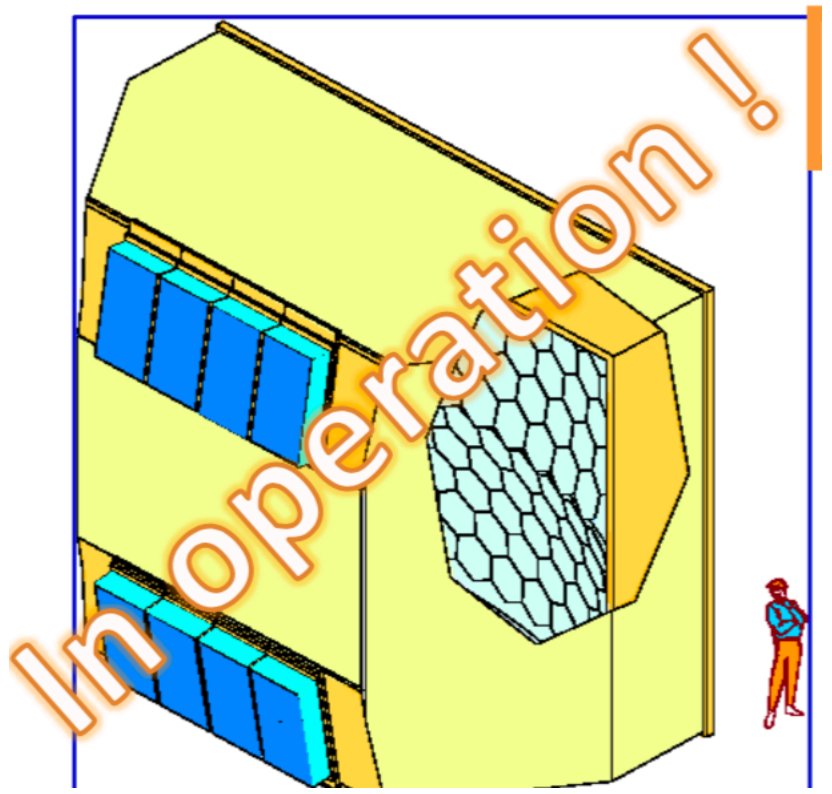


ATLAS NSW
Micromegas upgrade





COMPASS RICH
THGEM + Micromegas

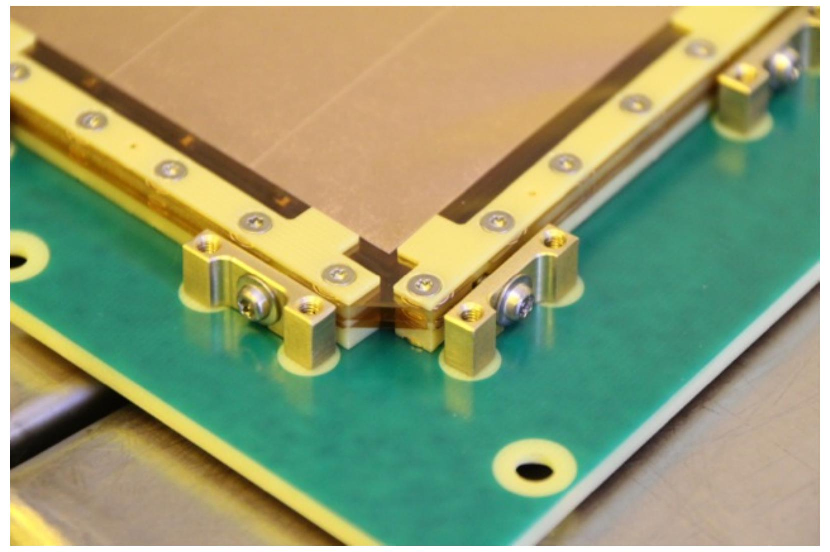


MPGD for experiments

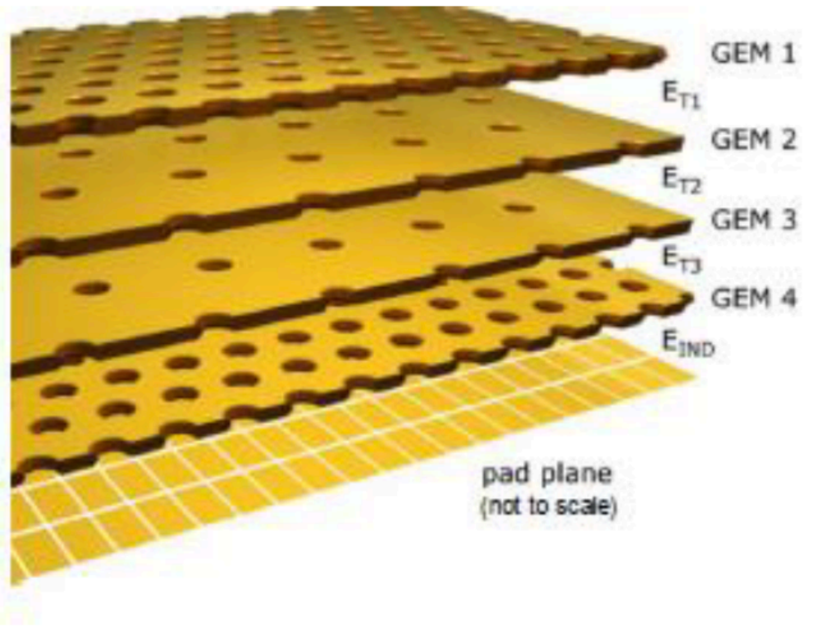
Major progress in the MPGD technologies development in particular large area GEM (single mask), MicroMegas (resistive), THGEM; some picked up by experiments (including LHC upgrades);

- ALICE, TPC read-out, ~ 500 m2 of GEM foils
- ATLAS, small wheels, 1200 m2 to be instrumented
- CMS, GE1/1 forward detectors, 250 m2 of GEM foils
- COMPASS RICH, 4.5 m2 to be instrumented, single photon detection

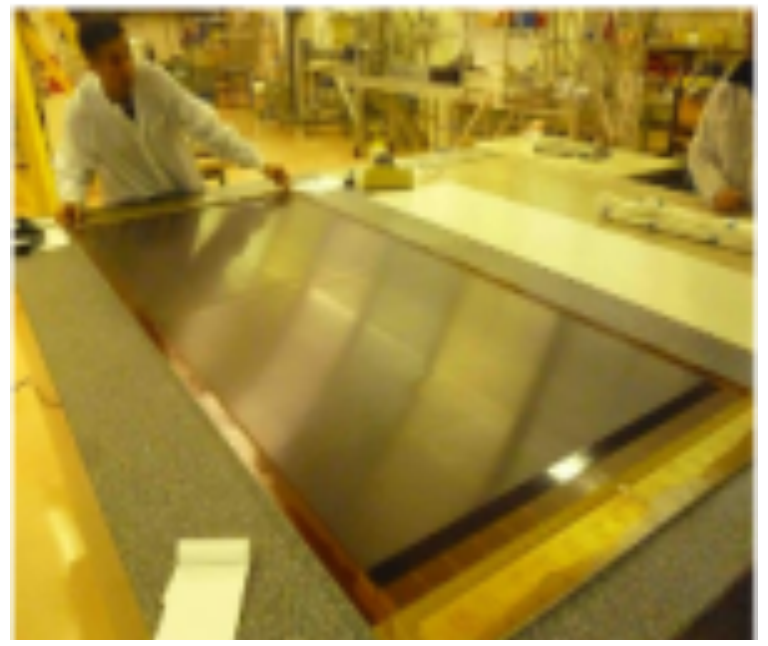
Single mask GEMs and NoStretch-NoSpacer mounting (CMS GEM)



Minimisation of ion back flow with quad-GEM (ALICE TPC)



Large area **resistive Micromegas** (ATLAS NSW)

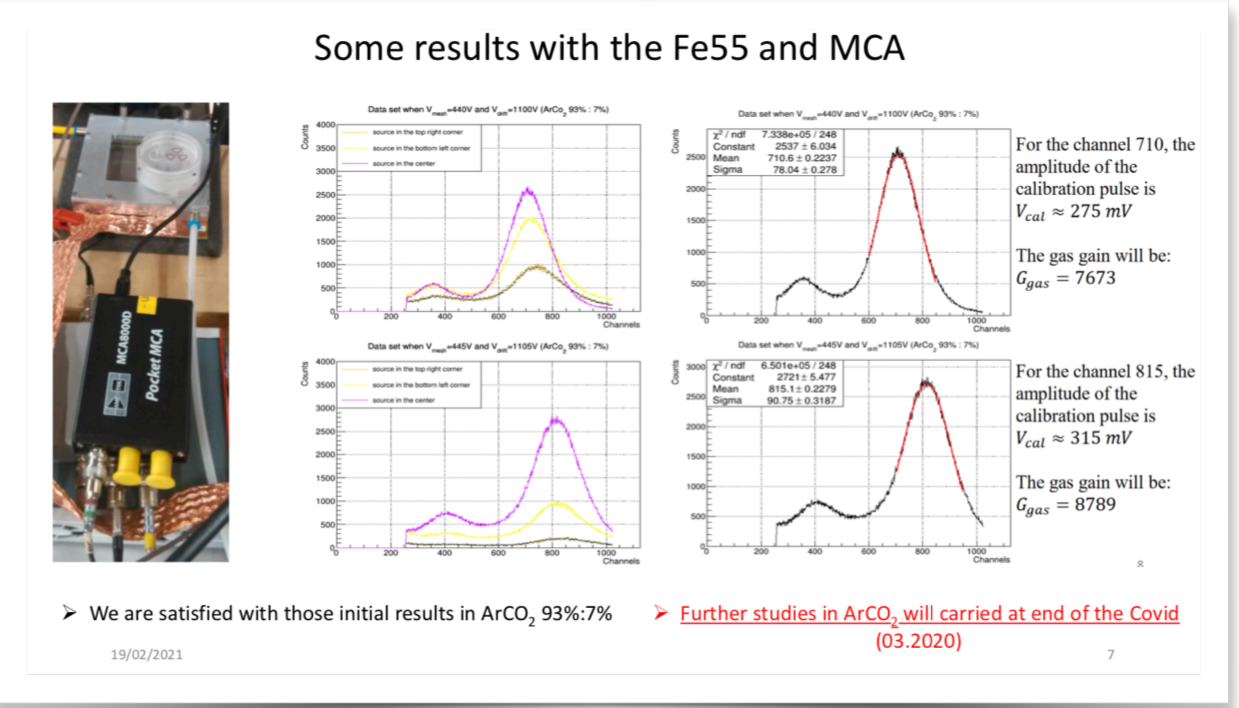


DLC
Large-area resistive foils

https://indico.cern.ch/event/843711/contributions/3607904/attachments/1931757/3199683/RD_progress_of_the_resistive_DLC.pdf

