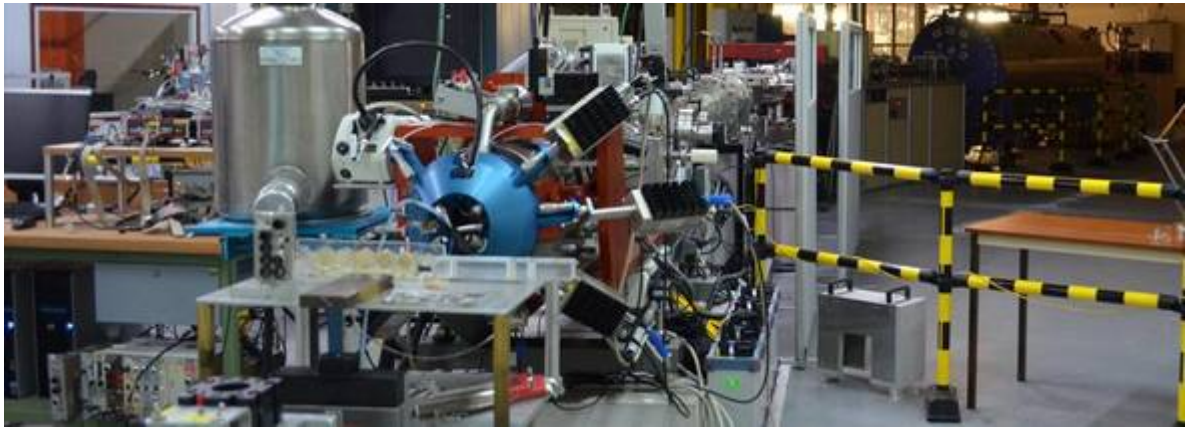
The accelerator under the Louvre
the *New AGLAE*



Claire Pacheco[1;2], Quentin Lemasson[1;2], Brice Moignard[1;2], Laurent Pichon[1;2], Marie Radepont[1;3], Didier Gourier[2;4]

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Contact email: **claire.pacheco@culture.gouv.fr**

CENTRE DE RECHERCHE ET DE RESTAURATION DES MUSÉES DE FRANCE

1931 : inauguration of the Louvre laboratory

1988: AGLAE is settled in Le Louvre premises

1995: Research Lab of French Museums

CENTRE DE RECHERCHE ET DE RESTAURATION DES MUSÉES DE FRANCE

Restoration

- Archaeology
- Sculpture
- Paintings
- Decorative arts

Research

- Objects
- Paintings & polychromy
- Dating (C14, TL)
- Imaging (daylight, UV, IR, 3D..)
- AGLAE+ (SEM, XRF, XRD)

Archives & Documentation

- Library
- Numeric database

Preventive Conservation

- Artefacts management
- Advise for museums for the best practice in exposing/storing collections

AGLAE beamtime:

1/ service : working for more than 1200 French museums

2/ Research projects: local (C2RMF), national, international

3/ instrument maintenance and development

IPERION CH

For more information, visit the website: *www.iperionch.eu*
Or write to *claire.pacheco@culture.gouv.fr*

Integrated trans-national access platforms. IPERION CH makes world-class scientific tools and knowledge available to Heritage scientists through three integrated Trans-National Access platforms

ARCHLAB

access to ARCHIVES (technical images, analytical data and conservation documentation) in datasets largely unpublished from 10 large archives of prestigious European museums, galleries and research institutions.

MOLAB

access to MOBILE INSTRUMENTS for NON-INVASIVE IN-SITU measurements on precious, fragile or immovable objects, archaeological sites and historical monuments.

FIXLAB

access to LARGE SCALE FACILITIES (synchrotron, neutron sources, ion accelerators)

IPERION CH

For more information, visit the website: *www.iperionch.eu*
Or write to *claire.pacheco@culture.gouv.fr*

BNC-WIGNER (Budapest, Hungary) with access to various neutron-based instruments to investigate elemental and structural composition

contact:
kasztovszky.zsolt@energia.mta.hu

synchrotron SOLEIL (Gif-sur-Yvette, France) 26 beamlines covering Fr IR to Hard X-ray range; analysis of µ-samples; imaging over all regions of the EM spectrum; structural analysis

contact:
frederique.fraissard@synchrotron-soleil.fr

WP 4
FIXLAB

MTA-ATOMKI, DEBRECEN

MTA-ATOMKI nuclear microprobe (Debrecen, Hungary) for high spatial resolution measurements with a focussed ion beam in vacuum and with external beam

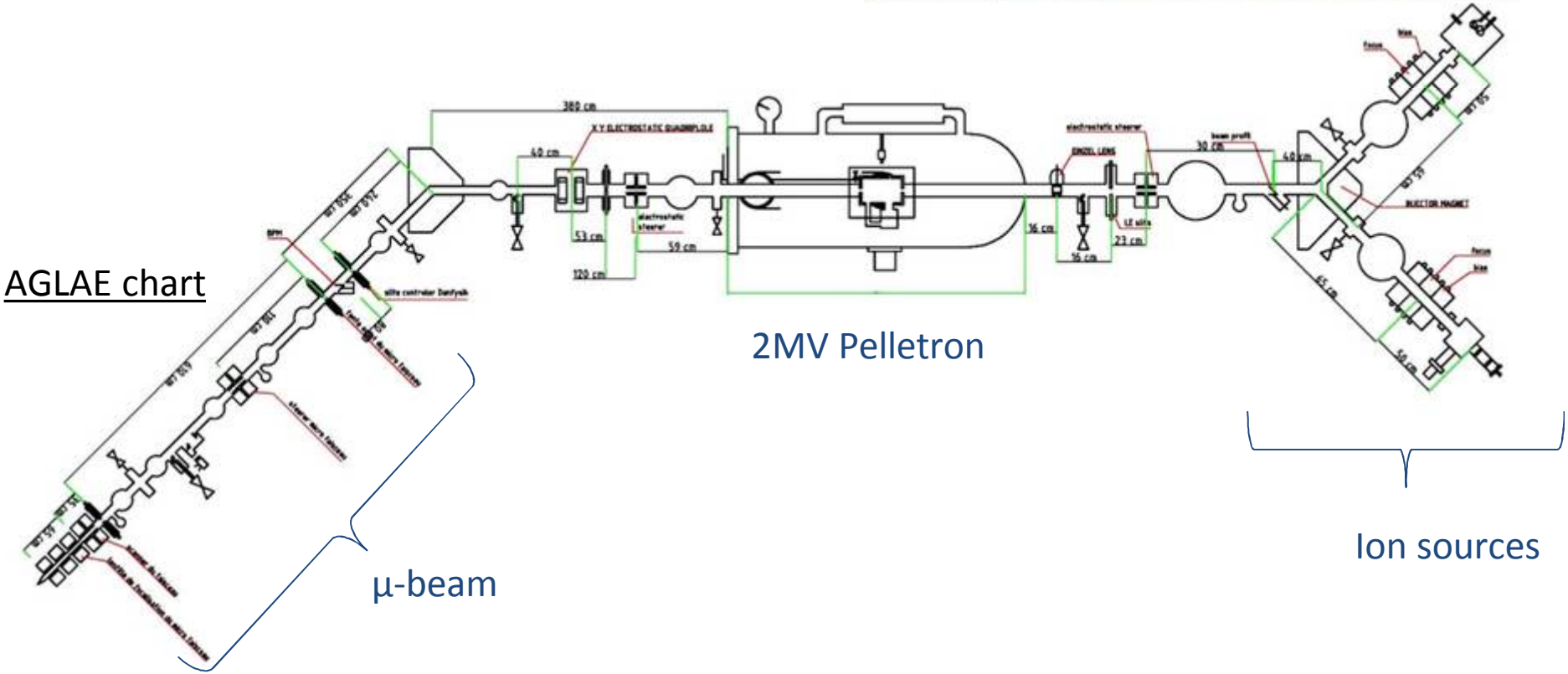
contact:
szikszai.zita@atomki.mta.hu

AGLAE ion beam accelerator at **C2RMF** (Paris, France), providing elemental analysis with an external beam for whole art objects

contact:
claire.pacheco@culture.gouv.fr


Accelerator
AGLAE: Accelerator Grand Louvre for Elemental Analisis
Unique for combining:
- Strategic localization
- 100% dedicated to the study of Cultural Heritage (CH)
- Data compiling from decades
- Beamline development for questions specific to CH questions and constraints of museum objects

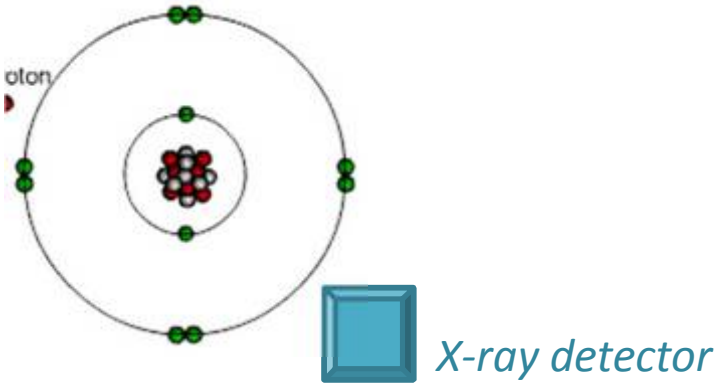
AGLAE chart



CENTRE DE RECHERCHE ET DE RESTAURATION DES MUSÉES DE FRANCE

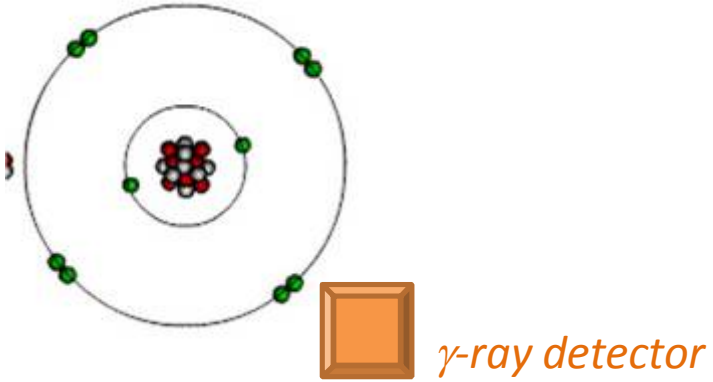
Ion Beam Analysis (IBA) in a nutshell…

PIXE: Particle Induced X-ray Emission



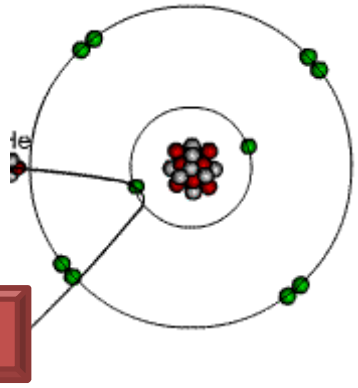
X-ray detector

PIGE: Particle Induced γ-ray Emission



γ-ray detector

(R)BS: (Rutherford) Bakscaterring Spectroscopy



particle detector

Which questions can answer AGLAE ?

- IBA on CH objects give knowledge on the studied material, which is part of the answer of a more general human science questioning

- Human science: a better understanding of societies and of their interactions in well defined geo-chronological contexts
  - How old is it ? → *production centres, worshops,…*
  - How was it made ? → *making process and technique history*
  - Where does it come from ? → *provenance, trade routes,…*

Case of provenance study

Guarrazar treasure

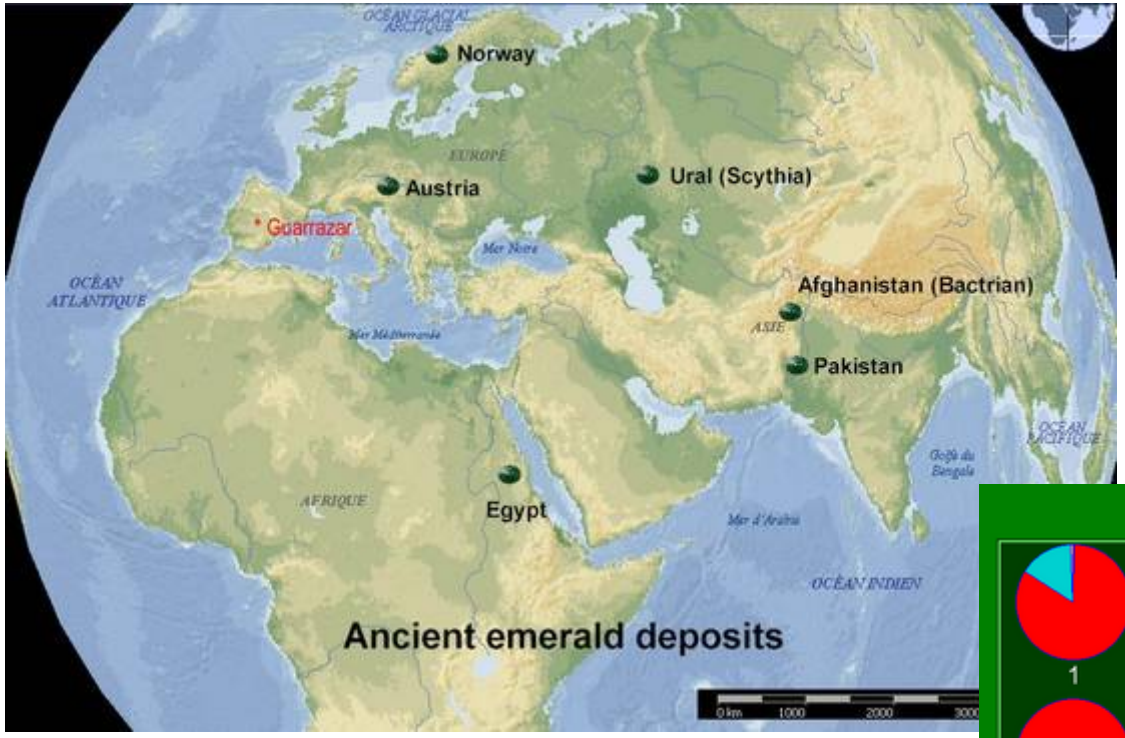
Spain, 7th c.

