Laser-accelerated proton beams as diagnostics for Cultural Heritage

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Context and motivation: chemistry and physics for Cultural Heritage analysis

Physics and Chemistry for Cultural Heritage: obtain a complete chemical/morphological analysis of artifacts, preventing damage

HORIZON 2020

European Commission

United Nations Educational, Scientific and Cultural Organization

"Accessibility and preservation of cultural heritage is needed for the vitality of engagement within and across European cultures by also considering the importance of cultural heritage as strong economic driver in a post-industrial economy and its contribution to sustainable economic growth."

- funds for tens of M€ -

XRF/EDX analys of Van Eyck's pigments

G. Van der Snickt et al., Angew. Chem. Int. Ed. Engl. 56, 4797-4801 (2017)

Chemical analysis:

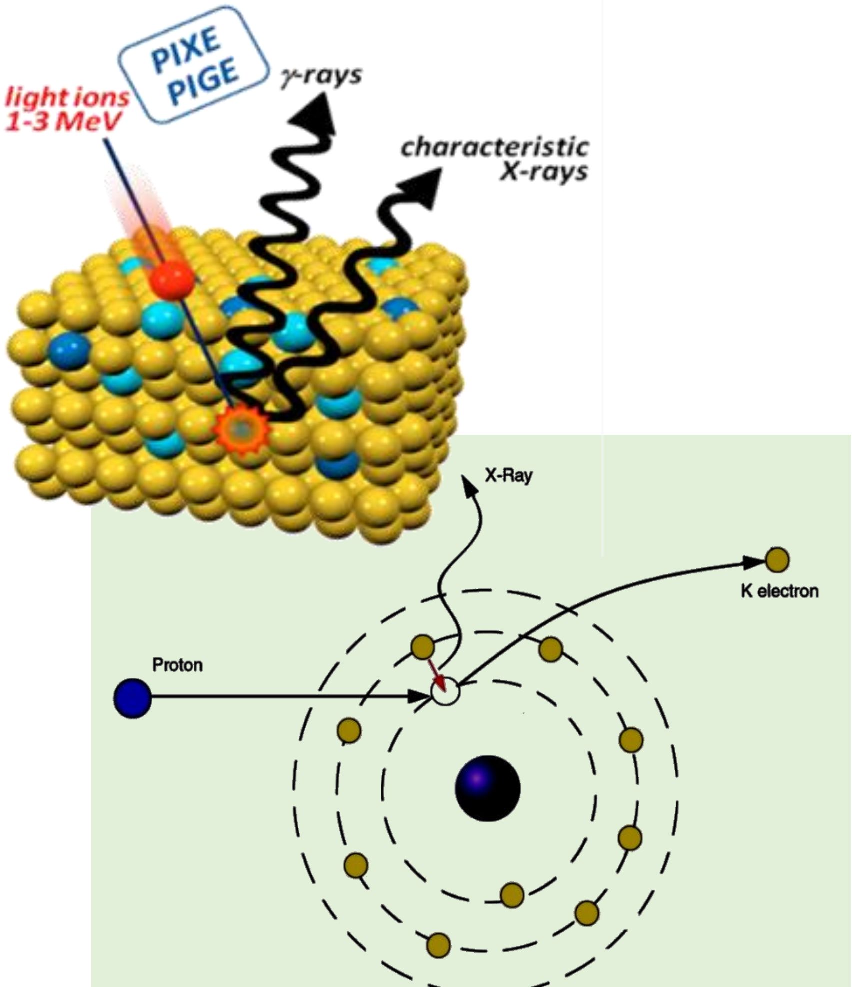
XPS
XRF
EDX
Photoluminescence
PIXE Proton-driven technique: Proton Induced X-ray Emission

Morphological analysis:

SEM
AFM

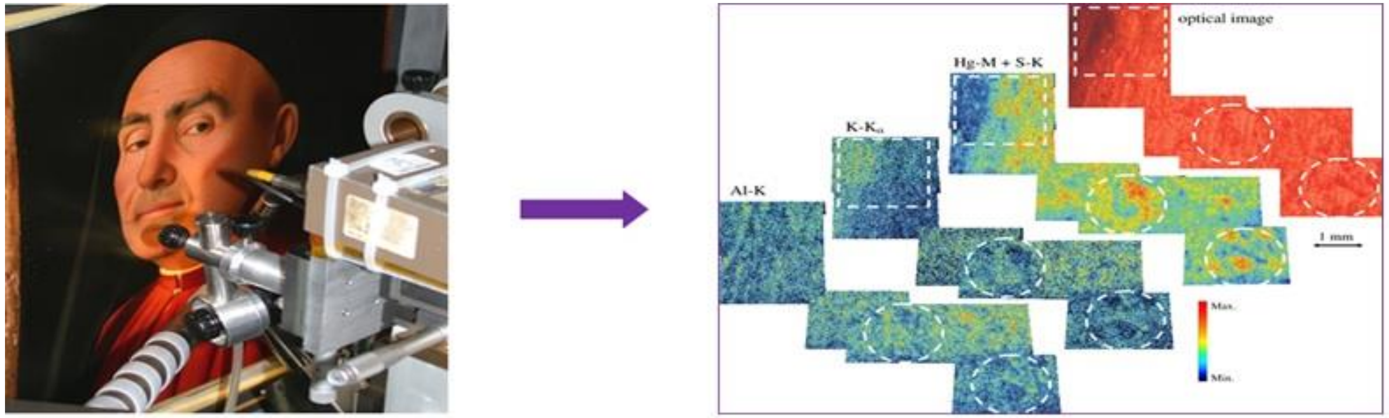
Proton induced X-ray emission (PIXE) for Cultural Heritage

PIXE: proton beams stimulate the emission X-rays, which allows performing a chemical analysis of the material.



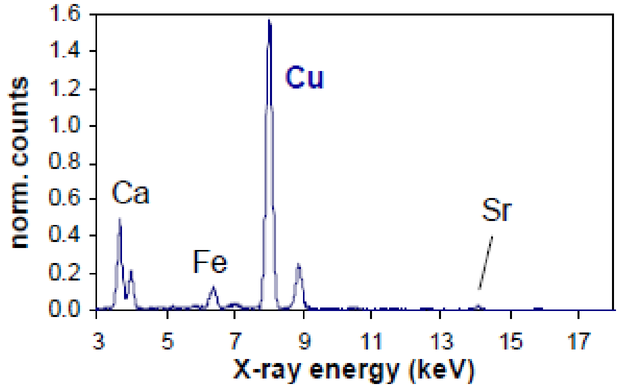
K and L shell X-ray emission

A technique used for Cultural Heritage analysis



Example of PIXE to analyze the pigment's composition of The Trivulzio portrait by Antonello da Messina

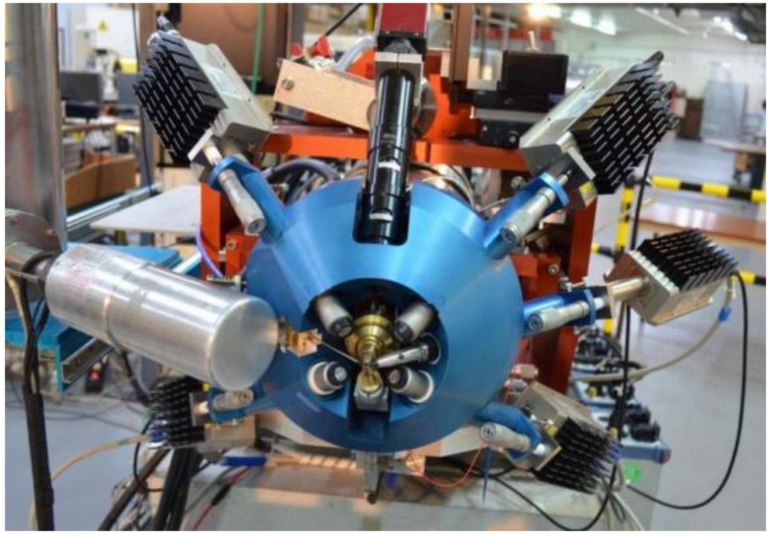
- Advantage over XRF: detection of low Z elements and higher spatial precision
- Detection of elements up to 20 ppb



Analysis performed at LABEC (Florence)

PIXE analysis with conventional accelerators

AGLAE @ Louvre



A well established technique in many laboratories: AGLAE (France), LABEC (Florence), CENBG (Bordeaux) etc.

