POLITECNICO MILANO 1863

Numerical Simulations of Laser-driven Ion Beam Analysis

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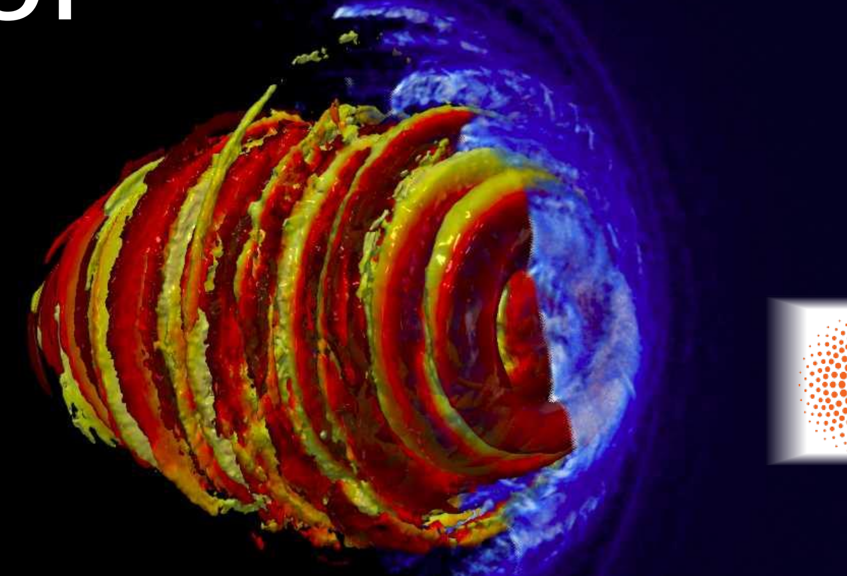


ERC-2014-CoG No. 647554 ENSURE

NanoLab

Motivations & Goals

✔ **Laser-driven ion sources** match the **requirements** of many materials characterization techniques (i.e. **Ion Beam Analysis**).

✔ Easily achievable with **near critical double-layer targets** and **reduced laser requirements**.

❑ **Peculiar** with respect to conventional accelerators properties (ions delivered in **bunches, broad energy spectra**).

❑ Only **one exp. evidence** of IBA with laser-driven ions.

M. Barberio, et al. *Sci. Rep.* 7. (2017).

Assessment of laser-driven Ion Beam Analysis feasibility with **multi-stage** (PIC + Monte Carlo) **numerical simulations**.

M. Passoni et al., *Sci. Rep.* (2018) under review

Laser-driven Ion sources

❑ **10s TW class lasers** (I > 10^{18} W/cm^2) → $10^8 \div 10^9$ p/shot, E_p ~ few MeVs, repetition rate ~ Hz.

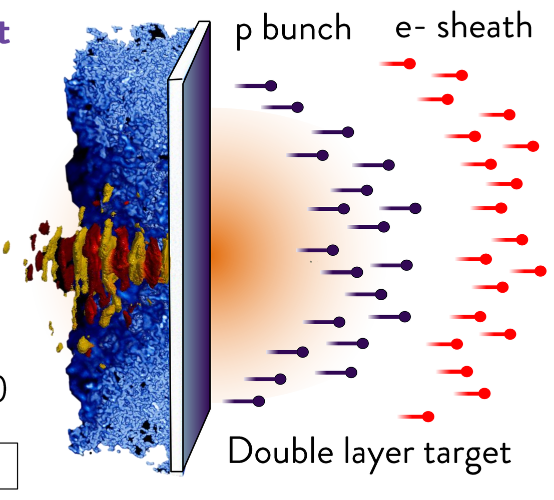
❑ **TNSA** → robustness among other schemes.