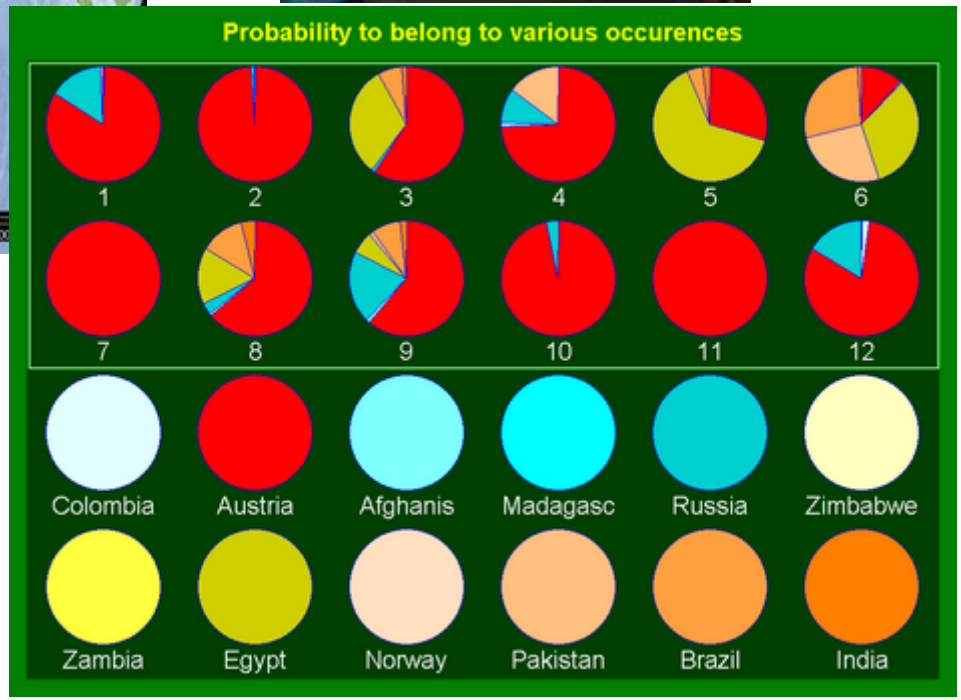
Gold, gems, pearls, rock cristals and glass jewellery

Musée National du Moyen Age, Paris

Discovered in 1859 next to Toledo: 26 votive crowns and gold crosses that had originally been offered to the Roman Catholic Church by the Kings of the Visigoths in the seventh century in Hispania, as a gesture of the orthodoxy of their faith and their submission to the ecclesiastical hierarchy.

Th. Calligaro et al., NIMB 161-163 (2000) 769





Results:

The $Be_3Al_2(SiO_3)_6$ structure of emeralds relies trace elements: Na, Mg, Ca, Ti, Rb, Ni, Cu, Zn, Cs and Li, F.

Most of the emeralds are likely to come from the Alps, a deposit that was known to be exploited only since 13th c. from the texts.

Th. Calligaro et al., NIMB 161-163 (2000) 769

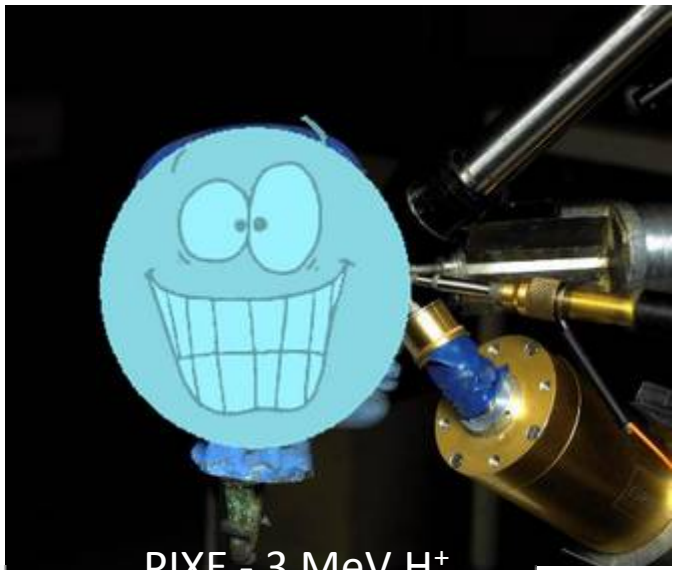
Which questions can answer AGLAE ?

- IBA on CH objects give knowledge on the studied material, which is part of the answer of a more general human science questioning

- Human science: a better understanding of societies and of their interactions in well defined geo-chronological contexts
  - How old is it ? → *production centres, worshops,…*
  - How was it made ? → *making process and technique history*
  - Where does it come from ? → *provenance, trade routes,…*

- Conservation science
  - Is it a fake ? → *authentication*
  - Why is it degraded ? → *degradation mecanism*
  - Will a restoration product be worse than doing nothing ?

Case study of authentication



PIGE: presence of F probably due the use of HF to depolish the glass and artificially age it.

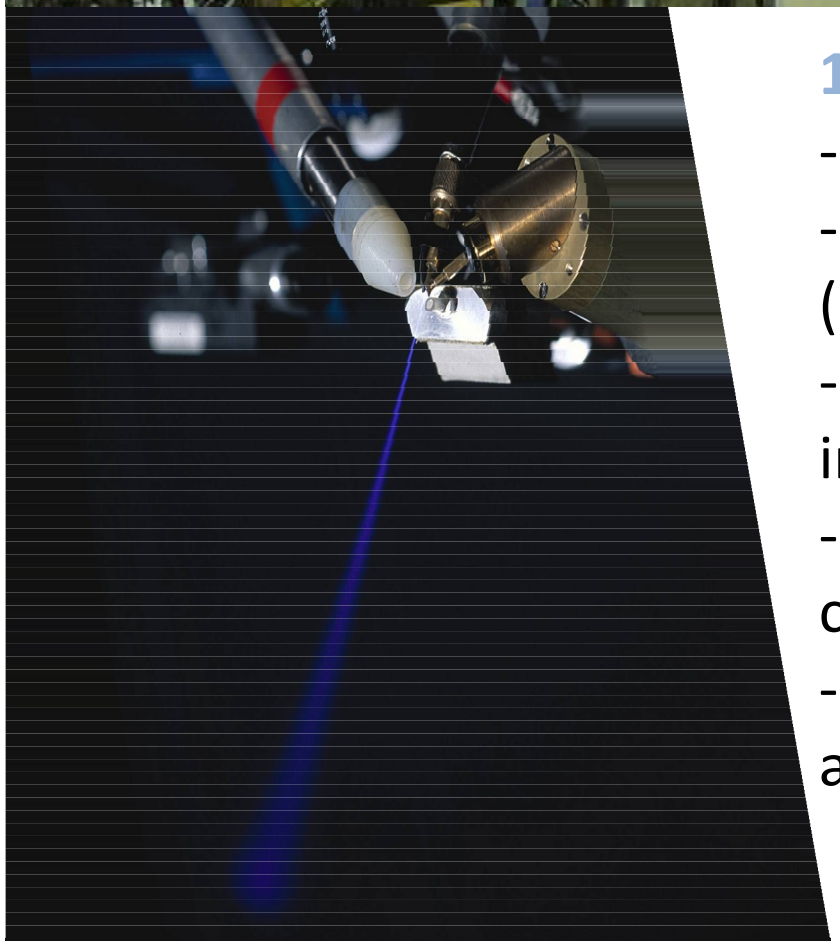
Référence : Geneviève Pierrat-Bonnefois et Isabelle Biron, La tête égyptienne en verre bleu : la conclusion d'une enquête, *La Revue du Louvre et des Musées de France*, n°3, 2003, 27-37.

Égypte ancienne

%	Bleu foncé	Turquoise	XVIII[e] dynastie
SiO_2	48 - 77	44 - 76	Sable
Al_2O_3	0.8 - 5.2	0.9 - 3.4	
FeO	0.39 - 1.48	0.33 - 0.99	
Na_2O	6 - 20	6 - 19	Source Na
MgO	2.3 - 4.9	0.7 - 6.1	végétale
K2O	0.9 - 2.6	0.9 - 3.3	cendre de plante
P_2O_5,	< 0.55	< 1	marine - salicorne
Cl, SO_3	< 3	< 3	
CoO	0.1 - 0.5	0	Source cobalt Égypte CoMnNiZn
CuO	0 - 0.7	0.8 - 3.2	
Sb_2O_3	5.5 - 9.7	2.6 - 9.5	opacifiant
As203	0 - 2.4	0.5 - 5.7	antimoniate de Ca

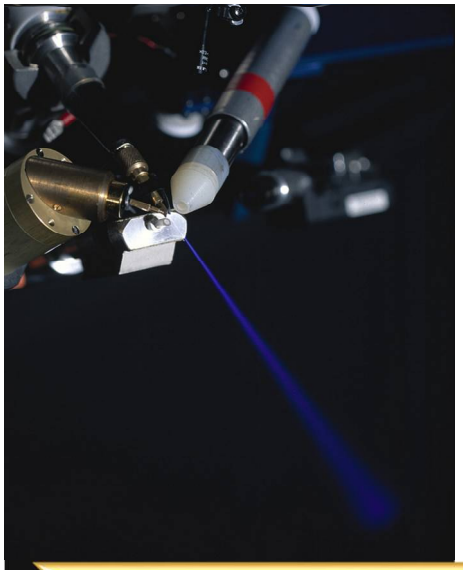
XIX[e] siècle

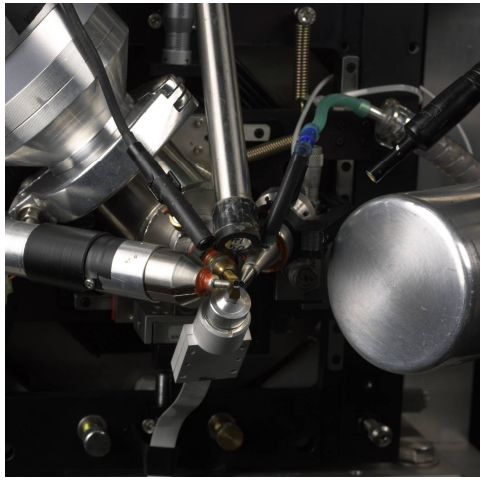
%	Bleu ciel	Bleu foncé	Tête bleue Louvre
SiO_2	47	40	Sable
Al_2O_3	1.4	2.4	
FeO	0.4	0.63	
CaO	1.9	2.1	
Na_2O	12	11.9	Source Na
MgO	2.1	1.9	non végétale
K2O	2.4	3.4	
P_2O_5,	0	0	
Cl, SO_3	0 - 0.23	0 - 0.48	
CoO	0.16	0.4	Source cobalt
CuO	0.08	0	CoAlNi
Sb_2O_3	0.1	0.3	opacifiant
PbO	25	28	arséniate de Pb
As203	5.4	4	



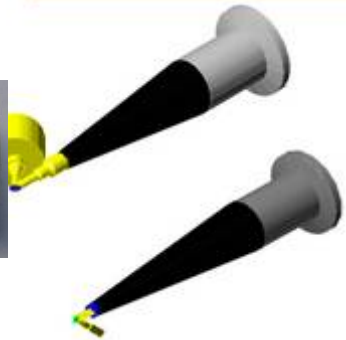
1/ External beamline applied to CH:

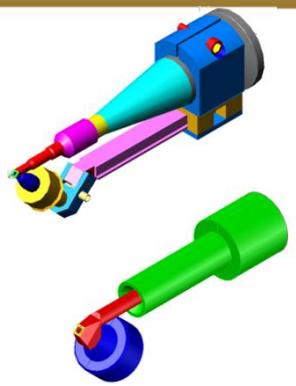
- analysis of items of any size and shape
- no degradation due to vacuum (dehydration, outgassing,…)
- reduces the risk of heating and beam-induced damage
- no sample preparation(no deposit of conductive coating)
- simplifies sample changing and positioning

