Development of full-field XRF imaging system for non-invasive investigation of artworks

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Outline

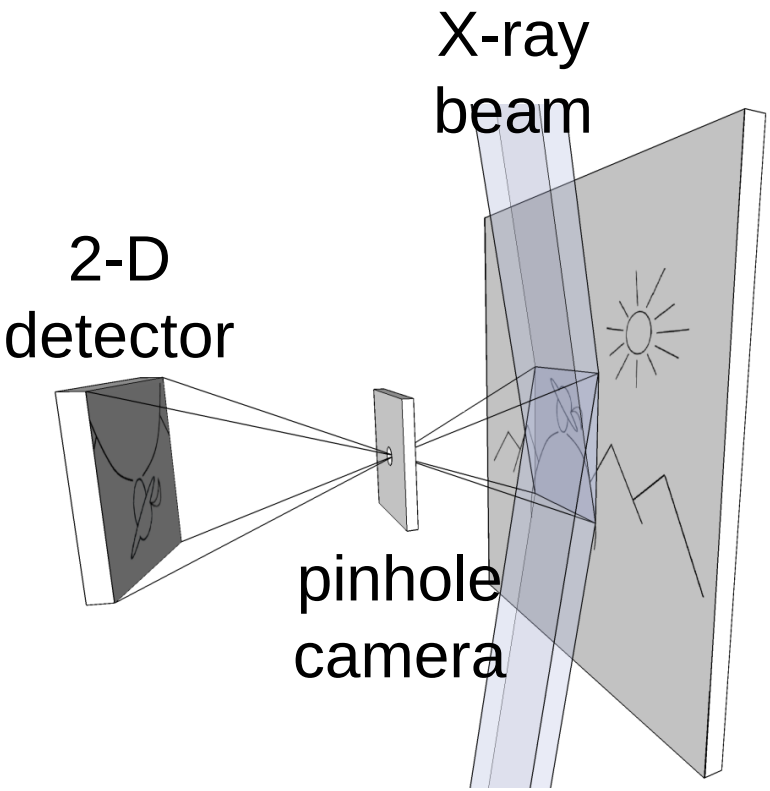
- Motivation
  - Full-flield vs. Macro-XRF imaging
  - XRF set-up design
  - Limitations of the pliot proof-of-principle set-up
- Measurement results
  - Differentation of pigments
  - Hiddedn layers
  - Curved surfaces
- Detector system upgrade
- Conclusions

Motivation

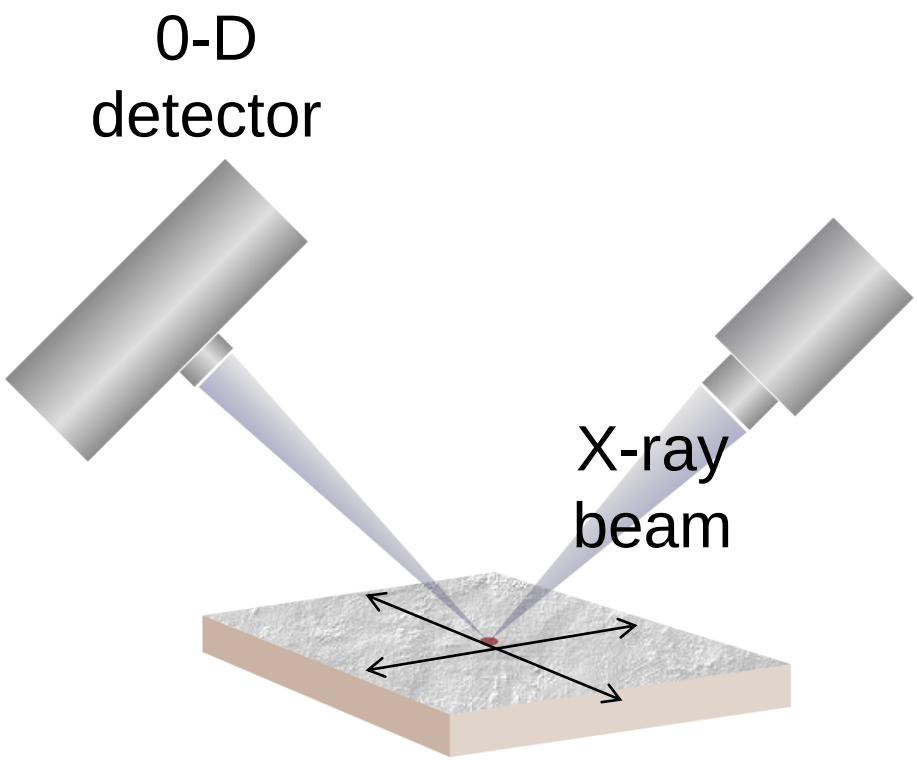
- Great interest in non-destructive techniques for investigation of large area historical art objects, mainly paintings
- Mapping of elemental distribution in non-visible layers, e.g. underpaintings using the X-ray fluorescence (XRF) technique
- Fast screening of large area objects with dimensions up to 1 m or more
- Investigation of large area non-flat objects

Full-field vs macro-XRF imaging

Full-field imaging



Macro-XRF imaging



Full-field vs macro-XRF imaging

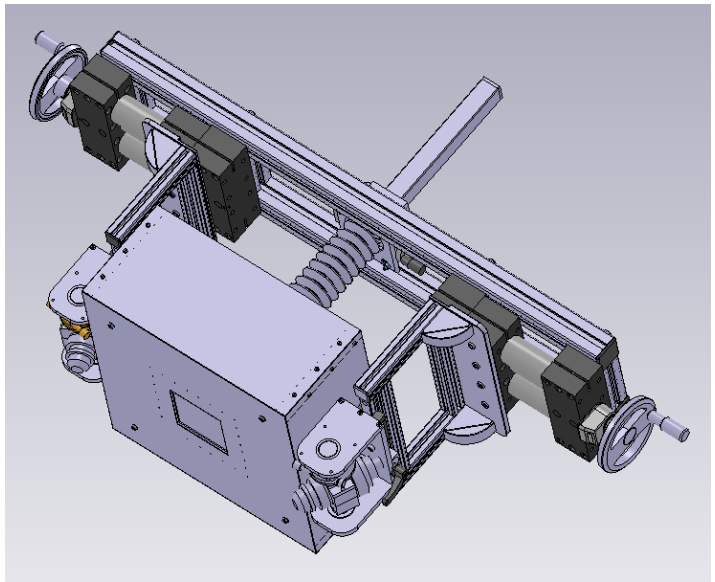
Full-field imaging

- Spatial resolution determined by the diameter of the pinhole camera and detector spatial resolution
- Simultaneus imaging of large area
- 2-D position sensitive and energy dispersive detector needed
- Custom-designed systems under developement

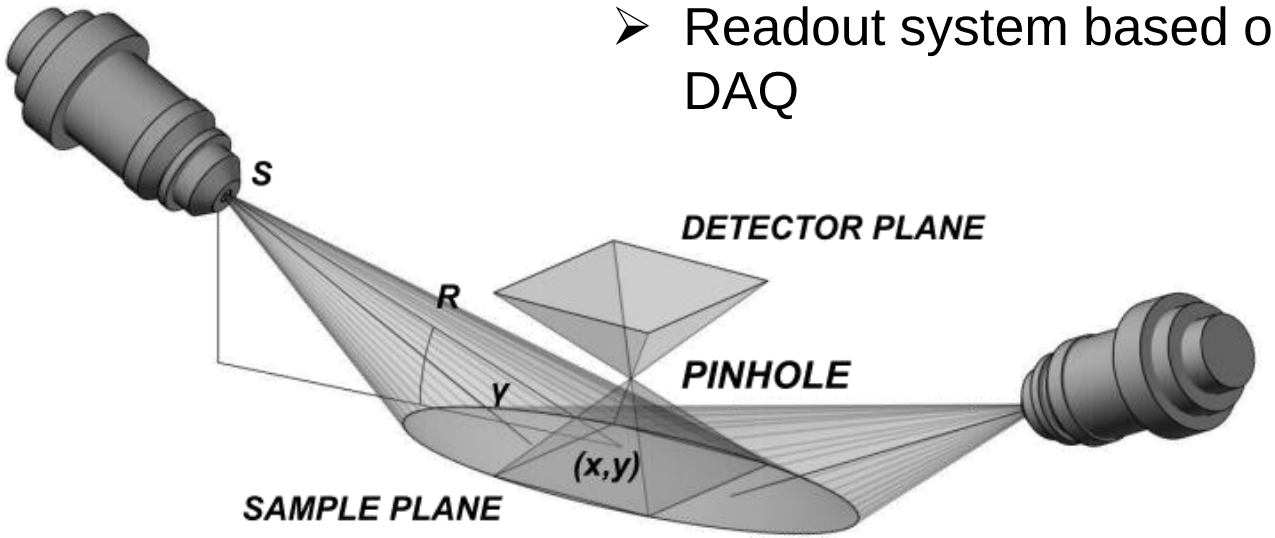
Macro-XRF scanning

- Spatial resolution determined by the diameter of exciting beam
- Time consuming scanning of large areas
- Possibility of employing high energy resolution 0-D detectors
- Commercial and custom developed system exist

