Laser-driven ion sources: Activities in Munich

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Funding: DFG-Cluster of Excellence Munich-Centre for Advanced Photonics, SFB TR18, Centre for Advanced Laser Applications, to-IFE

Collegues and Collaborators

Max-Planck-Institut für Quantenoptik/Ludwig-Maximilians-Universität München:
K. Parodi et al., S. Karsch et al., H. Ruhl et al.

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.

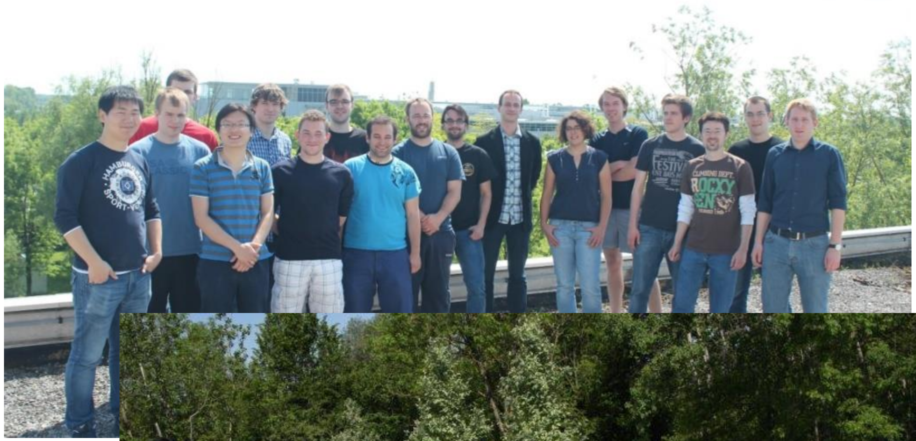
GSI Darmstadt (Germany):
B. Zielbauer, V. Bagnoud, et al.

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

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

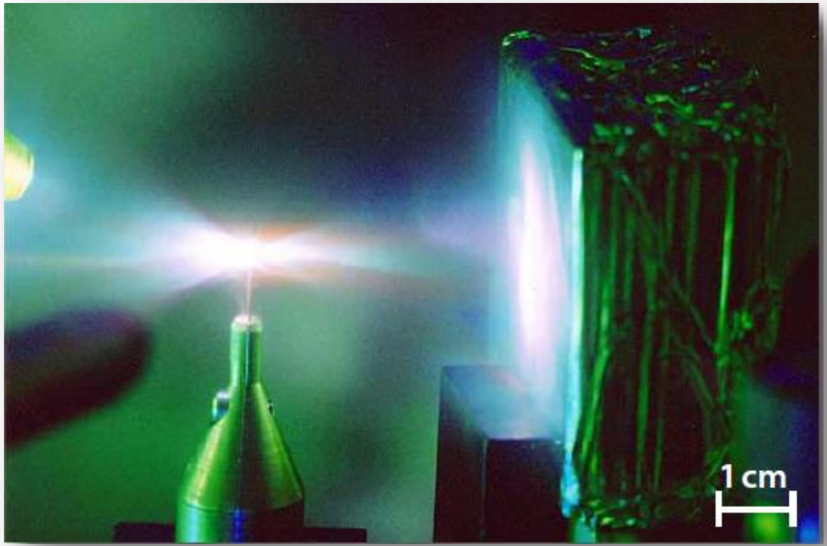
Peking University (China):
X.Q. Yan, et al.

J. Bin, W. Ma, D. Haffa, P. Hilz, C. Kreuzer, D. Kiefer, T. Ostermayr, K. Allinger, and students

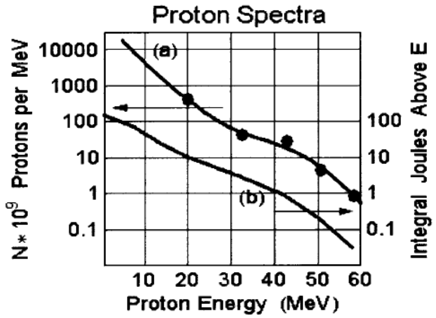


Interesting and rich physics – novel sources/approches to applications

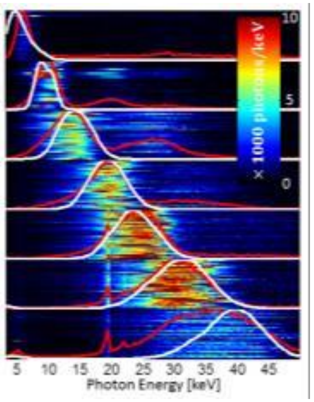
Relativistic electrons



Multi-MeV ions, Snavely PRL, 2000

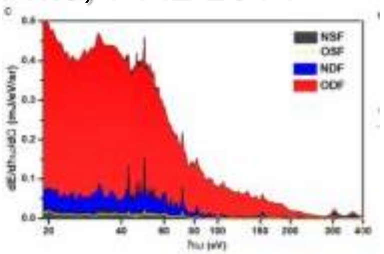


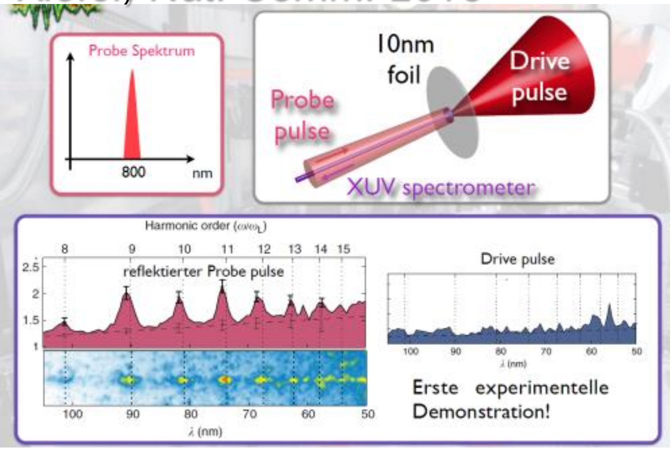
Einstein's relativistic mirror, Kiefer, Nat. Comm. 2013



Tunable, fs X-rays by Thomson-Back-scattering, Khrennikov, PRL 2015

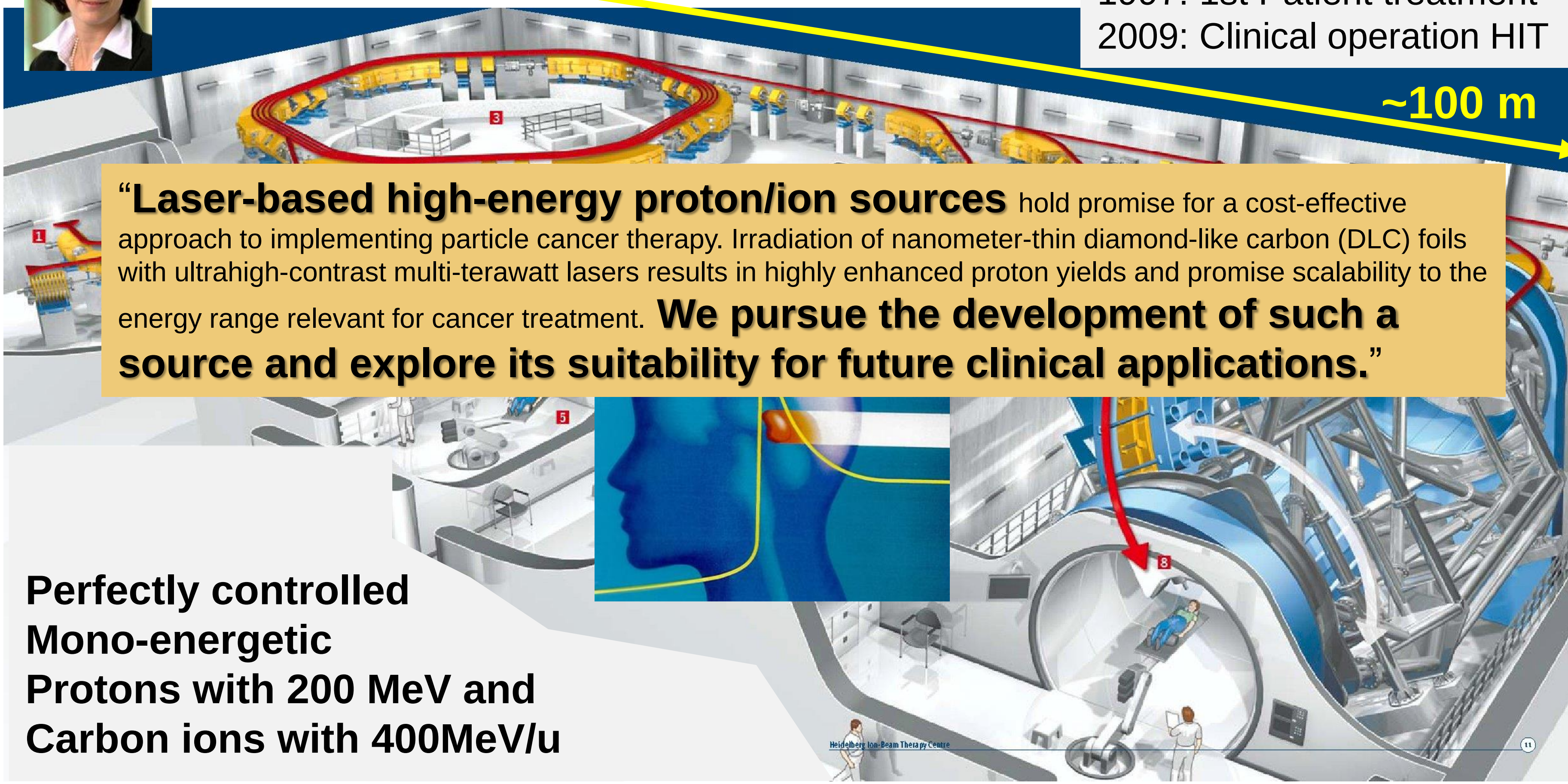
Giant Half-cycle attosecond pulse Ma, PRL 2014





Setting at LMU Munich: New chair for medical physics

1929: Cyclotron
1946: Idea (R.R.Wilson)
1952: Synchrotron (Protons)
1990: ESR @ GSI, Darmstadt
1997: 1st Patient treatment
2009: Clinical operation HIT

