POLITECNICO
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ERC-2014-CoG No. 647554
ENSURE

Simulations of Ion Beam Analysis with laser-driven proton sources at Politecnico di Milano

Francesco Mirani

Frascati, February 21st , 2018

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ERC-2014-CoG No. 647554
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ERC PoC INTER PROJECT

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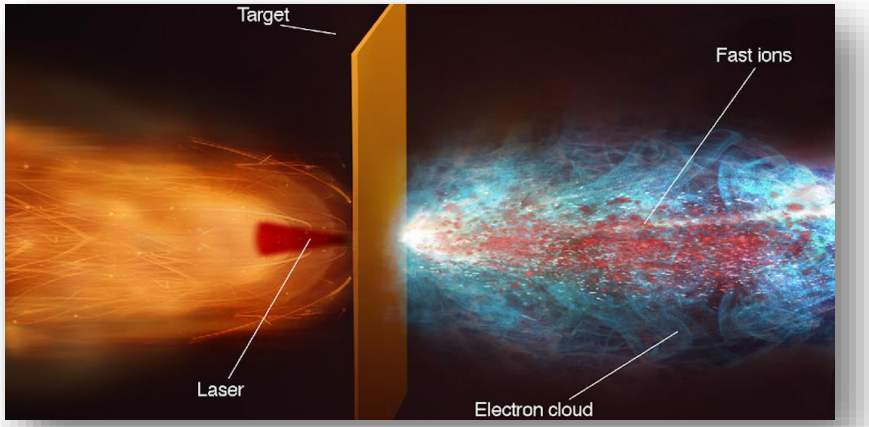
PhD student

Francesco Mirani
PhD student

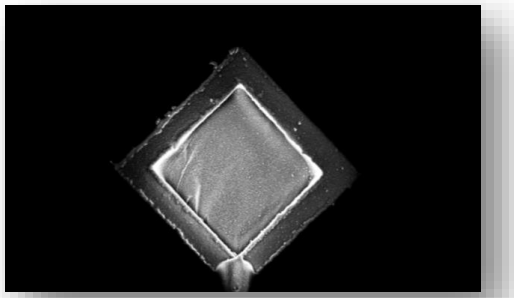
Alessandro Tentori
Master's student

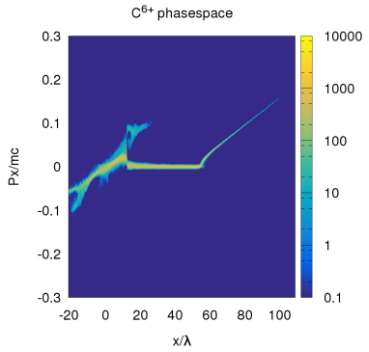
Main fields of research

- Theoretical & experimental investigation of **laser-driven ion acceleration**



- Fundamental physics and laboratory astrophysics (**collisionless shock waves** & **laser-driven secondary radiation** (e.g. Neutron))



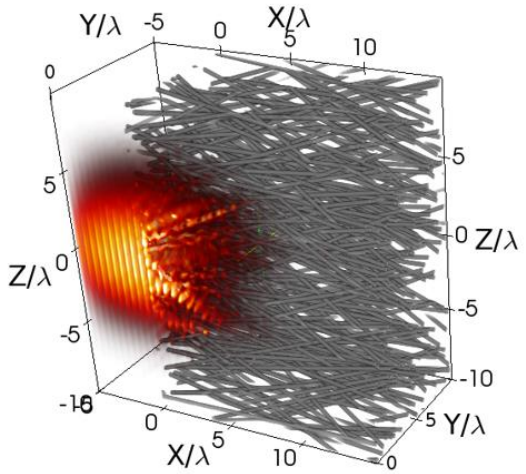


- Advanced target production (**low-density foams** & **multilayer targets**) for laser-plasma interaction experiments

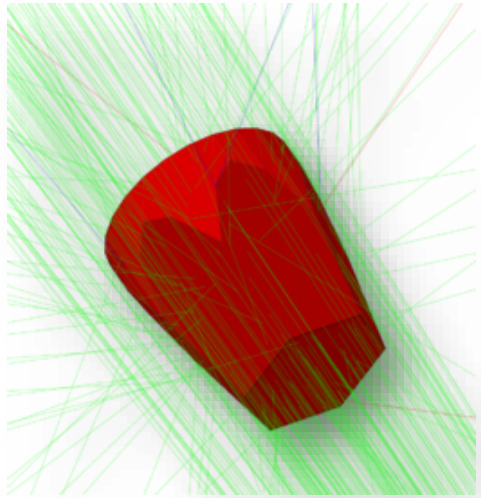
- Application of TNSA scheme to **material science**

Numerical Tools

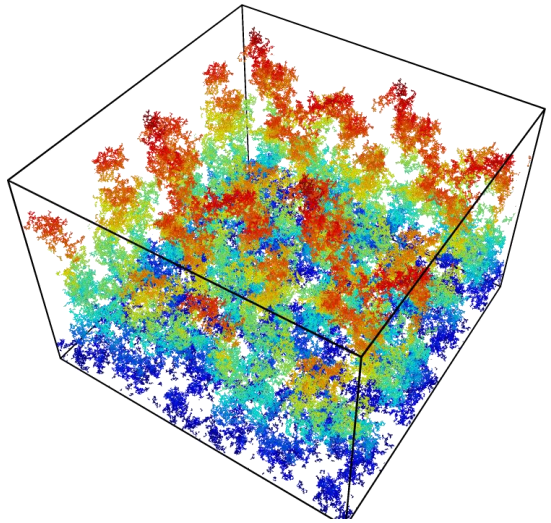
- **Particle-In-Cell (PIC) simulations** to study laser plasma interaction
- Open source codes: piccante, Smilei



- **Monte Carlo simulations** of particles propagation through matter
- Open source code Geant 4



- **Diffusion Limited Cluster-Cluster Aggregation (DLCA)** to model the foam growing process



- **Marconi @ CINECA, Bologna** HPC facility - Intel OmniPath Cluster access through ISCRA C & LISA & PoliMi grants (~ 100 kCPUhours each)

CINECA

Laser-driven ion sources: main features

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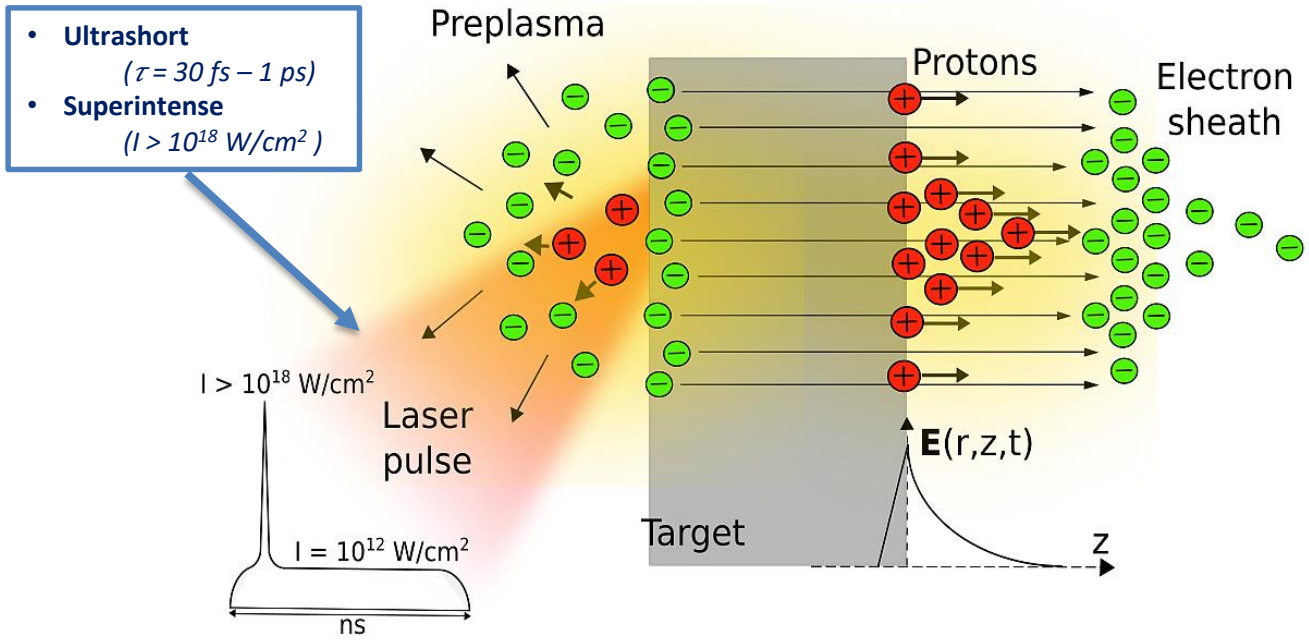
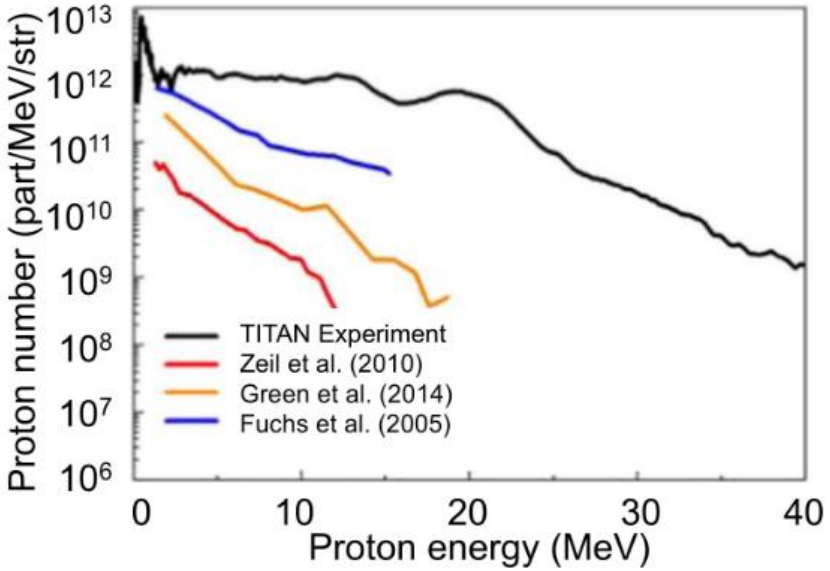
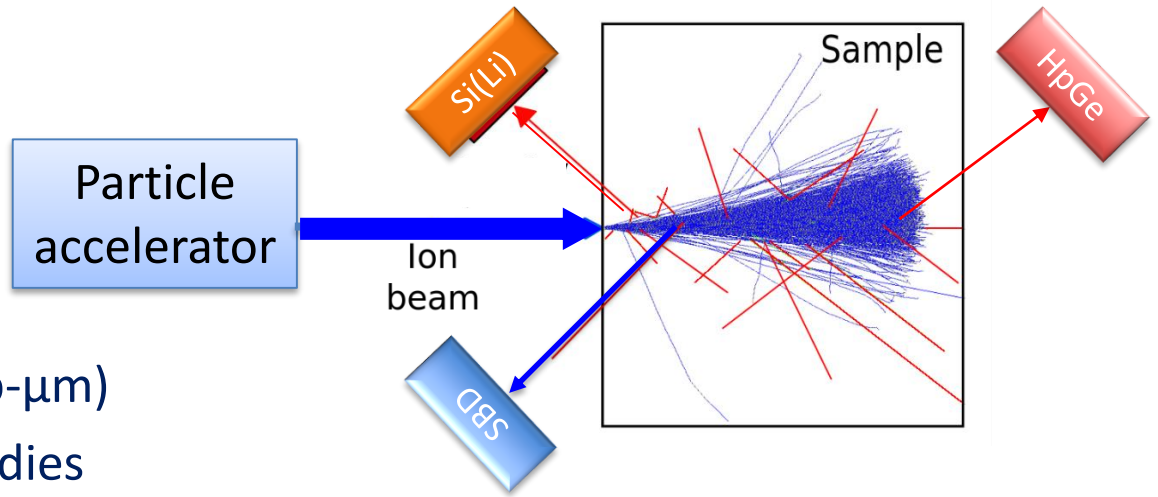




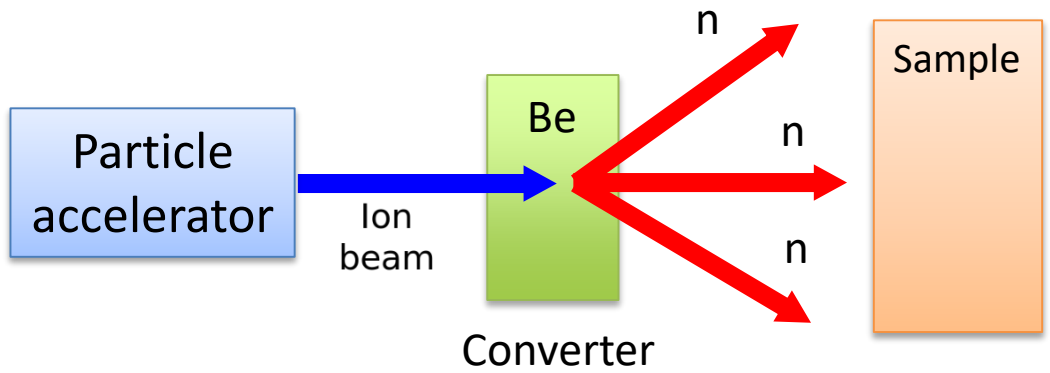
- **Proton bunches** emitted along the **target normal direction** (few degrees' divergence)
- Energies from **few MeV** to **almost 100 MeV**
- **Broad** energy **spectrum**
- Well defined **cut-off energy**

