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Laser-Ion acceleration in plasmas and short bunch applications

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March 19, 2024

Chair of Experimental Physics – Medical Physics
Laser-Ion Acceleration Group, Prof. Dr. Jörg Schreiber
CALA

Laser-ion acceleration in a nutshell

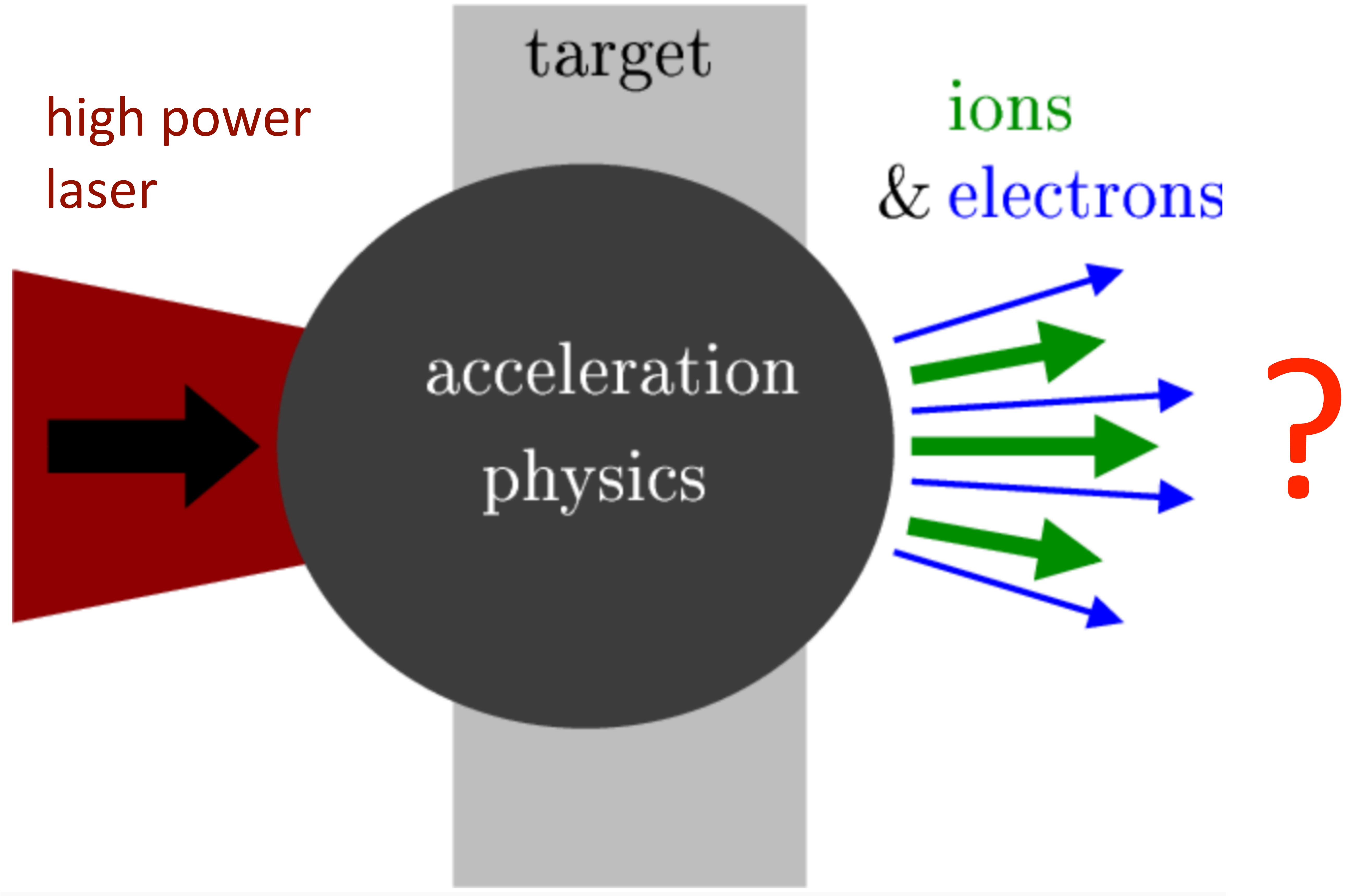


Fig: Macchi, 2017

Many interesting properties:

- Ultra-high peak currents
- Broad energy distribution
- multiple synchronous radiation modalities
- …

Many useful applications:

- Radiobiological experiments
- Probing of ultrafast processes
- Research in astrophysics
- …

Outline

1. Introduction
   - Centre for Advanced Laser Application
   - Theoretical background & state of the art

2. Applications
   - Bi-modal imaging
   - Radiation chemistry
   - Nuclear astrophysics

3. Laser-ion acceleration at the Centre for Advanced Laser Applications
   - Experimental set-up
   - Ion detection via ionoacoustics
   - Data based optimization of the ion acceleration

Centre for **A**dvanced **L**aser **A**pplications (CALA)

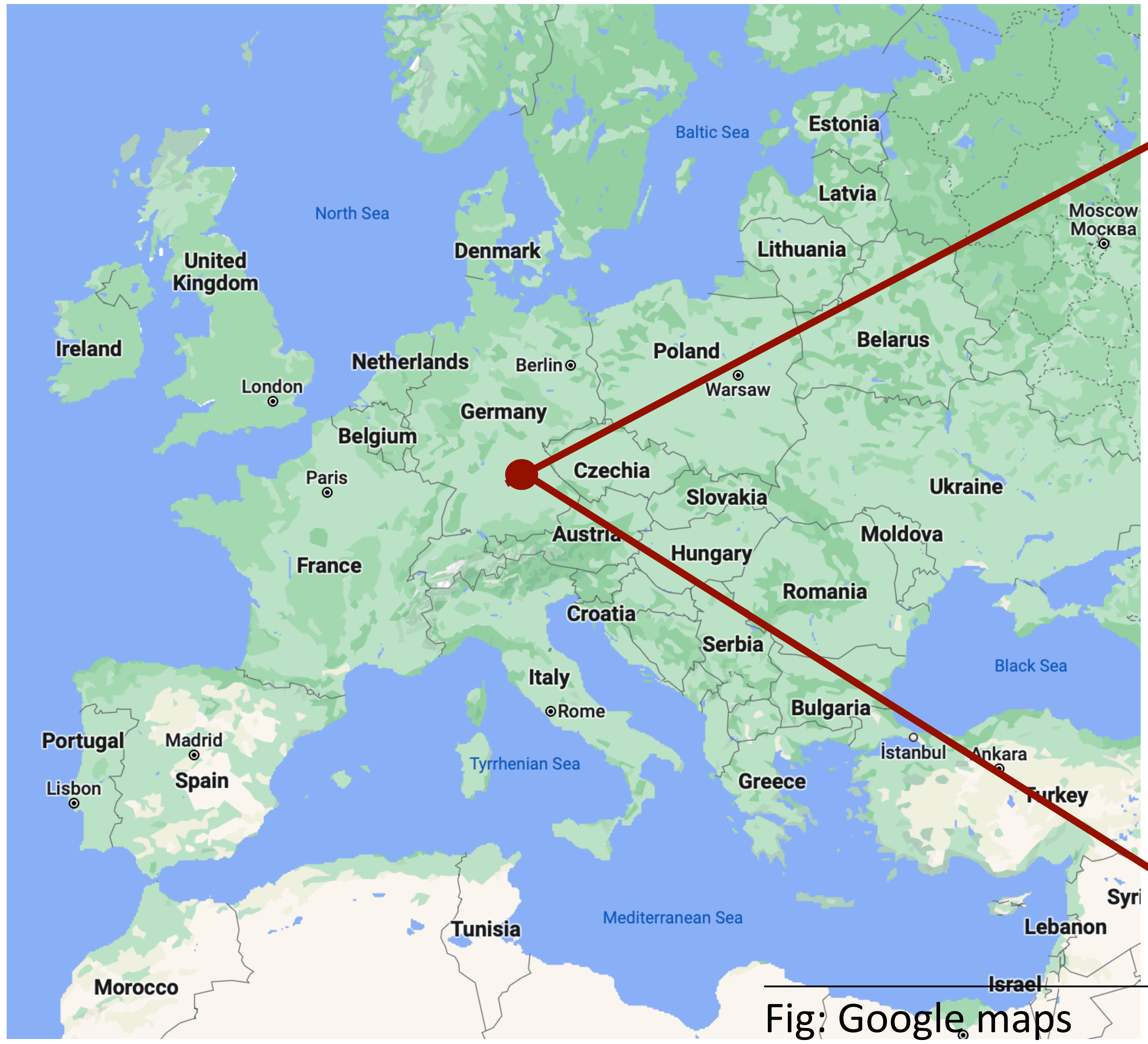
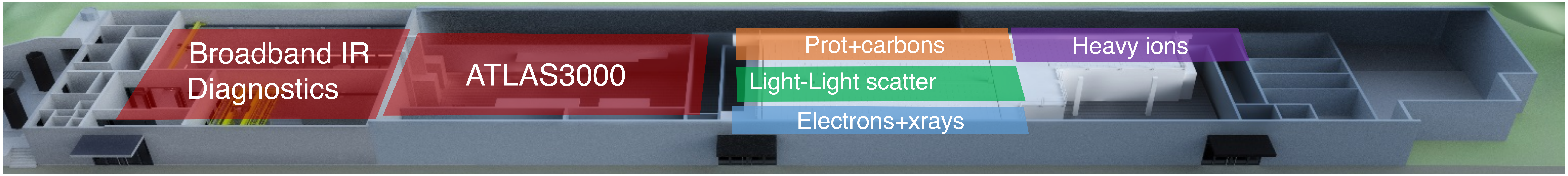
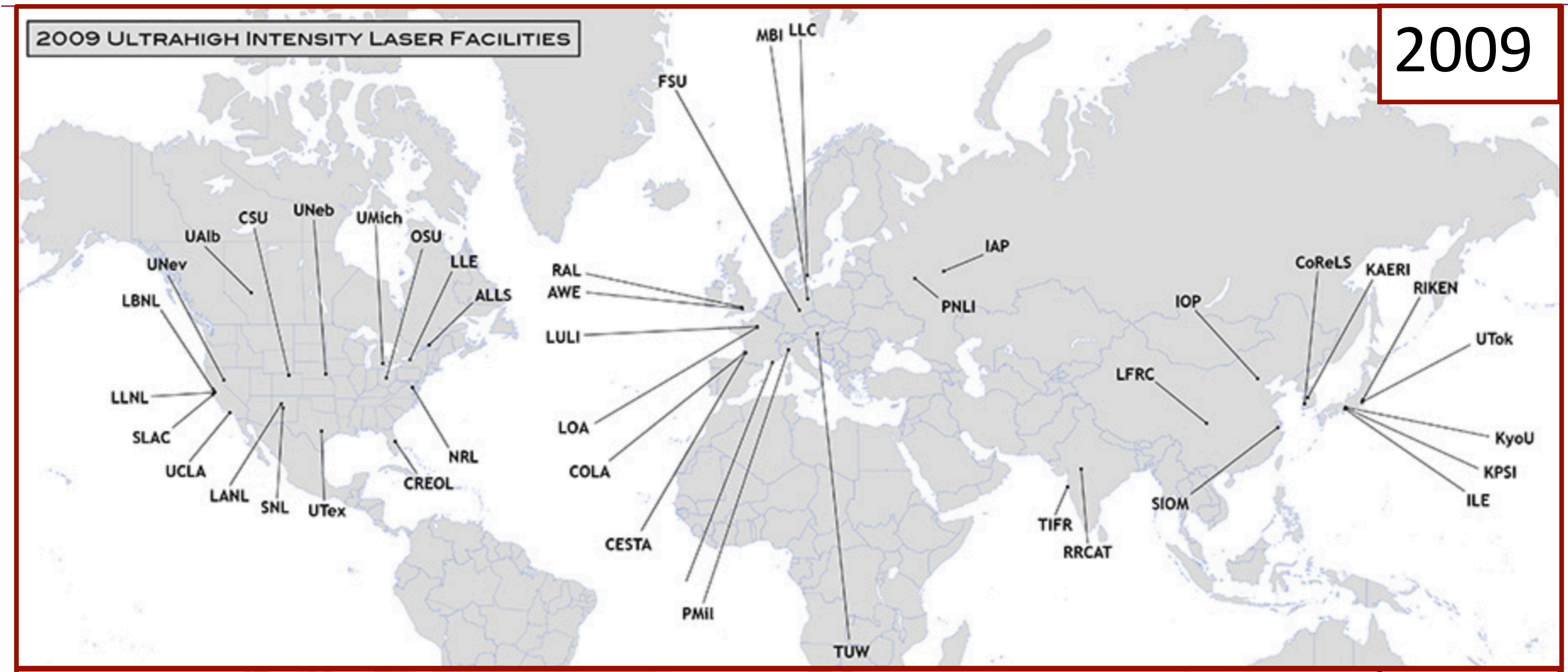


