GEM-based readouts and gas mixtures for optical TPCs

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Motivation and the Relevance of OTPCs

Optical time projection chambers (OTPCs) operated with pure noble gases [1,2] can approach the Fano limit in the reconstruction of the primary ionization, whereas in VUV-quenched admixtures point-spread functions as low as 30-50um/√mm are anticipated. In many implementations, OTPCs allow the reconstruction of the start time of the event (T_0) and thus to place the primary event in absolute space. GEM fine patterns are naturally matched to such small charge spreads and can be, by virtue of their staggering capabilities, used to generate large scintillation signals, at nearly no loss of topological information.

On the other hand, scintillating chambers coupled to CCD cameras are optimal for studying nuclear reactions whose 3D topology can be easily reconstructed in 2D+1D (eg, [3], [4]), as well as in imaging problems where the coordinate along the drift field is immaterial (see box *Applications*).

At the moment, however, there is no OTPC implementation that simultaneously guarantees a ~30um/√mm point-spread function and near-intrinsic calorimetric response, despite some promising attempts in this direction [5]. The limit stems from the known properties of noble gases' scintillation, quenching mechanisms and cooling processes, but it does not appear unsurmountable (see box *Technical challenges*). Our aim is to understand the current limits of the technology, and find ways to boost it further.

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[2] D. J. Nygren, Phys. Conf. Ser. 309 012006.
[3] M. Pomorski, Phys. Rev. C 90, 014311 (2014).
[4] William R. Zimmerman, Ph.D., University of Connecticut, 2013
[5] C. D. R. Azevedo, JINST 11 (2016) 02, C02007.

Technical challenges

Noble gases
- Electroluminescence/ Energy-resolution ☺
- Point-spread function ☹

→ Low diffusion/low quenching mixtures?

'Magic' mixtures

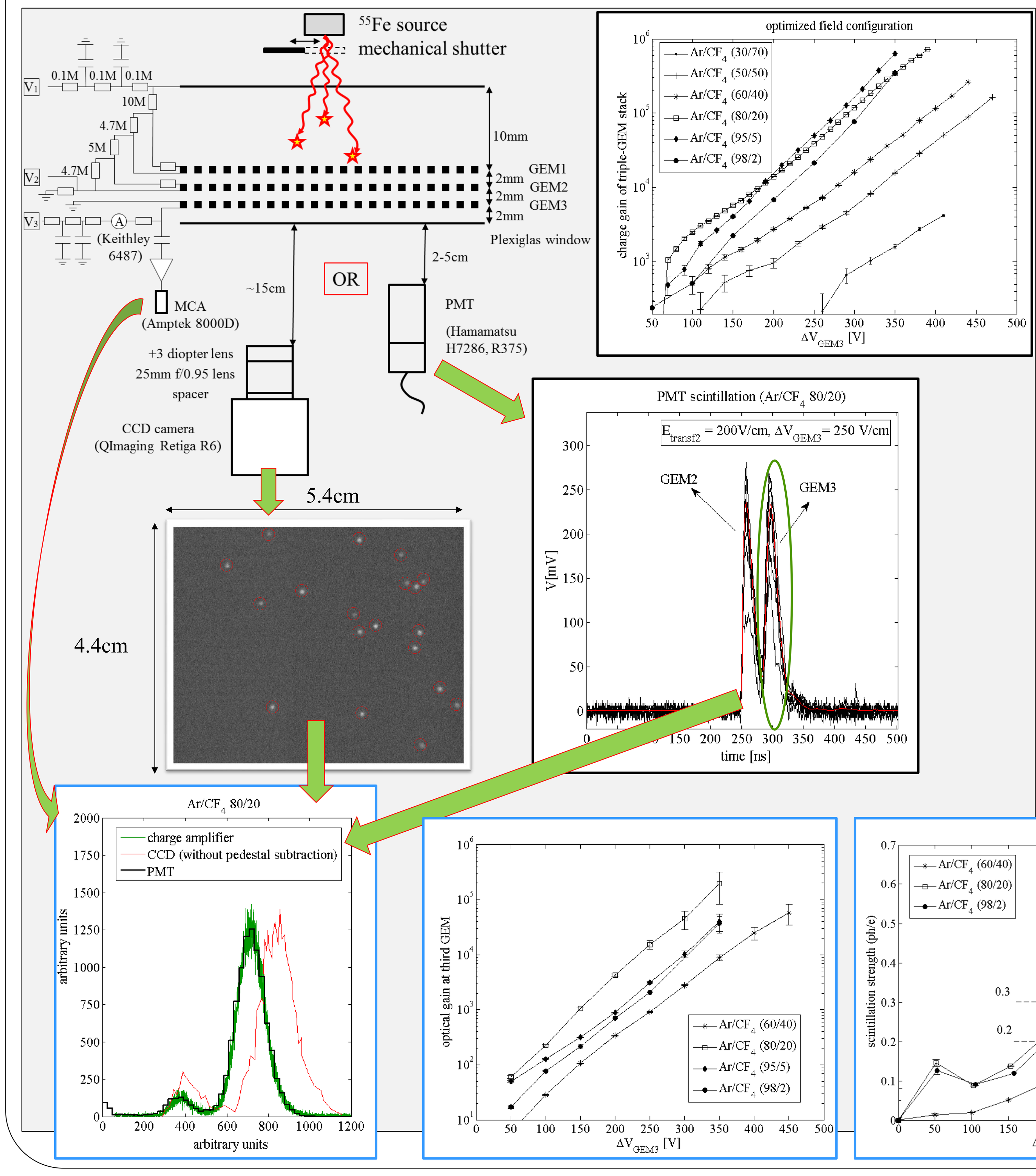
→ ?