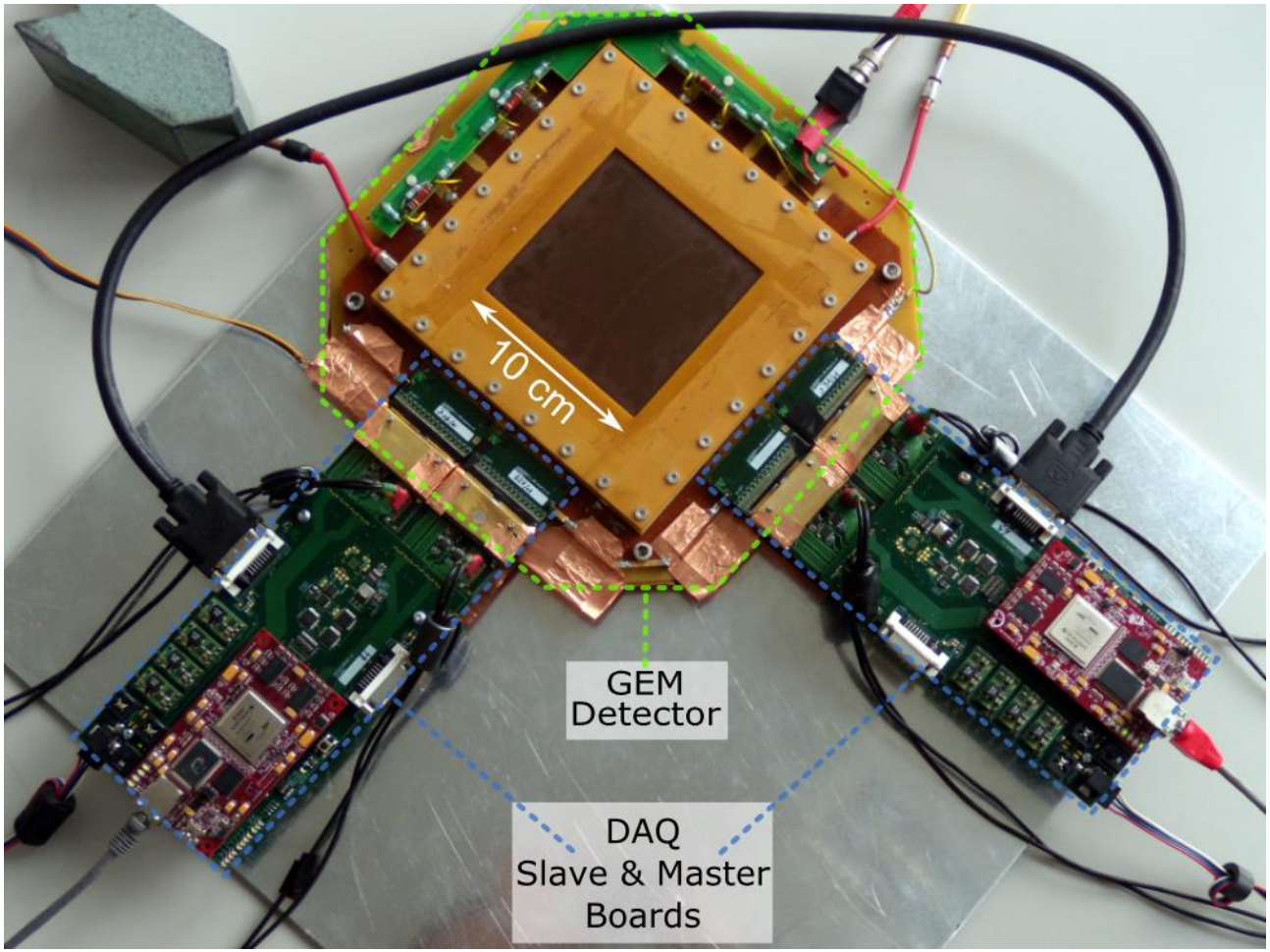
XRF set-up design



- **Two 50 W** Mo air-cooled **X-ray tubes**
- **Excitation geometry** optimized to obtain homogeneous illumination of **10×10 cm** area
- Projection by a **pinhole camera**
- Fixed magnification M=1
- 10×10 cm triple-**GEM** detector
- 2-dimensional Cartesian readout structure with a strip pitch of 0.8 mm
- Readout system based on full custom ASIC and DAQ



Detection system with triple-GEM (GEMROC ASIC)

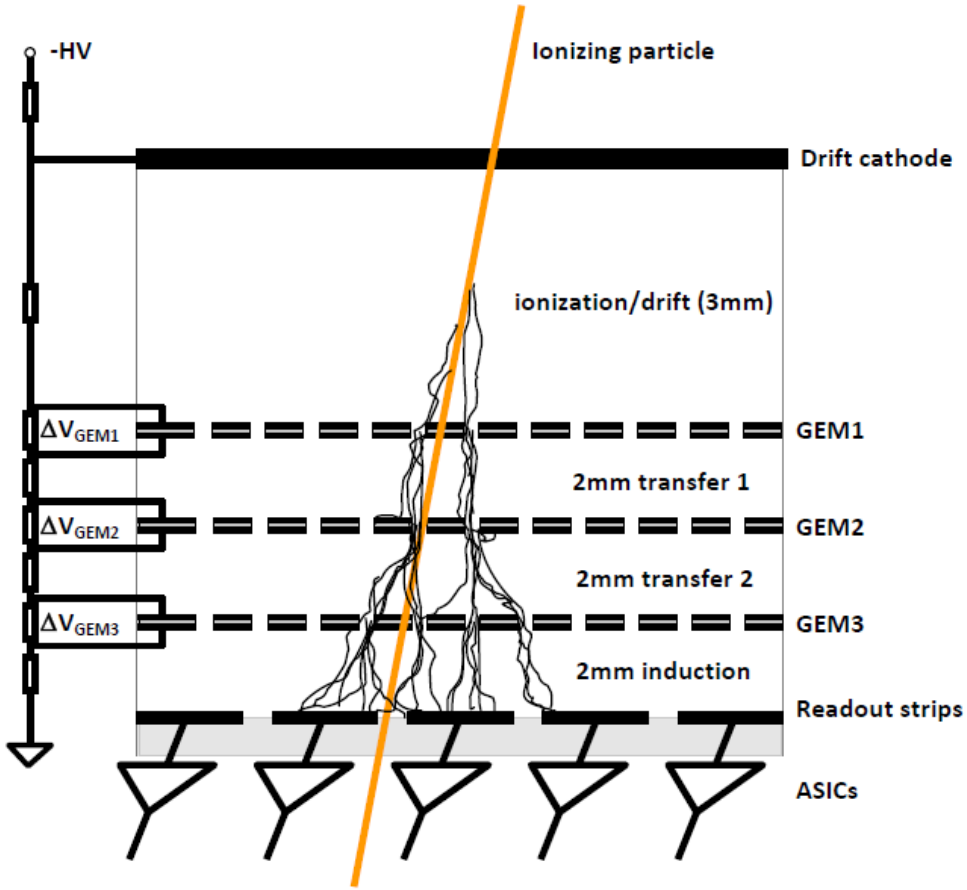


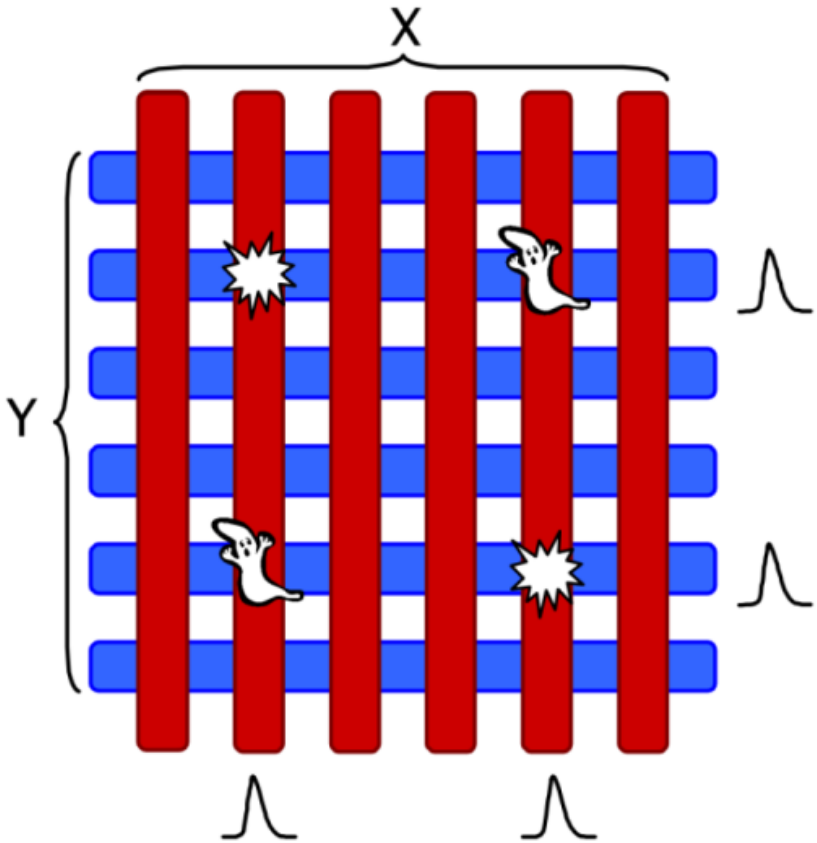
- Custom designed DAQ board with Ethernet based communication protocol
- Four 32-channel GEMROCs for each coordinate (one channel per two readout strips)
- Triple-GEM with 256 × 256 readout strips (pitch of readout strips is 800 μm)