Drawbacks:

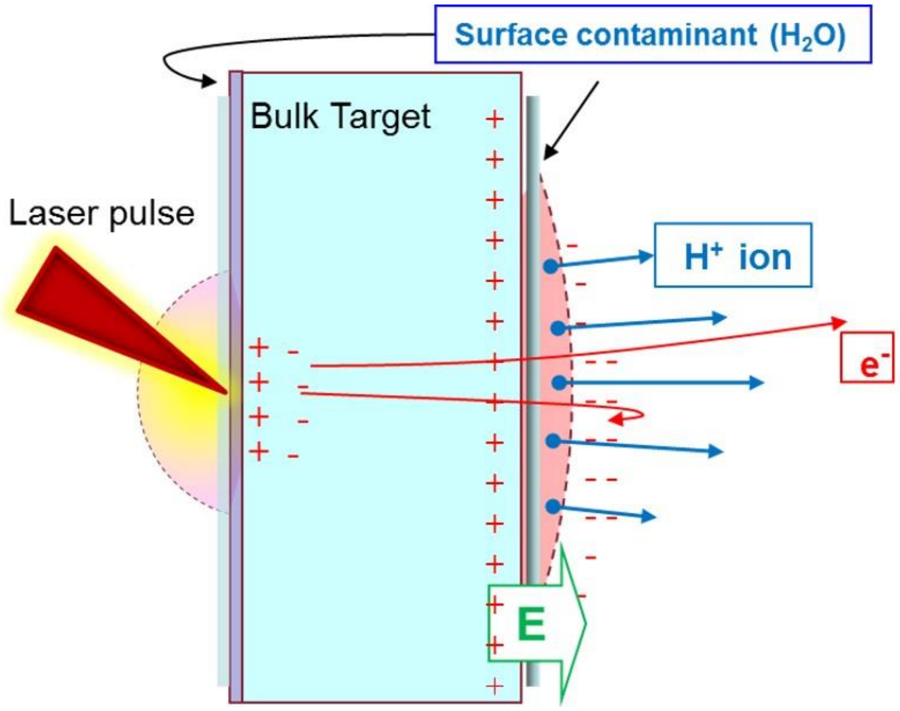
- large facility
- limited energy tenability (1-5 MeV)
- beam spot-size of a few tens μm
- Damages to the artifact are a concern
- extremely long measuring time (100-9000 sec) due to low proton flux

	DR-N	
	Total	Pixel
Scan size	1×1 mm^2	
Pixel resolution		10 µm
Beam charge	18 µC	1.8 nC
Av. current	8 nA	
Acquisition time	35 min	210 ms
Matrix count rate	11 kc/s	
Trace count rate	69 kc/s	
Average counts		2500

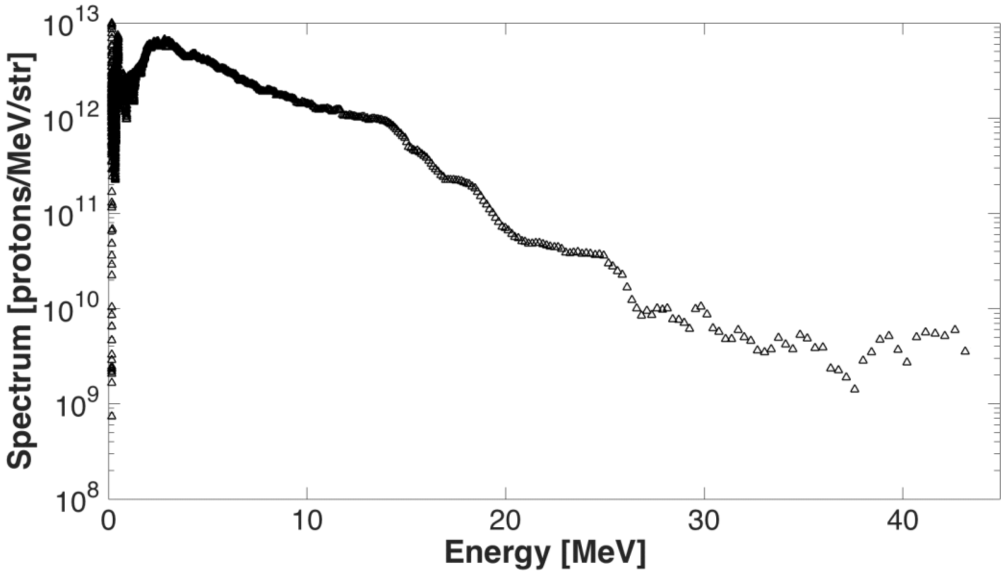
L. Pichon et al., Nucl. Instr. Methods Phys. Res. B 363, 48-54 (2015)

Alternative: laser-accelerated protons for PIXE analysis

Target Normal Sheath Acceleration (TNSA)



- Laser energy of a few Joules is sufficient
- Pulse duration of tens of fs, up to ps
- Target thickness from several μm to tens of nm
- Possibly high contrast ratio (especially for thin targets)



