Development of a position sensitive detection system based on the GEM detector for two-dimensional imaging using X-ray fluorescence and X-ray radiography methods.

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Abstract

Application of physical methods to investigation of cultural heritage objects becomes a standard nowadays. Especially, the experimental techniques, which are non-destructive, non-invasive and allow to perform *in situ* analysis, are of great interest. One of the very interesting and broad research area is examination of historical paintings to visualize hidden painting layers, under-drawing or conservation changes. The techniques commonly used in this area are X-ray fluorescence (XRF) and an X-ray radiography (XRR). The conventional XRF imaging technique uses a focused X-ray beam to scan the sample and a detector with high energy resolution but no spatial resolution (typically a Silicon Drift Detector - SDD). The spatial resolution of the image is then determined by the size of the exciting beam spot, which can be obtained either from a synchrotron source or from an X-ray tube with a micro-capillary lenses. The XRR technique is based on a wide beam and not energy dispersive detectors, like imaging plates. In case of XRR an attenuation of the beam intensity creates an image, which provides some information about density composition of the painting layers, but no information about abundance of specific elements.

The main goal of this work was to develop a two-dimensional position sensitive and energy dispersive detection system based on Gas Electron Multiplier (GEM) detector for imaging of hidden painting layers in historical artworks employing the XRF and XRR technique. The critical requirements for the system are: good energy and spatial resolution, short measurement time and possibility of imaging large areas in a fixed position, i.e. minimize mechanical scanning. The demonstrator has been built using a standard 10×10 cm^2 GEM detector, custom-developed readout electronics and a Data Acquisition System (DAQ),X-ray optics system consisting of a commercially available X-ray tube and a custom-made pinhole camera.

The key component of the detection system, which determines its final performance is the multichannel front-end electronics capable to extract amplitude and time information from the GEM detector at high count rates. An Application Specific Integrated Circuit (ASIC), named GEMROC, has been designed, manufactured and tested. The front-end electronics, comprising 256 channels in total, produces significant amount of digital and analogue data, which have to be received and processed in real time by the DAQ. The DAQ is based on a custom developed Analogue to Digital Converter (ADC) board and a Field Programmable Gate Array (FPGA). The FPGA works as a pre-processor, formats incoming data and transmits them to a powerful PC workstation equipped with a comprehensive dedicated DAQ software.

Author of this theses contributed significantly to the design and evaluation of front-end ASIC, which is responsible for extraction and amplification of signals from the GEM detector, pulse shaping and extraction of amplitude and time information for each pulse. All manufactured ASICs have been tested functionally and then the full parameterisation and calibration has been performed by author. Finally a dozen of the ASICs, with similar parameters and characteristics, have been selected to be used in the demonstrator system.

In addition to optimisation of the signal-to-noise ratio in the GEMROC ASIC, significant improvement of the energy resolution of the overall system has been achieved by parameterisation and calibration of the GEM detector. The gas amplification factor as a function of the position across the detector area and its variation in time has been measured and analysed systematically. Significant variation of the gas amplification factor across the detector and in time due to charge-up effects have been observed. Therefore, correction algorithms have been elaborated and applied to final analysis of images. After careful corrections of variation of the gas amplification factors energy resolution of 20 % at 5.9 keV has been obtained compared to about 30% measured typically without applying the correction procedures.

In order to find a compromise between the spatial resolution and the measurement time the pinhole optics implemented in the XRF system was analysed and optimised experimentally. Taking into account the effect of the pin-hole diameter on the spatial resolution, vignetting effect, and yield of the source radiation reaching the investigated object a diameter of 1 mm has been chosen. This results in the spatial resolution of about 1 mm, which is lower than the intrinsic spatial resolution of the GEM detector but still good enough for most of the research problems occurring in imaging of paintings.

Another important part of the thesis presents measurements performed on two dedicated painting phantoms prepared by the National Museum in Kraków. One phantom contains a pattern of alternating overlapping stripes painted on a wooden panel using historical pigments. This phantom allowed to assess the capabilities of the system in terms of recognition of different pigments and their different overlapping configurations. Another phantom – a mock painting "Man in a red coat" was prepared according to the XV century painting techniques and contains a hidden painting layer – a landscape. The obtained results show clearly that the presented system, thanks to the good energy and spatial resolution, is capable of imaging elemental distributions in the painting pigments and visualize hidden painting layers. One of the main advantage of the developed system is absence of quickly moving measurement parts located close to the object surface (in opposition to scanning systems), which largely improves safety of the investigated, often very valuable, artworks. The system can be easily re-arranged for the XRR configuration. Thus, it allows to use both methods and collect complementary information about the object.

The system and the measurement technique presented in the thesis are unique in the field of XRF imaging due to the usage of a large area position sensitive and energy dispersive GEM detector together with a wide primary X-ray beam. A pinhole camera with appropriate geometry allows to image significant area of investigated objects in a fixed position. The results of example imaging measurements presented in the thesis demonstrate clearly that the method is particularly suitable for fast screening of large area objects. The moderate energy resolution of the GEM detector puts some limitation on very detailed elemental analysis, however, in such cases a scanning system with a high energy resolution silicon detector can be used for investigation of selected areas of paintings.

Further possible improvements and modification of the system are feasible and have been discussed briefly in the thesis. For example, using a gas mixture based on a heavier, than argon, noble gas (xenon or krypton) will improve detection efficiency and hence reduce the measurement time. Additionally, using quenching gases to obtain a penning mixture, will improve energy resolution. Another area for possible improvements is the structure of the GEM chamber. The GEM foils are presently coated with copper and drift electrode is made of copper. Thus, photons with energy higher than Cu absorption edge are absorbed in the copper layers and generated some background signal corresponding to Cu fluorescence. Both effects affects the recorded spectra. Using aluminium coated GEM foils and aluminium drift electrode would reduce these effects significantly. The technology of Al-coated GEM foil is not available yet, however, the copper drift electrode can be easily replaced by an aluminium one. Other possible improvements of the system regard X-ray source and optics, including a multi-pinhole camera, and a new front-end ASIC with reduced noise.