Possible applications in material science

- **Ion Beam Analysis:**
  - ***Primary particles*** → Ions (MeV)
  - ***Multi-elem. analysis*** → Type (Z); Concent. (ppm); Depth profile (sub-µm)
  - ***Non-destructive*** → Cultural Heritage Studies

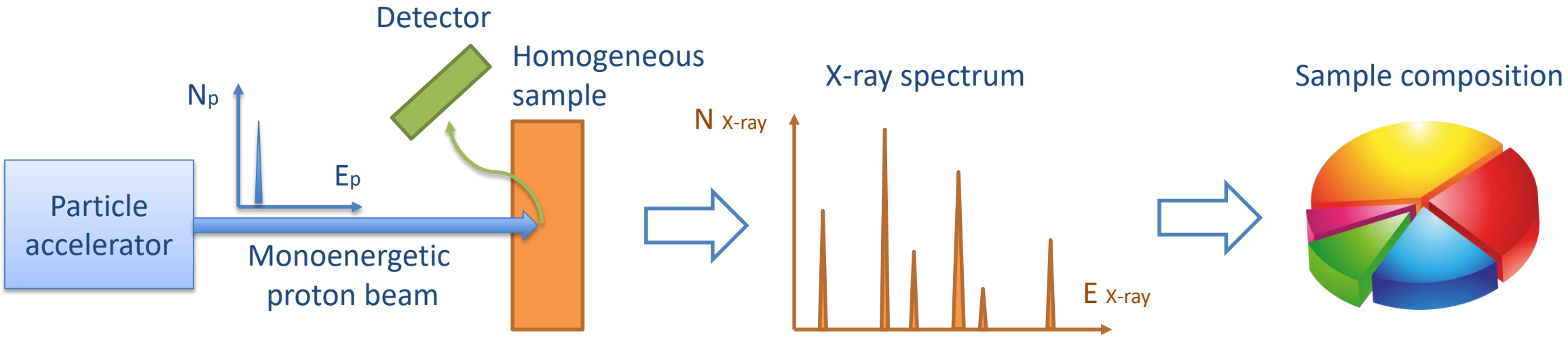


- **Neutron source:**
  - ***Neutron Activation Analysis (NAA)***
  - ***Neutron Radiography***



Particle Induced X-ray Emission (PIXE)

- Homogeneous sample



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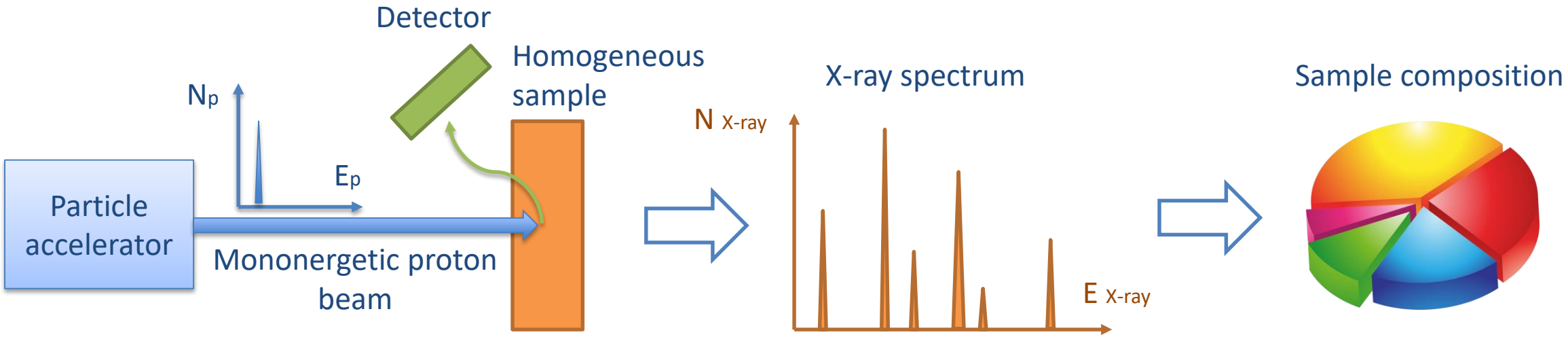


- Theoretical description of PIXE:

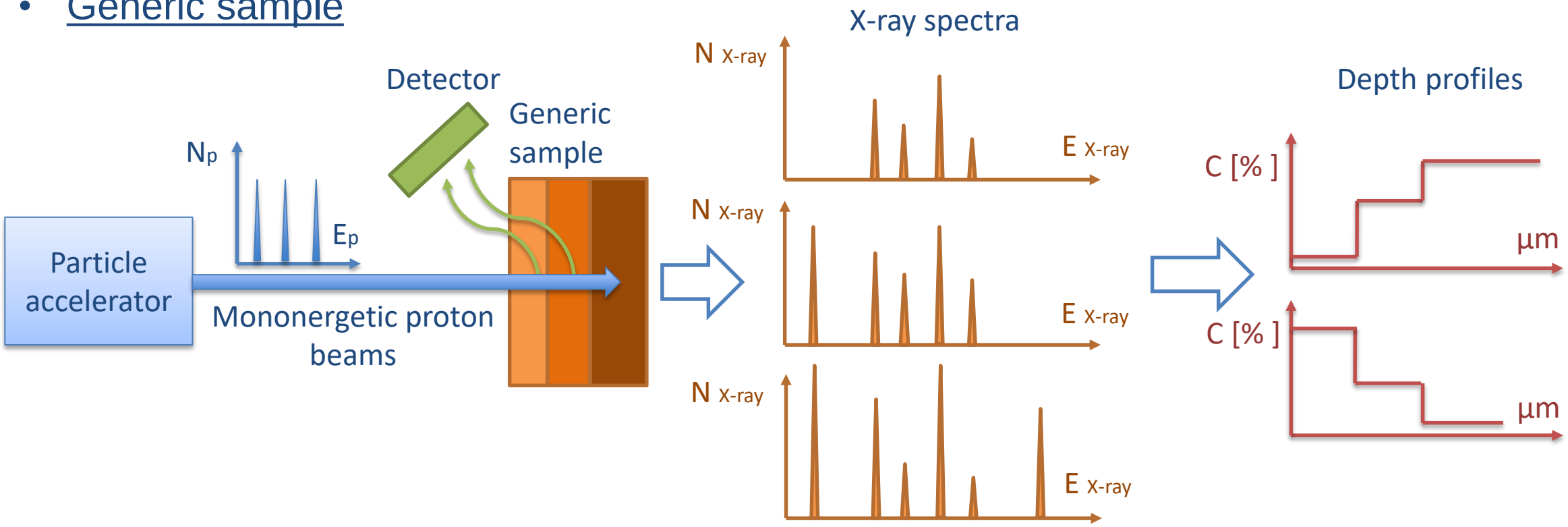
$$\frac{Y_j}{N_p} = \frac{\Delta\Omega}{4\pi}\varepsilon_j W_j \frac{N_{Av}}{M_j} \int_{E_p}^{0} \sigma_j(E)\ \omega_j\ exp\left(-\mu_j \int_{E_p}^{E} \frac{dE'}{S(E')} \frac{1}{\cos(\theta)}\right) \frac{dE}{S(E)}$$

- Numerical iterative procedure:

X-ray yields (Y_1, …, Y_j, …, Y_N) → *Iterative process* (Gupix, GeoPixe) → **Sample composition**

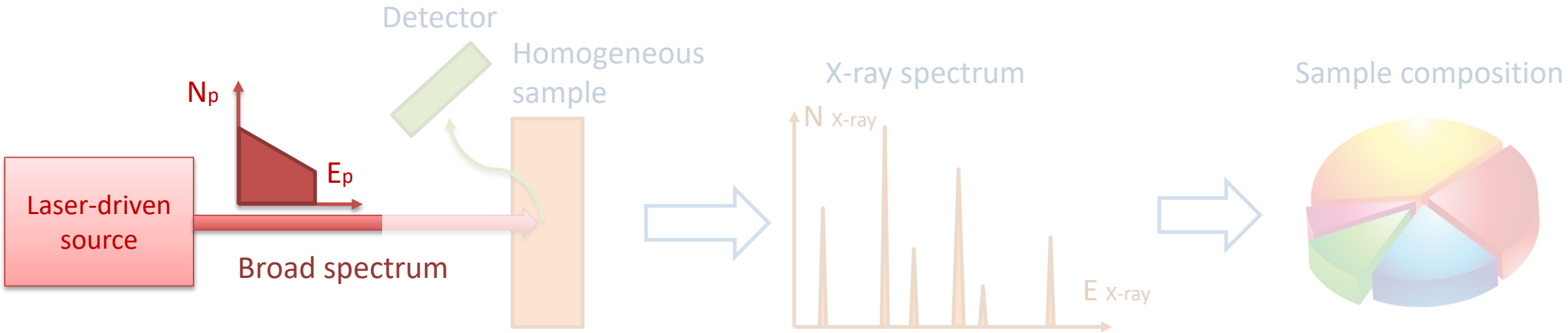
Particle Induced X-ray Emission (PIXE)

- Generic sample



…what about Laser-driven PIXE?

- Homogeneous sample analysis



…what about Laser-driven PIXE?

- Homogeneous sample analysis

Laser-driven proton source

- **Pure exponential function**
- PIC simulation result

Shaping function:

$$f_p(E_p) \sim e^{-\frac{E_p}{T_p}} \quad , \quad \int_{E_{p,min}}^{E_{p,max}} f_p(E_p) dE_p = 1$$

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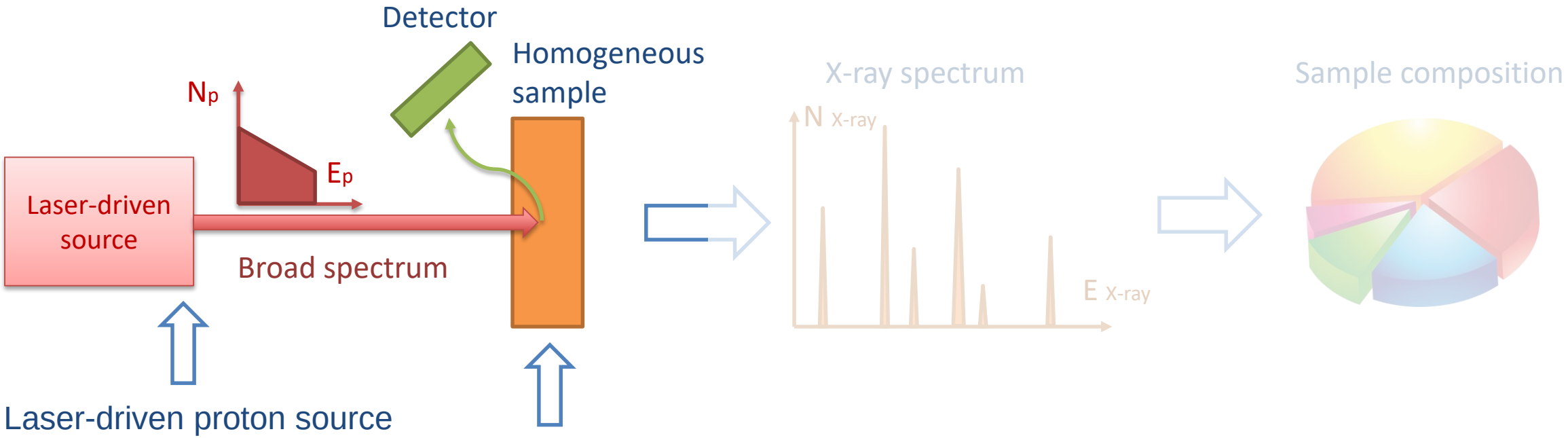

