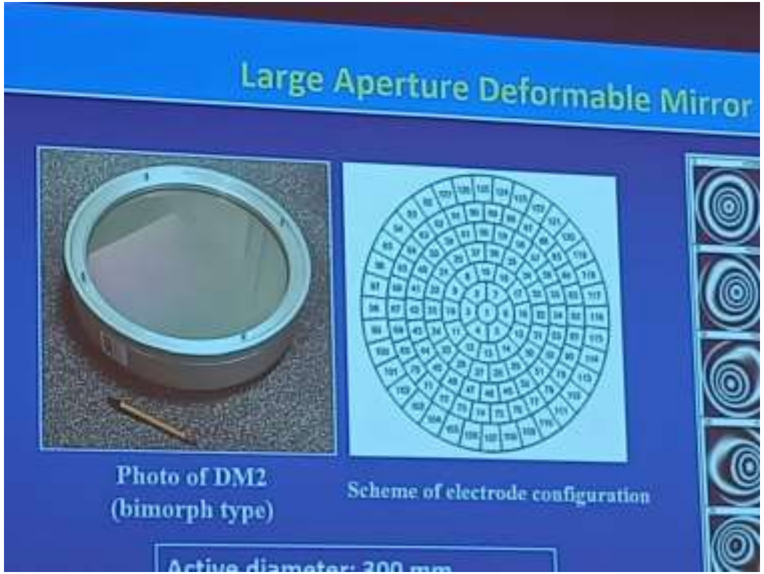
Where the Minoans first in other fields than plumbing?

Heraklion Archaeological Museum – 4th July 2023

Phaistos disc – picture courtesy https://luwianstudies.org/the-phaistos-disc/



Large Aperture Deformable Mirror

Photo of DM2
(bimorph type)

Scheme of electrode configuration

Active diameter: 300 mm

Chang Hee Nam – 5th July 2023

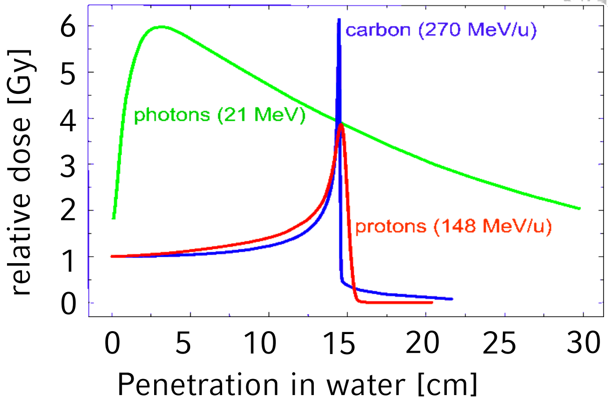
APPLICATIONS OF LASER-PLASMA BASED PROTON & ION SOURCES

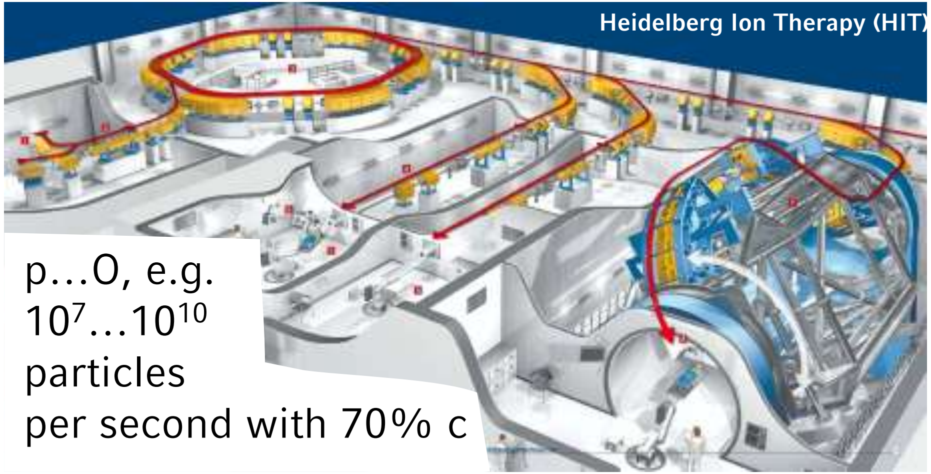
Laser-ION acceleration group
Jörg Schreiber et al.
Medical Physics, Ludwig-Maximilians-University Munich

Funding: BMBF, DFG, CALA

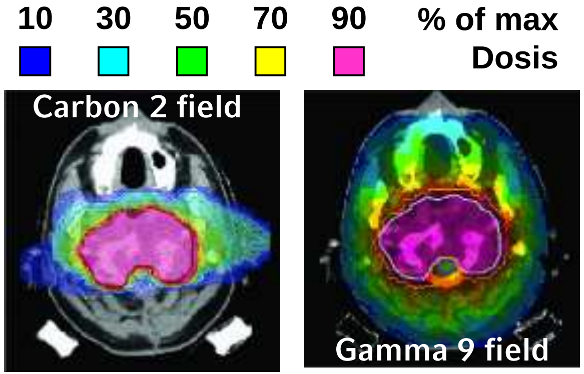
Ion Beam Therapy

1903: W.H. Bragg, **1929**: Cyclotron, **1946**: Idea Ion therapy (R.R.Wilson), **1952**: protons on patients (184“, Berkley) & Synchrotron, **1990**: ESR@GSI & hospital-based proton facility (Loma Linda) **1994:** HIMAC, Chiba, Japan (carbons), **1997**: patient study with C at GSI, **2009**: clinical use (HIT), **2009**: hospital based p-O therapy at HIT, **Today:** ~70 centers (mostly protons)





p…O, e.g. $10^7 \ldots 10^{10}$ particles per second with 70% c



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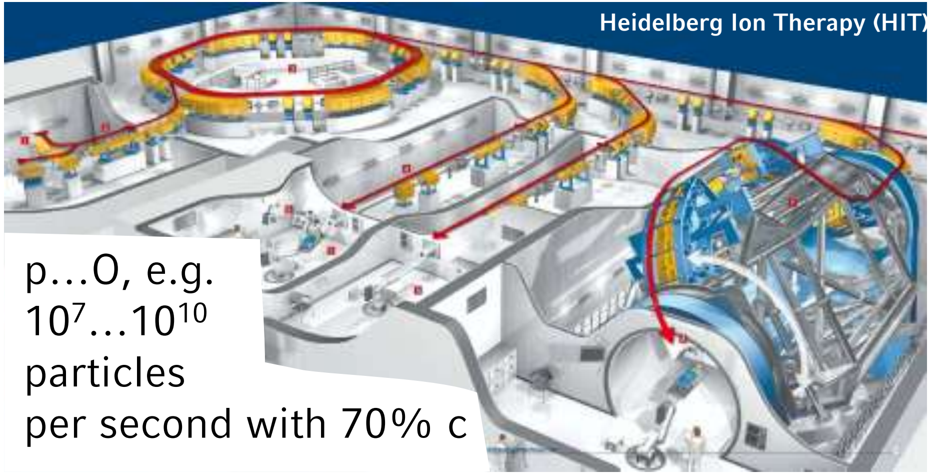

