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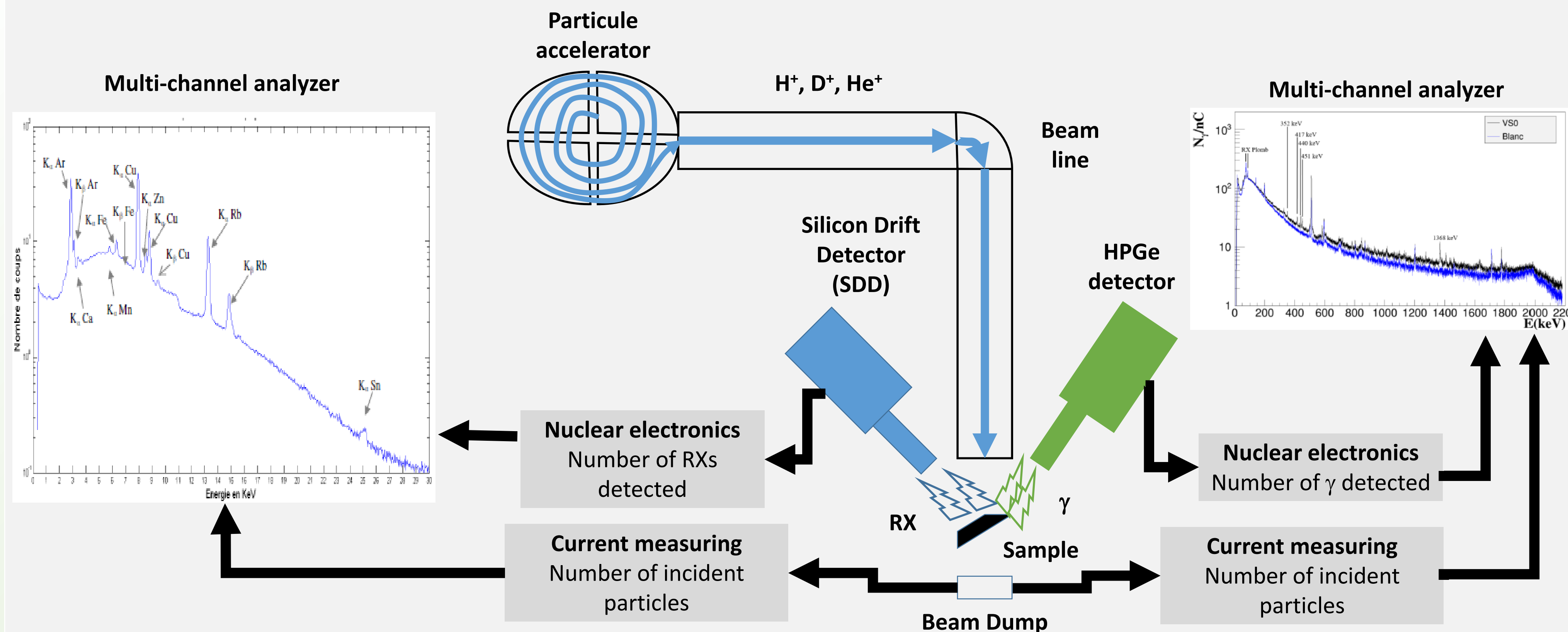
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