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Sample: 15 µm, Ni, Cr, Mo

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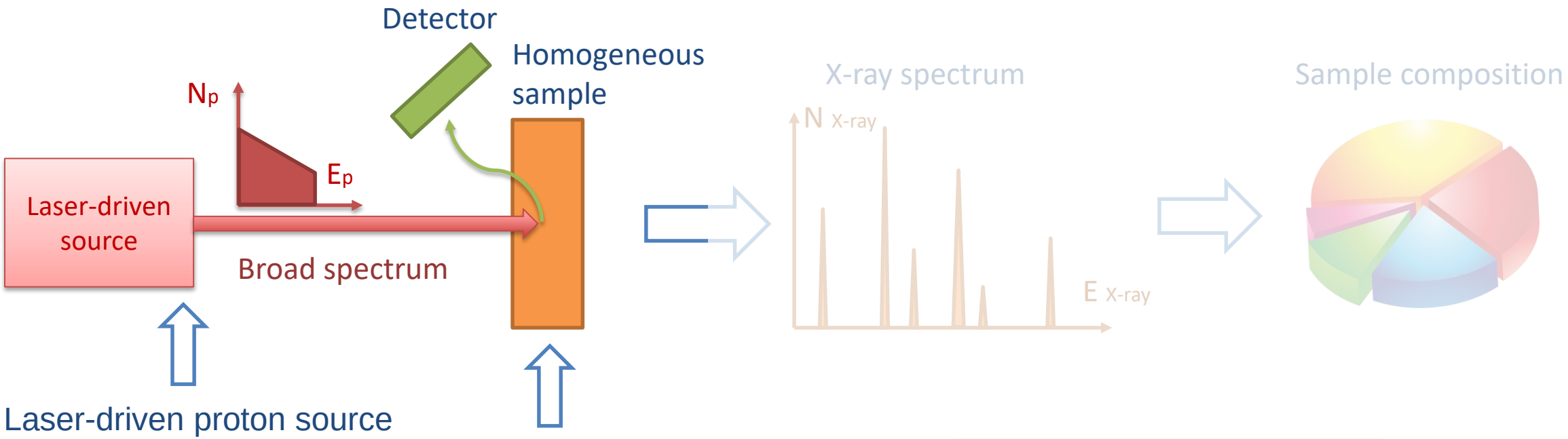

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Geant 4

Monte Carlo simulation

- **PIXE simulation with Geant 4**

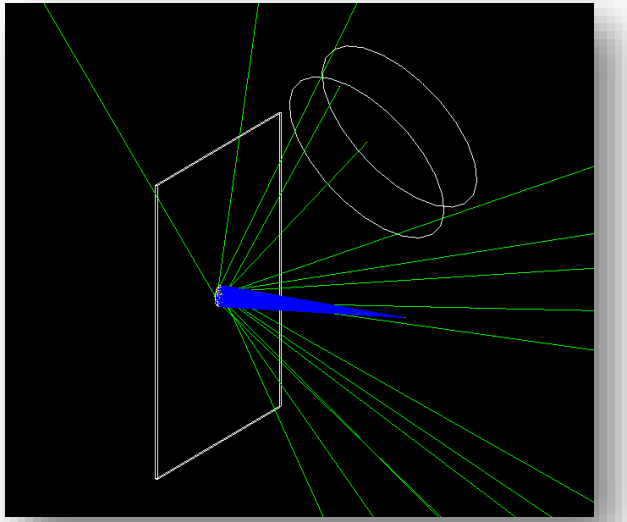
1) Primary particle generation

Proton energy spectrum → Inverse Transform Sampling method → Primary particle energy

2) Primary particle transport & X-ray generation

- Sequence of steps
- Emstandardopt_3

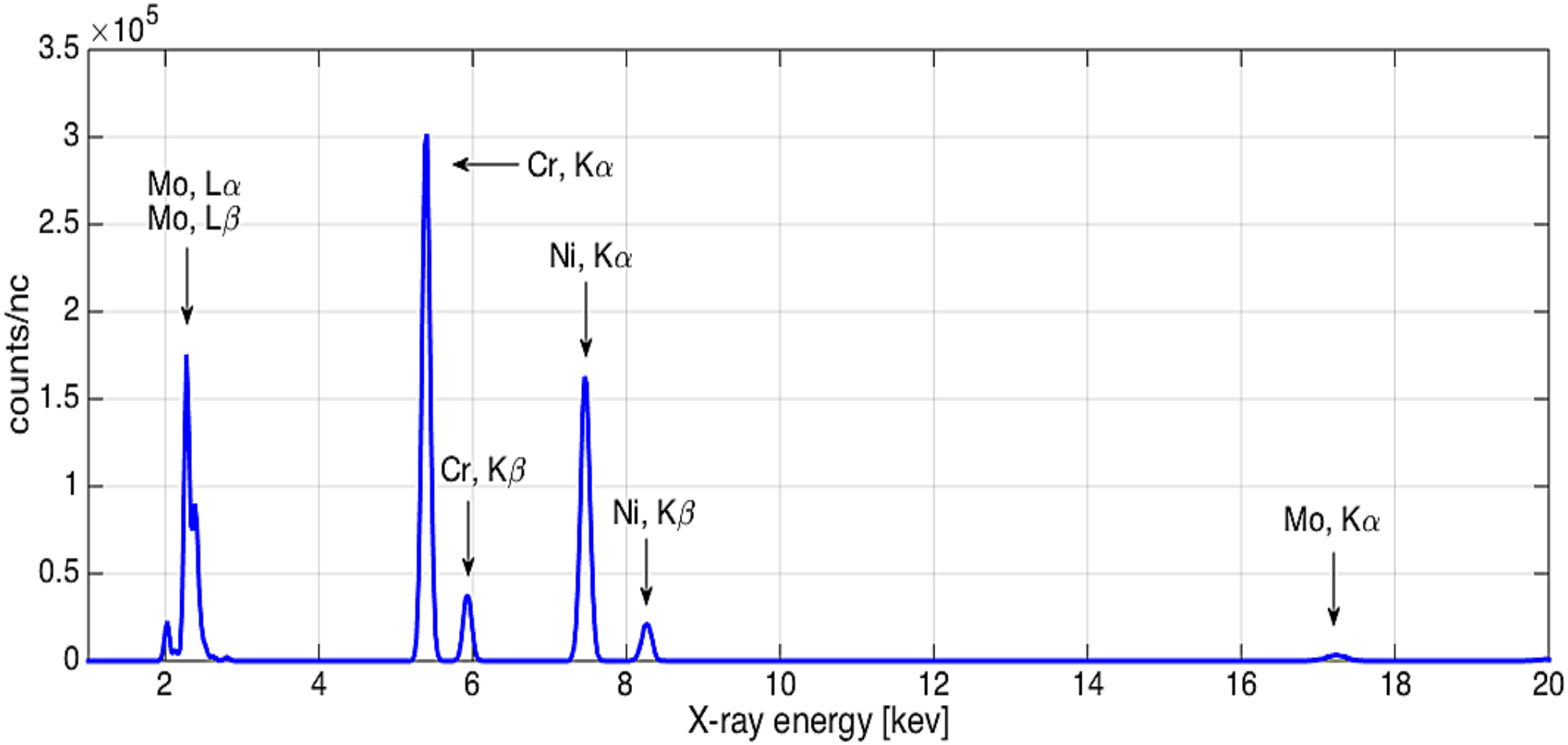
- Ionization (ECPSSR)
- De-excitation (EADL)



3) X-ray detection

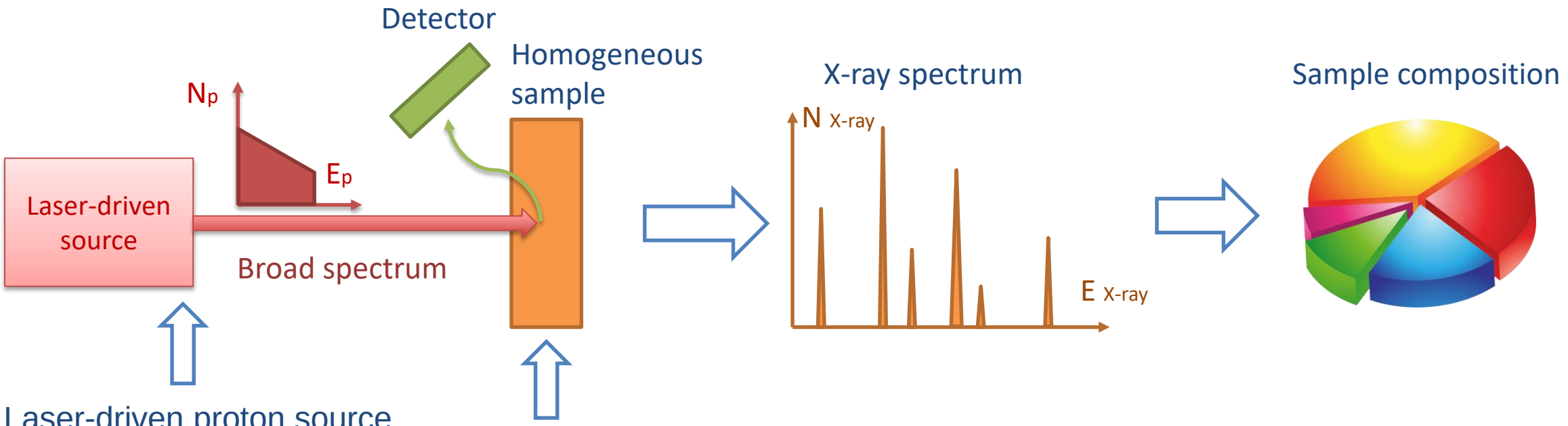
X-ray incident on detection volume → Application of detector efficiency → Collection in spectrum

Synthetic X-ray spectrum from Monte Carlo simulations



Laser-driven PIXE

- Homogeneous sample analysis



- **Pure exponential function**
- PIC simulation result

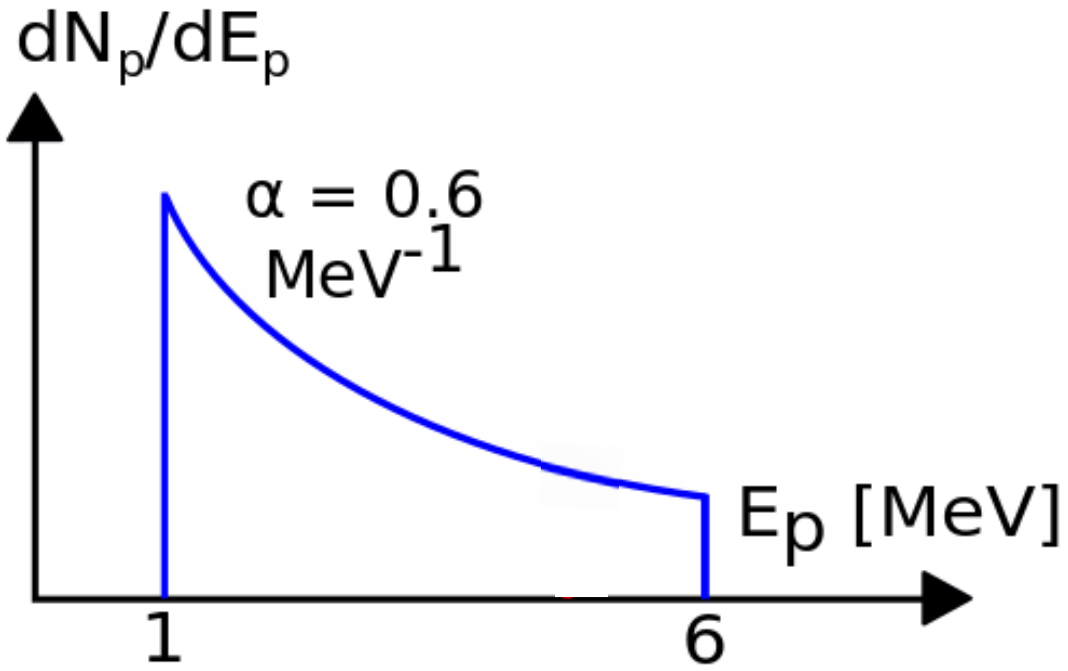
Sample:
15 µm, Ni, Cr, Mo

X-ray yields (Y_1, …, Y_j, …, Y_N) → ***New Iterative process*** → **Sample composition**

$$\frac{Y_j}{N_{p,tot}} = \frac{\Delta\Omega}{4\pi}\varepsilon_j W_j \frac{N_{Av}}{M_j} \int_{E_{p,min}}^{E_{p,max}} f_p(E_p) \int_{E_p}^{0} \sigma_j(E)\ \omega_j\ exp\left(-\mu_j \int_{E_p}^{E} \frac{dE'}{S(E')} \frac{1}{\cos(\theta)}\right) \frac{dE}{S(E)} dE_p$$

Laser-driven PIXE allows to retrieve target composition...

