LASER-ION ACCELERATION IN PLASMAS

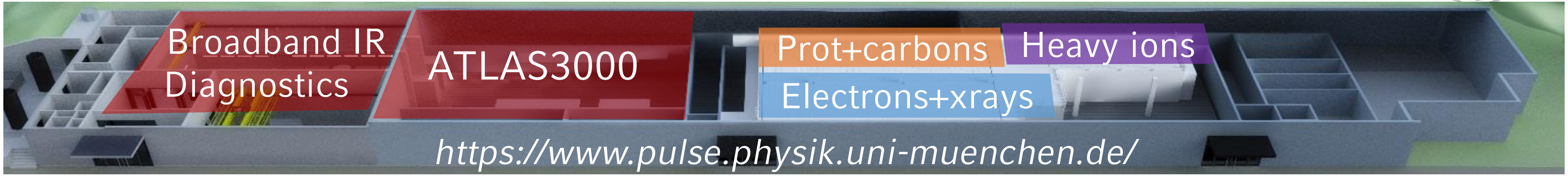
Laser-ION (LION) acceleration group – Jörg Schreiber et al.
Chair for medical physics (K. Parodi)
Ludwig-Maximilians-University Munich

LION-Group:
L. Doyle, S. Gerlach, F. Balling, A. Prasselsperger, L. He, M. Afshari, J. Liese, A. Schmidt, and students

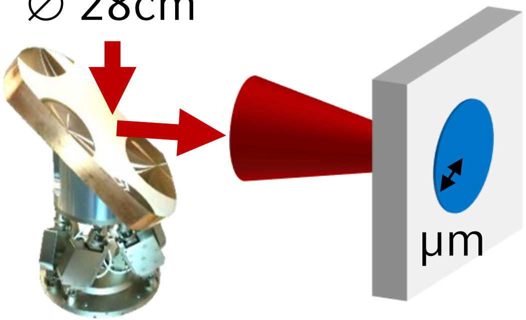
Picture: Centre for Advanced Laser Applications

Funds: BMBF, DFG, CALA, GSI-R&D

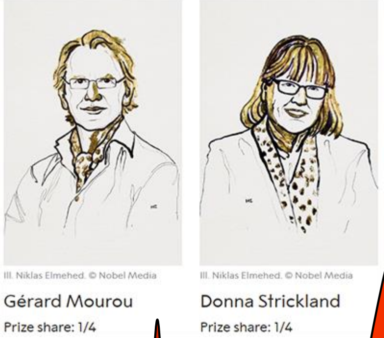
CALA-groups:
F. Krausz+, S. Karsch+, P. Thirolf+

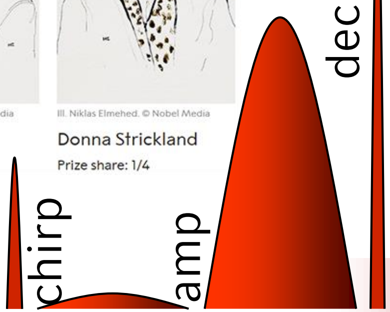


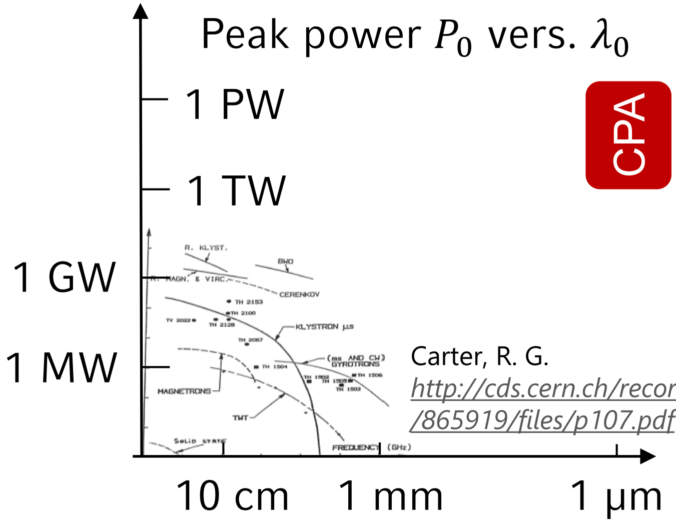
90J amp, 22fs dur, **(curr. ~5-10 J on target)**