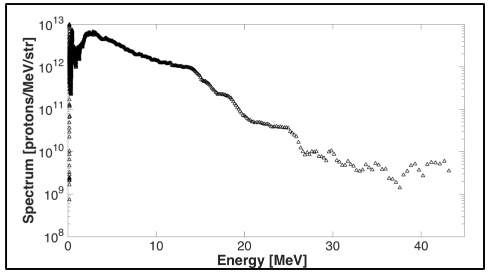
Typical TNSA spectrum @ JLF-TITAN

- ➢ Up to 10^{13} protons/shot
- ➢ Proton energy of up to tens of MeV
- ➢ Short bunch duration (ps at the source)

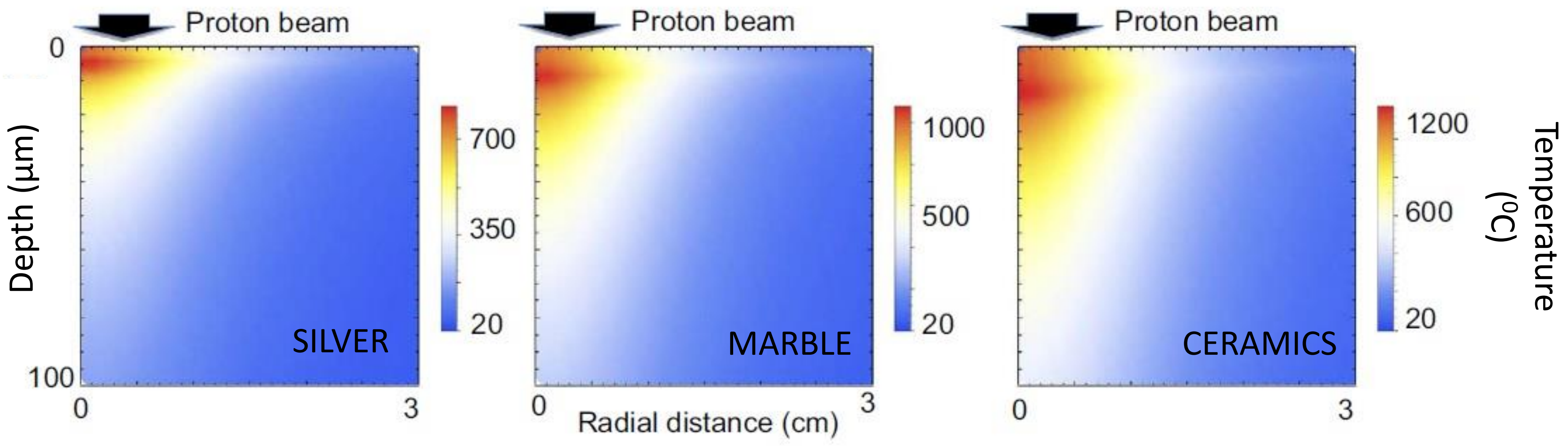
Advantages of PIXE with laser-driven proton beams:

- ➢ higher charge for each shot
- ➢ higher signal-to-noise ratio allows shorter measuring times
- ➢ larger analyzed surface due to larger beam spot-size
- ➢ layer-by-layer analysis by energy tuning

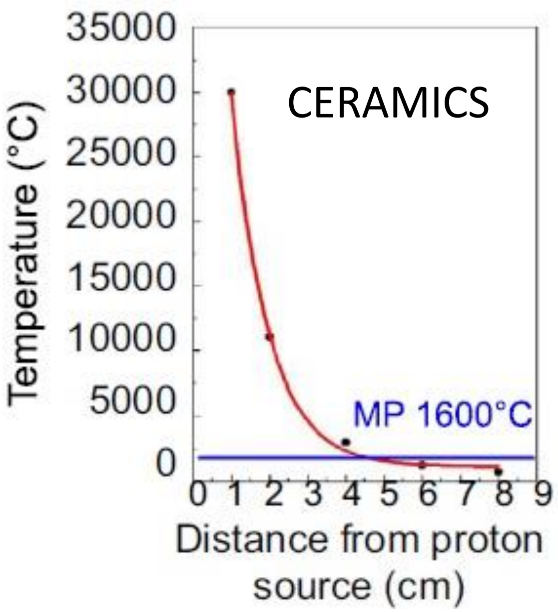
Numerical simulations for material sample heating



