Laser-plasma based hadron sources for materials science applications

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ENSURE
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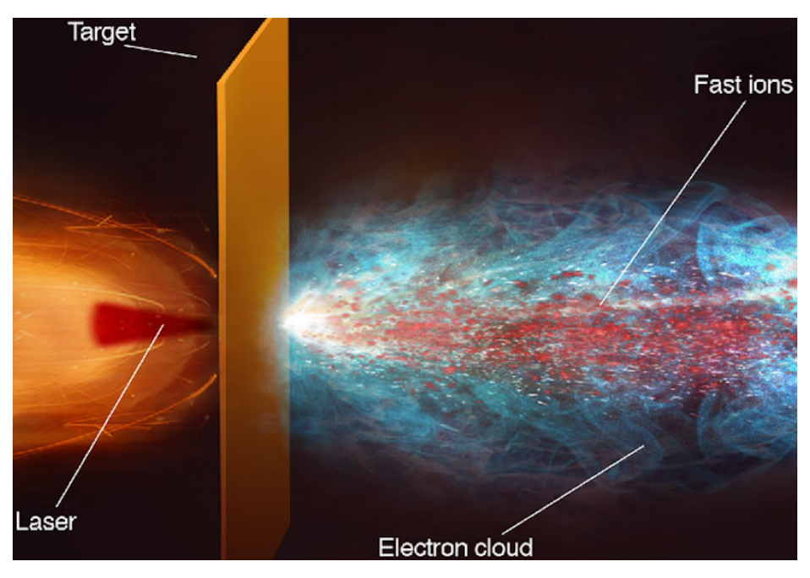
Laser-driven hadron sources could be suitable for materials science

Laser-driven ion acceleration[1] with sub-100 TW lasers:

- ~ 10^{10} proton bunches at < 1 Hz
- broad energy distribution
- several MeV cut-off energy

