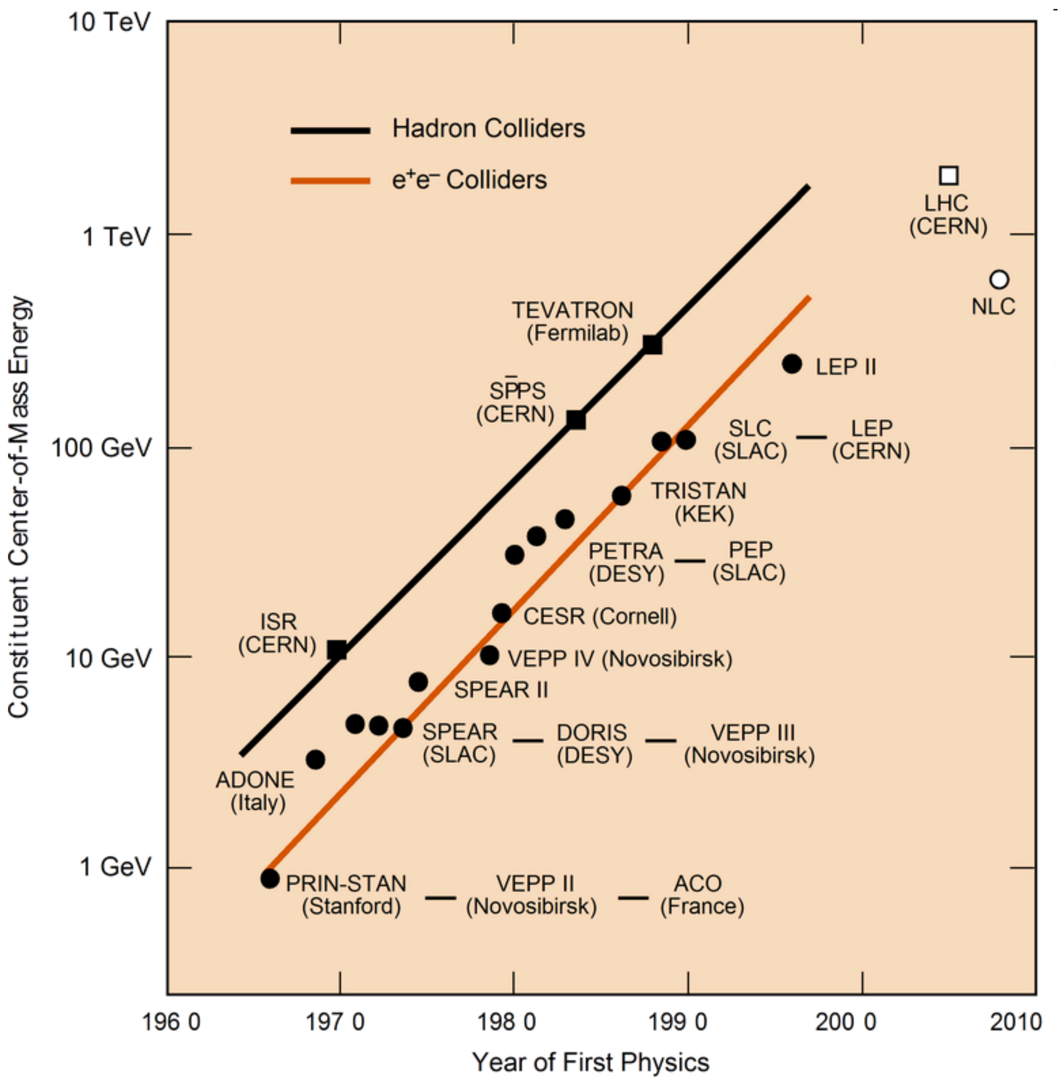
Mitglied der Helmholtz-Gemeinschaft

Autumn Lectures / Tbilisi / 2013

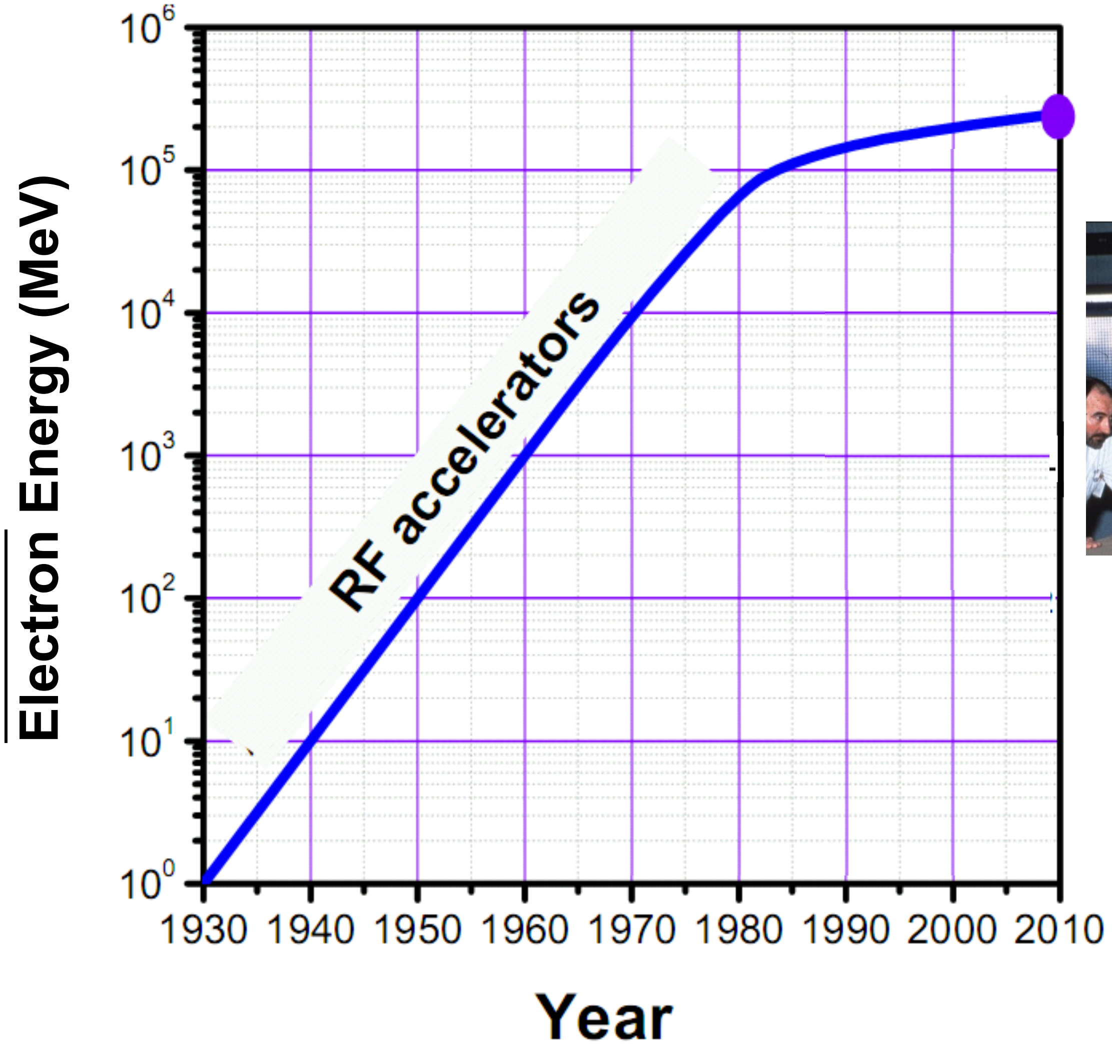
Laser-plasma interactions

22 October 2013 | Markus Büscher

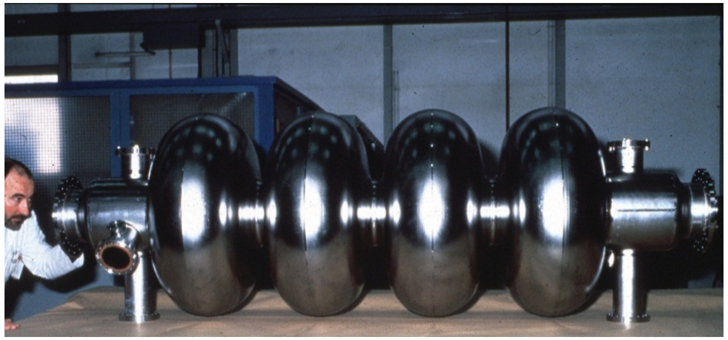
Conventional (RF) accelerators



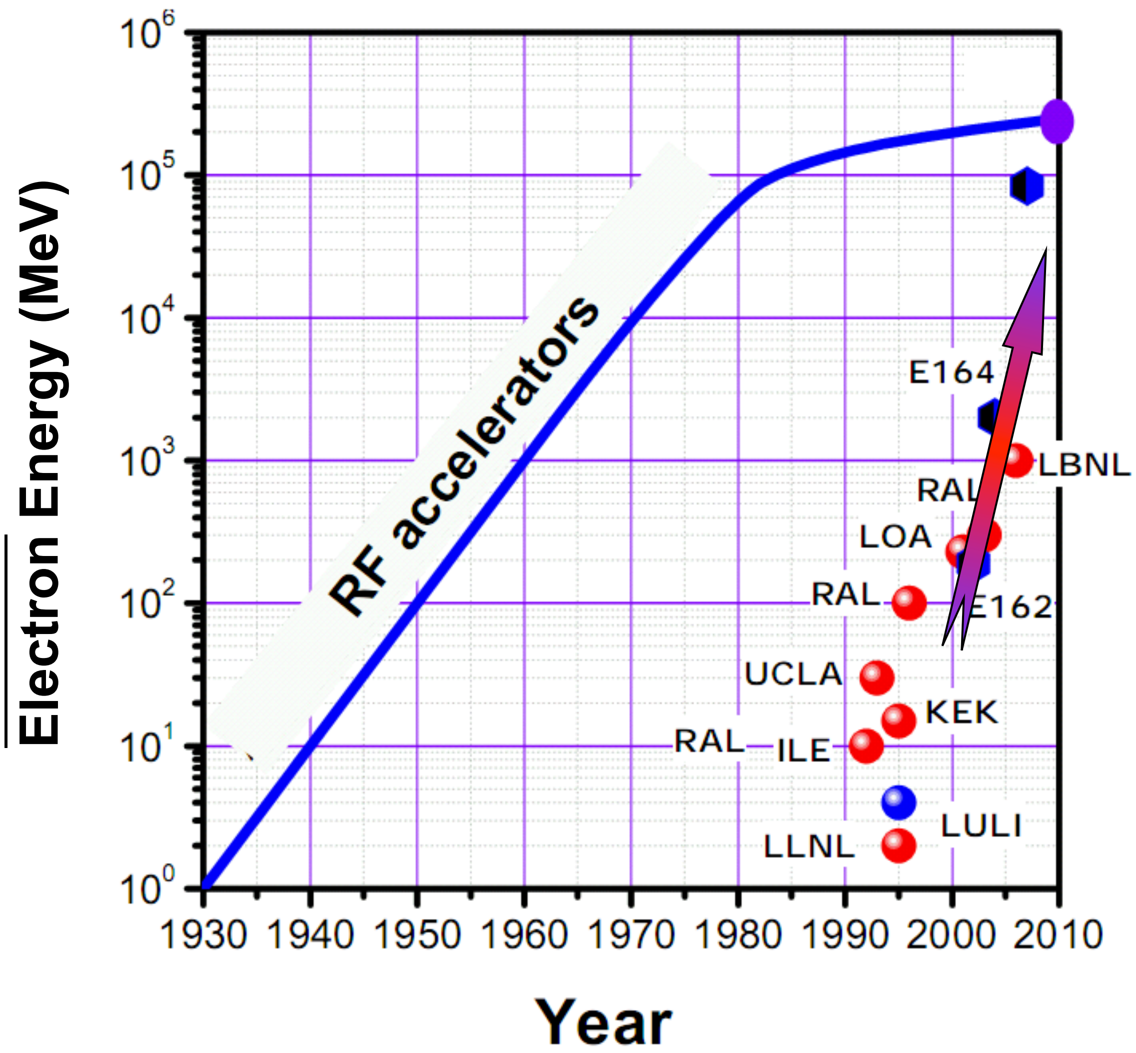
Need for novel approaches



→Accelerating fields ~ 1 MV/m



Need for novel approaches

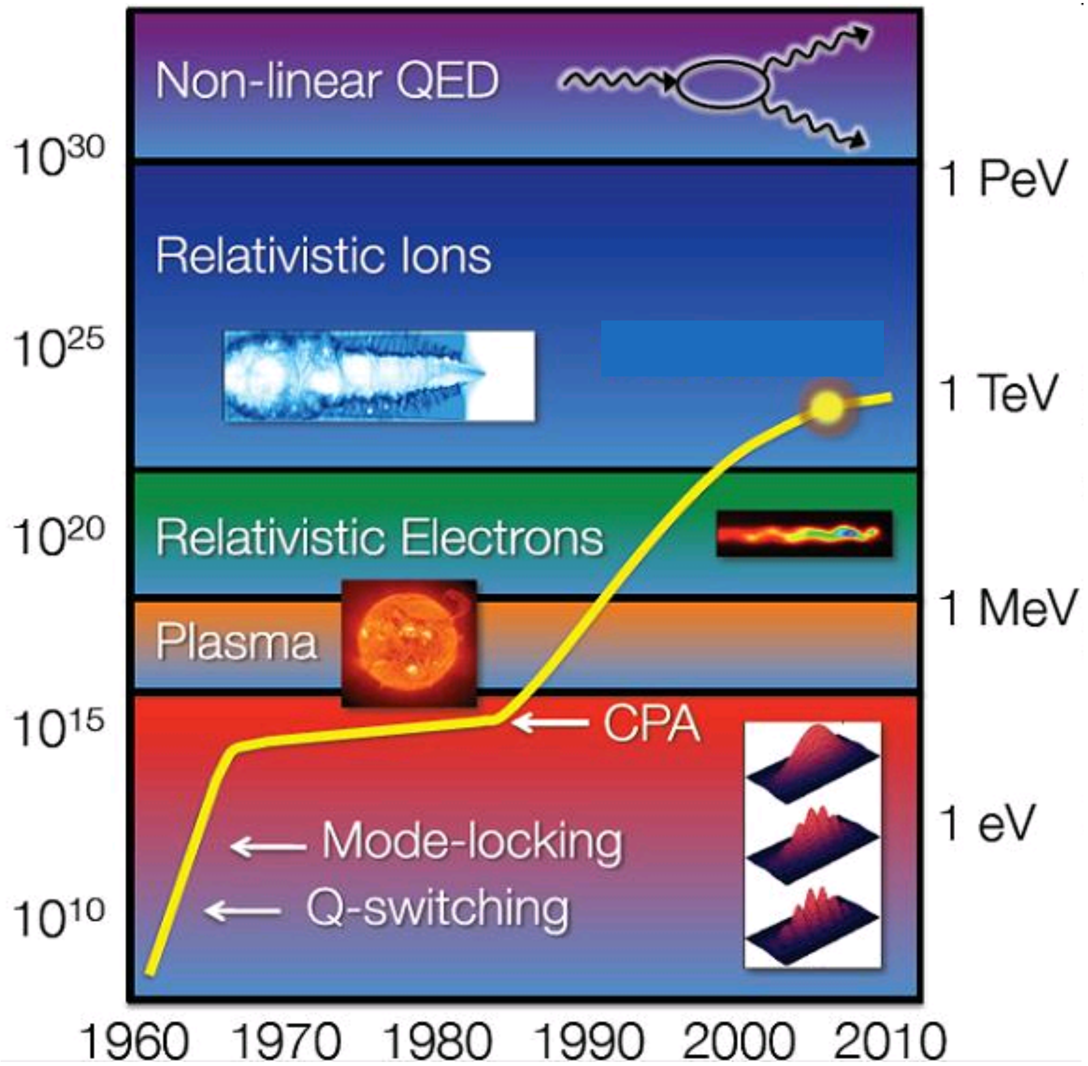


→Accelerating fields ~ 1 MV/m

Laser-induced particle acceleration ~ 100 GV/m

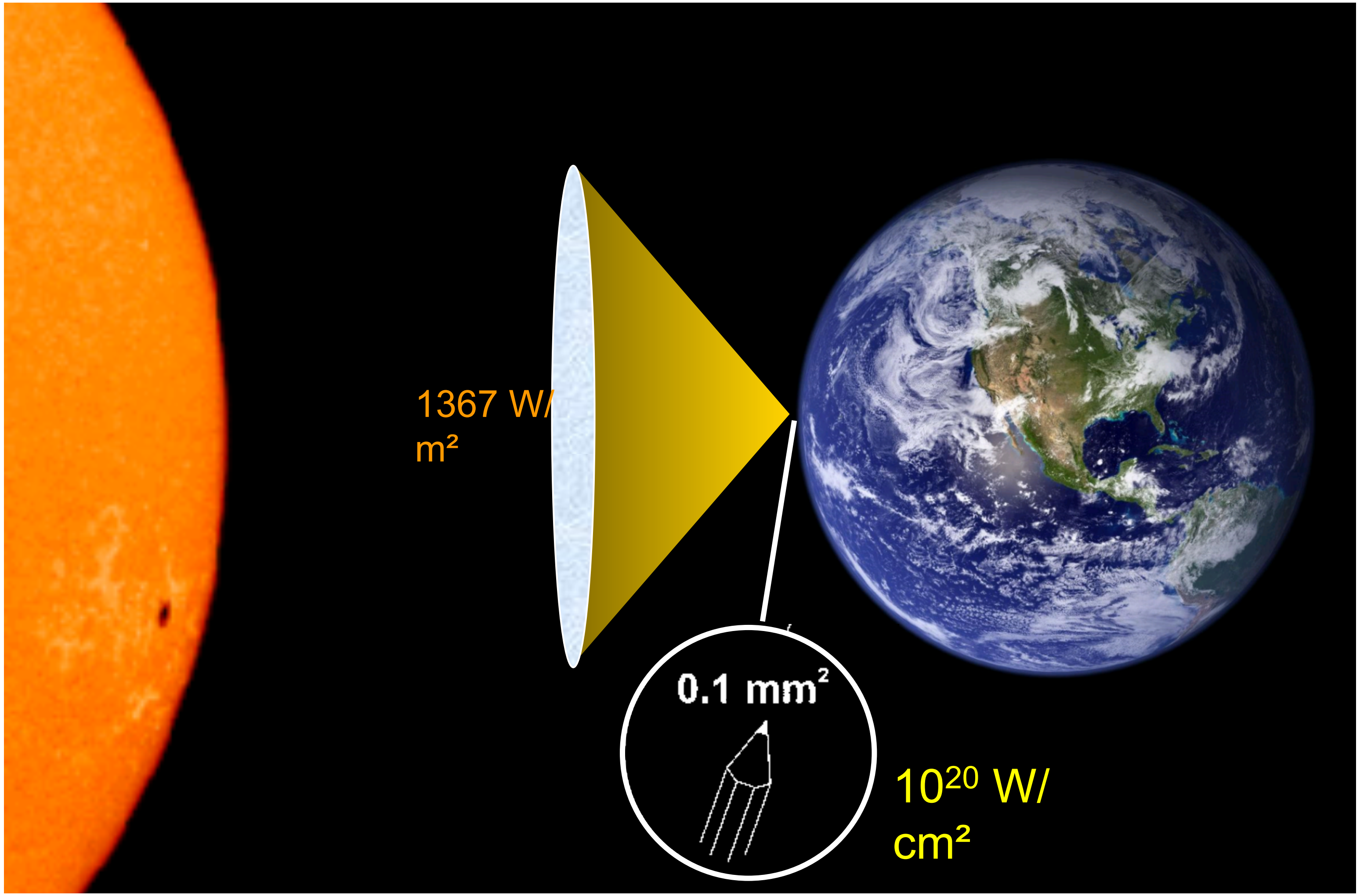
Development of laser intensities