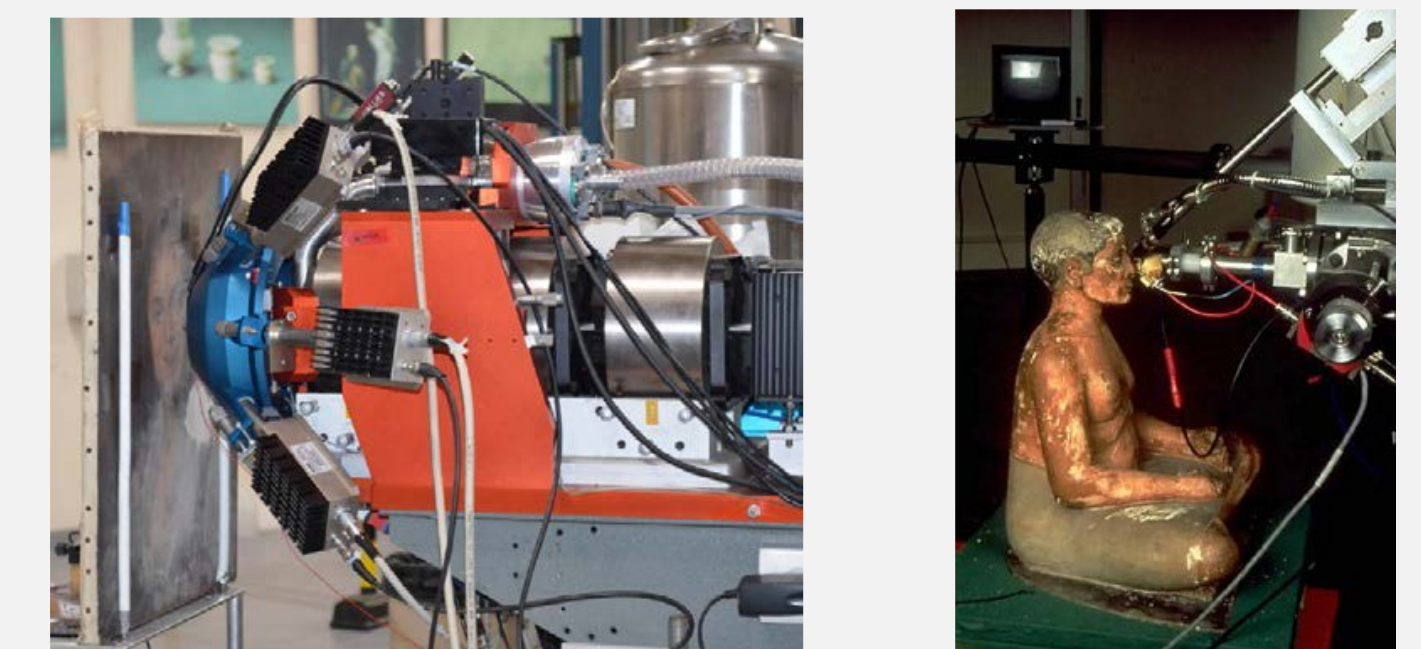
Non-destructive analysis: PIXE with high-energy ion beam at the ARRONAX cyclotron

