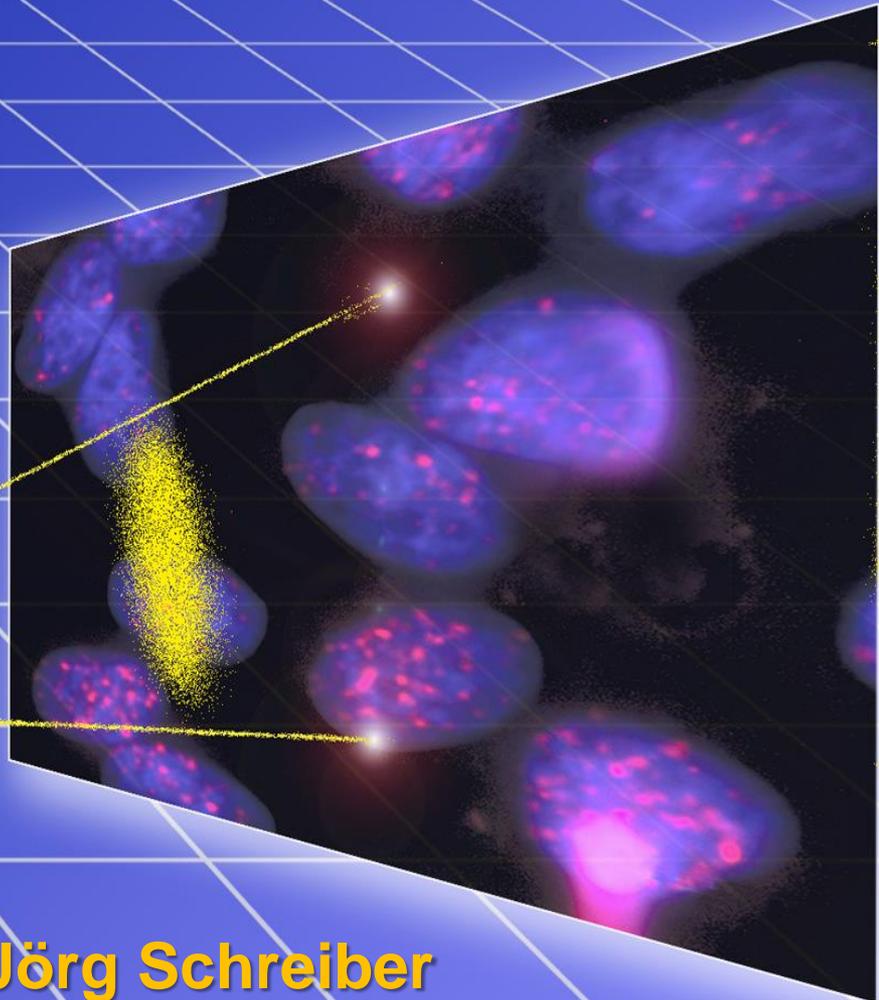
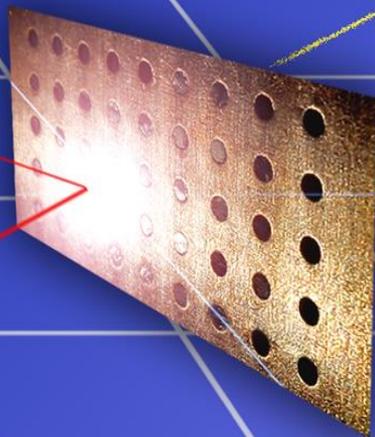
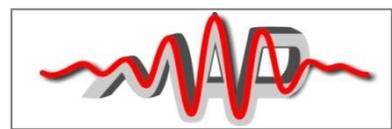


Laser-based ION acceleration (and “by-products”)



Jörg Schreiber

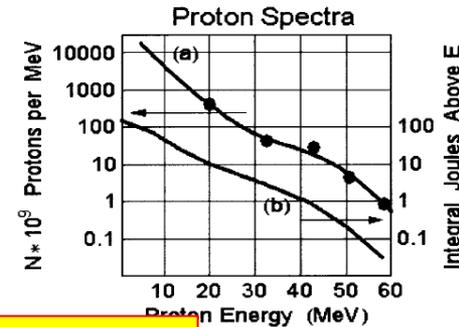
Ludwig-Maximilians-Universität München
Max Planck Institut für Quantenoptik



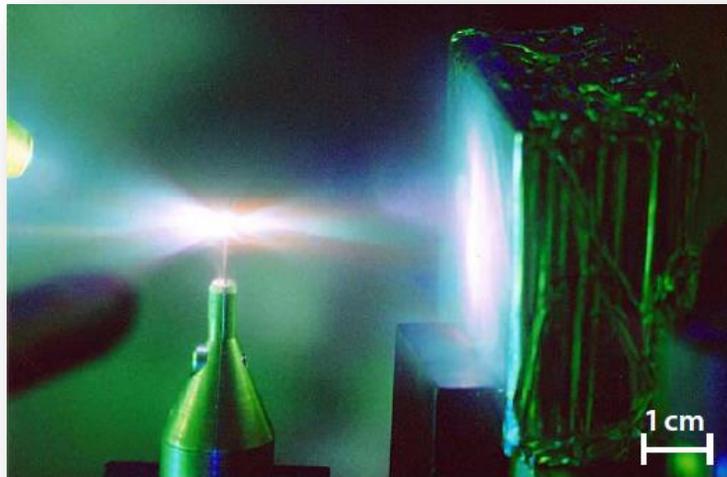
Interesting and rich physics – possibly revolutionary applications

Laser-Plasmas emit relativistic electrons, (multi-)MeV ions, neutrons, radiation (GHz ... MeV-Gammas)

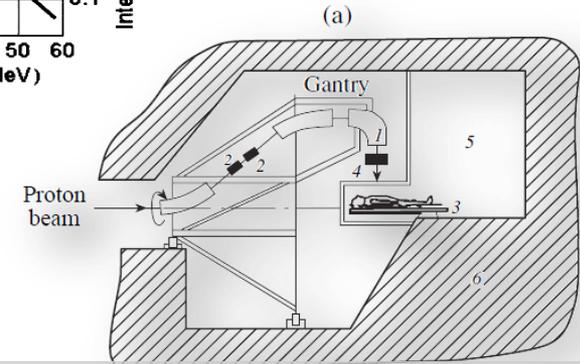
1st PW-laser: Snavely, PRL (2000)



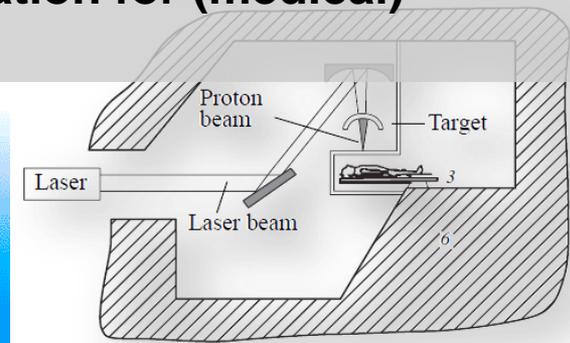
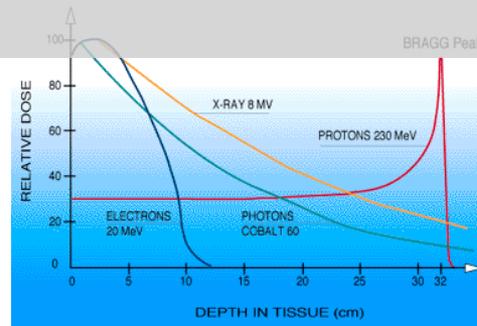
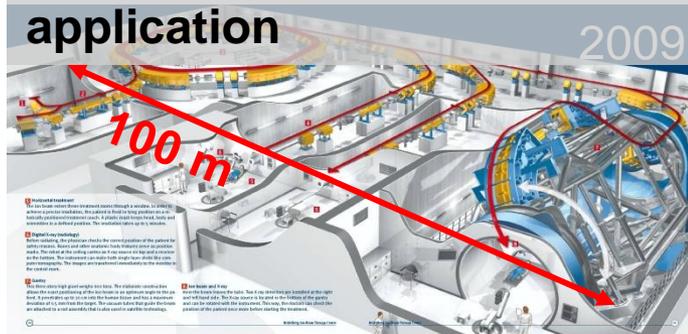
S.V. Bulanov et al.,
PPR 28, 453 (2002)

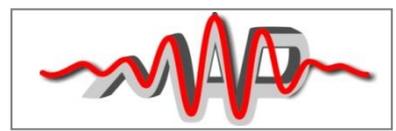


2012
Chair of
medical
physics
K. Parodi



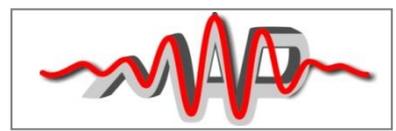
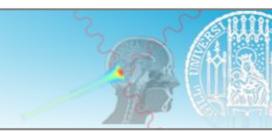
We investigate suitability of laser-driven ion acceleration for (medical) application



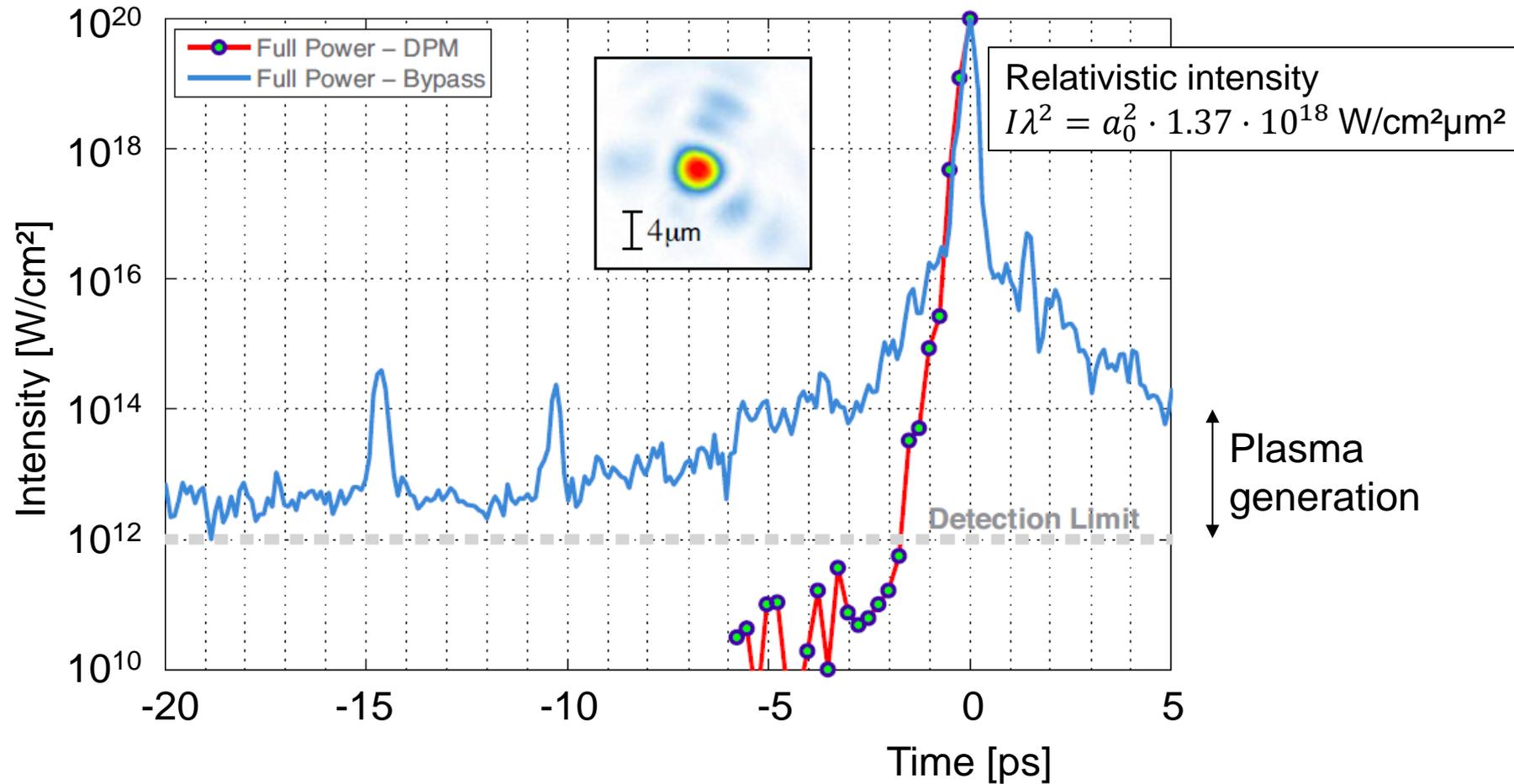


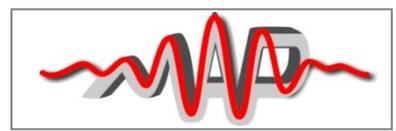
Outline

- ***Intense laser pulses and relativistic laser-plasma-interactions***
- ***Electron acceleration – progress in experiments***
- ***Ion acceleration and related topics – exploiting nano-materials***
- ***Applications of***
 - ***laser-driven particle accelerators***
 - ***nano-plasmas in particular***
- ***The (near-term) future***



Intense laser pulses: A typical temporal profile





Relativistic intensity and plasma interaction

Single electron: 10^{18} W/cm² (lin. pol.)

