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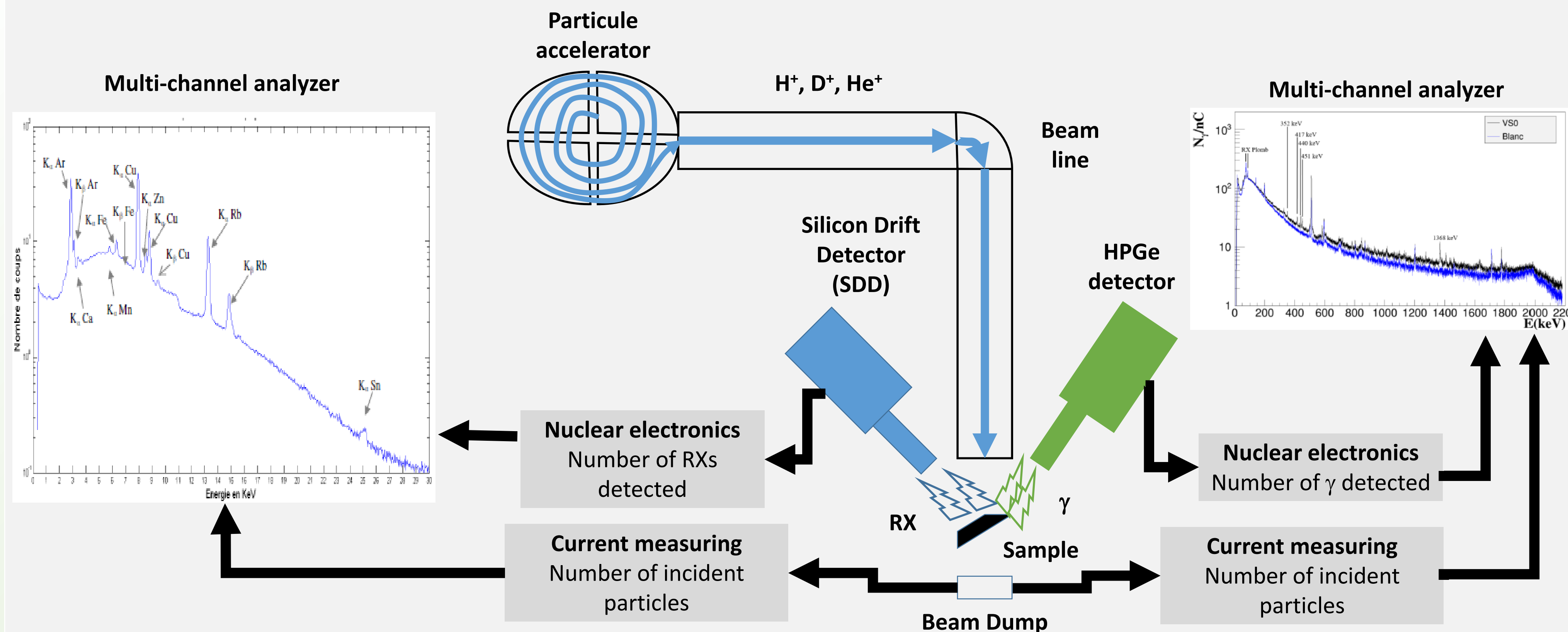
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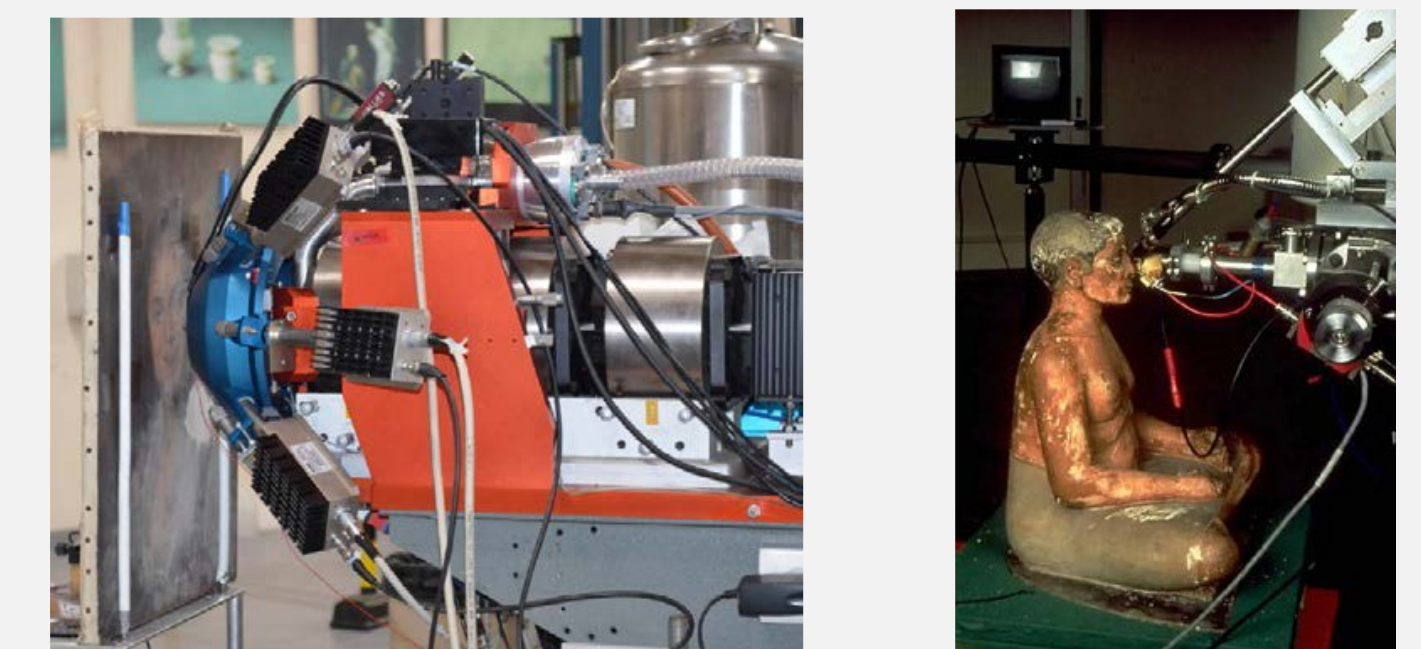
Non-destructive analysis: PIXE with high-energy ion beam at the ARRONAX cyclotron