Focussed intensity (W/cm²)



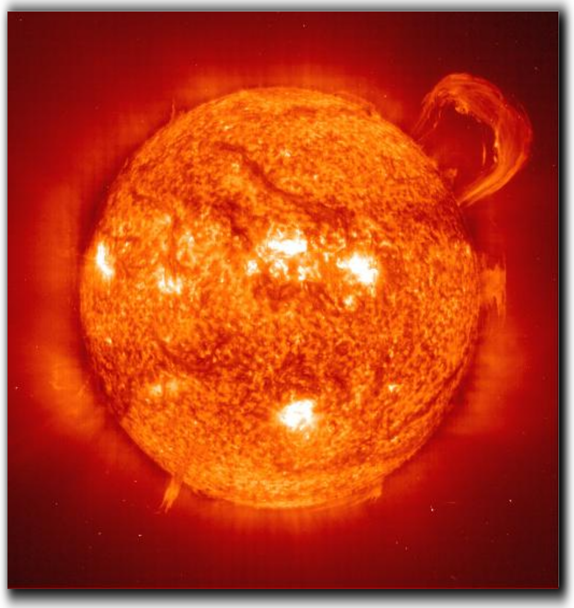
Characteristic electron energy

High intensities …



Extreme conditions …

In the core of the sun, the energy density is about 10^{10} J/cm^3



The energy density produced by a pulse of 500 J and 1 ps in duration, focused into a 5 μm focal spot, is about 10^{11} J/cm^3

The light pressure is in the order of Gigabar (10^9 atm)

This is the basis for the enormous application potential of powerful lasers

Laser: basic properties

LASER = „Light Amplification by Stimulated Emission of Radiation“

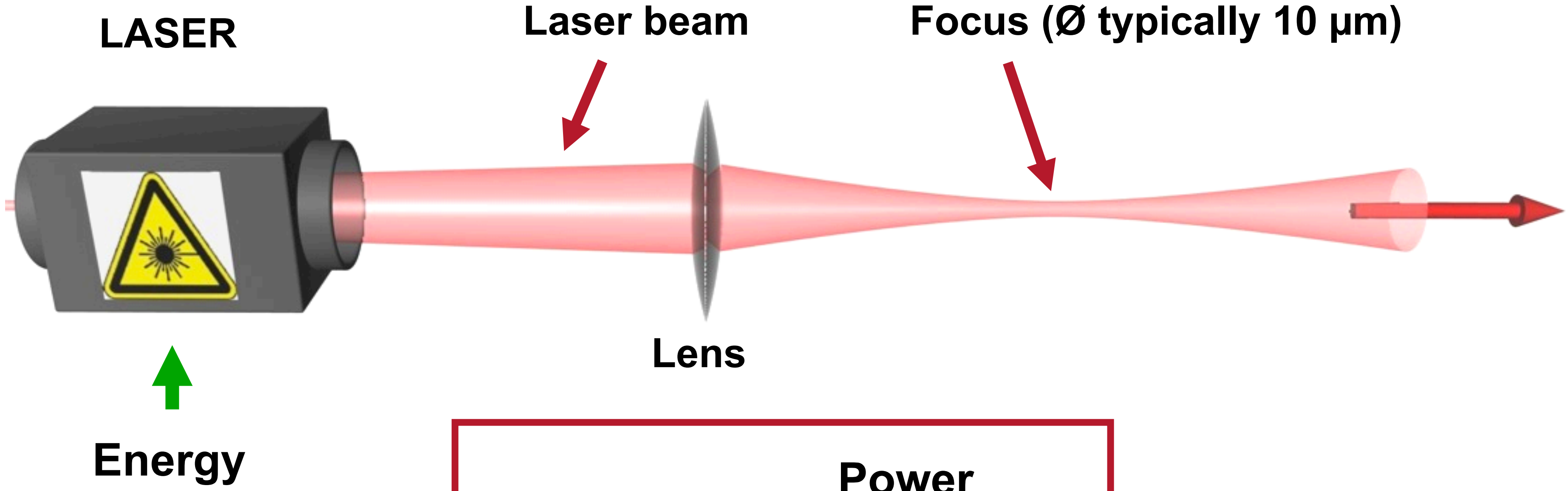
Well defined color (wavelength)

