

The Cyclotron Arronax for fundamental and applied research with light ion beams < 70 MeV

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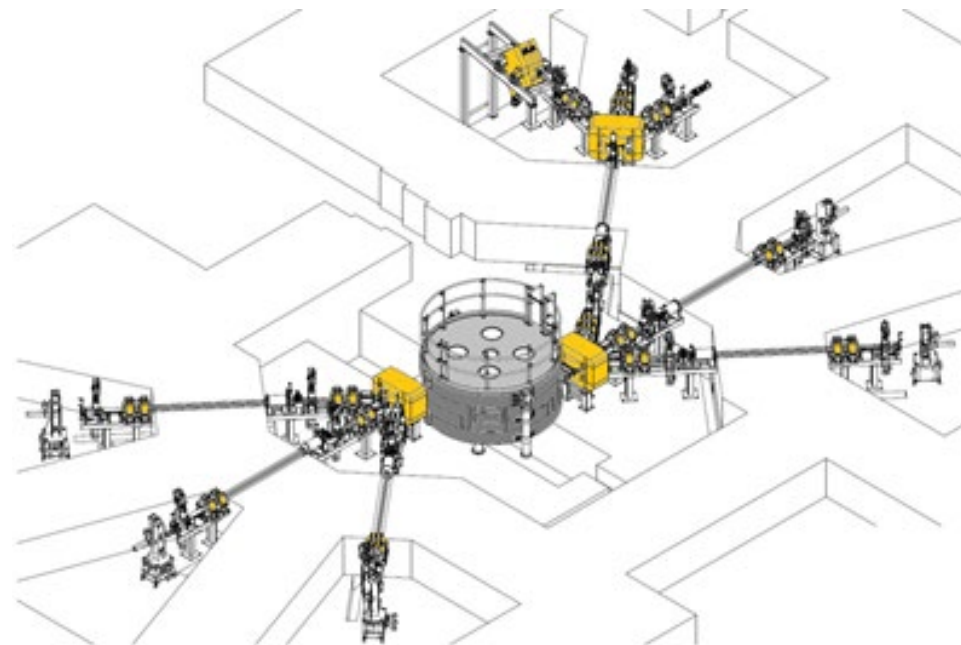
The cyclotron Arronax (Nantes, France)

Extrated Beam	Accelerated Particle	Energy (MeV)	Intensity (μA)	Dual Beam
Proton	H^-	30 to 70	≤ 350	Yes
	HH^+	17	≤ 50	No
Deuteron	D^-	15-35	≤ 50	Yes
Alpha	He^{2+}	68	≤ 70	No



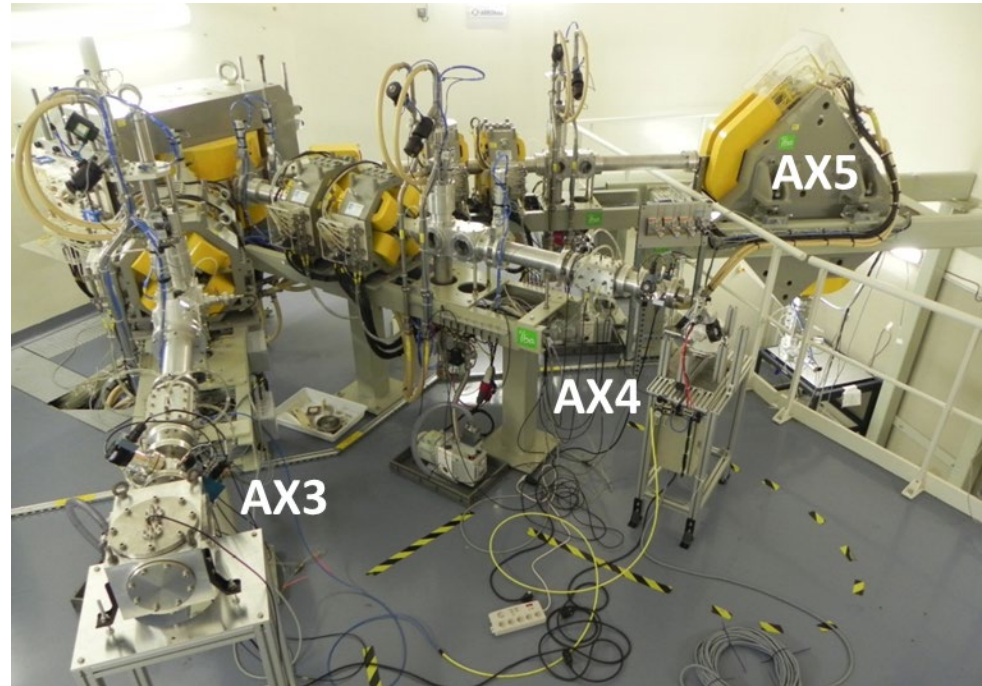
3 main fields of investigations

- + **Radionuclide production**
for nuclear medicine
(Oncology, Cardiology and Neurology)
- + **Inert and living matter under irradiation**
Nuclear Physics, Radiolysis,
Radiobiology, Ion beam Analysis
- + **Training**

