LASER-ION ACCELERATION AT THE CENTRE FOR ADVANCED LASER APPLICATIONS

Jörg Schreiber

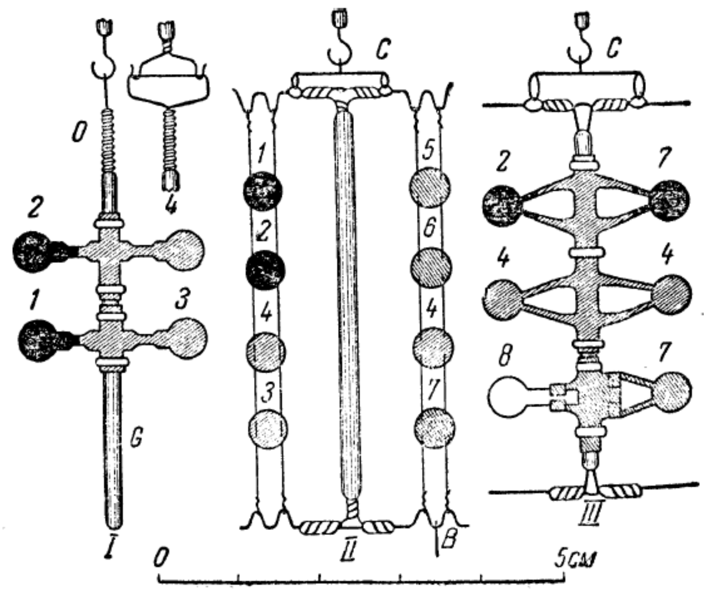
Laser-ION (LION) acceleration group
at the chair for medical physics at the
Ludwig-Maximilians-University Munich
Max-Planck-Institute for Quantumoptics Garching

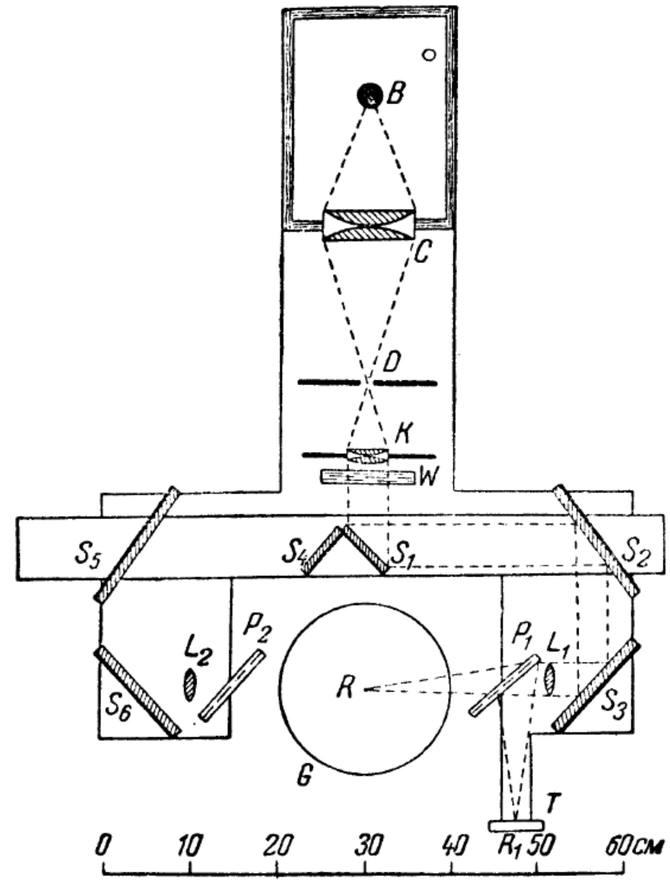
Funded by DFG-Cluster of Excellence Munich-Centre for Advanced Photonics, DFG Transregio 18, Eurofusion to-IFE and the spirit of student enthusiasm

The medical physics team at LMU

The force that drives the light mill?

P.N. Lebedev, Annalen der Physik, **6**, 433 (1901)

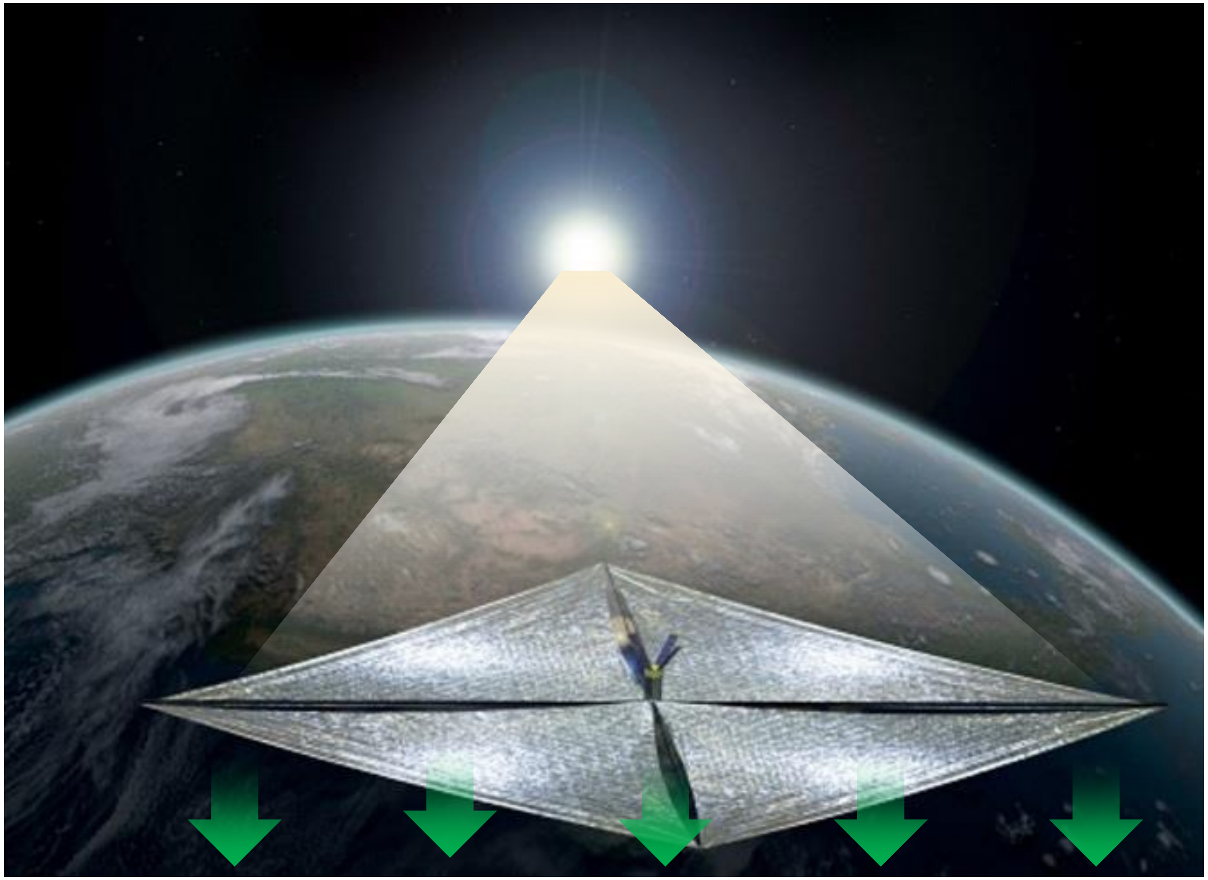




$$Light\ force = \frac{Light\ power}{velocity\ of\ light}$$

It couldn‘t be simpler – Photons have momentum and energy

Artist impression of LightSail in Earth orbit. Credit: The Planetary Society Rick Sternbach (additions by JS)
http://phys.org/news/2015-06-space-sunbeams-solar-satellite.html



acceleration

Incident light is

reflected (or absorbed)

and thereby transfers

momentum and energy

to the light sail

↓

„lots of light“ (energy/photon number) in short time results in large force that accelerates mass (for example a satellite)

↓

$$acceleration = \frac{force}{mass}$$

Light-powered satellite (e.g. 30 kg) in contest

Sun light on a 1m² sail near the earth: 1400 W $\longrightarrow$ $acceleration \approx 10^{-8}\ g$

or on a 400m² sail: 560.000 W (IKAROS-Mission) $\longrightarrow$ $acceleration \approx 10^{-5}\ g$

Hmm… not so great, e.g. my daugther at a 100 m run $\longrightarrow$ $acceleration \approx 0{,}1\ g$

Or a Ferrari, „0 to 65“ in 2,5 s $\longrightarrow$ $acceleration \approx 1\ g$

… and when it crashes $\longrightarrow$ $acceleration \approx 40\ g$

Still: Ionic propulsion of Deep-Space-1 $\longrightarrow$ $acceleration \approx 10^{-5}\ g$

Stellar vehicle and particle acceleration

fuel is avoided but at a cost. A laser of 10 GW powered over 10 years or so would provide an energy equivalent to about the rest mass of a vehicle of 30 kg, and so would be sufficient to accelerate it to relativistic speeds. In fact, the

über eine Distanz von 5×10^{13} km=300,000 AU (Proxima Centauri)

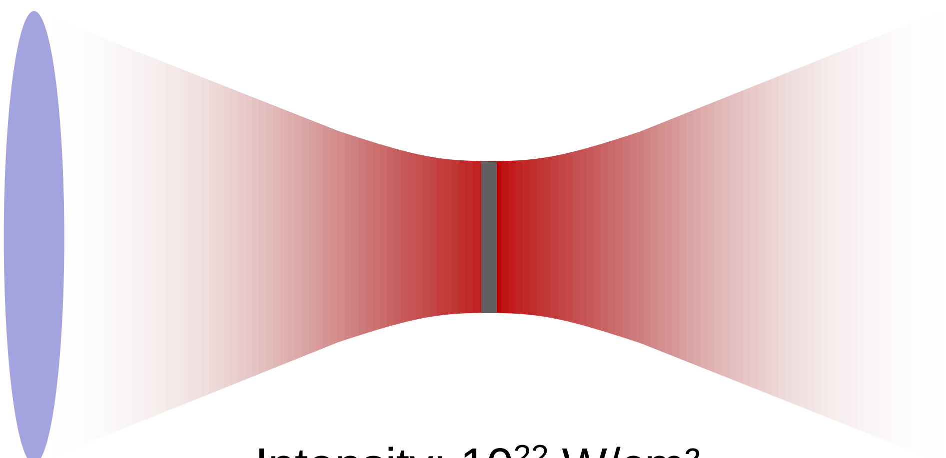
G. Marx, Nature 211, 22-23 (1966)

$$acceleration \approx 0{,}1\ g$$

↓

Around 70% c in 10 years only

A thin disc made out of carbon with 3 μm diameter and 5 nm thickness has a mass of only 10^{-16} kg und contains 5×10^{9} carbon atoms. Using 1 PW over 10 fs …