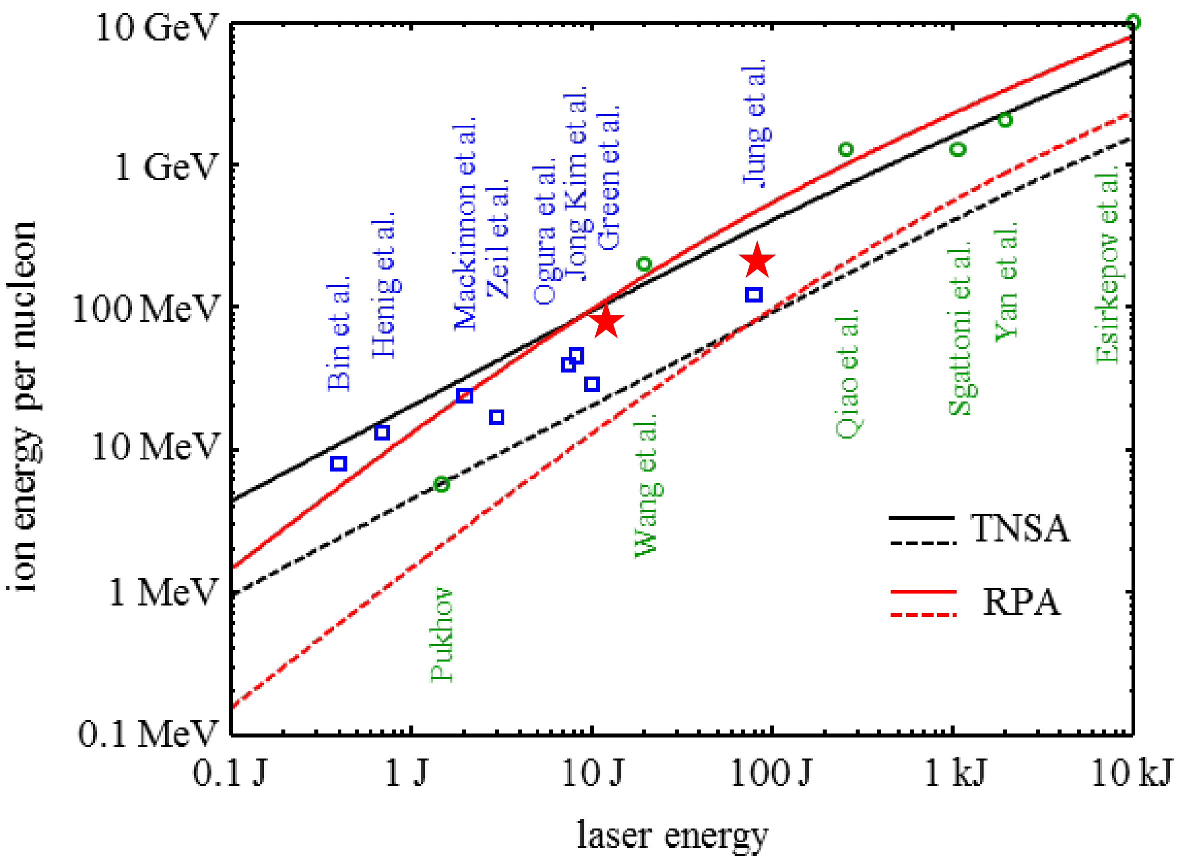


"**Laser-based high-energy proton/ion sources** hold promise for a cost-effective approach to implementing particle cancer therapy. Irradiation of nanometer-thin diamond-like carbon (DLC) foils with ultrahigh-contrast multi-terawatt lasers results in highly enhanced proton yields and promise scalability to the energy range relevant for cancer treatment. **We pursue the development of such a source and explore its suitability for future clinical applications.**"

Perfectly controlled
Mono-energetic
Protons with 200 MeV and
Carbon ions with 400MeV/u

Ion energy frontier

Latest records:
LANL, US: 160 MeV protons (80J/550fs), ~shot/hour
GIST Korea 80 MeV protons (~10J/30fs), ~shot/min



2 µm focus

20 µm focus

RPA: many ions, possibly mono-energetic

TNSA: few ions, exponential spectra

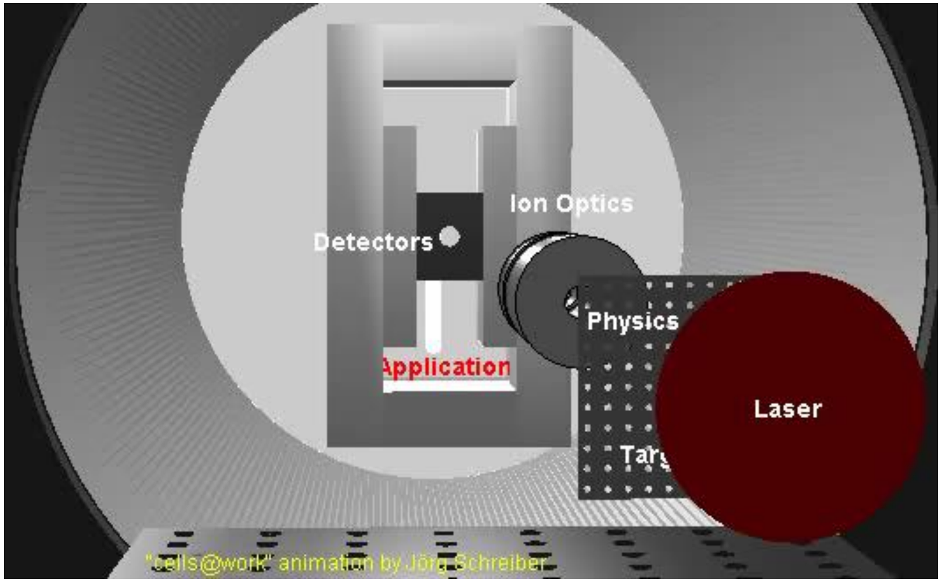
JS, *et al.*, High Power Laser Science and Eng. 2, e41 (2014)

Laser-ion accelerators require adapted technology and application

1. Particle source: Laser+Target (the Gun)

- 10’s -100 nC in <psec, ~ 10 MeV/µm, 1-100 MeV/u, few to >100 % energy spread, 1-10’s degrees divergence, ~10^{-3} mm mrad emittance

Variety of approaches:
Gas/Cluster-targets,
micrometer foils, nano-foils, Nano-foams, solid/liquid-hydrogen, …



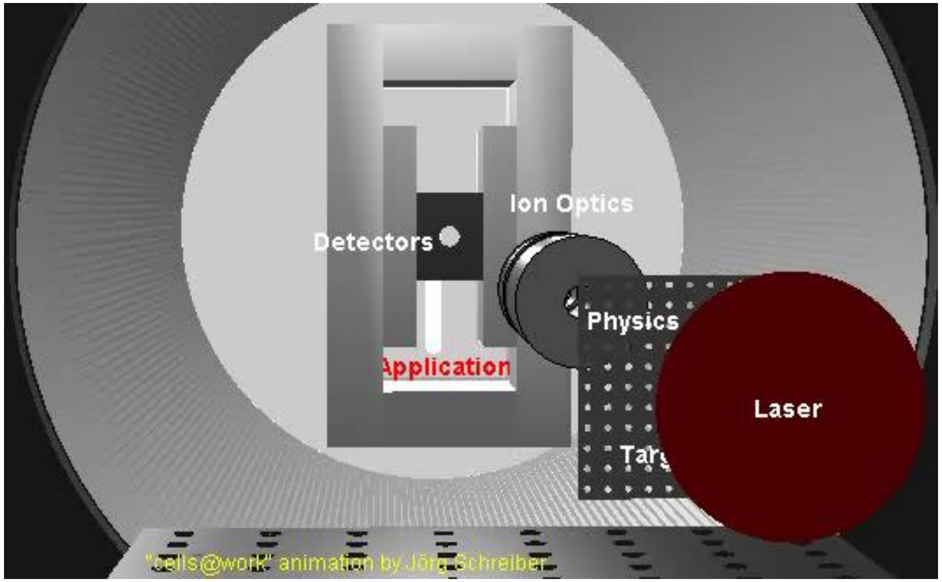
Autumn 2013

Paul Bolton @ LMU (DAAD)

Spring 2015

Autumn 2016

Laser-ion accelerators require adapted technology and application



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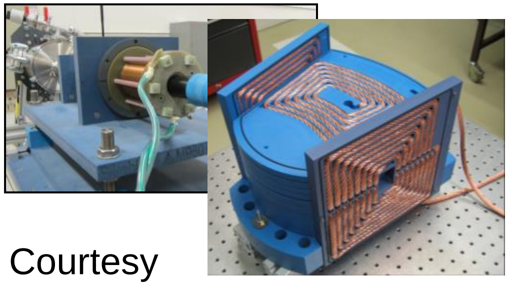
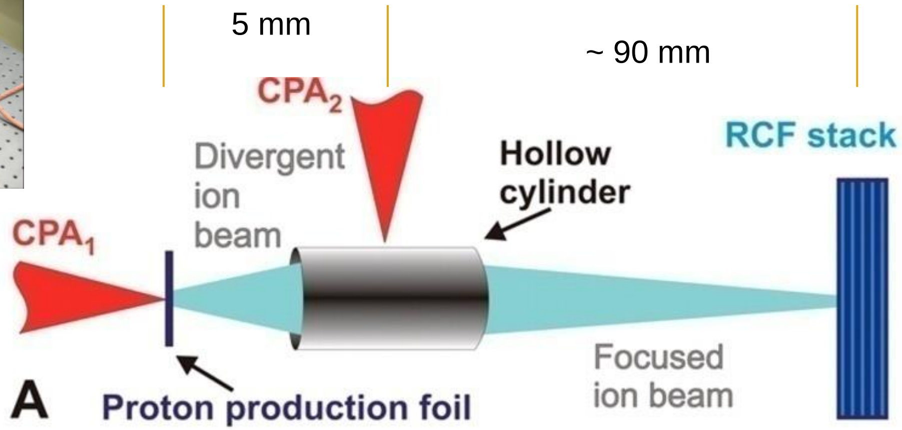
2. Particle-optics