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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

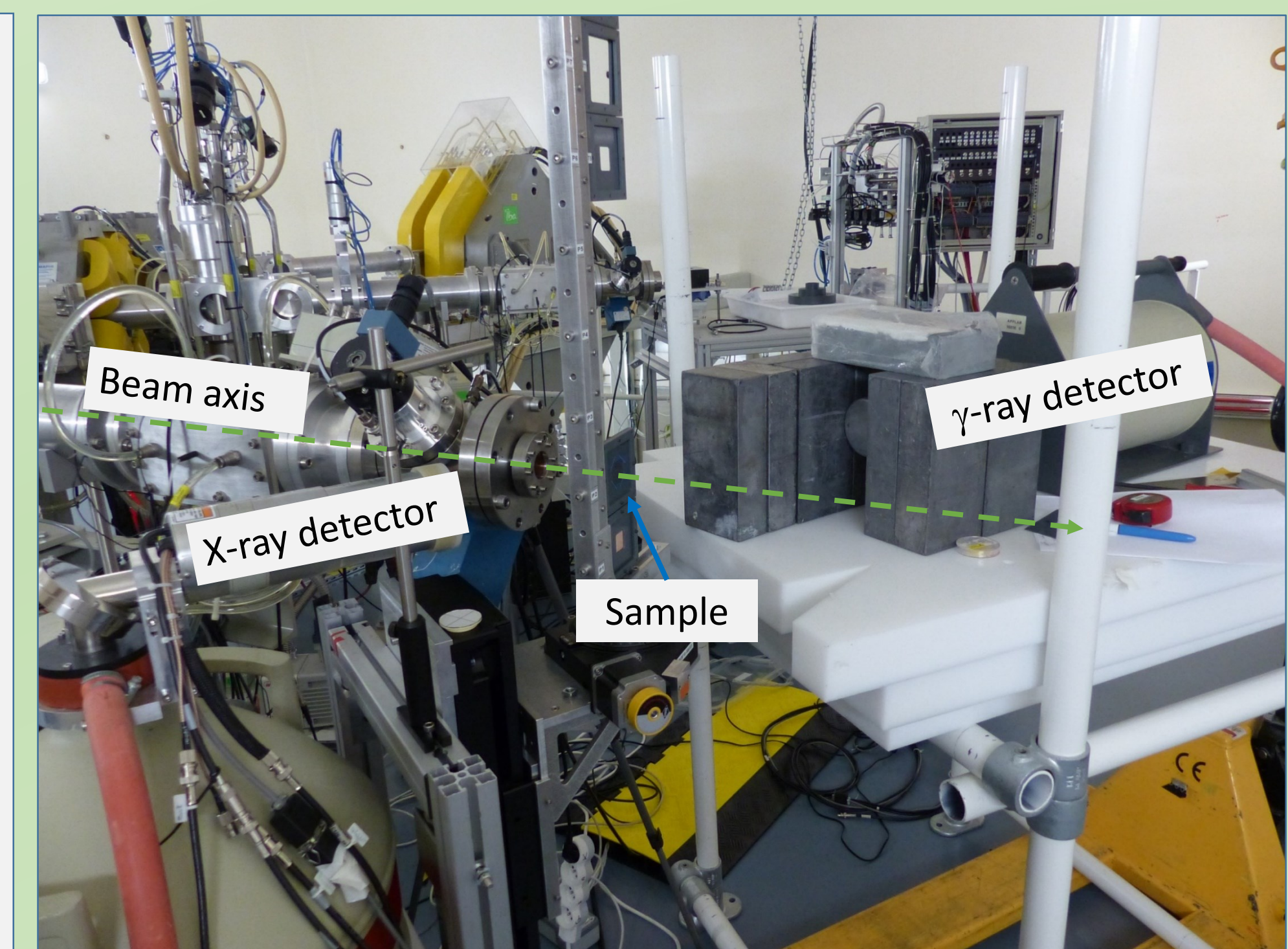
$$N_X^Z = N_p N^Z \omega b \varepsilon \sum_{E_f}^{E_i} \sigma_i(E) e^{-\mu_c \xi} \left(\frac{dE}{dx} \right)^{-1} dE$$