❑ **Near critical** double layer **target** to enhance laser absorption.

$$n_c = \frac{\pi m_e c^2}{e\lambda^2}$$

$$\approx 6\ mg/cm^3 (@\ \lambda = 800\ nm)$$

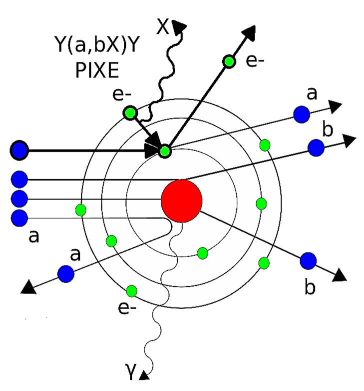
($n \approx n_c$ → strong laser-plasma coupling)



M. Passoni et al. *Phys Rev Acc Beams* 19.6 (2016)

Particle Induced X-ray Emission

PIXE is an **Ion Beam Analysis** (IBA) techniques → Retrieve the elemental composition of unknown samples.



❑ **2-5 MeV** monoenergetic **protons**.

❑ Electrostatic accelerators (Van de Graaff & TANDEM).

❑ Elemental **concentrations** & **Depth profiles**.

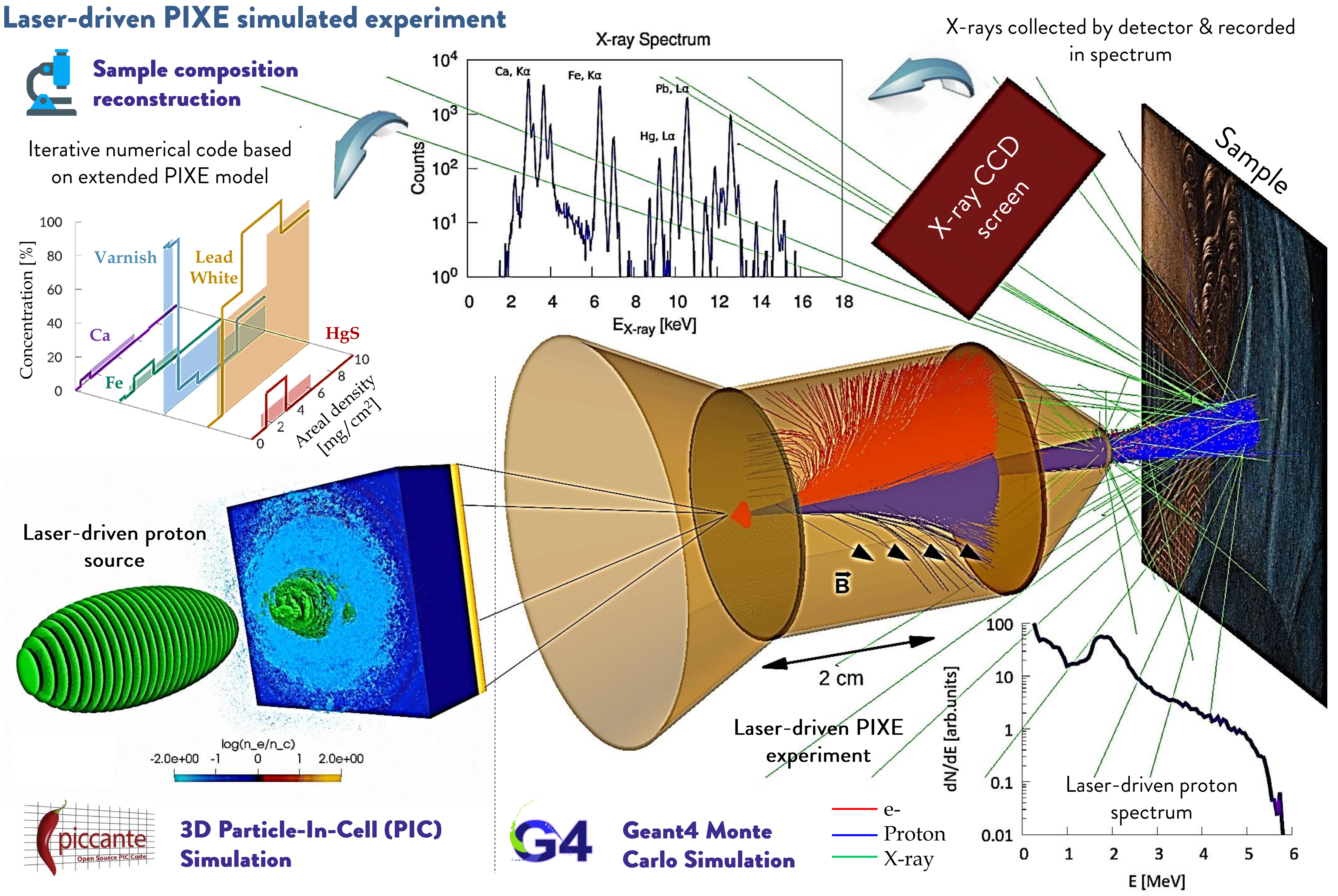
❑ **Cultural heritage**, environmental, biological and medical studies.

