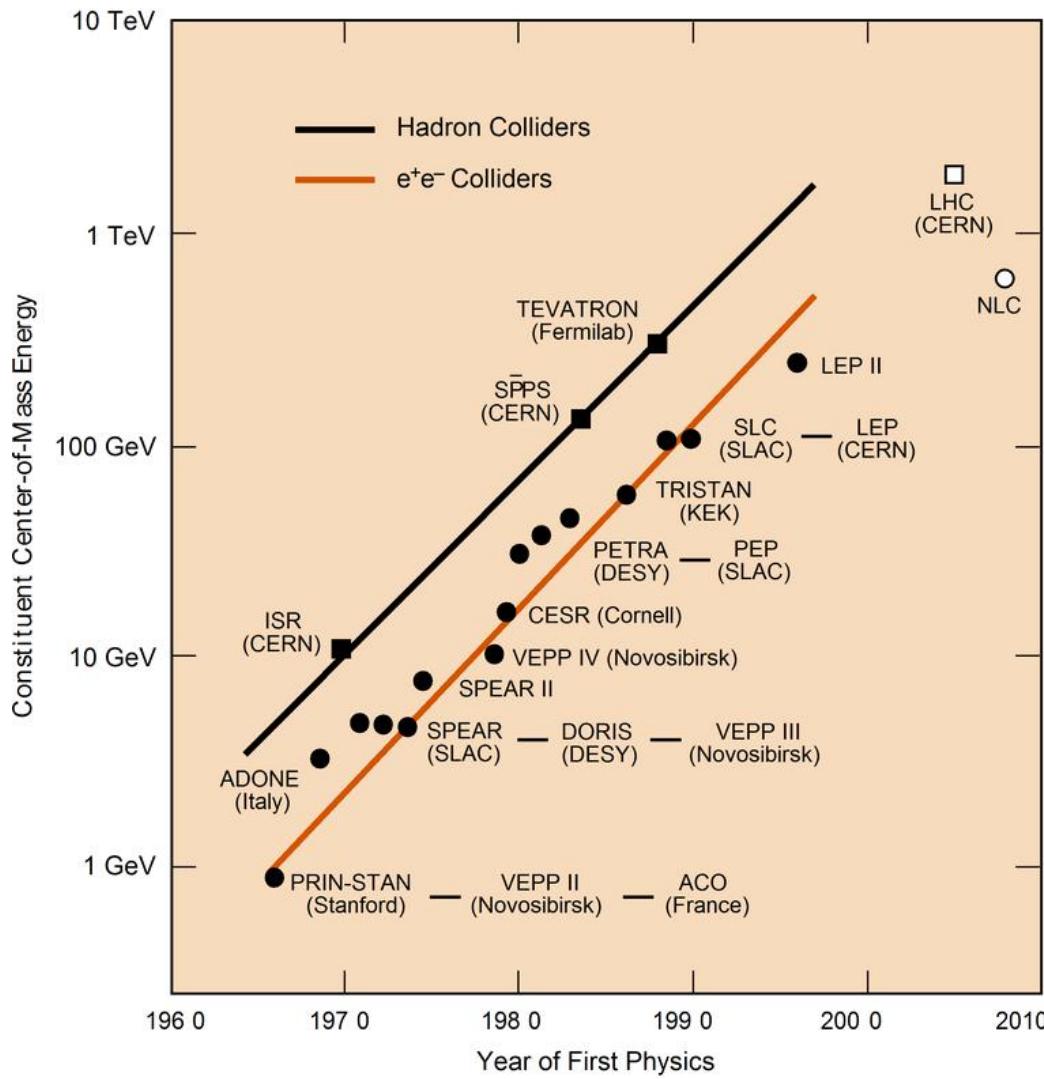


Joint DESY and University of Hamburg Accelerator Physics Seminar

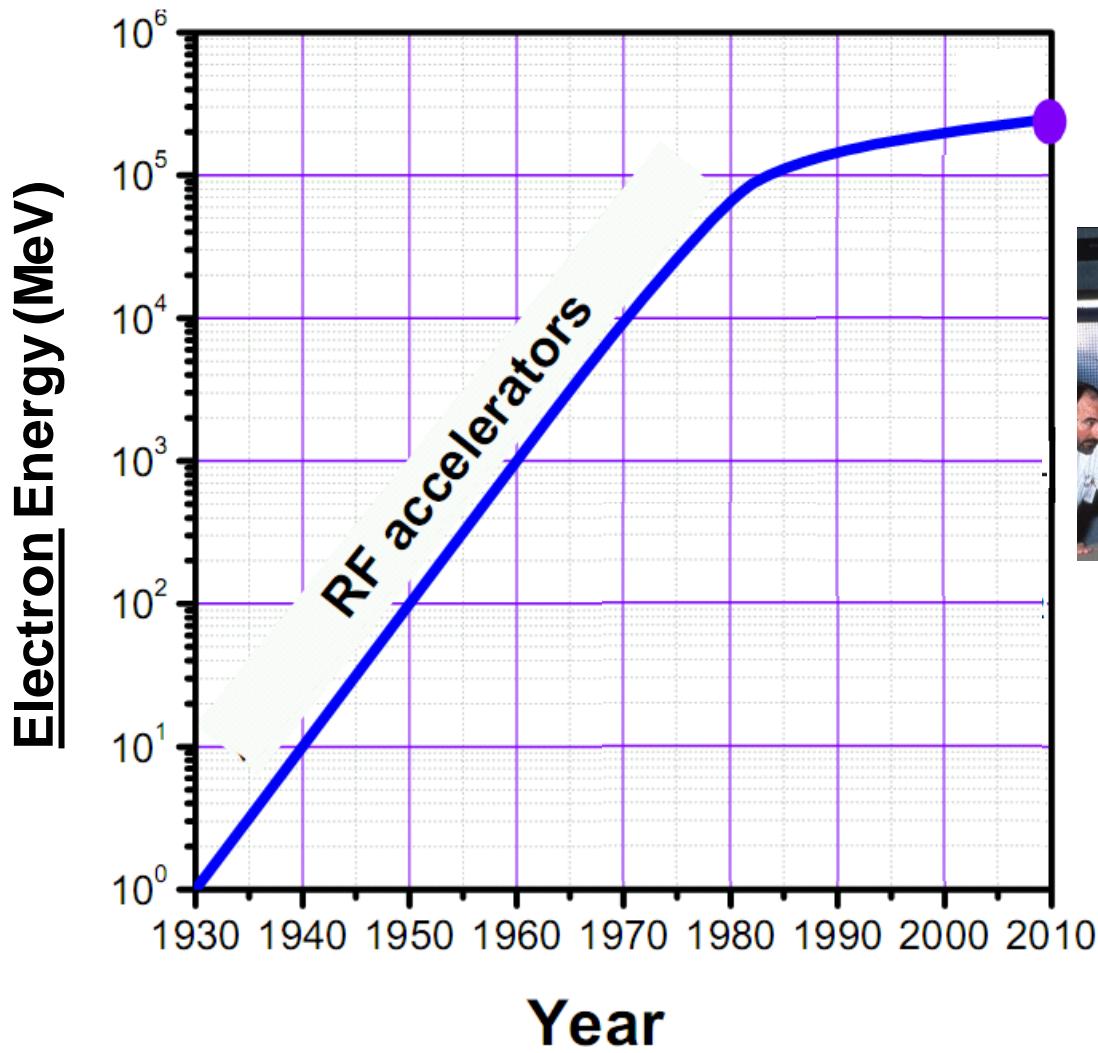
Particle Acceleration in Laser-Induced Relativistic Plasmas A Novel Approach for Polarized Sources?

