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

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Outline

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  - XRF set-up design
  - Limitations of the pliot proof-of-principle set-up

- Measurement results
  - Differentiation of pigments
  - Hidden 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

- X-ray beam
- 2-D detector
- Pinhole camera

Macro-XRF imaging

- 0-D detector
- X-ray beam
Full-field vs macro-XRF imaging

**Full-field imaging**
- Spatial resolution determined by the diameter of the pinhole camera and detector spatial resolution
- Simultaneous imaging of large area
- 2-D position sensitive and energy dispersive detector needed
- Custom-designed systems under development

**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)


B. Mindur et al., *A compact system for two-dimensional readout of Gas Electron Multiplier detectors*, JINST 8 T01005 (2013)
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/CO₂ (70/30)
# Commonly used historical pigments

<table>
<thead>
<tr>
<th>Pigment</th>
<th>X-ray characteristic lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umber</td>
<td>Mn-Kα – 5.90 keV, Fe-Kα – 6.40 keV</td>
</tr>
<tr>
<td>Carbon black</td>
<td>Fe-Kα – 6.40 keV</td>
</tr>
<tr>
<td>Cobalt blue</td>
<td>Co-Kα – 6.93 keV, Co-Kβ – 7.65 keV</td>
</tr>
<tr>
<td>Azurite</td>
<td>Cu-Kα – 8.05 keV, Cu-Kβ – 8.90 keV</td>
</tr>
<tr>
<td>Zinc white</td>
<td>Zn-Kα – 8.64 keV, Zn-Kβ – 9.57 keV</td>
</tr>
<tr>
<td>Vermilion</td>
<td>Hg-Lα – 9.99 keV, Hg-Lβ – 11.92 keV</td>
</tr>
<tr>
<td>Lead-tin yellow</td>
<td>Pb-Lα – 10.55 keV, Pb-Lβ – 12.62 keV</td>
</tr>
<tr>
<td>Lead white</td>
<td>Pb-Lα – 10.55 keV, Pb-Lβ – 12.62 keV</td>
</tr>
</tbody>
</table>
Objects used for system validation

Differentiation of pigments

Hidden layers

Curved surfaces
Results
Differentiation of pigments

- Fe$_3$O$_4$
- Fe$_2$O$_3$, MnO$_2$, AlO$_3$
- HgS
- Pb$_2$SnO$_4$
- Na$_{8–10}$Al$_6$Si$_6$O$_{24}$S$_{2–4}$
- Cu$_3$(CO$_3$)$_2$(OH)$_2$
- (PbCO$_3$)$_2$·Pb(OH)$_2$
- CaCO$_3$
Results

Differentiation of pigments

- iron oxide black
- umber
- cinnabar
- lead-tin yellow
- ultramarine
- azurite
- lead white
- chalk

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 Fe-55 (FWHM) - **17.4%** @ 3480V Ar/CO₂ (80/20)
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

Cu Map (7.6 - 8.4 keV)
Fe and Mn map (5.8 - 6.8 keV)
Pb and Hg map (9.6 - 13 keV)
Results
Curved surfaces
Ar vs. Kr based gas mixture

Energy resolution Fe-55 (FWHM) - 17.9% @ 3500V Ar/CO₂ (80/20)
Energy resolution Fe-55 (FWHM) - 17.6% @ 3680V Kr/CO₂ (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
Front-end

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)