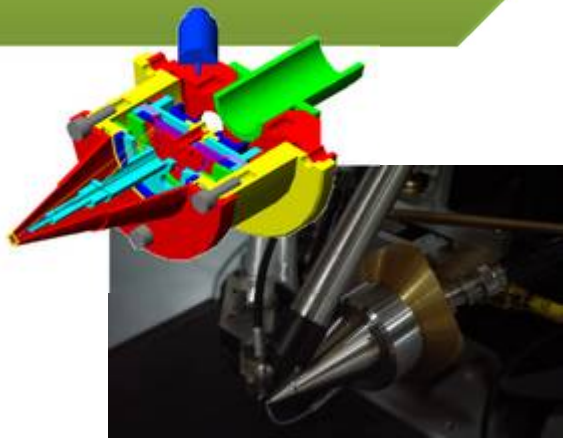




1989 | 1994-2003 | 2004-2009







Evolution of the extraction nozzle

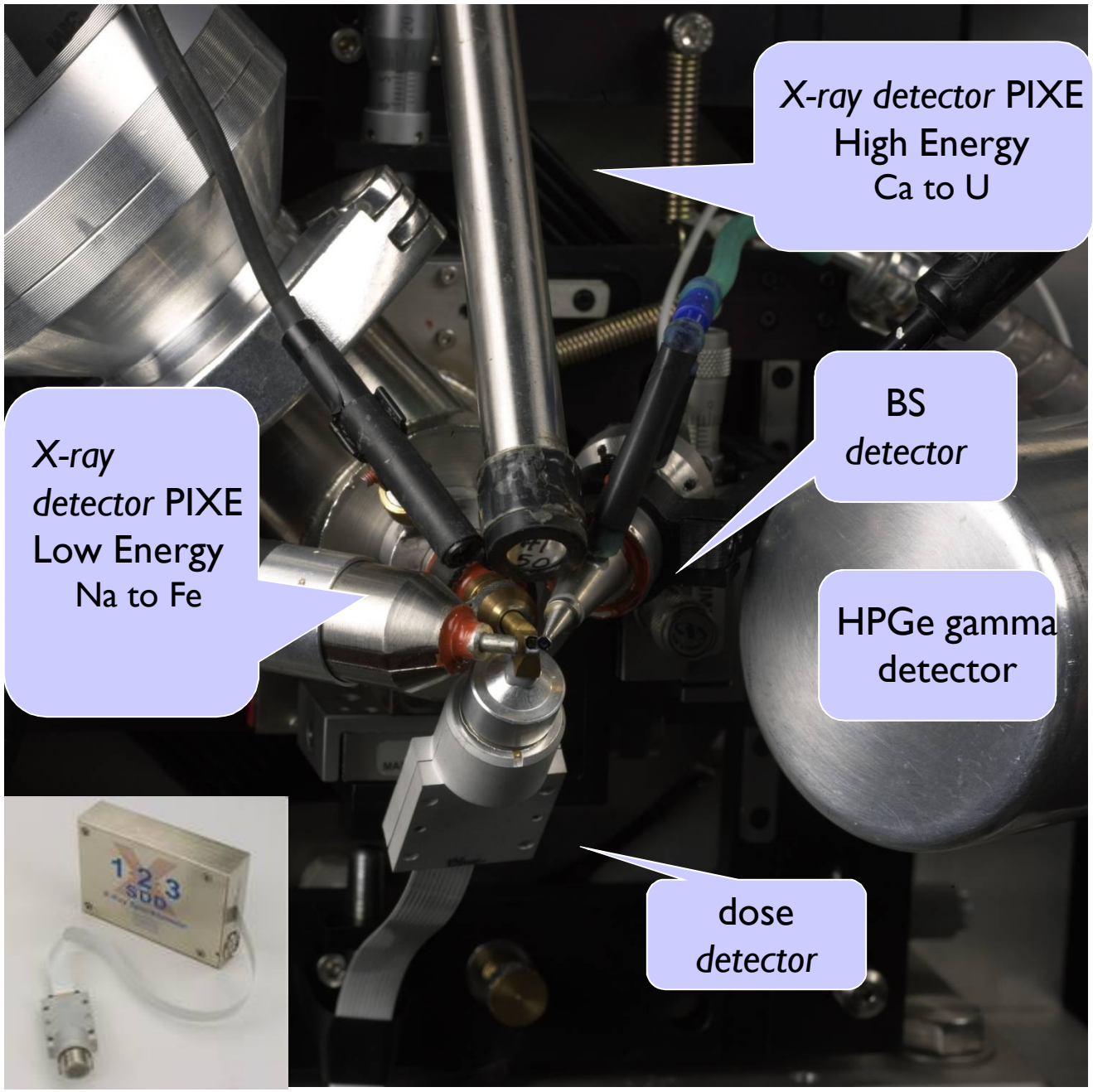
Annular RBS

Main contributors : J. Salomon, J.-C. Dran, Th. Calligaro, B. Moignard, L. Pichon, T. Guillou, F. Mathis

2/ Extending the range of measured elements in PIXE-PIGE

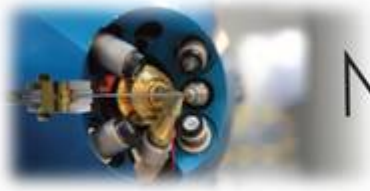
- at 1st, PIXE determined medium to high-Z elements at trace levels with a 3-MeV H+ irradiation; main components measured by XRF, SEM-EDS…
- to extend to Z<20, process based on 2 successive runs at low and high beam energies

  e.g. 1 run at 1 MeV (no X-ray absorber) and 1 run at 3 MeV with an appropriate absorber
- Introduction of a dual-detector system with a single run at 3 MeV developed by the Florence group McArthur et al., NIMB 45 (1990) 315


X-ray detector PIXE
High Energy
Ca to U
BS
detector
X-ray
detector PIXE
Low Energy
Na to Fe
HPGe gamma
detector
dose
detector
1 2 3
SDD

CENTRE DE RECHERCHE ET DE RESTAURATION DES MUSÉES DE FRANCE

Culture Communication Ministère



NewAGLAE

MAIRIE DE PARIS

INVESTISSEMENTS D'AVENIR

cnrs

1/ Multi-detector

2/ Systematic imaging

3/ Automation of the beamline

• Upgrades

Increase of detection solid angles
- better sensitivity for trace elements
- decrease of particle flux

→ Study of fragile materials

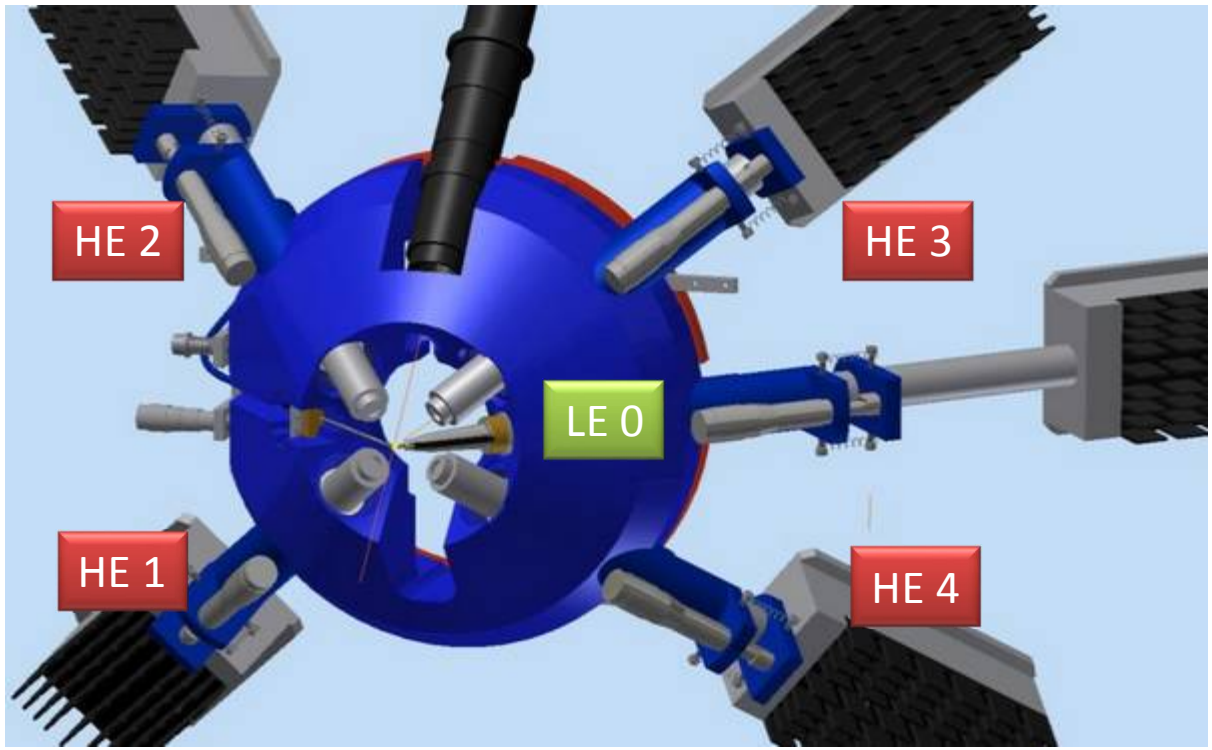
- PIGE :1 → 4 HPGe or CdTe
- PIXE - EDS:

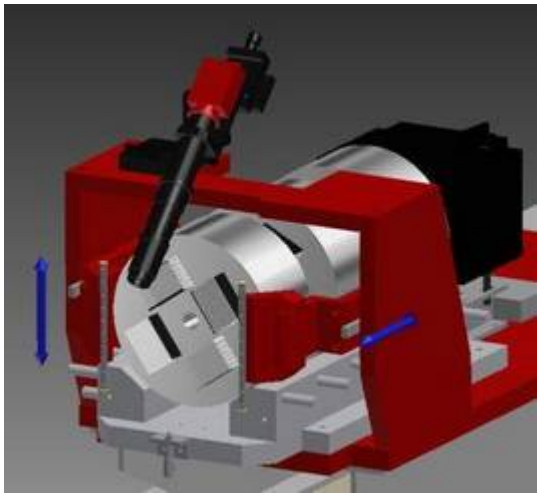
2 Si(Li) (1 BE 10 mm^2 + 1 HE 30 mm^2)
→ 5 SDD 50 mm^2

- RBS : annular detector and/or external detector
- Dose detector

• Novelties

- PIXE – WDS
- Iono-luminescence
- Systematic imaging





Support

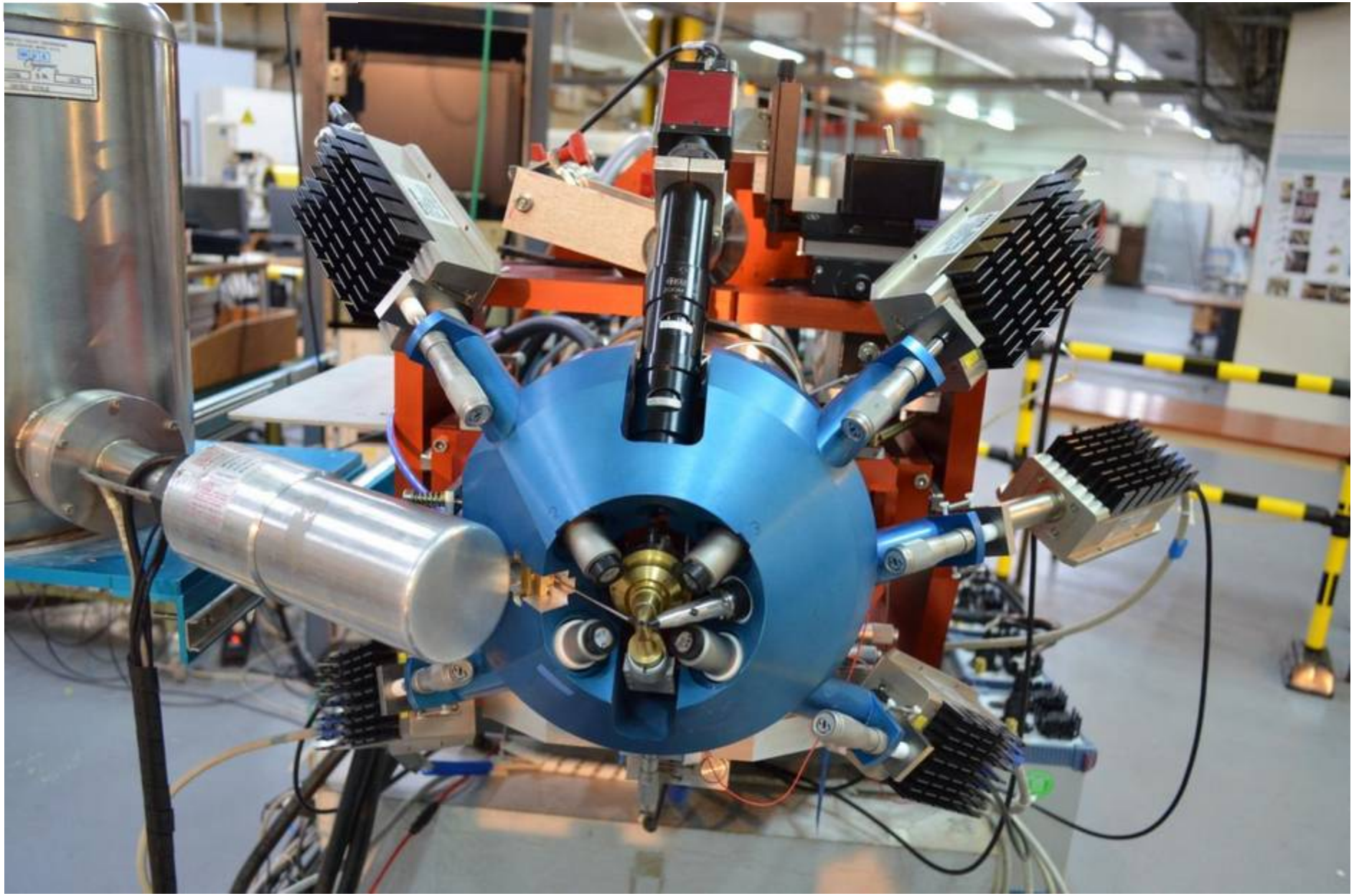
- Design of aluminum support
- HE 1-4, 50° relative to beam axis , Distance: 20mm to 45mm
- LE0, 45° relative to beam axis