❑ Quantitative analysis → commercial codes

GUPIX

Verma, H. R. *Atomic and Nuclear Analytical Methods* (Springer Berlin Heidelberg, 2007)

Laser-driven PIXE simulated experiment

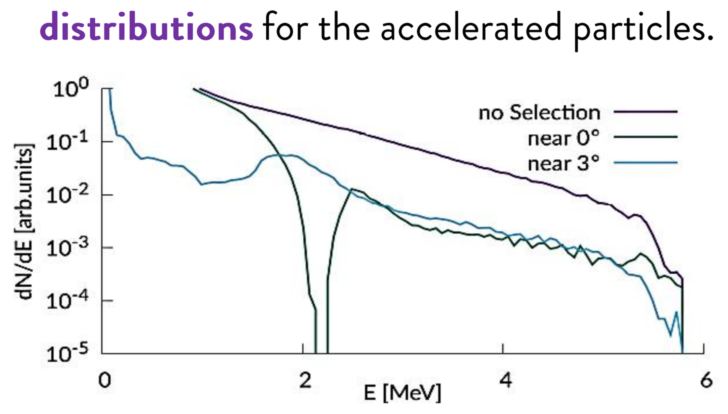


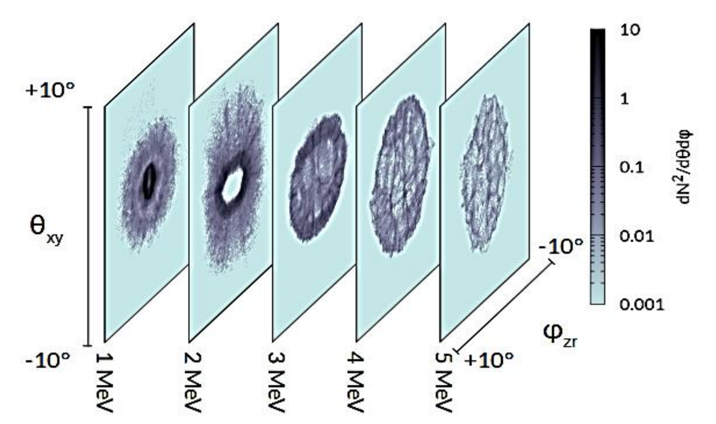
Particle-In Cell Simulations

CINECA

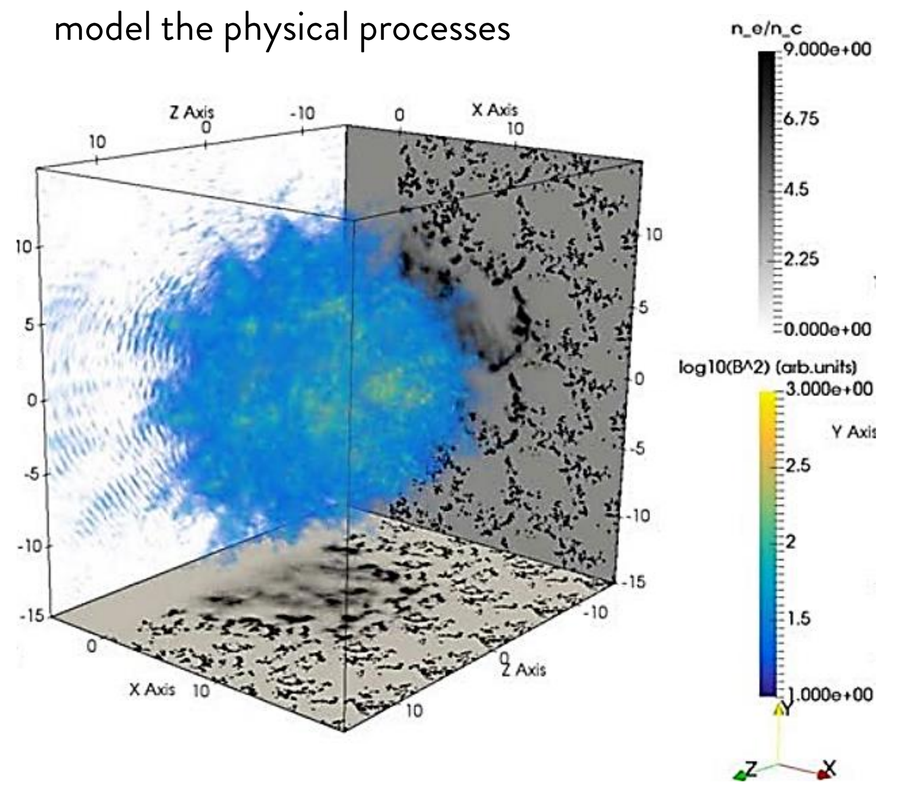
Well established and powerful tool to **study laser-plasma interaction**.

❑ 3D PIC -> provide **realistic energy & angular distributions** for the accelerated particles.





❑ Include **nanostructure morphology** to properly model the physical processes



L. Fedeli et al. *Sci. Rep.*, volume 8, Article number: 3834 (2018)

Monte Carlo Simulations