- Compact (pulsed) magnets
- plasma-lenses, …

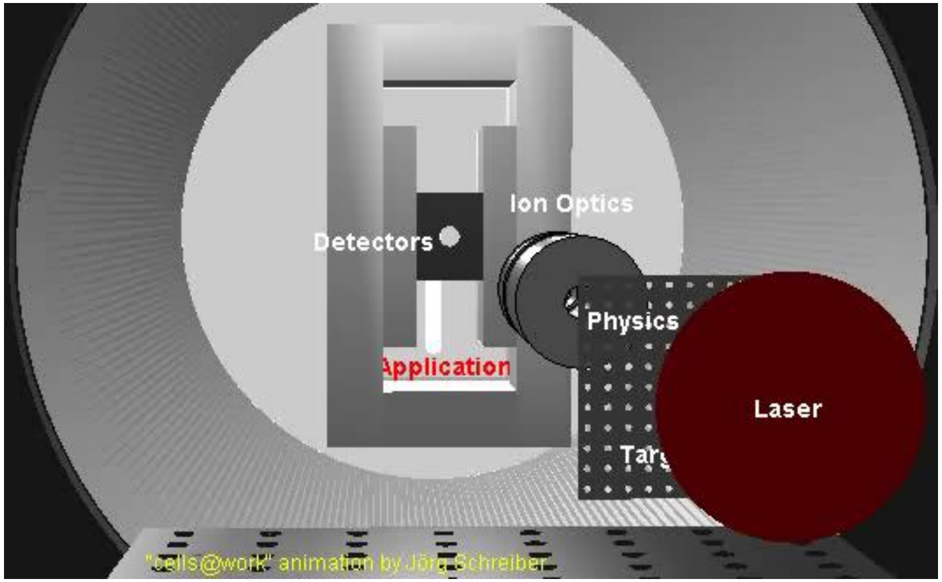


Courtesy
U. Schramm, HZDR



Toncian *et al.*, Science **312** [5772], 410 (2006)

Laser-ion accelerators require adapted technology and application



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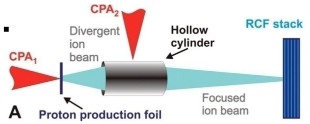


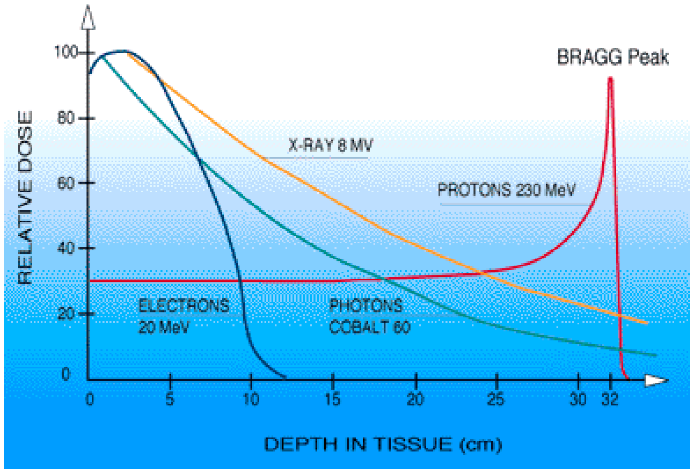
Toncian *et al.*, Science **312** [5772], 410 (2006)

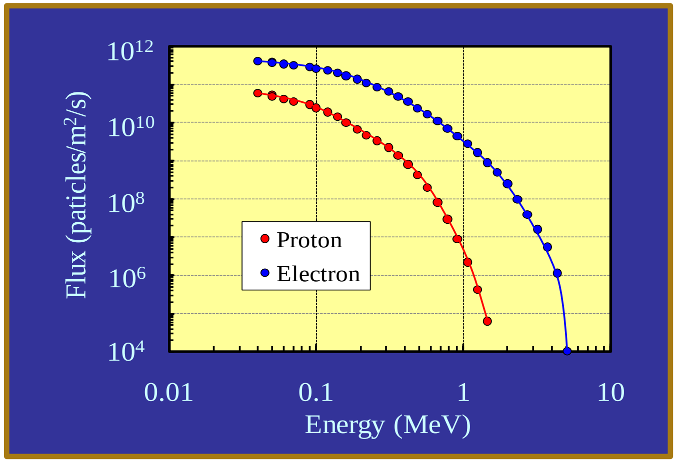
3. Application

- Laser/Ion-energy versus repetition rate/single shot
- broad energy distribution – can be beneficial
- Temporal/spatial structure and synchronism between very different types of radiation – pump-probe studies

Applications can require a broad range of (ion) energies

energies relevant to **'L-IBRT'** (liberty) (laser-driven ion beam radiotherapy) - ~ 100 - 250 MeV



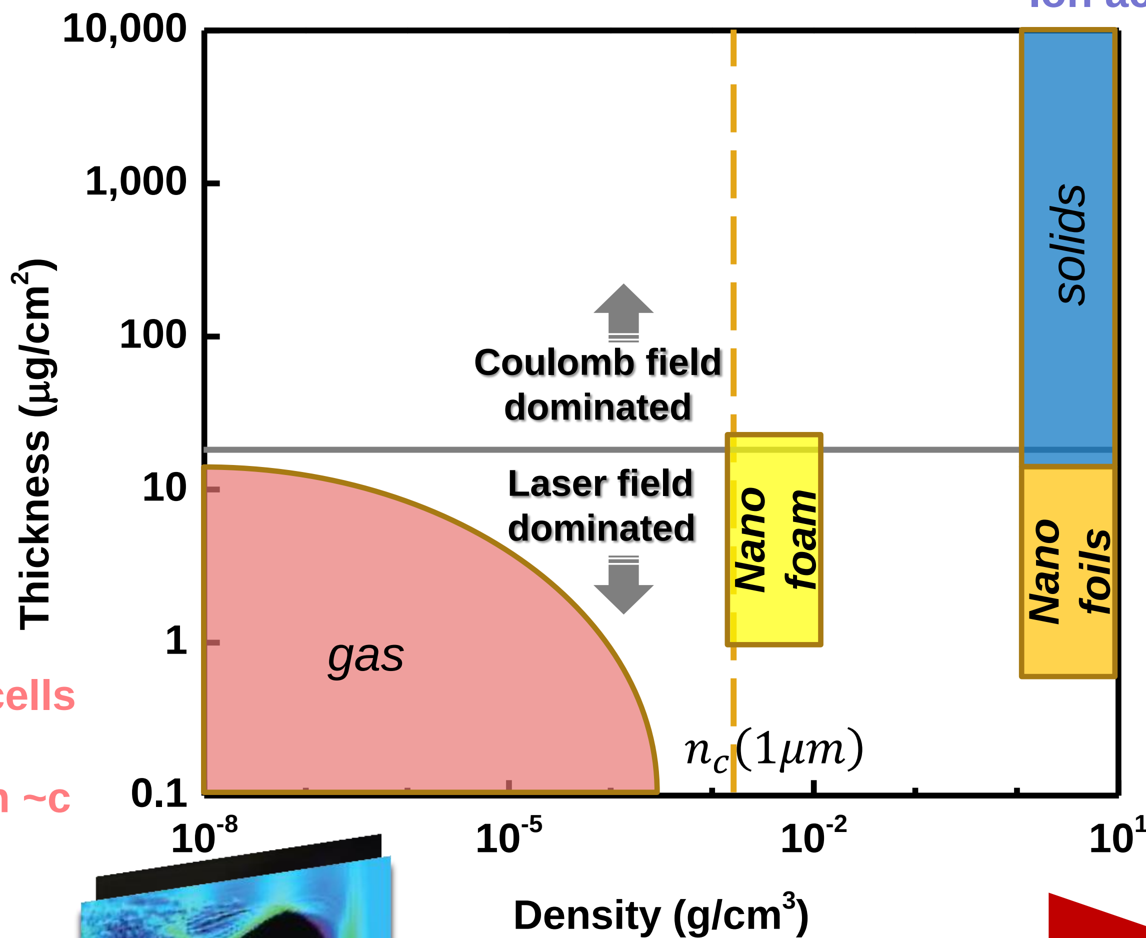


energies relevant to orbiting space environment - ~ 0.1 to 10's MeV

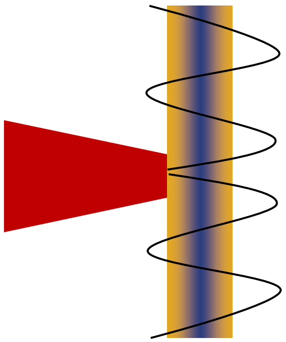
courtesy M. Imaizumi, JAXA (Japan Aerospace Exploration Agency), P. Bolton

Awareness for „Applications of laser-plasma accelerators (ALPA)" K. Parodi, P. Bolton, JS – Symposium Nov 2015

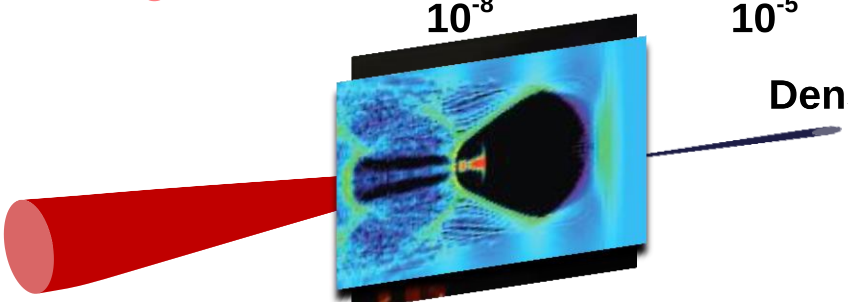
Parameter-space for laser-driven particle sources



Ion acceleration (TNSA)
µm-foils
10s MeV/µm
stationary



Electron acceleration
cm gas-jets/cells
~GeV/cm
traveling with ~c



Radiation Pressure Acceleration & related schemes

Radiation Pressure Acceleration

… or Maxwell-Bartoli pressure, „ponderomotive forces“

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

JFL Simmons et al, Am J Phys 1993 (Marx Nat 1966)

fu 5x10^{13}km=300,000 AU (Proxima Centauri) red 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