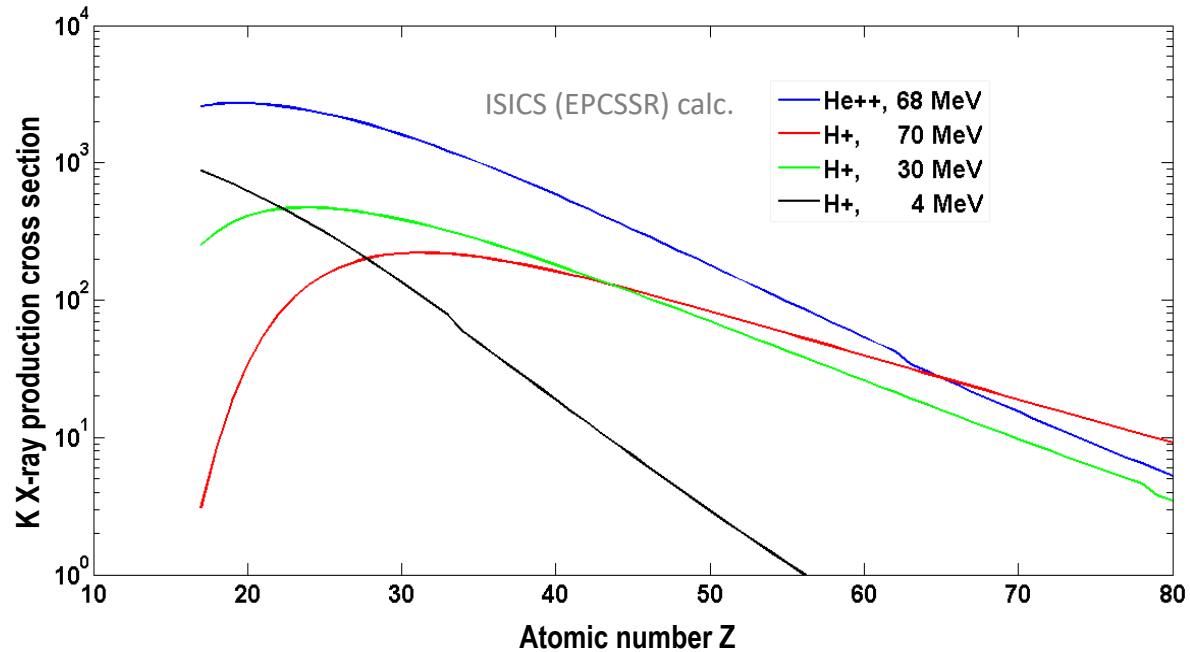
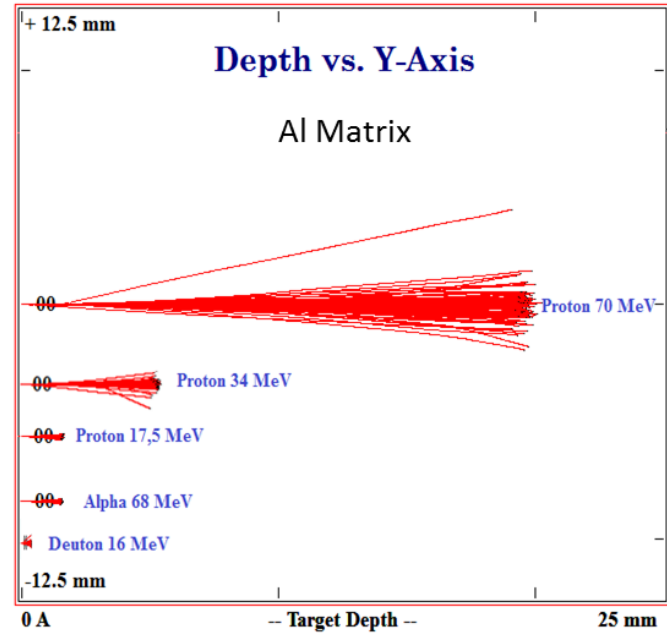
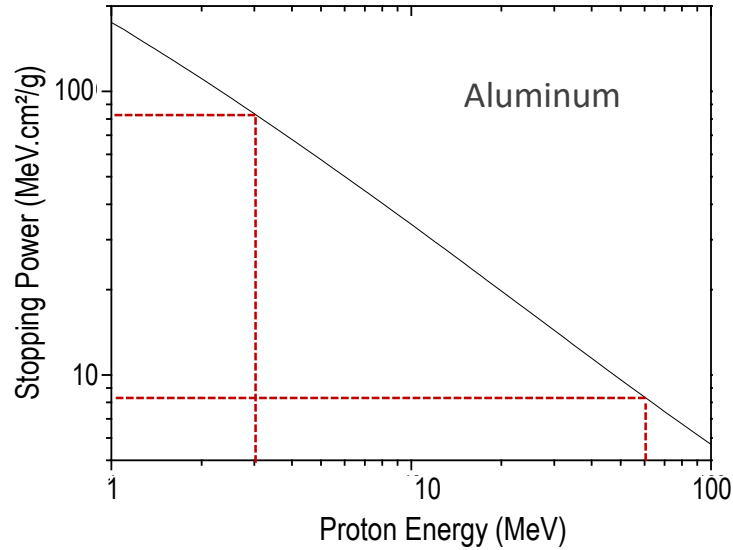


Inert and living matter under irradiation

- Radionuclide production cross section measurements
- Radiolysis studies
- **High Energy PIXE**
- Radiobiology studies



High energy PIXE ?



High energy PIXE

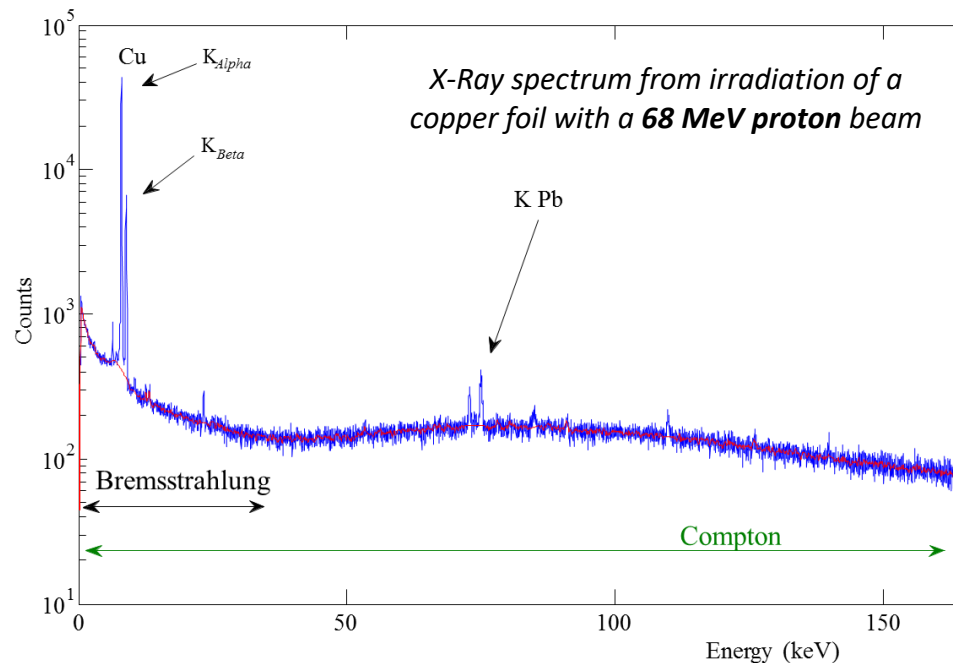
- **Pioneers:** Durocher et al. (1988), Pineda et al. (1990), Denker et al. (1999)

- **Advantages**

- + K X-rays: high E & σ
- + particle range
- + less damage
(if beam exits the sample)

