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Laser-driven Ion Acceleration

Matteo Passoni

Intensive School
Laser, Plasma & Fusion
Rethymnon, Crete, Greece, 3 September 2024

References about this lecture

…before to get started, if you like

compact, short lists of **references**…

IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. **75** (2012) 056401 (71pp) — doi:10.1088/0034-4885/75/5/056401

Review of laser-driven ion sources and their applications

Hiroyuki Daido[1,2,4], **Mamiko Nishiuchi**[3] and **Alexander S Pirozhkov**[3,4]

[1] Applied Laser Technology Institute, Tsuruga Head Office, Japan Atomic Energy Agency, Kizaki, Tsuruga-shi, Fukui-ken 914-8585, Japan
[2] Quantum Beam Science Directorate, 8-1-7 Umemidai, Kizugawa-shi, Kyoto-fu 619-0215, Japan
[3] Advanced Beam Technology Division, Quantum Beam Science Directorate (at Kansai Photon Science Institute), Japan Atomic Energy Agency, 8-1-7 Umemidai, Kizugawa-shi, Kyoto-fu 619-0215, Japan

REVIEWS OF MODERN PHYSICS, VOLUME 85, APRIL–JUNE 2013

Ion acceleration by superintense laser-plasma interaction

Andrea Macchi*

Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (CNR/INO), U.O.S. "Adriano Gozzini," Pisa, Italy, and Department of Physics "Enrico Fermi," University of Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy

Marco Borghesi†

Centre for Plasma Physics, The Queen's University of Belfast, BT7 1NN Belfast, United Kingdom and Institute of Physics of the ASCR, ELI-Beamlines Project, Na Slovance 2, 18221 Prague, Czech Republic

Matteo Passoni‡

Dipartimento di Energia, Politecnico di Milano, Via Ponzio 34/3, I-20133 Milan, Italy

These are two on the subject, not very up-to-date, but extensive, organic and with long lists of references therein about specific issues and topics

More review references about this lecture

…and additional references about

specific topics

Review: Production of nuclear medicine radioisotopes with ultra-intense lasers

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Published Online: 23 April 2021

View Online Export Citation CrossMark

Zhanliang Sun[a)]

AFFILIATIONS

Department of Nuclear Medicine, The Affiliated Hospital of Southwest Medical University, No. 25, Taiping St., Luzhou, Sichuan 646000, China and Nuclear Medicine and Molecular Imaging Key Laboratory of Sichuan Province, Academician (Expert) Workstation of Sichuan Province, School of Pharmacy, Southwest Medical University, Luzhou, Sichuan 646000, China

Analysis of laser-proton acceleration experiments for development of empirical scaling laws

M. Zimmer[1,*] S. Scheuren[1] T. Ebert,[1] G. Schaumann,[1] B. Schmitz[2] J. Hornung,[3,4,5] V. Bagnoud,[1,3] C. Rödel[1] and M. Roth[1]

[1]*Institute of Nuclear Physics, Technical University of Darmstadt, Schlossgartenstr. 9, 64289 Darmstadt, Germany*
[2]*Institute for Accelerator Science and Electromagnetic Fields, Technical University of Darmstadt, Schlossgartenstr. 8, 64289 Darmstadt, Germany*
[3]*GSI Helmholtz Centre for Heavy Ion Research, Planckstr. 1, 64291 Darmstadt, Germany*
[4]*Friedrich-Schiller-Universität Jena, Fürstengraben 1, 07743 Jena, Germany*
[5]*Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany*

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PAPER • OPEN ACCESS

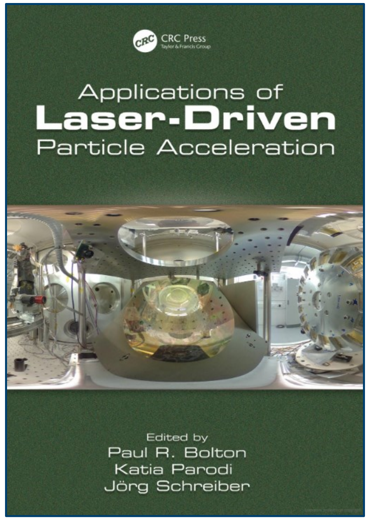
Laser-driven ion acceleration: methods, challenges and prospects

To cite this article: J Badziak 2018 *J. Phys.: Conf. Ser.* **959** 012001

Radiobiology Experiments With Ultra-high Dose Rate Laser-Driven Protons: Methodology and State-of-the-Art

Pankaj Chaudhary[1], Giuliana Milluzzo[2], Hamad Ahmed[2,3], Boris Odlozilik[2,4], Aaron McMurray[2], Kevin M. Prise[1*] and Marco Borghesi[2*]*

[1]The Patrick G. Johnston Centre for Cancer Research, Queens University Belfast, Belfast, Northern Ireland, [2]Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, Belfast, Northern Ireland, [3]Central Laser Facility, Rutherford Appleton Laboratory, Science and Technology Facilities Council, Didcot, Oxford, United Kingdom, [4]Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, Prague, Czech Republic



Advanced laser-driven ion sources and their applications in materials and nuclear science

M Passoni, F M Arioli, L Cialfi, D Dellasega, L Fedeli[1], A Formenti, A C Giovannelli, A Maffini, F Mirani, A Pazzaglia, A Tentori[2], D Vavassori, M Zavelani-Rossi and V Russo

Dipartimento di Energia, Politecnico di Milano, Milan, Italy

E-mail: matteo.passoni@polimi.it

Outline of the presentation

- **INTRODUCTION**:
  - Ultraintense ultrashort laser pulses and interaction with matter
- **CHARGED PARTICLE ACCELERATION IN PLASMAS**:
  - Electrons and ions
  - Main ion acceleration mechanisms (TNSA)
- **LASER-ION ACCELERATION**:
  - Main experimental evidences
- **APPLICATIONS**:
  - Nuclear medicine
  - Material science

Introduction:
laser-matter interaction

…long story, started after the invention of lasers…

Introduction of Chirped Pulsed Amplification (CPA) in 1985 determined a true revolution in the field

Basic principle of CPA:

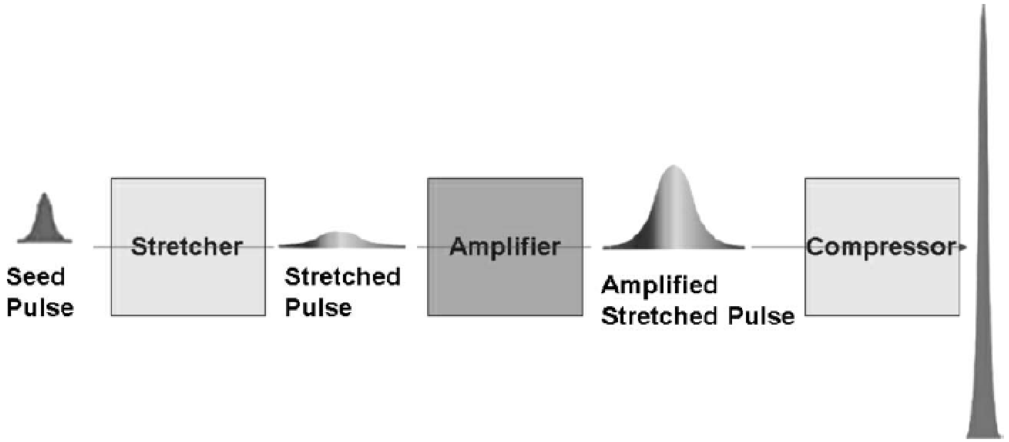


FIG. 4. Chirped pulse amplification concept. To minimize nonlinear effects the pulse is first stretched several thousand times lowering the intensity accordingly without changing the input fluence (J/cm^2). The pulse is next amplified by a factor of 10^6–10^{12} and is then recompressed by a factor of several thousand times close to its initial value.

! See Papadogiannis' lecture

"Optics in the relativistic regime"
G. Mourou, T. Tajima, S.V. Bulanov, *Rev. Mod. Phys.* **78**, 309 (2006)

Typical laser parameters with CPA for laser-driven proton acceleration

Laser **wavelength** (μm): ≈ 1 (Nd-Yag), 0.8 (Ti-Sa), ≈ 10 (CO_2)

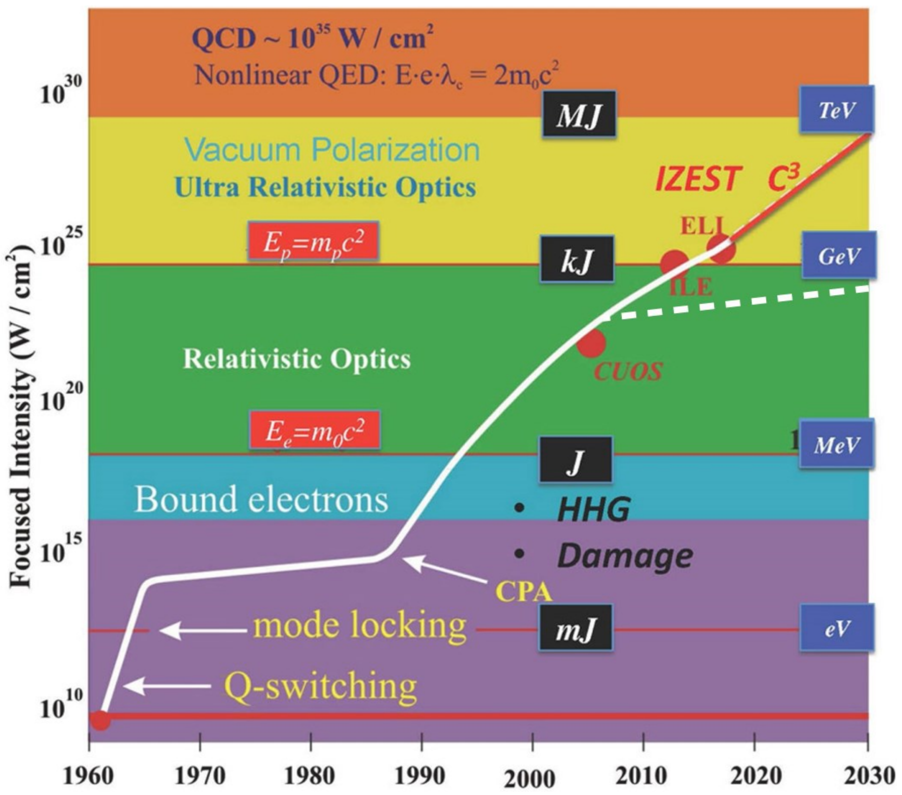
Energy (per pulse): 10^{-1} - 10^{3} J

Power: ≈ 10 TW - few PW

Pulse **duration**: ≈ 10 - 10^3 fs
(at λ = 1 μm, $\tau = c/\lambda$ = 3.3 fs)

Spot size at focus: down to diffraction limit
→ typically, ø < 10 μm

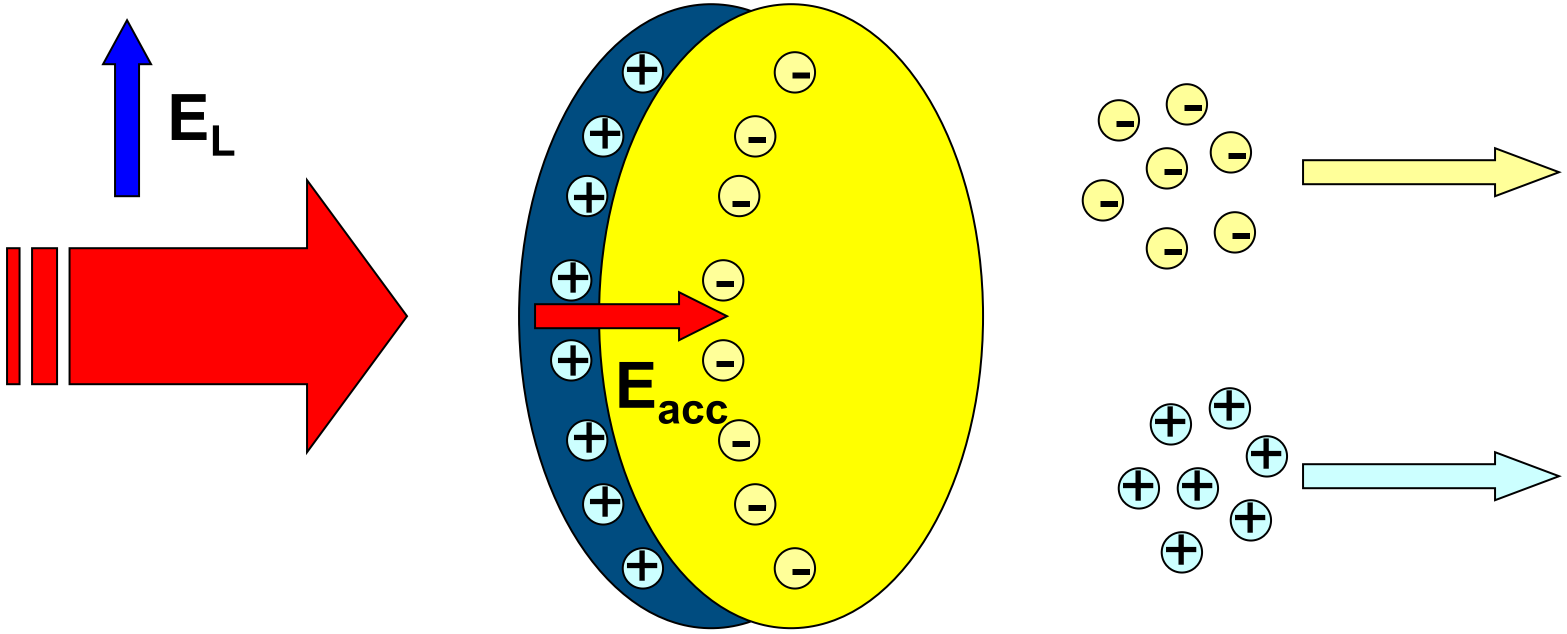
Intensity > few times 10^{18} W/cm^2 (max about 10^{23} W/cm^2)