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Presentation of the PIXE/PIGE method:



Some PIXE applications:



AGLAE – C2RMF – Musée du Louvre

- Art and archaeology
- Geology
- Biology
- Environment
- ...



APXS Project - NASA

Development of the high-energy PIXE method using the ARRONAX cyclotron

It is possible to determine the concentration of elements present in a sample, using the number of X-rays detected in the spectrum for each element N_X^Z .

N_p : Number of incident particles
 N^Z : Number of target atoms per unit volume
 ω : fluorescence yield of the considered layer
 b : relative intensity of the ray X
 ε : detection efficiency, $\varepsilon = \varepsilon_i \times \frac{\Omega}{4\pi}$; Ω : solid angle
 σ_i : Ionization cross section (constant for a thin target)
 μ_c : linear attenuation coefficient of the target
 E_i : initial particle energy; E_f : final particle energy

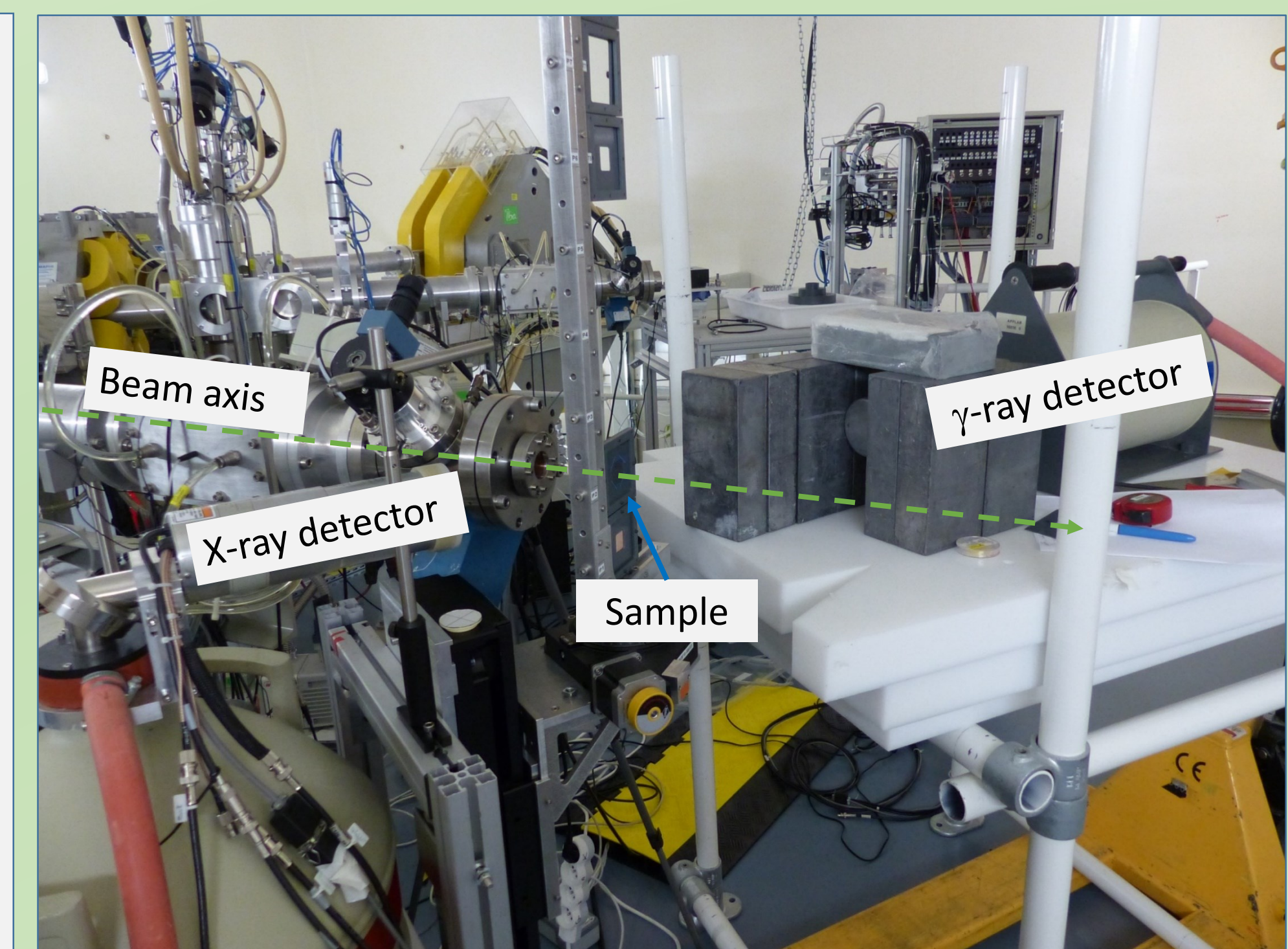
$$N_X^Z = N_p N^Z \omega b \varepsilon \sum_{E_f}^{E_i} \sigma_i(E) e^{-\mu_c \xi} \left(\frac{dE}{dx} \right)^{-1} dE$$

$$\xi = \frac{\cos \phi}{\cos \theta} \int_{E_f}^{E_i} \left(\frac{dE'}{dx} \right)^{-1} dE'$$

ϕ : angle of incidence of the beam
 θ : angle between detector and target normal

For quantitative measurement, the following 3 factors are to be measured: N_p , ε and σ_i