Intensity: 10^{22} W/cm²

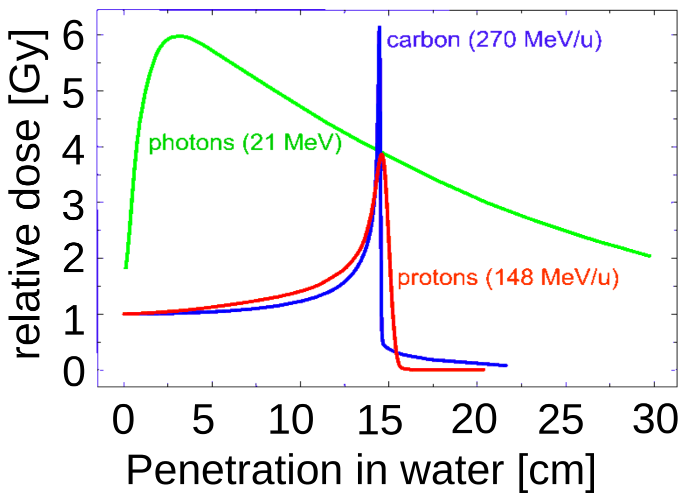
$$acceleration \approx 3 \times 10^{21}\ g$$

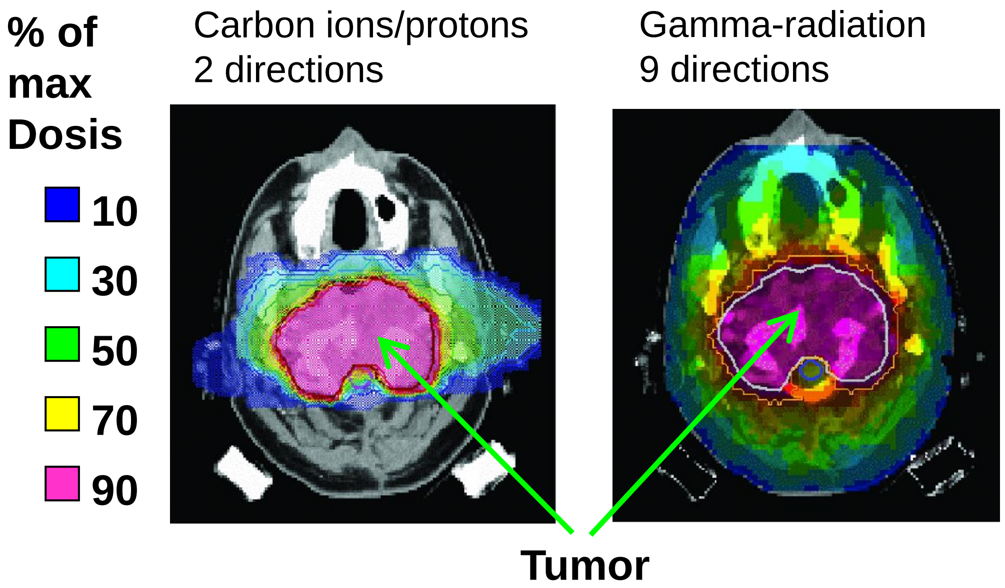
↓

~70% c in 10 fs, over a distance of only 1.5 µm

Ion-beam therapy

Particle accelerators (e.g. synchrotrons) accelerate around 10^8 carbon ions per second to 70% of the speed of light for treating specific tumors.

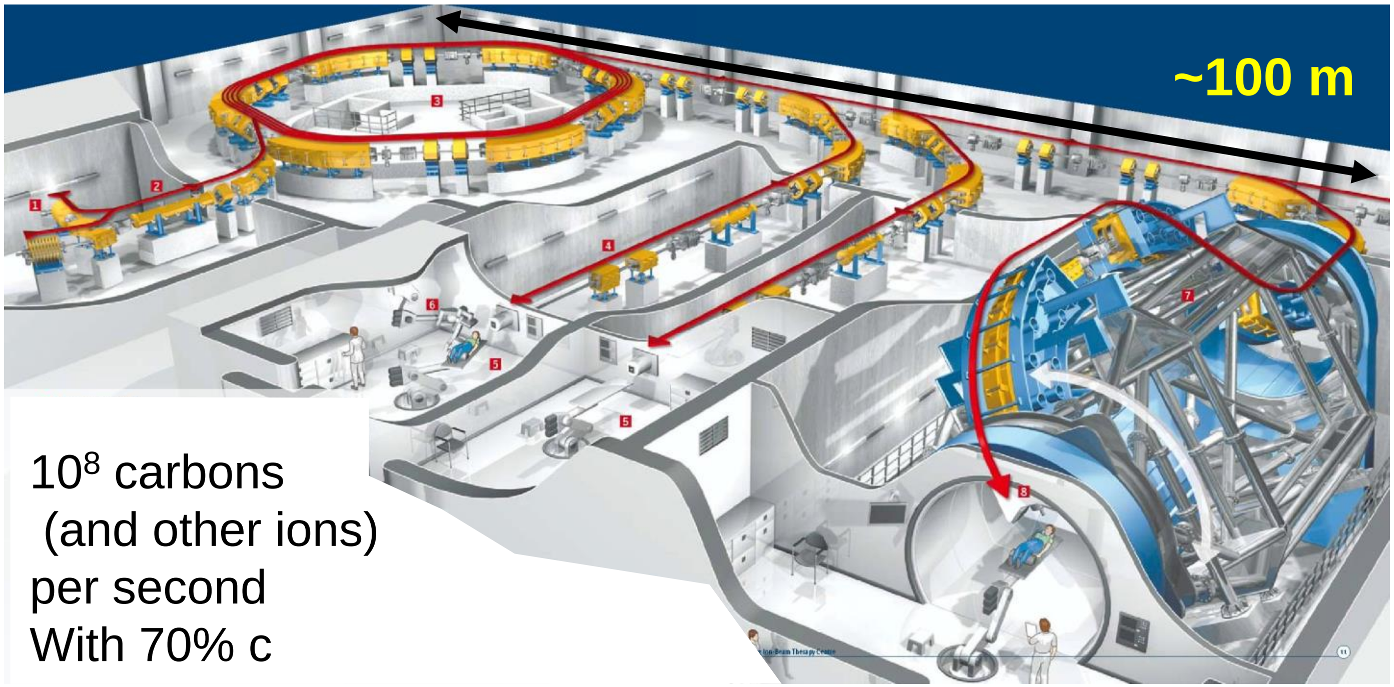




- Excellent success in resistent tumors (GSI-Darmstadt since 1993)
- Less effect on skin
- Young technique that is currently established in medicine

Heidelberg Ion Therapy (HIT) centre and our vision

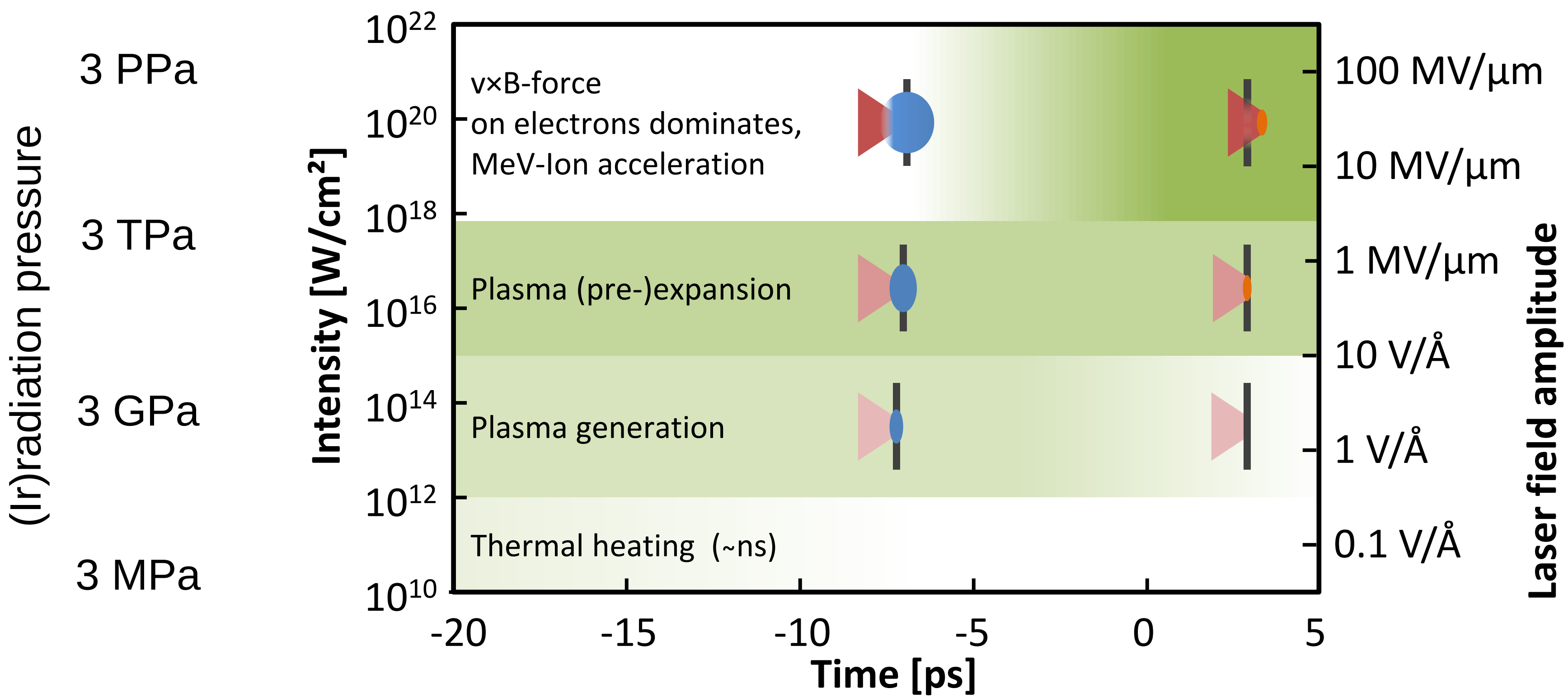
1903: W.H. Bragg (1915 Nobel-price), **1929**: 1. Cyclotron, **1946**: Idea Ion therapy (R.R.Wilson), **1952**: Synchrotron (protons), **1990**: ESR @ GSI, Darmstadt, **1997**: 1. patient threatment, **2009**: clinical use (HIT)



K. Parodi
Lehrstuhl für
Medizin-Physik
LMU

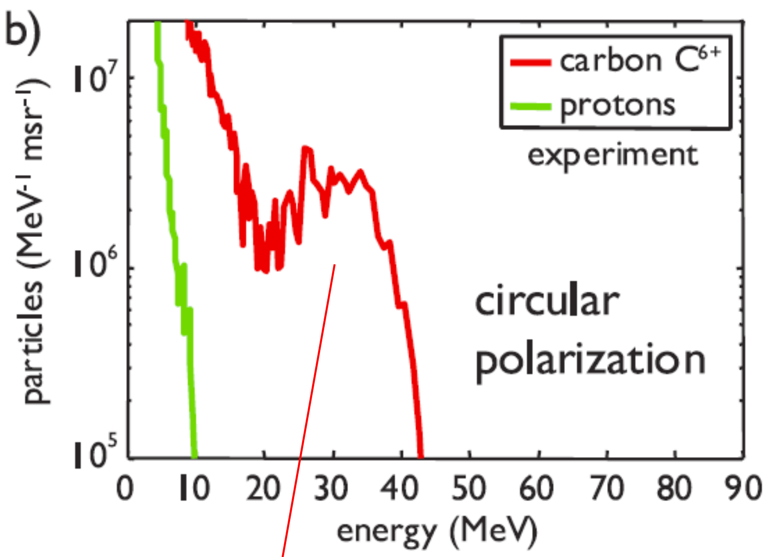
Our vision: laser-driven particle accelerators with novel characteristics for applications in research and medicine.