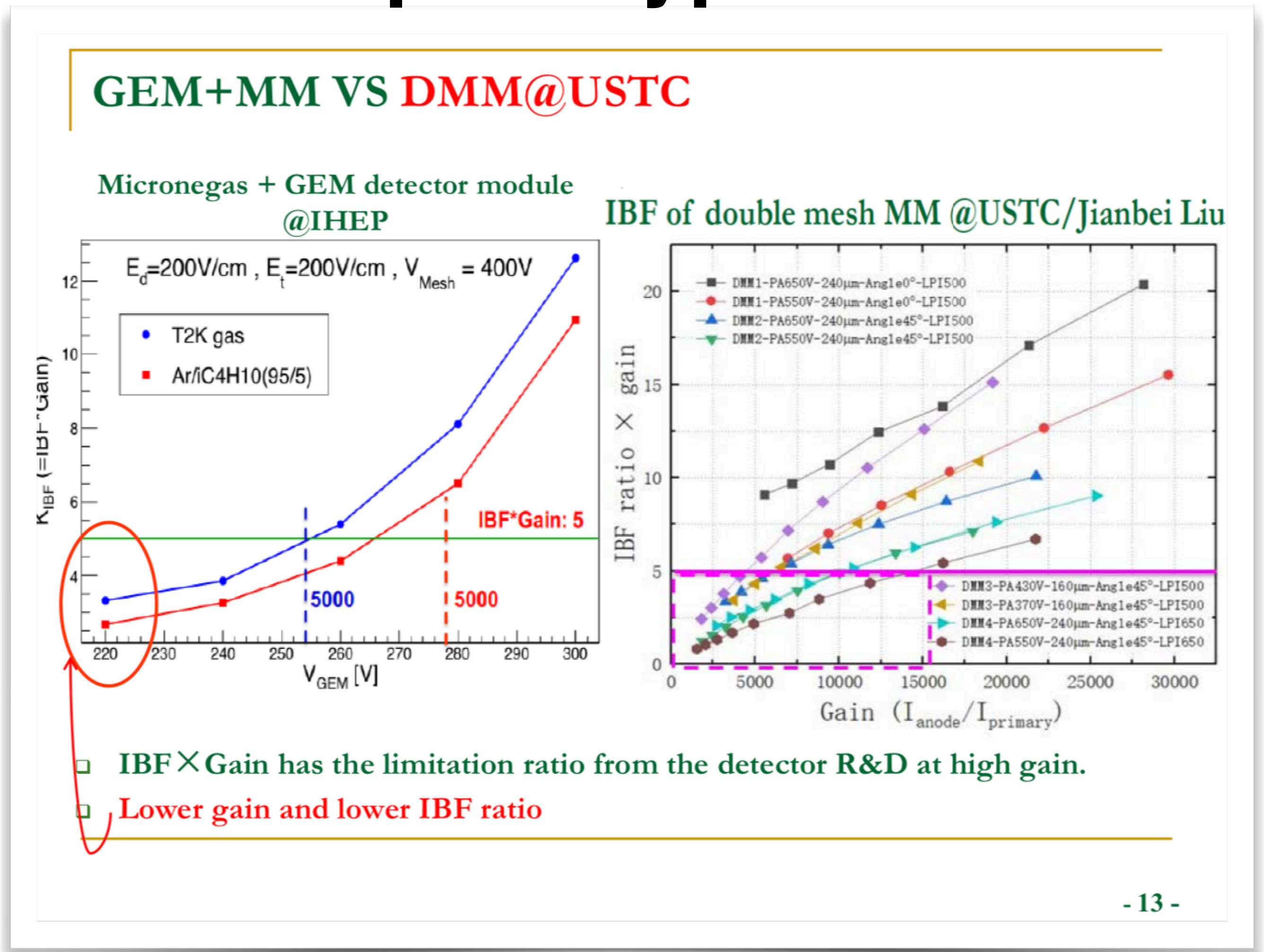
Beyond LHC & new proposals

MM prototyping & COMPASS++/ AMBER



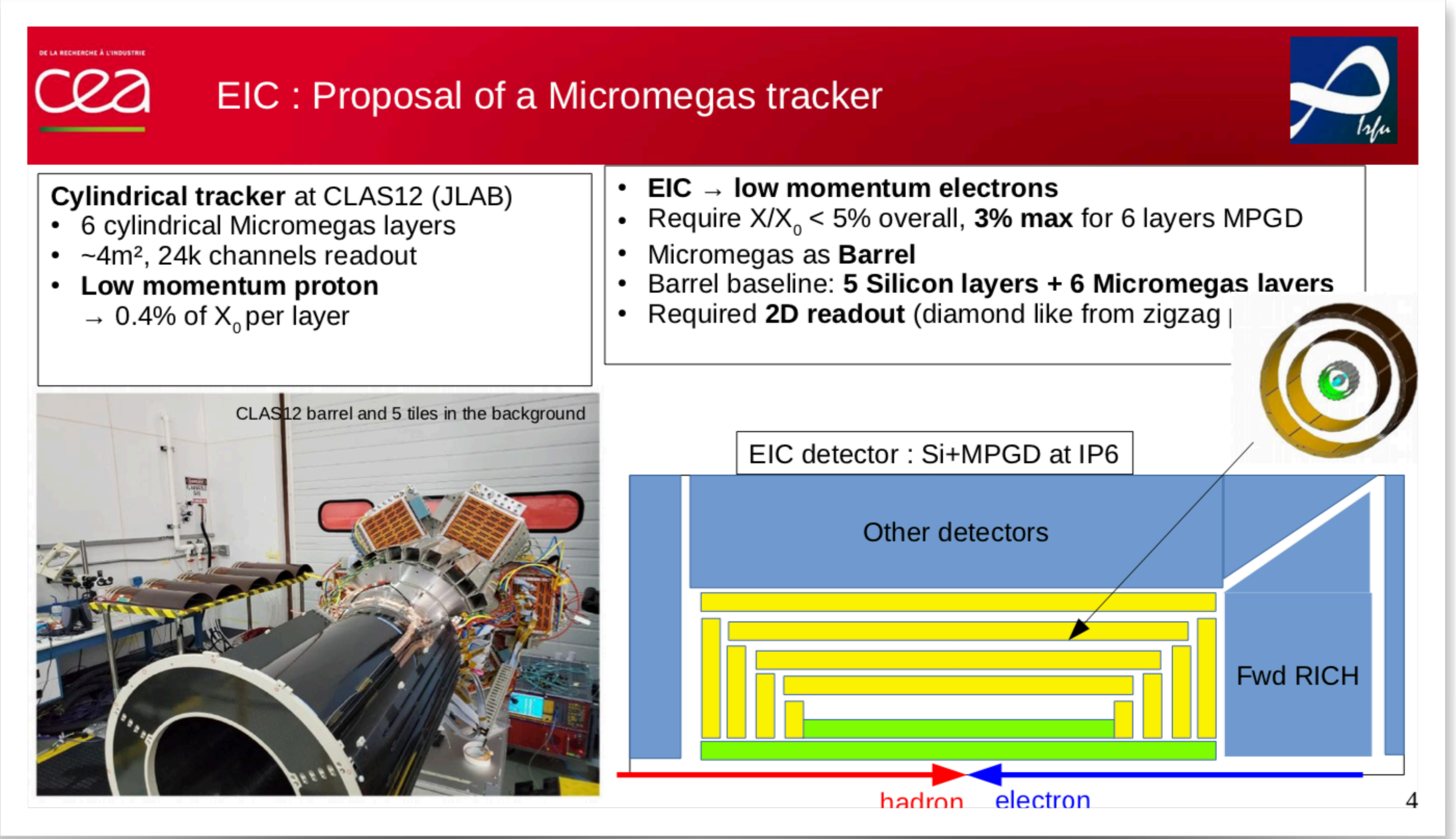
https://indico.cern.ch/event/989298/contributions/4228783/attachments/2193079/3707015/MM_prototyping_COMPASS_19_02_21.pdf

Status and requirements of CEPC TPC from IHEP : GEM / MM / DMM / GEM+MM prototypes



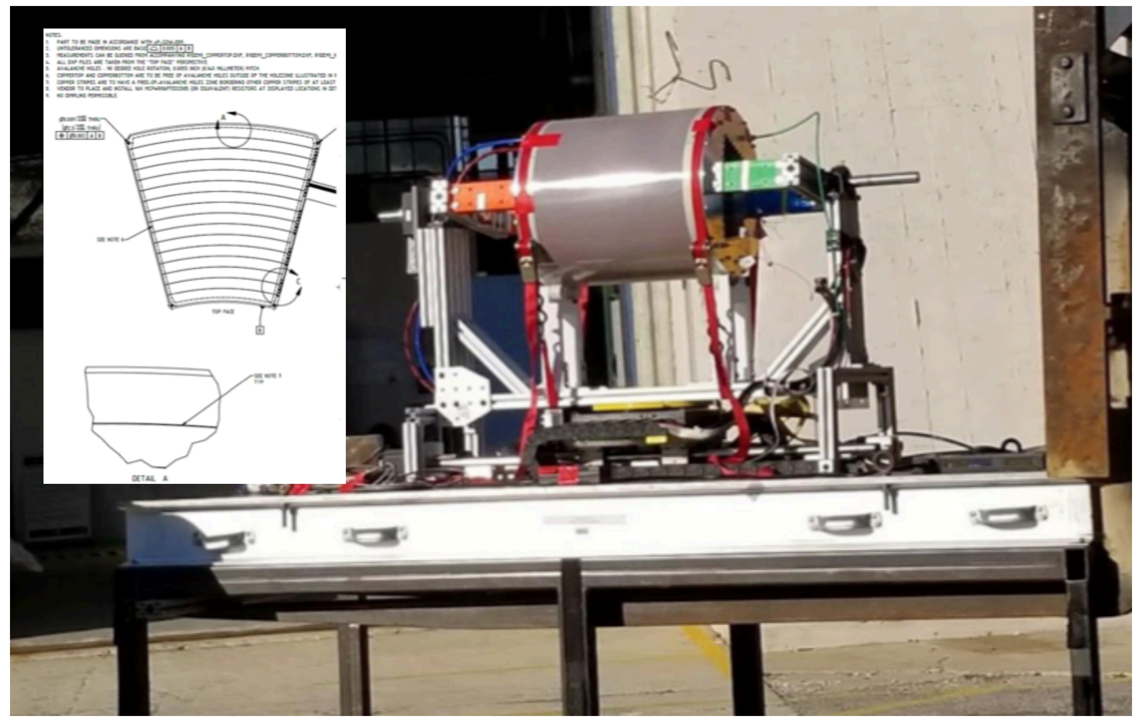
https://indico.cern.ch/event/889369/contributions/4051844/attachments/2116407/3561252/Huirong_CEPC_TPC_RD51_20201006.pdf

sPHENIX and EIC Micromegas tracker development



https://indico.cern.ch/event/1040996/contributions/4394627/attachments/2264192/3843929/sPHENIX_EIC_development_rd56_150621.pdf

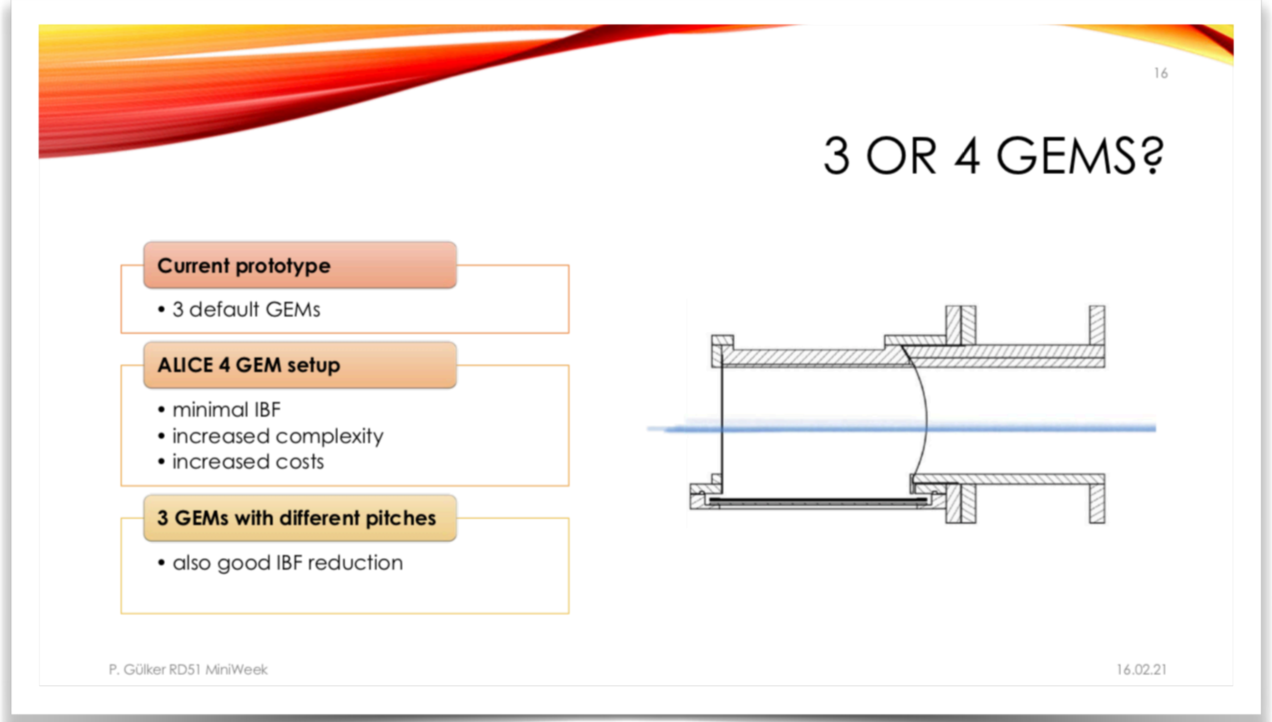
GEM production scheme for sPHENIX TPC

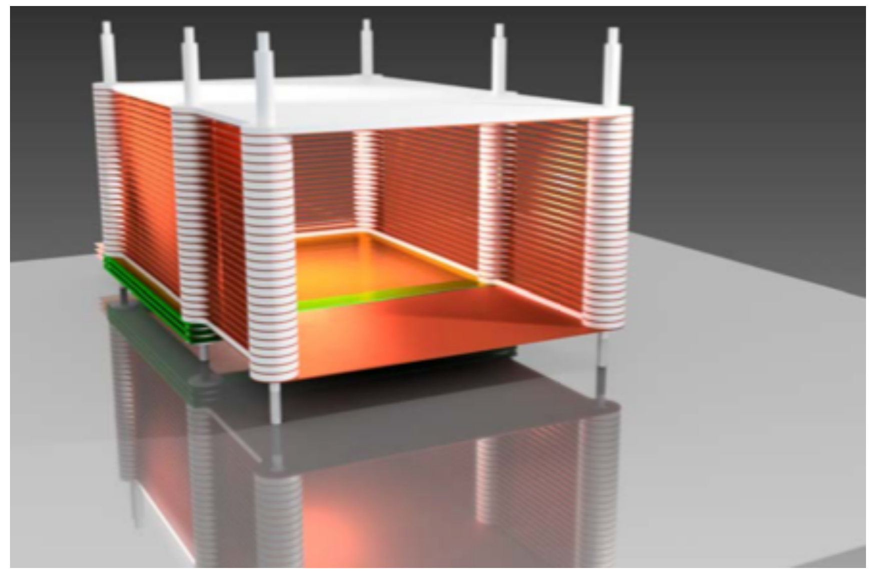


https://indico.cern.ch/event/889369/contributions/4042740/attachments/2119661/3567177/RD51_GEMproduction4sTPC.pdf