- **Drawbacks**

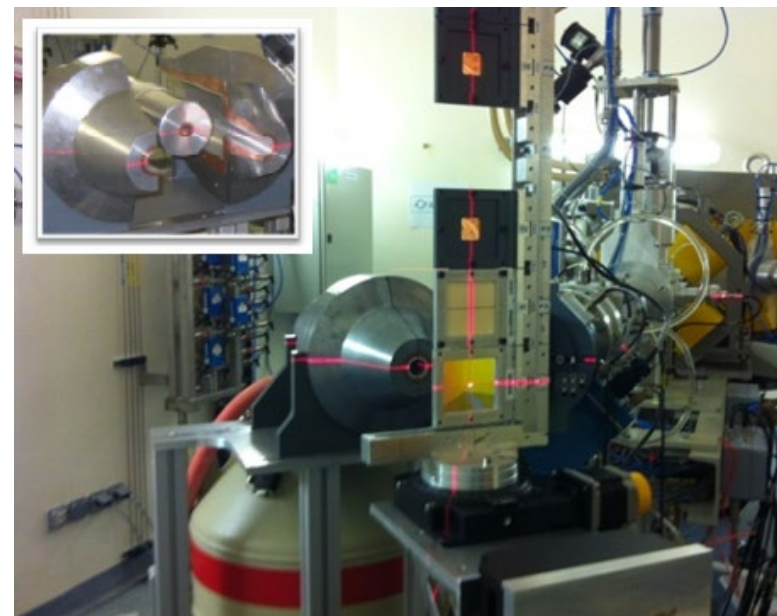
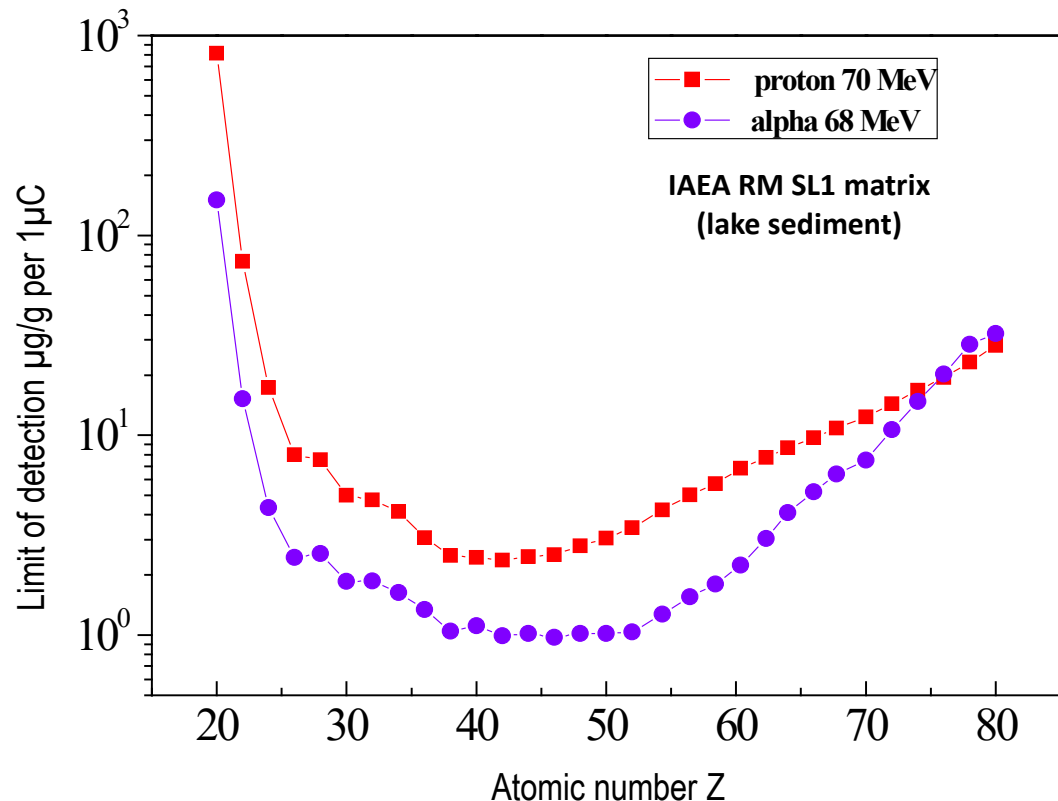
- + Nuclear reactions
- + Background (bremß + Compton)
- + Availability of facilities



HE PIXE at Arronax – limit of detection

D. Ragheb et al., J Radioanal Nucl Chem (2014) 302:895-901

LOD: ~ 1 µg/g from Z = 30 to 60

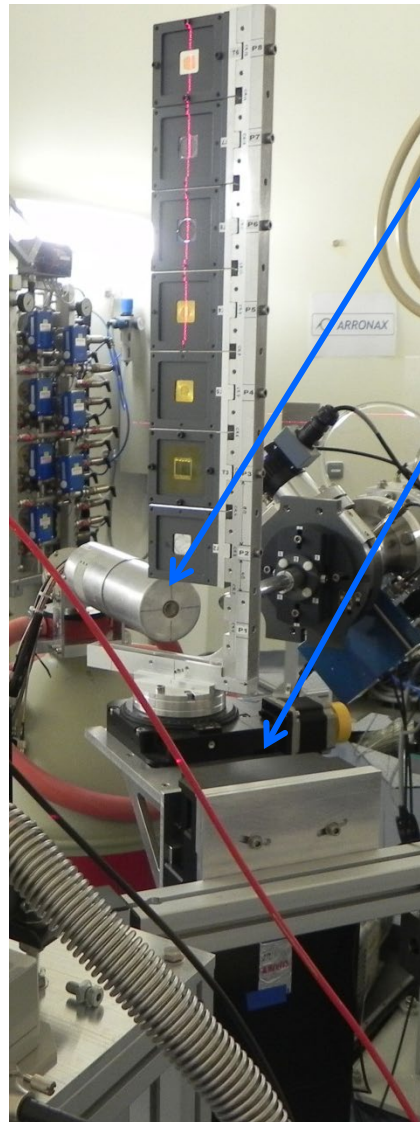


Distance target –LEGe detector: 16 cm

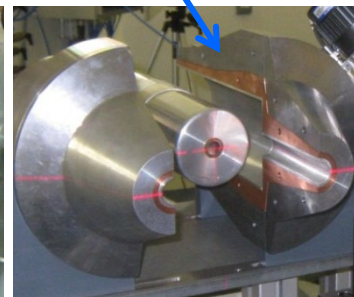
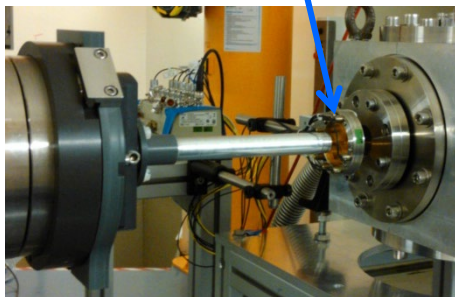
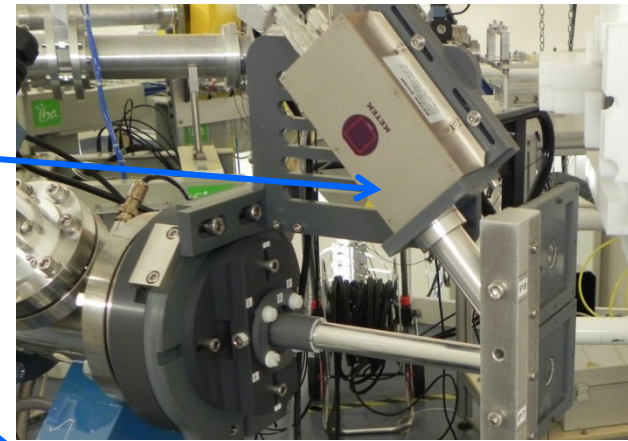
$$Ld [\mu\text{g/g}] = \frac{3\sqrt{NB} \cdot M_Z \cdot \frac{\mu}{\rho} \Big|_Z}{N_{av} \cdot N_p \cdot \sigma_{XK} \cdot \varepsilon_{XK} \cdot T_{abs} \cdot \cos\theta \cdot b \cdot \left(1 - e^{-\frac{\mu}{\rho} \Big|_{XK} \cdot \frac{\rho \cdot e}{\cos\theta}}\right)}$$

cf. J.L.Campbell et al. « Particle Induced X-ray Emission Spectrometry », John Wiley and sons, 1995

High energy PIXE at Arronax – set-up



- LEGe detector (X-rays)
- SDD detector (X-Rays)
- Ge detector (gamma rays)
- Automatized Sample holder
- shieldings
- Ionization chambers + electrometer + Faraday cup

