A new IBA imaging system for the transportable MACHINA accelerator

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Introduction

Ion beam analysis (IBA) techniques:

✅ non-invasive
✅ non-destructive
✅ quantitative
✅ high-sensitivity

Information on:

✅ Presence of an element
✅ Stratigraphical distribution

IBA techniques use MeV ion beams, so accelerators are needed.

Cultural heritage materials (e.g. artworks) cannot always be transported to the IBA laboratory.

Analysis must be carried out where the artworks are situated (*in-situ*).

❌ Traditional electrostatic accelerators are not transportable!

MACHINA is the first transportable accelerator in the world for in-situ IBA.

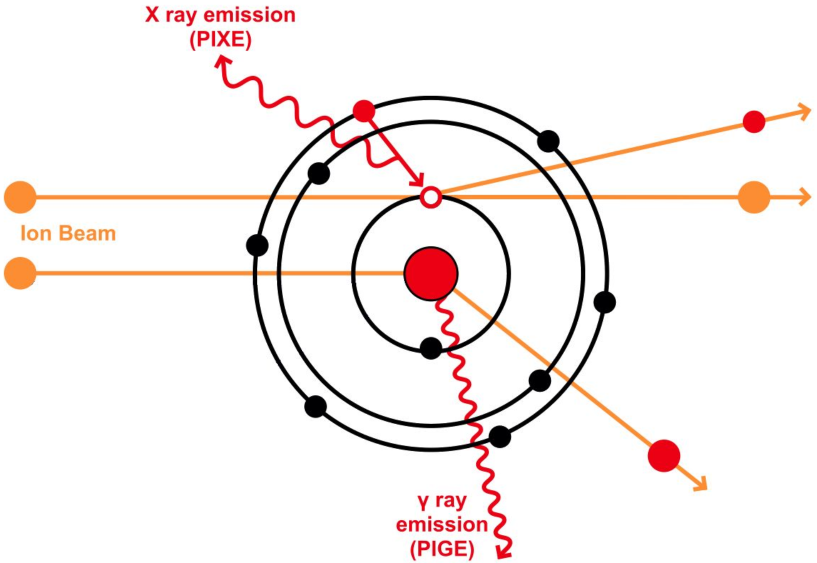
Compositional imaging using the IBA techniques:

- Spatial distribution of the elements

Often CH materials are:

- Not homogeneous
- Have a complex spatial structure

Ion-beam analysis (IBA) techniques



They exploit the radiation emitted by the sample following interactions between charged particles and matter to identify the elements present in the sample.

MACHINA will apply two techniques:

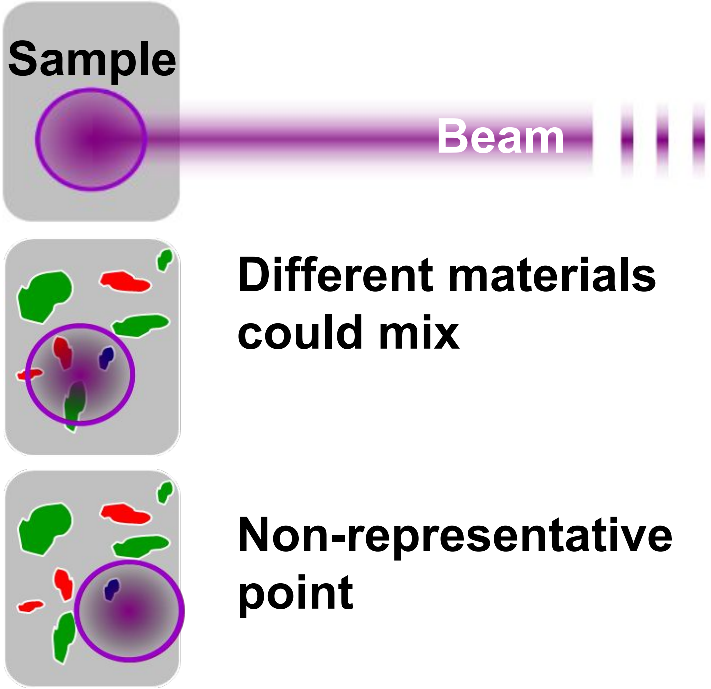
- (PIXE) X-rays emitted after an ionization event
- (PIGE) gamma rays emitted after an interaction with the nucleus

IBA techniques: single point analysis

Only a small area of the target is examined, corresponding to the size of the beam on the target.

In non-homogeneous materials, the macroscopic appearance may be due to a complex micro and mesoscopic structure.

Single point analysis can lead to misleading information.



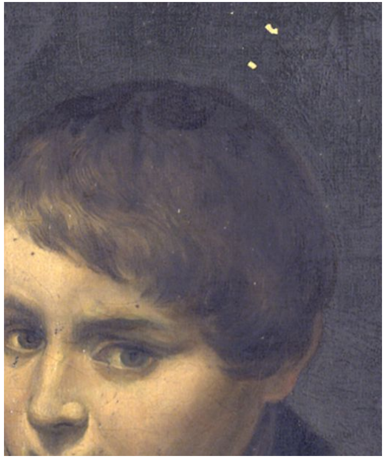
IBA techniques: scanning mode analysis

Reports the distribution of elements in the structural context of a non-homogeneous sample.

IBA techniques are a natural candidate for imaging because they:

- identify the elements present
- are non-destructive
- are sensitive (down to ~ ppm)

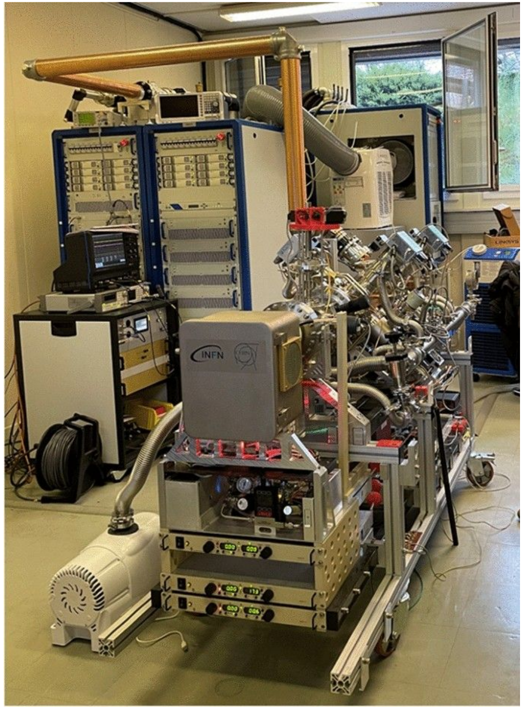
…but they use fixed instrumentation.