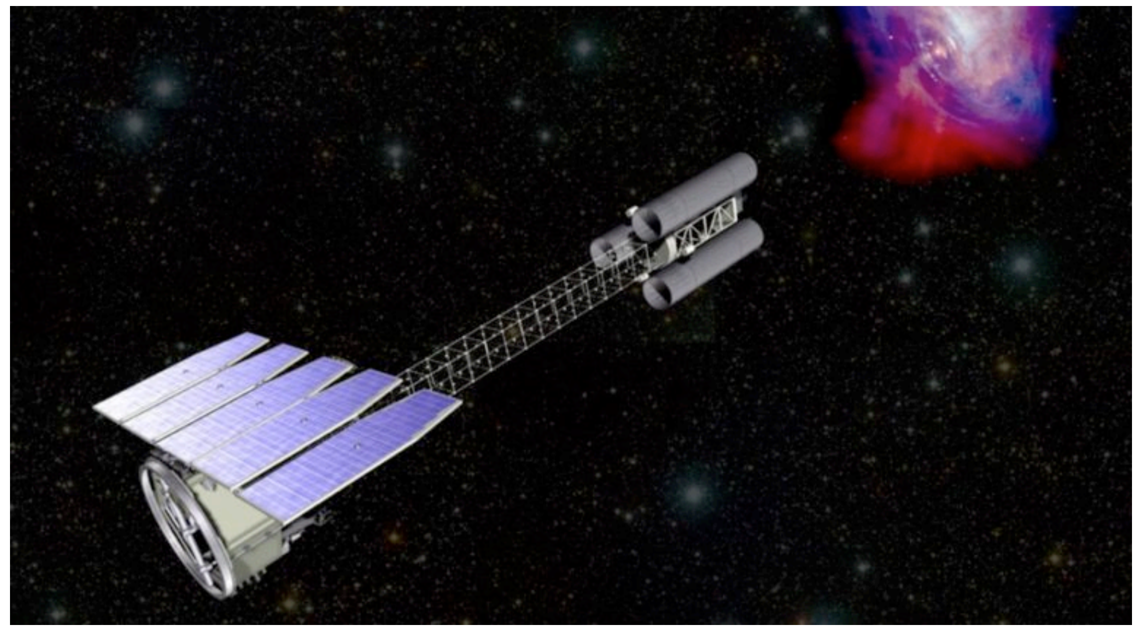
A NEW OPEN FIELD-CAGE TPC FOR THE MAGIX EXPERIMENT

https://indico.cern.ch/event/989298/contributions/4231415/attachments/2190534/3702180/miniweek_feb_2021_tpc_pepe_guelker_small.pdf





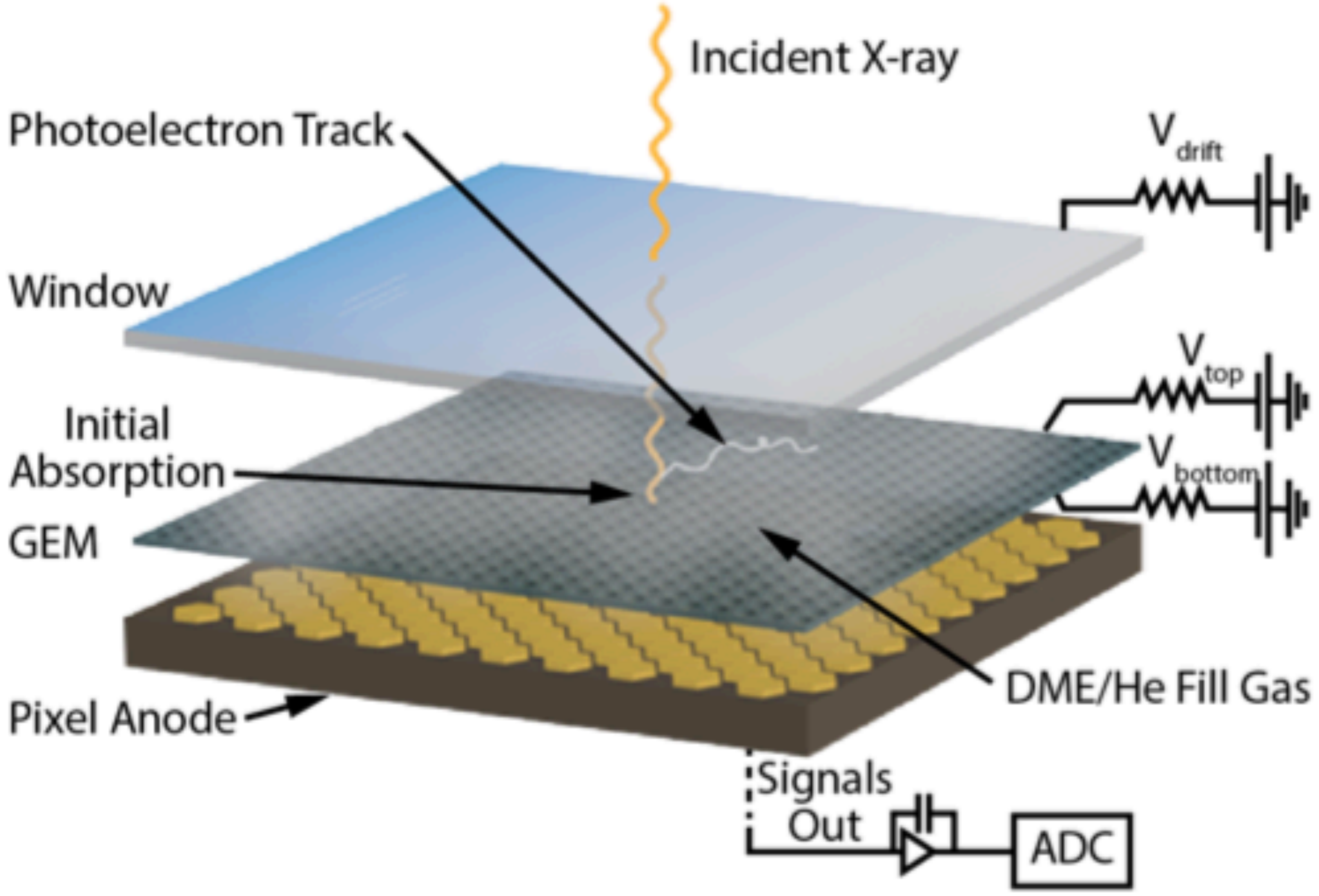
X-ray polarimetry



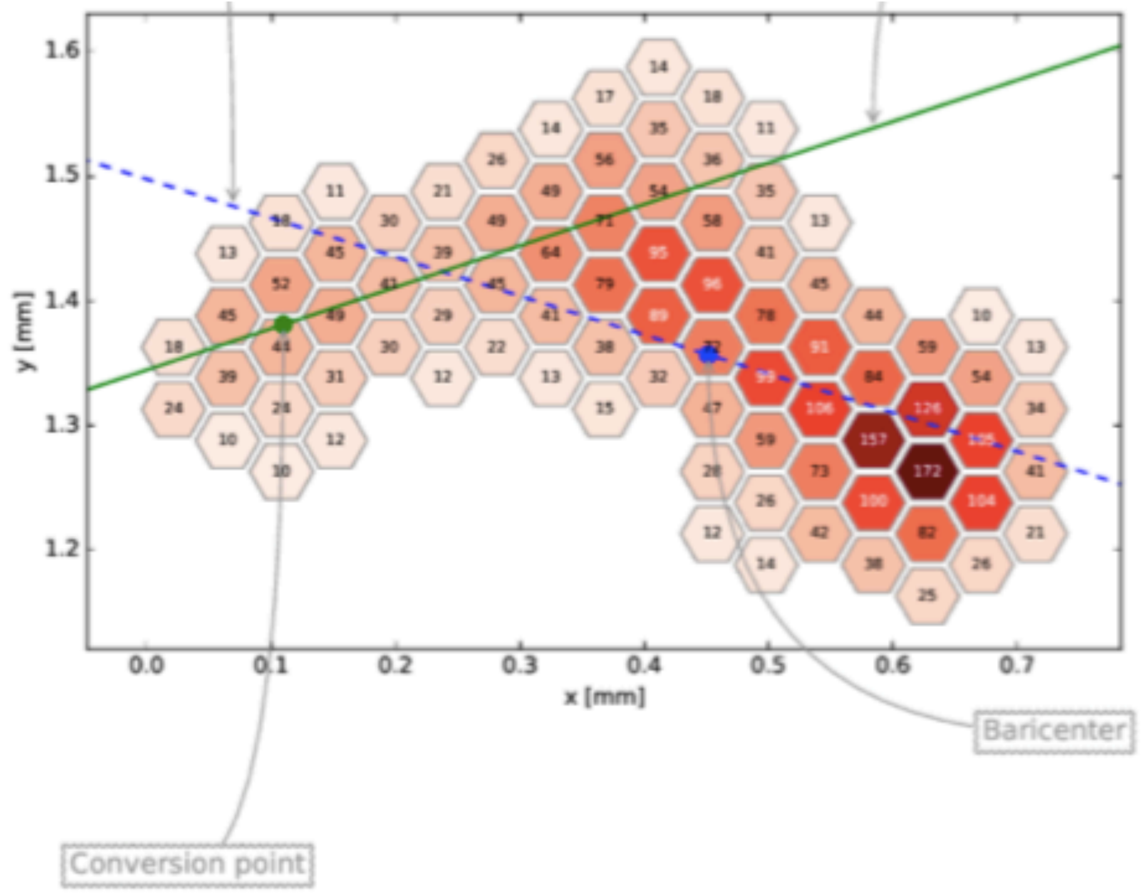
Gas Pixel Detector (GPD) for IXPE mission is based on a single GEM coupled to an ASIC as readout.

High spatial resolution is a key requirement leading to the adoption of a **50*μ*m pitch** hexagonal pattern for 30μm GEM holes as well as the readout pixels anode.

For **low outgassing**, support structures are made of ceramic. Liquid crystal polymer (LCP) used as insulator for GEM.



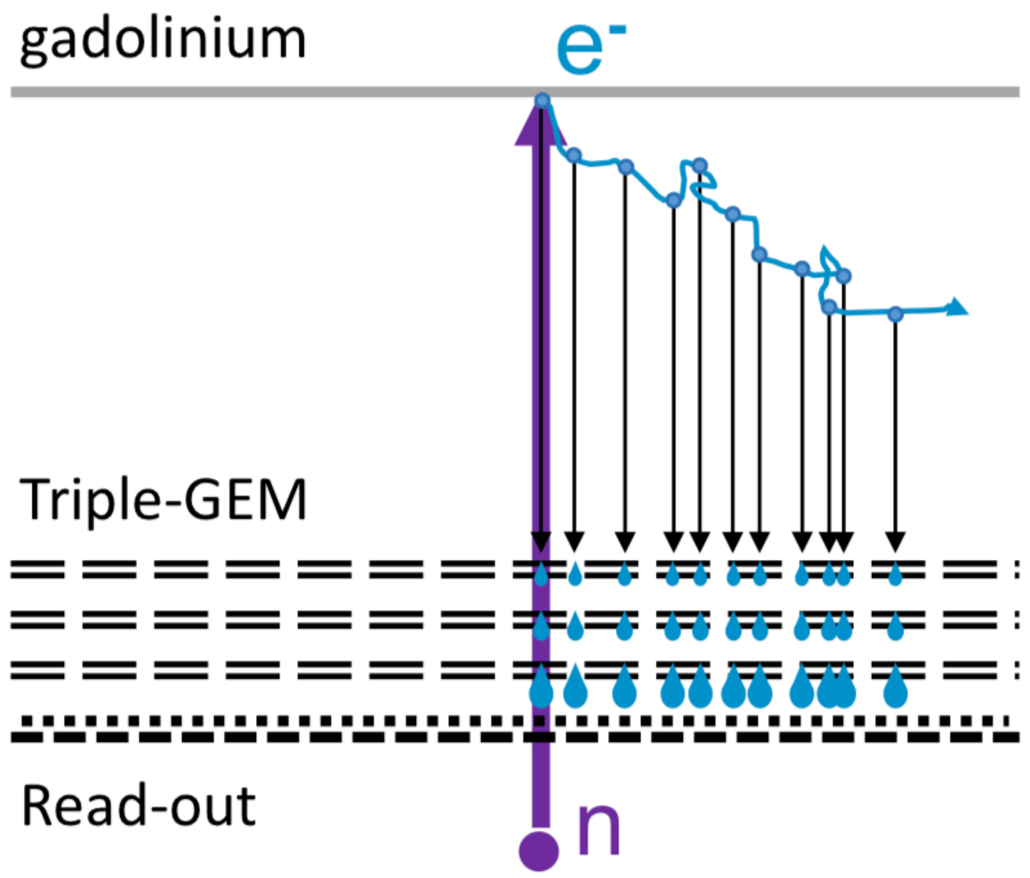
- Active area of 15x15 mm² with 300x352 hexagonal pads.
- Spatial resolution: **90*μ*m at 5.9keV**
- Energy resolution: <20% at 5.9keV
- Modulation factor: 20% (2 keV) to 70% (8 keV)
- Timing resolution: ≈ 10μs
- DME/He (80/20) gas mixture at 1bar

