Laser-driven Ion Acceleration

Jörg Schreiber

Ludwig-Maximilians-Universität München
Max Planck Institut für Quantenoptik

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DFG Transregio 18
Euratom

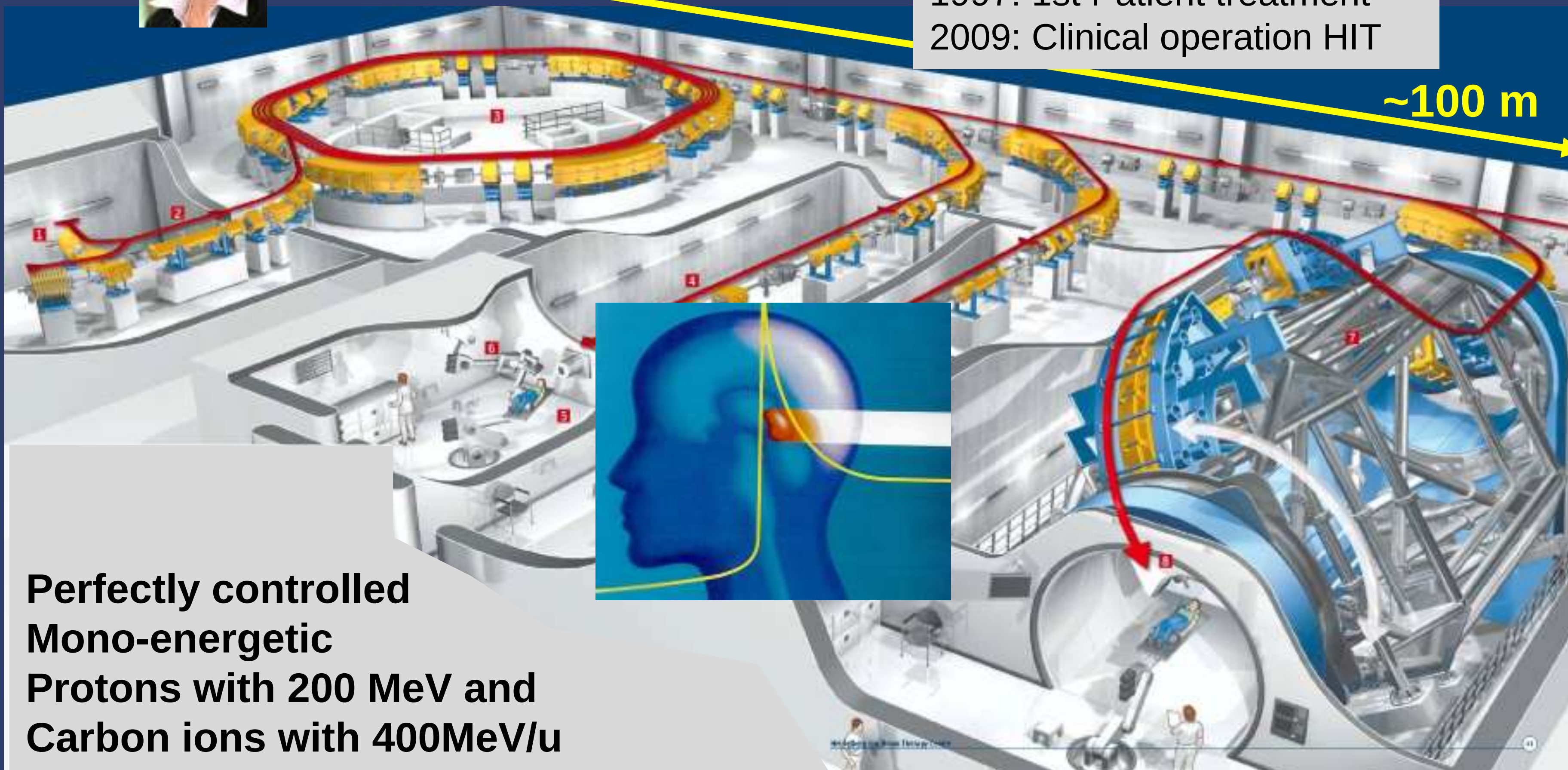
"Laser-based high-energy proton/ion sources hold promise for a cost-effective approach to implementing particle cancer therapy. Irradiation of nanometer-thin diamond-like carbon (DLC) foils with ultrahigh-contrast multi-terawatt lasers results in highly enhanced proton yields and promise scalability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

joerg.schreiber@mpq.mpg.de

Heidelberg Ion Therapy (HIT) Centre

Prof. K. Parodi

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



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

10 years ago versus now

Electron Acceleration/Xrays

Many peo ... er-electron

Bub ... hov)

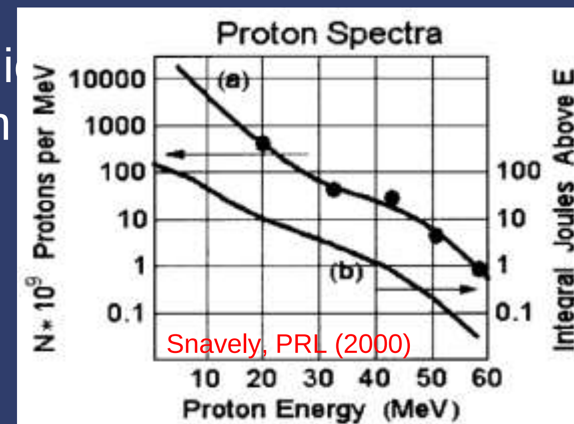
First ... ation

first ... ays)

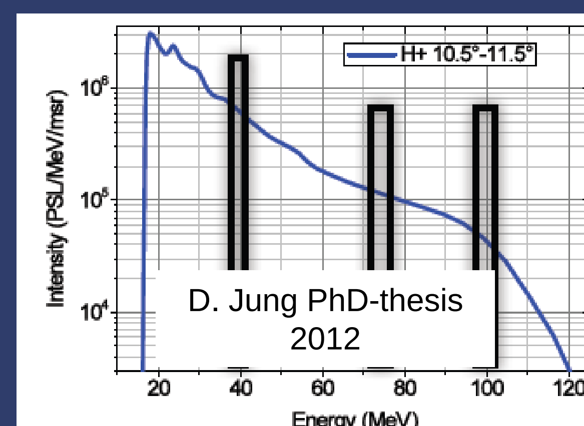

Courtesy S. Karsch/F. Pfeiffer

Ion Acceleration

(Not qui ... udied
laser-ion ... ansion)

