MPGD applications outside high-energy physics

F. M. Brunbauer (CERN)

May 8, 2019 - International Conference on Micro Pattern Gaseous Detectors

Applications

Medical: radiography, dosimetry and portal imaging

Cultural heritage studies: X-ray fluorescence

Muography: archeology and nuclear reactor imaging

Astrophysical: X-ray polarimetry and axion search

Fusion plasma imaging

Key features of MPGDs

Versatility

Low material budget

High spatial resolution

High-rate capability

Low energy threshold

Large active area

Radiation hardness

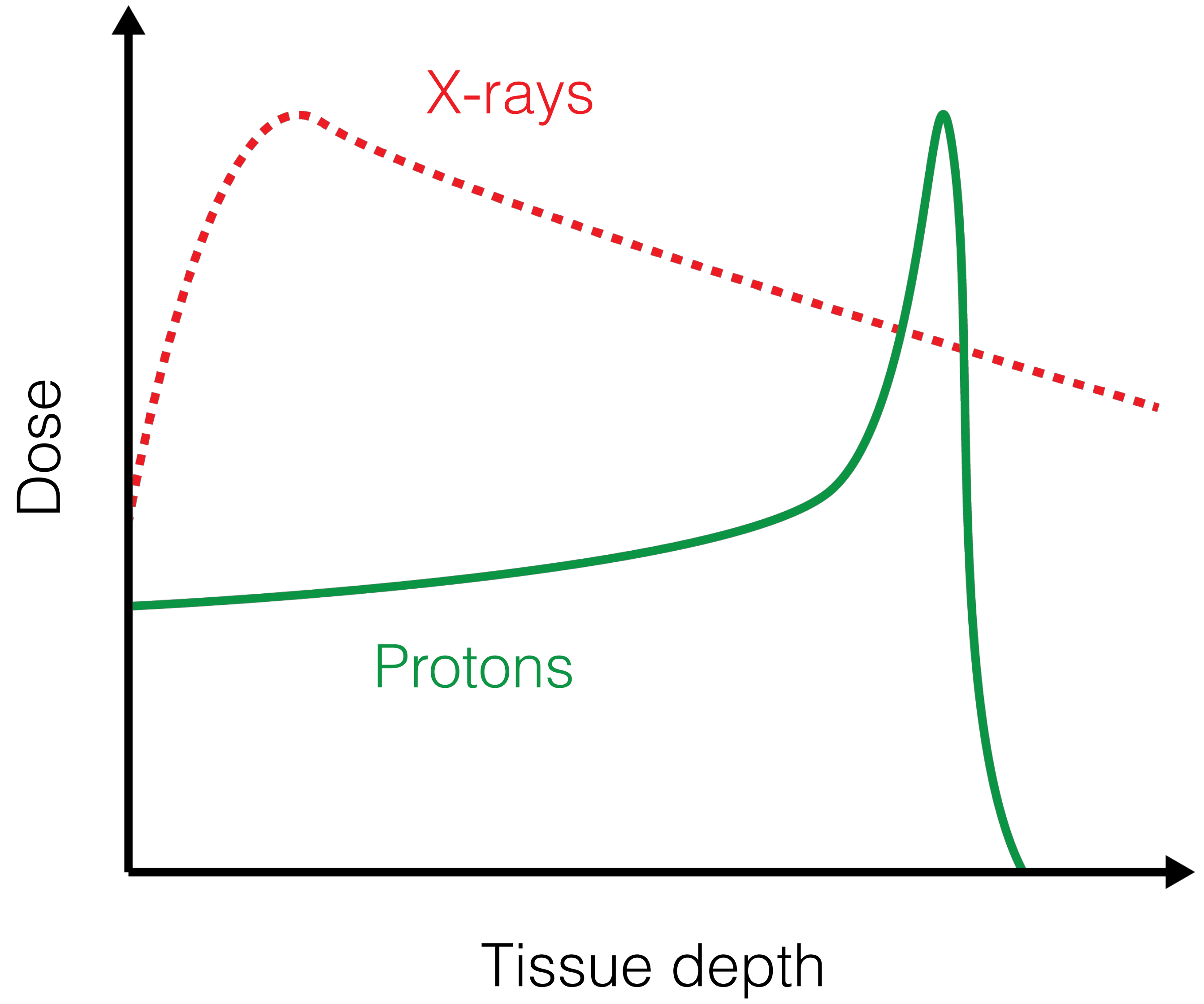
Medical applications

Hadron therapy

Due to its superior dose localisation capability, hadron therapy is becoming an increasingly popular and capable tumour treatment modality. Over 120.000 patients have been treated with particle beams, incl. more than 20.000 with carbon beams.

To fully exploit the dose localisation possibility of particle beams, tumour location and extent and scanning pencil beam characteristics have to be known accurately and precisely.

Dose depth curve



Existing instrumentation

Scintillator-based detector with active area of 30 x 30 cm²

1020 **ionization chambers** distributed over 24.4 x 24.4 cm² (7.6mm pitch)

Images and text adapted from http://www.iba-dosimetry.com

Potential MPGD applications

Proton radiography

Beam characterisation

Scanning pencil beam tracking

Proton radiography

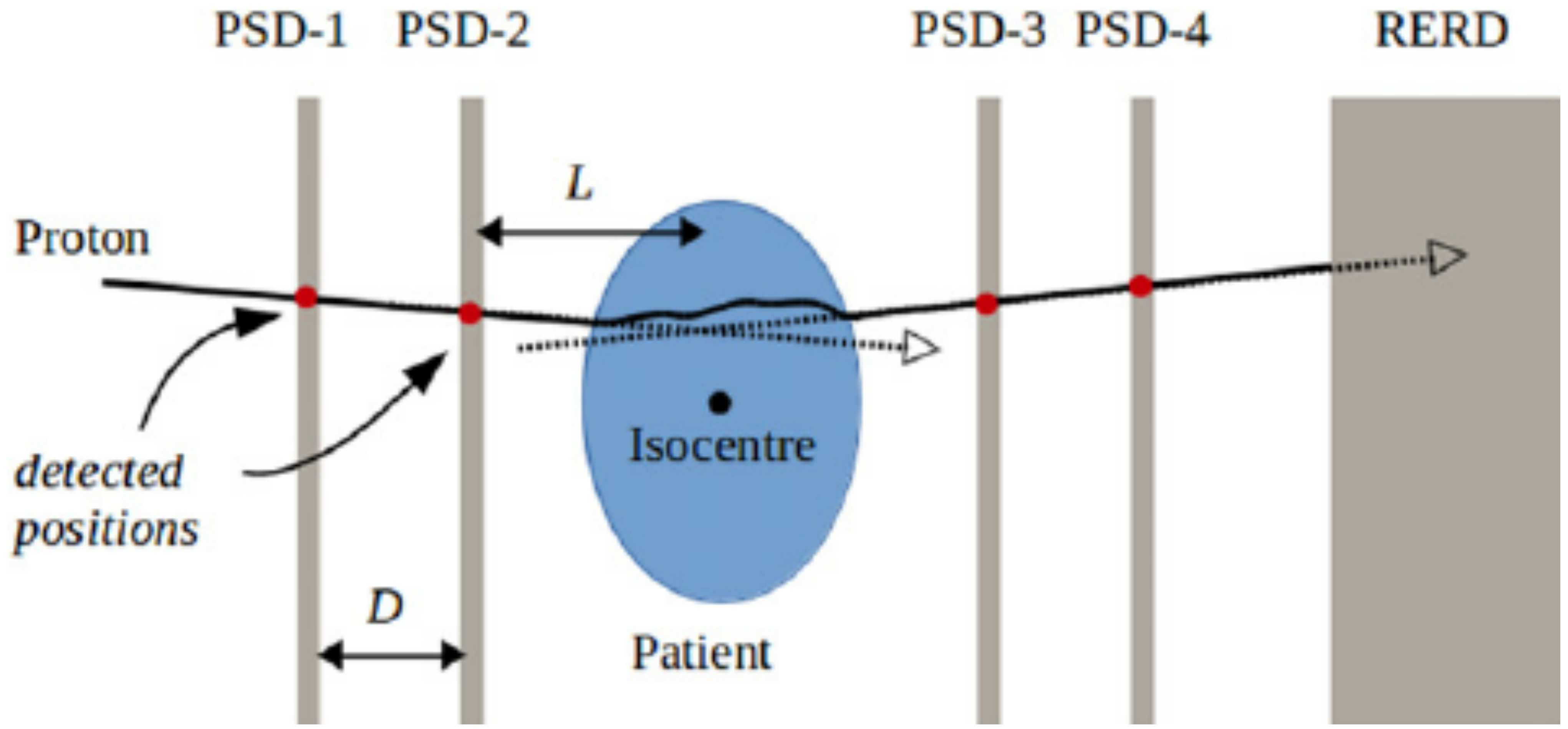
Proton radiography provides high quality images to determine organ location.

- Accurate patient positioning
- Minimise dose for tumour tracking

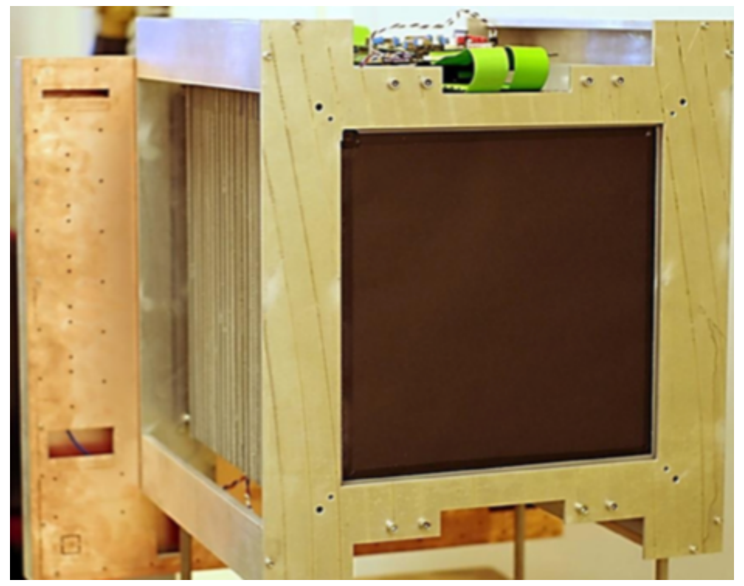
Detectors for proton radiography need to provide

- **High granularity**
- **Low material budget**
- **High-rate** capability
- Moderate active area

Additional application:
Interaction vertex imaging (IVI) dosimetry
Record secondary protons emerging from the target



Poludniowski et al., Br J Radiol;88:20150134 DOI: 10.1259/bjr.20150134



30x30cm^2 active area
2D readout anode (800μm strip pitch)

M. Bucciantonio et al. / Nuclear Instruments and Methods in Physics Research A 718 (2013) 160–163
http://dx.doi.org/10.1016/j.nima.2012.10.046

Radiography and small animal irradiator setup

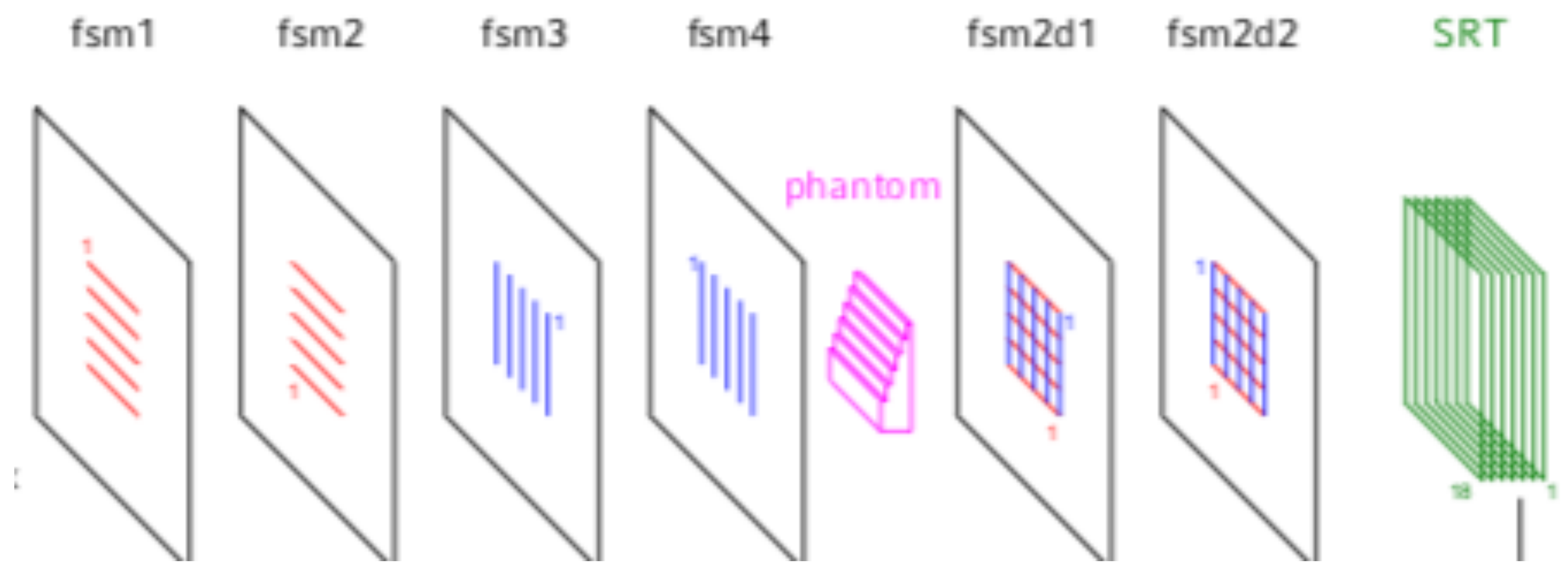
Floating strips Micromegas with low material budget for radiography and small animal irradiator setup for molecular image-guided radiation-oncology

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

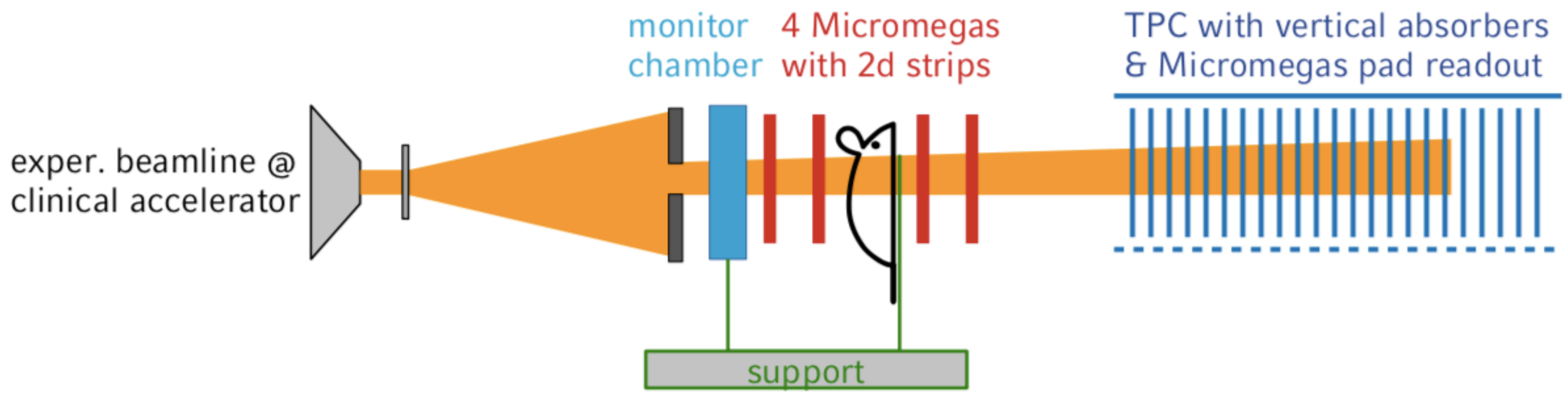
VMM3 ASIC for ≈2 MHz readout rate

J. Bortfeldt (Wed): Development of novel ultra-thin Micromegas and a Time Projection Chamber for animal ion transmission tomography

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

L. G. Manzano (Poster): A Large Area GEMPix detector for treatment plan verification in hadron therapy

Beam characterisation

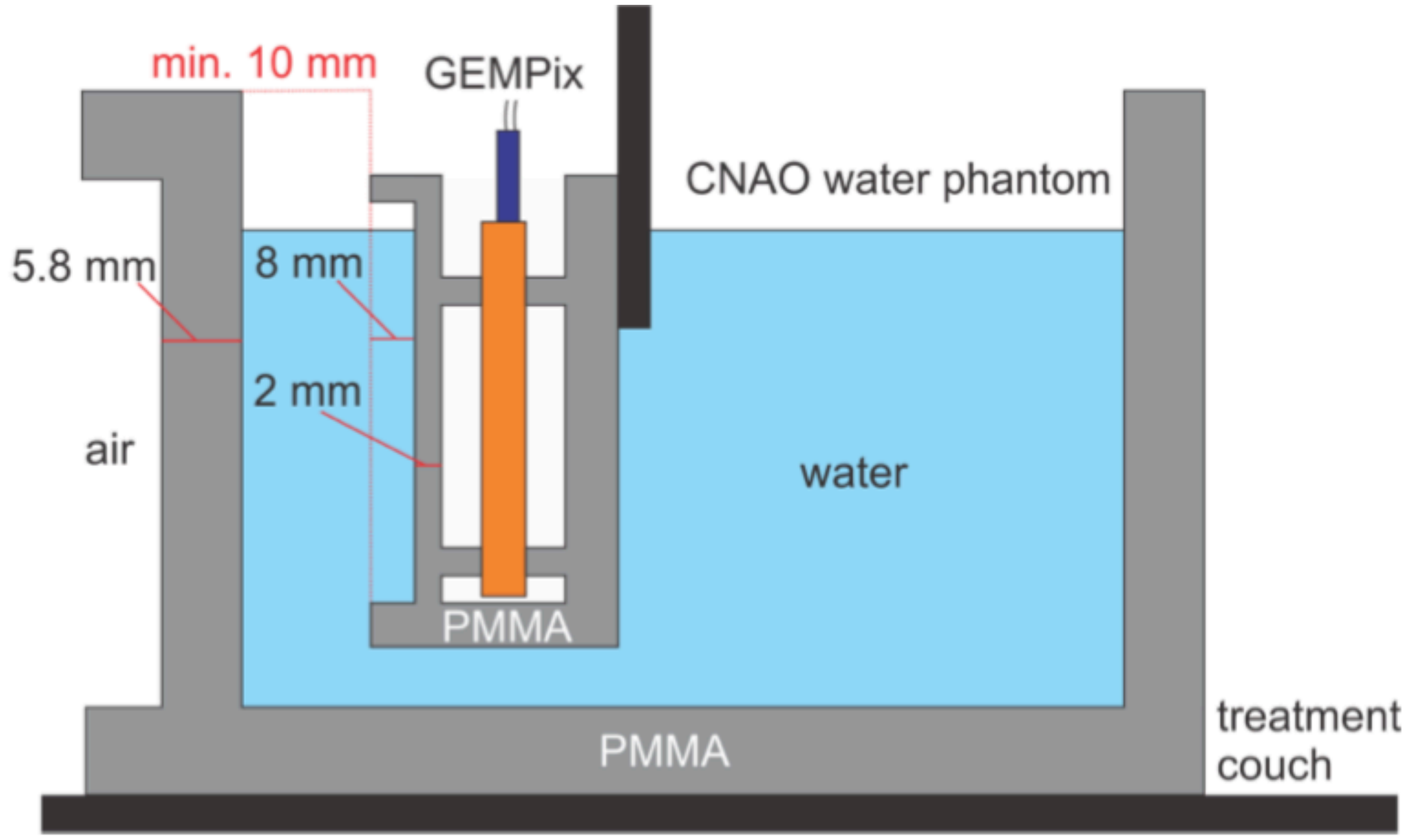
Ionisation chambers (ICs) are commonly used for energy deposition measurements in hadron therapy. To overcome the limited spatial resolution of IC arrays (≈5mm), a GEM can be coupled to a Timepix ASIC.

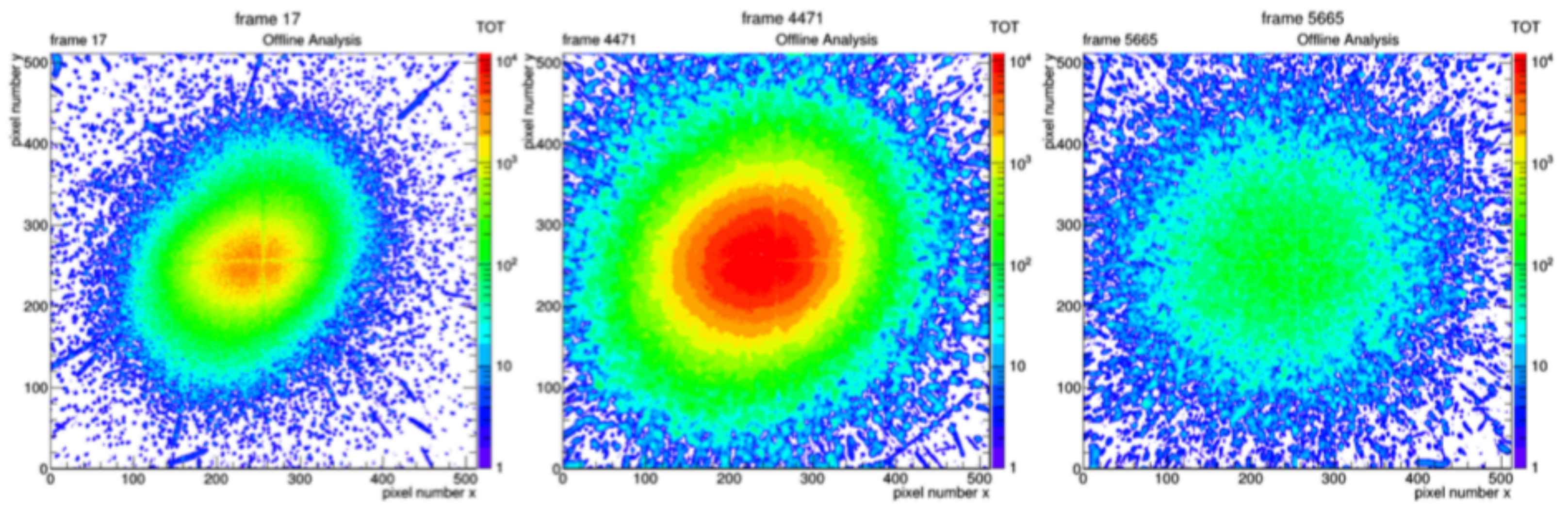
Timepix: 55µm pitch pixelated readout (512x512 pixels)

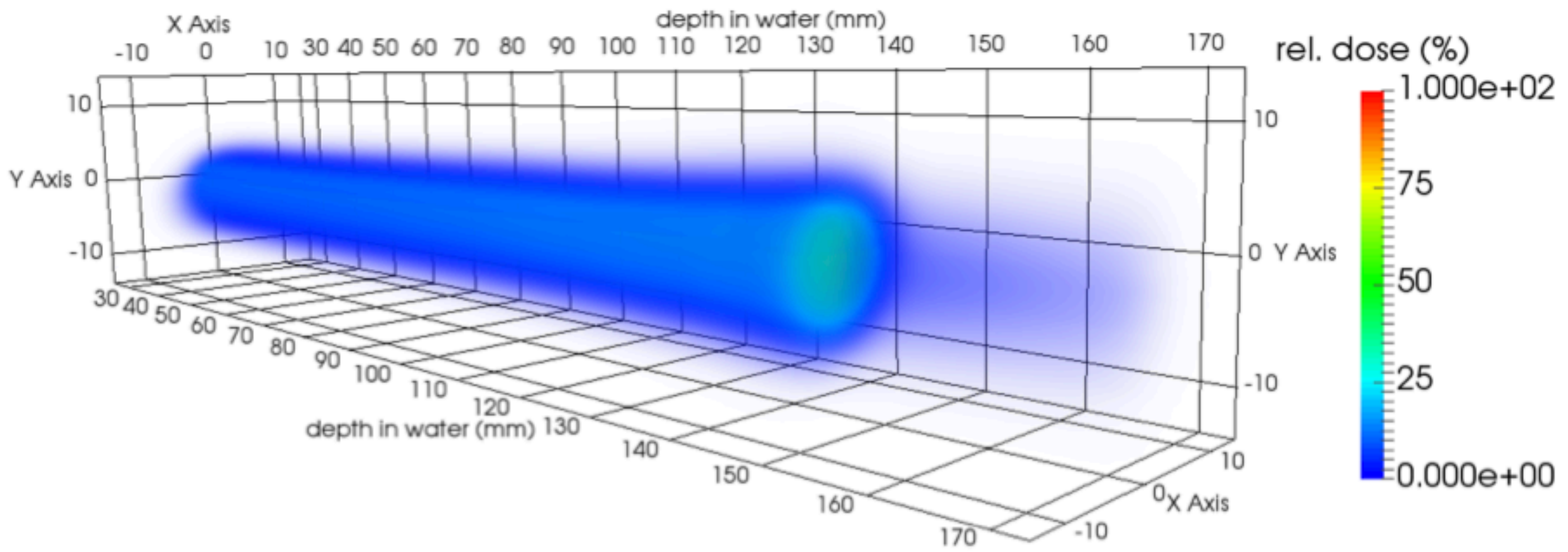
Operated in Ar:CO2:CF4 (45:15:40) gas mixtures and tested in carbon beams (280-332 MeV/u) at CNAO

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

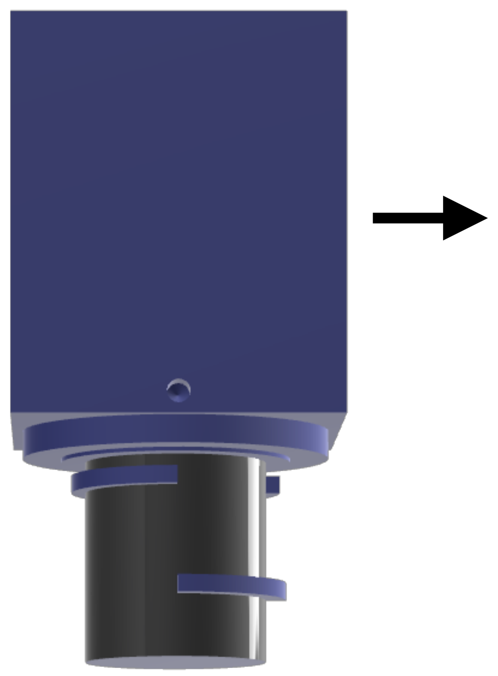
Hadron therapy monitoring

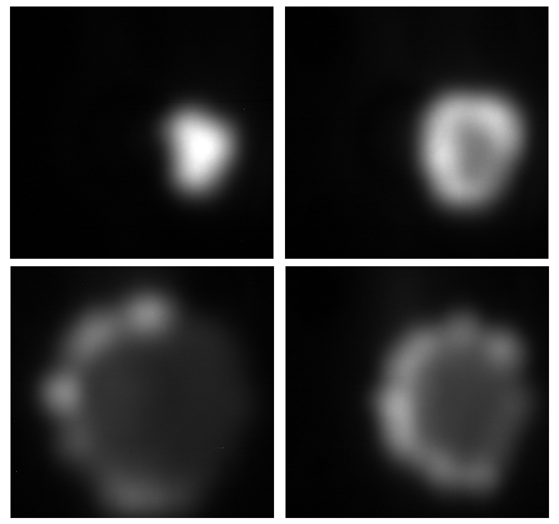
Optically read out GEMs can be used online monitoring in hadron therapy

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

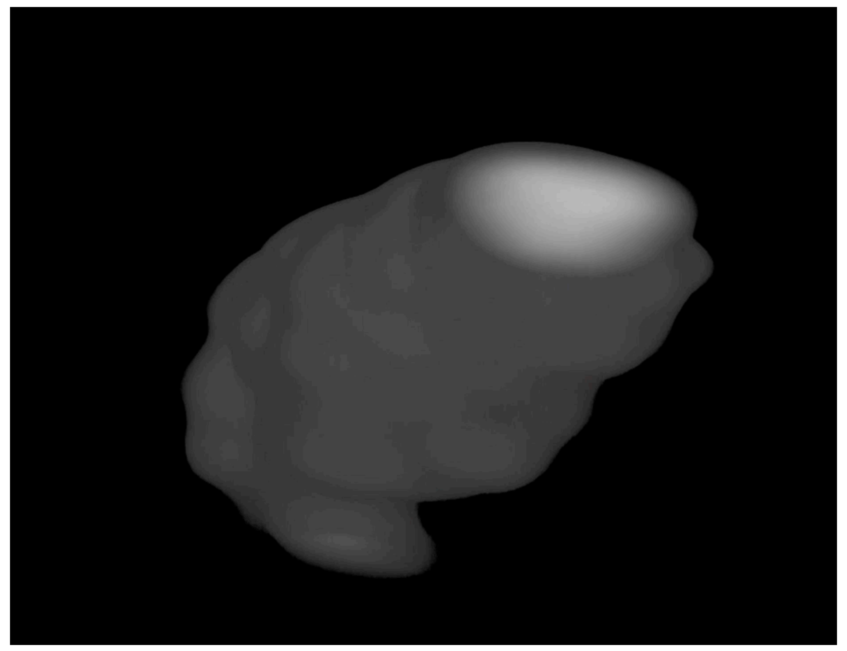
Optical readout permits placement of camera outside of beam path (lower material budget, lower radiation exposure of sensor)

This can provide **high spatial resolution** images of scanning pencil beams for beam characterisation and treatment plan verification