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





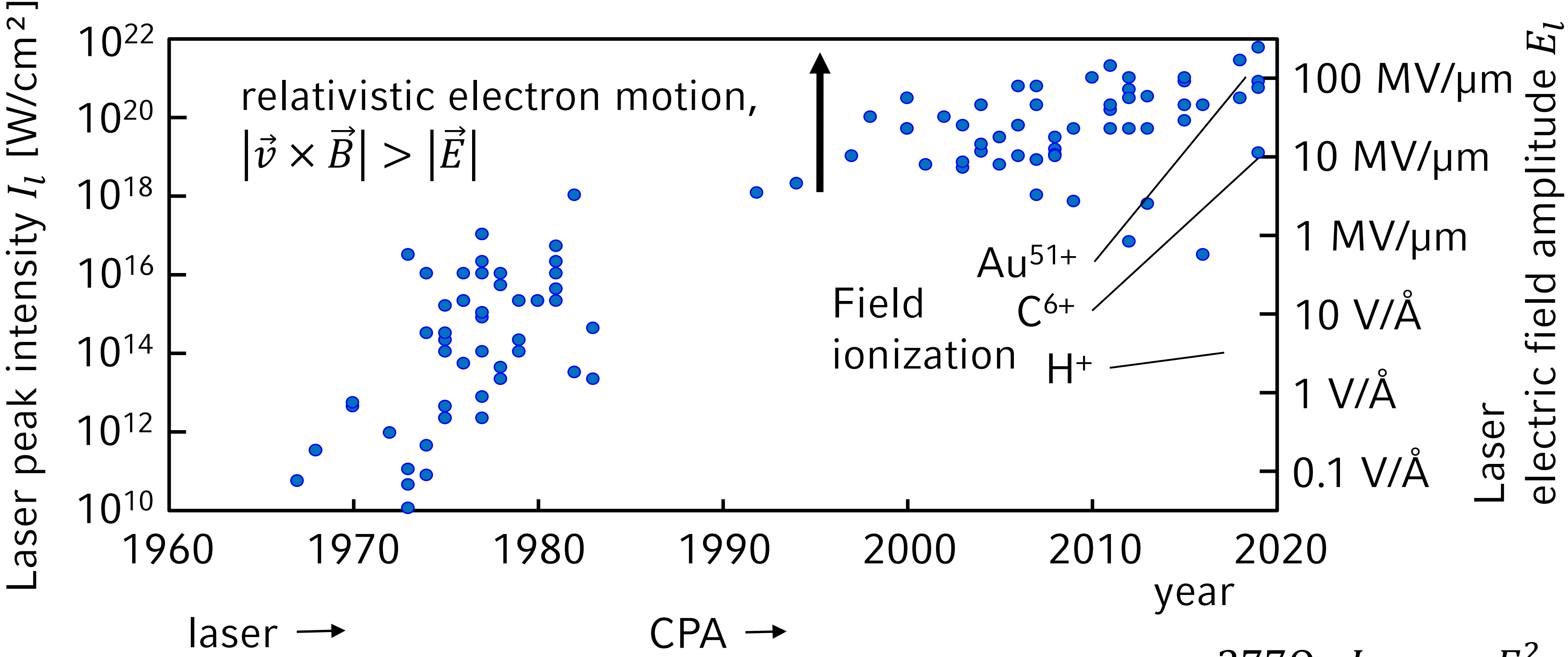


Carter, R. G.
http://cds.cern.ch/record/865919/files/p107.pdf

$$E \propto \sqrt{377\Omega \cdot \frac{P_0}{\lambda_0^2}}$$

i.e. large electric field

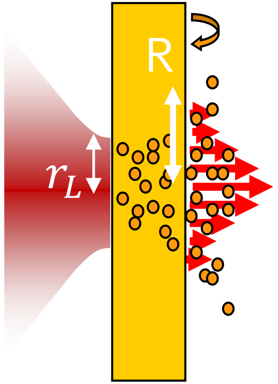
Drive intensity (vacuum value) in dense target experiments



$$377\Omega \cdot I_{peak} = E_{peak}^2$$

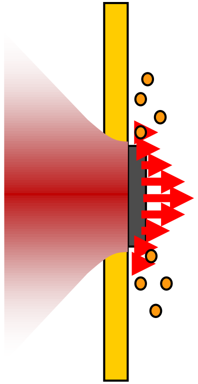
Rectification of laser field E_l in accelerating field E_a

thick target $\boldsymbol{d \gg l_{skin}}$
(TNSA)



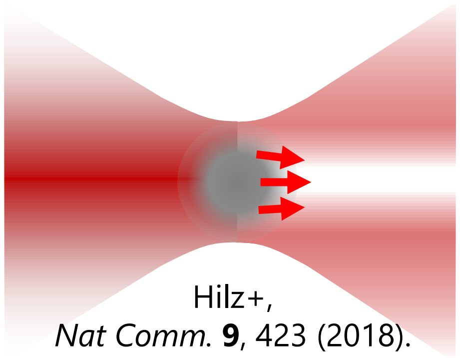
Ballistic e⁻ induce
$E_a \approx E_l \cdot \frac{r_L}{R}$

thin target $\boldsymbol{d \approx l_{skin}}$
(RPA)



$\vec{v} \times \vec{B}_{\mathrm{L}}$ balanced by charge seperation
$E_a \approx E_l \propto n_e d$

μ-plasma $\boldsymbol{d \approx l_{skin}, R \approx r_L, n_e \approx \gamma n_c}$
(relativistic tweezer)