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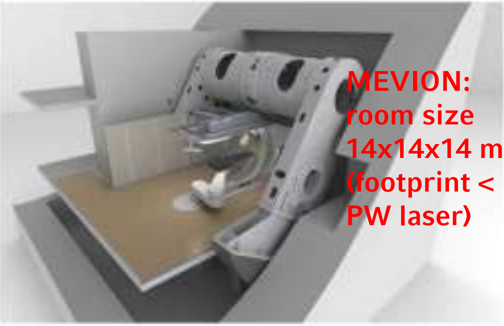
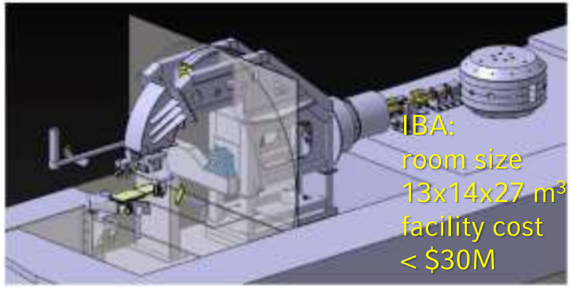
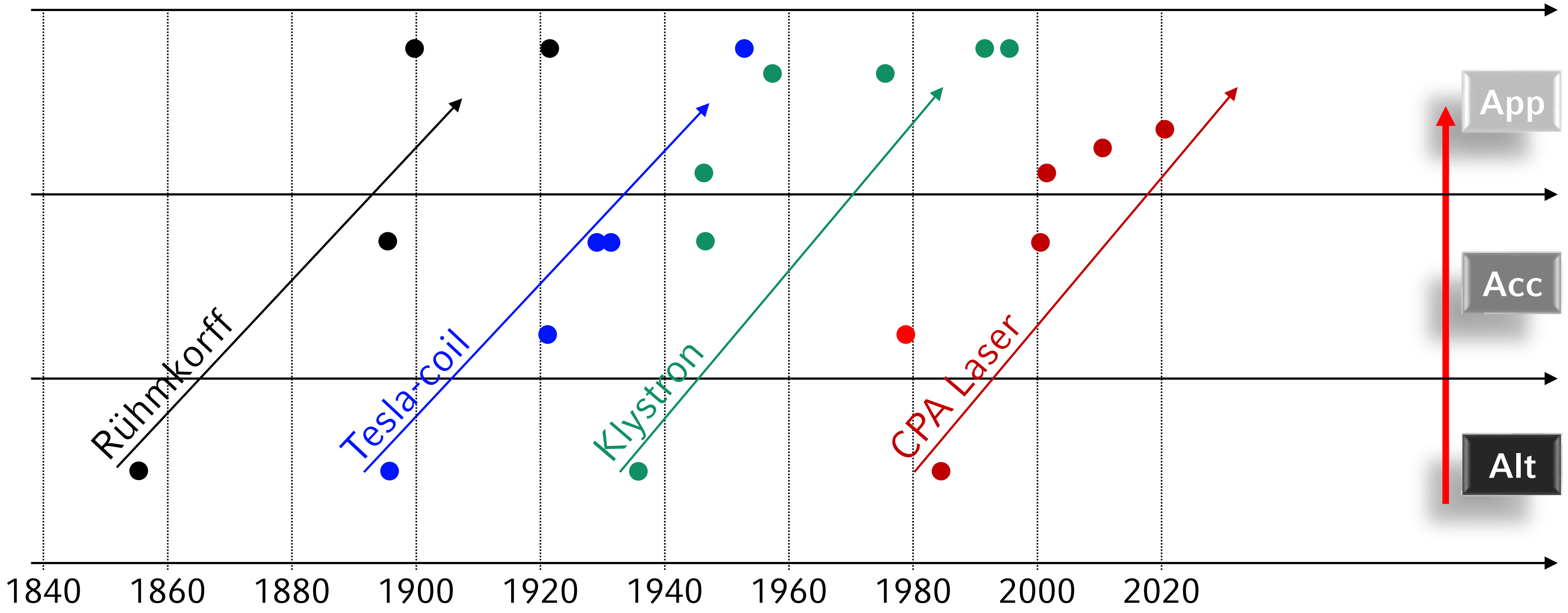

MEVION: room size 14x14x14 m^3 (footprint < PW laser)

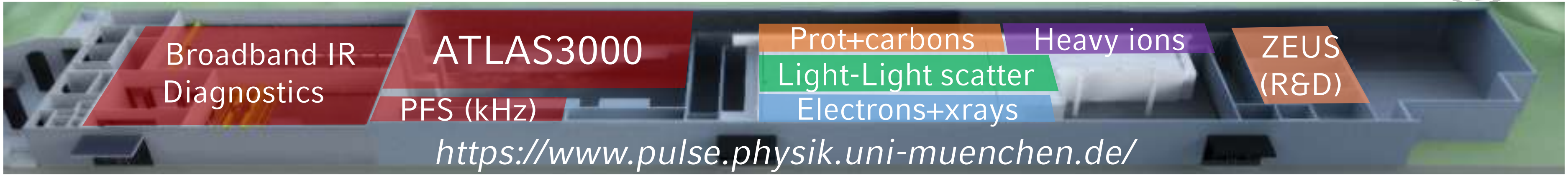

IBA: room size 13x14x27 m^3 facility cost < $30M

** U. Linz and J. Alonso Phys. Rev. Accel. & Beams* ***19****, 124802 (2016)*

Alternator, Accelerator, Applicator (ex. tumor diag & therapy)



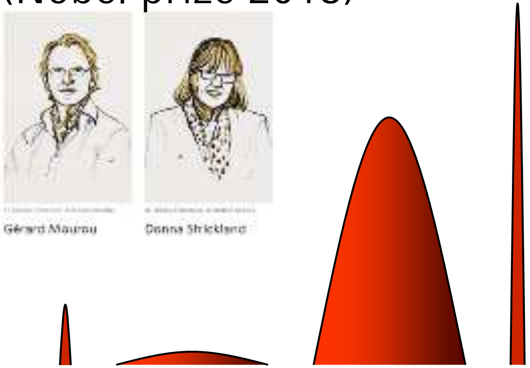
Petawatt-Laser – plasma acceleration under one roof

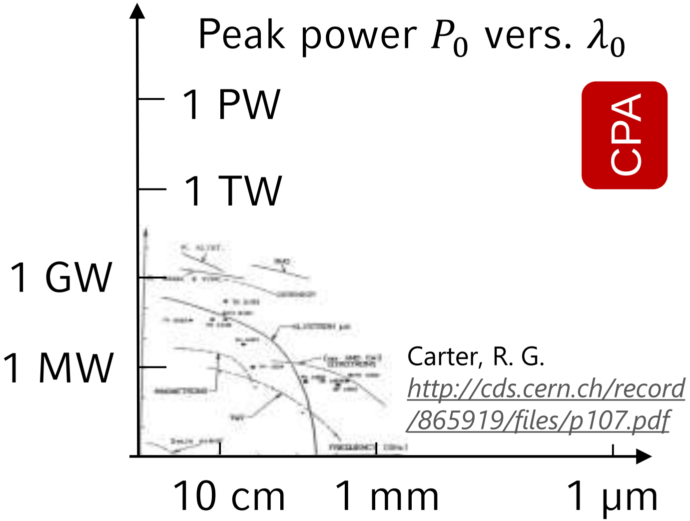


https://www.pulse.physik.uni-muenchen.de/

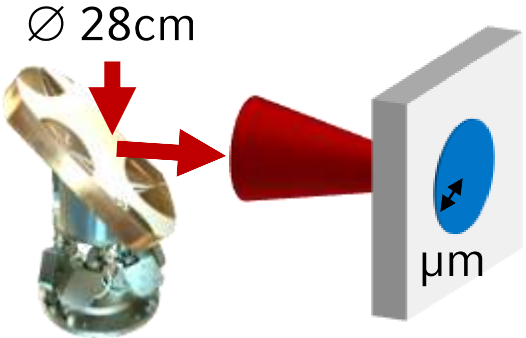
90J amp, 22fs dur, **(curr. ~5-10 J on target)**