Emission in narrow cone

Coherent oscillations

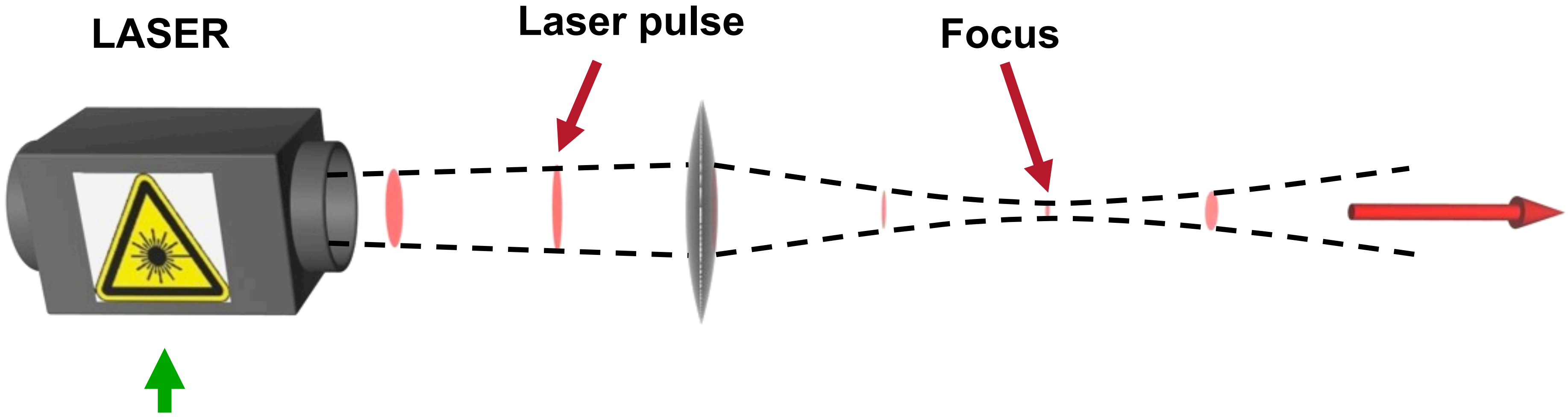
Very high intensities available

Laser: basic properties



$$\text{Intensity} = \frac{\text{Power}}{\text{Area}}$$

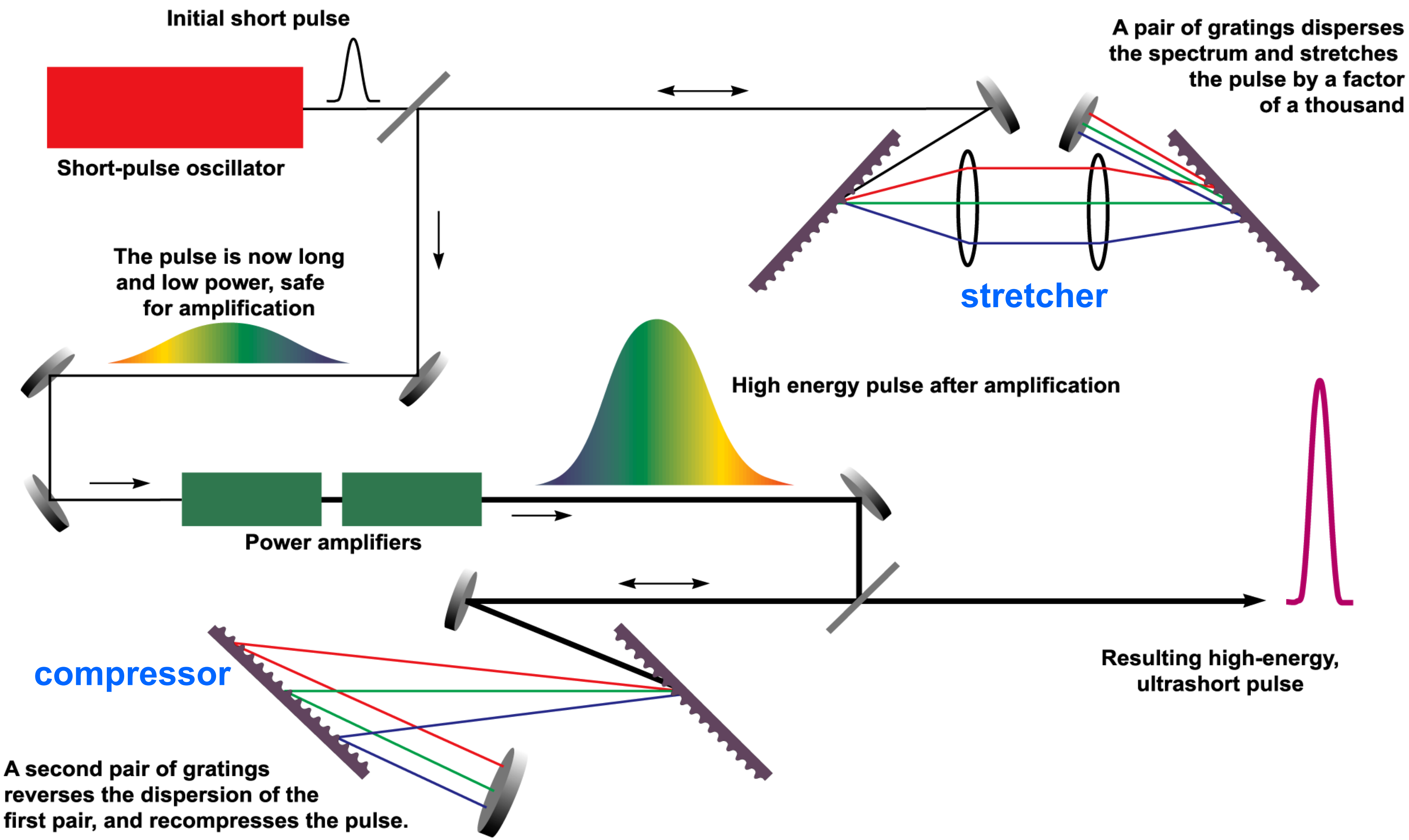
Laser: basic properties



$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

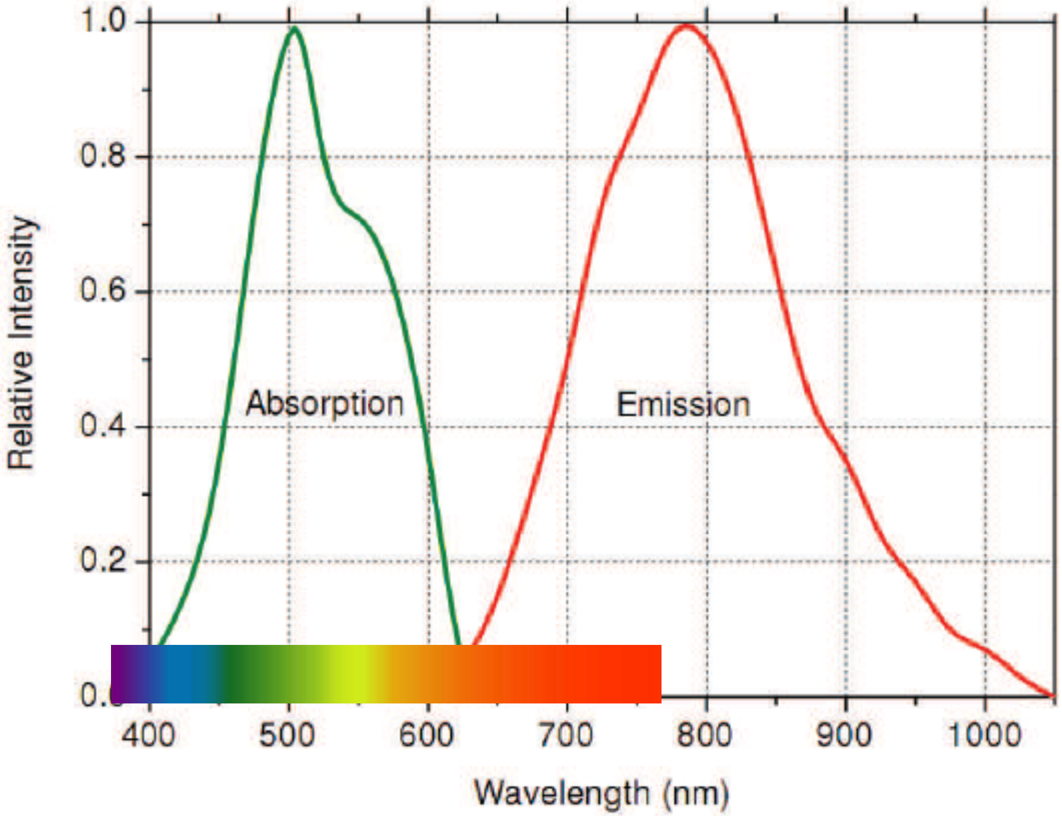
Nowadays peak powers up to Petawatt = 10^{15} Watt are available (*e.g.* 1 Joule in <u>1 fs</u>)

Chirped pulse amplification (CPA)



CPA: Ti:Sa crystals

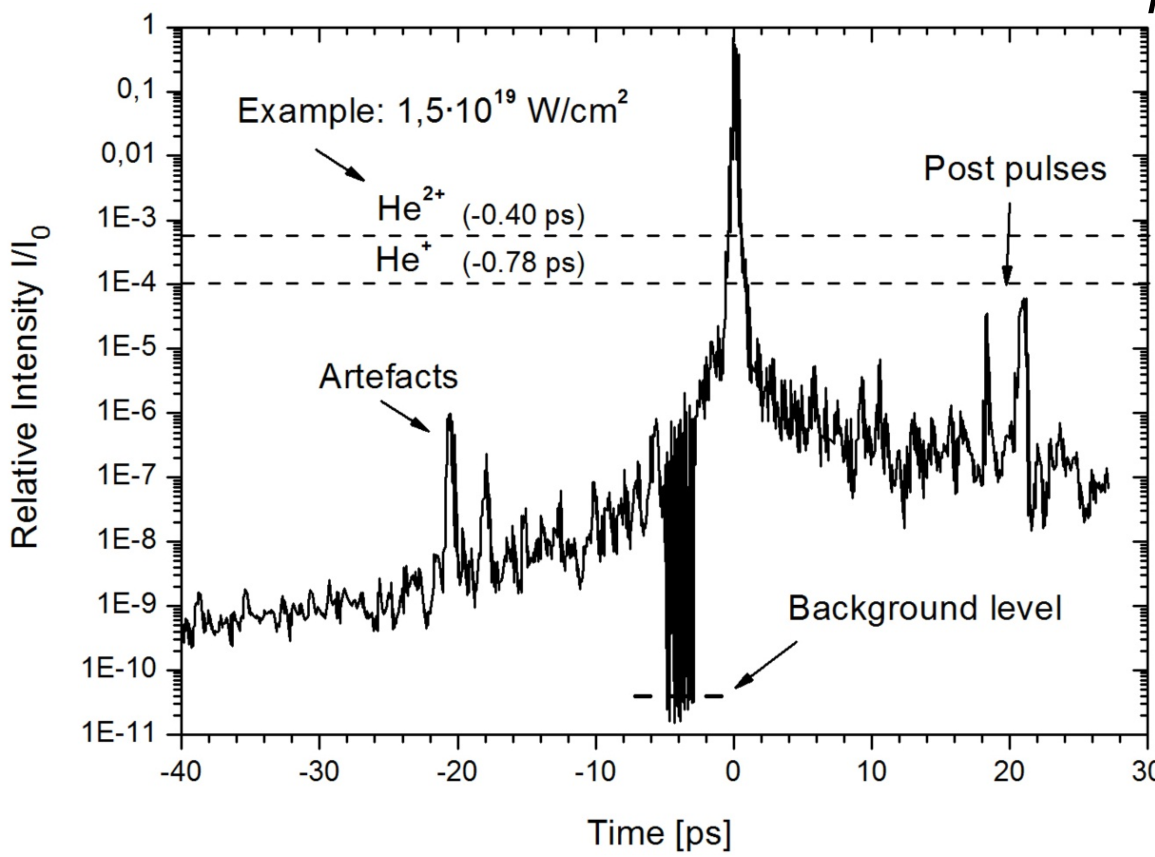
Emission and absorption spectrum



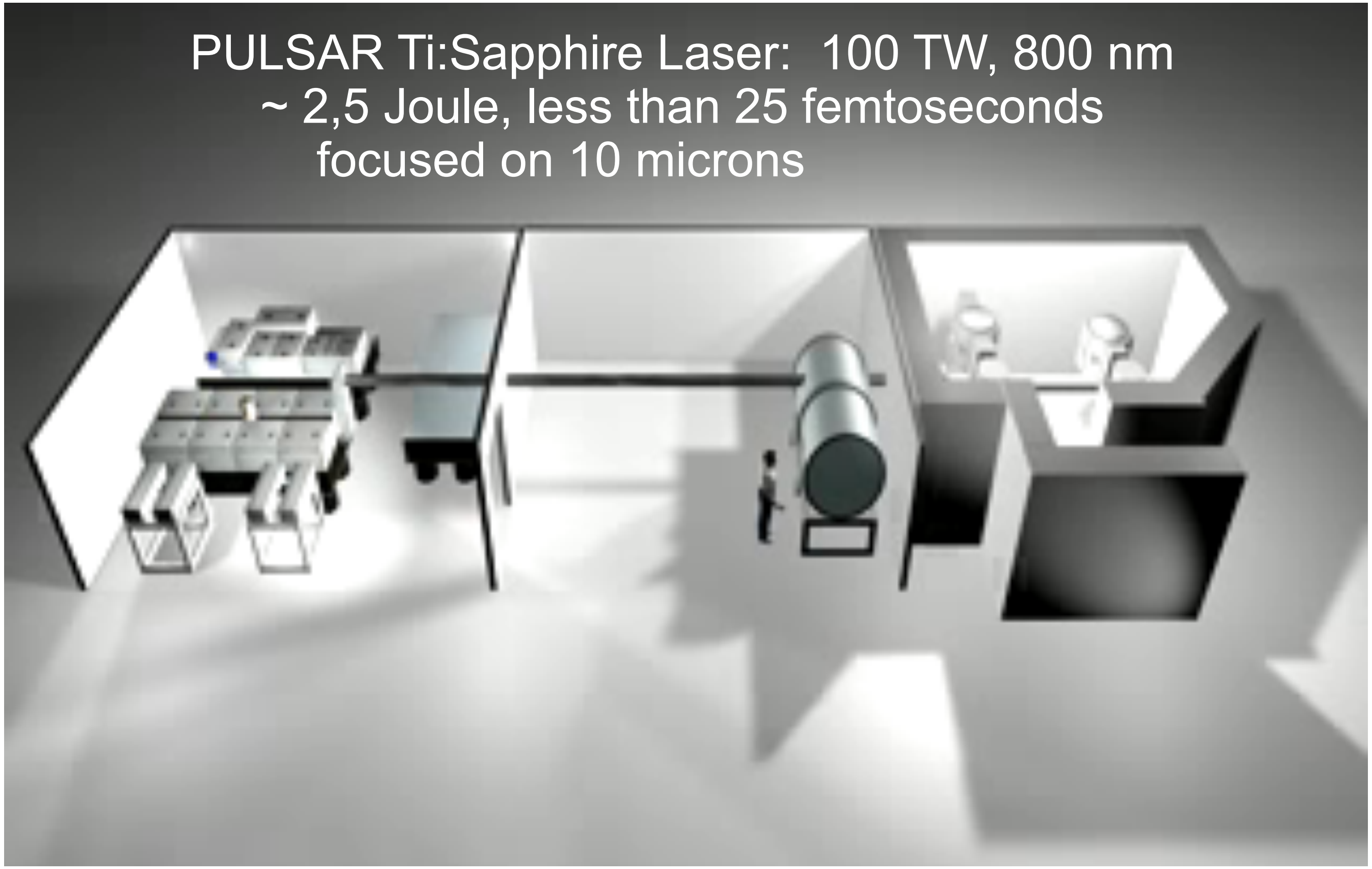
CPA: Pulse shape

Measured at ARCturus / Düsseldorf Univ.

$I_0 \approx 10^{20}$ W/cm²



Institute für Laser- und Plasmaphysik, Univ. Düsseldorf (Prof. O.Willi)