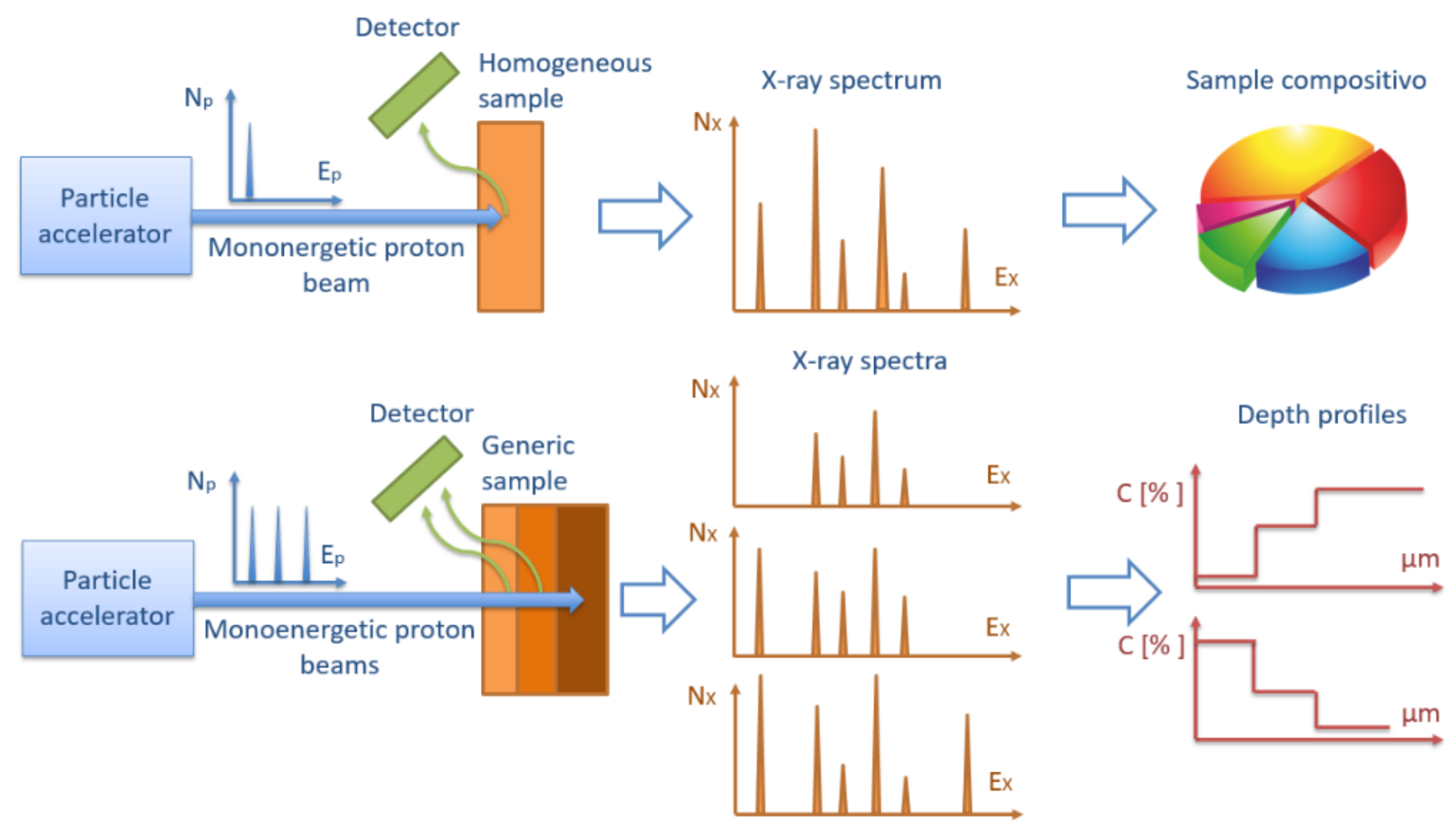


A number of materials characterization techniques rely on few MeV ions and in some cases only a limited flux is required

Laser-driven PIXE is a very promising candidate...

Proton-Induced X-Ray Emission[2,3] (PIXE): a powerful, non-destructive ion beam analysis technique.

- PIXE: retrieve elemental concentrations of a sample
- differential-PIXE: retrieve elemental concentration profiles



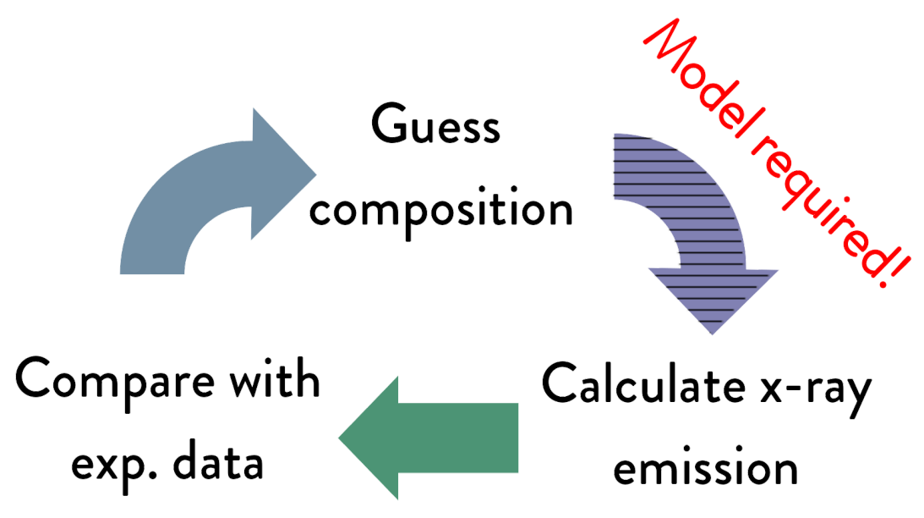
PIXE usually perfomed with large accelerators (e.g. Tandem)