Oil on canvas

Macro-areas of unknown composition

MACHINA project: transportable IBA instrumentation

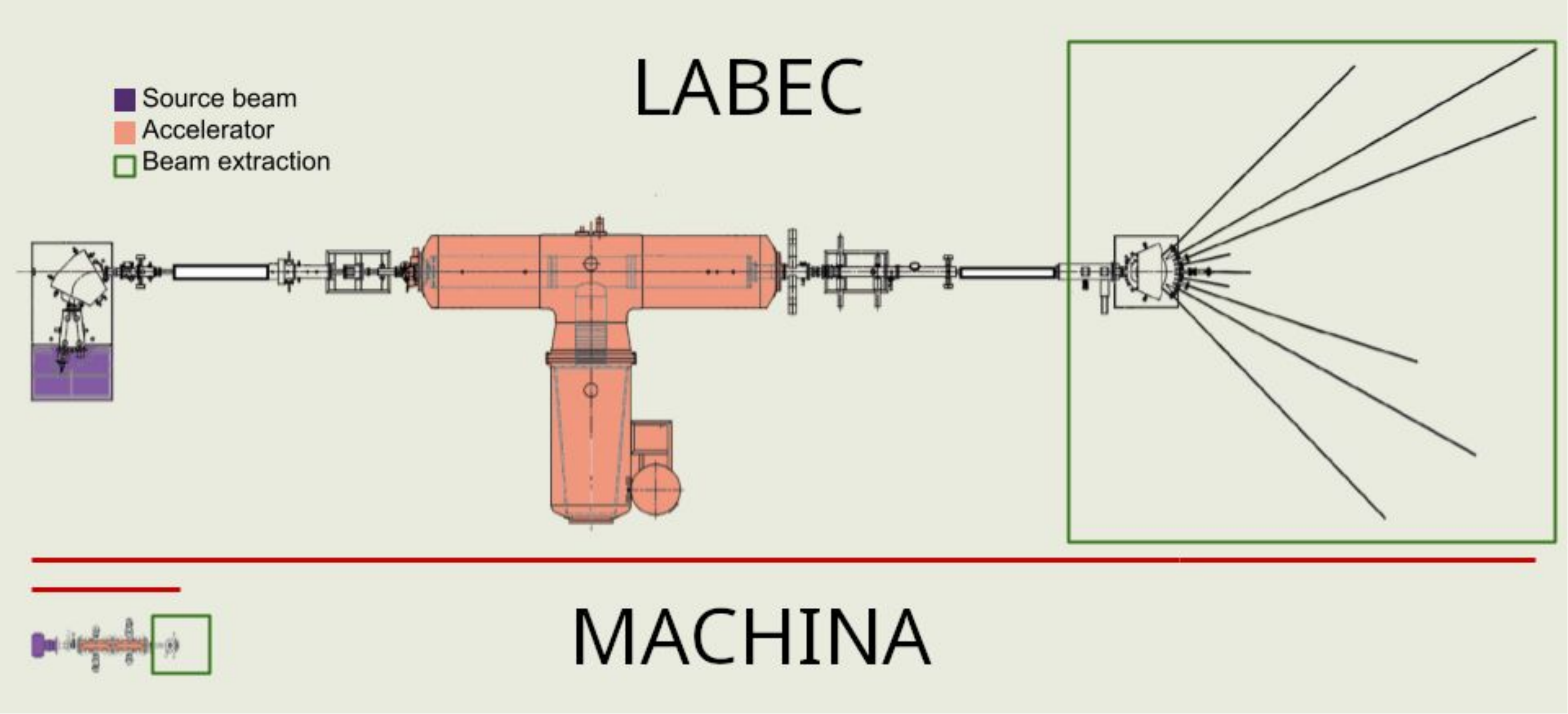


2018: start of a collaboration between INFN (LABEC) and CERN to create an accelerator that addresses the requests of the IBA analyzes for cultural heritage.

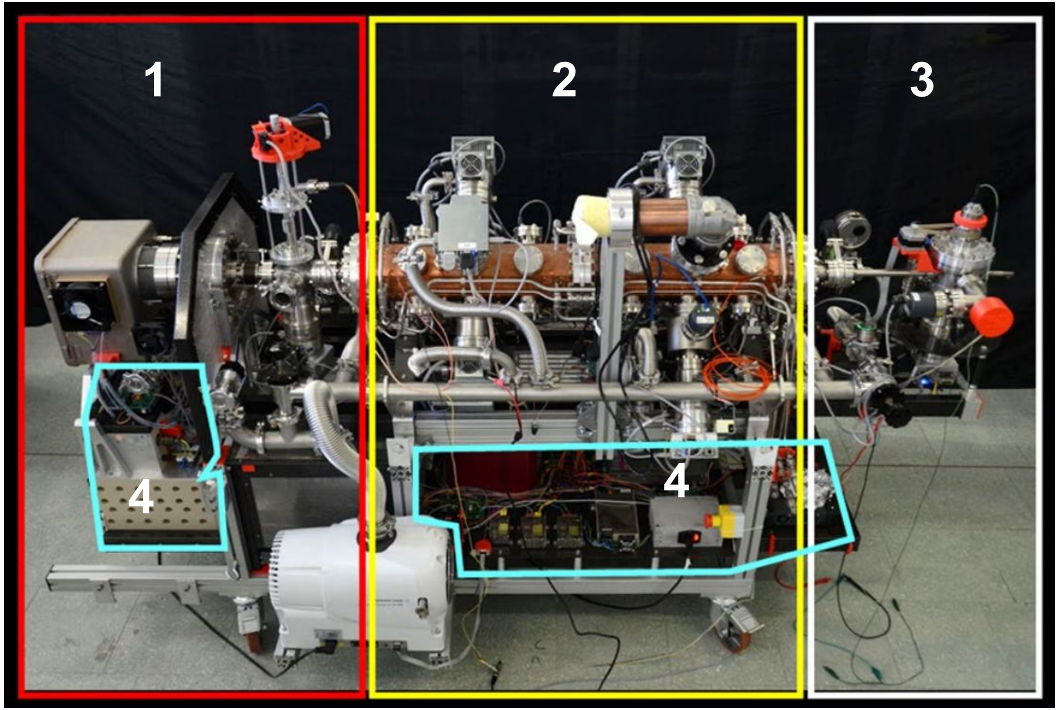
2022: First transportable accelerator in the world for in-situ IBA measurements, MACHINA.

- Dimensions of 2.5m x 1m
- Weight of 500 kg

The end user will be the Opificio delle Pietre Dure, which will use it for the study and conservation of works of art.


LABEC
Source beam
Accelerator
Beam extraction
MACHINA

MACHINA project: the accelerator



The beam line consists of:

(1) RF ion source producing a continuous beam of protons at 20 keV

(2) two resonant cavities of radio frequency quadrupoles delivering protons at 2 MeV

(3) beam extraction and radiation detectors

(4) control electronics

IBA imaging system overview

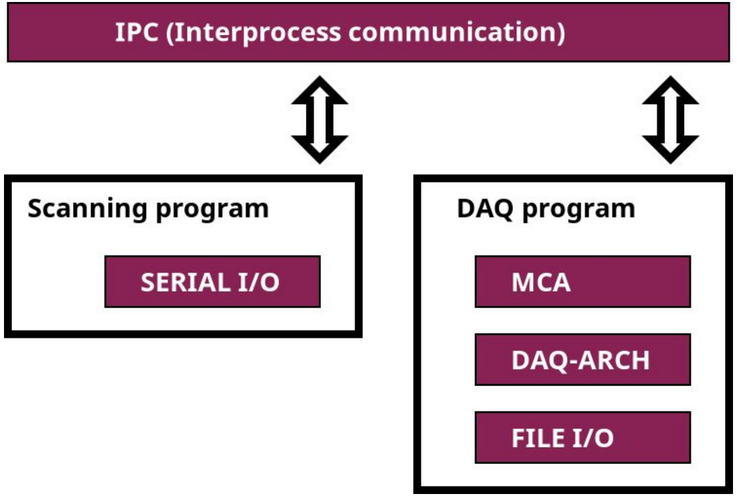
The objective: development of a scanning acquisition system for multi-detector compositional imaging of large areas (up to thousands of cm^2).

The philosophy: move the sample at a constant speed in front of a fixed beam and acquire in-flight spectra at all points of a target area of interest.

To do this:

- the IBA radiation detection and scanning system was set up
- a set of libraries and programs were prepared for managing the hardware
- multi-detector acquisition was developed
- the new system was tested

IBA imaging system overview : libraries and executables

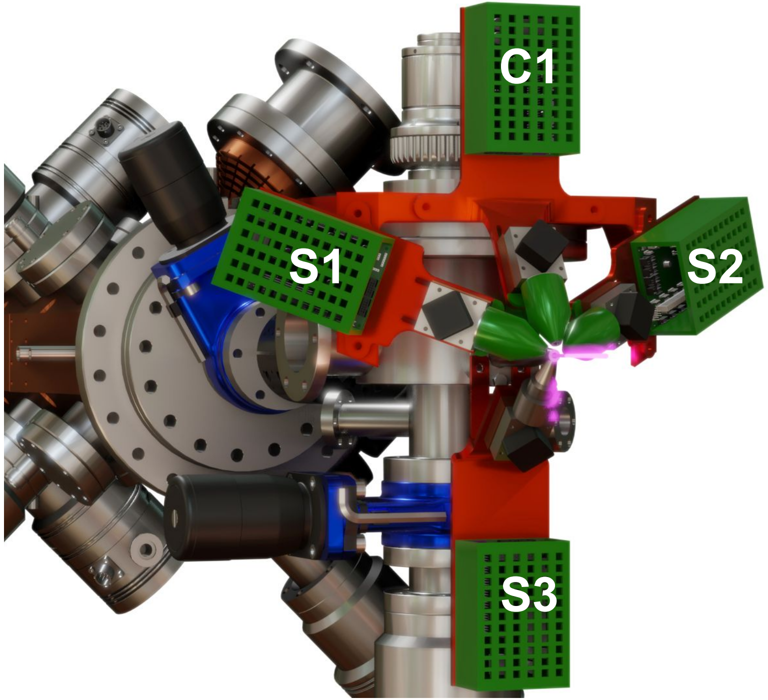


Two programs, one for data acquisition and one for scanning of the sample, which use code libraries to:

- command the motors of the positioning system (**serialio**)
- synchronize target motion with DAQ (**ipc**)
- manage PIXE signal detection hardware (**mca**)
- define and manage the data processing chain using a multi-detector architecture (**daq-arch**)
- define methods for storing, compressing, and re-reading data (**fileio**).