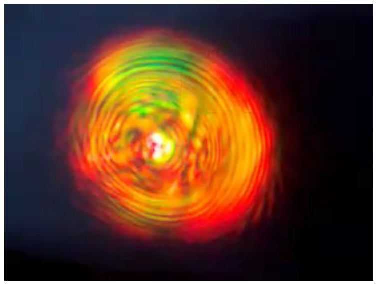
Particle acceleration: typical setup

ultra-short
high-intense
laser pulse

$I \sim 10^{20}$ W/cm^{2}*

target

gas jets
underdense plasma



solid targets
overdense plasma

particles

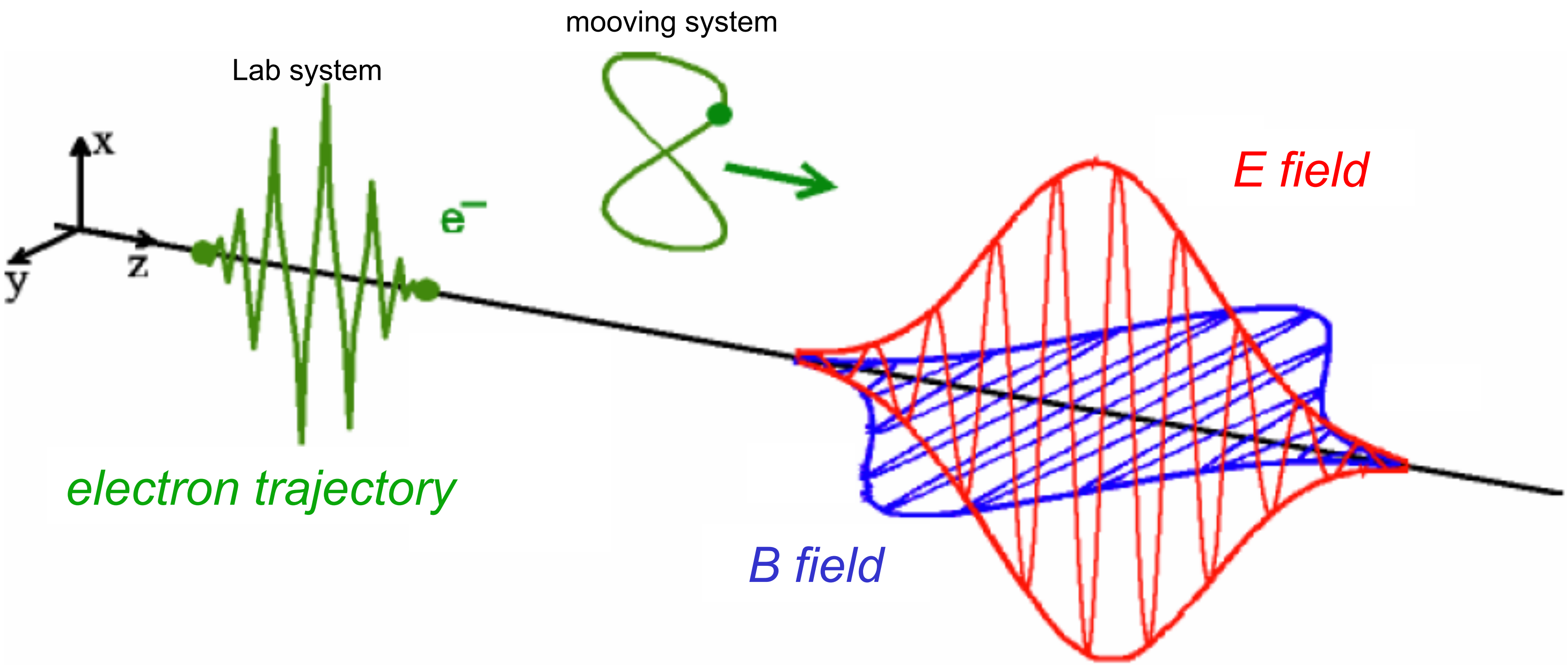
electrons
up to ~100 MeV*

protons / ions
up to ~10 MeV*

Video from: http://www.youtube.com/watch?v=jBjqT3AQkH0&feature=related

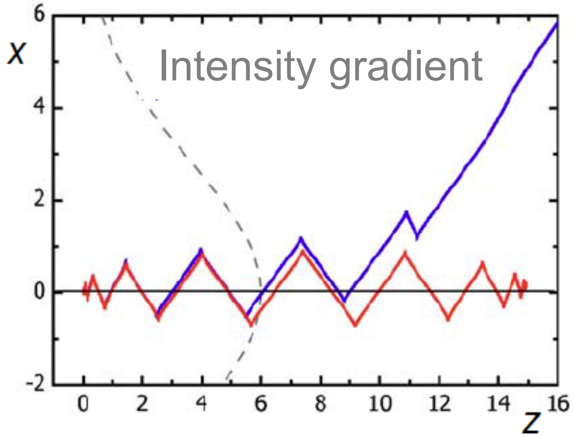
* typical values at HHUD

Response of electrons to plane waves



Electron is at rest again when laser pulse is gone!

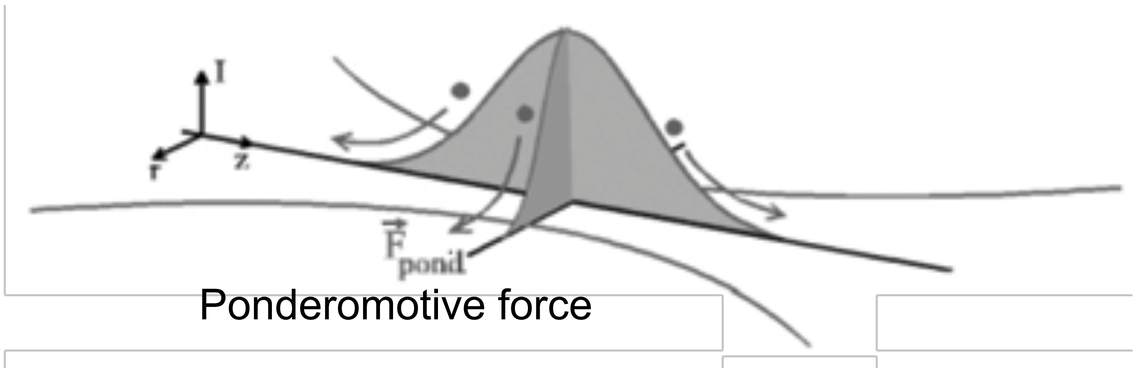
Response to finite wave packet



Response to

focused light pulse

plane wave



Ponderomotive force

Ponderomotive force

Force that a charged particle experiences in an inhomogeneous oscillating electromagnetic field

$$\vec{F}_p = \frac{-e^2}{4 m_e \omega^2} \nabla E_0^2$$

$$U_p\ [\mathrm{eV}] = 9.33 \cdot 10^{-14} \cdot I[\mathrm{W/cm^2}] \cdot \lambda[\mu\mathrm{m}]$$

Acceleration mechanisms

1) Radiation pressure („direct“, thin foil targets)

2) Wake fields / bubbles (gas targets)

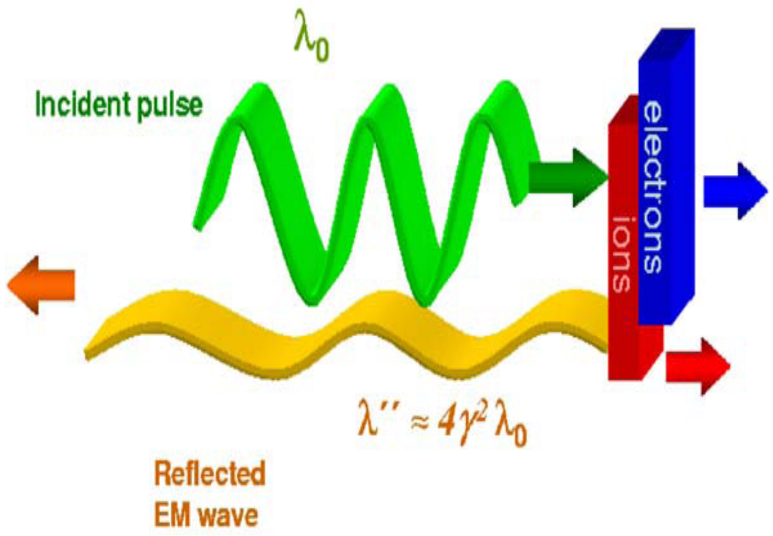
3) Target Normal Sheath Acceleration (foil & pellet targets)

4) Break-Out Afterburner (thin foil targets)

5) …

Radiation Pressure Acceleration (RPA)

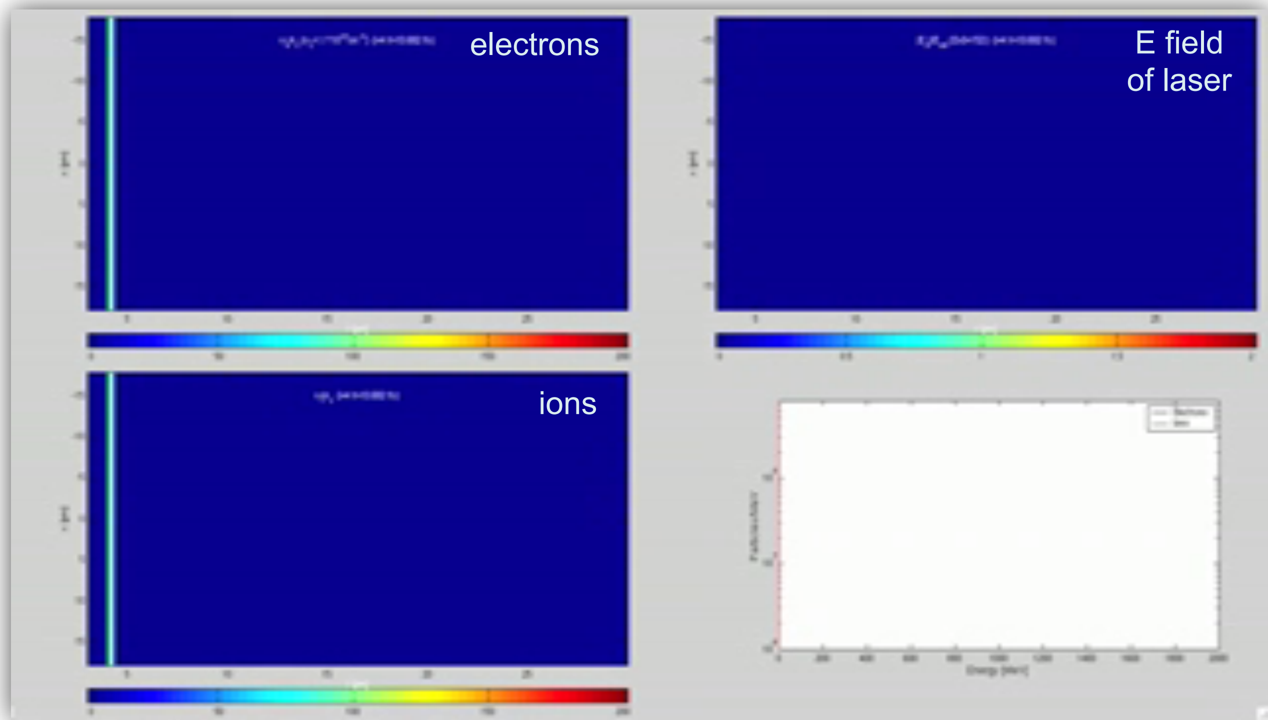
Strong electro-magnetic fields*) in the laser pulse accelerate charged particles



*) Typical values: $E = 3 \cdot 10^{13}$ V/m, $B \sim 10^5$ T @ $I = 10^{20}$ W/cm²

Radiation Pressure Acceleration (RPA)

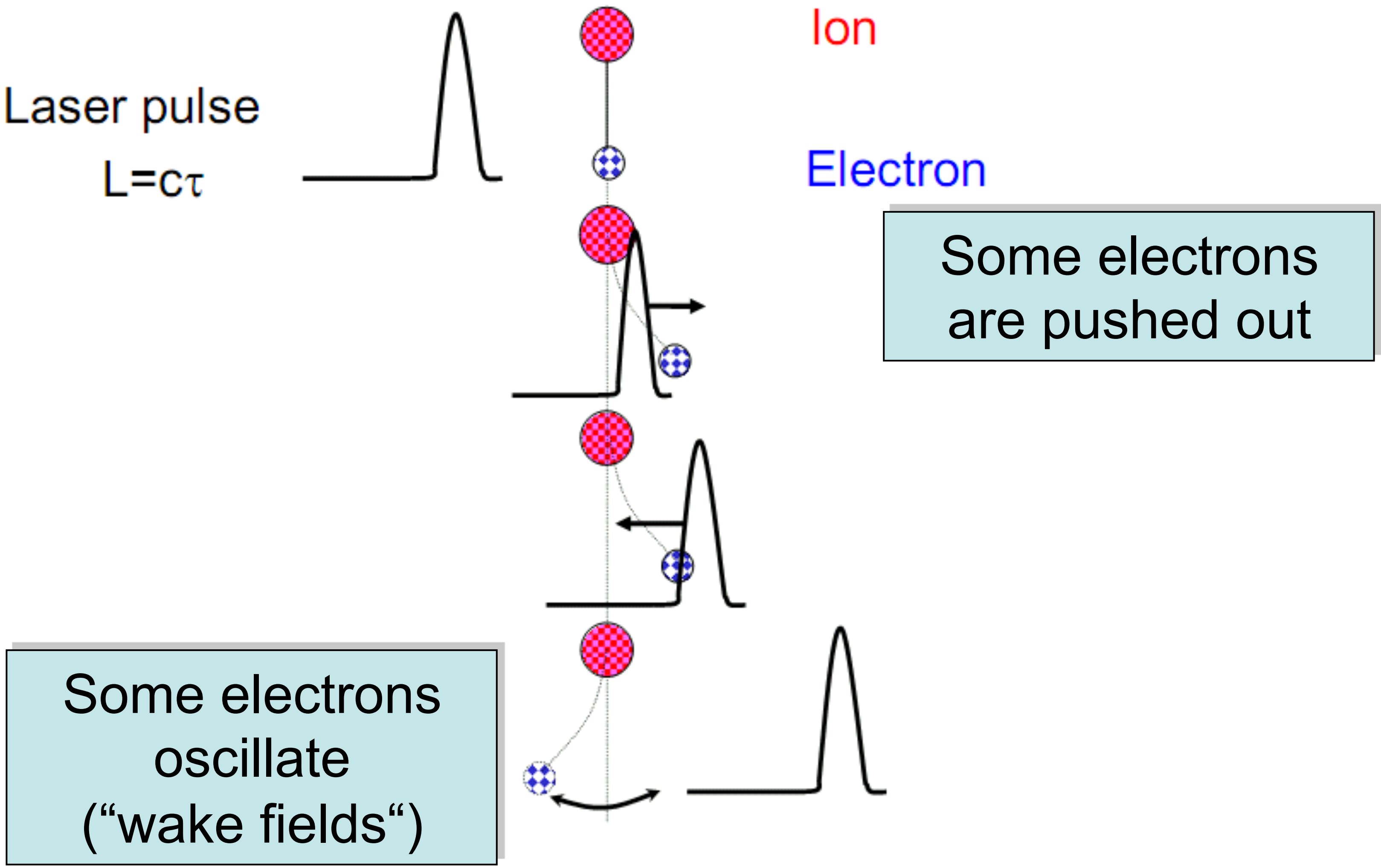
$I_0 = \underline{6 \cdot 10^{22}\ \text{W/cm}^2}$, $n_0 = 1.1 \cdot 10^{23}\ \text{cm}^{-3}\ (100n_c)$, $r_0 = 10\ \mu\text{m}$