NewAGLAE

1/ Multi-detector

2/ Systematic imaging

3/ Automation of the beamline



• Upgrades

Increase of detection solid angles
- better sensitivity for trace elements - decrease of particle flux

→ Study of fragile materials

- PIGE :1 → Ge or CdTe (Study in progress)
- PIXE - EDS:

2 Si(Li) (1 BE 10 mm² 1 HE 30 mm²) (Operational)

→ 5 SDD 50 mm²

- RBS : annular detector and/or external detector (Operational)
- Dose detector

• Novelties

- PIXE – WDS (Study in progress)
- Iono-luminescence (Operational)
- Systematic imaging

5 SDD detectors (Ketek) → 2 x 4-channel DSP Mercury-4 (XIA) → **Listmode** data MPA-3 acquisition system (FastComtec)

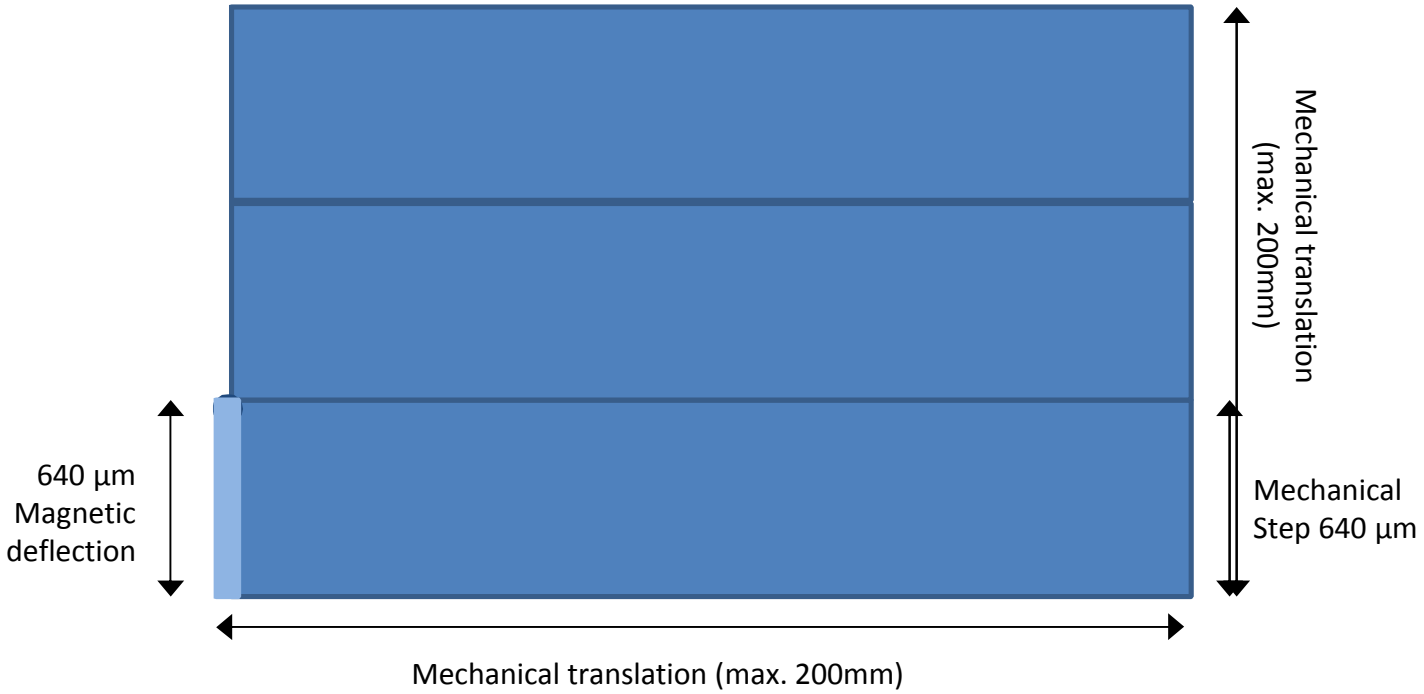
- Customize firmware of the Mercury-4 DXP to provide standard ADC interface (Data and protocol)

- Digital processor allows high output count rate 30k cps per channel (30% DT) → 150k cps total
- HE1-4 : 145 eV resolution
- LE0 : 135 eV resolution

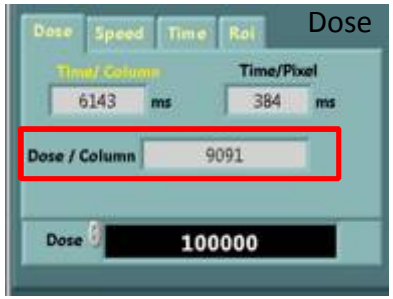
Nine channels :

- 5 - SDD
- 1 - RBS
- 1 - Gamma
- 1 - X positions
- 1 - Y positions

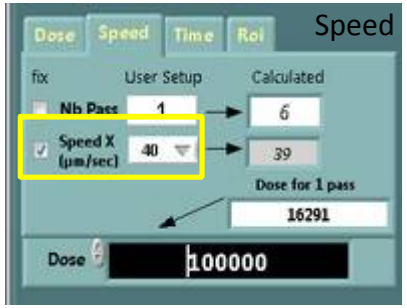
Vertical / Horizontal scanning



Two ways for mapping



- Dose monitoring by column
- Homogeneous dose/pixel



- No dose monitoring
- Fast map
  (max. 500µm /sec)

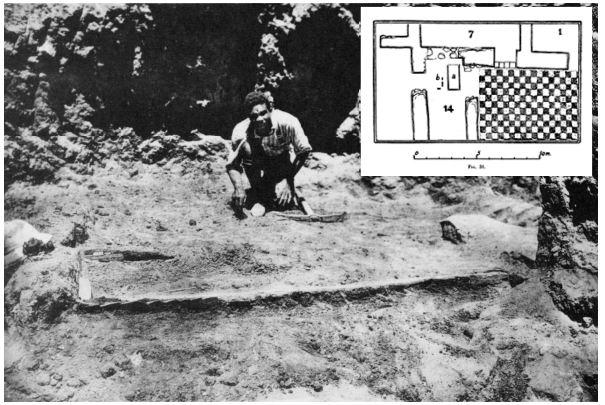
The case study of ivories from Arslan Tash site, Syria, 8th c. BC

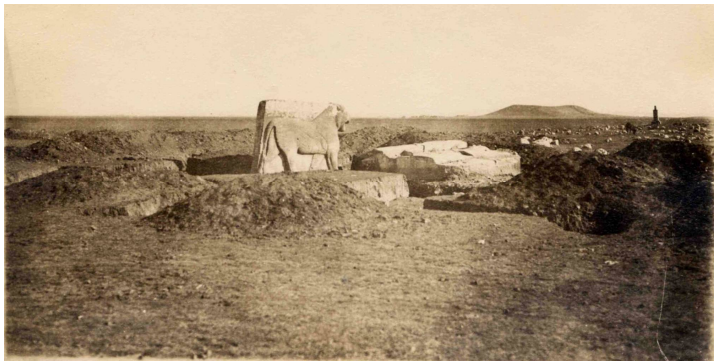
I. Reiche[1], M. Albéric[1], E. Apchain[1], K. Müller[1], C. Heckel[2], R. White[2], H. Floss[3], E. Fontan[4], L.Pichon[5], Q. Lemasson[5], B. Moignard[5], C. Pacheco[5]

[1] *LAMS UMR 8220 CNRS UPMC Paris VI, Paris, France*
[2] *Center for the Study of Human Origins, Department of Anthropology, New York University, USA*
[3] *Institut für Ur- und Frühgeschichte, University of Tübingen,*
[4] *Département des Antiquités Orientales, Musée du Louvre, Paris, France*
[5] *C2RMF, Paris, France and Fédération de Recherche New AGLAE (FR3506 CNRS)*

With additional contributions of T. Borel,
D. Bagault, S. Pagès-Camagna , D. Large (C2RMF)
A. Caubet, S. Cecchini, F. Poplin, M.G. Amadasi

The archaeological site of Arslan Tash, Syria

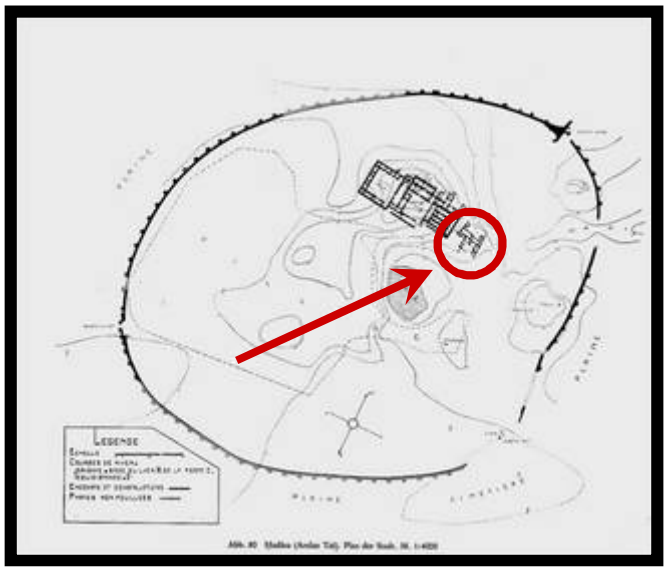




Aim of the study

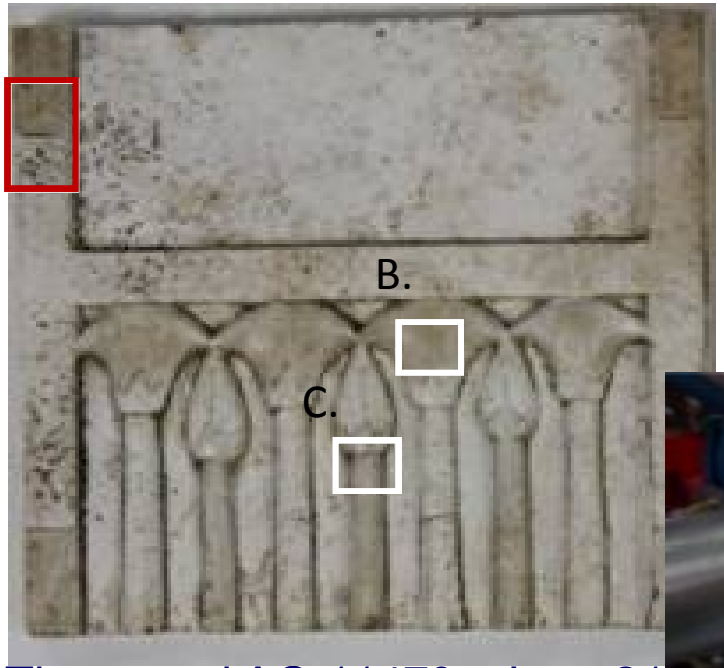
➔ Reconstructing the original appearance of the object

➔ Defining attribution criteria to the Arslan Tash site



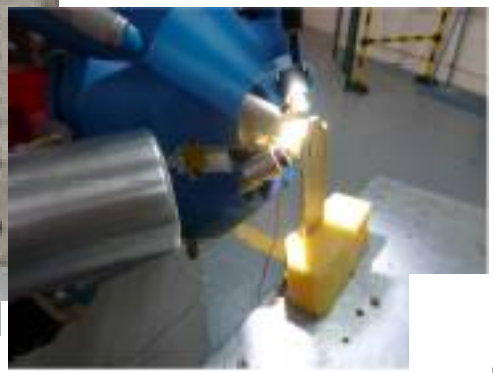
PIXE chemical imaging

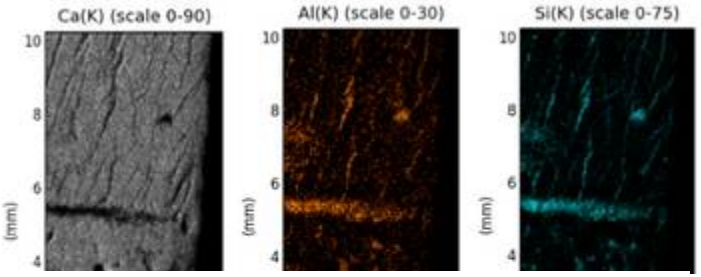
(enhancement factor)