Molecules
- Electroluminescence/ Energy-resolution ☹
- Point-spread function ☺

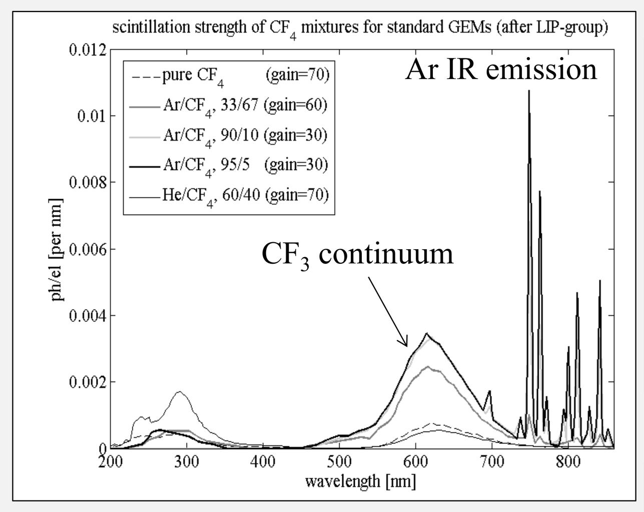
→ Electroluminescent molecules?

A survey of CCD-compatible gas mixtures (400-1000nm)

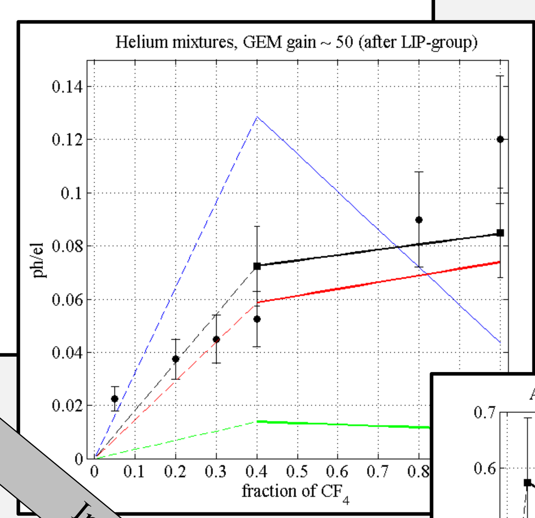
This work

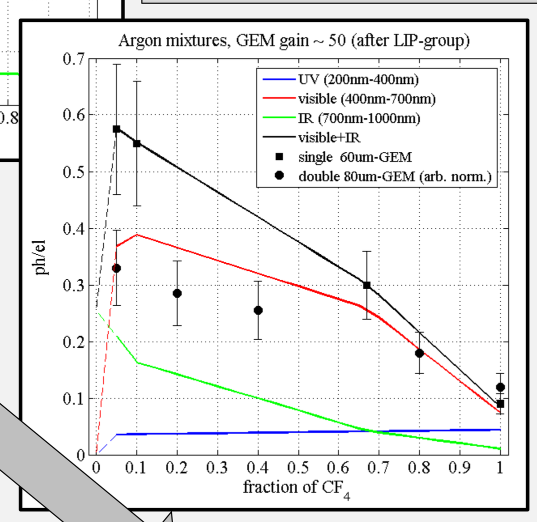


After Coimbra group



NG/TEA, NG/TMA, NG/N_2, NG/CO_2





Increasing scintillation strength

References

[1] M.M.R.Fraga et al., IEEE Trans. Nucl. Sci., 48, 3, 2001.
[2] F.A.F. Fraga et al., IEEE Trans. Nucl. Sci., 49, 1, 2002.
[3] F.A.F. Fraga et al., NIM A, 478(2002)357.
[4] M.M.F.R. Fraga, NIM A, 504(2003)88.
[5] A. Morozov, JINST 7 (2012) P02008.