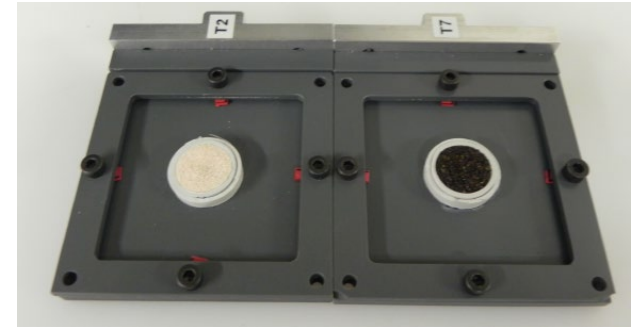
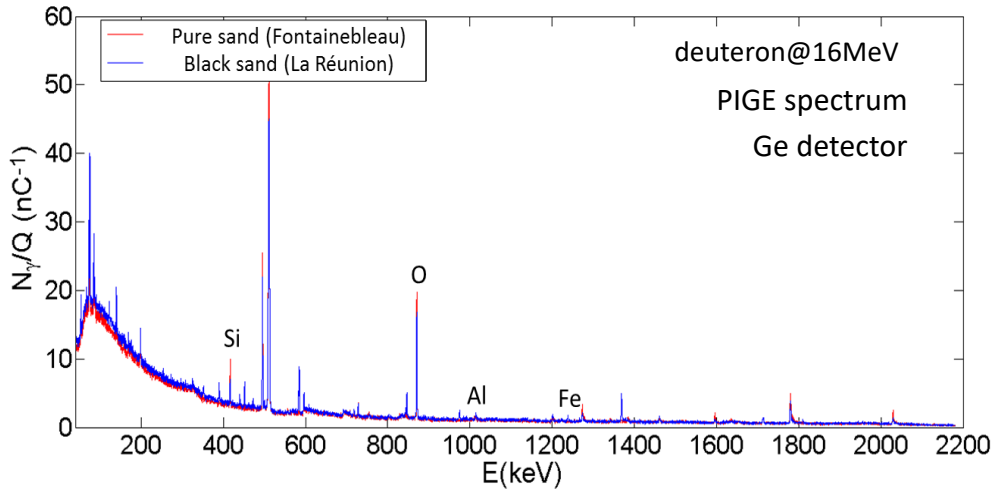


High energy PIXE/PIGE at Arronax

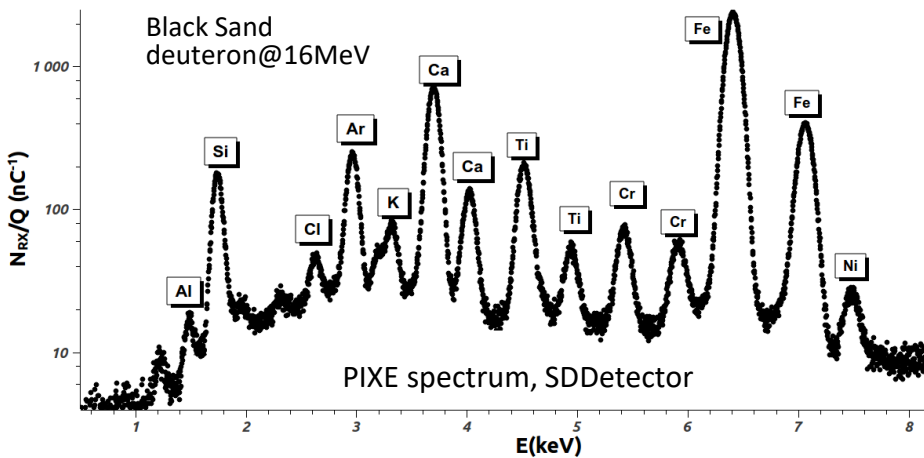
A. Subercaze et al., 7ème Colloque Interdisciplinaire en Instrumentation, 2016 (à paraître)

- Light element detection and quantification : SDD + PIGE
- Ex: volcanic sand analysis

(Pure Sand from Fontainebleau as reference)



Iterative calculation ← Si, O input

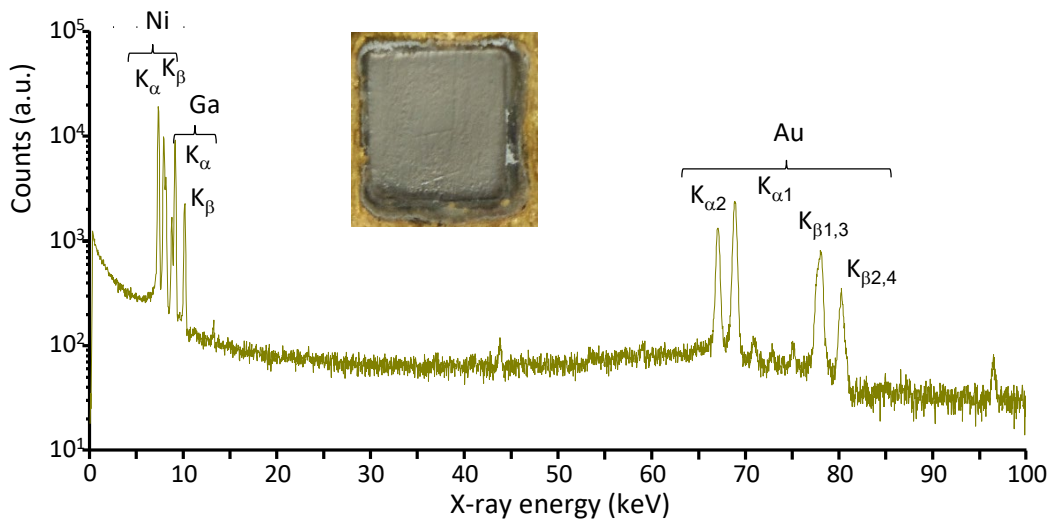


PIXE		PIGE	
Élément	$a_k(\%)$	Élément	$a_k(\%)$
O	$45,8 \pm 5,5$	O	$43 \pm 0,9$
Al	$11,4 \pm 1,4$	-	-
Si	$22,3 \pm 2,7$	Si	$21 \pm 1,3$
Ca	$5,75 \pm 0,69$	-	-
Ti	$1,60 \pm 0,2$	-	-
Cr	$0,41 \pm 0,05$	-	-
Mn	$0,29 \pm 0,03$	-	-
Fe	$11,9 \pm 1,4$	-	-
Ni	$0,16 \pm 0,02$	-	-

Thick sample analysis

▪ Ex: Ni/Ga alloy electrodeposited on gold carrier

- + the mass fraction and the density of the Ni/Ga alloy are calculated through an iterative process based on the K X-ray intensities of Ni and Ga.
- + the thickness of the alloy is then determined thanks to the attenuation of the K X-ray coming from the gold carrier.



X-Ray spectrum from irradiation of a Ni/Ga alloy (on gold substrate) target with a 70 MeV proton beam (LEGe detector at 25 cm).