The papyri AO 11479 – Louv21

A.: analyzed surface: 4.8 x 10.2 mm²
step size: 20 x 20 µm²





Ca distribution: indicative of surface stat
Al, Si, Fe: indicative of sediment traces
Cu and Pb: ancient polychromy

Position	CaO	Fe_2O_3	CuO	ZnO	PbO	PbO/Cu
zone A	512906	7260	1750	966	383	0,22
zone B	546188	2238	2964	532	1133	0,38
zone C	546265	937	2513	394	805	0,32

Paints: different ratios of lead white and a Cu pigment like Egyptian blue

Possible reconstruction

Albéric *et al.*, 2015, Talanta 137, 100-108
Fontan *et al.*, 2011, Archeosciences 35, 283-295

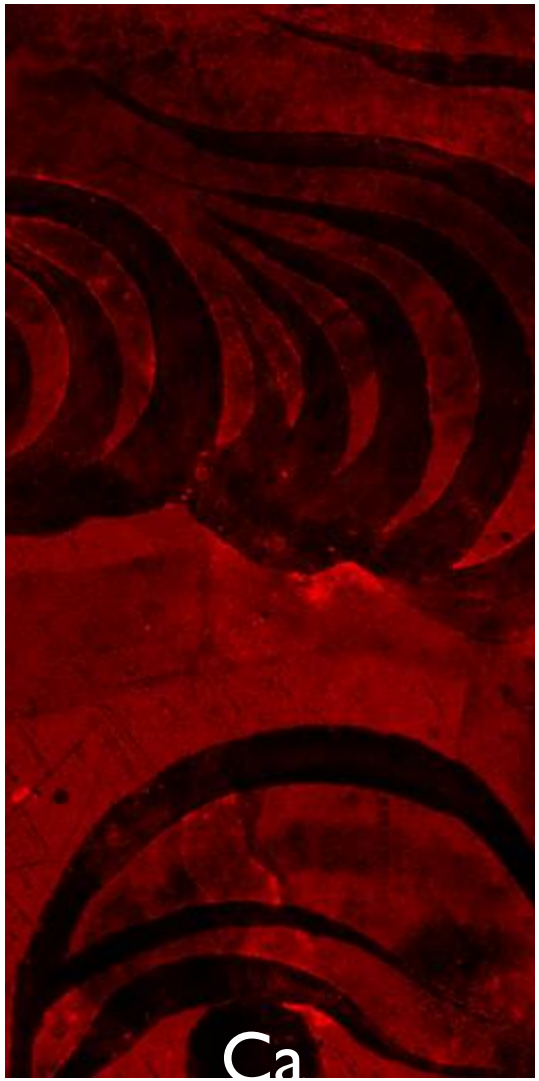
Stained glass window - Chartres Cathedral – 12th - 13thc.

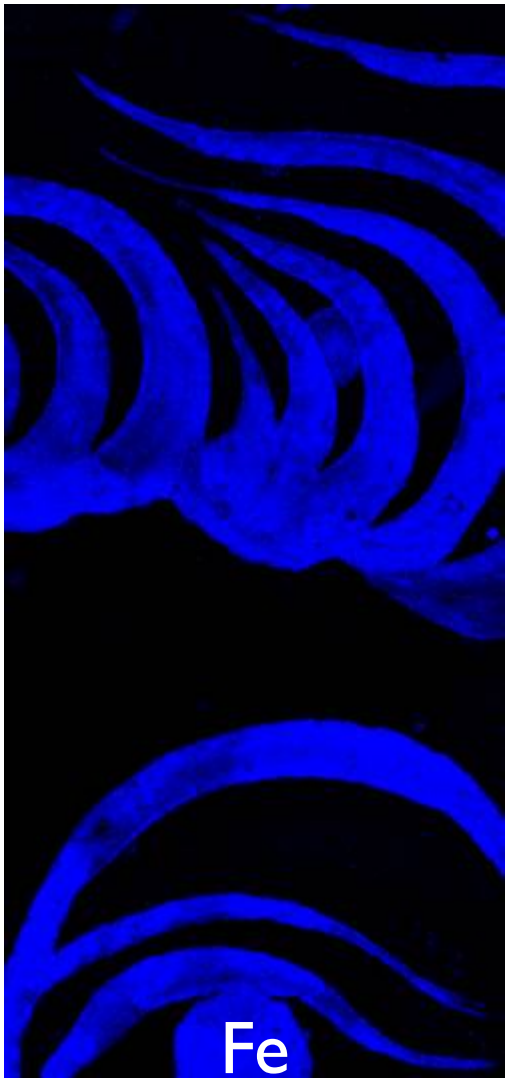
Grisaille: lead silicate + metallic oxides/salts + firing

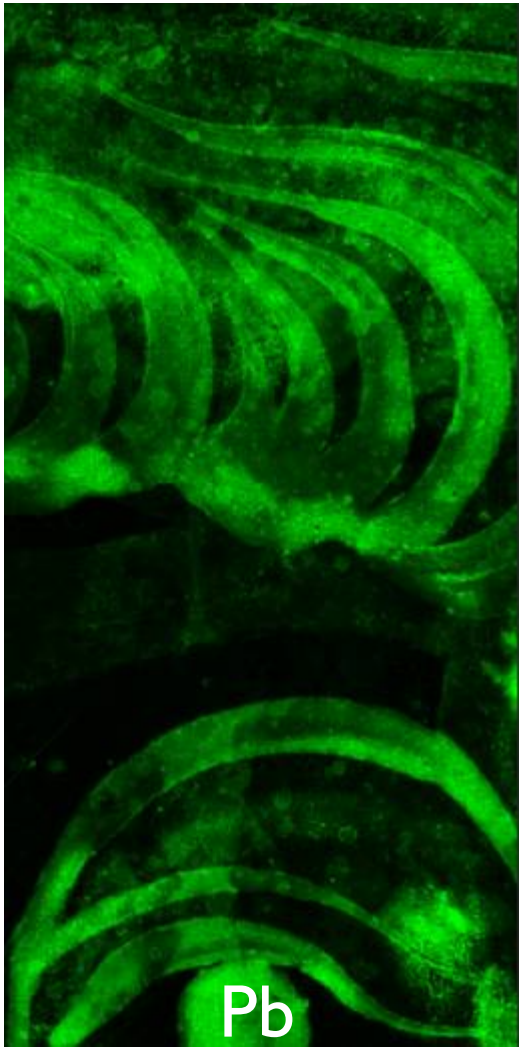
Lavis: diluted grisaille or only lead silicate ?

Claudine Loisel - LRMH

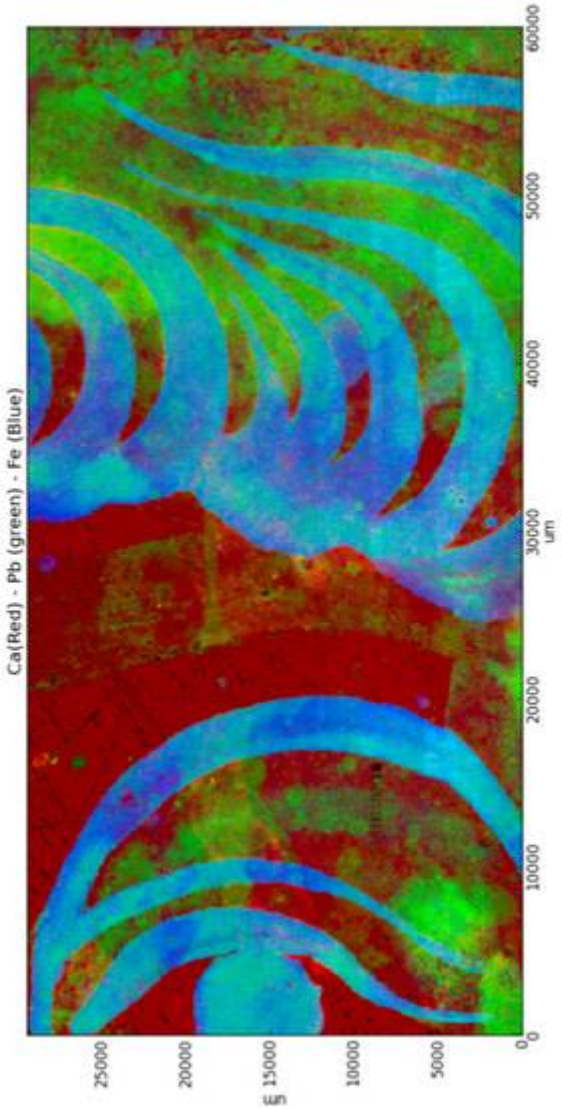
Stained glass window - Chartres Cathedral – 12th - 13thc.



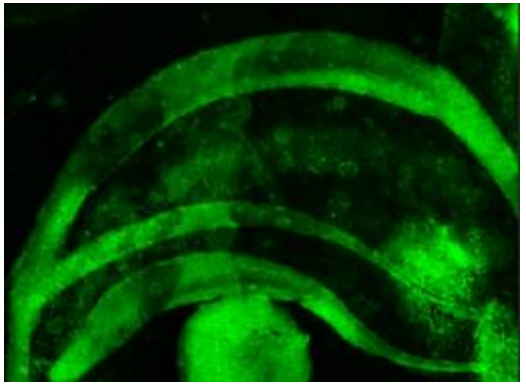




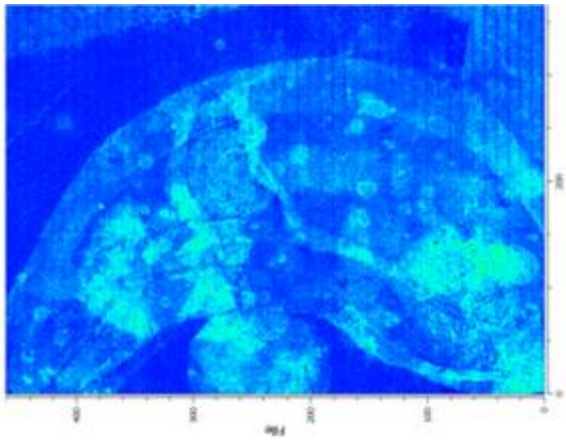
Stained glass window - Chartres Cathedral – 12th - 13thc.



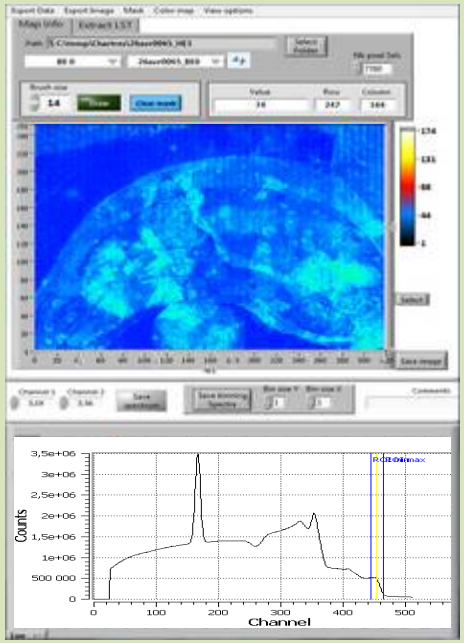
Pb PIXE



RBS



Methodology for (R)BS Mapping @ AGLAE



RBS Mapping Tool ⟷ **NDF engine**

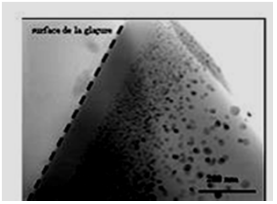
- Batch mode
- PIXE – PIGE
- roughness models