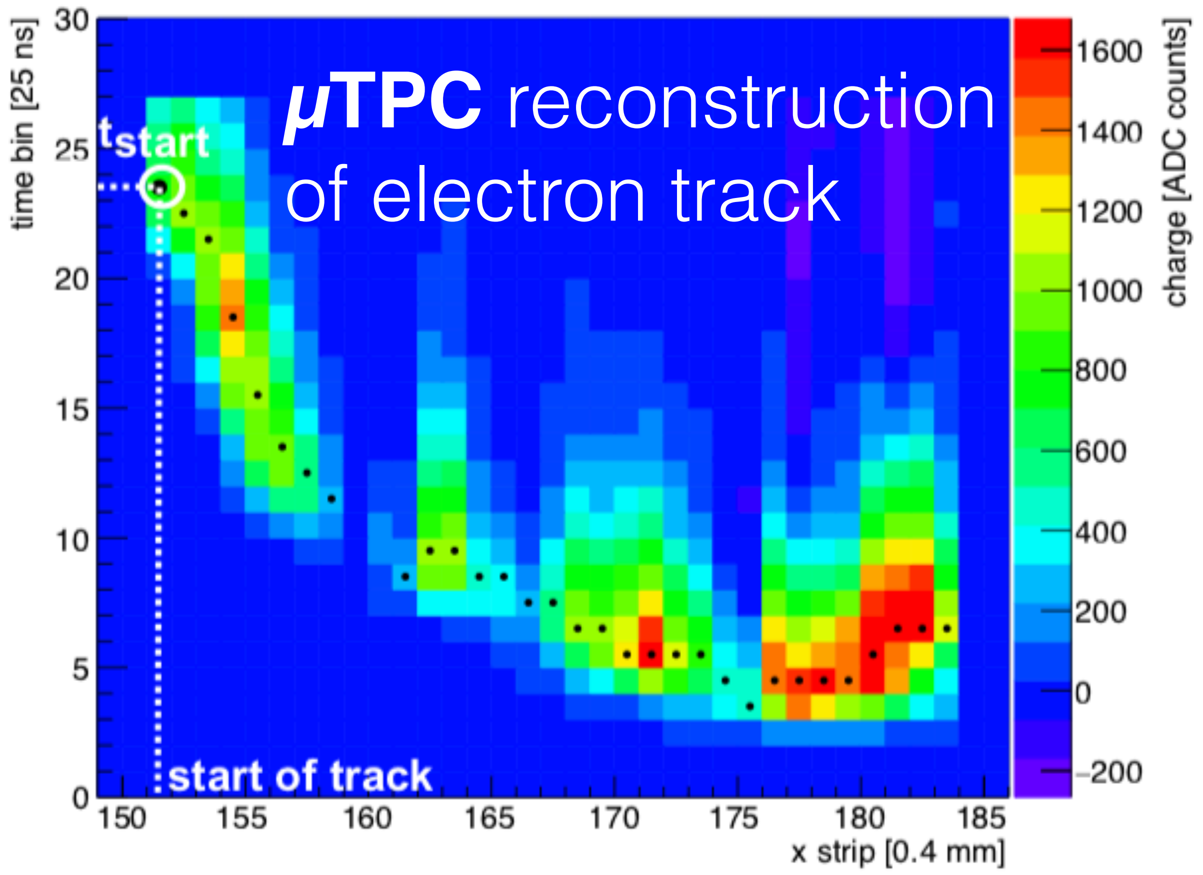


Carmelo Sgro for the IXPE team, The Gas Pixel Detector on board the IXPE mission
https://ixpe.msfc.nasa.gov/for_scientists/papers/2017spie_0829_sgro.pdf

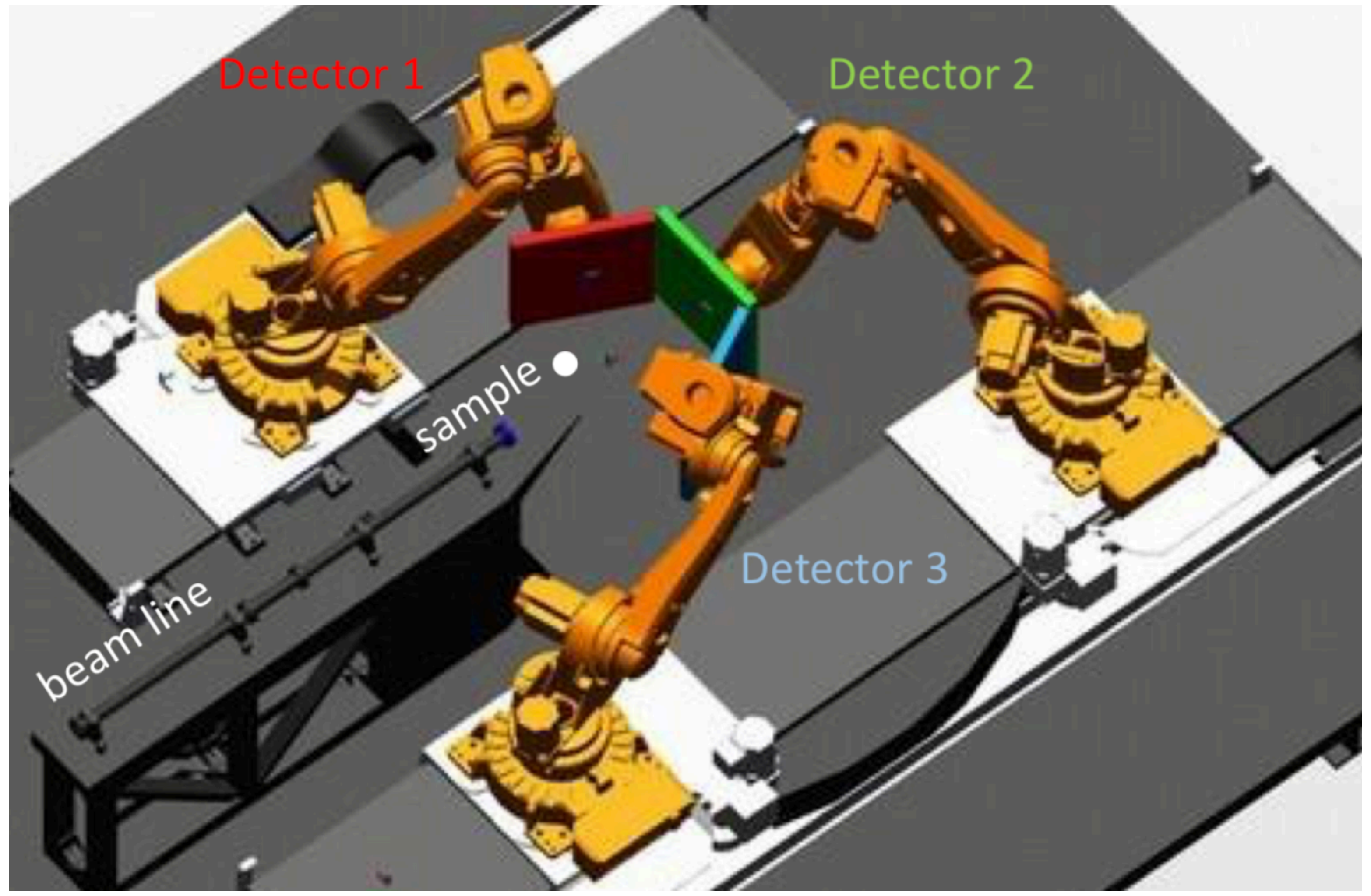
GEM-based neutron detector with Gd converter

Neutron macromolecular diffractometer (NMX): structure determination of biological macromolecules, locating hydrogen atoms relevant for function of macromolecules
Detector requirements: **high rate capability**, **high detection efficiency**, **good spatial resolution**, good time resolution, **radiation hardness**
µTPC readout with VMM3: **O(200µm) spatial resolution, O(ns) time resolution**
≈12% neutron detection efficiency with Gd-GEM (at 2Å)





3 modules mounted on robotic arms:
No fixed detector geometry



Detector Positioning System for ESS NMX, Final Design Report, J.-L. Ferrer

M. Lupberger, P. Thuiner et al. DT Training Seminar – CERN – 2018/02/15 M. Lupberger, P. Thuiner 10
https://indico.cern.ch/event/673355/attachments/1601054/2538407/20180215DTtrainingSeminarLupbergerThuiner.pdf
D. Pfeiffer et al, 2016 JINST 11 P05011

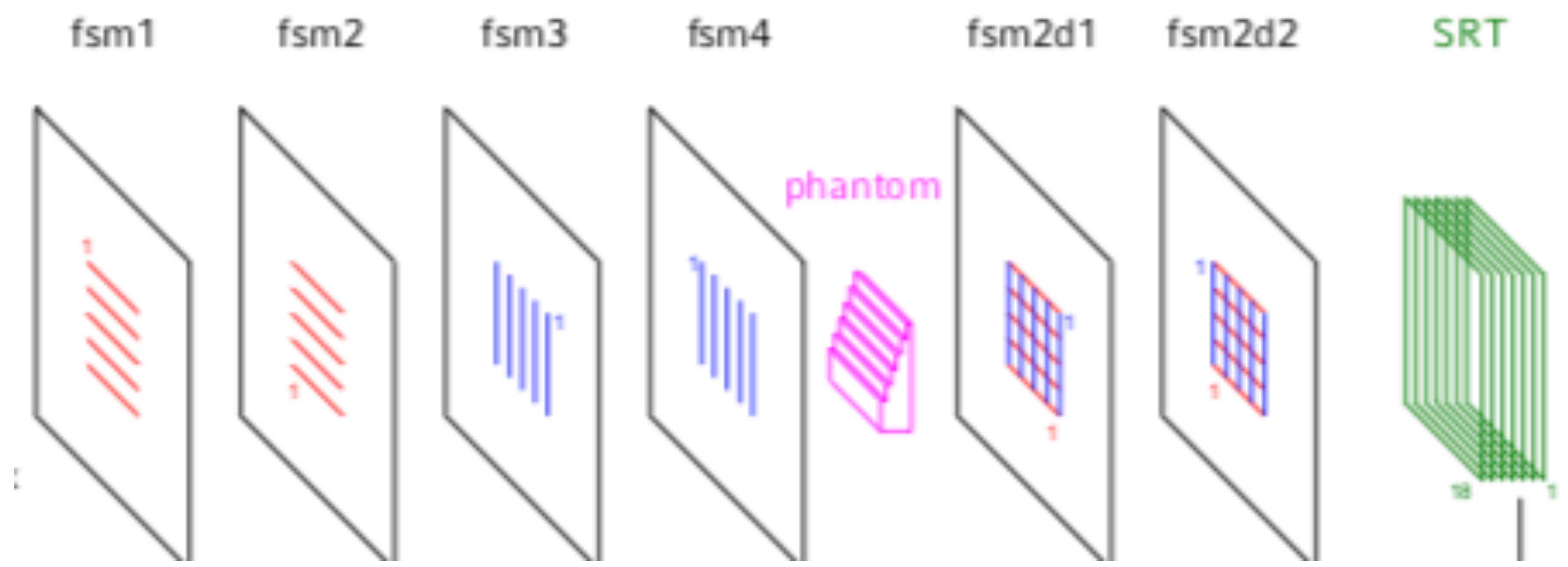
Radiography and small animal irradiator setup

Floating strips Micromegas with low material budget for radiography and small animal irradiator setup for molecular image-guided radiation-oncology

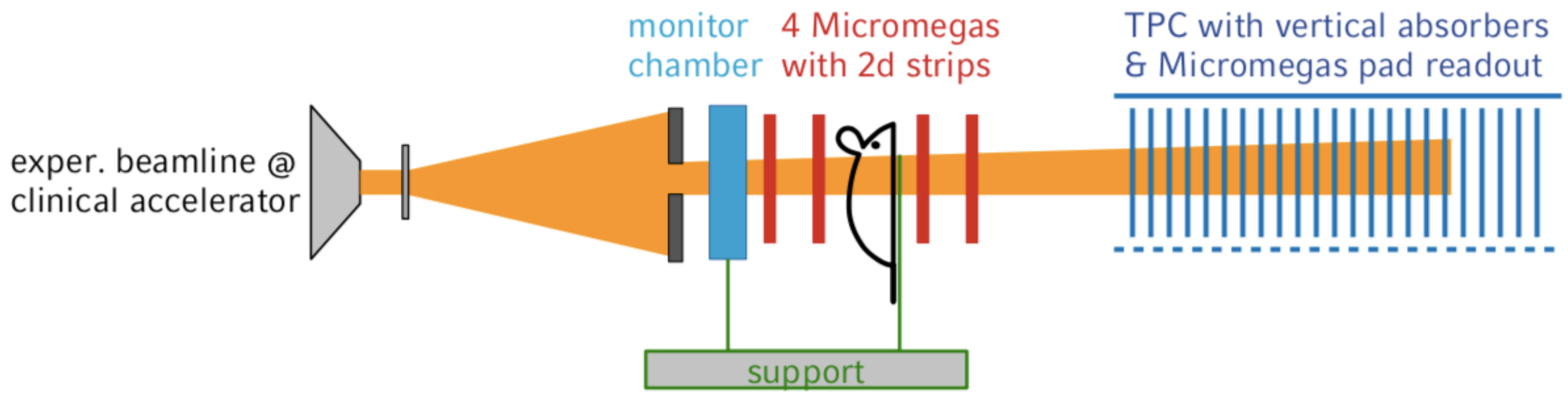
Requires good **high granularity** and **high-rate capability** as well as **low material budget** for multiple detector layers

VMM3 ASIC for ≈2 MHz readout rate

Radiography:
6 Micromegas layers + scintillator range telescope



Small animal irradiator setup:
Thin XY-readout Micromegas + pad readout Micromegas