T. Fiutowski et al., *Design and performance of the GEMROC ASIC for 2-D readout of gas electron multiplier detectors*, 2011 IEEE Nucl. Sci. Symp. Conf. Rec., (2011)

B. Mindur et al., *A compact system for two-dimensional readout of Gas Electron Multiplier detectors*, JINST 8 T01005 (2013)

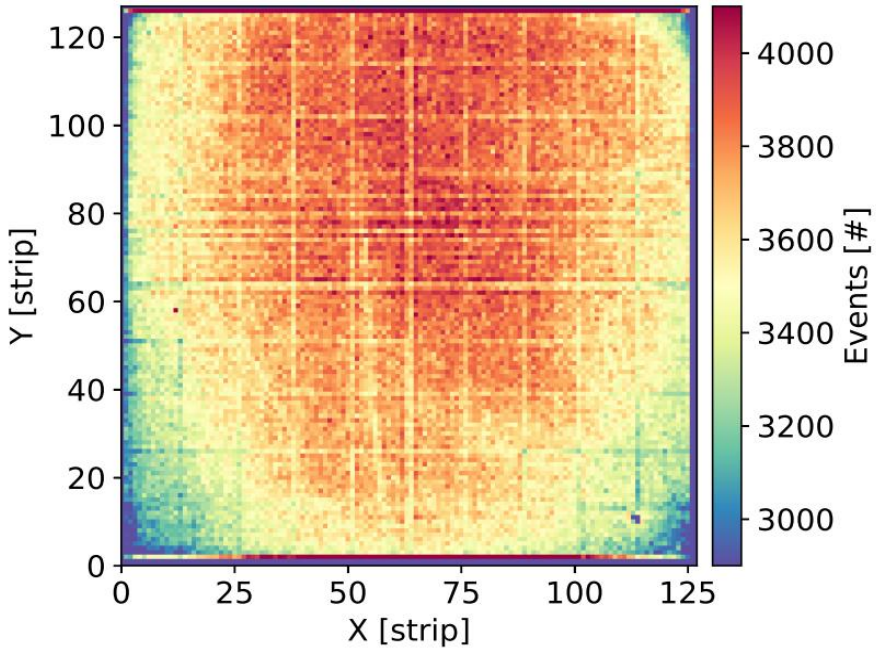
2-D strip-like readout

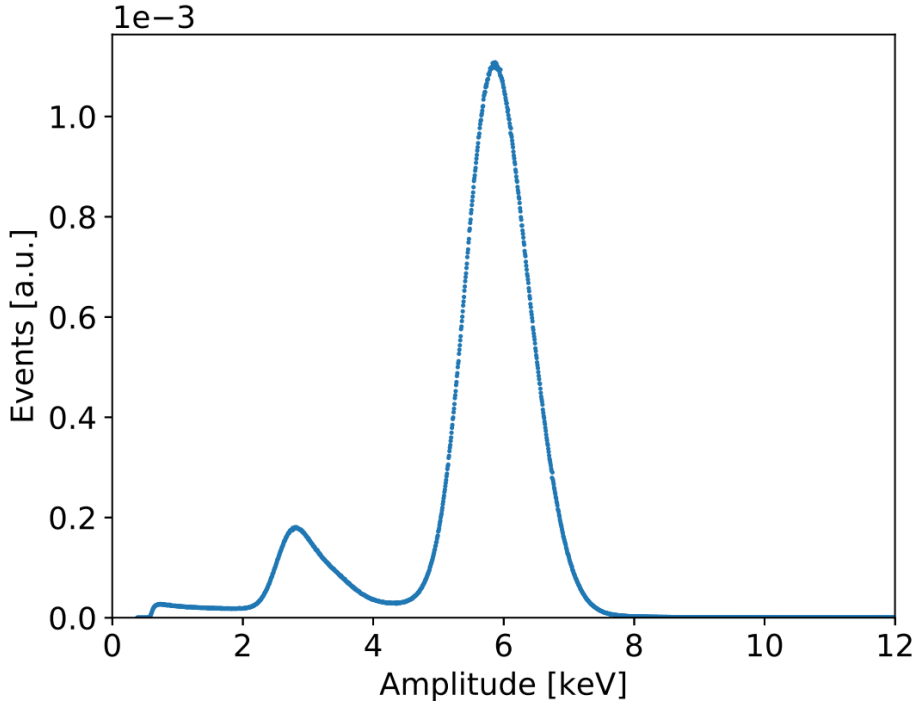




Position is derived from time stamp coincidences of X and Y clustered signals

Energy resolution (GEMROC set-up)



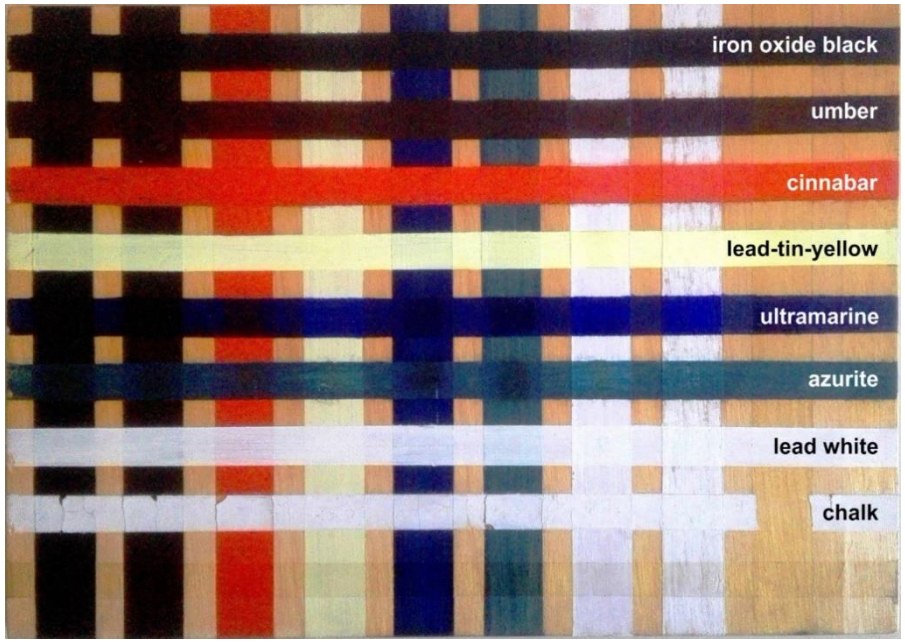


Energy resolution Fe-55 (FWHM) - 19.8% @ 3860V Ar/CO_2 (70/30)

Commonly used historical pigments

Pigment	X-ray characteristic lines
Umber	Mn-Kα – 5.90 keV, Fe-Kα – 6.40 keV
Carbon black	Fe-Kα – 6.40 keV
Cobalt blue	Co-Kα – 6.93 keV, Co-Kβ – 7.65 keV
Azurite	Cu-Kα – 8.05 keV, Cu-Kβ – 8.90 keV
Zinc white	Zn-Kα – 8.64 keV, Zn-Kβ – 9.57keV
Vermilion	Hg-Lα – 9.99 keV, Hg-Lβ – 11.92 keV
Lead-tin yellow	Pb-Lα – 10.55 keV, Pb-Lβ – 12.62 keV
Lead white	Pb-Lα – 10.55 keV, Pb-Lβ – 12.62 keV