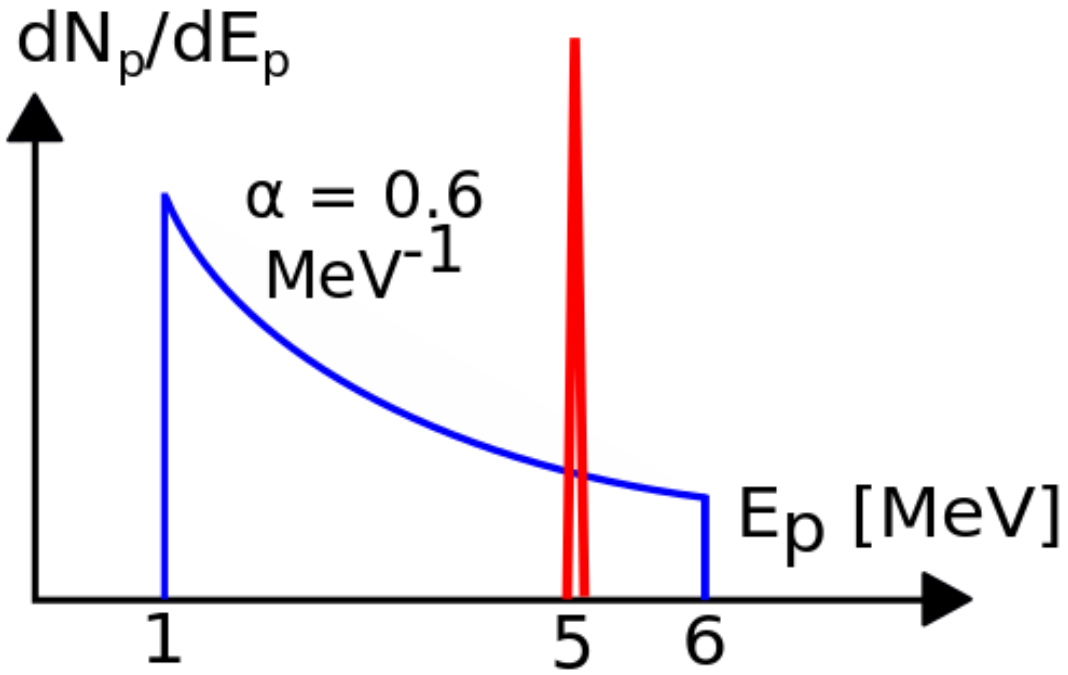
- Homogeneous sample analysis



Element	$W_{j,\,real}$ (%)	$W_{j,\,laser}$ (%)	
Ni	**40.0**	**41.6**	
Cr	**30.0**	**30.3**	
Mo	**30.0**	**28.1**	

...with the same accuracy of traditional PIXE

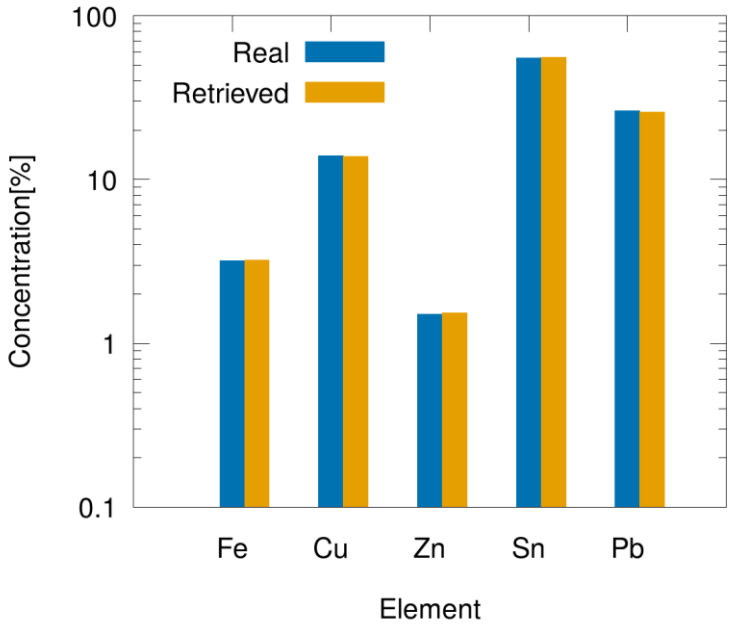
- Homogeneous sample analysis



Element	$W_{j,\ real}$ (%)	$W_{j,\ laser}$ (%)	$W_{j,\ mono}$ (%)
Ni	**40.0**	**41.6**	**40.5**
Cr	**30.0**	**30.3**	**29.8**
Mo	**30.0**	**28.1**	**29.7**

… and what about stability with respect the incident spectrum parameters?

- Homogeneous sample analysis (sword scabbard composition)
- **Pure exponential** energy spectrum



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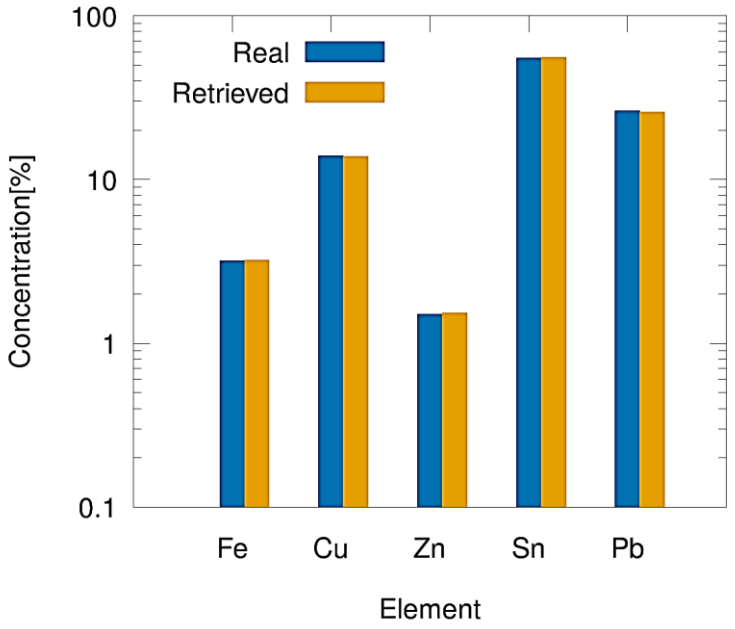
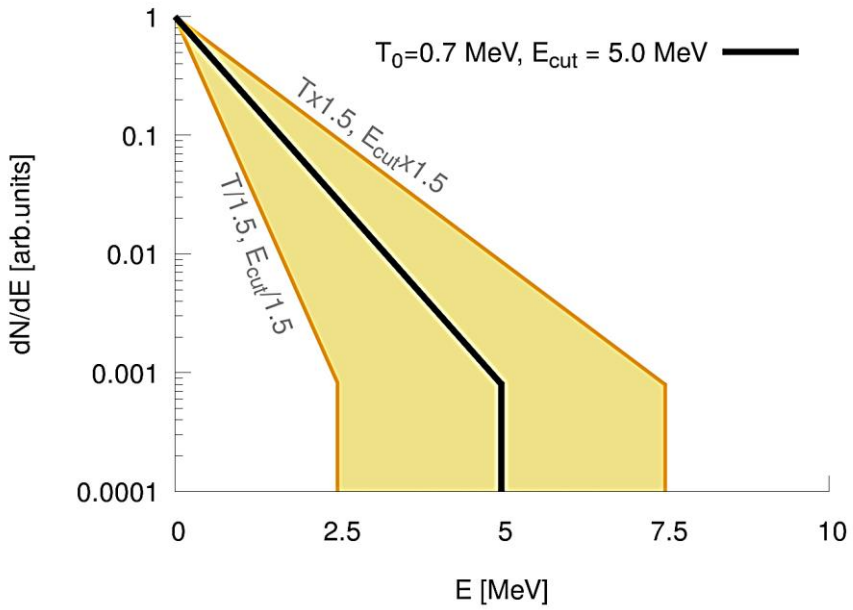
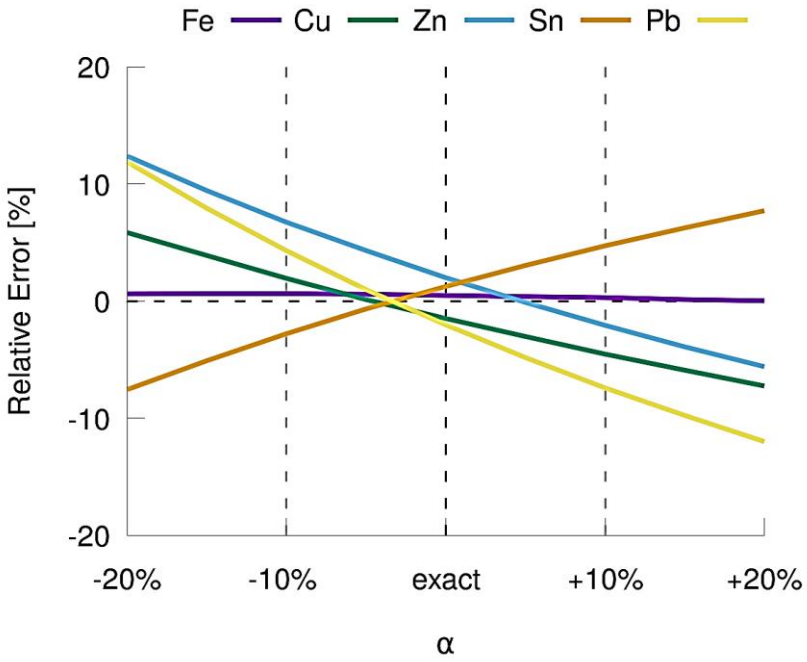
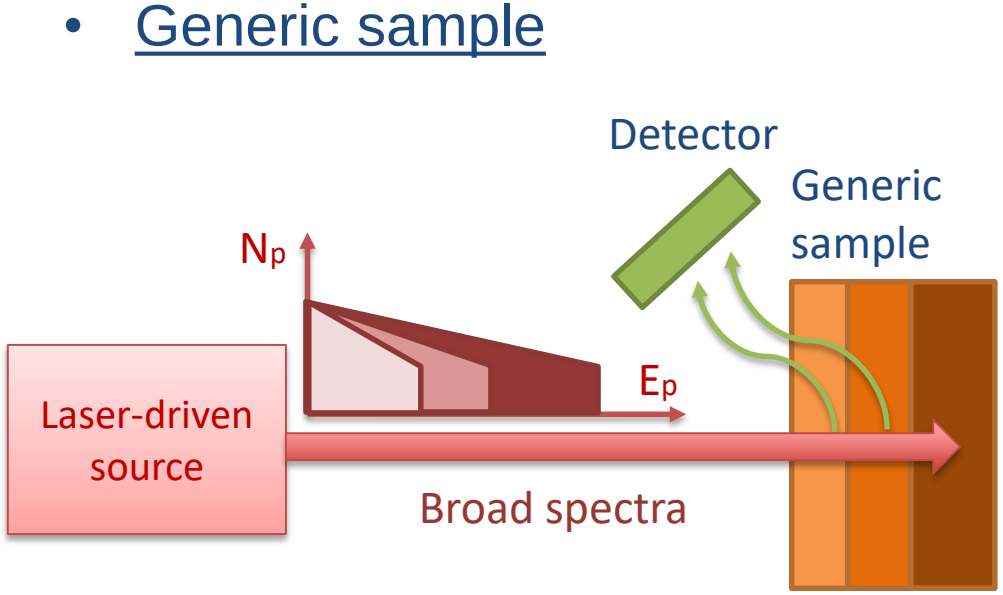