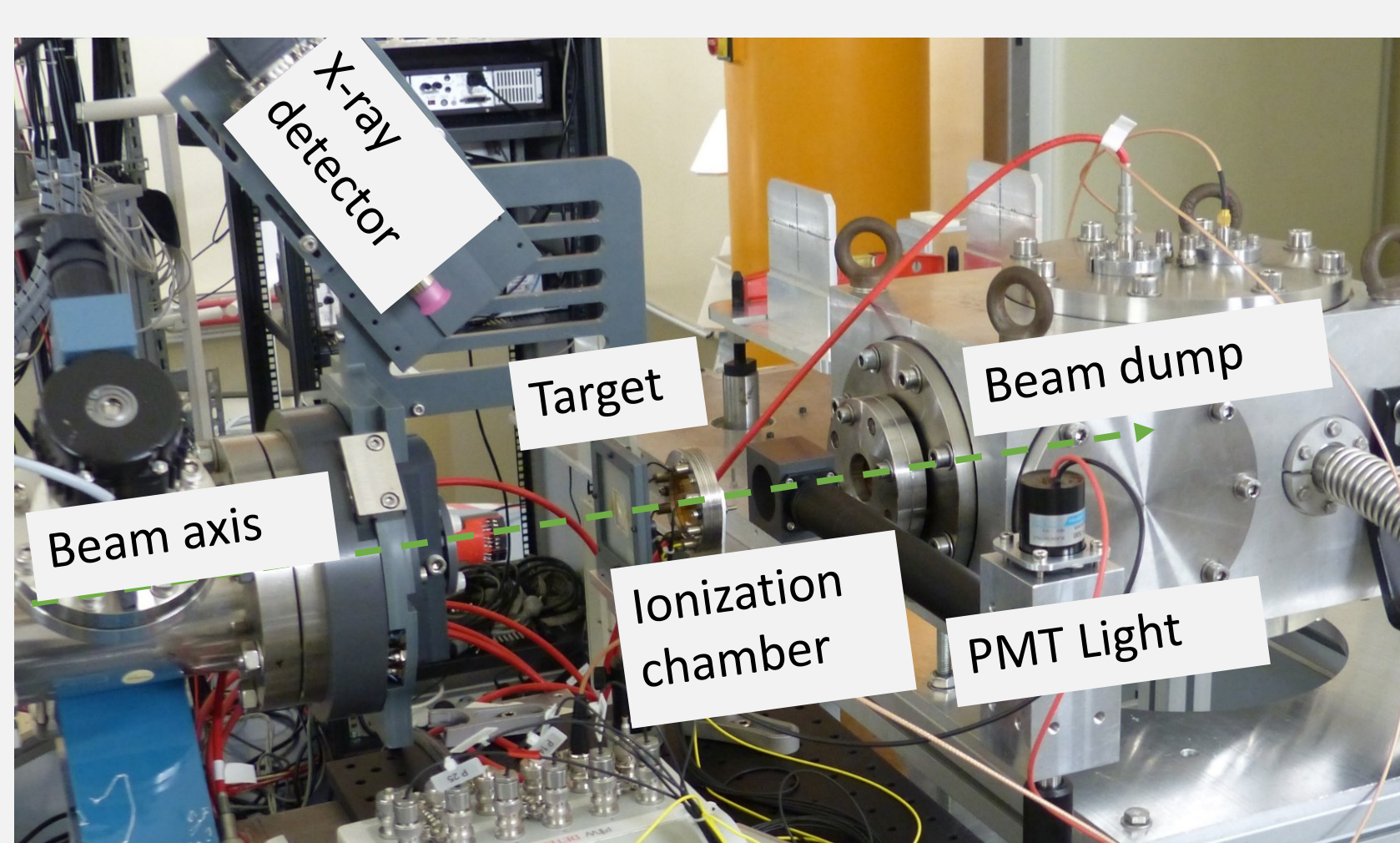
The combined use of the PIGE method, detection of γ emission, allows quantification for light elements ($Z < 11$).