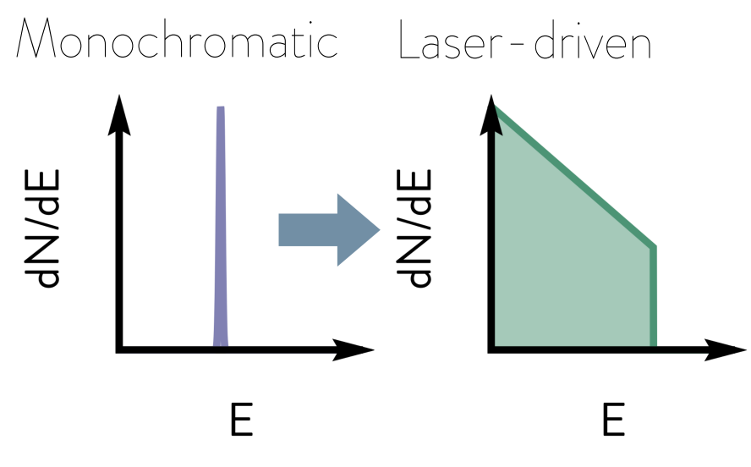
Can we do laser-driven PIXE with a compact laser?
✓PIXE relies on 2-5 MeV protons and ~ 100 pA currents
✓Proof-of-pricinple experiment exists[4]!

...but issues to solve

#1 Theoretical modeling of PIXE with broad-spectrum sources

PIXE relies on an iterative process to reconstruct sample compositions and elemental depth profiles from x-ray yields.


Guess composition
Calculate x-ray emission
Compare with exp. data
Model required!



Existing PIXE theory has been developed for monochromatic sources, thus modifications are needed for laser-driven PIXE[5]

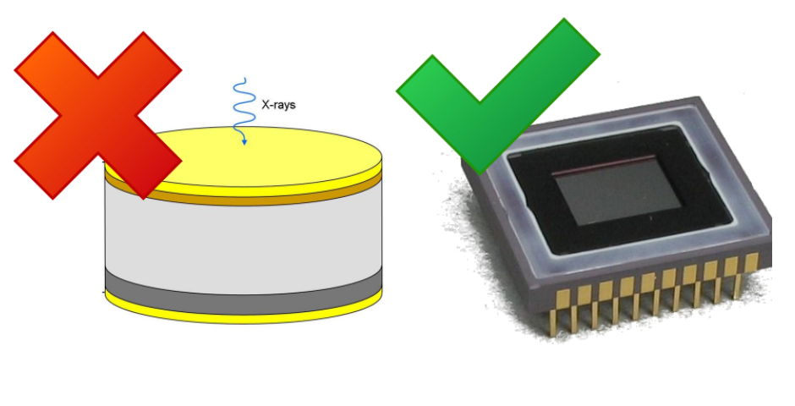
$$Y_i = N_p \frac{\Delta\Omega}{4\pi}\varepsilon_i \frac{N_{av}}{M_i} W_i \int_{E_0}^{E_f} \sigma_i(E)\omega_i e^{-\mu_i \int_{E_0}^{E'} \frac{dE'}{S(E')}\frac{\cos\theta}{\cos\phi}} \frac{dE}{S(E)} \Rightarrow$$

$$Y_i = \frac{\Delta\Omega}{4\pi}\varepsilon_i \frac{N_{av}}{M_i} W_i \int_{E_{p,min}}^{E_{p,max}} f_p(E_p) \int_{E_p}^{0} \sigma_i(E)\omega_i e^{-\mu_i \int_{E_p}^{E'} \frac{dE'}{S(E')}\frac{\cos\theta}{\cos\phi}} \frac{dE}{S(E)} dE_p$$

Yi: x-ray yield. ΔΩ: subtended solid angle, εi: detector efficiency, Nav: Avogadro's number, Ef: final proton energy, σi(E): ionization cross section, ωi: fluorescence yield, S(E): proton stopping power, σi: X-ray attenuation coefficient, θ: proton impact angle, φ: X-ray emission angle, fp(Ep): proton energy distribution (Ep,min and Ep,max : lower and upper cut-offs)