Critical electron density $n_c = \frac{\epsilon_0 m_e \omega_{Las}^2}{e^2}$

Refractive index $\eta = \sqrt{1 - \frac{n_e}{\gamma n_c}}$

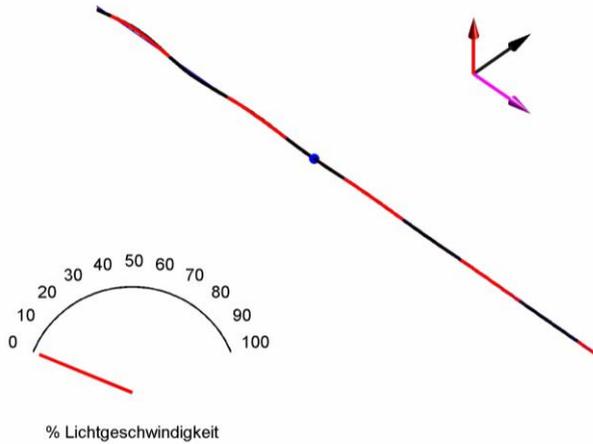
Group/phase-velocity $v_G = c\eta, v_p = \frac{c}{\eta}$

$$n_e < n_c$$

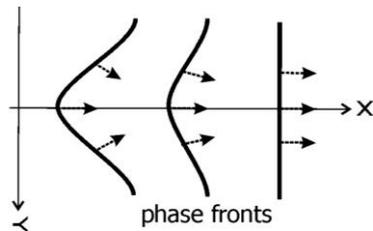
Electron acceleration

$$n_e \geq n_c$$

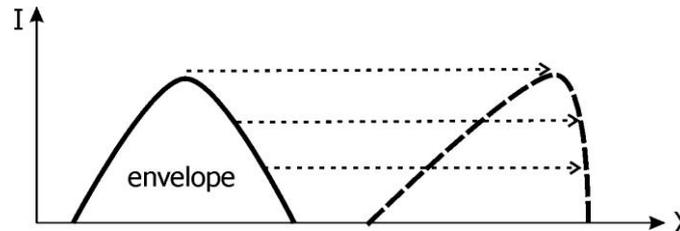
Ion acceleration



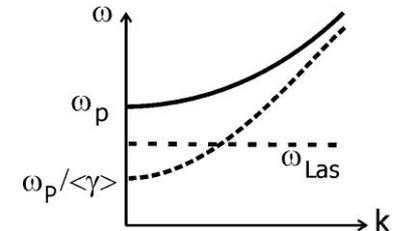
Self-focusing/guiding

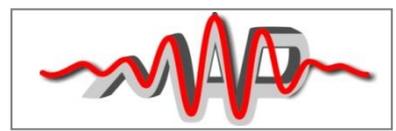


Pulse steepening

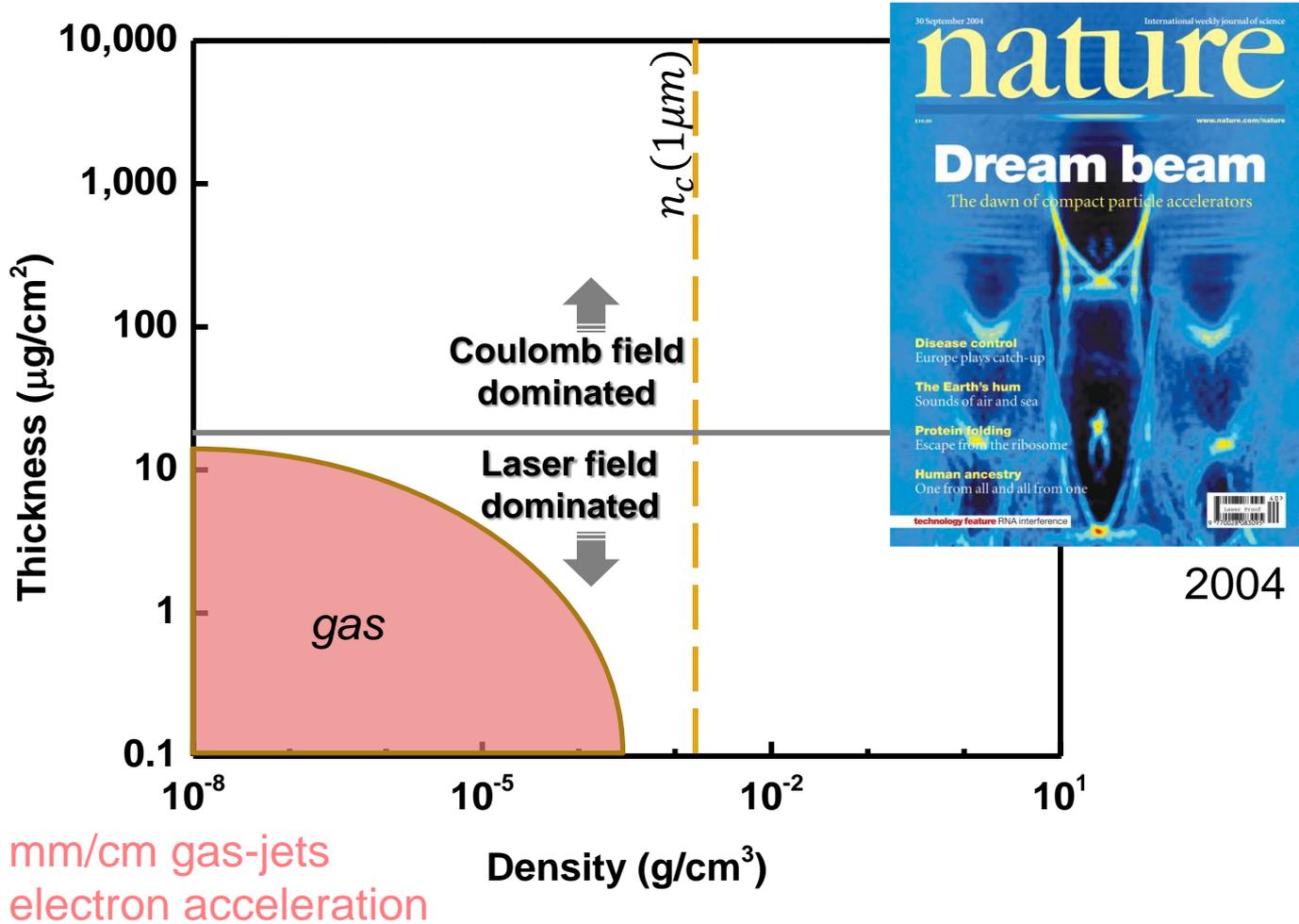


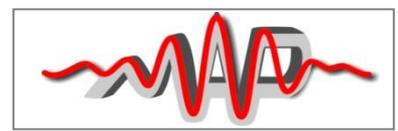
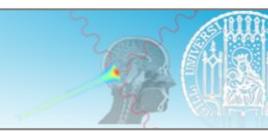
Induced transparency



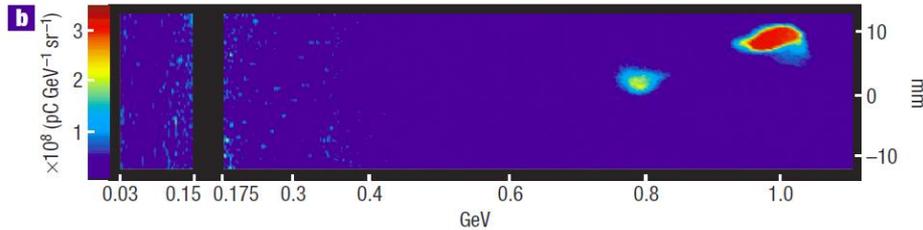
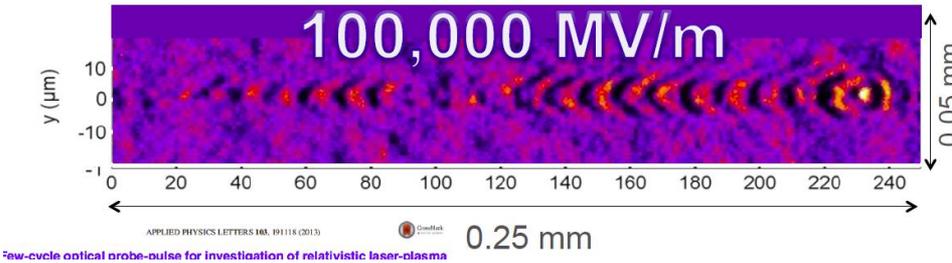
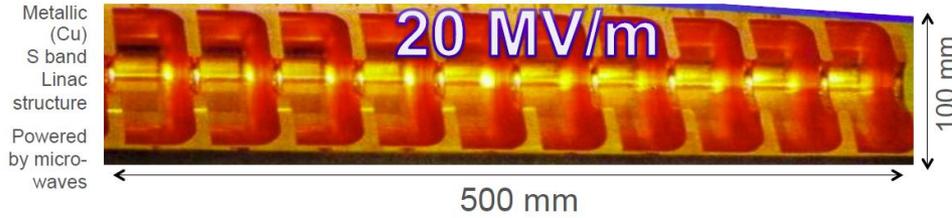


Target-Landscape: Laser-electron accelerators





Some examples: electron energies and stability

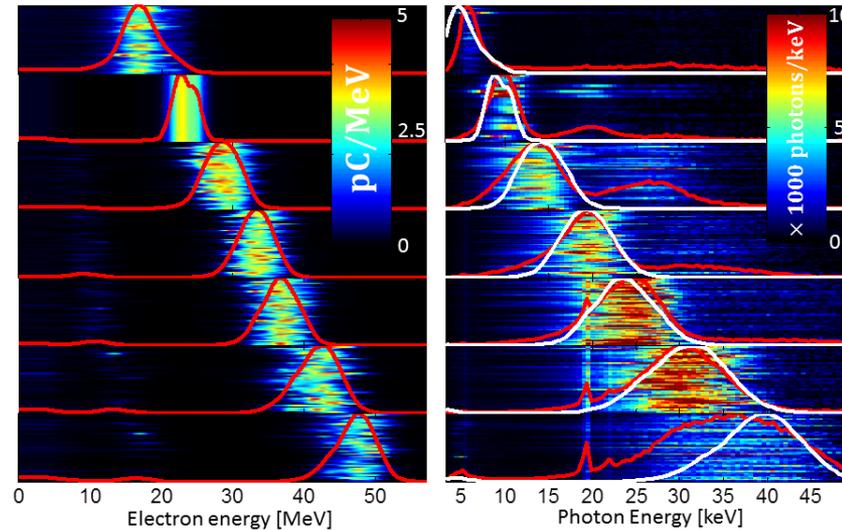


1st laser-driven 1 GeV electrons, current record: 5 GeV over ~5 cm

W.P. Leemans, *et al.*, Nat. Phys. 418, (2006)

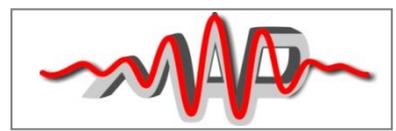
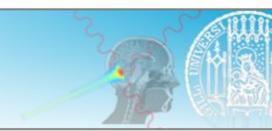
1st real-time visualisation of laser-driven plasma-wave, courtesy M. Kaluza (talk tomorrow)

M.B. Schwab, *et al.*, Appl. Phys. Lett. 103, 191118 (2013)

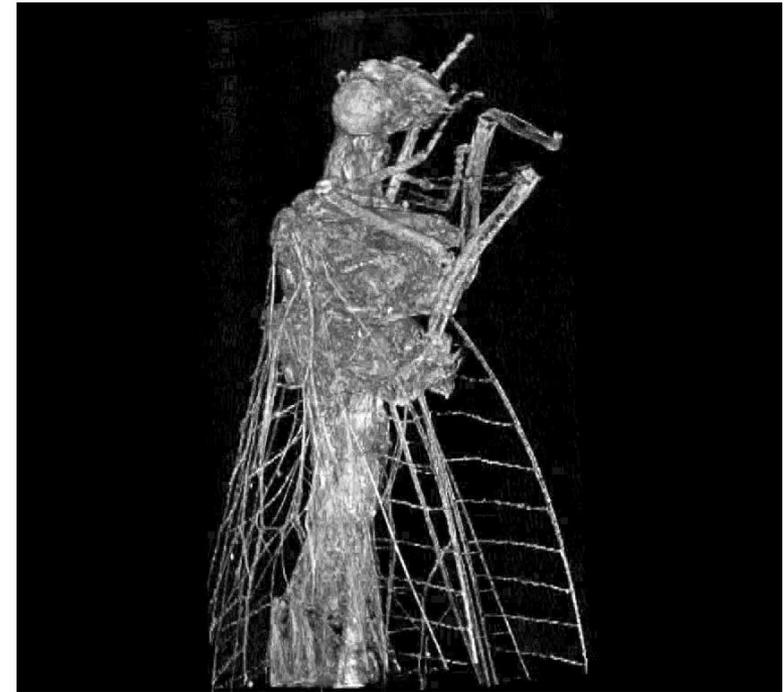
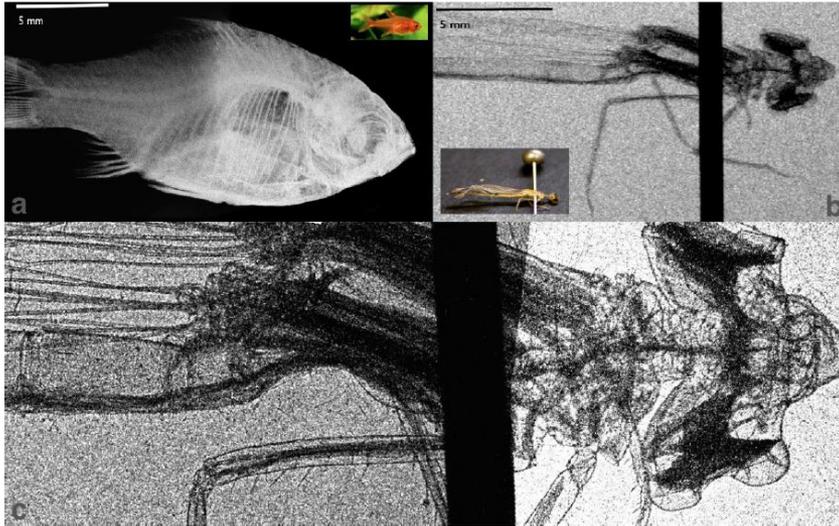


tunable multi-keV X-ray-pulses Thomson backscattering (10^6 – 10^7 photons/pulse)