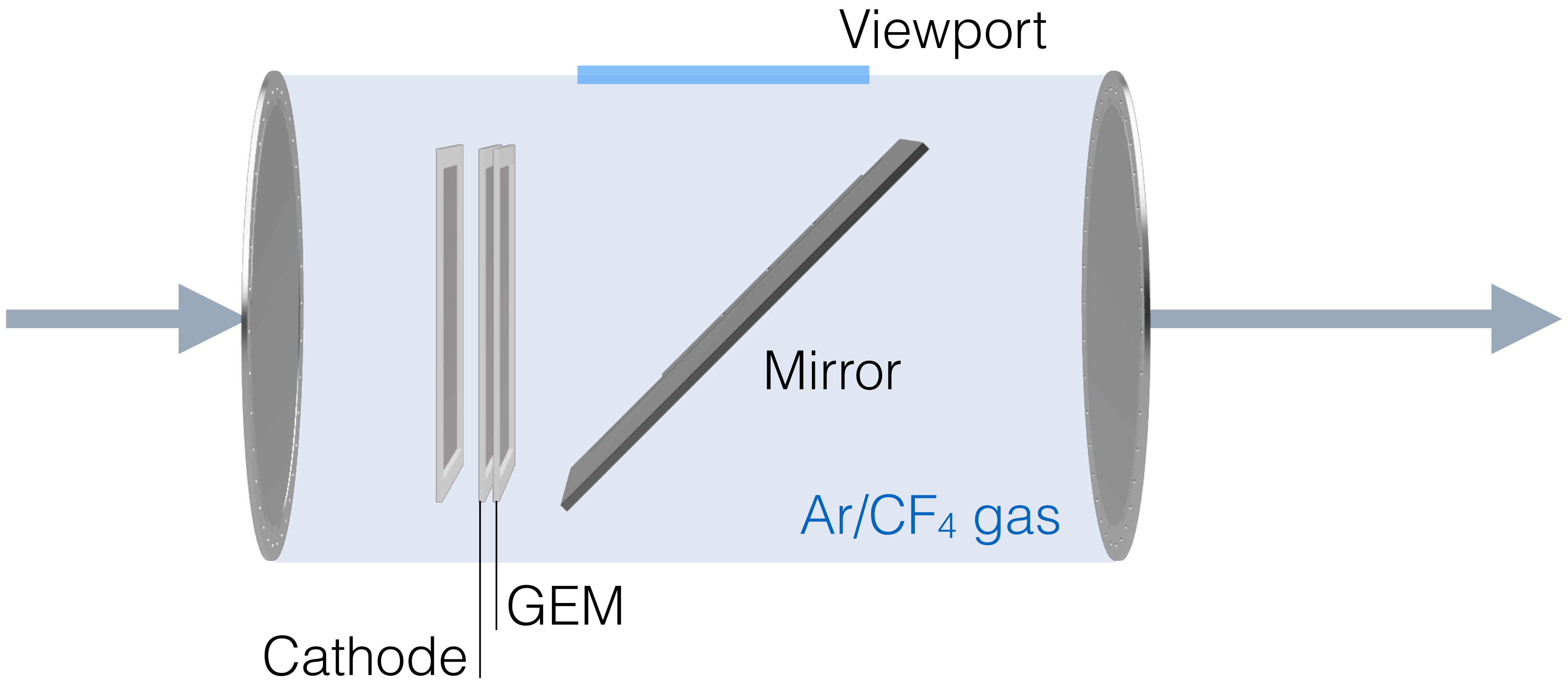




2D slice images



3D deposited charge distribution for brain tumour irradiation plan



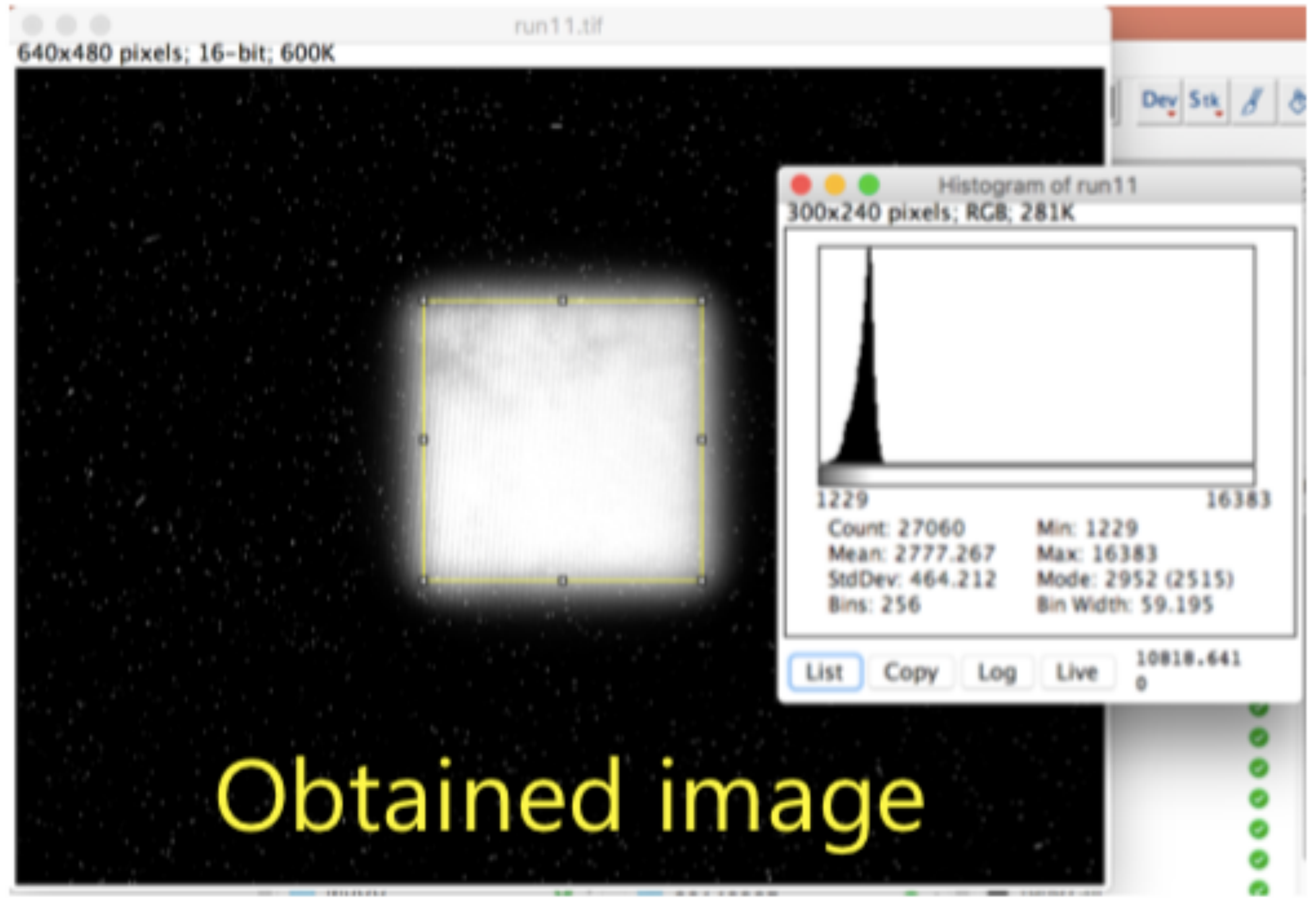
Hadron therapy monitoring

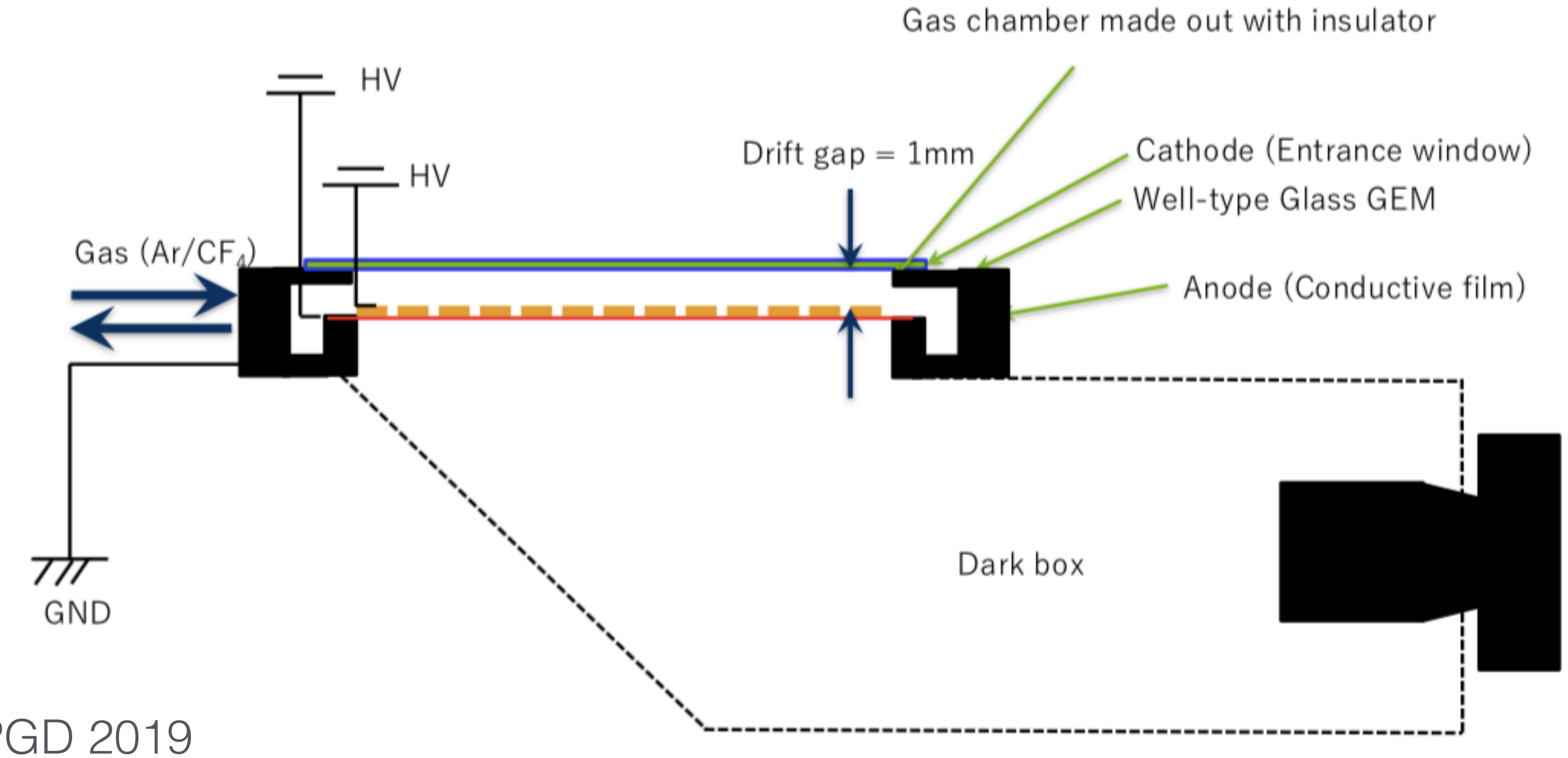
T. Fujiwara (Tue): Recent Development of Glass GEMs and Their Uses

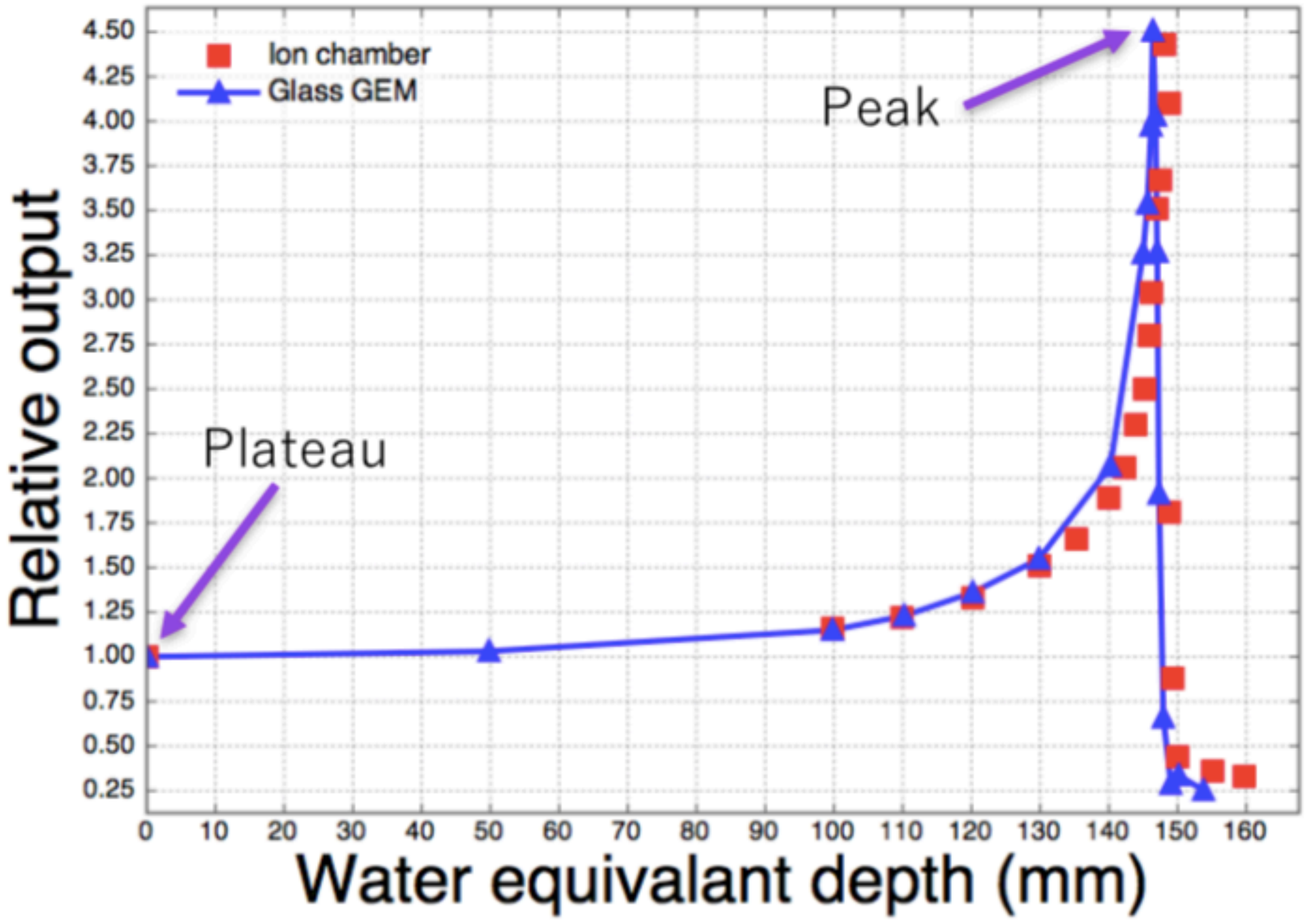
Optically read out **glass GEM** well suited for dose imaging and dose depth curve measurement

Peak-to-Plateau ratio of dose depth curve of carbon beams accurately reproduced

Scanning pencil beams imaged with **high spatial resolution** and short exposure time (10ms), low frame rate (3Hz)



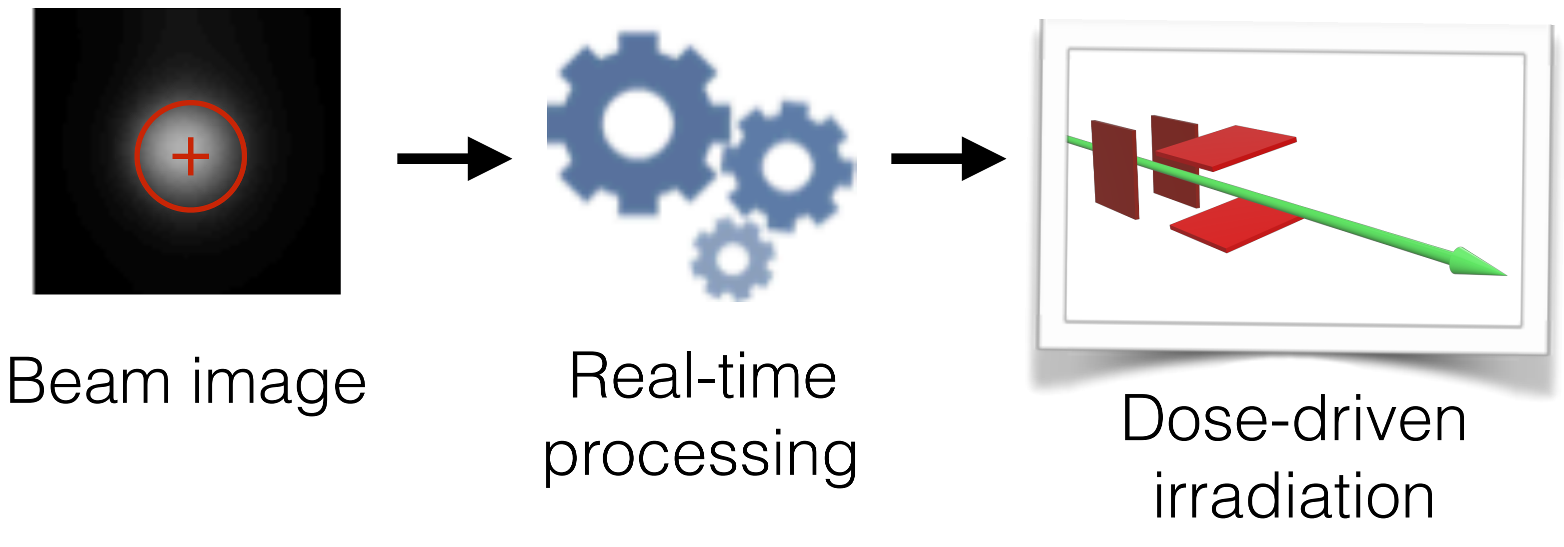




T. Fujiwara et al. MPGD 2019

High-speed cameras for scanning pencil beams

Ultra-high-speed cameras and **real-time image processing** might enable online irradiation monitoring and dose-driven irradiation



F.M. Brunbauer (Poster): Optical readout of MPGDs: developments and perspectives

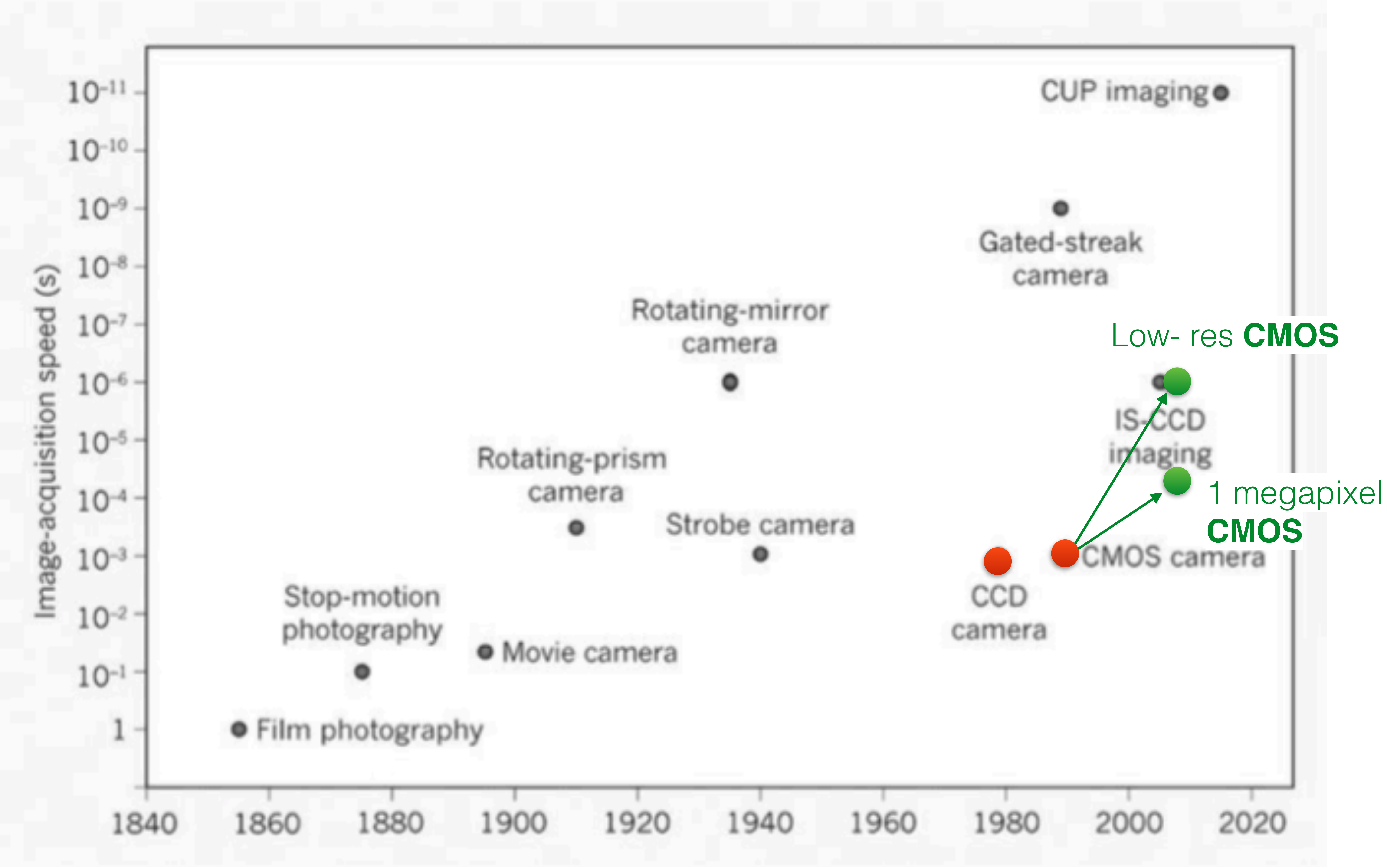
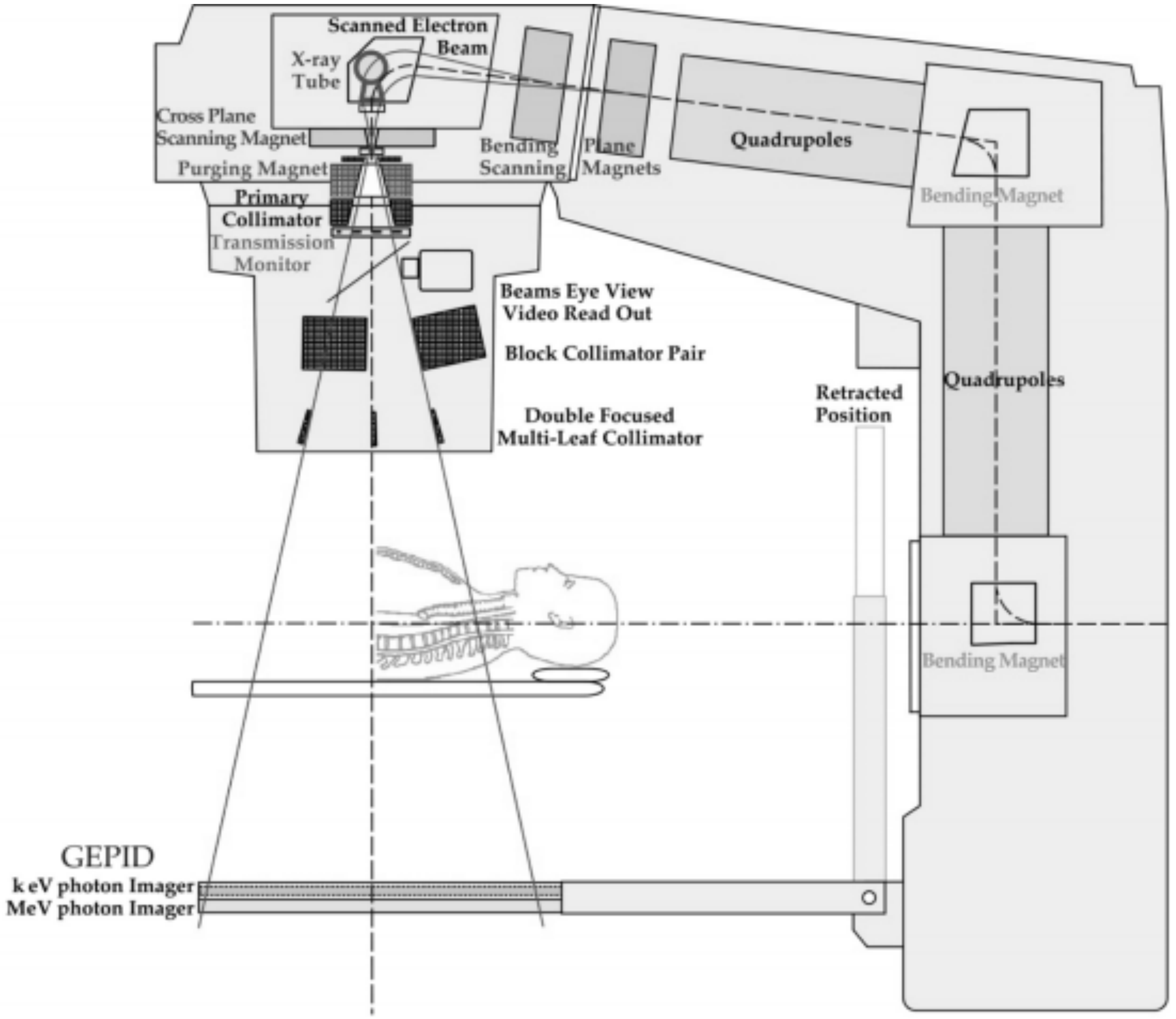


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Portal imaging in radiotherapy

Electronic portal imaging devices (EPIDs) are used for advanced beam monitoring and alignment of treatment beams with respect to tumour location.

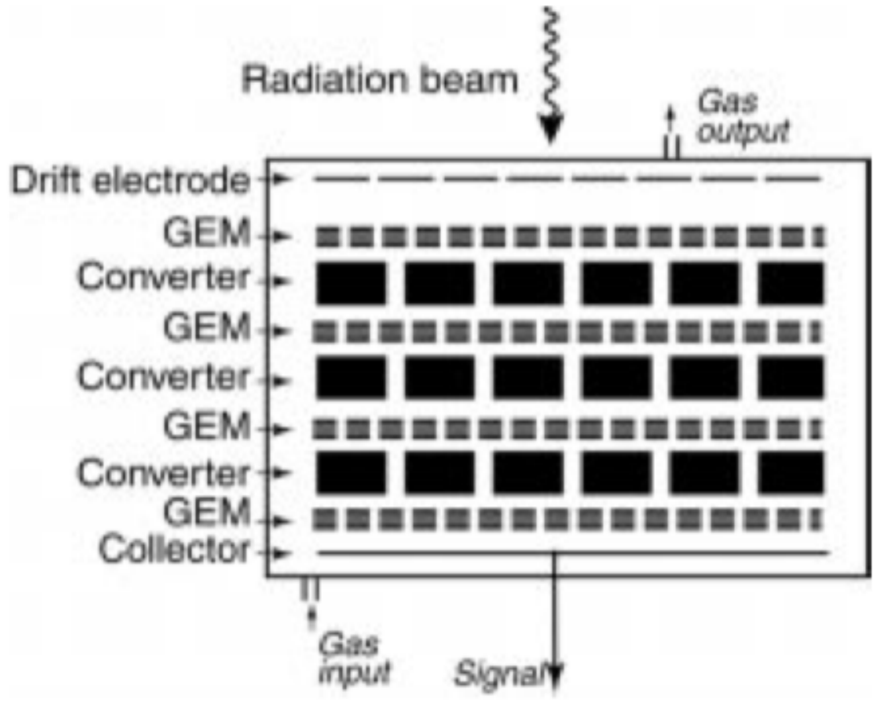


Detectors are required to be compatible with

- **high particle fluxes**
- **wide-range of photon energies**
- **moderate active areas**

Reliability and radiation hardness are key requirements of EPIDs.

Hybrid detector: Gaseous electron multiplier portal imaging device (GEPID)
keV photon detector: diagnostic tool, converter (photoeffect) + GEM
MeV photon detector: perforated metal converter (Compton electrons) + GEM



IACOBAEUS et al.: IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 48, NO. 4, AUGUST 2001
https://doi.org/10.1109/23.958386

Portal dosimetry in radiotherapy

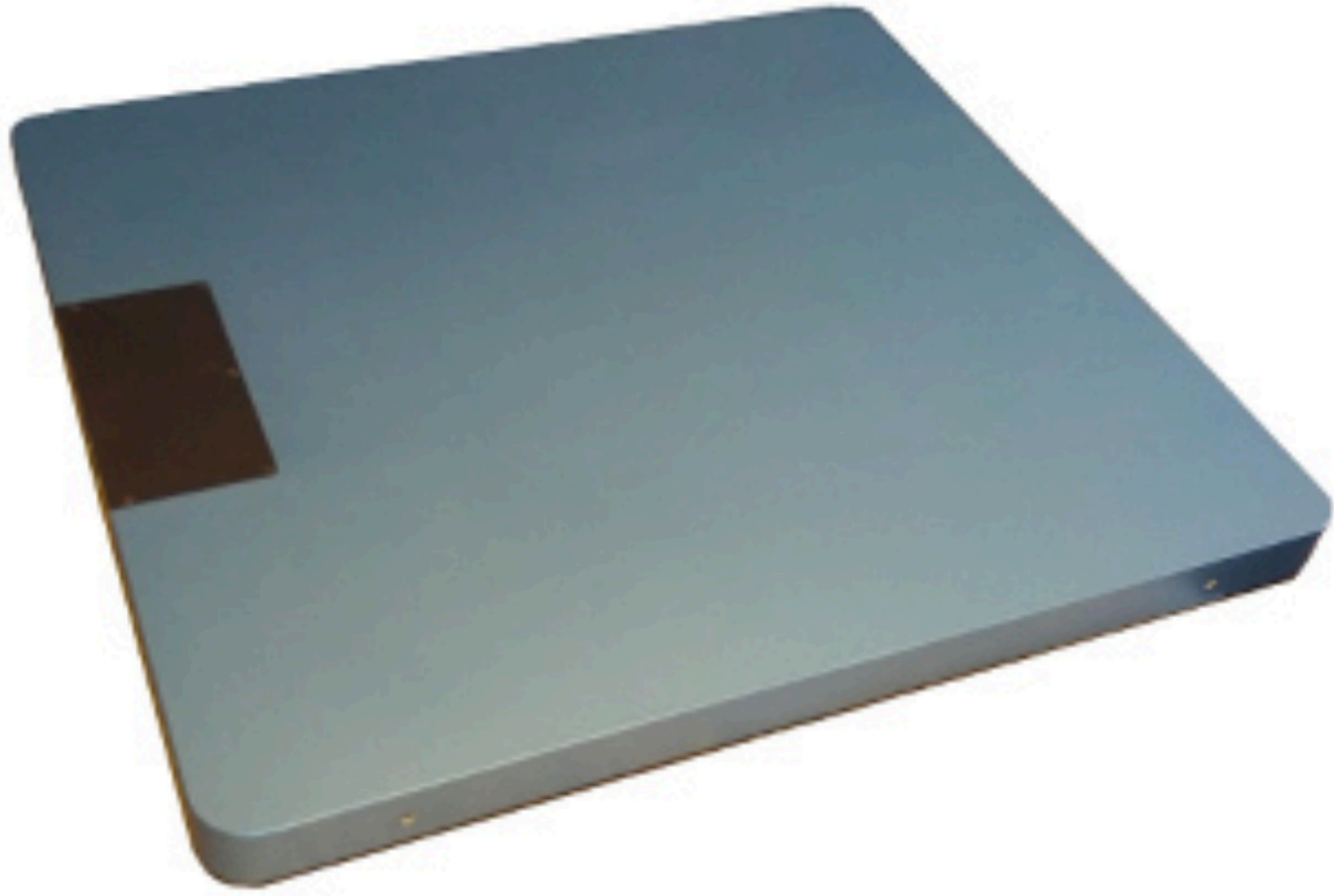
GEM-based X-ray detector **Gemini** optimised for Electronic Portal Imaging Device (EPID)