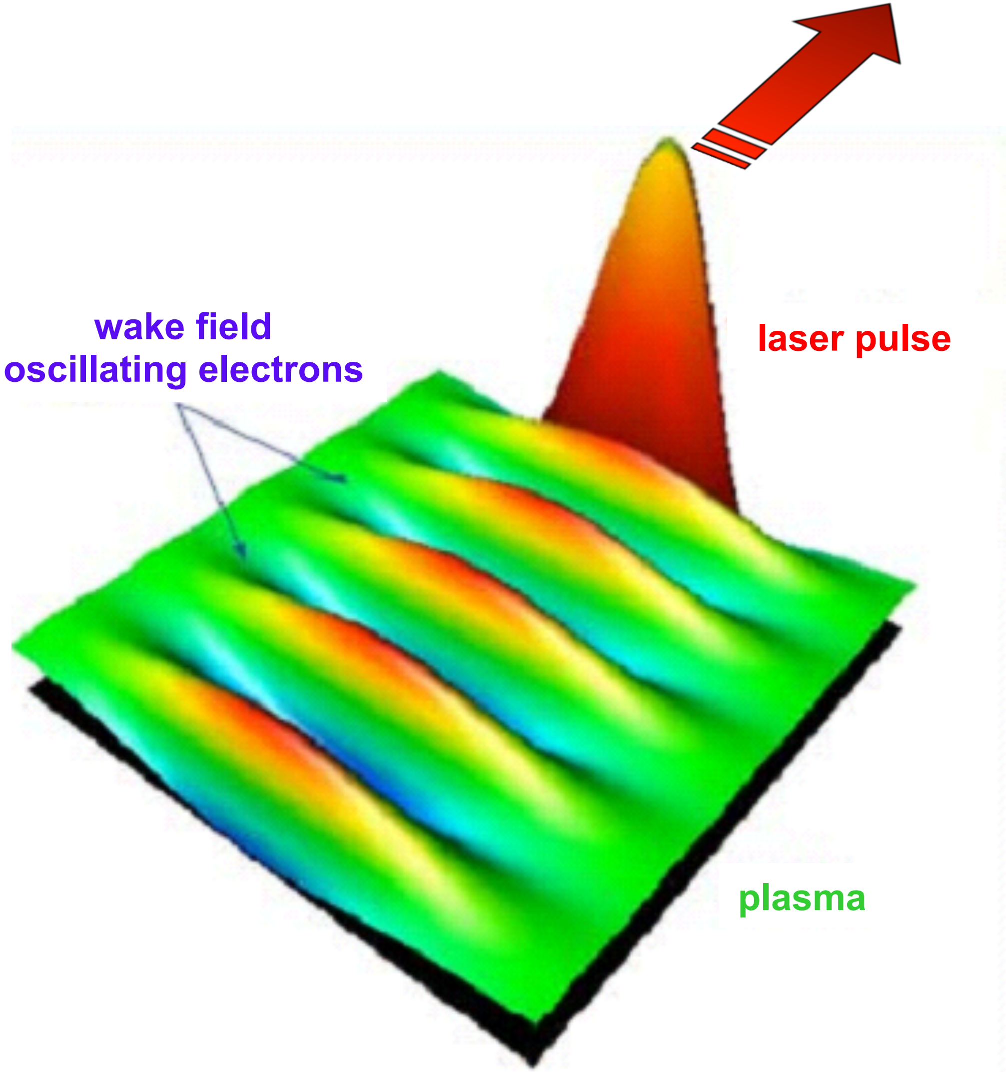
simulation: P.Gibbon, FZ Jülich

see also (for lower laser intensities):
B. Qiao et al., Phys. Rev. Lett. 105, 155002 (2010)
http://www.fz-juelich.de/portal/index.php?index=85#teilchenbeschleuniger

Laser-plasma interaction



Wake fields in plasmas



ϵ_0 m_e

Plasma oscillation

Rapid oscillations of the electron density in conducting media such as plasmas or metals

Frequency only depends weakly on the wavelength

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

$$f_p[\text{Hz}] \approx 8980\sqrt{n_e[\text{cm}^{-3}]}$$

n_e = electron density
e = electron charge
m_e = electron mass
ε_0 = permittivity of vacuum

Critical plasma density

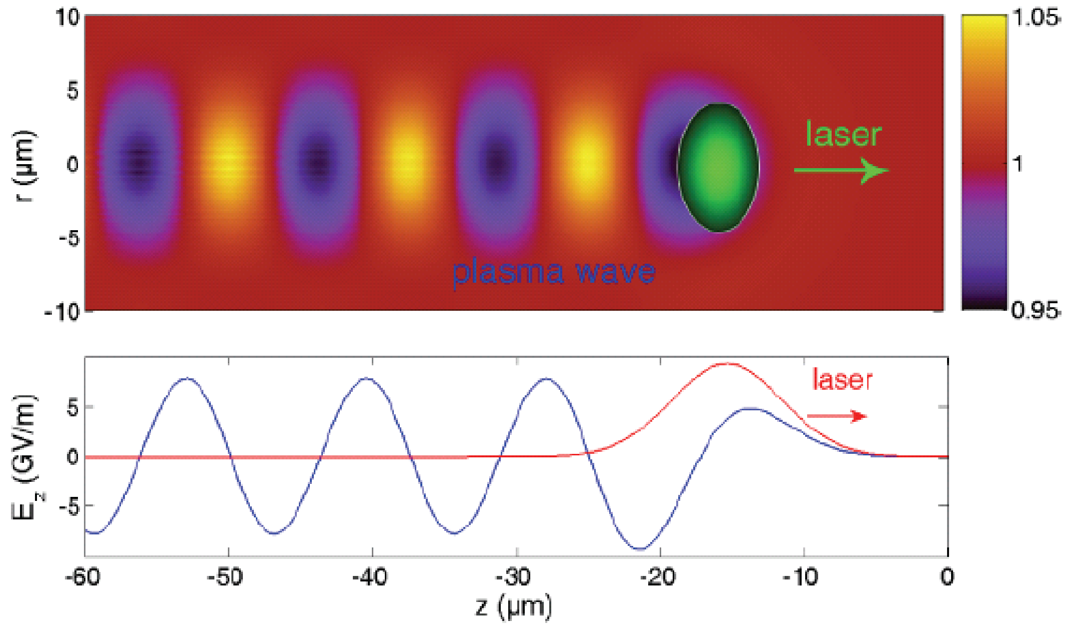
$$n_{\mathrm{cr}}[\mathrm{cm}^{-3}] \approx 1.1 \cdot 10^{21} / \left(\lambda_{\mathrm{Laser}}[\mu\mathrm{m}]\right)^2$$

$n_e \ll n_{cr}$ ⟶ wave speed = speed of light
⟶ plasma transparent, "under-dense plasma"
⟶ gas targets

$N_e \gg n_{cr}$ ⟶ plasma electrons "short-circuit" Laser *E*-field
⟶ wave is damped & reflected, "over-dense plasma"
⟶ solid (foil) targets

Wake fields: low laser intensity

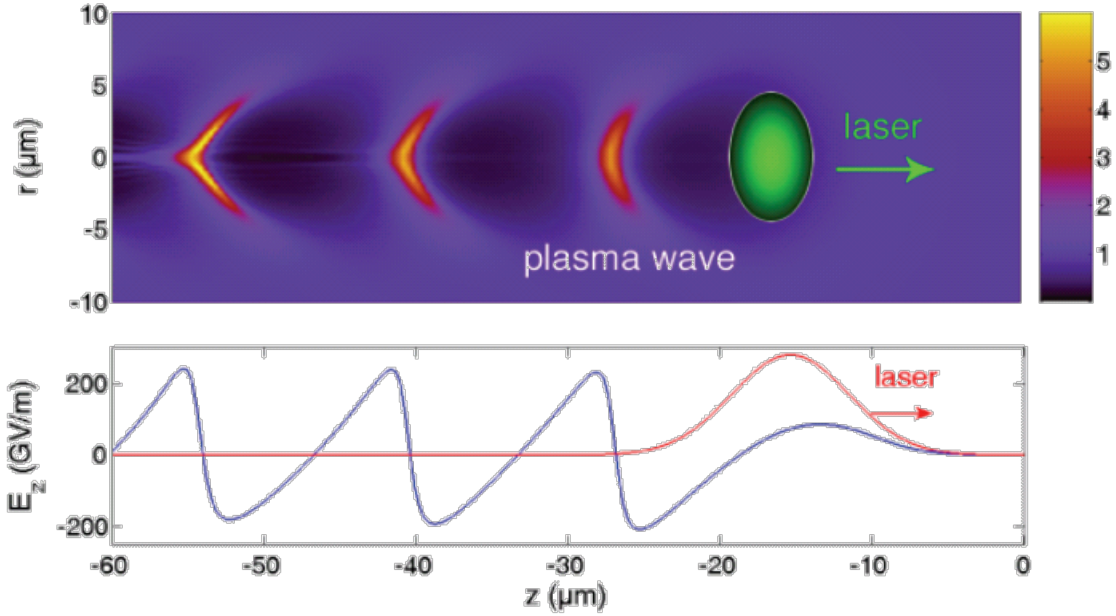
Electron density perturbation & longitudinal wake field



V.Malka et al., Nature Physics 4, 447–452 (2008)

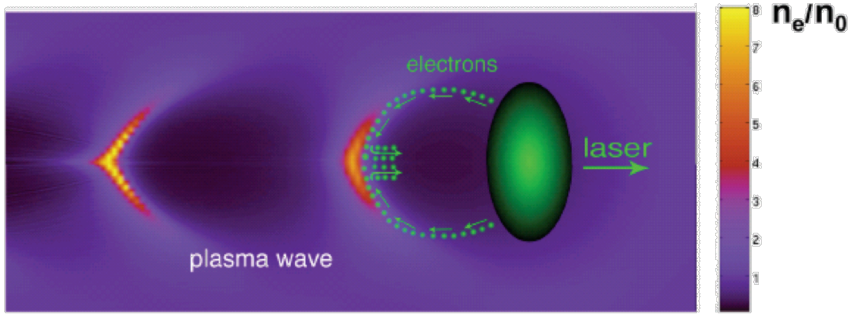
Wake fields: high laser intensity

Electron density perturbation & longitudinal wake field

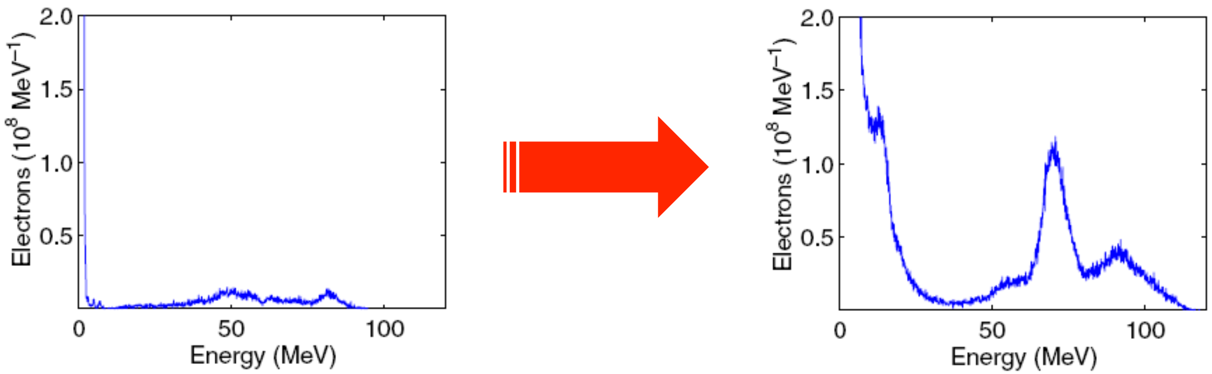


Wake fields: bubble regime

A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B 74, 355–361 (2002)