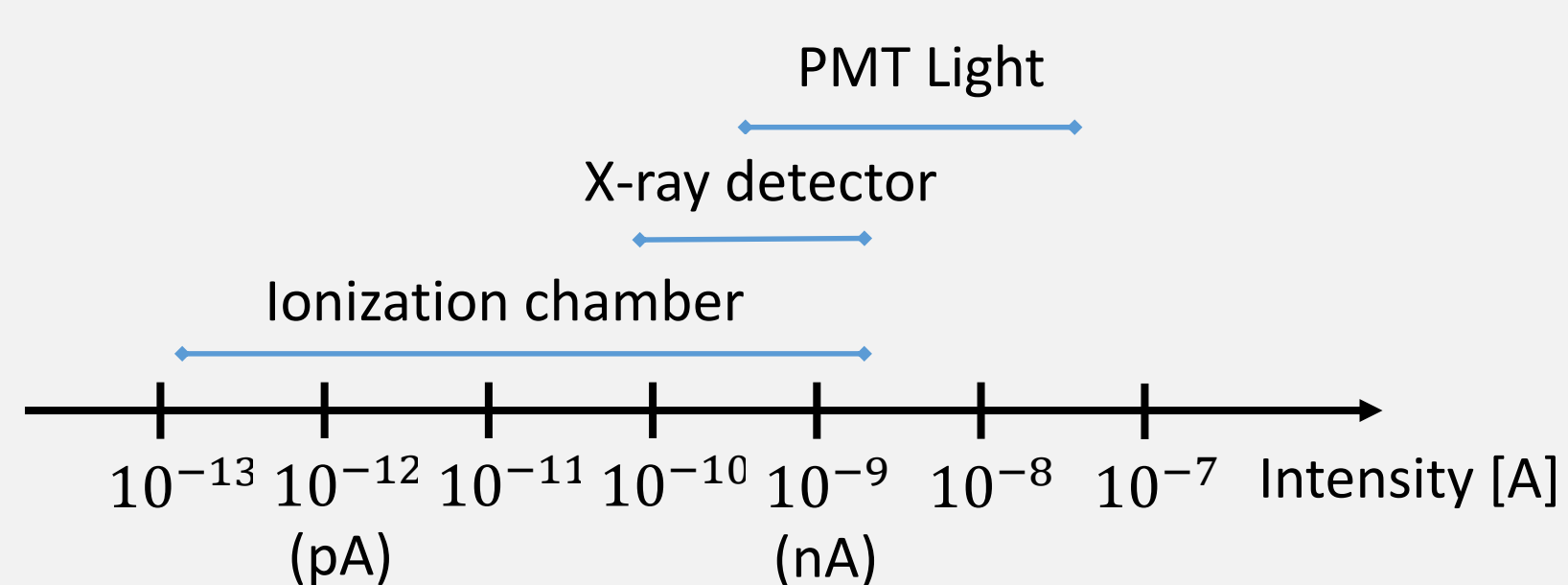
Experience with PIXE/PIGE technique

Number of incident particles N_p

The number of incident particles can be determined using a beam current measurement. Several detectors can be used, each with an optimal range of use.



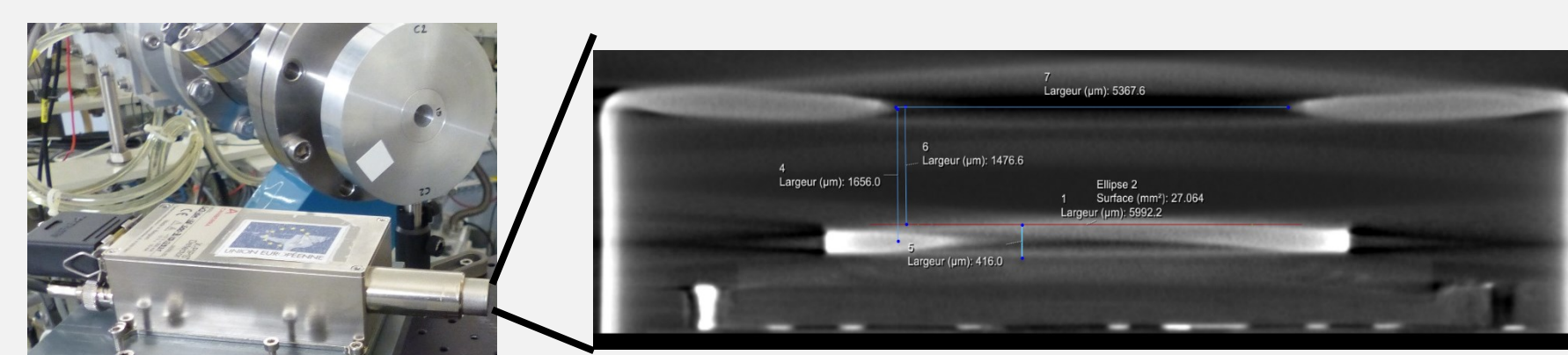
$$10^{-9} A \equiv 6.25 \cdot 10^{10} \text{ particles/s}$$