"Toolkit for the simulation of the passage of particles through matter" (https://geant4.web.cern.ch).

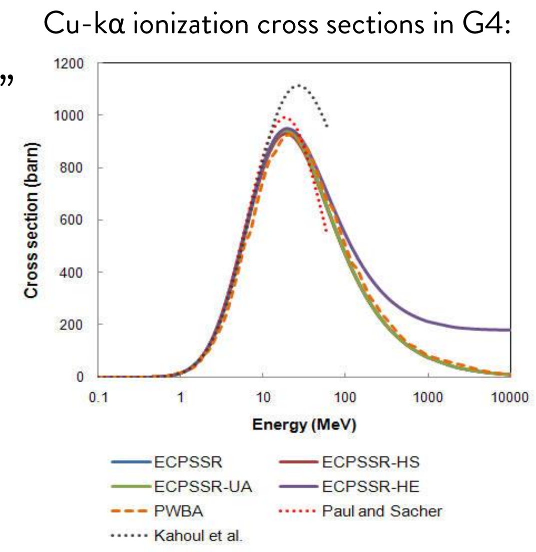
❑ **Simulation** of laser-driven **PIXE experiments**.

❑ Performed using ~10^{10} primary particles with momenta selected in accordance with 3D PIC outputs.

❑ From a certain sample composition →obtain a **X-ray "synthetic" spectrum.**

Agostinelli, S. et al., *Nucl. Instr. Meth. Phys. Res. A* 506, 250 – 303 (2003)

Cu-kα ionization cross sections in G4:



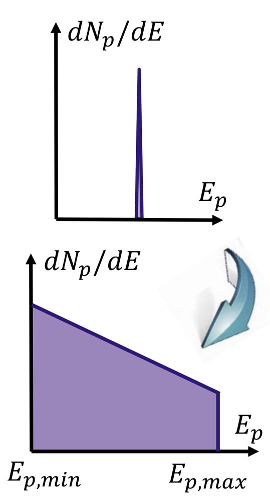
Pia, Maria Grazia, et al., *IEEE T. NUCL. SCI.* 56.6 (2009): 3614-3649.

Extended PIXE Model & Sample composition reconstruction

❑ **PIXE theory** only for monoenergetic protons → Necessary to **include** a **broad** energy **spectrum**!