Main CF_4 scintillation features

- Time constant ~10ns.

400-1000nm

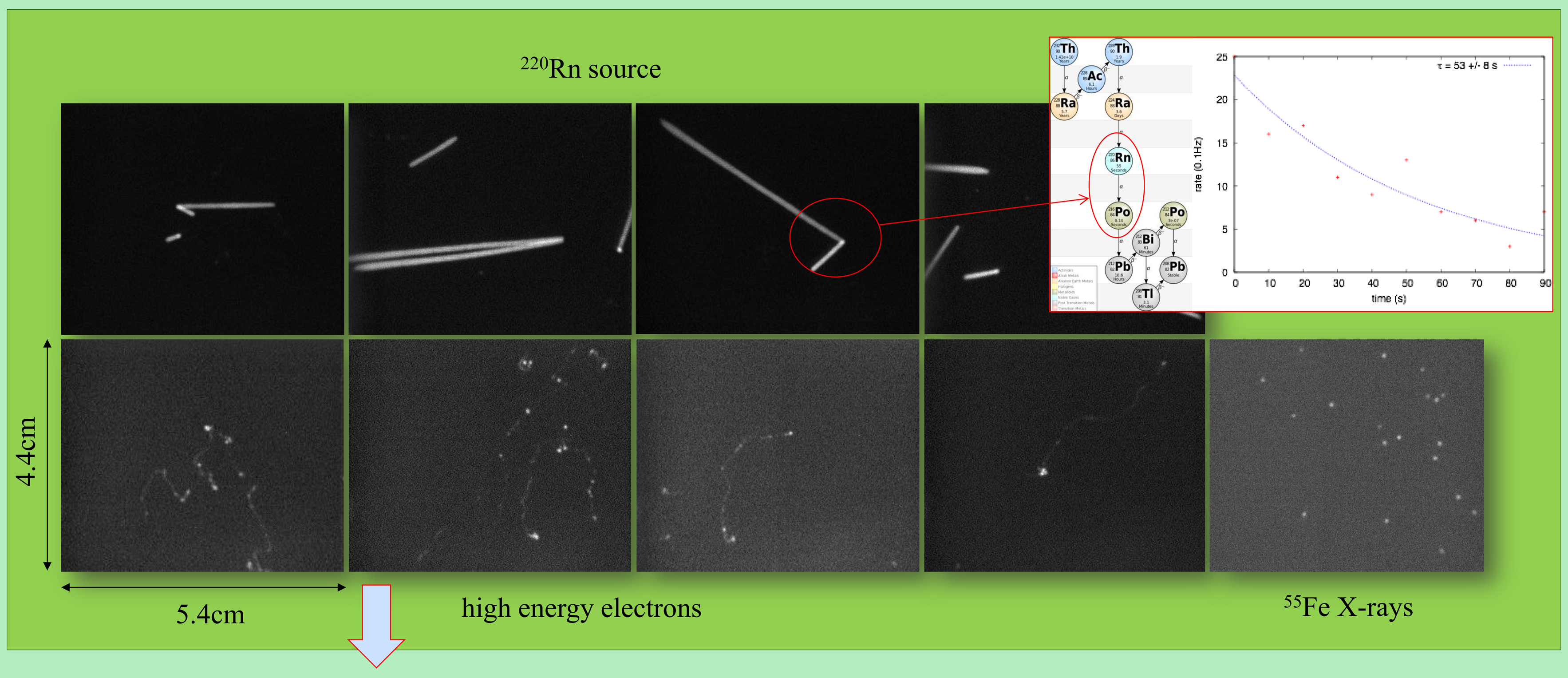
- Lower scintillation strength (ph/el) in He/CF_4 compared to Ar/CF_4 by about 1/3-1/5.
- Optimum scintillation strength of 0.3-0.5 in CF_4 concentration range 5-40%.

200-400nm

- Higher scintillation strength in He/CF_4 mixtures compared to Ar/CF_4 in about x2-x3.