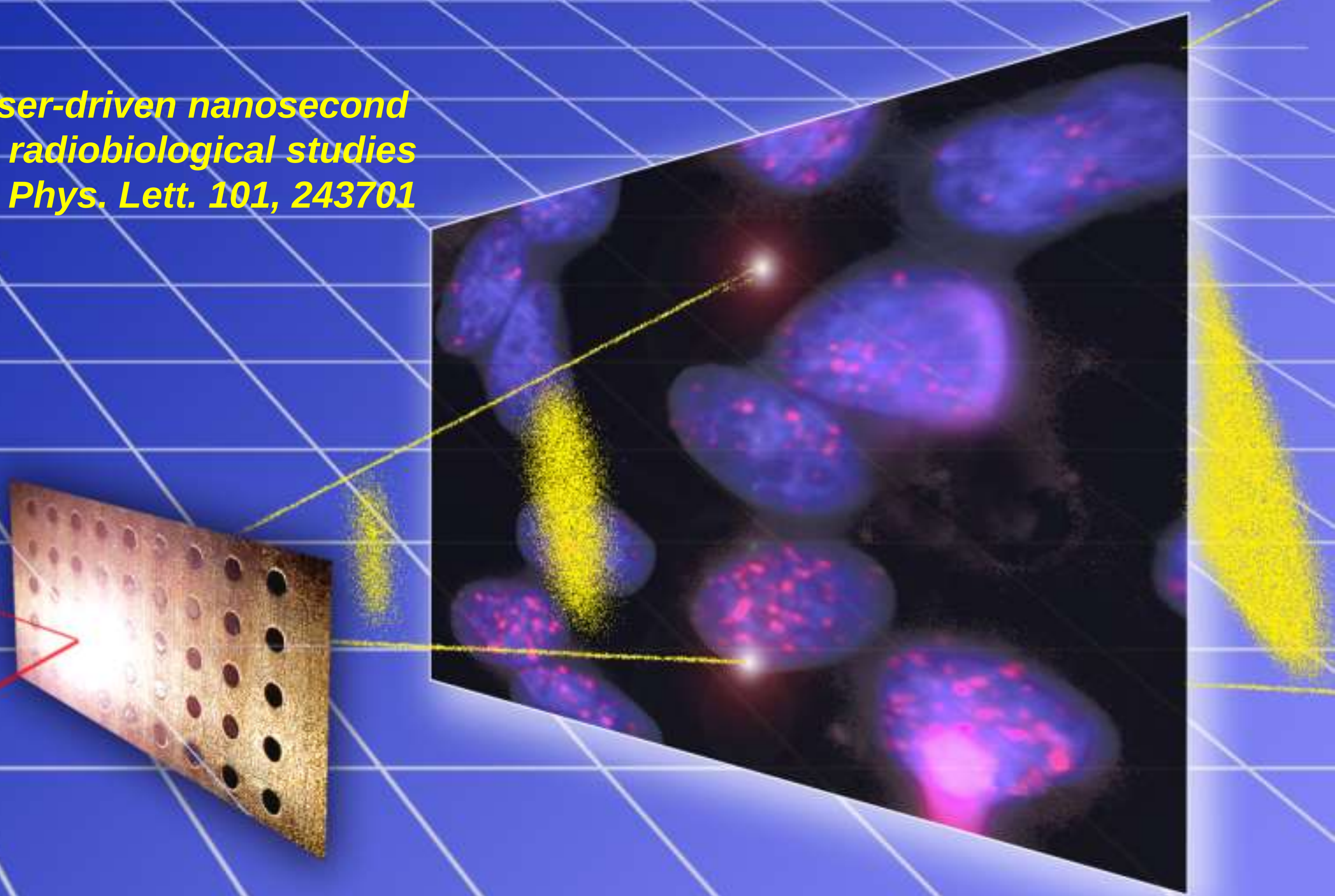


120 MeV protons/1 GeV carbons (2012)



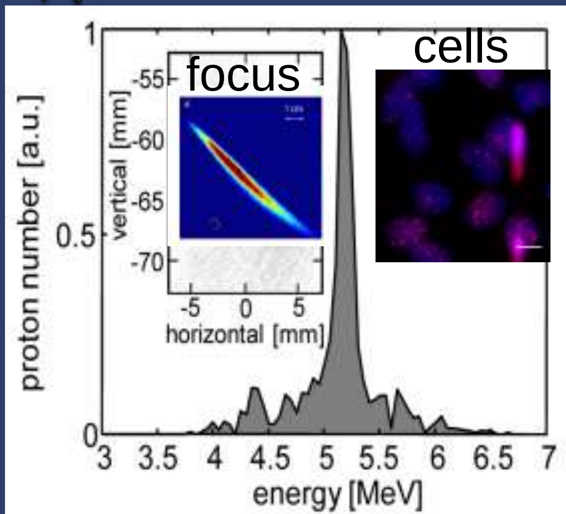
Cell-Experiments with laser-driven ions

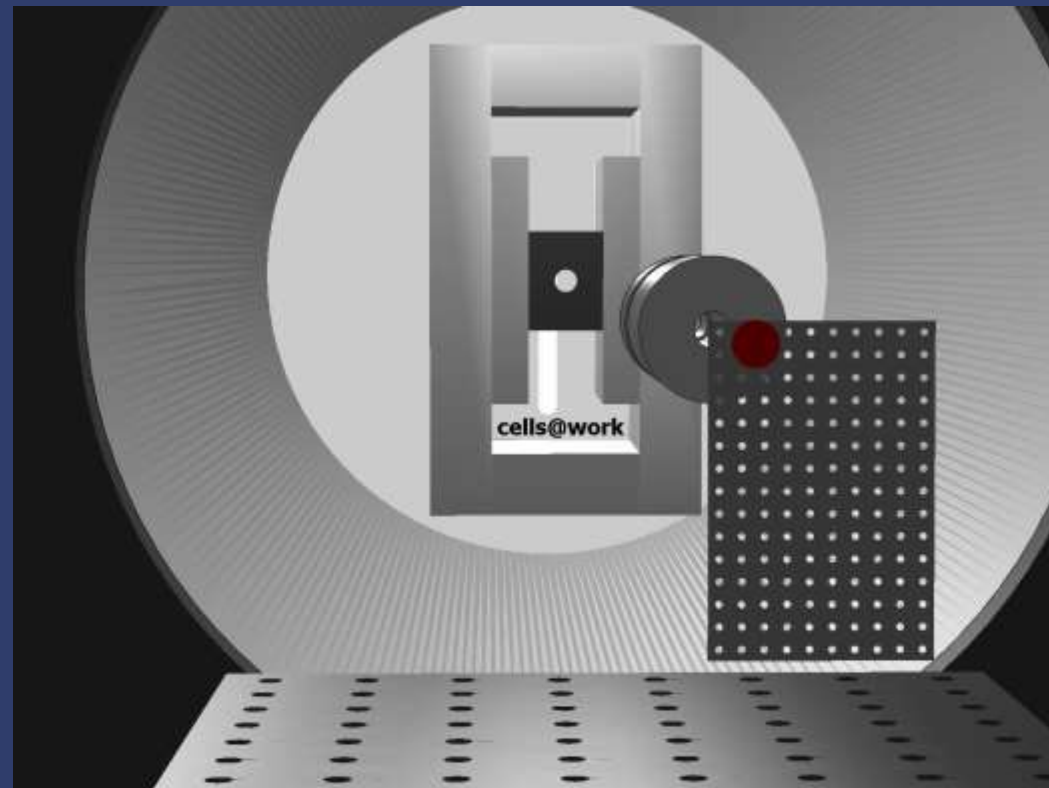
Picture from: A laser-driven nanosecond proton source for radiobiological studies J. Bin et al., Appl. Phys. Lett. 101, 243701 (2012)