Khrennikov *et al.*, PRL accepted



Coherence of and phase contrast imaging with betatron-X-rays

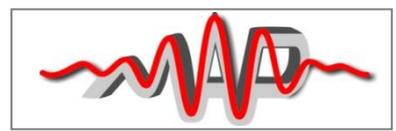


μm -source size, phase contrast imaging

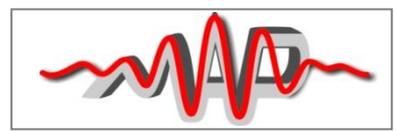
S. Kneip, JS, *et al.*, *Nature Phys.* 6, 980 (2010);
Appl. Phys. Lett. 99, 093701 (2011)

1st laser-driven X-ray-phase contrast tomography with ~ 5 keV, X-rays 4×10^8 photons/keV/msr at MPQ Garching

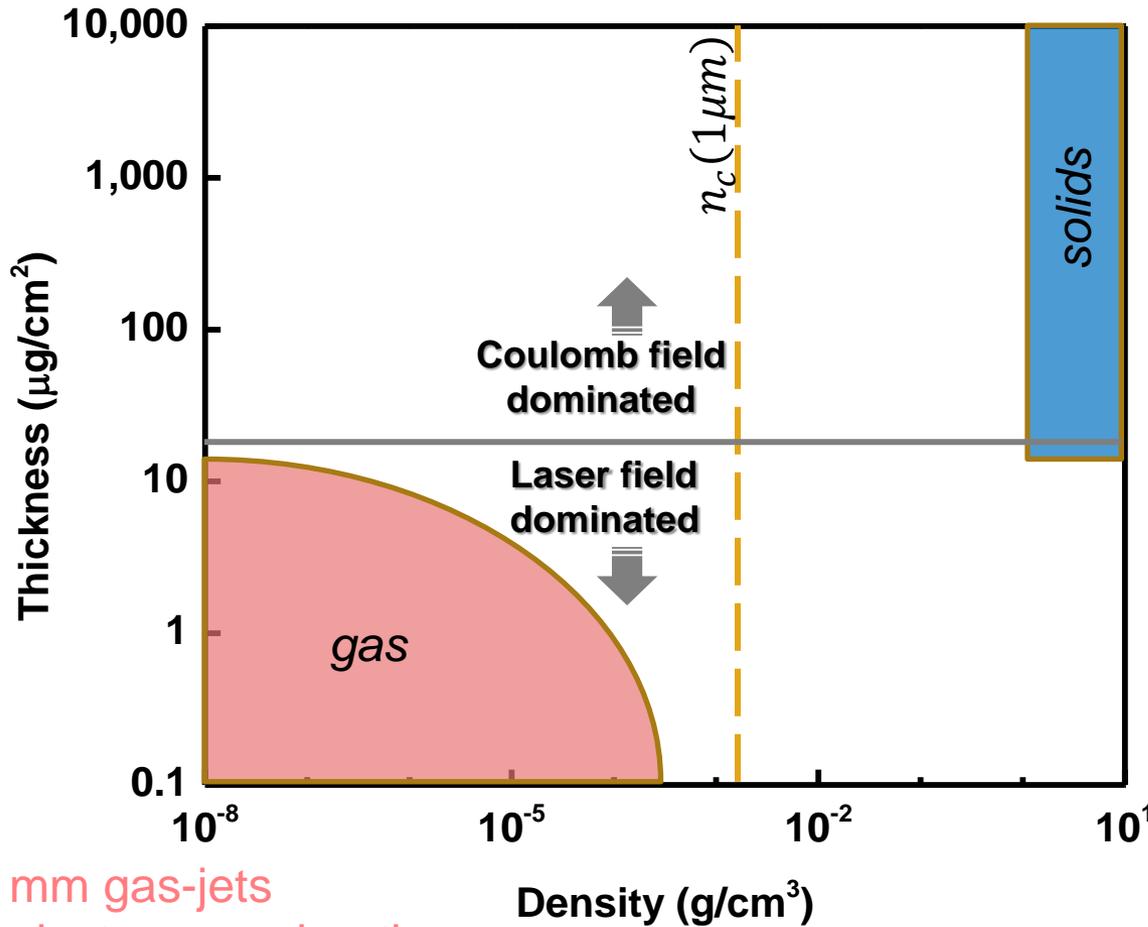
J. Wenz *et al.*, submitted, courtesy S. Karsch (LMU) / F. Pfeiffer (TUM)



Moving on to my main topic
... laser ion accelerators

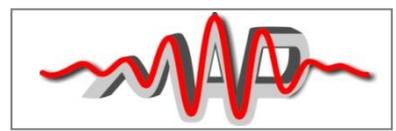


Target-Landscape: Laser-ion „accelerators“



µm foils
Ion acceleration
TNSA

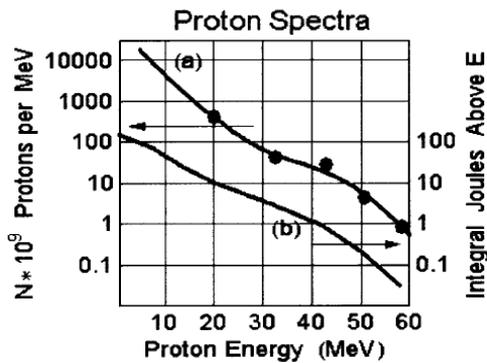
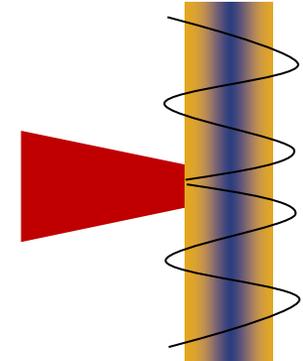
mm gas-jets
electron acceleration



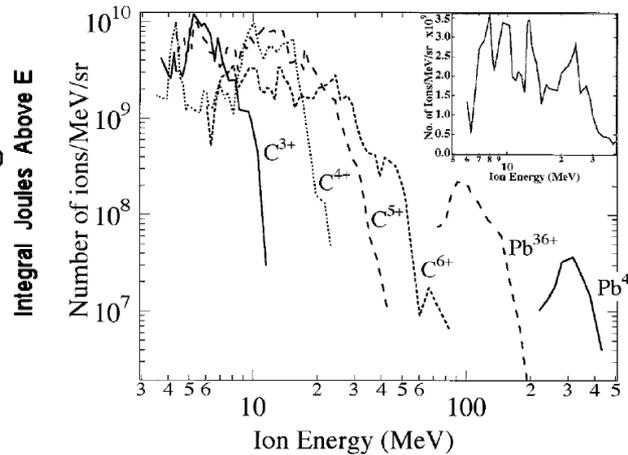
Ion acceleration: Basic principles

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

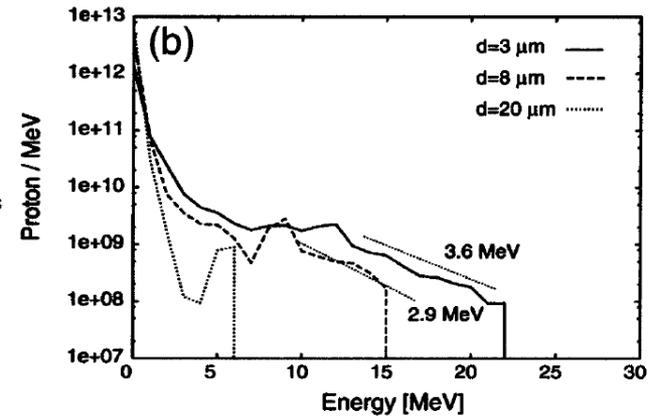
Plasma expansion / Target Normal Sheath Acceleration (TNSA)
Any micrometer thick foil works
... some early examples



Snively, PRL (2000)

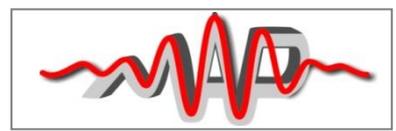
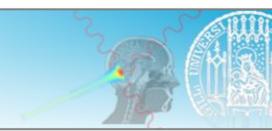


Clark, PRL (2000)

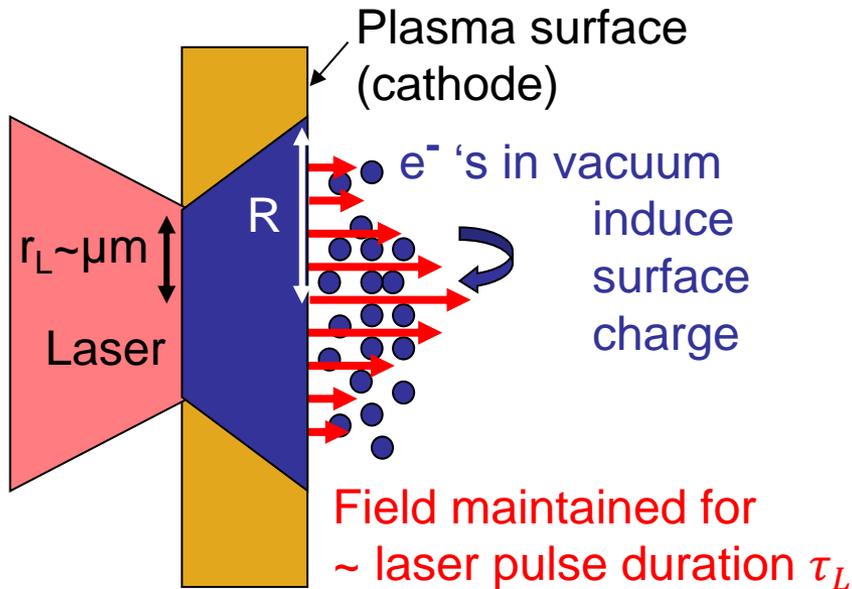


Mackinnon, PRL (2002)

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



„On the back of an envelope“-model

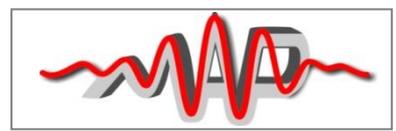


Main Conclusions

- Optimization procedure (Pulse duration & target thickness)
- Thinnest foils beneficial
- Monoenergetic ions possible

Ion source: Laser+Target (the Gun)