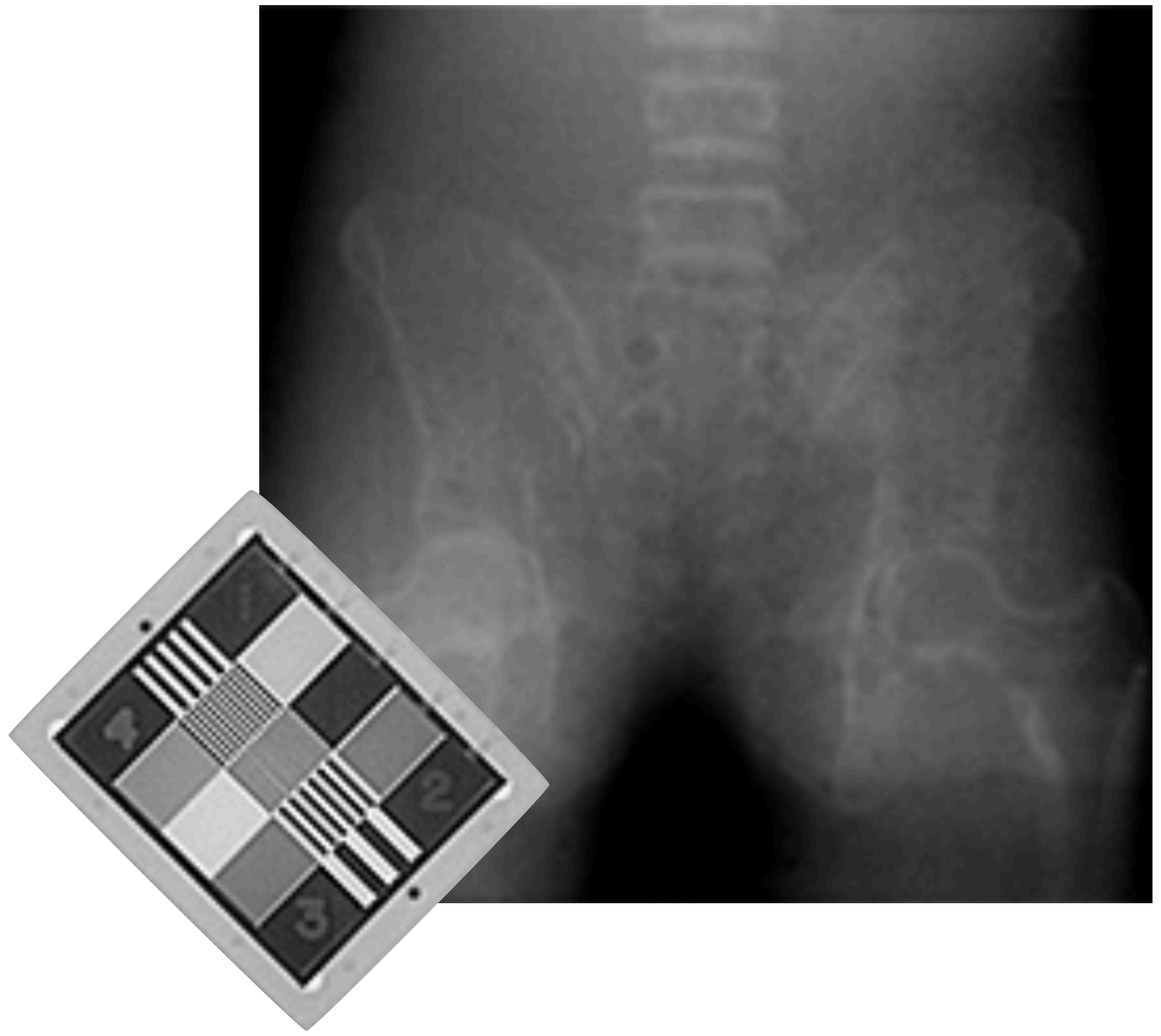
Intended for online verification of delivered dose distribution in radiotherapy treatments (Portal Dosimetry)

Detector requirements:

- **High spatial resolution**
- **High rate capability**
- **Dose accuracy**
- High **radiation hardness**

40 cm x 40 cm read out with 886 x 886 TFT pixel matrix
Sensitive to energy range of 1-50MeV
16 bit ADC
> 0.7 lp/mm at 6MV accelerator





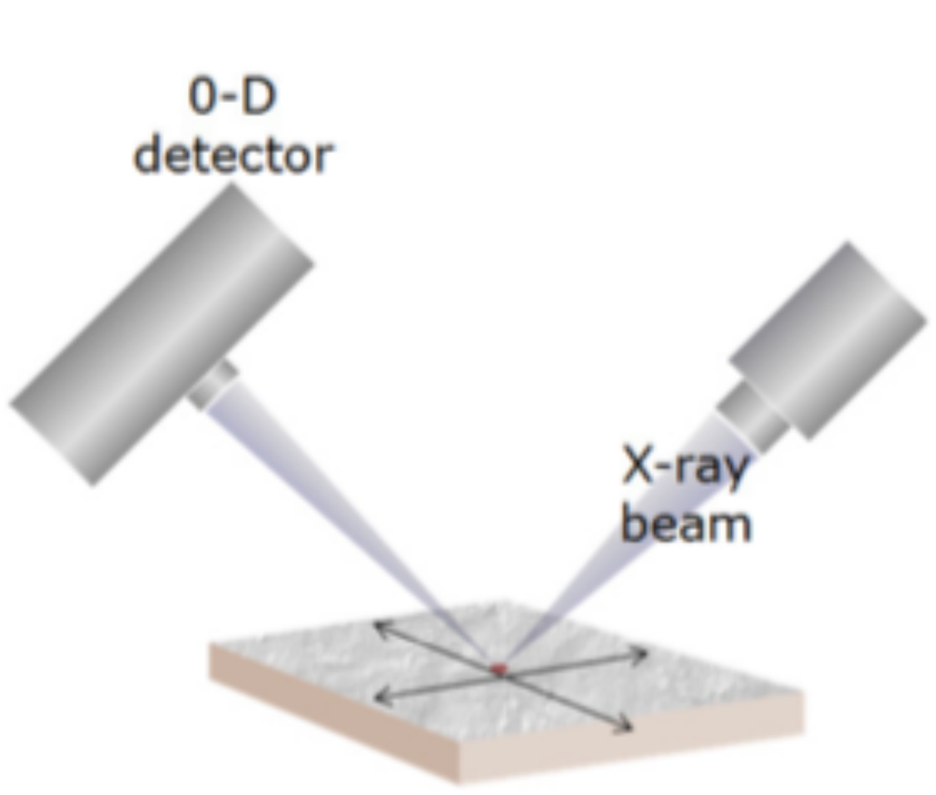
https://c-rad.se/product/gemini/

Cultural heritage studies

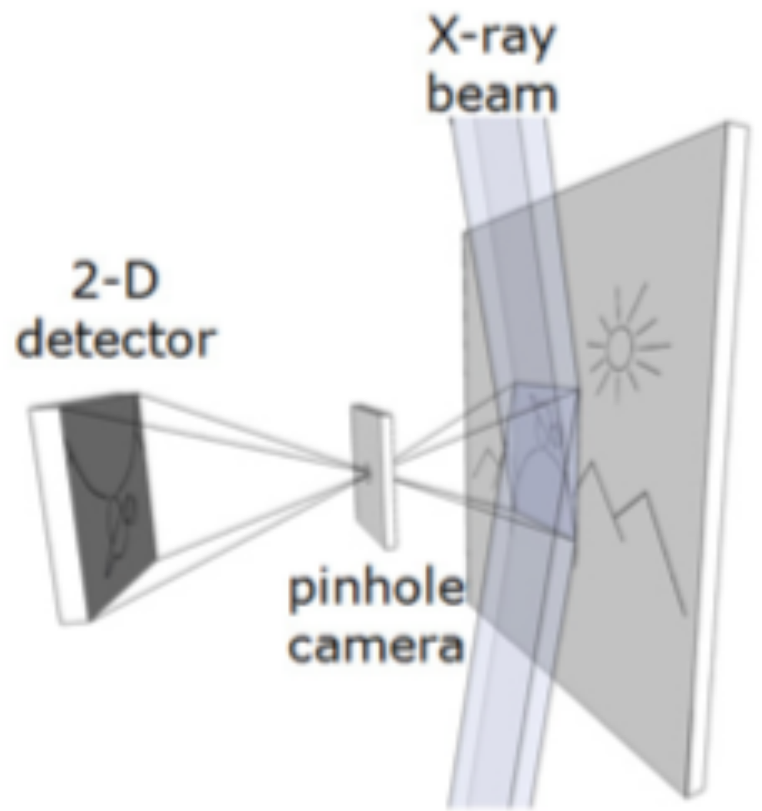
X-ray fluorescence

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.

Macro XRF

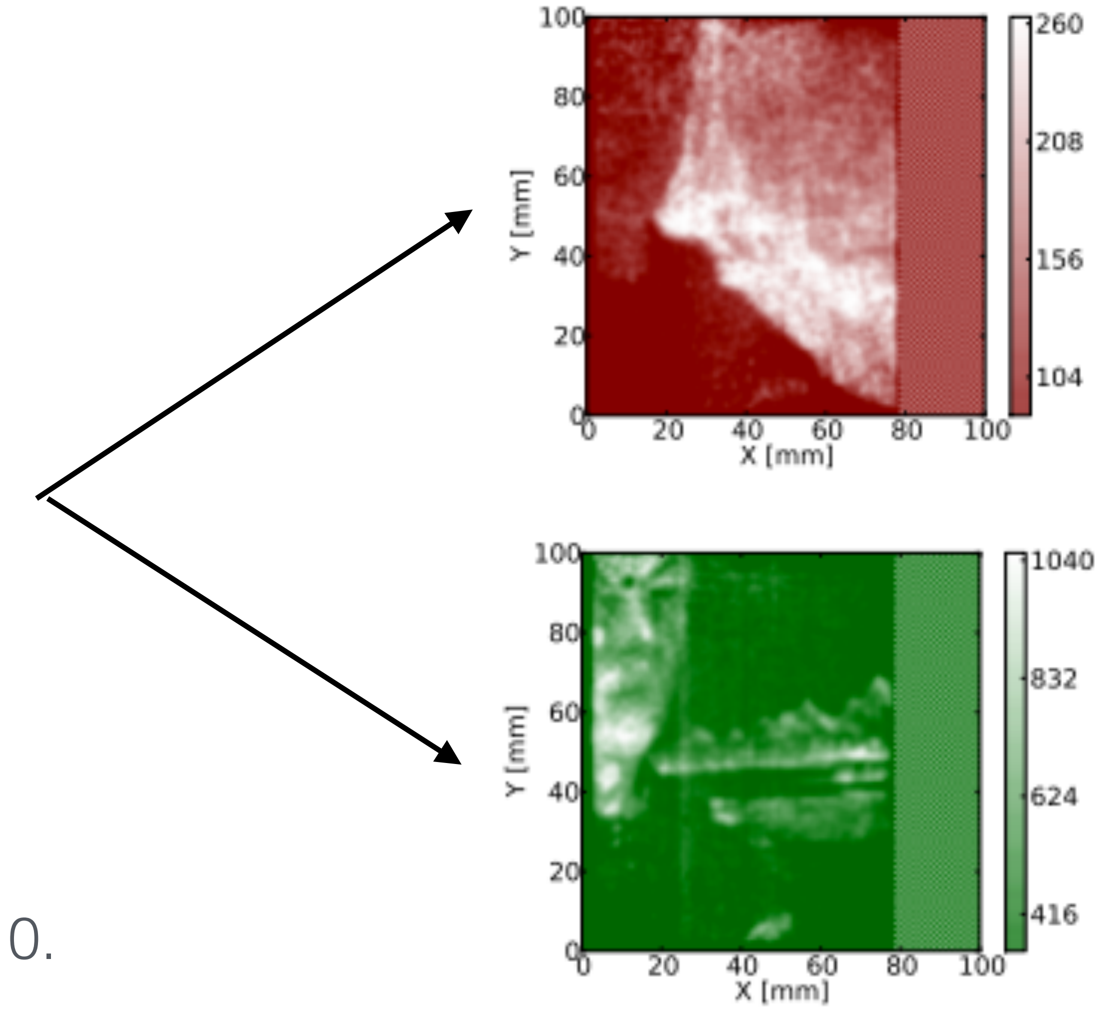


Full-field



W. Dbrowski et al 2016 JINST 11 C12025

Zielińska et al. JINST 8 (2013) 10.



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

Key advantages of MPGDs for EDXRF include:

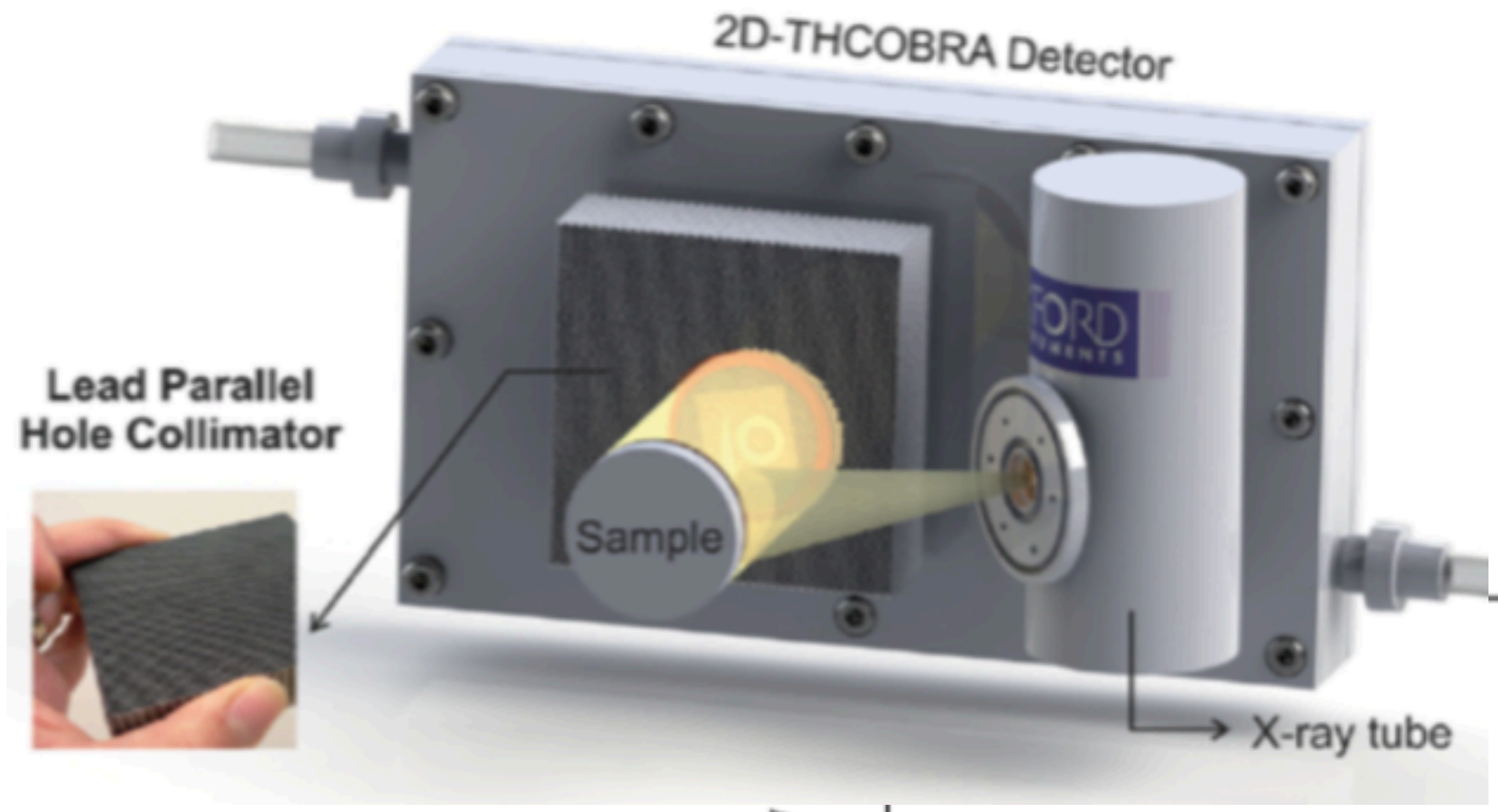
- 2D imaging with **high spatial resolution**
- **Versatility and in-situ operation**
- **High rate capability**
- **Low energy threshold** (sensitivity <1 keV)

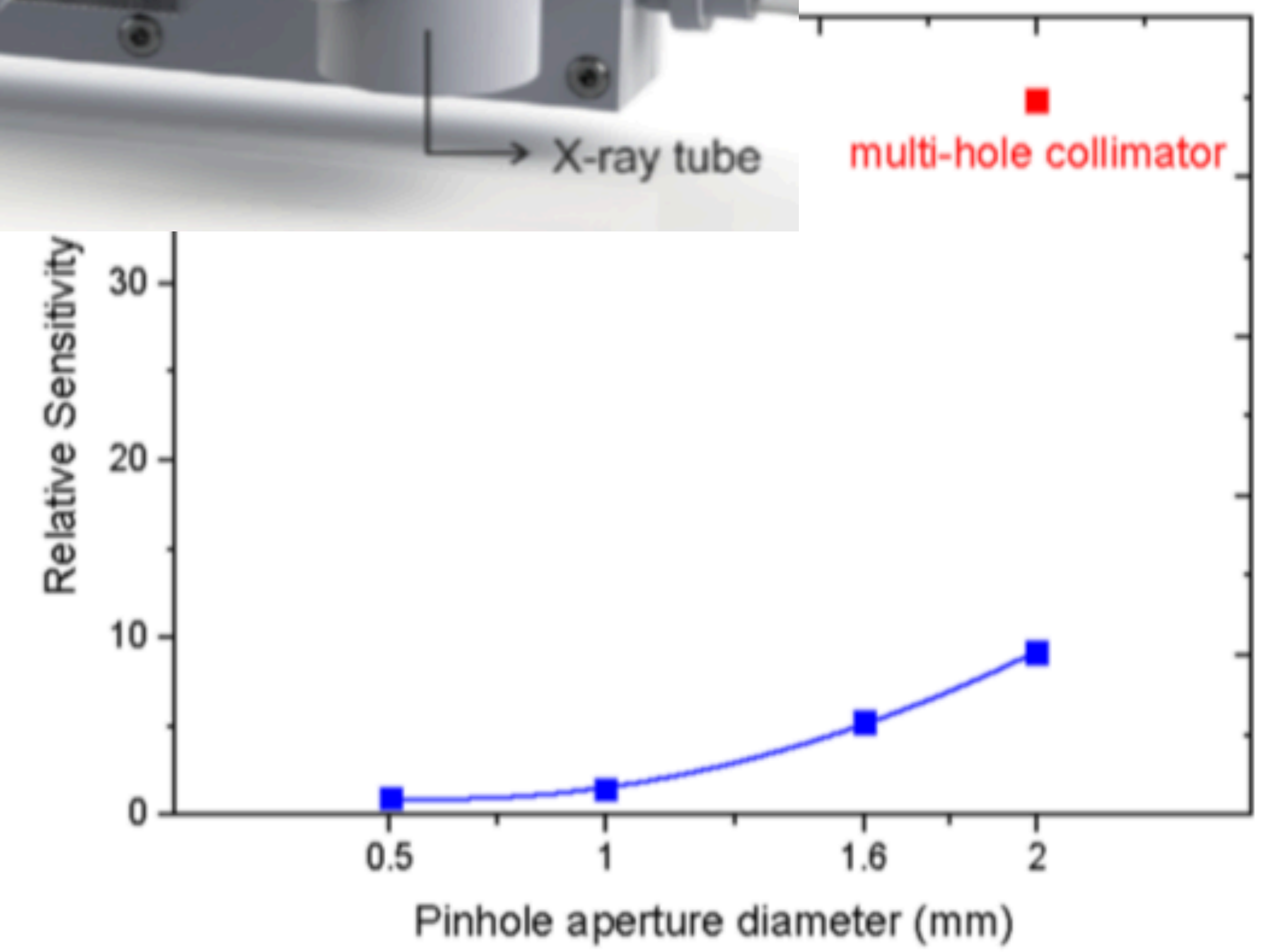
X-ray fluorescence

Structures >550μm can be distinguished (6 keV) with 0.5mm pinhole

Pinhole diameter strongly impacts sensitivity

Different MPGD varieties used including GEM, THCOBRA, Micromegas

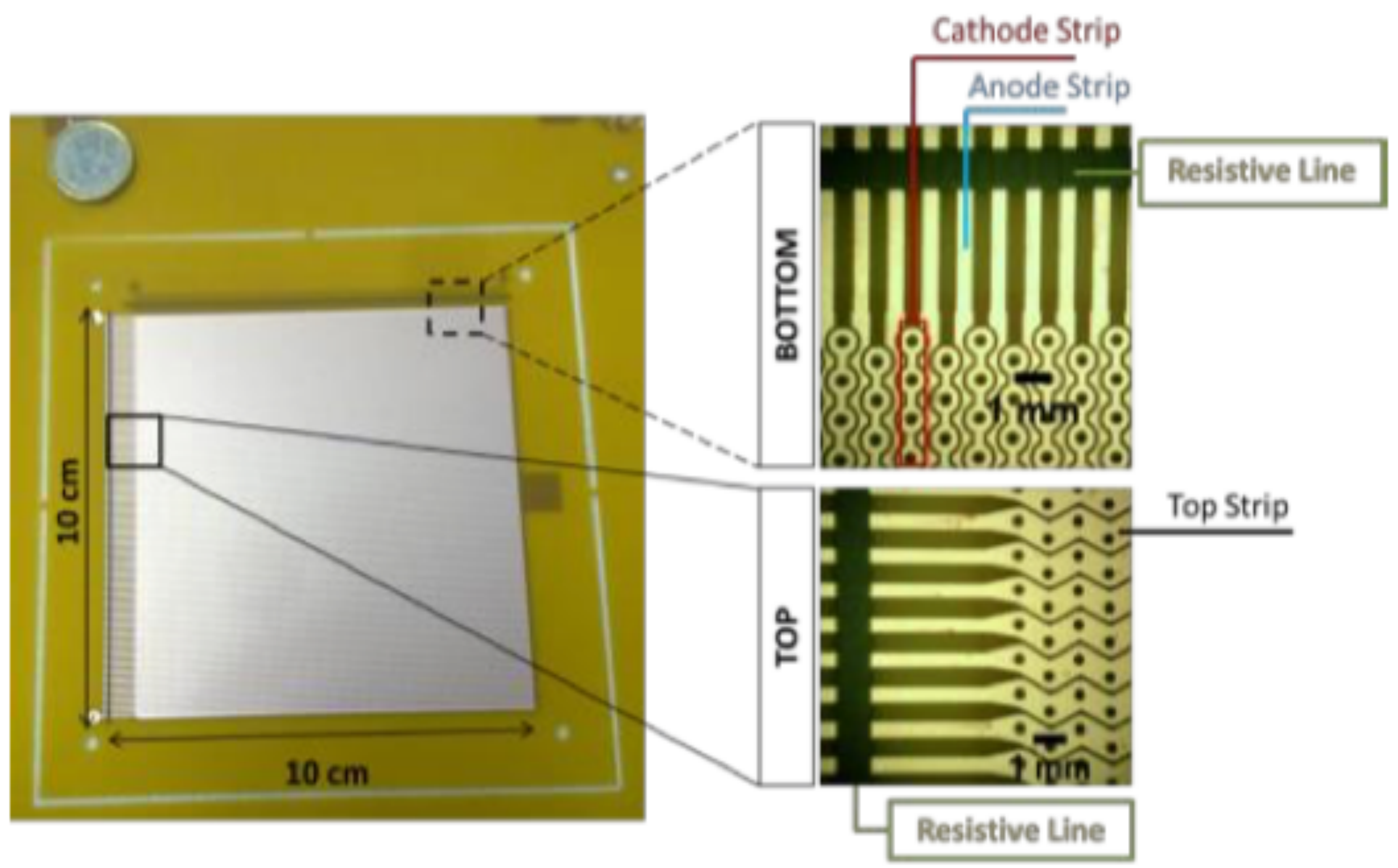




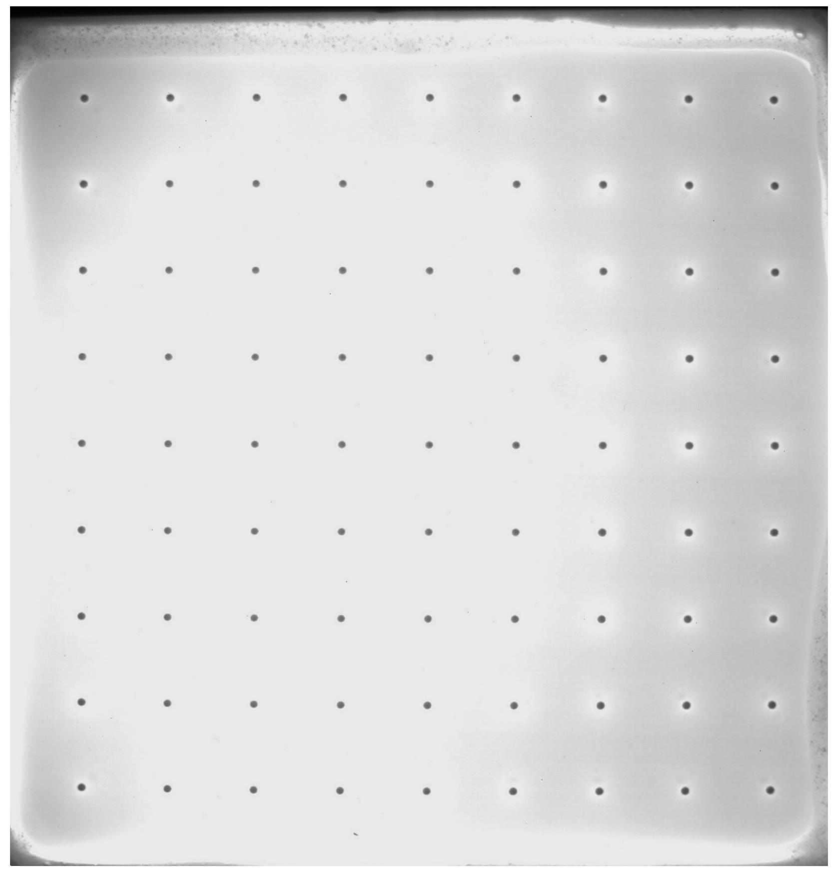
A.L.Silva (Poster): Technological aspects and properties requirements of MPGDs for Energy Dispersive X-ray imaging analysis

T.A. Fiutowski (Poster): Noise optimisation of GEM-based full-field XRF imaging system

Silva et al. J. Anal. At. Spectrom., 2015,30, 343-352
DOI: 10.1039/C4JA00301B



THCOBRA



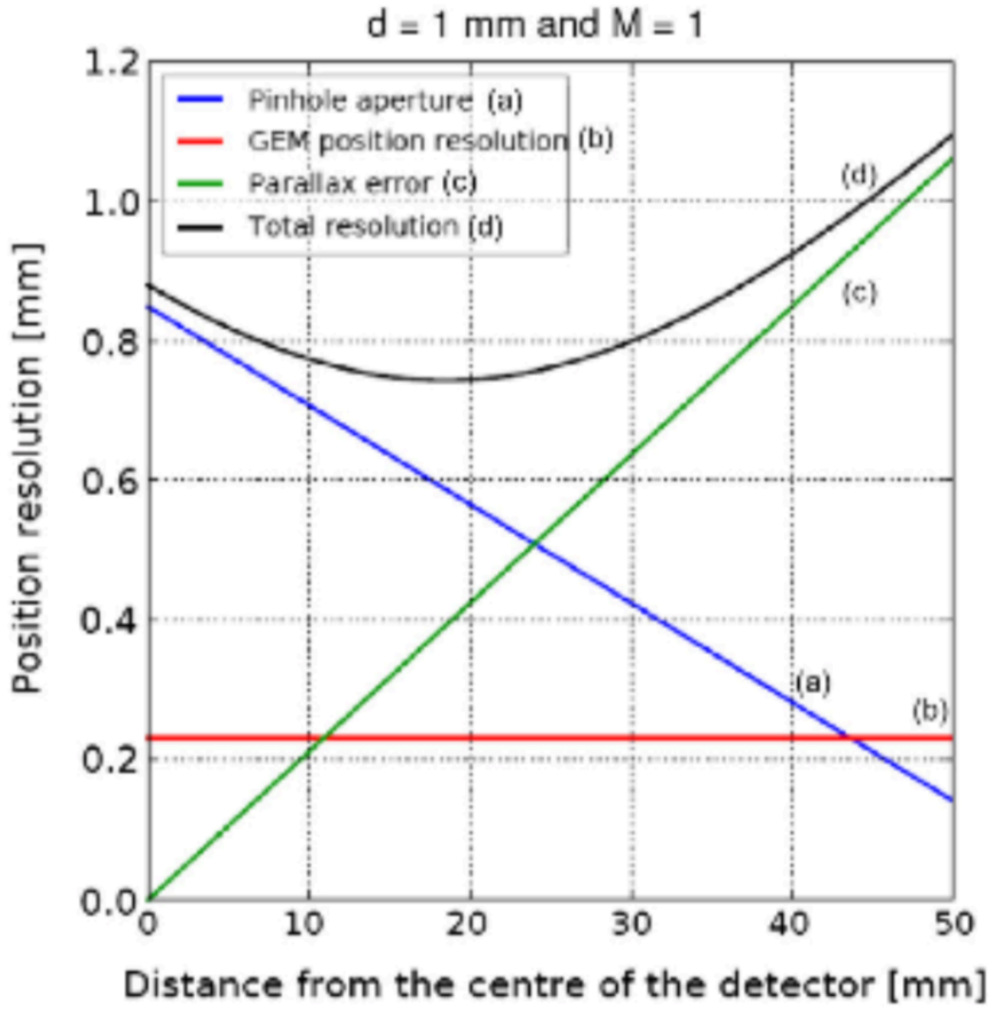
Micromegas

Minimising parallax error

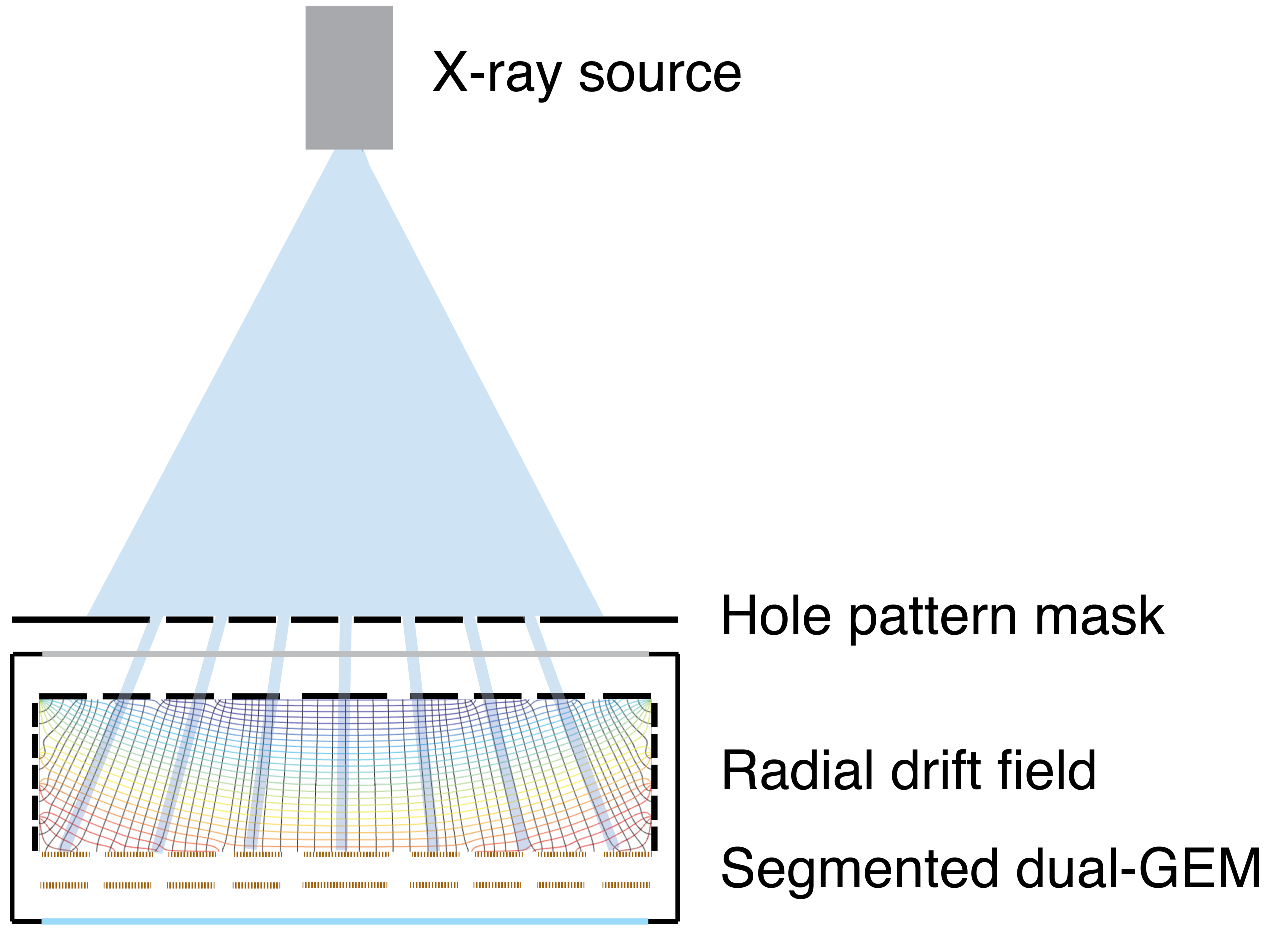
Parallax-induced broadening degreased spatial resolution in outward regions of detector used for EDXRF.