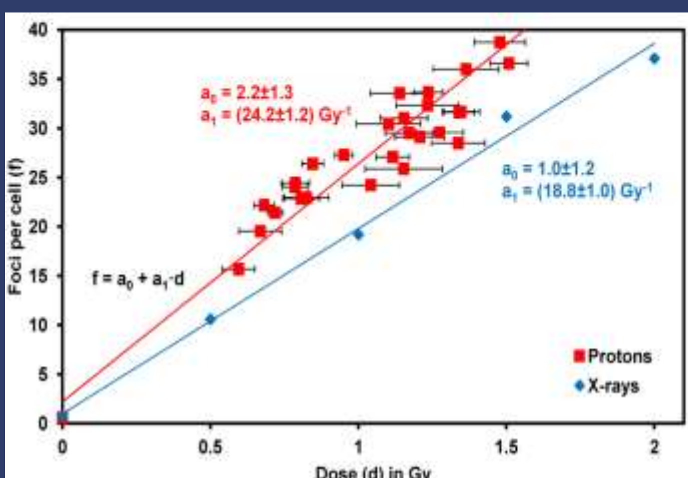


Kyoto (2009), Dresden (2010), Kyoto (2011), Belfast (2012), Garching (2012)

A laser-driven nanosecond proton source for radiobiological studies

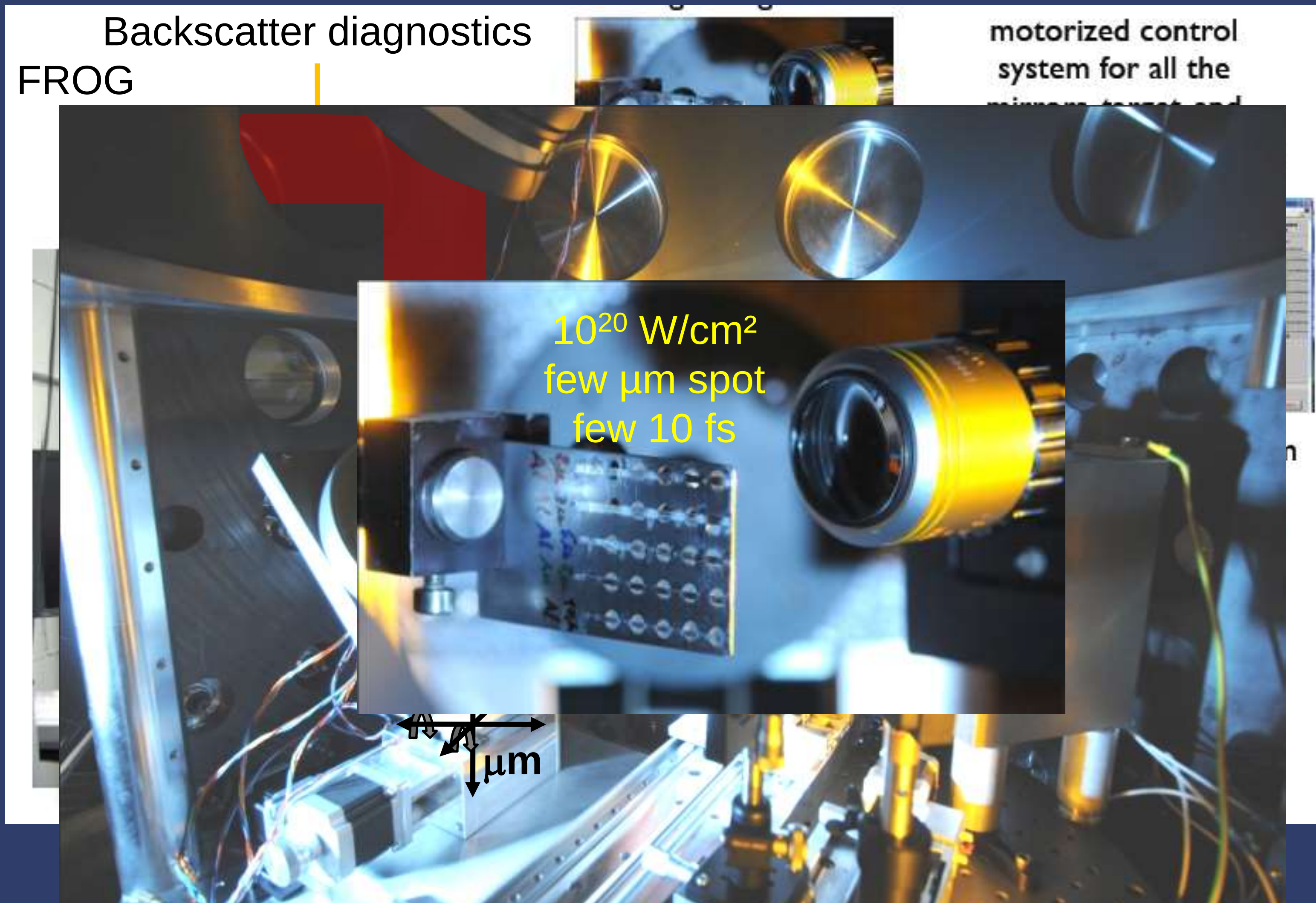






- radiate **2-7 Gy** (“lethal”) dose in **one** single ns pulse
- dose response curve from a single shot
- low laser energy (400 mJ, in principle 10 Hz)
- low background radiation
  - thick foils: few microSv / shot
  - DLC: 1-2 microSv / 50 shot