#2 Design a realistic setup

- Beam handling: we should remove electrons from ion beam

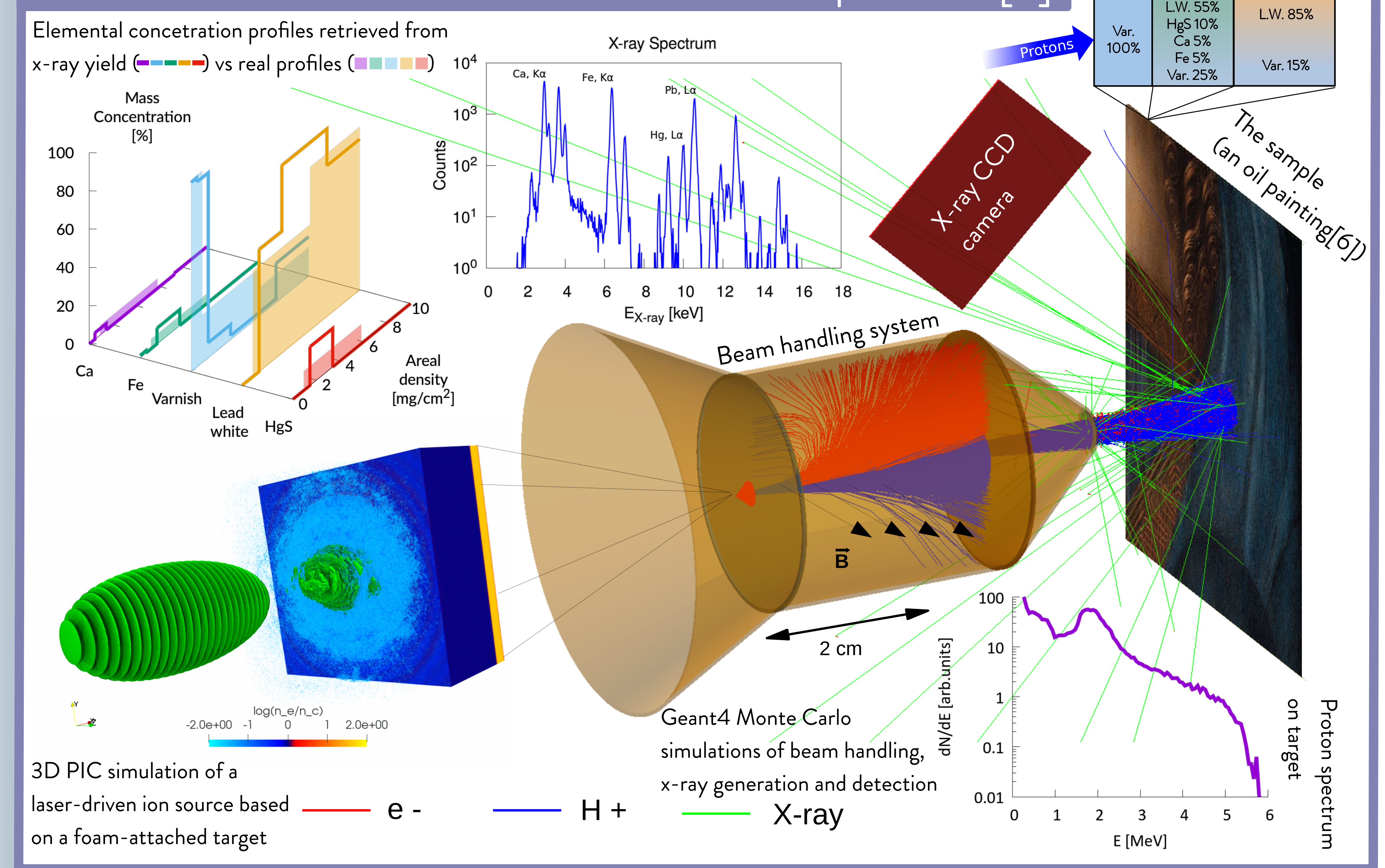


- X-ray detectors: traditional Si-Li unsuitable for laser-driven PIXE (μs dead time). X-ray CCD in single photon counting mode should work.

Will this really work?

We simulated a complete laser-driven PIXE experiment!