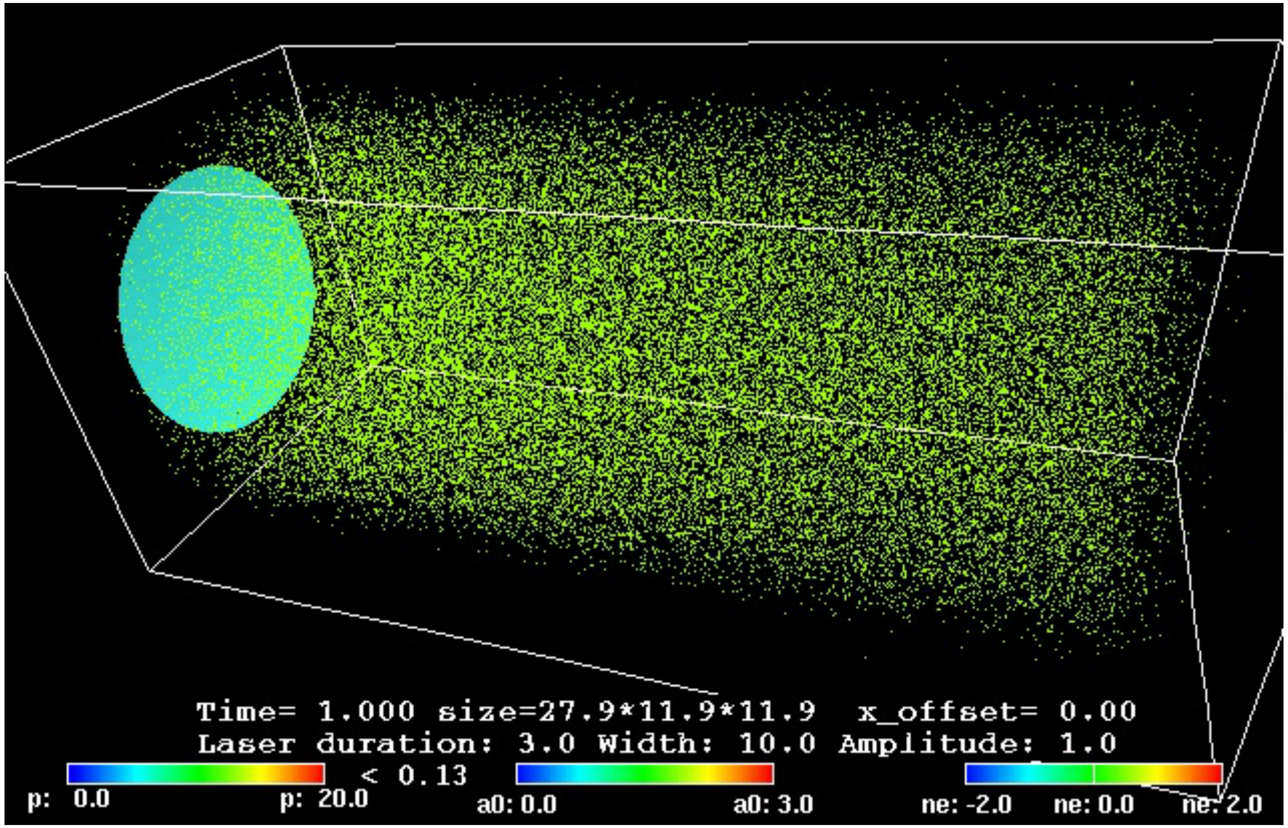
surfing behind a wake boat



M. Geissler et al., New J. of Phys. 8, 186, (2006)

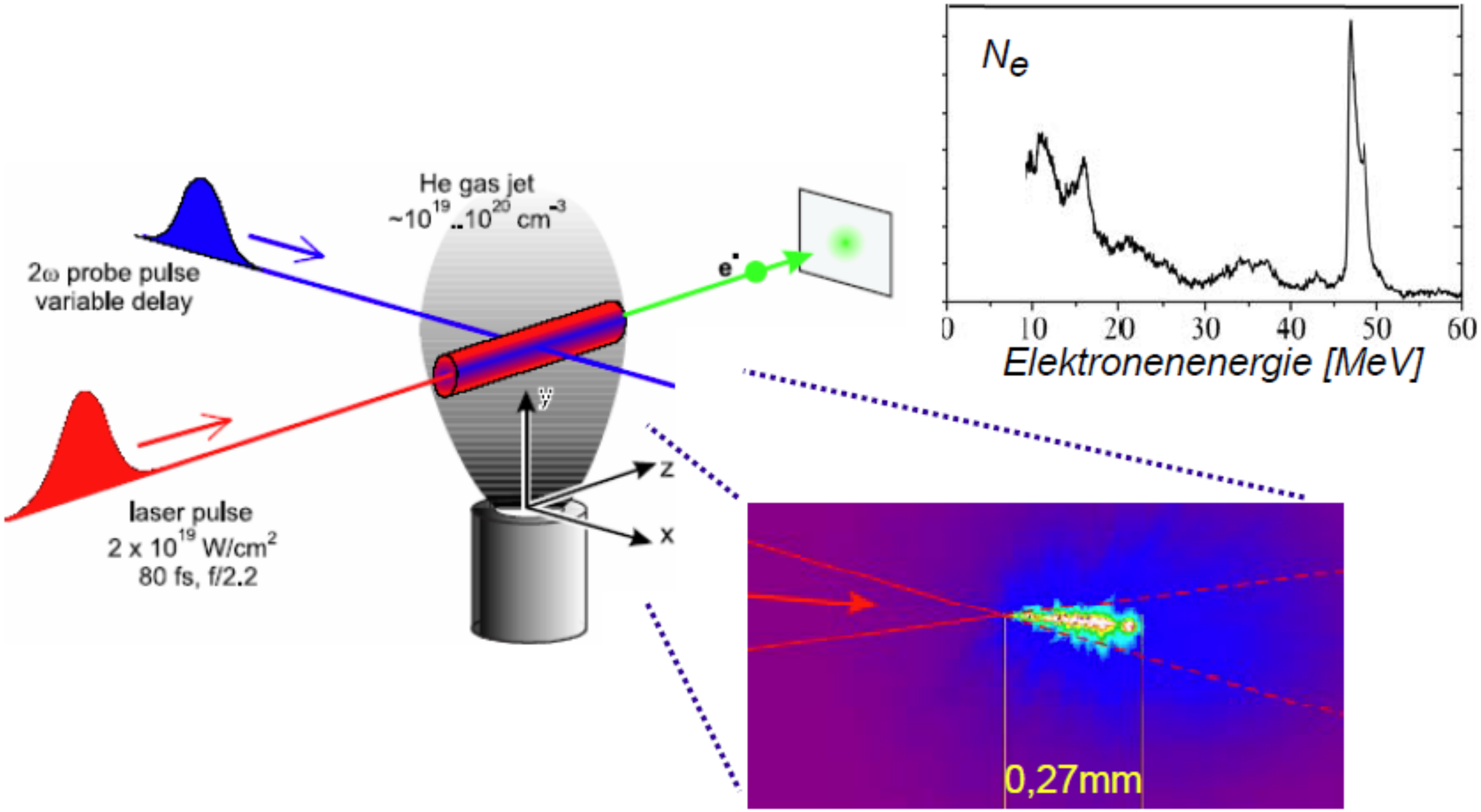
“Bubble“ acceleration (gas targets)

simulation: P.Gibbon, FZ Jülich



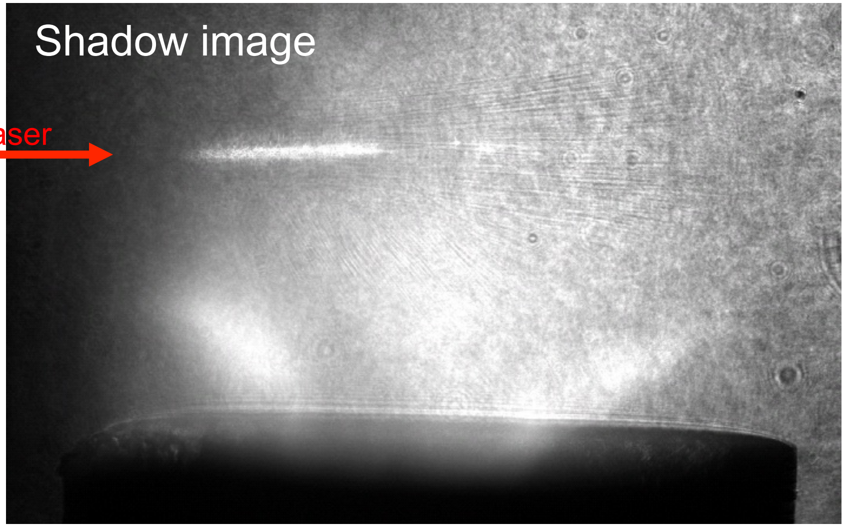
accelerates electrons

Observation of plasma channel



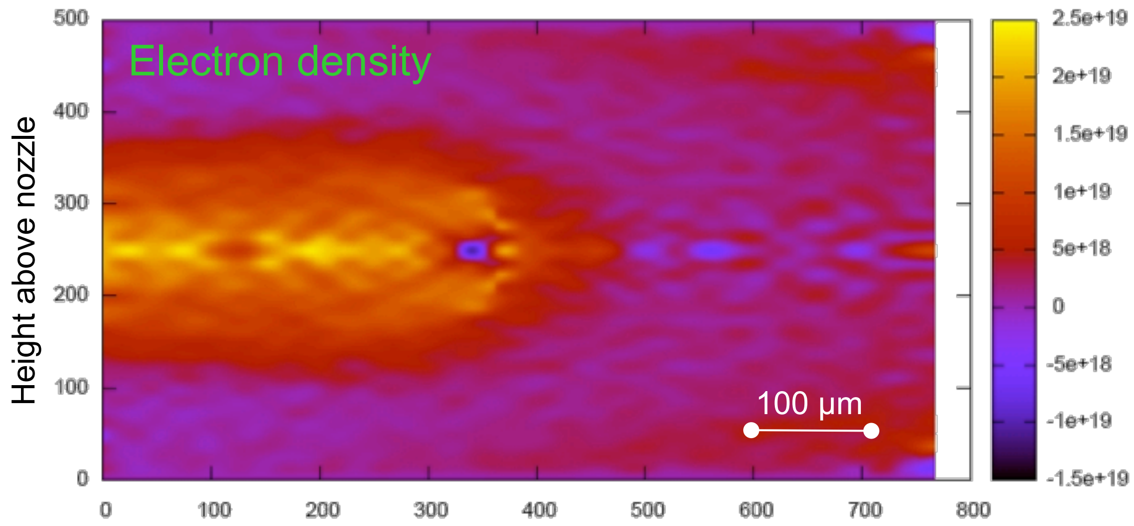
J.Hein, R.Sauerbrey, Generation of ultrahigh light intensities and relativistic laser-matter interaction, in Springer Handbook of Lasers and Optics (2007), ISBN 978-0-387-95579-7

Plasma observation: shadow images

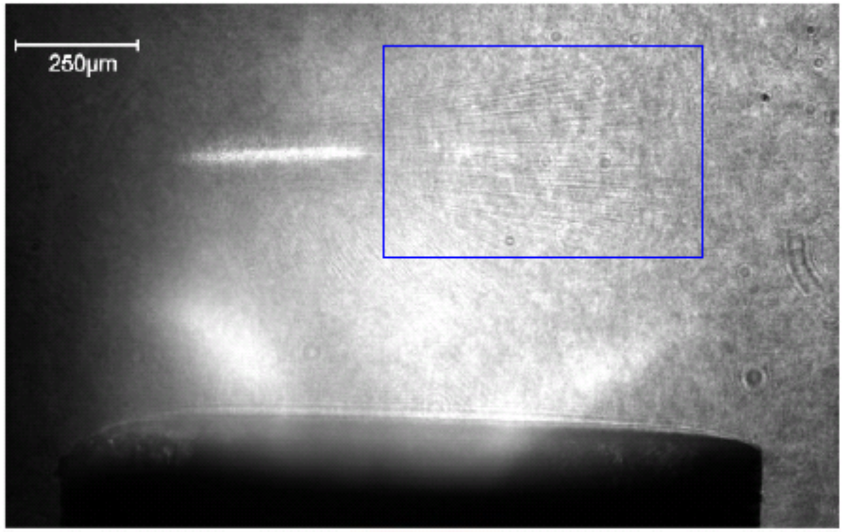


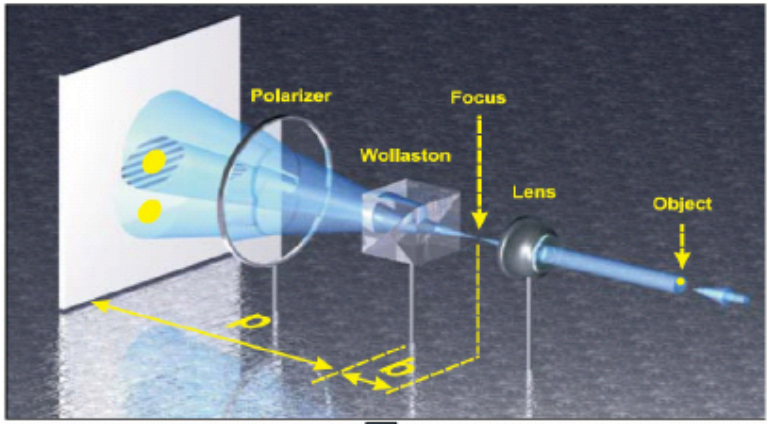
60 TW, 7.8 bar He

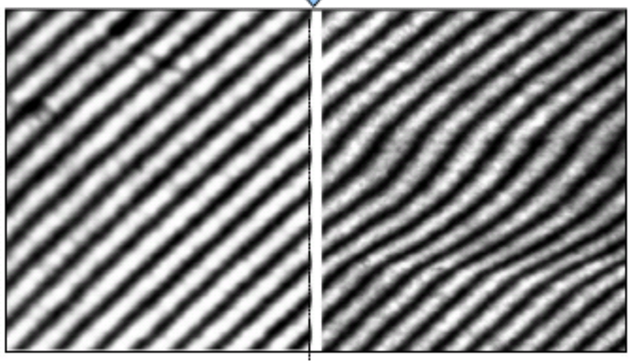
Images reveal plasma development
and rapid filamentation
Time resolution: few 10 fs (!)