Typical experimental setup



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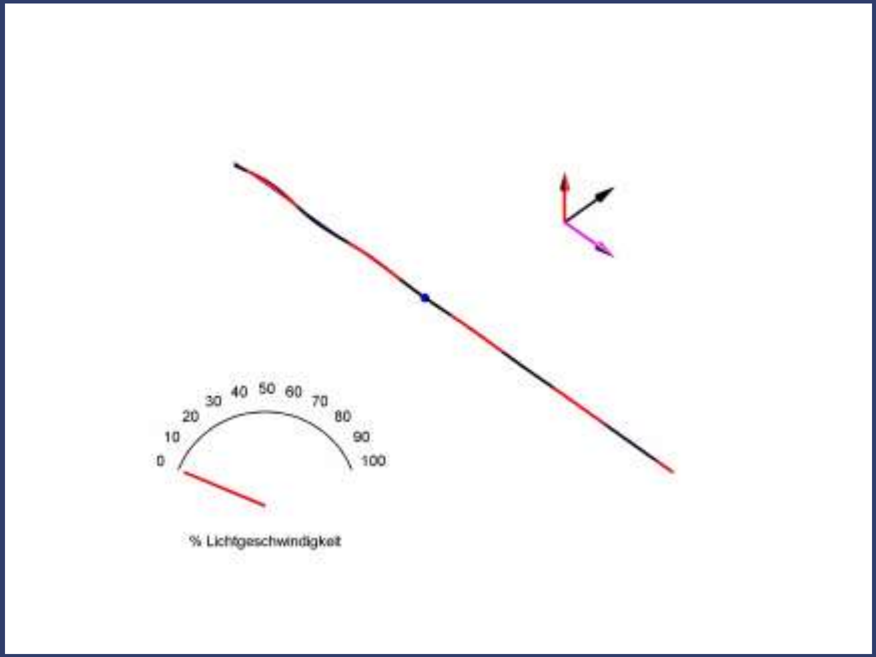
What complicates laser-ion acceleration



Electrons become relativistic at 10^{18} W/cm^2 (and can furtheron be accelerated to high energies (GeV) in a plasma wake-field).

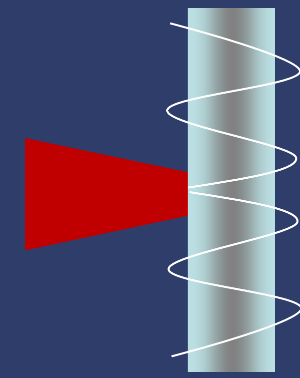
Ions become relativistic at 10^{24} W/cm^2 which is beyond our capabilities (and will be for a while).

Moreover, for therapy non-relativistic ions are required.

The many ways to accelerate ions

Daido, Nishiuchi, Pirozhkov, RPP **75**, 056401 (2012) *Review of laser-driven ion sources and their applications*

Plasma expansion / Target Normal Sheath Acceleration (TNSA)



A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys. 85, 751–793 (2013) *Ion acceleration by superintense laser-plasma interaction*

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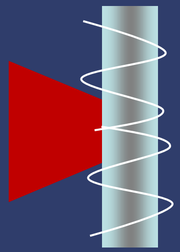

"Slow down laser"
Hole-boring/shock acceleration/BOA, relativistic transparency

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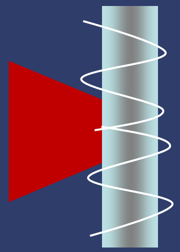

“Slow down laser”
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Radiation Pressure Acceleration

A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys. 85, 751–793 (2013) *Ion acceleration by superintense laser-plasma interaction*

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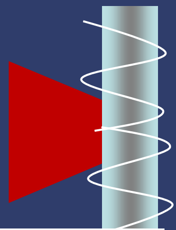


Optimised for thin targets such that the radiation pressure force (I_L/c) equals the Coulomb attraction ~$(N_e/A)^2$

$$a_0 = n/n_c \cdot d/\lambda$$

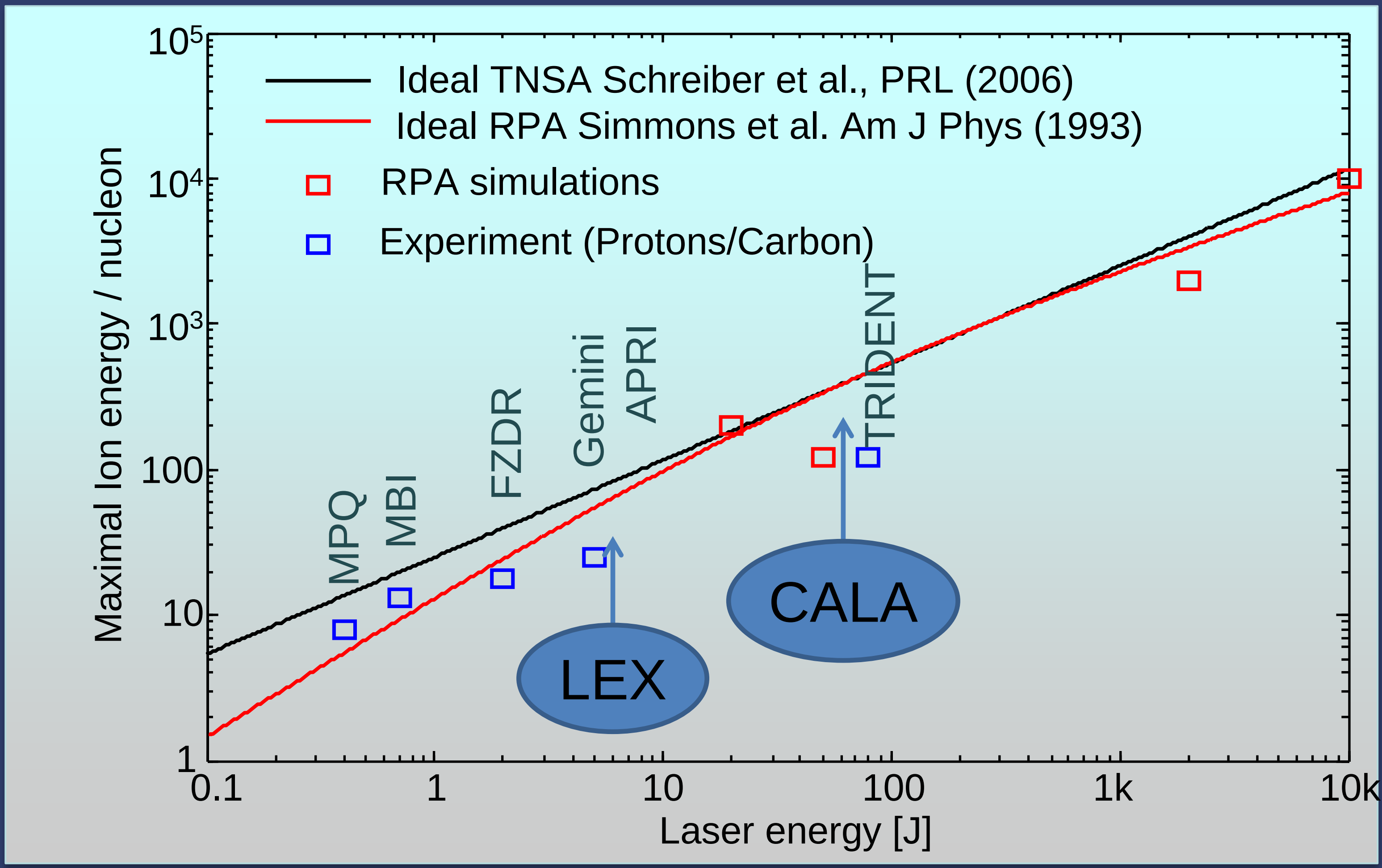
It is also the condition required to remove all electrons from the focal volume, Schreiber PhD (2006)