A simulated laser-driven differential-PIXE experiment[5]



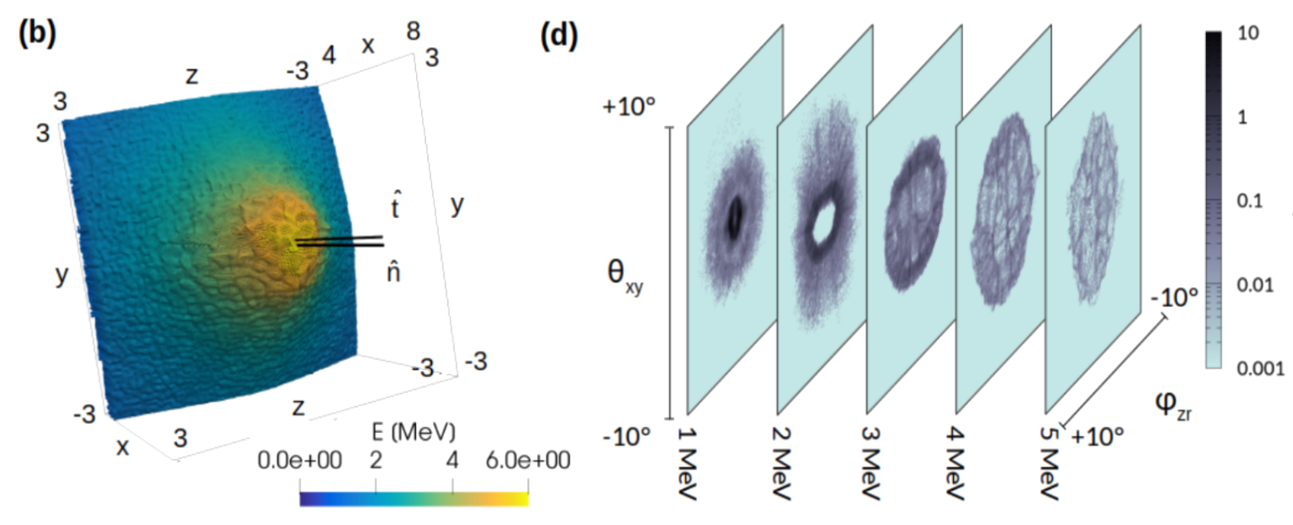
Elemental concetration profiles retrieved from x-ray yield (▬▬▬▬▬) vs real profiles (■■■■■)

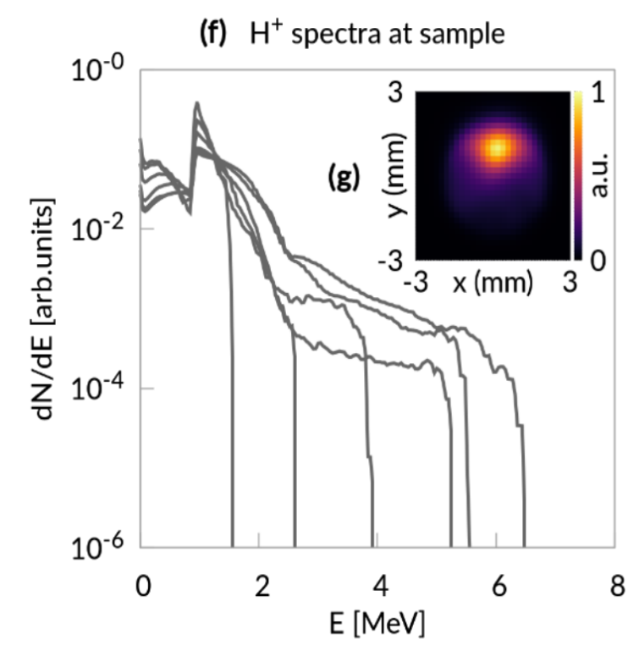
3D PIC simulation of a laser-driven ion source based on a foam-attached target