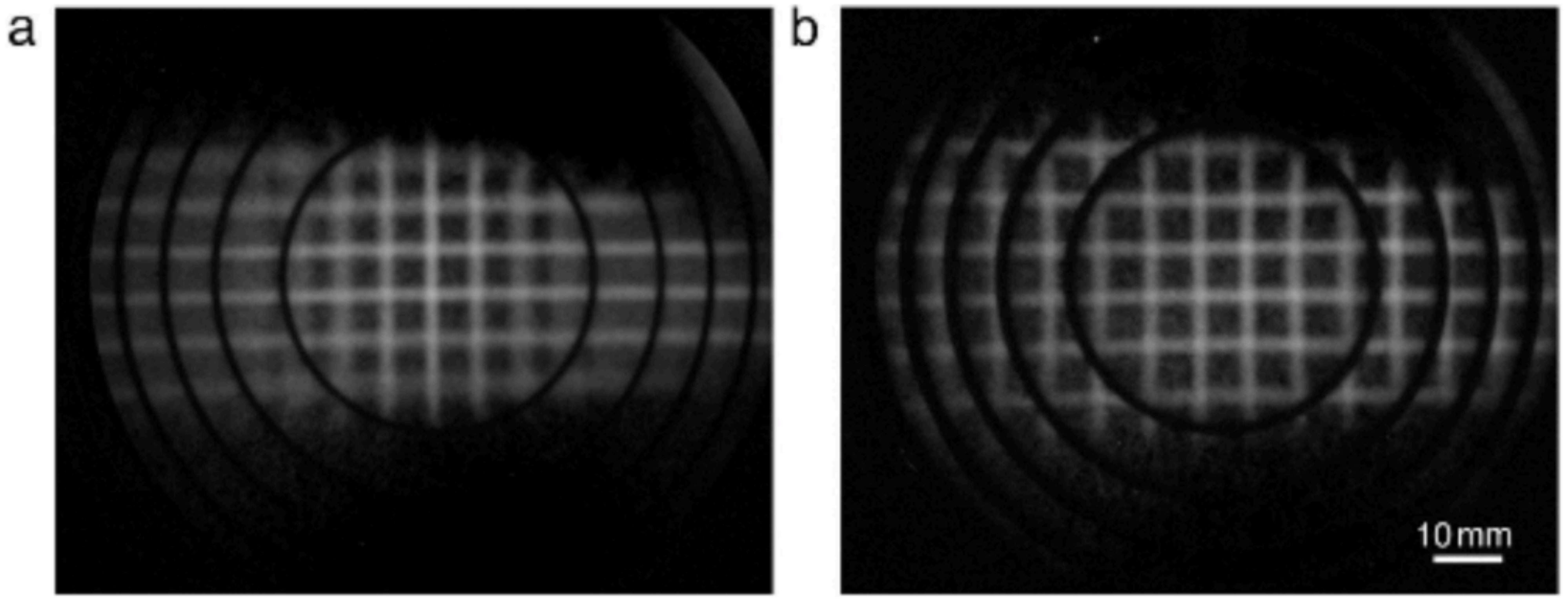
A radially focused drift field can be used to **mitigate the parallax error** and preserve **high spatial resolution** across the active area

The improvement of the radially focused case (b) in comparison to the standard drift field (a) can be seen in the Cu grid fluorescence image.



Veloso et al. Nuclear Inst. and Methods in Physics Research, A 878 (2018) 24–39



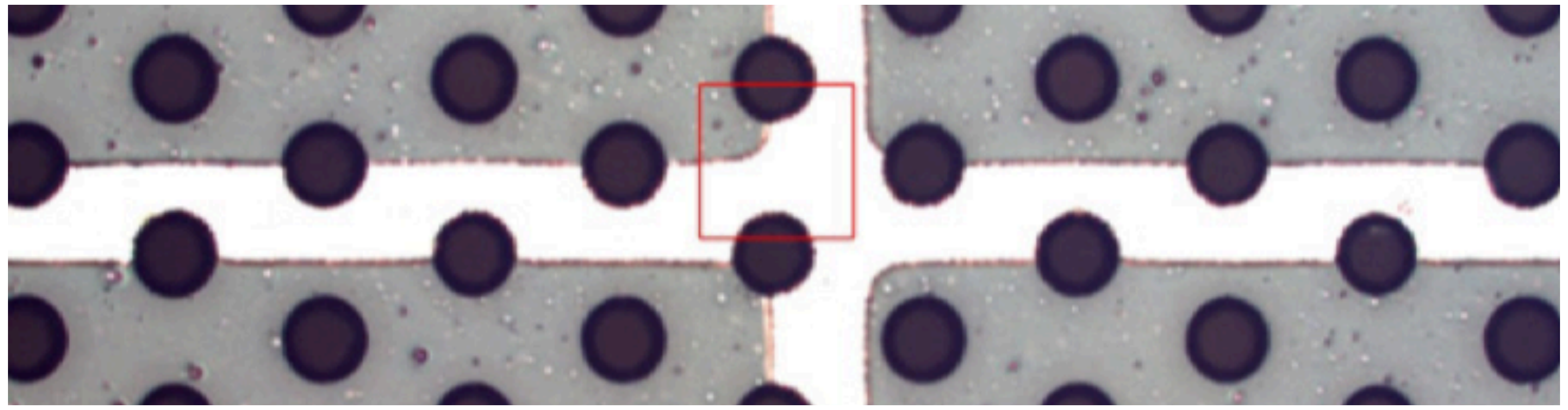


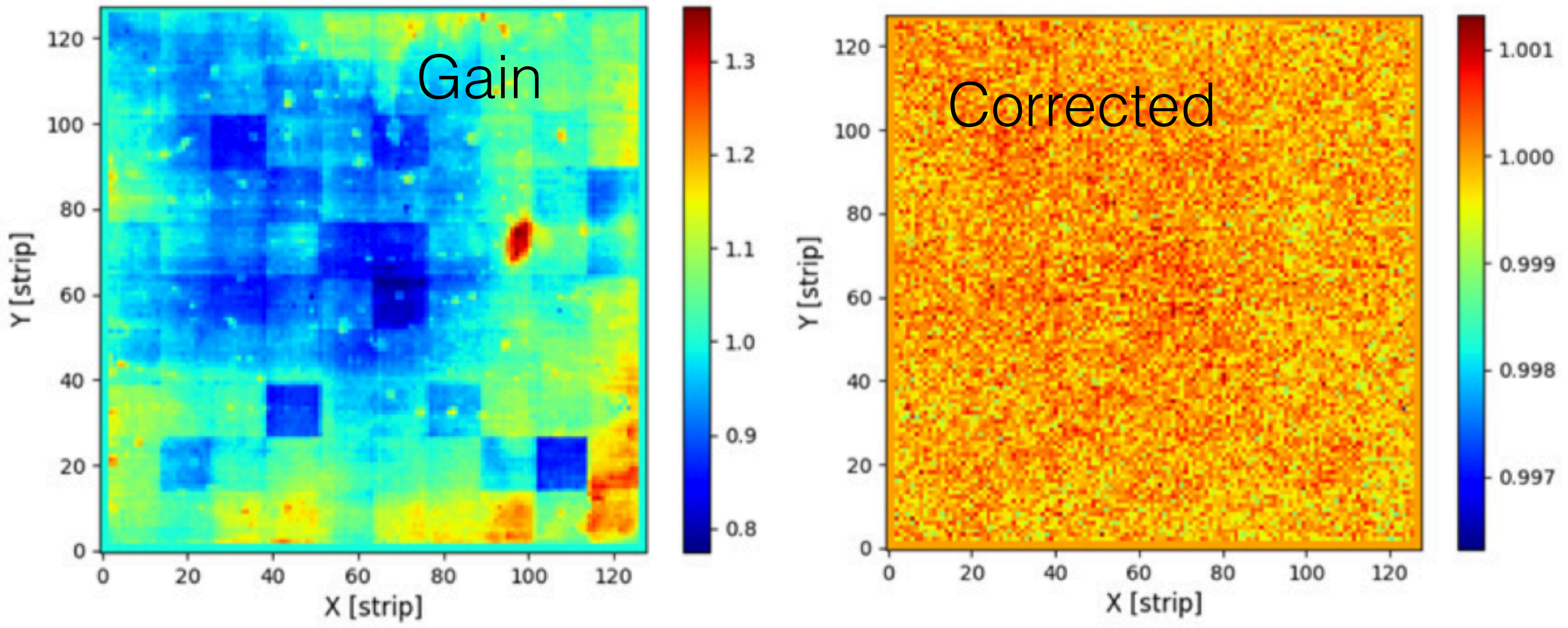
F.M. Brunbauer et al. al. Nuclear Inst. and Methods in Physics Research, A 875 (2017) 16–20
https://doi.org/10.1016/j.nima.2017.08.060

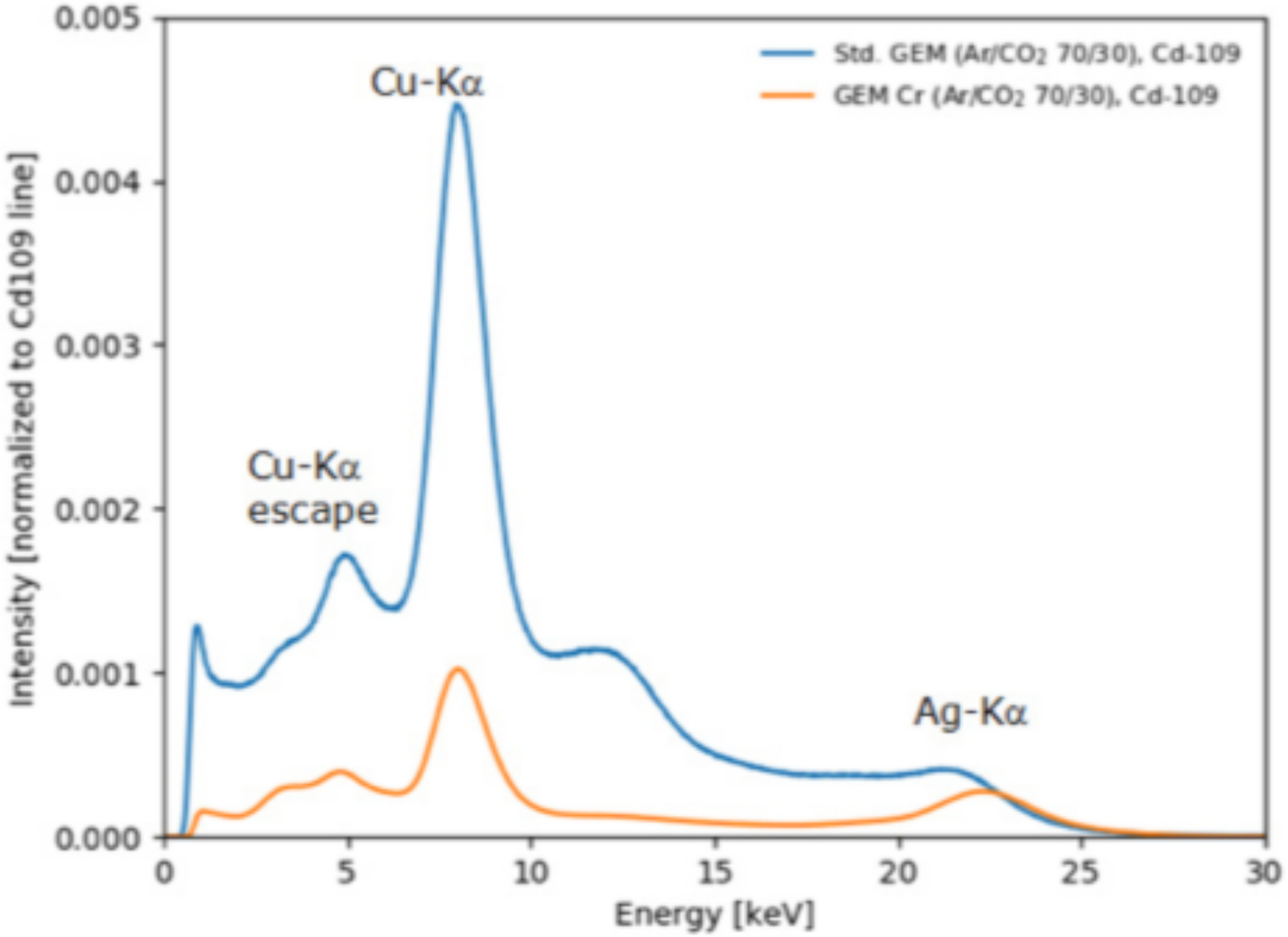
Chromium GEM

5μm **Cu layers** of standard GEM foils contribute **8 keV characteristic Cu fluorescence** which is close to several commonly used pigments

Cu layer can be removed with thin Cr layer acting as electrode in low rate environment (XRF)
Thin Cu grid (100μm strips) remaining for mechanical stiffness and electrical contact







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

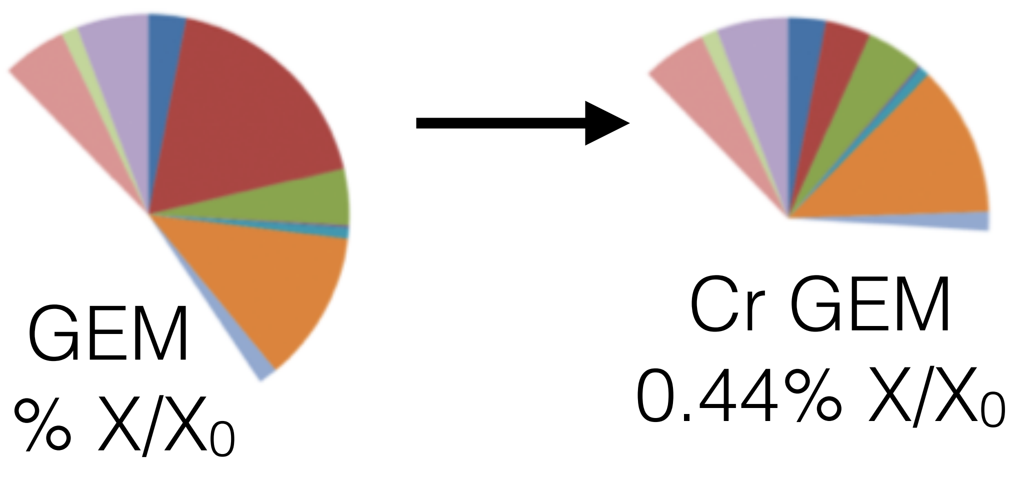
Low material budget

S. Caiazza (Wed): GEM detectors for the MAGIX focal plane: minimising materials for low energy experiments

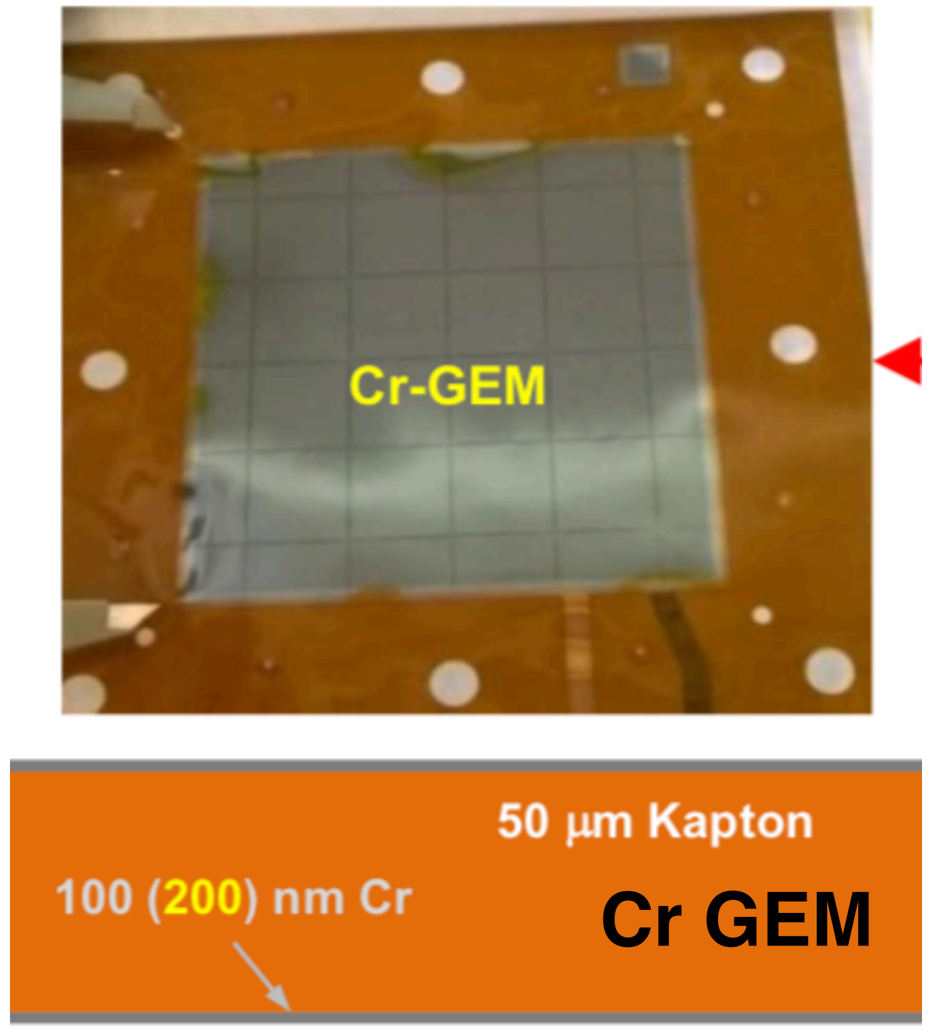
B. Mindur (Poster): Chromium GEM detectors performance studies

L. Shang (Thu): Development of high-performance DLC resistive electrodes for MPGDs

Chromium GEM

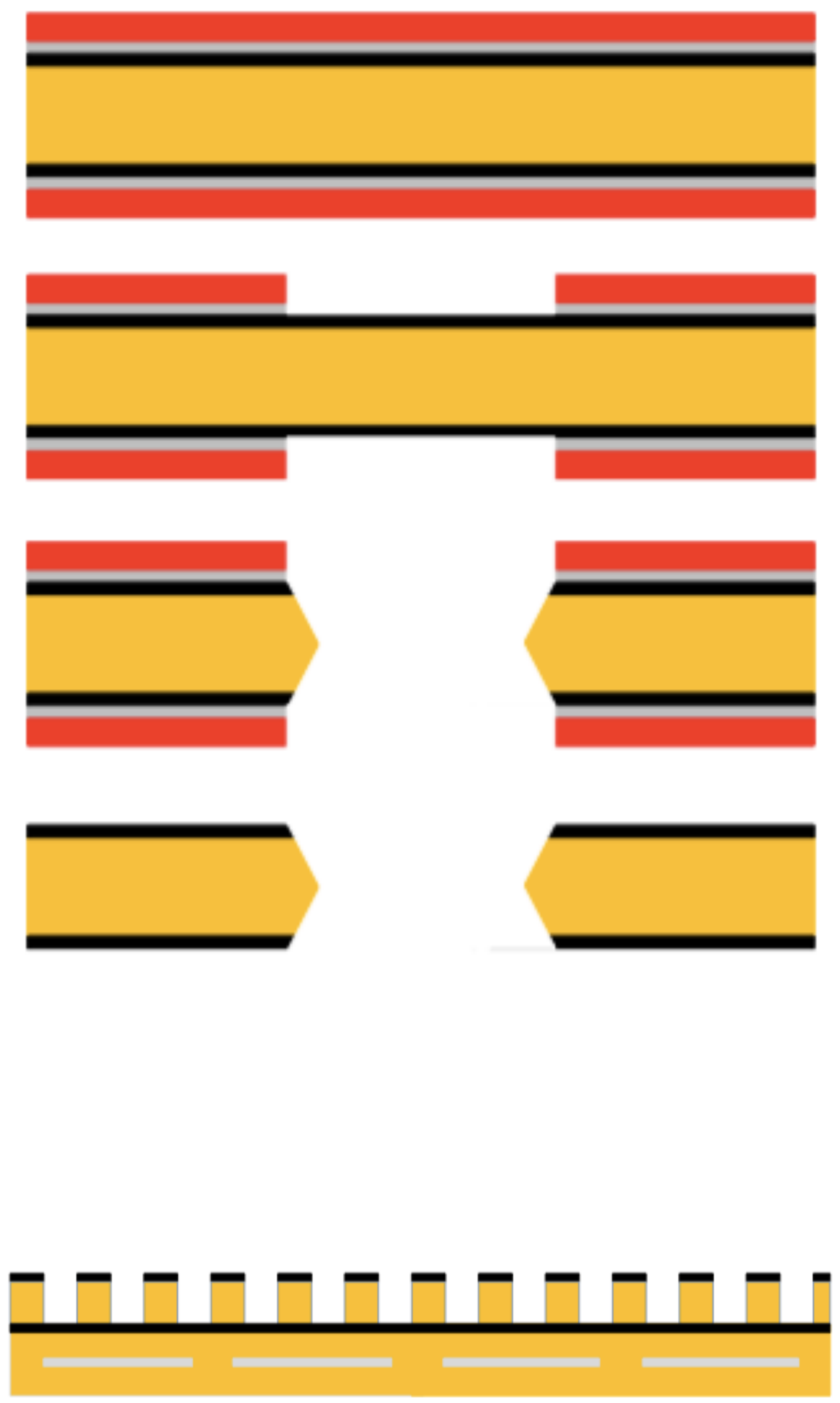


S.Caiazza, RD51 Mini week, Feb, 2018
https://indico.cern.ch/event/702782/



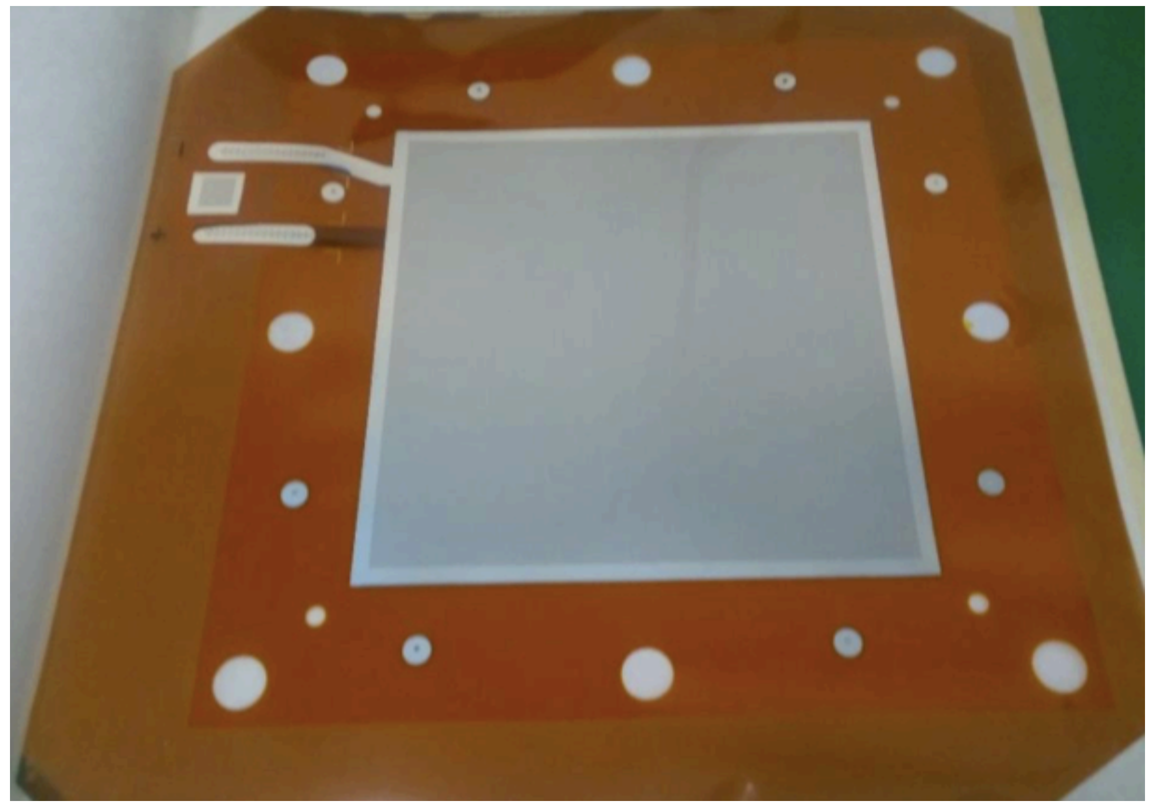
K. Gnanvo, RD51 Mini week, Dec 2017
https://indico.cern.ch/event/676702

DLC GEM & μRWELL



R. De Oliveira, RD51 Collaboration meeting, Jun 2018
https://indico.cern.ch/event/709670

Aluminium GEMs



R. De Oliveira, RD51 Mini week, Dec 2017 https://indico.cern.ch/event/676702

Muography

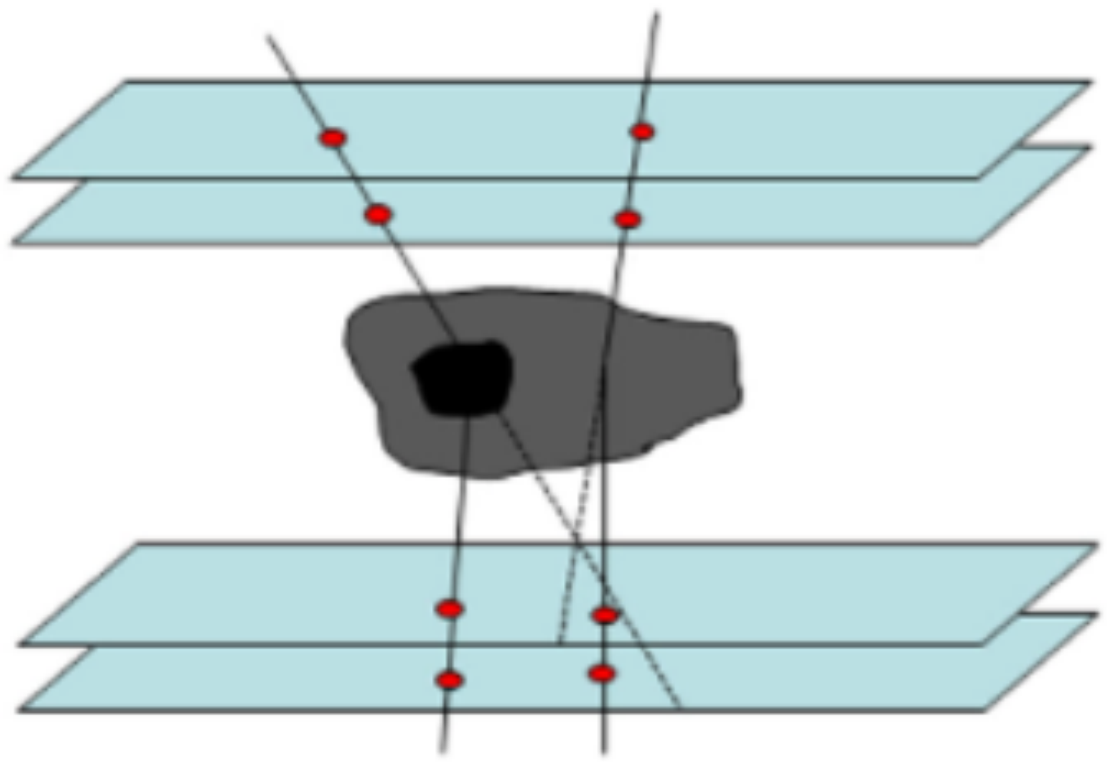
Muography

Muon imaging can be performed in deviation or transmission modes.