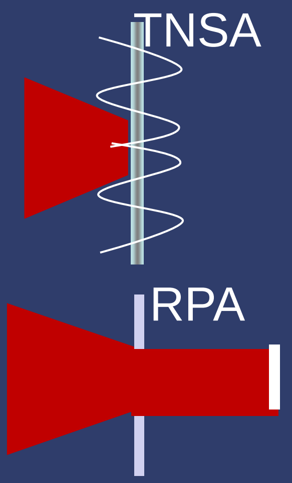
Hole
relat

Radiation Pressure Acceleration

A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys. 85, 751–793 (2013) *Ion acceleration by superintense laser-plasma interaction*

Laser energy is essential (quality, focus, contrast, too)

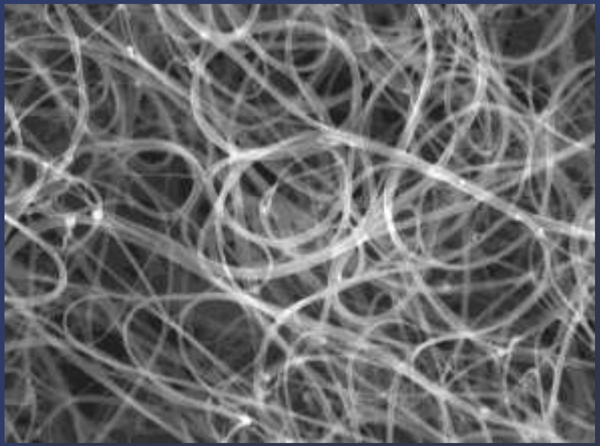




Nano-targetry at LMU

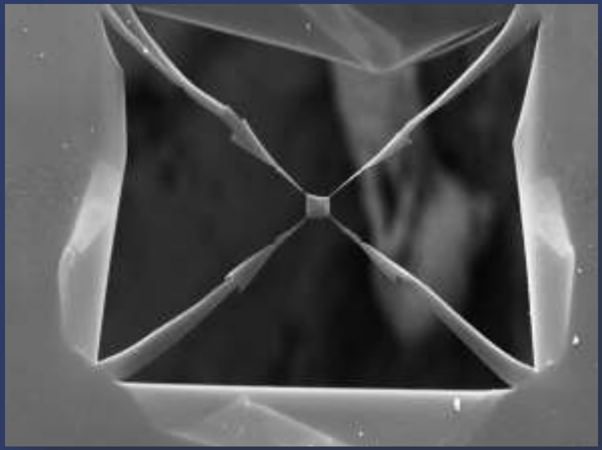
DLC Nanofoils