Every RBS sprectrum/pixel fitted

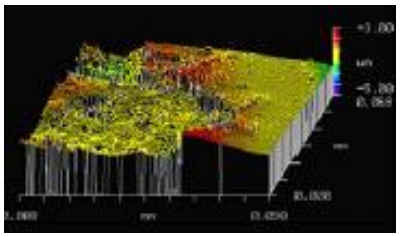
DataImaging

Imaging reconstruction with data extracted from RBS fitted spectra

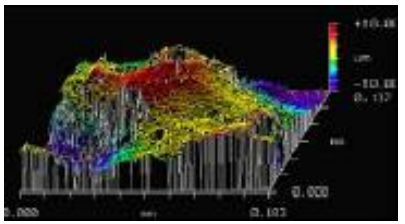
nm scale



µm scale



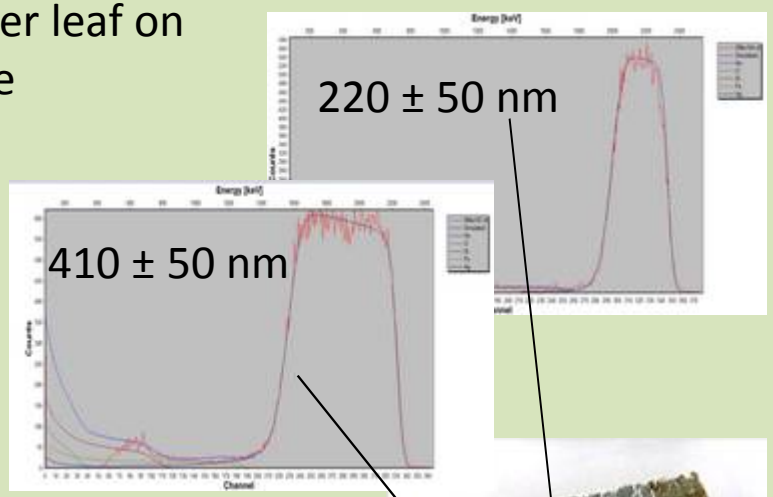
… and above



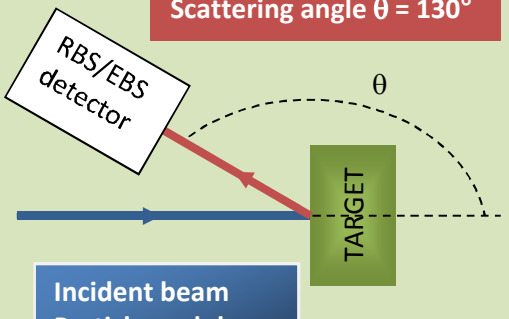
Simple model to test the feasibility of the methodology for (R)BS Mapping @ AGLAE

Simple model = folded silver leaf on a microscope slide

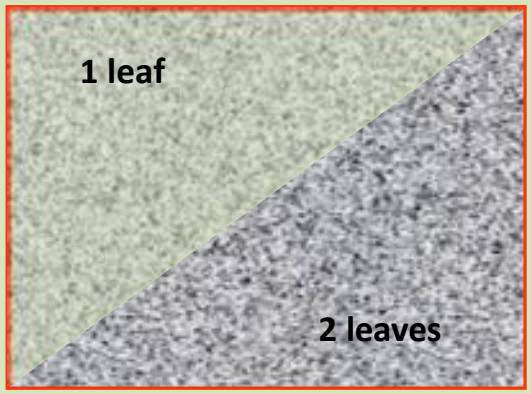
Berta Battiloro - Venice



2 x 3 cm²



Thickness (nm)



Projection of the expected thickness mapping

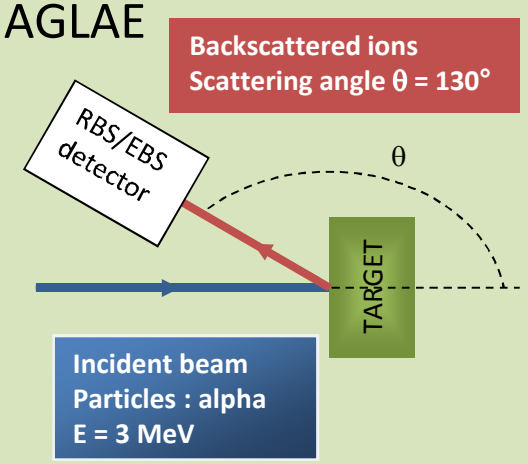
Simple model to test the feasibility of the methodology for (R)BS Mapping @ AGLAE

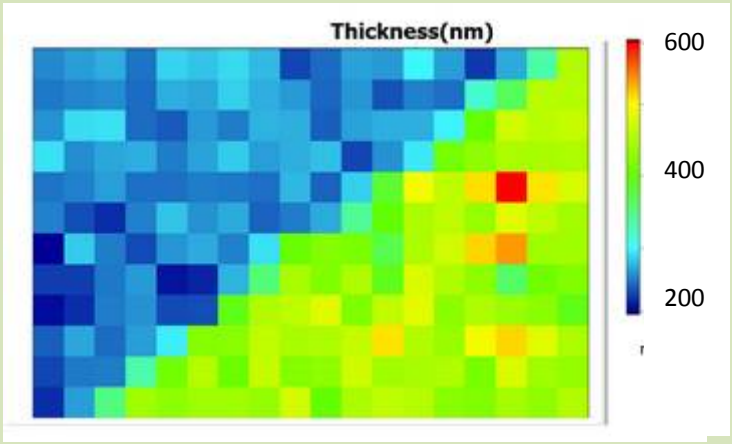
- Construction of NDF batch :
  each pixel imported as a sample

- 1 sample is fitted by annealing

- fit OK → local search for the whole batch

- reconstruction of the image from fitted concentration depth profile





2 x 3 cm²

Simple model to test the feasibility
of the methodology for (R)BS Mapping @ AGLAE

- Construction of NDF batch :
 each pixel imported as a sample

- 1 sample is fitted by annealing

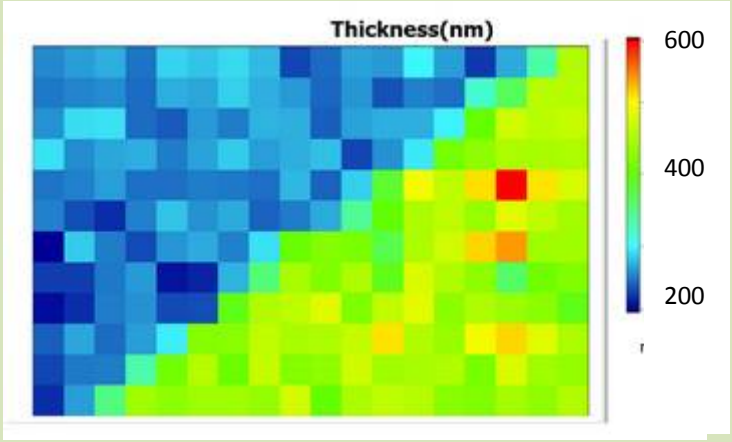
- fit OK → local search for the whole batch

Batch mode: limited number of pixels

TrauNDF

NDF is simultaneously launched on several processors

- reconstruction of the image from fitted concentration depth profile



A new philosophy…

… that must adapt to long-term projects !

Exchange networks of variscite during Neolithics

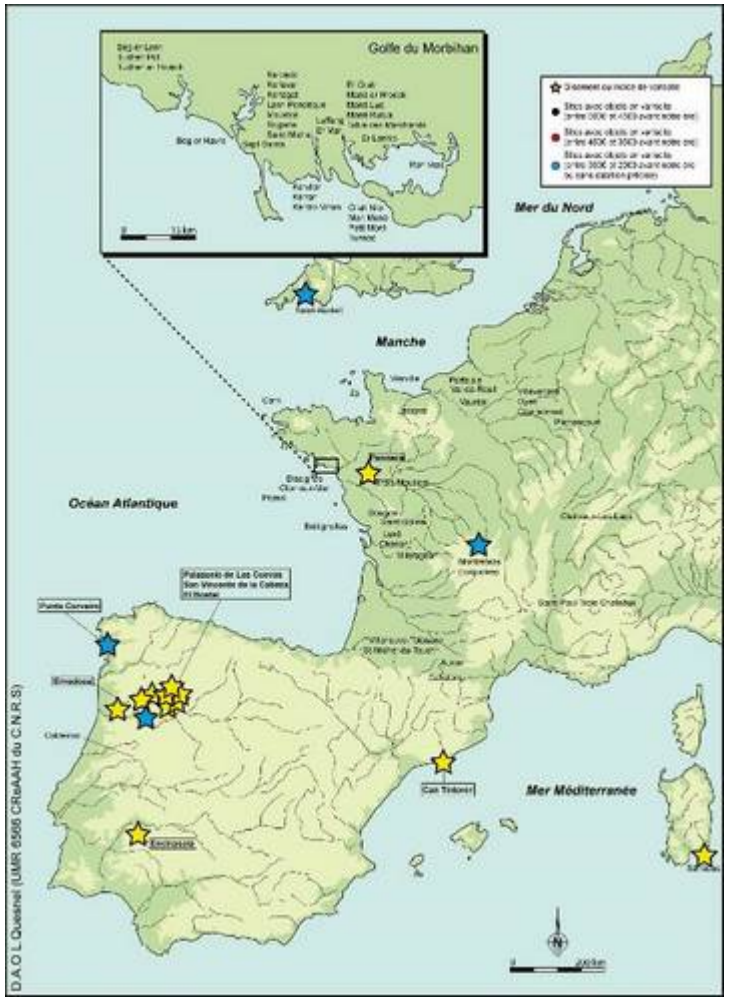
G. Querré[1], Th. Calligaro[2], S. Cassen[3], S. Domínguez-Bella[4]

[1] *CREEAAH, Université de Rennes, France*

[2] *C2RMF, Paris, France*

[3] *CREEAAH, Université de Nantes, France*

[4] *Universidad de Cadiz, España*



Various ores and deposits of variscite and turquoise are known in occidental Europe.

Exchange networks of variscite during Neolithics

G. Querré[1], Th. Calligaro[2], S. Cassen[3], S. Domínguez-Bella[4]

[1] *CREEAAH,* UMR 6566 CReAAH*, France*

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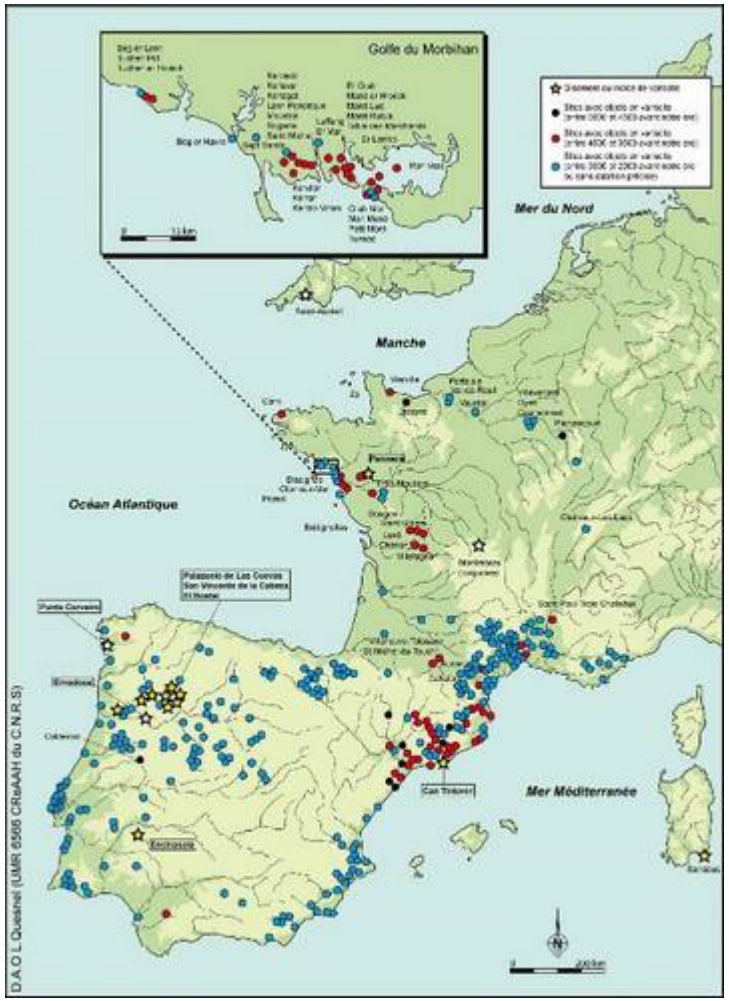
[4] *Universidad de Cadiz, España*



Prehistoric sites with jewels made from variscite.