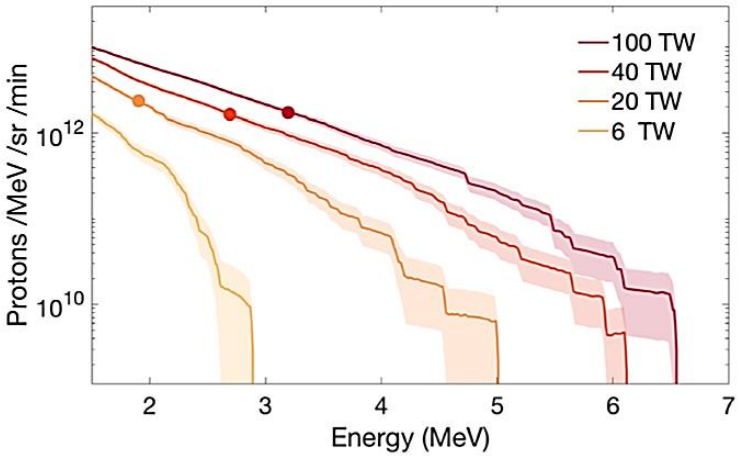


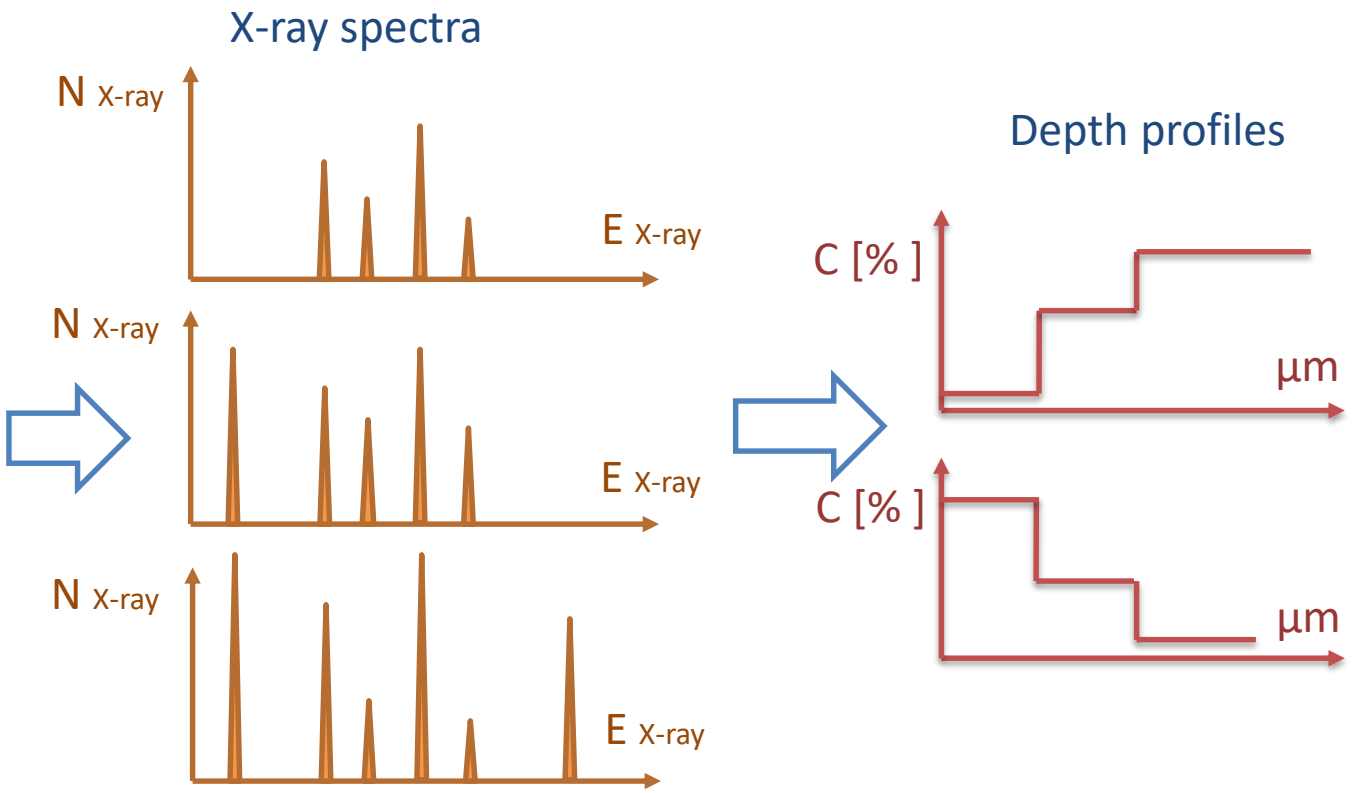


Laser driven differential PIXE

- Generic sample





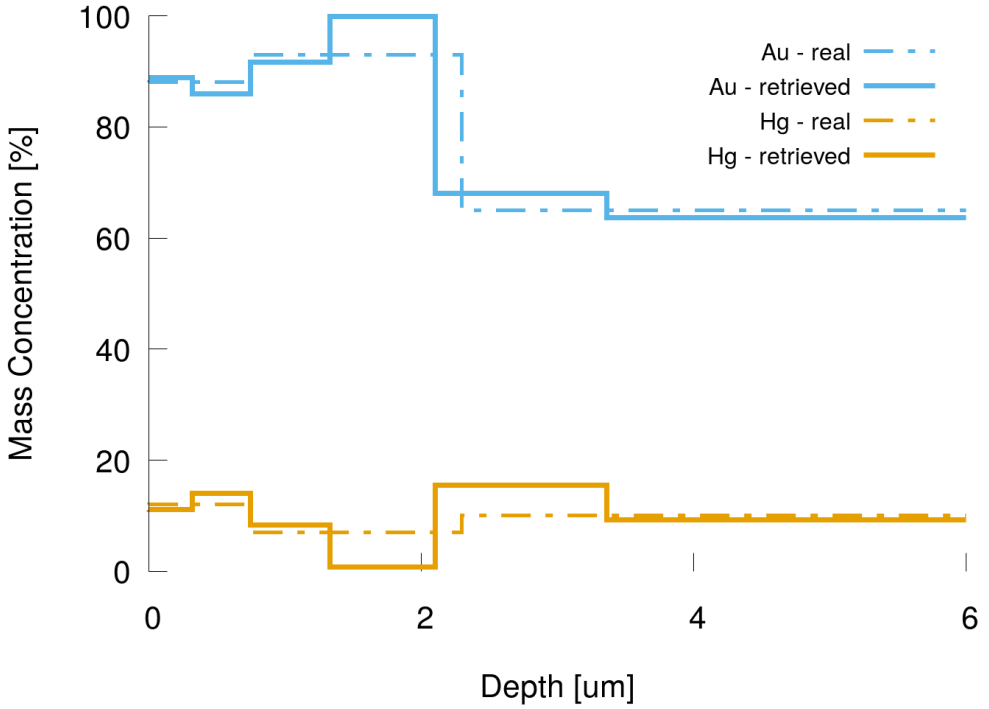


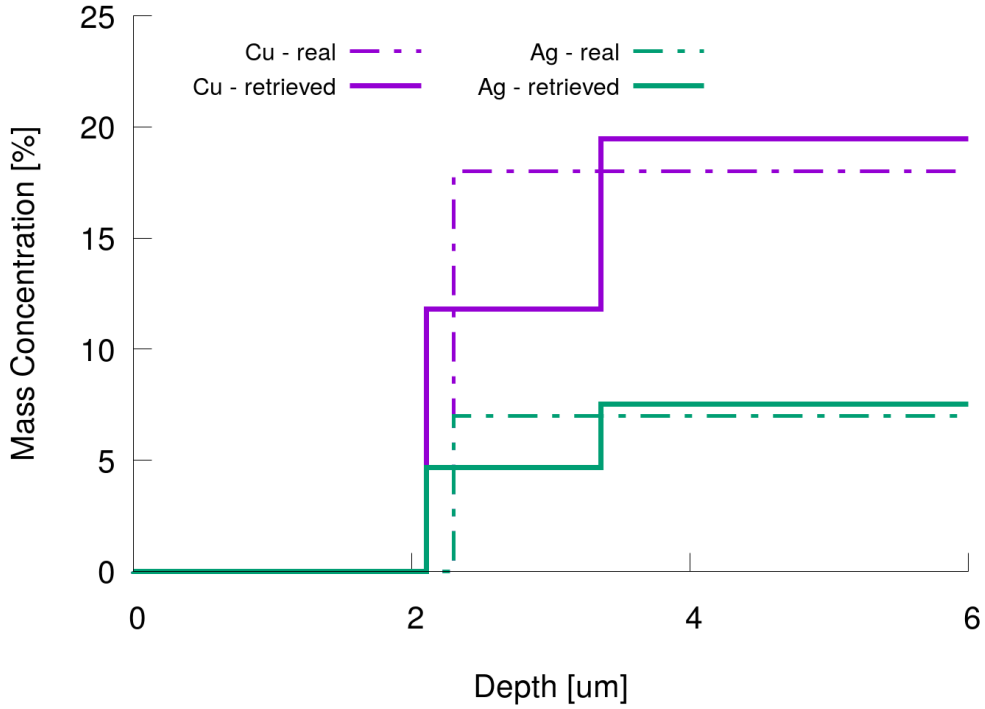
M. Gauthier, et al. High repetition rate, multi-MeV proton source from cryogenic hydrogen jets. Applied Physics Letters, 111(11):114102, 2017.

Laser driven differential PIXE

- Generic sample (gilding layer)

Z. Smit, J. Istenic, and T. Knific. Plating of archaeological metallic objects – studies by differential pixe. ˇ Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 266(10):2329 – 2333, 2008. Accelerators in Applied Research and Technology



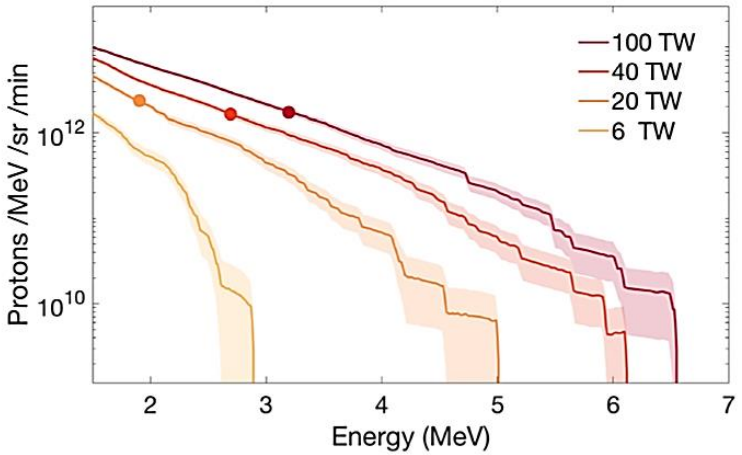


…toward a more realistic laser-driven PIXE simulation…

Compact laser system

- Laser-driven proton acceleration experiments with **10s TWs lasers** documented in literature.

Proton energies suitable for PIXE:



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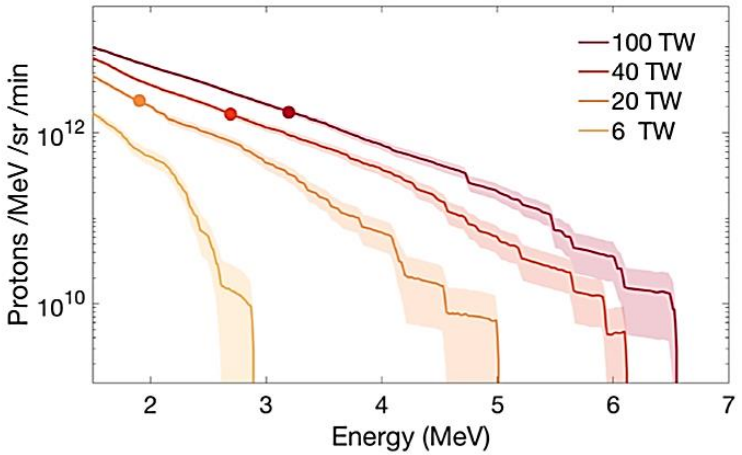

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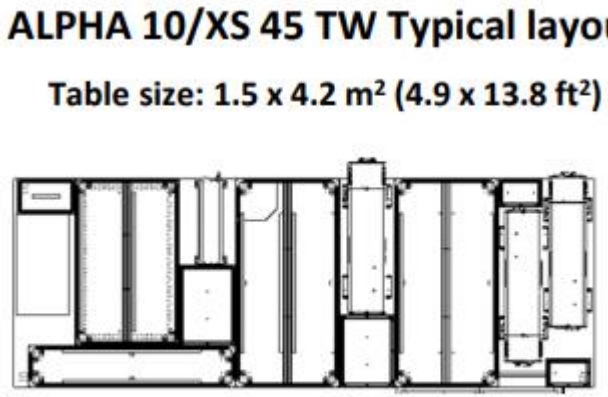
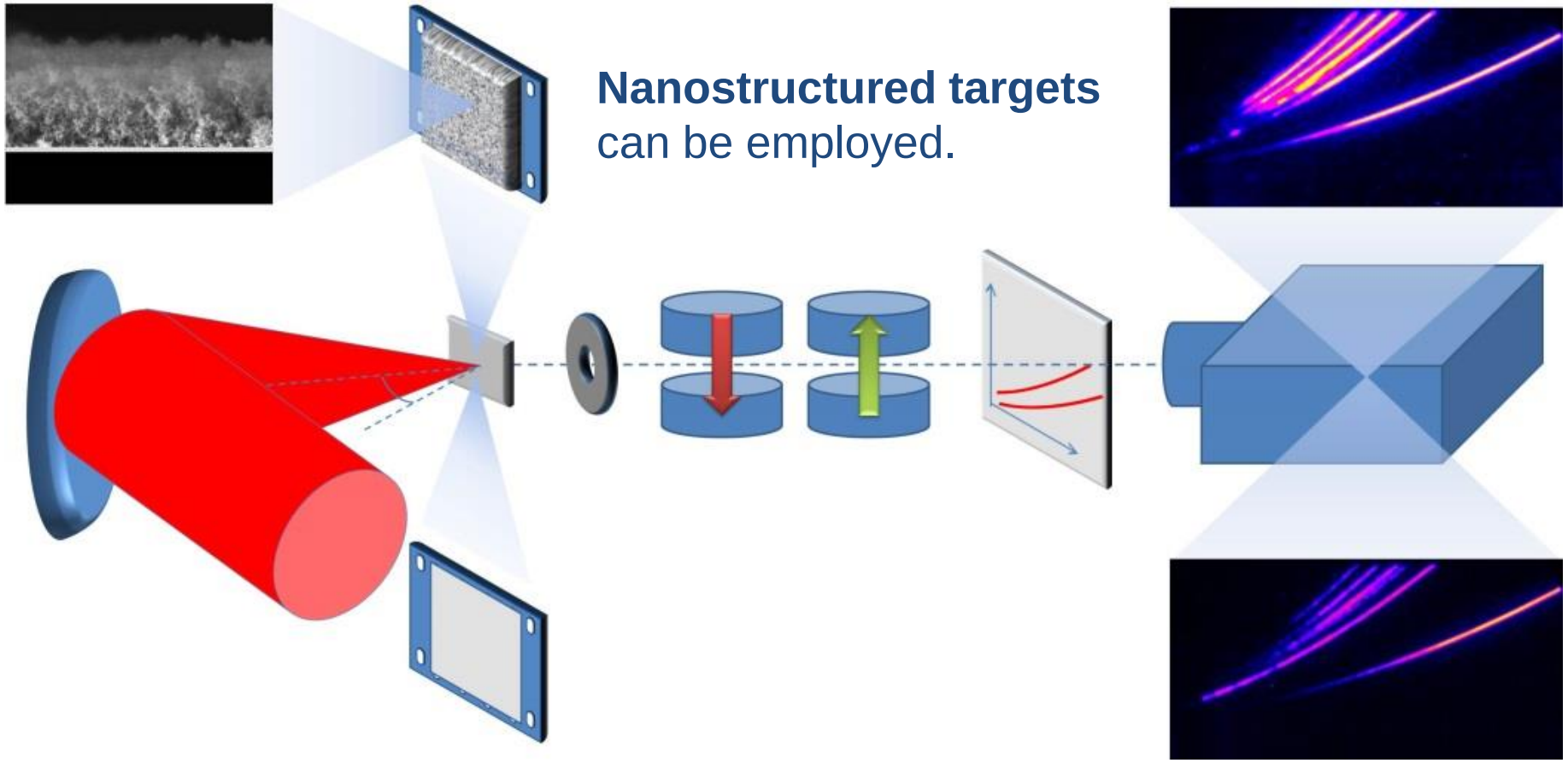