+ Mass fraction (wt%):

	HE PIXE	ICP-AES	SEM/EDX
Ni	34.81 ± 0.7	34.15 ± 0.4	34.04 ± 0.3
Ga	65.19 ± 0.8	65.85 ± 1.6	65.96 ± 1.3

+ thickness: **317 ± 32 μm**

+ density: **6.9 g.cm⁻³**

Multilayer analysis

cf. A. SUBERCAZE presentation, Monday, April 3.

C. Koumeir et al., AIP Conf. Proc. 1412, pp. 105-112

D. Ragheb et al., J Radioanal Nucl Chem (2014) 302:895-901

A. Subercaze et al., ECAART12 (2016), NIMB, in press

Target 1		Target 2	
Element	Position	Element	Position
Titanium	1	Aluminium	1
Silver	2	Titanium	2
Gold	3	Aluminium	3
-	-	Silver	4

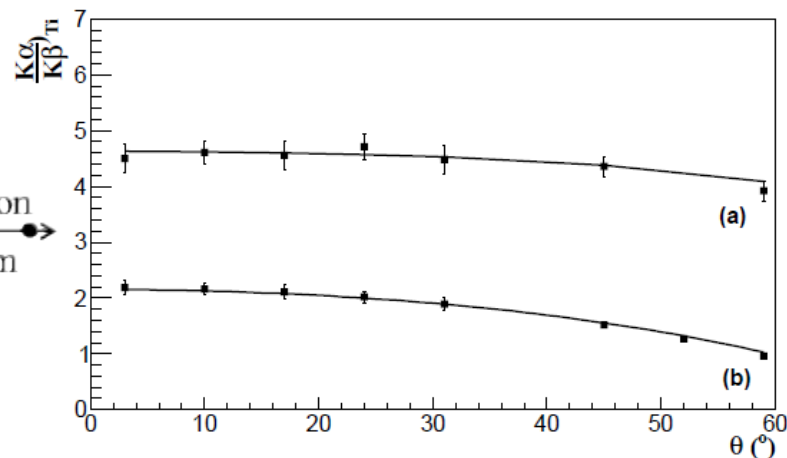
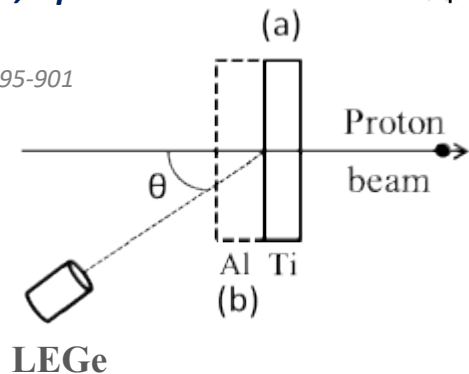


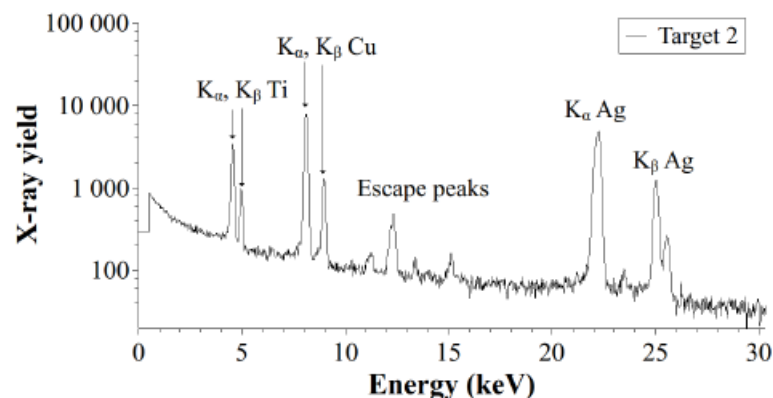
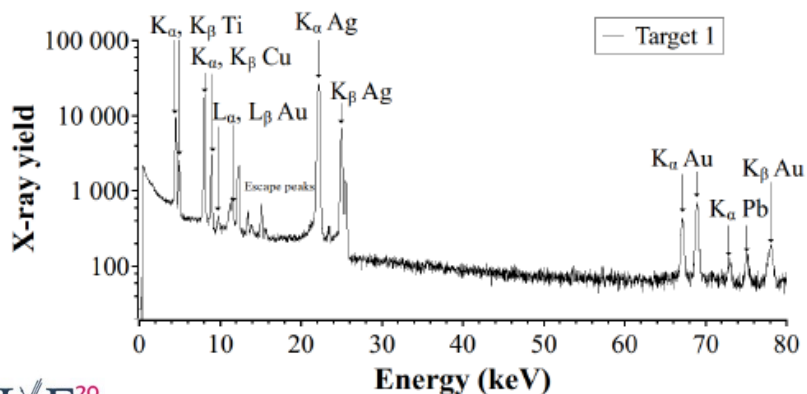
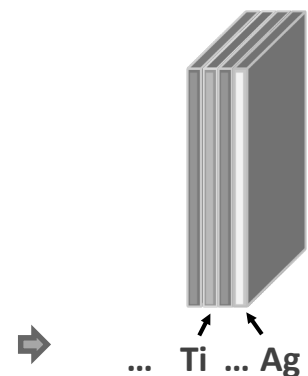
Table 3: Results of the multi-layers analysis using detection angles of 3° and 45°