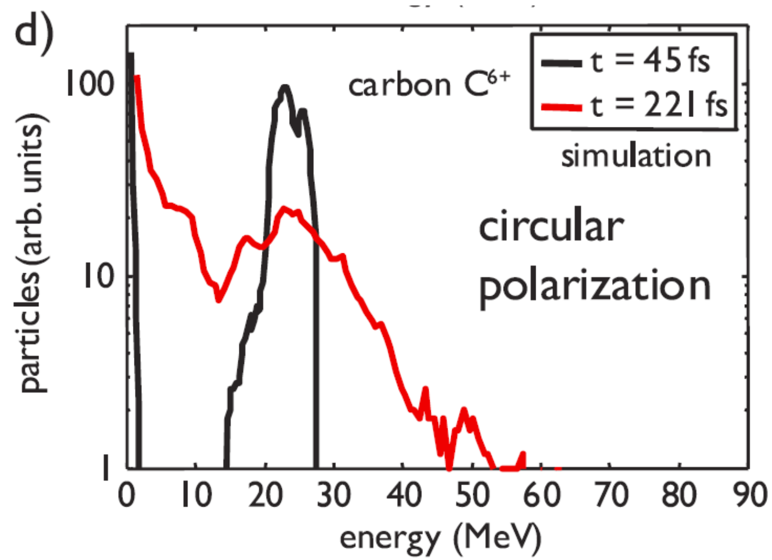
Laser-Ion acceleration in a nutshell



First experimental demonstration of radiation pressure acceleration

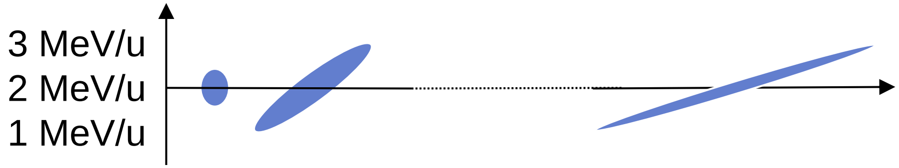
A. Henig, JS, et al., Phys Rev. Lett. 103, 245003 (2009)





- ~10^8 carbon ions out of a 5 nm thin Diamond-Like Carbon foil accelerated by radiation pressure to ~7% c
- Laser-power „only“ 0,015 PetaWatt (MBI-Berlin)

- ion bunch quickly broadens in energy (expansion) and time (dispersion)



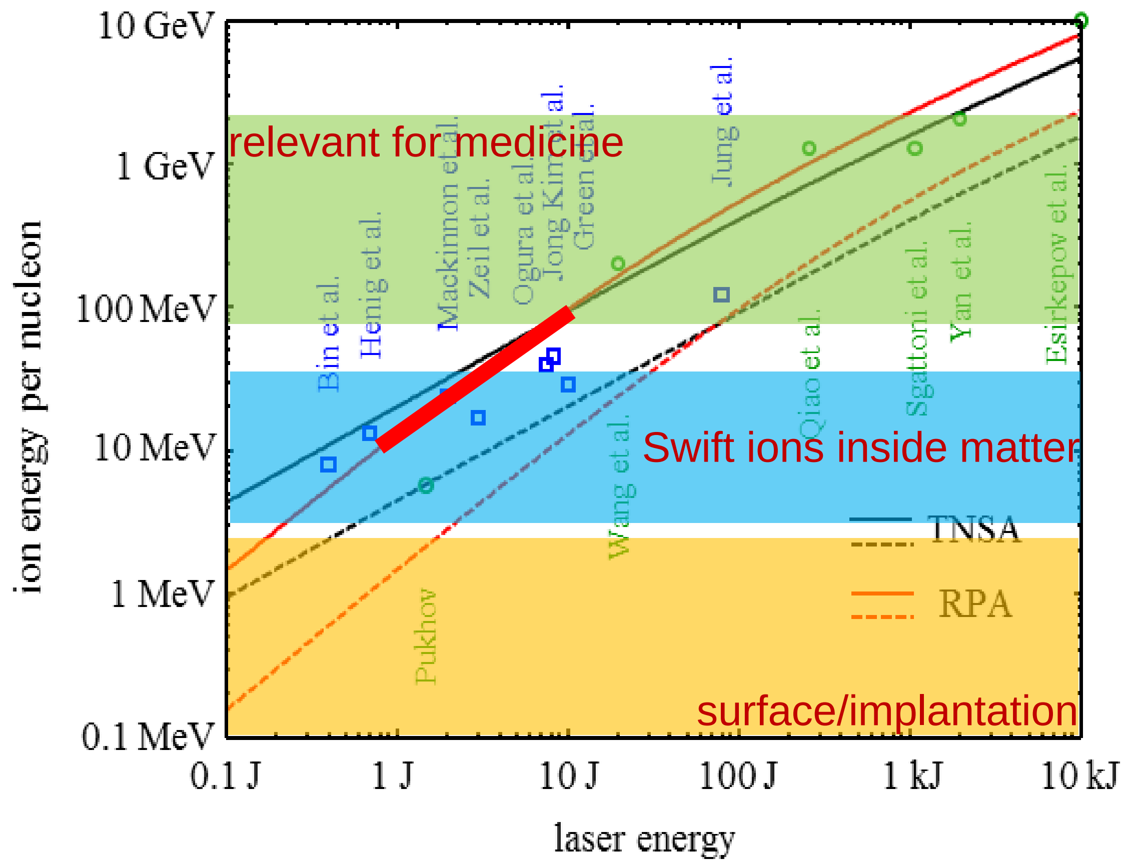
Distance	1µm	4.3µm	100 µm
time	50 fs	221 fs	5ps
duration	50 fs	150 fs	3ps

Ion energies and practicability

Current experiments are often „single shot“ with performance measure „maximum ion energy“

Laser	Experiment
Shot/s	Shot/min
Shot/min	Shot/10 min
Shot/h	Shot/h

Rule of thumb:
10 MeV/J laser energy on target (A. Macchi)

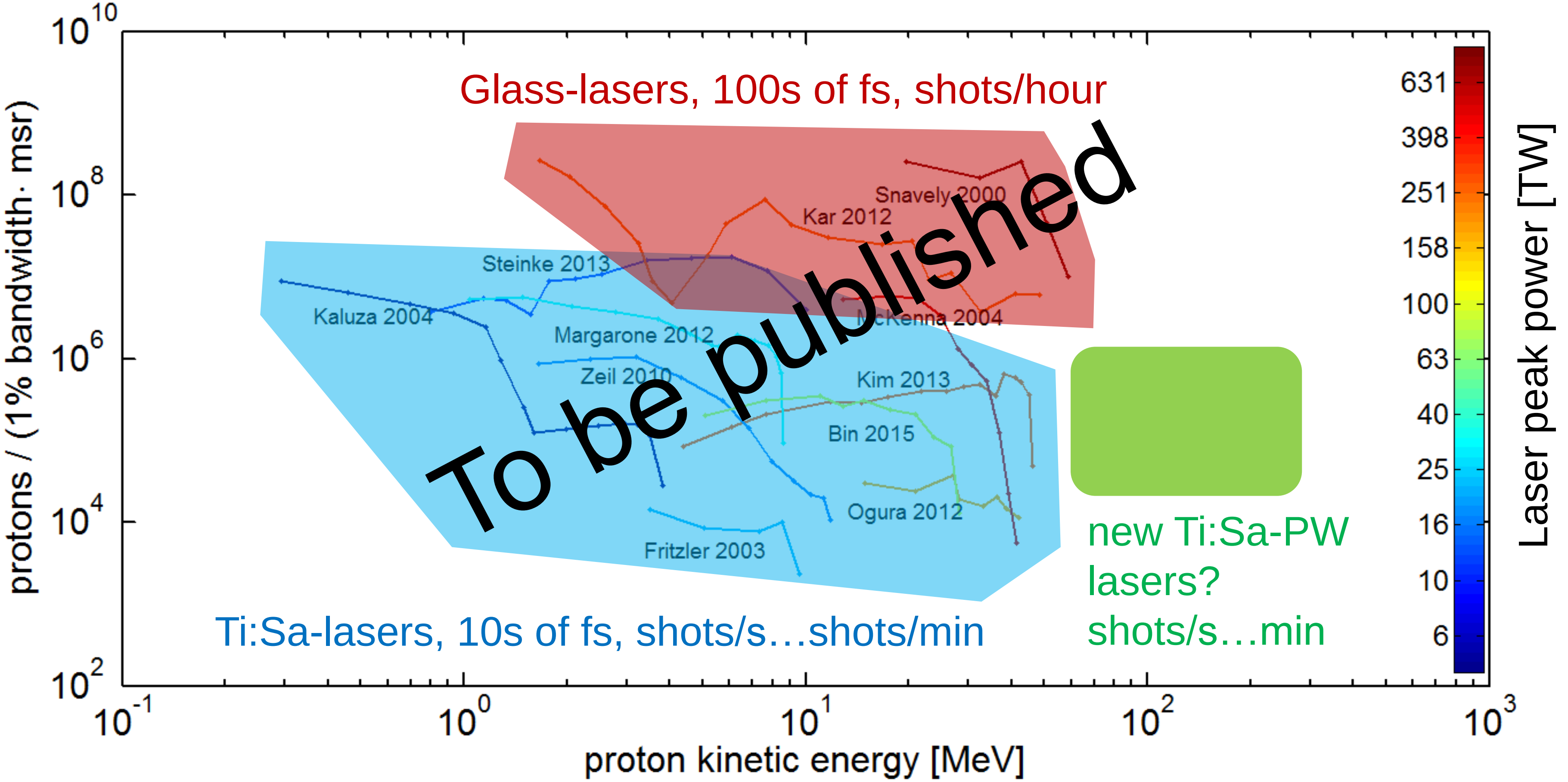


J. Schreiber, F. Bell, and Z. Najmudin, High Power Laser Science and Engineering **2**, e41 (2014).

More useful „interface“-definition: particle numbers (protons)