In addition, there are graphical interfaces for viewing IBA spectra and images.

Signal acquisition: MACHINA DAQ hardware

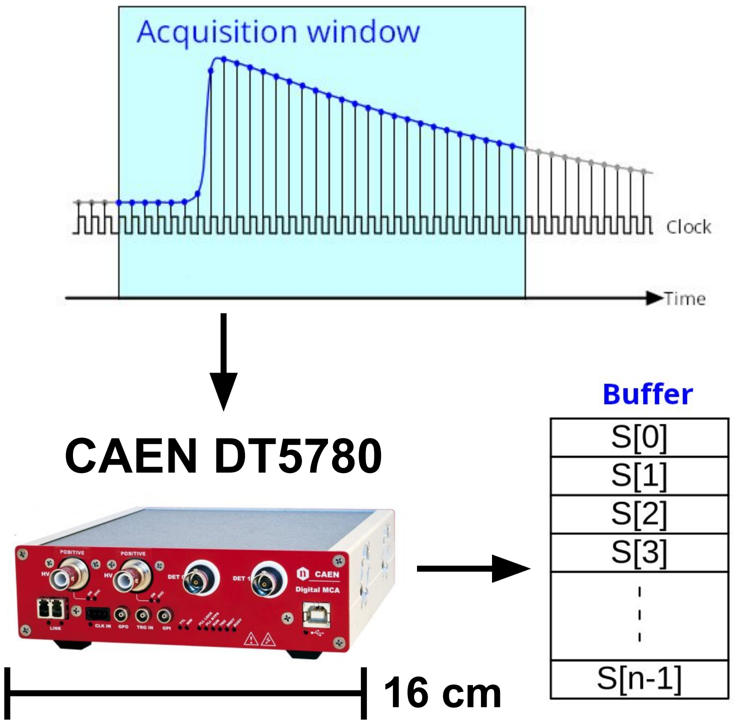


Four semiconductor detectors:

- two silicon (SDD) for PIXE at low (**S1**) and medium (**S2**) energies
- a silicon one to normalize the beam current (**S3**)
- one at CdTe for PIGE (**C1**)

The detectors produce a voltage step signal, which is then transformed into an exponential pulse by a CR filter.

Signal acquisition: Digitalization



The analog signal is processed by a digitizer (MCA) which:

- samples the signal using a 14-bit, 100 MHz analogue-to-digital converter
- applies digital algorithms to the digitized samples

The algorithms generate:

- an autonomous trigger
- a trapezoidal signal with amplitude proportional to the energy

From pulse-height analysis (PHA) of the trapezoid pulses we get the energy spectra.

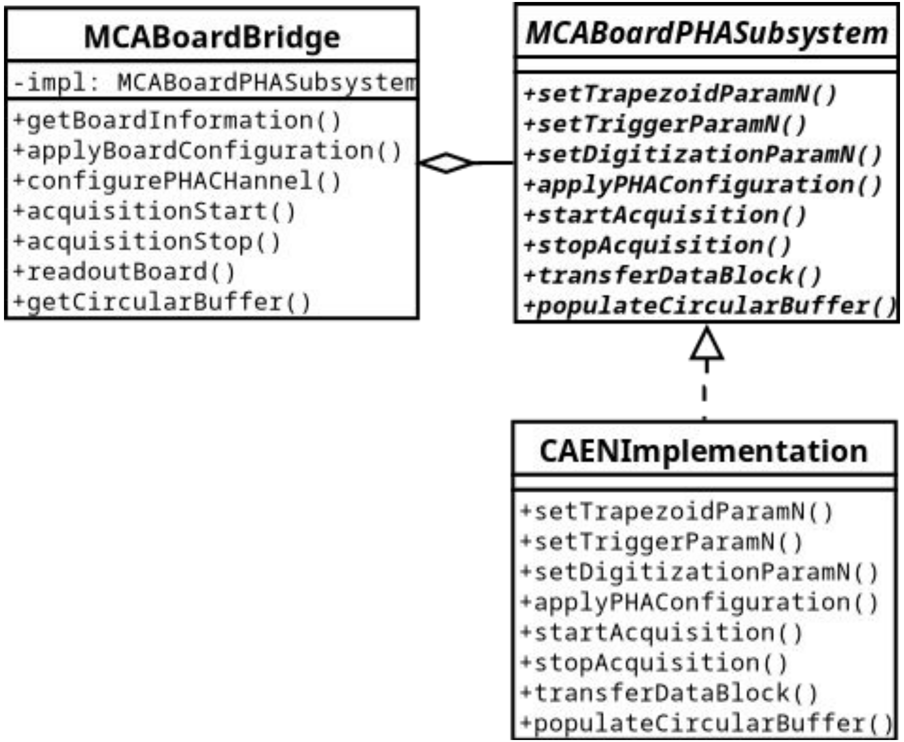
Signal acquisition: the MCA library

To control the CAEN digitizers, a library was written to manage:

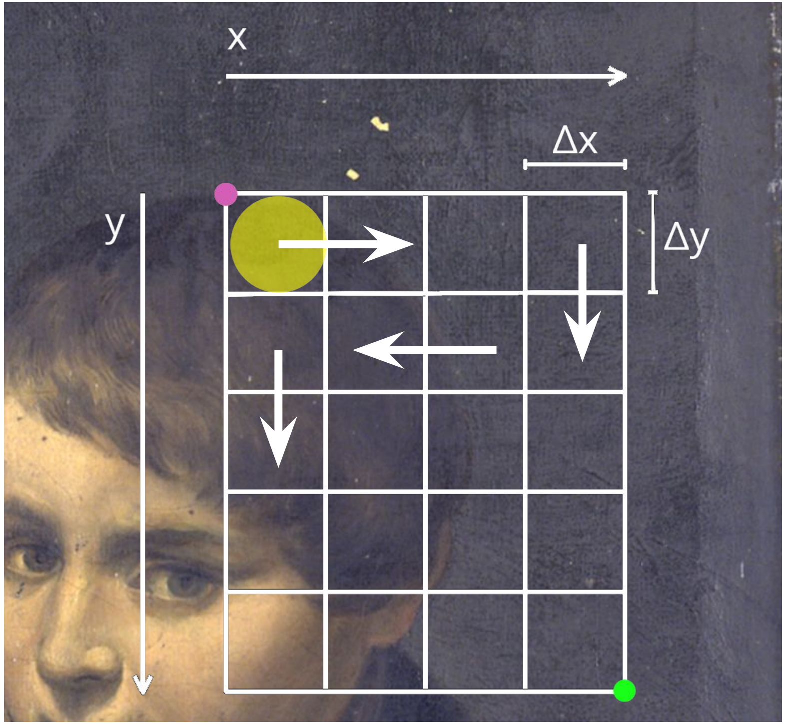
- CPU - digitizer connection
- parameters of digital algorithms
- data readout
- synchronization of the DAQ start/stop between different boards

Up to 4 independent digitizers (or up to 8 acquisition channels)

Fully configurable with a JSON text file.



Data construction: scanning of a region



Two points define a rectangle and delimit the analysis area.

The area is divided into intervals Δx and Δy. The cell centers correspond to the pixel coordinates in the images.