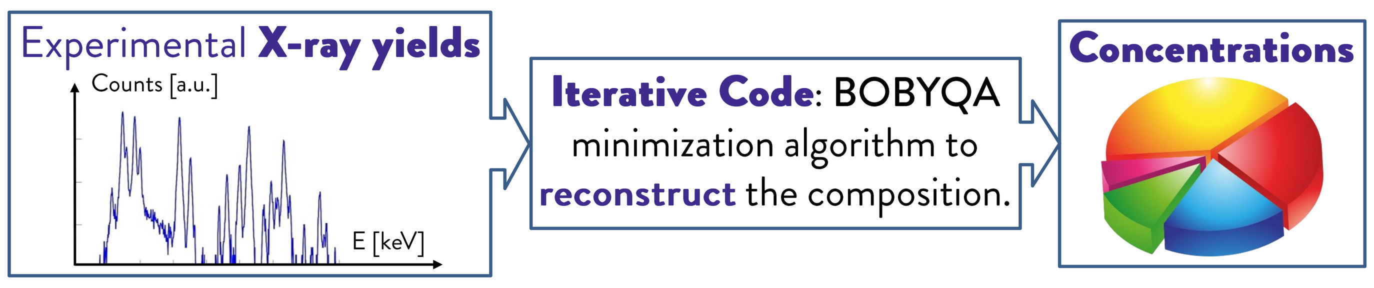
$$Y_j = N_p \frac{\Delta\Omega}{4\pi}\varepsilon_j W_j \frac{N_{Av}}{M_j}\int_{E_p}^{0}\sigma_j(E)\,\omega_j exp\left(-\mu_j\int_{E_p}^{E}\frac{dE'}{S(E')}\frac{\cos(\varphi)}{\cos(\theta)}\right)\frac{dE}{S(E)}$$

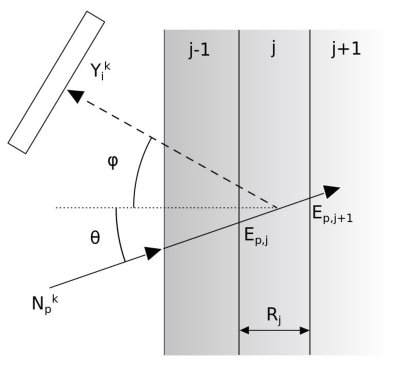
$$Y_j = \frac{\Delta\Omega}{4\pi}\varepsilon_j W_j \frac{N_{Av}}{M_j}\int_{E_{p,min}}^{E_{p,max}} f_p(E_p)\int_{E_p}^{0}\sigma_j(E)\,\omega_j exp\left(-\mu_j\int_{E_p}^{E}\frac{dE'}{S(E')}\frac{\cos(\varphi)}{\cos(\theta)}\right)\frac{dE}{S(E)}dE_p$$



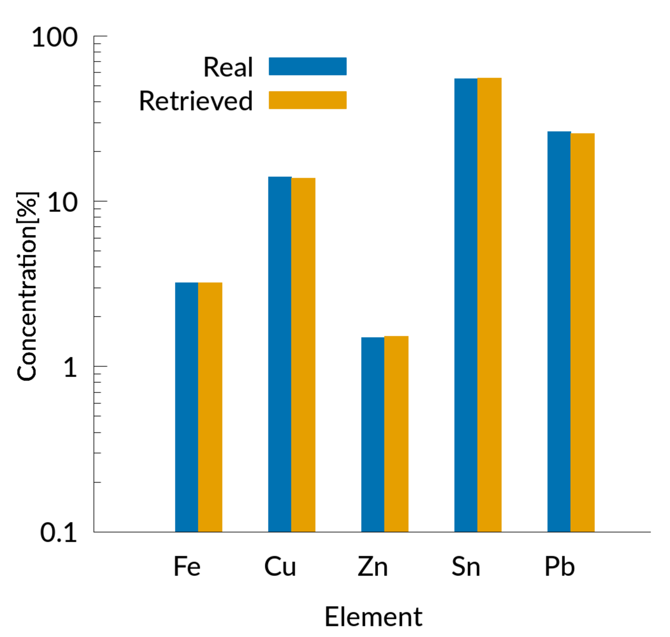
Y_j: X-ray yields, $\Delta\Omega$: detector solid angle, ε_j: detector efficiency, W_j: element concentration, N_{Av}: Avogadro's number, M_j: atomic weight, E_p: proton energy, σ_j: ionization cross section, ω_j: fluorescence yield, μ_j: X-ray attenuation coefficient, S: proton stopping power, φ: proton impact angle, $f_p(E_p)$: proton energy distribution ($E_{p,min}$ & $E_{p,max}$: upper and lower energy cutoff).