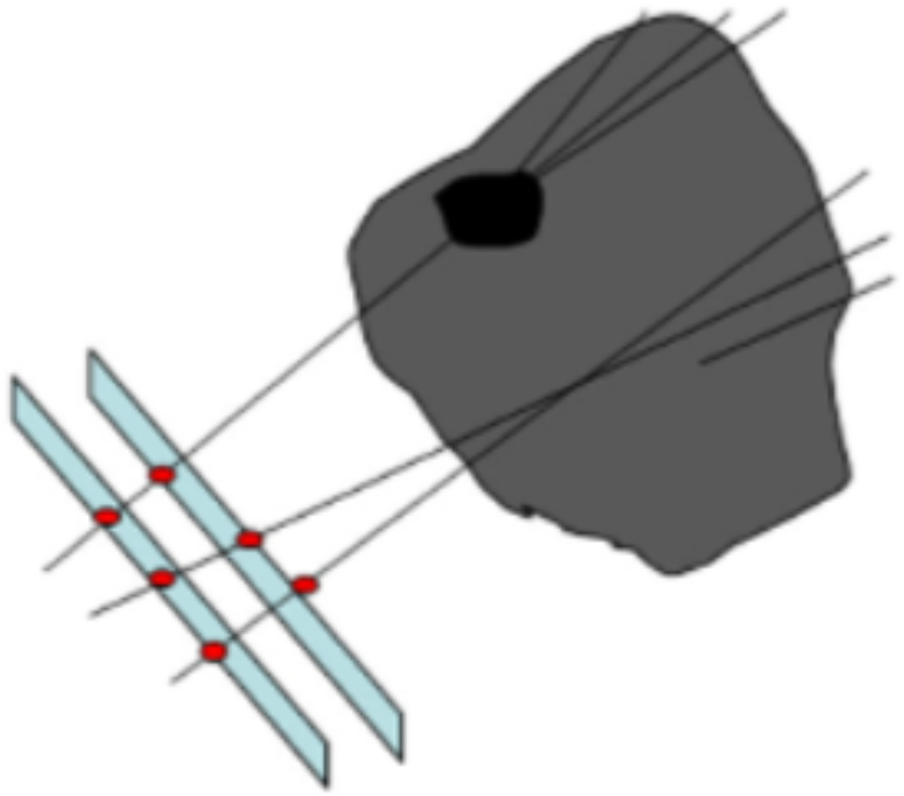
Key requirements for muography systems:

- **Large detection area** due to low muon flux (≈m^2)
- **Angular resolution** for accuracy (sub-mrad for deviation to 10mrad for transmission)
- **Versatility** and robustness for in-situ application

Deviation muography



Transmission muography



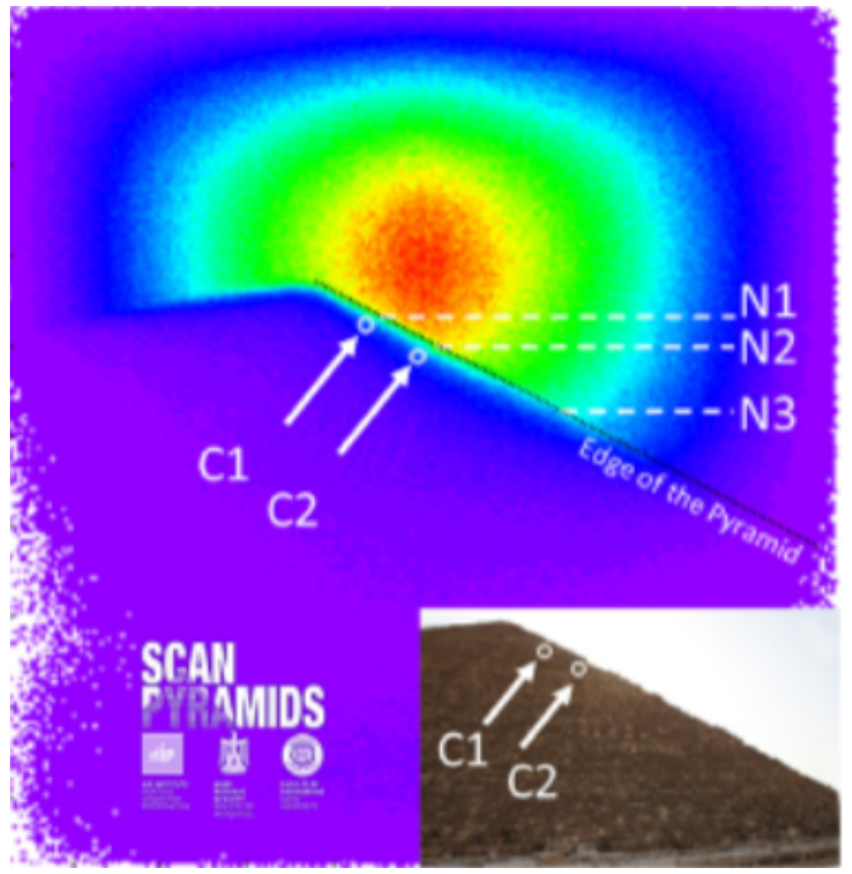
S. Procureur (Thu): New MPGD-based muon telescopes for ScanPyramids and associated R&D on gas consumption

H. Gomez (Poster): 3D Muography with a gaseous TPC equipped with 2D multiplexed Micromegas

I.L. Roche (Poster): T2DM2 muography project

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

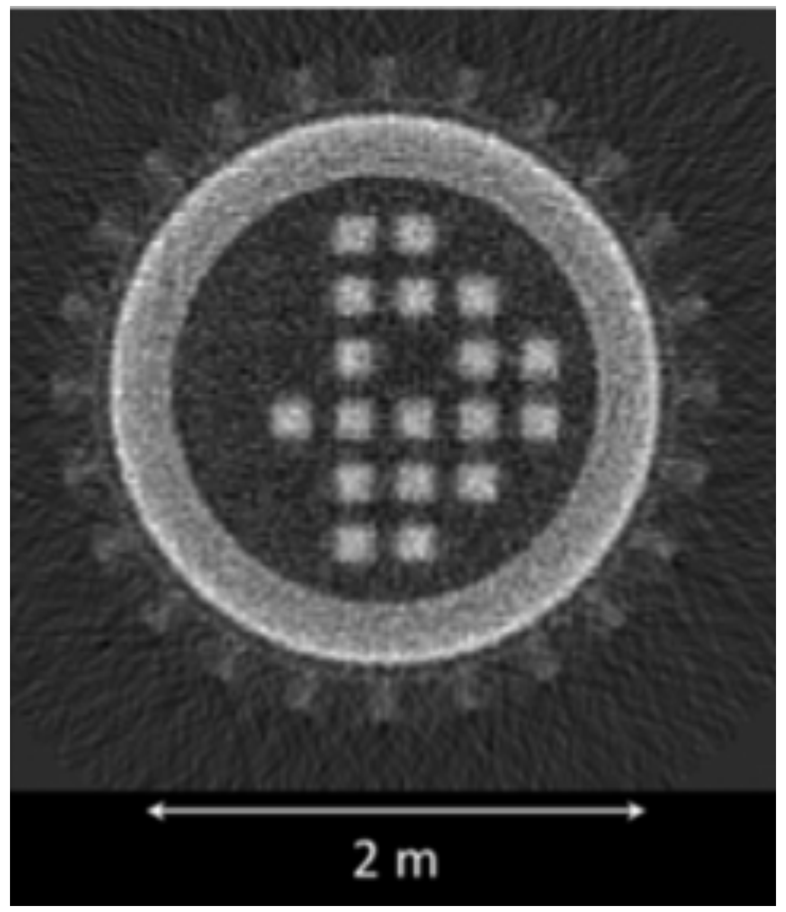
Muography



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.
Detectors had to be operated in harsh-conditions demonstrating high **versatility** and robustness.

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

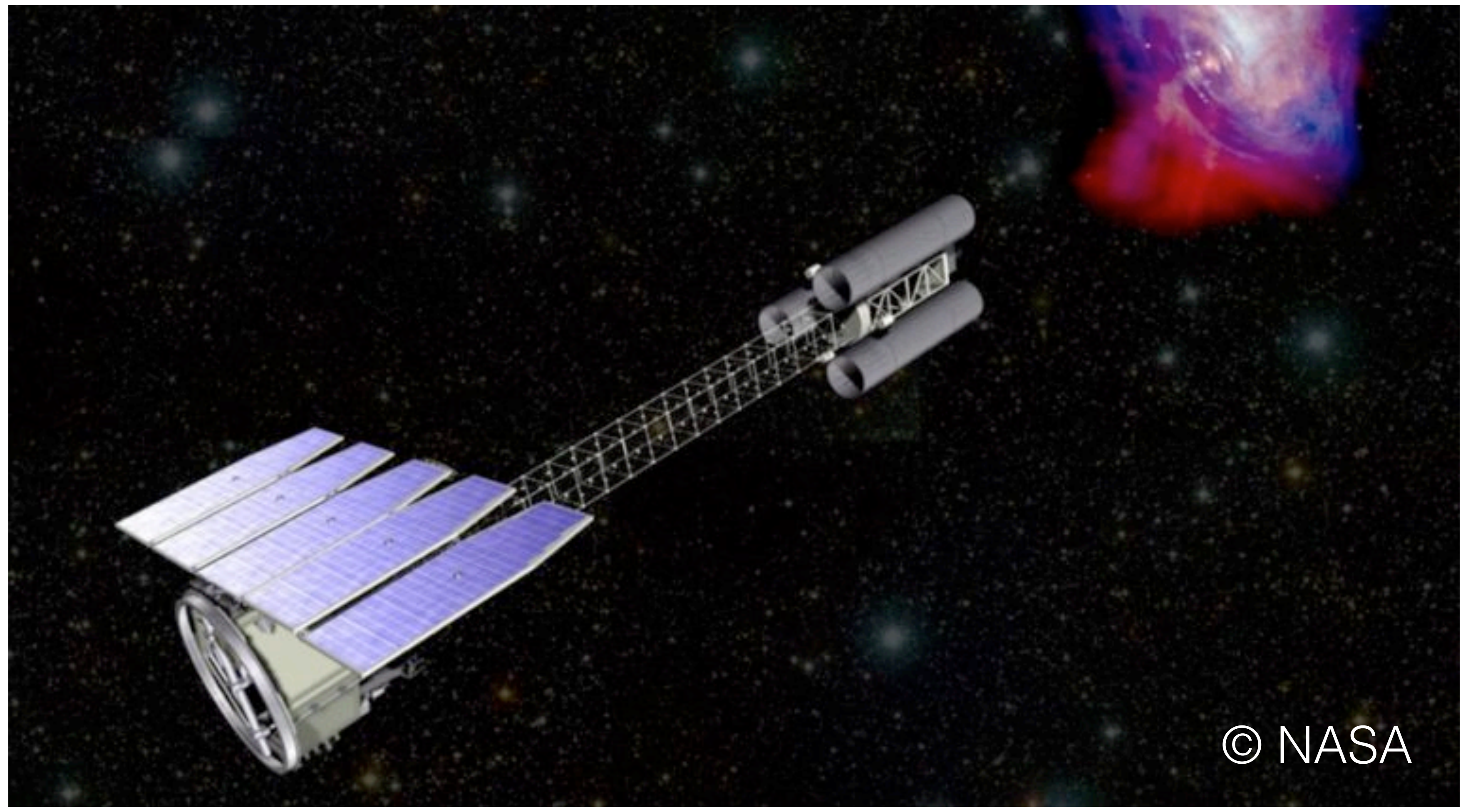
Astrophysical applications

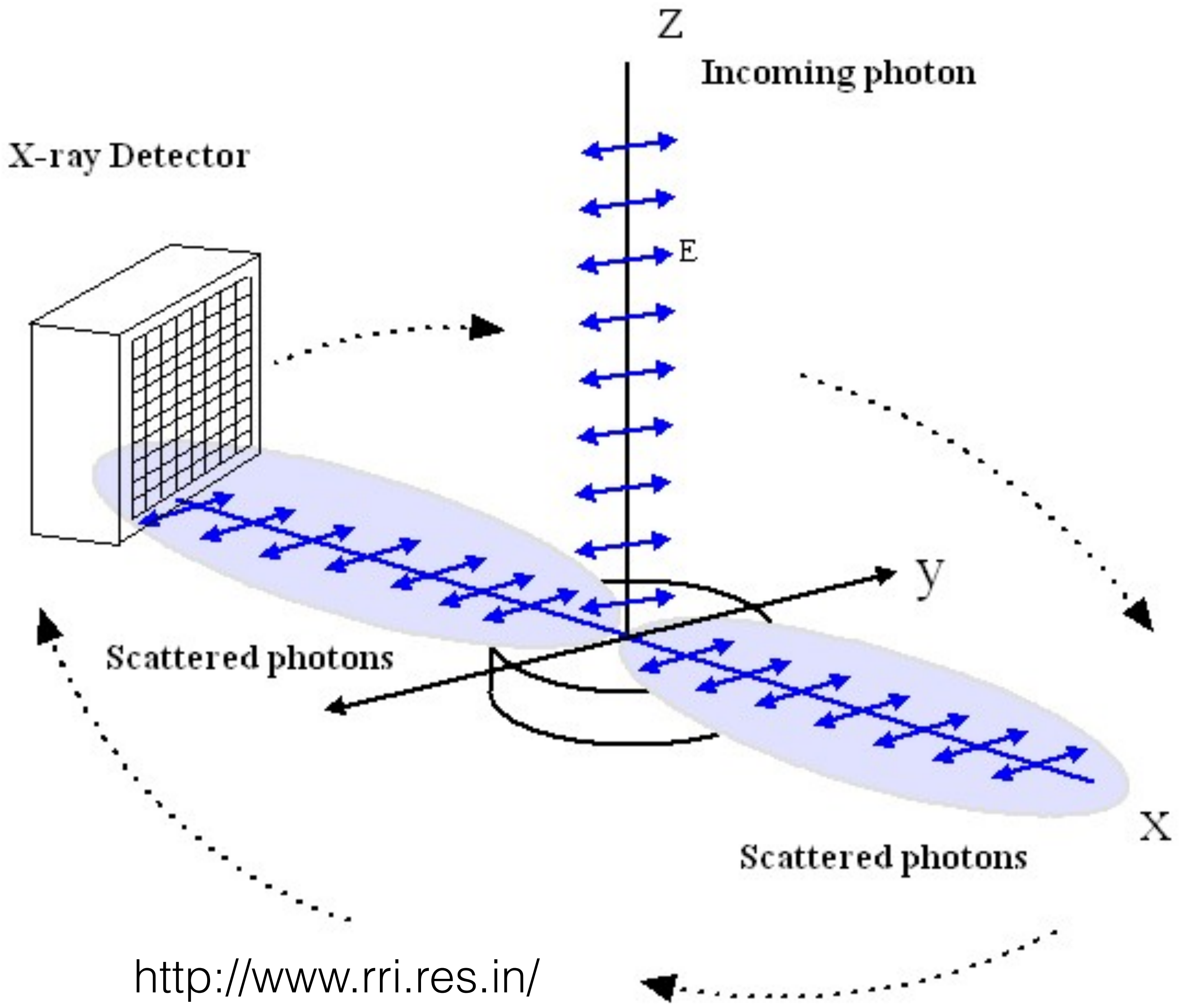
X-ray polarimetry

X-ray polarimetry can be used to study acceleration processes in astrophysical sources such as supernova remnants, the strong magnetic fields of neutron starts.
It relies on the correlation between the photoelectron emission direction and the electric field vector of the incident photon.

A main achievement was the detection of X-ray polarisation from the Crab Nebula.

The NASA mission Imaging X-ray Polarimetry Explorer (**IXPE**) is scheduled to launch 3 identical telescopes composed of Gas Pixel Detector (GPDs) in 2020. The detectors are targeted to the **2-8 keV energy band**.



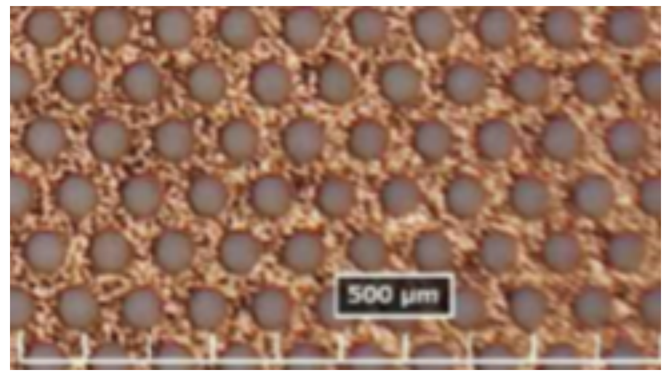


http://www.rri.res.in/~bpaul/polix.html

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

X-ray polarimetry

K. Uchiyama (Poster): Irradiation test with heavy ions of fine-pitch LCP-GEMs for the IXPE satellite mission

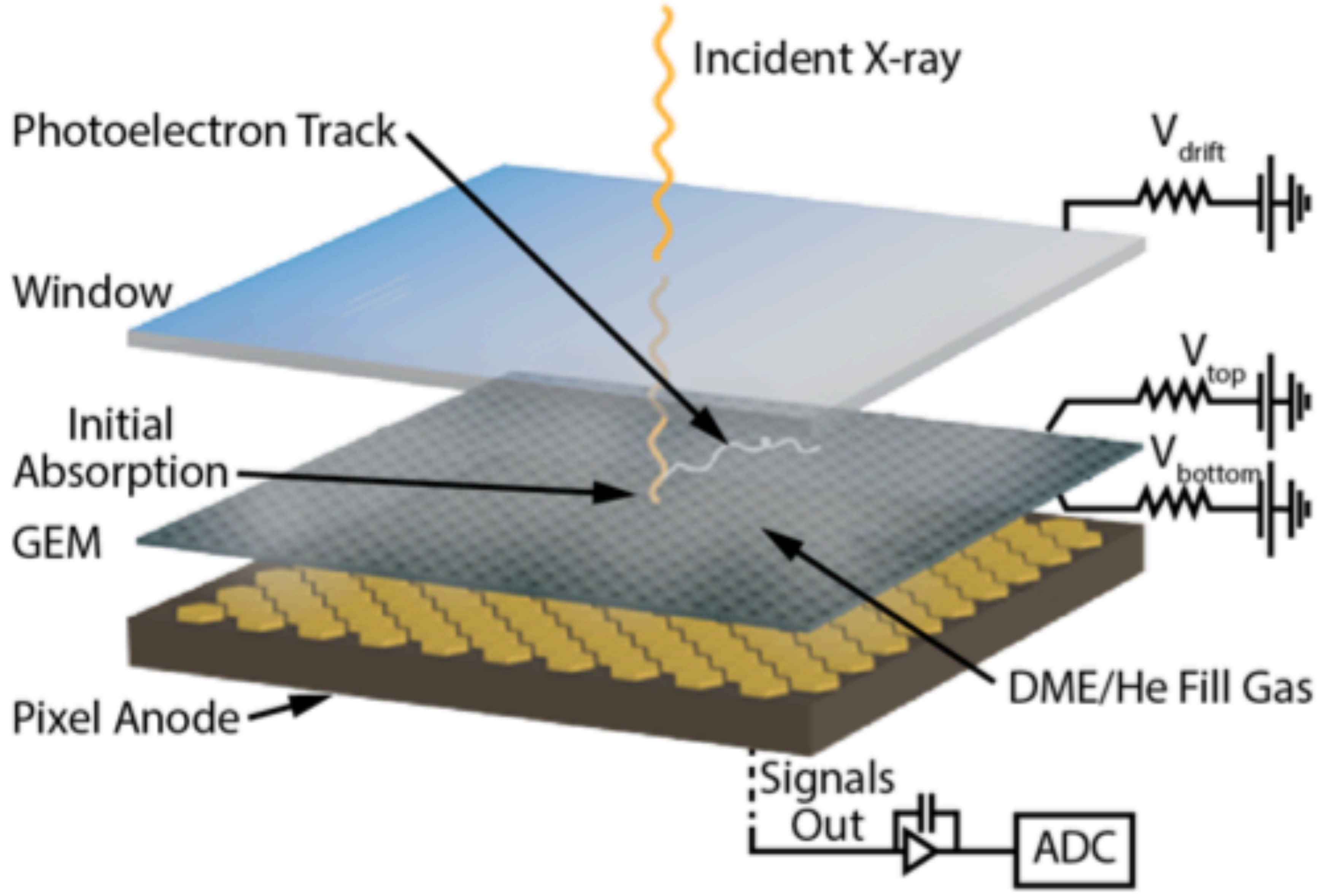


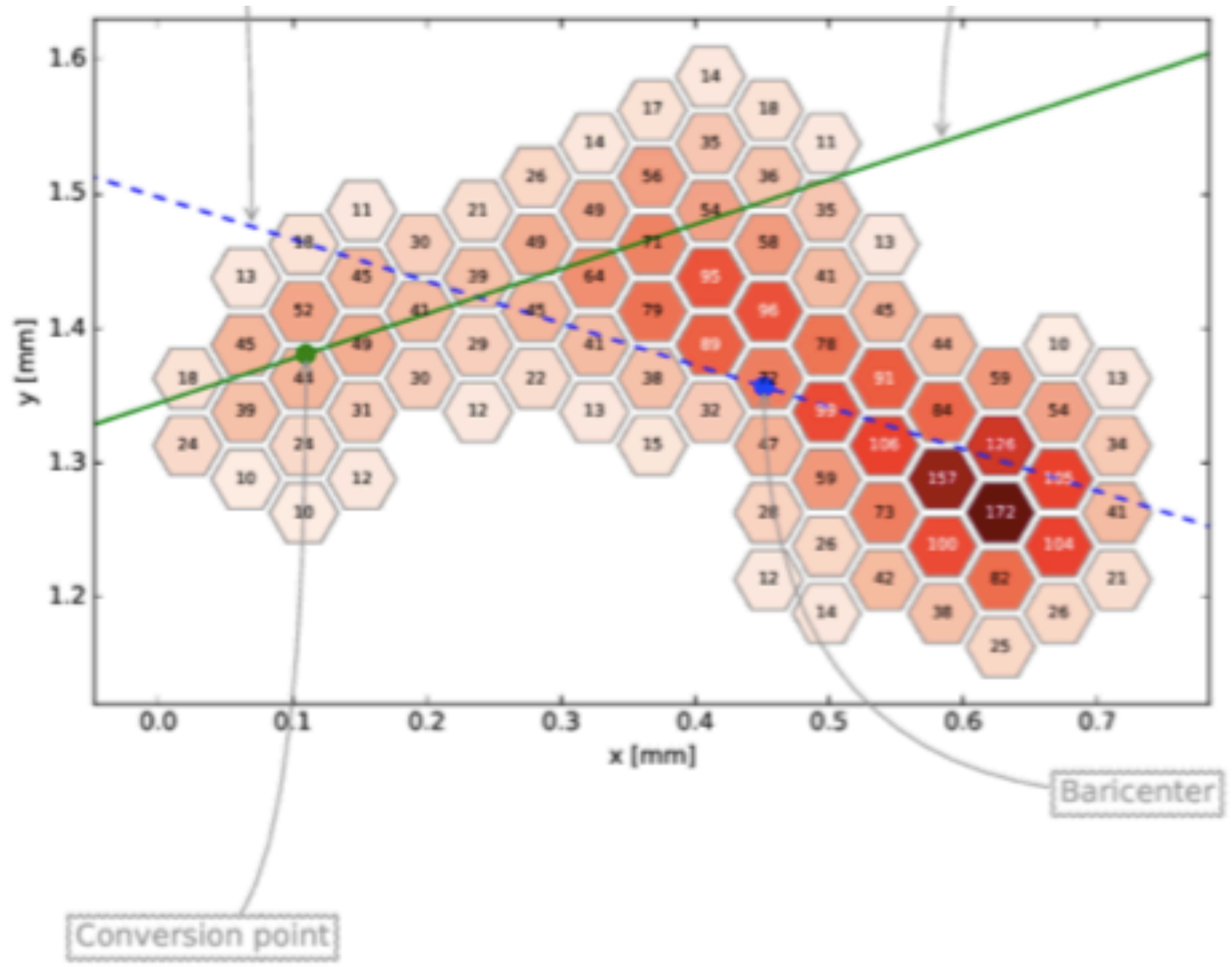
Gas Pixel Detector (GPD) for IXPE mission is based on a single GEM coupled to an ASIC as readout.

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 mm^2 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

Axion search

CERN Axion Solar Telescope (CAST) searching for axions and other exotic particles (e.g. chameleon) as candidate particles for Dark Matter and Dark Energy

Strong magnetic field (CAST: LHC dipole) is used to induce conversion of axions to soft X-ray photons

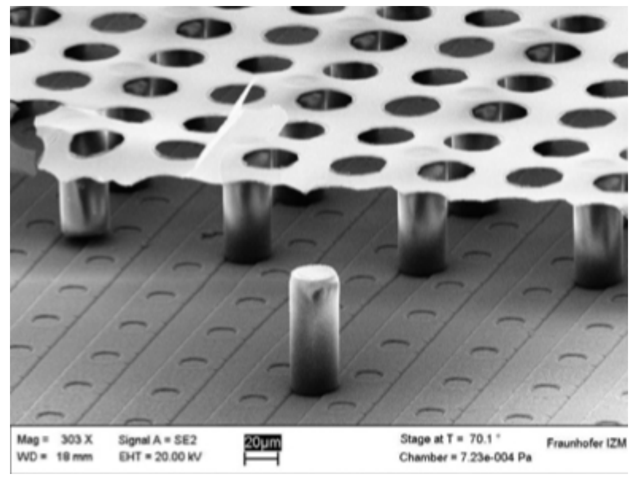
Detector requirements:

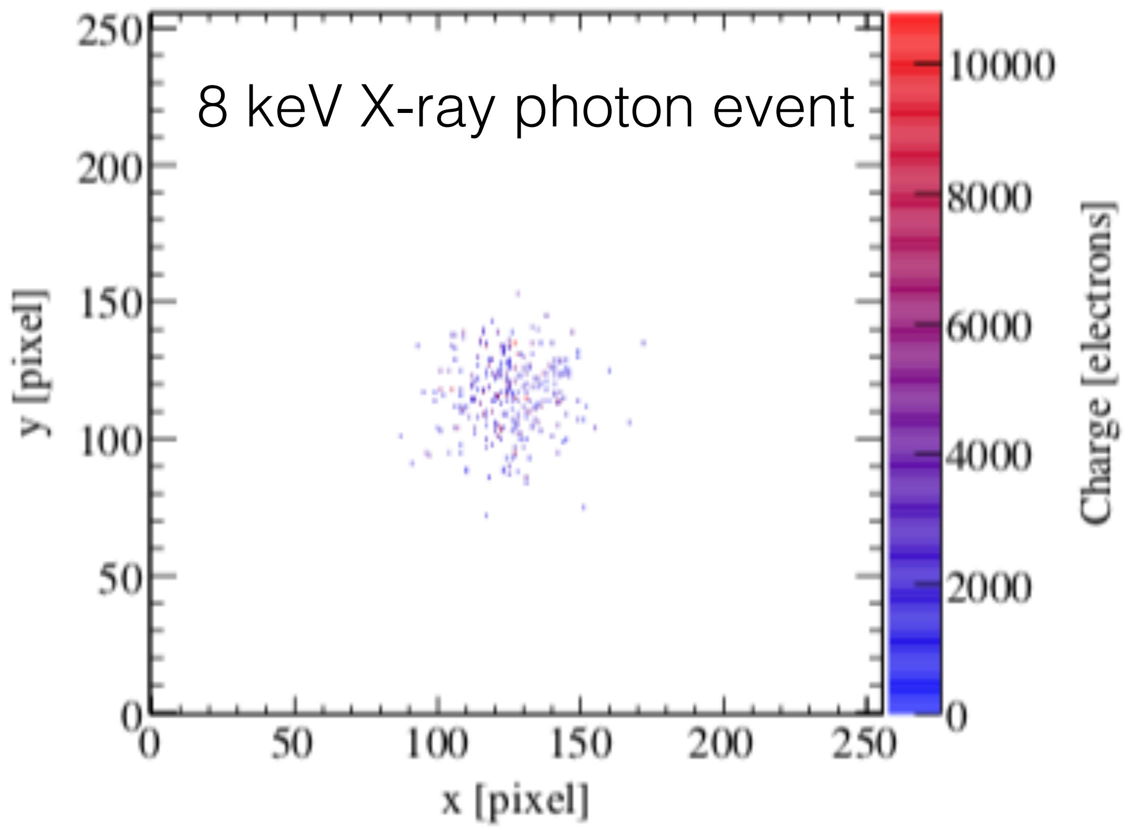
- **Low energy threshold**
- **Low background**, for **soft X-ray <1keV**
- **High spatial resolution**

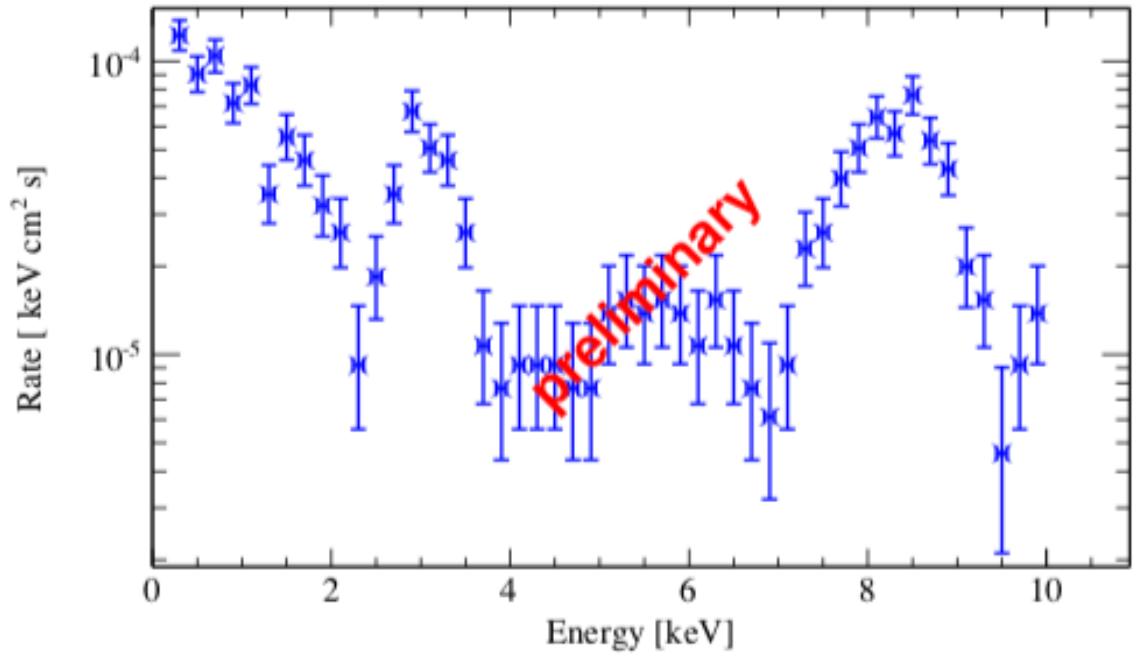
Micromegas directly coupled to Timepix ASIC: 256x256 pixels at 55µm pitch

Very low threshold (≈277eV) detection demonstrated
Background rates of $\mathbf{10^{-4}\ keV^{-1}\ cm^{-2}\ s^{-1}}$ below 2 keV achieved.