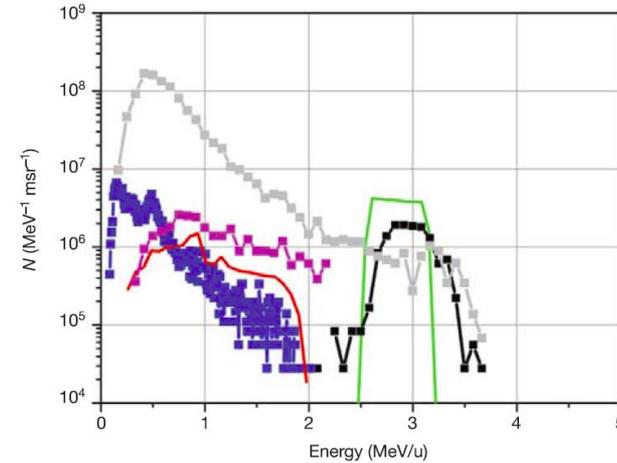
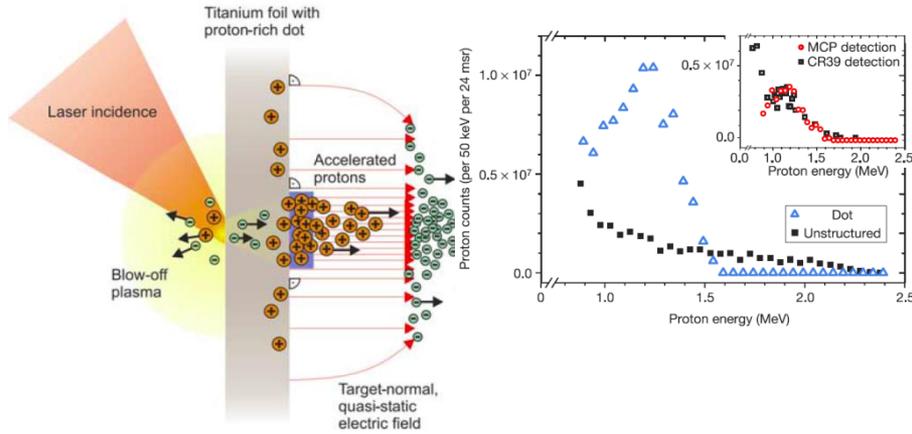
- high bunch charge and **high peak current**
(10's -100 nC in psec \Rightarrow 10's-100 kiloamperes)
- high extraction field and maximum proton energy
($\sim 10 \text{ MeV}/\mu\text{m} \Rightarrow 100 \text{ MeV}$ protons)
- relatively high energy conversion efficiency
(0.1 to few % - laser energy to proton energy)
- **broad energy spread**, $\frac{\Delta E}{E}$ (can be > 100 %)
- **large angular divergence**
(full angle can be ~ 10 's degrees)
- laminar bunch (record low emittance 'at source' $\sim 10^{-3} \text{ mm mrad}$)



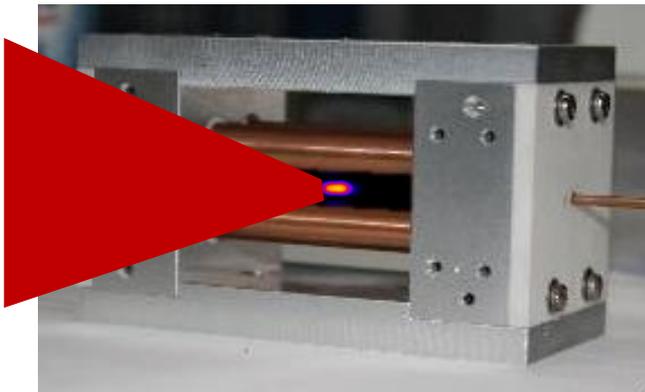
Small energy spread: limited proton/carbon layer on μm support foil

H. Schwörer, *et al.*, Nature 439, 445 (2006)

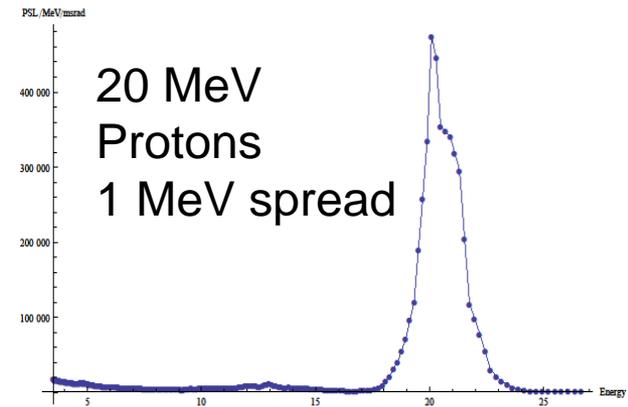
M. Hegelich, JS, *et al.*, Nature 439, 441 (2006)



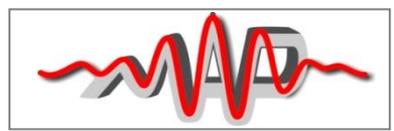
↓ Truly isolated targets



Granted experiments
@
MBI Berlin
GSI Darmstadt
Texas PW

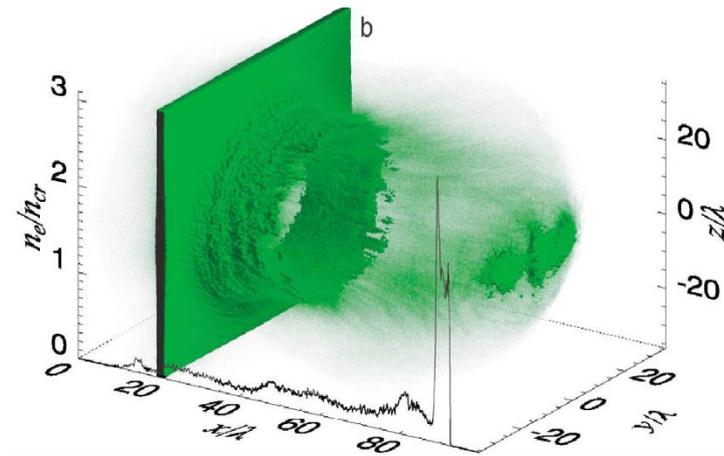


P. Hiltz, JS, *et al.*, in preparation

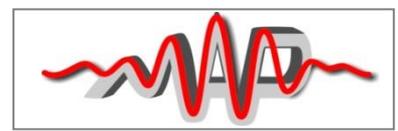
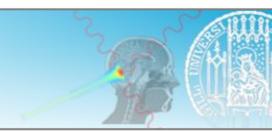


What is the potentially most elegant way to accelerate ions?

...



Esirkepov *et al.*, PRL 92, 175003 (2004): 10^{23} W/cm²



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)

for $5 \times 10^{13} \text{ km} = 300,000 \text{ AU}$ (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

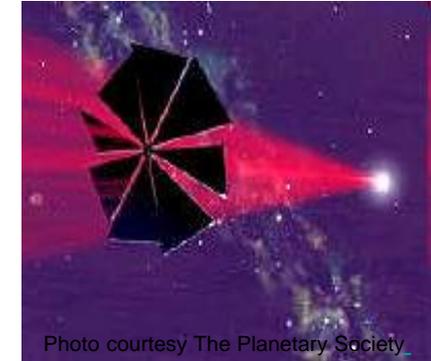
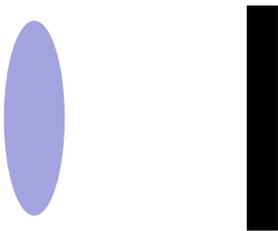


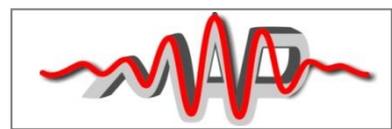
Photo courtesy The Planetary Society



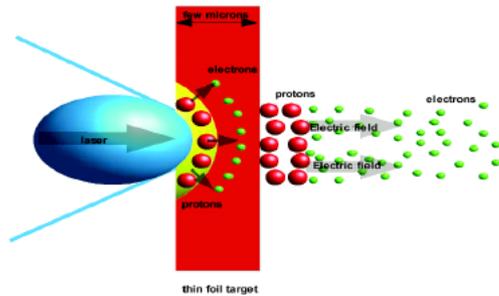
$$v / c = (1+R) \cdot E_L / Mc^2$$

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

Rayleigh-Length $\sim 2 \mu\text{m}$ (20 fs)
Intensity $\sim 5 \times 10^{21} \text{ W/cm}^2$



Optimisation: Target-thickness versus laser intensity



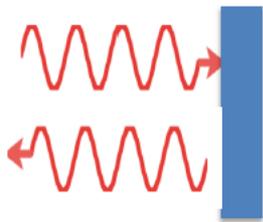
Laser Field

$$a_L = \frac{eE_L}{mc\omega}$$

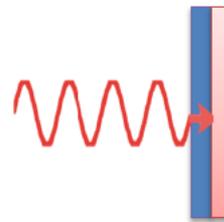
Maximum Coulomb Field
in a Thin Foil

$$E_s \sim \frac{n_e}{n_c} \cdot \frac{d}{\lambda}$$

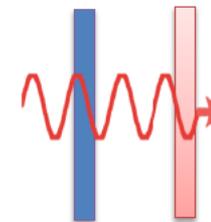
$a_L \ll E_s$



$a_L \sim E_s$



$a_L > E_s$

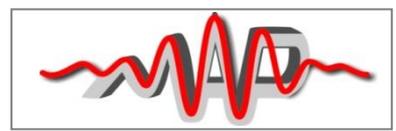


$d \sim 5 - 10 \text{ nm}$

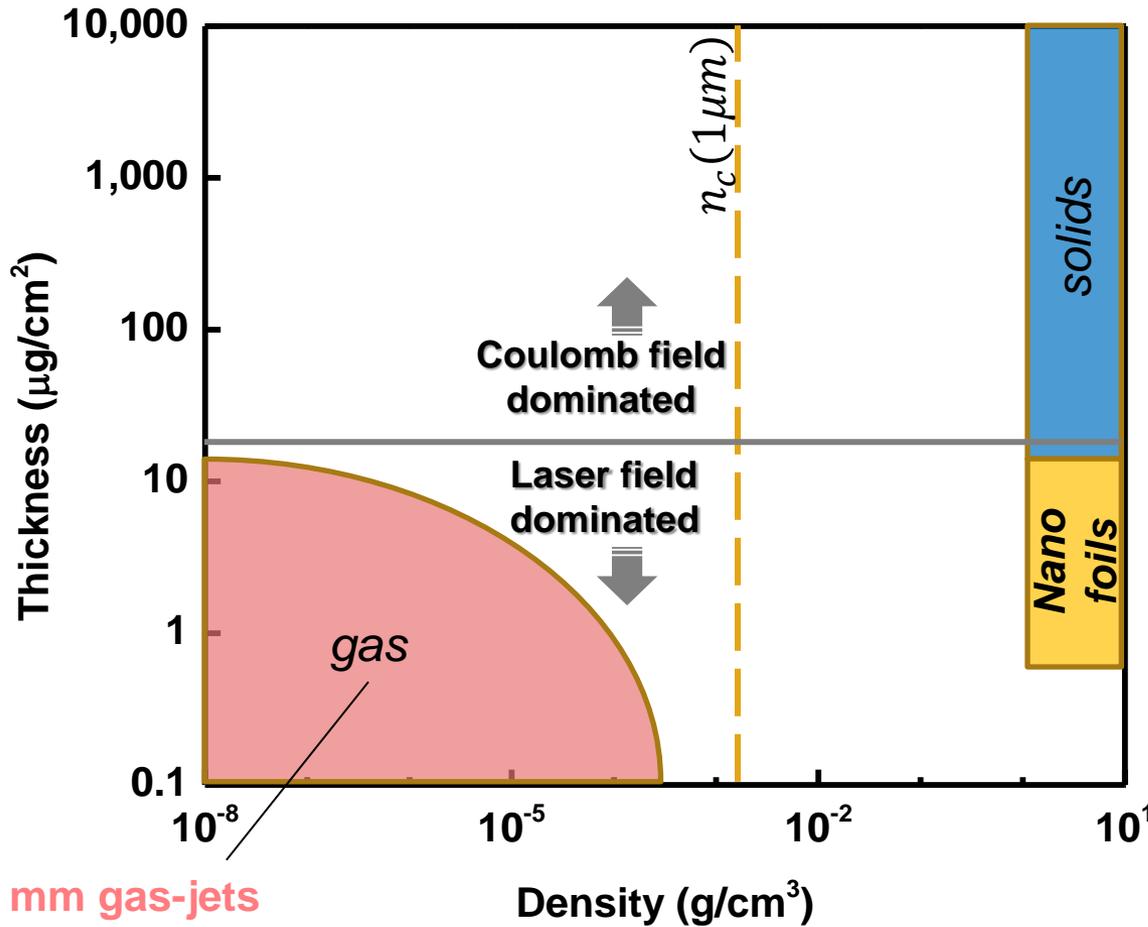
Ion Acceleration

$d < 5 \text{ nm}$

Dense Electron
bunches & Radiation



Conquering the target-MAP



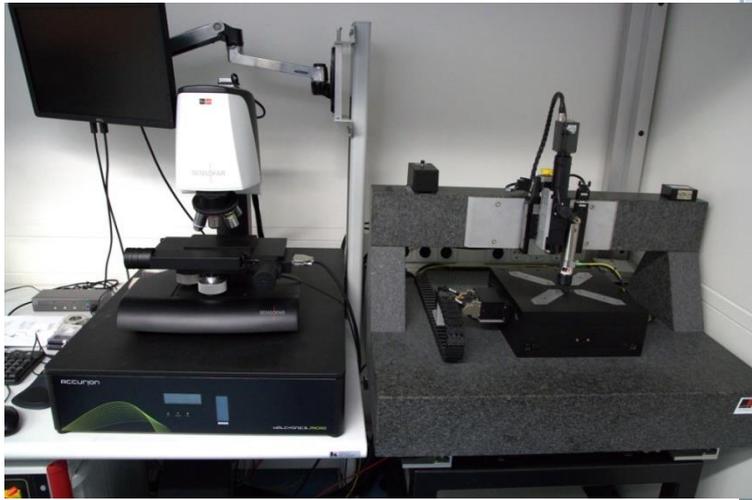
mm gas-jets
electron acceleration

Ion acceleration
Plasma
expansion
(TNSA)