Fig: Google maps

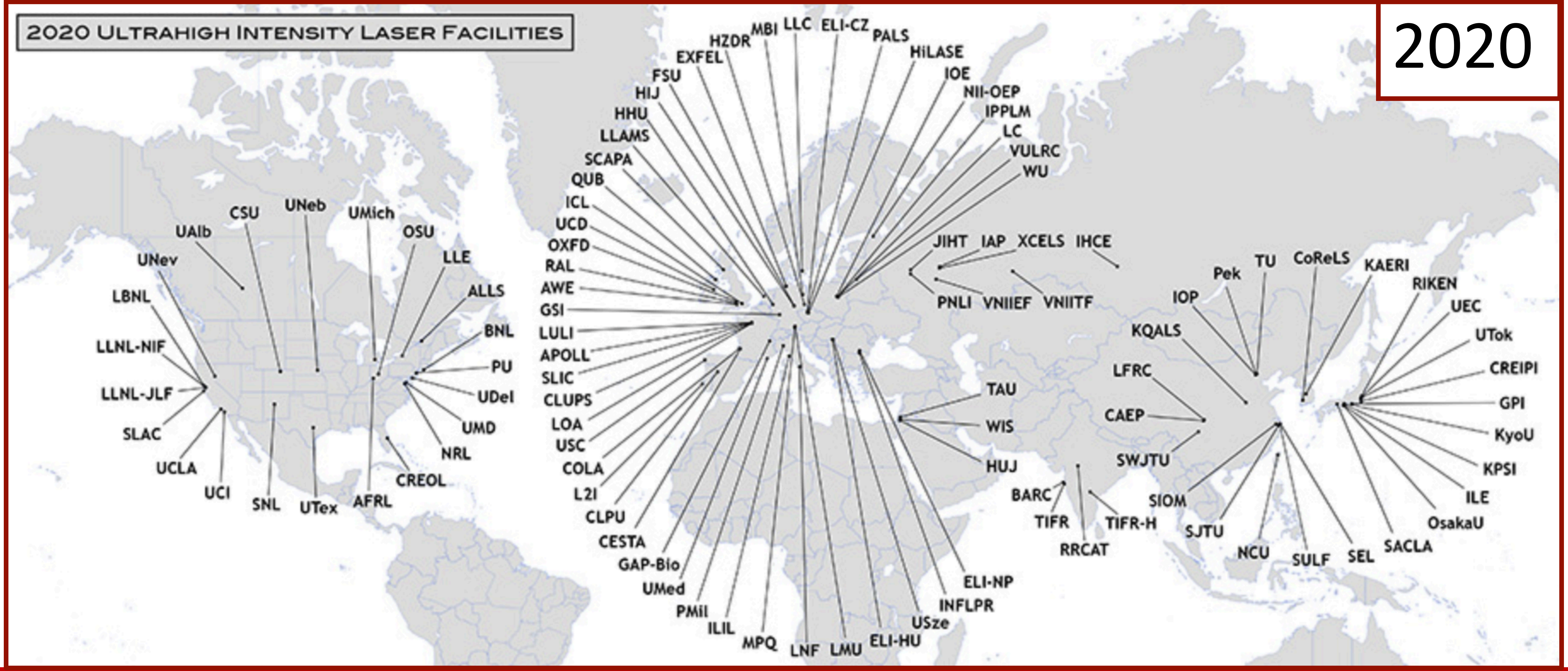
www.pulse.physik.uni-muenchen.de



High power lasers around the world:



2009



2020

Maps:

High power lasers with Intensities > 10^{19} W/cm^2

ATLAS 3000 @ CALA:

Nominal power: 60J, 25fs -> 2.5 Petawatt
Current power: 10 J, 25 fs -> 0.4 Petawatt
Current Intensity: approx. 10^{21} W/cm^2

Why high Intensities?:

$$E_{\text{ions}} \propto \sqrt{I_{\text{Laser}}}$$

Fields: ≈100 MV / µm

Trick:
Chirped **P**ulse **A**mplification (Nobel prize 2018)

Ill. Niklas Elmehed. © Nobel Media

Gérard Mourou

Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media

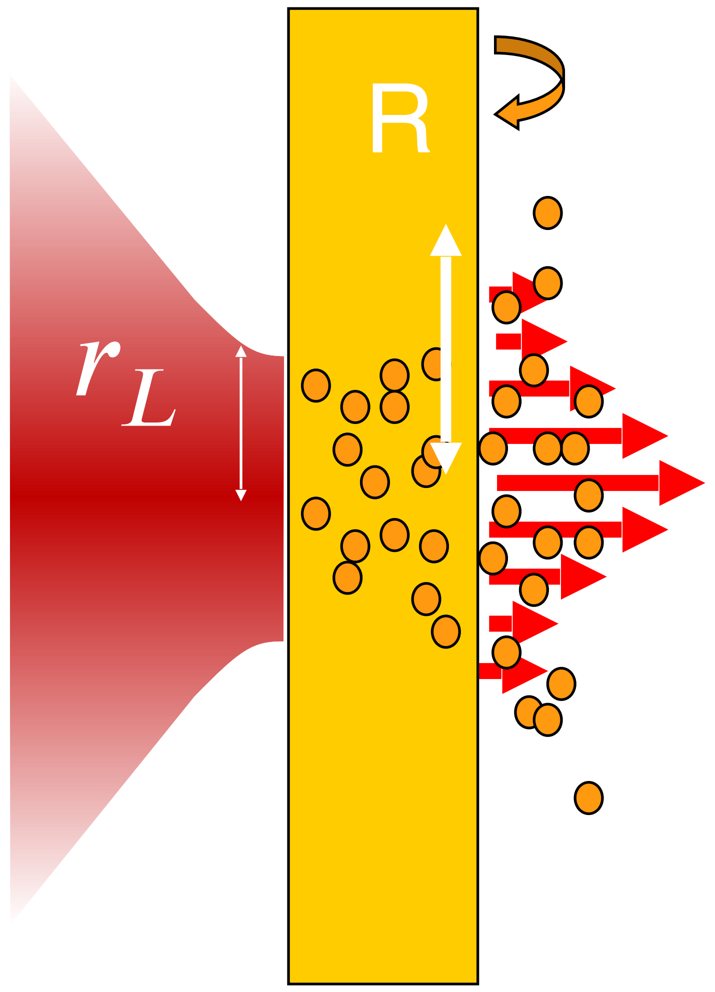
Donna Strickland

Prize share: 1/4

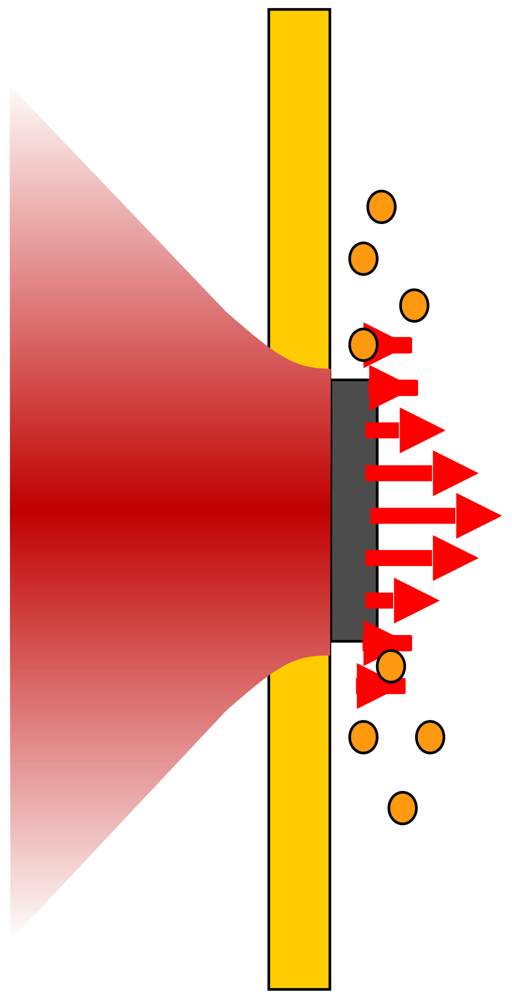
Map: Courtesy of the International Committee on Ultrahigh Intensity Lasers - www.icuil.org

Acceleration physics

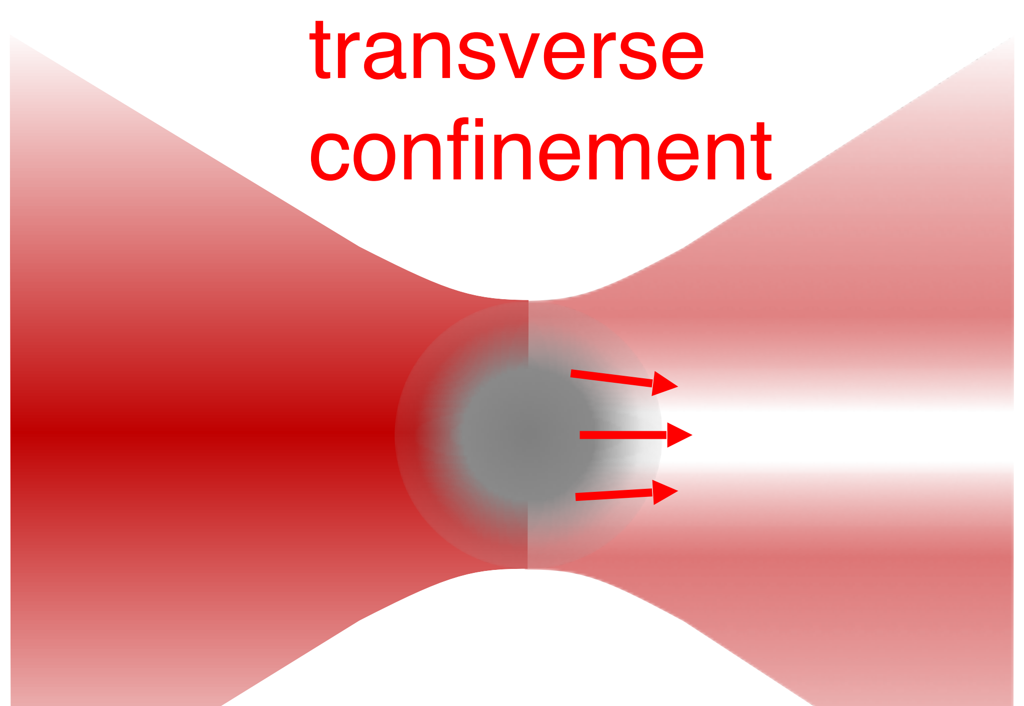
Thick target $\boldsymbol{d} \gg \boldsymbol{l_{skin}}$ (TNSA)
‚Target normal sheet acceleration‘



Thin target $\boldsymbol{d} \approx \boldsymbol{l_{skin}}$ (RPA)
‚Radiation Pressure Acceleration‘



μ-plasma in Paul trap $\boldsymbol{d} \approx \boldsymbol{l_{skin}}$

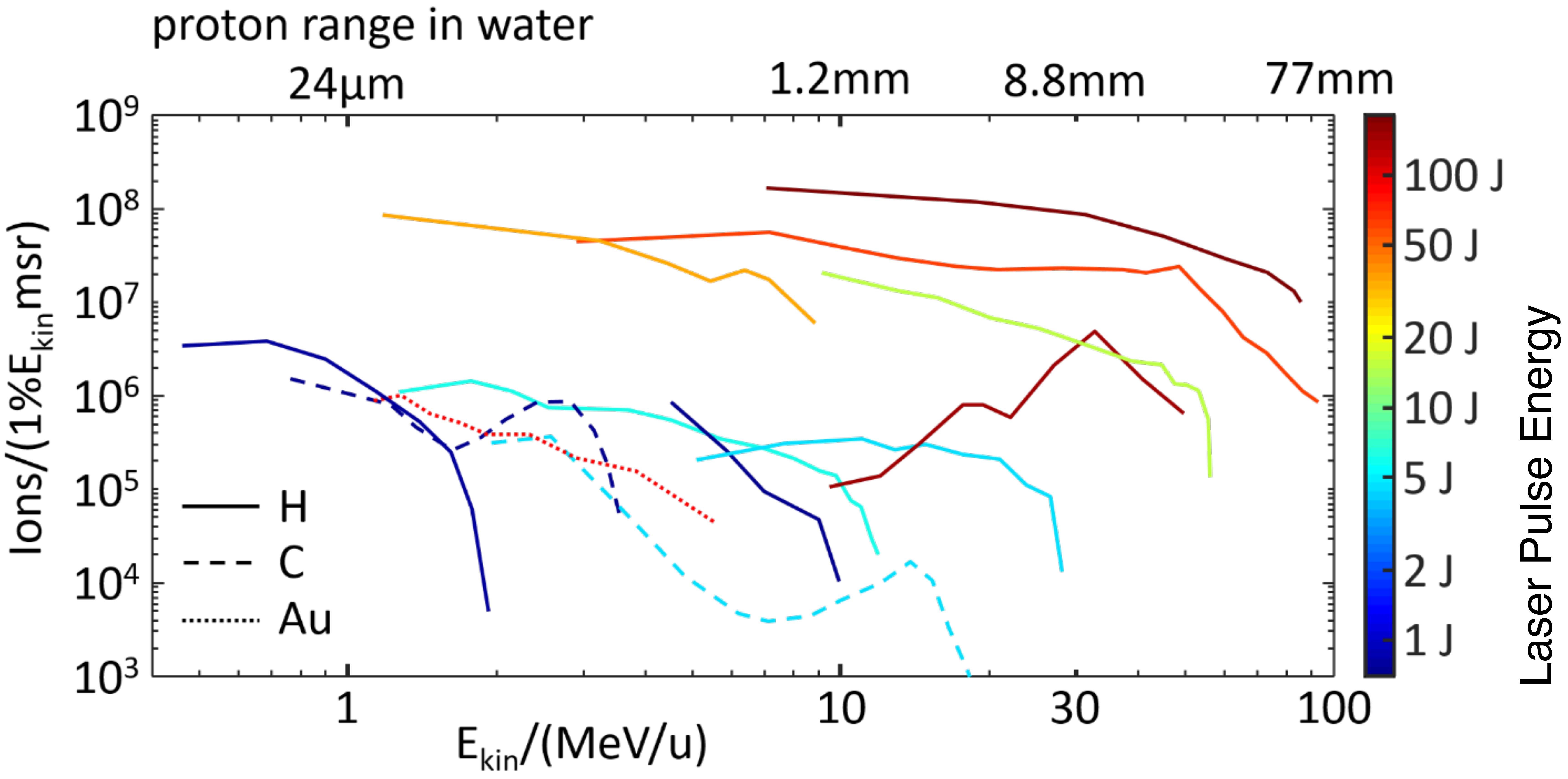


Hilz+,
Nat Comm. **9**, 423 (2018).