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





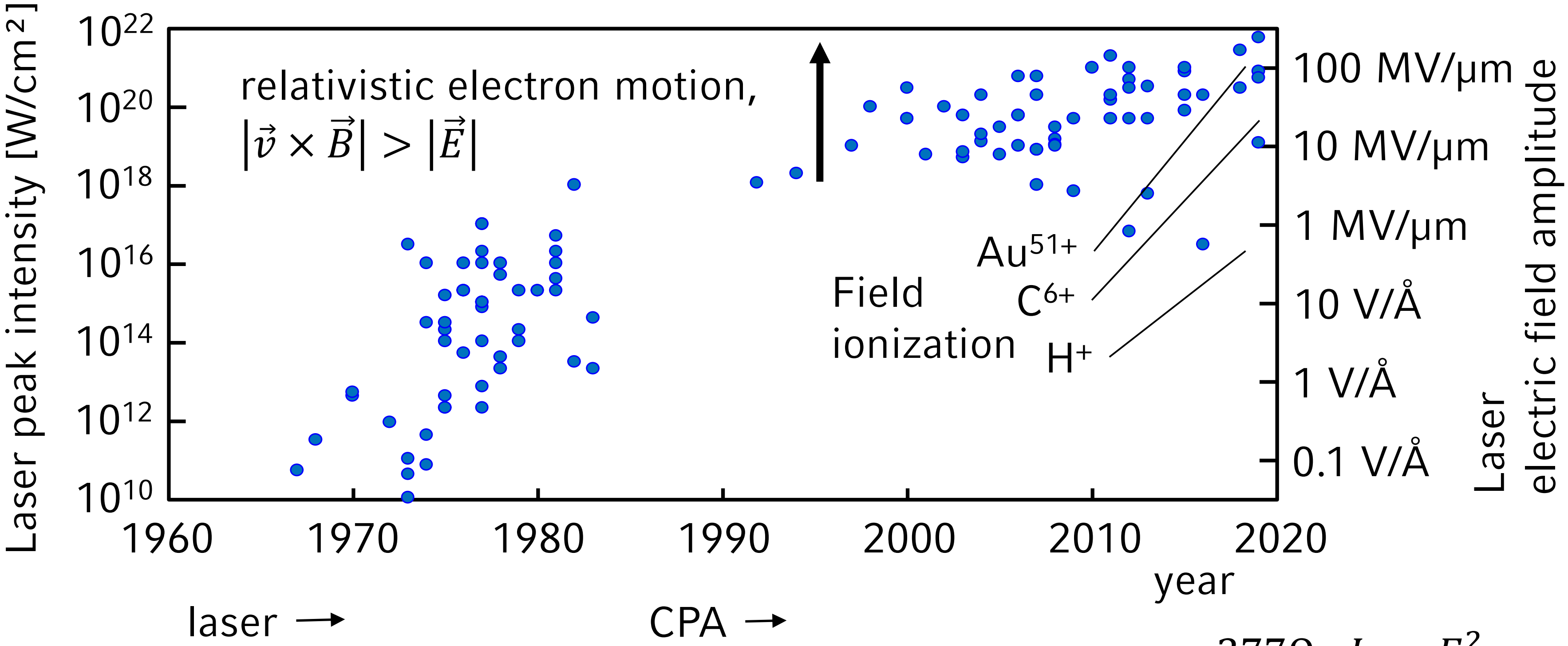
Carter, R. G.
http://cds.cern.ch/record/865919/files/p107.pdf



$$E_L = \sqrt{377\Omega \cdot \frac{P_0}{\lambda_0^2}}$$

i.e. large electric field

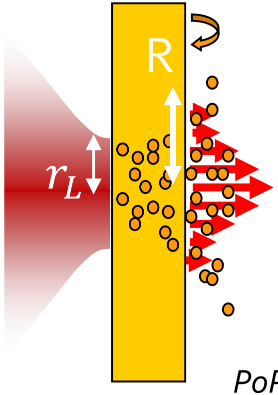
Drive intensity (vacuum value) in dense target experiments



$$377\Omega \cdot I_L = E_L^2$$

Laser-ion acceleration (field-rectification)

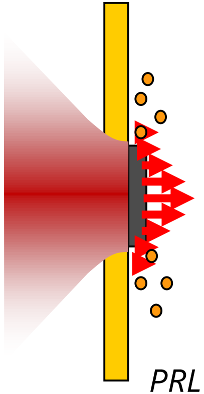
thick target $\boldsymbol{d \gg l_{skin}}$
(TNSA)



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

Wilks+,
PoP **8**, 542 (2001)

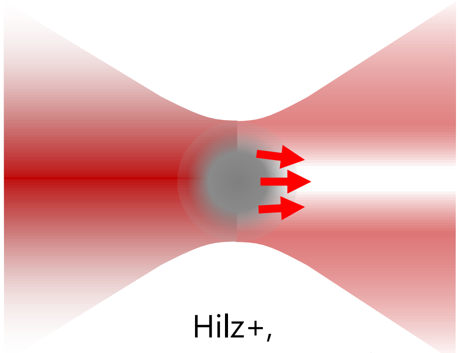
thin target $\boldsymbol{d \approx l_{skin}}$
(RPA)



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

Henig+,
PRL **103**, 245003 (2009)

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



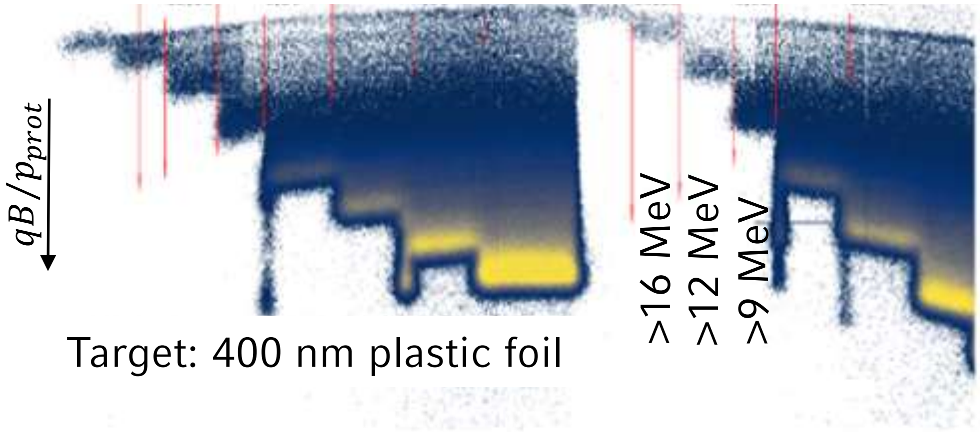
$\vec{v} \times \vec{B}_\mathrm{L}$ dyn. balanced + transverse confinement + reduced density

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

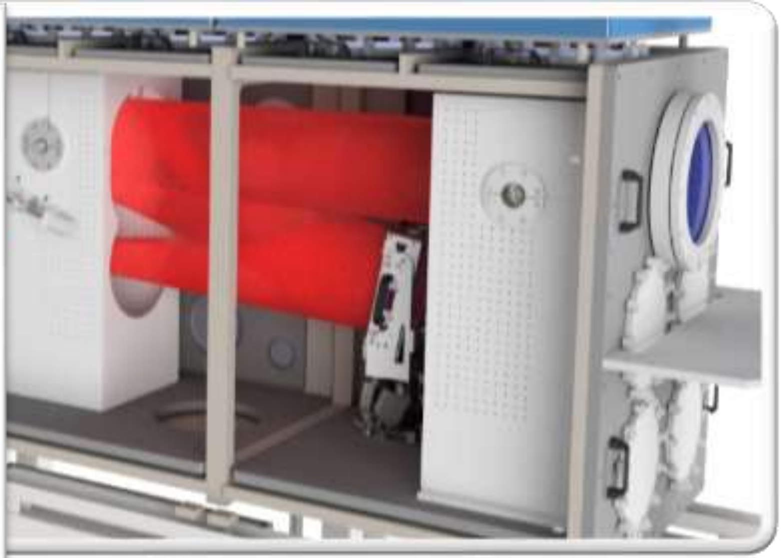
Optimization strategy during last 20 years: laser-pulse energy ↑, pre-pulses ↓, target thickness (size) ↓, repetition rate ↑, reproducibility ↑ …