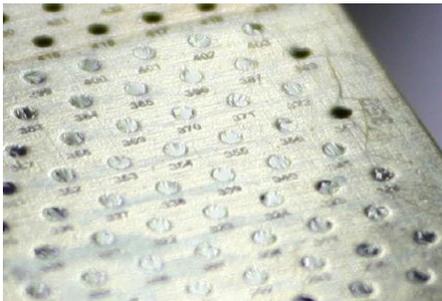
Radiation
Pressure
Acceleration
&
dense
electron
bunches

LMU target fabrication – controlled production & characterisation

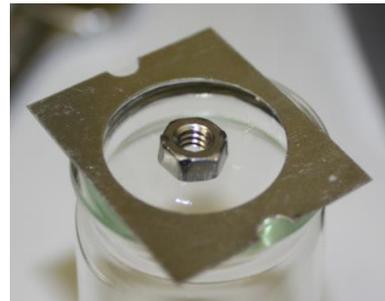
Atomic force, confocal, white-
light interferometric microscopy



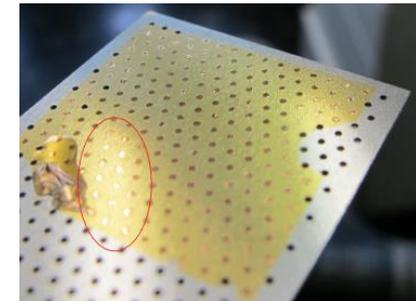
3-50 nm DLC foils

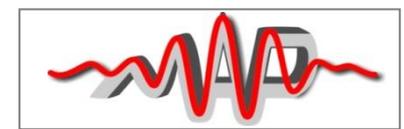
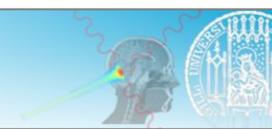


10nm-3 μ m Formvar



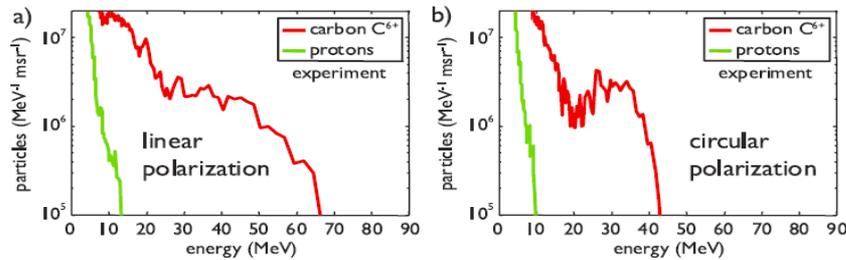
5 nm Gold



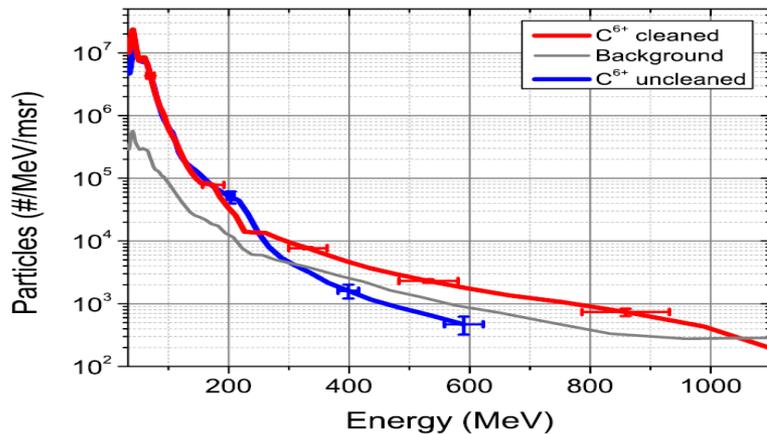
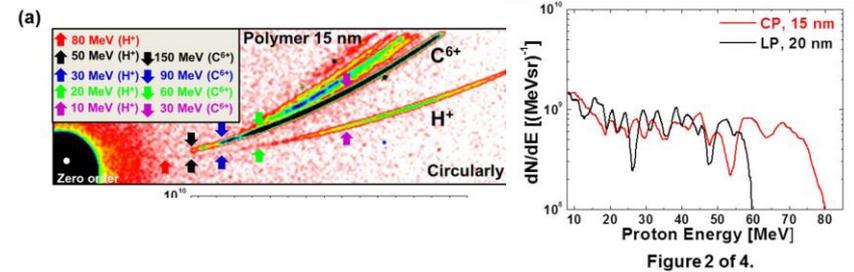


Prominent experimental results with nanometer thin targets

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

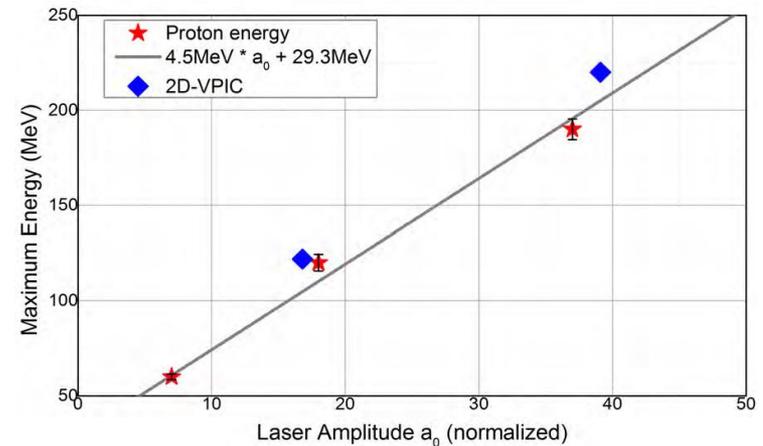


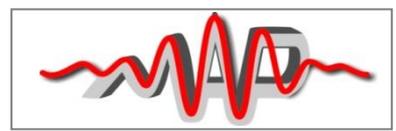
I.J. Kim, et al., arXiv: 1411.5734 (2014)
30J/30fs, 10s nm targets
RPA protons to 80 MeV



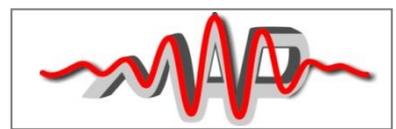
D. Jung, JS, et al., Phys. Plasmas **20**, 083103 (2013):
80J, 550fs, 100-200 nm DLC
record carbon energy > 1 GeV

M. Hegelich, et al., arXiv:1310.8650 (2014)
80J, 550fs, 200-300 nm CH₂ nano-targets
~ 5×10⁵ protons/(MeV·msr) @ 160 MeV

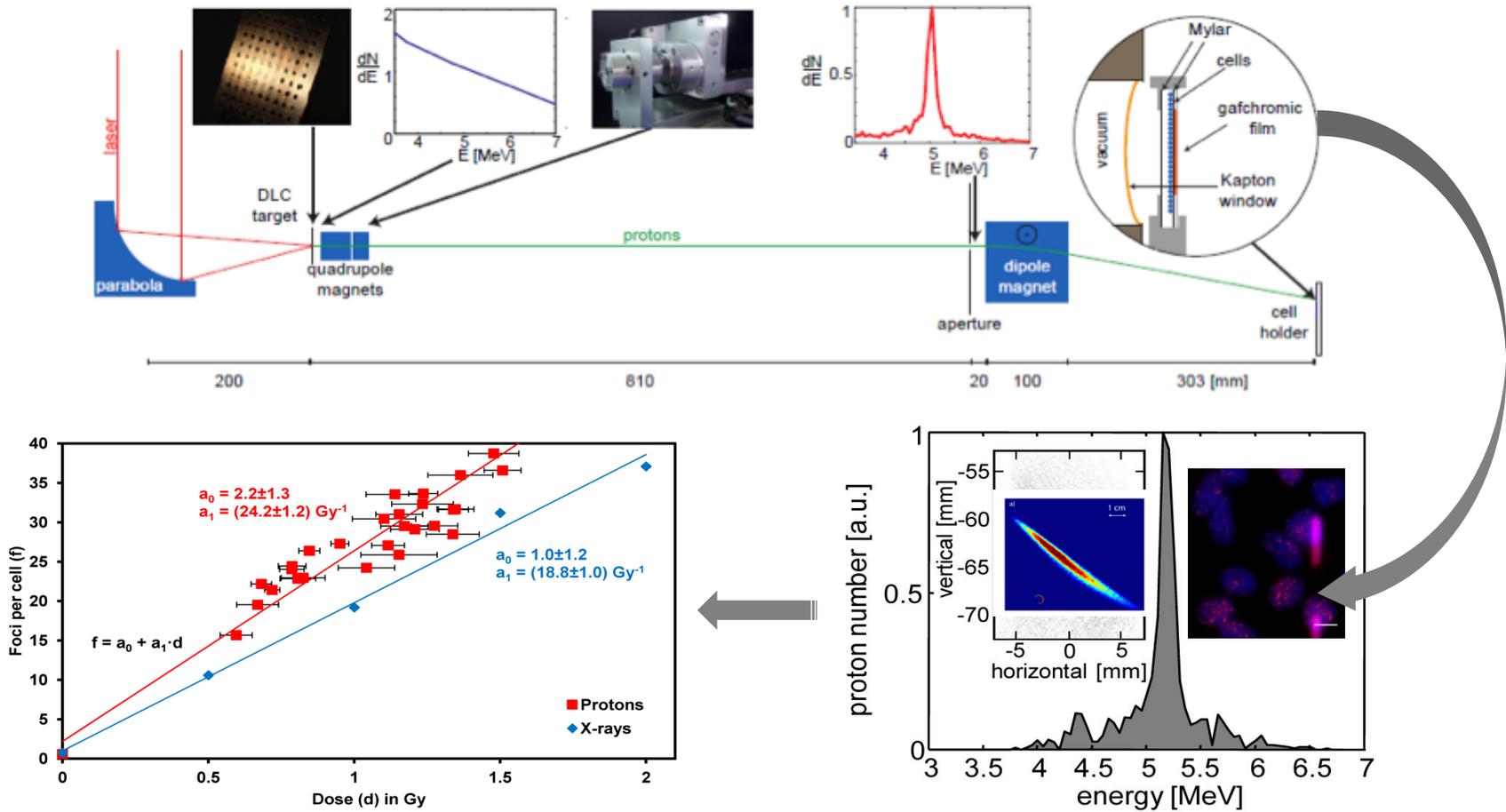




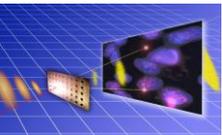
Novelties enabled by nano-foil-plasmas ... some examples



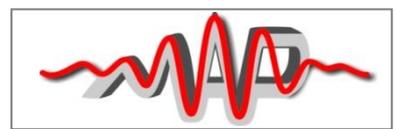
Single-shot dose response of living cells @ MPQ



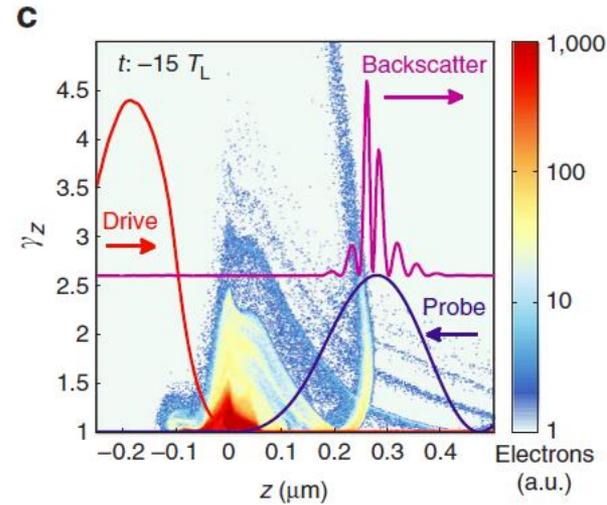
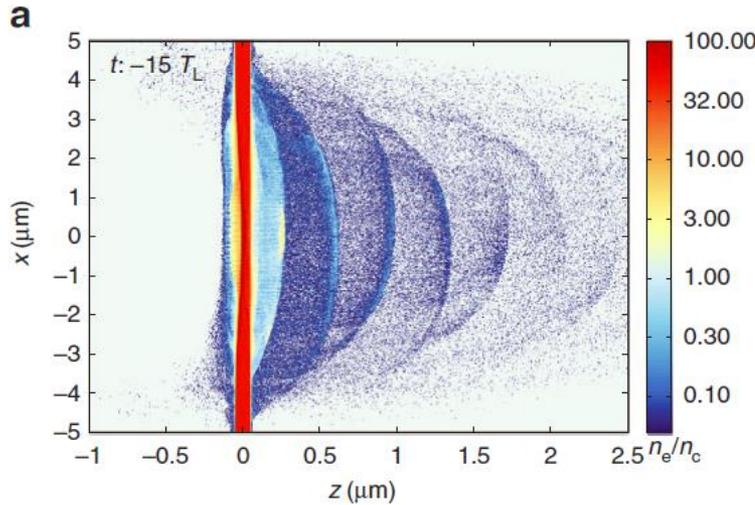
Other experiments: Kyoto (2009), Dresden (2010),
Kyoto (2011), Belfast (2012)