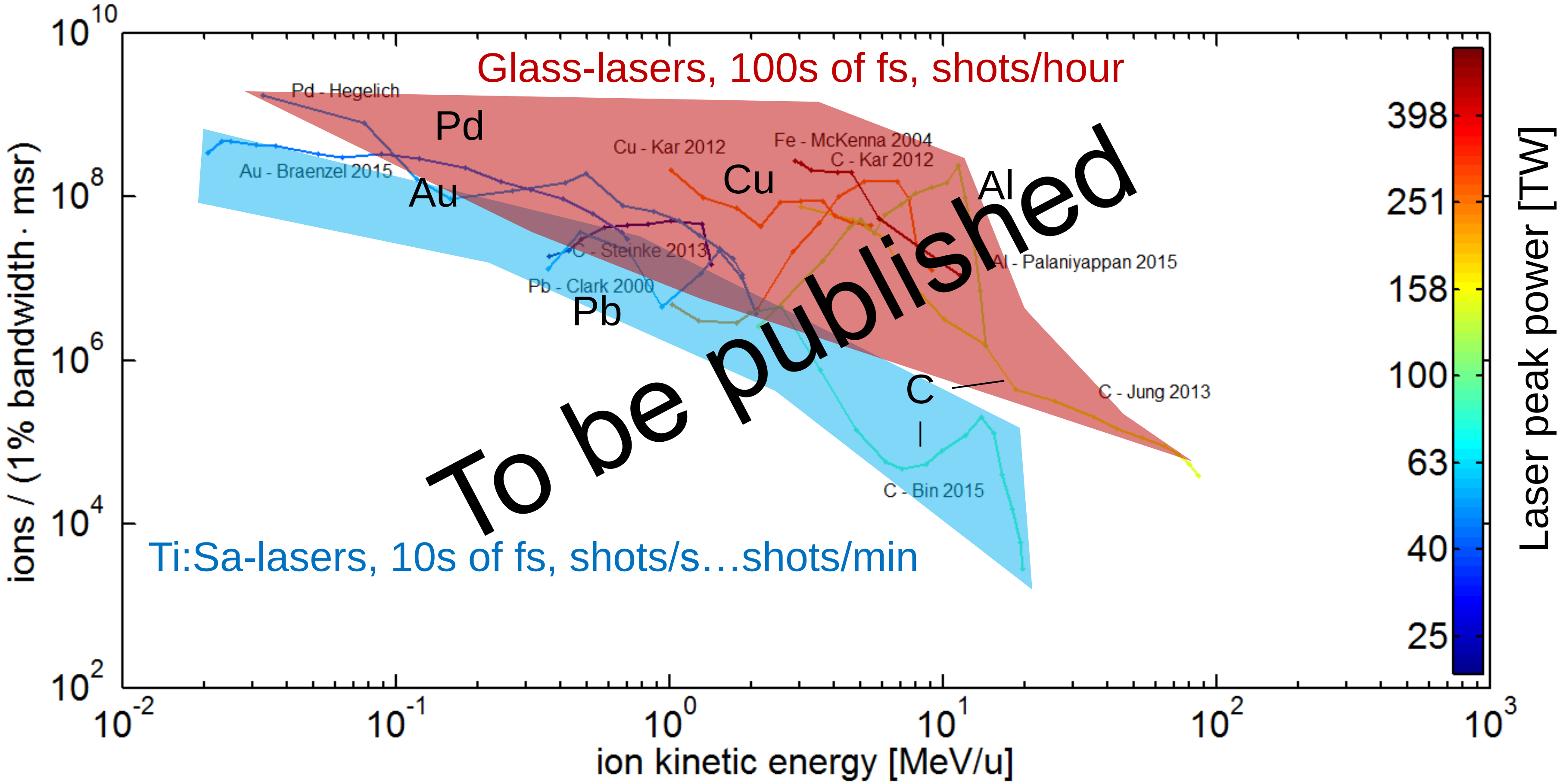
Ti:Sa: typically 10^4-10^7 protons/(1% bandwidth and msr) per shot
Glass: typically 10^7-10^8 protons/(1% bandwidth and msr) per shot