Optimization strategy during last 20 years: laser-pulse energy ↑, pre-pulses ↓, target thickness (size) ↓, repetition rate ↑, reproducibility ↑,
… meanwhile ~100 MeV protons with PW, first tumor irradiation in mice at HZDR
Kroll et al Nat Phys 18, 316-322, (2022).

Proton energy distribution

State of the art:



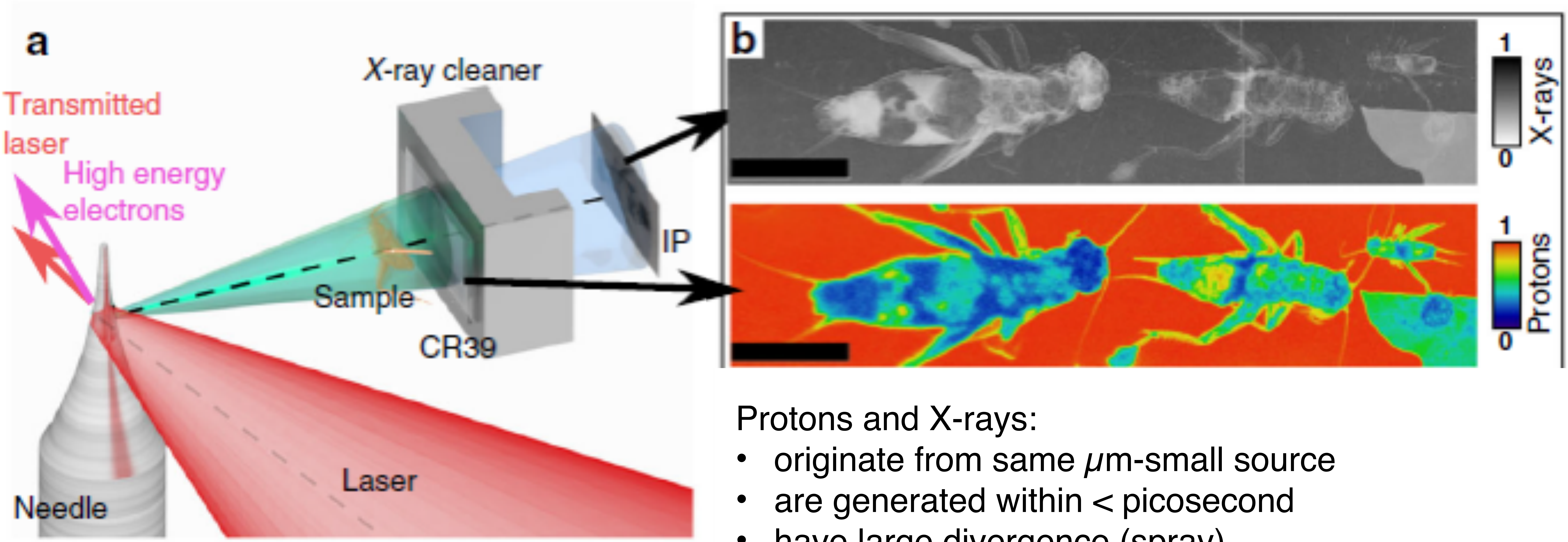
Albert et al 2020 roadmap on plasma accelerators *New J Phys* 23, (2021).

Laser vs RF acceleration

Laser-plasma	**Non-laser (RF)**
Single bunch every second (large particle number ≈10^{12} per bunch)	Continuous beam (micro-bunch train)
Broad energy distribution (100%) yet short bunch (fs…ps…ns)	Mono-energetic (ns…μs bunches)
Spray (10° divergence) yet small source (μm)	Beam
Intrinsically synchronous to multiple radiation modalities	Non-trivial in sub-ns (unless operated with photo-cathode (-anode)
Source and acceleration combined (high field, high temperature, high density)	

What are interesting application of the “back-illuminated photo-anode”?

Application example 1:
Bi-model imaging (X-ray phase contrast + proton projection)



Ostermayr et al Nat Comm 11, 6174 (2020)

Protons and X-rays:

- originate from same μm-small source
- are generated within < picosecond
- have large divergence (spray)

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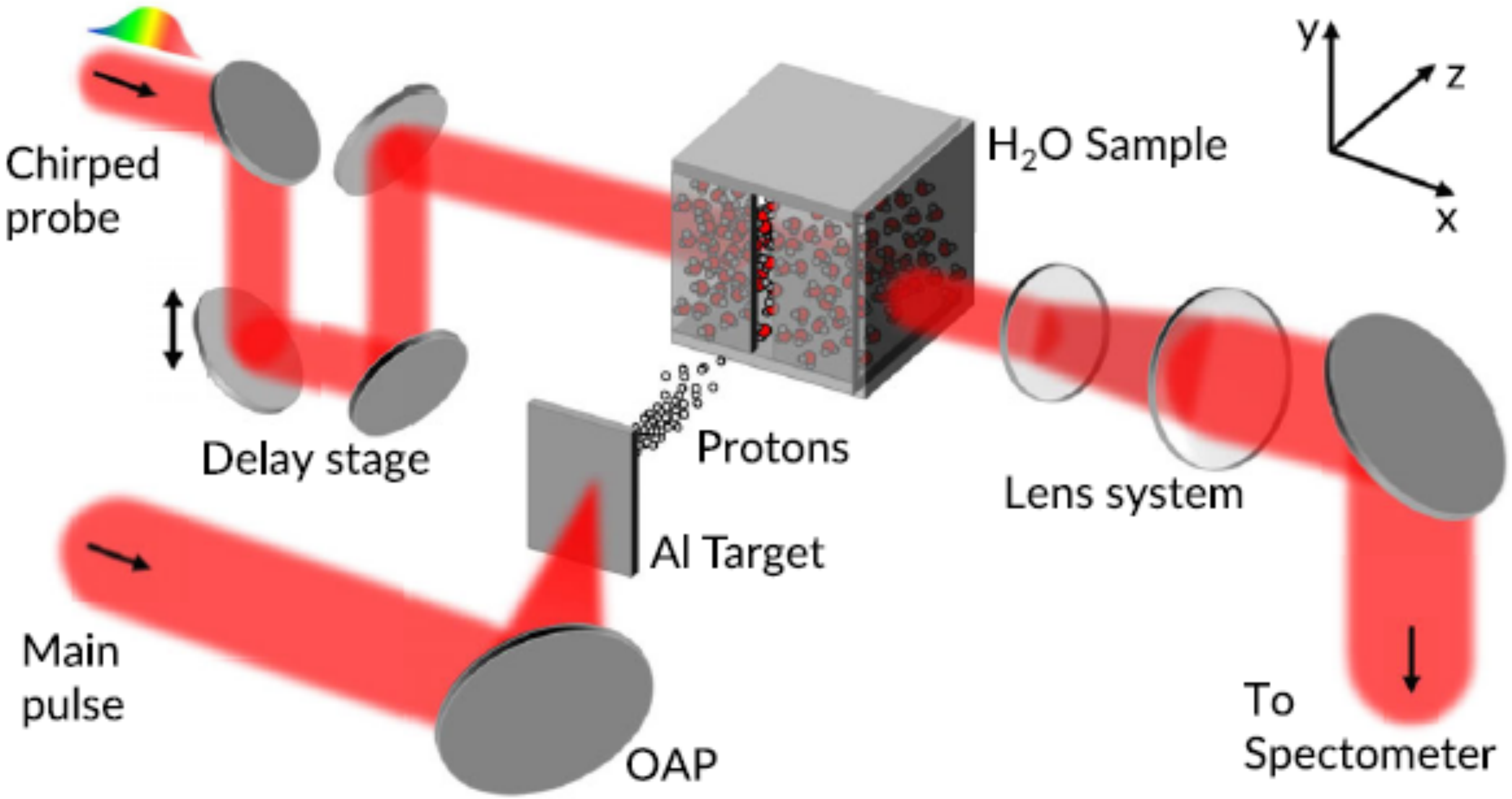
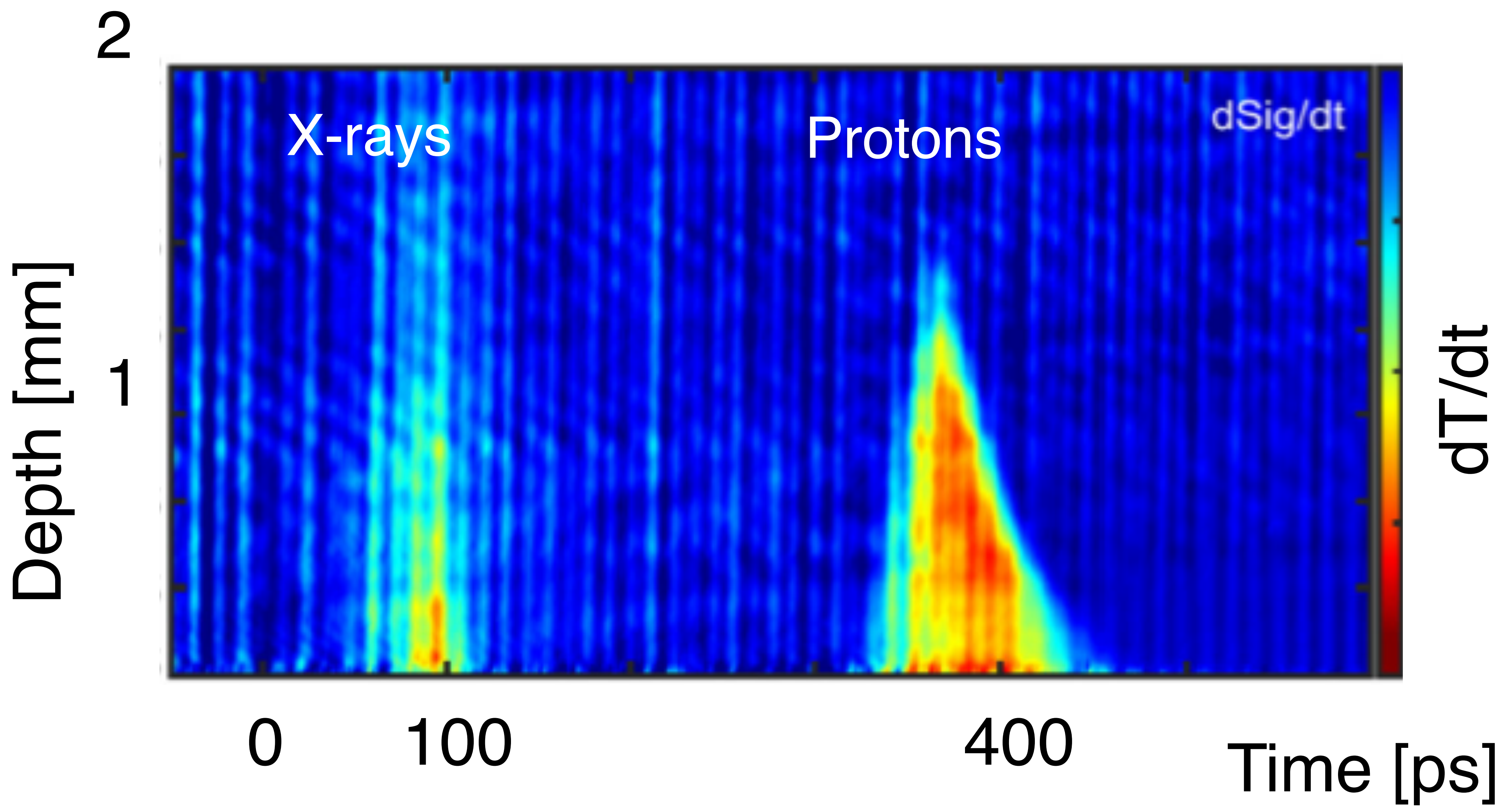
Application example 2:
Time resolved spread out Bragg curve





Derive accelerating and probe laser from same pulse:
Proton pump – optical probe with picosecond time and μm spatial resolution

Solvation of electron takes 65 ps after proton impact (>20 ps longer than in photolysis) … charge effect?