Objects used for system validation

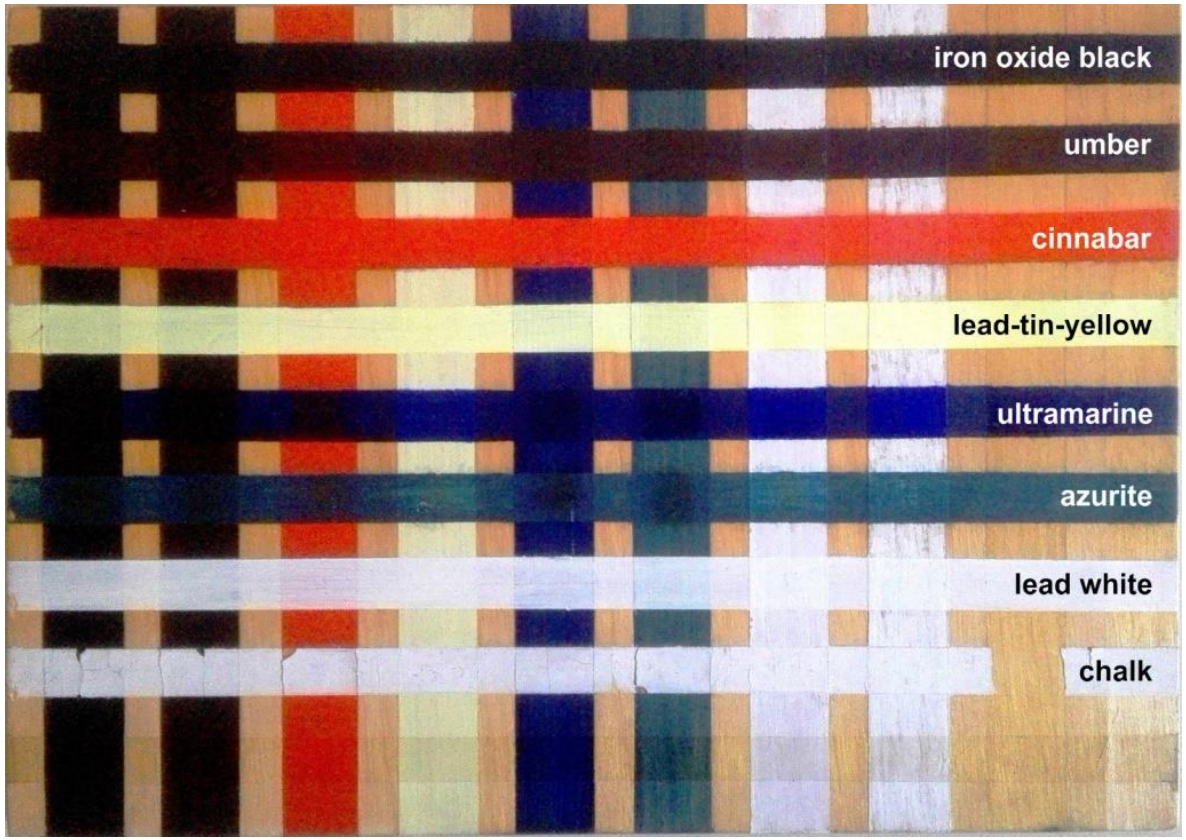


Differentiation of pigments

Hidden layers

Curved surfaces

Results
Differentiation of pigments



→ Fe_3O_4

→ Fe_2O_3, MnO_2, AlO_3

→ HgS

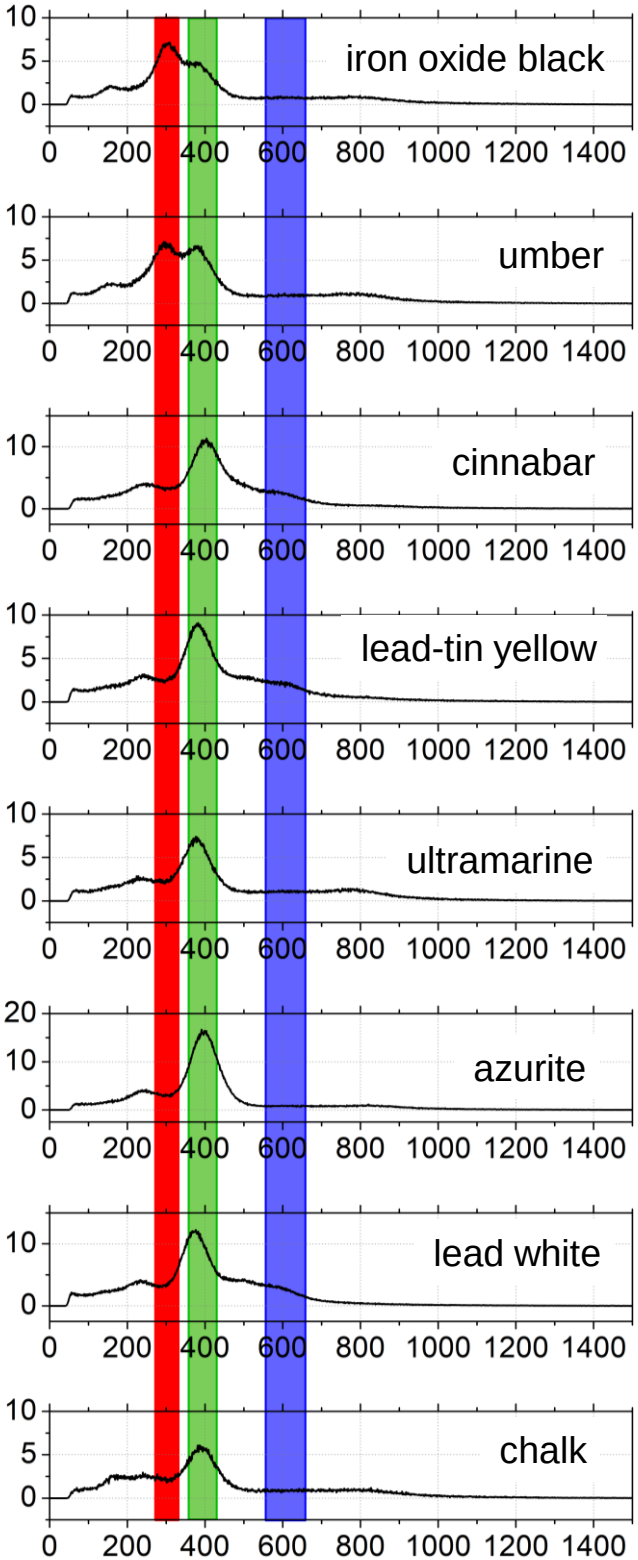
→ Pb_2SnO_4

→ $Na_{8–10}Al_6Si_6O_{24}S_{2–4}$

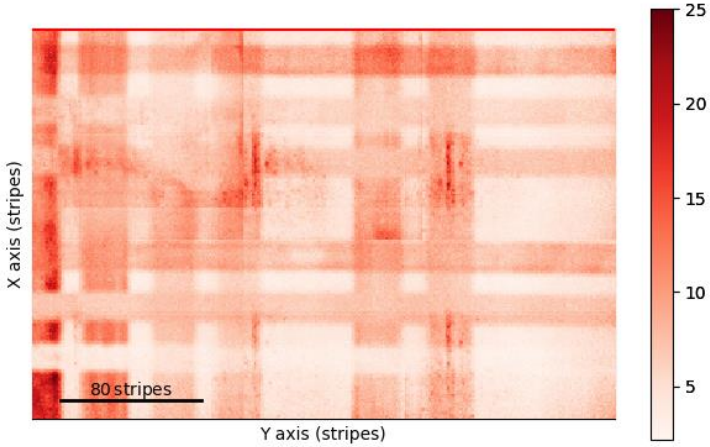
→ $Cu_3(CO_3)_2(OH)_2$

→ $(PbCO_3)_2 \cdot Pb(OH)_2$

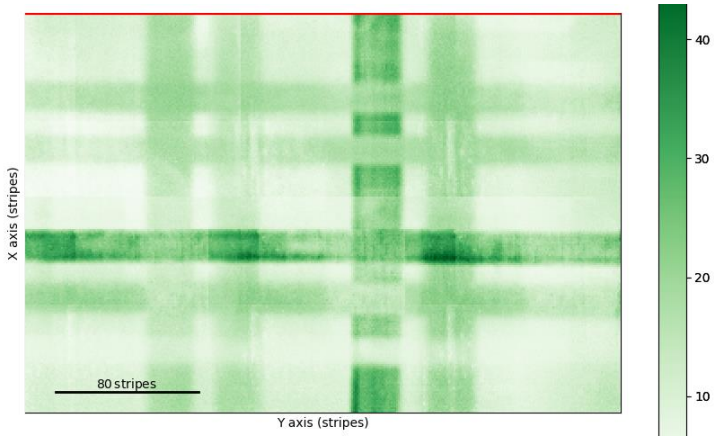
→ $CaCO_3$