Reminder: 1msr means 1mm² area in 30 mm distance

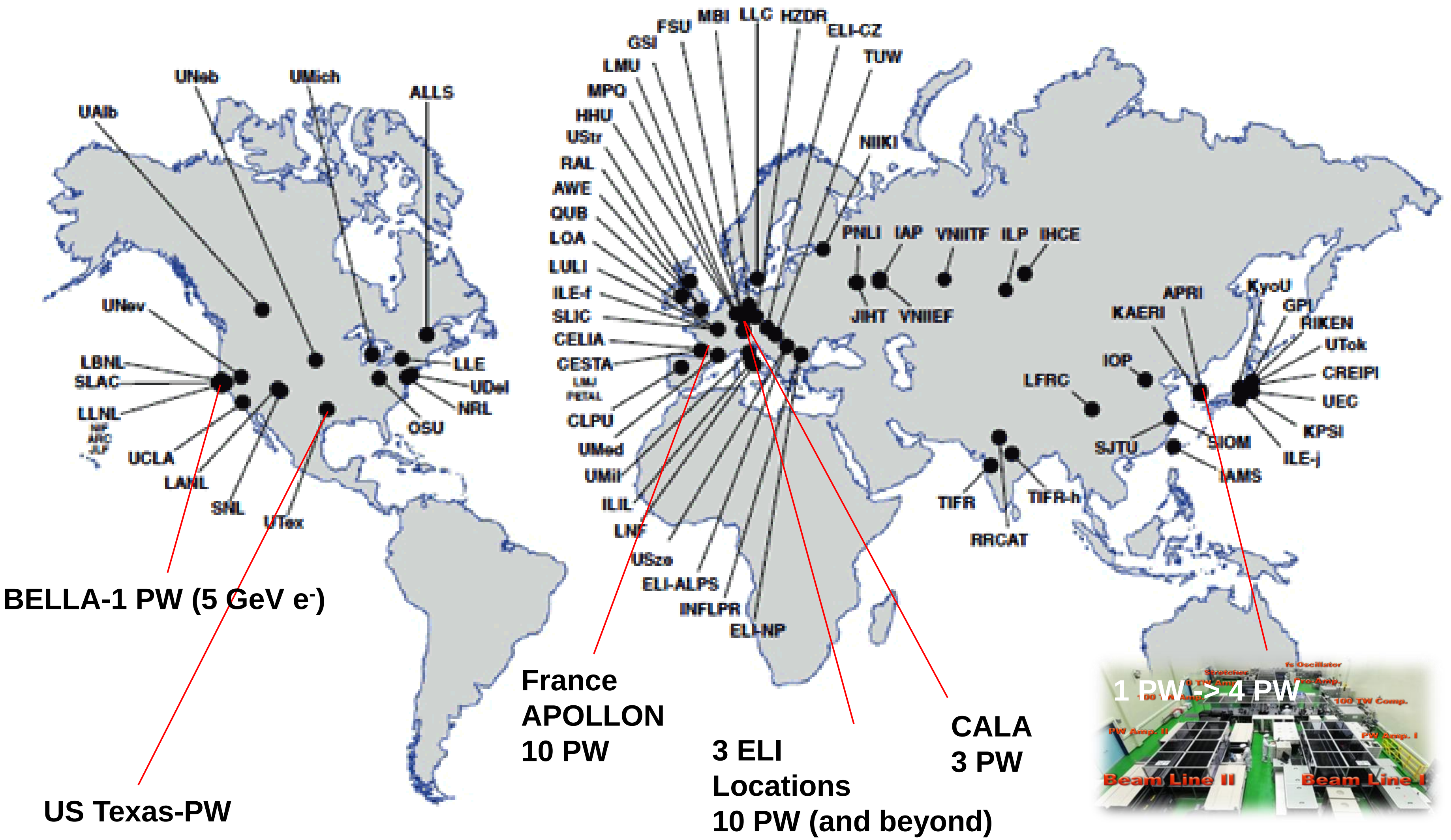


Particle numbers: heavy ions

Ti:Sa (rep-rate) systems become effective for accelerating heavier ions

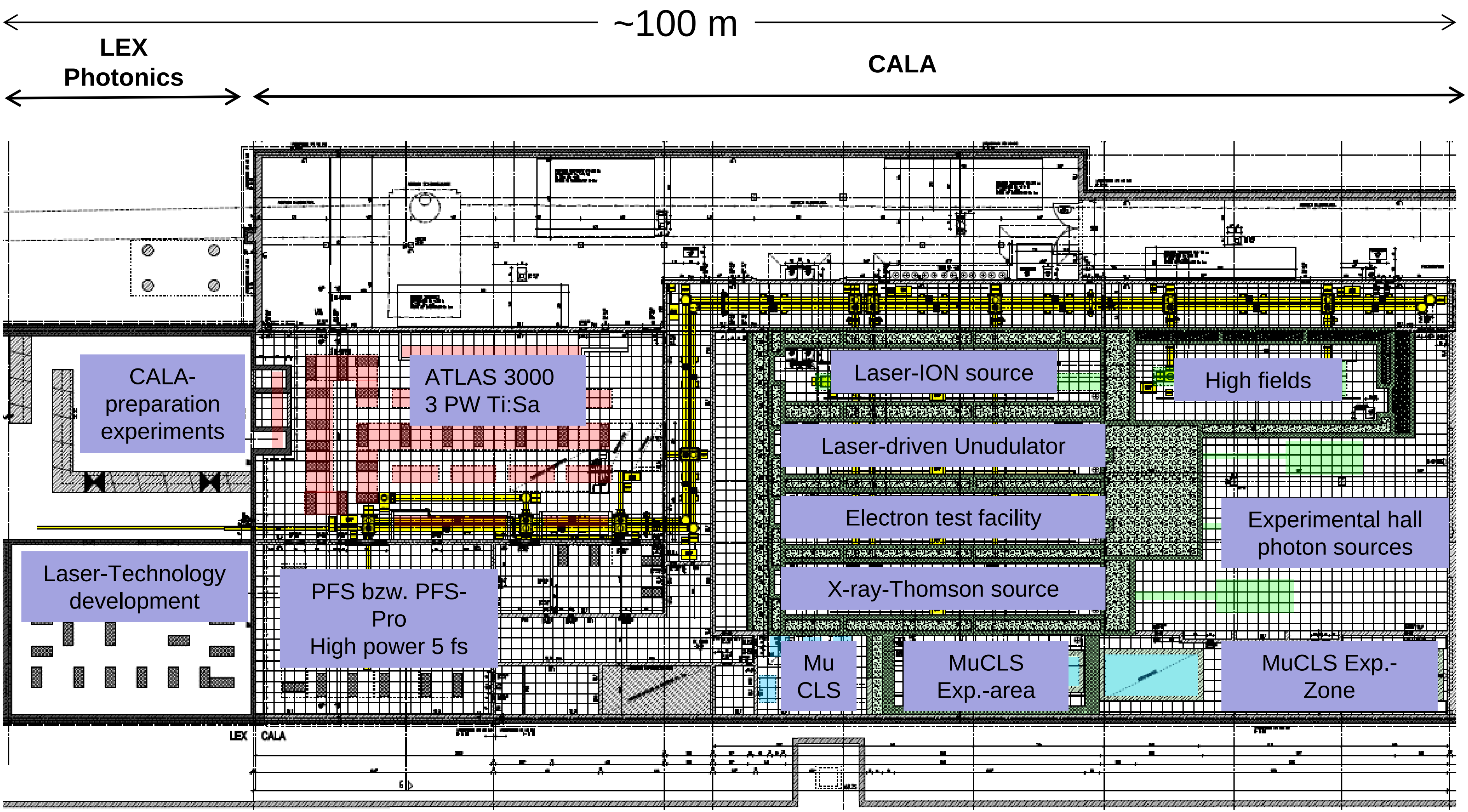


The world of TW- and PW-lasers (compiled by ICUIL)



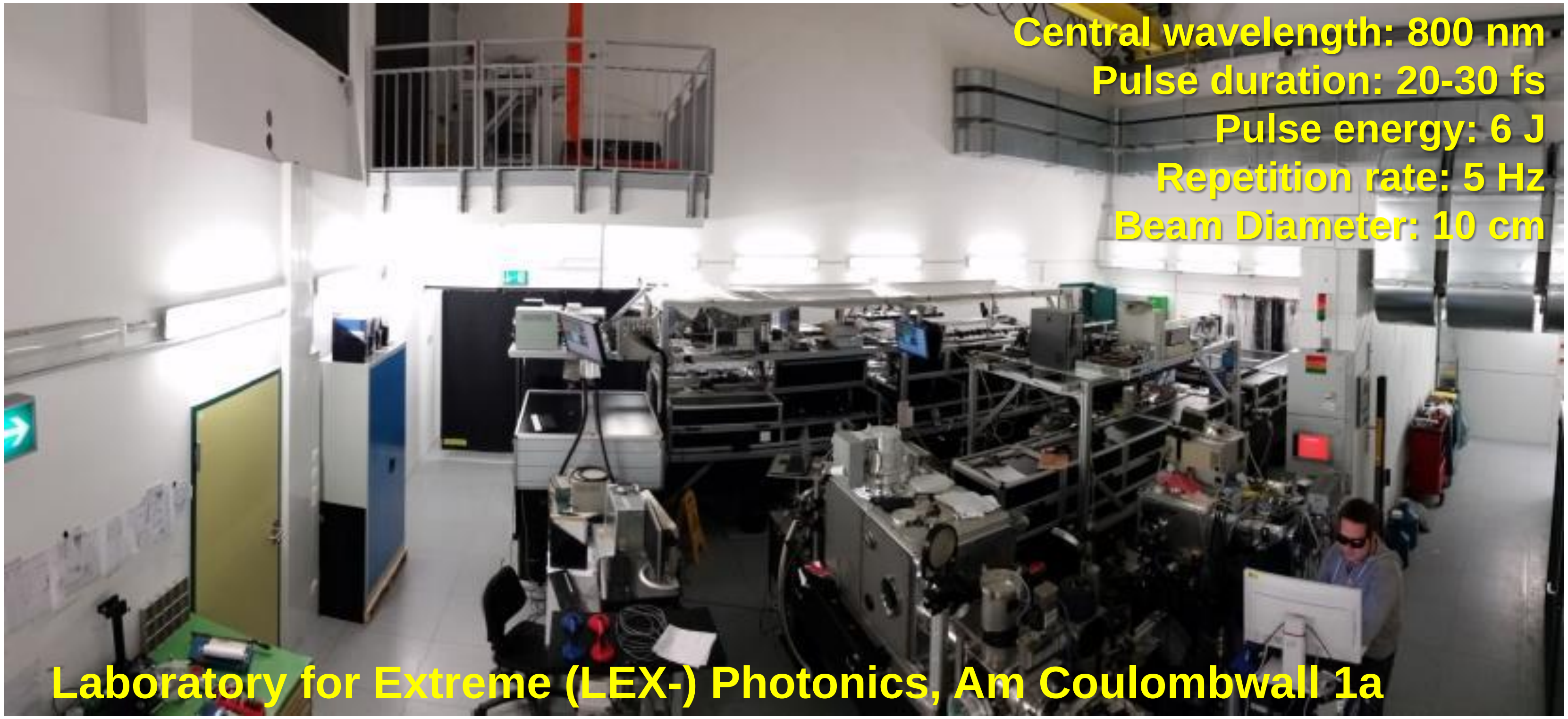
Development in Garching b. München – Compact Laser Systems

Centre for Advanced Laser Applications (CALA) in Garching



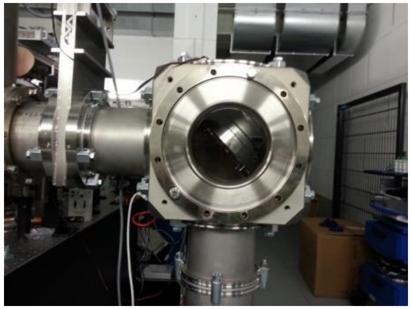
High-power Chirped Pulse Amplification (CPA) laser system ATLAS 300

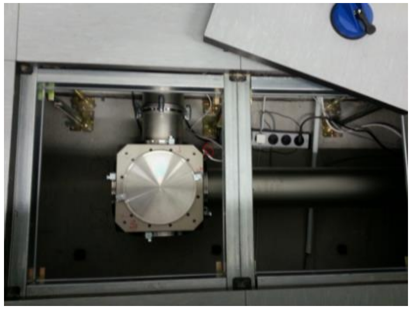
Peak power 0,3 PetaWatt



Laser-beam delivery and ion accelerator system

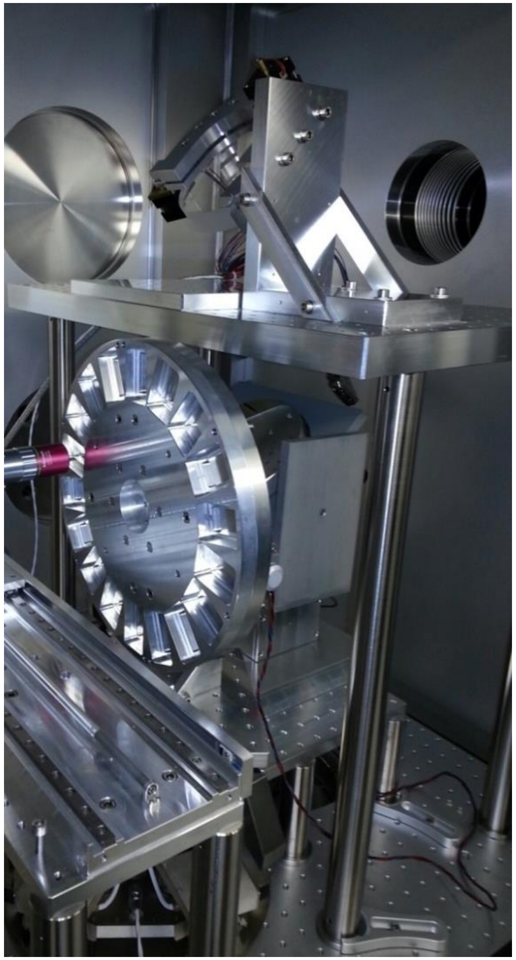
Beam-Guide (in vacuum): 10-25 cm
beam diameter limited by *Laser damage*



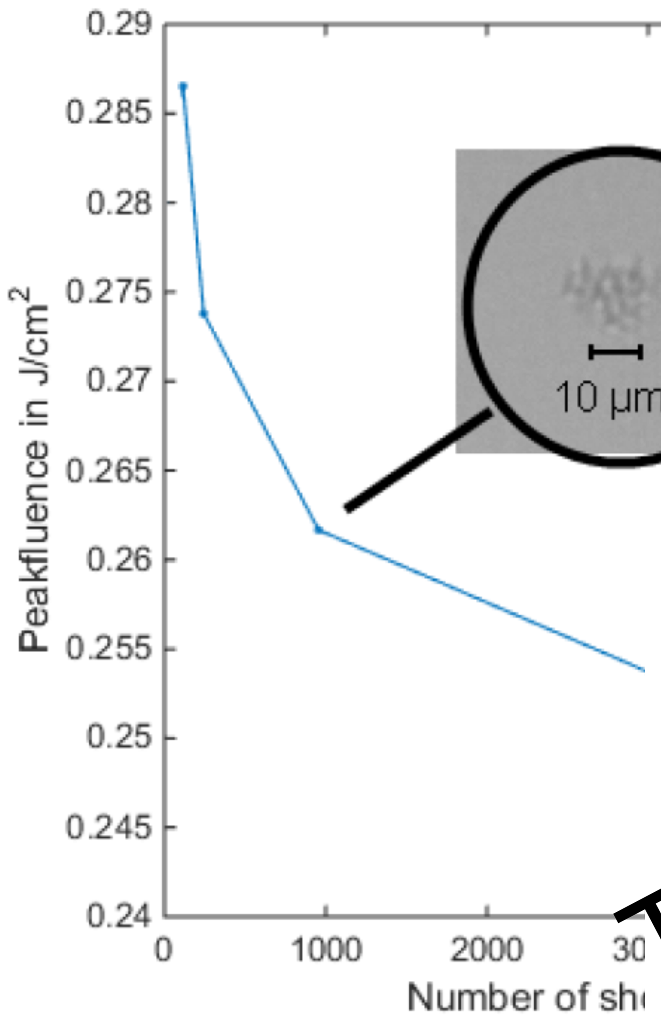


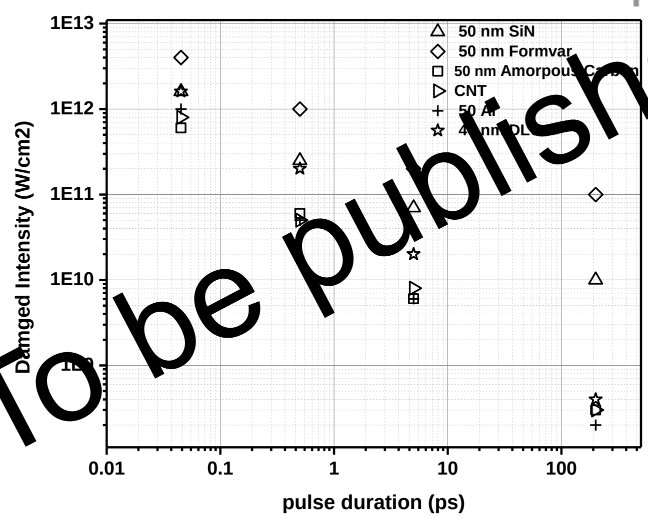
Target chambers (in the cave)