Target 1

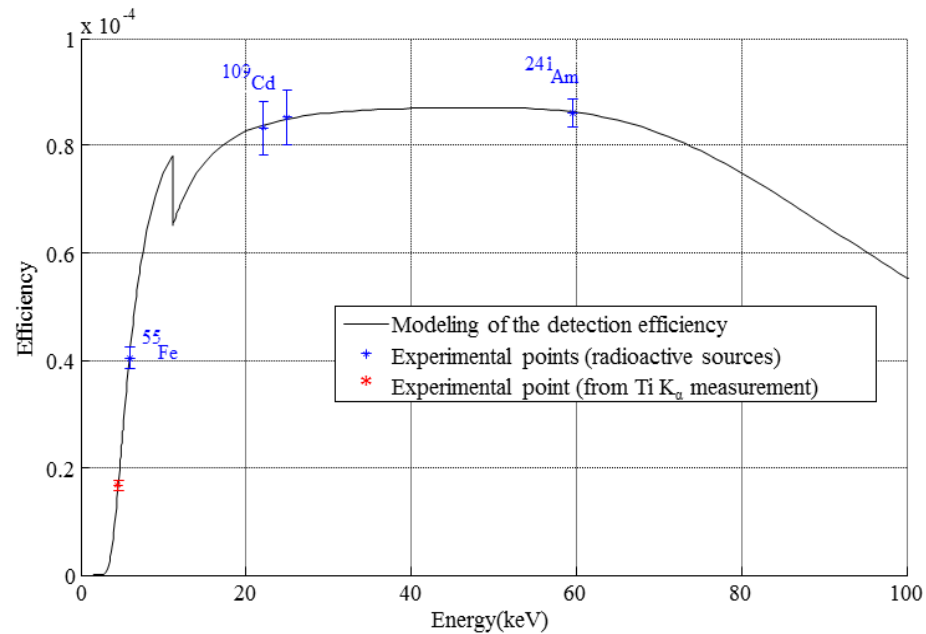
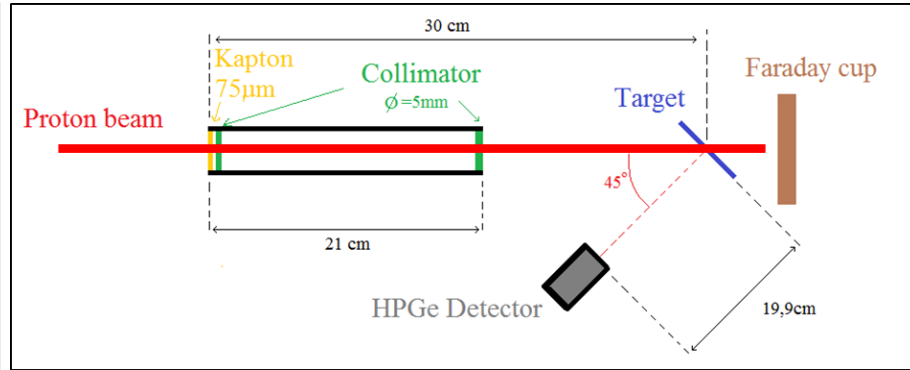
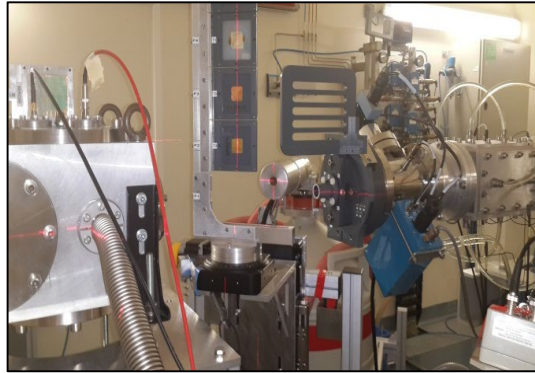
Element	$(\Delta\mu \cdot d)'$	Calculated thickness (μm)	Calibrated thickness (μm)
Titanium	92 ± 6	10.40 ± 0.62	10.03 ± 0.02
Silver	860 ± 40	25.82 ± 1.29	24.87 ± 0.04
Gold	12200 ± 600	9.11 ± 0.59	10.74 ± 0.02

Target 2

Element	$(\Delta\mu \cdot d)'$	Calculated thickness (μm)	Calibrated thickness (μm)
Titanium	664 ± 62	9.25 ± 0.93	10.06 ± 0.02
Silver	4168 ± 348	10.33 ± 0.21	10.32 ± 0.02



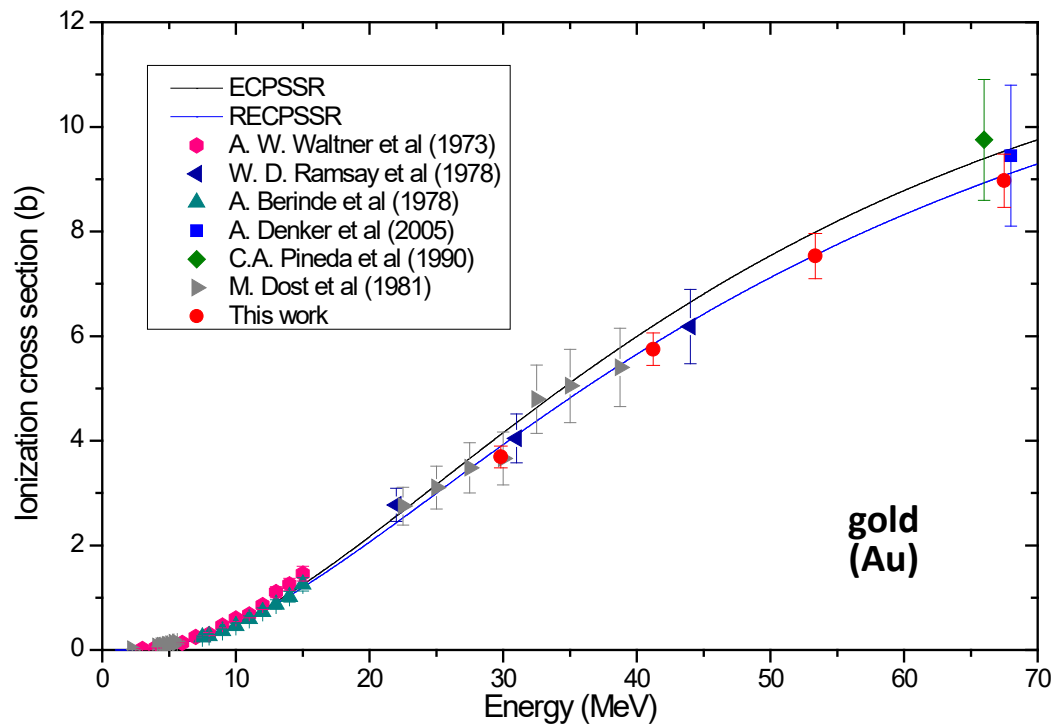
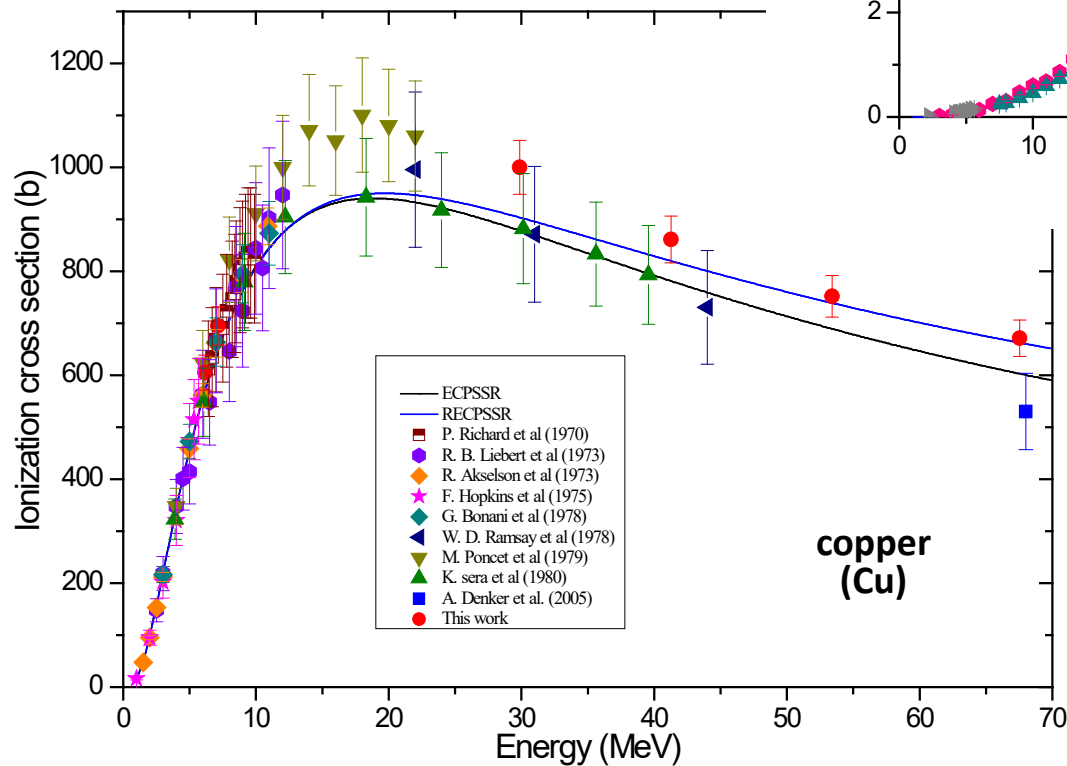
K-shell ionization cross sections measurement



K-shell ionization cross sections measurement

Cf. M. HAZIM presentation, Monday, April 3.