On the cover: A laser-driven nanosecond proton source for radiobiological studies, J. Bin, JS, et al., Appl. Phys. Lett. 101, 243701 (2012)
J. Bin, JS, et al., Phys. Plasmas 20, 073113 (2013)

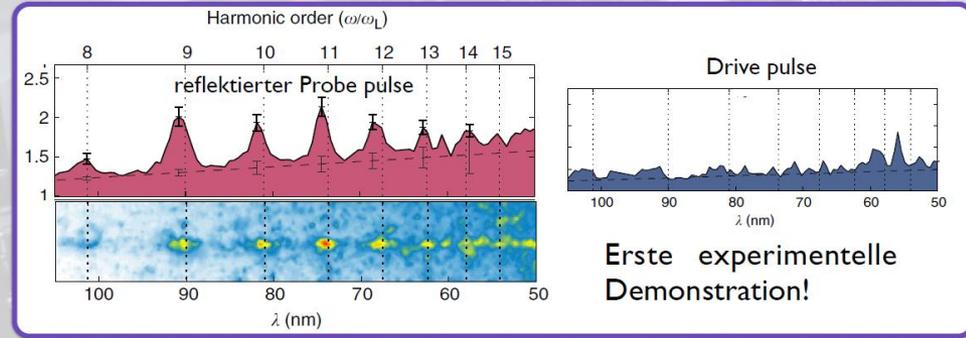
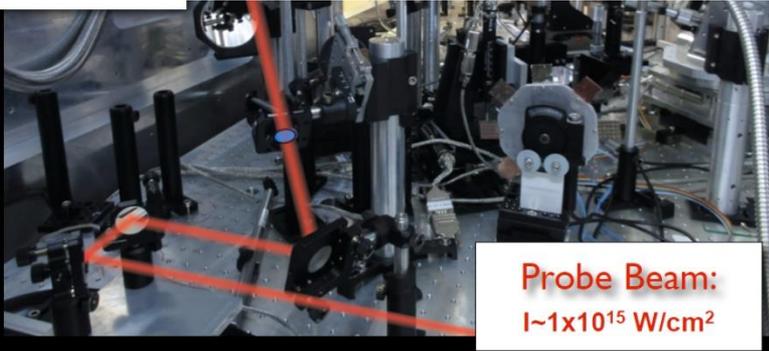


Relativistic mirror – Einstein’s Gedankenexperiment in reality

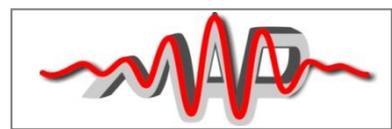


XUV spectrometer

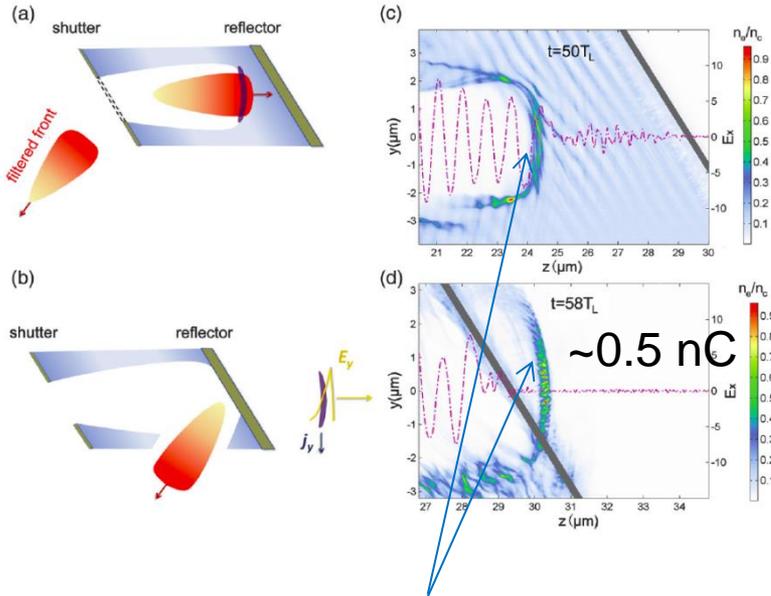
Spektro
Ionen, Electr



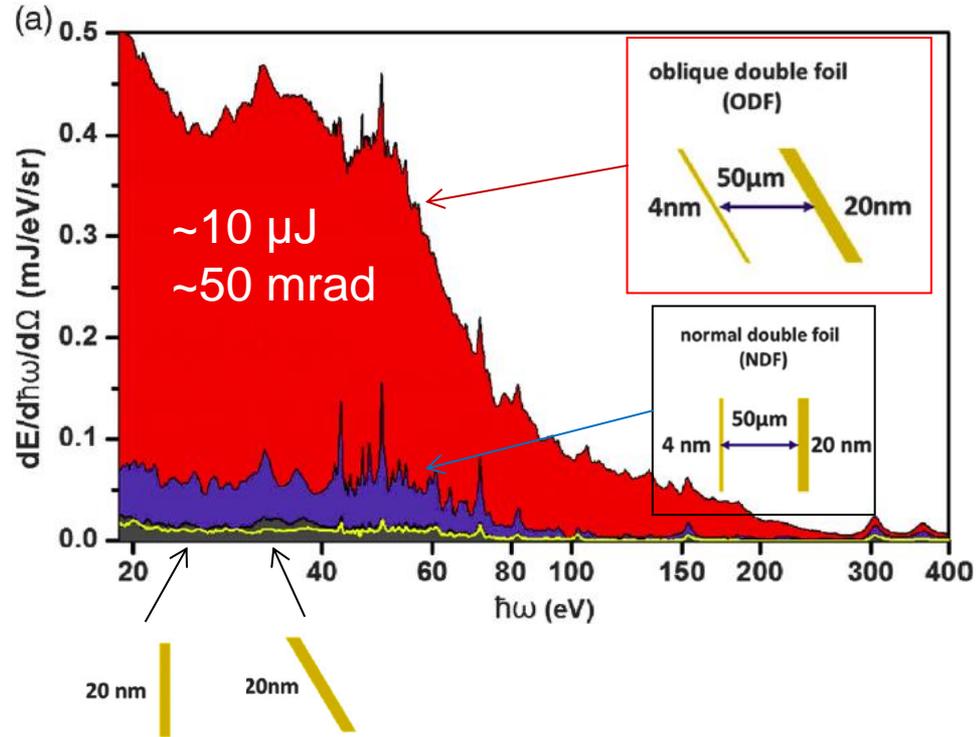
D. Kiefer, JS, et al., Nature Comm. 4, 1763 (2013)

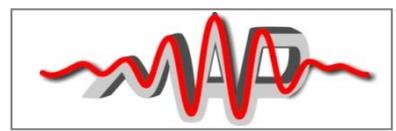


Single, XUV-half-cycle radiation burst from double-DLC foil

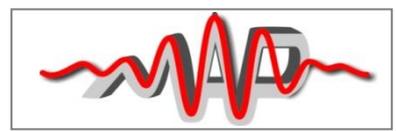


Dense electron bunch is created in Near-critical plasma

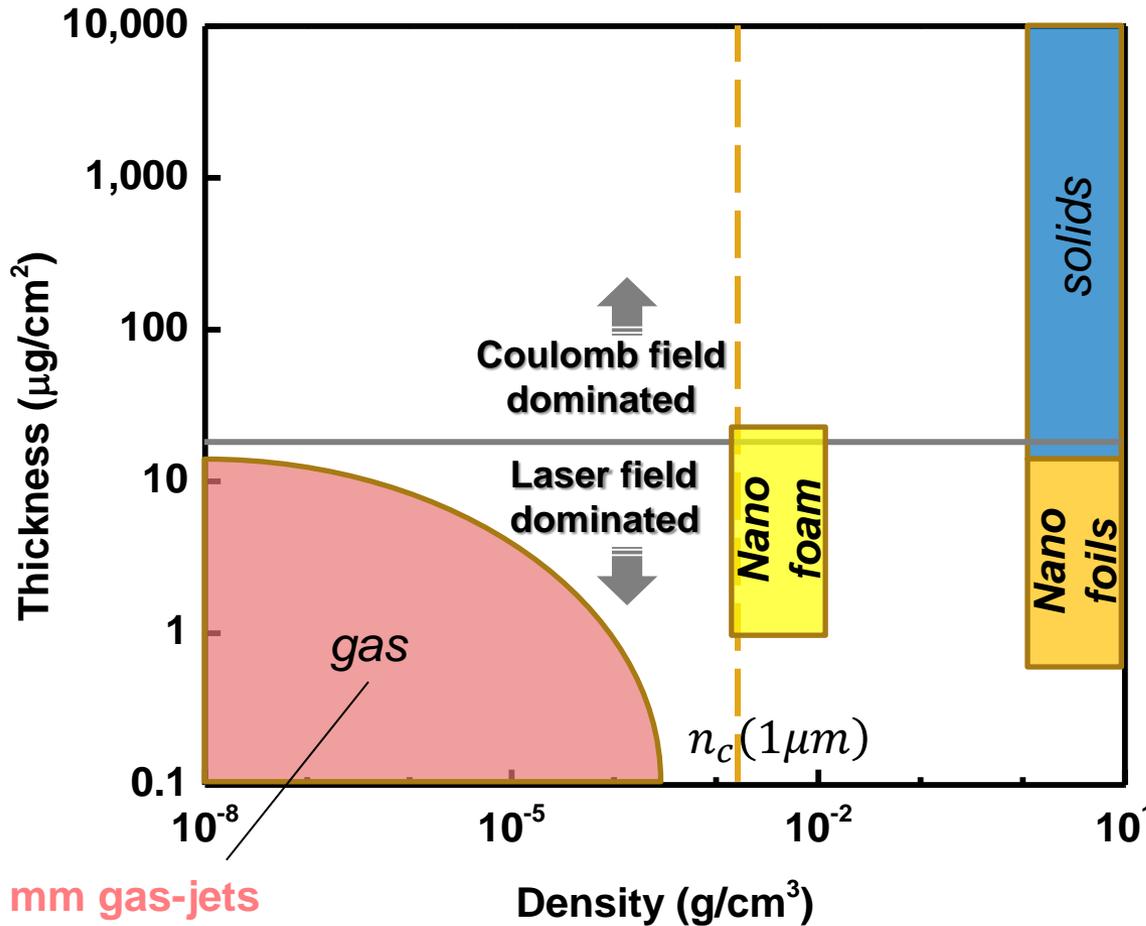




Filling the gap in the target-MAP
... near-critical plasmas



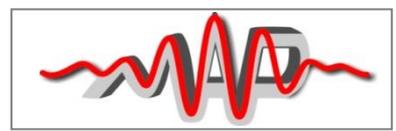
Target-Landscape: Near-critical density for Ti:Sa-lasers



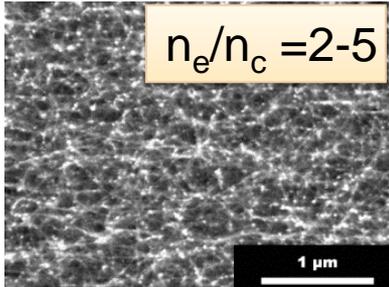
mm gas-jets
electron acceleration

Ion acceleration
Plasma
expansion
(TNSA)

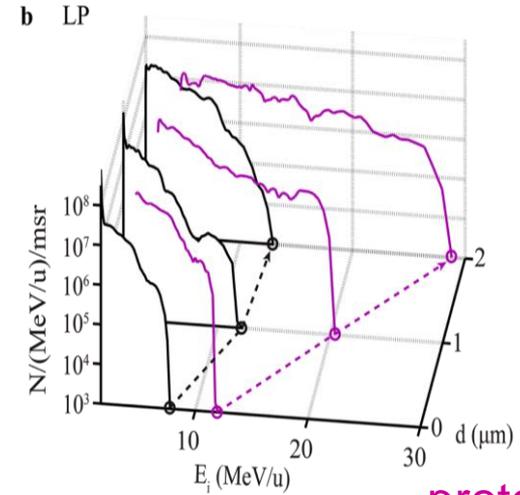
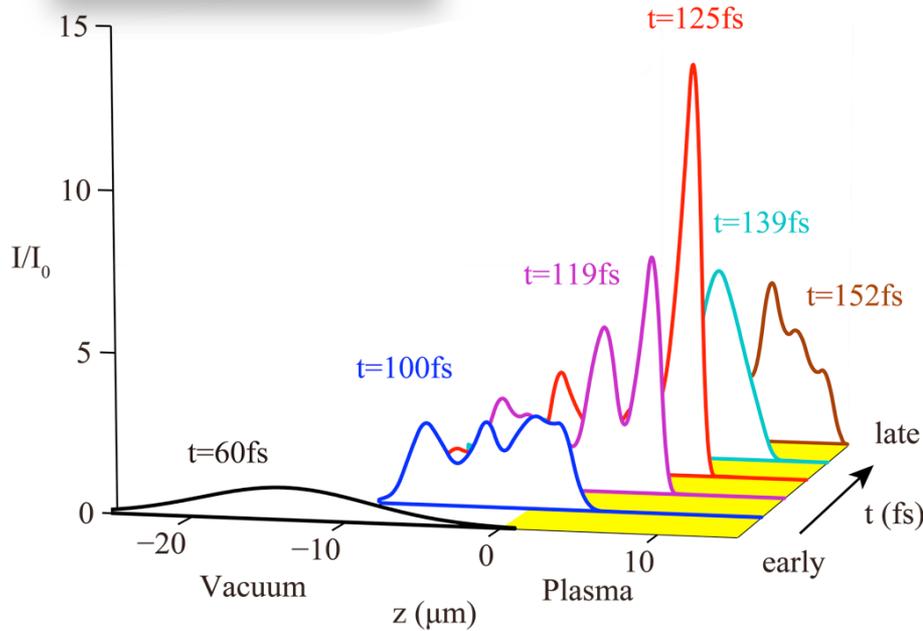
Radiation
Pressure
Acceleration
&
dense
electron
bunches