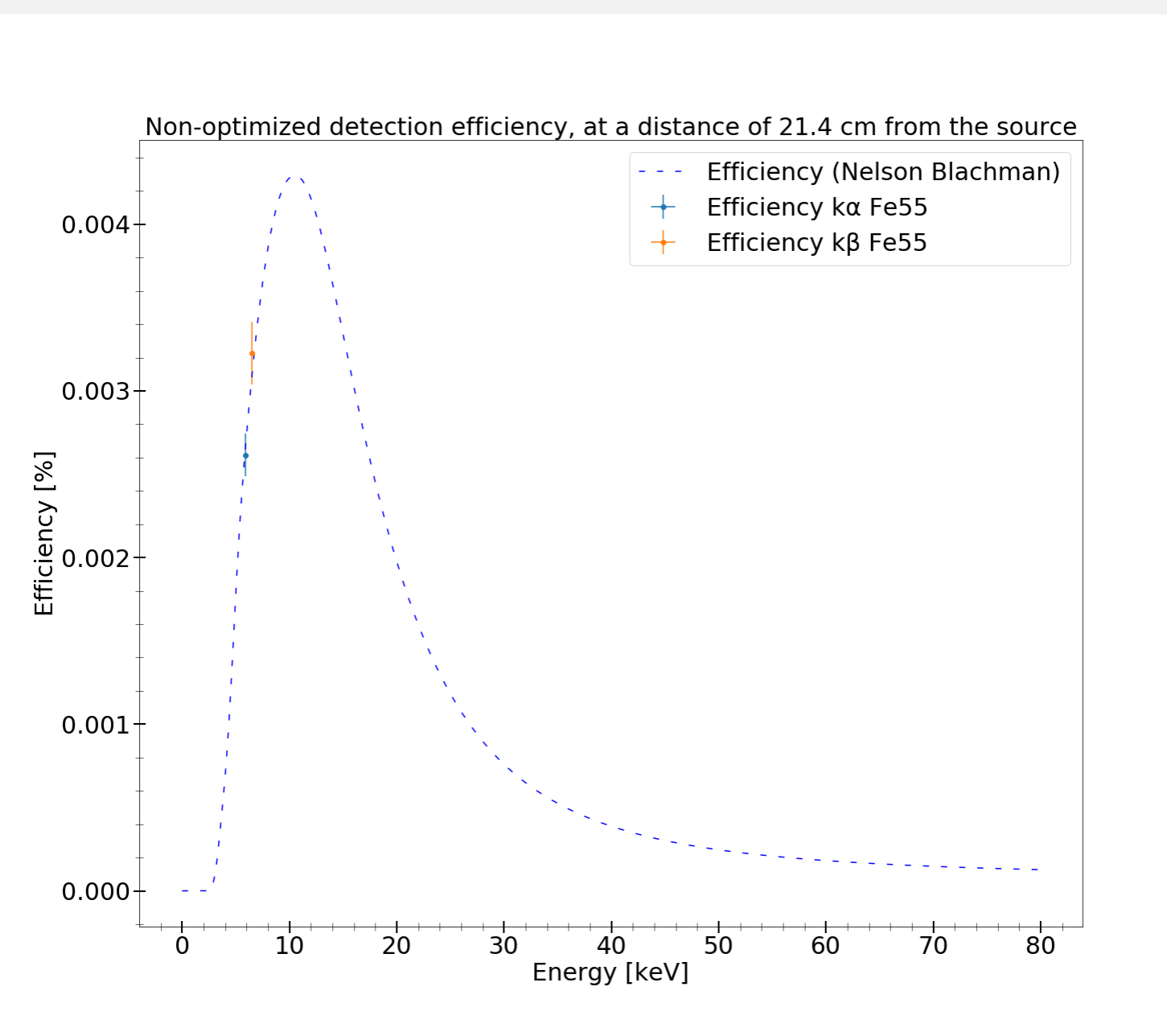
Optimal range of use of the different detectors