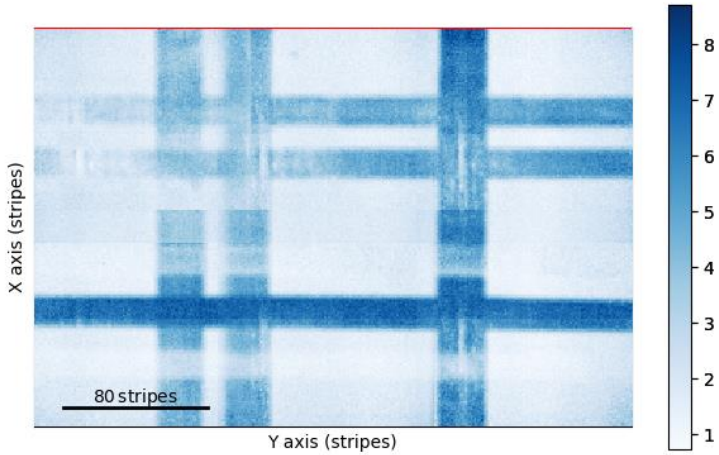
Results
Differentiation of pigments



Fe map

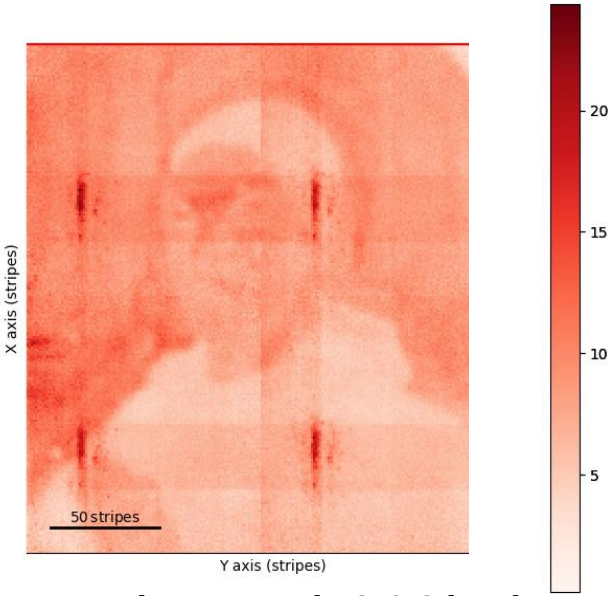


Cu map

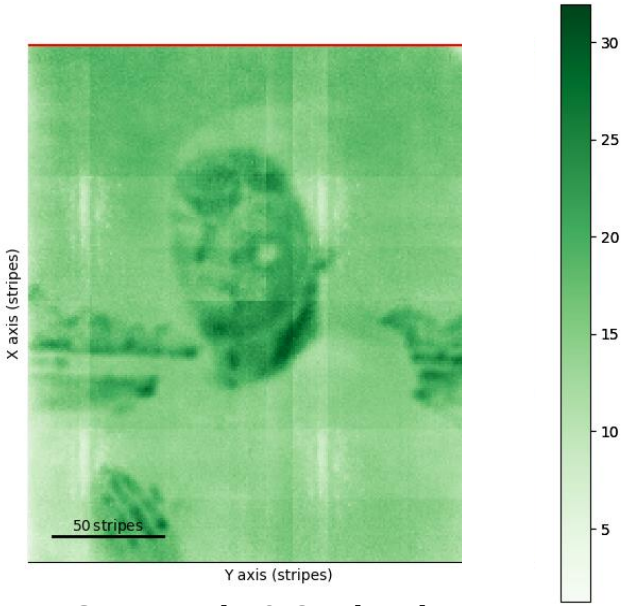


Pb and Hg map

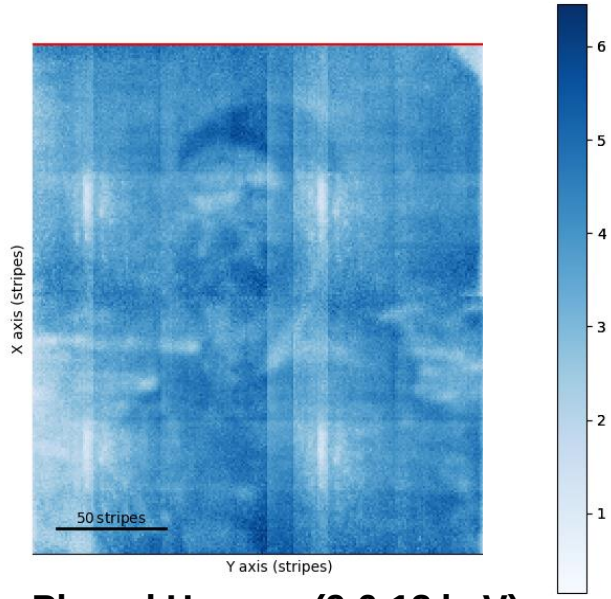
Results
Hidden layers



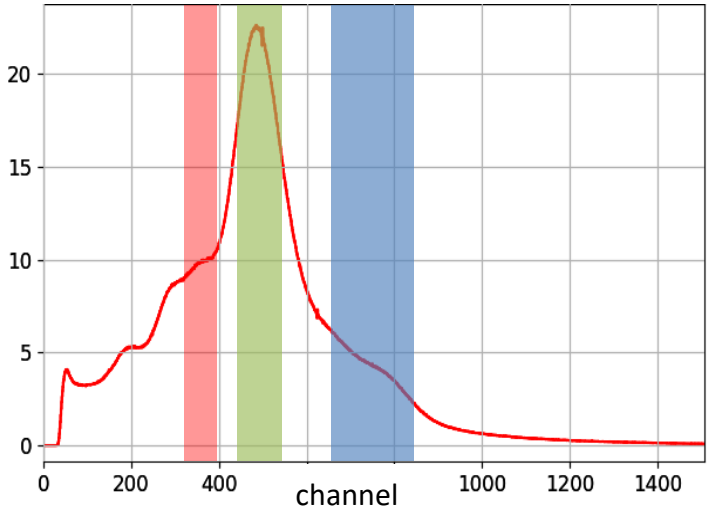
Fe and Mn map (5.8-6.8 keV)



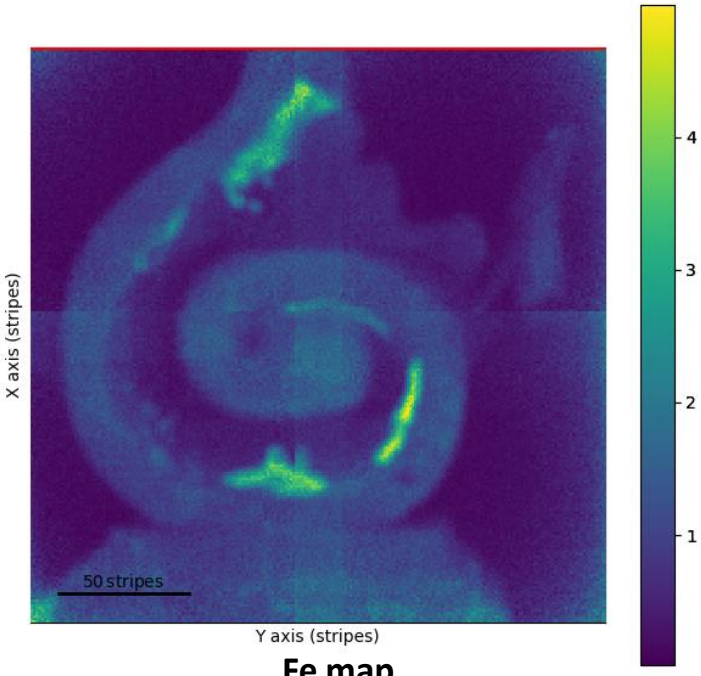
Cu Map (7.6-8.4 keV)



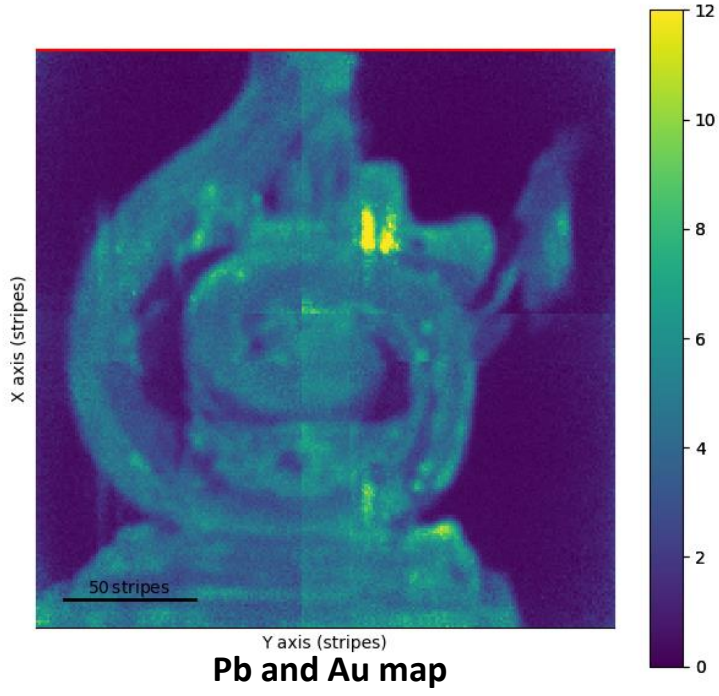
Pb and Hg map (9.6-13 keV)