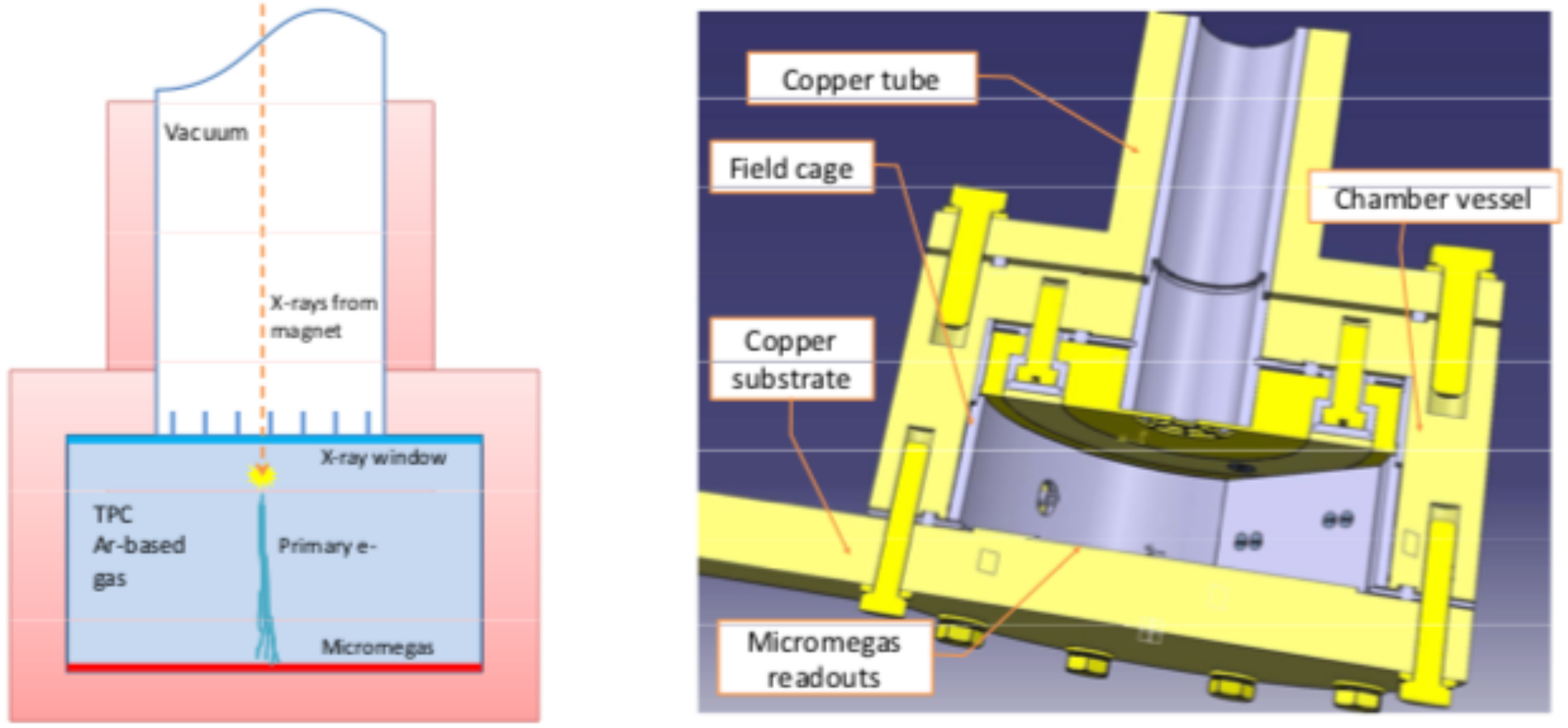
C. Krieger et al., EPJ Web of Conferences 174, 02008 (2018)
https://doi.org/10.1051/epjconf/201817402008







International Axion Observatory (IAXO)



E Armengaud et al 2014 JINST 9 T05002
doi: doi:10.1088/1748-0221/9/05/T05002

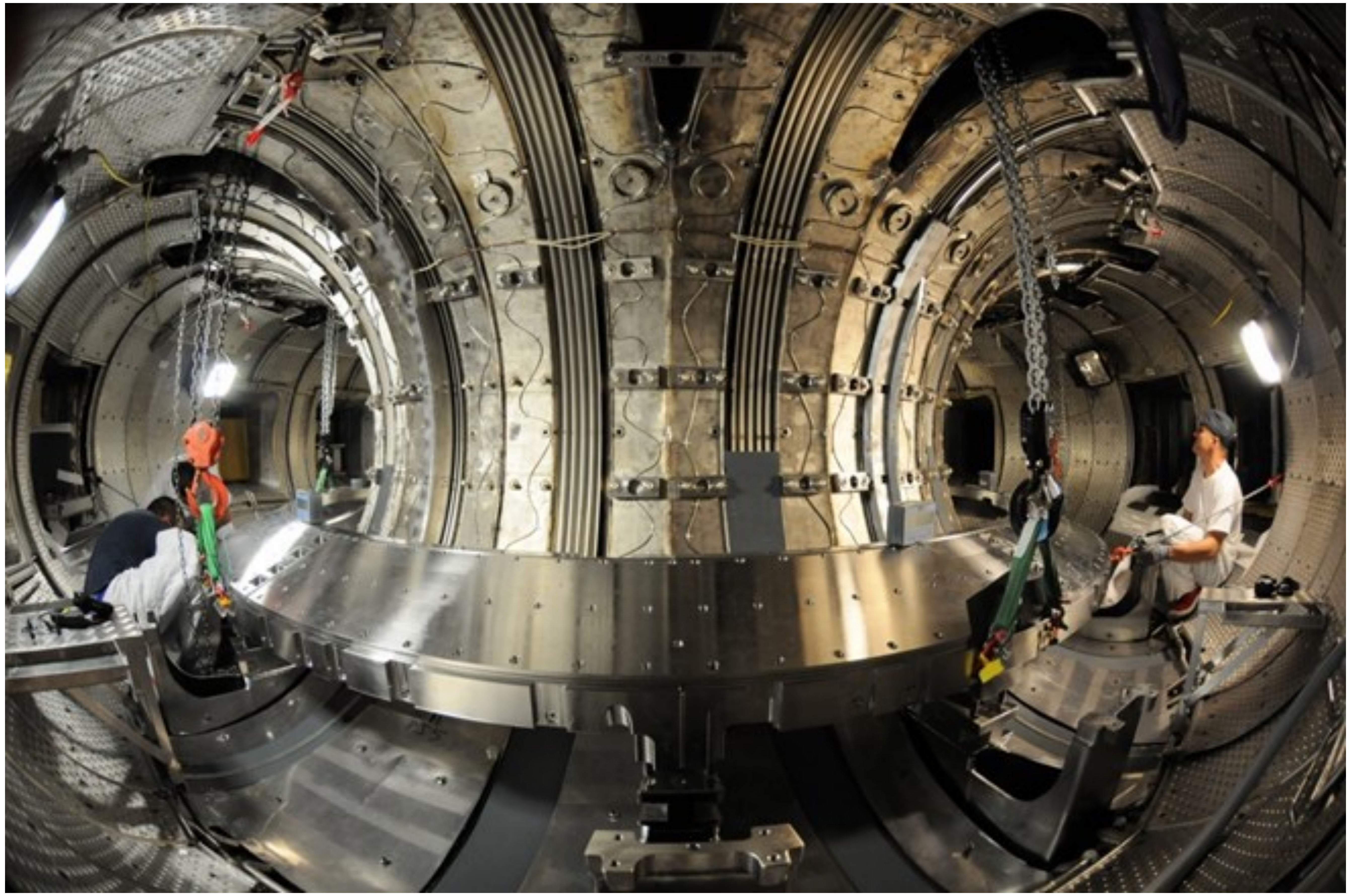
Fusion plasma monitoring

GEMs for fusion plasma imaging

Diagnostic tool for plasma tomography

Detector requirements:

- **Soft X-ray 2-15 keV sensitivity**
- Spectra information
- Good spatial resolution (1cm at equatorial plane)
- Time resolution ≈ms
- **Radiation hardness**



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

M Chernyshova et al., EUROFUSION WP15ER-CP(16) 15513
http://www.euro-fusionscipub.org/wp-content/uploads/WP15ERCP16_15513_submitted.pdf

GEMs for fusion plasma imaging

Current SXR Si diodes limit number of tomographic lines to perform general tomographic reconstruction

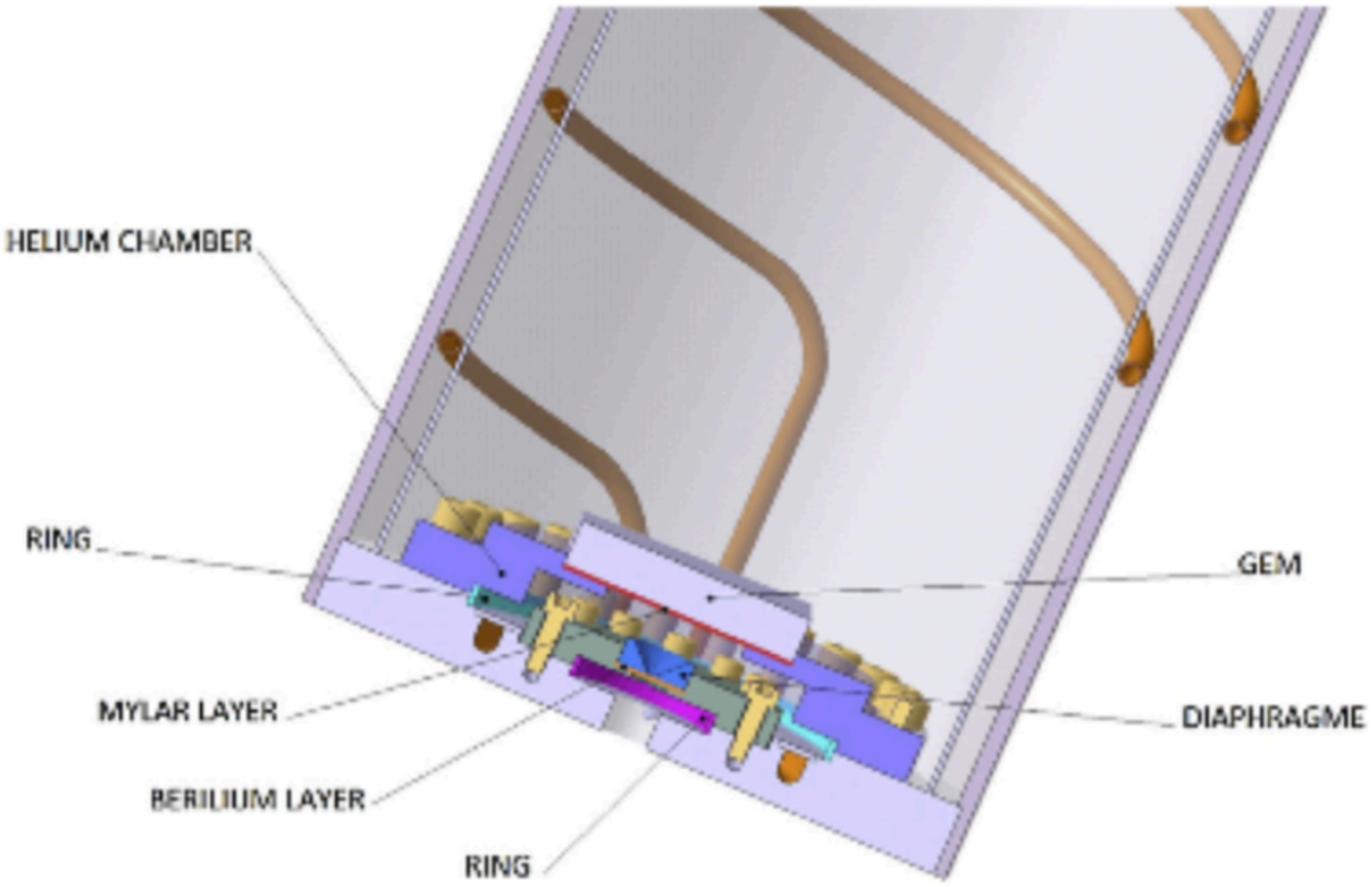
Proposed GEM system: Two 1D cameras

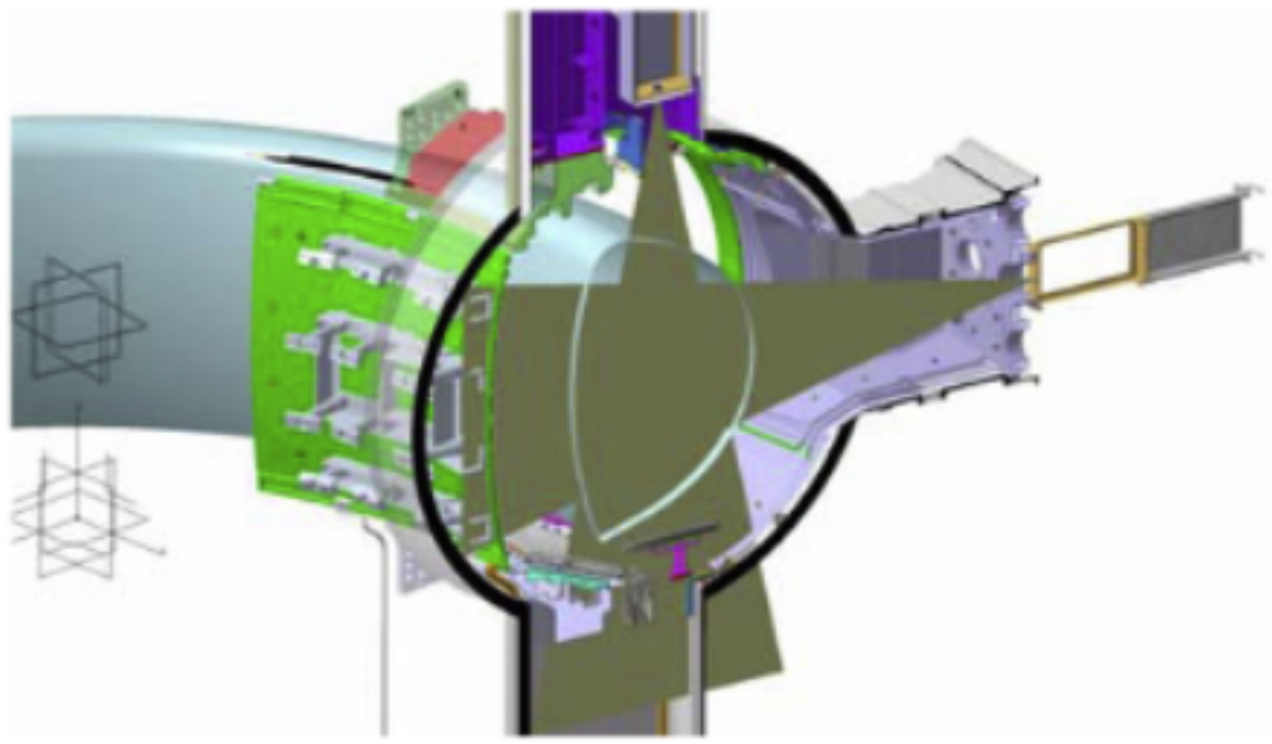
- Operating in 0.3 T
- Photon flux: 10^8 ph/s/cm2
- Neutron rate: 10^{12} n/s/m^2

GEM detector with 2 x 20 cm^2 active area would provide up to 128 viewing lines

10^3 gas gain for high dynamic range

1kHz real-time data (selected data) and 10kHz to offline-storage





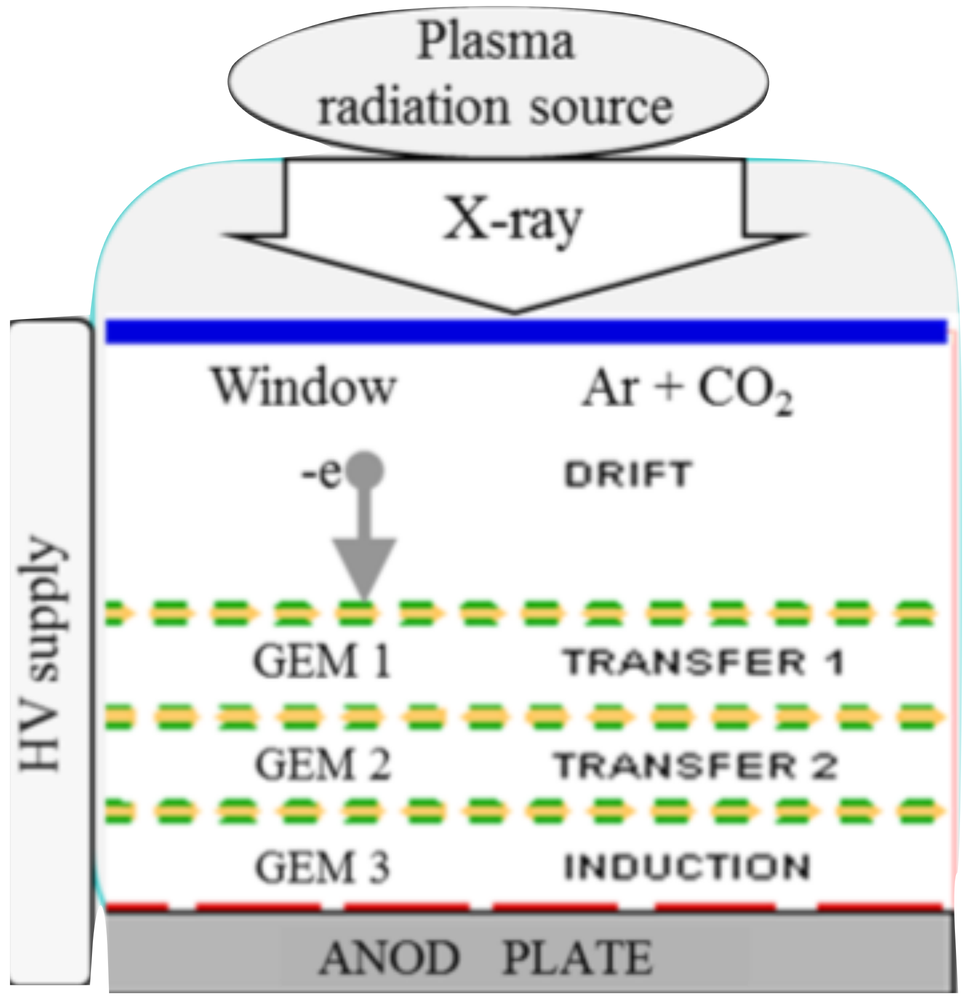
D. Mazon et al. / Fusion Engineering and Design 96–97 (2015) 856–860
https://doi.org/10.1016/j.fusengdes.2015.03.052.

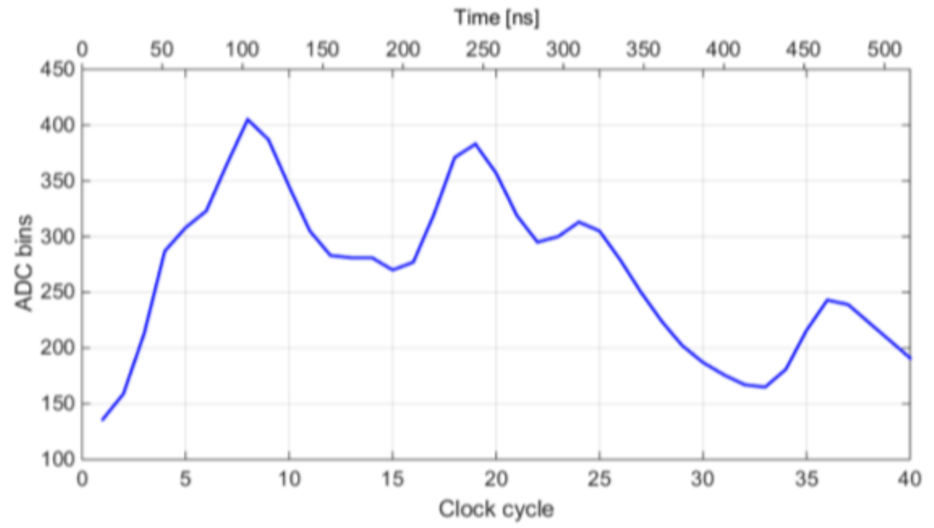
GEMs for fusion plasma imaging

EUROfusion

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



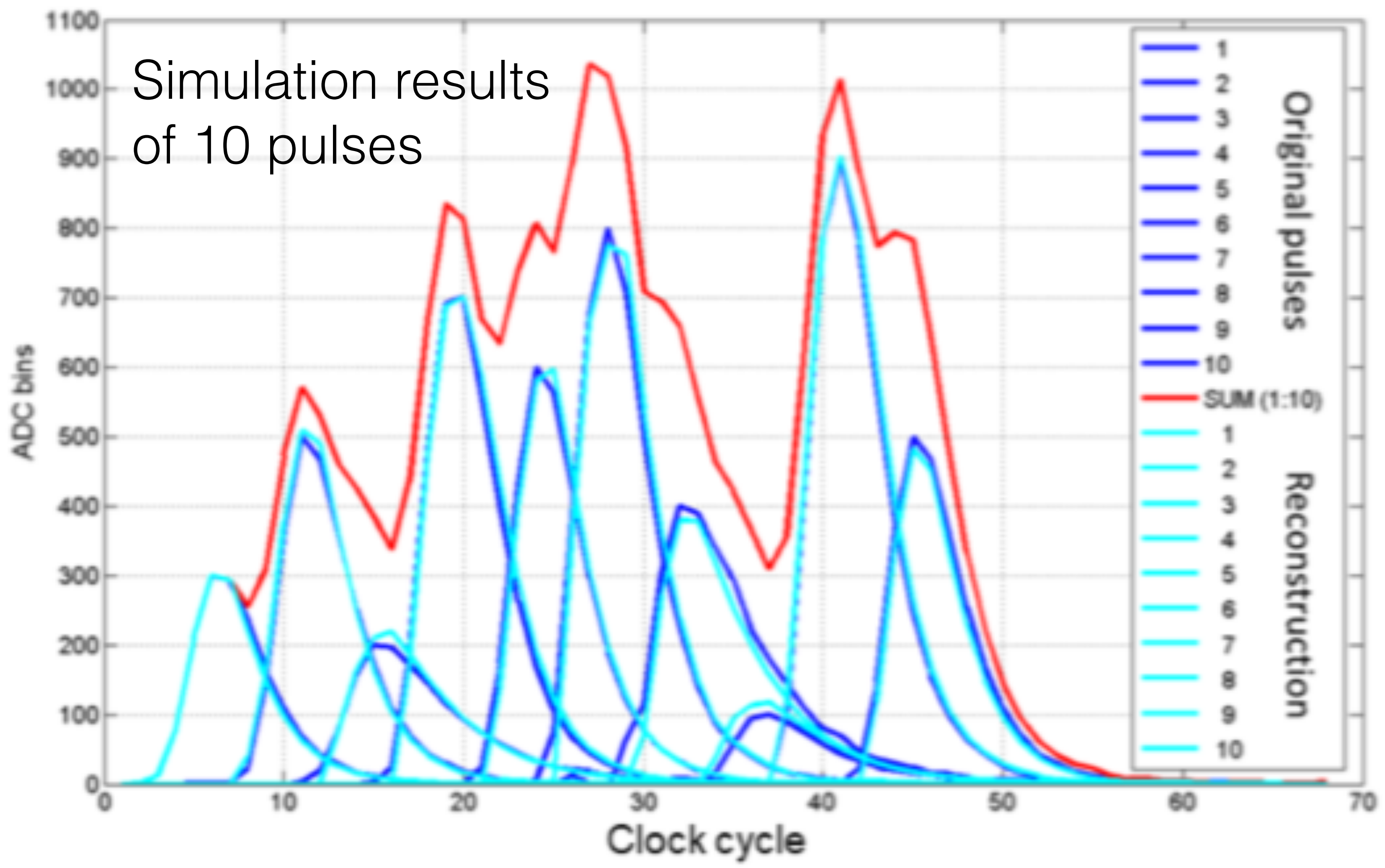


Charge cluster identification

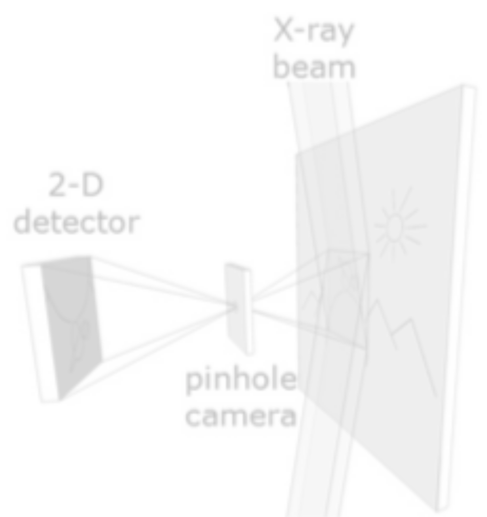
Data acquired by serial data acquisition system

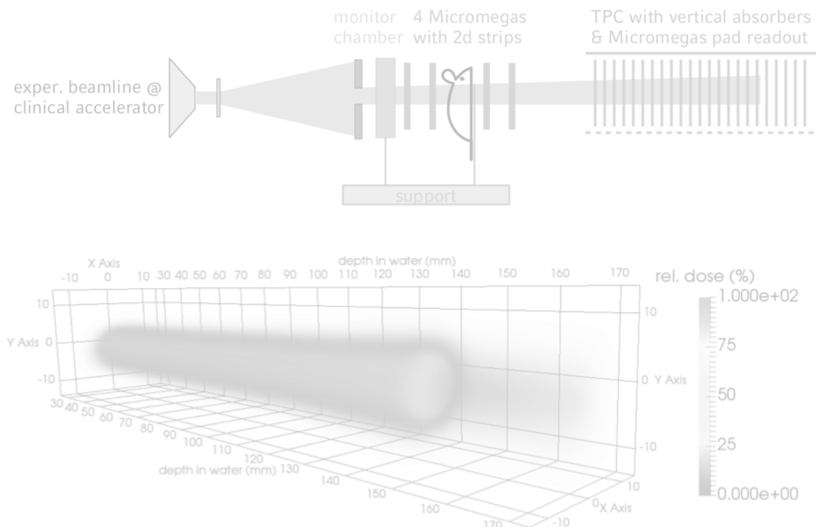
ADC is sampled in 40 cycles (10bit, ≈13ns per cycle, 77MHz)

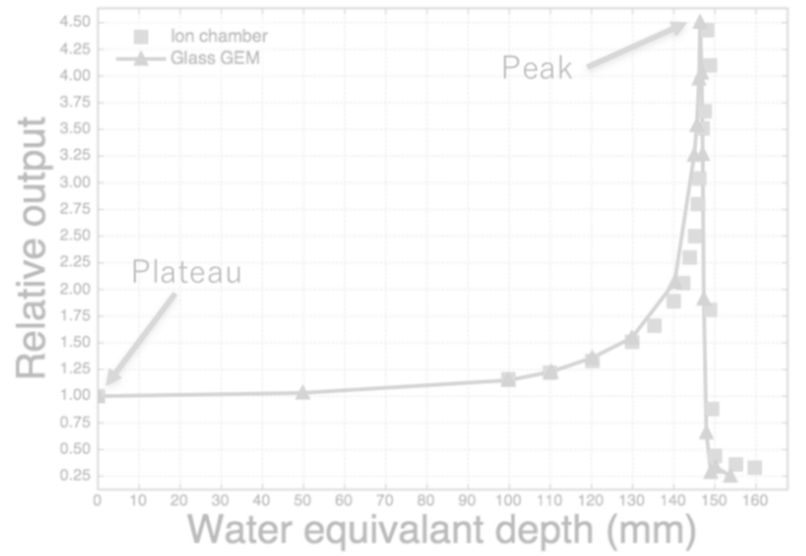
- "Characteristic point" shortly after local maximum is determined to predict falling phase
- Effective for pulse separation >50ns (3 cycles) and can be applied to subsequent pulses

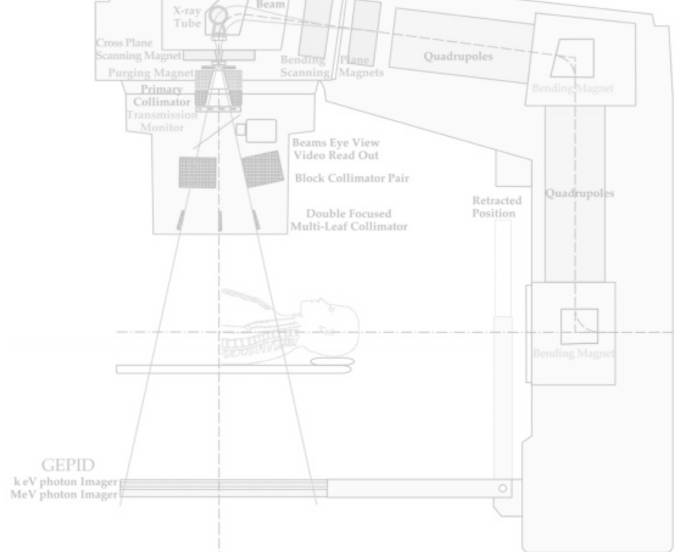


T. Czarski et al., Rev. Sci. Instrum. **87**, 11E336 (2016); https://doi.org/10.1063/1.4961559
T. Czarski et al 2018 JINST 13 C08001









Medical: radiography, dosimetry and portal imaging

Cultural heritage studies: X-ray fluorescence

Muography: archeology and nuclear reactor imaging

Astrophysical: X-ray polarimetry and axion search

Fusion plasma imaging

Versatility

Low material budget

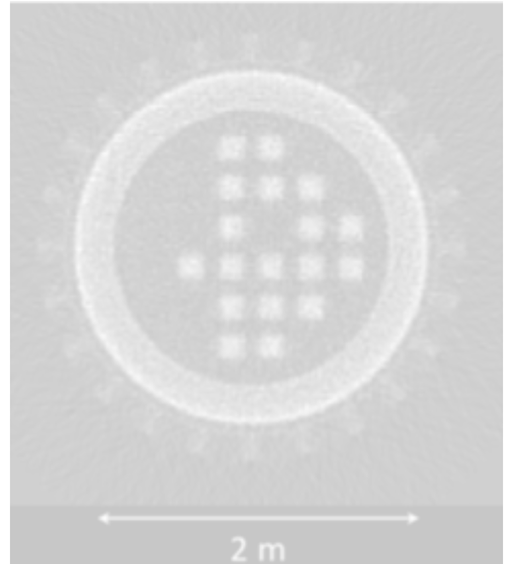
High spatial resolution

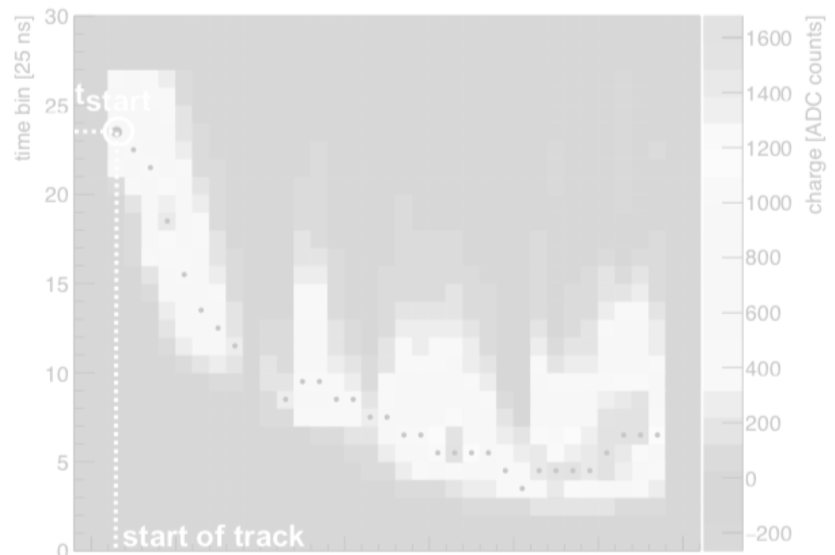
High-rate capability

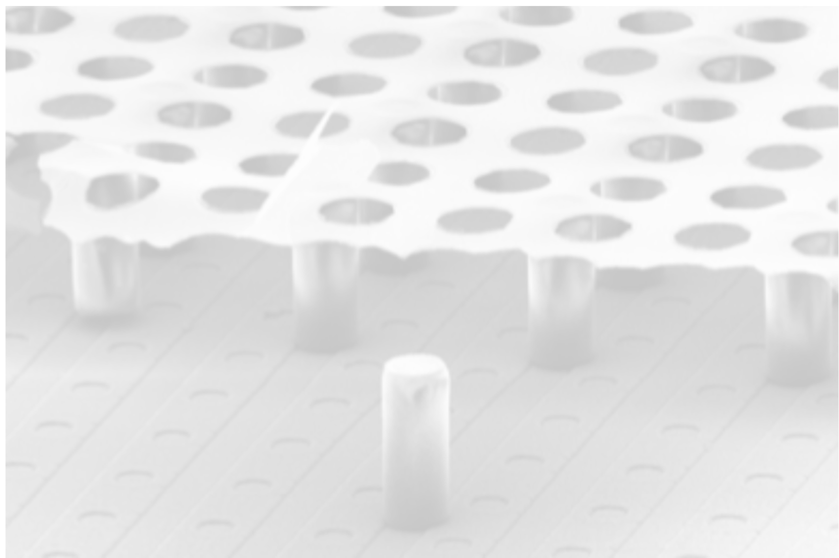
Low energy threshold

Large active area

Radiation hardness





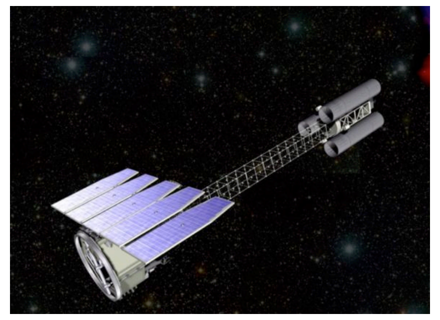


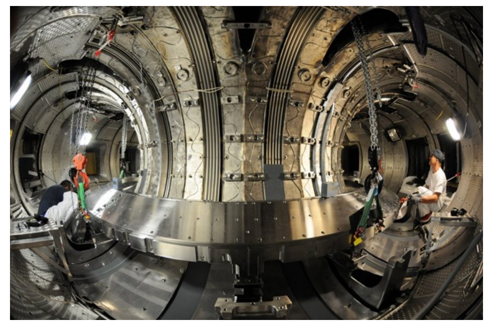
Outlook

Versatility

Adaptability of gaseous detectors and possibility of in-situ operation important for medical applications as well as cultural heritage studies