Laser-plasma based charged particle acceleration: acceleration fields due to charge separation

10 - 1000 fs high-intensity laser pulse causes strong charge separation (directly acting on e^-)

"electric field rectification" ($\tau_{1\mu m}$ = 3 fs)

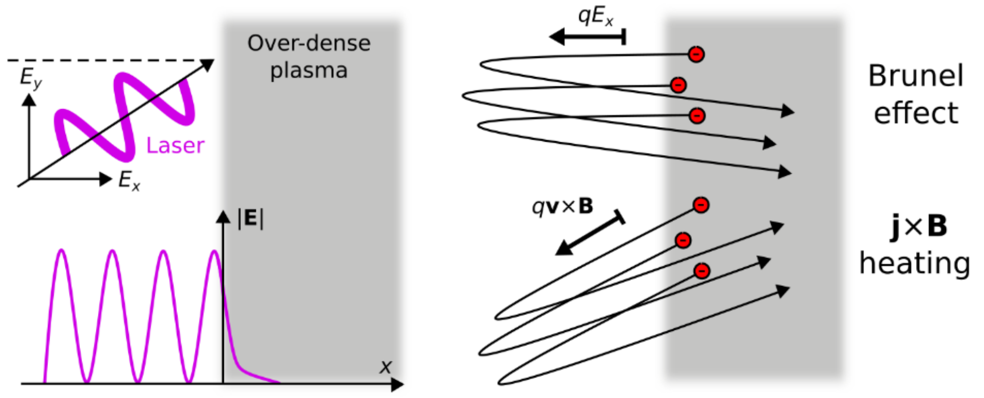


- $E_L \approx E_{acc} \approx$ tens GeV/cm or more $\Rightarrow$ efficient charged particle acceleration
- huge quasi-stationary electric (and magnetic) fields are produced

Laser-plasma based charged particle acceleration: solid (overdense) matter - creation of hot electrons

The dominant interaction **mechanisms** @ ultra-high intensities with solid (overdense) matter are:

- Brunel effect (F. Brunel, Phys. Rev .lett., 59, 52 (1987))
- "J x B" heating (W. L. Kruer et al., Phys. Fluids, 28, 430 (1985))
- **Ponderomotive** electron acceleration

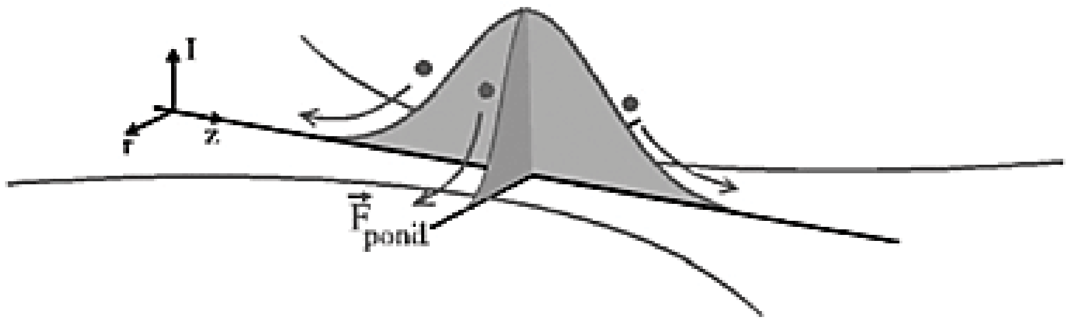


Ponderomotive force (acting mainly on electrons) arises from non-linear terms when the field is spatially not uniform

$$\mathbf{f}_p = -\nabla U_p$$

$$U_p \approx \begin{cases} \dfrac{e^2}{2mc^2}|\mathbf{A}|^2 & \text{non-relativistic} \\ mc^2\left(1+\dfrac{e^2}{mc^2}|\mathbf{A}|^2\right)^{1/2} - 1 & \text{relativistic} \end{cases}$$

$$(eA/m_e c^2)^2 \equiv a^2 \propto I\lambda^2$$



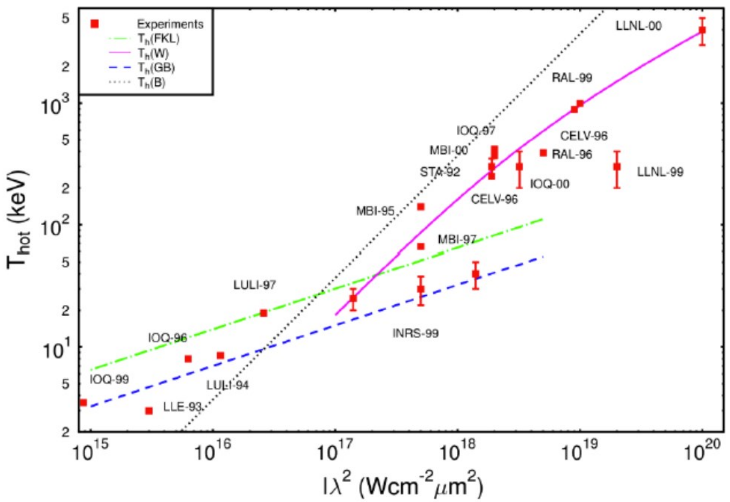
Laser-plasma based charged particle acceleration: hot electron features

Generally speaking, because of the interaction, **laser energy** is partially transferred **to electron kinetic energy**

The properties of this e- population depend on:

- pulse properties (intensity, polarization,…)

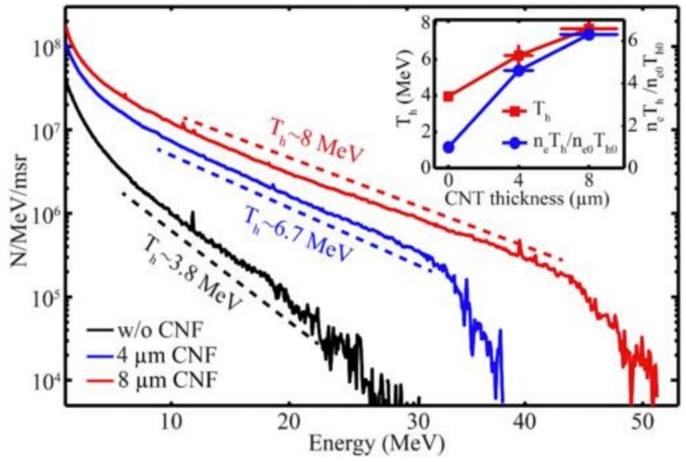
(Fig. 5.19 from Gibbon)



$$T_e \approx U_p = m_e c^2 (\sqrt{1 + c_1 I \lambda^2} - 1)$$

(Collection of exp. data. Solid curve)

- target properties (density, density profile,…)



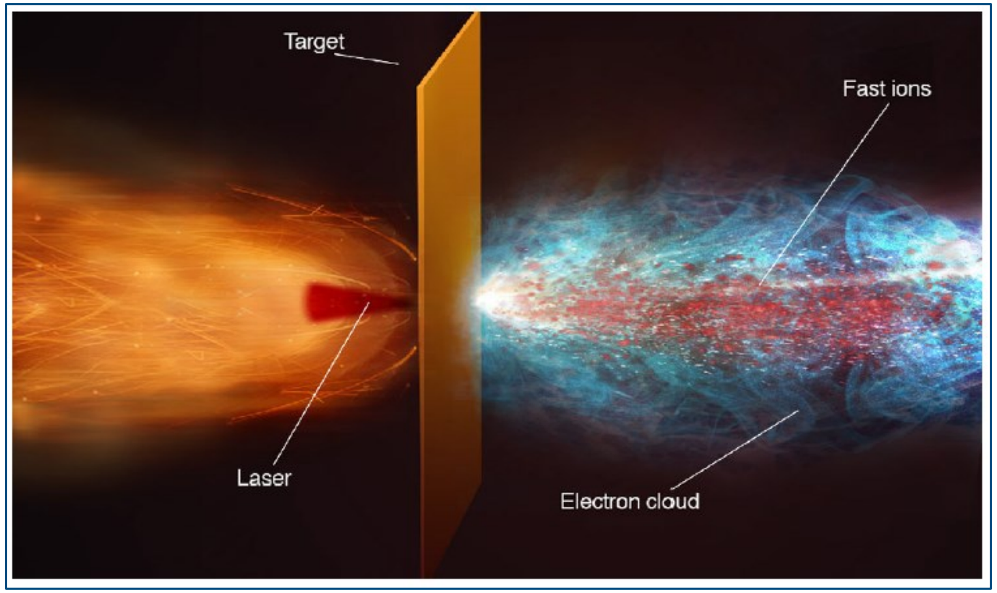
Low-density targets enhances electron heating (…but also ultrathin, mass limited etc.)

Bin, J. H., et al. *Phys. Rev. Lett.* 120.7 (2018): 074801.

Usual condition: broad **thermal-like energy spectrum** up MeV energies

Laser-driven ion acceleration in solid targets

If an ultraintense and ultrashort laser pulse hits the surface of a thin solid film, intense and energetic (Multi- MeV!) ion beams are effectively produced and observed rear side



(Before 2000, MeVs ions had been observed in several high-intensity laser-matter interaction experiments…

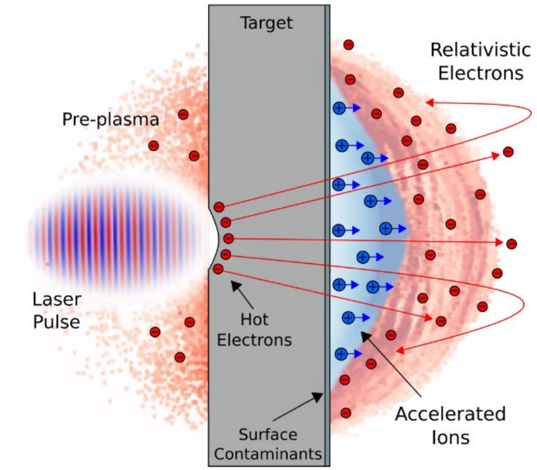
…but front side, rather isotropic ion emission and resulting low brilliance...)