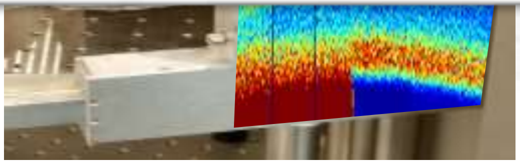
Experiment setup Laser-ION acceleration @CALA

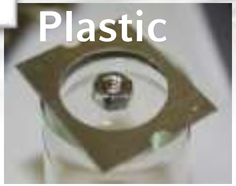
Proton signal on 10x5cm² Radeye sensor + Al degrader stripes

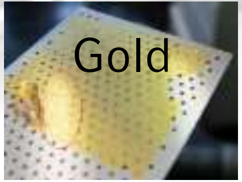


Target: 400 nm plastic foil



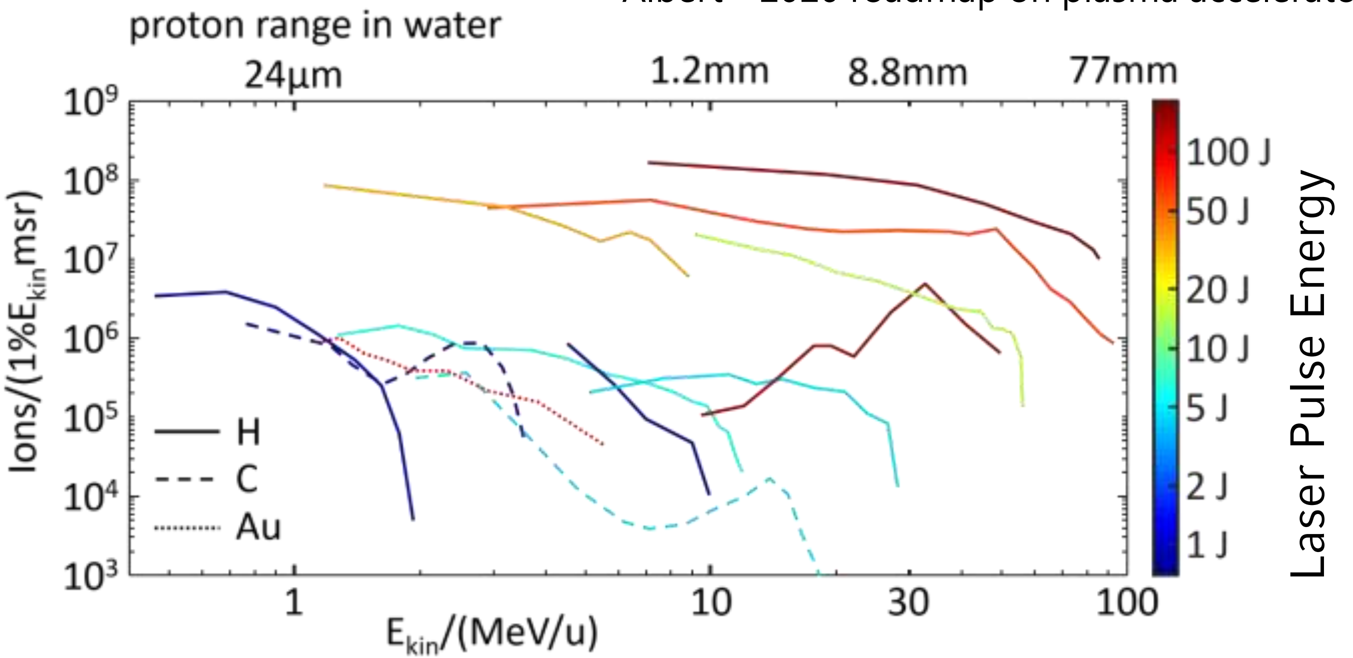


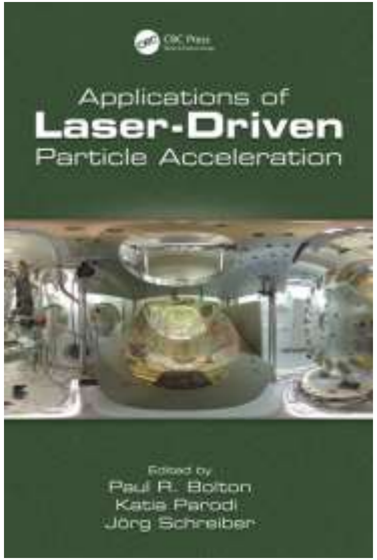




Ion energy distributions (exemplary experimental results)

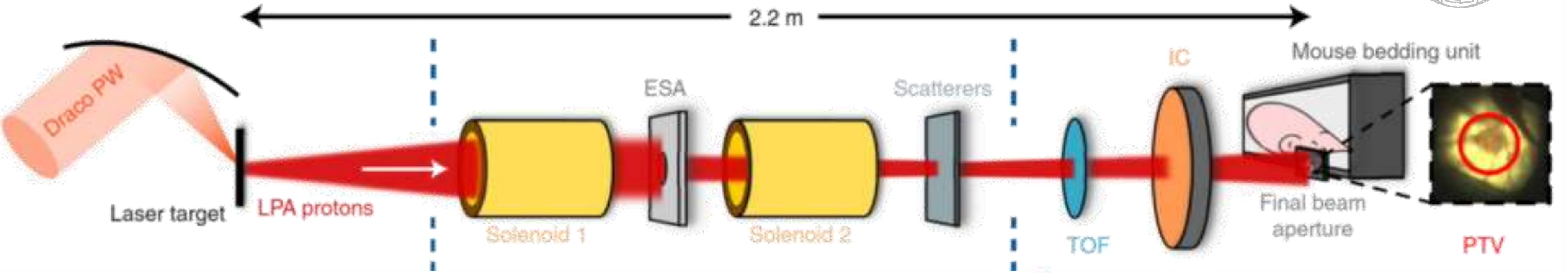
Albert+ 2020 roadmap on plasma accelerators *New J Phys* **23**, (2021).