Sealed mode for field and space operation

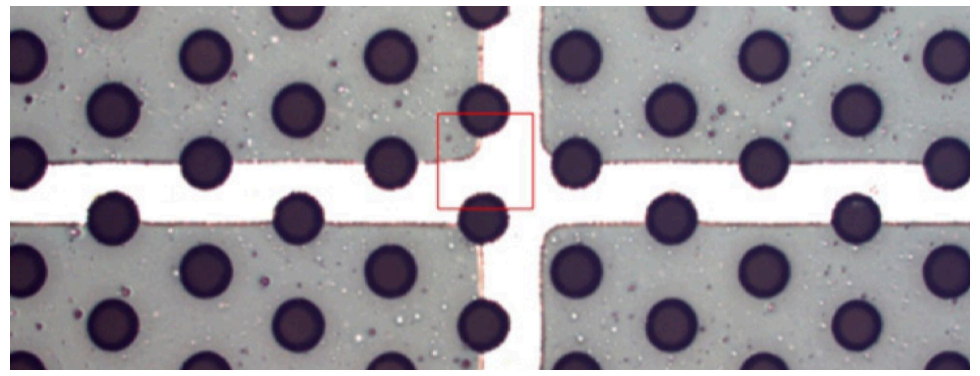


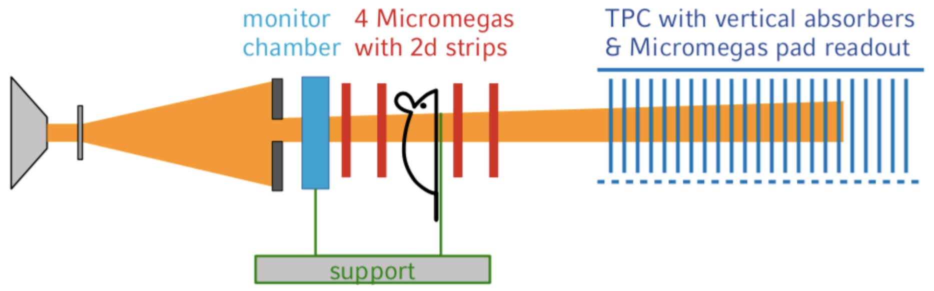


Low material budget

Alternative electrodes (Cr, Al, DLC) and thin electrodes to minimise material budget

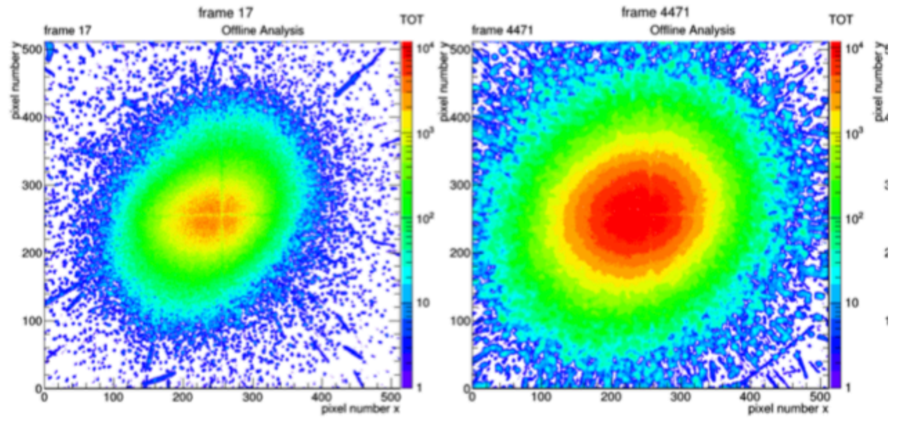
Enabling online beam monitoring and dosimetry for medical applications

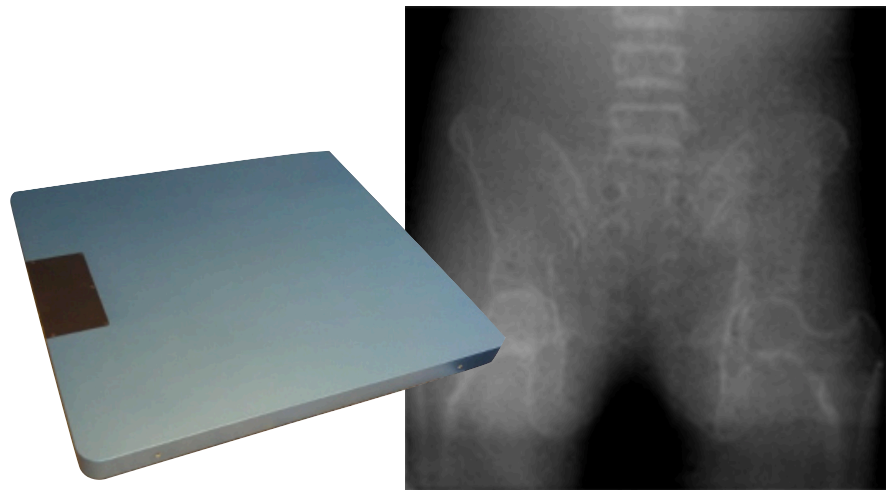




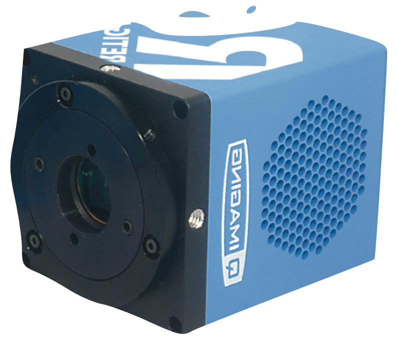
High spatial resolution

Proton radiography, beam monitoring and portal dosimetry, X-ray polarimetry, axion search





Increasing resolution of cameras

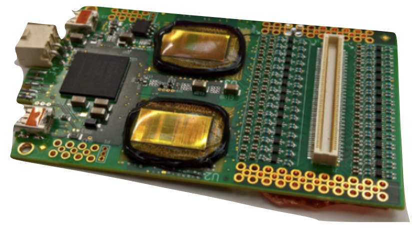


High-speed readout

Rapid full-field X-ray fluorescence, X-ray fluoroscopy and real-time radiation imaging

High-speed CMOS cameras

High-speed front-end ASICs



Online applications enabled by real-time reconstruction and analysis

Backup

Neutron detectors

GEM-based neutron detector with Gd converter

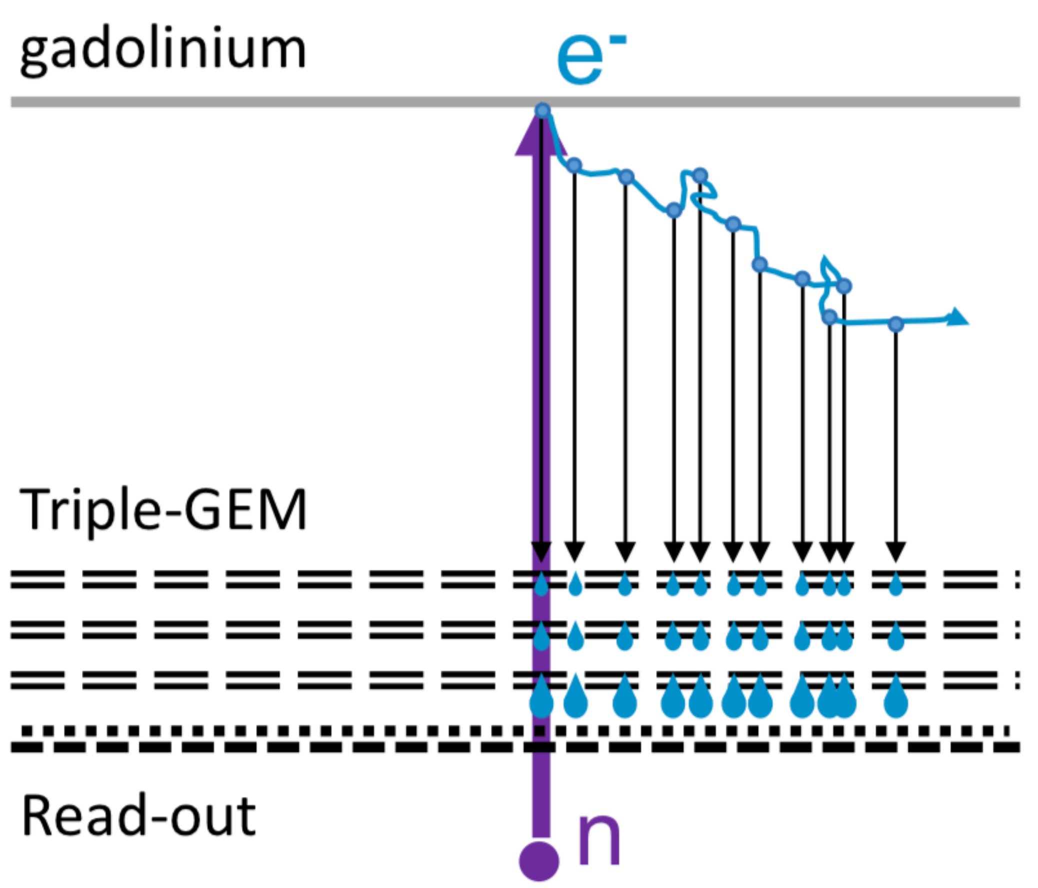
Neutron macromolecular diffractometer (NMX): structure determination of biological macromolecules, locating hydrogen atoms relevant for function of macromolecules

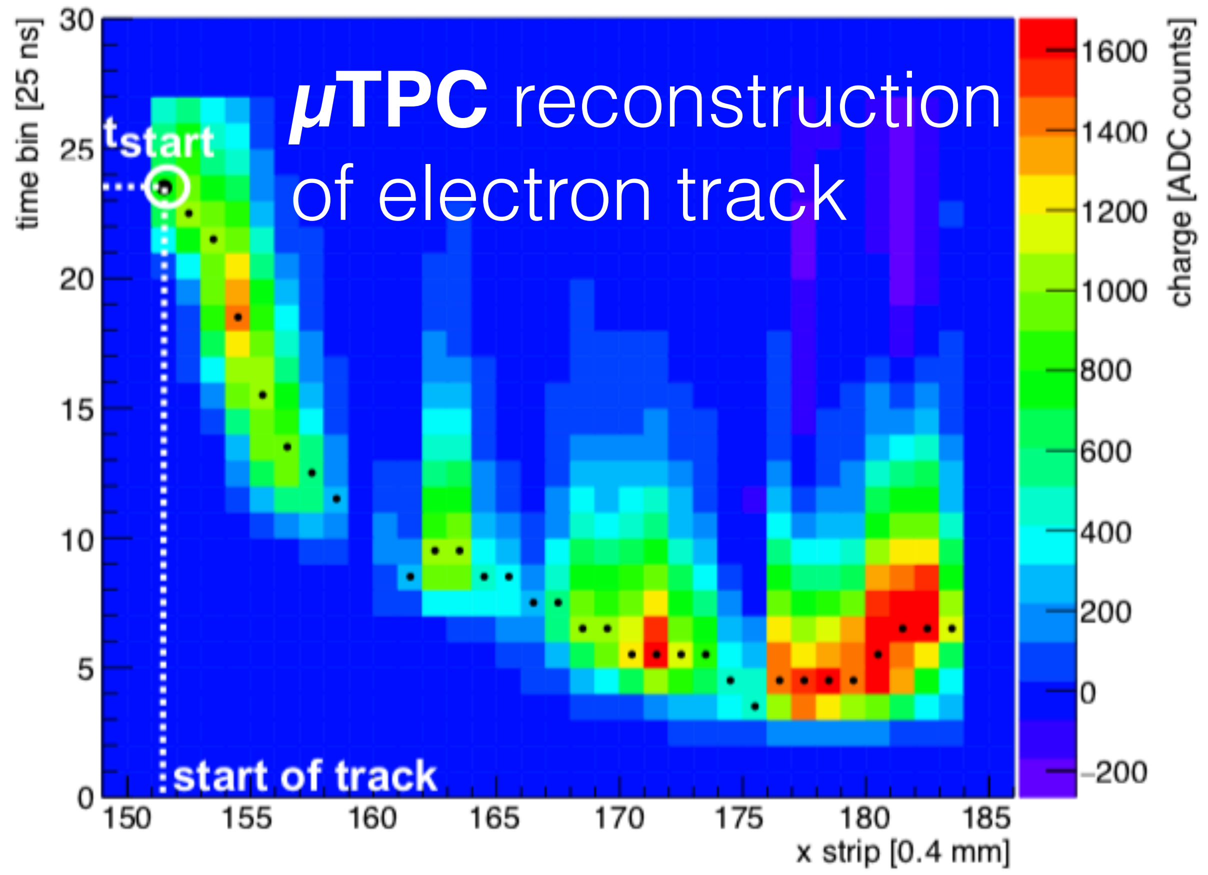
Detector requirements: **high rate capability**, **high detection efficiency**, **good spatial resolution**, good time resolution, **radiation hardness**

µTPC readout with VMM3: **O(200*µ*m) spatial resolution, O(ns) time resolution**

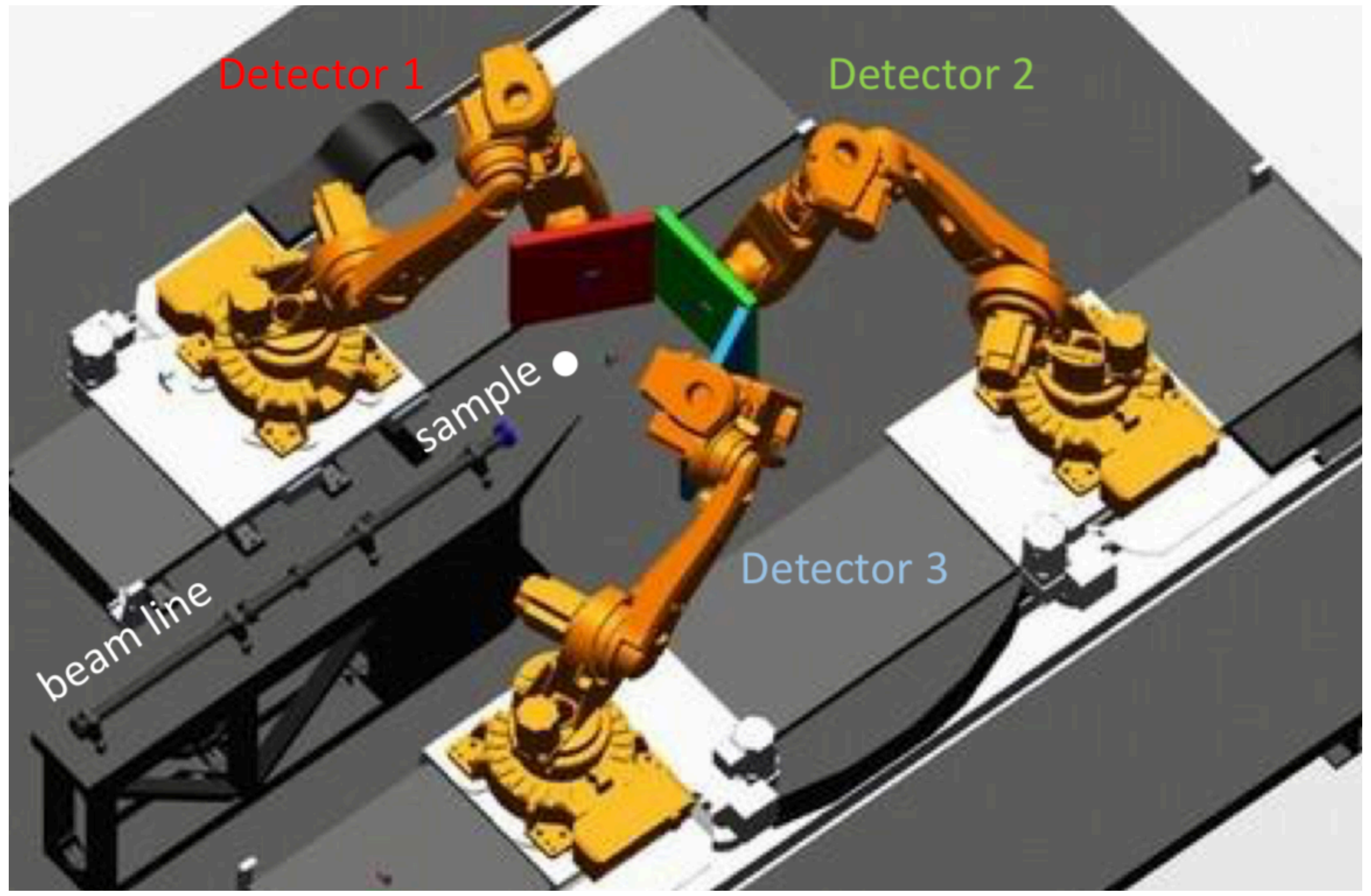
≈12% neutron detection efficiency with Gd-GEM (at 2Å)

M. Lupberger (Tue): SRS VMM readout for Gadolinium GEM-based detector prototypes for the NMX instrument at ESS





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

Multi-layer boron-10 neutron detector

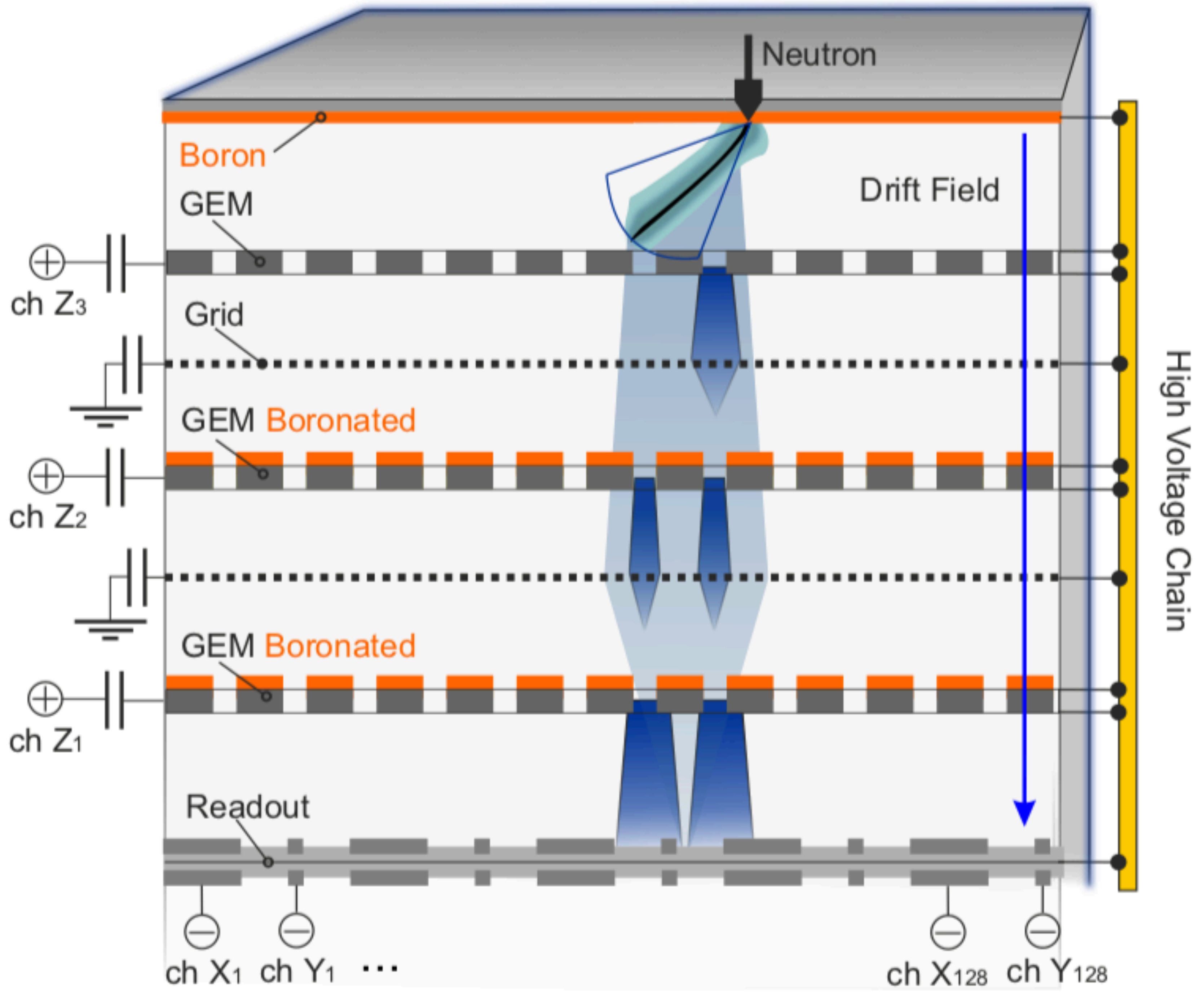
As an alternative for ^{3}He-based detectors, the **CASCADE** project aimed at instrumentation at ESS based on solid ^{10}B converters and GEMs for signal amplification.

Core detector requirements are **2D spatial resolution** for **thermal neutrons at high rate**.

20x20cm^2 detection area with Al window
Crossed strip readout (1.57mm width)

Ar/CO2 70/30 - 90/10 gas mixture
CIPix charge sensitive preamplifier + FPGA data acquisition board

Signal induced on GEMs while charge is traversing stack is also recorded to get **time-of-flight resolution**.



$$^{10}\mathbf{B} + \mathbf{n} \rightarrow {}^{7}\mathbf{Li} + {}^{4}\mathbf{He} + 2.8\ \mathrm{MeV}$$

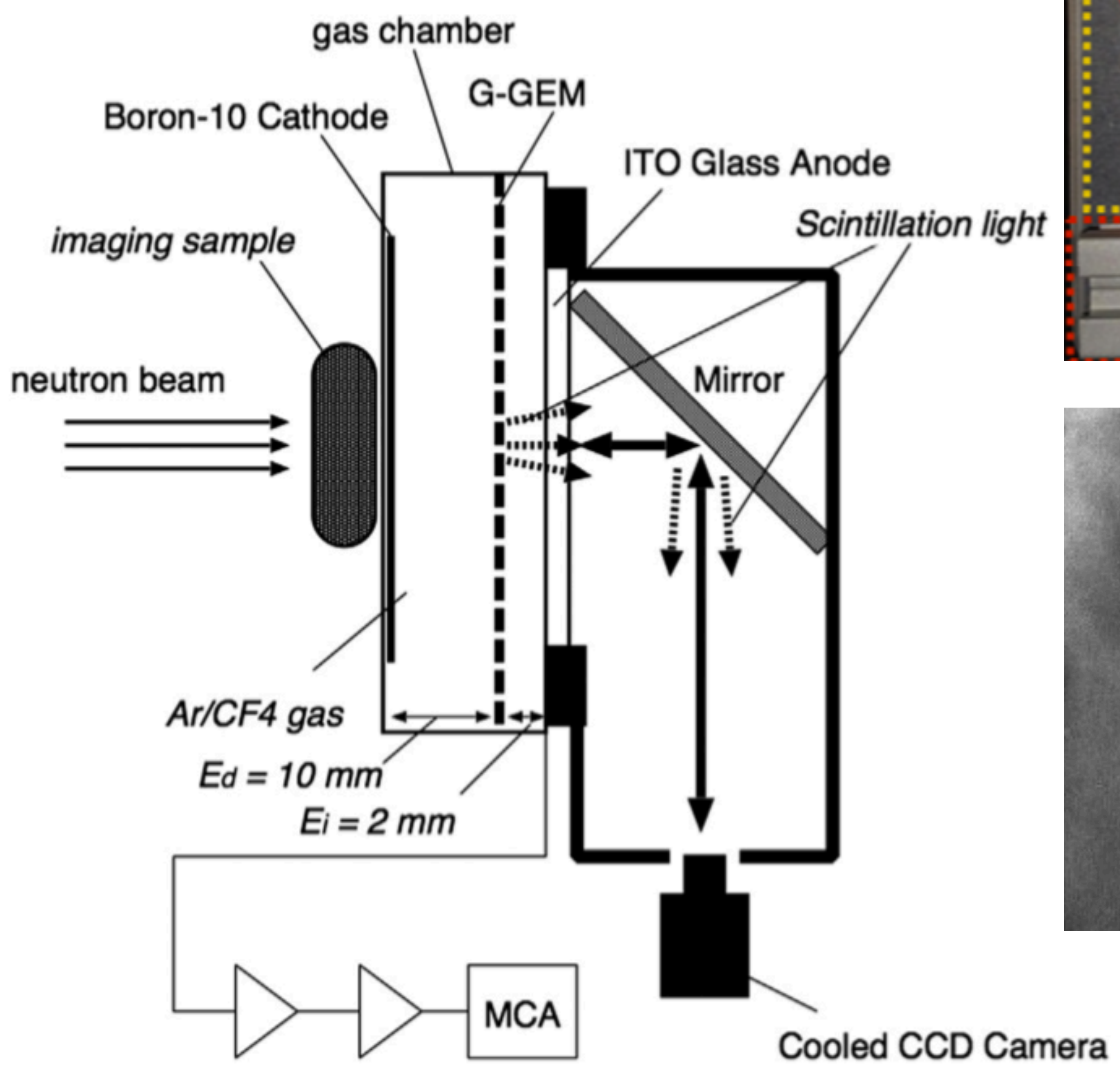
M Köhli et al 2016 J. Phys.: Conf. Ser. 746 012003
doi:10.1088/1742-6596/746/1/012003

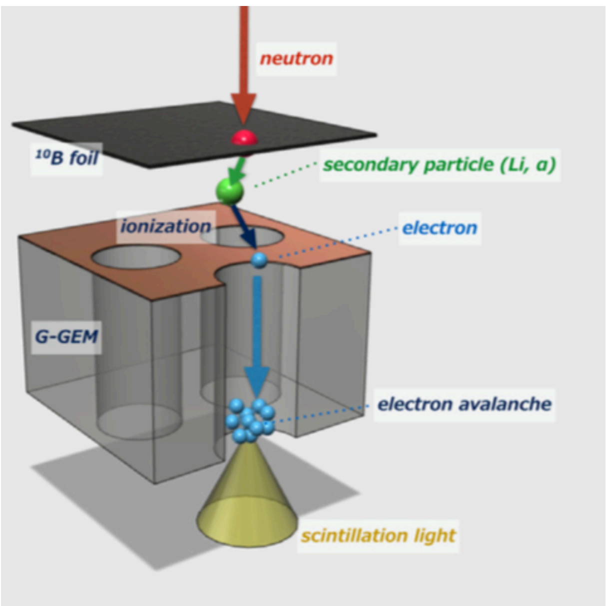
Glass-GEM with micro-structured ^{10}B converter

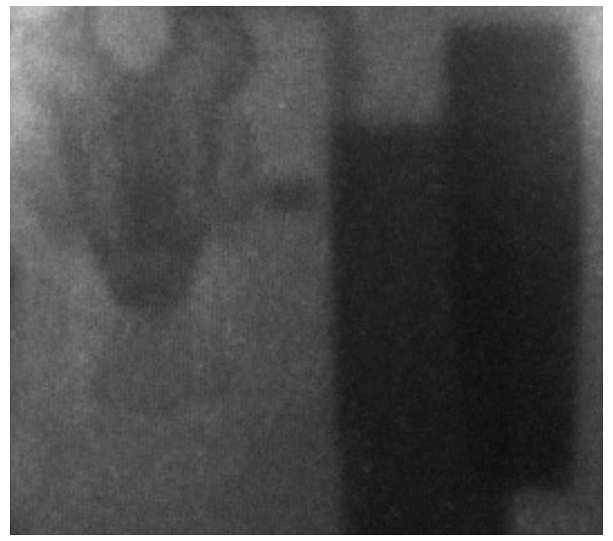
10x10 cm^2 Glass GEM: single stage amplification stage reaching a gain of up to 1x10^3 in Ar/CF$_4$ (90/10)

Operated in thermal neutron beam line at a flux of 1.5x10^4 n/cm2/s
Thin boron layer results in **low gamma-ray sensitivity** and therefore low-background neutron image without discrimination.