<u>Typical physical parameters of the accelerating system:</u>

Laser – *energy*: 0,1-1000 J, *pulse duration*: 10-1000 fs, *intensity:* 10^{18}-10^{21} W/cm^2
solid target – *type*: conductors, insulators, *thickness*: 0,01-100 μm
accelerated ions – **protons** in usual conditions, **other ions** in proper conditions

E. Clark et al. *Phys. Rev. Lett*. **84**, 670 (2000)
A. Maksimchuk, et al., *ibid.* **84**, 4108 (2000)
R. Snavely et al. *ibid.* **85**, 2945 (2000)

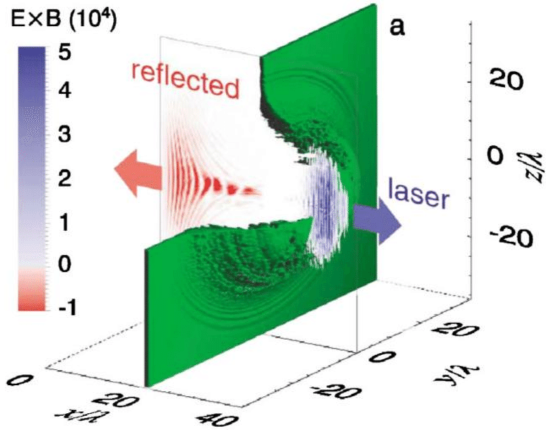
Ion acceleration mechanisms: TNSA, RPA, others



IF THE e - POPULATION IS DOMINATED BY A THERMAL SPECTRUM

- accelerating field due to charge separation between hot e- expanding in vacuum and bulk target

Target Normal Sheath Acceleration (TNSA)



IF THE ROLE OF THE THERMAL e- POPULATION IS “SUPPRESSED”

- accelerating field induced by balance between radiation pressure and electrostatic force

Radiation Pressure Acceleration (RPA)

IF LASER-TARGET PARAMETERS ARE MATCHED TO INDUCE SPECIFIC REGIMES

Collisionless Shock Acceleration (CSA), Break Out Afterburner (BOA), …

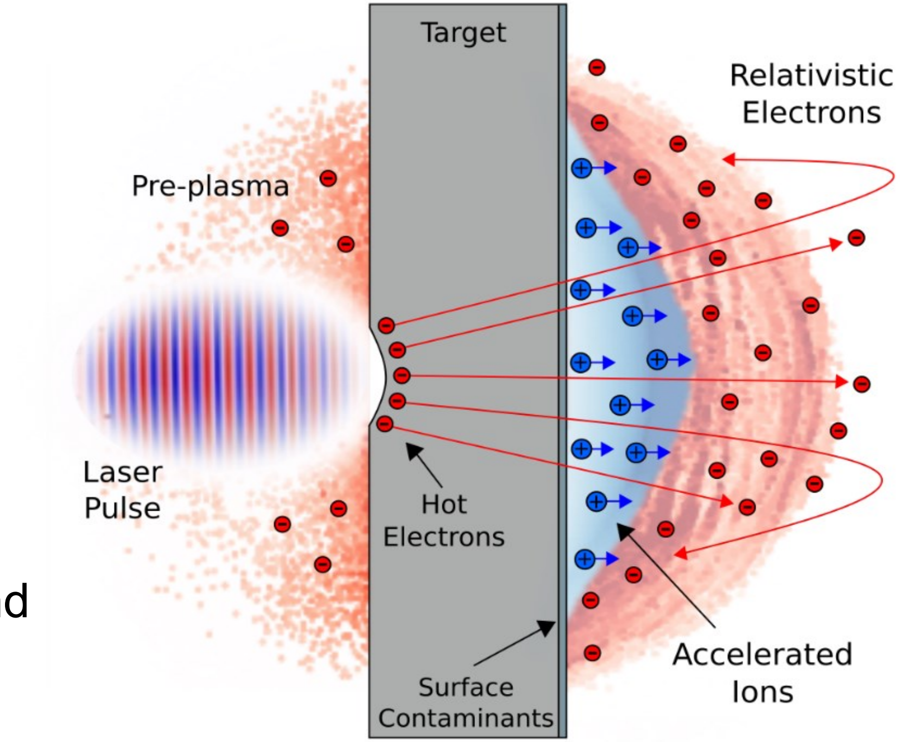
Ion acceleration mechanism: TNSA, RPA, others

Focus on

Target Normal Sheath Acceleration (TNSA)

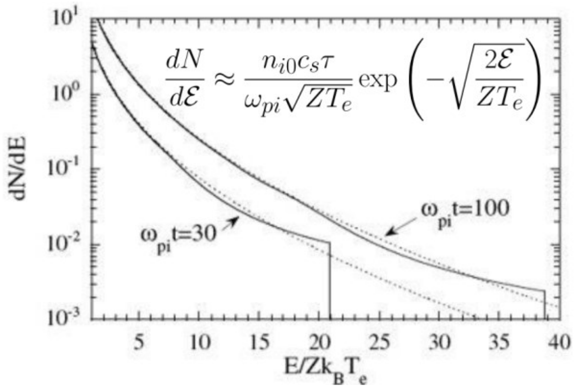
- **Dominant** in the **most common** and less stringent **experimental conditions** + difficult to avoid anyway
- Relevant for near-future **applications**
- Didactically interesting! Analytical, semi-analytical and numerical approaches

Note: most of the focus will be on the ion maximum energy and spectrum (in line with experiments)



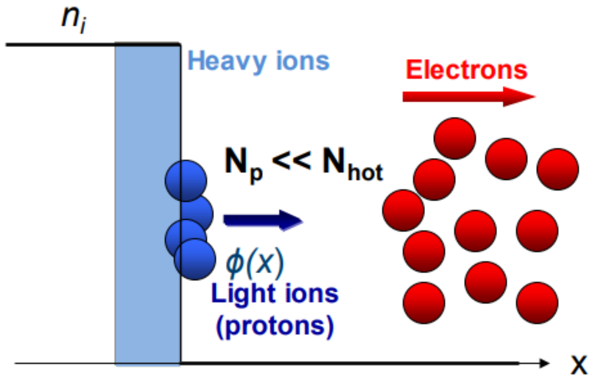
Theoretical description of Target Normal Sheath Acceleration

How to develop analytical models of the acceleration process in TNSA?
…two main "complementary" approaches have been developed!



1. **PLASMA EXPANSION IN VACUUM**: accelerated ions and hot electrons constitute an expanding plasma which is described with fluid or kinetic models
- accelerated ions are the positive component of a globally neutral plasma
- focus on the collective time evolution of ion dynamics

2. **QUASI-STATIC MODELS**: describe in detail the accelerating field as a quasi-static sheath electric field set up by the hot electrons
- light ions treated as test particles forming a thin low-density layer
- heavier ions considered almost immobile on the time scales of light ion acceleration
- focus on the early stages of ion acceleration (energetic ions)



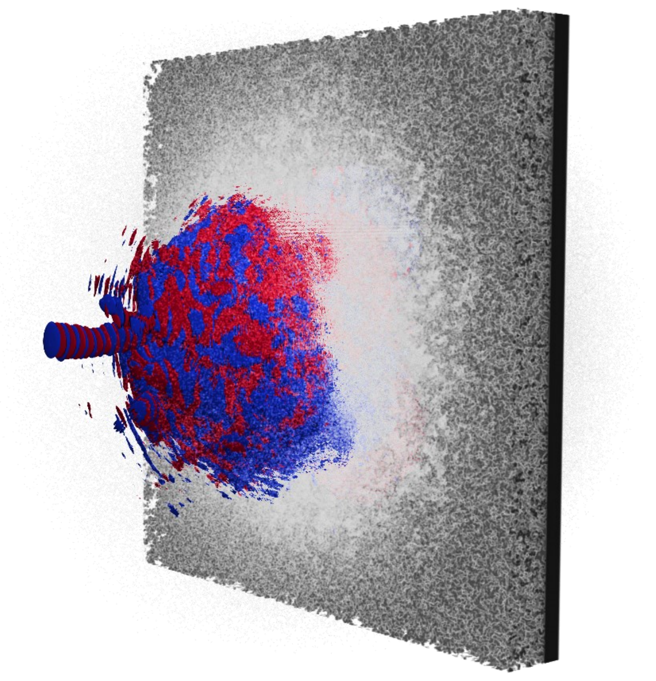
! See second lecture

Numerical simulation of high-power laser interaction with matter

Analytical descriptions are very useful but oversimplified and often limited to specific configurations

- **Numerical simulations**, in principle, provide more general tools, i.e. can be **easily adapted to many different situations**
  - Complex configurations can be simulated (e.g. 2D, 3D, non-uniform density profiles, etc.)
  - Different mechanisms and regimes can be explored
  - Easier than performing some type of experiments, especially in wide parametric scans

- **Support experimental observations** (including the early laser-ion acceleration experiments from years ~ 2000)



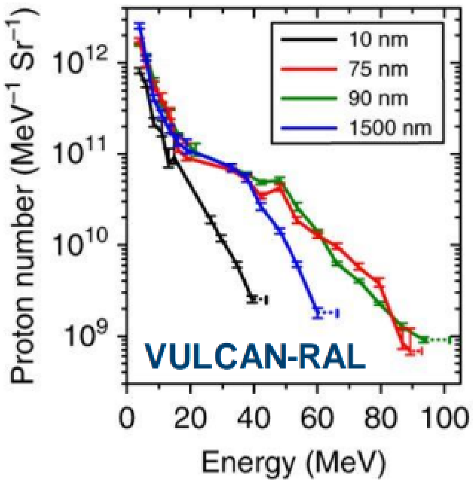
By far most-established numerical tool: particle-in-cell (PIC) simulations

! See Dimitriou's lecture

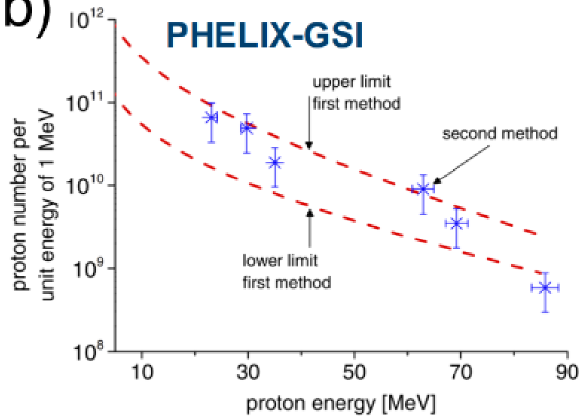
Arber, T. D., et al. *PPCF* 57.11 (2015): 113001.

Characteristics of ion emission: ion energy spectra and number

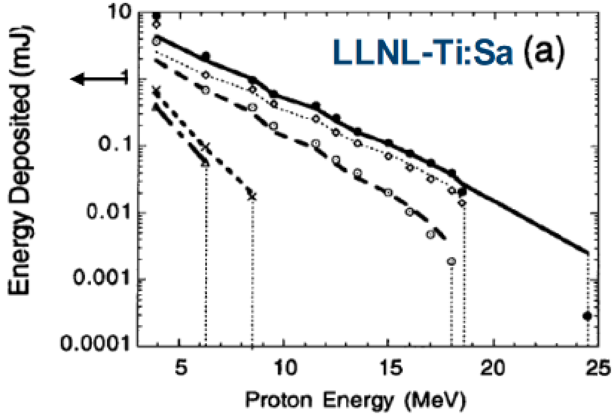
a)



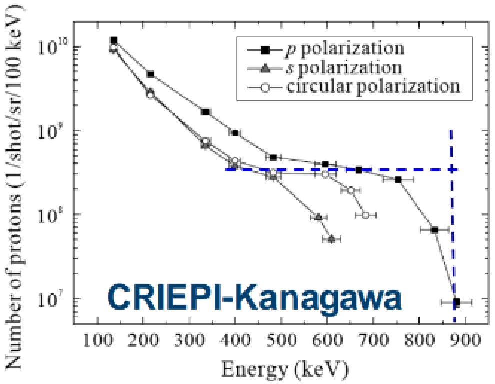
b)



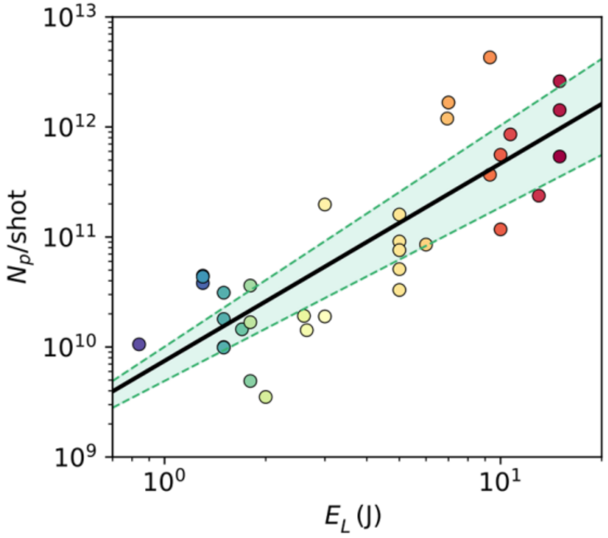
c)



d)



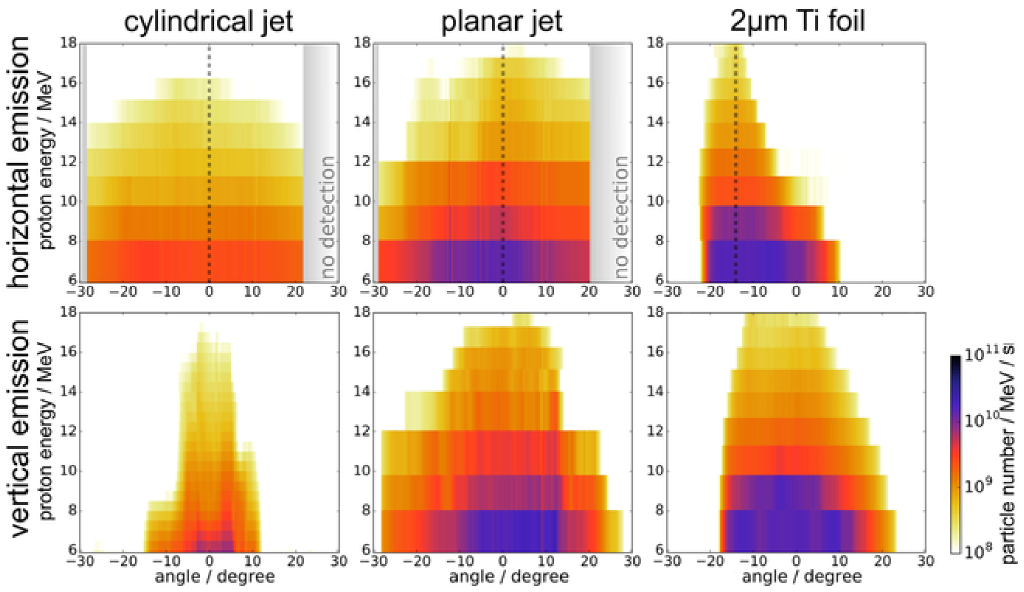
- Broad **quasi-exponential energy spectra**
- Well **defined cutoff** energy
- **10^9-10^{12} protons** accelerated in forward direction