The LION chamber

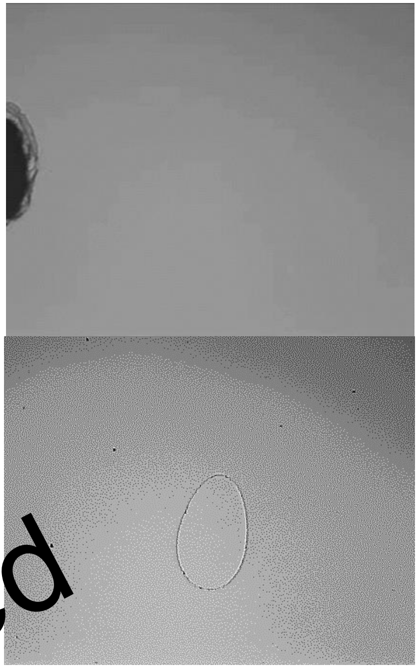


Laser-induced damage threshold – an issue for mirrors and targets



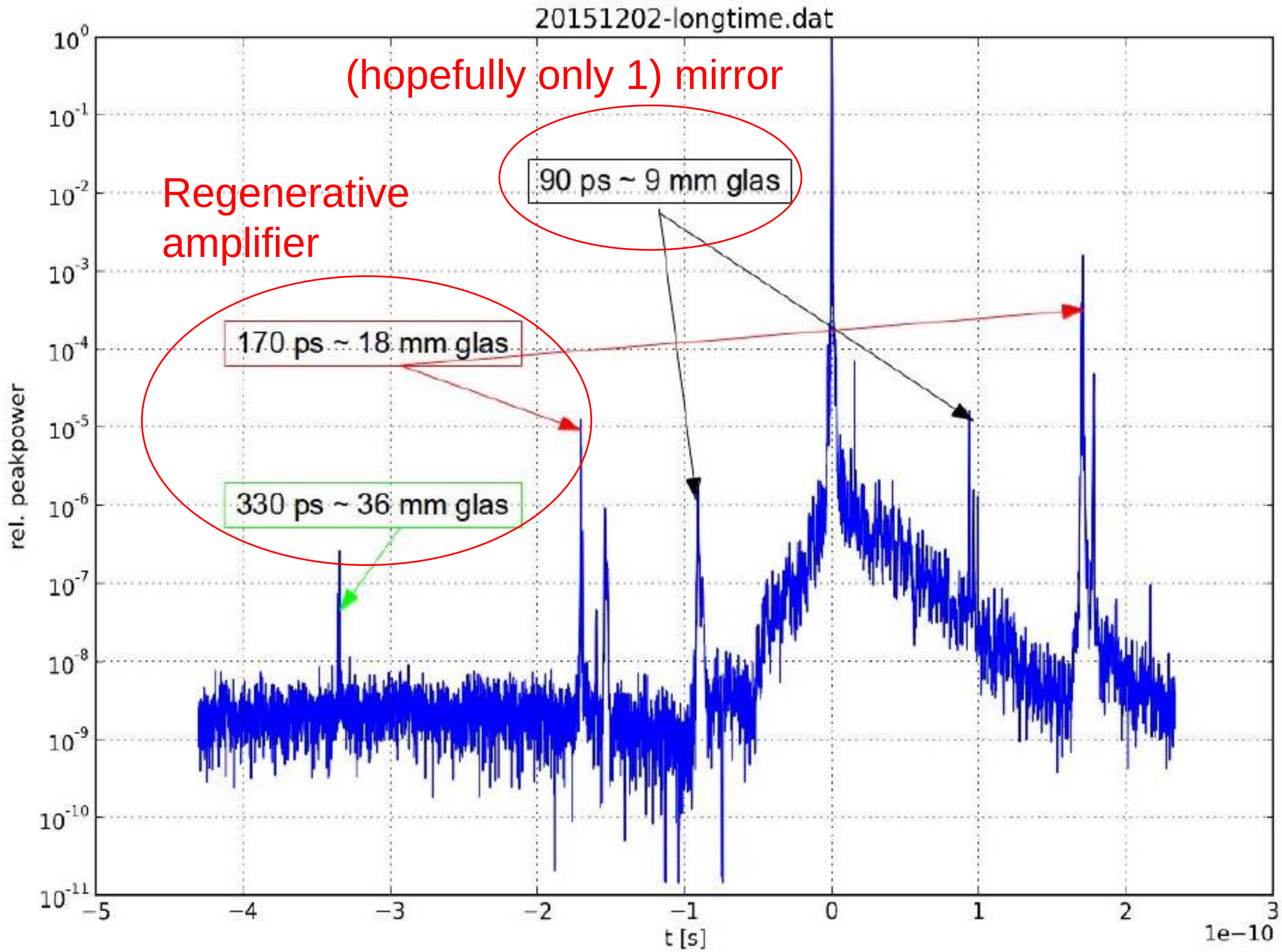


To be published



One shot damage

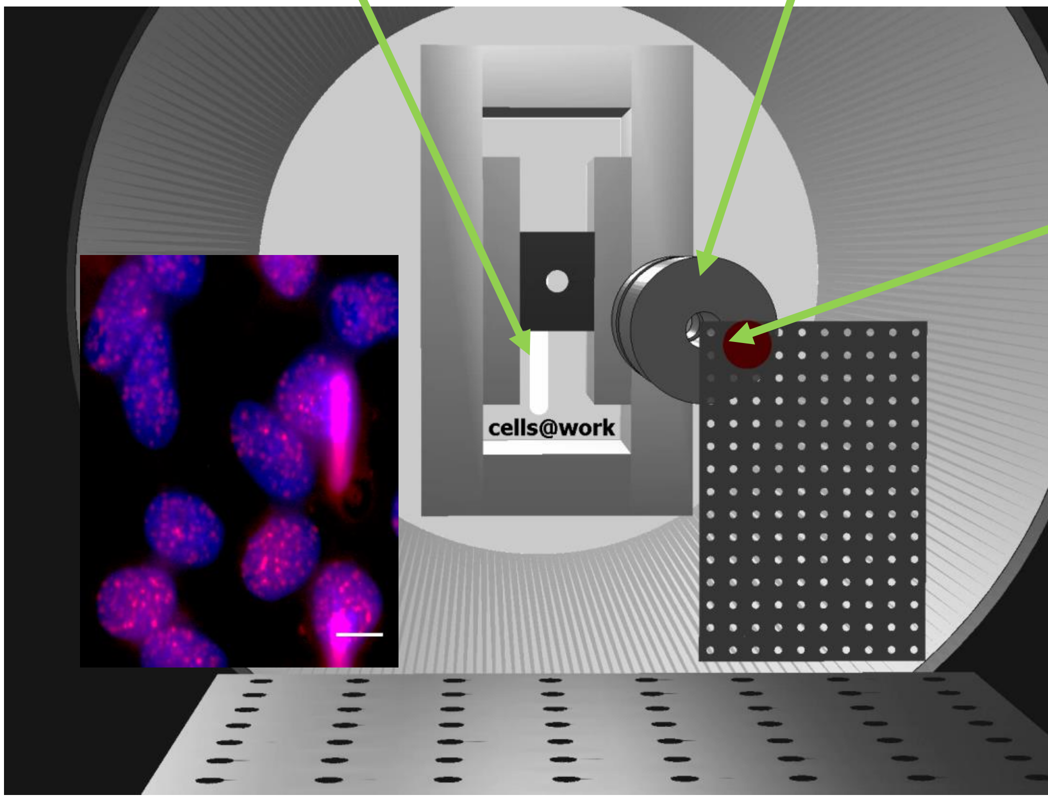
… and targets – temporal contrast



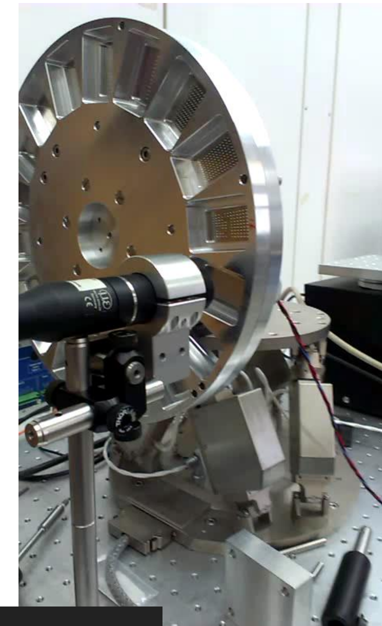
Laser-ion accelerators – holistic approach