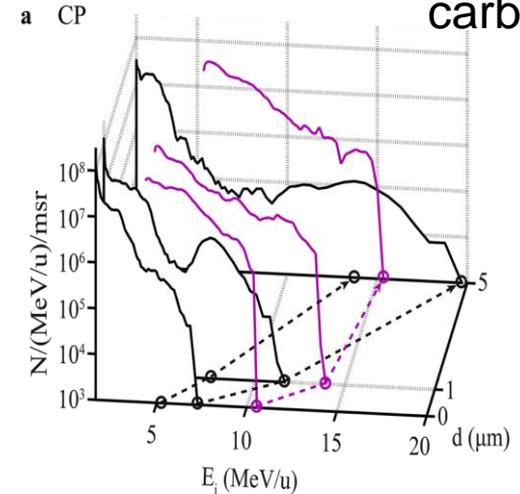
Relativistic self-focusing for ion acceleration (Astra-Gemini, UK)



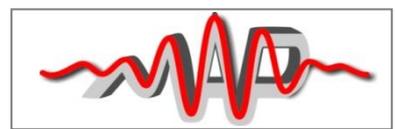
Combination of Carbon-Nano-Tube (CNT) foam with Diamond-like Carbon (DLC) foils



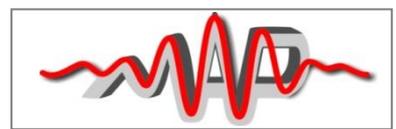
protons
carbons



J. Bin, JS, et al., submitted



What's next? ... Some thoughts, comments.

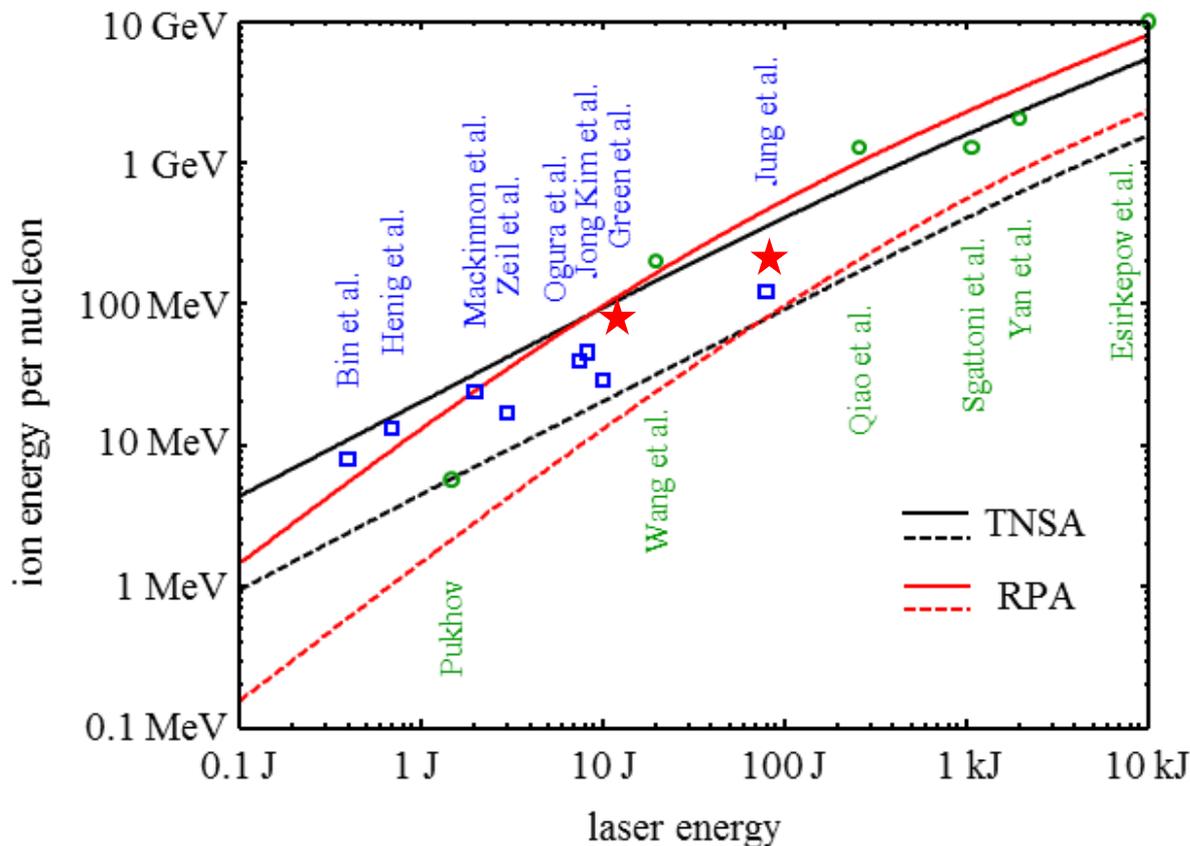


Ion energy frontier

Latest records:

LANL, US: 160 MeV protons (80J/550fs), ~shot/hour

GIST Korea 80 MeV protons (~10J/30fs), ~shot/min



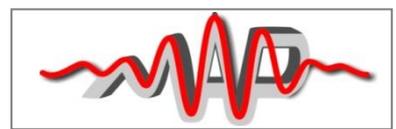
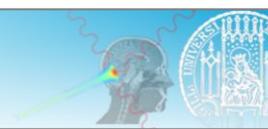
2 μm focus

20 μm focus

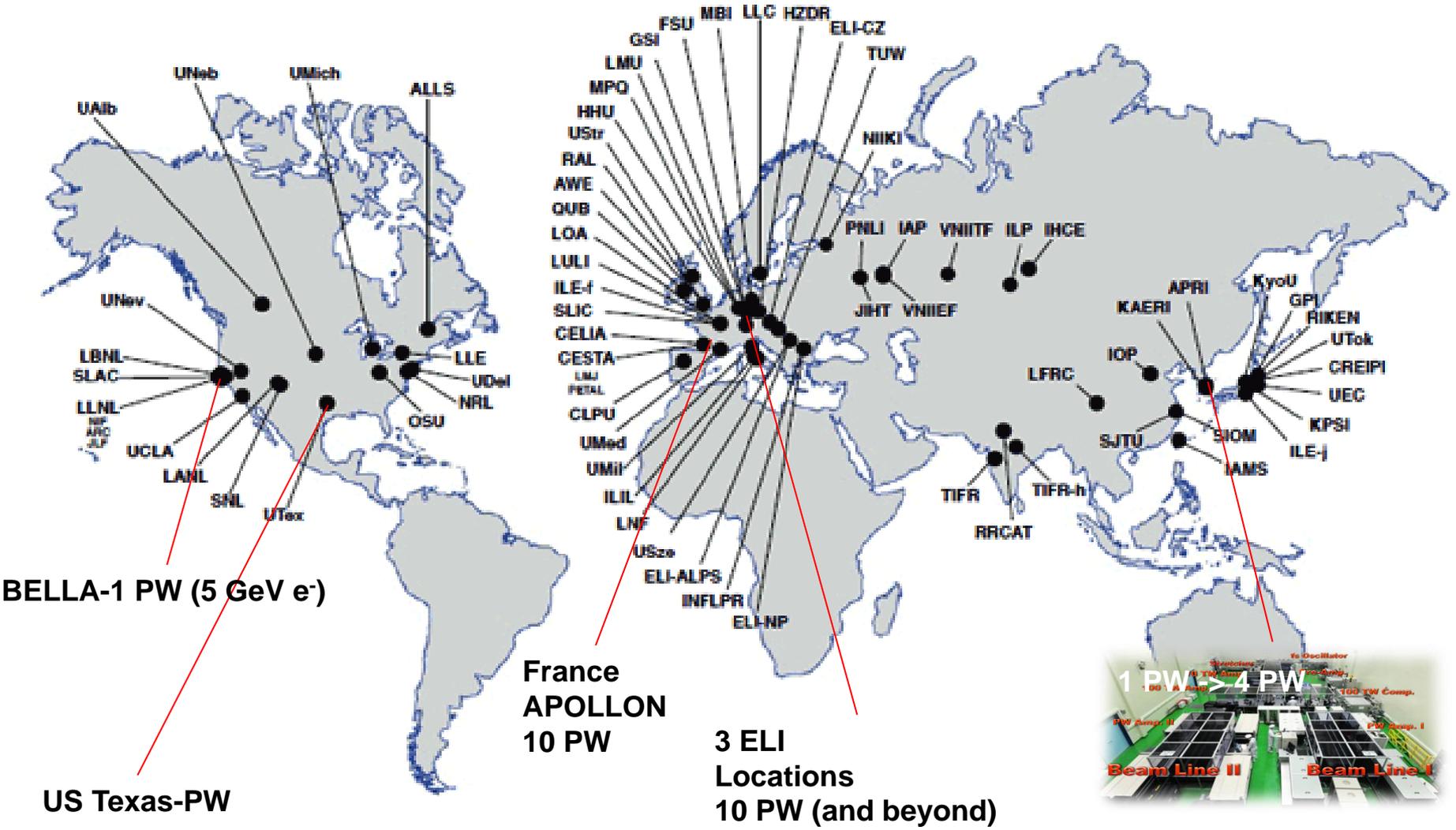
RPA: many ions, possibly mono-energetic

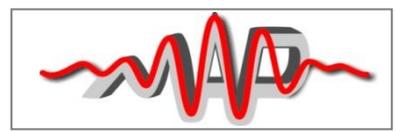
TNSA: few ions, exponential spectra

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

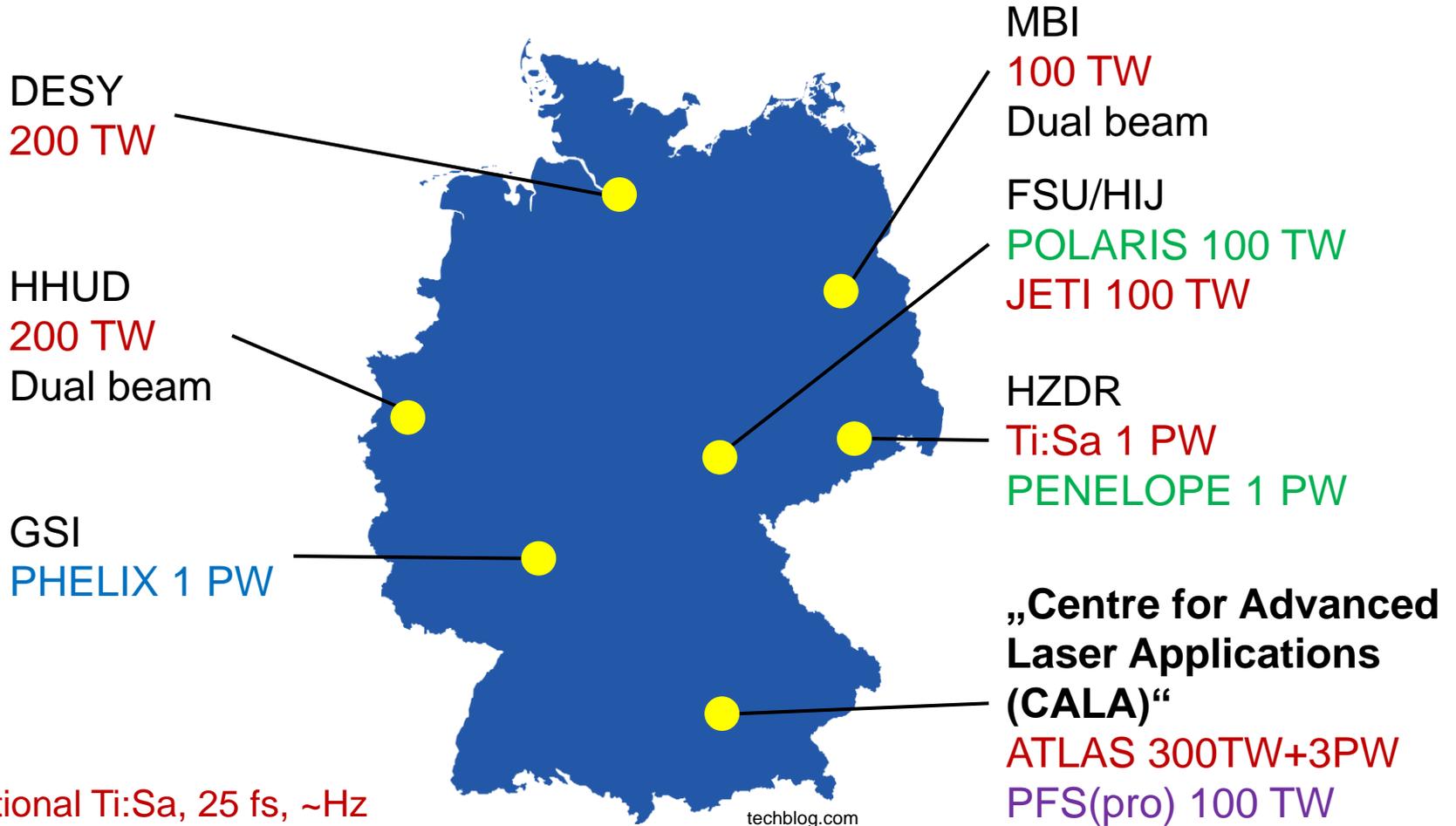


The world of TW- and PW-lasers (compiled by ICUIL organization)