15 January 2013 | Markus Büscher (*m.buescher@fz-juelich.de*)

Conventional (RF) accelerators



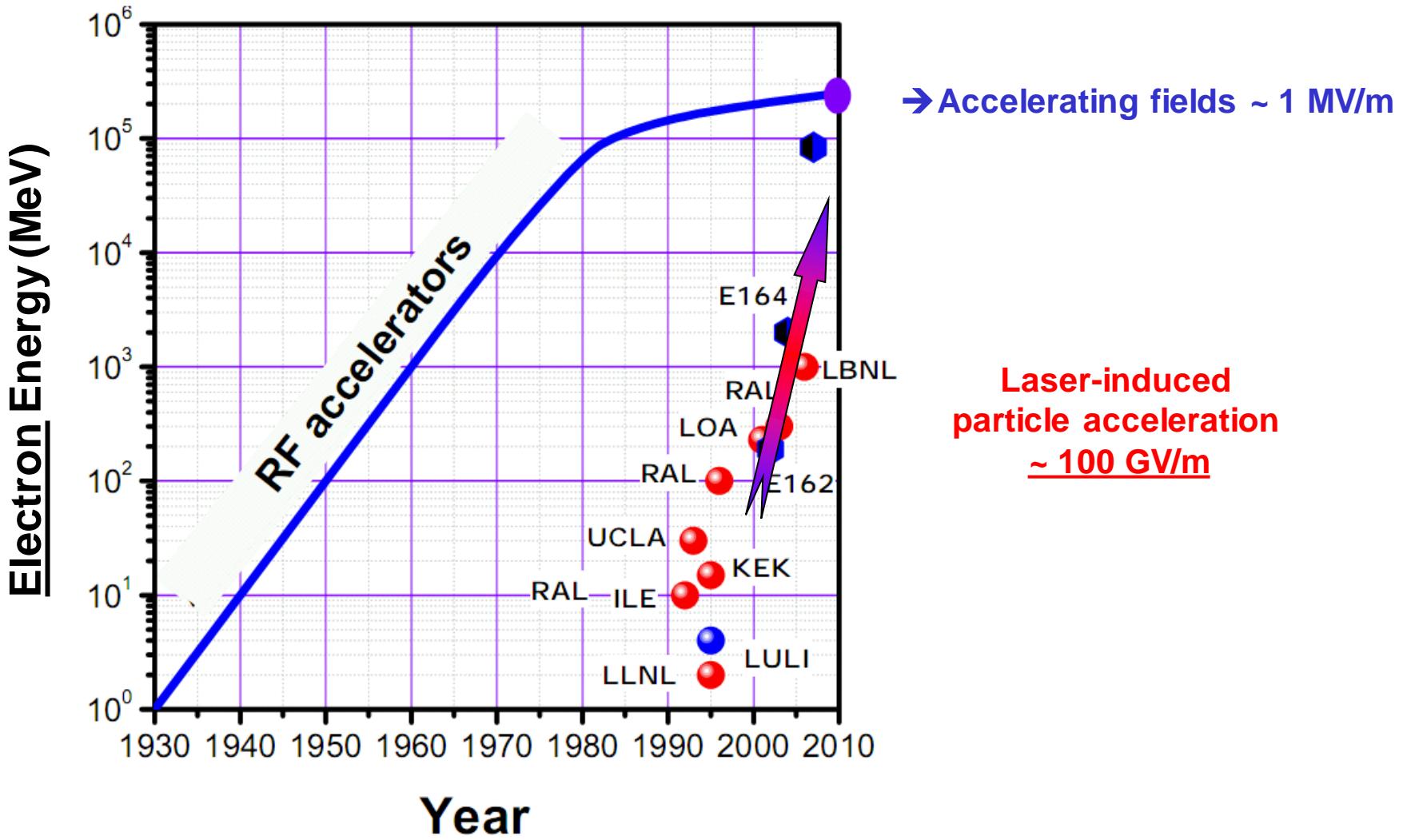
Need for novel approaches



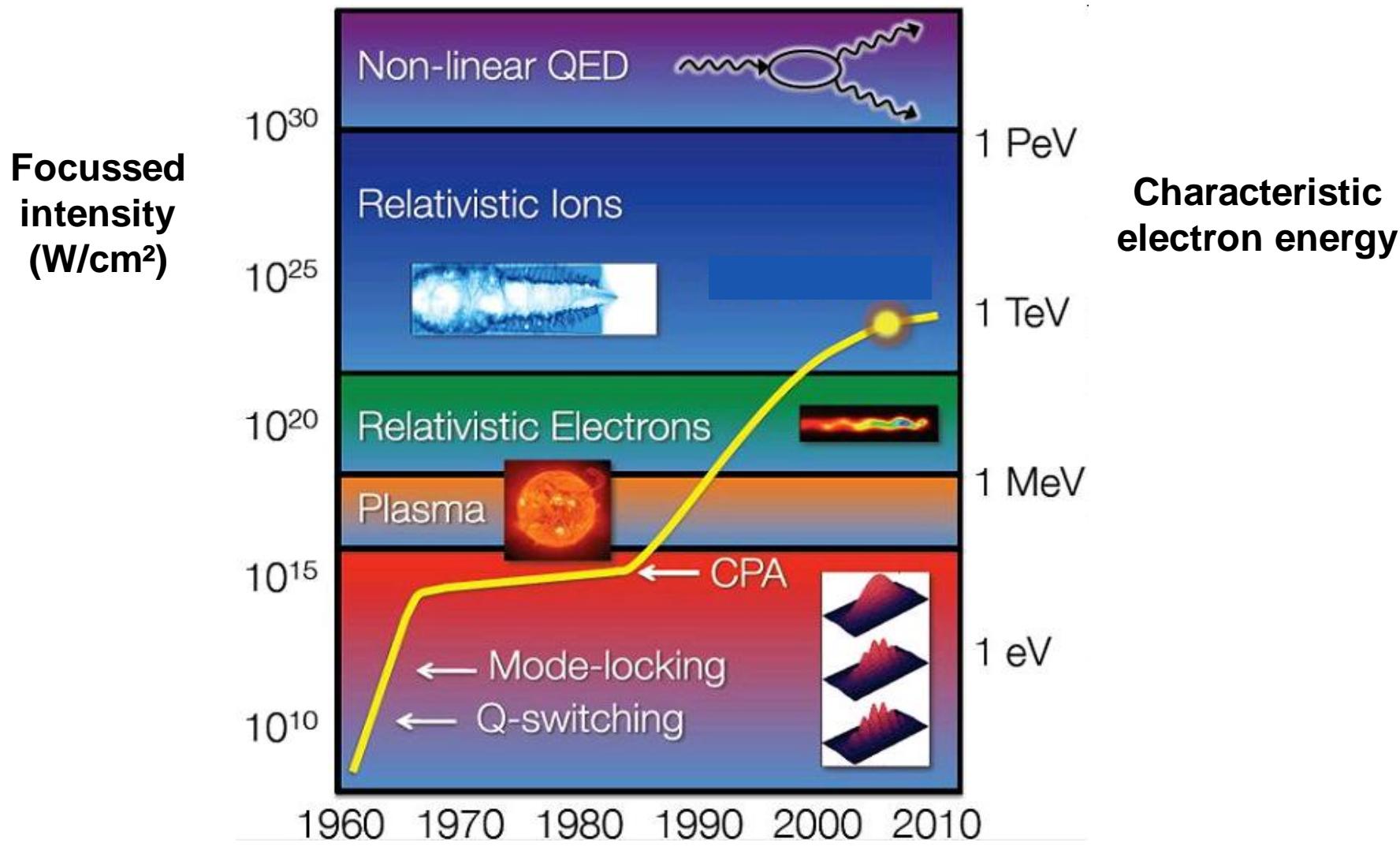