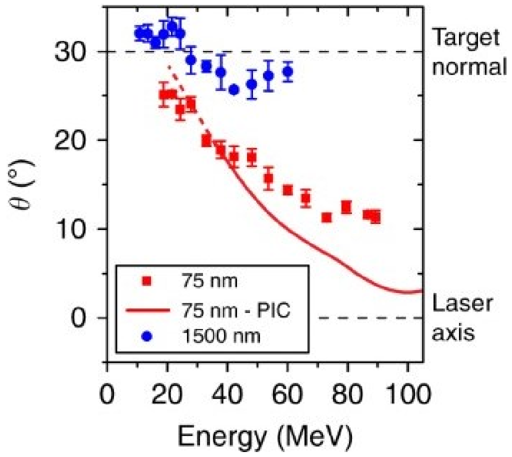


a) A. Higginson et al., Nature Comm. 9, 724 (2018)
b) F. Wagner et al., Phys. Rev. Lett. 116, 205002 (2016)
c) A.J. Mackinnon, et al., Phys. Rev. Lett. 88, 215006 (2002)
d) A. Fukumi, et al., Ph. Pl. 12, 100701 (2005)

F. Mirani, et al. Physical Review Applied 19.4 (2023): 044020.

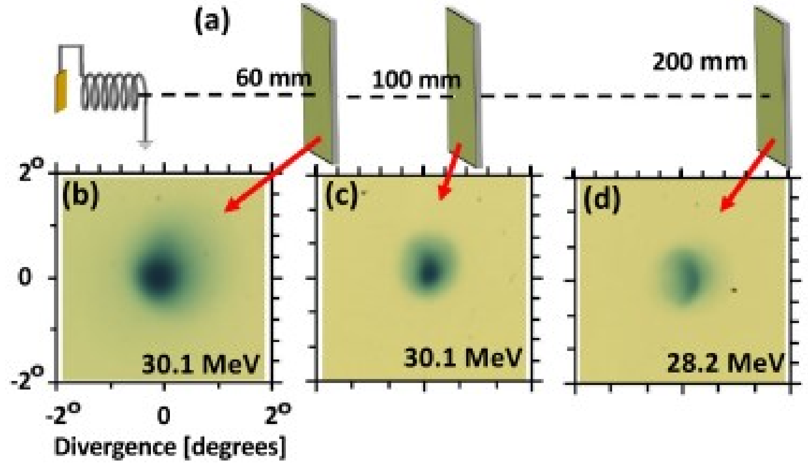
Characteristics of ion emission: angular divergence





- **Broad** energy dependent angular distribution (± 20°)
- Dependent on **target properties**

- Advanced schemes for **post-acceleration and collimation** (e.g. coil-target scheme, transport with beamlines, ...)



H. Ahmed, et al. *Scientific Reports* 11.1 (2021): 699.

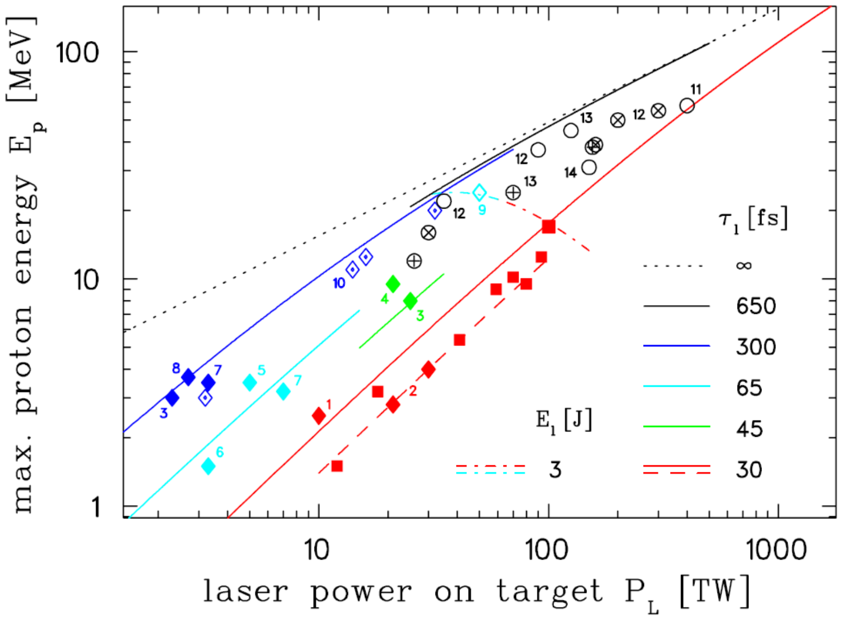
L. Obst, et al. *Scientific reports* 7.1 (2017): 10248.

A. Higginson et al., *Nature Comm*. 9, 724 (2018)

Characteristics of ion emission: dependence on laser parameters

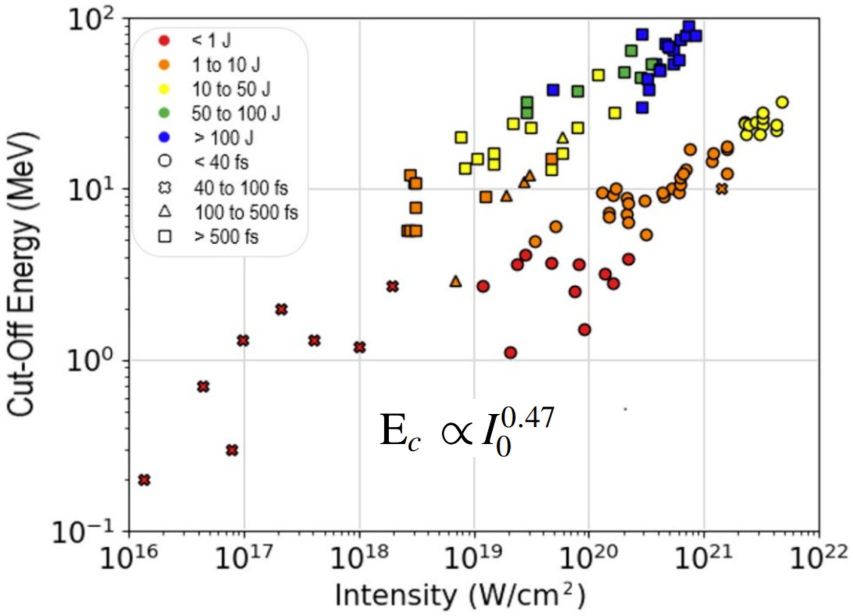
A large number of experiments have been performed to study the dependence of the accelerated ion properties on the laser parameters (rear side acceleration)

- Dependence on **laser IRRADIANCE**



K. Zeilet al., *New J. Phys*. 12, 045015 (2010)

- Dependence on **laser INTENSITY**

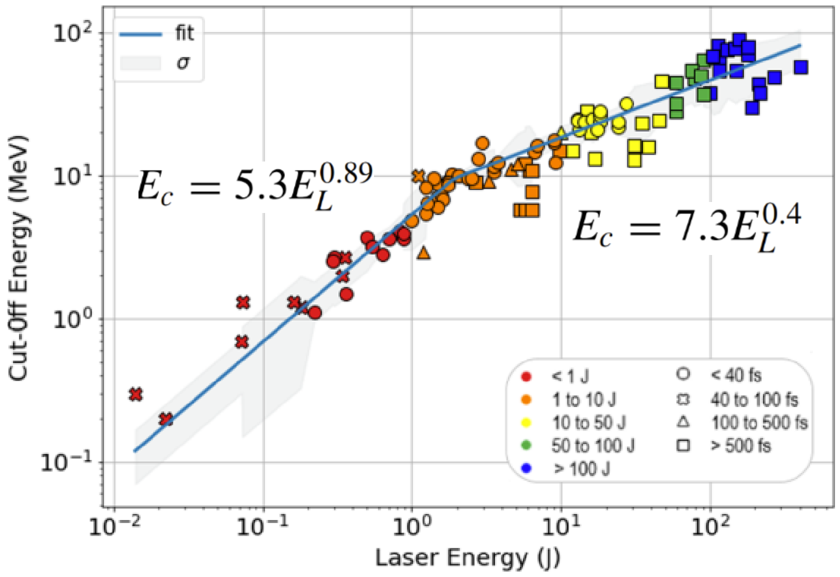


Zimmer, M., et al. *Physical Review E* 104.4 (2021): 045210.

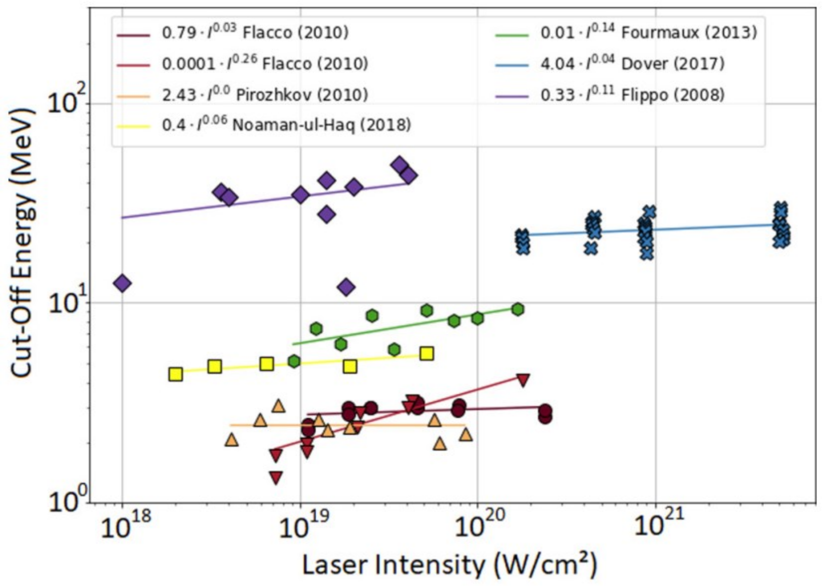
Characteristics of ion emission: dependence on laser parameters

A large number of experiments have been performed to study the dependence of the accelerated ion propertieson the laser parameters (rear side acceleration)

- Dependence on **laser ENERGY**



- Intensity varied changing **TIME DURATION**

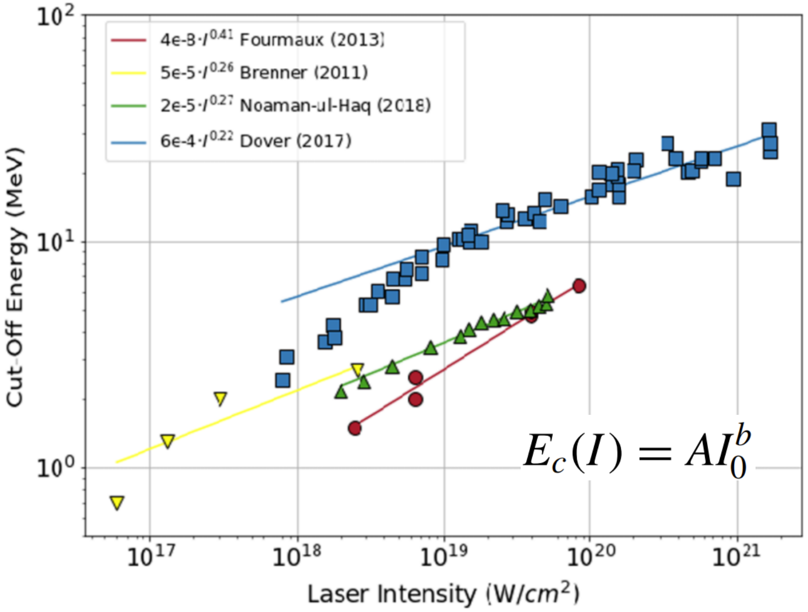


Zimmer, M., et al. *Physical Review E* 104.4 (2021): 045210.