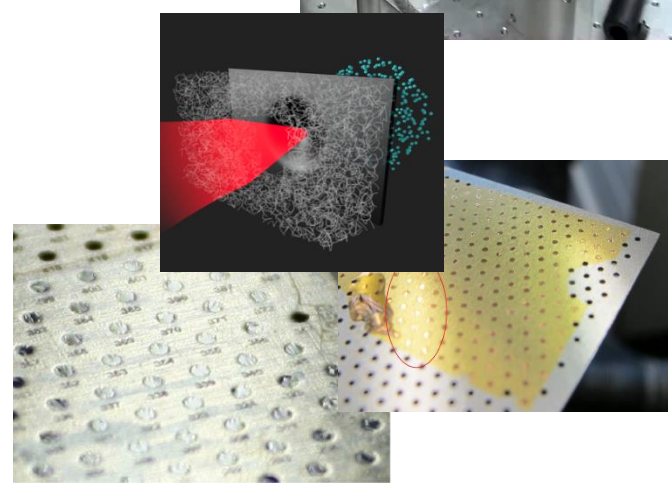
Particle **Diagnostics**

Particle **Transport**



Targetry
and
the physics of laser-plasma interaction, relativistic engineering

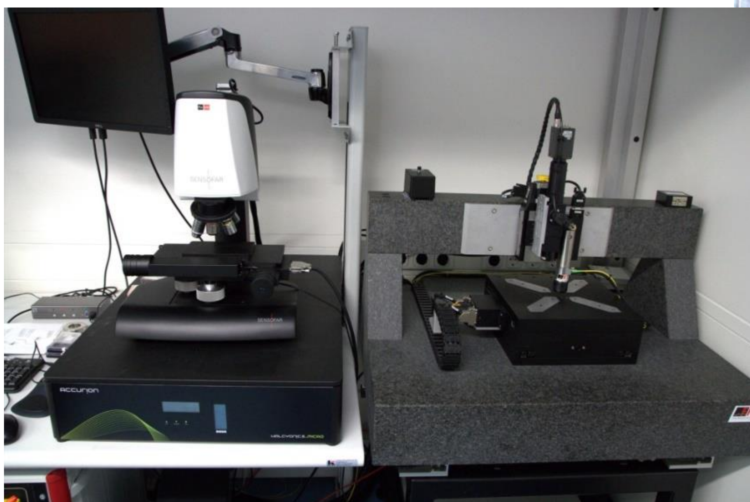




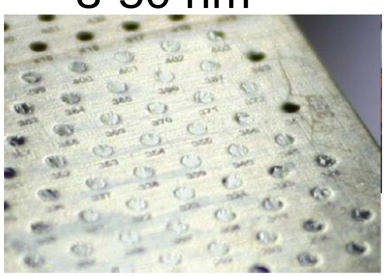
Application (e.g. cell-irradiation with single 1 ns proton pulses J. Bin et al., APL 2012).

Targetry in Garching

Atomic force, confocal, white-light interferometric microscopy

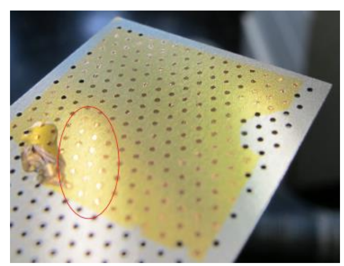


DLC foils
3-50 nm

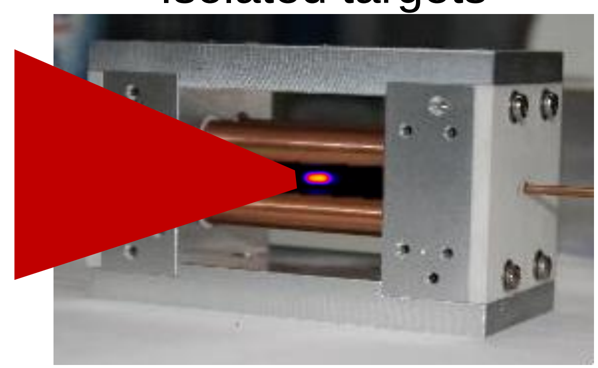


Formvar
10nm-3µm

Gold
5 nm +

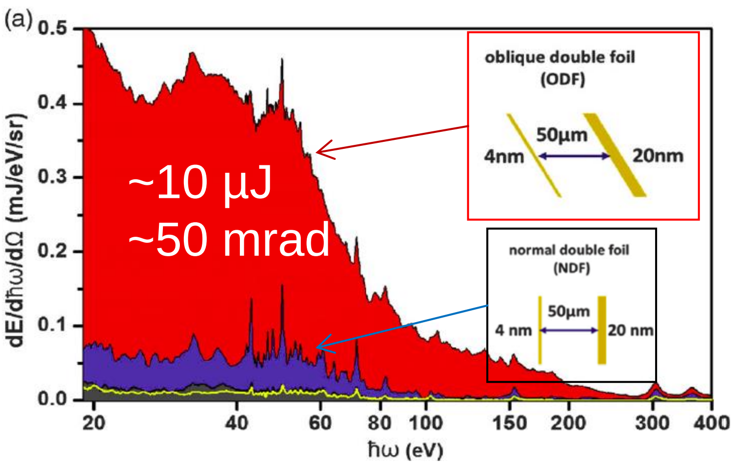


Isolated targets

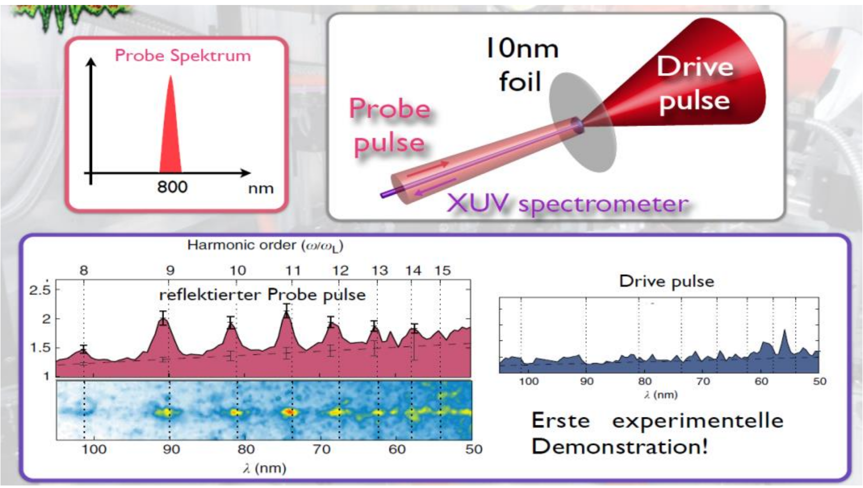


Recent achievements building on nano-targetry and ASTRA Gemini

W. Ma et al. PRL 2014:
Giant Half-cycle attosecond pulse

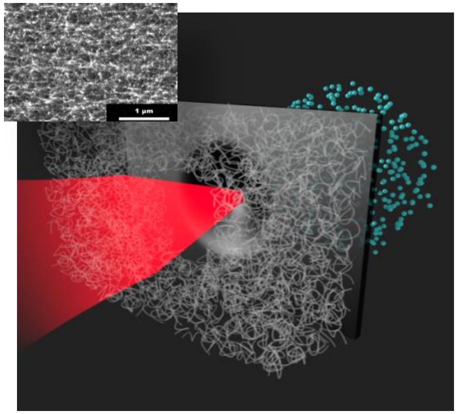


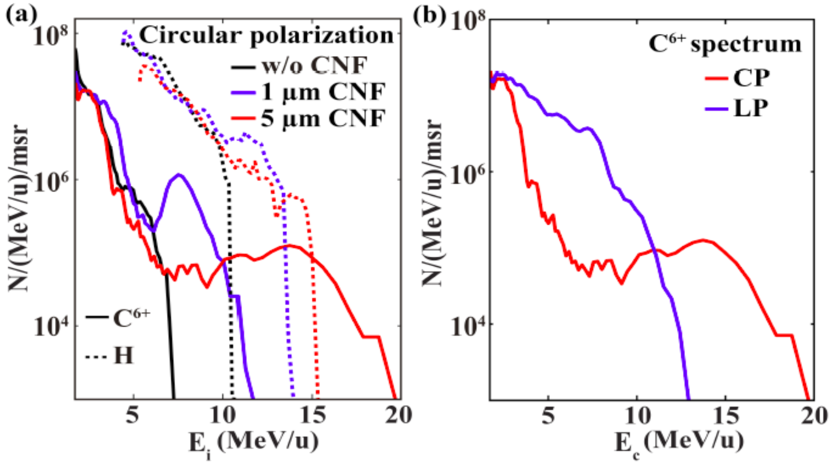
D. Kiefer et al., Nat. Comm. 2013:
Einstein's relativistic mirror



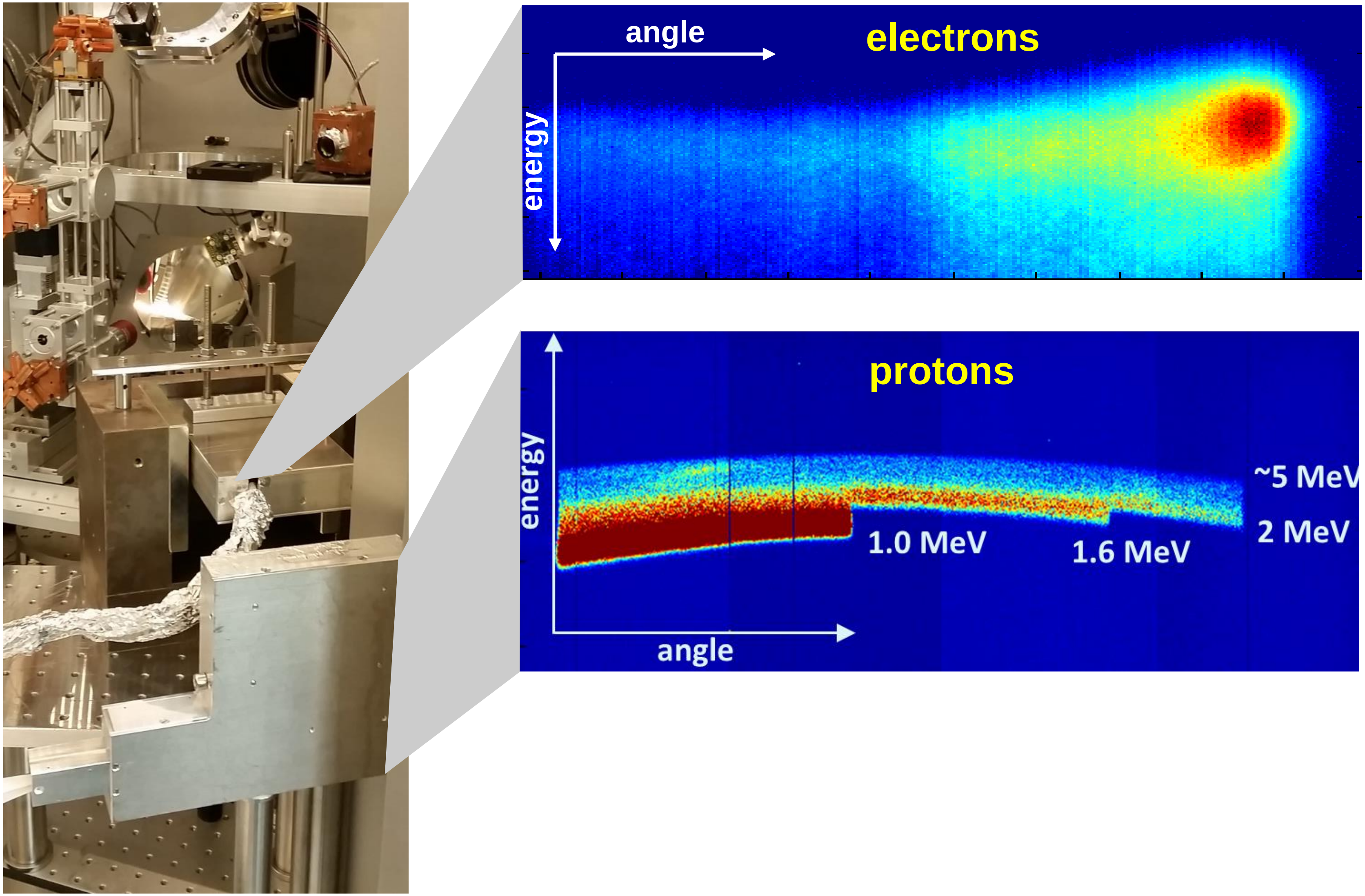
J. Bin et al., PRL 2015: ***Relativistic self-focusing improves RPA***