→ Accelerating fields ~ 1 MV/m



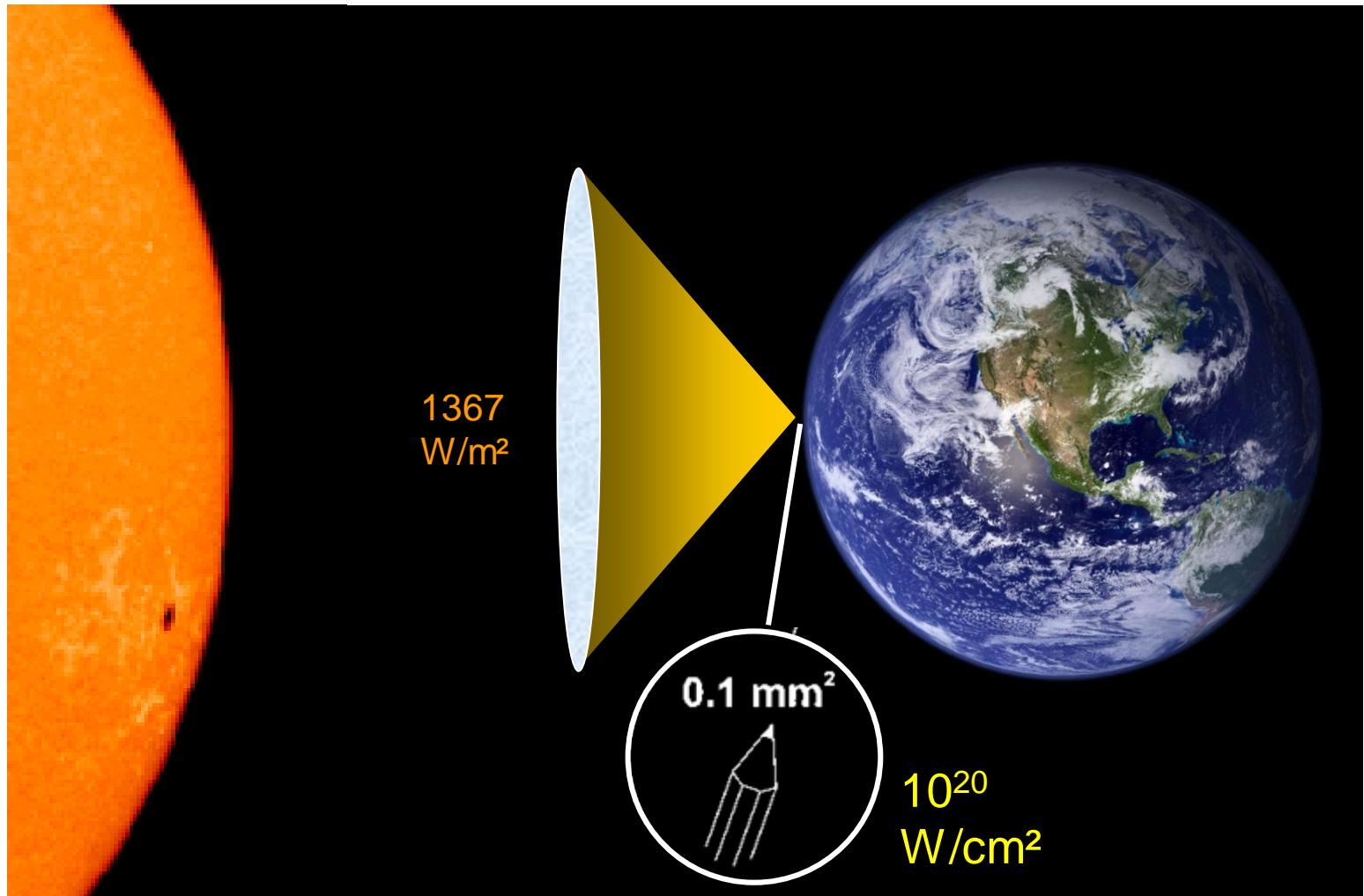
Need for novel approaches



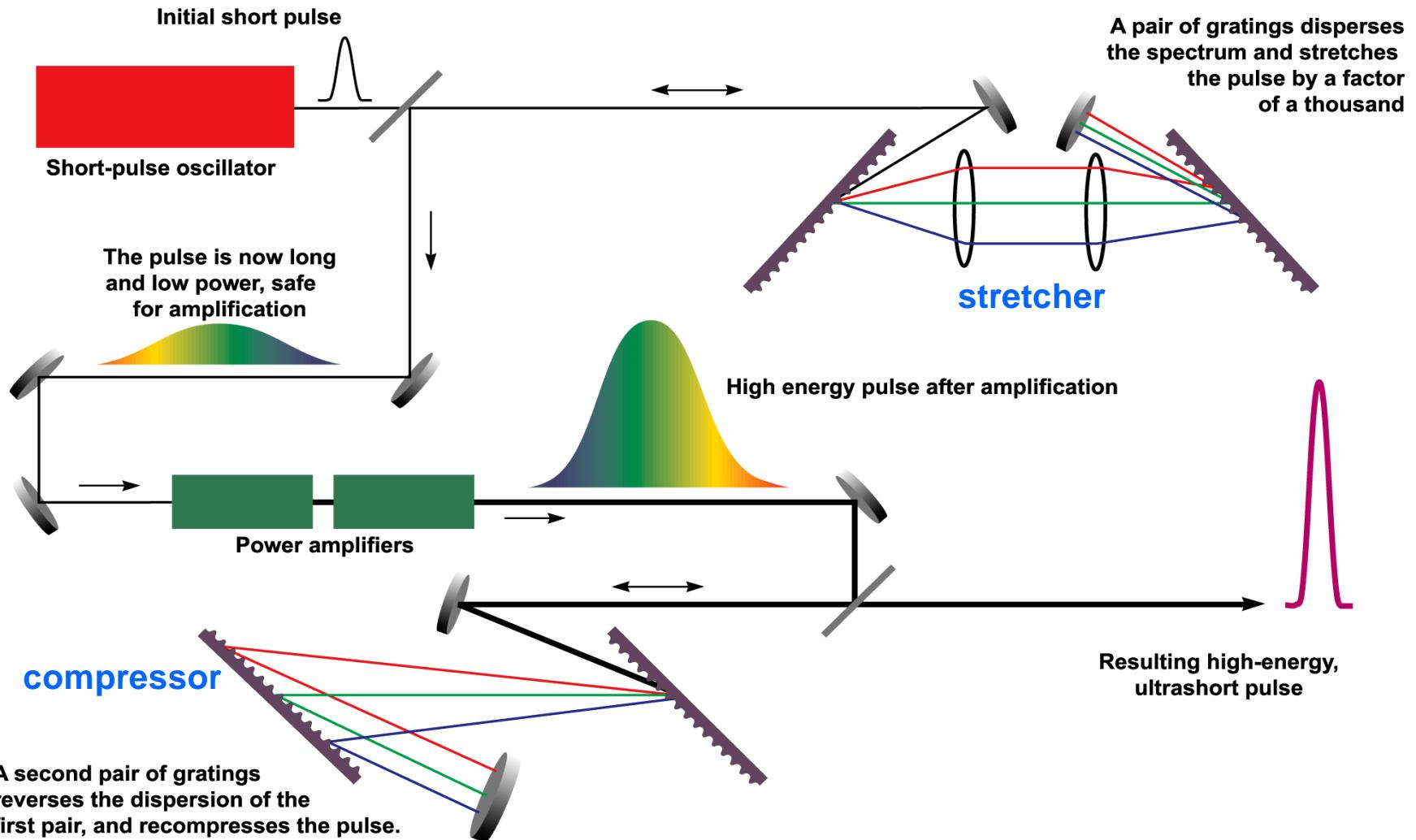
Development of laser intensities



High intensities ...