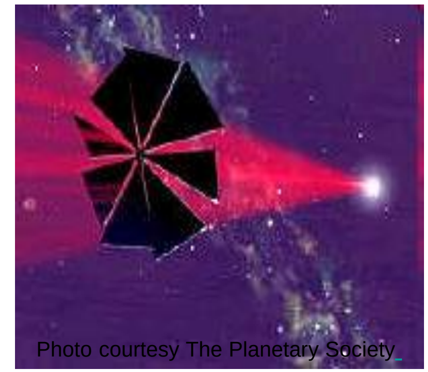
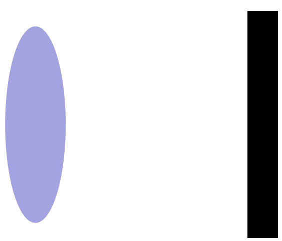


Photo courtesy The Planetary Society



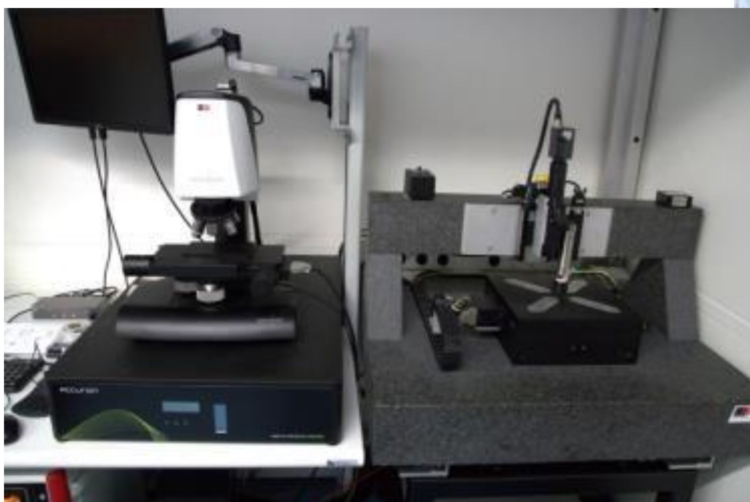
$$\frac{v}{c} \sim \frac{E_L}{Mc^2}$$

Carbon disc with 1 μm diameter and 5 nm thickness (10^{-17}kg, Mc^2=1J)

Rayleigh-Length ~ 2 μm (20 fs)
Intensity ~ 5x10^{21}W/cm^2

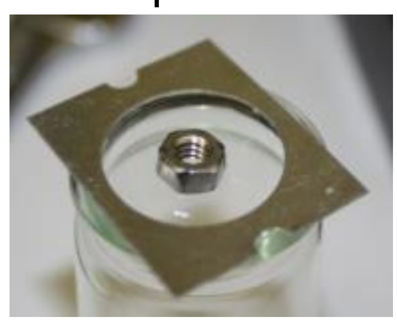
LMU target fabrication – controlled production & characterisation

Atomic force, confocal, white-light interferometric microscopy

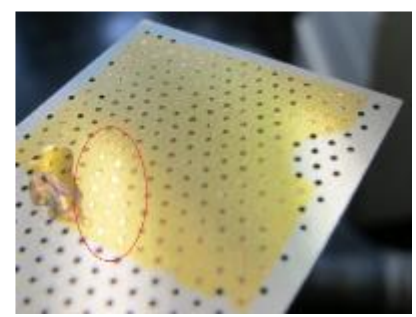


3-50 nm DLC foils

10nm-3µm Formvar



5 nm Gold



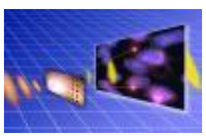
The added value of ultra-thin nanotargets

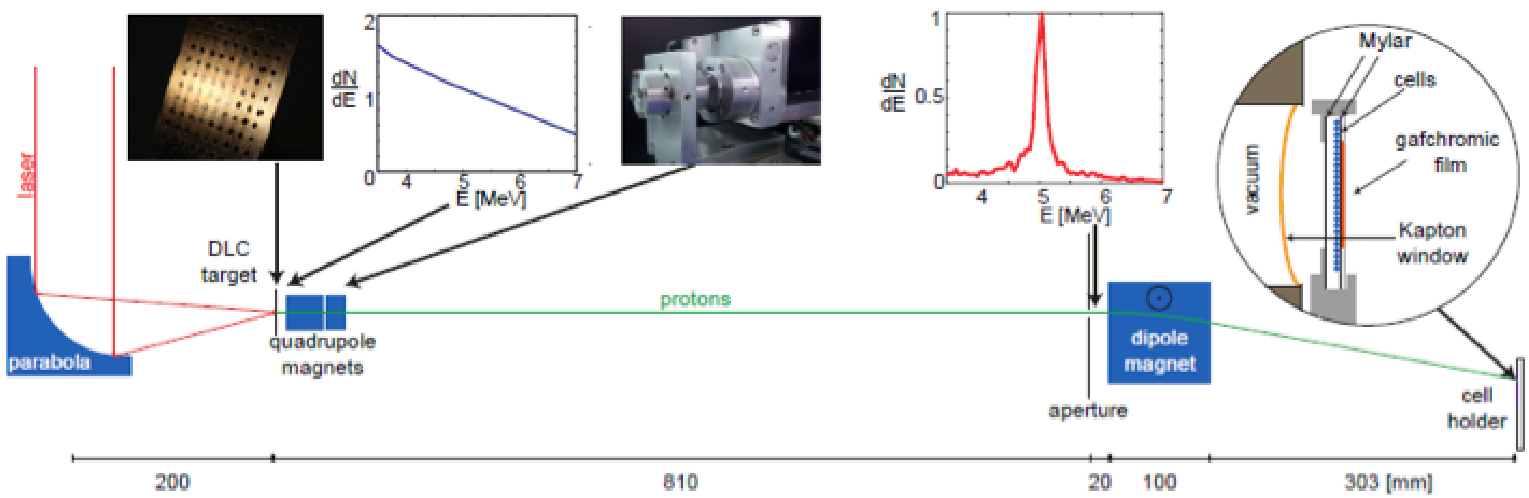
- 2° instead of 10-20° divergence: 100x higher ion flux
- Higher conversion efficiency as we proceed to higher energies
- Less background radiation (X/Gamma-rays)
- Efficient acceleration of heavy ions (C, Al, Au, …)

… one example

Cell-experiment with single proton bunches: 2 Gy in 1 ns

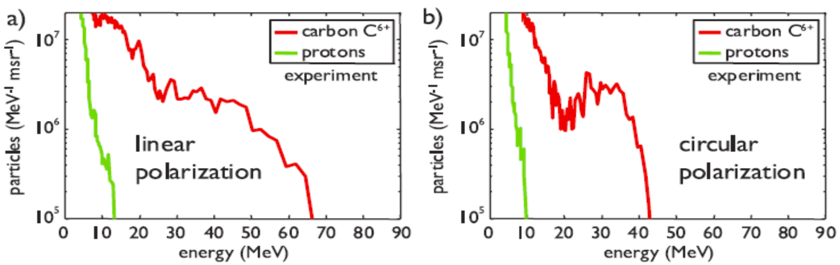
J. Bin, JS, *et al.*, Appl. Phys. Lett. 101, 243701 (2012); J. Bin, JS, *et al.*, Phys. Plasmas 20, 073113 (2013)



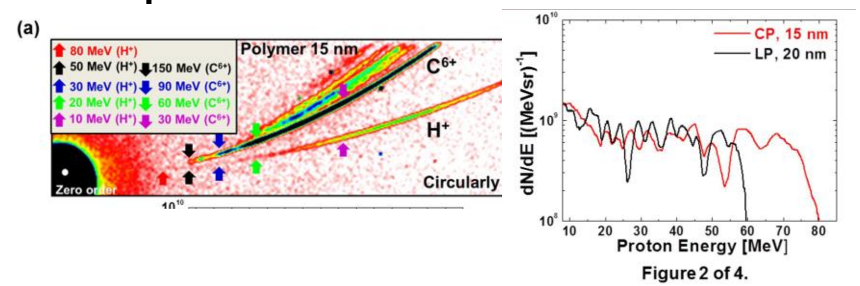


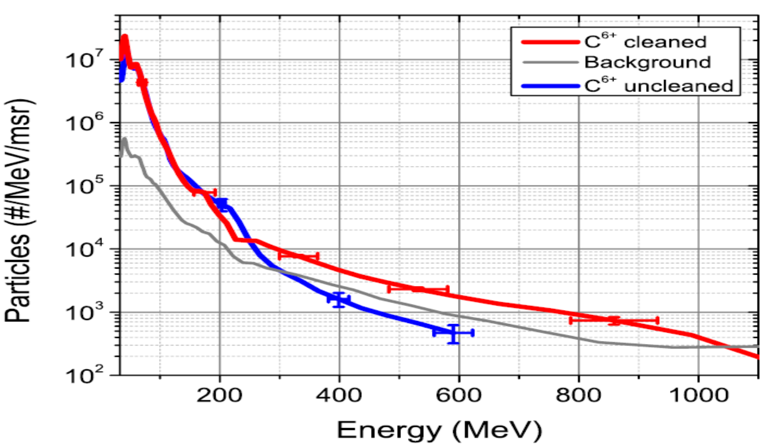
Prominent experimental results with nanometer thin targets

A. Henig, JS, et al., Phys Rev. Lett. 103, 245003 (2009):
1st experimental demonstration of RPA

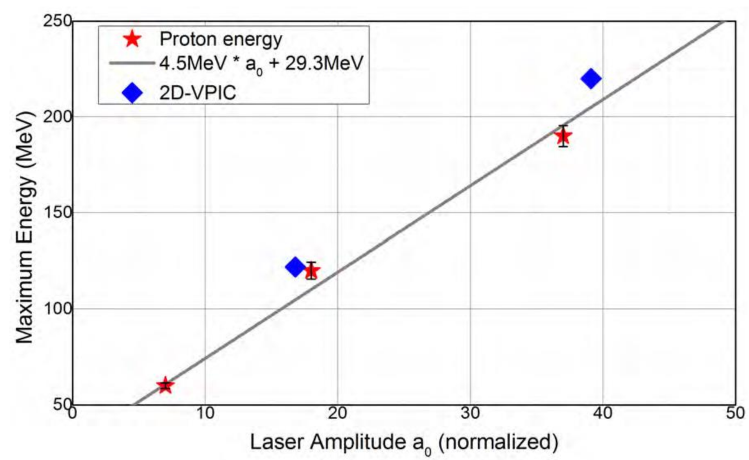


I.J. Kim, *et al.*, arXiv: 1411.5734 (2014)
30J/30fs, 10s nm targets
RPA protons to 80 MeV