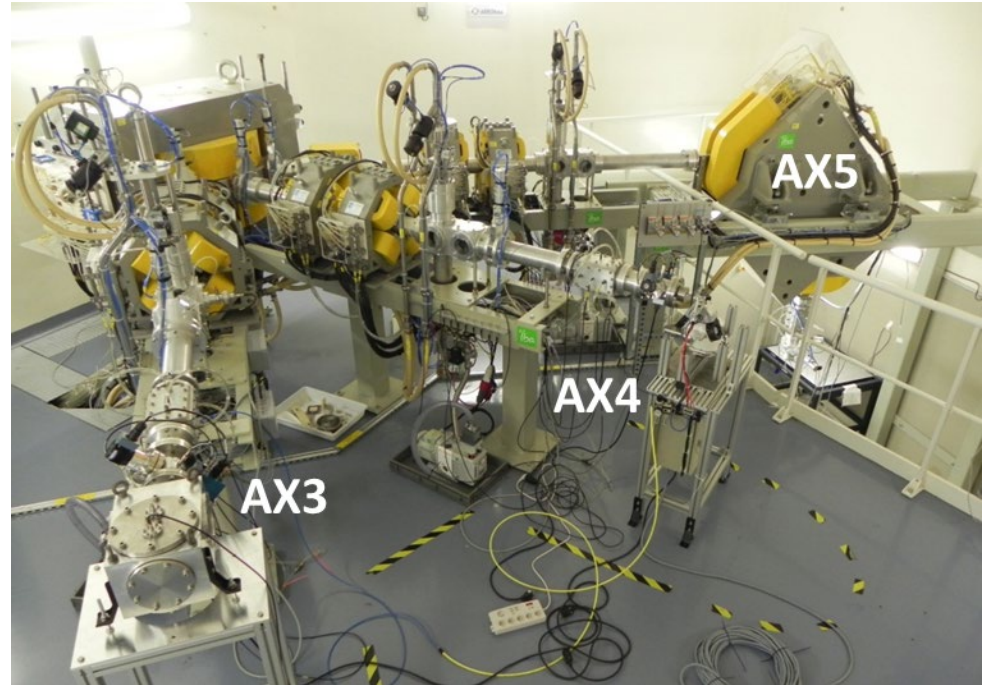
Target thicknesses: 10 μ m



- + RECPSSR well reproduces data at low and high energies
- + ... but not near the maximum of ionization cross section
- + Possible discrepancy with some existing experimental points ...

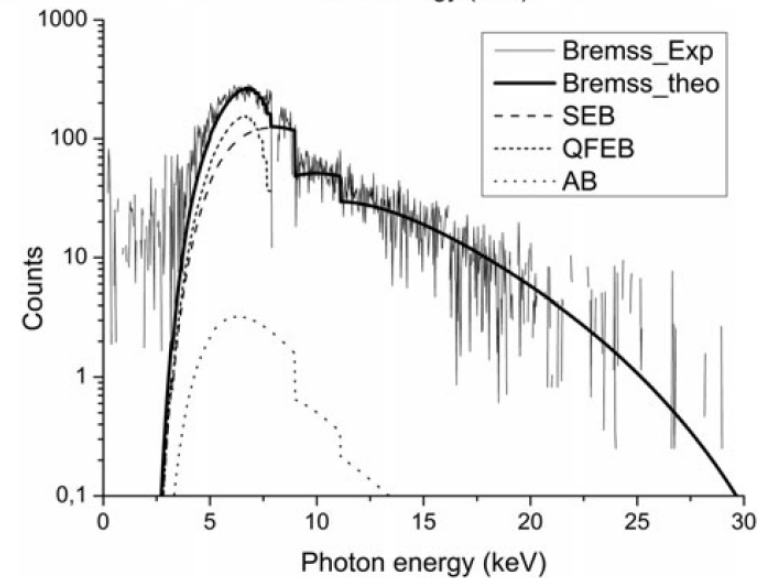
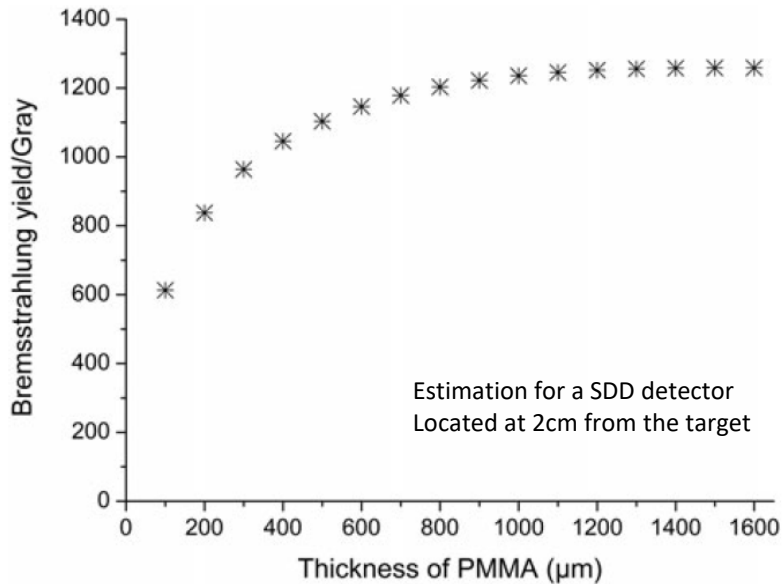
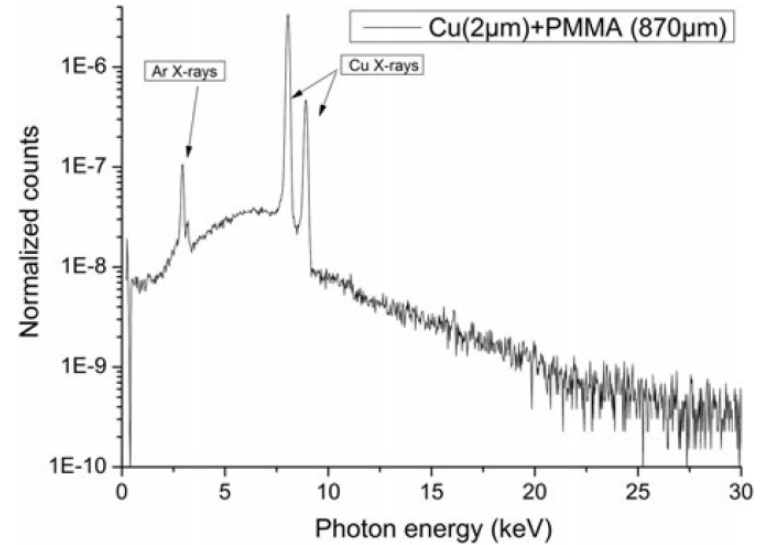
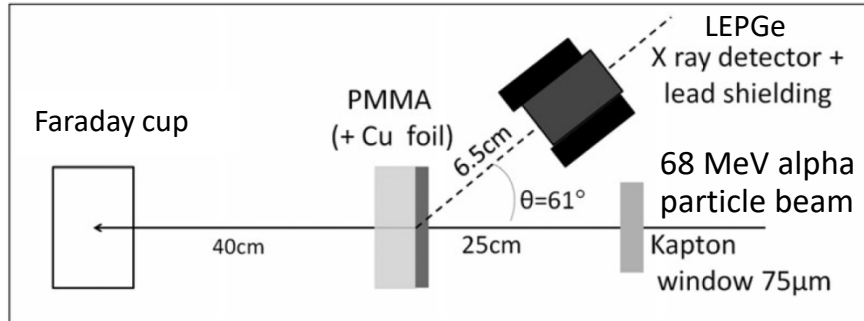
Inert and living matter under irradiation