For scanning, the target moves in front of the fixed beam (transparent yellow):

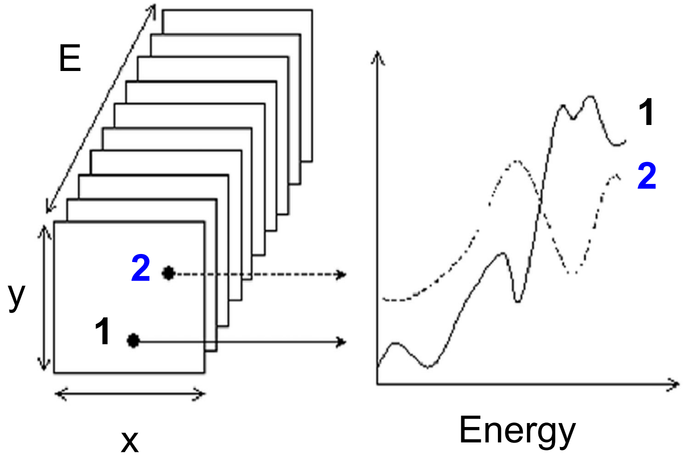
- horizontally line by line at constant speed
- vertically in steps of Δy

Data construction: spectral multidimensional array

Spectra are acquired in-flight and assigned to each cell of the grid.

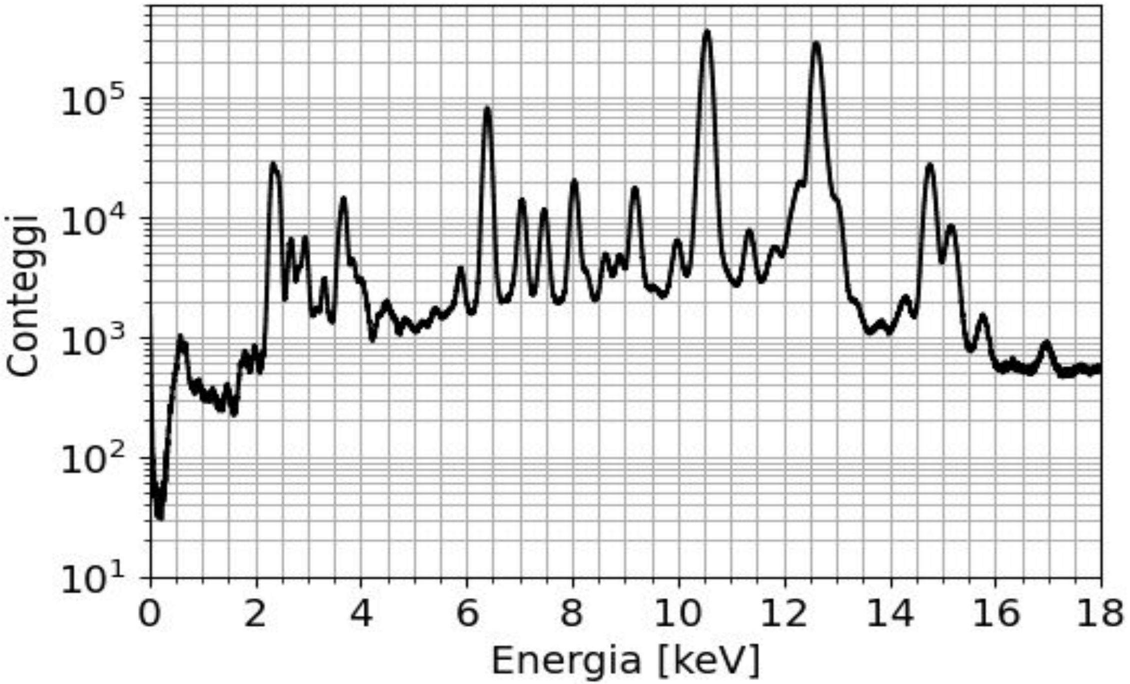
The cell coordinates and spectra are saved in a *datacube*, a 3-dimensional array such that:

- the first two indices constitute a matrix of positions (the pixels)
- the third index is an array of MCA bin counts (the spectrum)



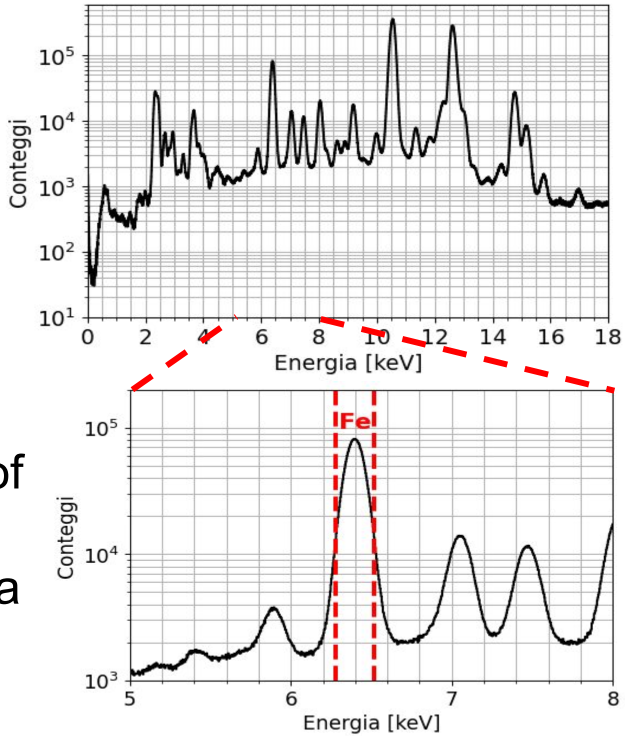
Data construction: compositional image

One spectrum
in each pixel



Data construction: compositional image

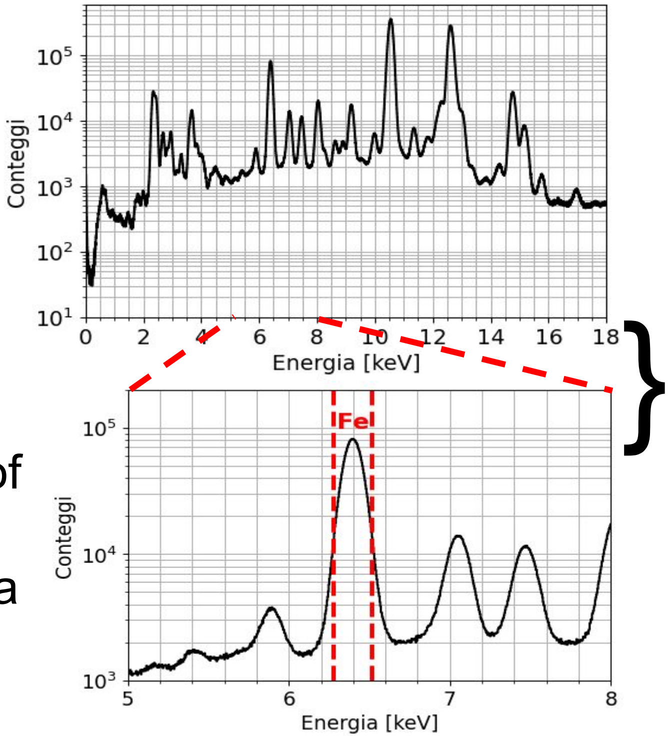
One spectrum
in each pixel



Choose a region of interest (ROI) and determine the area

Data construction: compositional image

One spectrum in each pixel

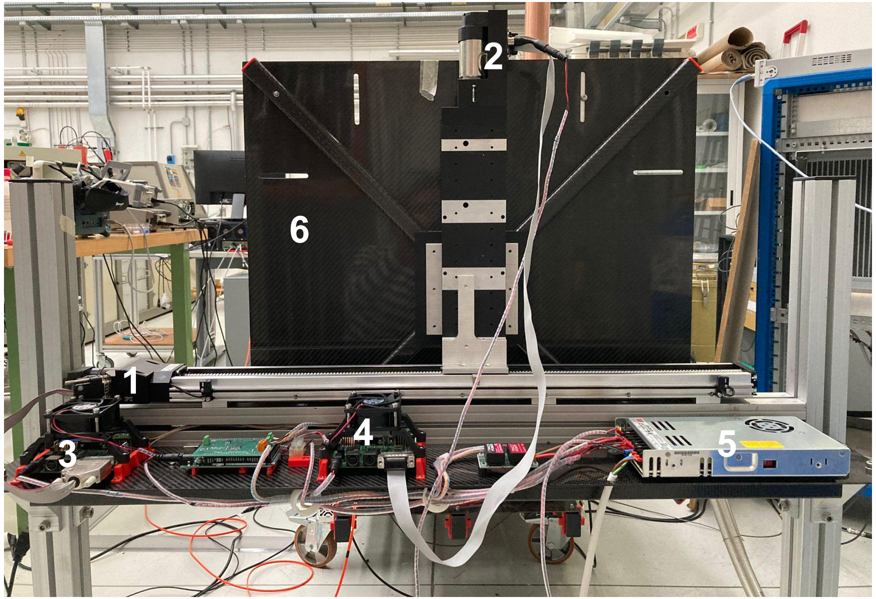


Choose a region of interest (ROI) and determine the area

Pixel by pixel…

Compositional image

Setting up the scanning system



The scanning system consists of:

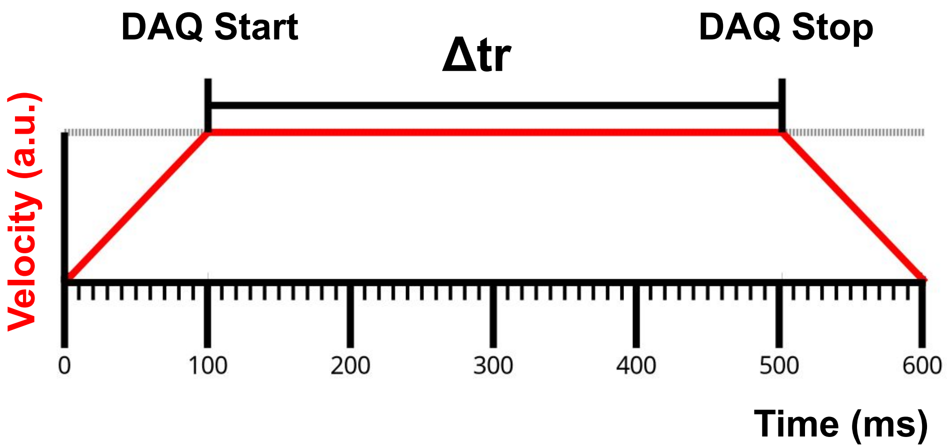
- two DC motors with rotation encoder (1,2)
- managed by a controller (3,4)
- power supply (5)
- controlled by the DAQ CPU via USB.

The system moves the sample holder (6) also providing an X-Y coordinate system.

Movement profile of the sample holder

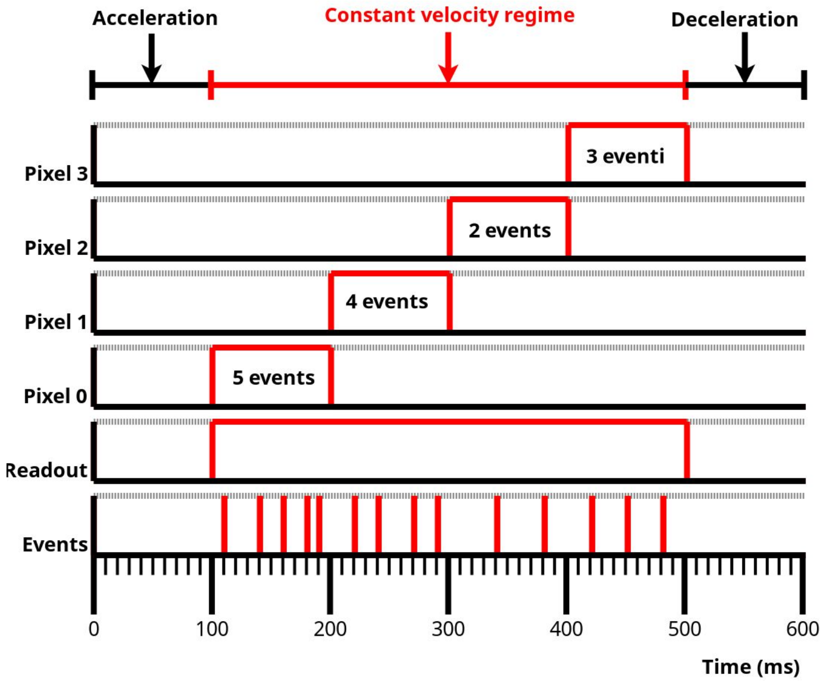
Acquisition is active only during the **Δtr** interval when the speed is constant.

During this interval the motor must traverse the length of the scanning area, therefore:



- the motor starts its motion before the edges of the area and ends it after
- a semaphore signals the start of the Δtr interval to the DAQ program
- the DAQ starts with this semaphore and has a duration equal to Δtr

Data processing: assigning events to pixels

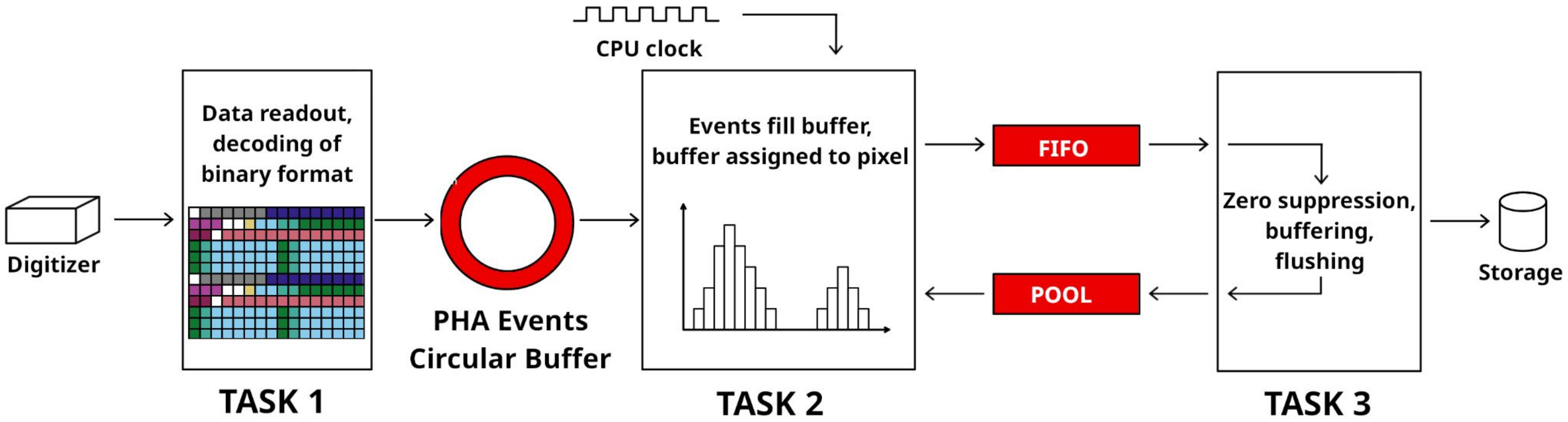


The DAQ program defines a time interval for reading the data (readout) for each scan line with a duration equal to Δtr.

It also defines an acquisition time interval for each pixel in the row.

The events acquired for each pixel are saved in an array of MCA bin counts (spectrum).

Data processing: the DAQ library and program



The processing chain is divided into three concurrent threads (tasks). Each task performs a different job in the data processing chain.

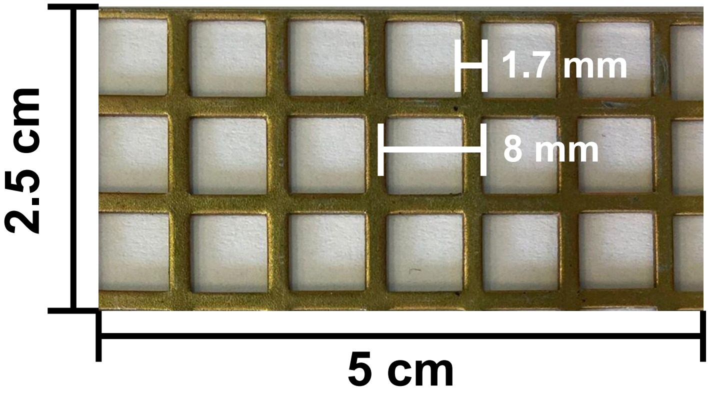
Tests of the imaging system

The imaging system must:

- perform acquisition in multi-detector mode
- correctly reconstruct the space-time correlation of events
- correctly reconstruct the spatial distribution of the elements in the target region of interest
- obtain images without distortion

Scans of samples with known geometry and fine structures from a few mm down to ~500 μm were performed using an X-ray source.