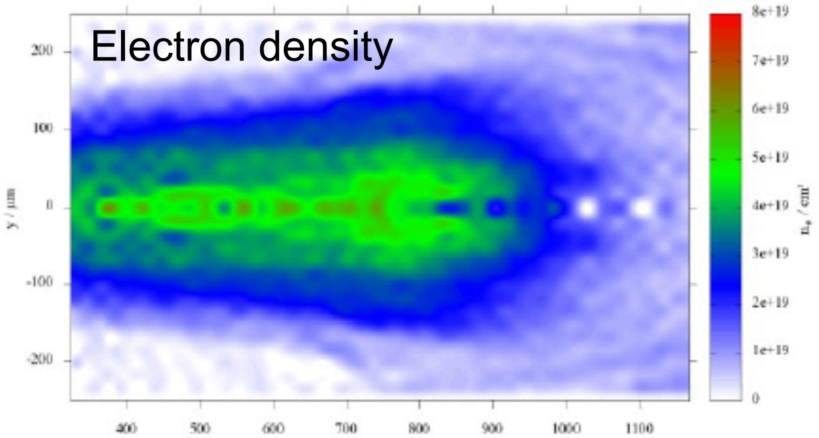


Plasma observation: interferometry

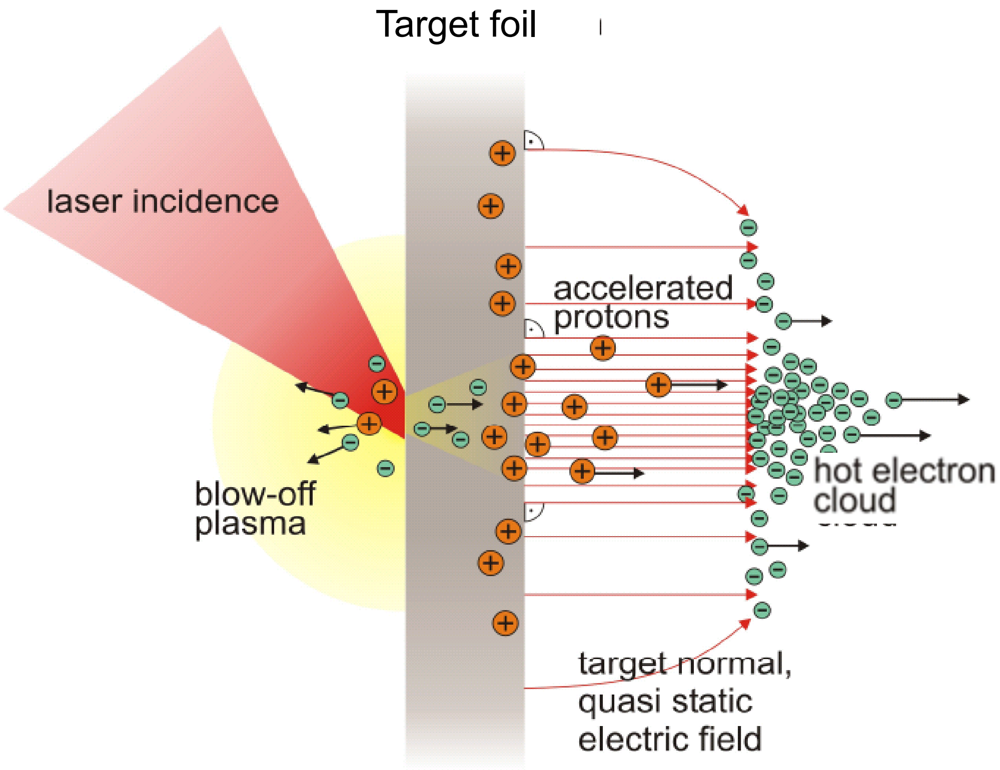






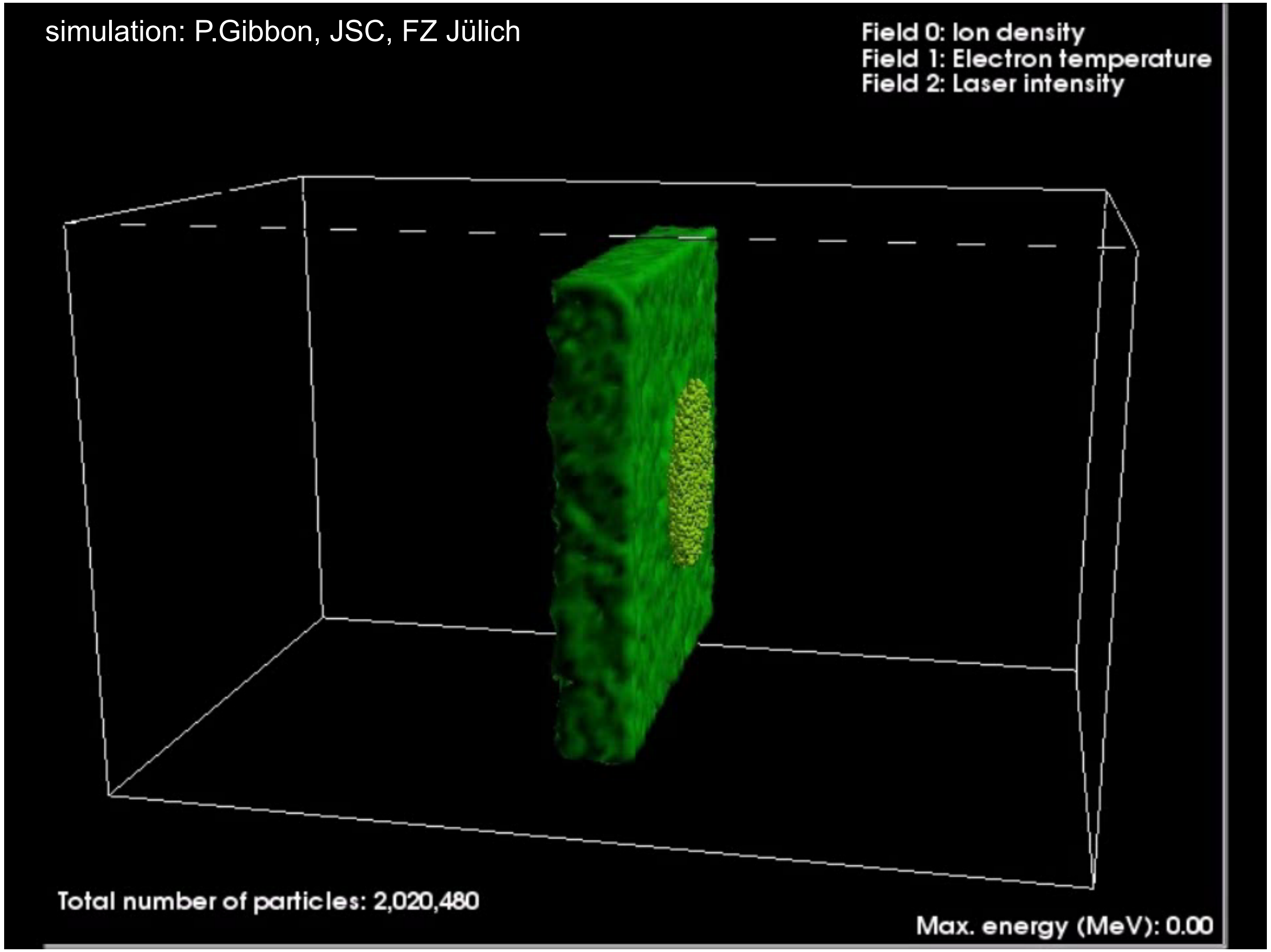


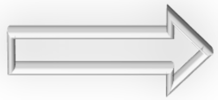
Target Normal Sheath Acceleration (TNSA)



~ 100 GV/m

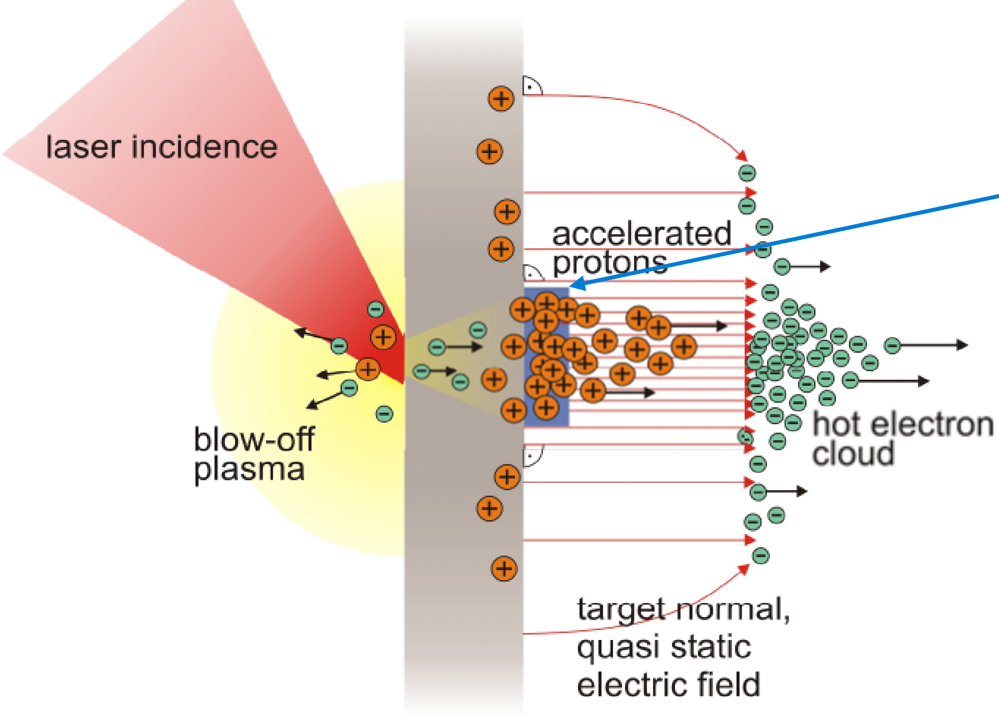
TNSA: foil targets





accelerates protons/ions

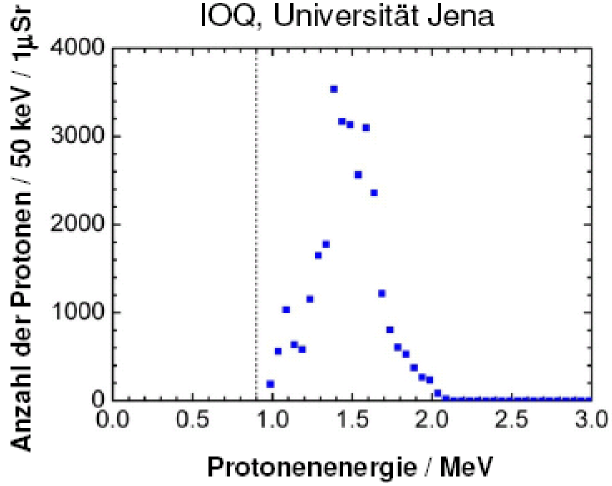
TNSA: mass limited targets



~ 100 GV/m

Proton rich dot
20x20x0.5 µm

Laserparameter:
E = 600 mJ, τ = 80 fs, P = 7.5 TW
I = 3·10^{19} W/cm^2
IOQ, Universität Jena



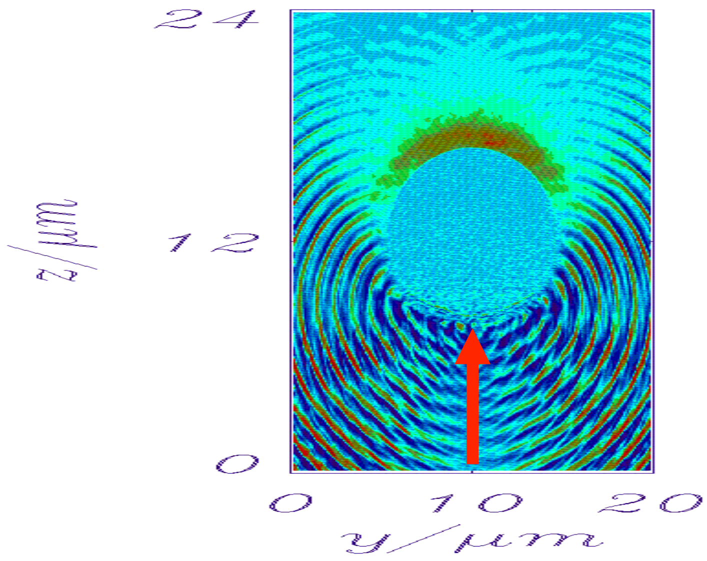
E_p=1.5 MeV ± 10%
Anzahl der Teilchen: n_p= 10^8 in 24mSr

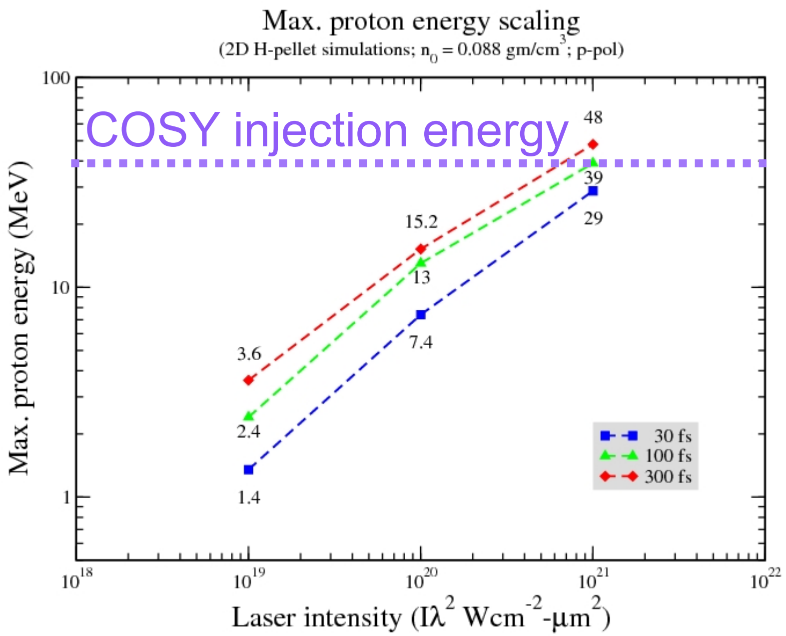
H. Schwörer et al., Nature 439, 445 (2006)

TNSA: Hydrogen pellet targets

2-D Simulations from the JSC Jülich

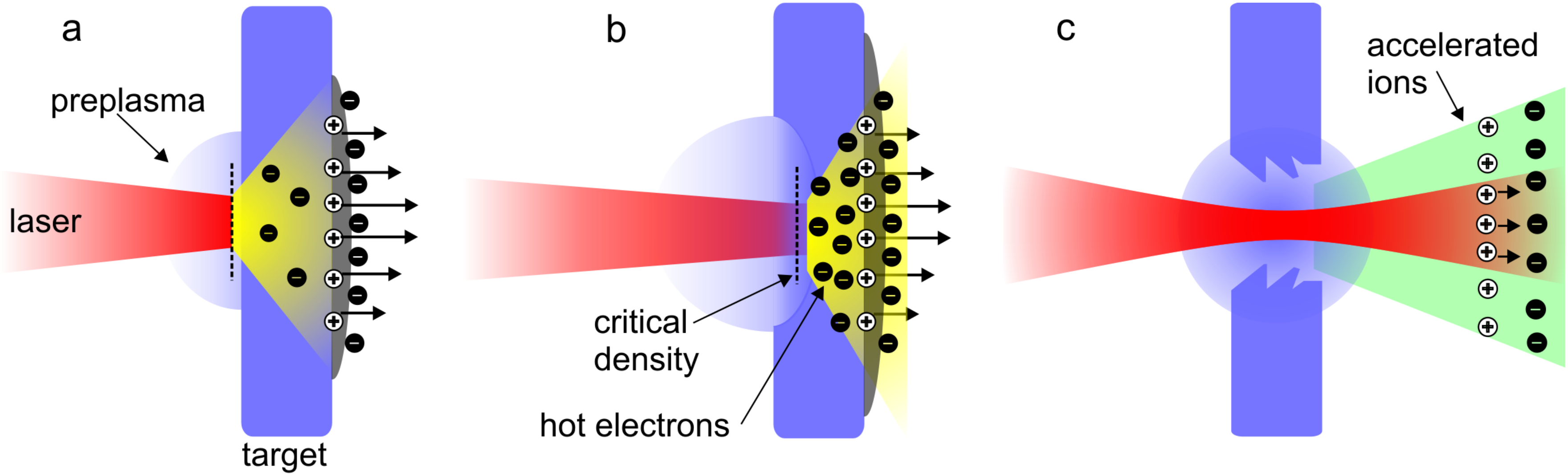
Laser pulse with λ=1 μm and fokus Ø =10 μm hits a 10 μm frozen H_2 pellet