Applications of scintillating GEM chambers

Small 'exposure × rate' (tracking/OTPC mode)



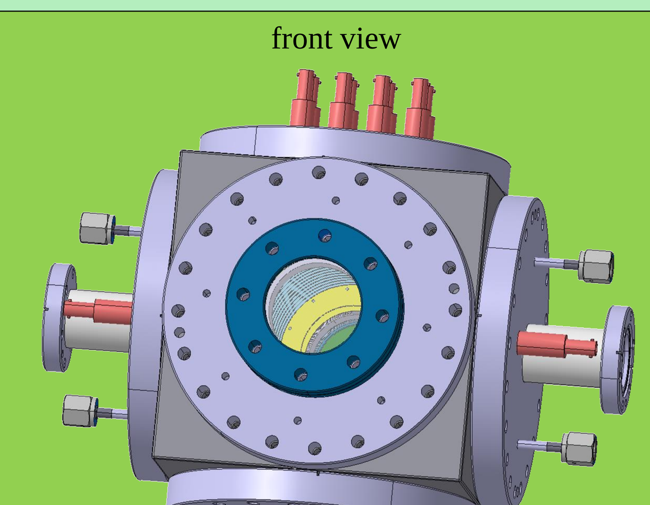
Main results (Phase 0)

- Effective pixel size 160um over 25cm² active region (optical magnification 1/5, pixel grouping 8x8).
- Point spread function = 30-50um (Magboltz).
- Optical gain 5x10⁴, stable with independency from the primary particle (up to 2x10⁵ for X-rays).
- Good optical sensitivity to ⁵⁵Fe X-rays and unaffected calorimetric response (dominated by the avalanche/transfer processes in the GEMs).
- Sensitivity to MIP-like energy deposits.

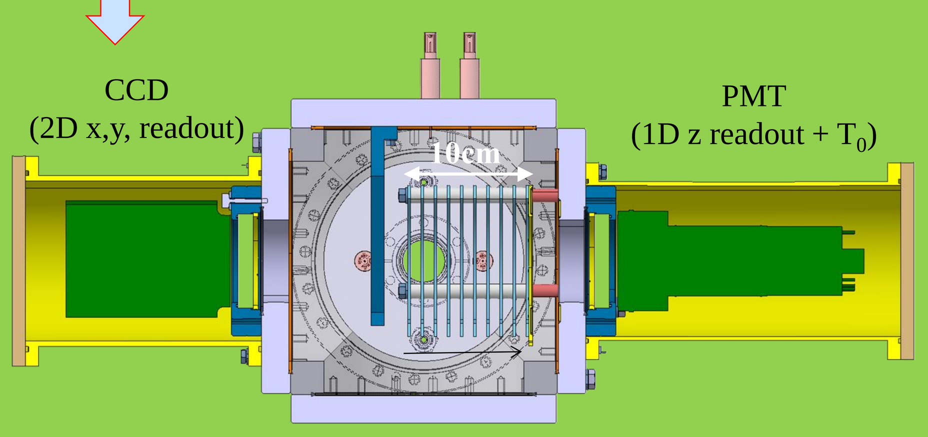
Phase 1

- Stainless steel 800cm³ vessel, rated for 0-2bar.
- Only vacuum-grade elements, gas getters, possibility to evaluate the gas quality with RGA.
- Additional broad-band PMT for measuring the primary scintillation and the *z*-profile.
- Containment of α's and up to ~100keV e⁻ tracks.
- Field and vacuum tightness verified.
- Measurements with α tracks ongoing.