Energy deposition code simulating the TITAN spectrum

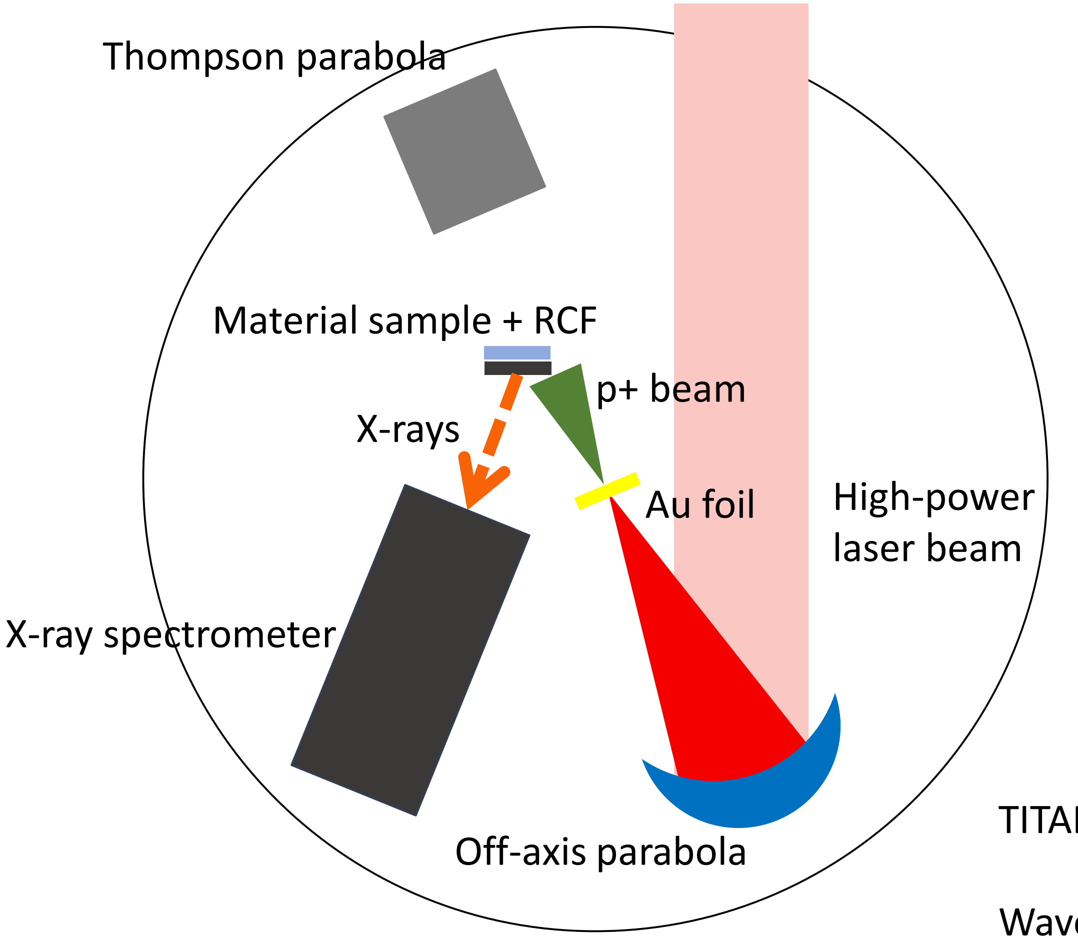


6 cm distance from laser-plasma source



- ➢ Temperature below meting point
- ➢ “Safe” distance in the cm range
- ➢ Bunch duration in the ps range, cooling phase in the ns range

Experimental setup @ JLF-TITAN (Aug. 2016)



Experimental goals:

1) Damage investigation: direct irradiation of a ceramics artifact (6 cm distance from the source)

2) PIXE spectroscopy: direct irradiation of a known material sample and X-ray spectrum analysis