The Germany of TW- and PW-lasers



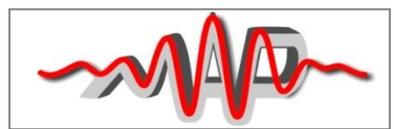
Conventional Ti:Sa, 25 fs, ~Hz

Diode pumped Glass, 150 fs, ~Hz, high wall-plug efficiency

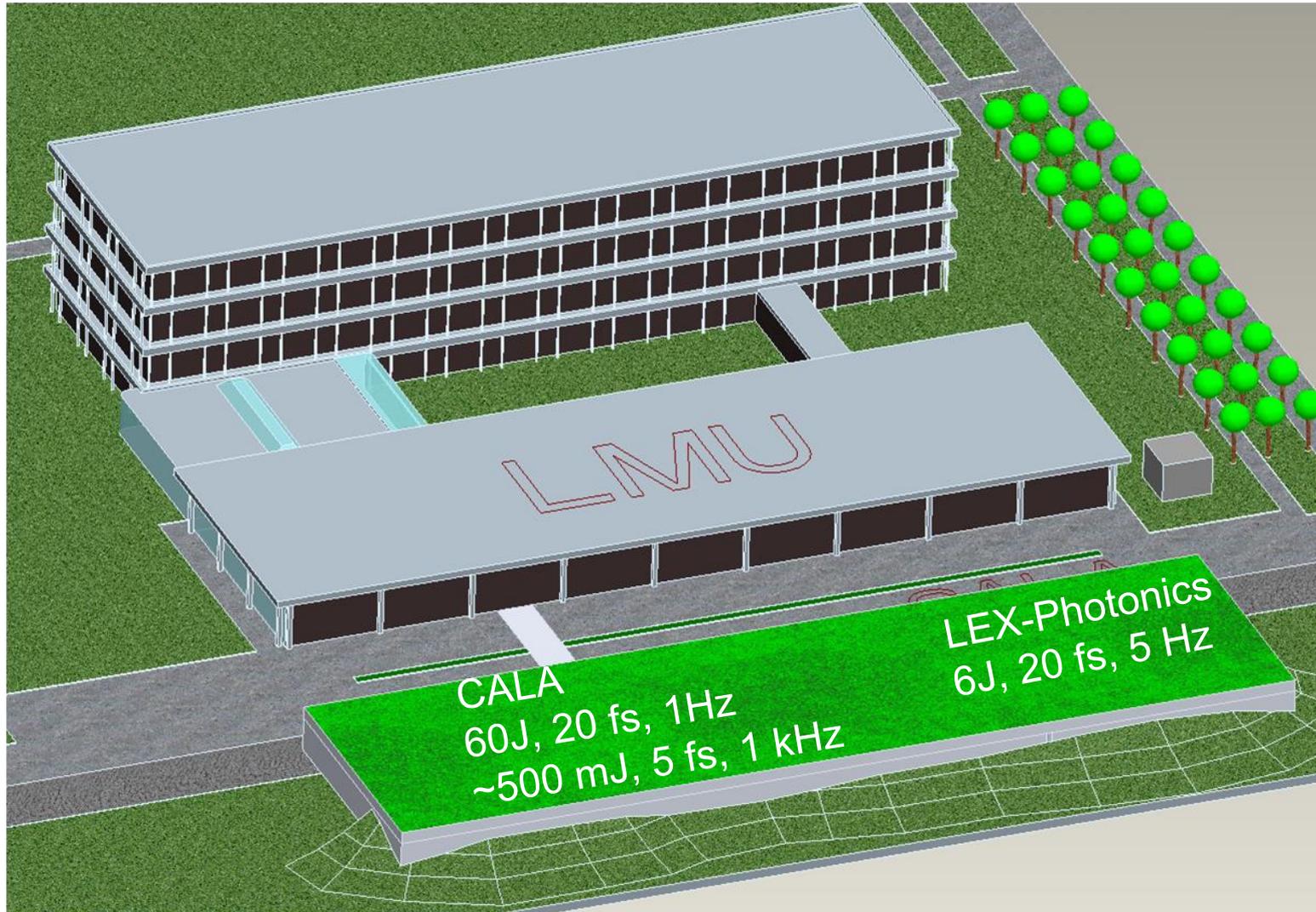
Conventional Glass, 500fs, ~shot/h

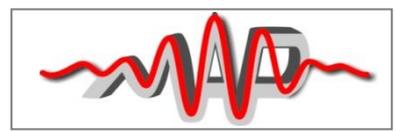
OPCPA, 5 fs, 10Hz~kHz

techblog.com



Centre for Advanced Laser Applications (and LEX-Photonics)





Some impressions

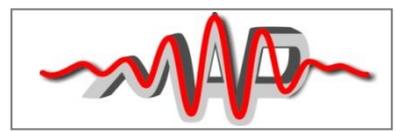
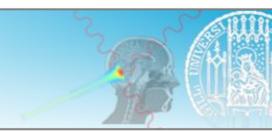
2008

Laboratory for Extreme
Photonics - 2010

Centre for Advanced Laser
Applications - 2014



©2010 Google - Grafiken ©2010 DigitalGlobe, GeoCon

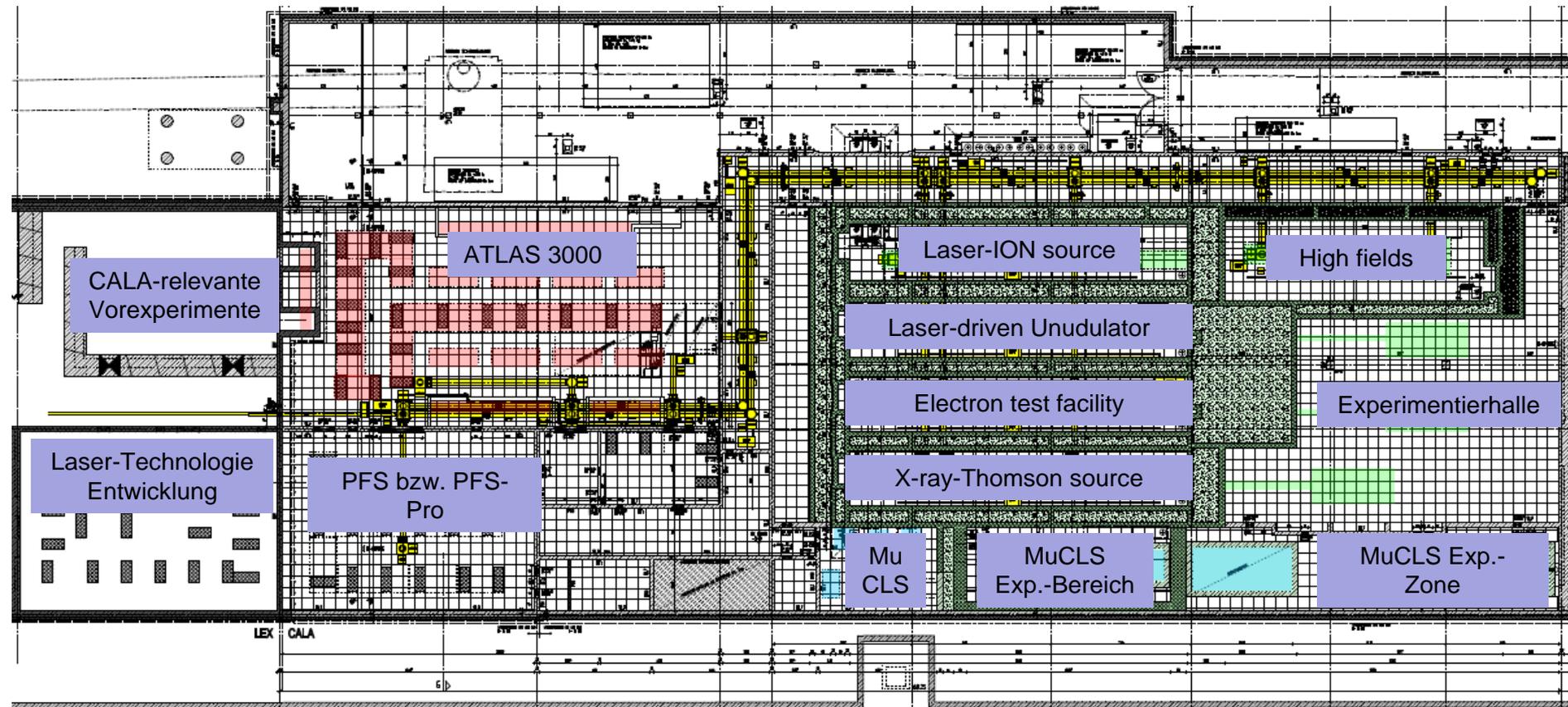


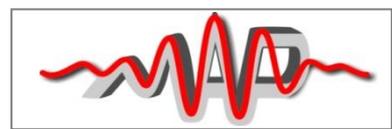
CALA-Layout

~100 m

LEX Photonics

CALA





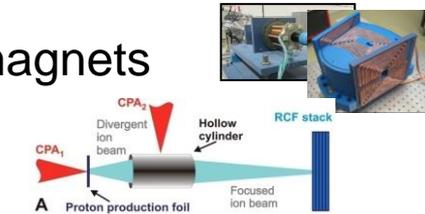
Laser-ion accelerators require adapted technology and application

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

2. Particle-optics

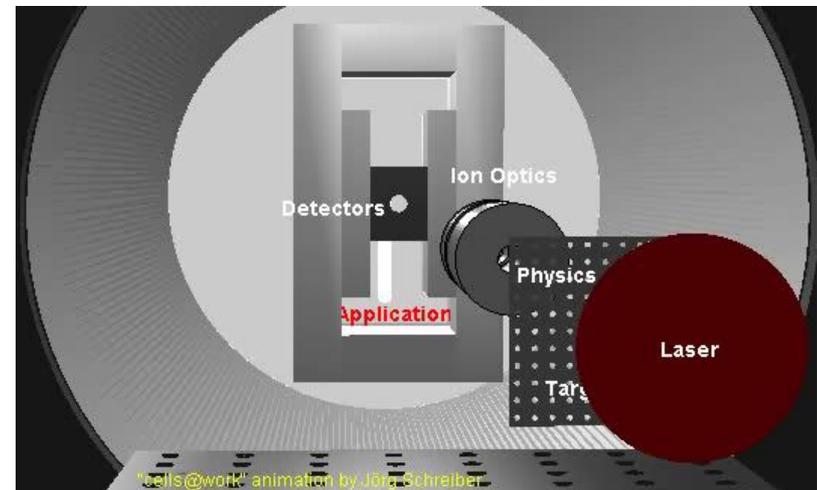
- Standard solutions
- Compact (pulsed) magnets
- plasma-lenses, ...

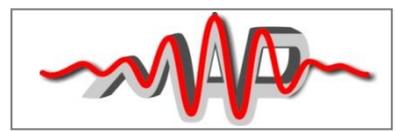


Toncian *et al.*, Science **312** [5772], 410 (2006)

3. Application

- Laser/Ion-energy versus repetition rate/single shot
- broad energy distribution – not a bug but a feature
- Temporal/spatial structure, synchronism between very different types of radiation





Summary and remarks

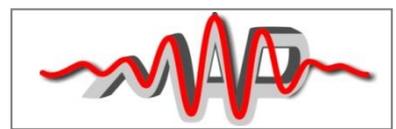
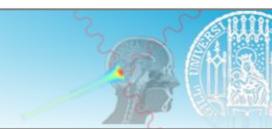
I (We) have witnessed astonishing progress of laser-driven particle accelerators over the past 20 years
(lasers, stability, control)

Intriguing ideas for and novel approaches to applications arise from collaborations amongst the particle and laser-plasma accelerator community, and the respective users of these sources
(MAP/CALA in Munich, ARD of Helmholtz association, AWAKE at CERN)

Realising (and establishing) the Centre for Advanced Laser Applications (and other large-scale facilities, e.g. ELI) is an incredible opportunity. Exploiting laser-based accelerators for medicine remains the grand goal, exploiting laser-driven-features will be mandatory.

We consider complementary (experimental) approaches in many scientific fields

- 2nd workshop targetry for laser-acceleration (April 15, Paris)
- 1st International Symposium on Applications of Laser-particle Accelerators, Nov. 2015 Venice)



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., 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.