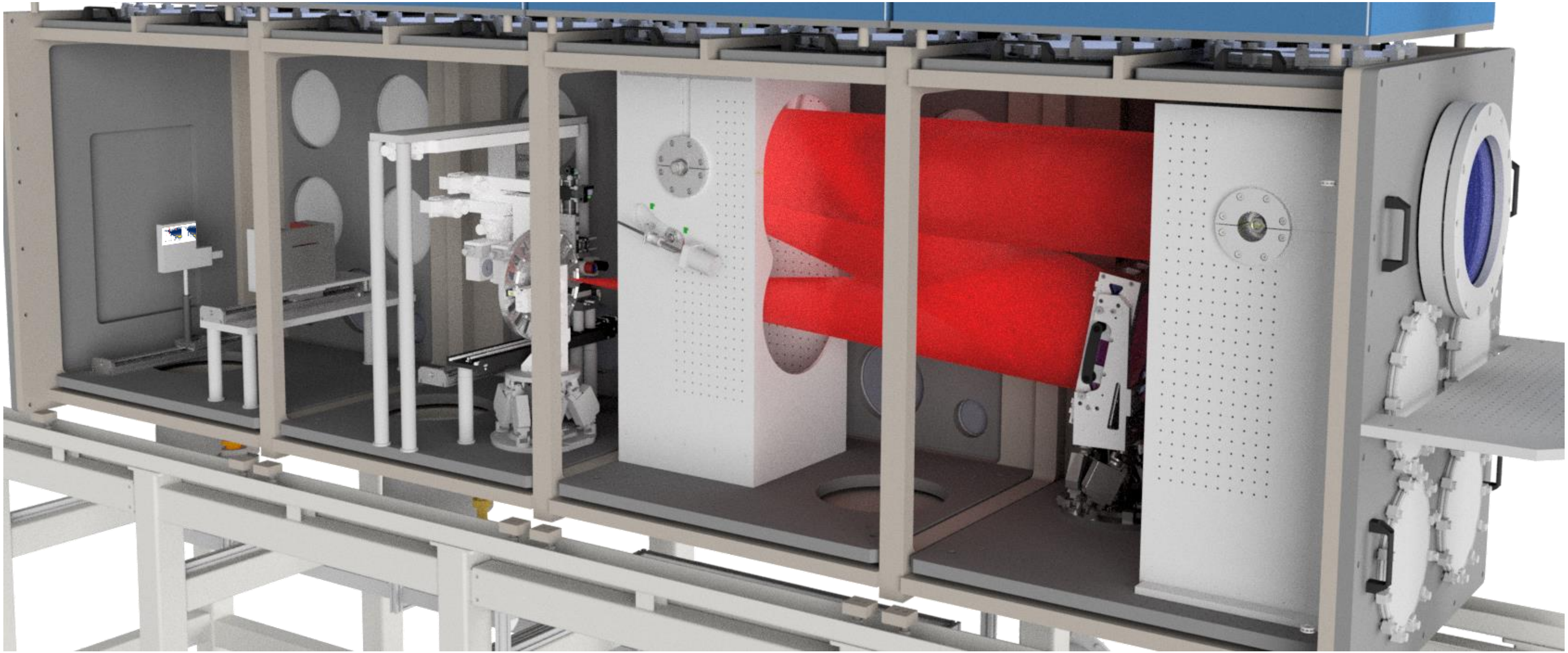


Hilz+, *Nat Comm.* **9**, 423 (2018).

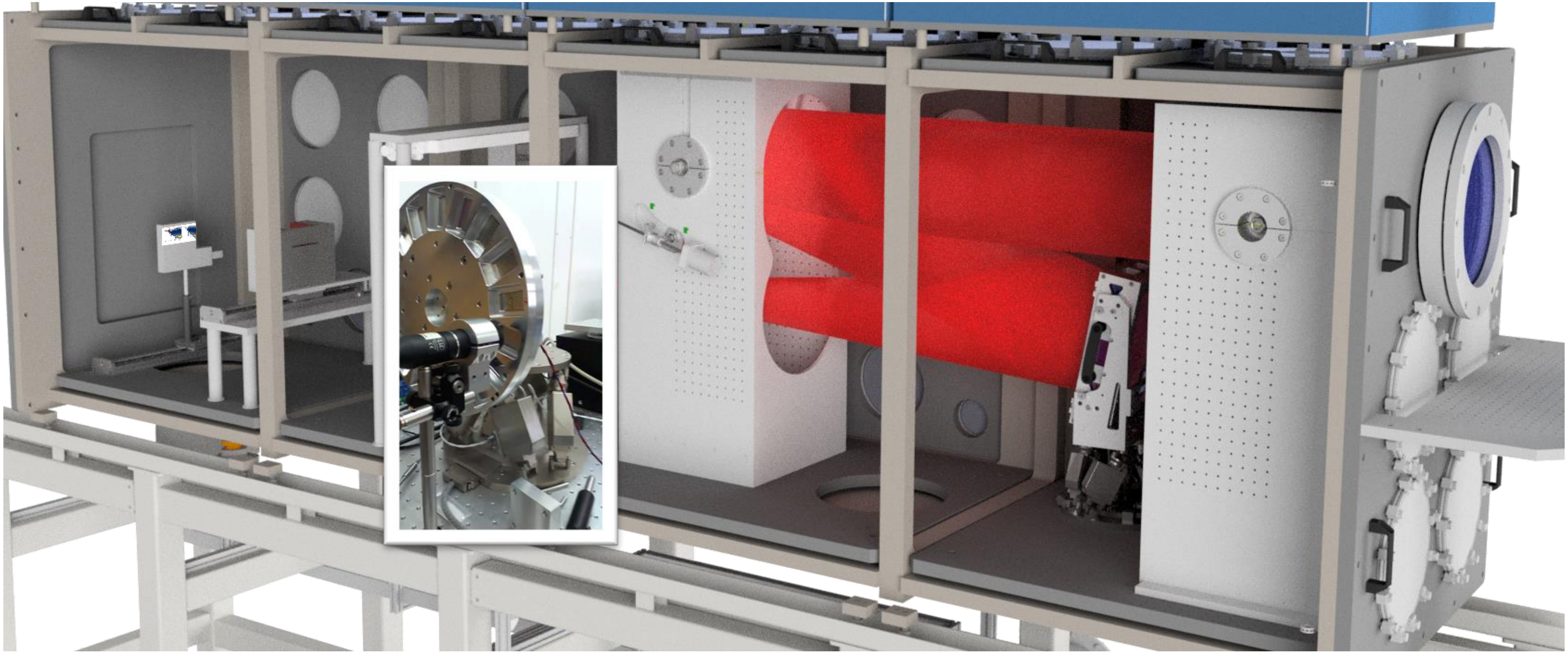
$\vec{v} \times \vec{B}_{\mathrm{L}}$ dyn. balanced + transverse confinement + reduced density

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+ *Nat Phys* **18**, 316-322, (2022).

Example experiments (Laser-ION@CALA)

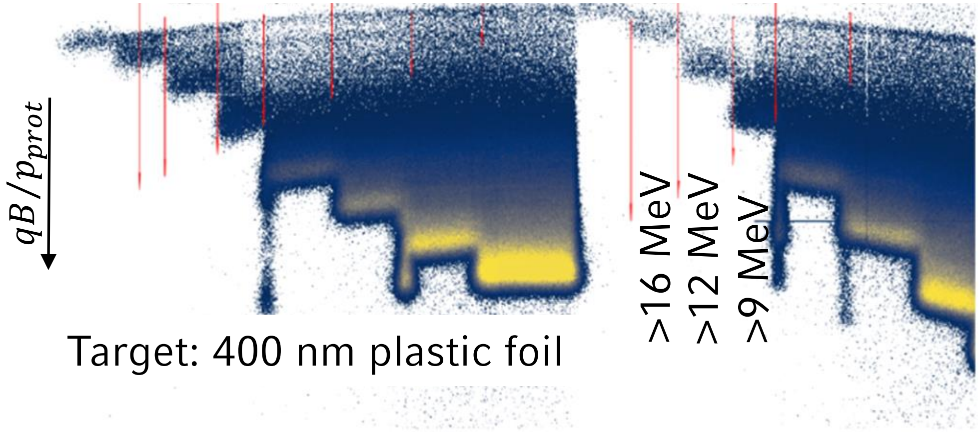


Example experiments (Laser-ION@CALA)