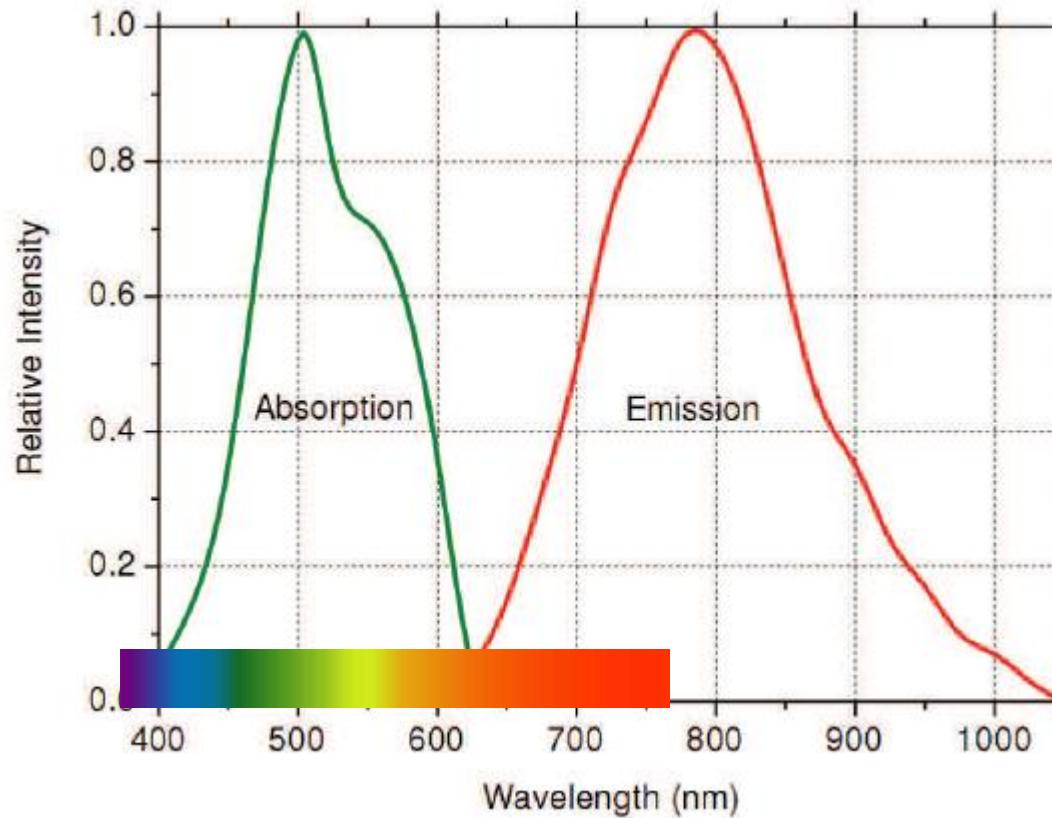


Chirped pulse amplification (CPA)