Exchange networks of variscite during Neolithics

VARISCITE

Chemical composition: Al PO4.2H2O
system: orthorrhómbic grup of phosphate,arsenite, vanadate (XO4) ·2H2O A: Fe3 + o Al; X: P o ACE

Punto Corveiro

Palazuelo

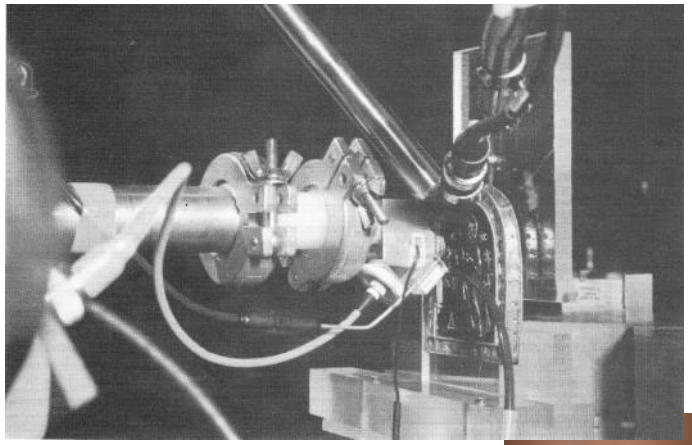
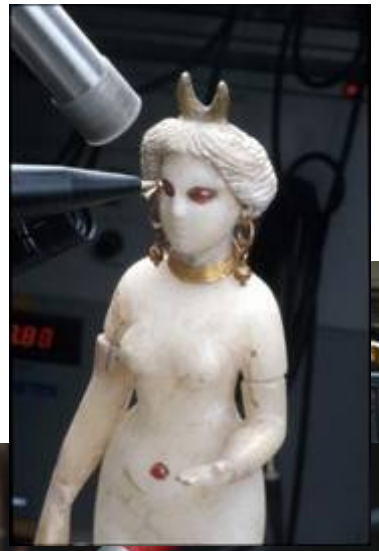
Encinasola

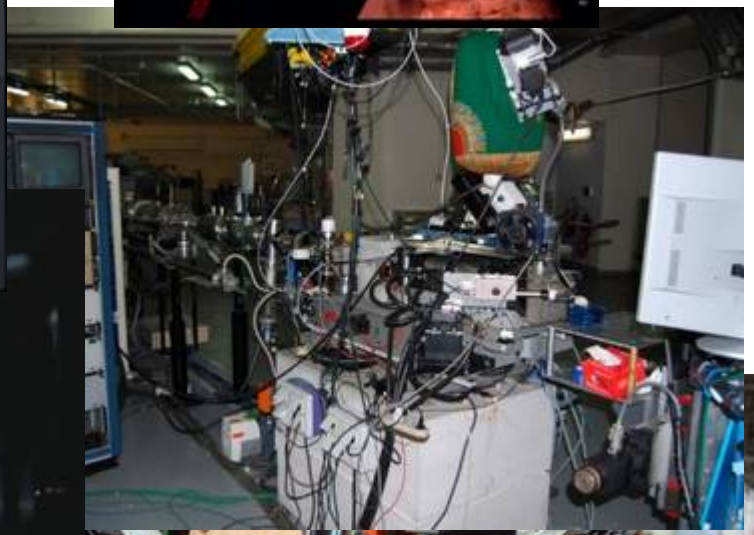
Pannecé

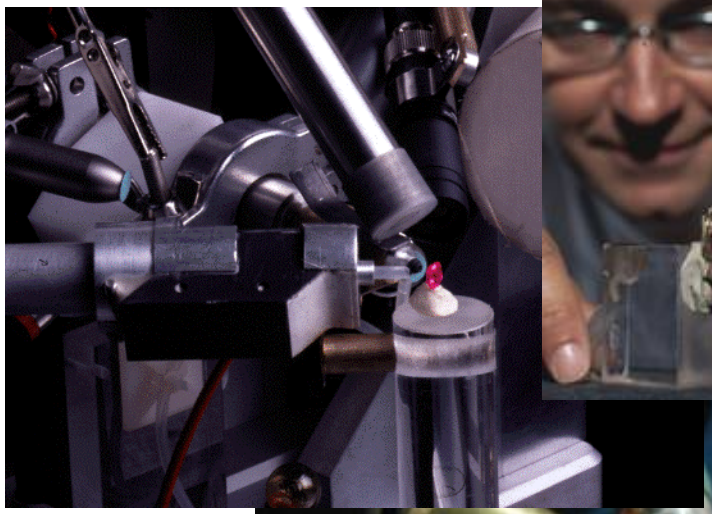
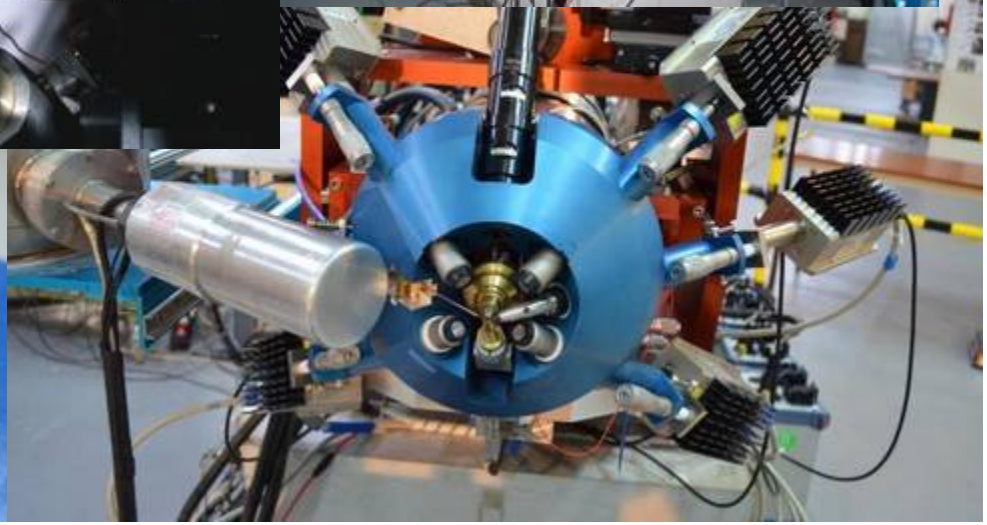
Ervedosa

Gavà

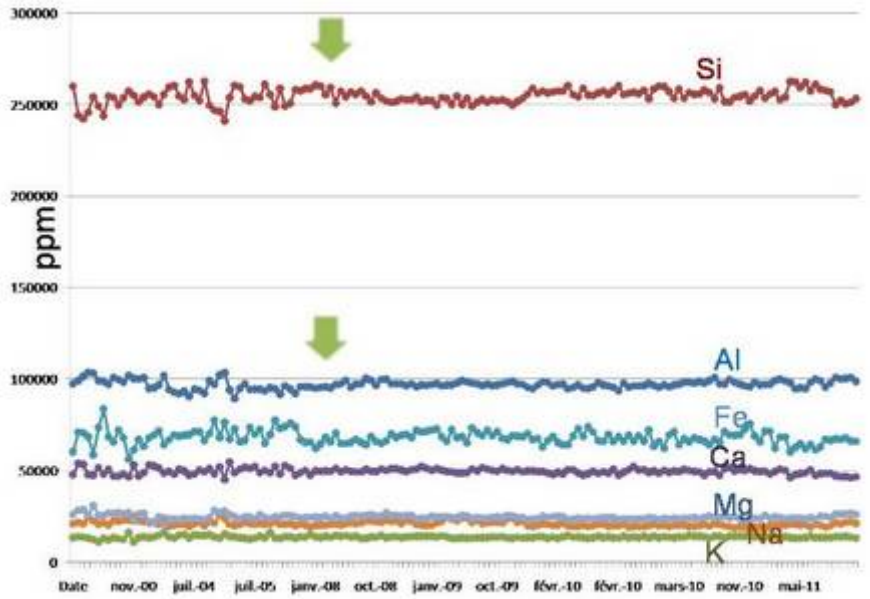
Variscite has been studied at the AGLAE for 15 years…

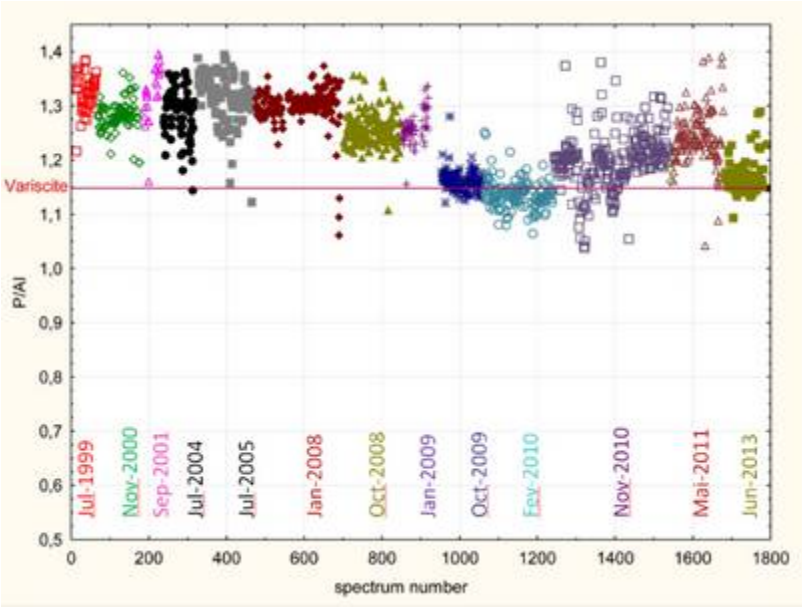


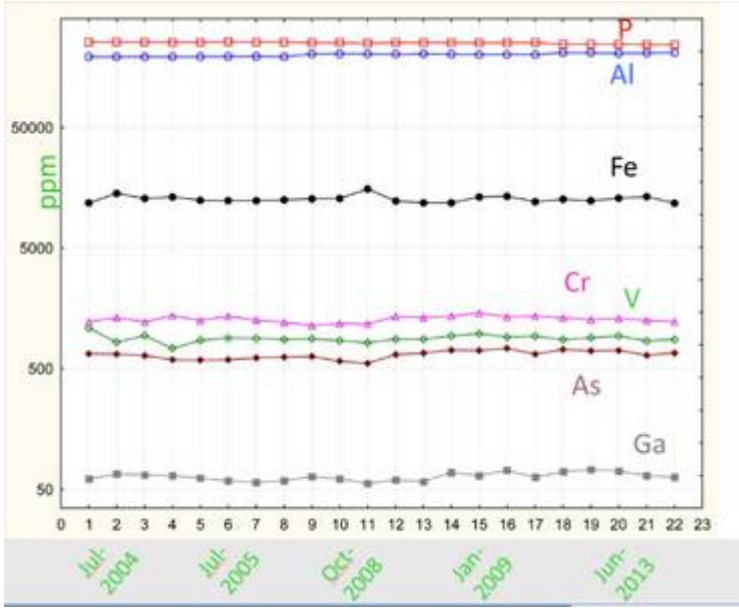

Evolution of PIXE results through time…



International standard Dr-N



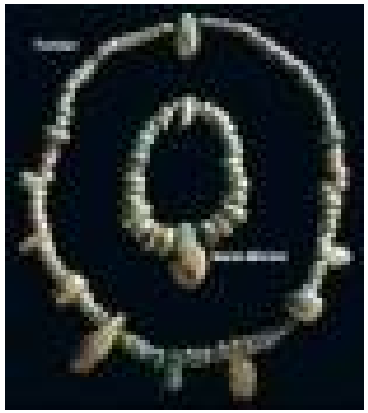
Variscite samples

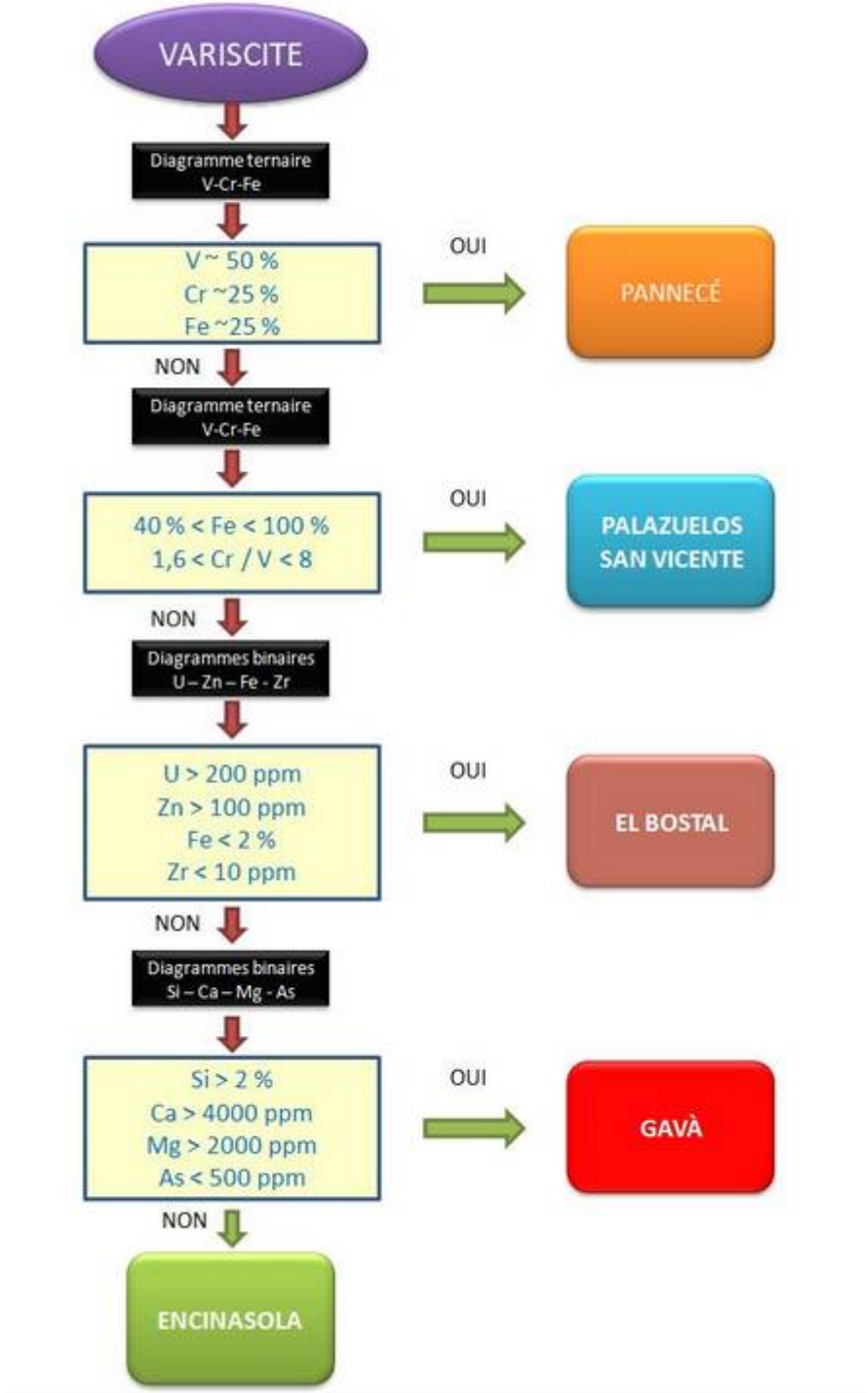


Variscite standard MeH

Development of a chemiometric model for provenance

Determination of the geochemical characteristics of each variscite ore





Evolution of the provenance of variscite found in France during Neolithic period

5.000 – 4.800 av. J.C.