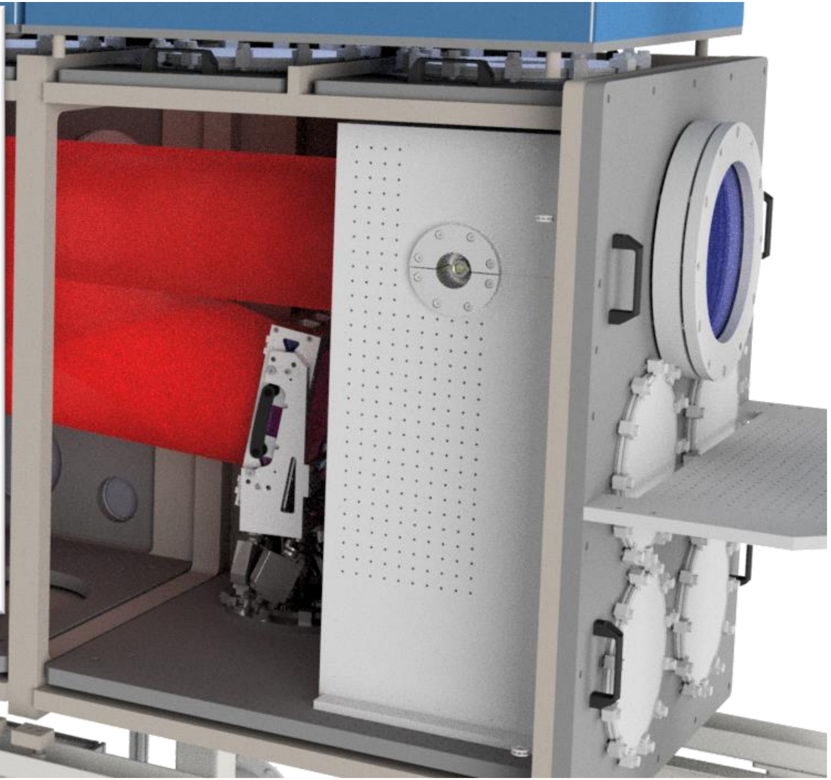


Example experiments (Laser-ION@CALA)

Proton signal on 10x5cm² Radeye sensor + Al degrader stripes

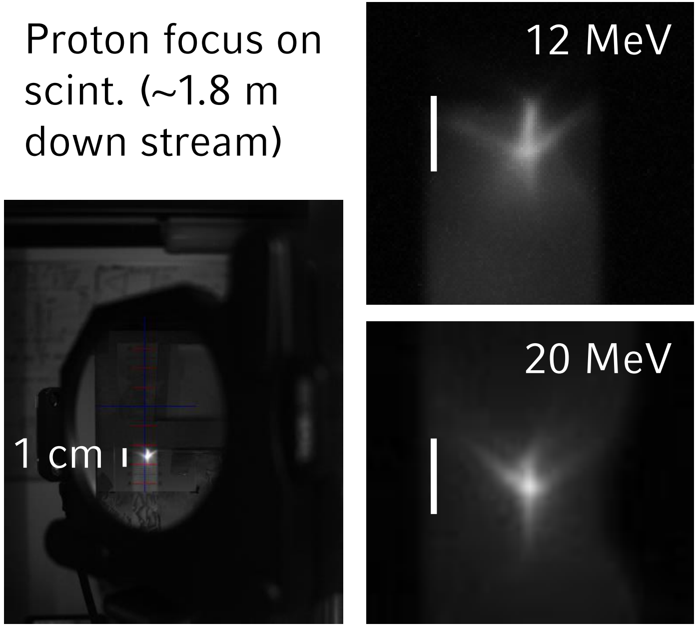


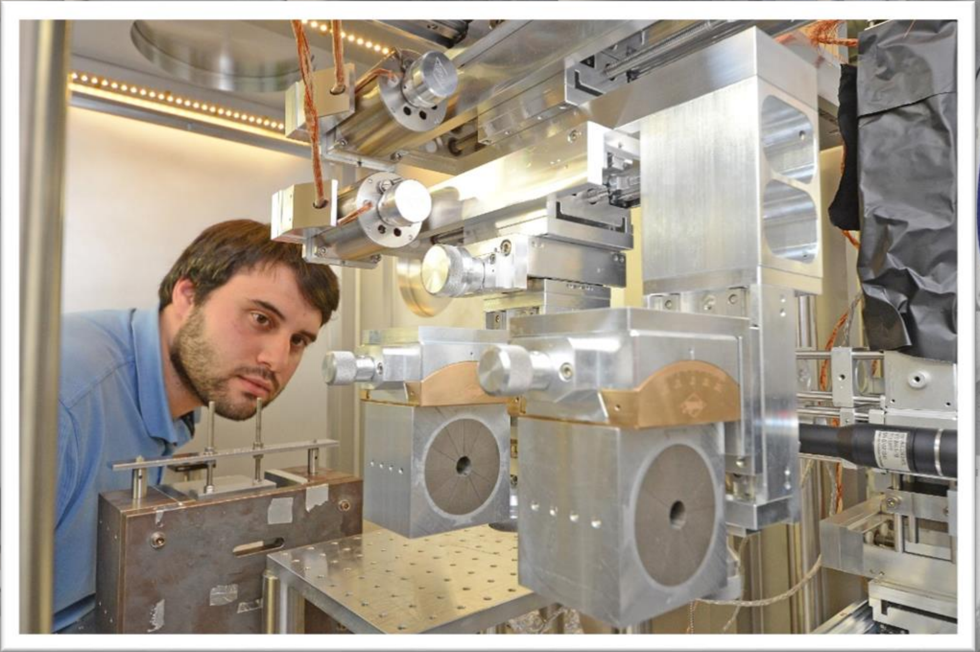
Target: 400 nm plastic foil



Example experiments (Laser-ION@CALA)