CPA: Ti:Sa crystals

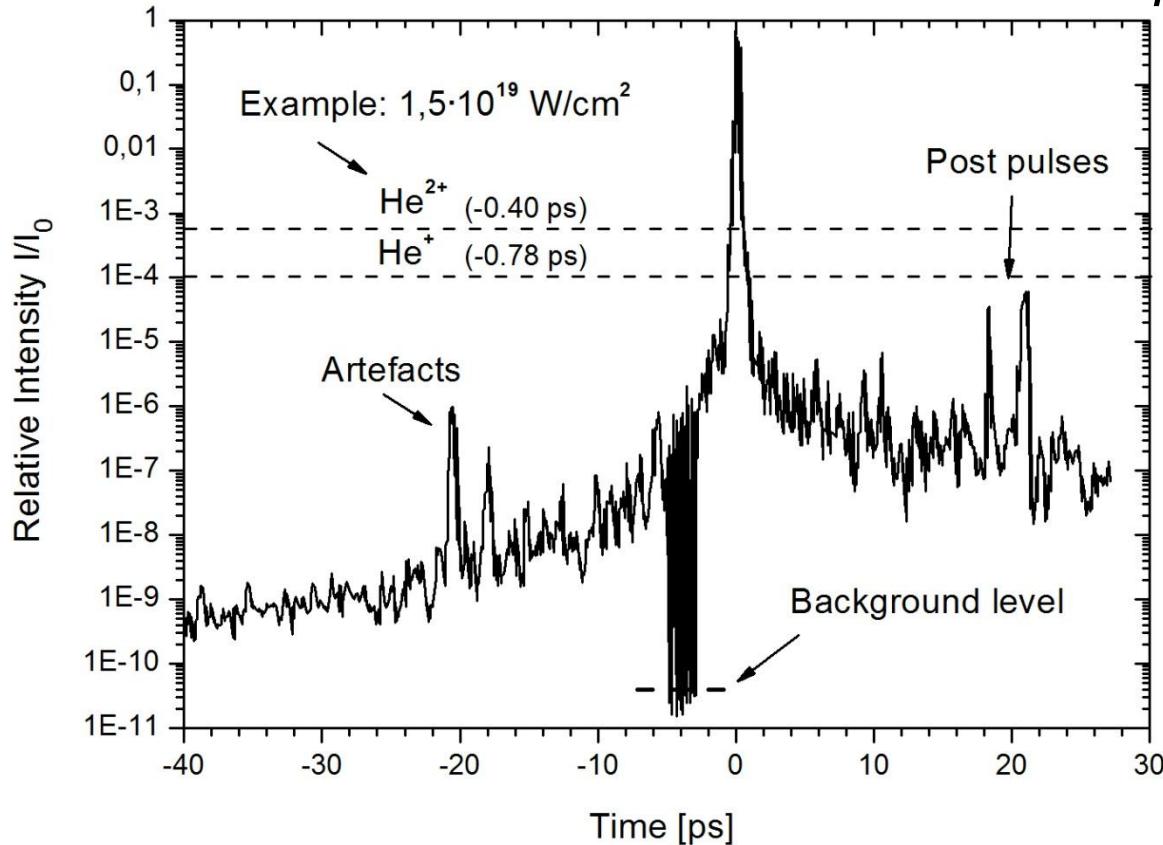
Emission and absorption spectrum



CPA: Pulse shape

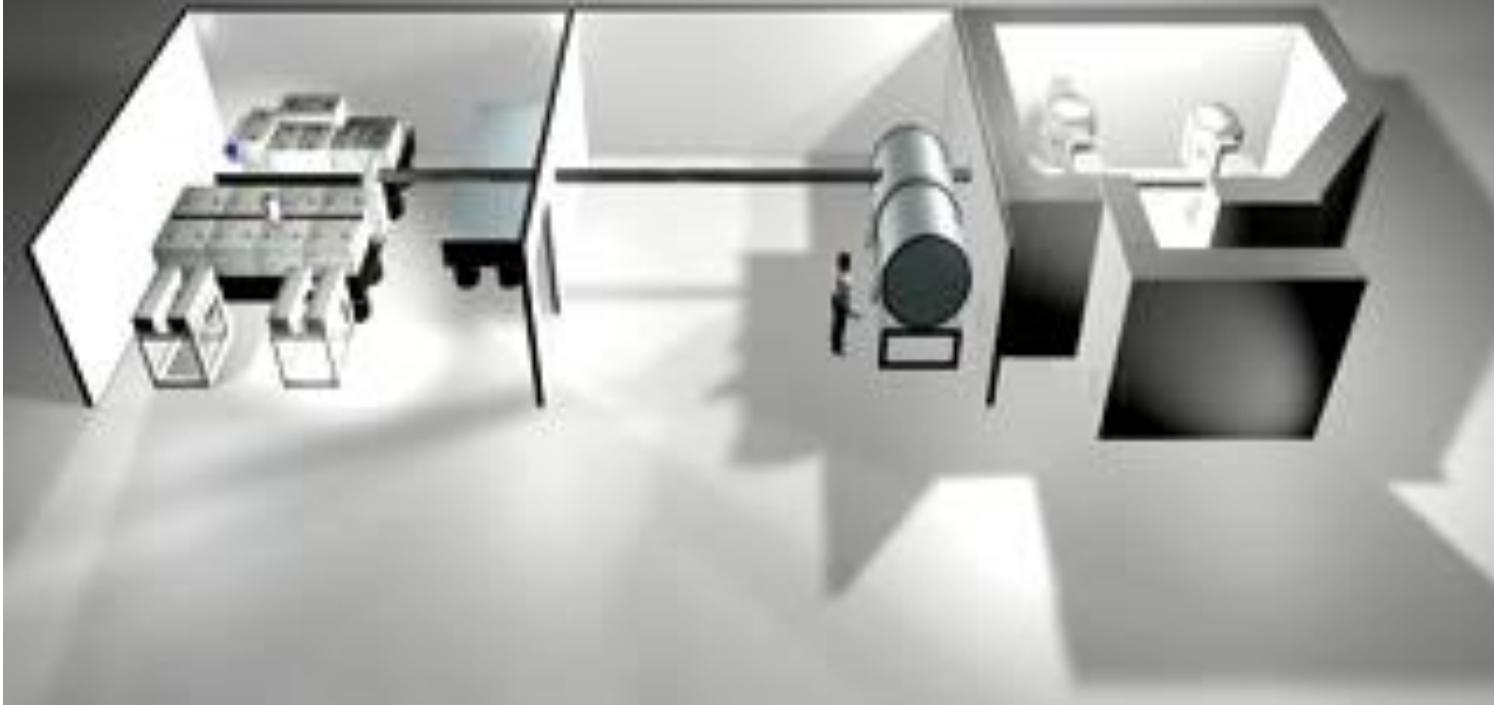
Measured at ARCTurus / Düsseldorf Univ.

$$I_0 \approx 10^{20} \text{ W/cm}^2$$

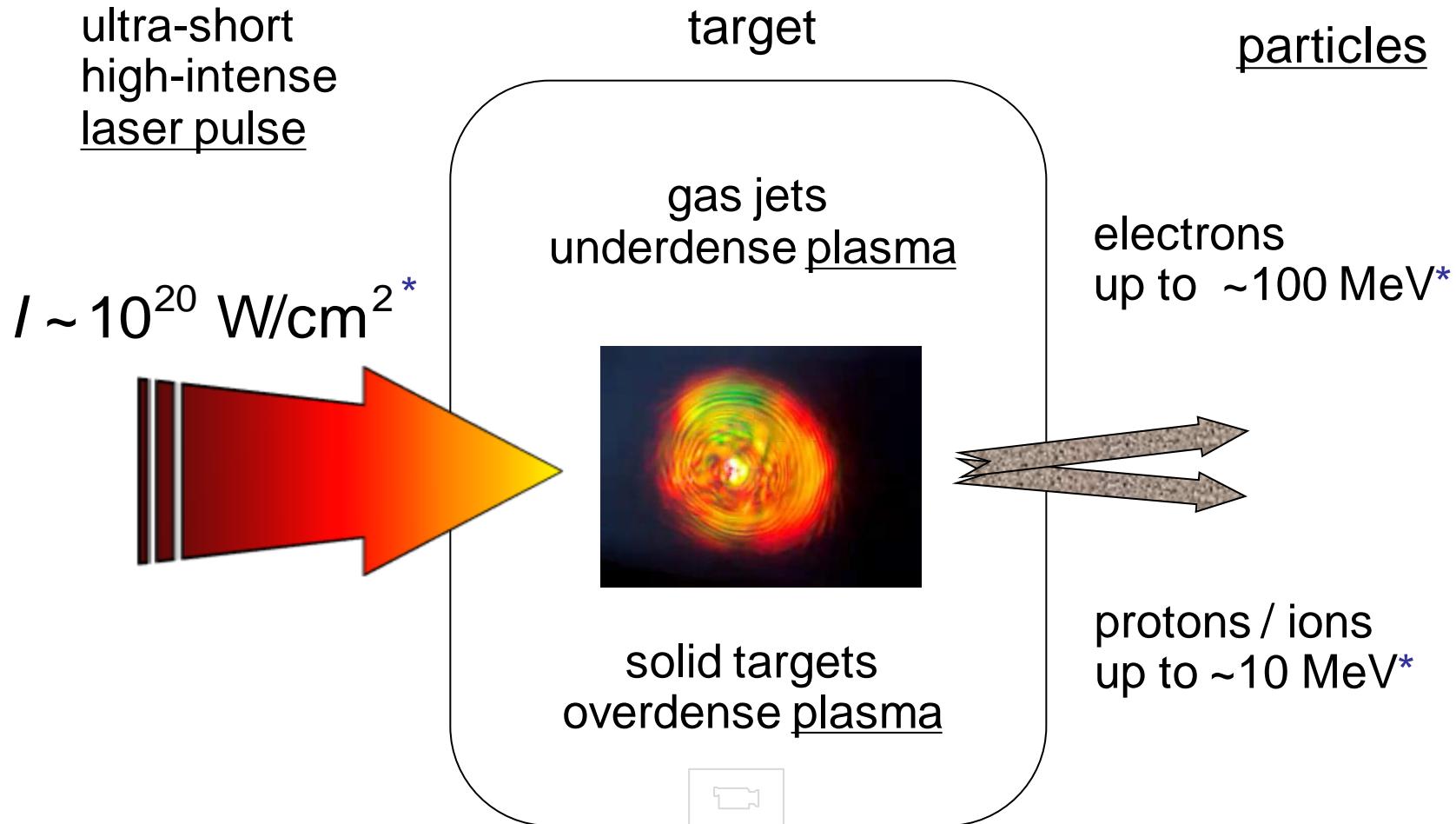


Institute für Laser- und Plasmaphysik, Univ. Düsseldorf (Prof. O.Willi)

PULSAR Ti:Sapphire Laser: 100 + 200 TW, 800 nm
~ 2,5 Joule, less than 25 femtoseconds
focused on 10 microns