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

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

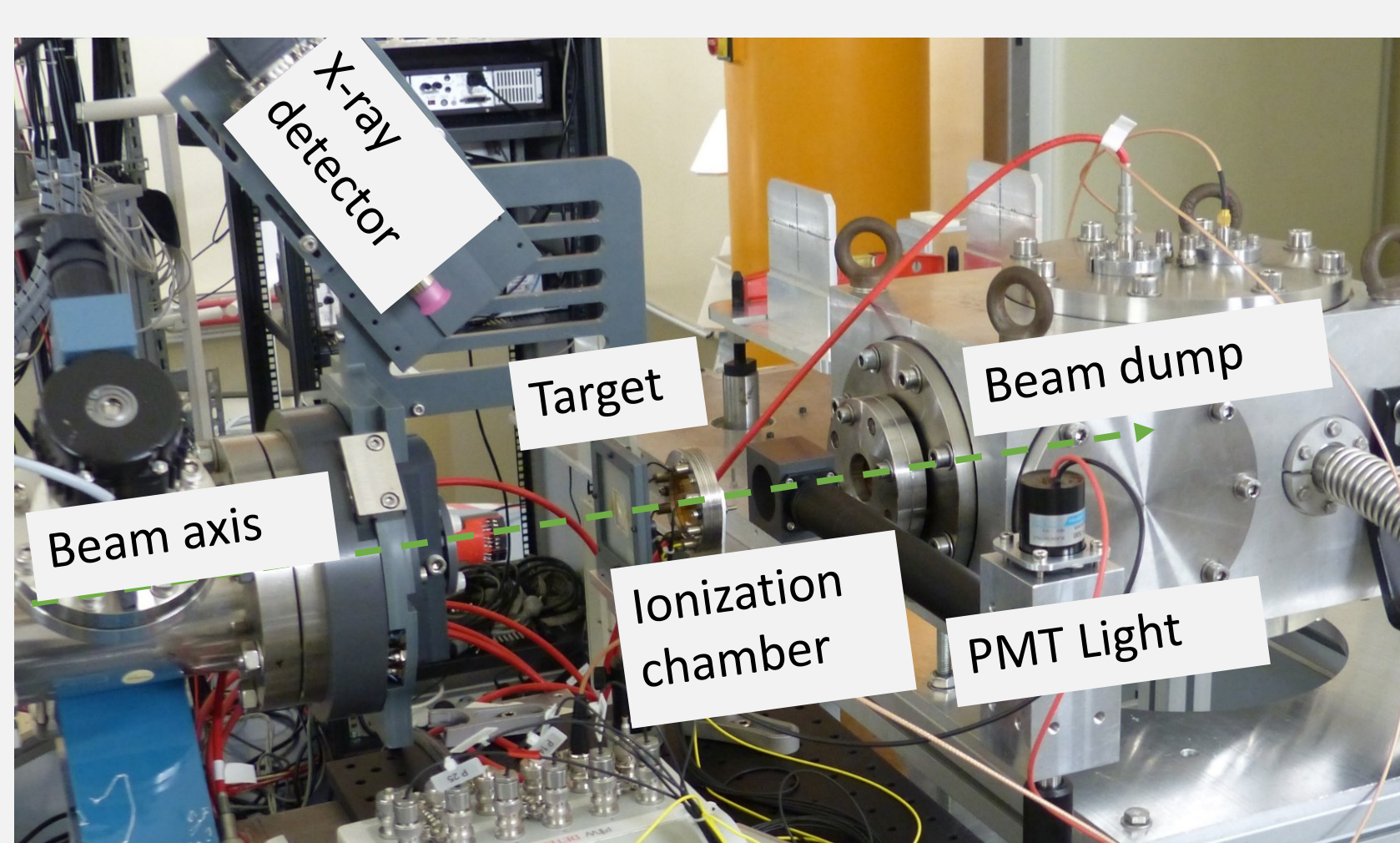
The combined use of the PIGE method, detection of γ emission, allows quantification for light elements ($Z < 11$).