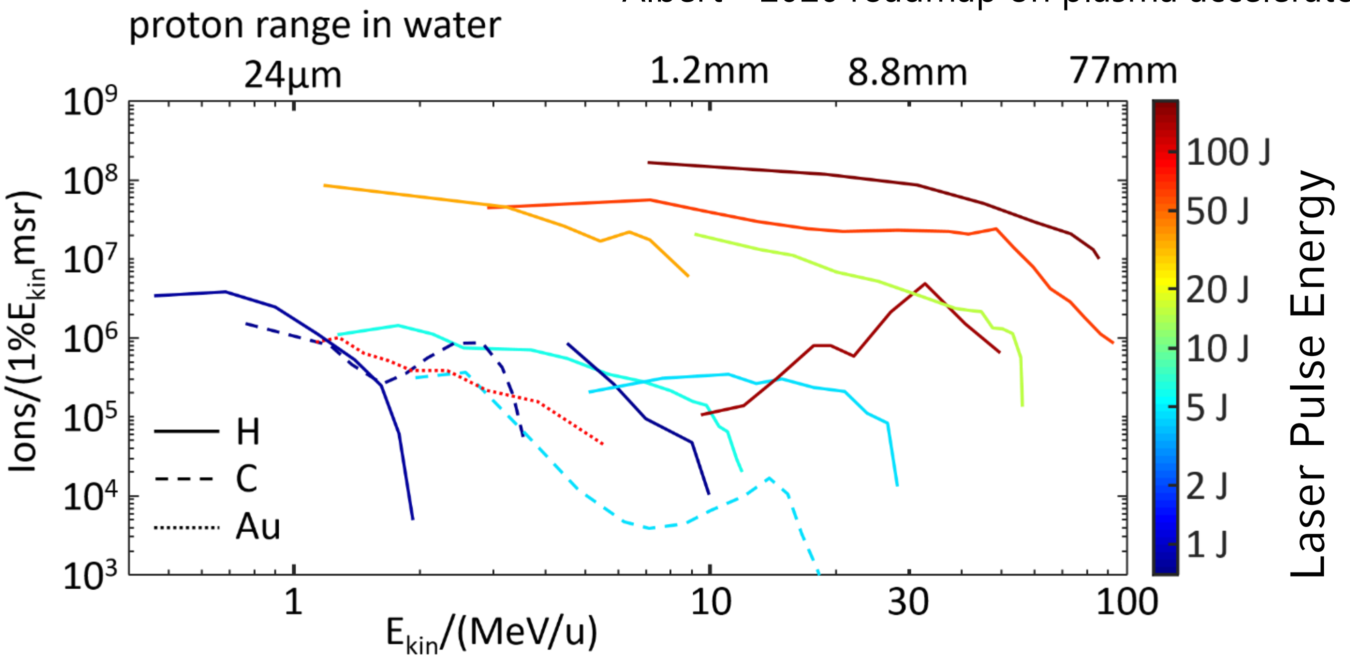
Proton focus on scint. (~1.8 m down stream)

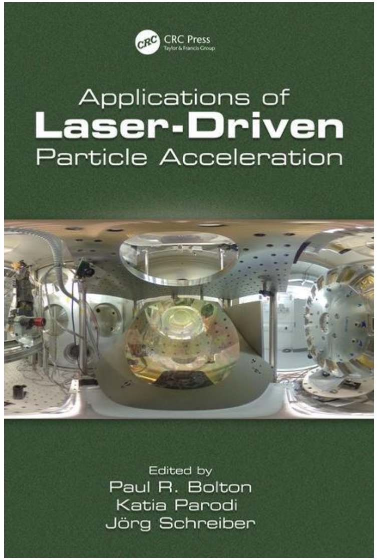




Ion energy distributions (exemplary experimental results)

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





https://www.alpa.physik.uni-muenchen.de/

Specifics of laser-ion source

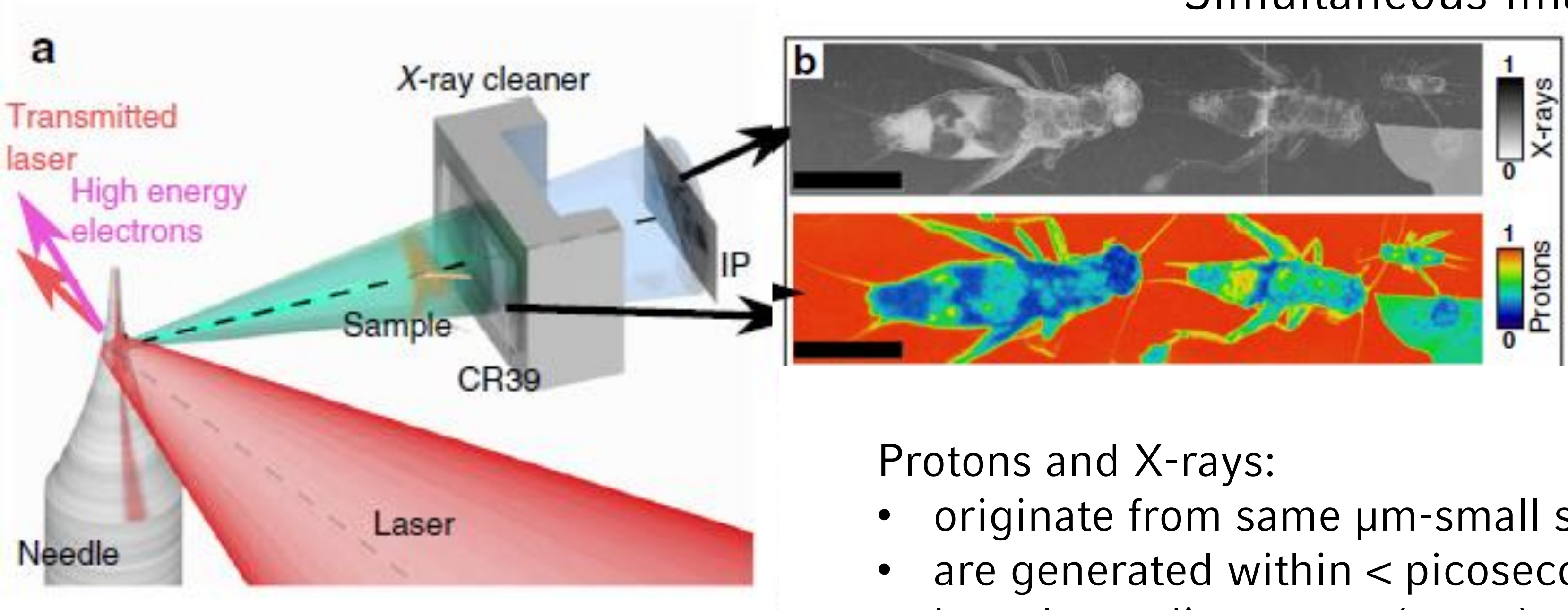
Laser-plasma	Non-laser (RF)
Single bunch every second (large #!)	Continuous beam (micro-bunch train)
Broad energy distribution (100%) yet short bunch (fs…ps…ns)	Mono-energetic (ns…µs bunches)
Spray (10° divergence) yet small source (µm)	Beam
Intrinsically synchronous to multiple radiation modalities	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"?