4.700 – 4.300 BC.

4.300 – 4.000 BC

4.000 – 3.800 BC

3.500 – 3.300 BC

Evolution of the provenance of variscite found in France during Neolithic period

4.700 – 4.300 BC.

And if we could automate….?

4.300 – 4.000 BC

4.000 – 3.800 BC

3.500 – 3.300 BC

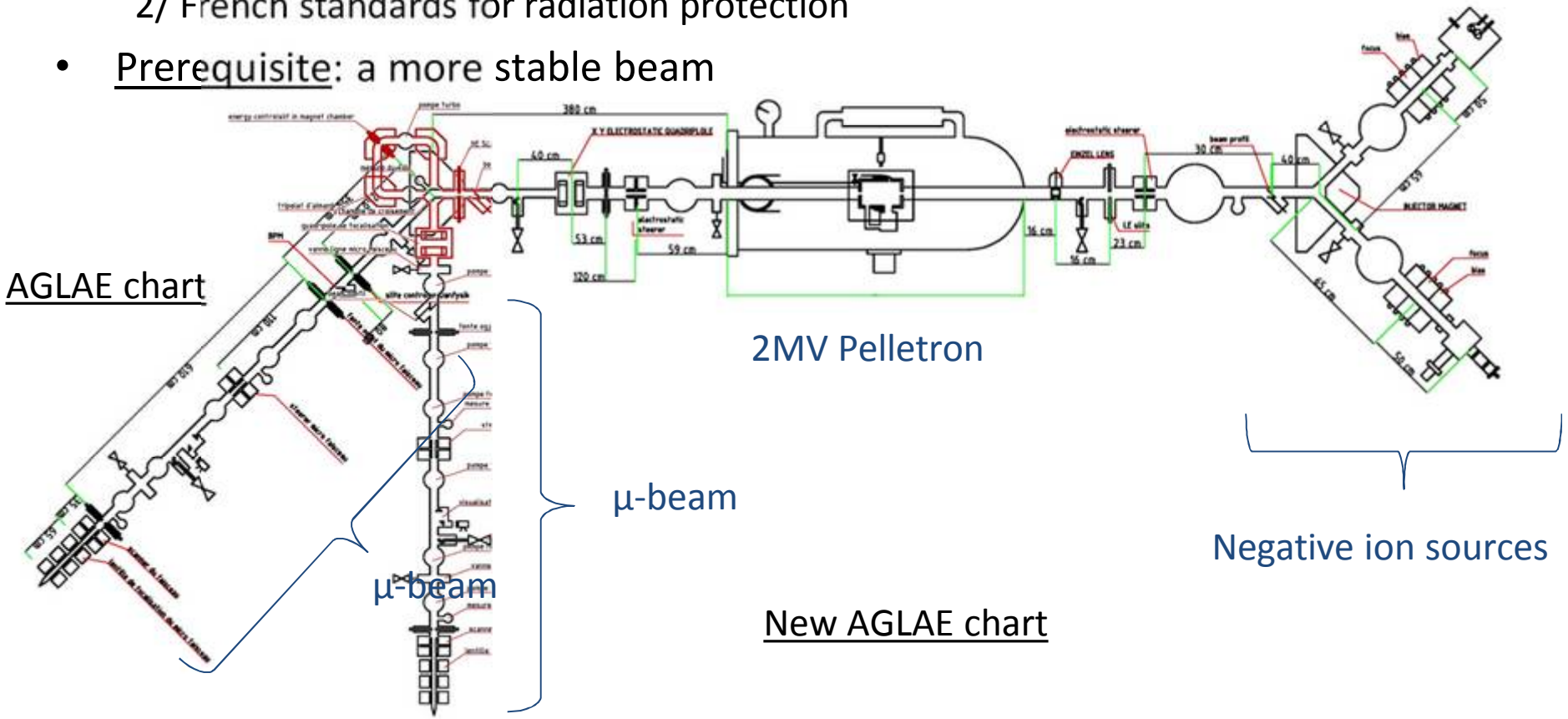
- Purposes:

  1/ More proposals → increase of beamtime

  - By day: objects from museum collections
  - By night: samples series, long mapping acquisition, etc. → remote command and control system

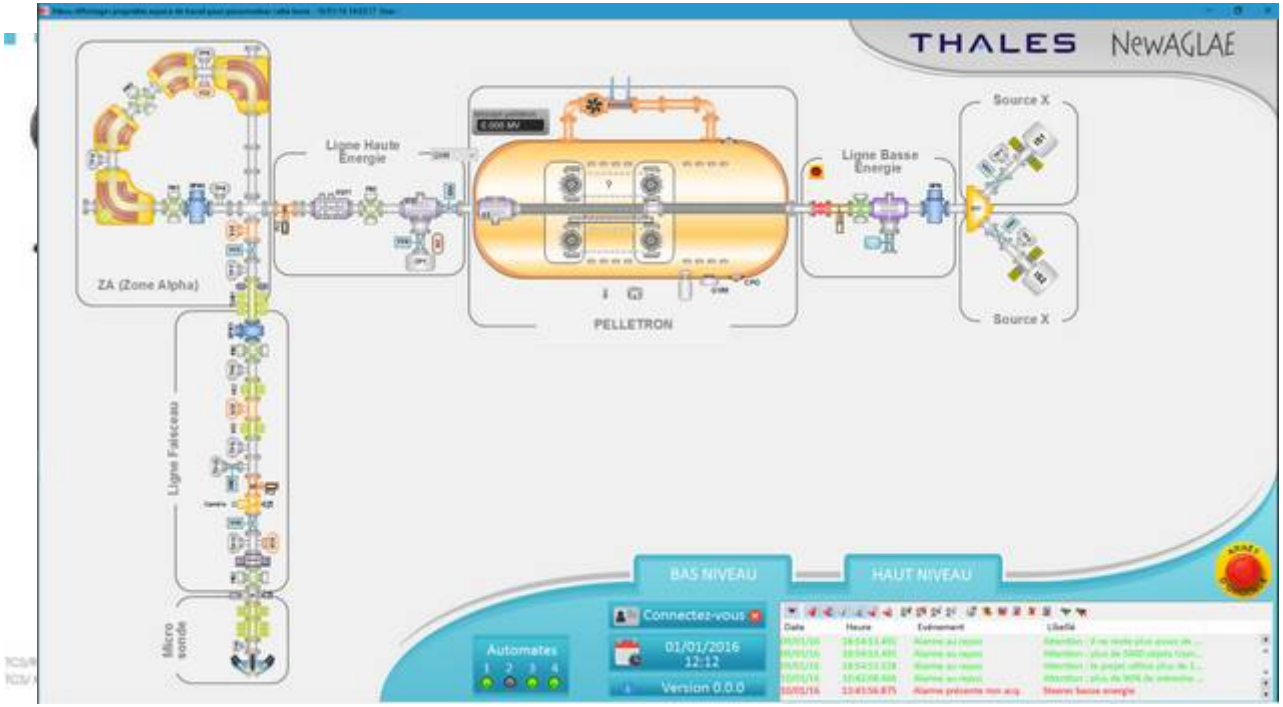
  2/ French standards for radiation protection

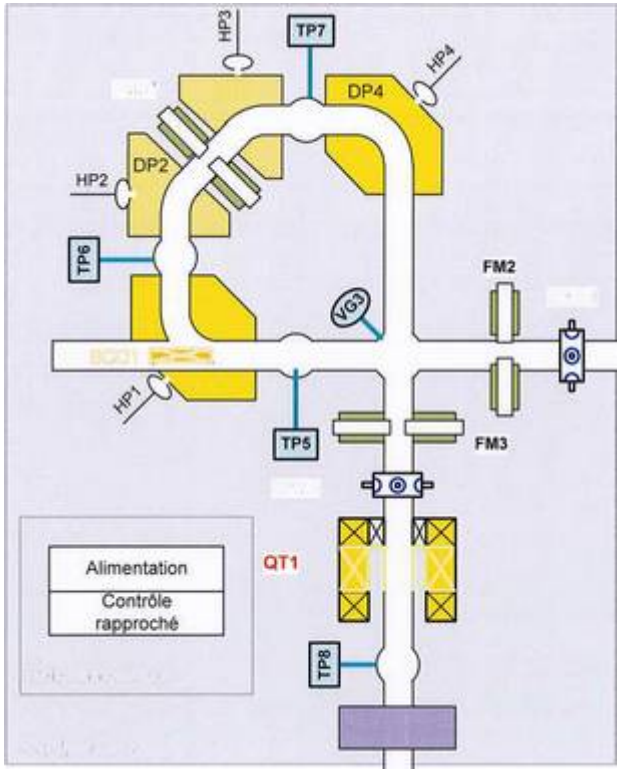
- Prerequisite: a more stable beam



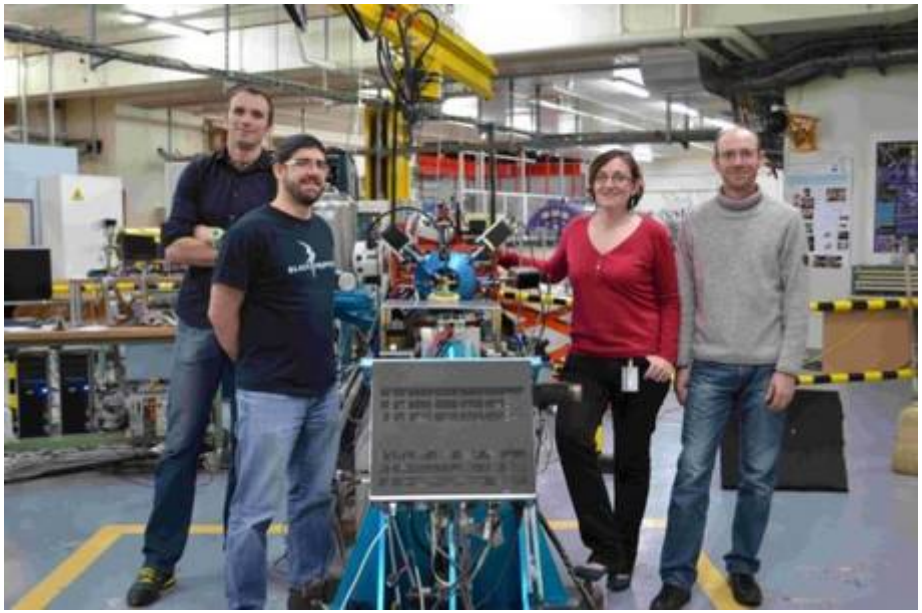
Thalès company won the bid with the following proposal:

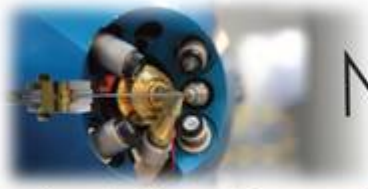
- The Terminal Voltage is controlled through a digital system directly integrated to industrial automated machine
- New devices for the alpha-zone:
  - Two 90° magnets
  - Two 45° magnets
  - A magnetic quadrupole triplet
- A custom-made HMI





NewAGLAE





NewAGLAE

	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17
Asbestos removal									
Demolition -New walls									
CAC works (ventilation ducts)									
High Voltage works									
Security automation									
Delivery									
End of snag list									
2nd restitution									
Thalès – settlement ofNew AGLAE									
Final tests withNew AGLAE									
Thalès – delivery of New AGLAE									

New AGLAE Opening to users

Aknowledgement

- The AGLAE team: Quentin Lemasson, Brice Moignard & Laurent Pichon
- Thomas Calligaro, Isabelle Biron, Rolland Février, Marie Radepont, Sandrine Pagès, Brigitte Bourgeois
- Ina Reiche
- Laurianne Robinet
- Claudine Loisel
- Julien Colaux
- Guirec Querré

Funding

- ANR-10-EQPX-22
- Ville de Paris
- Rennes Metropole

Thank you for your attention

Every science begins as philosophy and ends as art…

Will Durant (1885-1981)