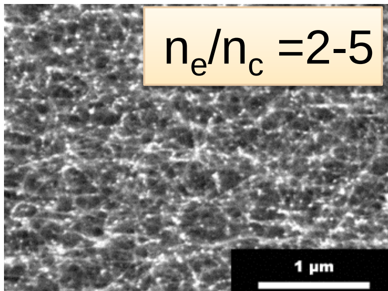


D. Jung, JS, *et al.*, Phys. Plasmas **20**, 083103 (2013):
80J, 550fs, 100-200 nm DLC
record carbon energy > 1 GeV

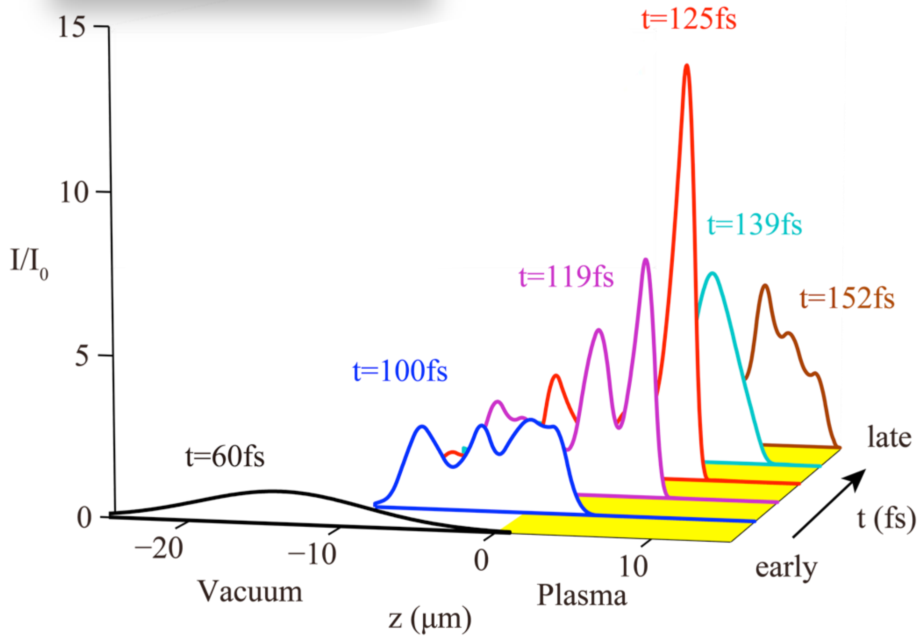


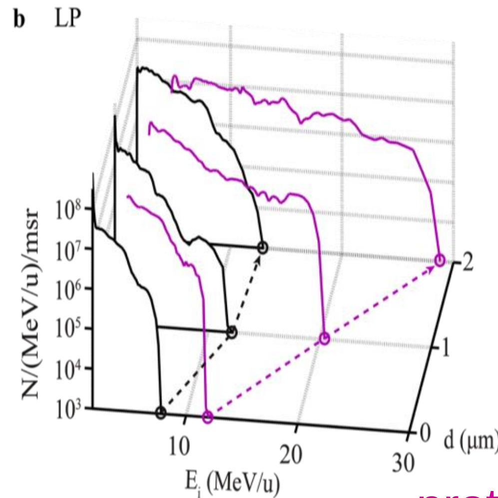
M. Hegelich, *et al.*, arXiv:1310.8650 (2014)
80J, 550fs, 200-300 nm CH_2 nano-targets
~ 5×10^5 protons/(MeV·msr) @ 160 MeV

Relativistic self-focusing for ion acceleration (Astra-Gemini, UK)

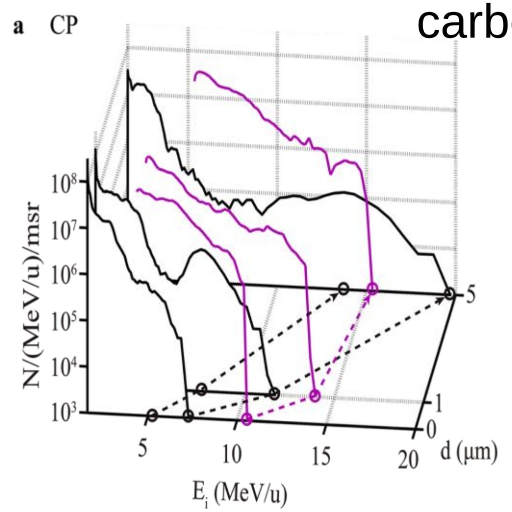


Combination of Carbon-Nano-Tube (CNT) foam with Diamond-like Carbon (DLC) foils





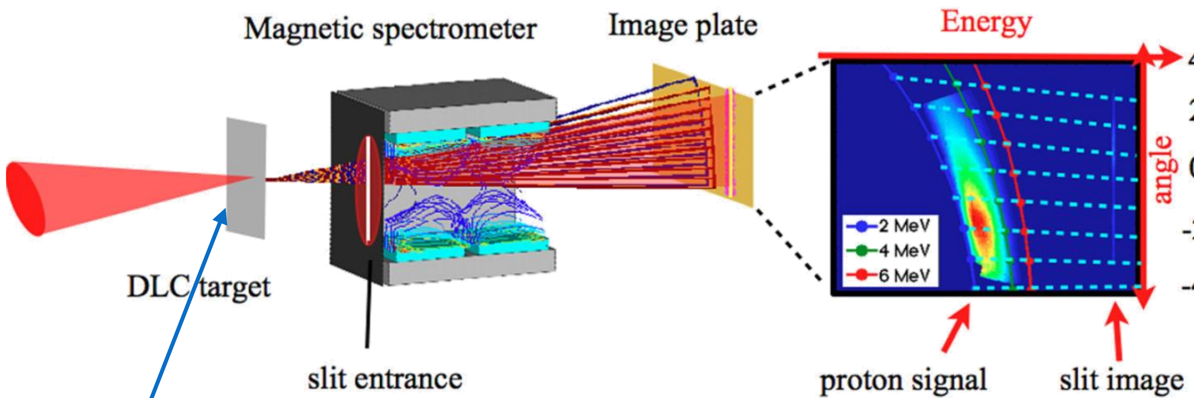
protons
carbons

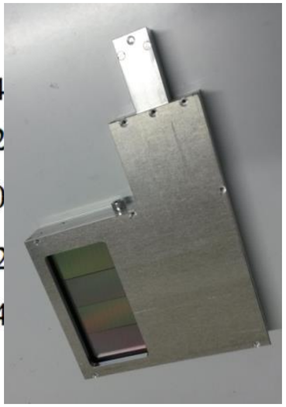


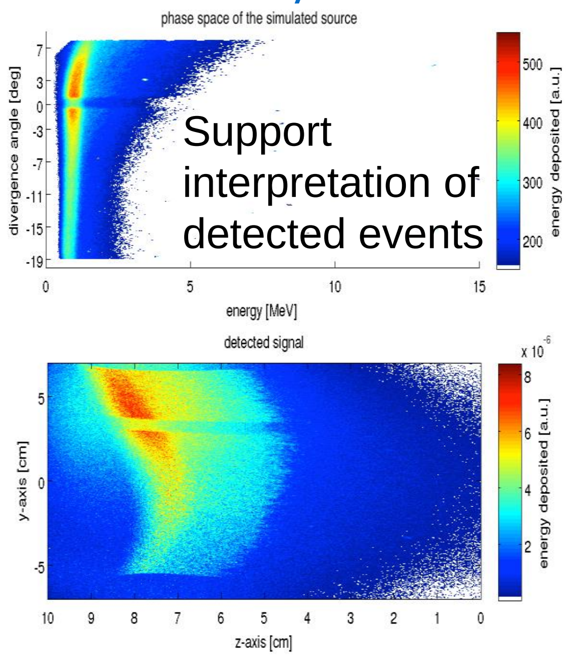
Meanwhile also demonstrated on other laser systems (Jena, Gwangju)

J. Bin, JS, *et al.*, submitted

Monte-Carlo modelling: towards online monitoring (and optimisation …)