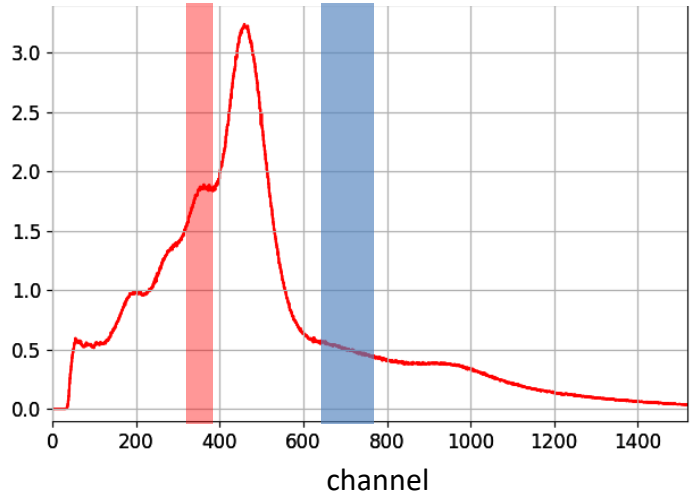
Results
Curved surfaces



Fe map



Pb and Au map

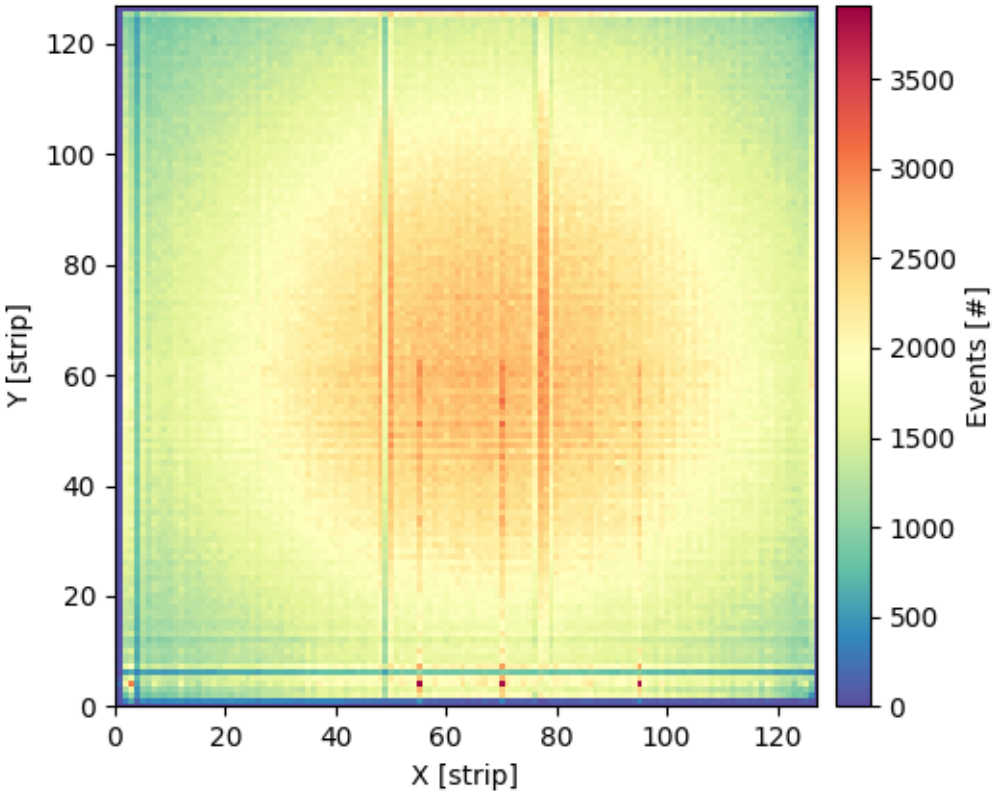


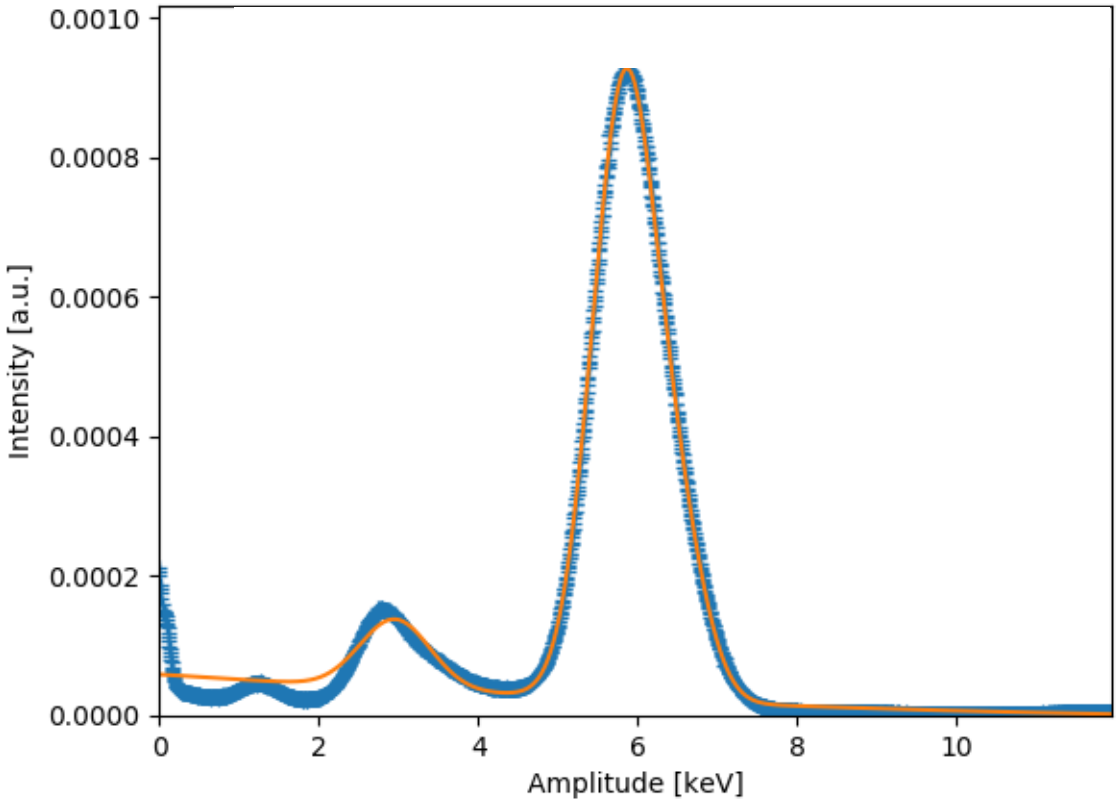
Detector system upgrade

- Front-end electronics
  - New 64-channels ASIC (ARTROC)
    - Higher dynamic range
    - Lower electronic noise level
    - Higher front-end gain
    - Integrated input protection against discharges

- GEM detector
  - Copper-less GEM and drift foils
  - Different gas mixtures:
    - Kr – moderate cost and detection efficiency
    - Xe – higher cost and detection efficiency

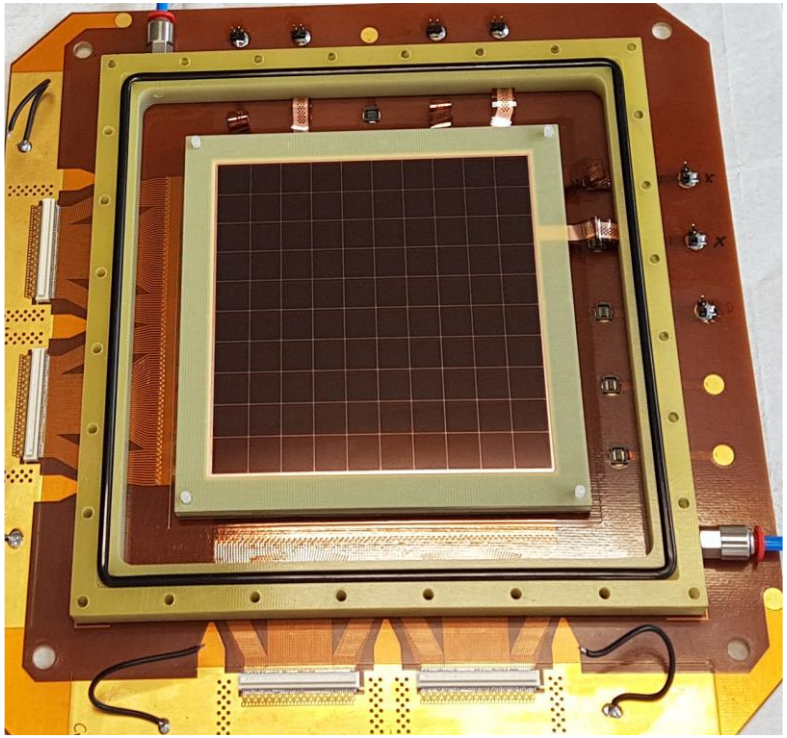
Energy resolution (ARTROC set-up)

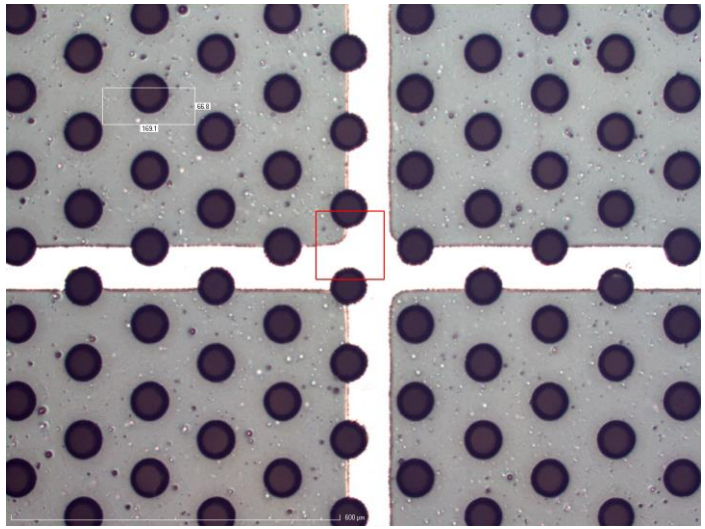




Energy resolution Fe-55 (FWHM) - **17.4%** @ 3480V Ar/CO_2 (80/20)

Copper-less GEM detector

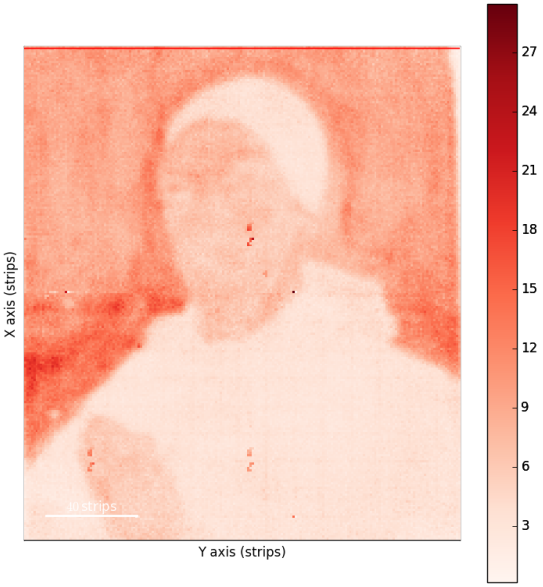




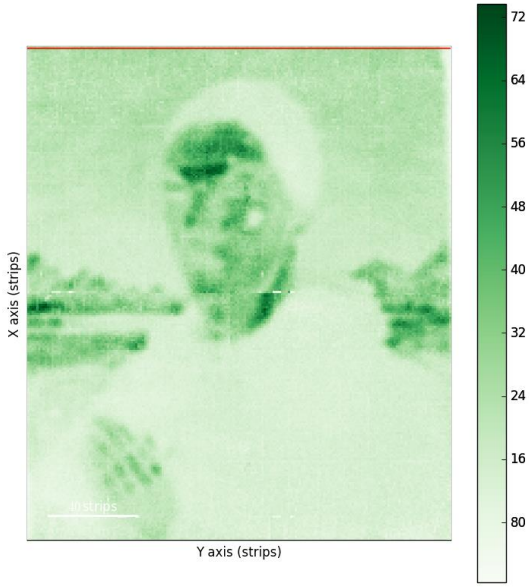
Copper layers removed from the GEM foils and the drift electrode.
Only 1 cm grid of 100 μm wide copper strips left