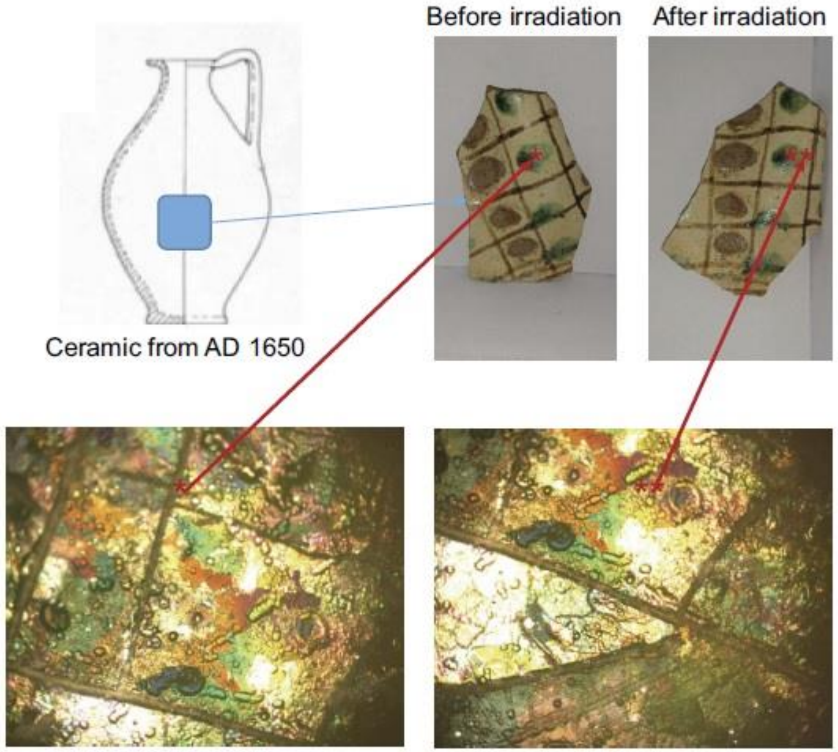
TITAN Laser parameters:

Wavelength $\lambda_0 = 1.053\ \mu m$
Pulse energy $\sim 200\ J$
Pulse duration $\sim 700\ fs$
On-target spot size $\sim 10\ \mu m$ diam.
On-target intensity $\sim 10^{20} W \cdot cm^{-2}$
On target incidence ~ 10 deg.

Investigation of damage induced in a ceramic sample

Ceramics artifact from AD 1650 (archeological situ of Nicastro), provided by the Cultural Heritage department of Regione Calabria

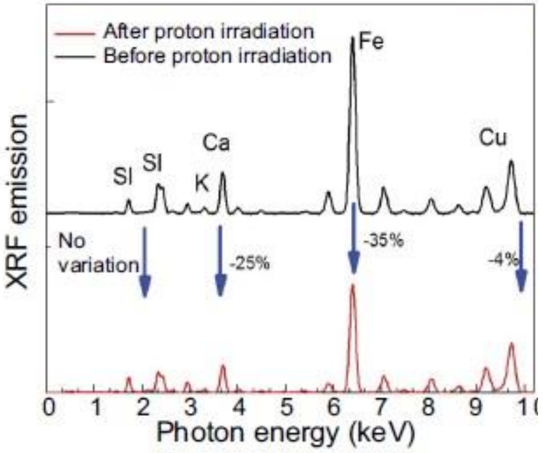
Morphological analysis: optical microscopy (100x mag.)