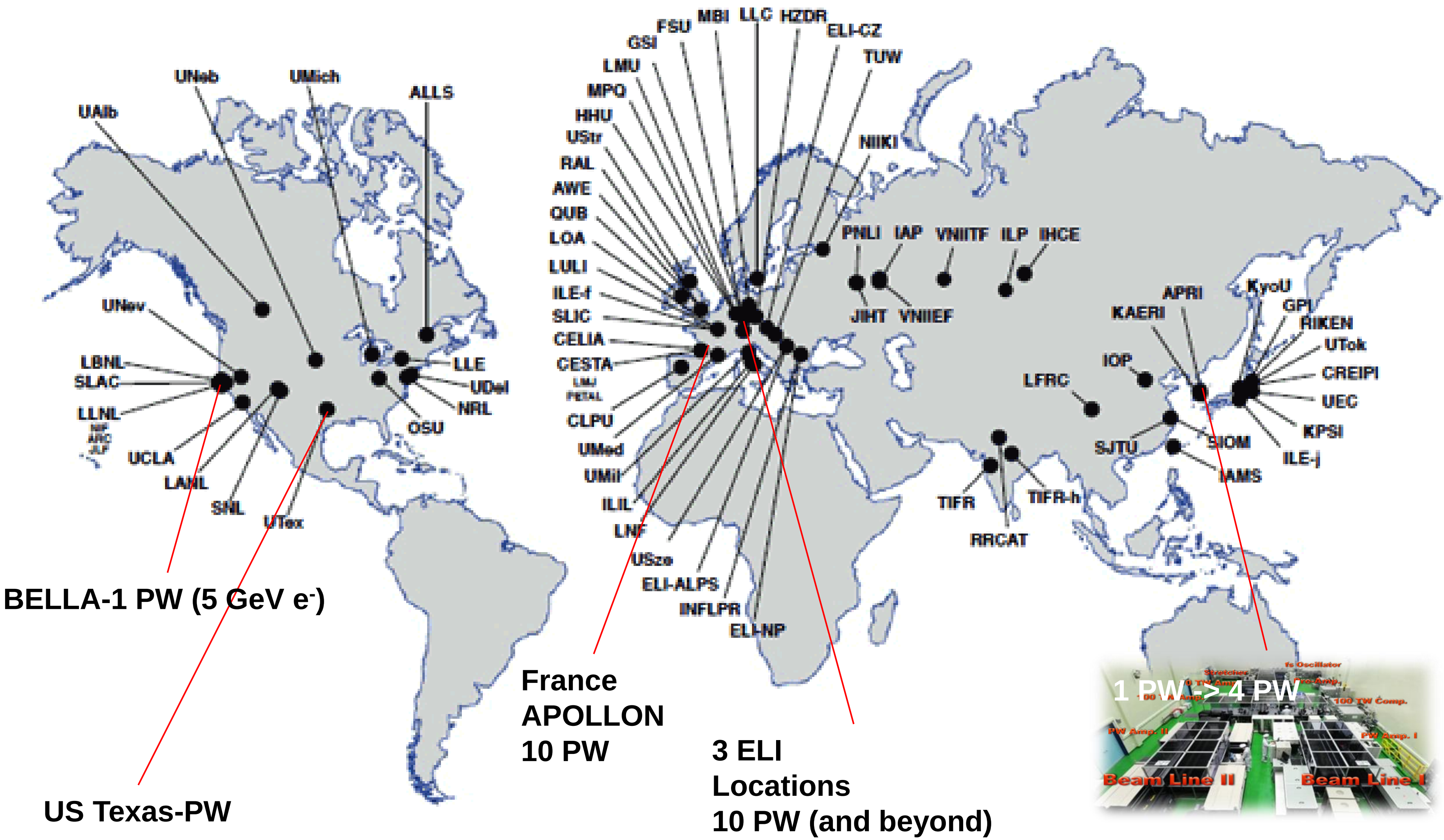


Support interpretation of detected events

Monte Carlo simulations (Deddes, Parodi)

(Reinhardt, Parodi)

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

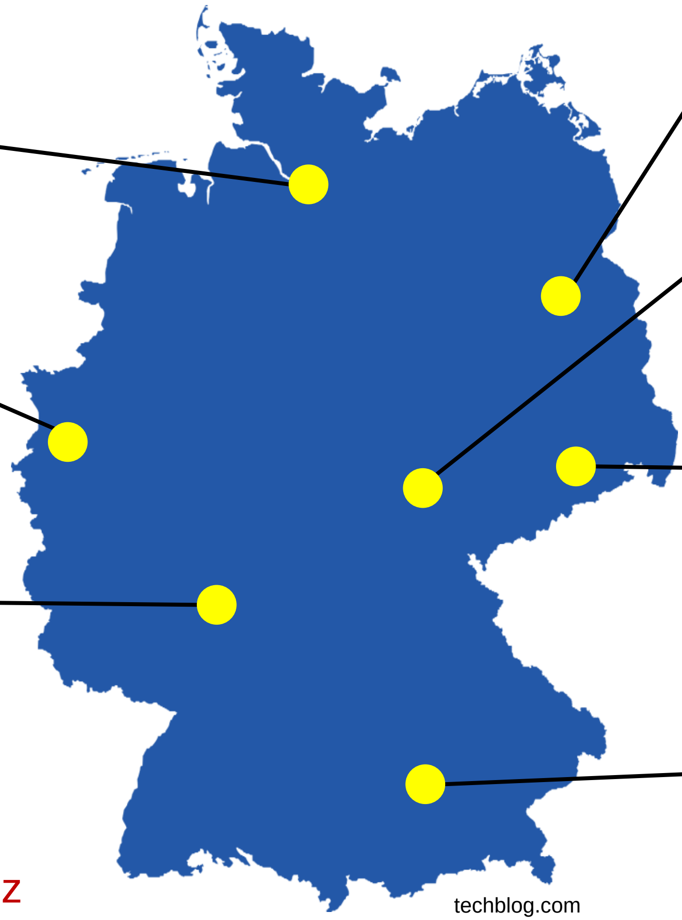


The Germany of TW- and PW-lasers

DESY
200 TW
(+1PW)

HHUD
200 TW
Dual beam

GSI
PHELIX 1 PW



MBI
100 TW
Dual beam

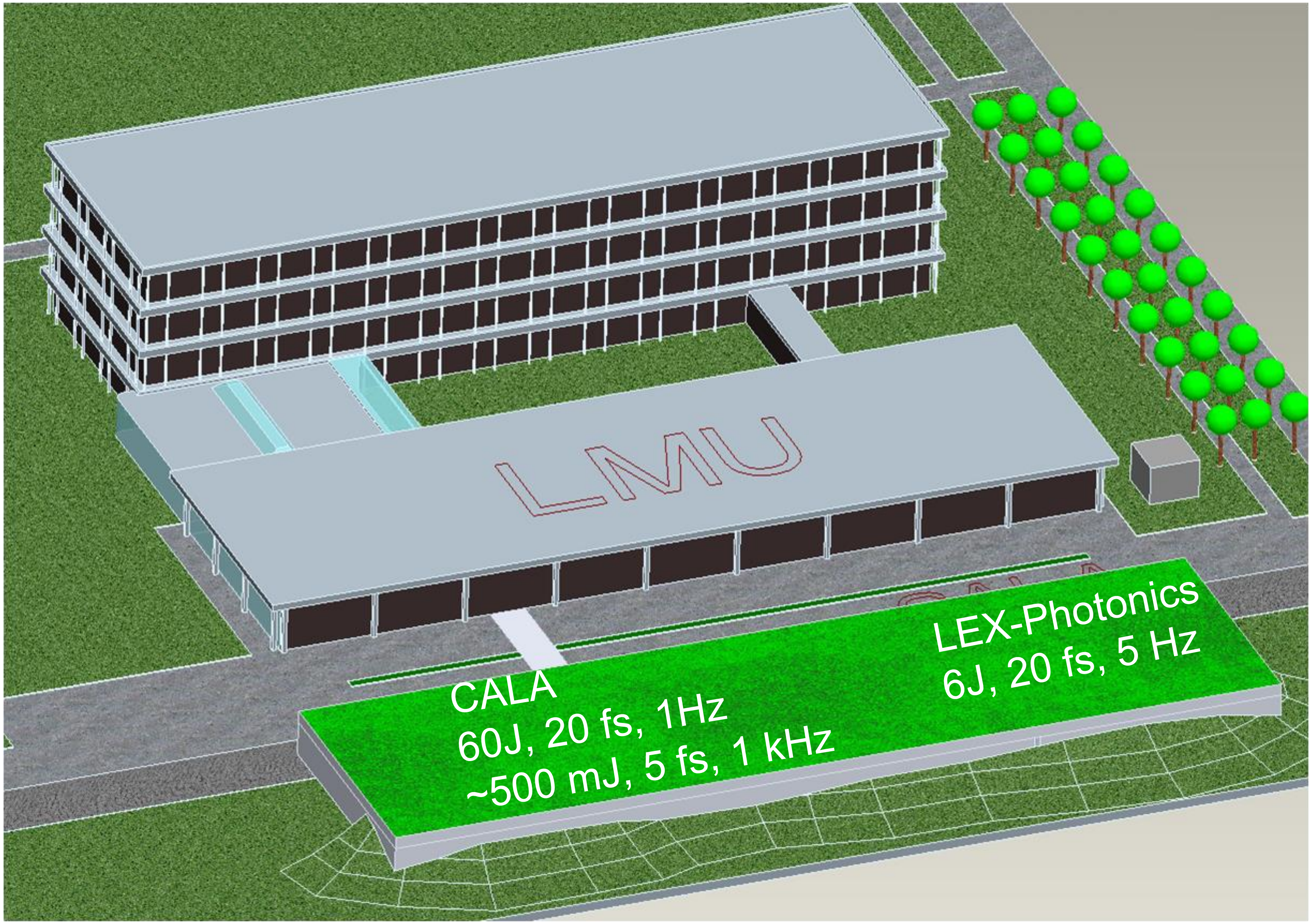
FSU/HIJ
POLARIS 100 TW
JETI 100 TW

HZDR
Ti:Sa 1 PW
PENELOPE 1 PW

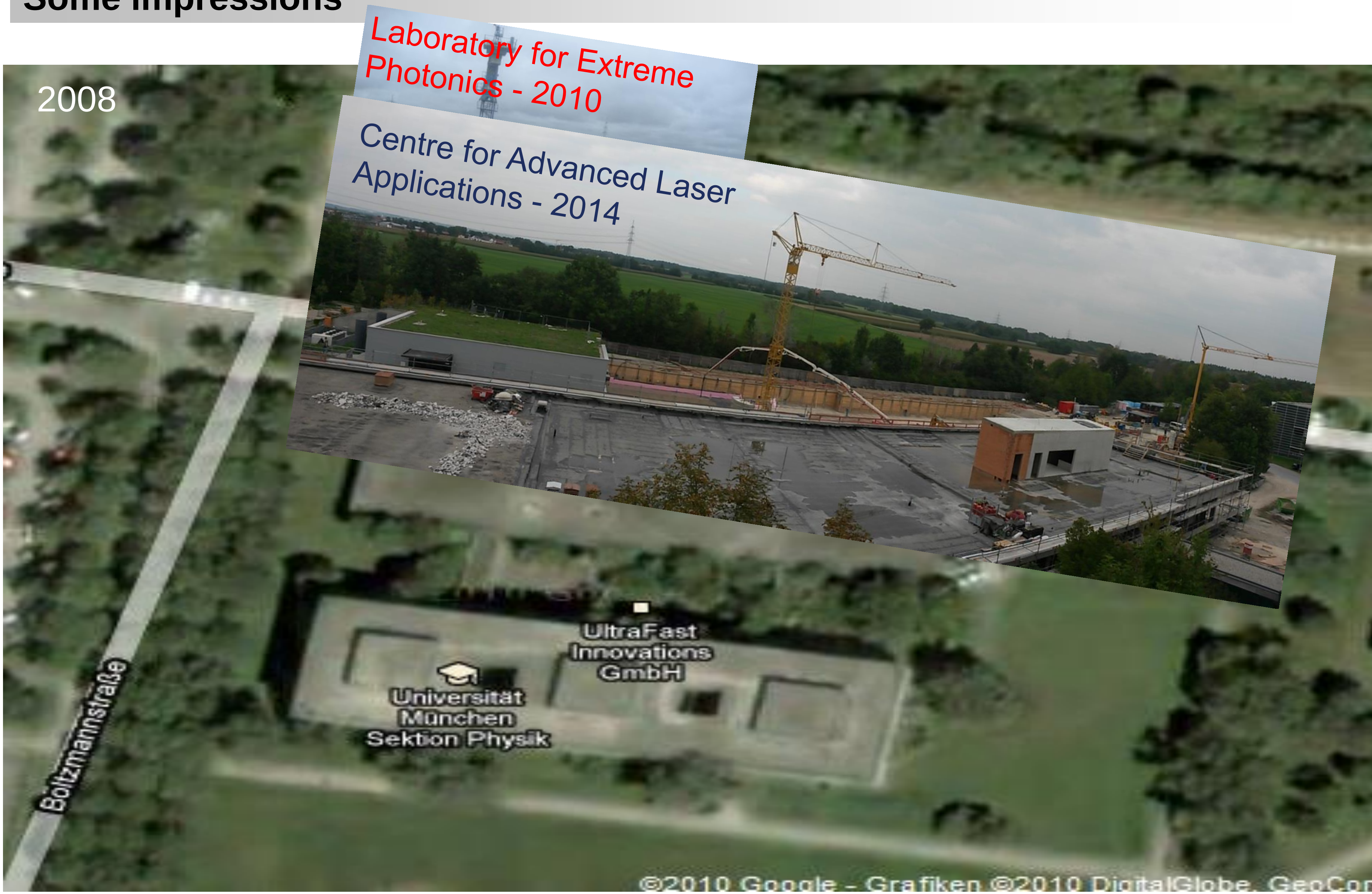
„Centre for Advanced Laser Applications (CALA)"
ATLAS 300TW+3PW
PFS(pro) 100 TW