Prasselsperger et al PRL 127, 186001 (2021)

Application example 3:
Heavy ion acceleration

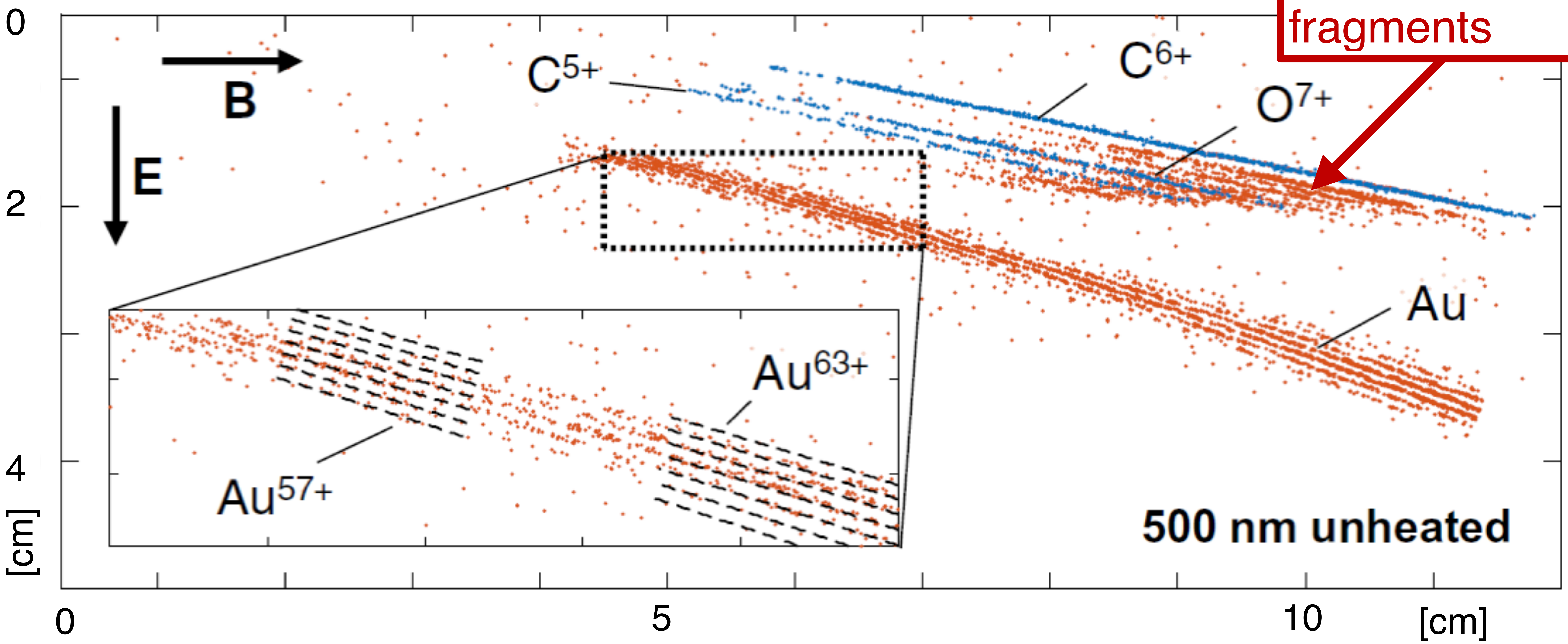
Acceleration of Gold beyond 7 MeV/u

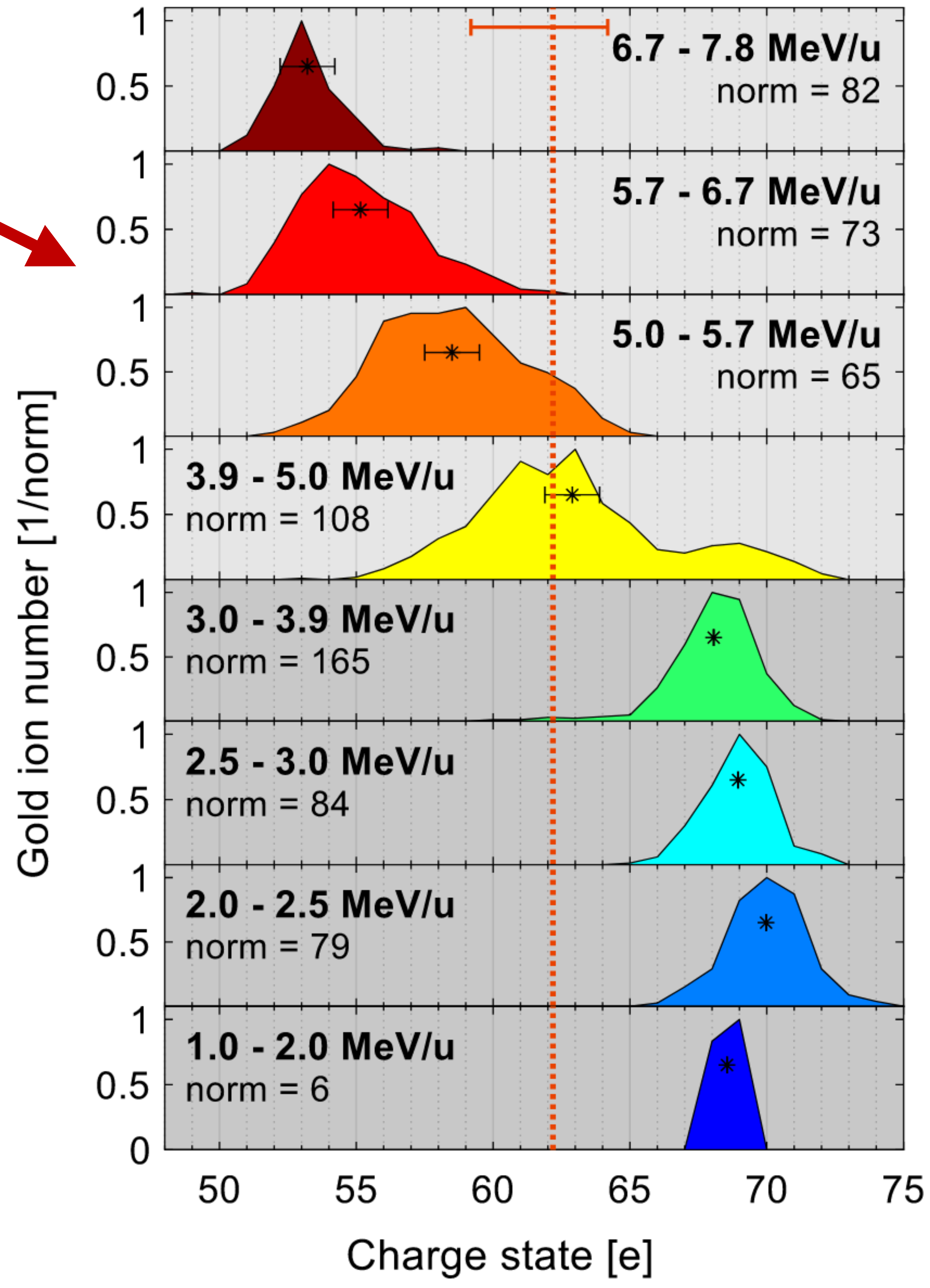
-> fission barrier of heavy ions

-> Important for nuclear astrophysics:
Investigation of elements close to the waiting point of the rapid neutron capture process

Charge higher than expected from field ionization

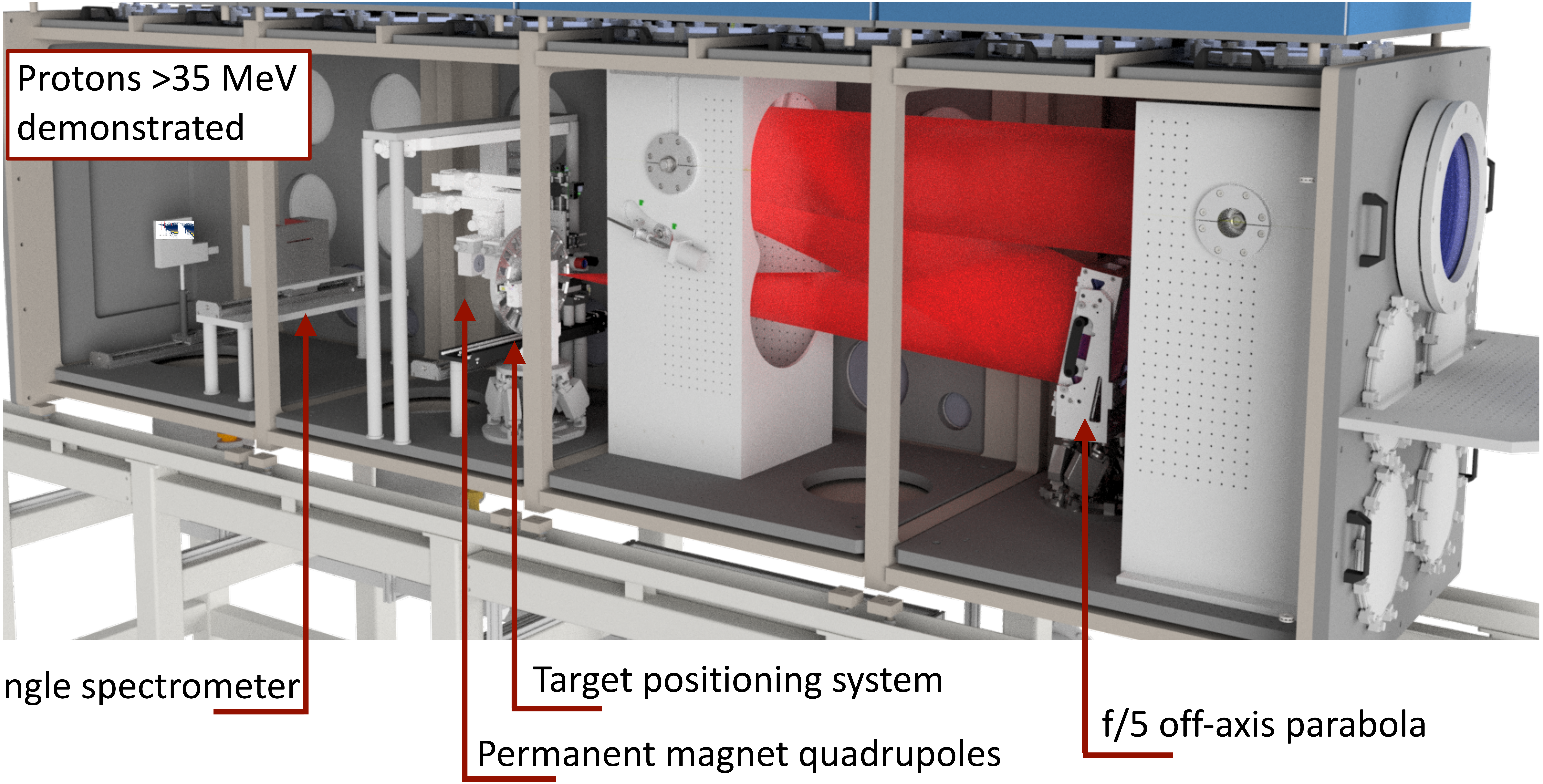
Indications of swift Au-fission fragments





Lindner et al, *Sci Rep* 12, 4784 (2022)