Characteristics of ion emission: dependence on laser parameters

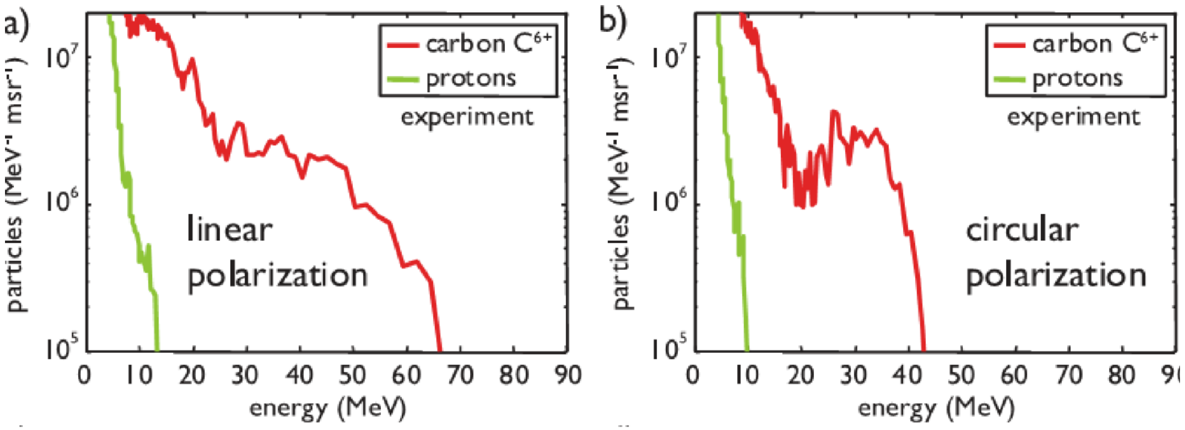
A large number of experiments have been performed to study the dependence of the accelerated ion propertieson the laser parameters (rear side acceleration)

- Intensity varied changing **SPOT SIZE**



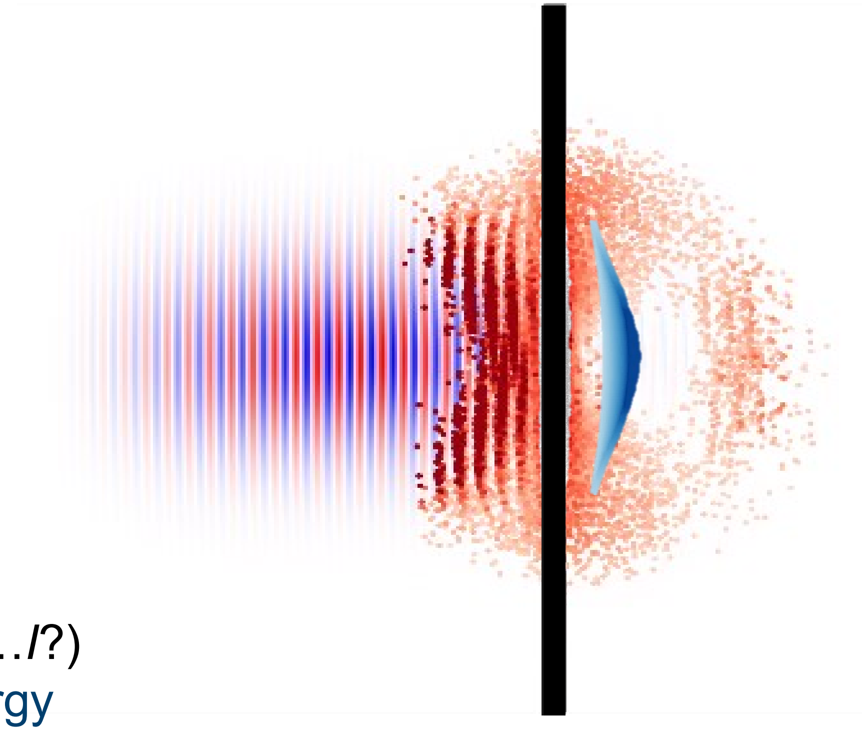
Zimmer, M., et al. *Physical Review E* 104.4 (2021): 045210.

- Effect of **laser POLARIZATION**



Henig, et al. *Phys. Rev. Lett.* 103, 245003 (2009).

Dependence on laser parameters: first summary from experiments



Experiments show that in general ion properties depend on

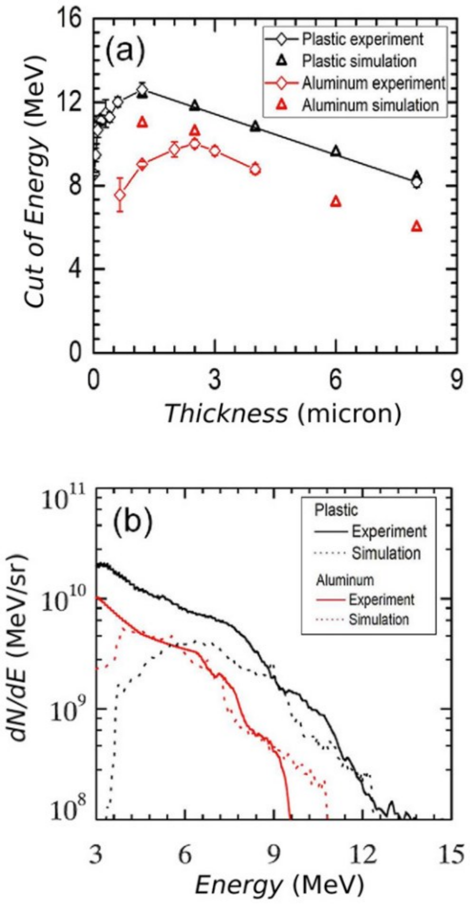
- irradiance (intensity, for fixed wavelength)
- energy
- pulse duration
- contrast ratio (ASE/pedestal)
- polarization: linear (s, p) vs circular

In particular some quite general features can be established:

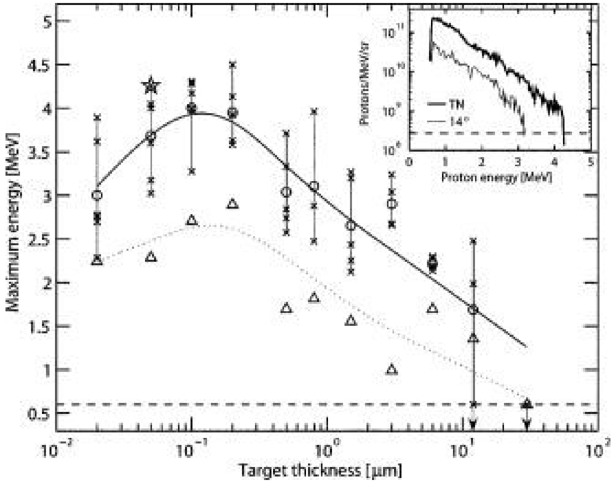
- Maximum ion energy mainly depends on laser intensity: $E_{max} \sim I^{1/2}$ (…I?)
- Energetic spectrum and maximum energy depend also on laser energy
- Total number of ions increases with laser energy and duration (10^9 – 10^{13} protons)
- With short pulses (10-50 fs) a BEAM current may be obtained exploiting higher repetition rate (Hz): current = charge/shot x rep.rate

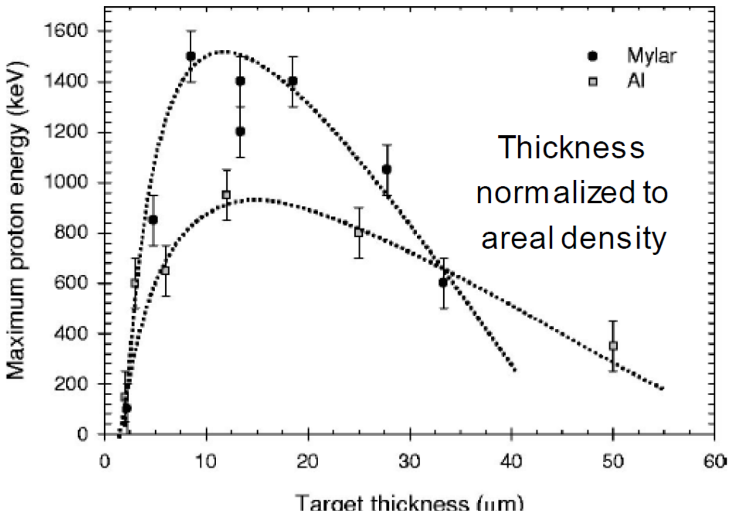
Characteristics of ion emission: dependence on target parameters

- Target **MATERIAL**



- Target **THICKNESS**



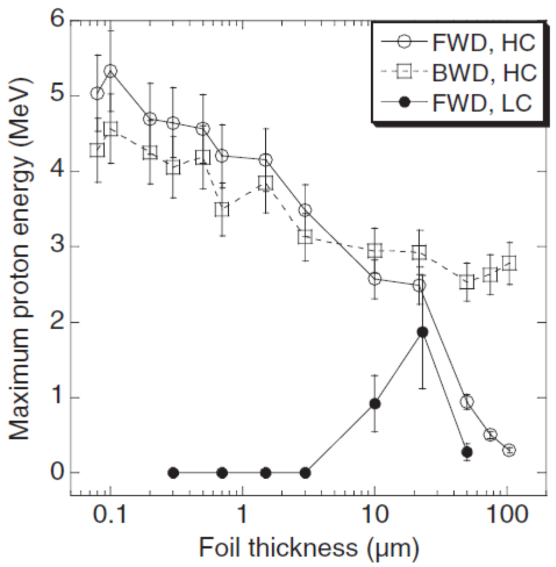


- Thickness: from <μm (~λ) up to ~100 μm
- Maximum ion energy indication of an "optimal" thickness depending on pulse properties: mainly the pre-pulse pedestal level/contrast ratio.
- Other properties (number, spatial distribution, …): they can differ in metals vs plastic

Geng, Y. X., et al. *Matter and Radiation at Extremes* 5.6 (2020).
Neely, D., et al. *Applied Physics Letters* 89.2 (2006).
Spencer, *et al.*, *Phys. Rev. E*67, 046402 (2003)

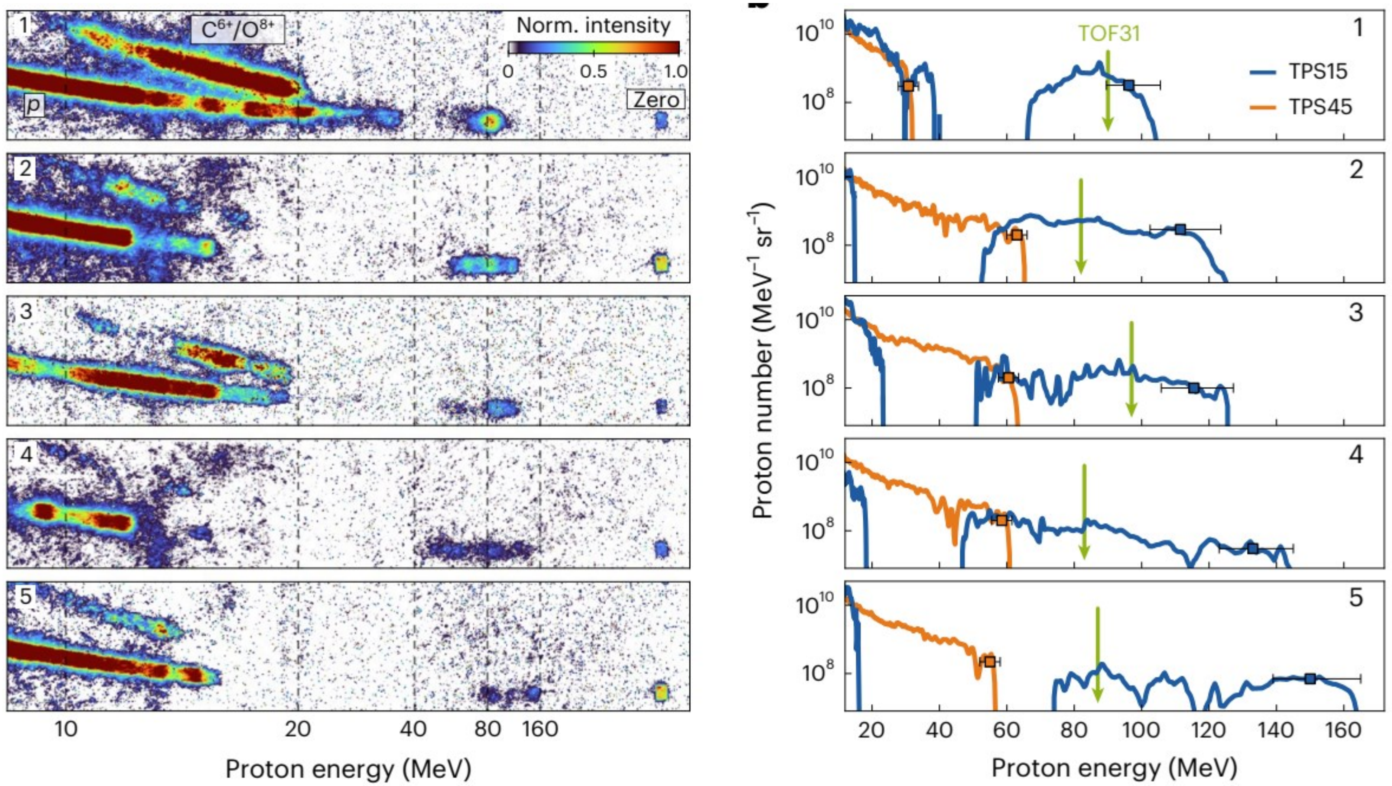
Characteristics of ion emission: dependence on target parameters

- **Ultrathin targets** (down to few tens nm) investigated (using ultrahigh contrast pulses!)