❑ **Iterative algorithm** to reconstruct the sample composition (based on the extended PIXE model):

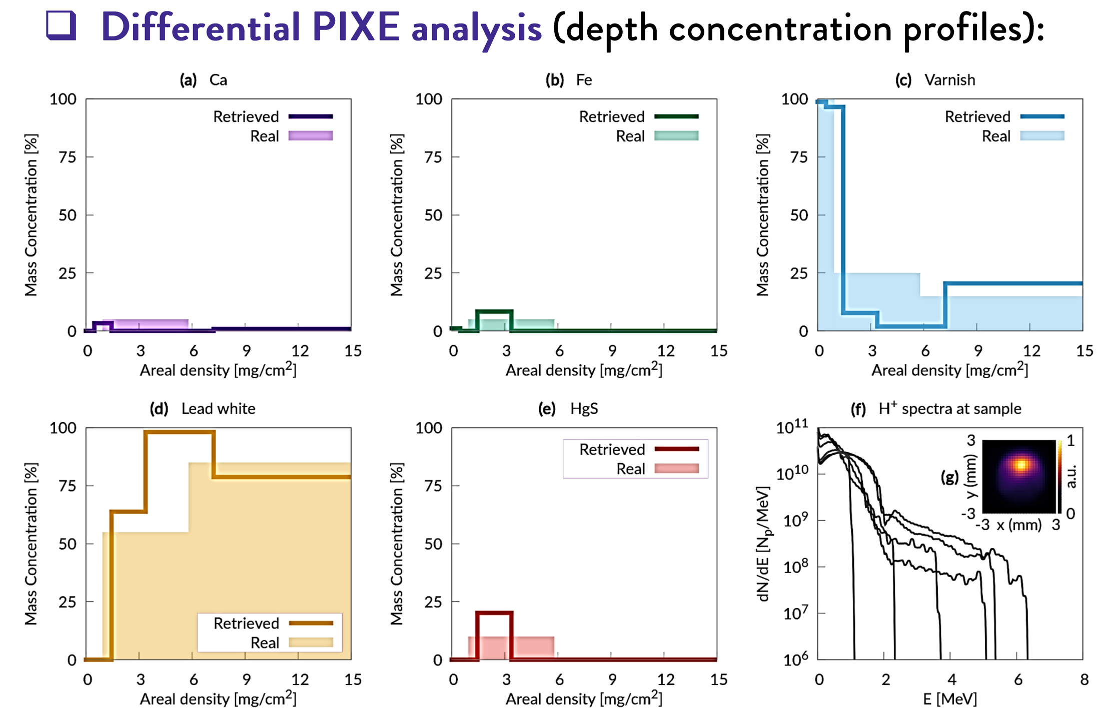




❑ **Homogeneous** sample **analysis**:



❑ **Differential PIXE analysis** (depth concentration profiles):



M. Passoni et al., *Sci. Rep.* (2018) under review

Conclusions & Perspectives

✔ We provide a **theoretical description of PIXE** performed with a **non-monoenergetic ion** sources.

✔ We assesse the possibility to perform **quantitative laser-driven PIXE** & **Differential PIXE** (i.e. retrieve the concentrations and concentration depth profiles of the elements).

Carry out an **experimental** campaign to **test quantitative laser-driven PIXE** on multi-elemental and multilayer samples.

Analyse other possible IBA techniques to be performed with laser-driven ion sources, like **Particle Induced Gamma Rays Emission (PIGE)** & **Proton Activation Analysis (PAA).**

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