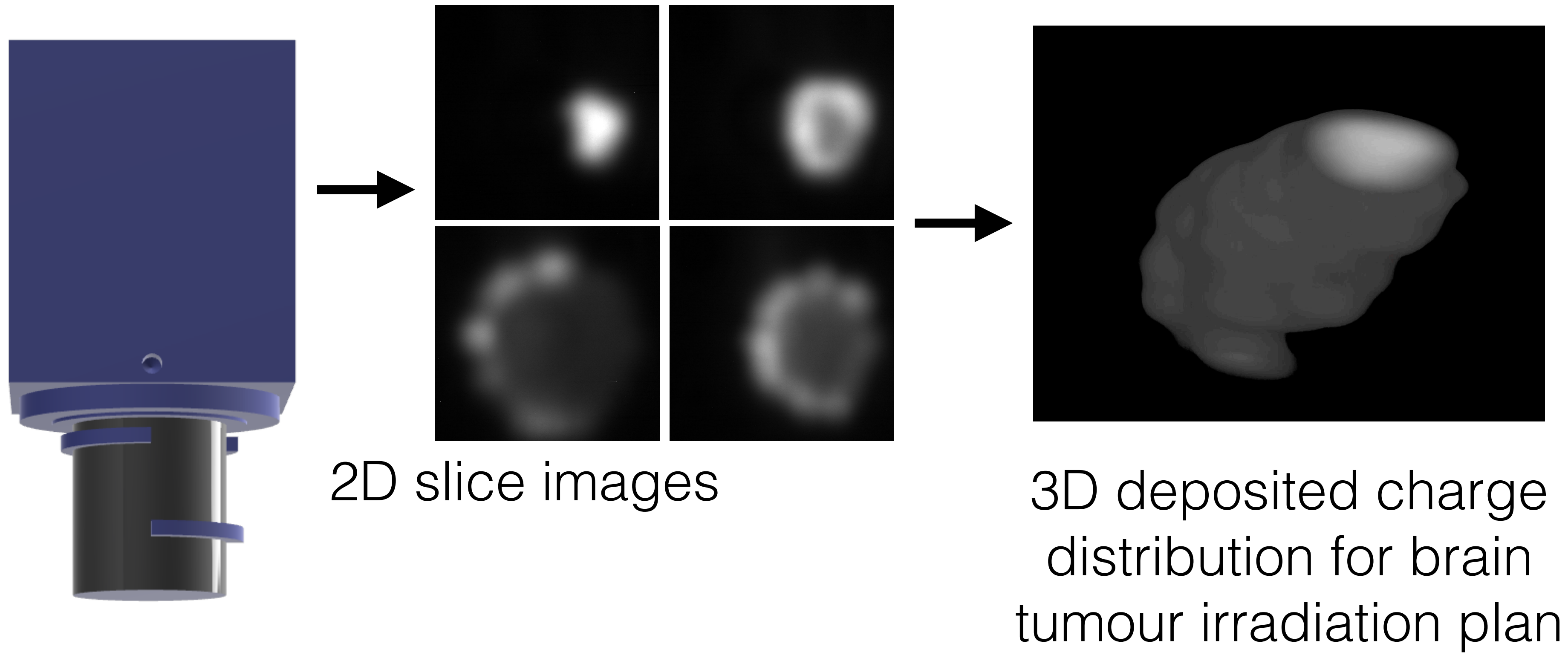
Jona Bortfeldt, Radiation Detection in Medical Physics Workshop, Aarhus, 2018
https://www.med.physik.uni-muenchen.de/personen/mitarbeiter/bortfeldt/bortfeldt_180504_aarhus.pdf

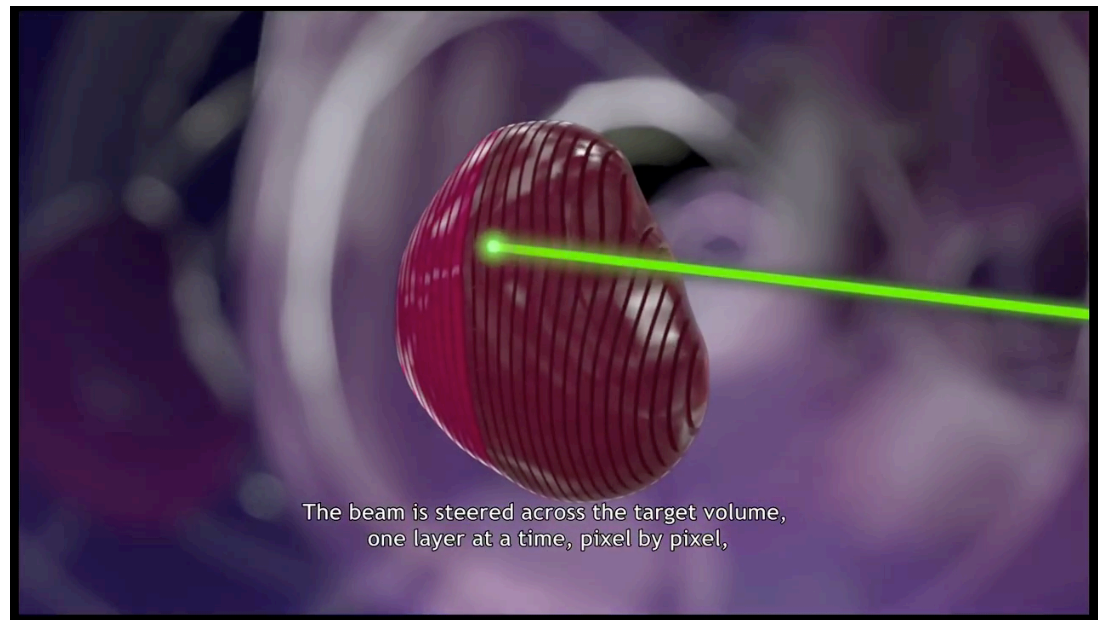
Beam monitoring for hadron therapy

Due to its superior dose localisation capability, hadron therapy is becoming an increasingly popular and capable tumour treatment modality.

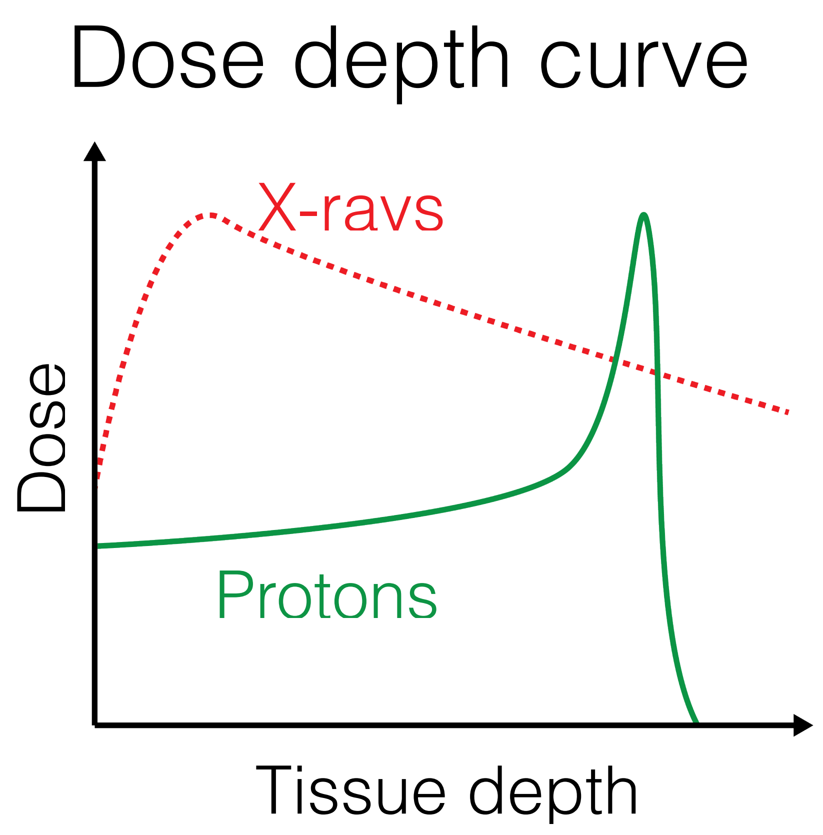
Optically read out GEMs can be used online monitoring in hadron therapy

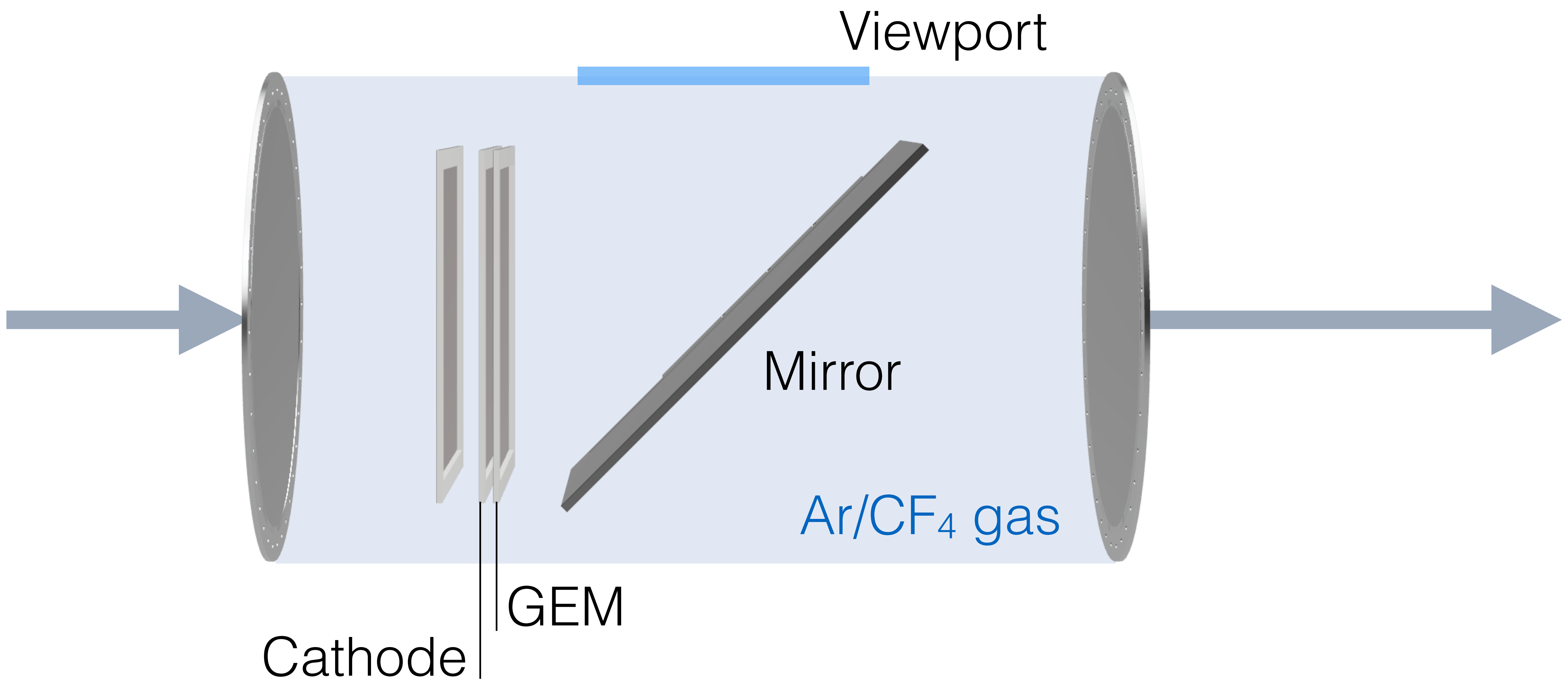
Low material budget of gaseous detector minimises beam attenuation and multiple scattering