Particle acceleration: typical setup



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

15 January 2013

Markus Büscher

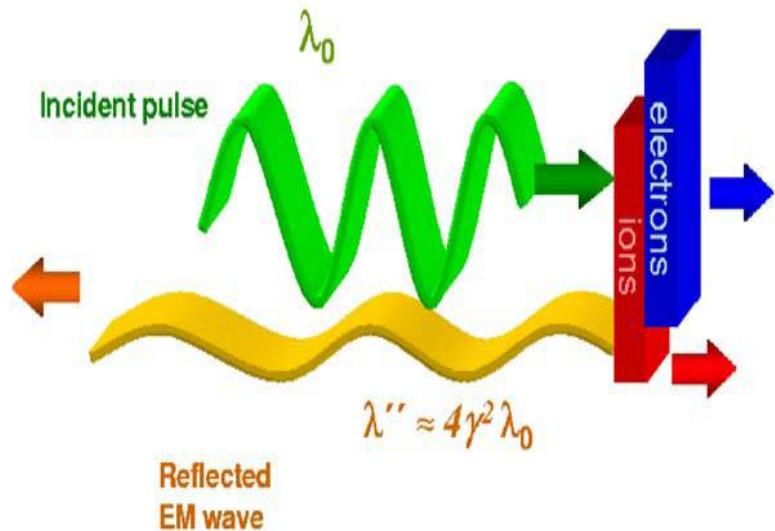
* typical values at HHUD

Acceleration mechanisms

- 1) Radiation pressure („direct“, thin foil targets)
- 2) Wake fields / bubbles (gas targets)
- 3) Target Normal Sheath Acceleration (foil & pellet targets)
- 4) ...

Radiation Pressure Acceleration (RPA)

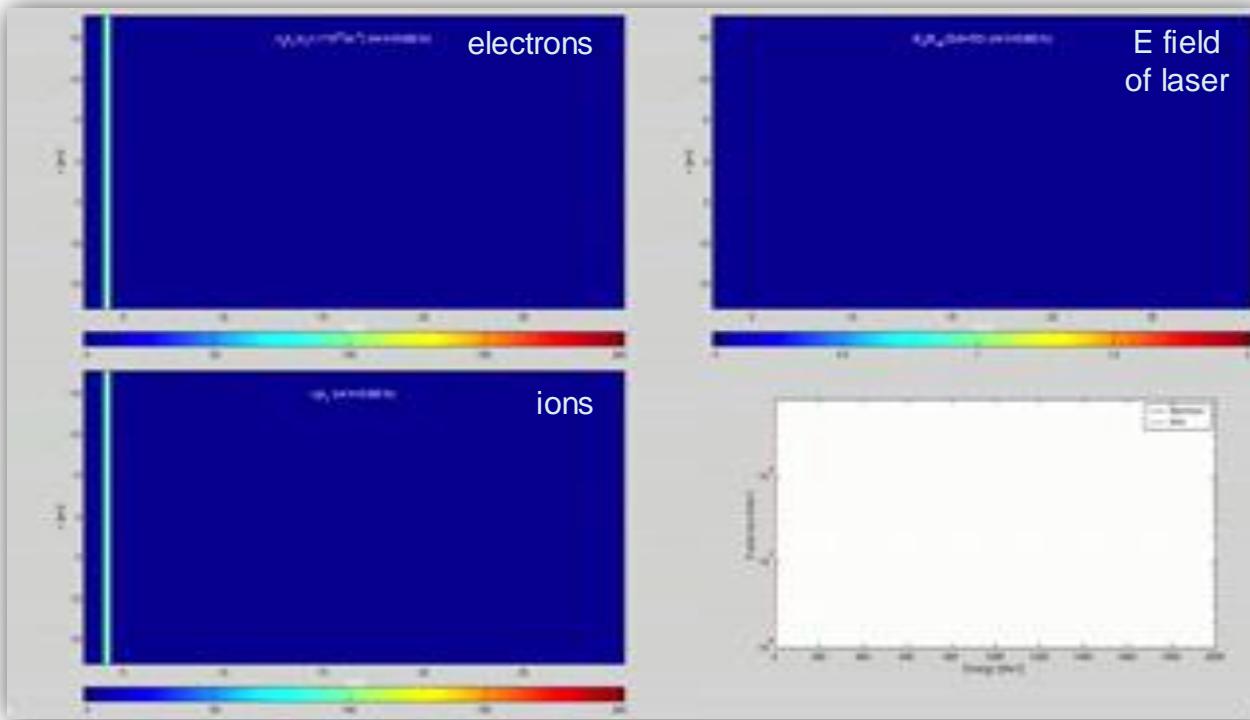
Strong electro-magnetic fields^{*)} in the laser pulse accelerate charged particles (“ponderomotive force”)



^{*)} Typical values: $E = 3 \cdot 10^{13} \text{ V/m}$, $B \sim 10^5 \text{ T}$ @ $I = 10^{20} \text{ W/cm}^2$

Radiation Pressure Acceleration (RPA)

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



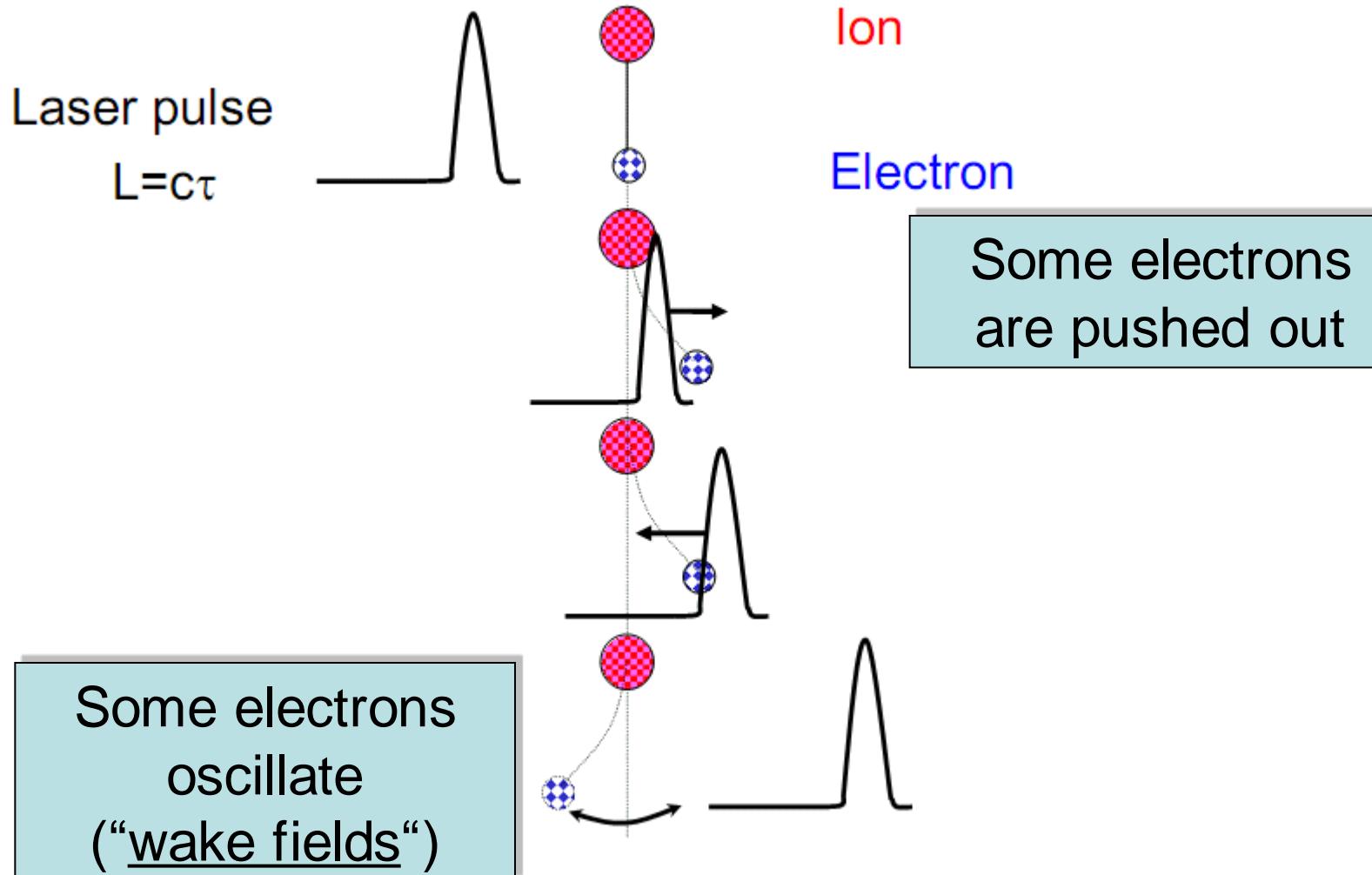
simulation: P.Gibbon, FZ Jülich

see also (for lower laser intensities):