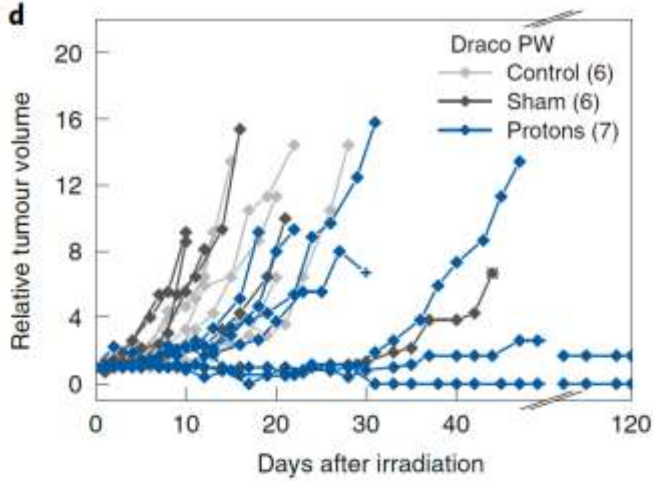




https://www.alpa.physik.uni-muenchen.de/

First laser-proton irradiation of tumors in mice (Dresden)





- Exponential proton spectrum up 70 MeV shaped by transport line for hom. Irradiation of a 5 mm diameter, 4 mm depth Planning Target Volume
- (4.0±0.4) Gy within ~ 3 min, i.e. 6 to 9 accumulated bunches with **nanosecond duration**
- 92 animals irradiated, 7 with laser-acc. protons

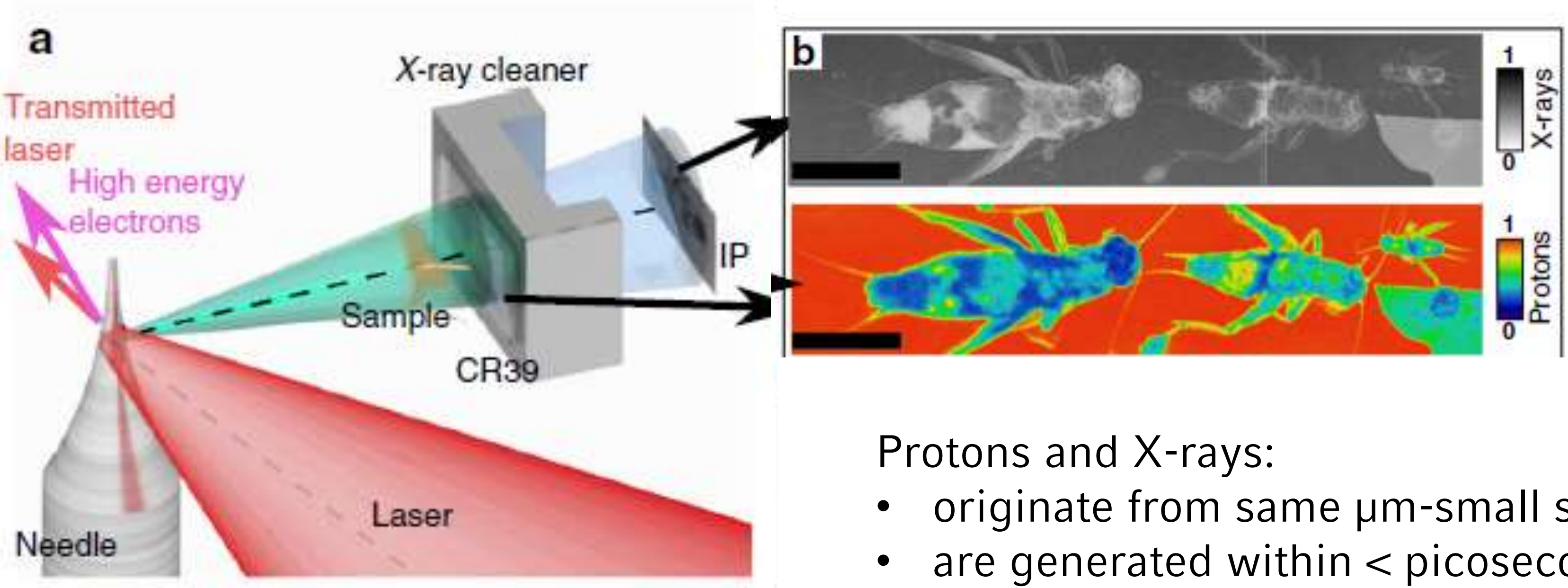
Kroll+, Nature Physics 18(3), 316-322 (2022)

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 density, small emittance)	

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

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



Simultaneous Imaging by

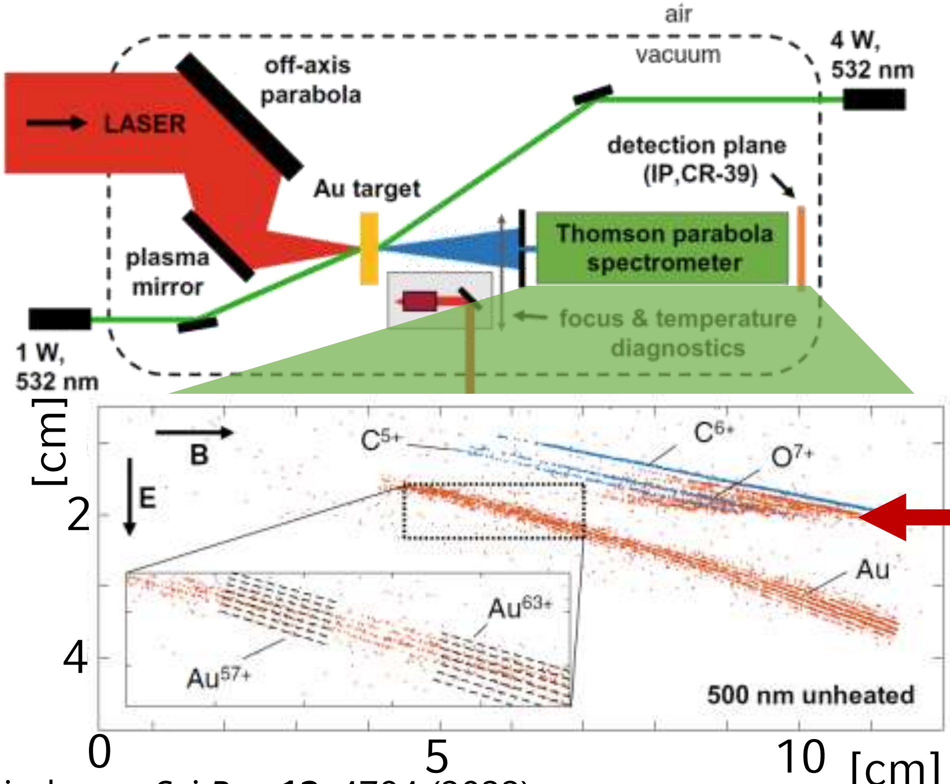
X-rays & protons

Protons and X-rays:

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

Ostermayr+ Nat Comm 11 (2020) 6174

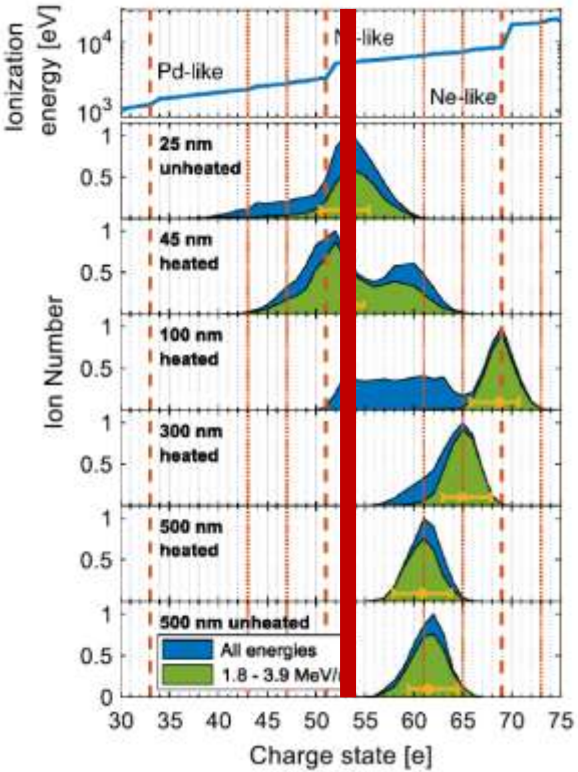
Heavy ion acceleration (example Gold @Phelix, GSI)