Carbon Nanotubes



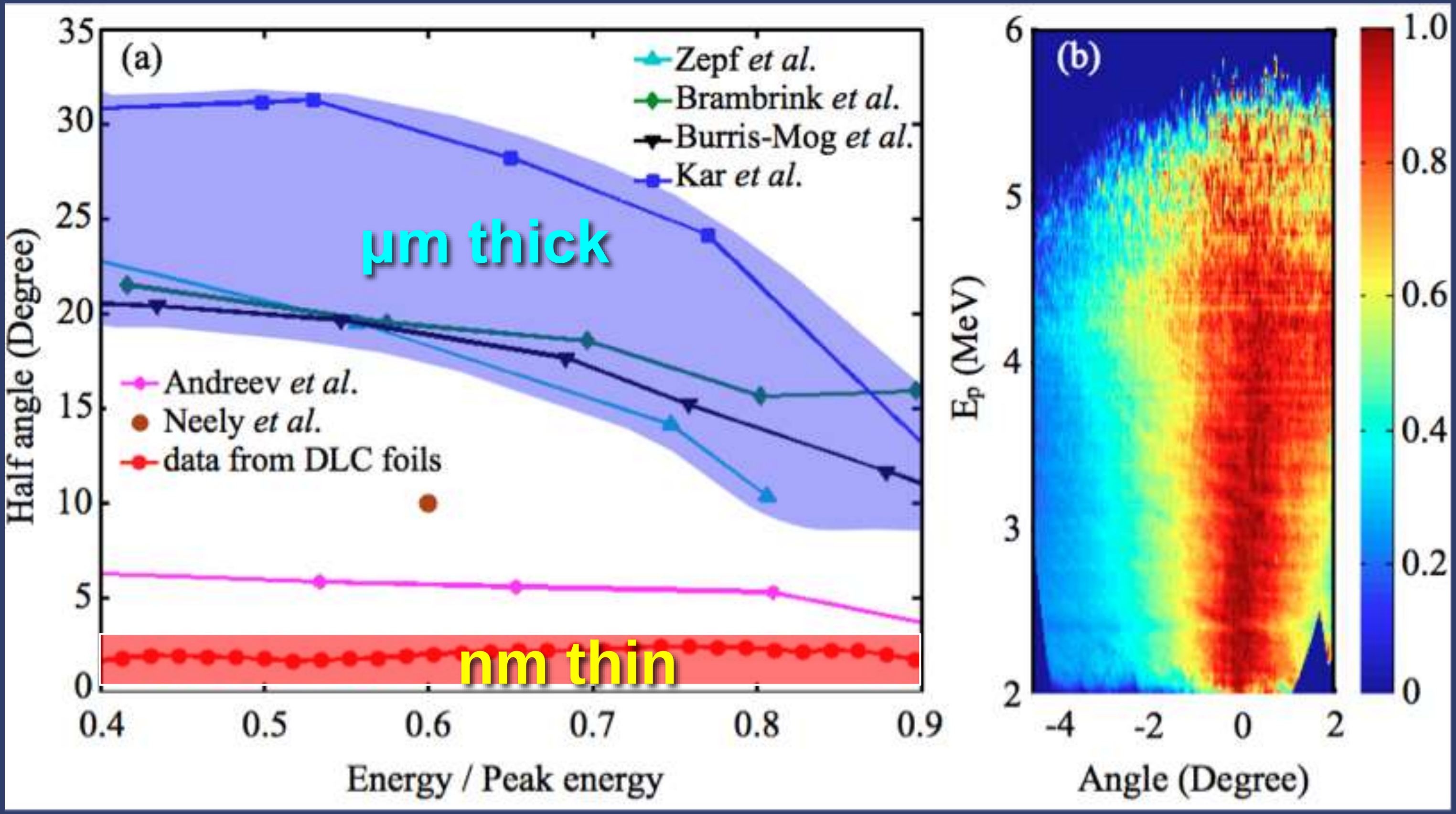
Nano-spheres

Structured/Masslimited Nano-targets



Low divergence from nm DLC foils

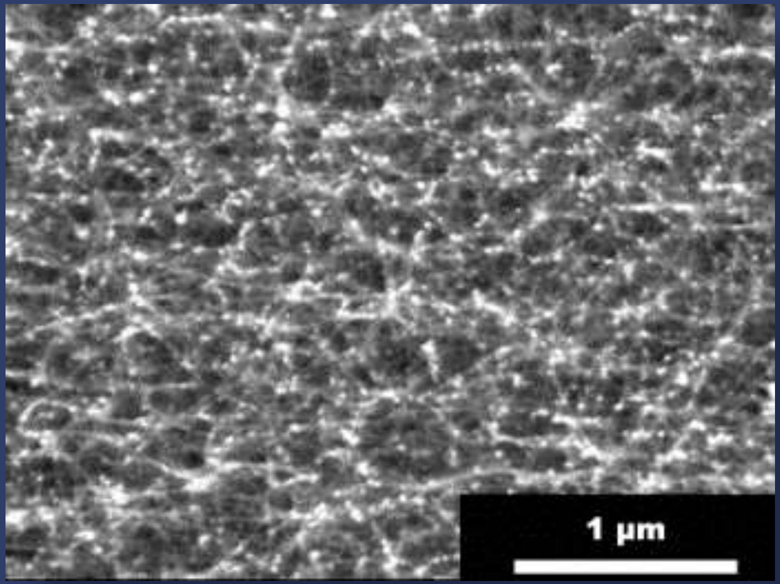
ATLAS @ MPQ, 0.5 J, 30 fs



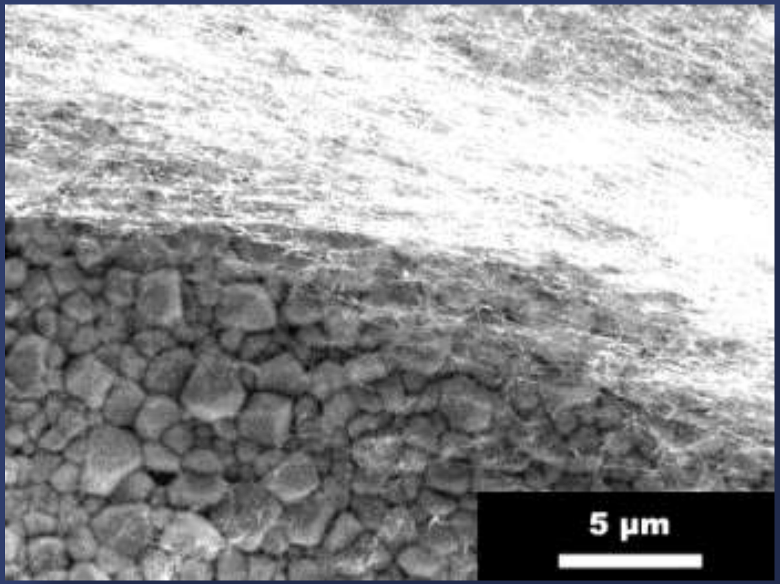
J. Bin et al., On the small divergence of laser-driven ion beams from nanometer thick foils, Physics of Plasmas 20, 073113 (2013)

Carbon Nanotube Foam (CNT foam)