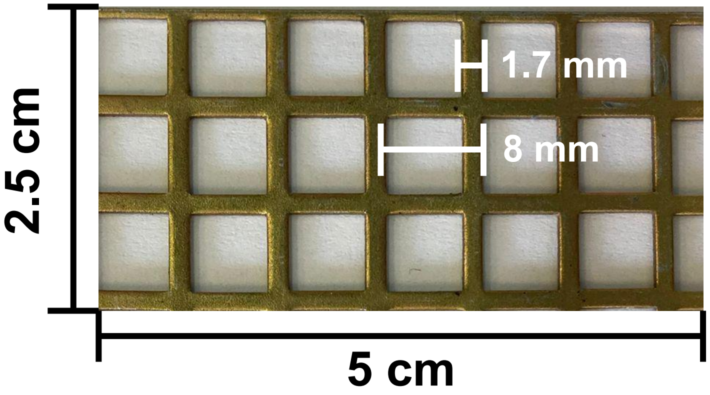
Tests of the imaging system: metal alloy grid

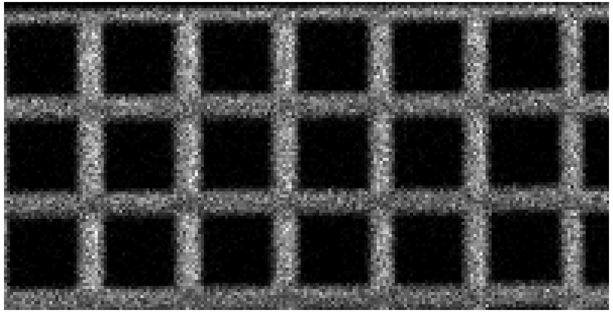


A first test of the imaging system was to scan a small area of a sample with known geometry.

With the imaging system it was possible:

Tests of the imaging system: metal alloy grid





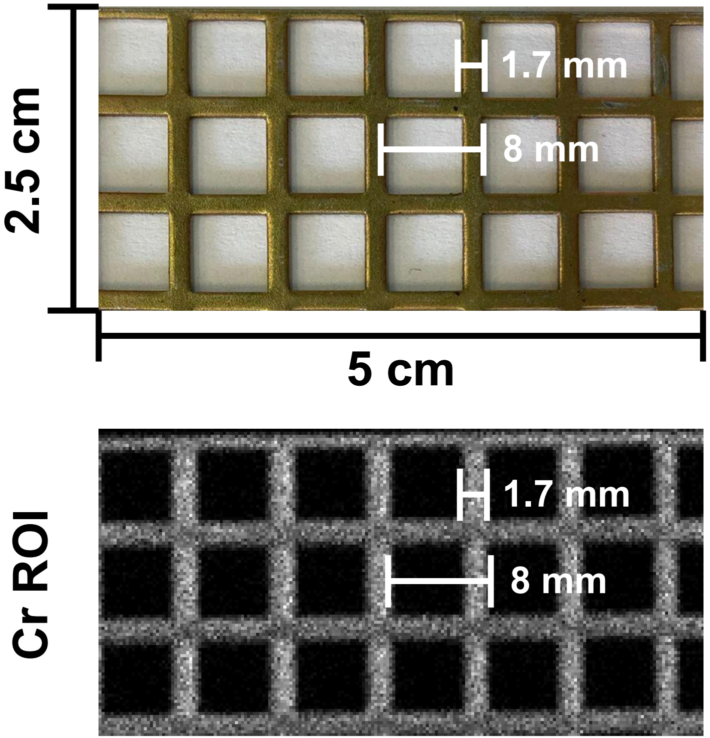
Cr ROI

A first test of the imaging system was to scan a small area of a sample with known geometry.

With the imaging system it was possible:

- reconstruct compositional images starting from ROIs of the spectra

Tests of the imaging system: metal alloy grid

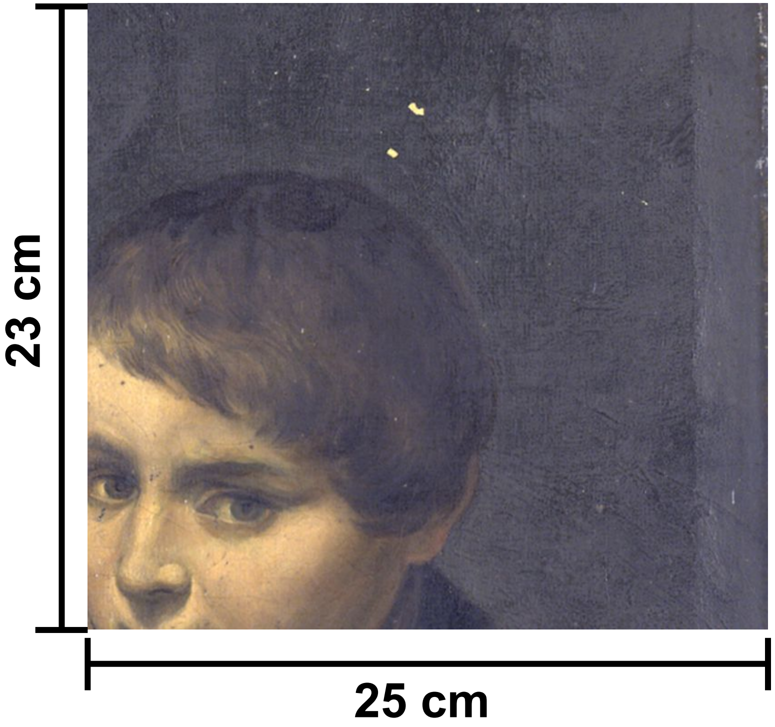


A first test of the imaging system was to scan a small area of a sample with known geometry.

With the imaging system it was possible:

- reconstruct compositional images starting from ROIs of the spectra
- correctly reconstruct the geometry of the object using the information contained in the images

Tests of the imaging system: painting (oil on canvas)