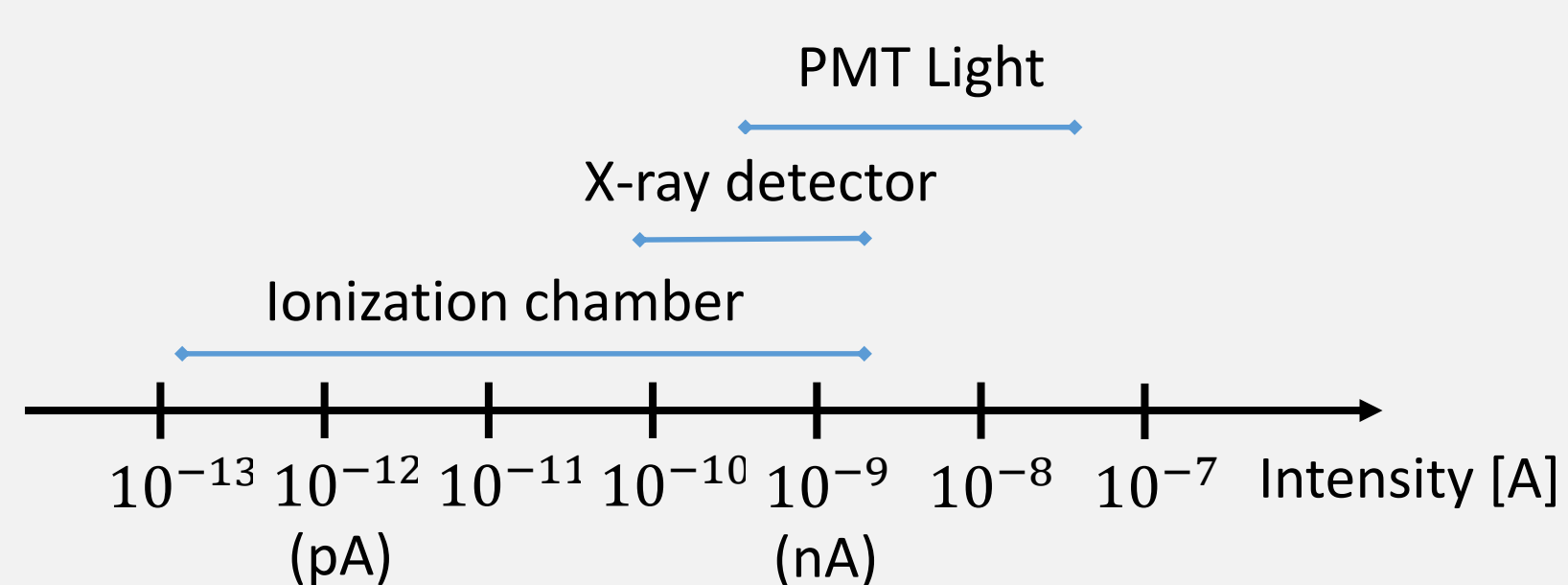
Experience with PIXE/PIGE technique

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.