See also J. Bin talk





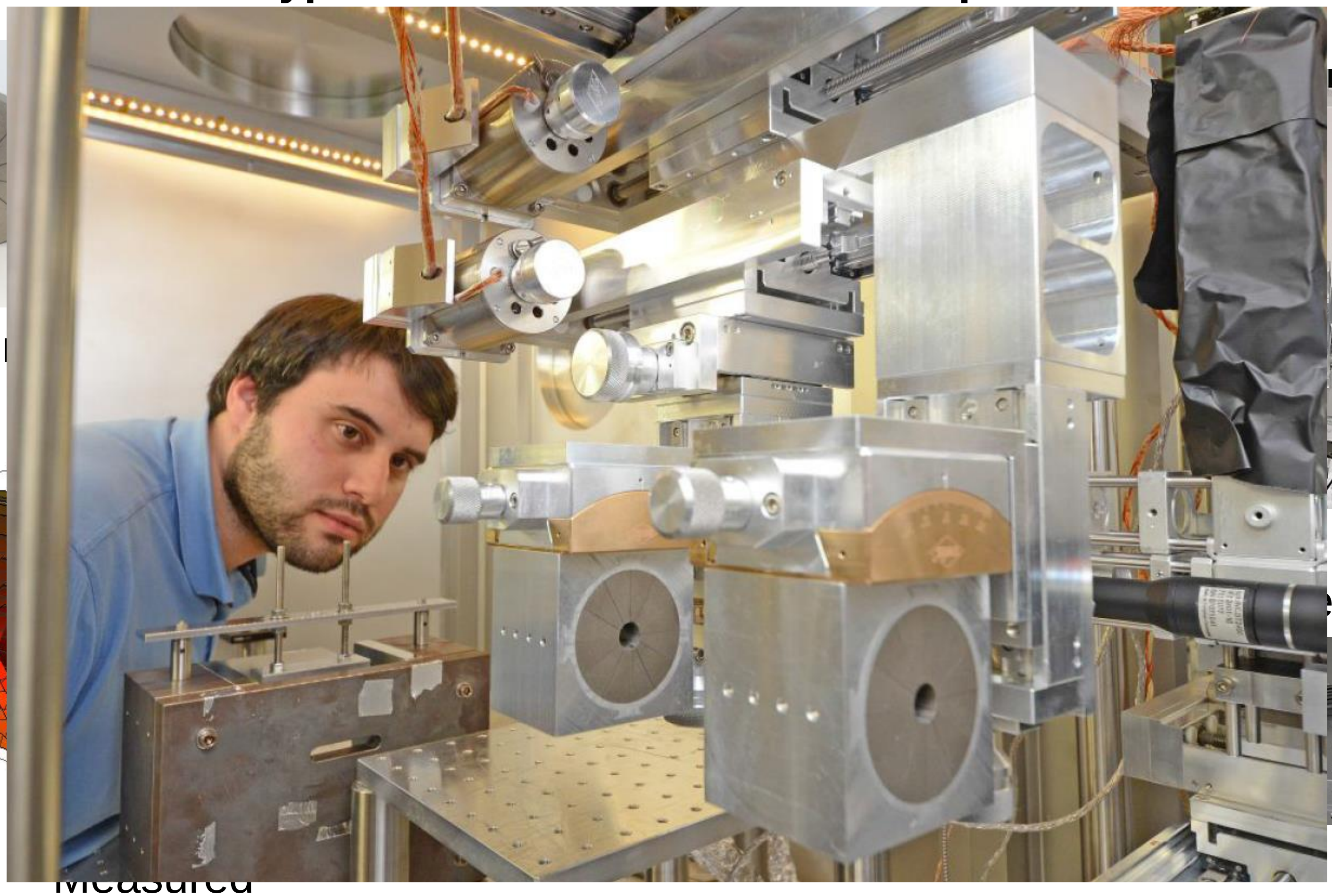
Online detection and quantitative proton radiography (with K. Parodi)

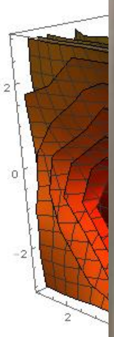


Accurate Permanent Magnet Quadrupole Doublets Characterisation

First Prototype for collimation of 5-30 MeV protons

Permanen





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Measured
3D field map

Potentially interesting aspects of laser-driven ions for applications

- Any ion species in the target is accelerated (mixed species/charge states), largest q/m to highest velocity
- Divergence angle at least a few degree (10s of mrad), source size ~µm (small transverse emittance)
- Typically broad energy distributions (with a few exceptions dE/E~few %), but short initial bunch duration (<ps) (small longitudinal emittance)
- Synchronized to laser and (co-)emited electrons, X-/Gamma-pulses, THz-pulses, …

Applications of Laser Particle Acceleration (ALPA2015)

Applications of Laser-driven Particle Acceleration

International Symposium during November 19 - 21, 2015

www.med.physik.uni-muenchen.de/aktuelles/alpa2015

Organizers:

Paul Bolton, Katia Parodi, and Jörg Schreiber

Contact:

Andrea Leinthaler (andrea.leinthaler@physik.lmu.de)

Location:

Venice International University, Venice, Italy

Important Dates:

Sept. 15 (registration & early fee, title & abstract, VIU accom. form),
Oct. 16 (late registration)

Scope:

As a focus on Applications of Laser-driven Particle Acceleration, ALPA 2015 will highlight uniqueness and potential for diverse fields. Raising awareness of laser-driven source capabilities in a growing community of users can facilitate advancement of relevant science and technology to maturity levels needed for more challenging applications.

Laser-driven Sources:

- Electrons
- Photon Sources (X-ray / gamma-ray)
- Protons and other Ions
- Neutrons

Applications:

- Materials
- Magnetism
- Matter in Extreme Fields
- Space Environment
- Medicine
- Radiobiology
- Radiochemistry
- Imaging
- Nuclear Physics
- Element Detection

Venice International University

International Program Committee:

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Marco Borghesi, UK
Peter Böni, Germany
Tom Cowan, Germany
Joel England, USA
Wolfgang Enghardt, Germany
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Luis Roso, Spain
Markus Roth, Germany
Wolfgang Sandner, Germany
Ulrich Schramm, Germany
Reinhard Schulte, USA
Noaya Shikazono, Japan
Sanjeev Srivastava, India
François Sylla, France
Peter Thirolf, Germany
Jan Wilkens, Germany

Concluding remarks

We are lucky to witness the emerging Petawatt era. As lasers develope, particle accelerators need to mature to become viable tools for applications. On the path to Laser-Ion Beam Radiation Therapy (L-IBRT), we seek to exploit the unique features of "laser-driven" for applications in science and medicine.

We encounter common challenges at the border of (relativistic) engineering and physics. Strategizing and monitoring our progress is helpful, educative, and essential.

Applications
broad energy, bunched, high flux, synchronised, …

Diagnostics	Targetry	Transport
on-target single-shot laser/plasma parameters	Gas, fluid, solid, nano, …	(Semi-) conventional
bunched radiation/particle detectors/monitors	TNSA, RPA, BOA, (D-)CE, SA, HB-A	All-optical/other plasma optics
…	…	conventional/plasma post-acceleration
		…

Concluding remarks

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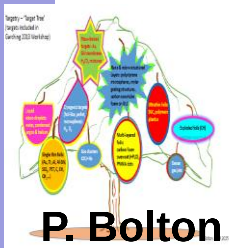
Applications
1st WS – 2015 (ALPA2015 Venice)

Diagnostics
1st WS – 2010 (Abingdon)
2nd WS – 2013 (Paris)
3rd WS – 2015 (Garching)

Targetry
1st WS – 2013 (Garching)
2nd WS – 2015 (Paris)
3rd WS – 2017 (Salamanca)



Transport
1st WS – to be announced

Thank you - Group and collaborators

Ludwig-Maximilians-Universität München:
K. Parodi et al., P. Bolton, F. Krausz et al., S. Karsch et al., H. Ruhl et al., A. Friedl et al., M. Groß, H. Wirth, J. Szerypo, T. Näser, I. Cortrie

Technische Universität München
J. Wilkens et al., G. Multhoff, T. Schmid, et al.

Max-Born-Institut Berlin (Germany):
M. Schnuerer, J. Braenzel, et al.

Imperial College London (UK):
Z. Najmudin et al.

Queens University Belfast (UK):
M. Zepf, M. Yeung, B. Dromey, D. Jung

Rutherford Appleton Lab (UK):
C. Spindloe, R. Pattathil et al.

Texas University at Austin (US):
M. Hegelich et al.

GSI Darmstadt (Germany):
B. Zielbauer, V. Bagnoud, et al.

HZDR Dresden (Germany):
U. Schramm, M. Bussmann, et al.

FSU Jena (Germany):
M. Zepf, M. Kaluza, et al.

Peking University (China):
X.Q. Yan, et al.

J. Bin, Y. Gao, D. Haffa, P. Hilz, C. Kreuzer, T. Ostermayr, M. Zhou, F. Englbrecht, S. Lehrack, M. Würl and students
Alumni: K. Allinger, D. Kiefer, W. Ma, S. Reinhardt

Using BELLA for ion acceleration is a great move, I am looking forward to fruitful collaborations and healthy competition.