Bi-Modal imaging (X-ray phase contrast + proton projection)

Simultaneous Imaging by

X-rays
&
protons



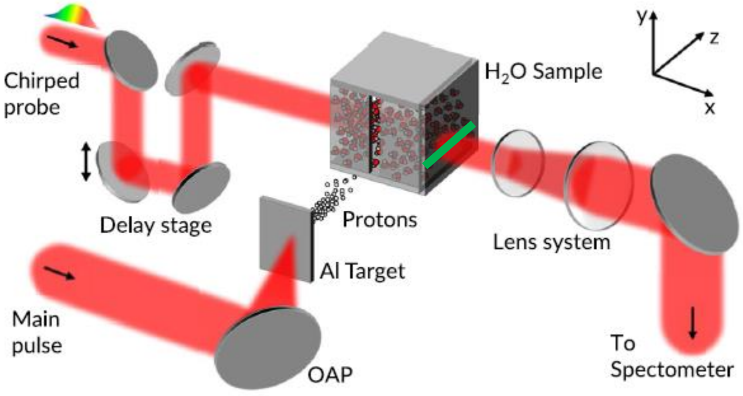
Protons and X-rays:

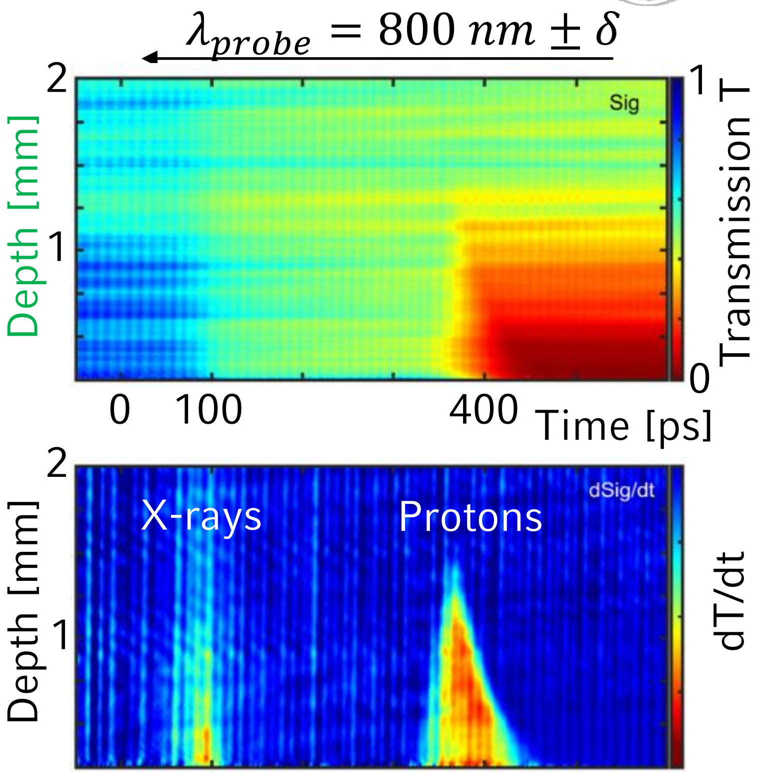
- originate from same µm-small source
- are generated within < picosecond
- have large divergence (spray)