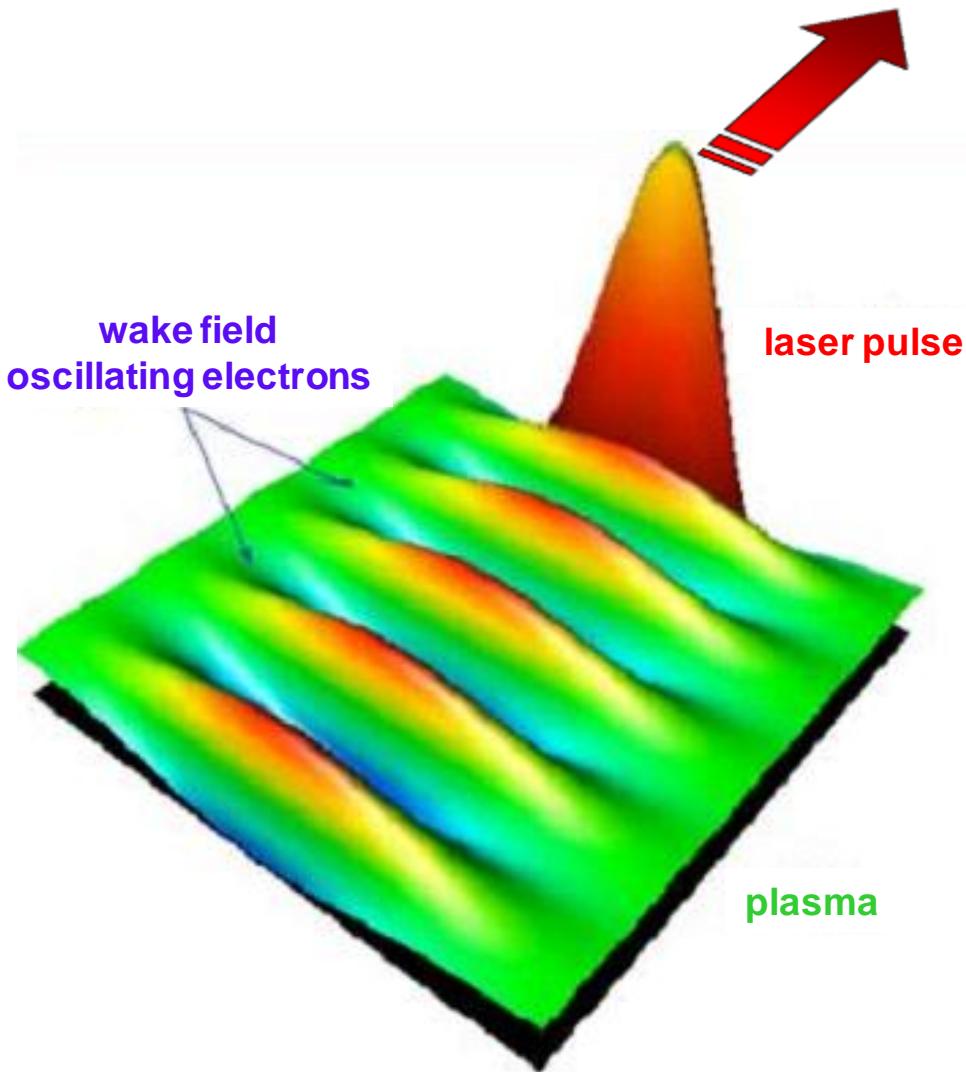
B. Qiao et al., Phys. Rev. Lett. 105, 155002 (2010)