T. Ceccotti, *et al.*, *Phys.Rev.Lett.* **99**, 185002 (2007)

- Maximum ion energy can significantly increase reducing thickness (e.g. 250 nm)

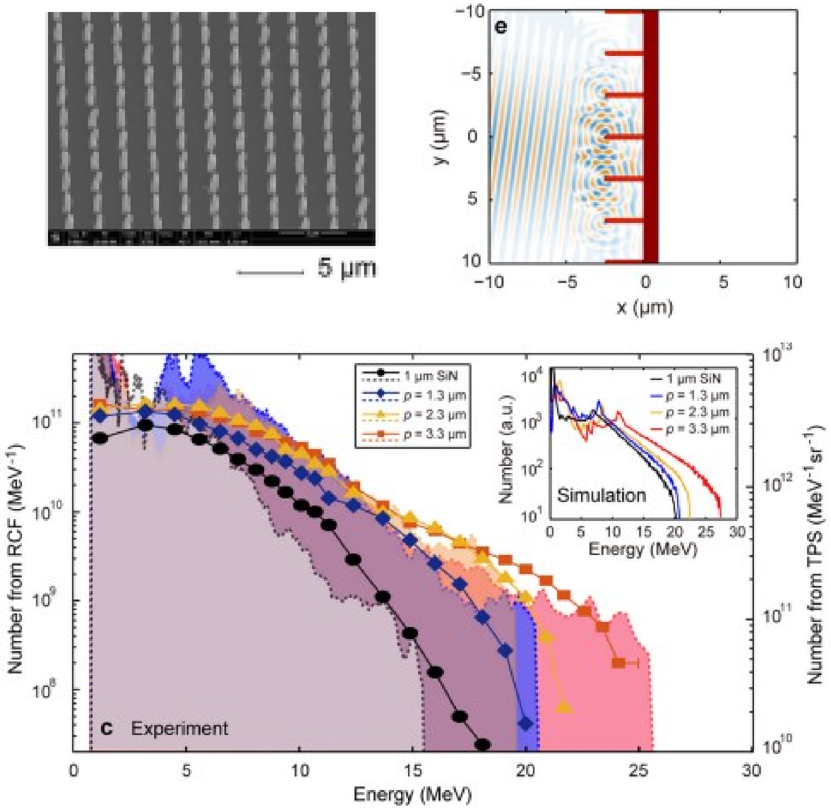


- Transition to non-TNSA acceleration schemes (e.g. cascaded acceleration regimes)

T. Ziegler, et al. *Nature Physics* (2024): 1-6.

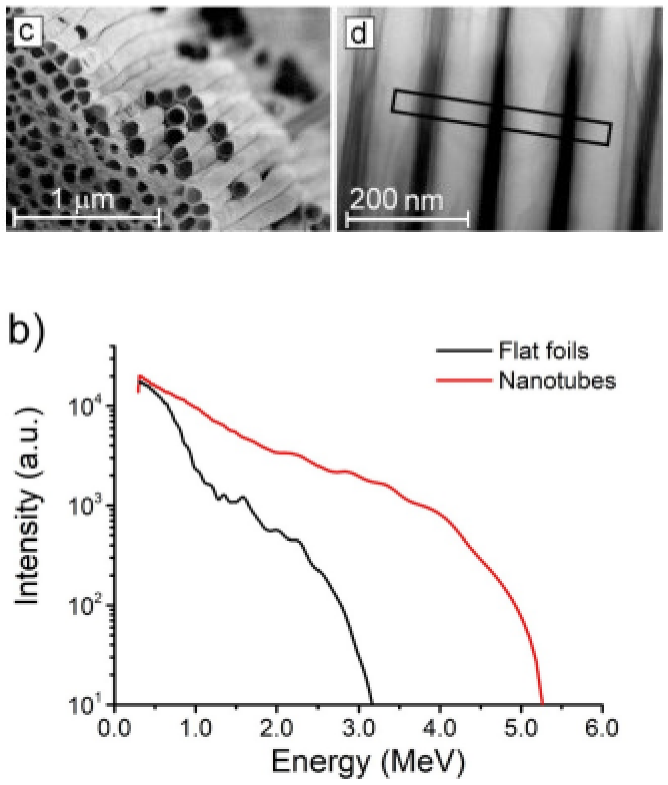
Characteristics of ion emission: dependence on target structure

- **Microstructured targets**



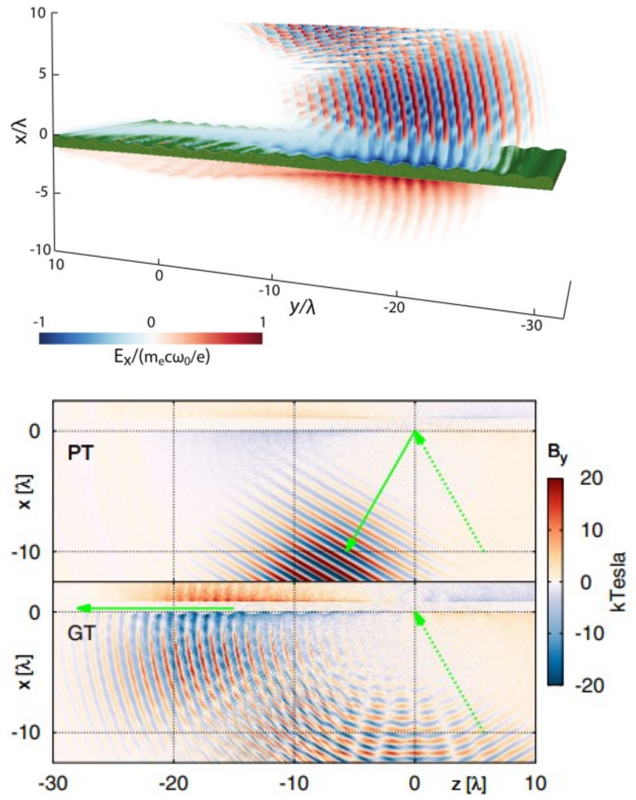
Qin, Chengyu, et al. *Communications Physics* 5.1 (2022): 124.

- **Nanotubes**



G. Cristoforetti, et al. *PPCF* 62.11 (2020): 114001.

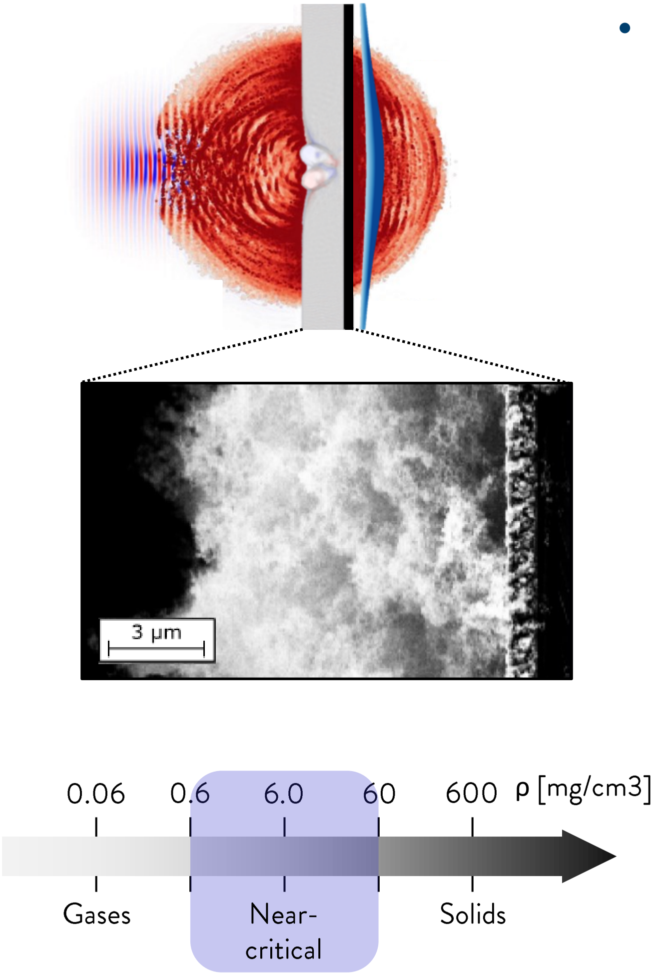
- **Grating targets**



L. Fedeli, et al. *PRL* 116.1 (2016): 015001.

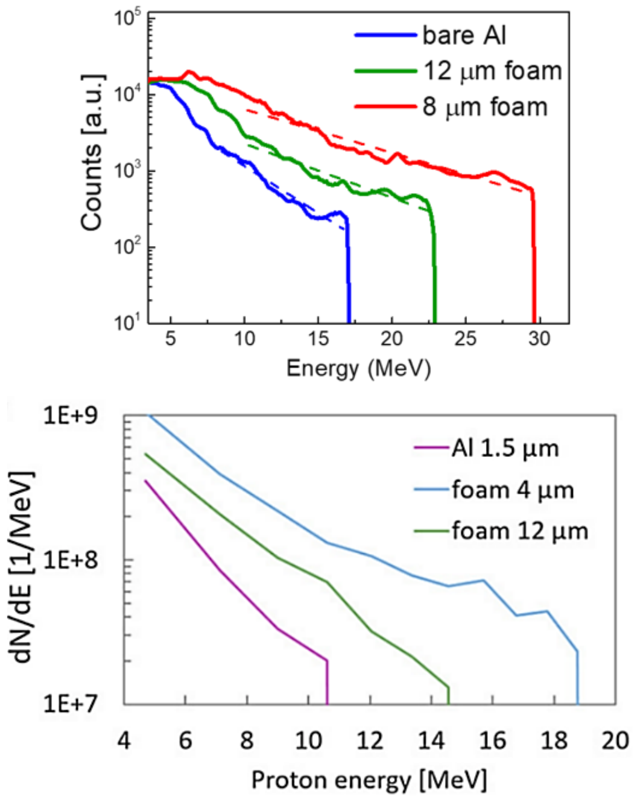
T. Ceccotti, et al. *PRL* 111.18 (2013): 185001.

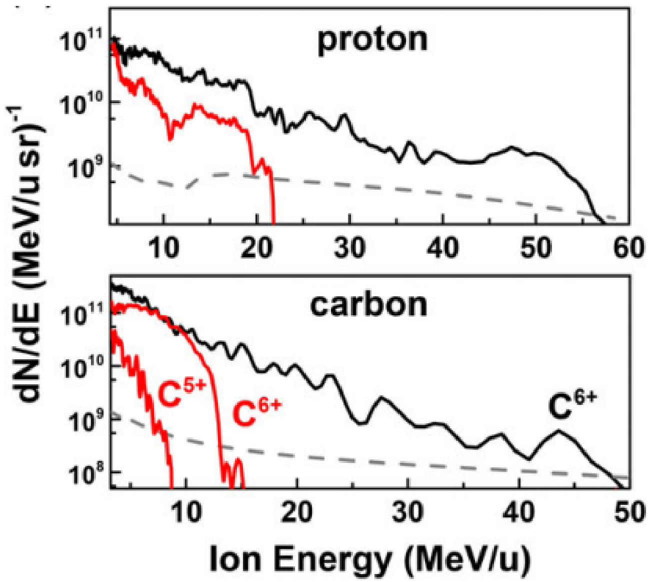
Characteristics of ion emission: dependence on target structure



- **Near-Critical, nanostructured double-layer targets**

  Carbon foam-based DLT allows a higher laser absorption → Increase both energy and number of accelerated particles.





A. Maffini, et al. *Appl. Surf. Sci.* (2022): 153859.

W. J. Ma, et al. *PRL* 122.1 (2019): 014803.

I. Prencipe, et al. *PPCF* 58.3 (2016): 034019.

I. Prencipe, et al. *New J. Phys.* 23.9 (2021): 093015.

Characteristics of ion emission: summary of the main exp. results

- Ions can be effectively accelerated in laser-solid interaction
- Protons are mainly accelerated (from surface contaminants), unless the target is properly cleaned
- In usual conditions, ions from the rear surface have these protperties:
  - total number (depending on conditions, 10^9 – 10^{13} protons)
  - maximum energy (uo to several tens MeV for protons)
  - energetic spectrum (mostly wide spectrum with sharp cut -off)
  - beam properties (very well collimated ps bunches)

- There is a dependence on the target conditions
  - target thickness and material
  - smart target engineering can allow control of the acceleration

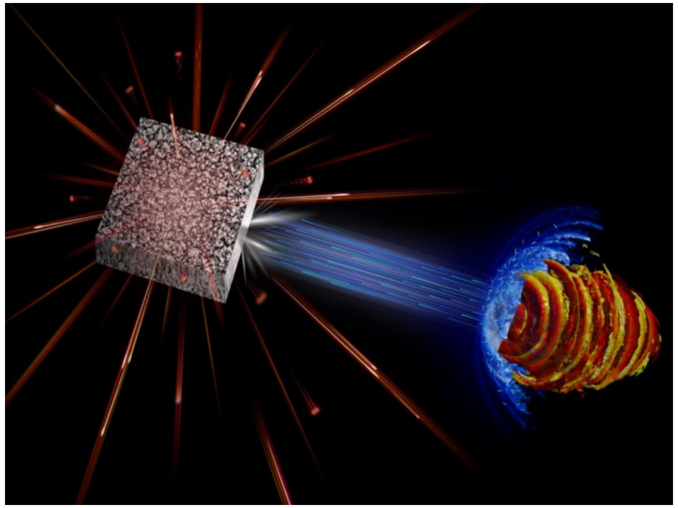
- Laser intensity: Emax ~ I 1/2 (…I?) - dN/dE & Emax ↔ laser energy
  - ↑ laser energy and duration → ↑ N_{tot}
  - contrast ratio (ASE/pedestal) & polarization (L vs. C)
  - short pulses (10-50 fs) at higher repetition rate (Hz) can generate an ION BEAM: current = charge/shot x rep. rate

Potential applications

…many applications of the UU laser-matter interaction are foreseen…
…this is true especially for laser-accelerated ions!