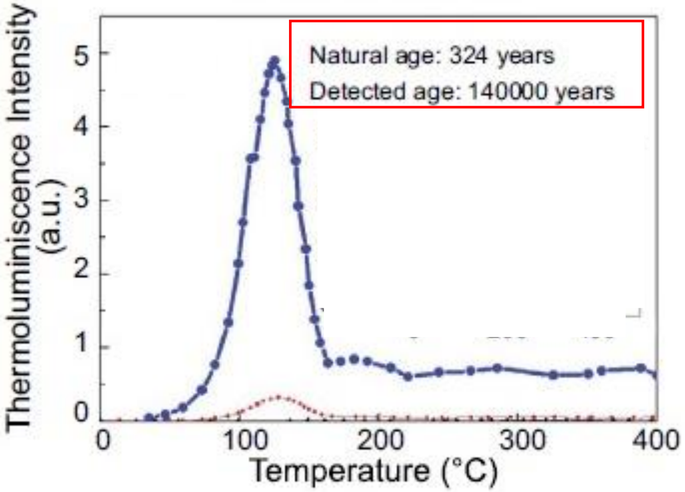


Ceramic from AD 1650

- No aesthetical change after irradiation

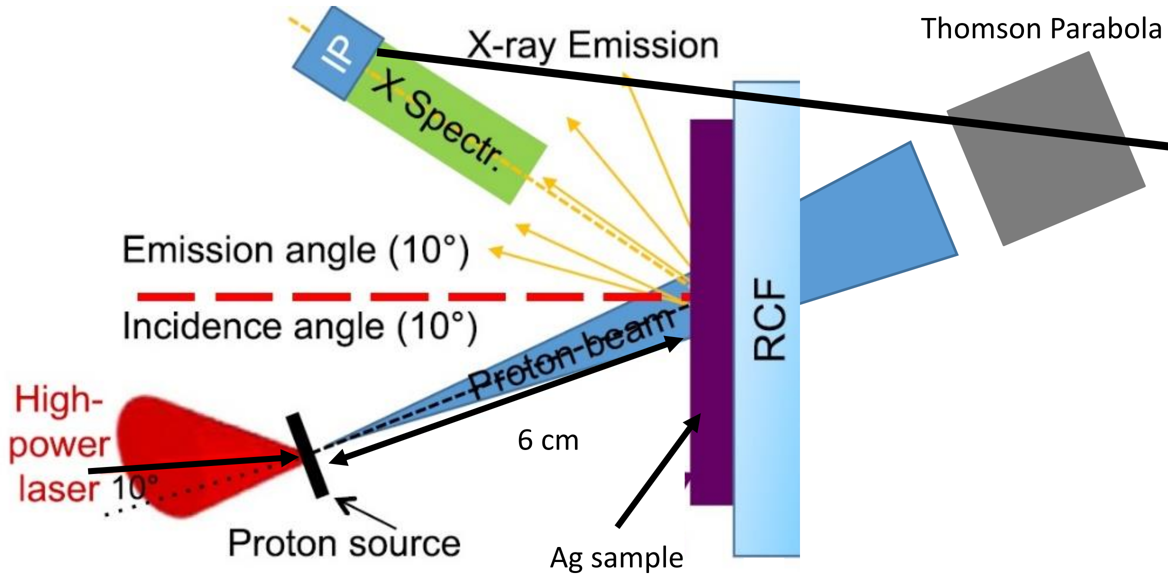
Chemical analysis: Conventional XRF spectroscopy and Thermoluminescence

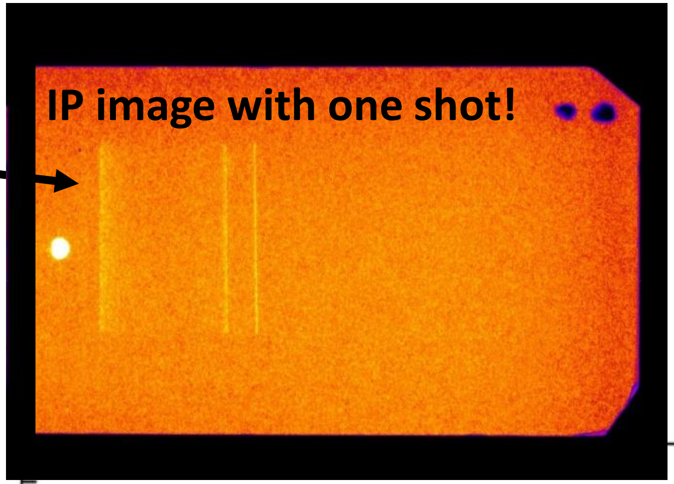




- XRF: no chemical modifications of the irradiated sample
- Absorbed dose alters the thermoluminescence of the materials: the age of the sample is artificially increased