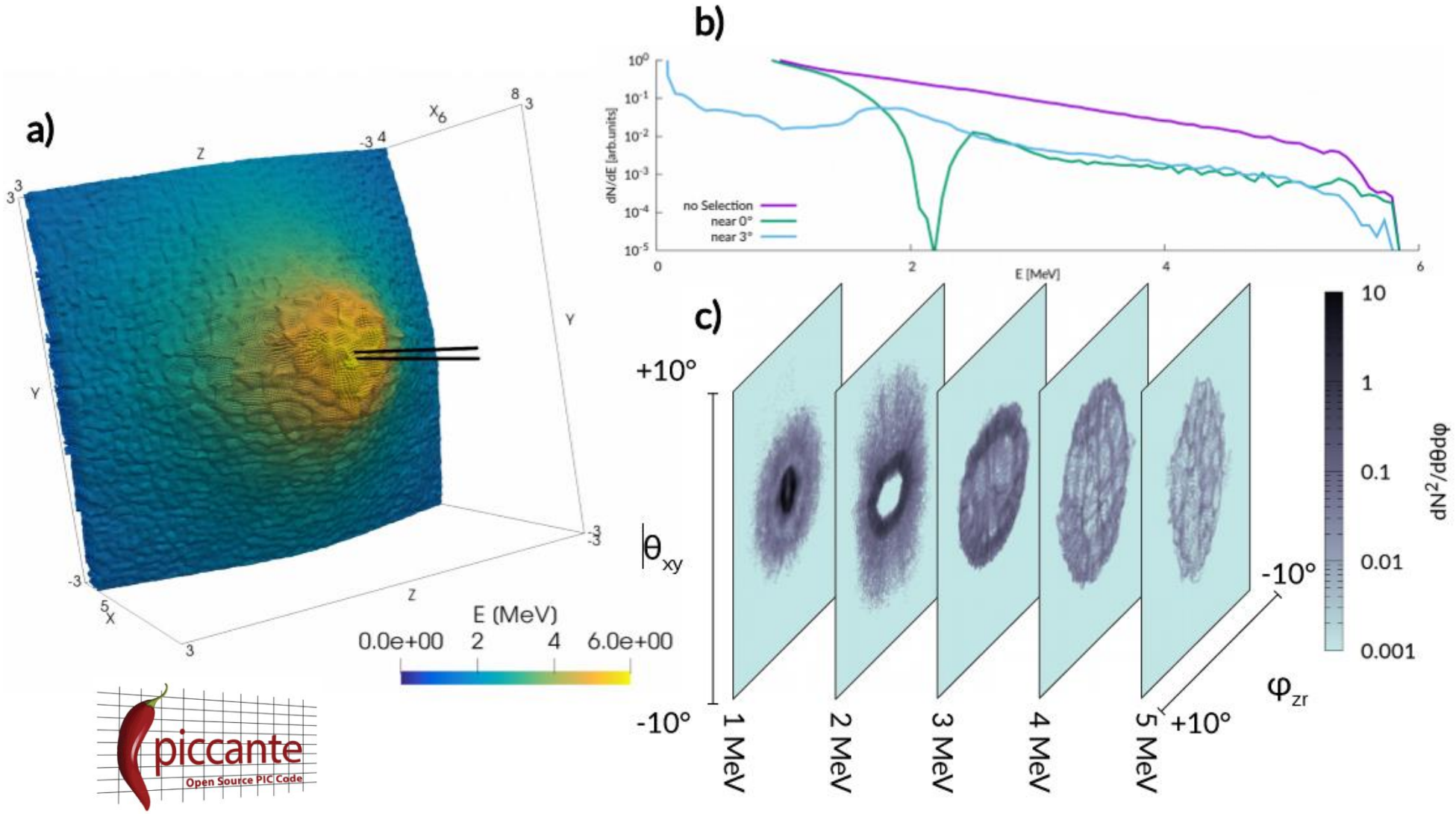
- 10s TW **compact / table–top systems** are **already available**

To further increase the proton energy and number …



M. Passoni, at al. Toward high-energy laser-driven ion beams: Nanostructured double-layer targets. Phys. Rev. Accel. Beams, 19:061301, Jun 2016.

1) Particle In Cell simulations



2) Choice of appropriate X-ray detectors

- **Si(Li)** detector usually employed in PIXE experiments are **unsuitable for laser-driven PIXE**

Dead time ~ μs **VS** X-ray emission time window ~ 10s ns

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- **Si(Li)** detector usually employed in PIXE experiments are **unsuitable for laser-driven PIXE**

Dead time ~ μs **VS** X-ray emission time window ~ 10s ns

Possible solutions:

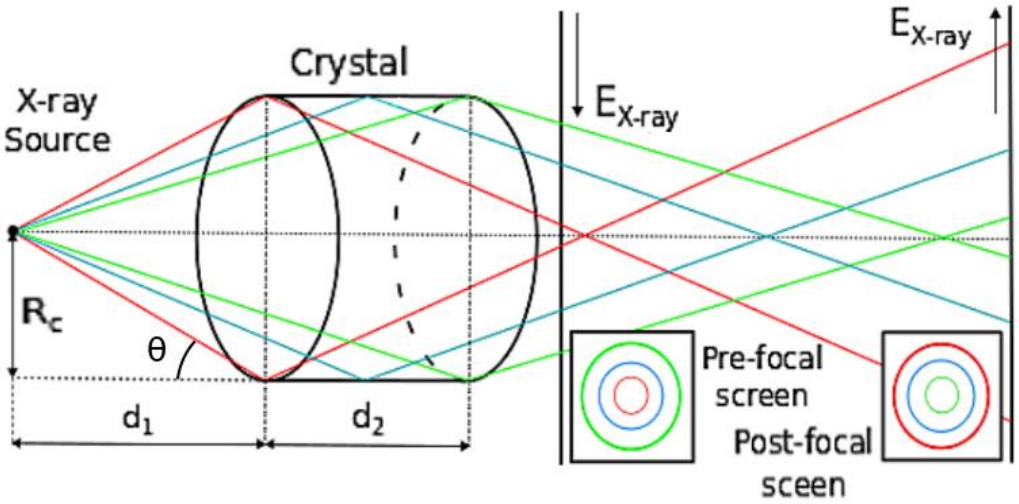
a) **Passive** X-ray **Von Hamos spectromer**

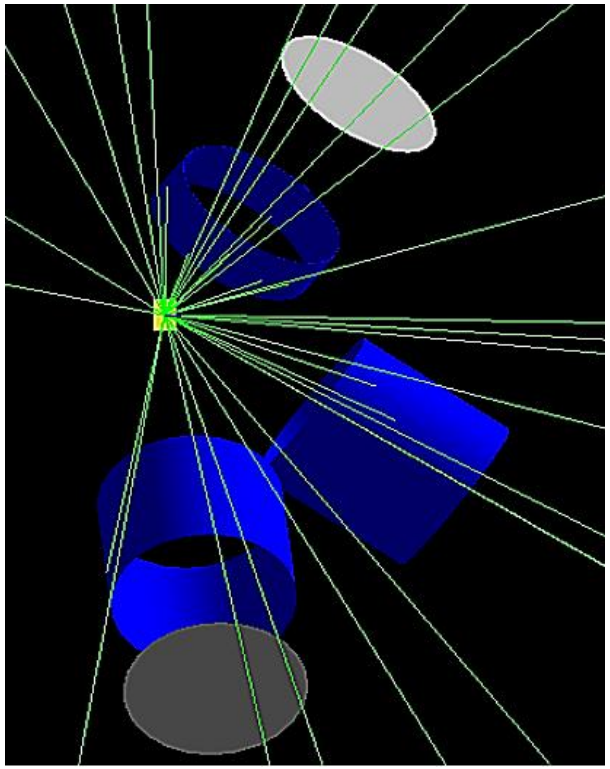
Lars Anklamm et al. A novel von Hamos spectrometer for efficient X-ray emission spectroscopy in the laboratory, 2014

b) **Ultrafast X-ray CCD** working in single shot X-ray absorption spectroscopy

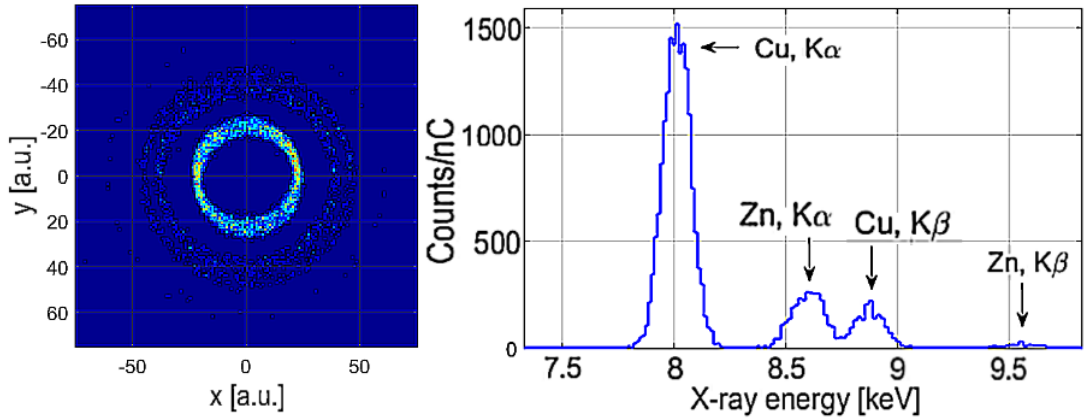
Wei Hong, et al. Detailed calibration of the pi-lcx:1300 high performance single photon counting hard x-ray ccd camera. Chinese Physics B, 26(2):025204, 2017.

a) Full cylinder Von Hamos spectrometer configuration

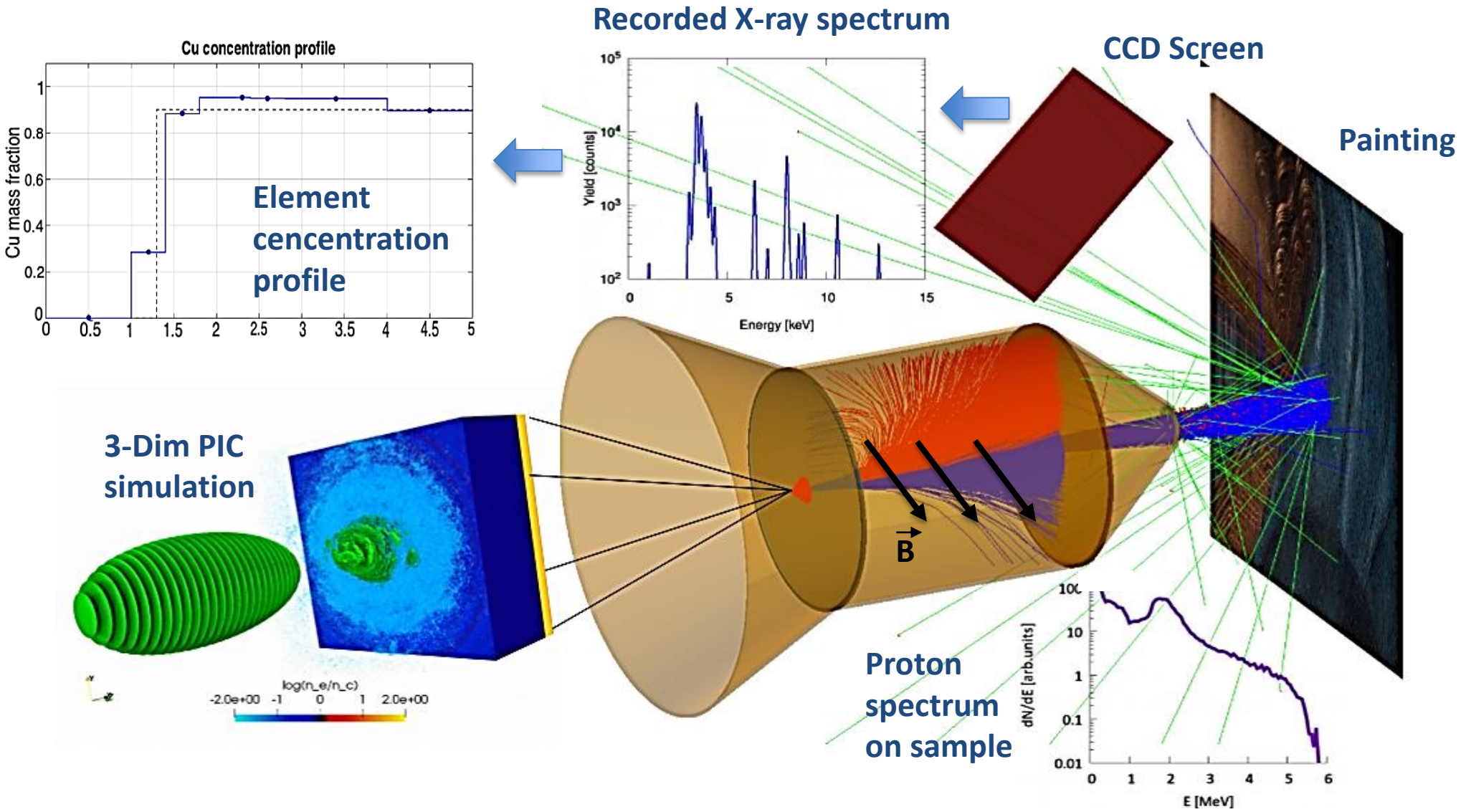




- **Bragg reflection:** $n\lambda = 2dsin\theta$



b) In-air laser-driven PIXE with CCD: …work in progress



Summary:

Extensive theoretical / numerical **investigation** of **Laser-driven PIXE feasibility**

- **Monte Carlo** simulations **with** exponential, **pure analytical proton energy spectra**
- Coupling of **Monte Carlo** simulations and **Particle in Cell** simulations
- Study of possible **experimental setups**

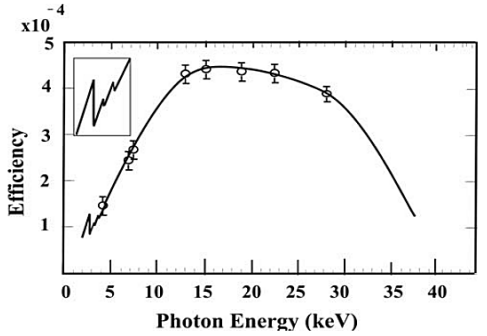
Laser-driven Particle Induced X-ray Emission is really possible!

More info on our website:
www.ensure.polimi.it

francesco.mirani@polimi.ti

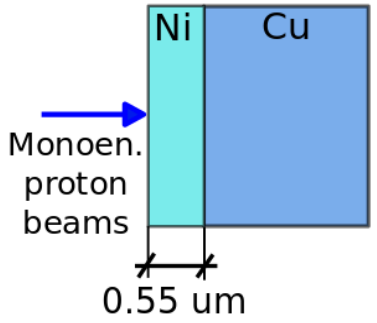
Thank you
for your kind attention

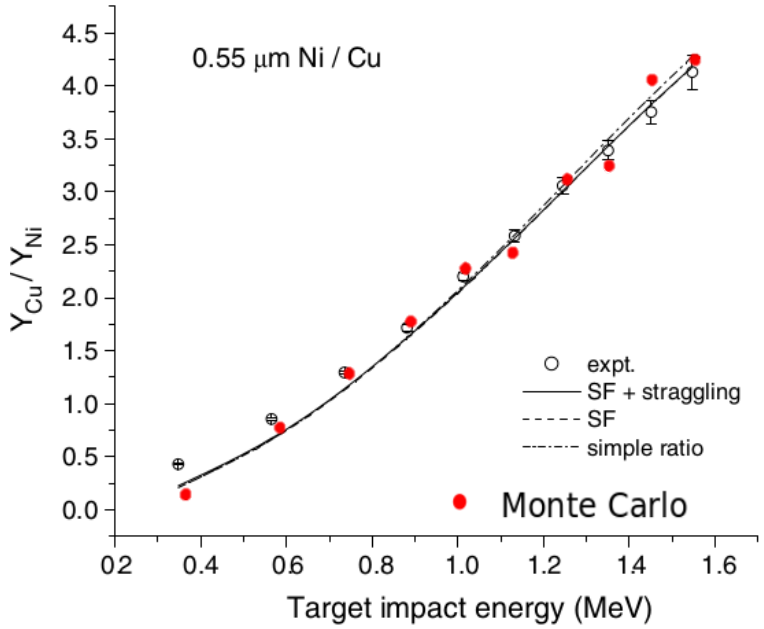
- **Si(Li) detector efficiency**

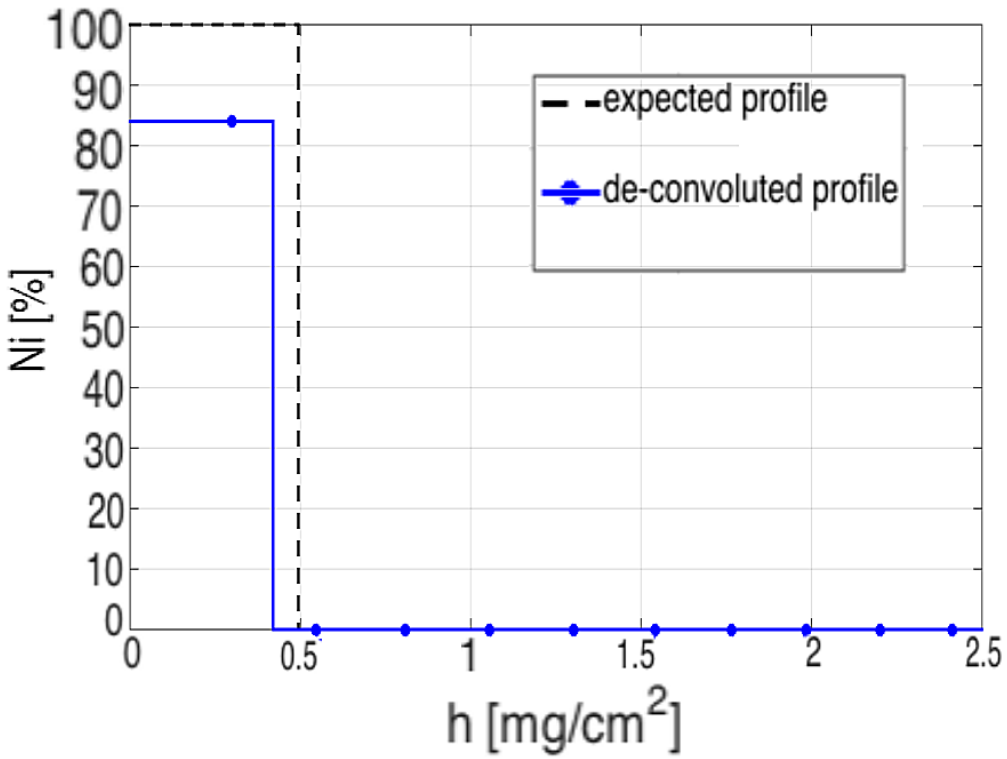


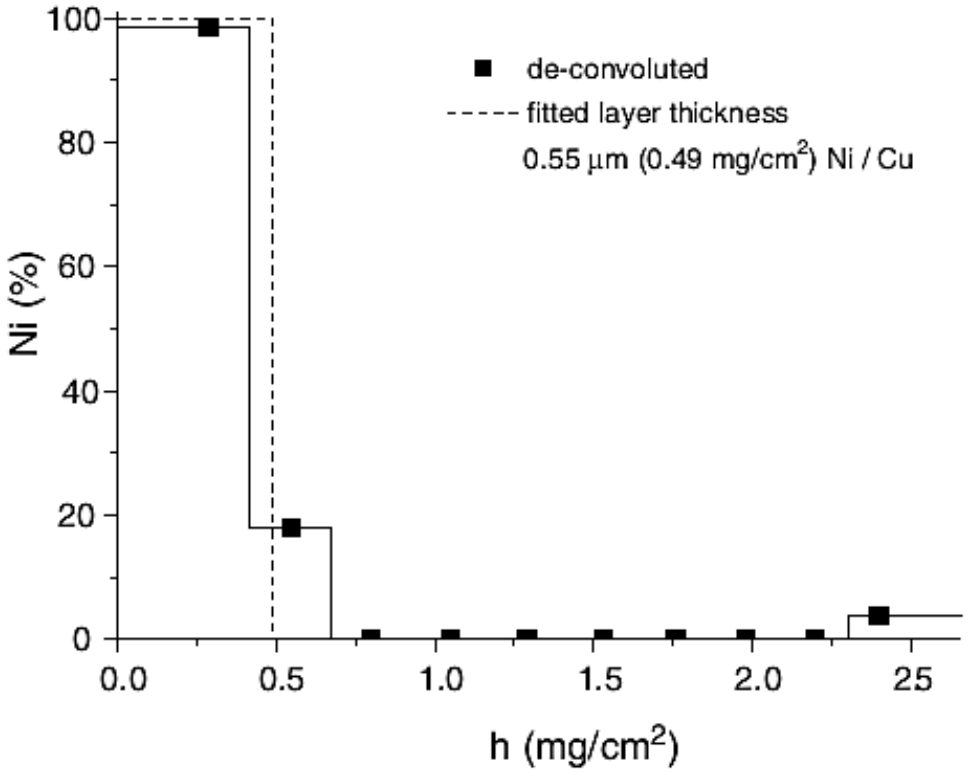
- **Simulation of Differential PIXE experimental results reported in literature [3]**

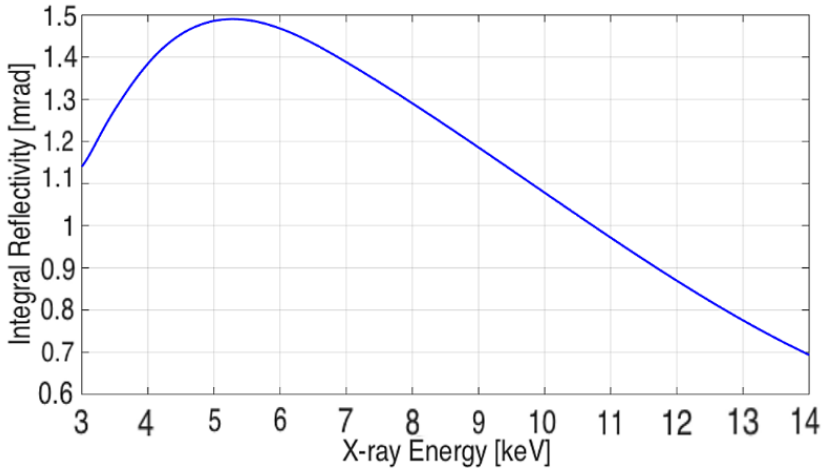
[3] O. Smit: *Differential PIXE measurements of thin metal layers,* 2004