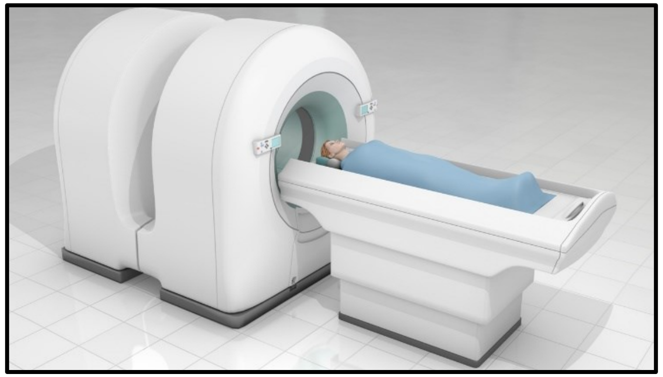
- intense X-ray sources; relativistic nonlinear optics (underdense plasmas); laboratory investigations of matter in extreme conditions; laboratory astrophysics; nuclear physics, nuclear fusion, …

- **ion acceleration**:
  - diagnostics for laser plasmas (proton imaging)
  - "fast ignitors" (electron- or proton-driven)
  - warm dense matter studies
  - **medical applications** (PET, radiobiology, hadrontherapy)
  - **material science** (characterization, irradiation, production)
  - laser-induced nuclear physics (e.g. **neutron production**)

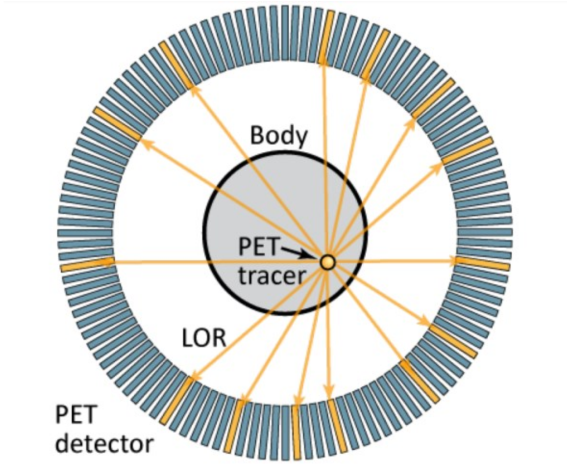


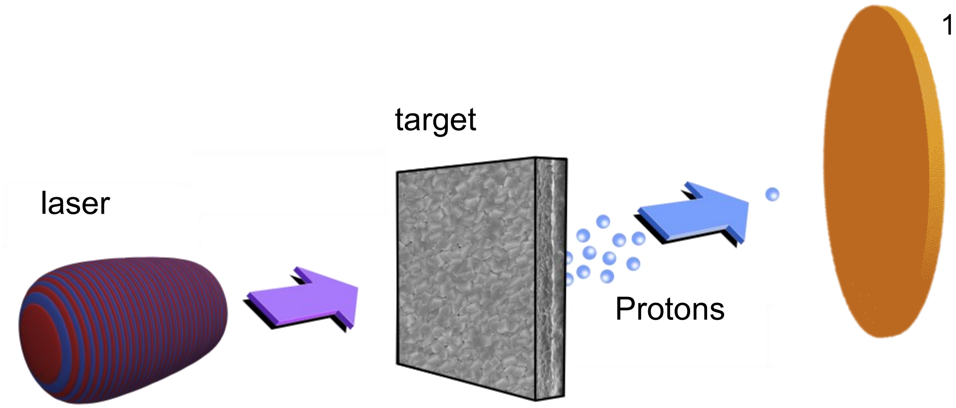
Potential applications: production of radioisotopes

- Production of positron active isotopes (^{18}F, ^{11}C, ^{13}N) for **Positive Emission Tomography**



- Now: cyclotrons or Van de Graaff accelerators
- potential advantages:
  - ✓ E > 100 GV/m ⇒ acceleration length ≈ fraction of mm
  - ✓ compact, flexible and cheap (especially for novel isotopes: ^{82}Sr, ^{68}Ge..)
  - ✓ no radioprotection shielding required up to where protons are generated



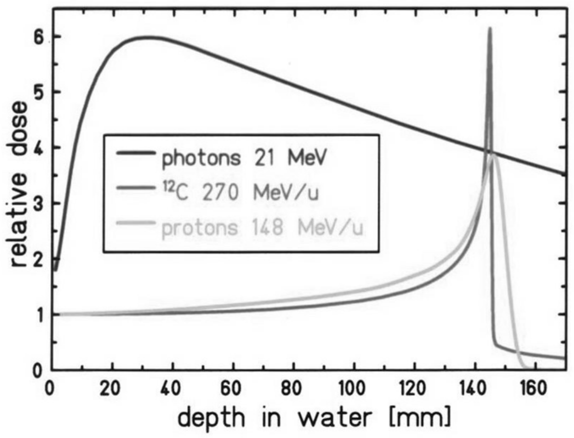


A. Maffini, et al. *Frontiers in Physics* 11 (2023): 1223023.

Z. Sun, *AIP Advances* 11.4 (2021).

Potential applications: hadron-therapy

- Using ions, the energy is released mostly in the region where the tumor is localized (Bragg peak)

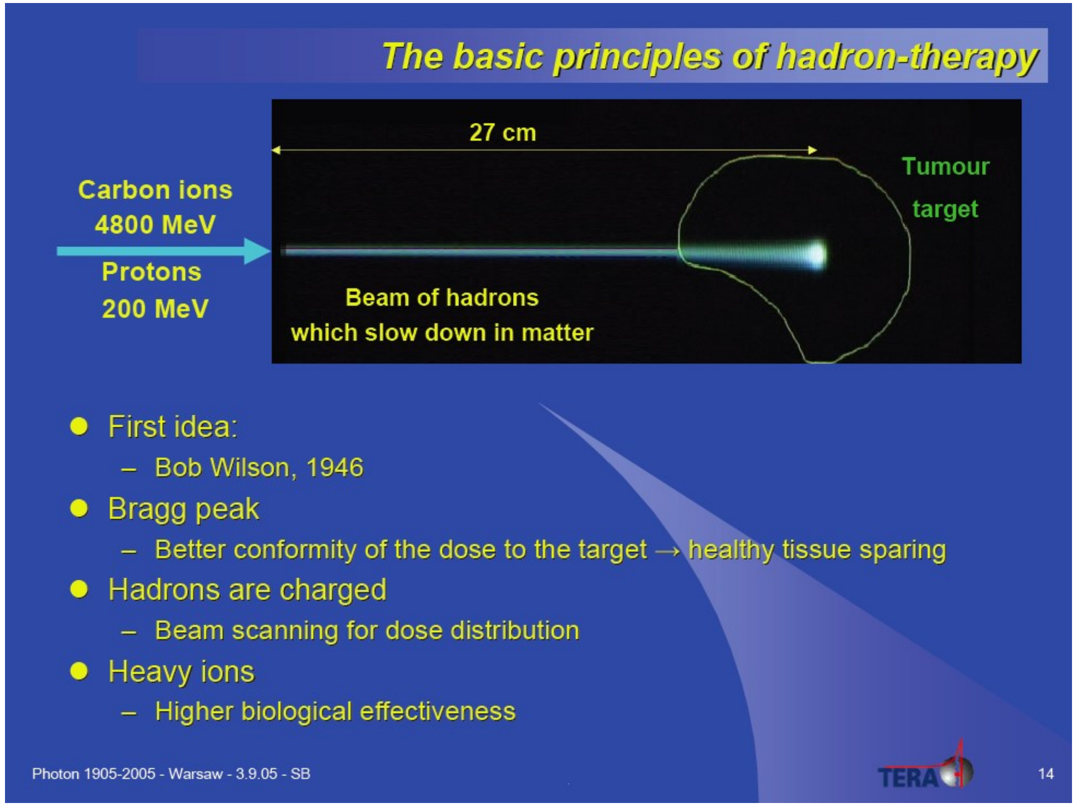


Conventional method: Syncrotron/Cyclotron

- beam requirements:

  $N = 1\text{-}5\times10^{10}$ pr/s, ε_M = 230-250 MeV

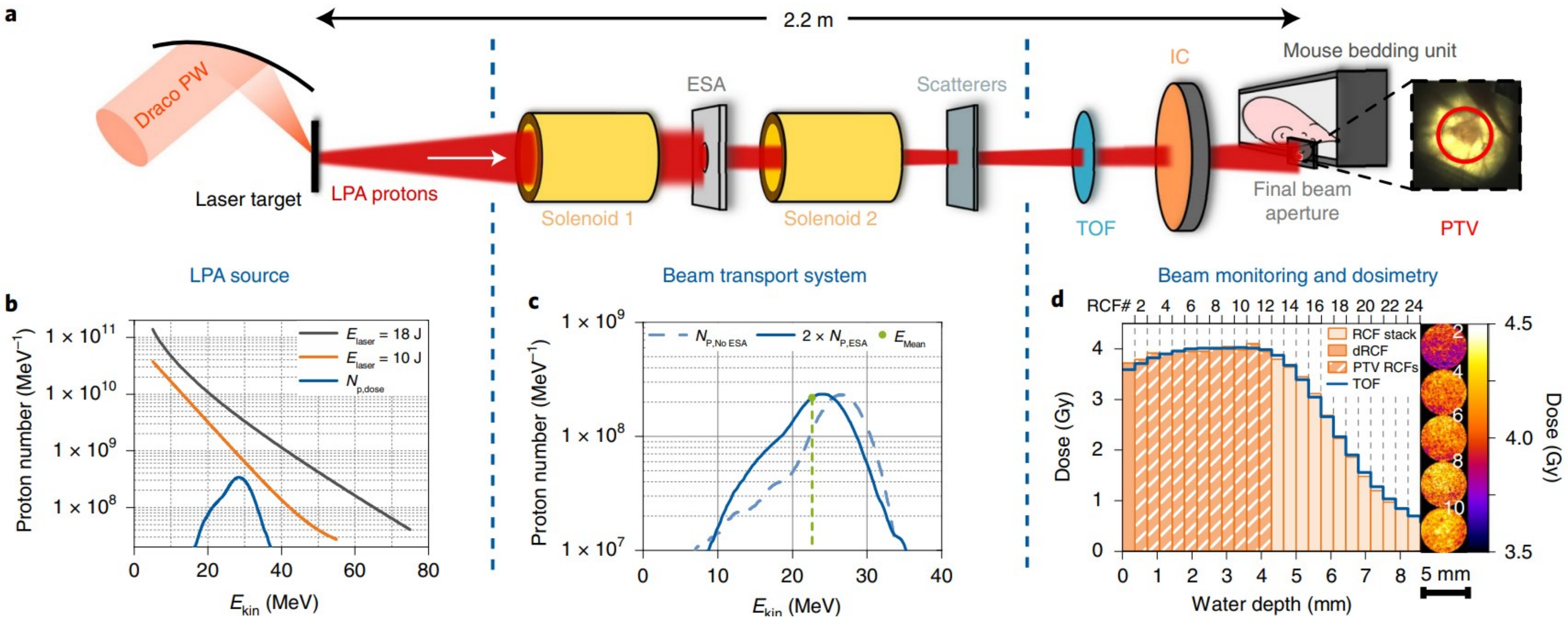
  $\Delta\varepsilon/\varepsilon \leq 10^{-2}$



- Arguably, one of the most **challenging applications**!

Potential applications: hadron-therapy

- Main **radiobiological models** used with laser-driven ions are (1) in vitro assays, mice and Zebrafish embryos
- **Stability**, **manipulation** and **monitor** of proton bunches required!