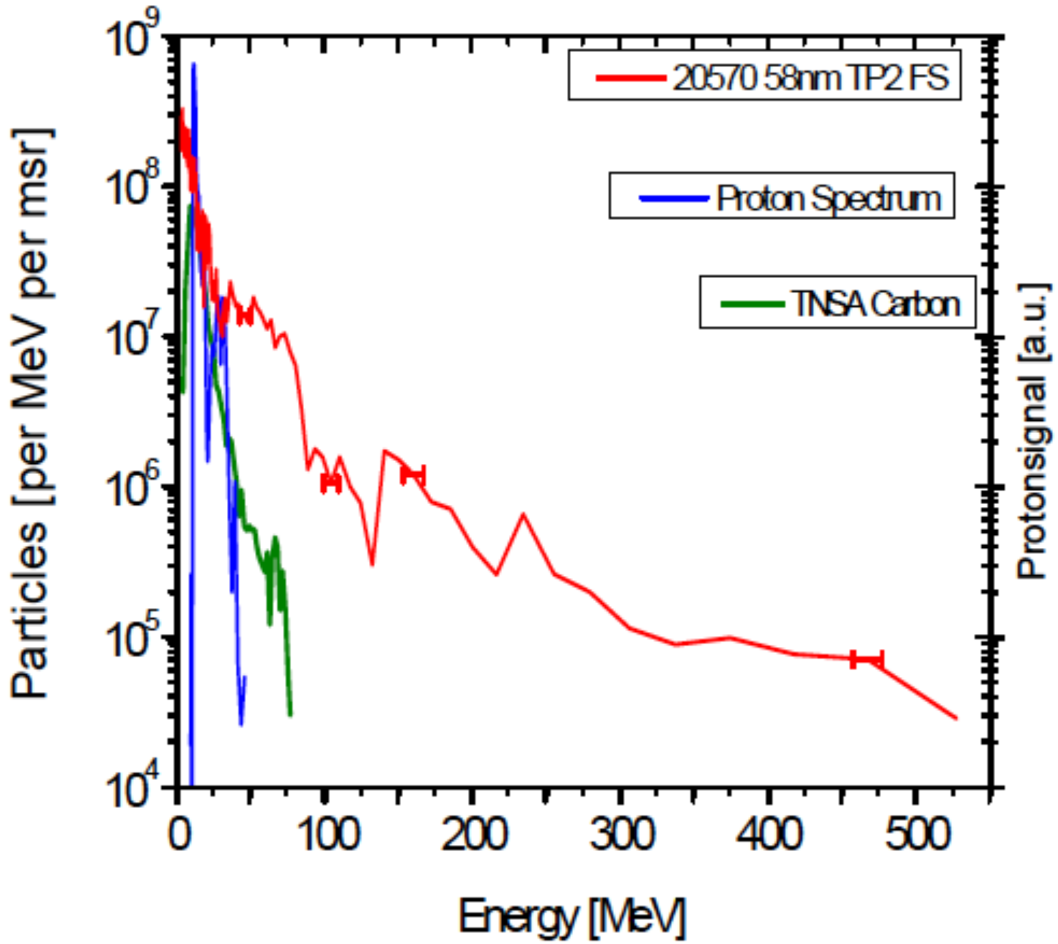
maximum proton energy can further be increased (factor 4) by optimization of the focus size

Break-Out Afterburner (BOA)



a) Target Normal Sheath Acceleration (TNSA) phase
b) Intermediate phase
c) Laser Breakout Afterburner (BOA) phase (plasma becomes underdense)

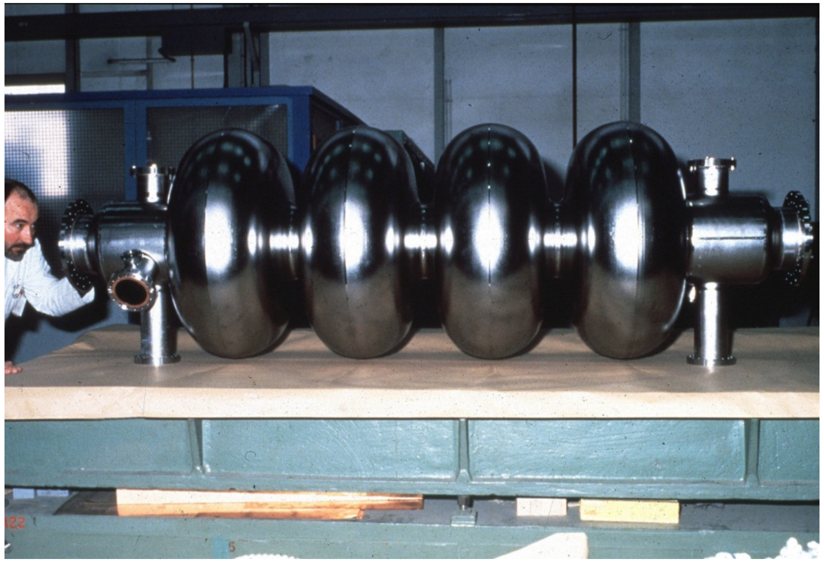
TNSA vs. BOA



20570 58nm TP2 FS
Proton Spectrum
TNSA Carbon
Particles [per MeV per msr]
Protonsignal [a.u.]
Energy [MeV]
10^9
10^8
10^7
10^6
10^5
10^4
0
100
200
300
400
500

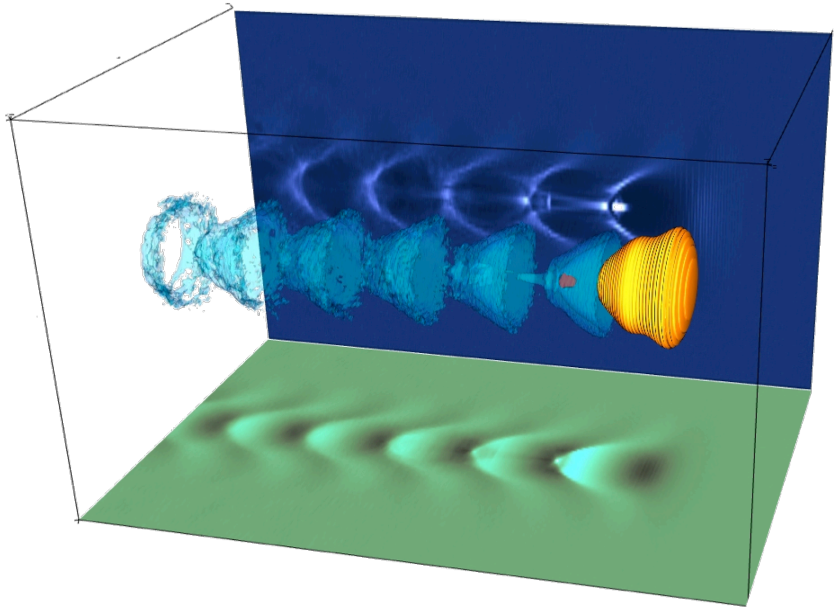
RF vs. laser acceleration

RF cavity



1 m
1 MV/m } 1 MeV

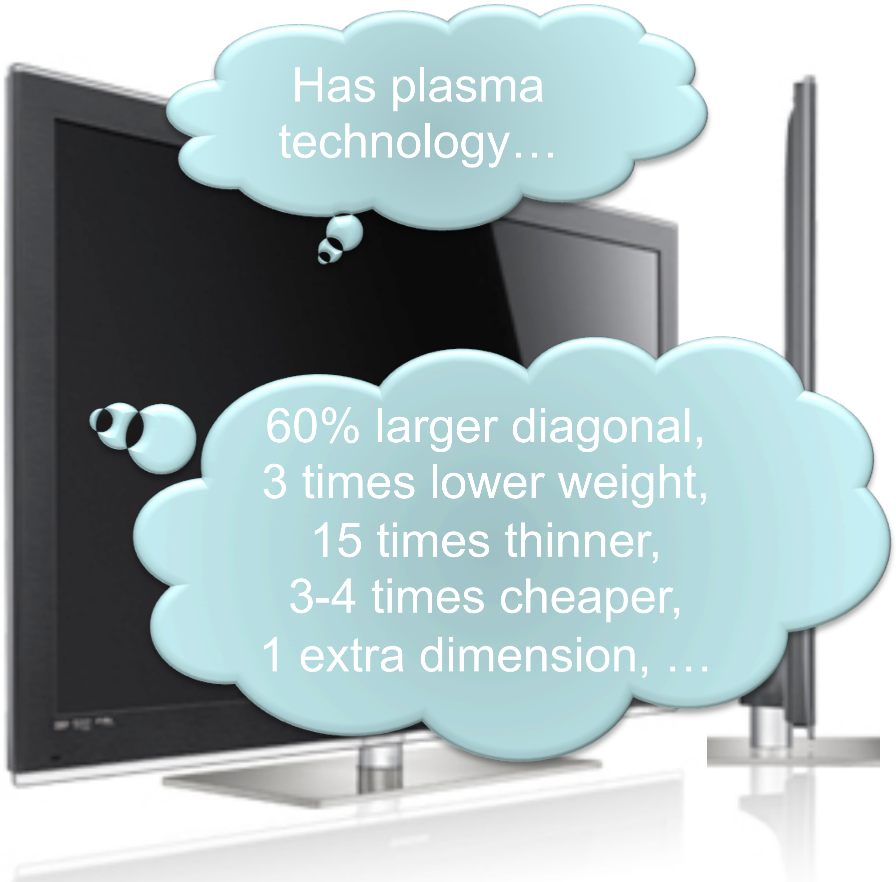
Plasma "cavity"



100 µm
100 GV/m } 10 MeV

An up-and-coming technology …

Technological revolutions do happen!



Oct 2002: largest CRT display,
102cm diagonal,
$15,000, 63cm deep, 92kg

Oct 2010: plasma display,
159cm diagonal,
$4,000, 3.6cm deep, 33kg

Helmholtz Association HGF

Research Centers: 18

Total staff: ~ 33 000

Total budget ~ 3.4 billion €

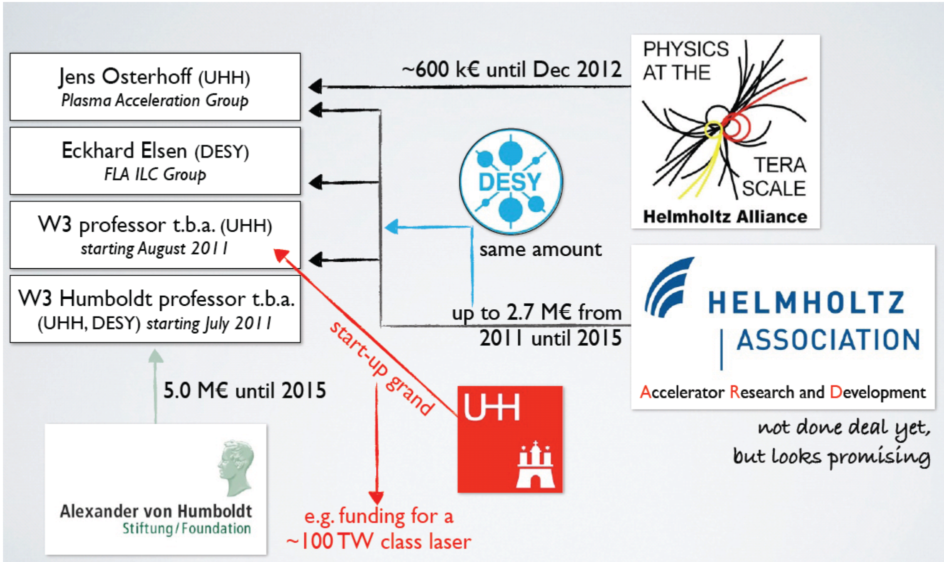
Research Fields:

- Energy
- Earth and Environment
- Health
- Key Technologies
- **Structure of Matter**
- Aeronautics, Space and Transport

JÜLICH FORSCHUNGSZENTRUM

“Big” lasers in the HGF: *e.g.* DESY Hamburg

Sept. 2010:
Laser/plasma group established



J. Osterhoff, Talk at 470 W.-E. Heraeus-Seminar, 12/2010

→ Plasma-based particle accelerators

JÜLICH
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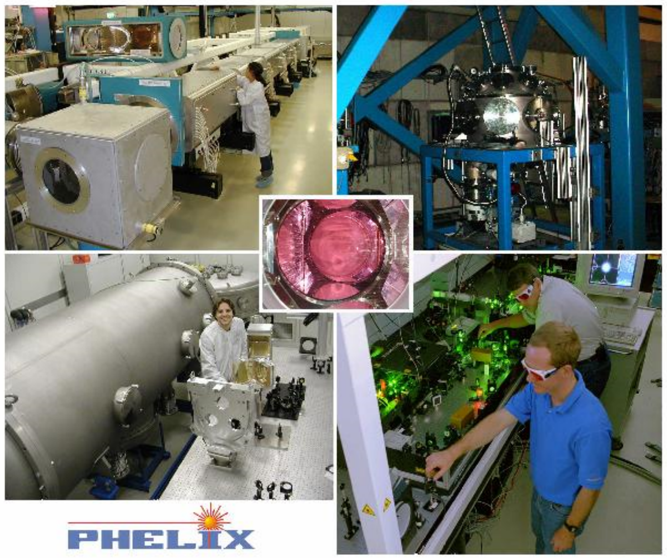
“Big” lasers in the HGF: *e.g.* GSI Darmstadt

<u>2008</u>:
PHELIX (Petawatt Hoch- Energie Laser für SchwerIoneneXperimente)
500 TW

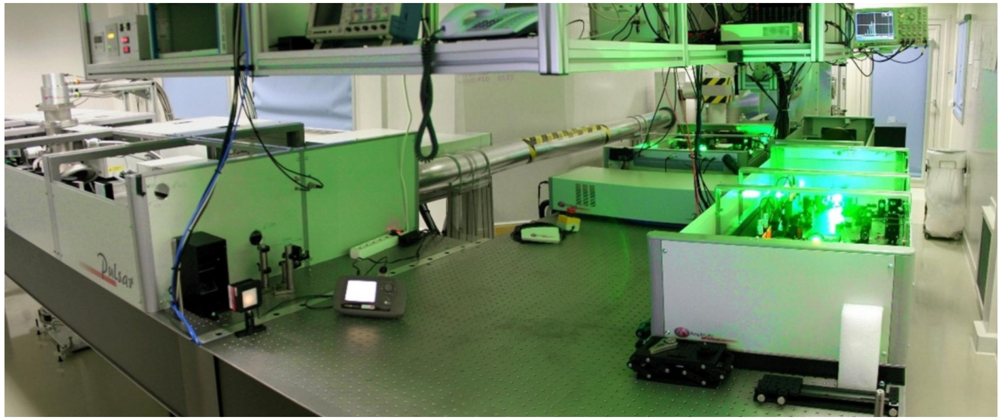


- → Ion-laser interactions
- → X-ray laser

“Big” lasers in the HGF: *e.g.* Dresden-Rossendorf

<u>2008:</u> High-Power Laser Laboratory
150 TW laser DRACO (Dresden laser acceleration source)

<u>2012</u>:
PW Laser



➔ Laser particle acceleration
➔ Cancer research

JÜLICH
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JuSPARC =
Jülich short-pulse particle and radiation centre

Manufacturer	Amplitude Technologies
Wave length	800 nm
Focus Ø	20 µm
Peak power	1.5 PW
Pulse energy	40 J
Pulse length	25 – 40 fs
Repetition rate	5 Hz