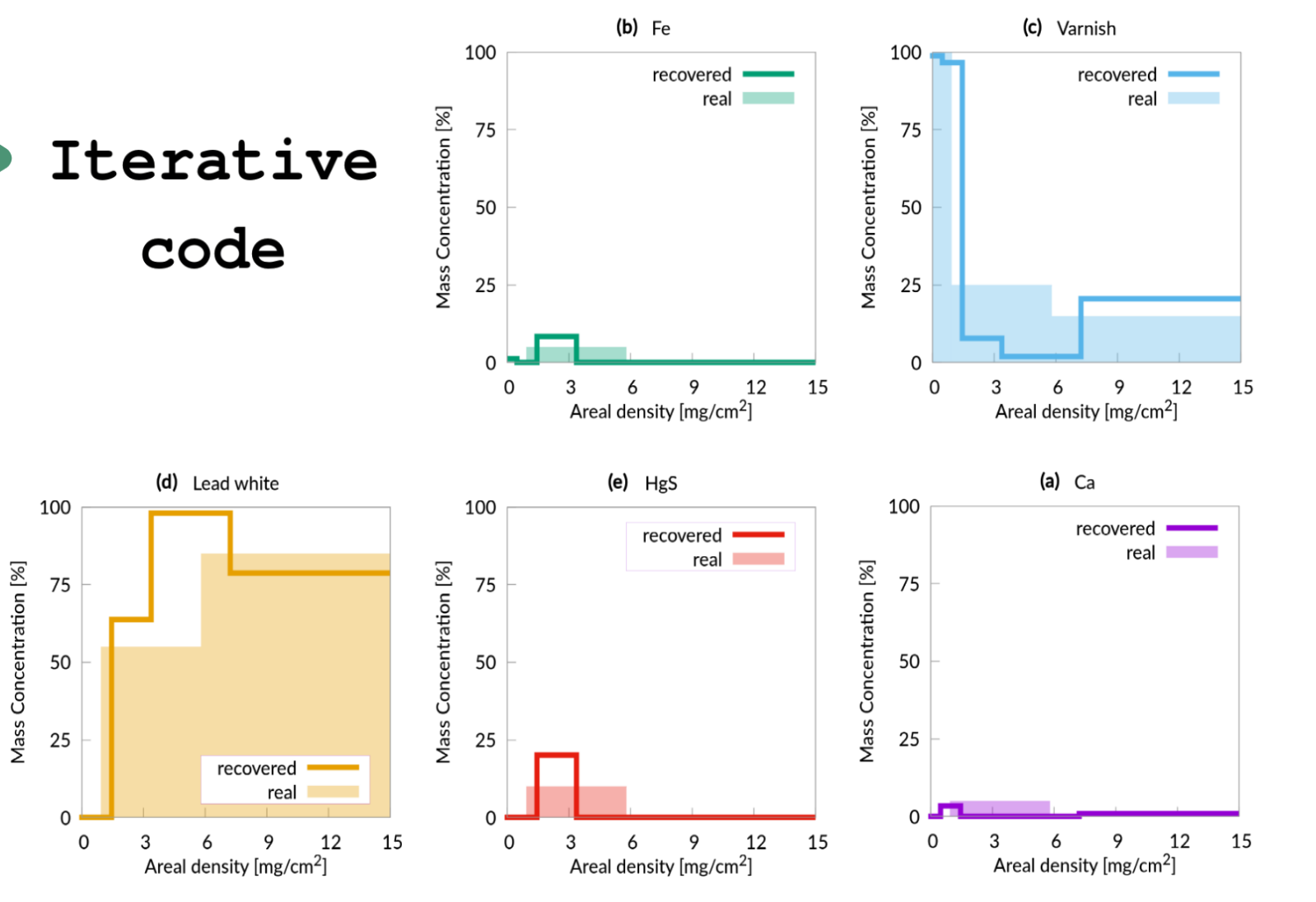
Geant4 Monte Carlo simulations of beam handling, x-ray generation and detection

We performed hybrid PIC-Geant4 simulations...