Ostermayr+ Nat Comm 11 (2020) 6174

Solvated electron after proton irradiation

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

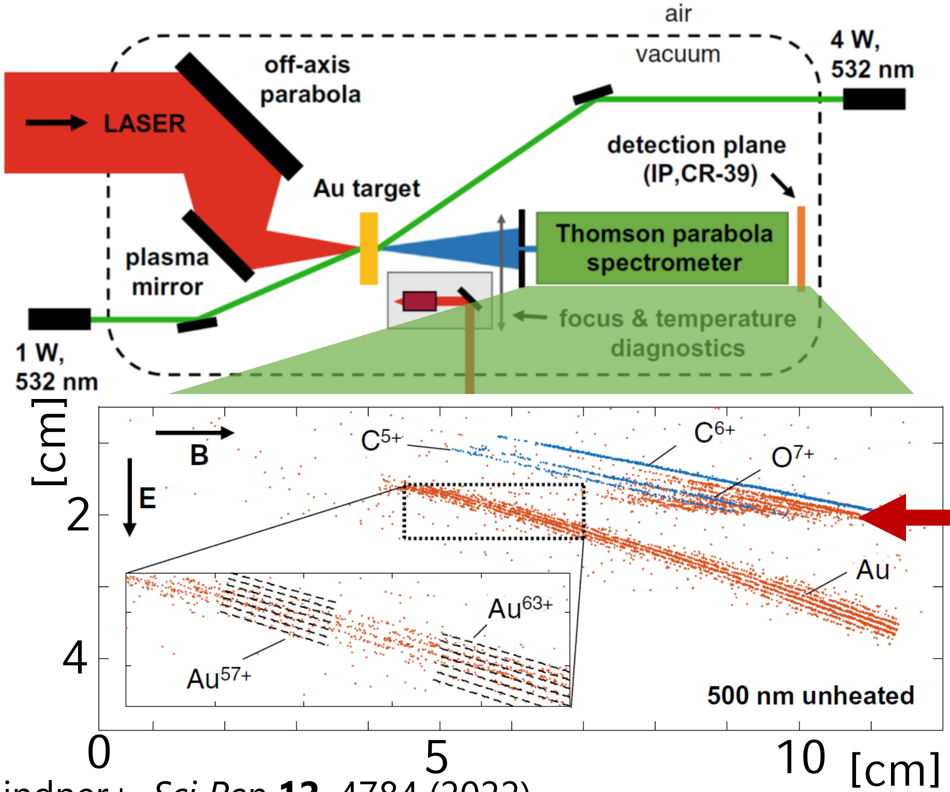




Solvation of electron takes 65 ps after proton impact (>20 ps longer than in photolysis) … charge effect?

Prasselsperger+ PRL 127, 186001 (2021)

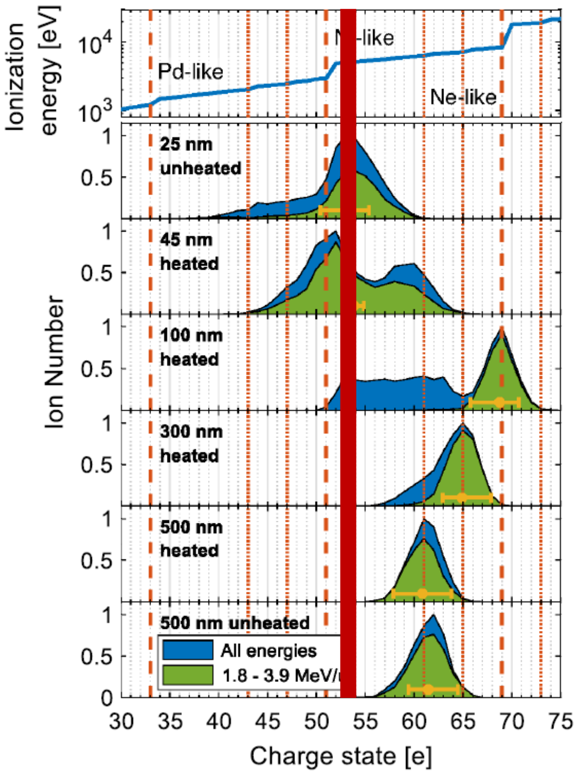
Heavy ion acceleration (example Gold @Phelix, GSI)



Lindner+, *Sci Rep* **12**, 4784 (2022)

Charge higher than expected from field ionization

Indications of swift Au-fission fragments



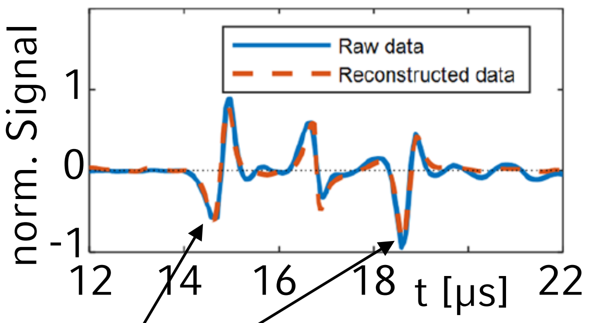
https://www.alpa.physik.uni-muenchen.de/: Progress from acceleration to accelerator

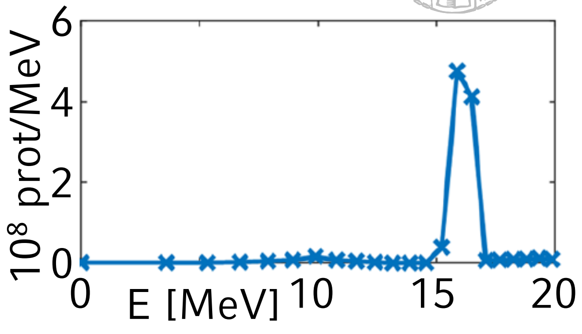
TARG Series (Targetry for laser-driven sources)	BLIN Series (Beam Line optics and INstrumentation)	ALPA Series (Applications of Laser-driven Particle Acceleration)
TARG1 - 2013 (Garching)	BLIN1 - 2010 (Abingdon)	ALPA1 - 2015 (Venice)
TARG2 - 2015 (Paris)	BLIN2 - 2012 (Paris)	ALPA2 - 2019 (Prague)
TARG3 - 2017 (Salamanca)	BLIN3 - 2016 (Garching)	ALPA3 - 19-23 April 2021 (Prague-online)
TARG4 - 2019 (Milano)	BLIN4 - 2020 (Garching)	ALPA4 - 2023 (Prague)
TARG5 - Oct 25 - 27, 2021 (Dresden)	BLIN5 - 2022 (Garching)	ALPA5 - 2025 (Prague)

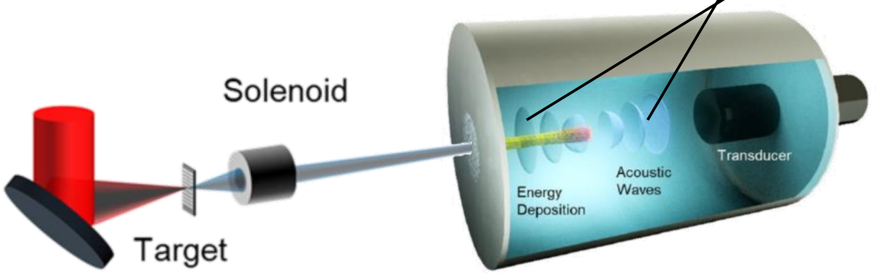
One particular example instrumentation: I-BEAT