B. Mindur et al., *Performance of a GEM detector with copper-less foils,* JINST 12 P09020 (2017)

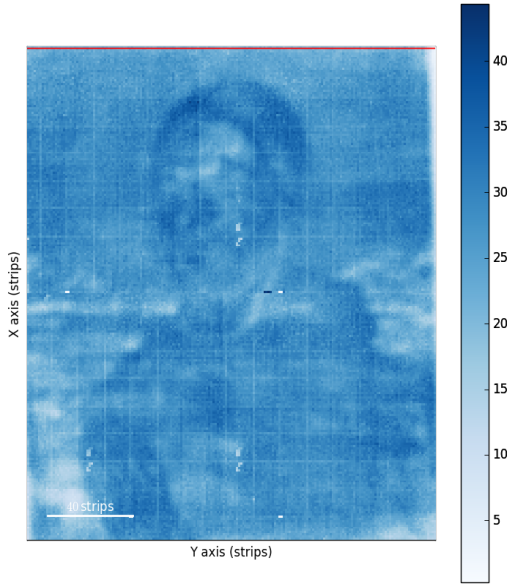
Hidden layers
standard vs. copper-less GEM



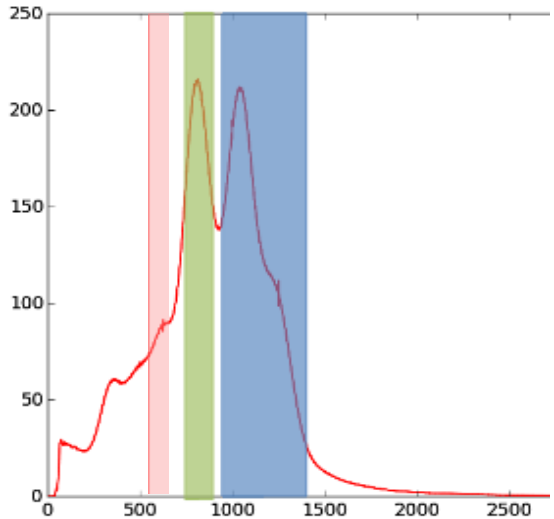
Fe and Mn map (5.8-6.8 keV)



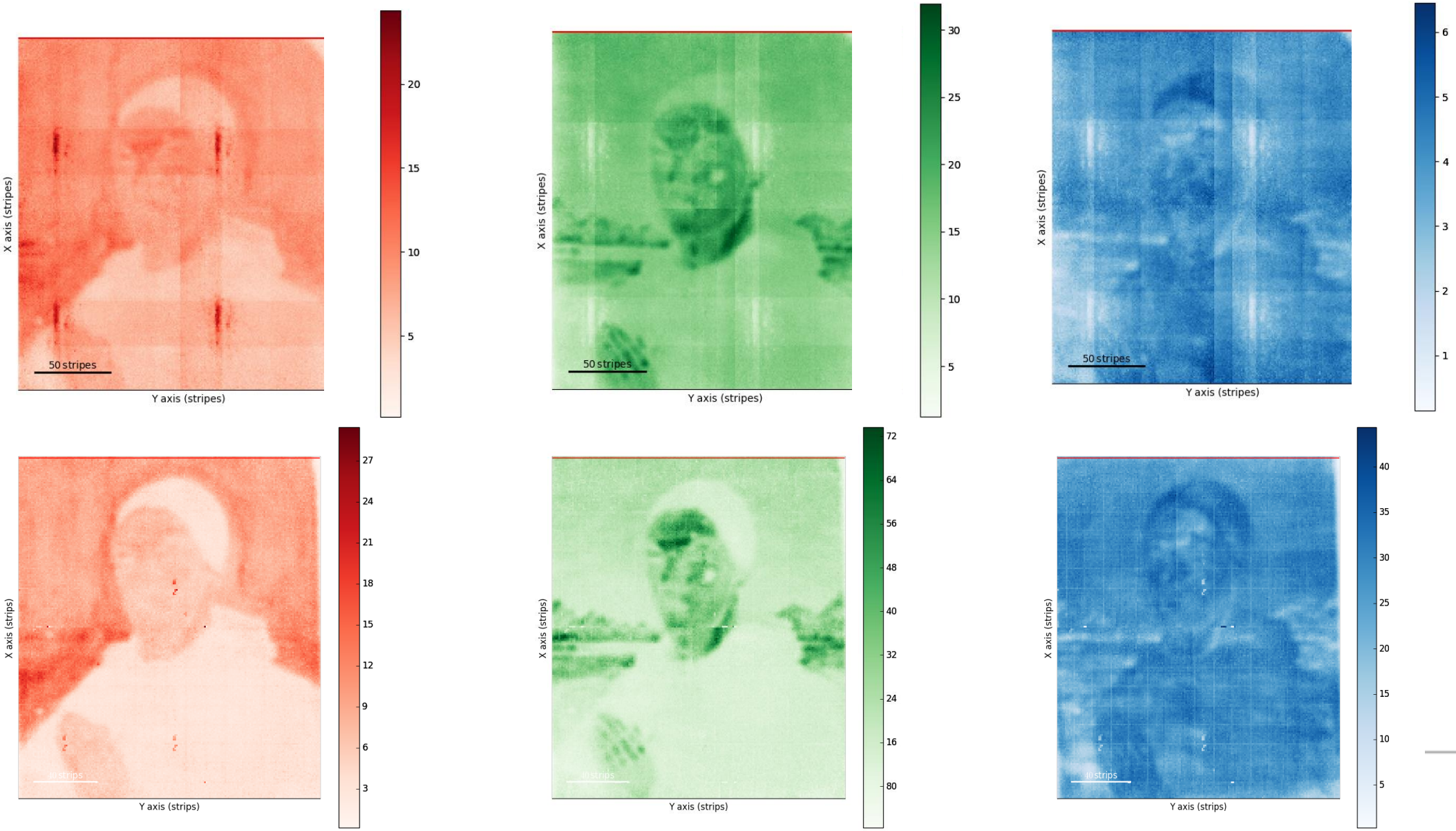
Cu Map (7.6-8.4 keV)



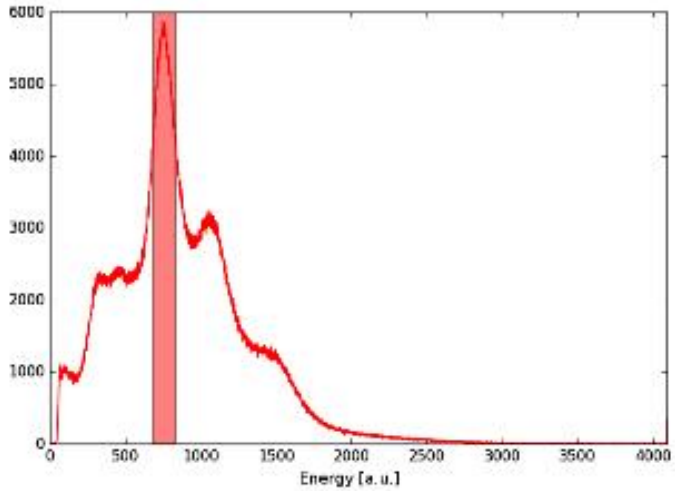
Pb and Hg map (9.6-13 keV)