Adapted from iba Proton Therapy
https://www.youtube.com/watch?v=MS590Xtq9M4&t=5s





Schematics not drawn to scale

Beam characterisation

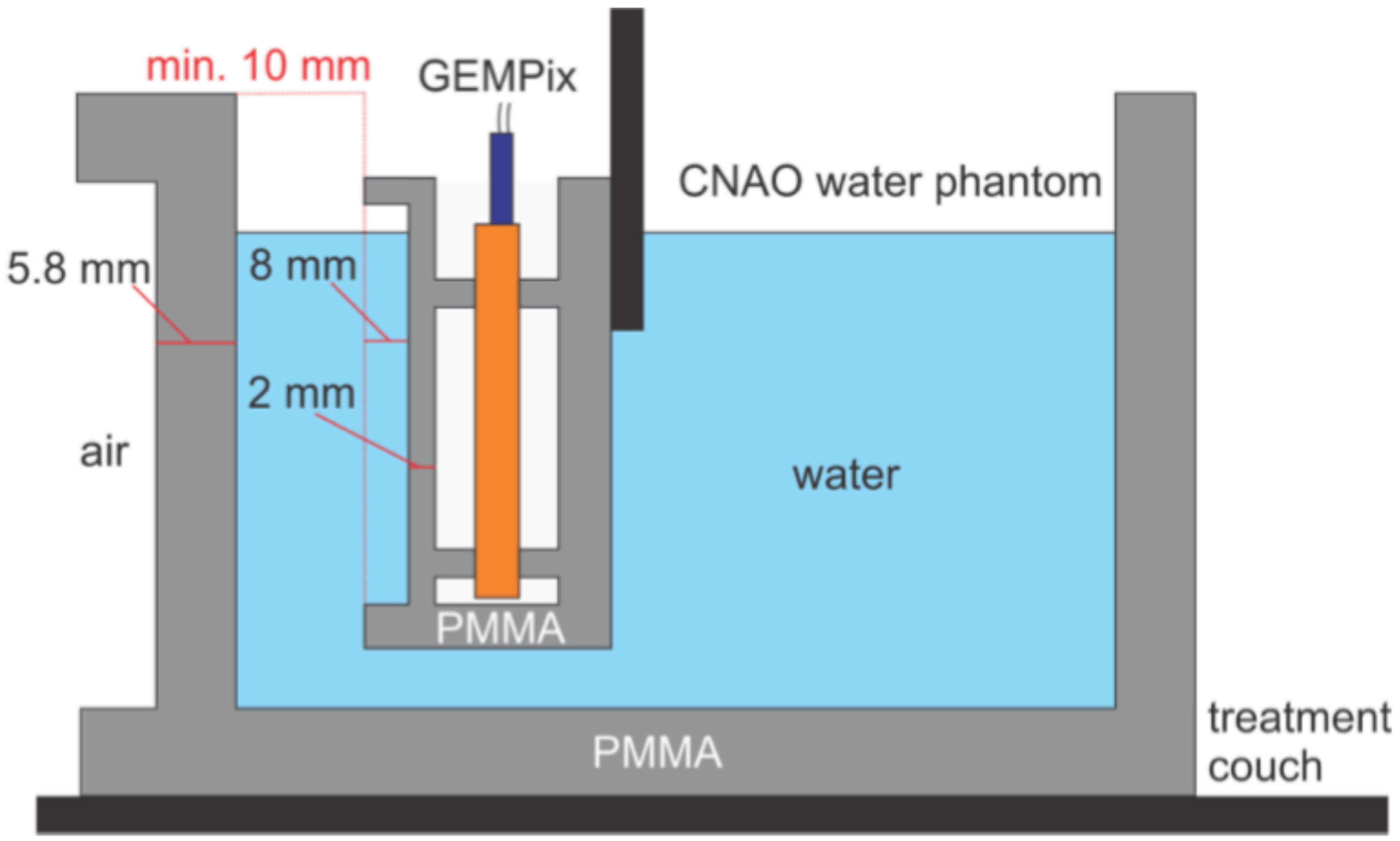
Ionisation chambers (ICs) are commonly used for energy deposition measurements in hadron therapy. To overcome the limited spatial resolution of IC arrays (≈5mm), a GEM can be coupled to a Timepix ASIC.

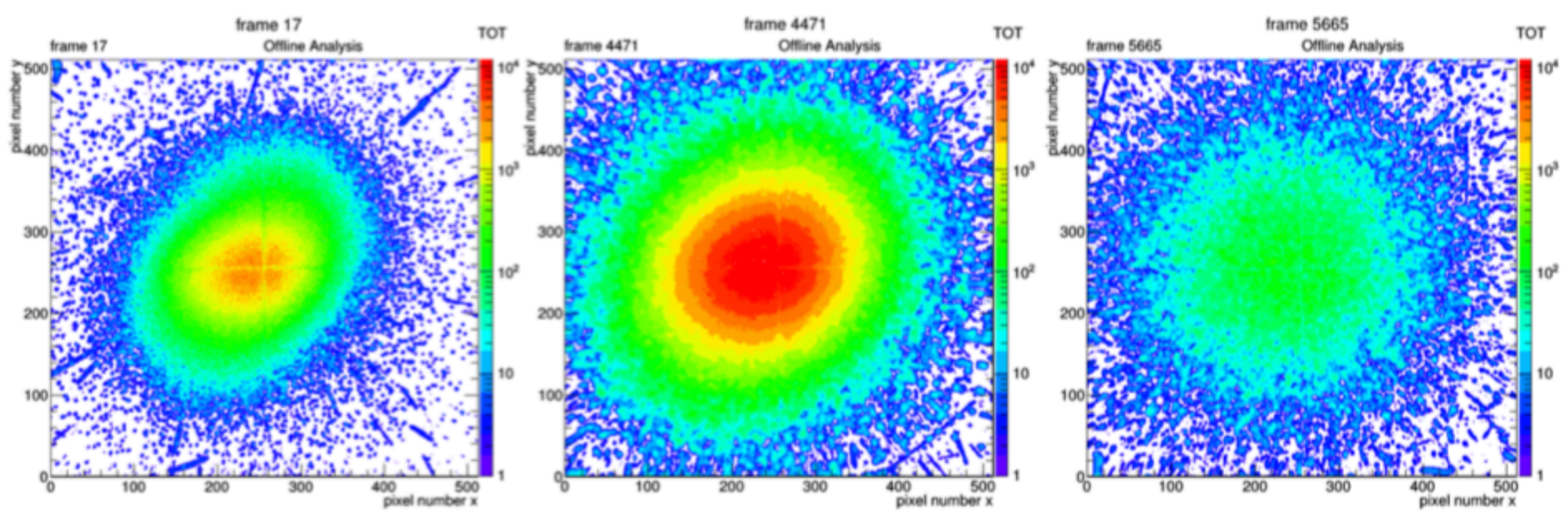
Timepix: 55µm pitch pixelated readout (512x512 pixels)

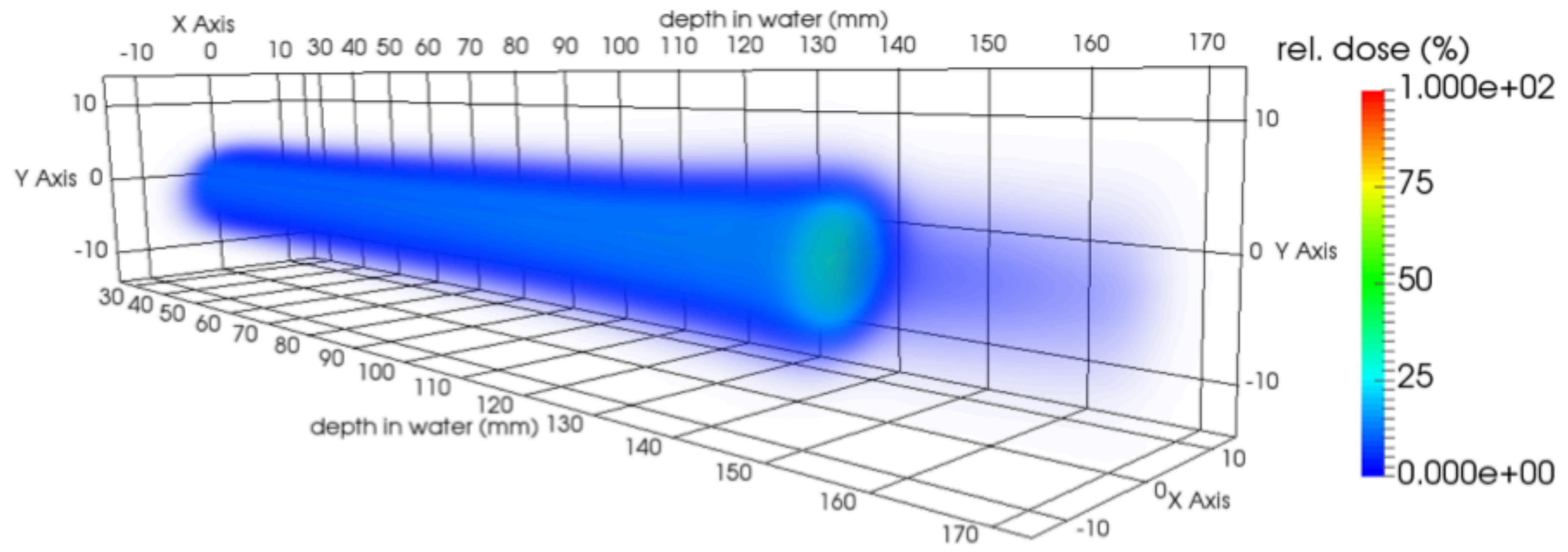
Operated in Ar:CO2:CF4 (45:15:40) gas mixtures and tested in carbon beams (280-332 MeV/u) at CNAO

3D energy deposition profile of carbon beam in water phantom obtained in 15min

Mismatches between Bragg curve measured and reference may be due to small active area of detector, heating of the ASIC, stopping power differences of air (IC) and Ar:CO2:CF4 (GEMPix)







J. Leidner et al 2018 JINST 13 P08009
https://doi.org/10.1088/1748-0221/13/08/P08009

GEMs for fusion plasma imaging

Triple GEM operated in photon counting mode with energy discrimination

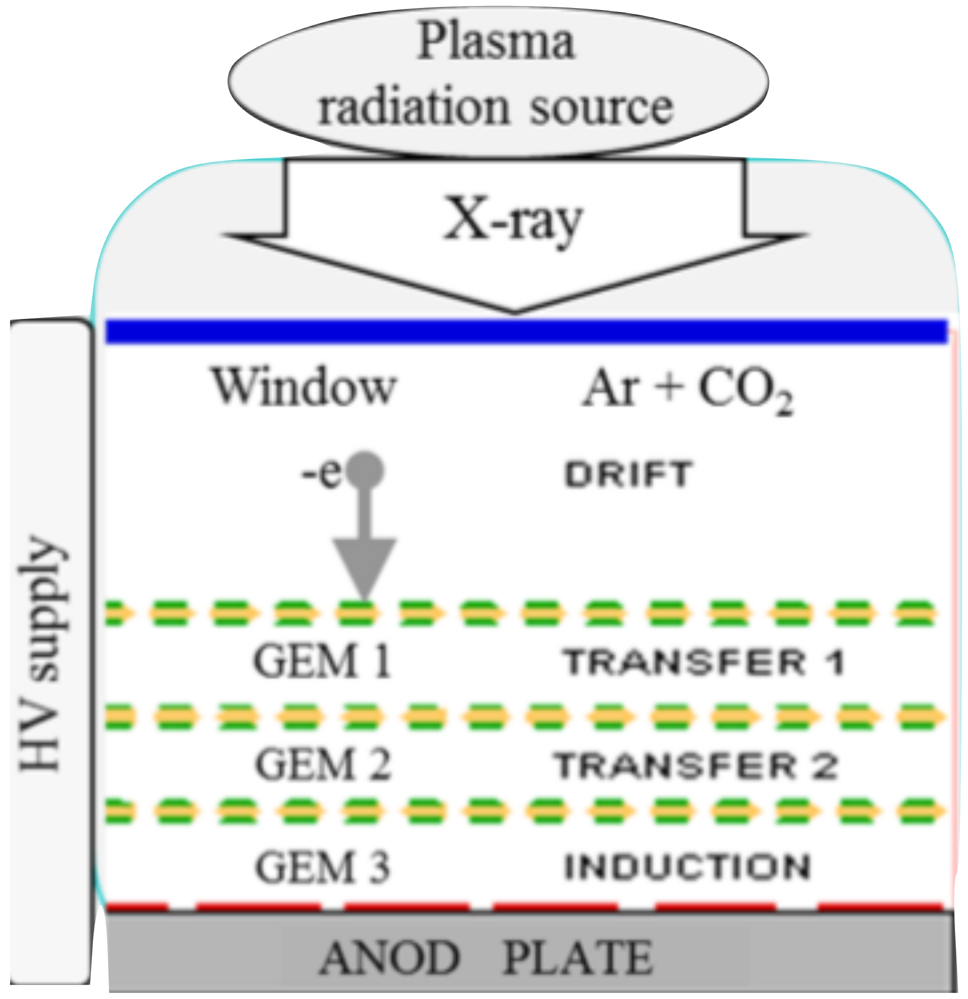
- 5-15mm drift gap
- 2mm induction gap
- Thin entrance window (12μm Mylar + 200nm Al) for **low energy threshold**
- Ar/CO2 70/30 or Ar/CO2/CF4 45/15/40