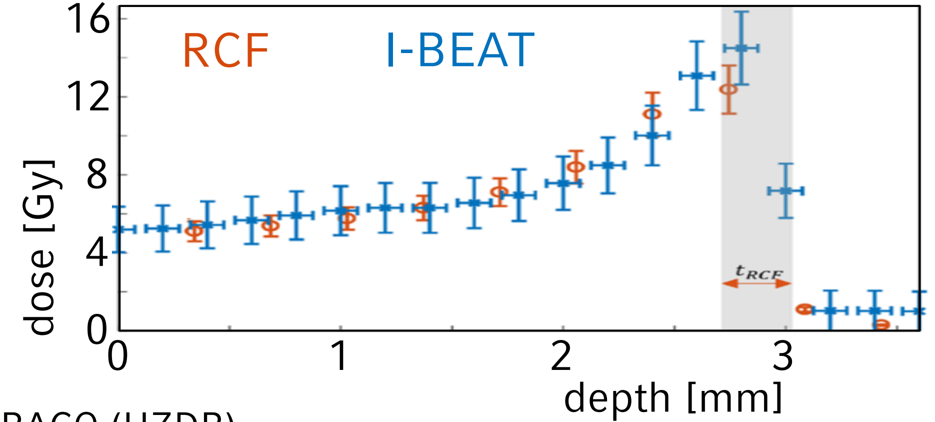
Ionoacoustic detection (Ion-Bunch Energy Acoustic Tracing)

Instead of **dose** (RCF, CR39, Scint, …), we measure the acoustic pulse from the "heat" deposited by ions (~ spatial **dose gradient**) Askaryan, Hydrodynamic radiation from the tracks of ionizing particles in stable liquids. (1957), Assmann+ Med Phys 42, 567-574 (2015).



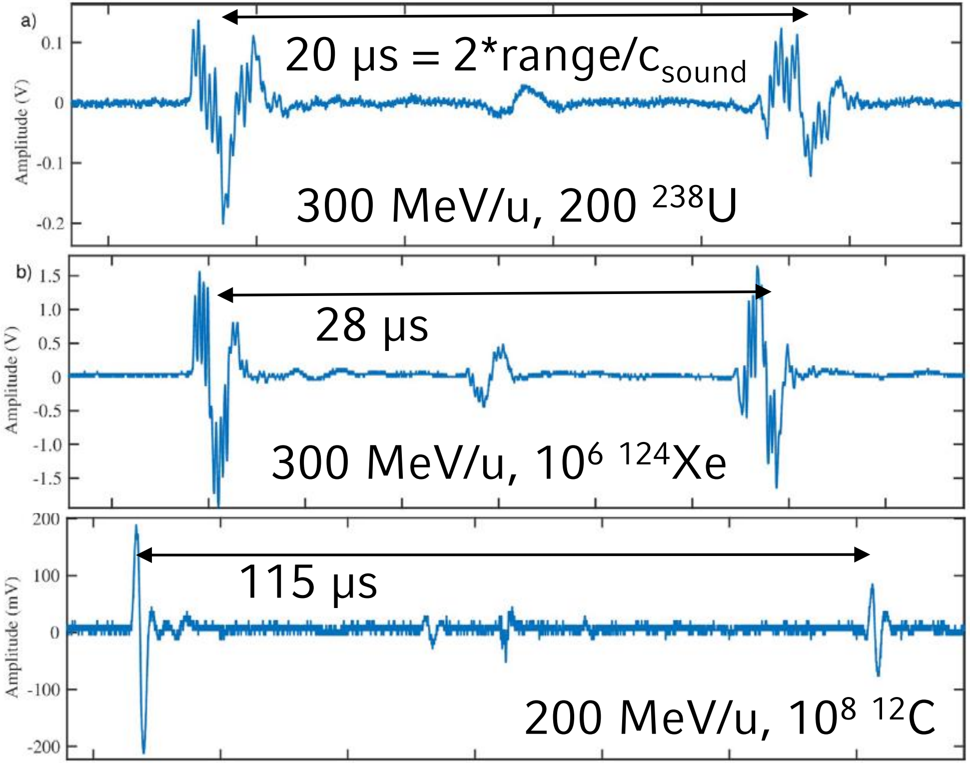






Haffa+ Sci Rep 9 (2019) 6714, Example results from DRACO (HZDR)

Range monitor for heavy ions (SIS18 results)



Accurate measurement of relative range: ~µm resolution realistic!
Large dynamic range, indistructable, compact, cheap

(PhD Leon Kirsch, C. Trautmann, W. Assmann, K. Parodi, et al.)

Ionoacoustics at water temperatures around 4°C?

(GSI/LMU R&D Koll., PhD A. Schmidt, DFG-PhD J. Liese)

Lehrack+, Ionoacoustic detection of swift heavy ions. *NIMA* **950**, 162935 (2020).

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,…).

Thank your for your attention and interest!

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

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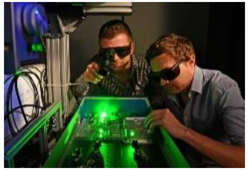
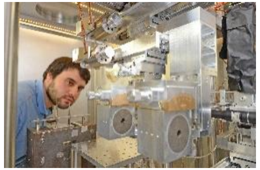
H. Wirth, O. Gosau, N. Gjotev, F. Saran, G. Schilling

Recent and ongoing collaborations

Queens University Belfast (UK): B. Dromey+
GSI/TU Darmstadt (Germany): B. Zielbauer, V. Bagnoud+, C. Trautmann+
Frankfurt: A. Tauschwitz
HZDR Dresden (Germany): U. Schramm+
FSU Jena (Germany): P. Hilz, M. Zepf+
APPA





CALA