LION: Laser-ION acceleration at CALA



Protons >35 MeV demonstrated

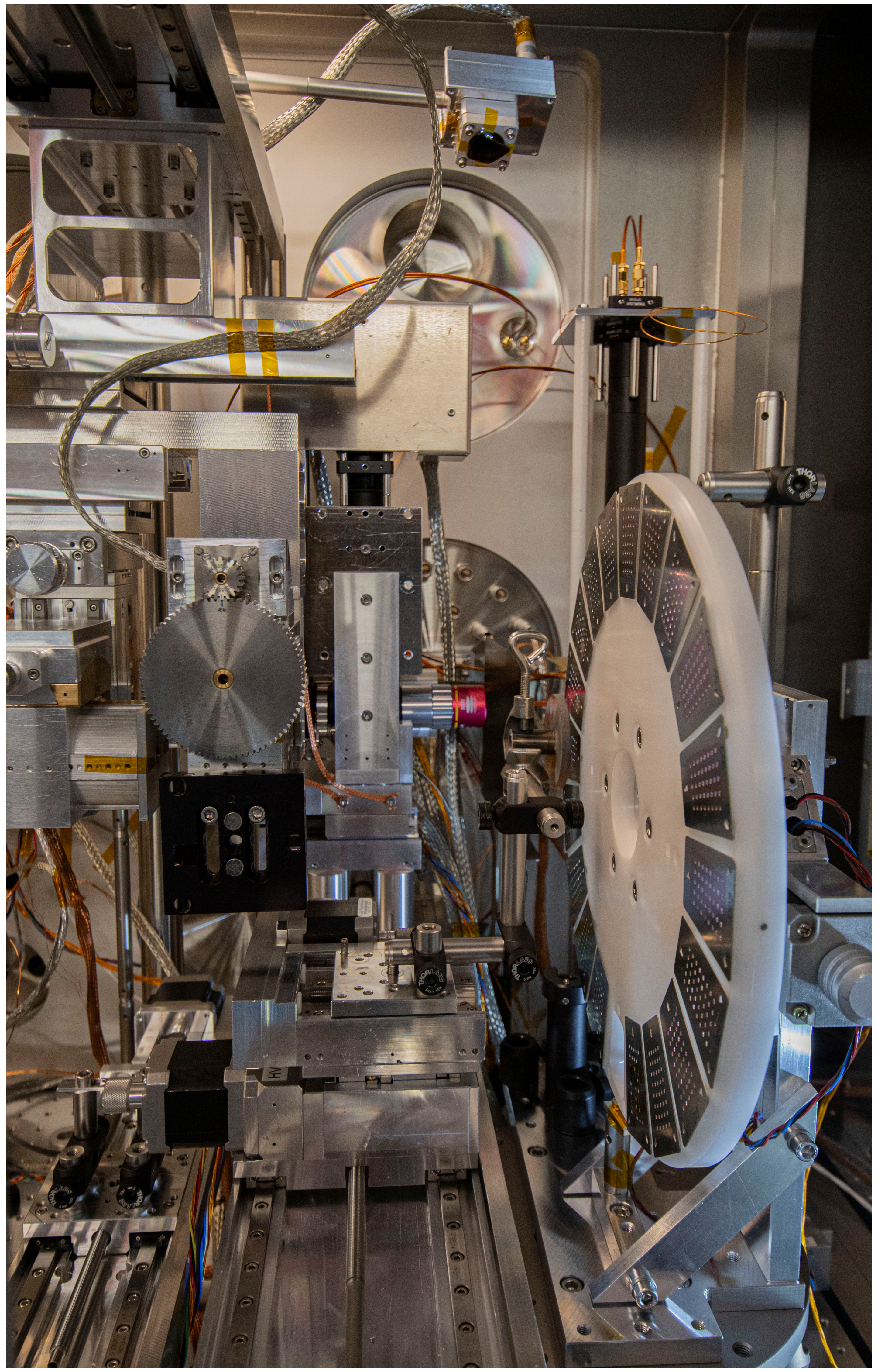
Wide-angle spectrometer

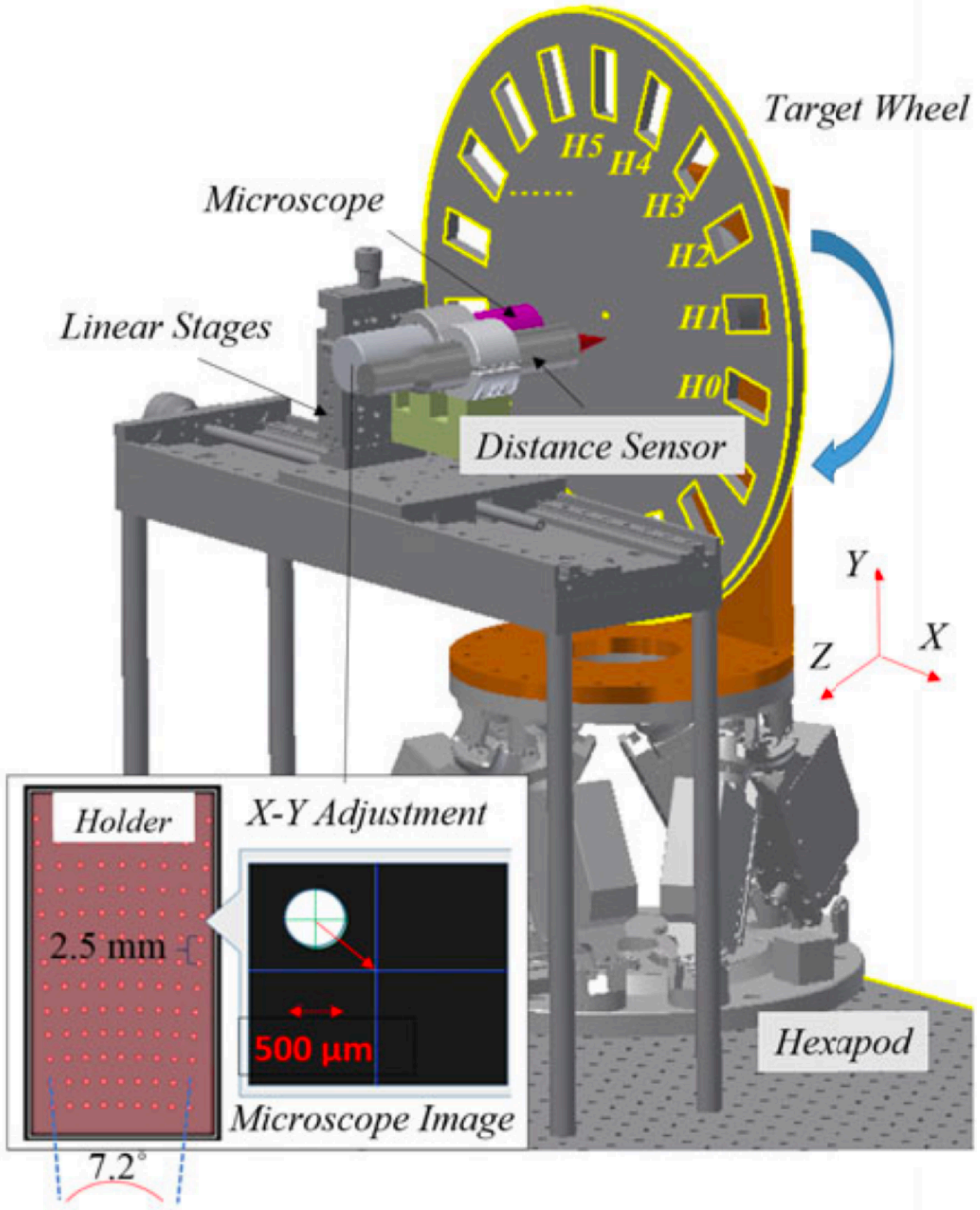
Target positioning system

Permanent magnet quadrupoles

f/5 off-axis parabola

LION: Foil target positioning system





Gao et al HPLSE 5 (2017)

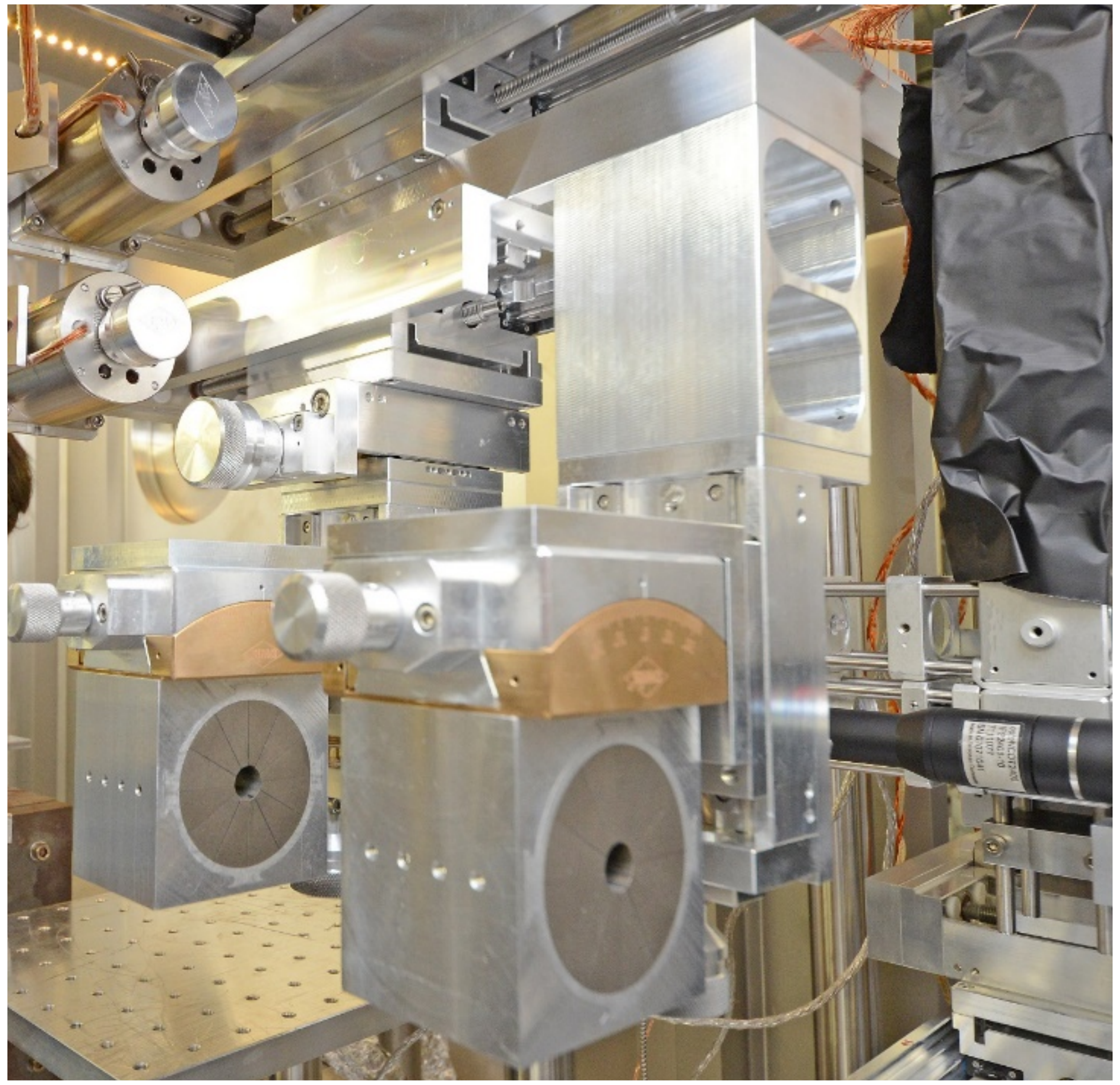
Key parameters:

- 0.5 Hz operation
- 4 um precision
- Up to 800 targets
- Various foils can be mounted, e.g. 400 nm Formvar
- Automated target positioning

Alternative target systems:

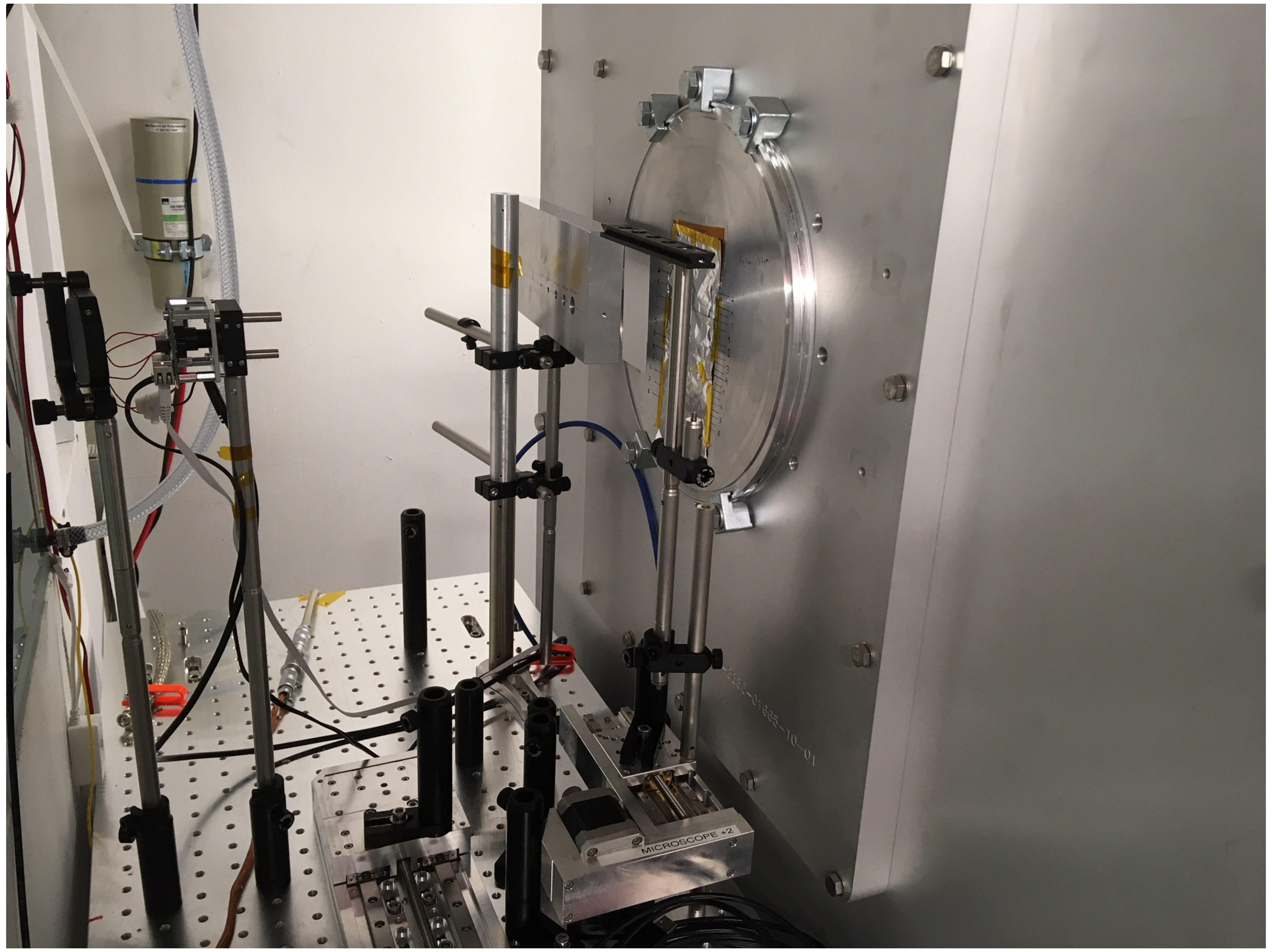
- Levitating spheres
  -> Better conversion of laser into ion energy
- Liquid water leaf
  -> Reproducible & high repetition rate

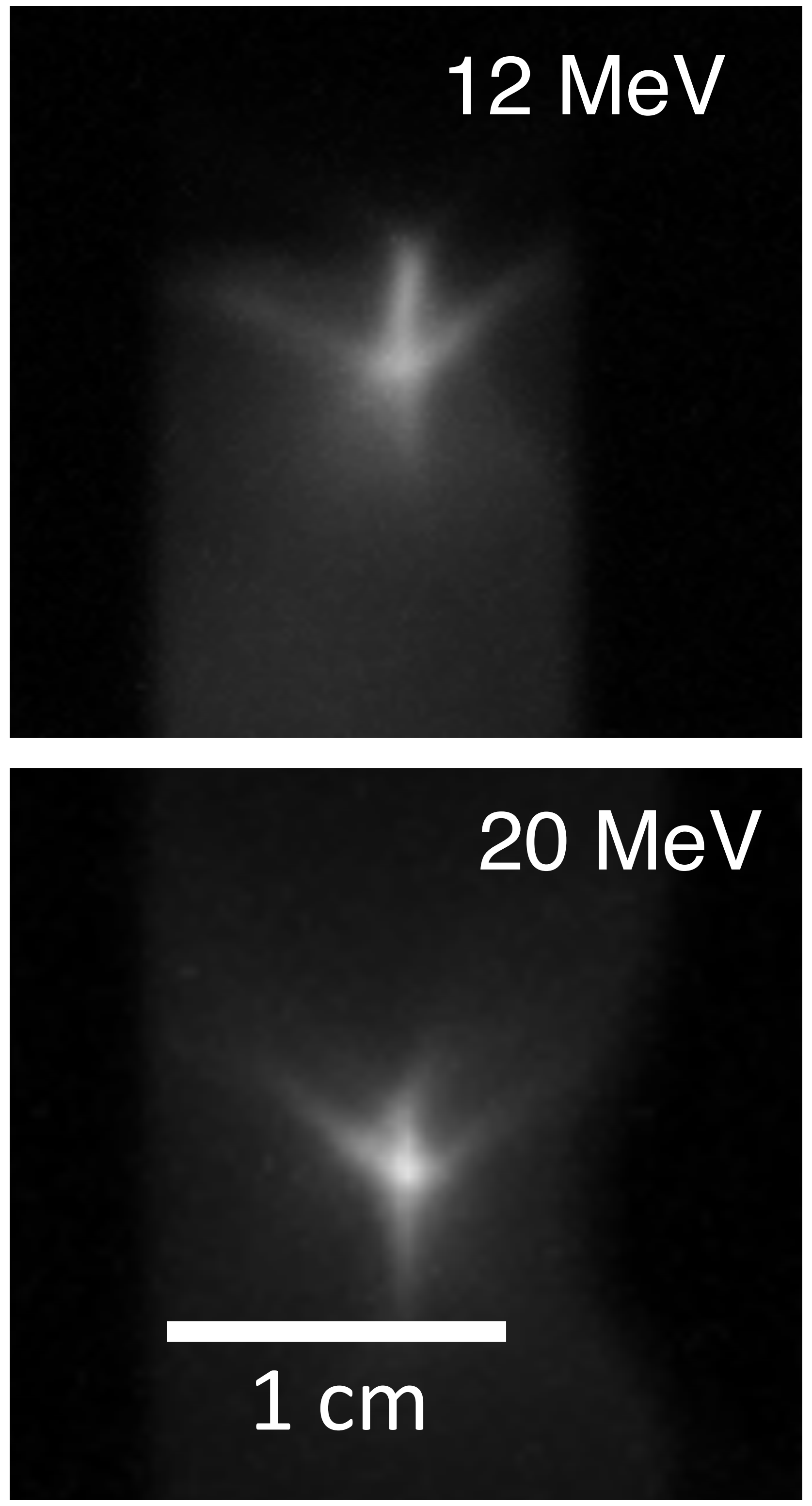
LION: Ion Focusing lens



Permanent magnet quadrupoles

- Duplet / quadruplet available
- Magnets motorized in x/y position & rotation
- PMQ position defines transported proton energies