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

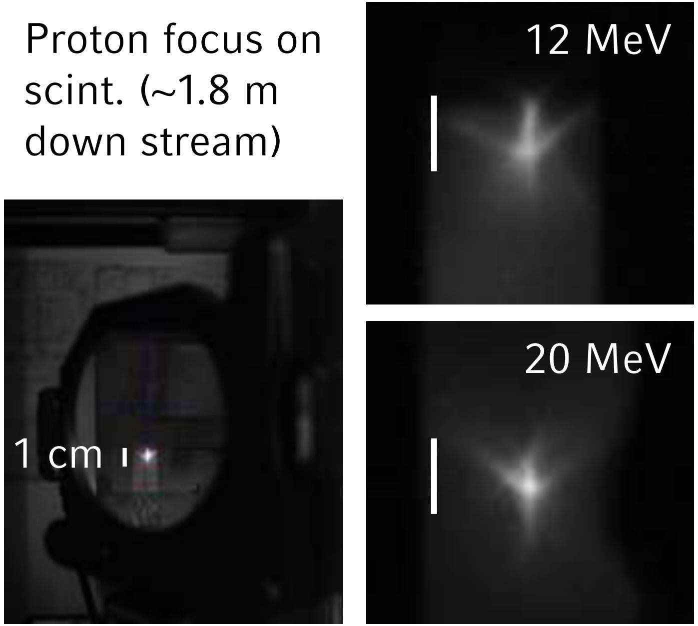
Charge higher than expected from field ionization

Indications of swift Au-fission fragments



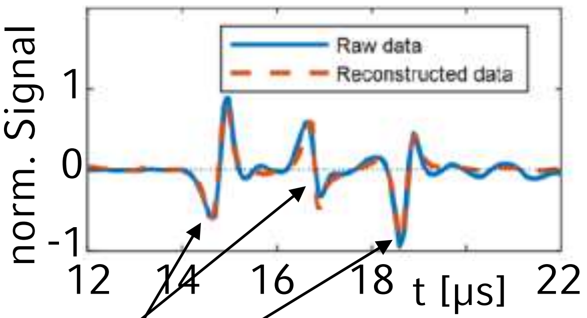
Experiment setup Laser-ION acceleration @CALA

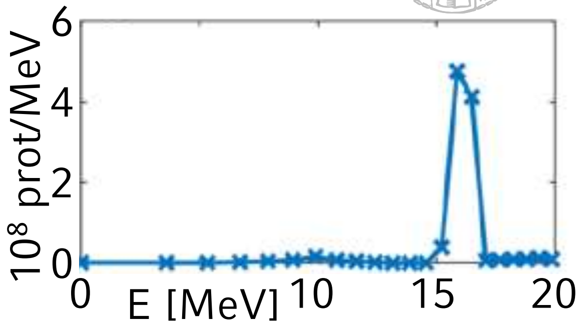
Proton focus on scint. (~1.8 m down stream)

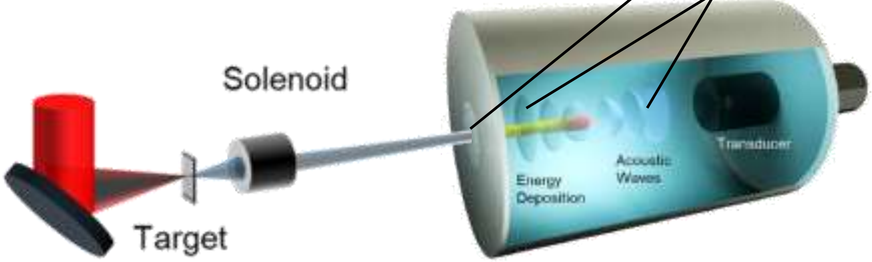


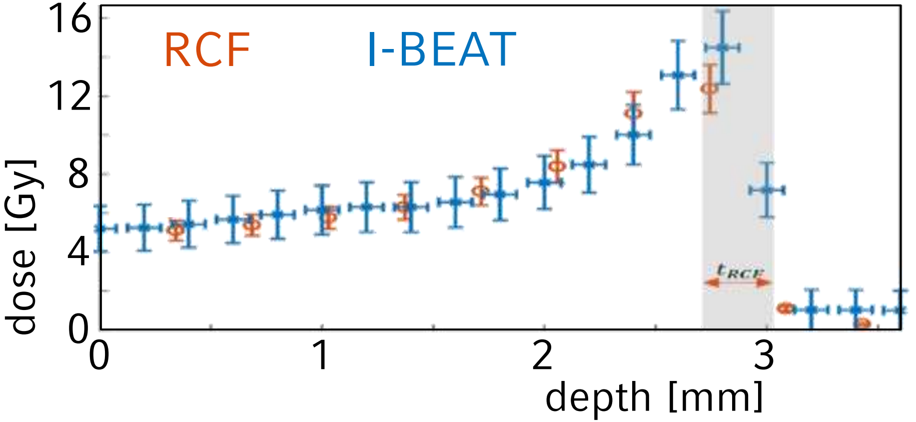
Ionoacoustic detection (**I**on-**B**unch **E**nergy **A**coustic **T**racing)

Instead of **dose** (Scint, RCF, CR39, …), 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).





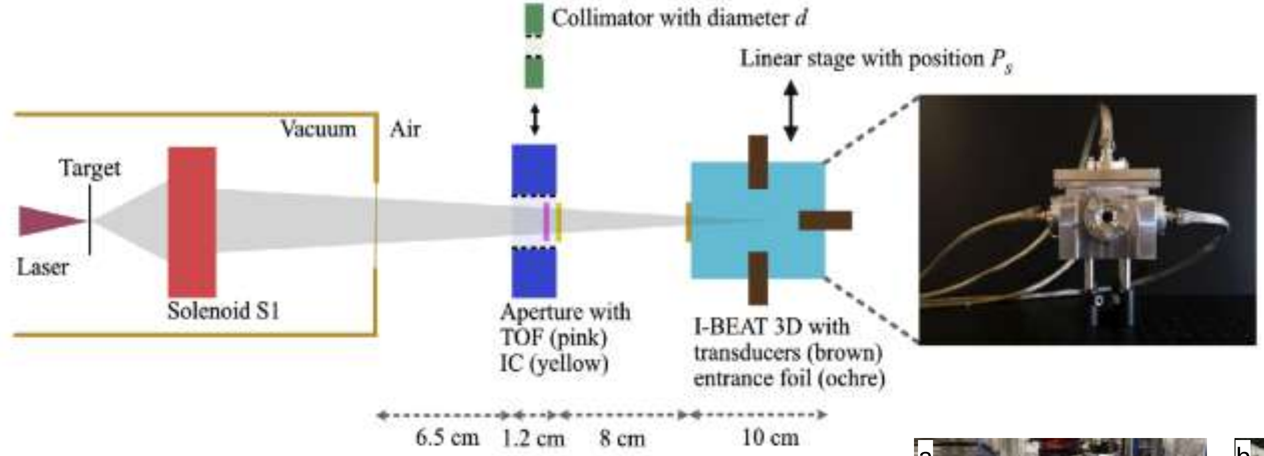




Haffa+ Sci Rep 9 (2019) 6714

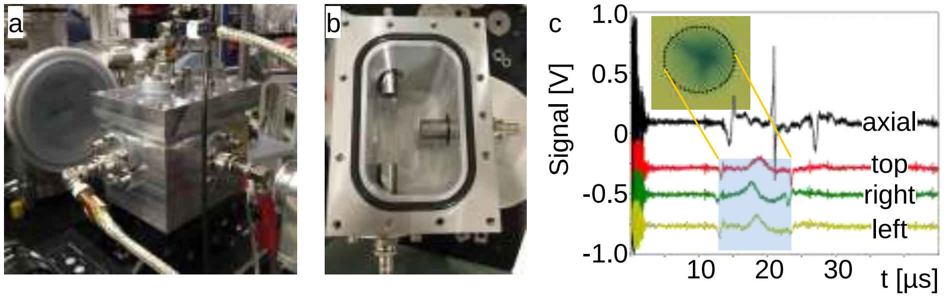
A typical reconstruction problem …

I-BEAT 3D



Experiments at HZDR (DRACO PW) with 10 … 30 MeV protons

4 transducers reveal energy, energy spread, lateral position & size, particle number