CINECA
piccante Open Source PIC Code
>>>
GEANT4 A SIMULATION TOOLKIT
>>>
Iterative code







3D Particle-In-Cell simulations with piccante[7]: 30fs laser pulse interacting with uniform-foam coated targets (5 μm, 1 nc + 0.8 μm, 40 nc) at a0 = 2 - 4.5 (3 μm waist, P-pol).
Box: 120λ × 80λ × 80λ, resolution: 40 ppλ

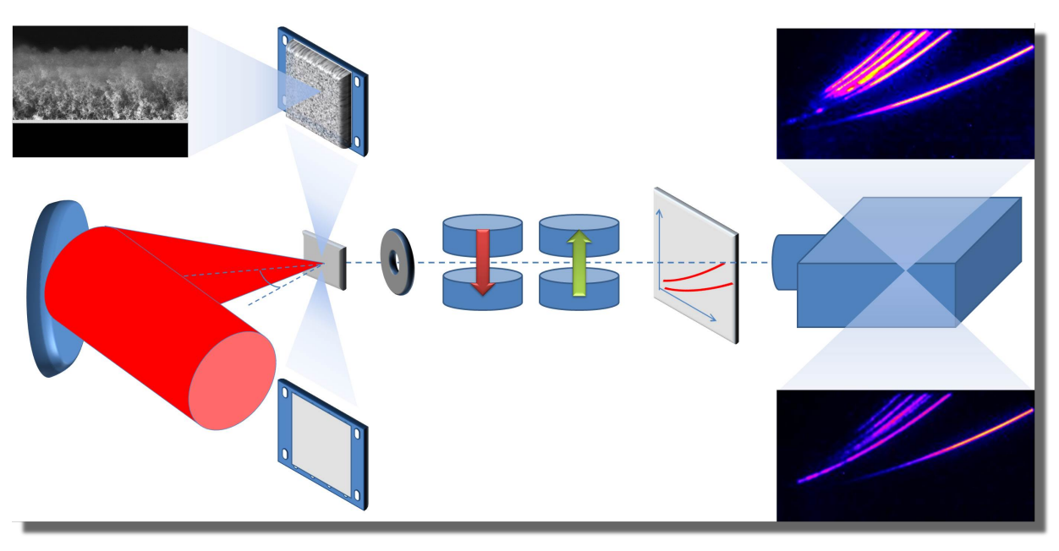
Geant4[8] simulations: performed using ~ 1E10 protons with momenta extract from PIC simulations.

Iterative code:
uses BOBYQA minimization alogirithm to reconstruct elemental depth profiles from exp. yields and knowledge of proton energy distrib.

...and **we think it should work!**

Foam-attached targets to enhance the features of the ion source

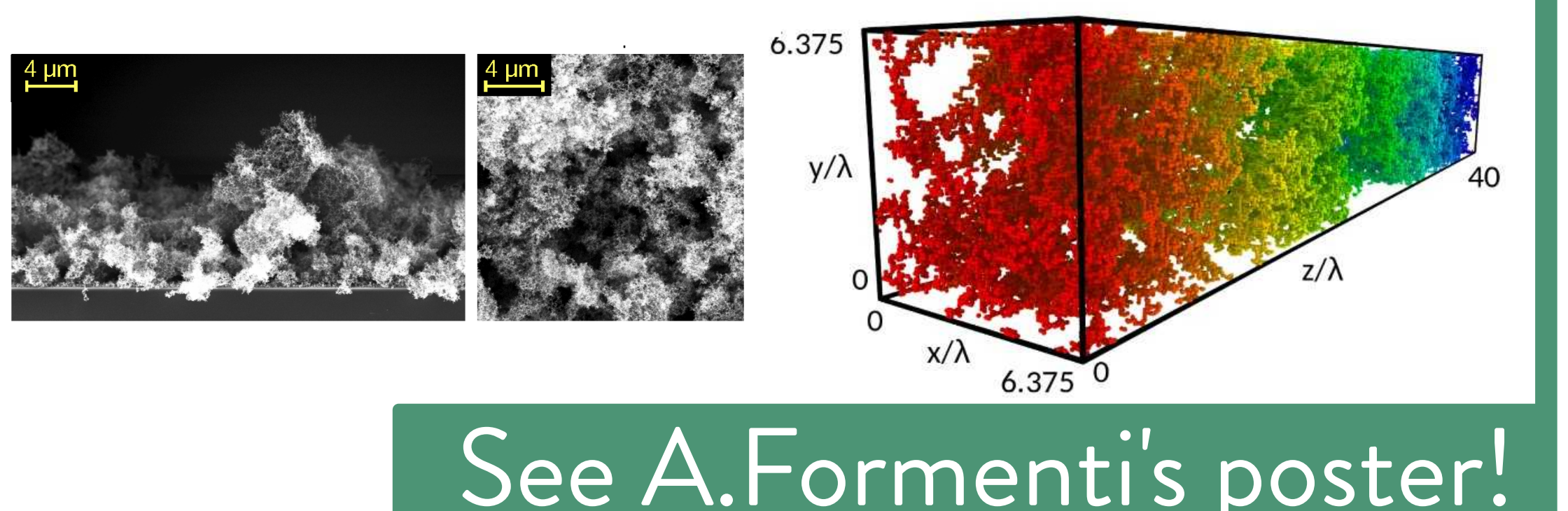
Near- critical foam-attached targets can be used to enhance energy and number of accelerated ions[9,10].