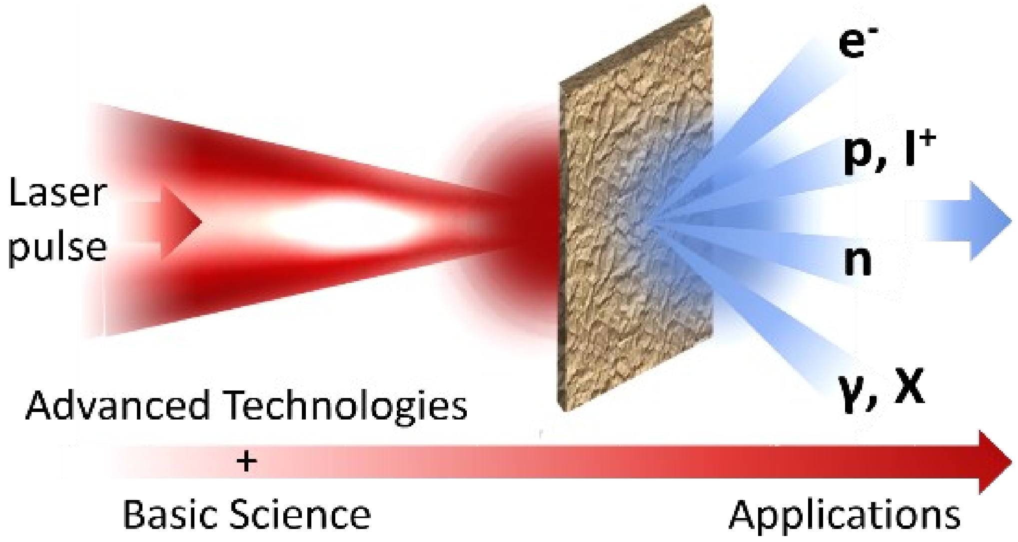


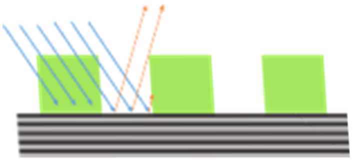
F. Kroll, et al. *Nature Physics* 18.3 (2022): 316-322
P. Chaudhary, et al. *Frontiers in Physics* 9 (2021): 624963.

Potential applications: material science

- **Ion beam analysis**: RBS, NRA, PIXE,…
- Neutron **imaging** and radiography….

- Ion implantation
- Radiation damaging…

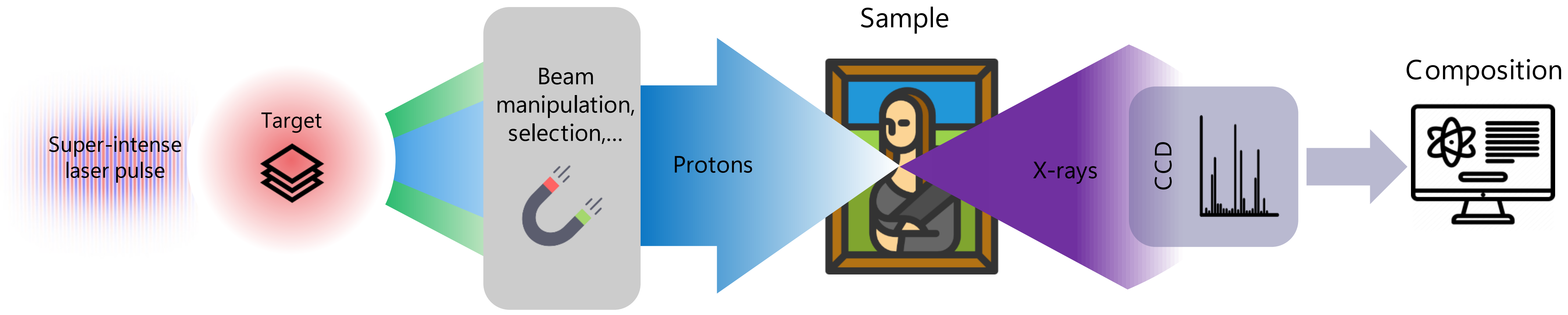




Laser-driven ion beams may ensure major advantages!

Potential applications: material science

- As an example, we can consider laser-driven **Particle Induced X-ray Emission** for elemental analysis of materials



- MeV protons → X-rays
- ~10 μm range, homogeneous and stratigraphic
- Also, in air

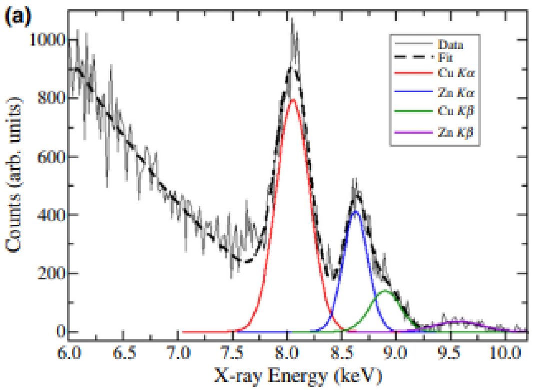
…many potential appealing features with lasers!

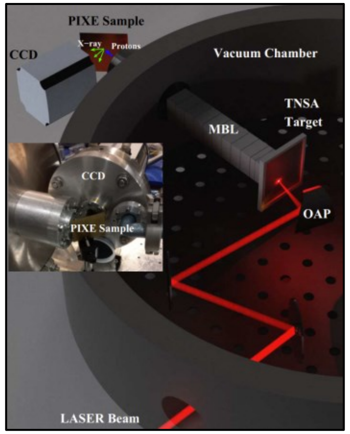
- **Compact**, potentially **portable** in future
  - Cheap
    - Energy tunability (**flexibility**)

M. Barberio, et al. *Sci. Rep.* 7.1 (2017): 1-8. P. Pilar, et al. *Sci. Rep*. 11.1 (2021): 1-10.

Potential applications: material science

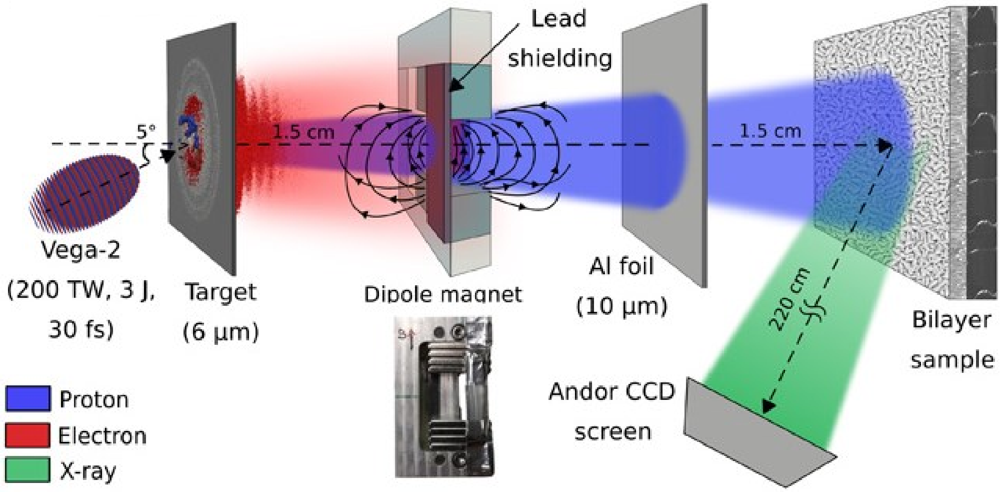
- Experiment of **in-air laser-driven PIXE** quantitative analysis with a compact source
  - Magnetic beamline to transport and collimate protons out of the interaction chamber.
  - Retrieve concentrations in a homogeneous sample and comparison with EDXS.



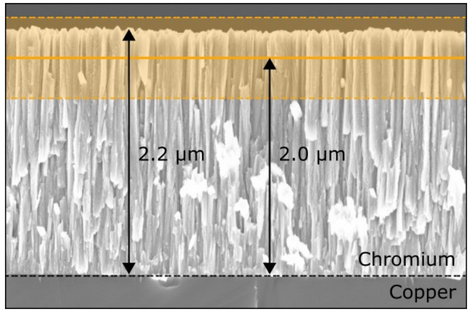


M. Salvadori, et al. Phys. Rev. Appl. 21.6 (2024): 064020.

- Experiment of combined **laser-driven PIXE stratigraphic analysis**



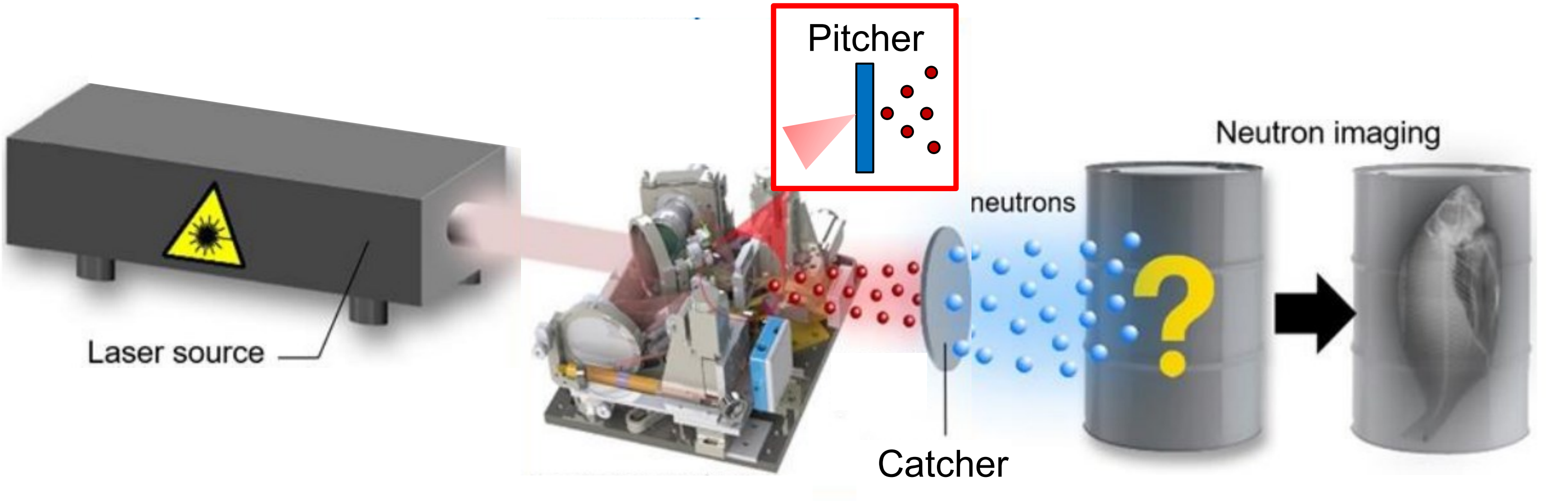
- Retrieve the thickness of a micrometric thick layer.

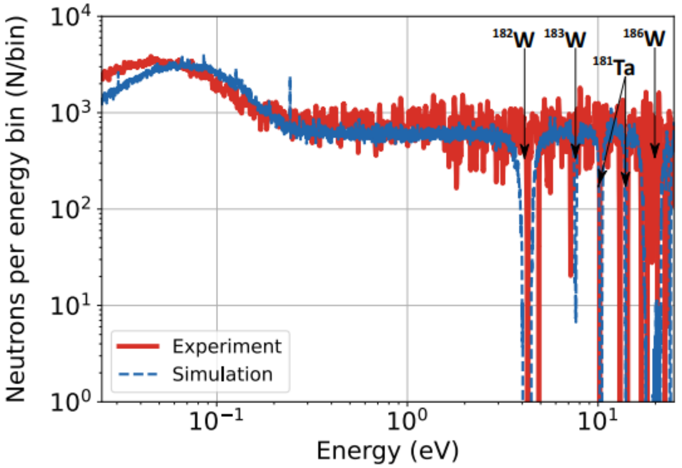


F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

Potential applications: neutron production

- Neutron sources exploiting a **pitcher-catcher** (e.g. ^{9}Be p – n) **configuration**





- Compact neutron sources for **material characterization**
  - fast-neutron spectroscopy
  - neutron radiography

- Very active research field!

Roth, M., et al. *Physical review letters* 110.4 (2013): 044802.

Fedeli, L., et al. (2020) *New Journal of Physics*, *22*(3), 033045.

M. Zimmer, et al. *Nature communications* 13.1 (2022): 1173.

F. Mirani, et al. *Physical Review Applied* 19.4 (2023): 044020.

Conclusions

- **ULTRAINTENSE ULTRASHORT (UU) LASER PULSE INTERACTION WITH MATTER**
  - It is an exciting and growing area of reaserch!

- **LASER-DRIVEN ION ACCELERATION IS OF PARTICULAR INTEREST**

- **PHENOMENOLOGY OF THE LASER-ION ACCELERATION:**
  - many experimental data available
  - ion spectrum depends on pulse properties (energy, intensity, pre-pulse)
  - ion spectrum depends on target properties (composition, thickness)

- **A NUMBER OF SIGNIFICANT APPLICATIONS IS FORESEEN/UNDER DEVELOPMENT**
  - material science (PIXE, imaging)
  - medical applications (PET, hadrontherapy)

Thank you for the attention! – 2° lecture…now

matteo.passoni@polimi.it