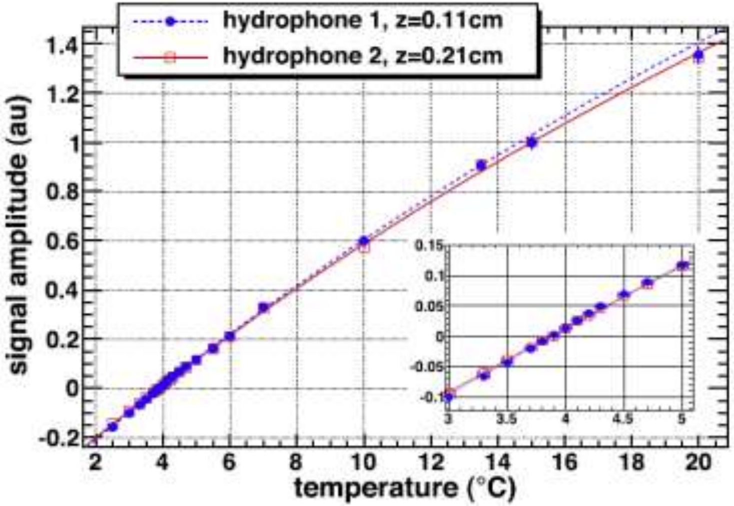
Gerlach+ HPLSE **11** doi:10.1017/hpl.2023.16 (2023).

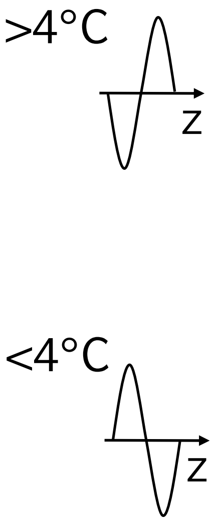
Iono-acoustics in water at 4° C --- a puzzle

Excitation → heating →
Expansion/contraction → acoustic pulse

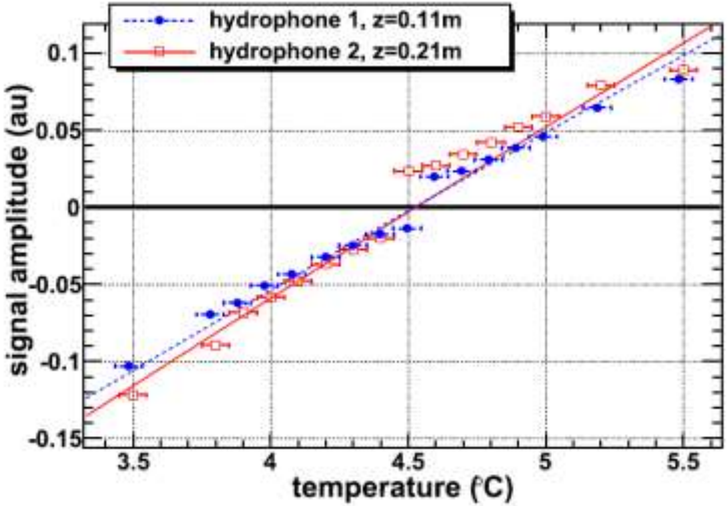
Lahmann, R. *et al.* Thermo-acoustic sound generation in the interaction of pulsed proton and laser beams with a water target. *Astroparticle Physics* **65**, 69-79, doi:10.1016/j.astropartphys.2014.12.003 (2015).

Opto-acoustics (laser pulse)



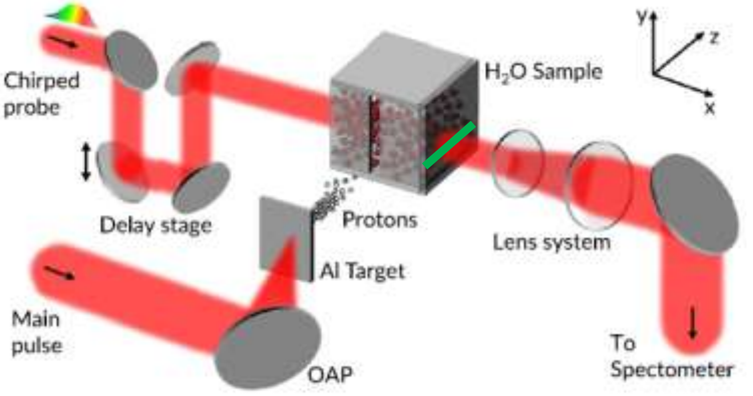


Iono-acoustics (protons)

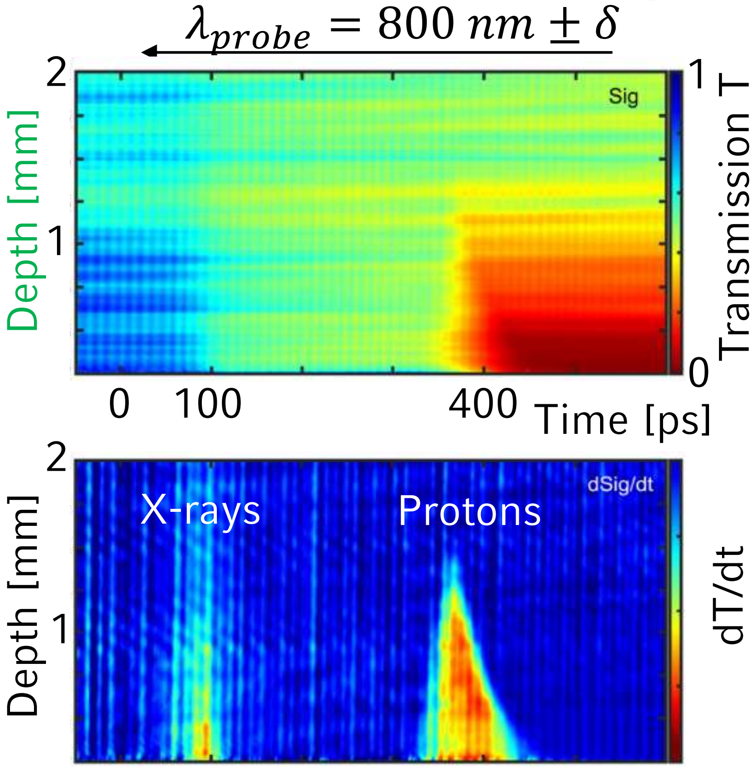


Optical probing of irradiated volume

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?