The enhancement is due to several processes: better coupling with near-critical plasmas, self focusing...

Foam attached targets could lower the requirements on the laser system for laser-driven PIXE.

Low-density foams are inherently nanostructured[11]. Does this affect laser-plasma interaction[12-14]?

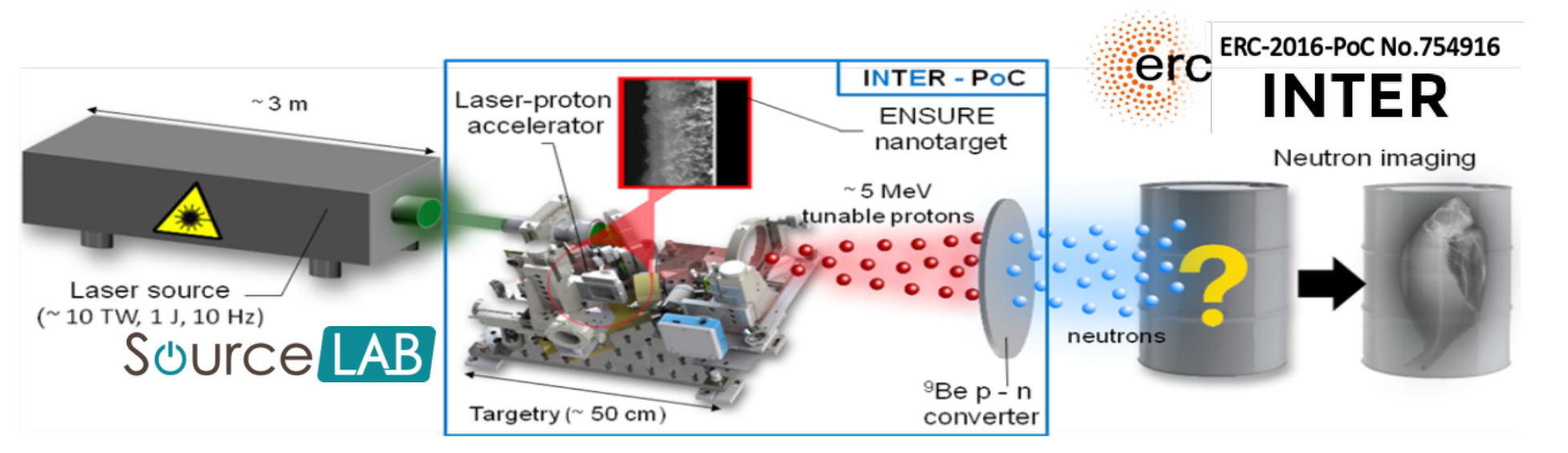


See A.Formenti's poster!

What's next? PIGE & neutrons

PIGE (Proton Induced Gamma-ray Emission): analogous to PIXE, but relies on nuclear reactions. We expect few photons/shot with sub-100 TW lasers.

MeV protons can be used to generate neutrons with Li/Be converters for radiography/spectroscopy applications.



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