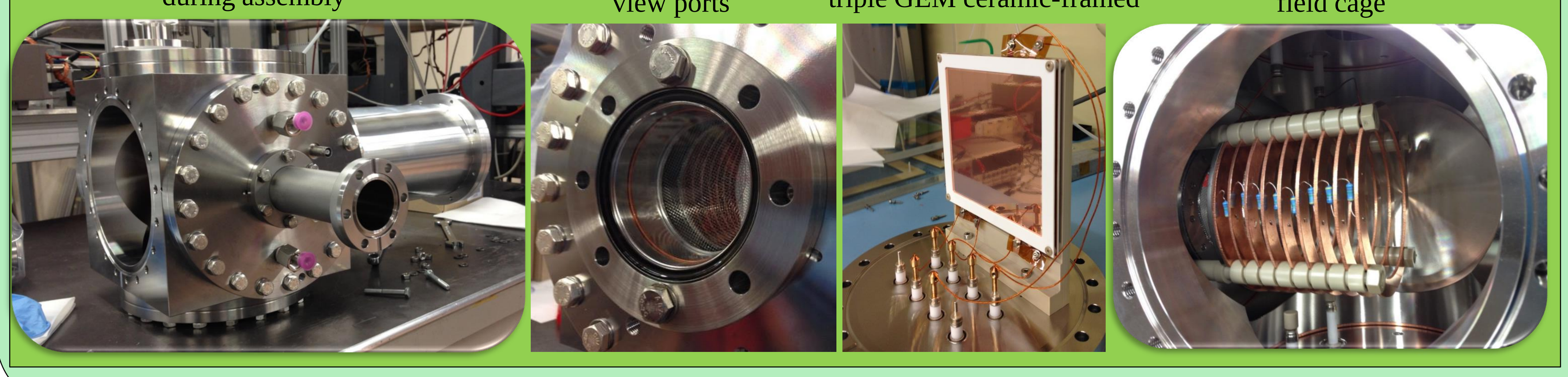
front view



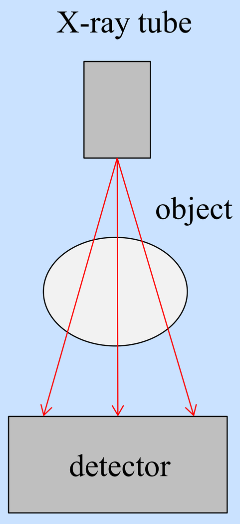
cross-section



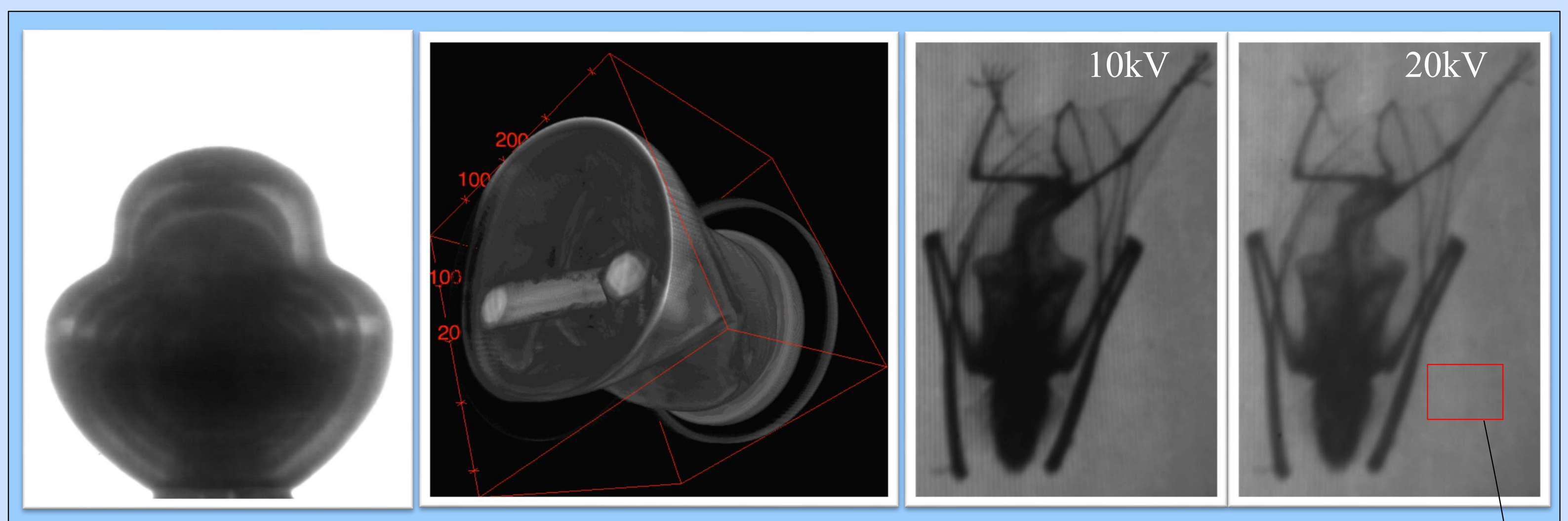
during assembly — view ports — triple GEM ceramic-framed — field cage



Large 'exposure × rate' (imaging mode)