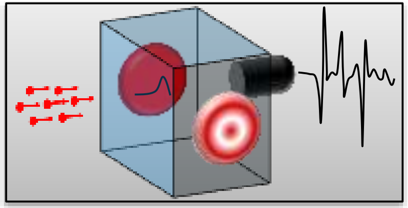


Prasselsperger+ PRL 127, 186001 (2021)

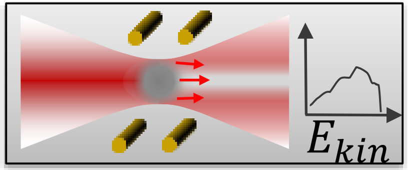
Current goals & research questions (mid-term)

Provide a reliable source of energetic protons and carbons for applications (Laser, Controls, Targets, Simulation, …)

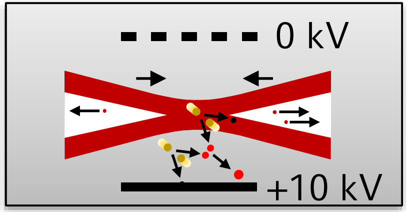
Can we measure processes that initiate radiation damage by energetic protons and carbons with micrometer spatial and picosecond temporal resolution?



Can we reach ion kinetic energies beyond 100 MeV/u with PW-laser pulses and what is the appropriate target (converter)?



Can we measure light-by-light scattering in pure vacuum?



Summary

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

Laser-based sources, beamlines and instrumentation mature (e.g. mouse irradiation at HZDR).

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

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

Laser-plasma acceleration and applications is a vibrant field and can be exploited now!

Thank your for your attention and interest!

Acknowledgements

LION: M. Bachhammer, A. Schmidt, J. Liese, L. He, A. Prasselsperger, L. Doyle, S. Gerlach, F. Balling,
HF: E.G. Fitzpatrick, L. Geulig, M. Weiser

and students!

Alumni: M. Afshari, J. Gebhard, J. Hartmann, M. Speicher, T. Rösch, F. Englbrecht, P.R. Bolton, F. Lindner, P. Hilz, Y. Gao, T. Ostermayr, D. Haffa, K. Allinger, J. Bin, D. Kiefer, W. Ma, M. Würl, M. Zhou, C. Kreuzer, S. Lehrack, S. Reinhardt

Funding: BMBF, DFG, CALA

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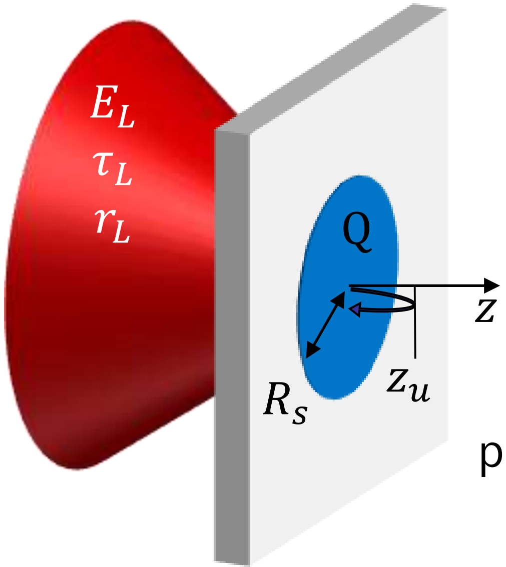
H. Wirth, O. Gosau, N. Gjotev, F. Saran, G. Schilling

Queens University Belfast (UK): B. Dromey+
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
TAU (Israel): I. Pomerantz+

Optimization of relativistic laser–ion acceleration



Number of energized electrons: $N_e = \eta E_L / E_e$

Induced charge: $Q = N_e\, 2z_u/(c\tau_L) \ll N_e$

on-axis Potential: $-e\Phi(z, r=0) = E_\infty \left(1 + z/R_s - \sqrt{1+(z/R_s)^2}\right)$

potential barrier: $E_\infty = \dfrac{Qe^2}{2\pi\varepsilon_0 R_s} = 2m_e c^2 \sqrt{\eta P_L / P_{Re}}$

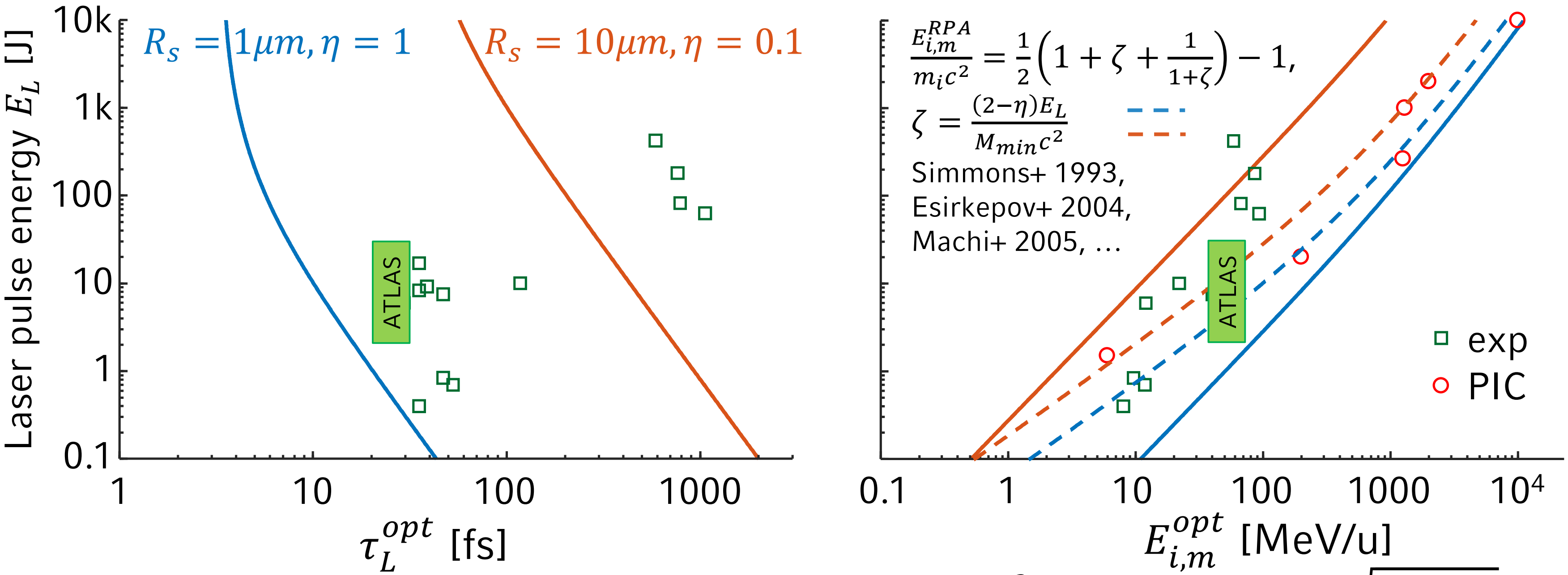
potentially (finite) highest kinetic ion energy: $E_{i,\infty} = q_i E_\infty \propto \sqrt{\eta P_L}$

Integrating the (relativistic) eom of a single ion from 0 to τ_L yields definition formula for maximum ion energy $E_{i,m} = X^2 E_{i,\infty}$: $\dfrac{\tau_L}{R_s/c} = F_R(X; E_{i,\infty})$

Schreiber+ HPLSE 2 (2014) e41

→ optimum pulse duration $\boldsymbol{\tau_L^{opt}}$ (and $\boldsymbol{E_{i,m}^{opt}}$) for a given $\boldsymbol{E_L}$ (and choice of $\boldsymbol{\eta}$ and $\boldsymbol{R_s}$)

Optimization of relativistic laser–ion acceleration



electron confinement requires $E_e = \eta E_L / N_e < E_\infty = \frac{N_e e^2}{2\pi\varepsilon_0 R_s} \rightarrow N_e = q_i N_i > \sqrt{\frac{\eta E_L}{2mc^2}\frac{R_s}{r_e}}$

Schreiber+ HPLSE 2 (2014) e41

Veksler, The principle of coherent acceleration of charged particles (1957)