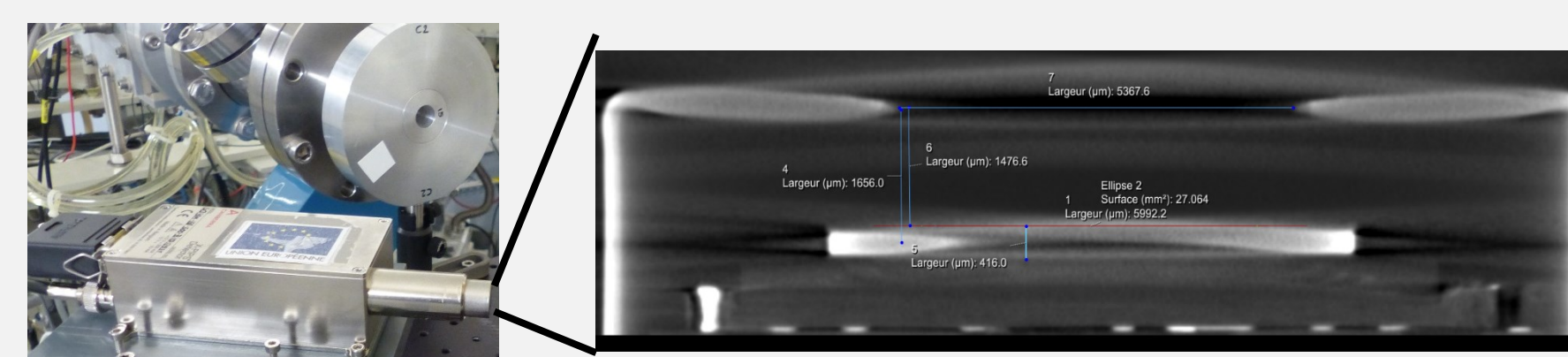
$$10^{-9} A \equiv 6.25 \cdot 10^{10} \text{ particles/s}$$



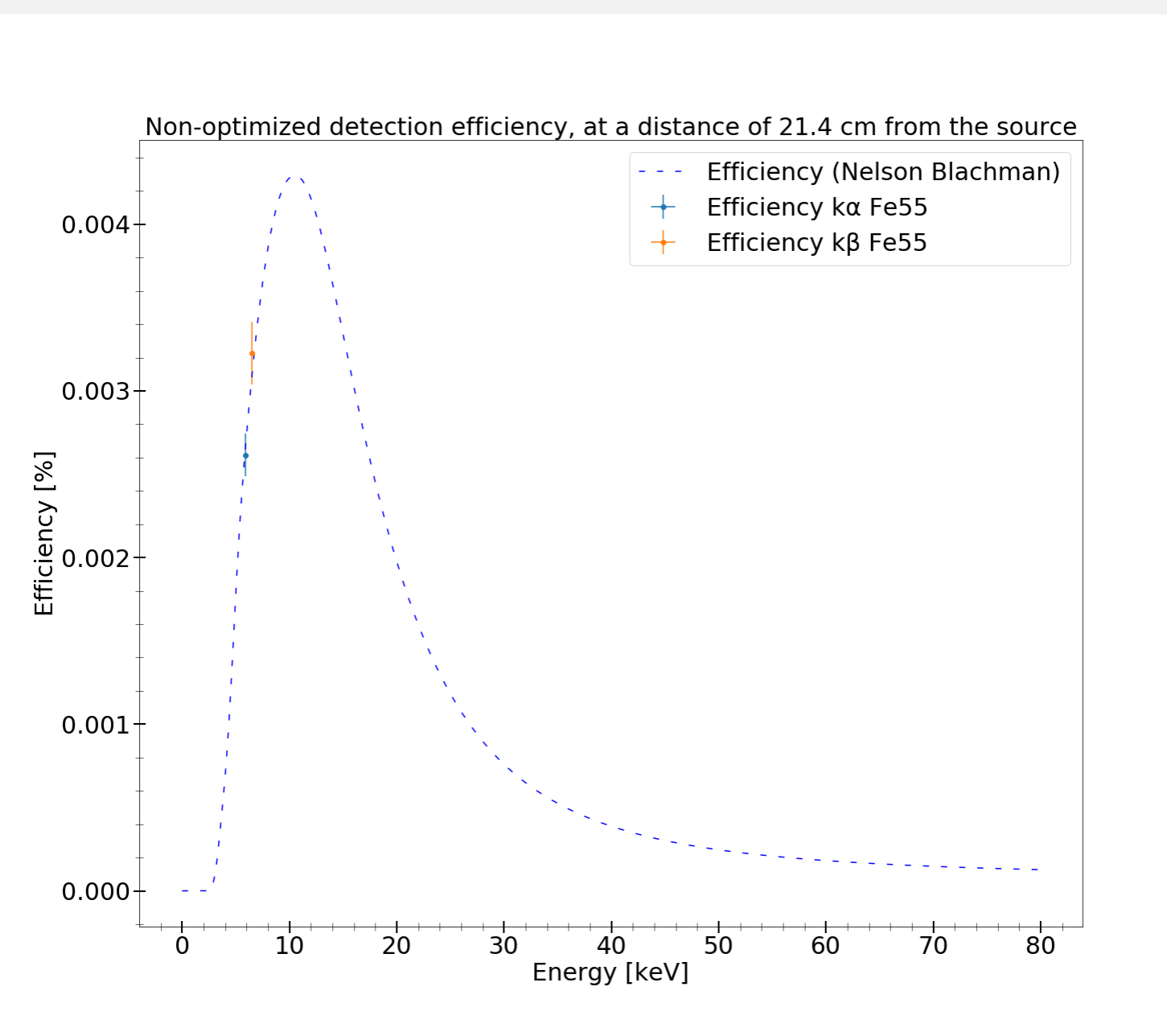
Optimal range of use of the different detectors