Detection efficiency ε

Use of an X-ray tomograph to determine some detector characteristics:



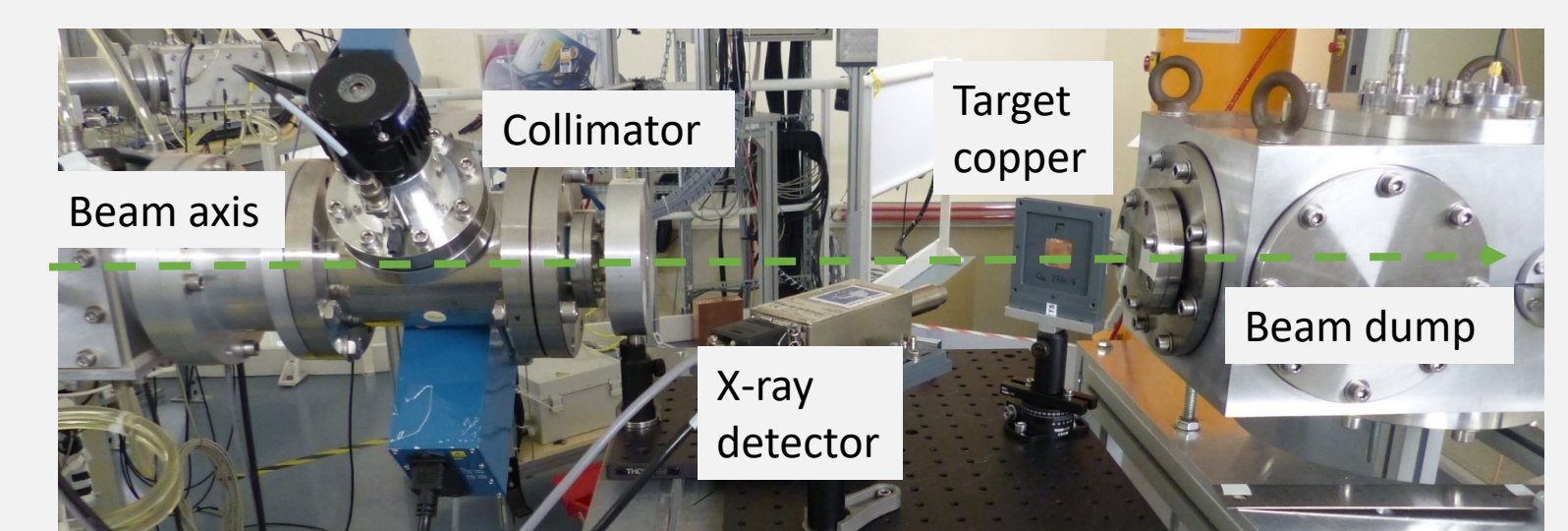
Experimental measurement of detection efficiency using a ^{55}Fe source:



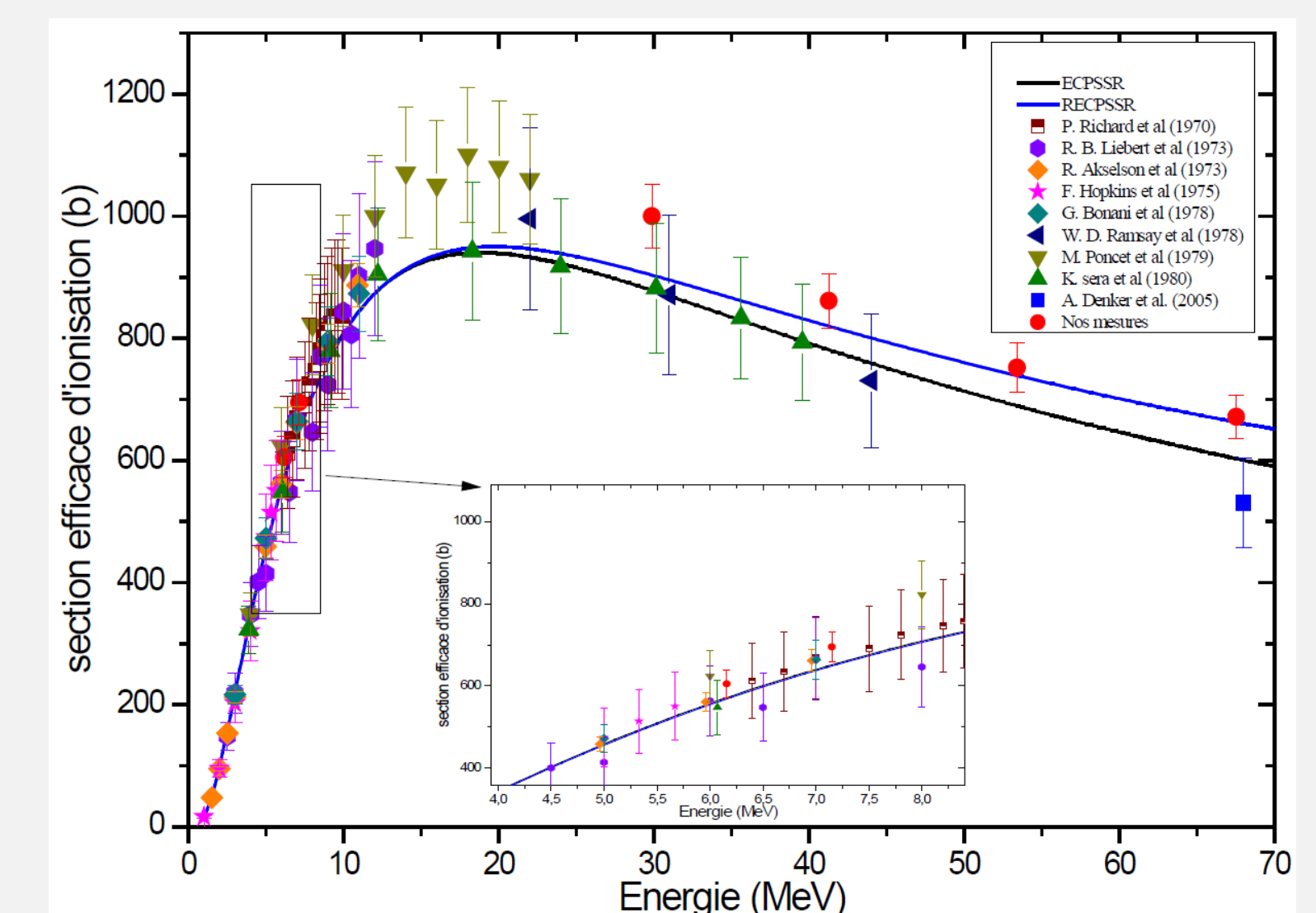
The geometric efficiency is based on the Blachman solid angle model. (B.P. Burtt, *Nucleonics* (1942) 42)
 Further measures are necessary to be able to constrain the efficiency curve.

Ionization cross section σ_i

Ionization cross-section measurement, at the energies available at the ARRONAX cyclotron (17 to 68 MeV), are required to validate the theoretical RECPSSR model for high energies.



Experimental set-up for measuring the ionization cross-section of a copper target



Experimental values of the ionization cross-sections of copper K-layer as a function of the energy protons incident, compared with the theoretical models ECPSSR and RECPSSR (Hazim M., 2017)

Future HE PIXE application at GIP ARRONAX

- Study of cement for the storage of radioactive waste (Landesman C. – SUBATECH):
 - Investigation of the concentration of different elements in the layers of the sample
- Geological sediment study (Mouret A. – LPG BIAF):
 - Investigation of the concentration of different elements along a burrow created by a worm