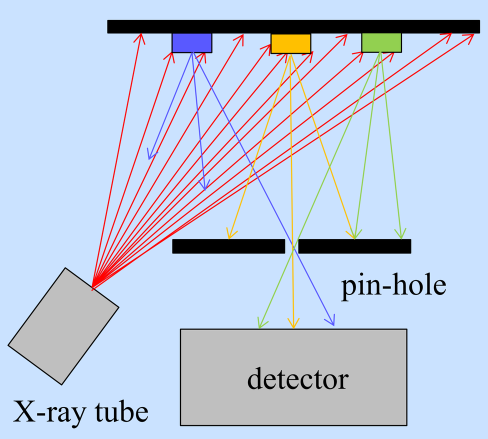


Standard and energy-resolved X-ray imaging in the <30keV region

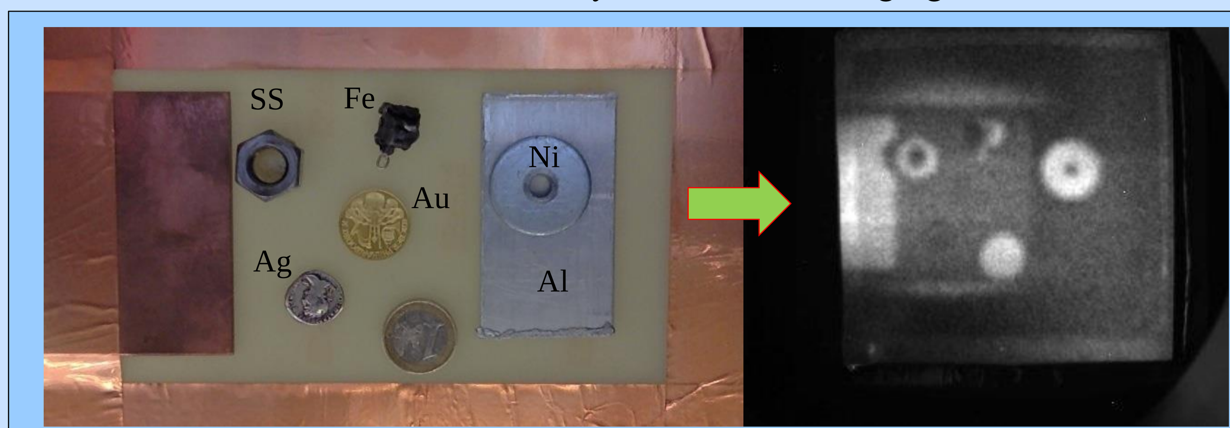


matrioska — 'pencil box' — bat

substrate + different materials

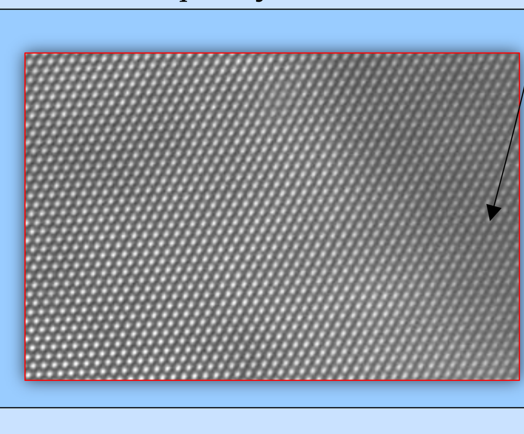


X-ray fluorescence imaging



- All images are taken for an X-ray tube HV in the range 10-30kV.
- Exposures in the range <1s-60s.
- 3D images obtained with a rotary table and a filtered back-projection on a set of 2D images at different angles.
- Effective pixel size at 3rd GEM plane: 20um-320um (optical magnification 1/5-1/10, pixel grouping 1x1->8x8).
- Ionization spread function ~100's um (energy-dependent).
- Ability to do energy-resolved X-ray imaging shown through the spectral reconstruction of ⁵⁵Fe X-ray source (see above).

Avalanche studies and GEM quality assurance



Conclusions and outlook

- We have performed a comprehensive systematic study of gas mixtures known to scintillate in the 400-1000nm range.
- The maximum optical gains in a 3-GEM stack can reach 2×10^5 under X-rays, with a scintillation strength of approximately 0.3, similar to that observed in previous works. The optimum CF_4 admixtures are in the range 5-20%.
- Such optical gains allow to reconstruct from nearly-MIPs to α-tracks over 100cm², with a position resolution of 100's of um and an energy resolution of ~20%FWHM@5.9keV, using a standard scientific camera (~5e⁻ noise).

- We have started a strong R&D effort and are set to determine the limits of the optical readout technology, both from the imaging and from the tracking point of view. Future activities will focus on the light generation structures and the search for new gas mixtures.

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