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- High Energy PIXE
- **Radiobiology studies**



Bremsstrahlung as monitoring tool for radiobiology experiments

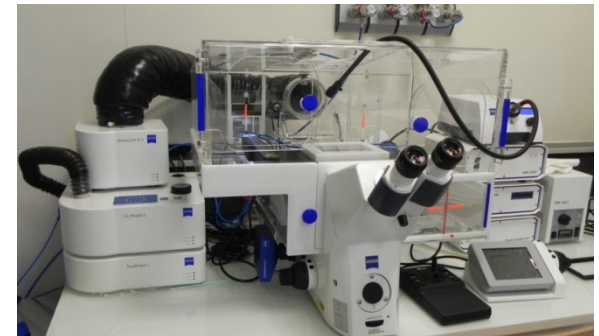
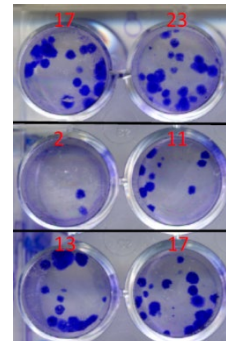
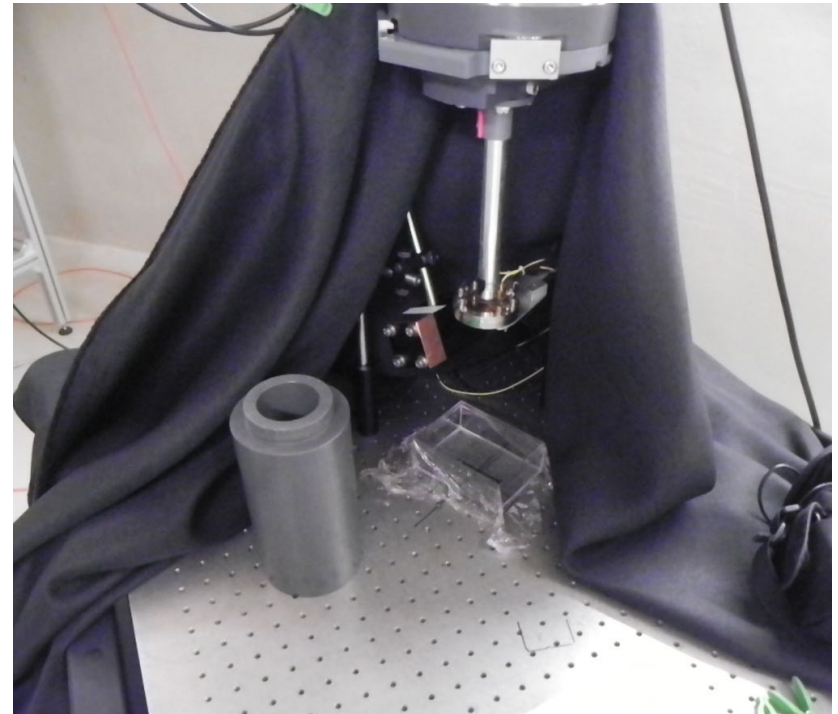
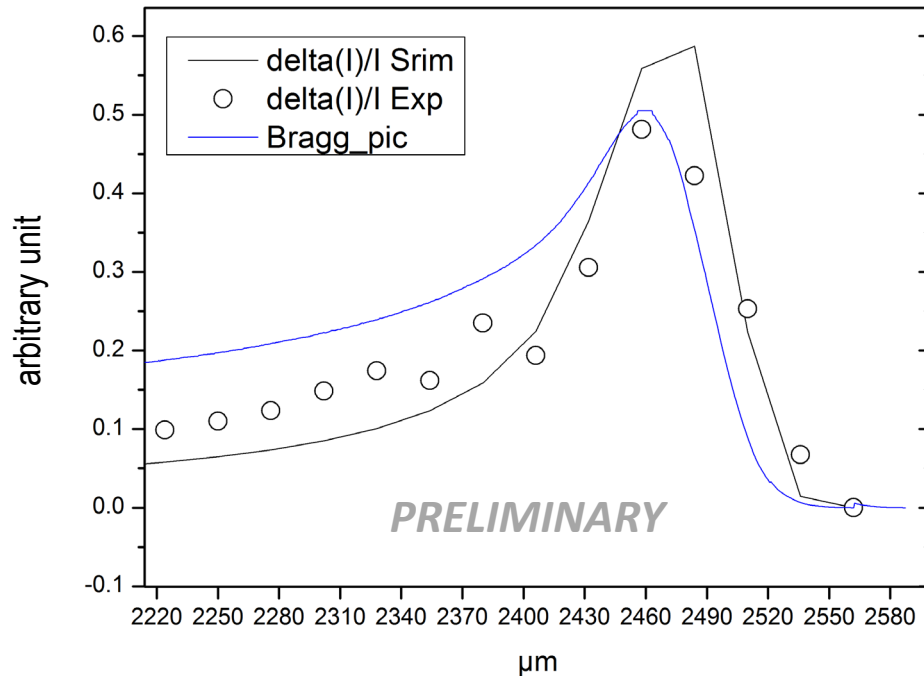
L. Schwob et al., Rad. Prot. Dos. 166 (2015) 257-260



Bremsstrahlung modeling from K. Ishii, Rad. Phys. And Chem. 75 (2006)

Bragg Peak detection

- cell culture irradiation
- 68 MeV alpha particle beam
- Range ~ 2.5mm (water eq.)
- Bremsstrahlung signal saturates
- → Luminescence component (UV/vis.)
PMT counting (current int.)



Conclusions & Perspectives

■ High Energy PIXE

- + PIXE/PIGE Platform well suited to thick and multilayer samples, and especially to quantification of medium and heavy elements in light matrix
- + Benefits of the various available beams at Arronax (p, d, He)
- + X-ray production cross section measurements (experimental cross-comparison)
- + « Real » multilayer samples (paintings?)
- + Monitoring of Metallic nanoparticle (radiosensitization in hadrontherapy)

■ Radiobiology

- + Development of on-line non intrusive dosimetry tools
- + Monitoring of deposited dose during cell irradiation (Bragg peak/plateau)

Thank you for your attention

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