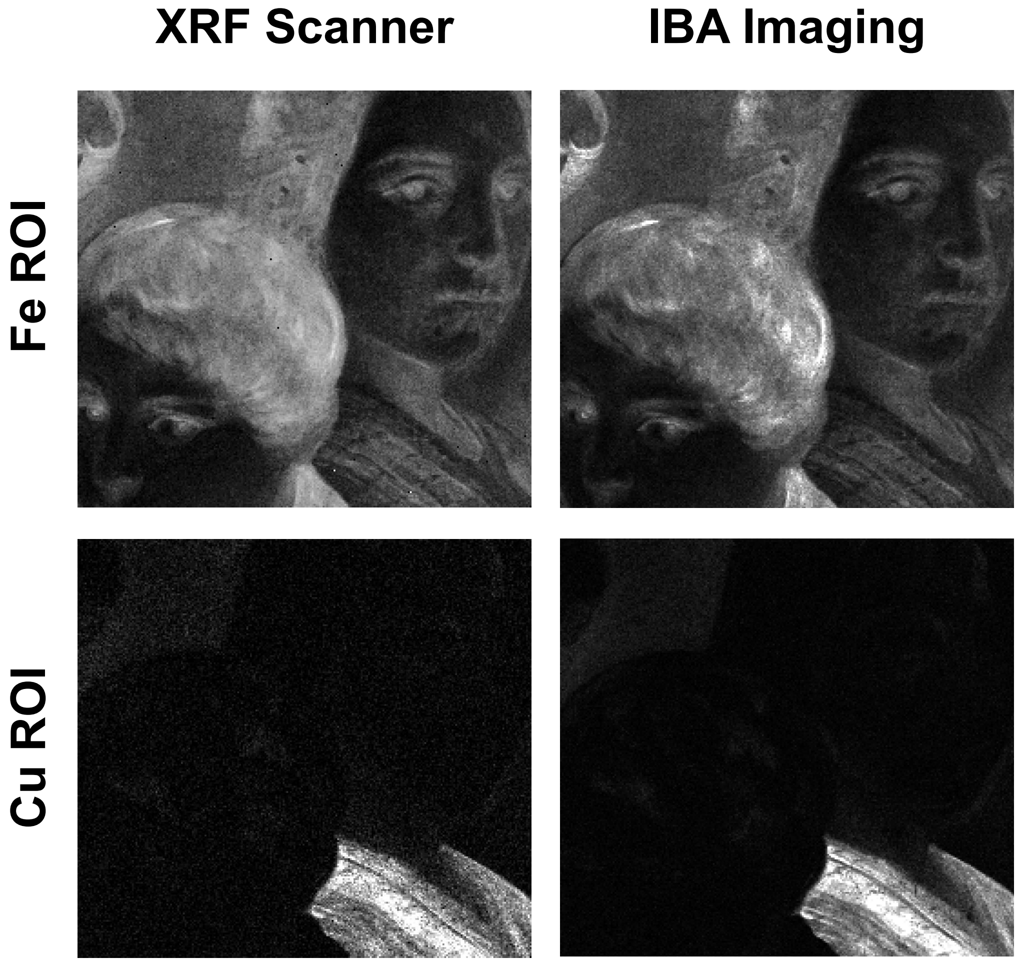


Representative sample of cultural heritage with a complex structure.

Object of analysis in a campaign of previous measurements.

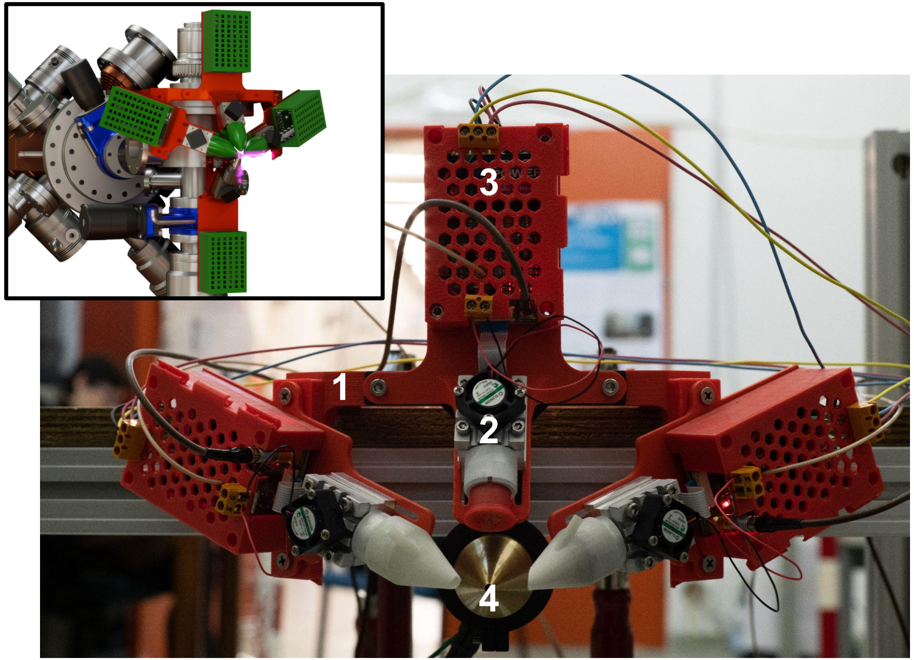
Two analyzes of a large area in the same experimental conditions with two different acquisition programs:

- XRF scanner at LABEC
- system presented here



- The structures visible reproduce the expected results.
- There are no differences between the two systems.
- Total number of events is compatible within the expected system fluctuations.
- The data file size is significantly smaller for the new system by a factor of approximately 2.5

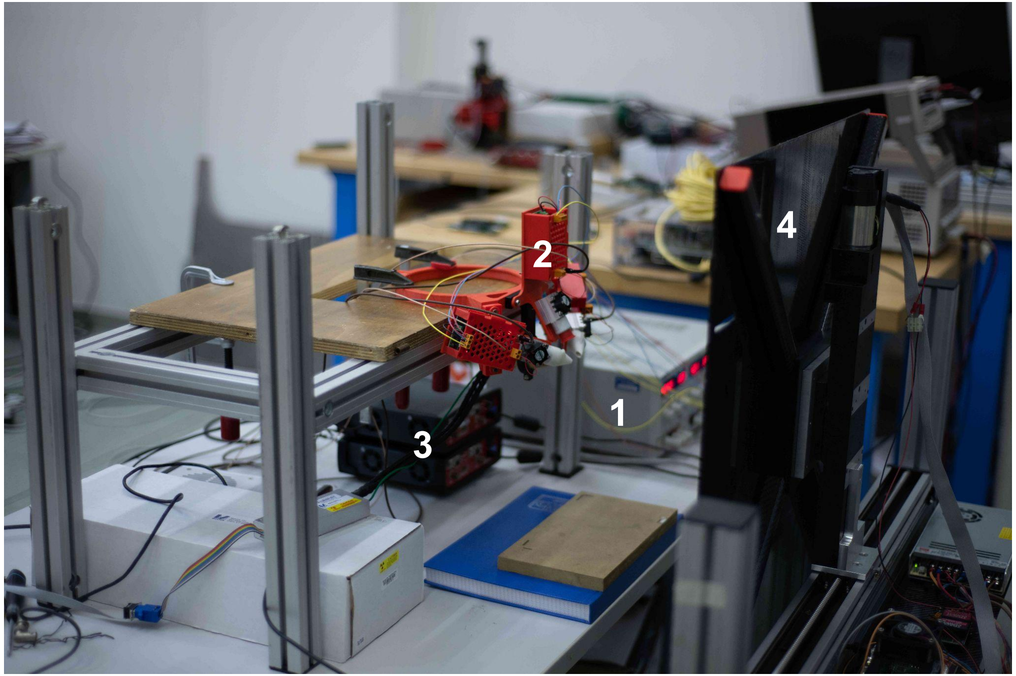
Setting up the multi-detector crown



The detection system was set up using:

(1) a support structure (crown) for the detectors made with 3D printing
(2) three SDD detectors
(3) board for controlling the thermoelectric cooling, the bias voltage, the preamp voltage
(4) a support structure for the X-ray tube

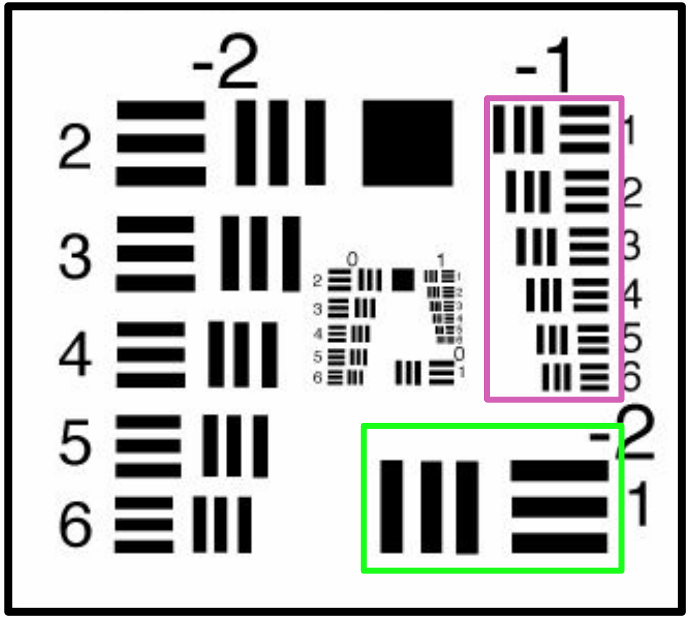
Setting up the multi-detector crown



The setup for the multi-detector tests:

(1) power supply
(2) multi-detector crown on a support structure
(3) two independent digitizers
(4) motorized sample holder