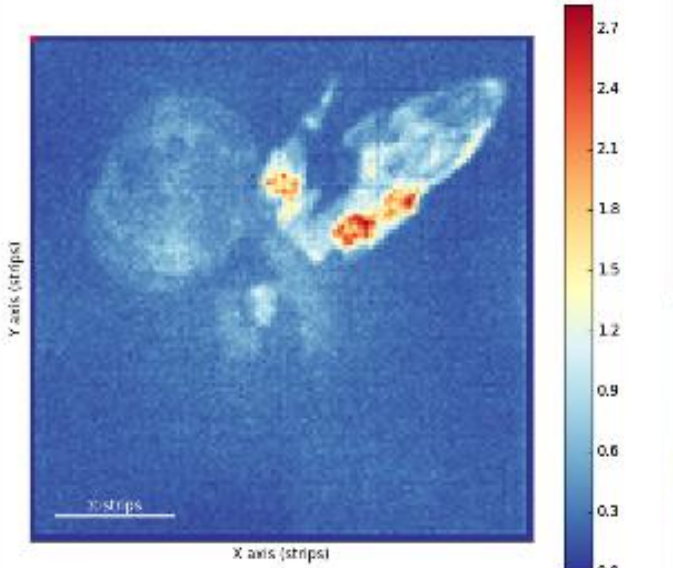


Hidden layers
standard vs. copper-less GEM

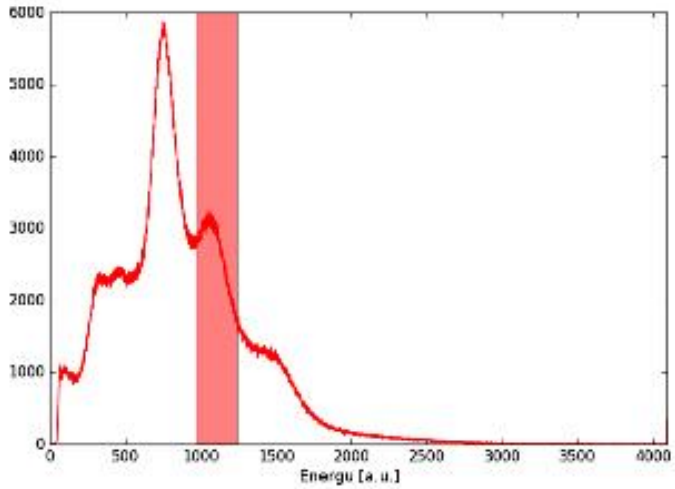


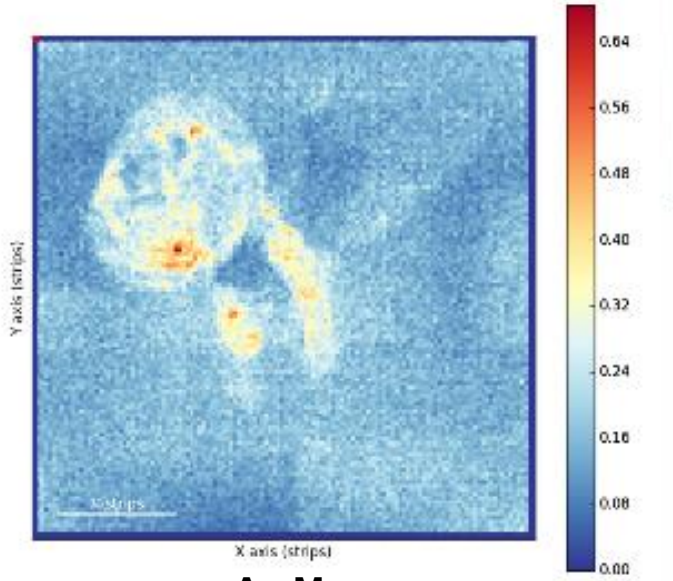
Results
Curved surfaces





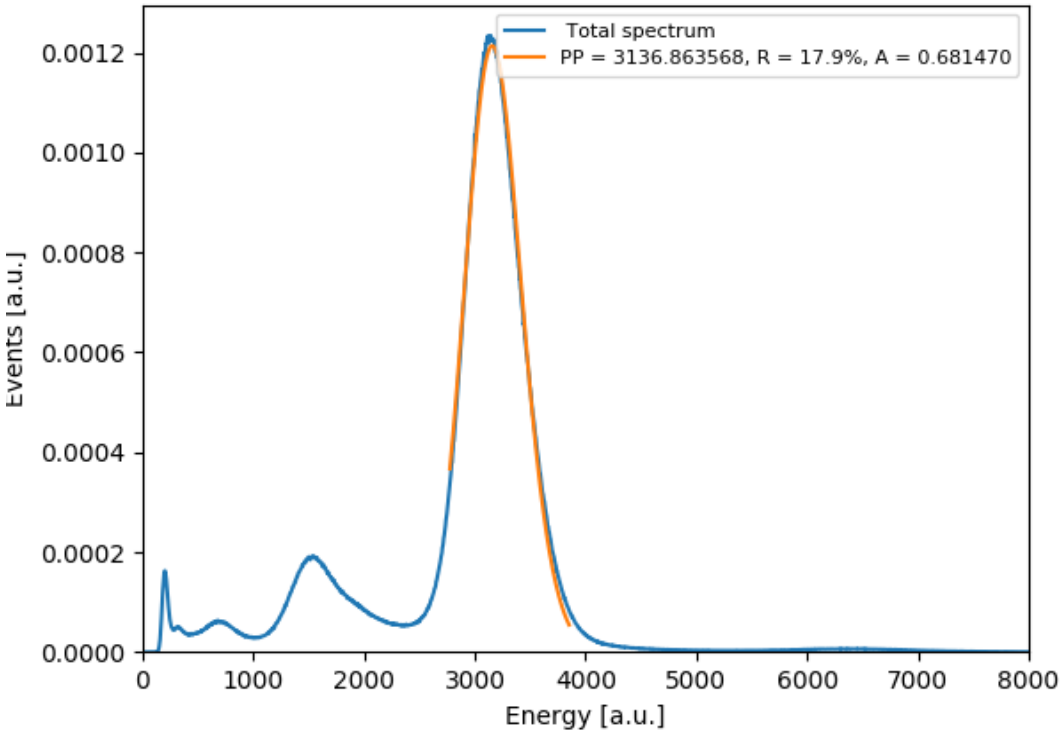
Cu Map

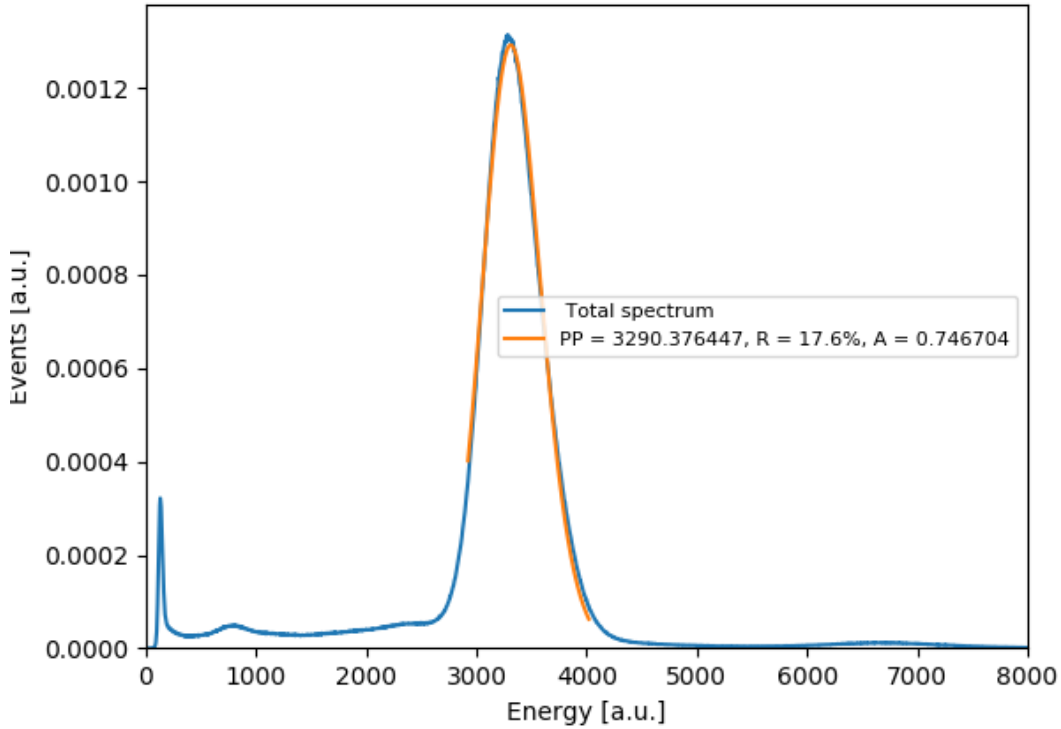




Au Map

Ar vs. Kr based gas mixture





Energy resolution Fe-55 (FWHM) - **17.9%** @ 3500V Ar/CO_2 (80/20)
Energy resolution Fe-55 (FWHM) - **17.6%** @ 3680V Kr/CO_2 (90/10)

Conclusions

- Full-field XRF with GEM detector is feasible
- The technique is very promising for:
  - fast elemental imaging of paintings
  - imaging of curved surfaces (infinite depth of view)
- Most of the important aspects of this measurement technique have already been investigated and are understood
- More systematic tests with different gas mixture (Kr and Xe) are needed
- Integration with robot based automated scanning system in National Museum in Kraków in progress

Scanning robotic arm

References

- Front-end
  - T. Fiutowski et al., *Design and performance of the GEMROC ASIC for 2-D readout of gas electron multiplier detectors*
    2011 IEEE Nucl. Sci. Symp. Conf. Rec., (2011)
  - T. Fiutowski et al., *ARTROC – a readout ASIC for GEM-based full-field XRF imaging system,*
    JINST 12 C12016 (2017)
- DAQ hardware and software
  - B. Mindur et al., *A compact system for two-dimensional readout of Gas Electron Multiplier detectors,*
    JINST 8 T01005 (2013)
- Copper-less GEM
  - B. Mindur et al., *Performance of a GEM detector with copper-less foils,*
    JINST 12 P09020 (2017)
- Application
  - A. Zielińska et al., *X-ray fluorescence imaging system for fast mapping of pigment distributions in cultural heritage paintings,*
    JINST 8 P10011 (2013)
  - W. Dąbrowski et al. *Application of GEM-based detectors in full-field XRF imaging*.
    JINST 11 C12025 (2016)