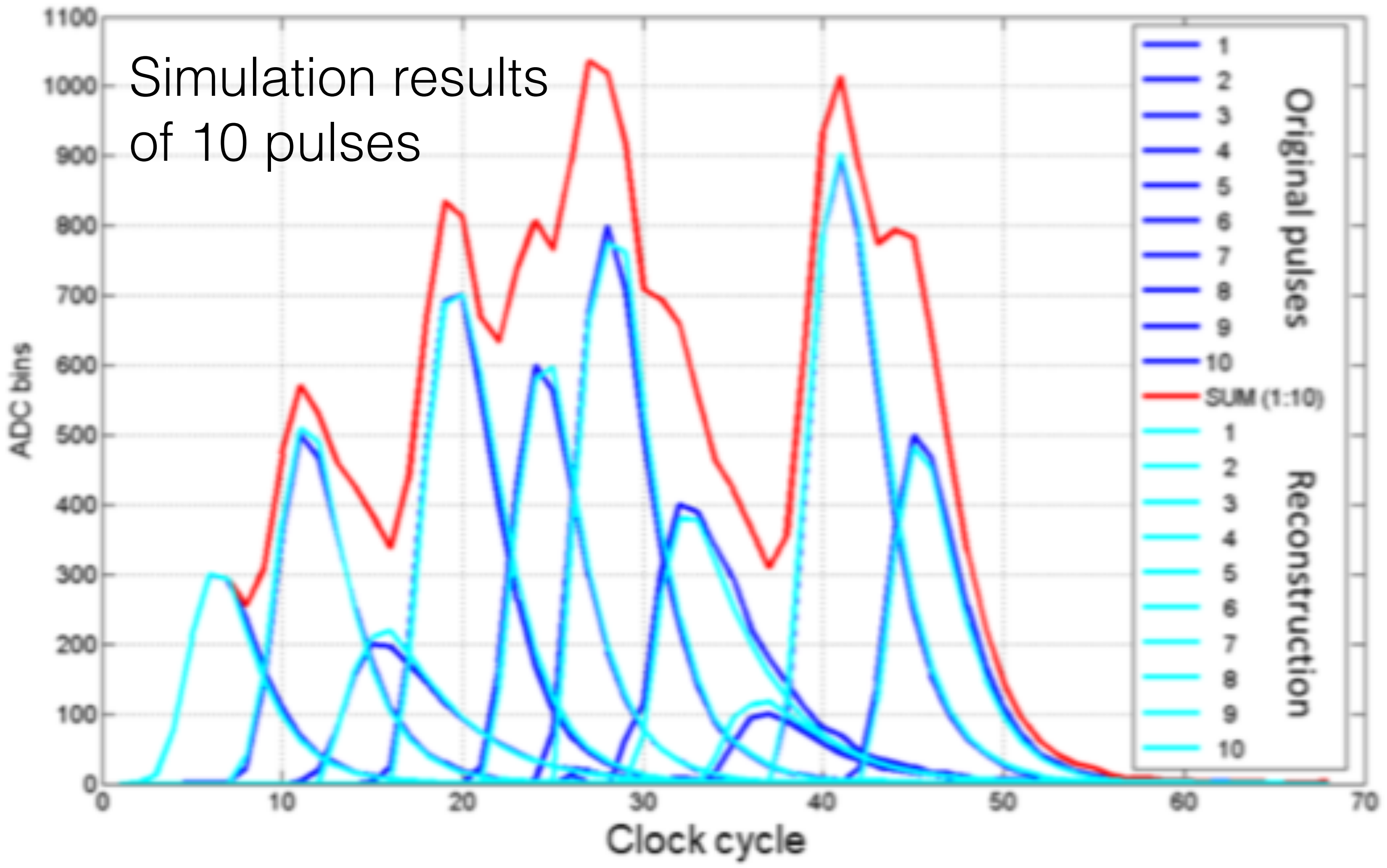
https://www.iter.org/newsline/-/2266

Charge cluster identification

Data acquired by serial data acquisition system ADC is sampled in 40 cycles (10bit, ≈13ns per cycle, 77MHz)

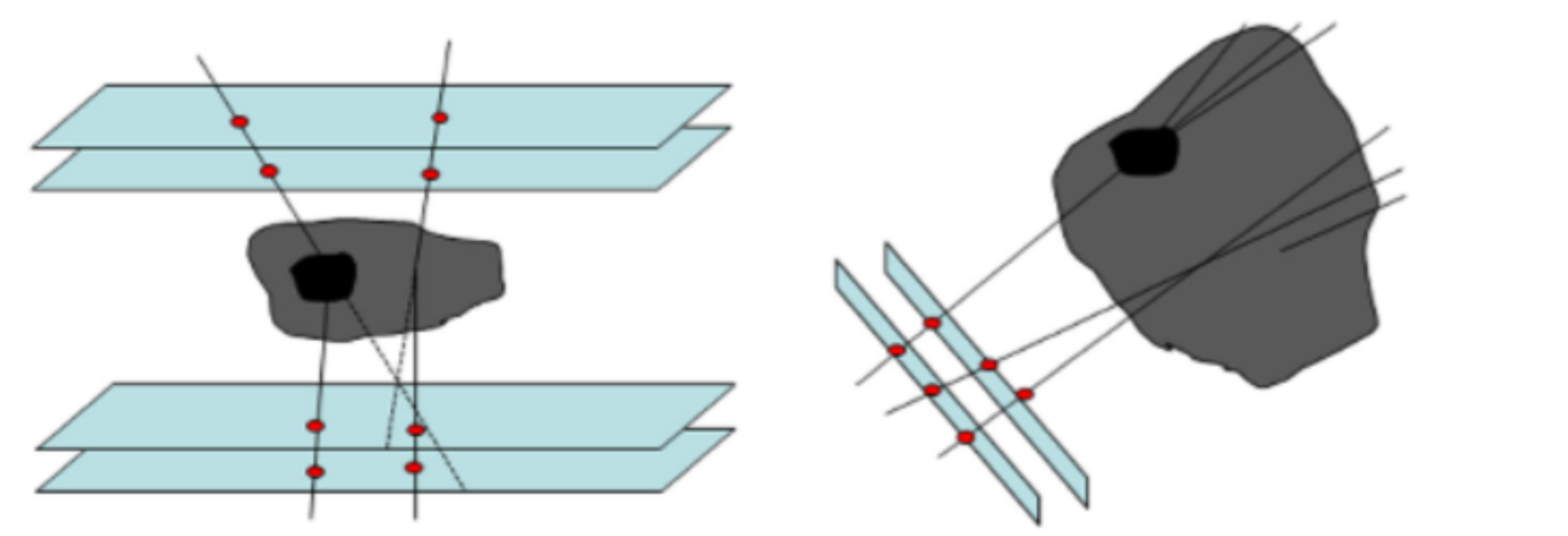
- “Characteristic point” shortly after local maximum is determined to predict falling phase
- Effective for pulse separation >50ns (3 cycles) and can be applied to subsequent pulses

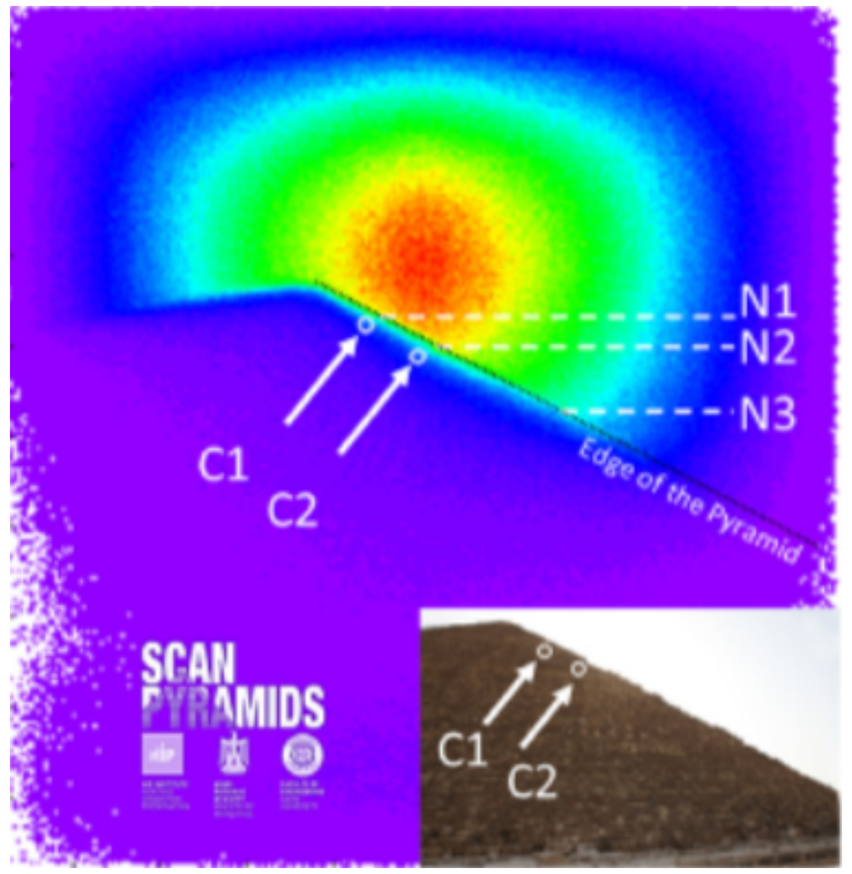




T. Czarski et al., Rev. Sci. Instrum. **87**, 11E336 (2016); https://doi.org/10.1063/1.4961559
T. Czarski et al 2018 JINST 13 C08001

Muography



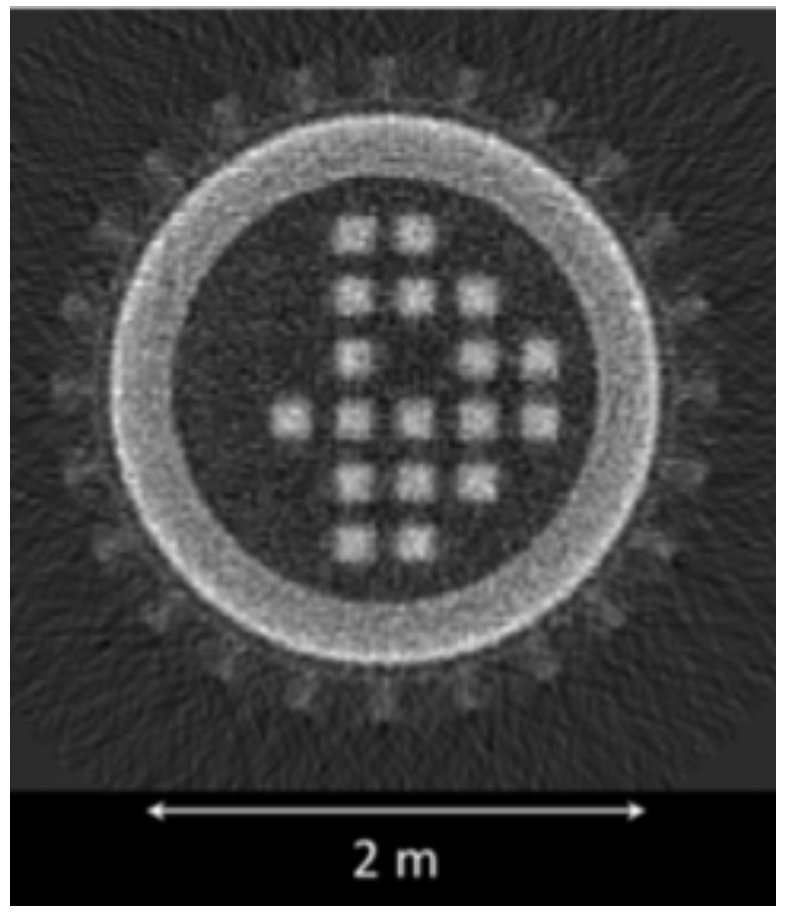


ScanPyramids (https://www.primapagina.sif.it/article/683/muons-unveil-the-secrets-of-a-pyramid#.XMgSpC2B2Vk)

Archeology
Three Micromegas-based telescopes from CEA used for scanning edges in combination with emulsion plates (Cairo) and a scintillator telescope (KEK) were used to image Khufu pyramid at Giza. Three months data taking found several cavities including unknown ones.

S. Procureur, Nuclear Inst. and Methods in Physics Research, A 878 (2018) 169–179 https://doi.org/10.1016/j.nima.2017.08.004

Nuclear reactor and waste imaging
Radiaoactive materials in containers or shielding boxes can be identified by muography. kg scale of material should be detected in 1-2min to be applicable.



D. Poulson et al., Nuclear Instruments and Methods in Physics Research A 842 (2017) 48–53 https://doi.org/10.1016/j.nima.2016.10.040

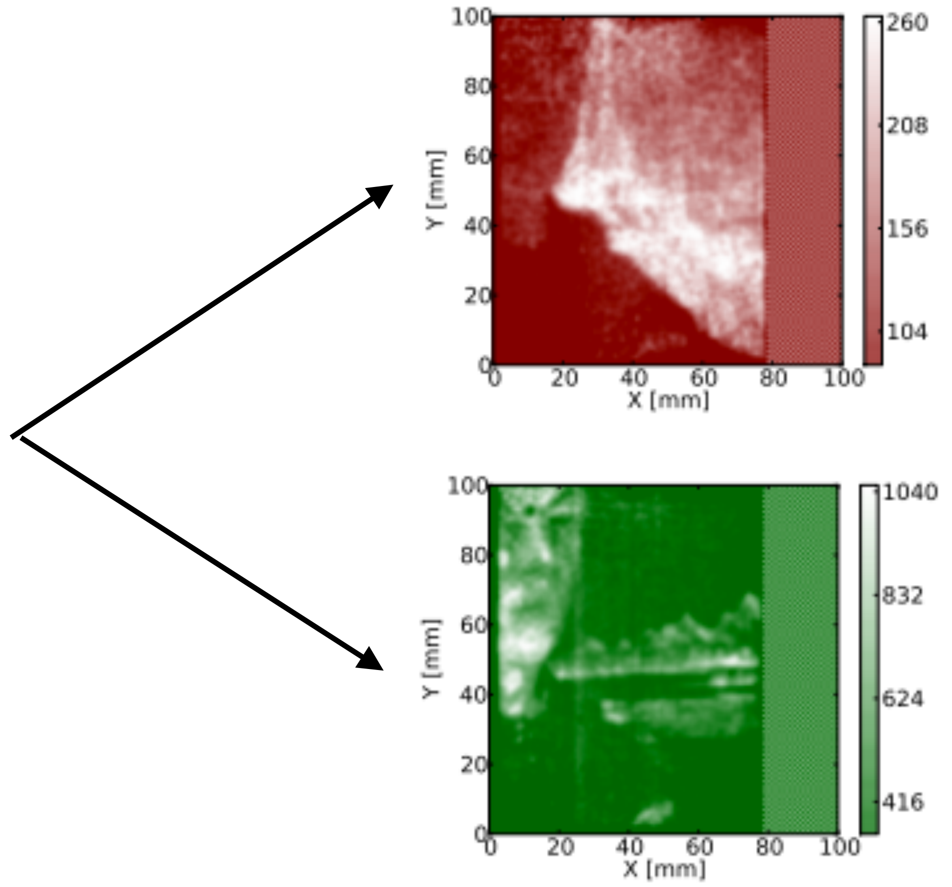
X-ray fluorescence

Energy resolved imaging taking advantage of characteristic X-ray energies emitted by different elements when excited by incident radiation is a widely used non-destructive elemental analysis technique.