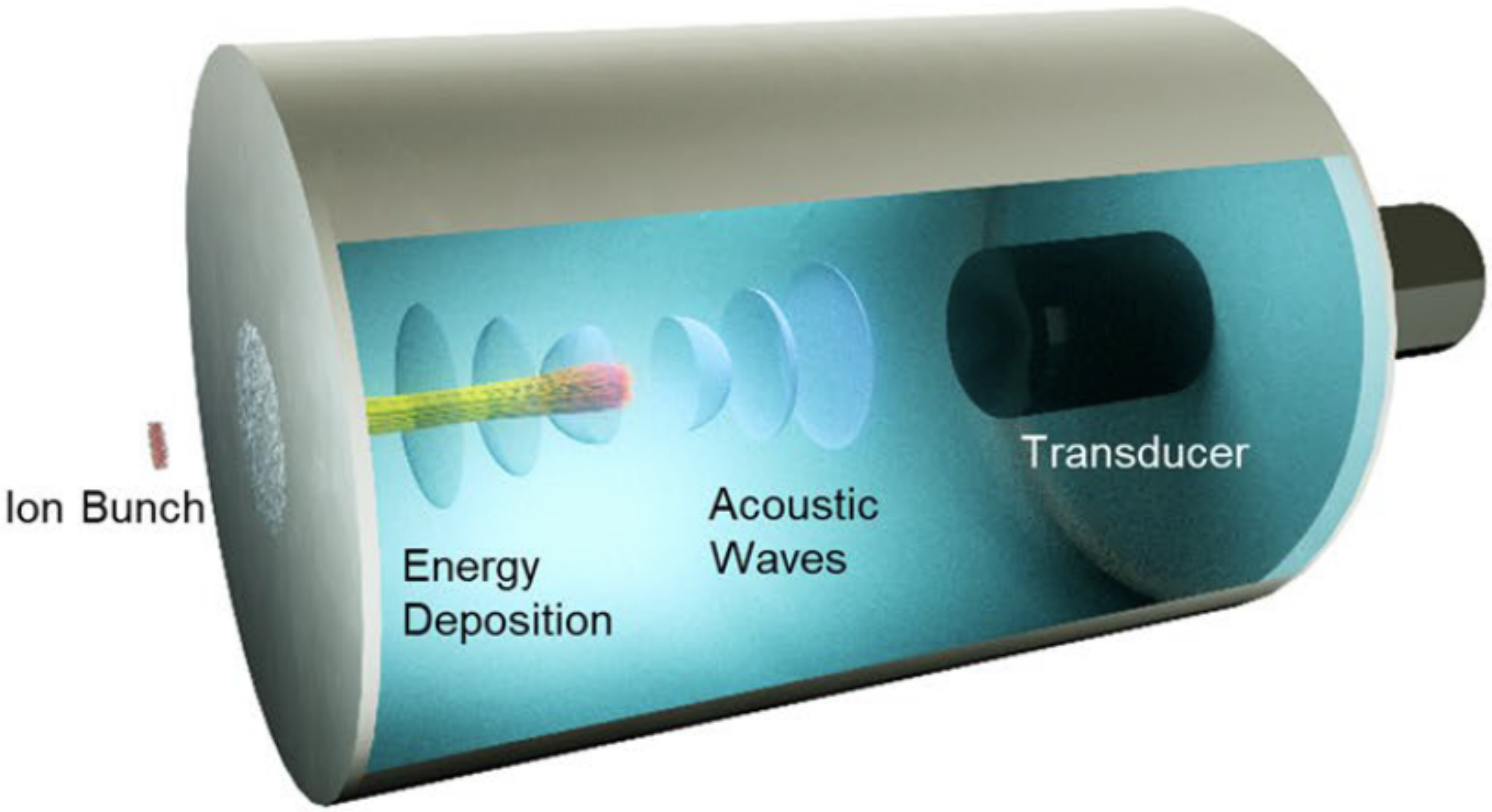




Application plattform

- 1.8 m downstream in air
- <1 mm proton foci
- Detection: Scintillator

Ion detection: Ionoacoustics



Haffa et al Sci Rep 9, 6714 (2019)

- Ions deposit their energy in a water reservoir
- Energy deposition leads to localized heating
- A pressure wave originates from gradients in thermal expansion
- Ultrasonic signal is recorded by a transducer

Ion detection: Ionoacoustics

- General wave equation with source term describes pressure wave:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)p\left(\vec{r},t\right) = -\frac{\Gamma}{c^2}\frac{\partial}{\partial t}H\left(\vec{r},t\right)$$

Γ: Grüneisen parameter (material constant)

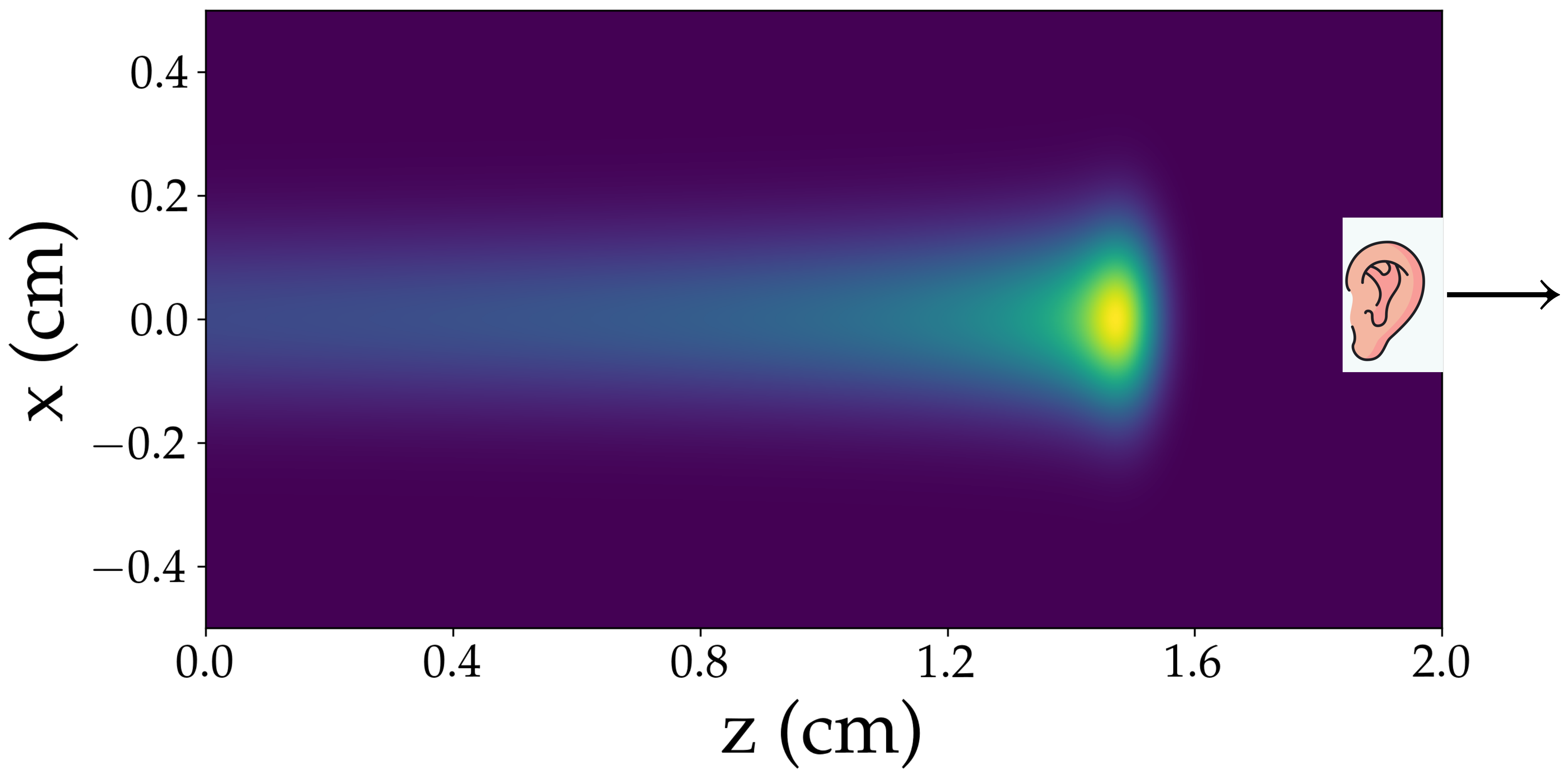
c : Phase velocity 1.5 mm/µs

H: ‚Heating function', $H(\vec{r}) = D(\vec{r})$

- Solution:

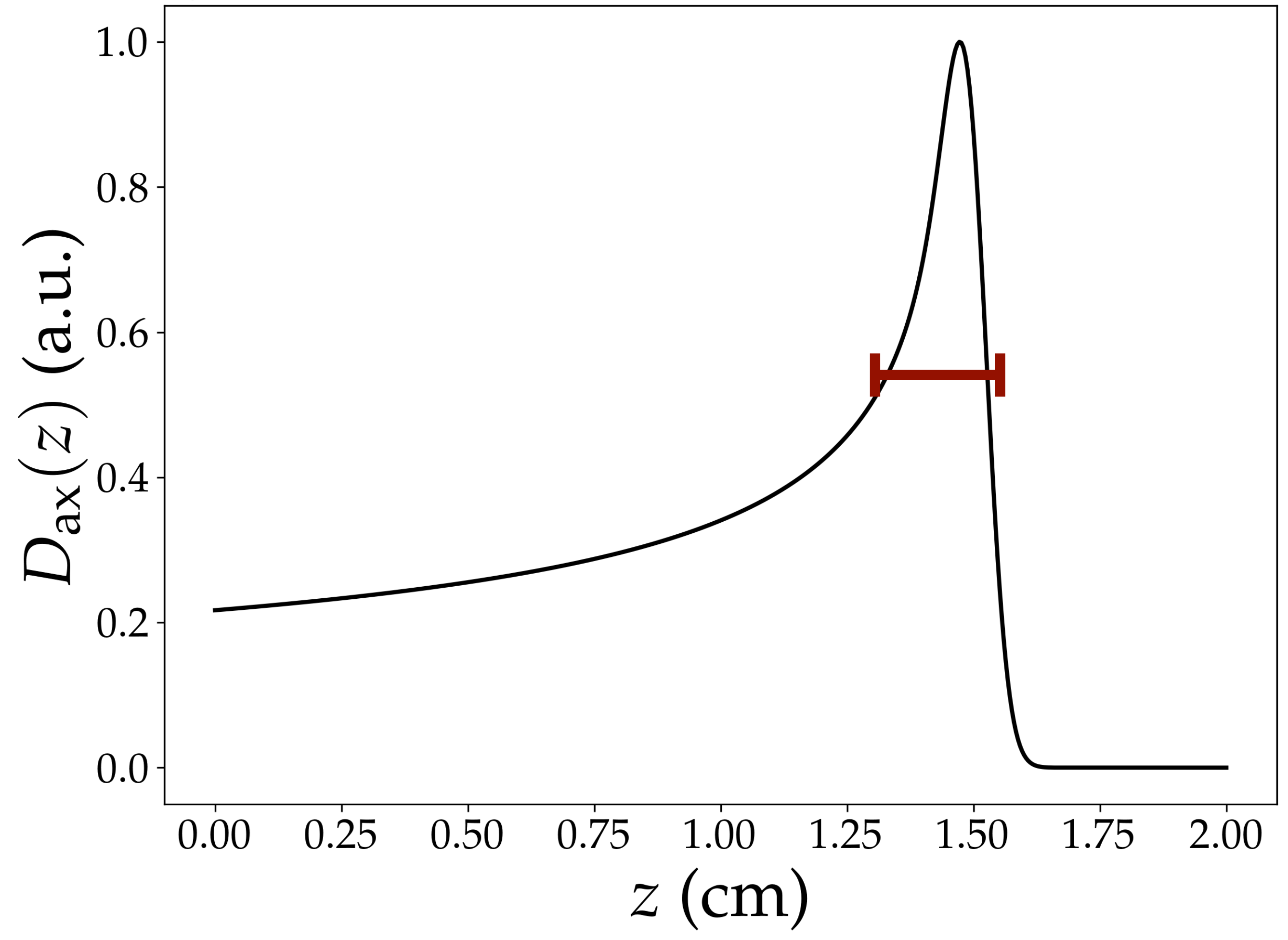
$$p(\vec{r},t) = \frac{\Gamma}{c^2}\frac{\partial}{\partial t}\int d^3\vec{r}'\frac{1}{|\vec{r}-\vec{r}'|}H(\vec{r}',t-\frac{|\vec{r}-\vec{r}'|}{c})$$