T. Fujiwara (Tue): Recent Development of Glass GEMs and Their Uses



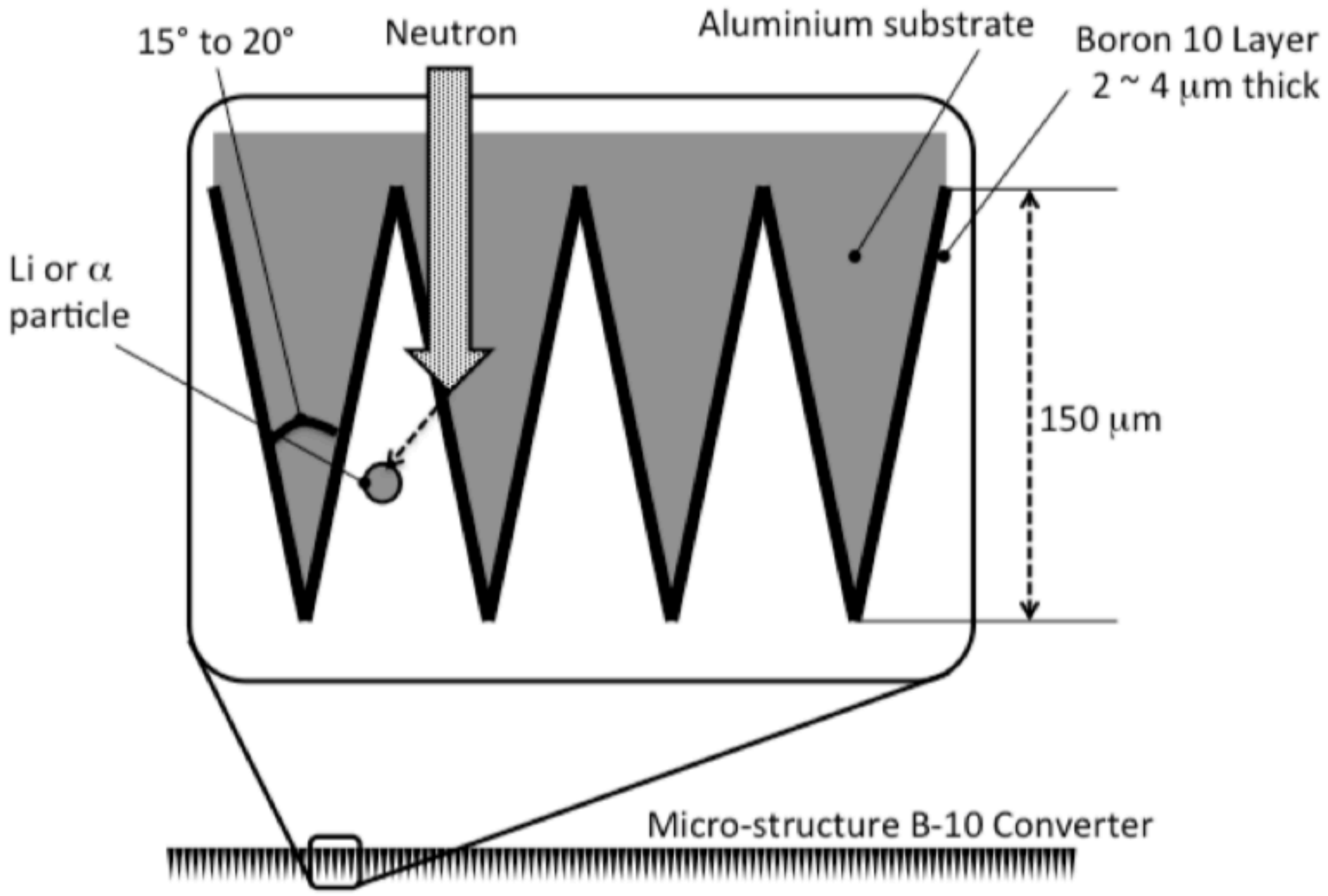




T. Fujiwara et al. / Nuclear Instruments and Methods in Physics Research A 838 (2016) 124–128 125 http://dx.doi.org/10.1016/j.nima.2016.09.005

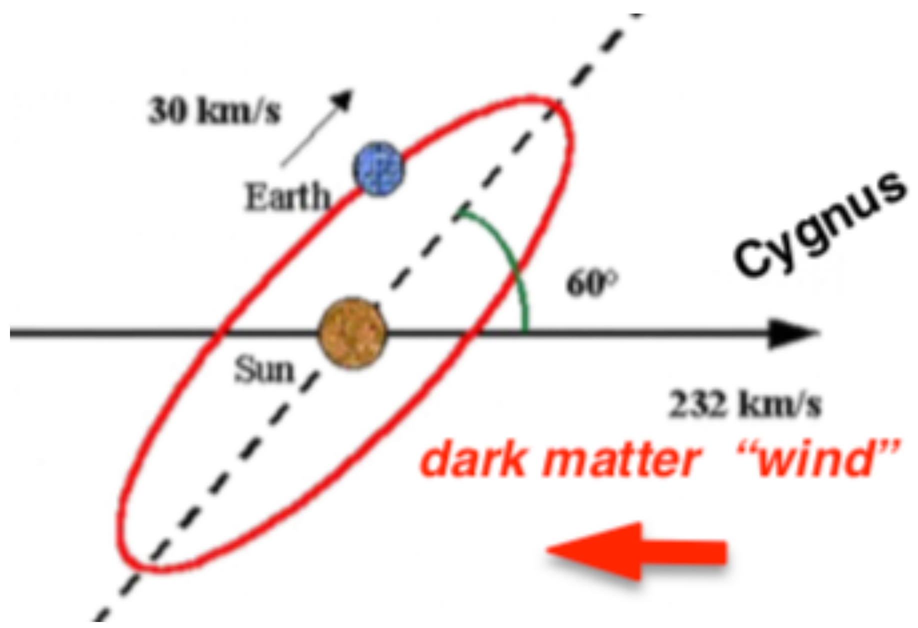
150 µm deep canyons are structured in Al substrate and coated with 2-4 µm of ^{10}B layer.

Grazing incident angle allows for higher fraction of neutrons to be absorbed in ^{10}B layer.



T. Fujiwara et al. / 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference 10.1109/NSSMIC.2013.6829580

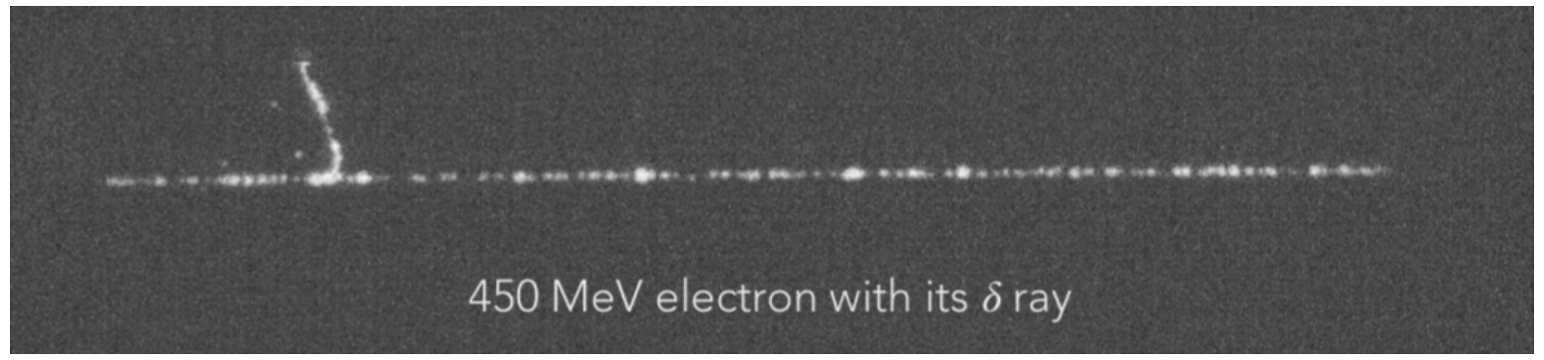
Directional dark matter search

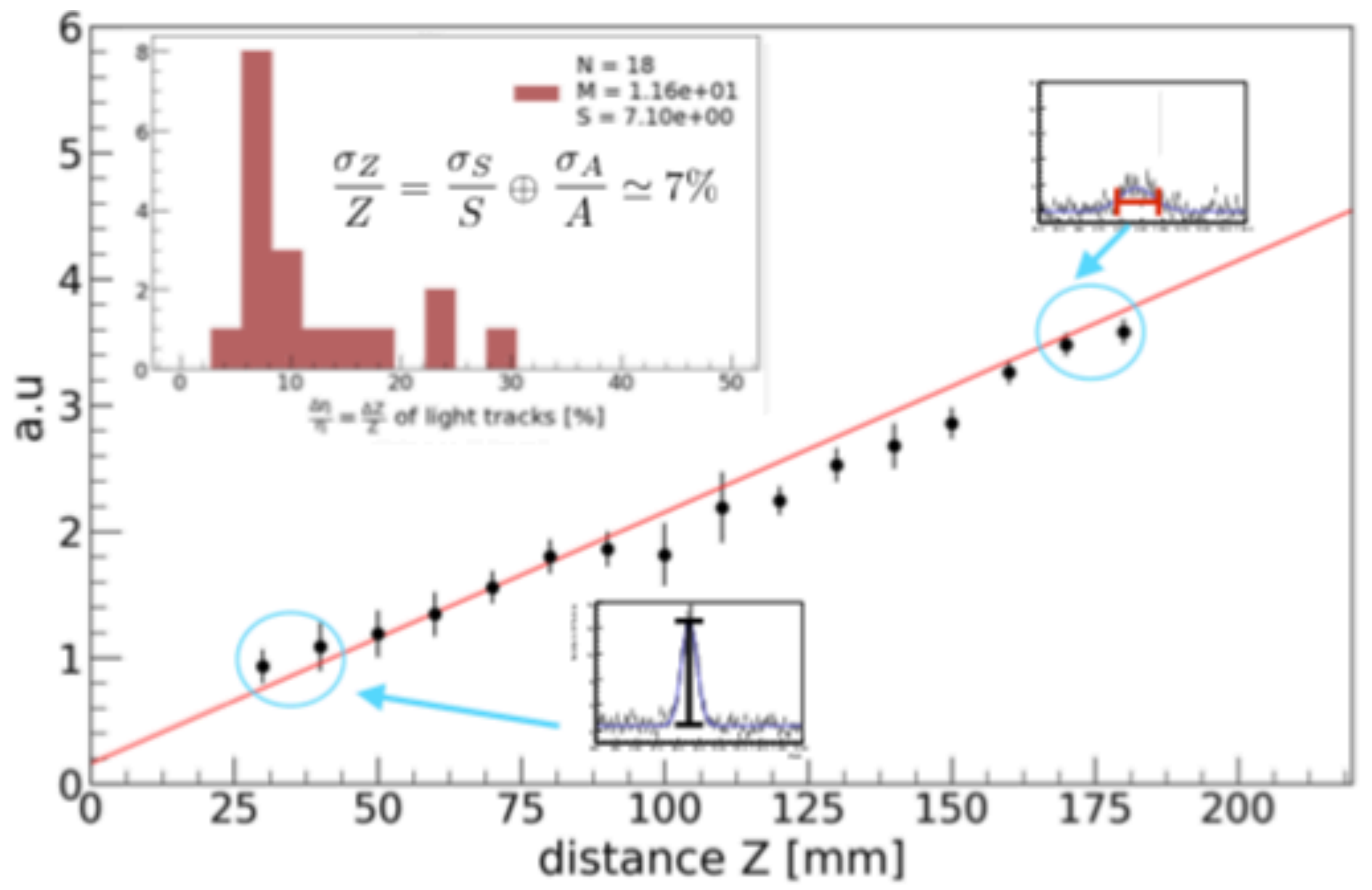


G. Cavoto (CYGNO, INFN)

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



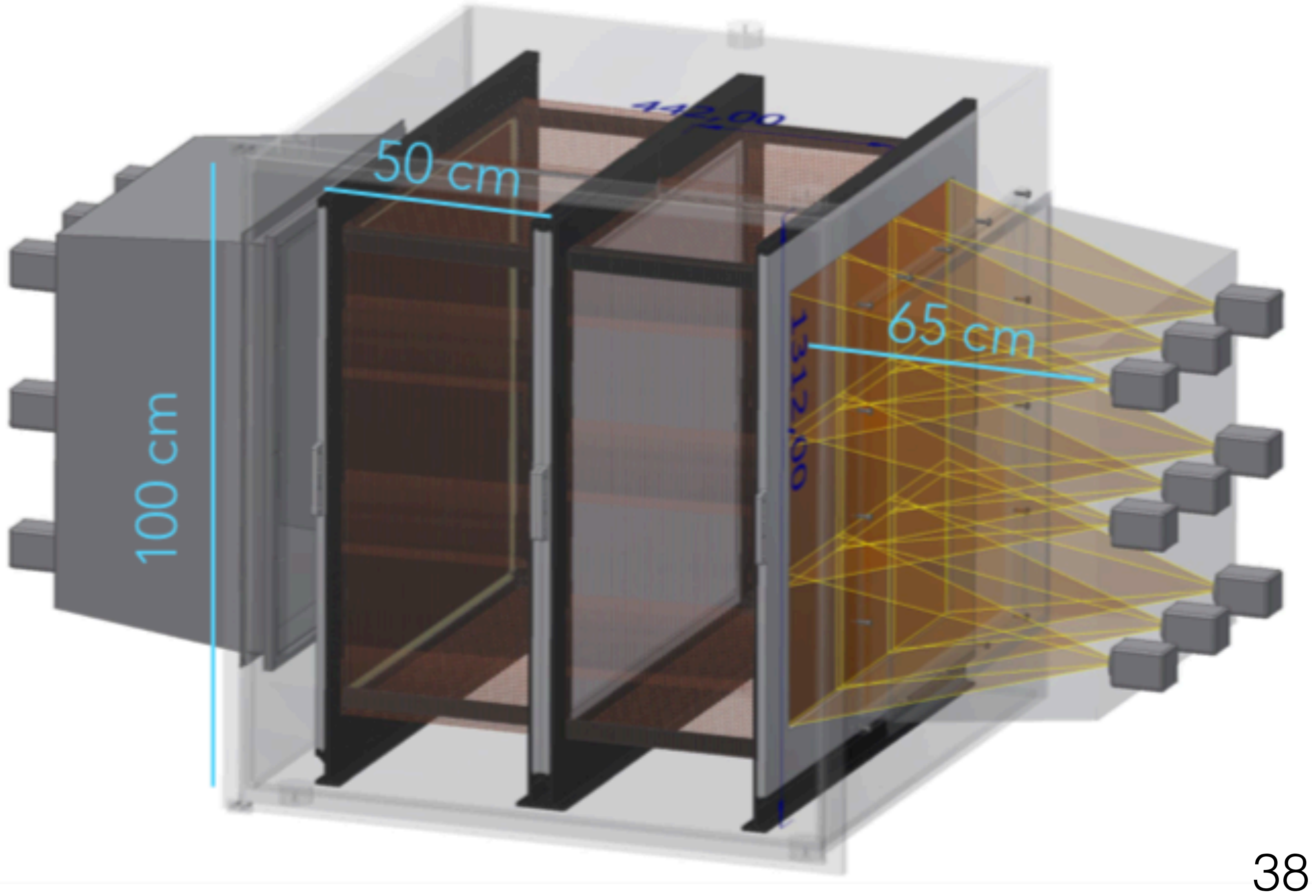


Optical TPCs based on GEMs well suited to provide high granularity 2D images

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: 1m^3 of He/CF4 60/40 (1.6kg) with 72x10^6 pixels



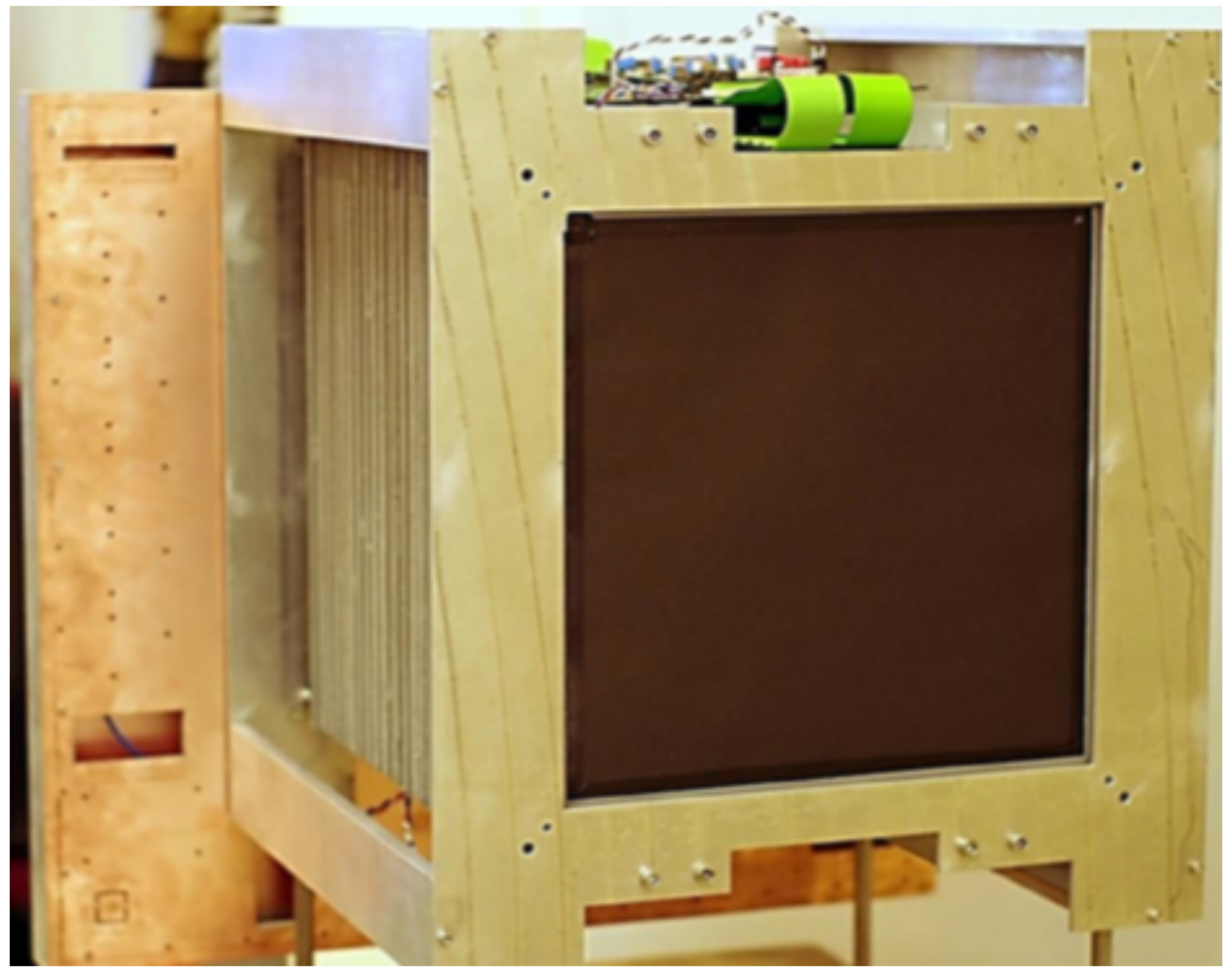
D. Pinci (Wed, Poster): CYGNO: Triple-GEM Optical Readout for Directional Dark Matter Search

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

Proton radiography

GEMs for particle tracking for proton radiography.

A prototype detector was realised with:
30x30cm^2 active area
2D readout anode (800μm strip pitch)
Capable of operation above 10^5 tracks / mm^2
GEMROC ASIC readout (12 front-end boards, random rate>1MHz)
Ar/CO2 70/30



Position determination accuracy limited by **multiple scattering** in tissue

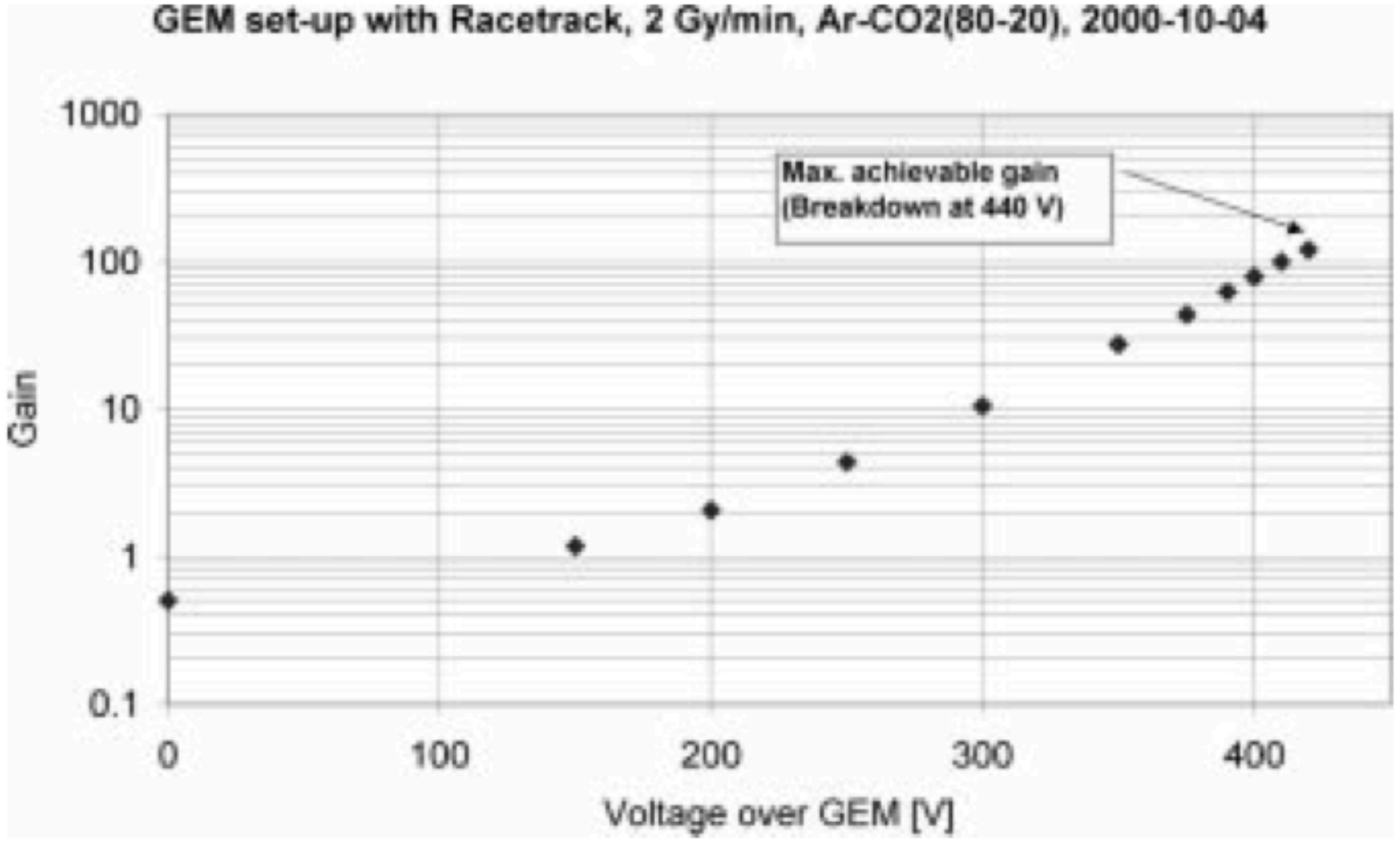
Additional application:
Interaction vertex imaging (IVI) dosimetry
Record secondary protons emerging from the target

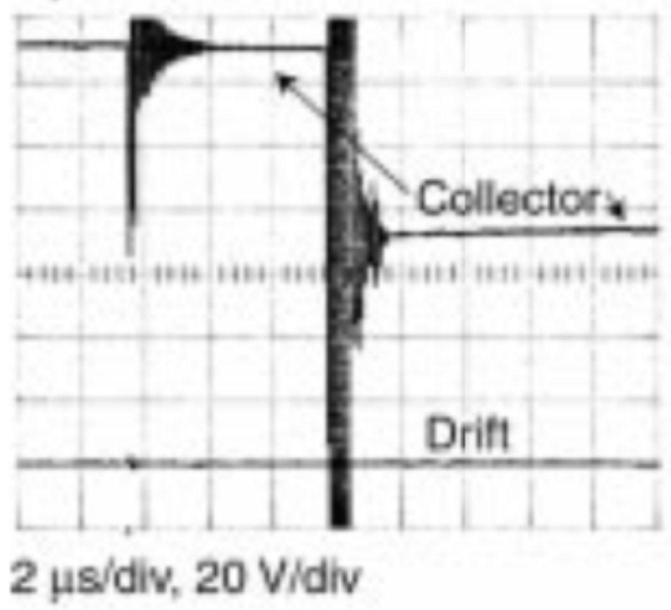
M. Bucciantonio et al. / Nuclear Instruments and Methods in Physics Research A 718 (2013) 160–163
http://dx.doi.org/10.1016/j.nima.2012.10.046

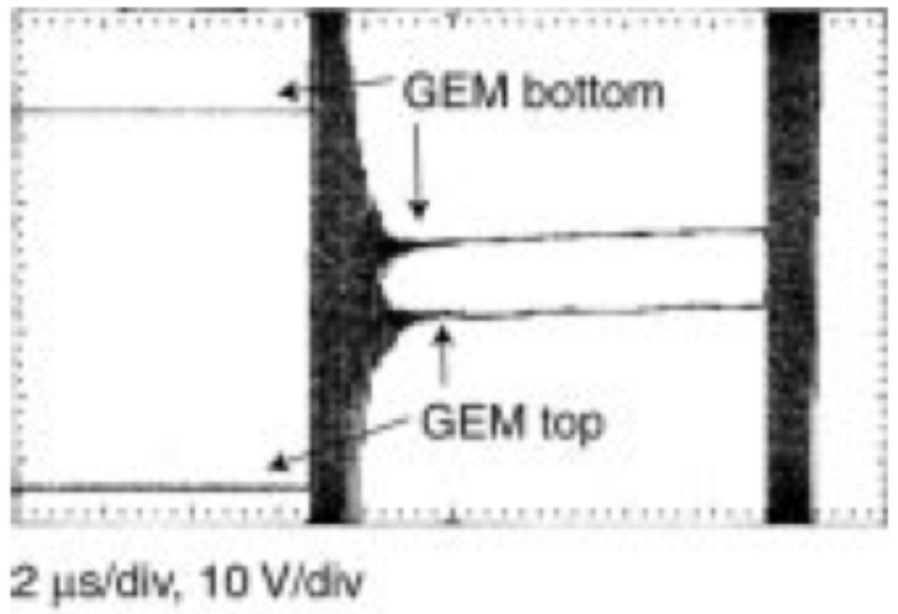
Portal imaging

10x10cm^2 double-GEM detector with single pad anode prototype tested (Ar/CO2 80/20)

Operated in clinical environment in **high-rate environment** >10^10 ph/s/mm^2
No sign of radiation-induced deflation or instability observed
Maximum achievable gain drops with beam intensity but stable gain of ≈100 in second GEM is sufficient for EPID







IACOBAEUS et al.: IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 48, NO. 4, AUGUST 2001
https://doi.org/10.1109/23.958386

GEMs for fusion plasma imaging

Triple GEM
To be operated in photon counting mode with energy discrimination
5-15mm drift gap
2m induction gap
Thin entrance window (12μm Mylar + 200nm Al)

Ar/CO2 70/30 or Ar/CO2/CF4 45/15/40

Charge cluster identification
Data acquired by serial data acquisition system
ADC is sampled in 40 cycles (10bit, ≈13ns per cycle, 77MHz)
FPGA used to collect data, select signals, estimate charge (center samples)

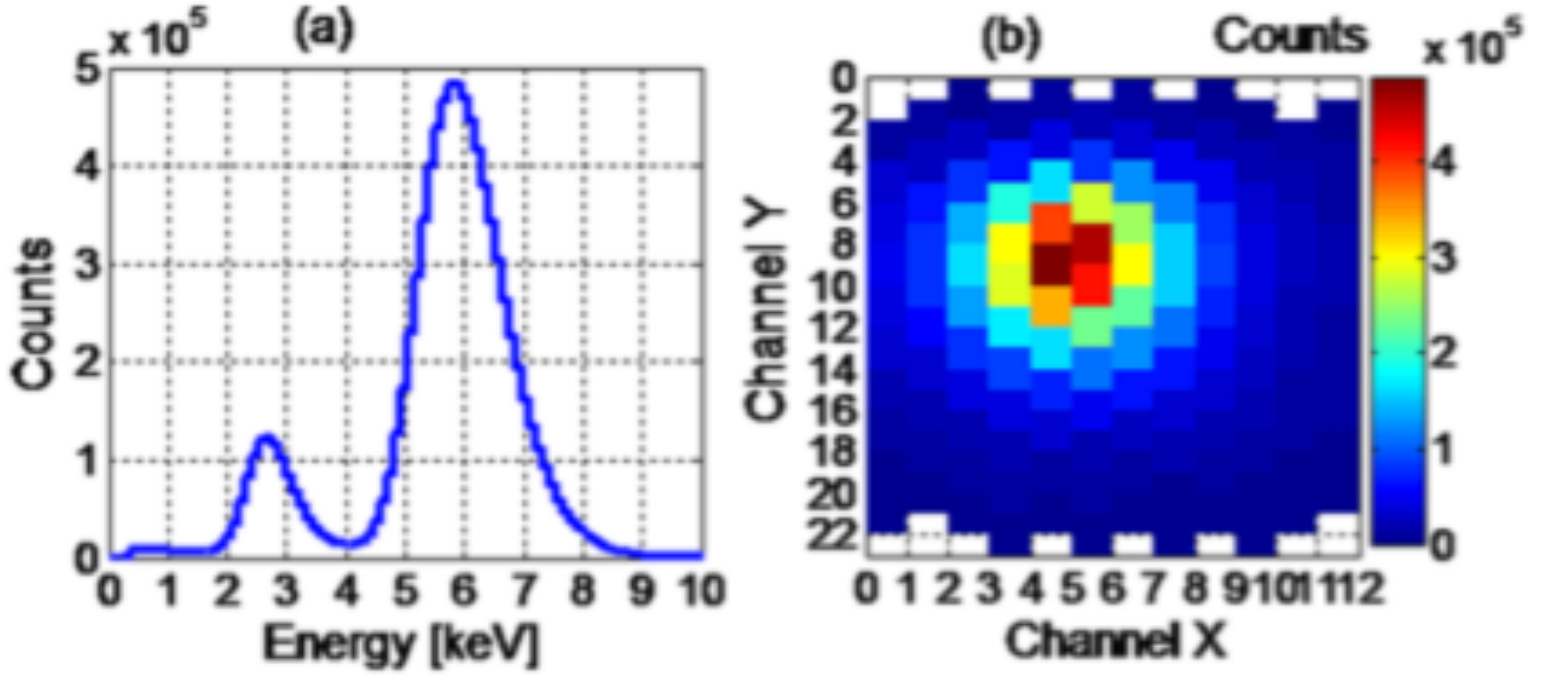
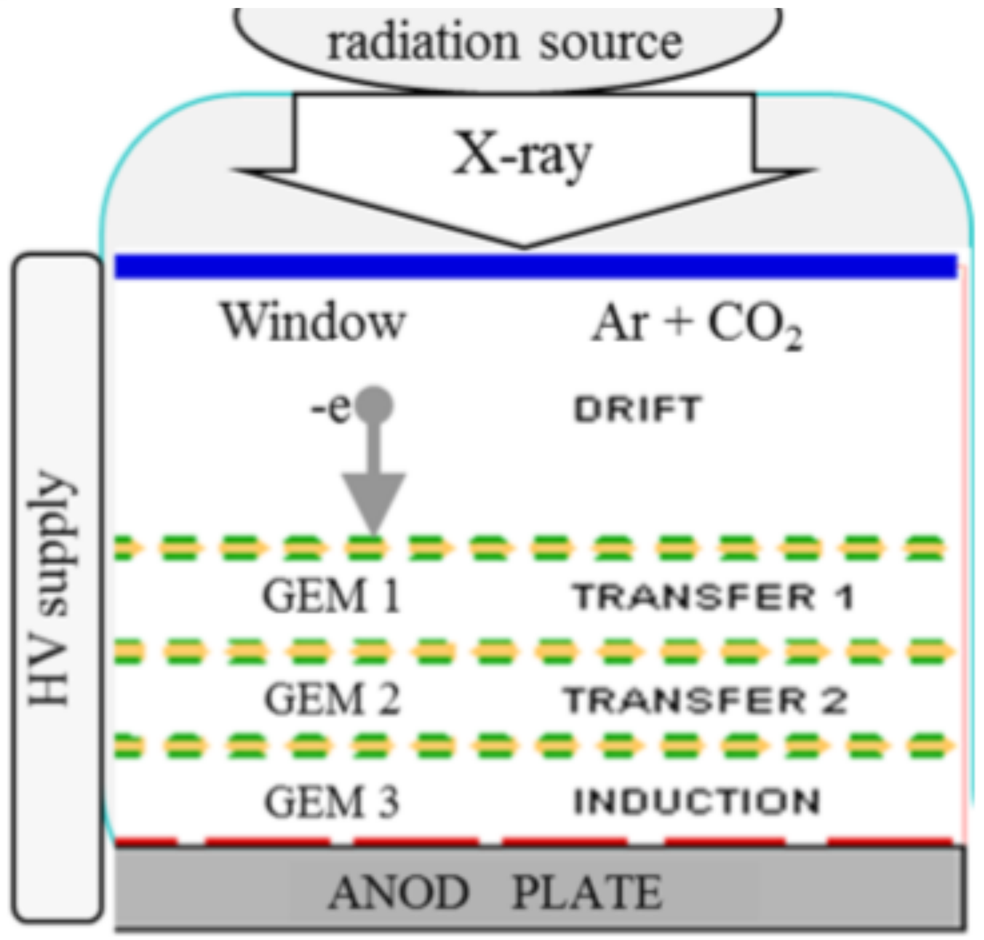


FIG. 11. (a) The energy spectra for ^{55}Fe source. (b) The cluster counts planar distribution for hexagonal array detector structure.



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