Detection efficiency ε

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



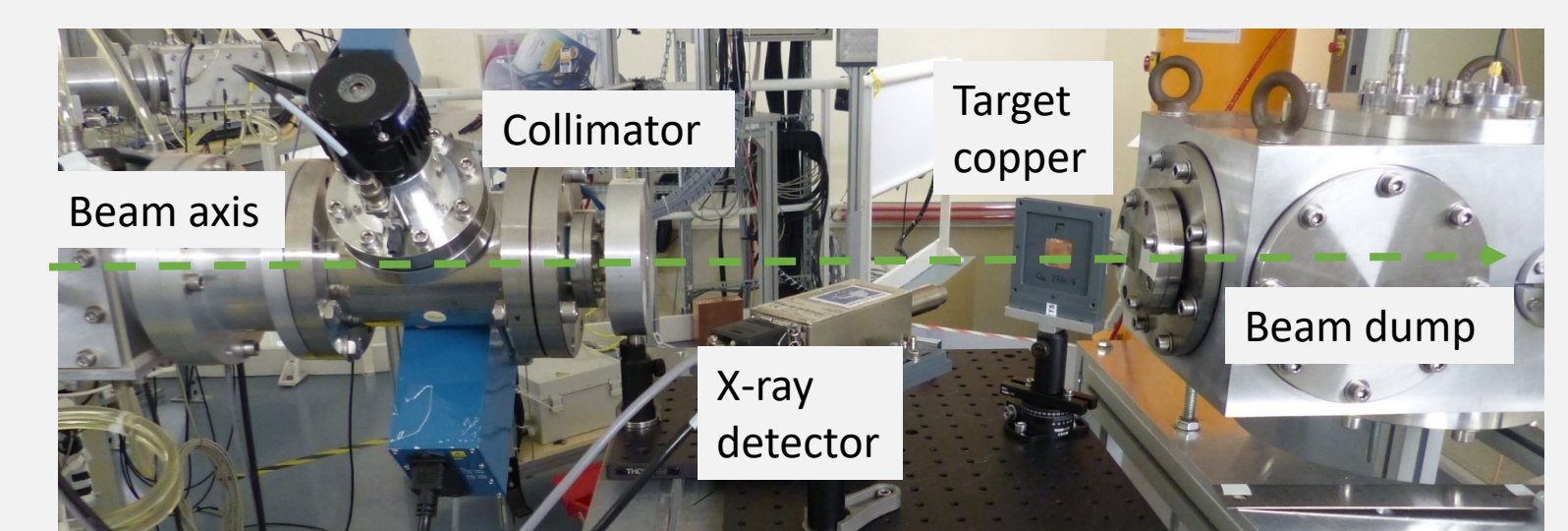
Experimental measurement of detection efficiency using a ^{55}Fe source:



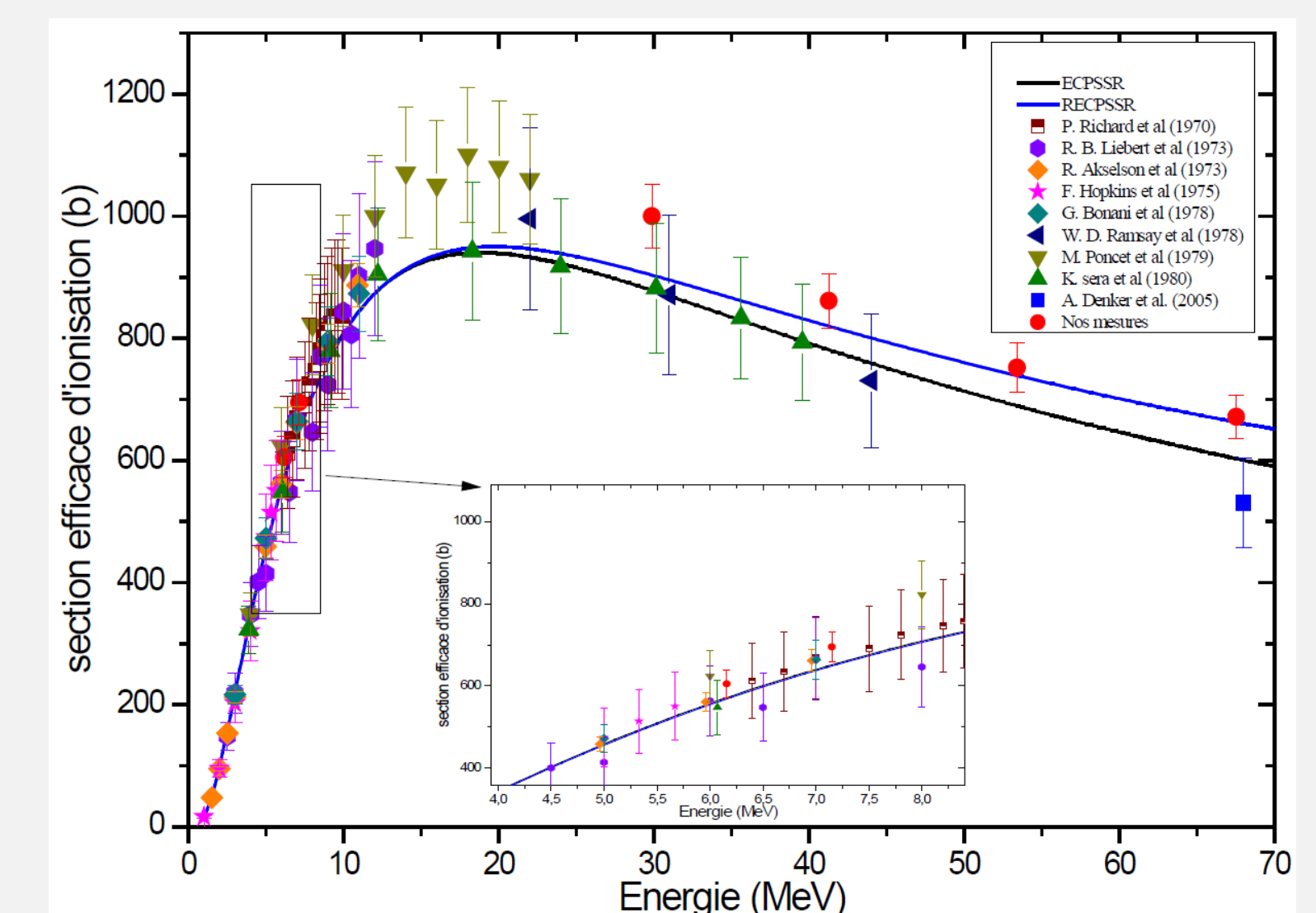
The geometric efficiency is based on the Blachman solid angle model. (B.P. Burt, Nucleonics (1942) 42)
 Further measures are necessary to be able to constrain the efficiency curve.

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