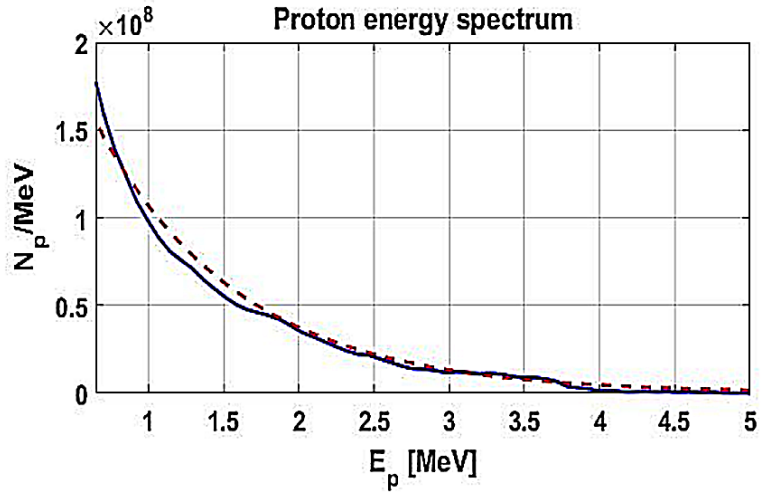


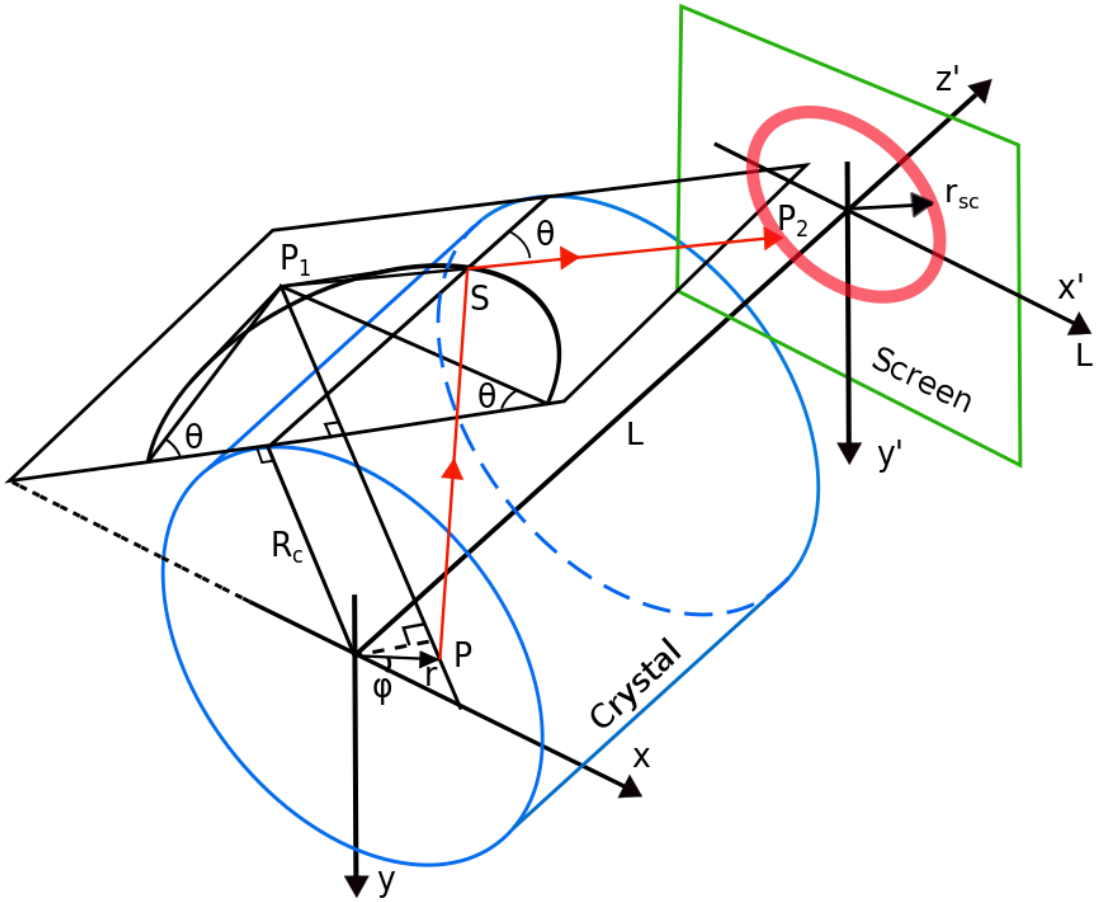



100
90
80
70
60
50
40
30
20
10
0
Ni [%]
0
0.5
1
1.5
2
2.5
h [mg/cm2]
expected profile
de-convoluted profile


100
80
60
40
20
0
Ni (%)
0.0
0.5
1.0
1.5
2.0
25
h (mg/cm2)
de-convoluted
fitted layer thickness
0.55 µm (0.49 mg/cm2) Ni / Cu

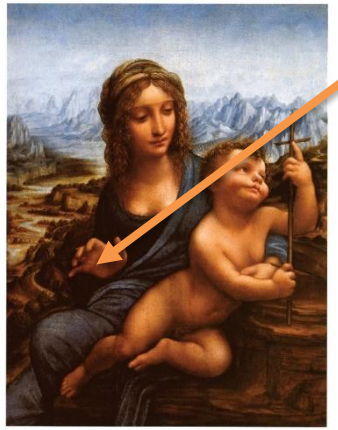

Integral Reflectivity [mrad]
X-ray Energy [keV]


Proton energy spectrum
×10^8
N_p /MeV
E_p [MeV]


z'
x'
y'
L
Screen
r_sc
P_2
P_1
θ
S
R_c
P
φ
Crystal
x
y

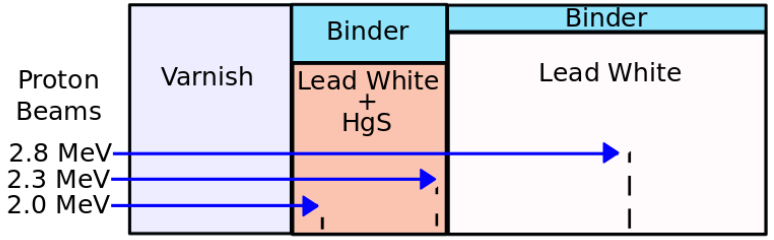
○ Differential PIXE with monoenergetic protons

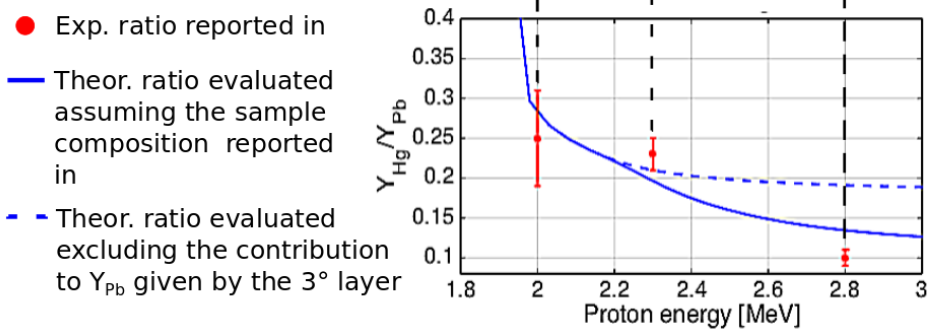
[1] P. A. Mandò: *Differential PIXE measurements for the stratigraphic analysis of the Madonna dei Fusi by Leonardo da Vinci*, 2005



Ratio Y_{Hg} / Y_{Pb} for different E_p

Ratio W_{Hg} / W_{Pb} for different **thicknesses**

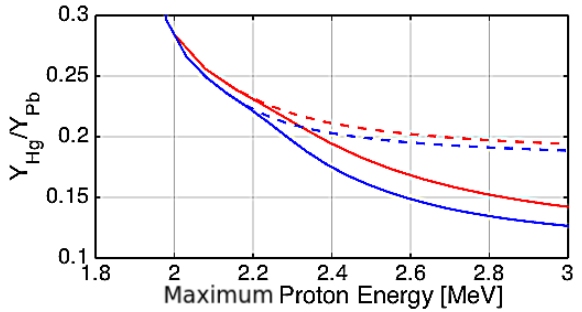


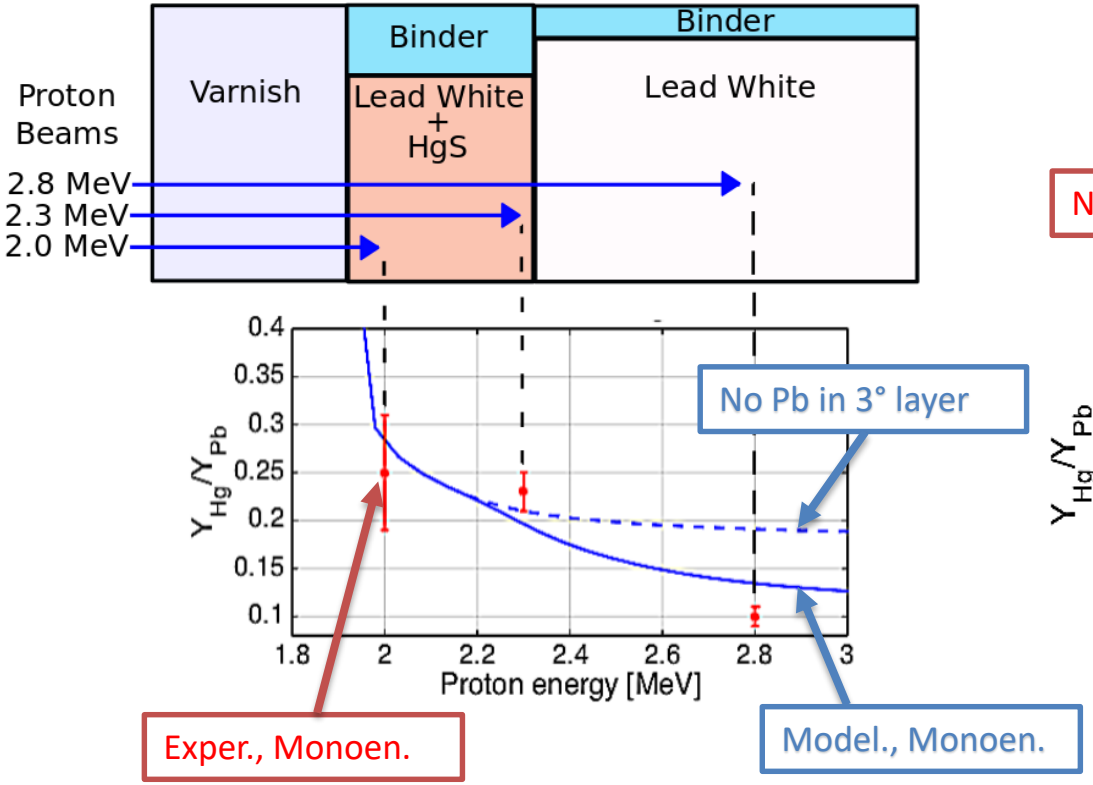


Assessment of the composition

Reconstruction of the sample composition → **Developed model for non-monoenergetic protons** → ○ **Laser-driven PIXE**

○ **Comparison:**

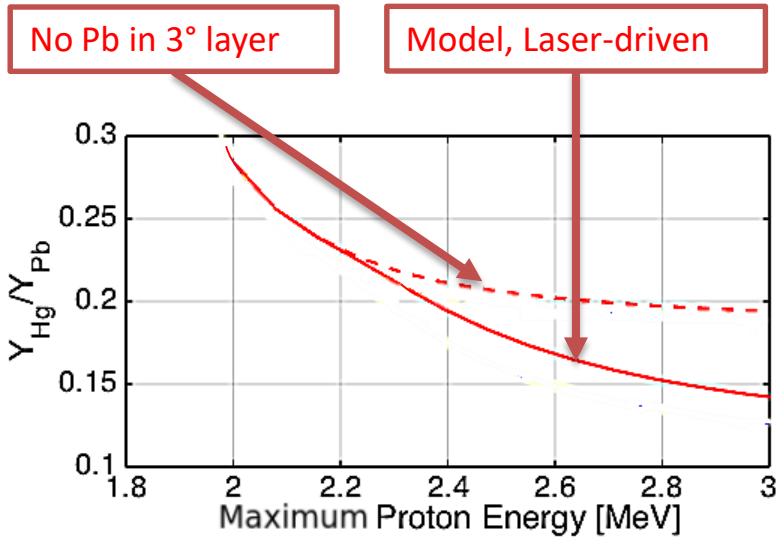




Reasonable hp.
+
Information in [5]

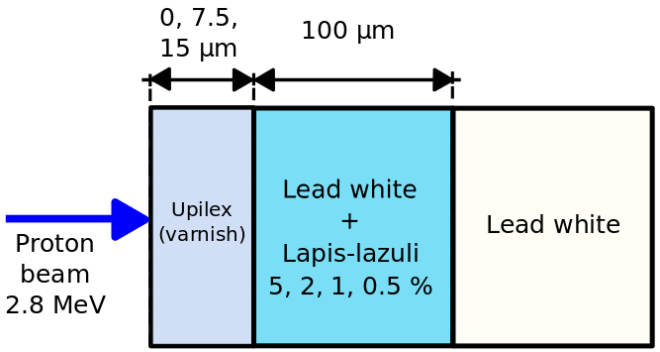
Assessment with the model

- **Laser-driven PIXE:**

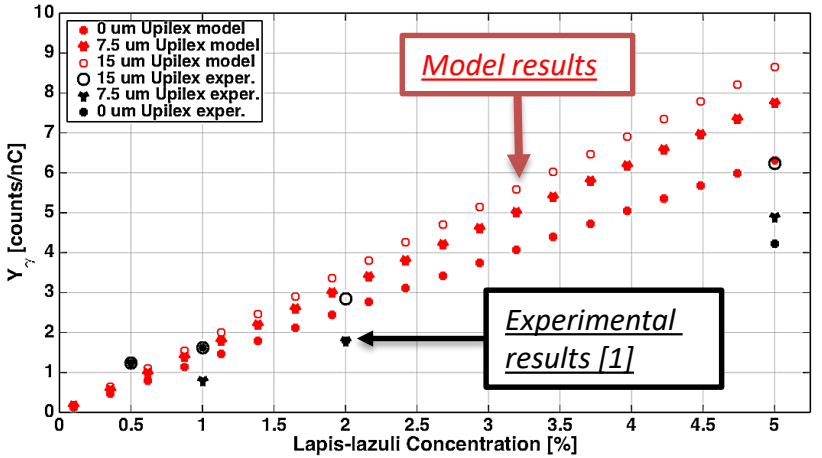


○ Identification of Na with monoenergetic protons

[1] P. A. Mandò: *Identification of lapis-lazuli pigments in paint layers by PIGE measurements*, 2004



Assessment of the composition with model



○ Laser-driven PIGE sensitivity to Na

Sample composition from [1] → **Developed model for non-monoenergetic protons** → **γ-ray yields**