Microscopy standard test: USAF 1951

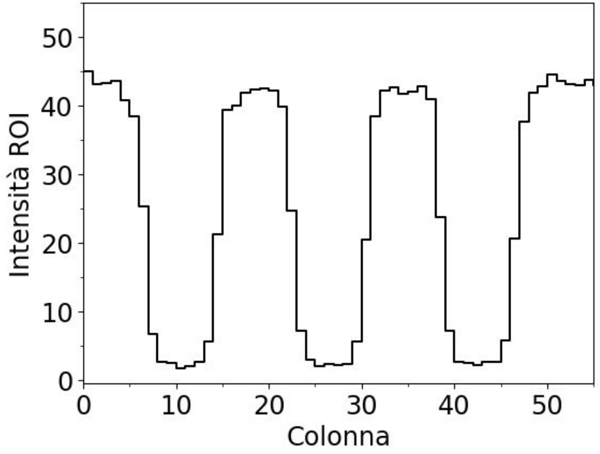


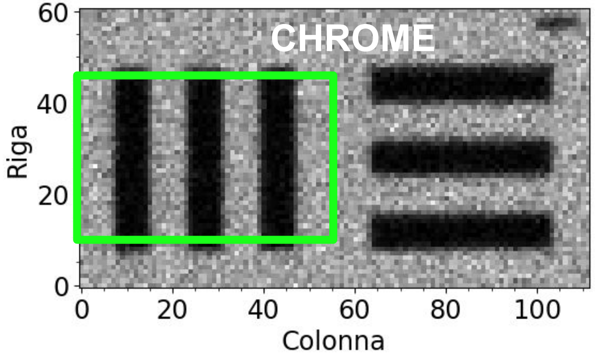
Standard consisting of a glass (black) covered with a chrome mask (white).

The width and spacing of bars in the same series is the same. The series range from 2 mm down to 2 µm.

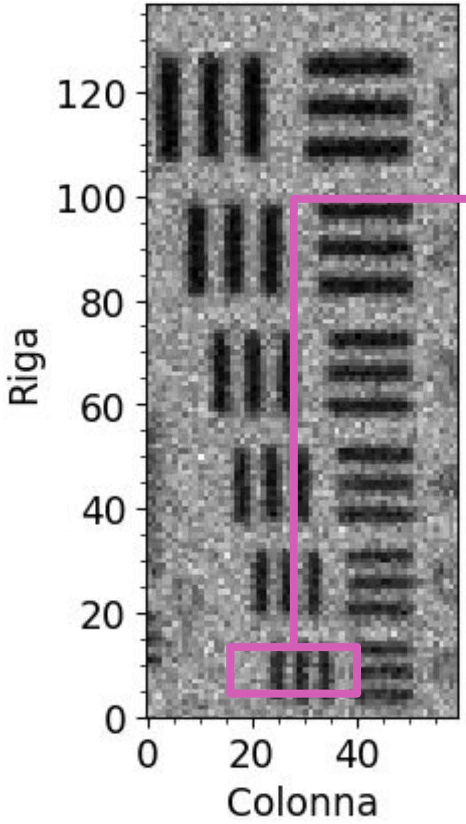
Three-detector scan using an X-ray source with a 400 µm collimator of two areas with:

- 2 mm bars (in green)
- 1 mm down to 540 µm bars (in magenta)

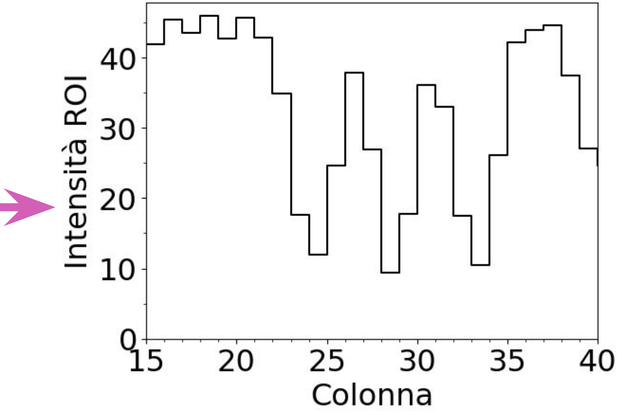




Bar thickness: 2 mm



Bar thickness: 540 μm



Pixel dimensions: 250 μm

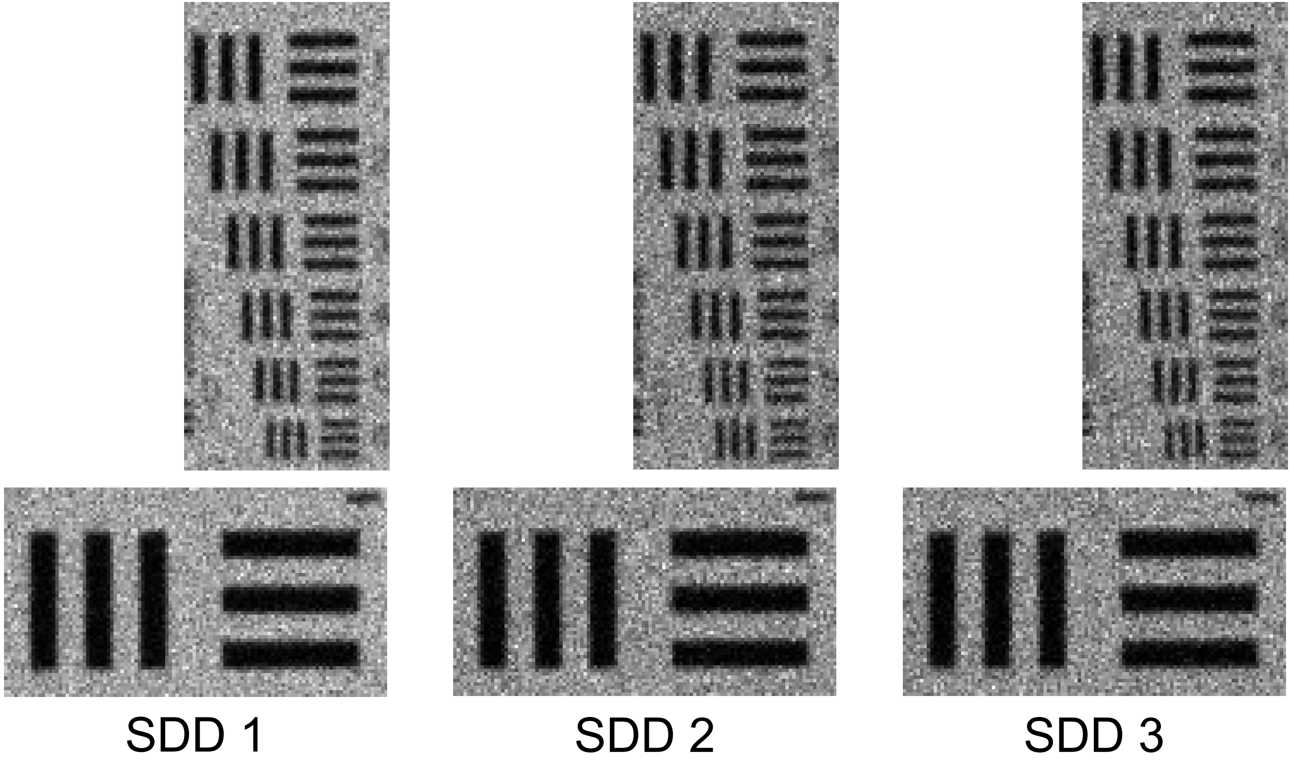
Aperture: 400 μm

Microscopy standard test: three SDDs simultaneously

Imaging using three SDDs simultaneously.

In the final MACHINA setup, 3 SDDs will be used:

- 2 for PIXE
- 1 for normalization



Conclusions

The new scan acquisition system:

- it is ready to be used with MACHINA at the Opificio delle Pietre Dure
- it is flexible and applicable to all IMAGING activities in the laboratory
- will equip mobile and fixed PIXE, PIGE, XRF imaging systems for cultural heritage

Next steps

- complete the system characterization using the MACHINA accelerator
- simultaneous PIGE spectroscopy
- procedures for beam current normalization in IBA analyses
- integration with the MACHINA control system