X-ray spectrum analysis of a Silver sample with Bragg-spectrometer

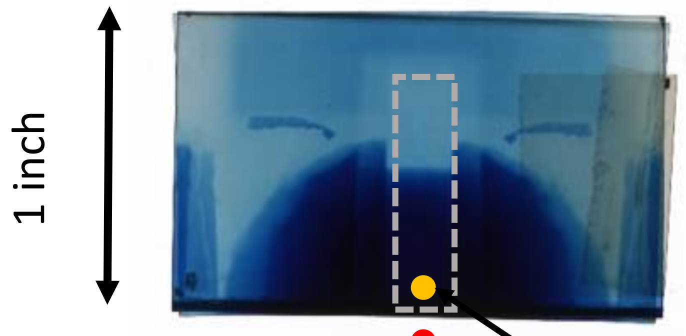


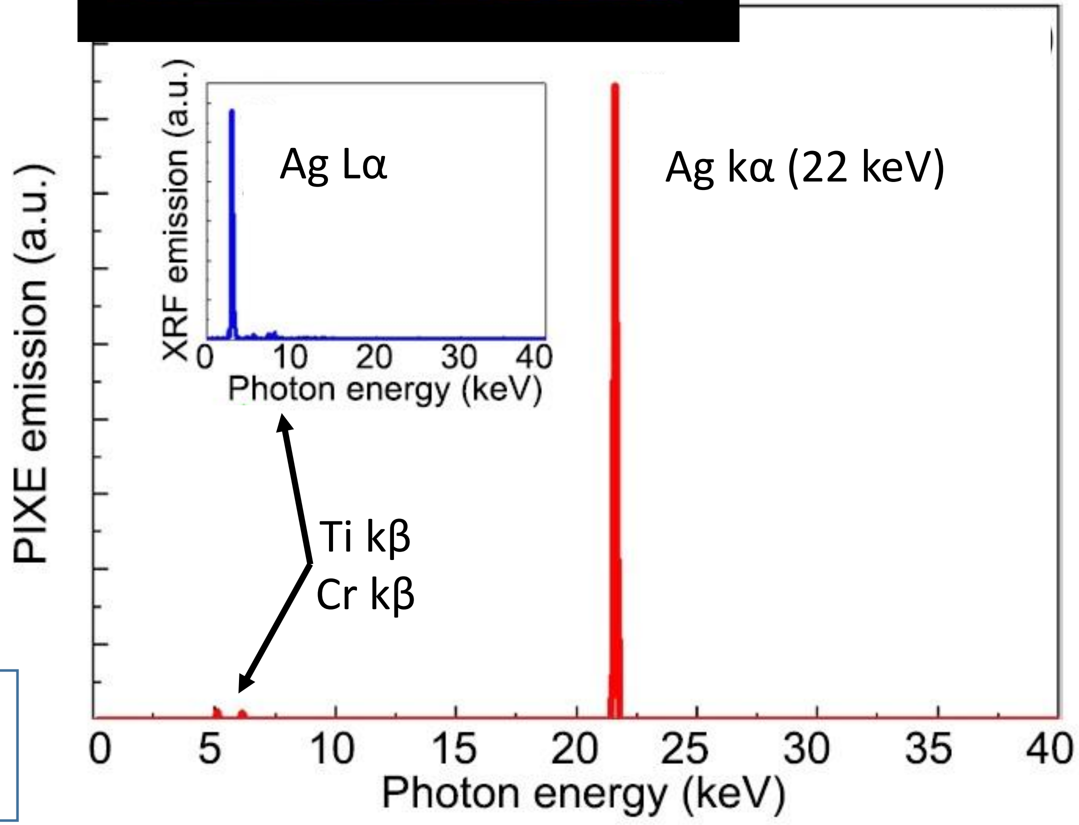


Bragg's law

$$\lambda = 2d \sin \frac{\vartheta}{2}$$

$$E = \frac{hcR}{2dx}$$





- Chemical composition of the sample successfully retrieved (Ag 97%, impurities of Ti, Cr and Cu)

✓ The laser-accelerated proton beam obtained at JLF-TITAN did not induce any aesthetical change in the ceramics artifact

✓ PIXE spectroscopy of a Silver sample in one single shot

M. Barberio, S. Veltri, M. Sciscià and P. Antici, Sci. Rep. 7, 40415 (2017)

Patented technique - US 62/166962 (M.Barberio and P.Antici)

Work in progress…

➢ Compare laser-driven PIXE with conventional PIXE: induced damage, necessary dose, time necessary for a complete analysis

…future steps.

➢ Perform PIXE spectroscopy on further materials of interest: marbles, silicates, noble metals, pigments, cellulose
➢ Perform PIXE using a lower power laser (i.e. a lower proton flux)
➢ Layer-by-layer analysis using an energy-selected proton beam
➢ GEANT4 simulations for PIXE

Proposals for upcoming experiments (2018) sent to JLF-TITAN and LULI-ELFIE.

Collaborations with CENBG/Louvre, Uni. Pisa, INFN Genova…..interest in joining?

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Laser-Accelerated Proton Beams as Diagnostics for Cultural Heritage

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This paper introduces the first use of laser-generated proton beams as diagnostic for materials of interest in the domain of Cultural Heritage. Using laser-accelerated protons, as generated by interaction of a high-power short-pulse laser with a solid target, we can produce proton-induced X-ray emission spectroscopies (PIXE). By correctly tuning the proton flux on the sample, we are able to perform the PIXE in a single shot without provoking more damage to the sample than conventional methodologies. We verify this by experimentally irradiating materials of interest in the Cultural Heritage with laser-accelerated protons and measuring the PIXE emission. The morphological and chemical analysis of the sample before and after irradiation are compared in order to assess the damage provoked to the artifact. Montecarlo simulations confirm that the temperature in the sample stays safely below the melting point. Compared to conventional diagnostic methodologies, laser-driven PIXE has the advantage of being potentially quicker and more efficient.

Thanking the collaborators…

M. Barberio, S. Veltri, M. Sciscìò, A. Morabito, S. Vallieres and P. Antici

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…and thank you for the attention !

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