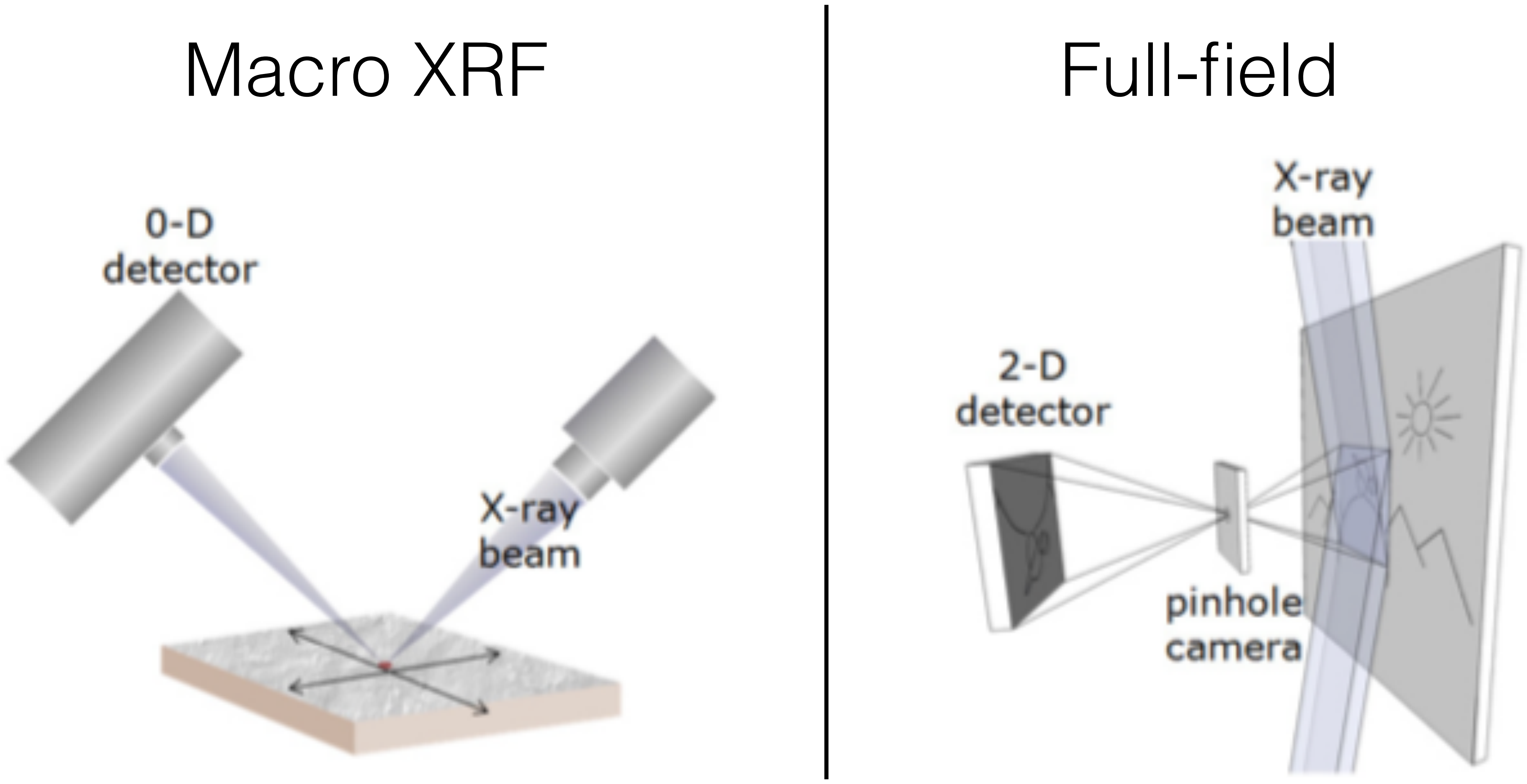
Key advantages of MPGDs for EDXRF include:

- 2D imaging with **high spatial resolution**
- **Versatility and in-situ operation**
- **High rate capability**
- **Low energy threshold** (sensitivity <1 keV)

Zielińska et al. JINST 8

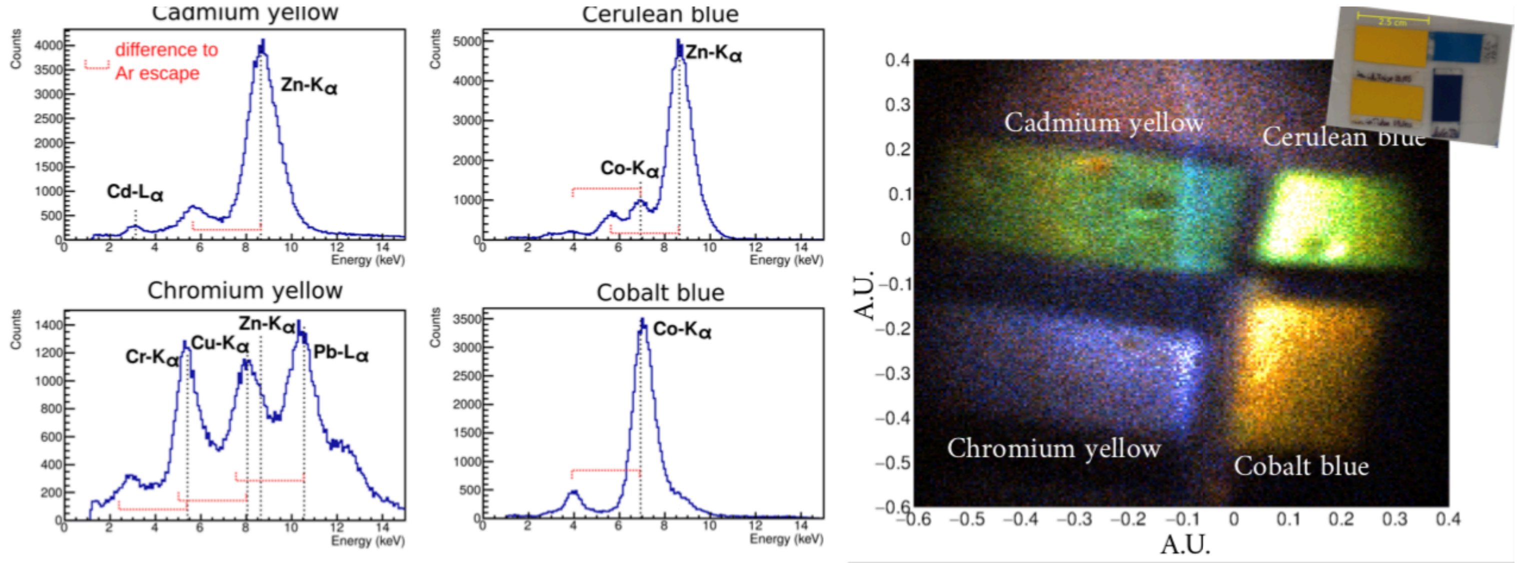


(b) Cu and Zn map (7.6-9.0 keV).



W. Dbrowski et al 2016 JINST 11 C12025

Optimization of gaseous detectors for low energy XRF



https://indico.cern.ch/event/889369/contributions/4039478/attachments/2115044/3558612/optimization_rd51.pdf

Conclusions

MPGD technologies

Amplification
High/low gain, single/multi stage

Gases
Mixture, quencher, electro-negative

Pressure
High pressure, low pressure, dual-phase

Flushed/ sealed

Radio purity

Conversion
Gas, photocathode, converter, emitter

Production
Photolithography, machining, printing

Rate
high rate / low rate

Drift
Electron / negative ion drift

Readout
Electronic, optical, hybrid

Shape
Planar, cylindrical, spherical

Readout geometry
Strips, pads, pixels, multiplexed

Resistive / non-resistive

Low material budget

Detection
MIPs, photons, neutrons, charged particles

Size
cm^2 to m^2

Conversion gap
Thin gap, thick gap, field shapers

Application
Tracking, calorimetry, reconstruction, imaging

MPGD technologies

Versatility

- Choice of **gas mixture** (He/Ar/Ne/Xe/… + quenchers)
- Operating **pressure** from mbar to several bar
- **Readout** approach (electronic/optical/hybrid)
- **Conversion**: gas ionisation / converter / photocathodes / secondary emitters
- Detector **geometries** and shape (planar / cylindrical / spherical)

Low energy threshold (≈ few keV)

Good spatial resolution (≈ tens of μm)

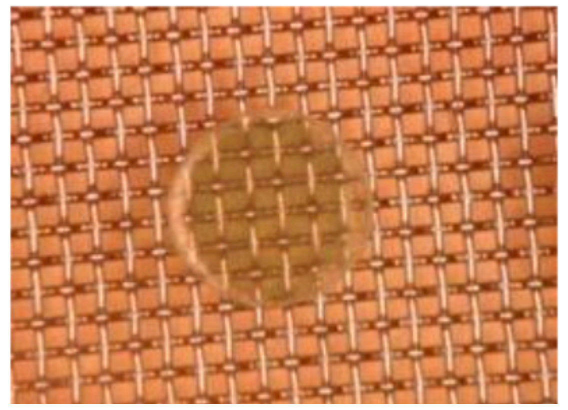
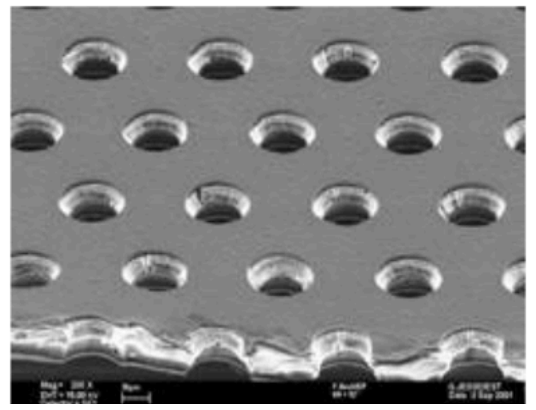
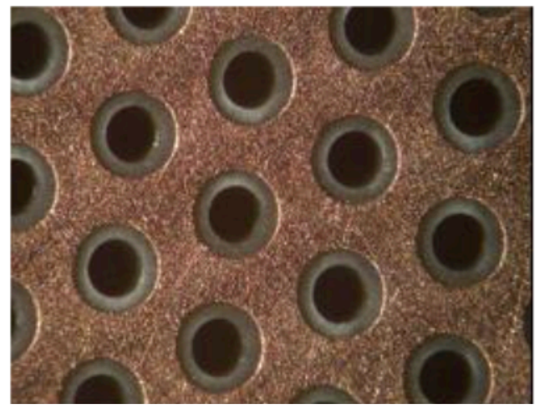
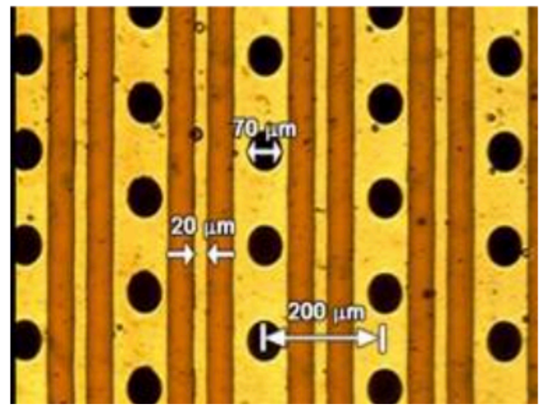
Low material budget (gas as active medium)

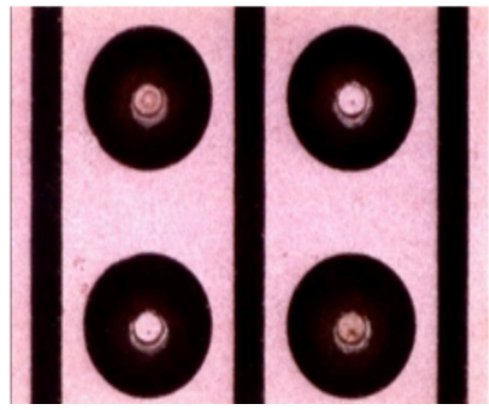
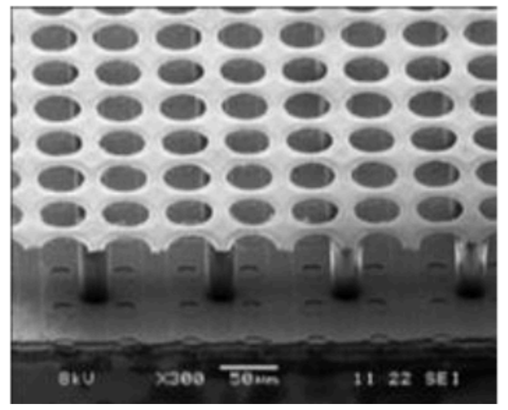
High-rate capability (up to MHz / mm^2)

Large active area (up to hundreds of m^2)

Radiation hardness

Summary

MPGDs are a **highly versatile** and **mature technology** for a wide range of experimental requirements ranging from high-energy physics to applications beyond fundmental research.

A global community driven by the **RD51 collaboration** is focused on increasing the understanding of detector physics to optimise existing structures and exploit technological advances to introduce **novel detector geometries.**

The requirement for **precise timing**, advances in **additive manufacturing** and **new materials** can lead to next-generation MPGD technologies and detectors for future experimental needs.