Axial signal:

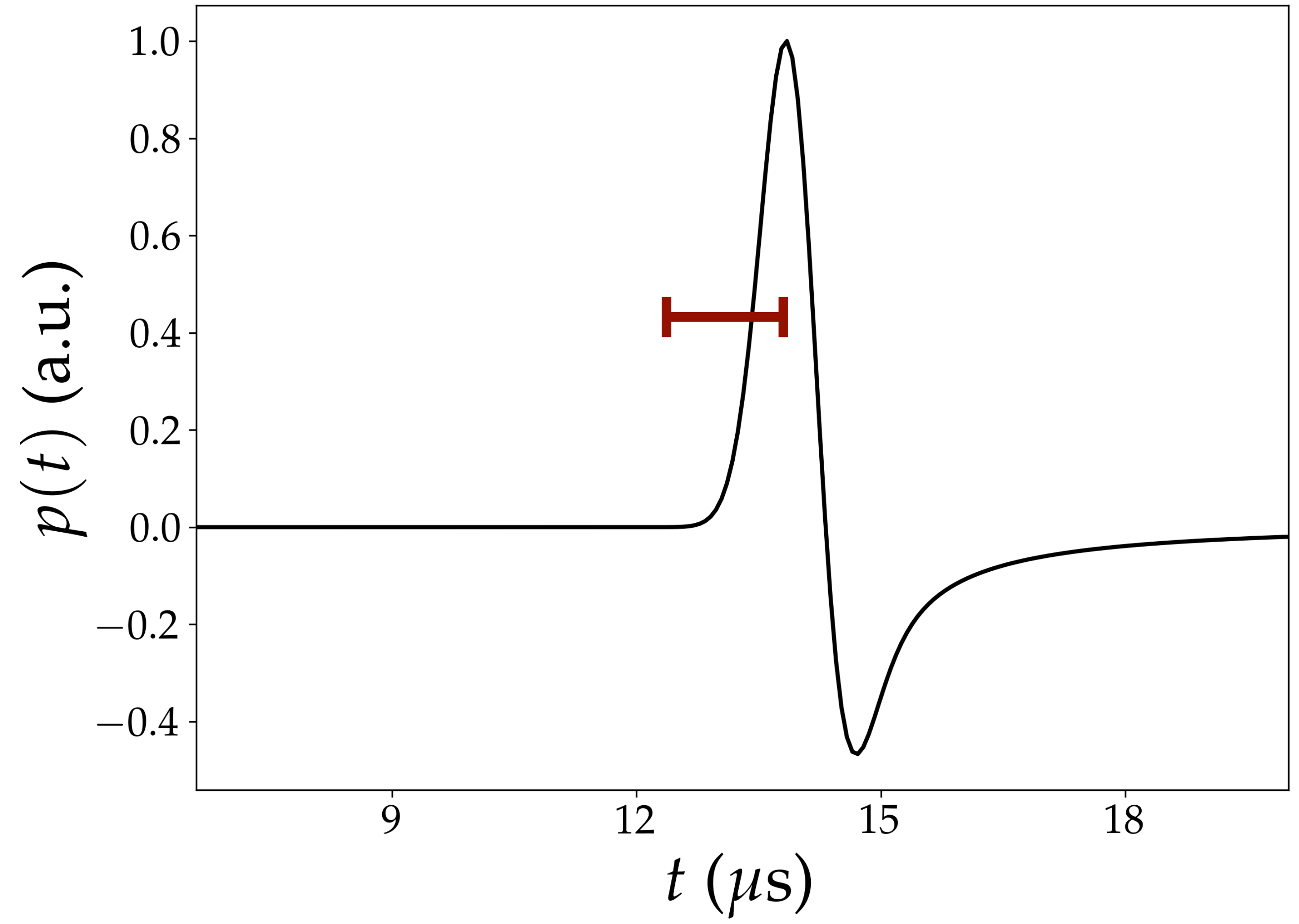


E=40 MeV, σ_E=1MeV, σ_{lat}=0.1 cm

Longitudinal BP position and width



Axial signal position and width



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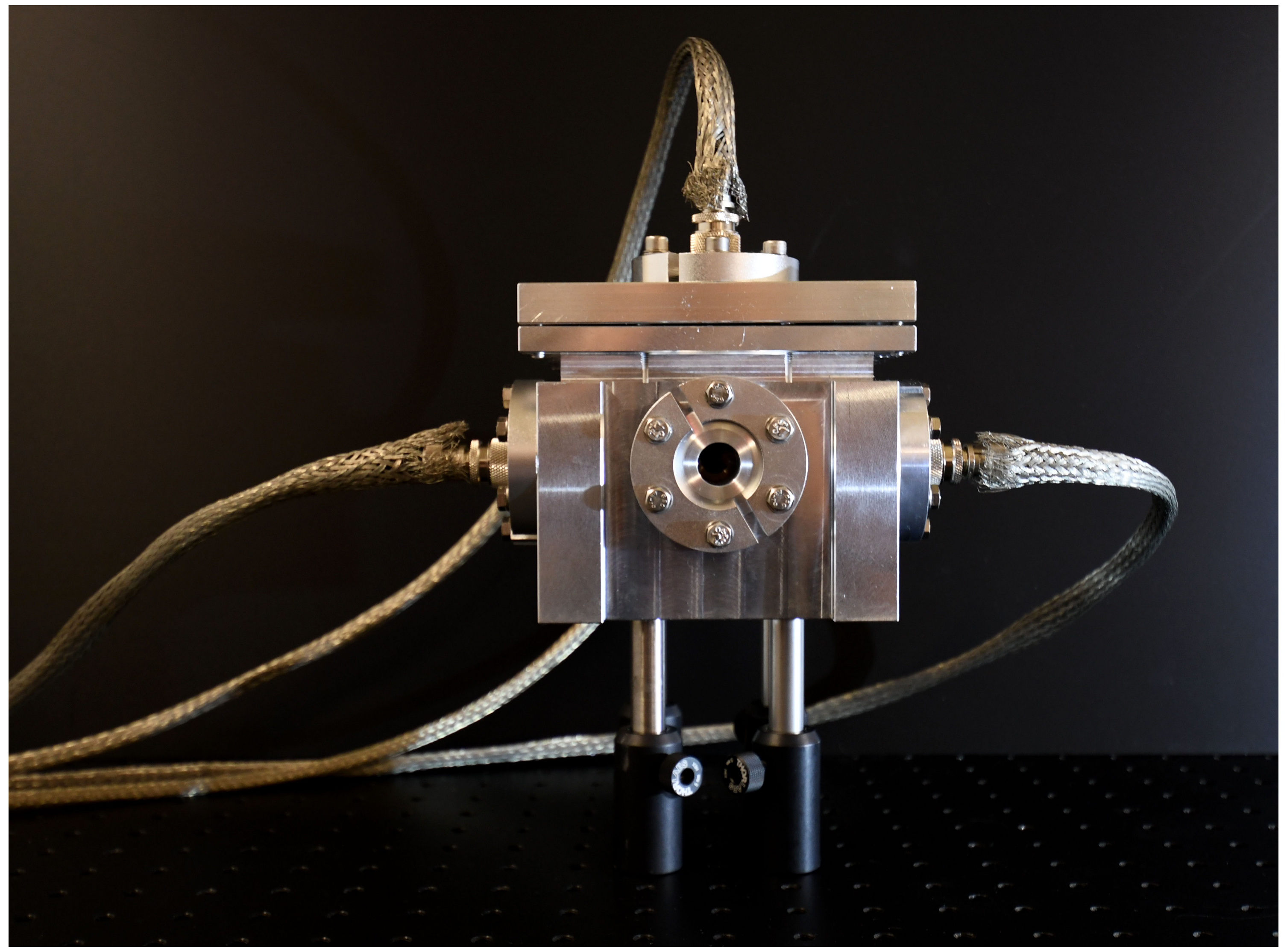
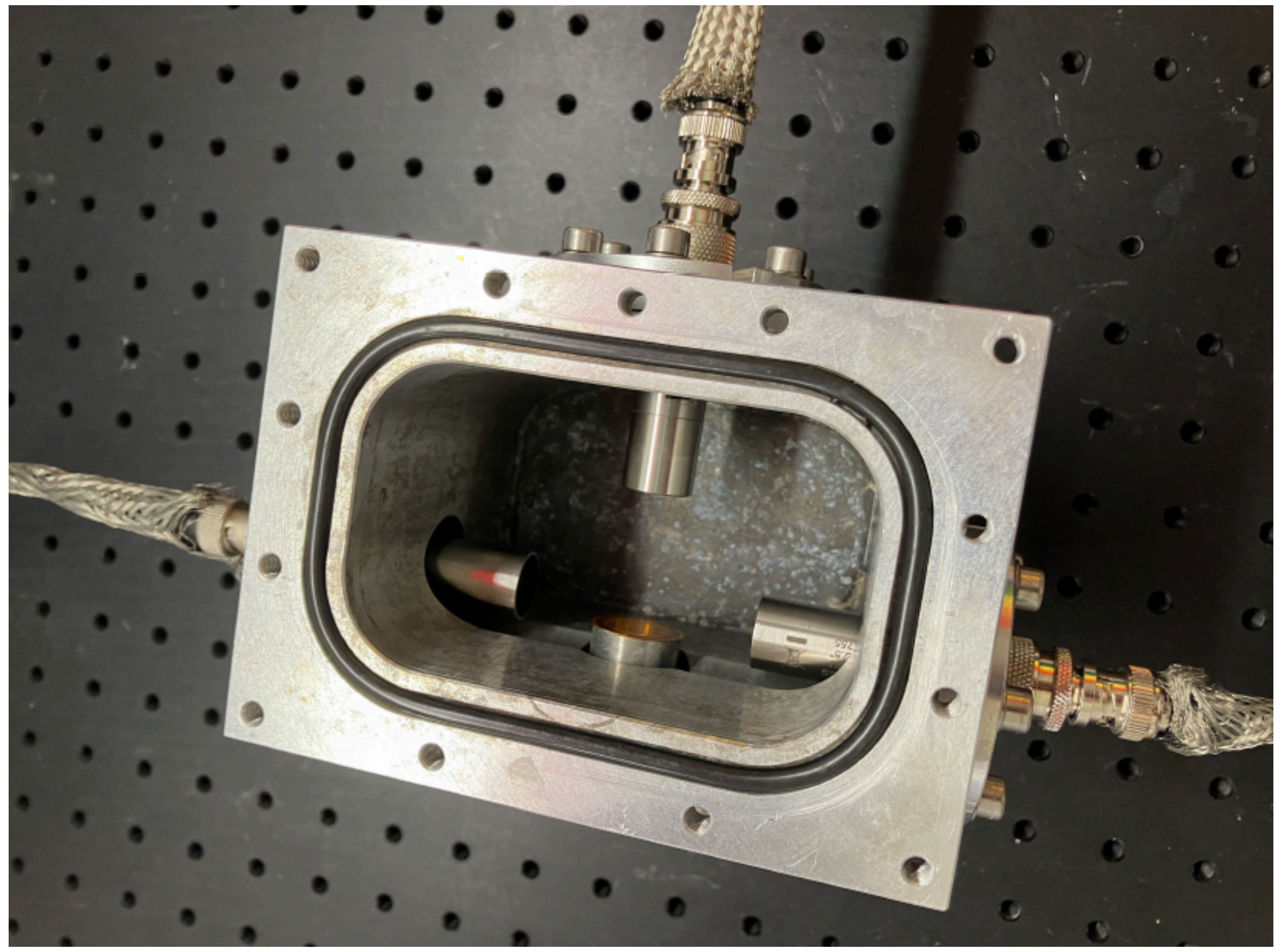
Ionoacoustics requires gradient in energy deposition & temporal bunch structure

Ion detection: Ionoacoustics





I-BEAT 3D: Measures 3D particle bunch properties

- Energy & energy spread:
  5 MeV - 1 GeV per nucleon, sub-MeV resolution
- Lateral position and size:
  sub-mm resolution
- Particle number:
  10^6-10^9 per bunch

Experimentally confirmed, not the limit…

Additional properties:

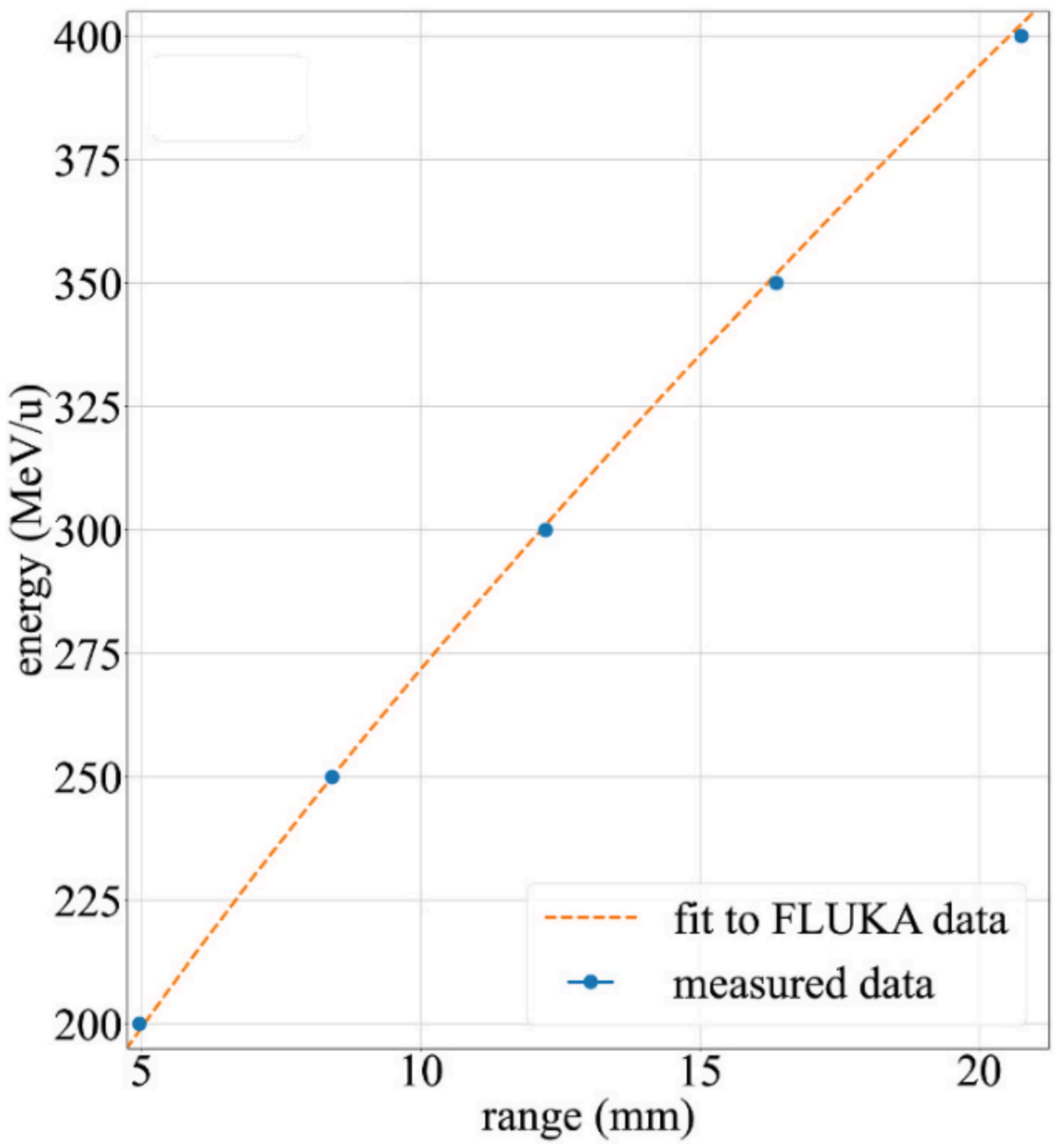
- Radiation hard & electromagnetic pulse resistant
- Simple & cheap set-up
- Online readout & fast data analysis available

Gerlach et al HPLSE 11 (2023)

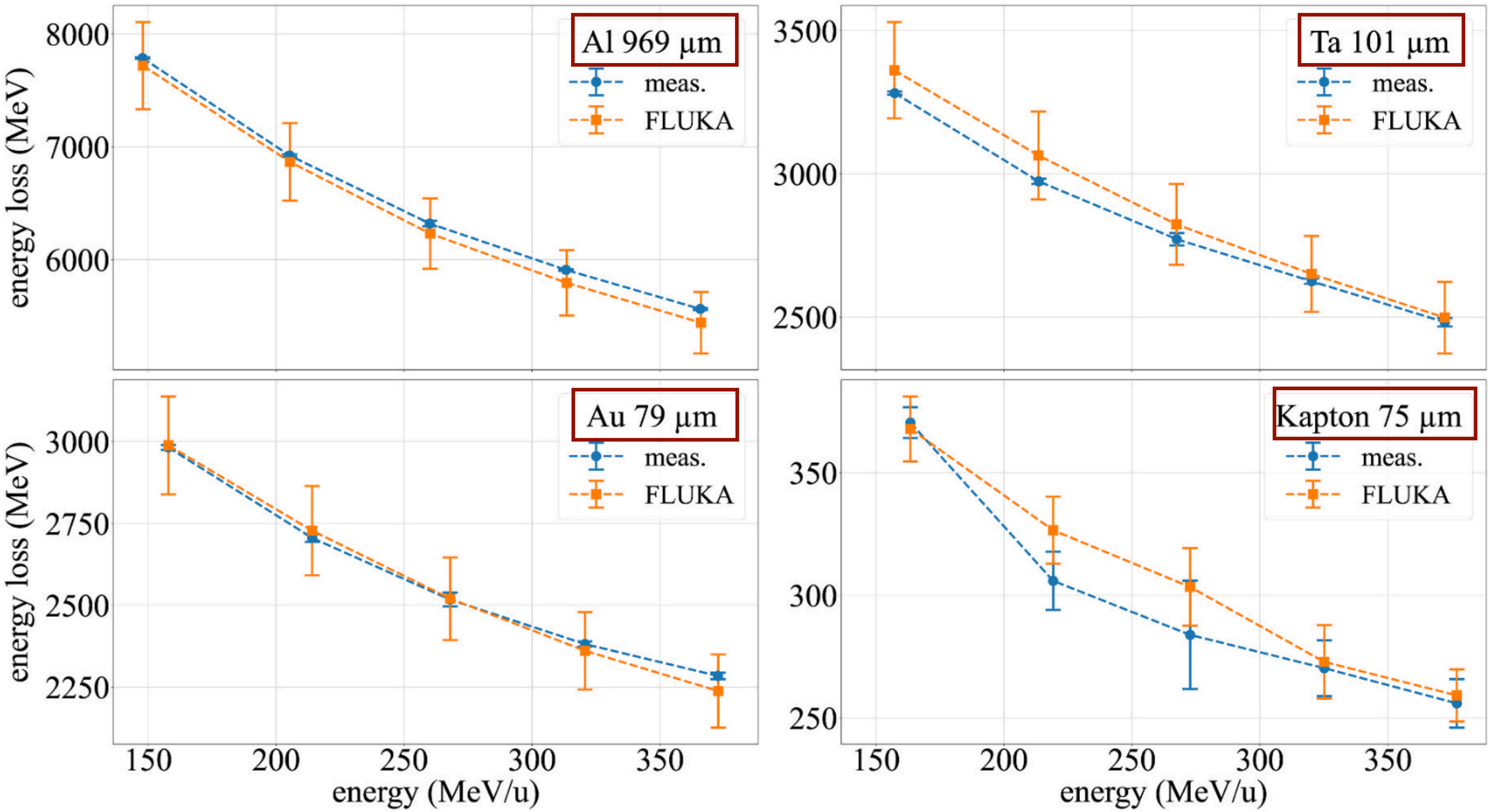
Ion detection: Ionoacoustics

Application (example): Stopping power measurements

Set-up: I-BEAT 3D, ^{238}U ions, SIS18 synchrotron at GSI Darmstadt



< 1% energy resolution



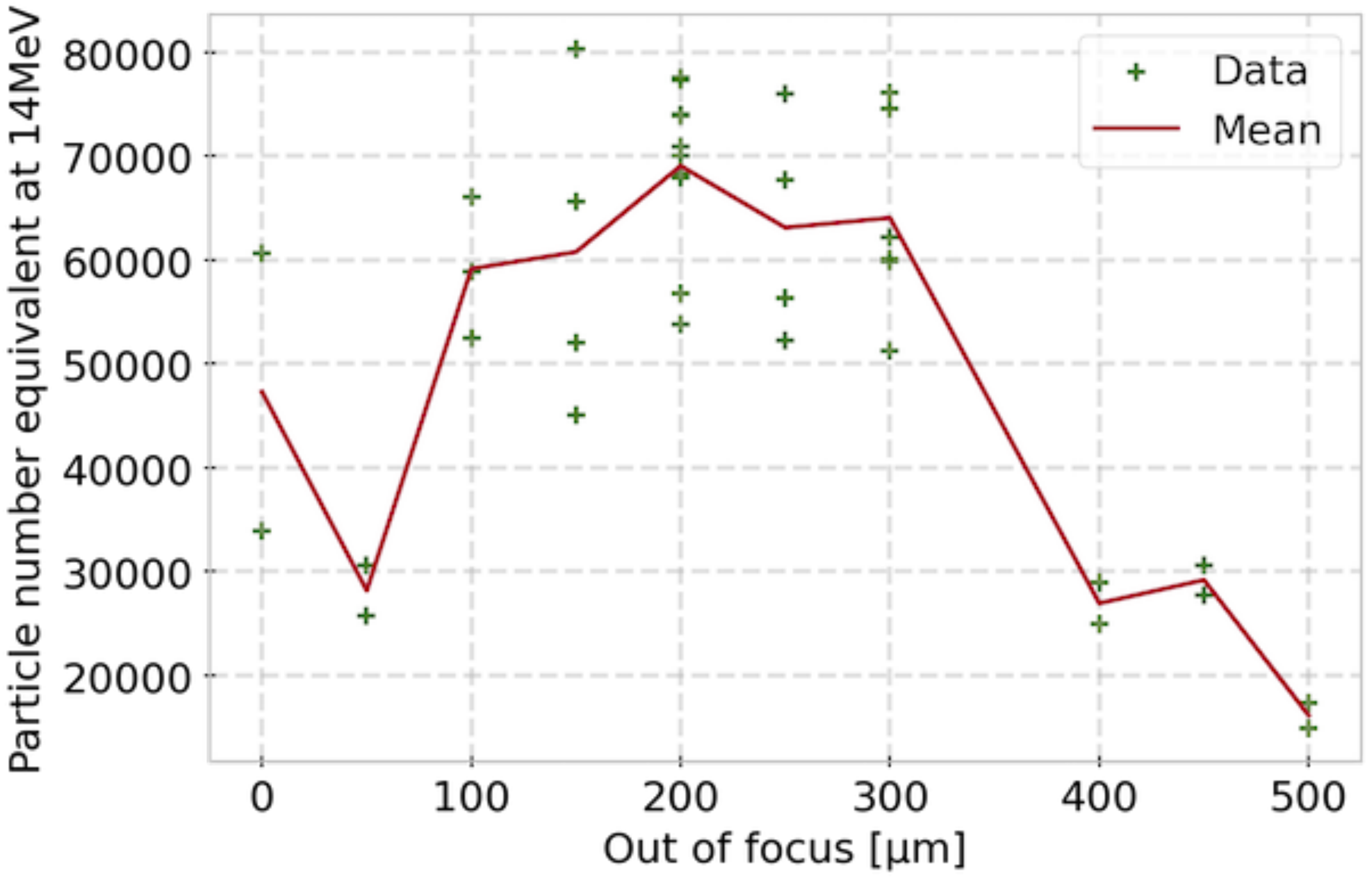
Kirsch et al Nuc Inst Meth A (2023)

Optimization of the ion source at CALA

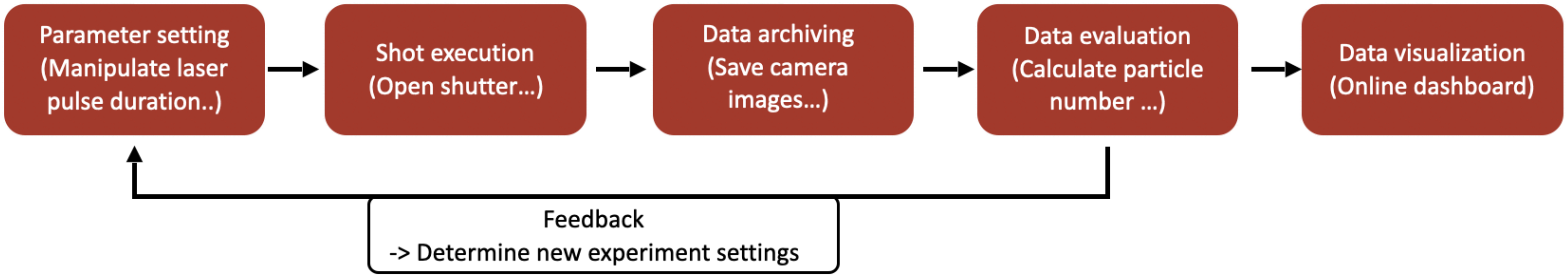
- Complex interplay between laser, target and ion parameters caused by non-linear laser-plasma interaction

- Machine learning could help to optimize ion parameters

- First automated Bayesian optimization of proton number demonstrated



Automated experimental workflow



Parameter setting (Manipulate laser pulse duration..)

Shot execution (Open shutter...)

Data archiving (Save camera images...)

Data evaluation (Calculate particle number ...)

Data visualization (Online dashboard)

Feedback
-> Determine new experiment settings

Summary

- Laser-ION source can provide intense bunches of protons ($\lesssim$100 MeV), and/or heavier ions ($\lesssim$ 50 MeV/u ^{12}C, $\lesssim$ 7 MeV/u ^{197}Au) with very high charge.

- Sources mature (e.g. mouse irradiation at HZDR).

- Many new application possibilities (small emittance, synchronous, multimodal, large #/ bunch) … more than just ions.

- Synergistic developments with non-laser accelerator technology (photo-anode for hybrid accelerators, ionoacoustic detection,…).

- Research fields especially in high energy density physics, medical physics, nuclear astrophysics, inertial confinement fusion,…

Thank your for your attention and interest!

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Texas University at Austin (US): M. Hegelich+
GSI Darmstadt (Germany): B. Zielbauer, V. Bagnoud+
TU Darmstadt (Germany): M. Roth+, G. Schaumann,
HZDR Dresden (Germany): U. Schramm, M. Bussmann+
FSU Jena (Germany): M. Zepf, P. Hilz, +
Peking University (China): W. Ma+
SIOM (China): J. Bin