Freestanding ultrathin carbon nanotube foam



CNT foam on DLC foil



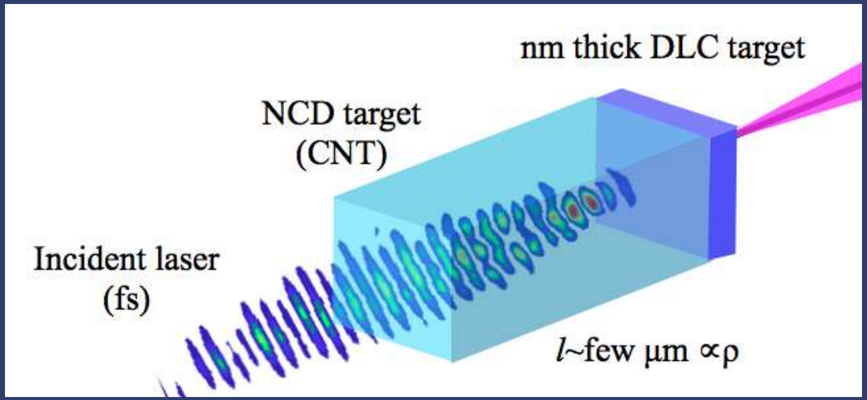
Density: ρ= 13~30 mg/cm^3

Thickness: d= 0.2~20 µm

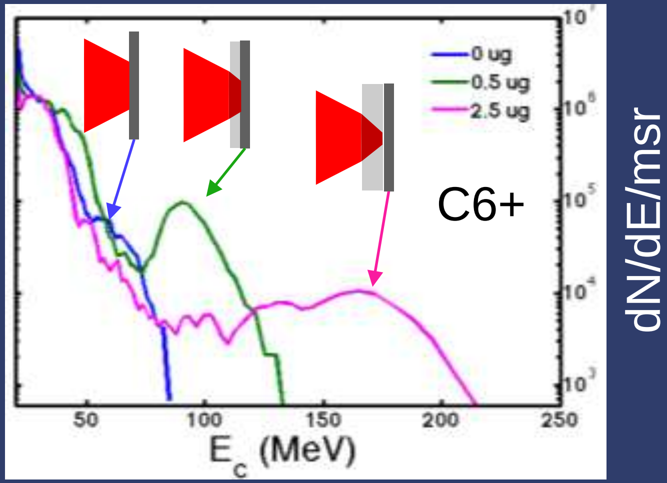
n_e/n_c =2~5

Near-critical plasma from CNT – laser shaping

CNT foam + DLC



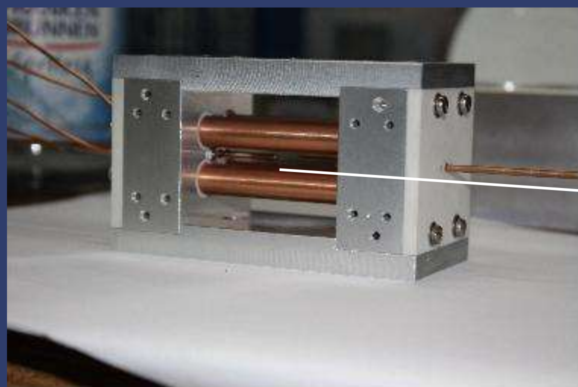
Astra Gemini (CLF, QUB, IC, LMU)

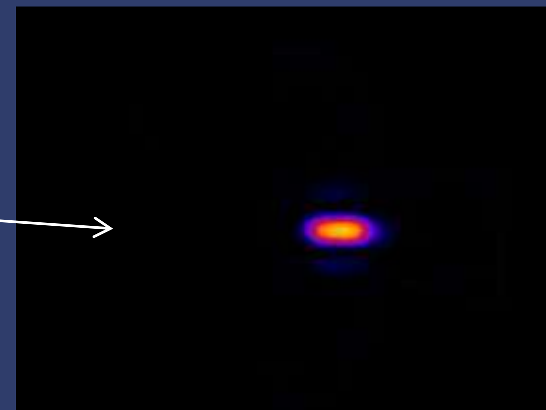


Relativistic plasma optics enabled by near-critical density nanostructured material, J.Bin et al.
arXiv:1402.4301v1

Levitating isolated micro-spheres

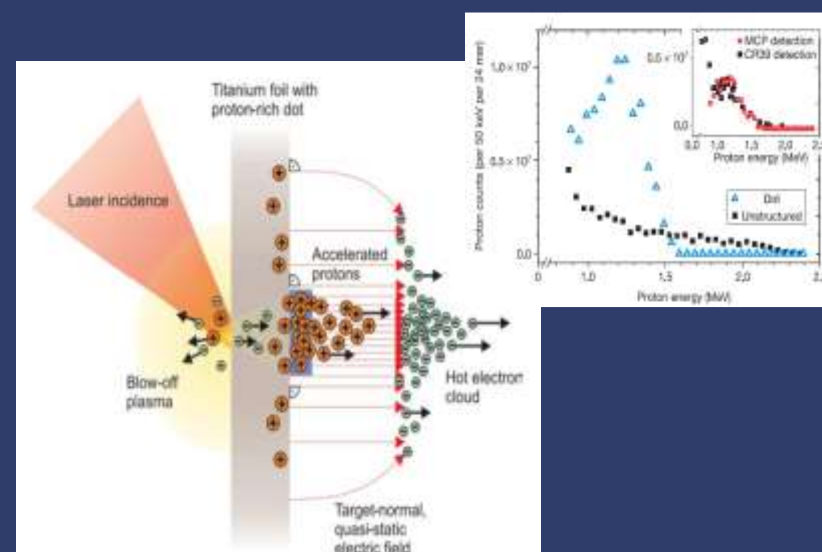
1.8 micron sphere in Paultrap





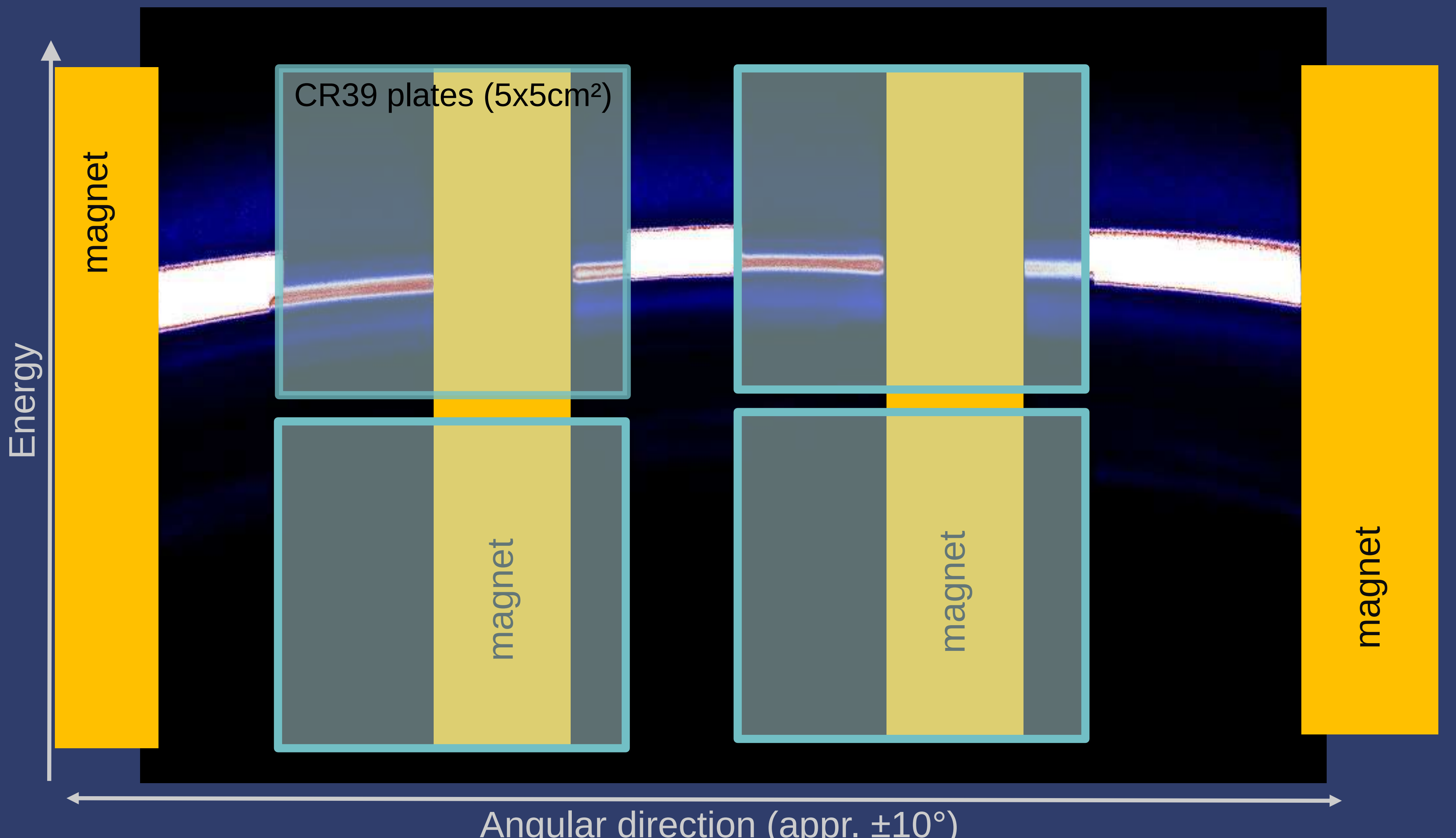
Experiments at various facilities:

- MBI,Berlin: 1 J in 30 fs
- GSI, Darmstadt: 200 J in 500 fs
- Texas PW, Austin: 80 J in 150 fs



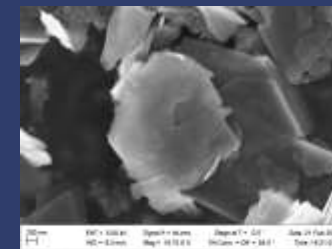
Schwörer *et al.*, Nature 439, 441 (2006)

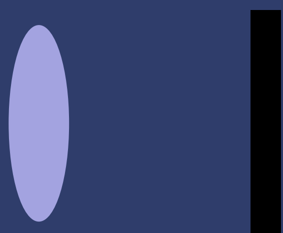
Narrow energy spread from micro-spheres



Light-sail acceleration

Combine small (narrow energy spread) and thin (higher energy), e.g. graphene nanoplatelets





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

$$v / c = (1+R)\cdot E_L / Mc^2$$

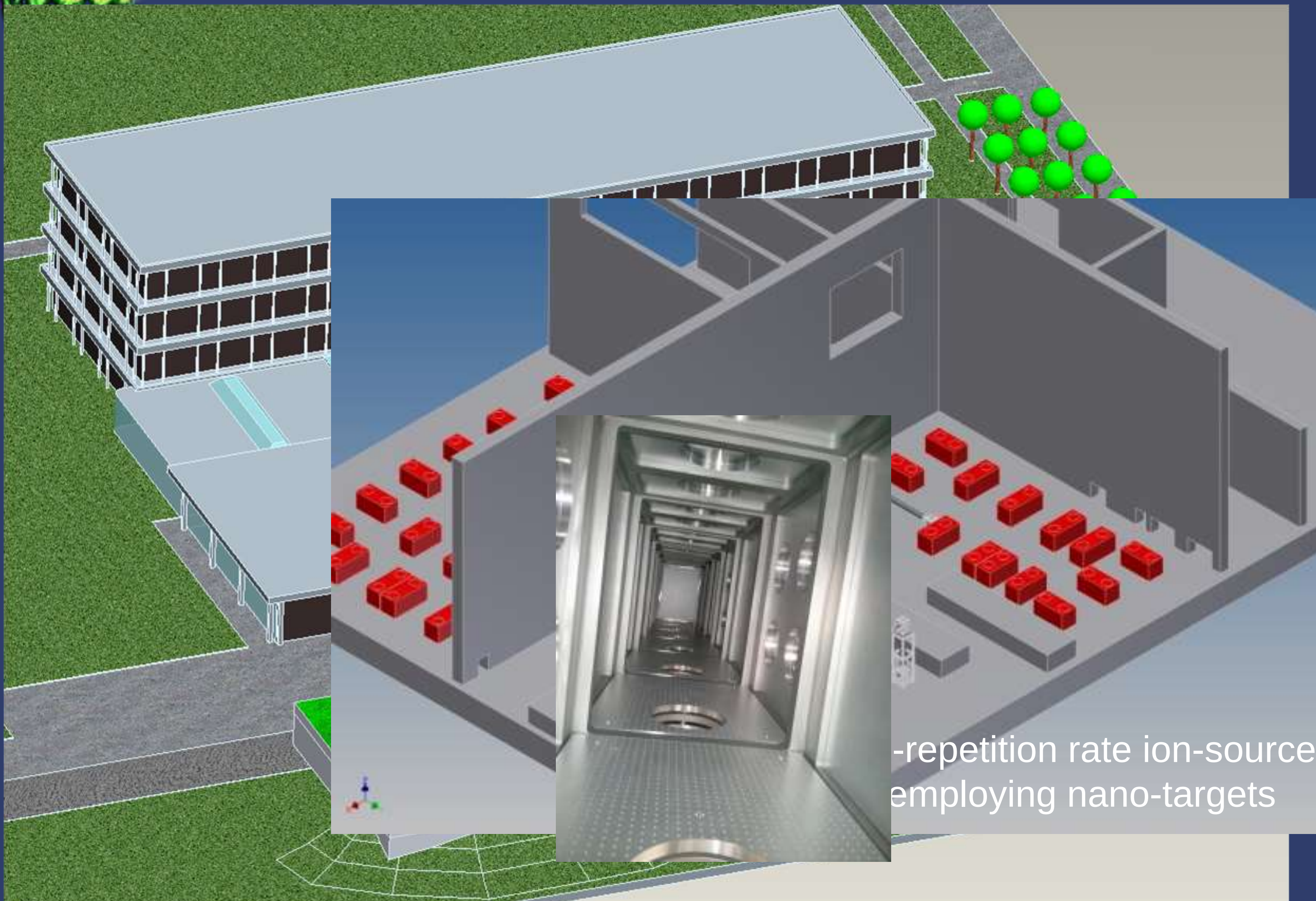
JFL Simmons et al, Am J Phys 1993 (Marx Nat 1966)

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

fu … 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

2014: Experiments in the Lab for Extreme Photonics



-repetition rate ion-source
employing nano-targets

joerg.schreiber@mpq.mpg.de

2017: Center for Advanced Laser Applications (CALA)

Summary / Remarks / Vision

Relevant energies have been demonstrated, laser systems that enable applications (repetition rate) come online.

Mature technology needed (Automation, Beam-transport, detectors, Reliability, repetition rate, targets)

“Compactness” will depend on the required laser energy and the laser technology that is available in the future (fibre lasers?)

Harvesting complementary features, nanosecond pulsed, mixed ion species, shaped energy distributions, synchronism to X-rays, …

Colleagues 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.

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

Imperial College London:
Z. Najmudin et al.

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

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

Texas University at Austin:
M. Hegelich et al.

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

HZDR Dresden:
U. Schramm, M. Bussmann, et al.

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