Conventional Ti:Sa, 25 fs, ~Hz
Diode pumped Glass, 150 fs, ~Hz, high wall-plug efficiency
Conventional Glass, 500fs, ~shot/h
OPCPA, 5 fs, 10Hz~kHz

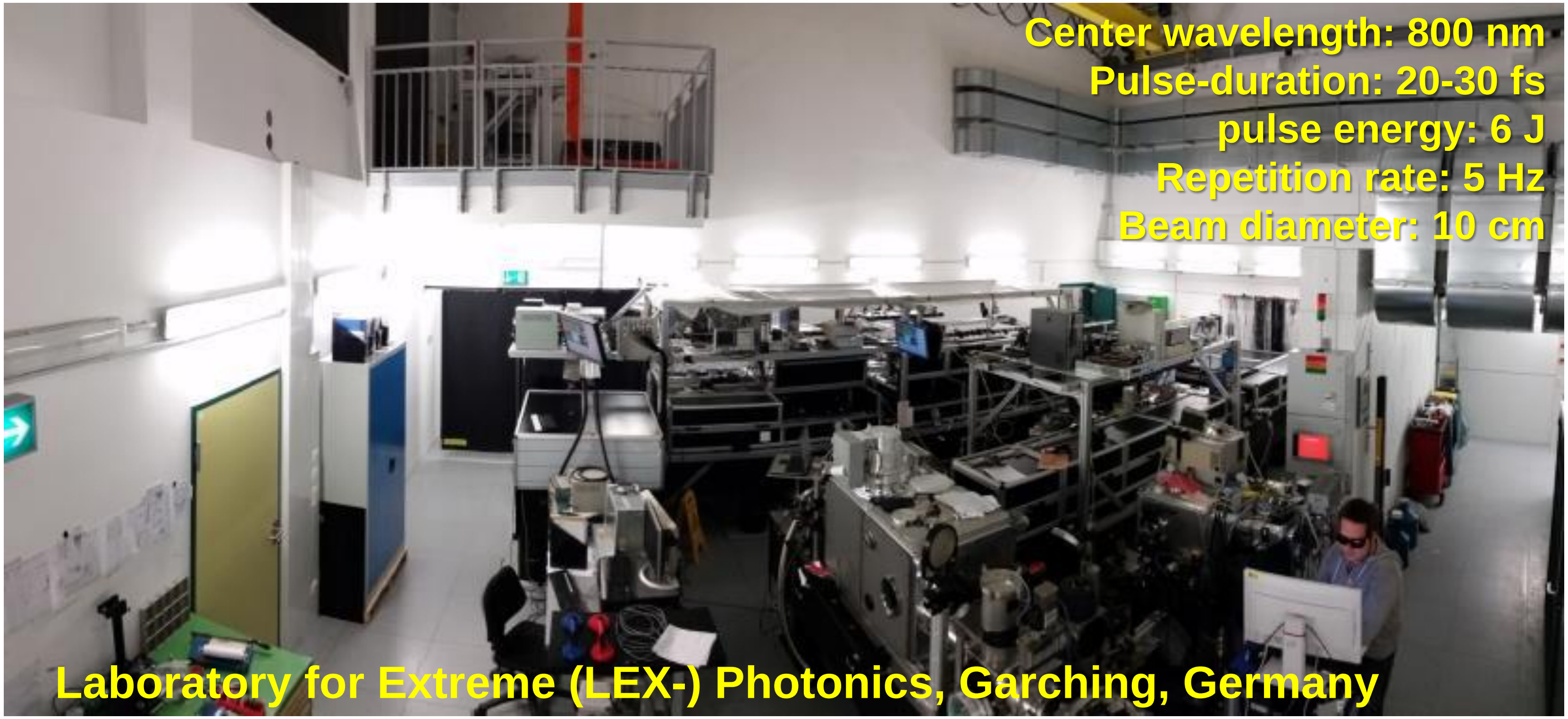
Centre for Advanced Laser Applications (and LEX-Photonics)



Some impressions



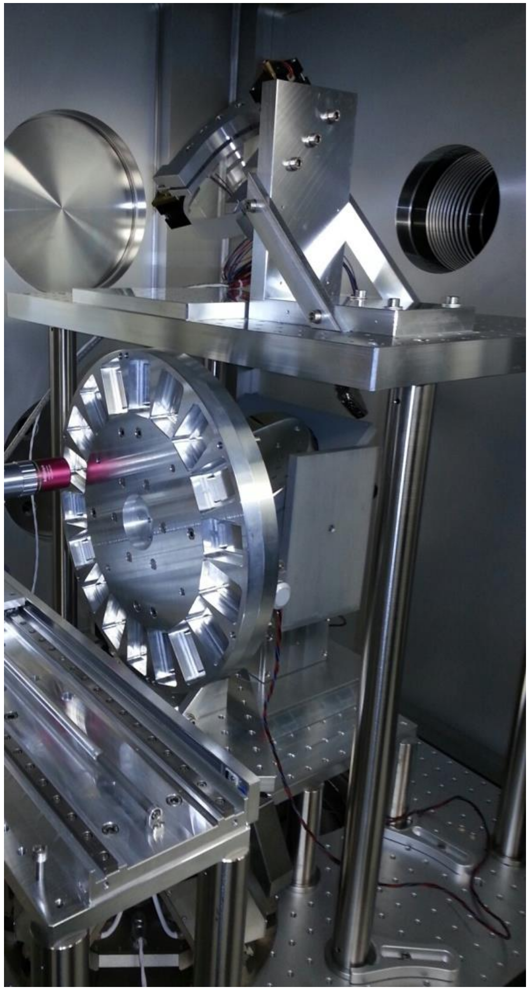
High-power Chirped Pulse Amplification (CPA) laser system ATLAS 300 TW



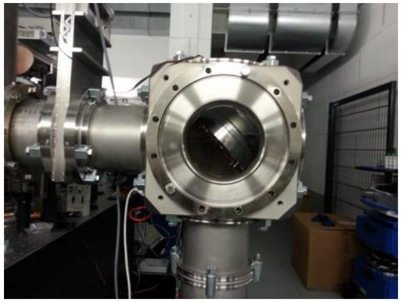
Laser-ION (LION) target chamber: Prototype

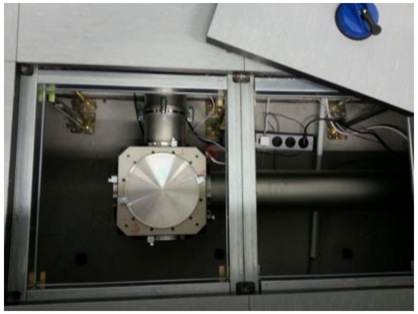
Target chamber (prototype for CALA)

Ion source: ready to rep-rate

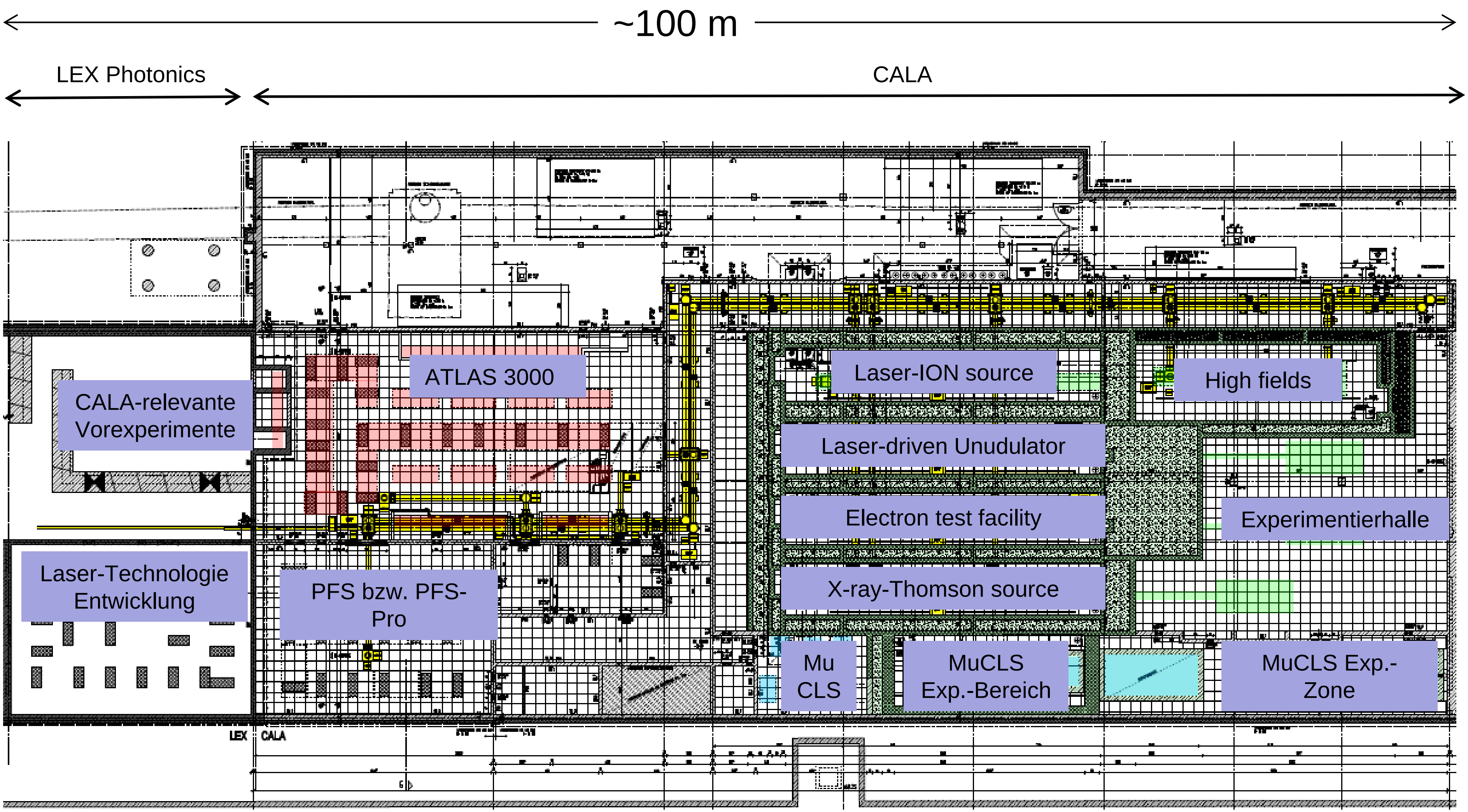


Laser-Beam Delivery



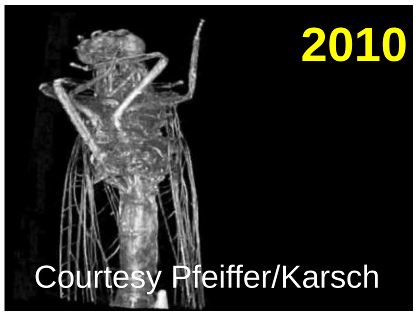


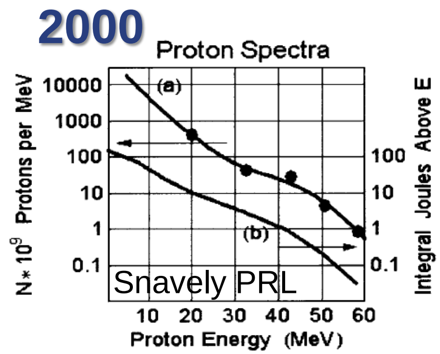
CALA-Layout


~100 m
LEX Photonics
CALA
ATLAS 3000
CALA-relevante Vorexperimente
Laser-ION source
High fields
Laser-driven Unudulator
Electron test facility
Experimentierhalle
Laser-Technologie Entwicklung
PFS bzw. PFS-Pro
X-ray-Thomson source
Mu CLS
MuCLS Exp.-Bereich
MuCLS Exp.-Zone
LEX
CALA

Remarks and motivation for discussion on technological challenges

I (We) have witnessed astonishing progress of laser-driven particle accelerators over the past 20 years (lasers, stability, control, compactification)



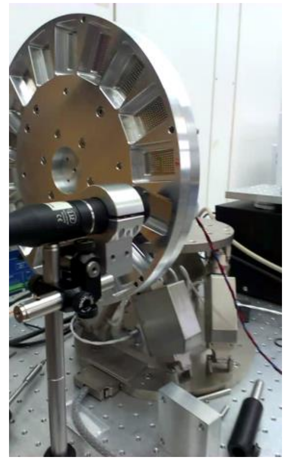


Exploiting laser-based accelerators for medicine remains the grand goal, utilizing the benefit of laser-driven will be mandatory. We think of complementary (experimental) approaches in other scientific fields – international Symposium on Applications of Laser-particle Accelerators, Nov. 2015 Venice)

Realising (and establishing) large-scale facilities such as the Centre for Advanced Laser Applications, the Extreme-Light-Infrastructure, … is an incredible opportunity (and responsibility), AND TECHNOLOGICAL CHALLENGE.

Technological challenges – short/mid-term

Target
Gas-targets and µm-foils „easy“, nano-targets not yet, production, positioning, damage

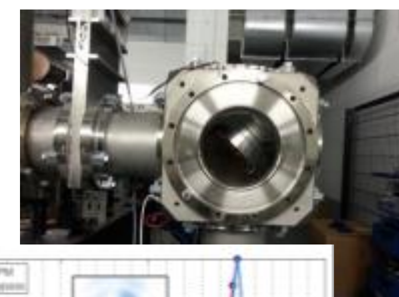


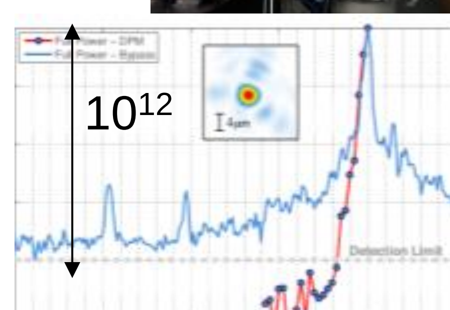
Before shot

after shot

Laser (table-top, but we‘ve got large tables)

- damage threshold of optics limits: 25 cm beam diameter for 3 PW, in principle: fused silica LIDT 10^{14} W/cm² -> 6 cm beam would be possible!
- Temporal contrast, essential for nano-targets, current solutions are destructive (Plasma-mirrors)





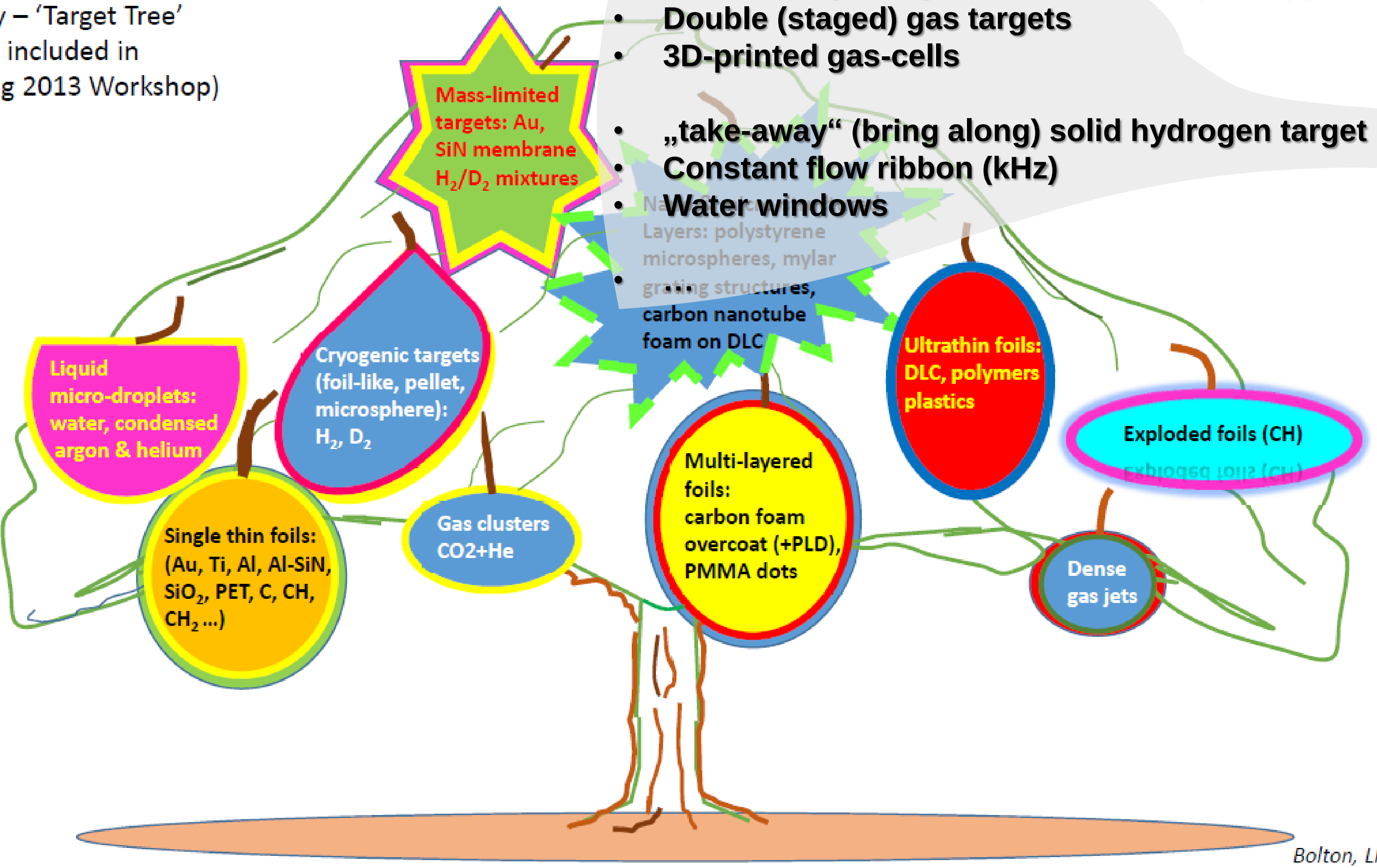
The ‚Target Tree‘ as of the 1st workshop in 2013

New topics/approaches

- **Gas-flow tayloring**
- **Double (staged) gas targets**
- **3D-printed gas-cells**

- **„take-away“ (bring along) solid hydrogen target**
- **Constant flow ribbon (kHz)**
- **Water windows**
- **….**

Targetry – ‘Target Tree’
(targets included in
Garching 2013 Workshop)



Bolton, LMU 2015