<http://www.fz-juelich.de/portal/index.php?index=85#teilchenbeschleuniger>

Laser-plasma interaction

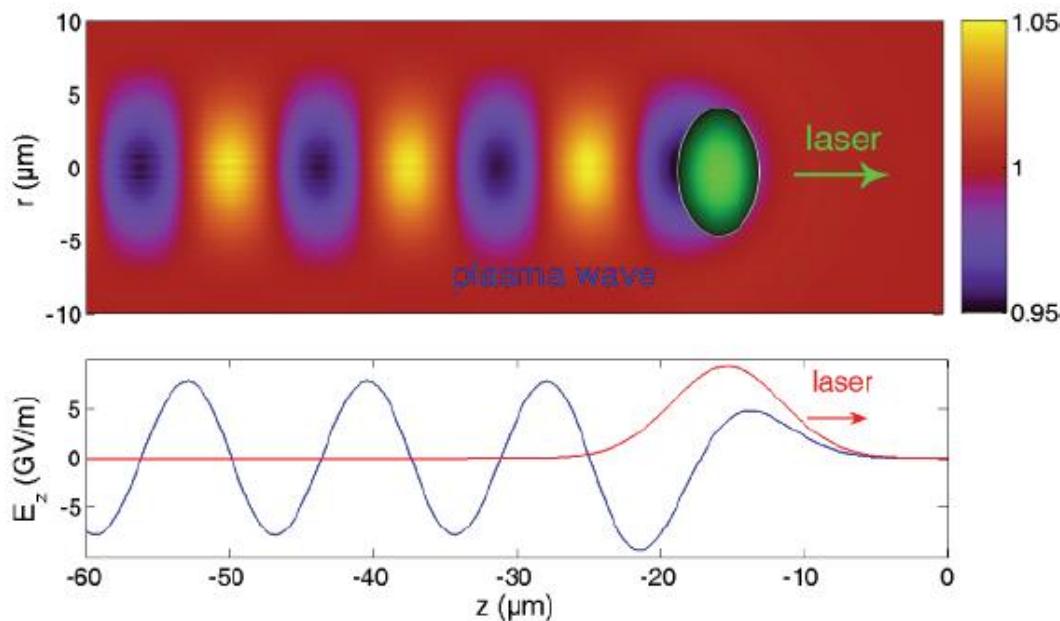


Wake fields in plasmas



Wake fields: low laser intensity

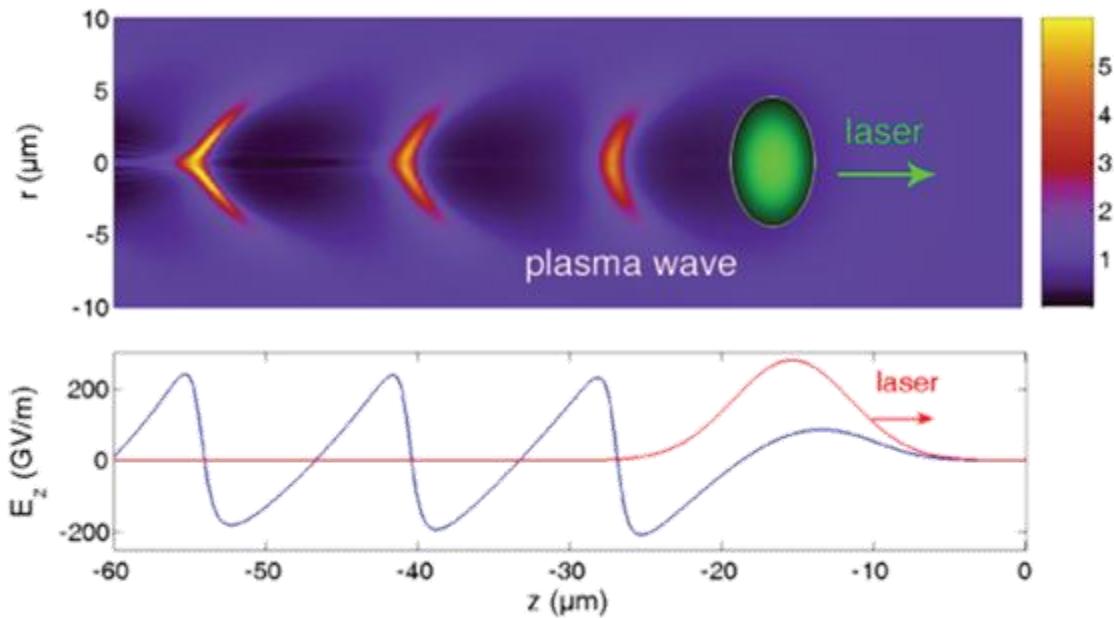
Electron density perturbation & longitudinal wake field



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

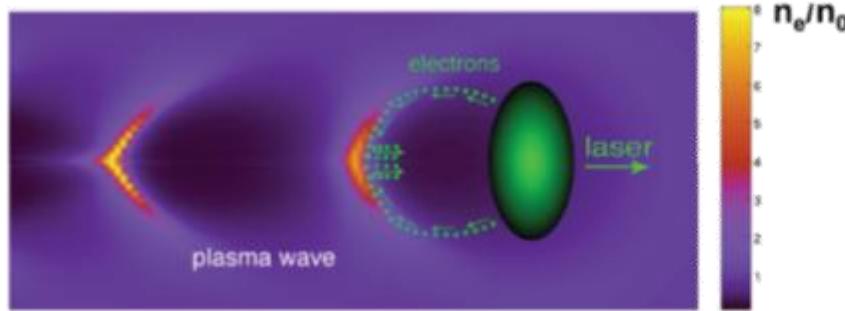
Wake fields: high laser intensity

Electron density perturbation & longitudinal wake field

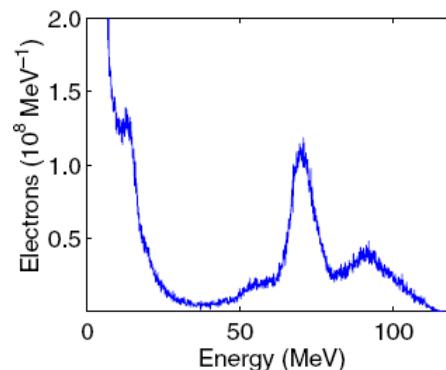
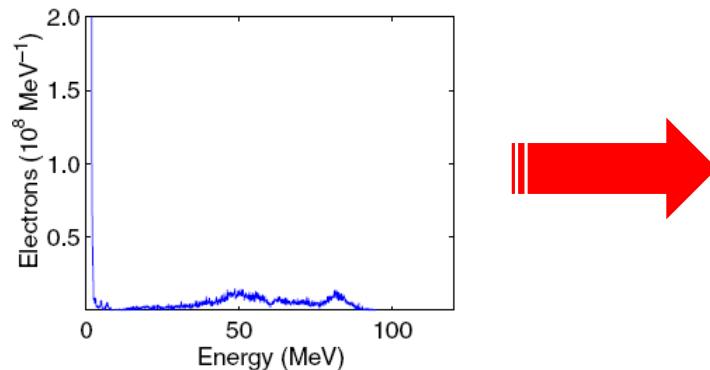


Wake fields: bubble regime

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



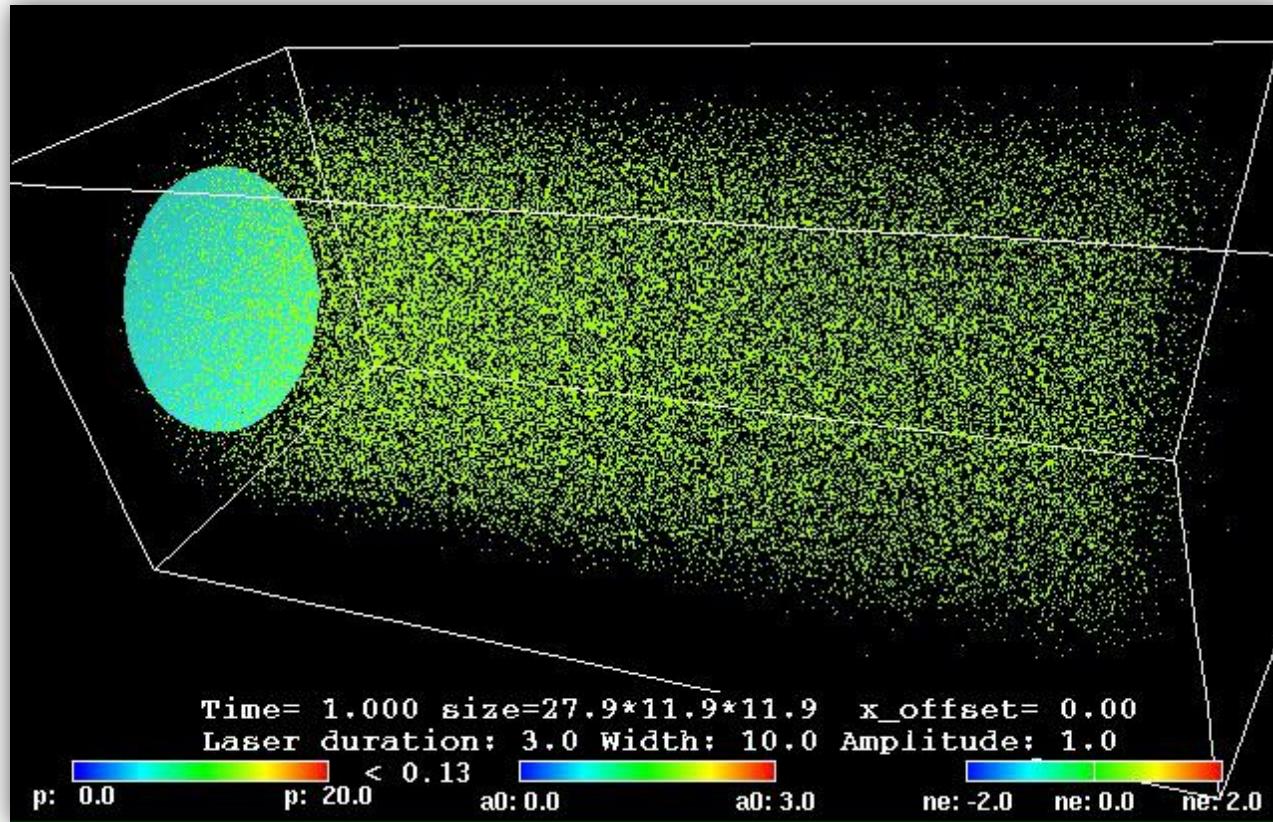
surfing behind a wake boat



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

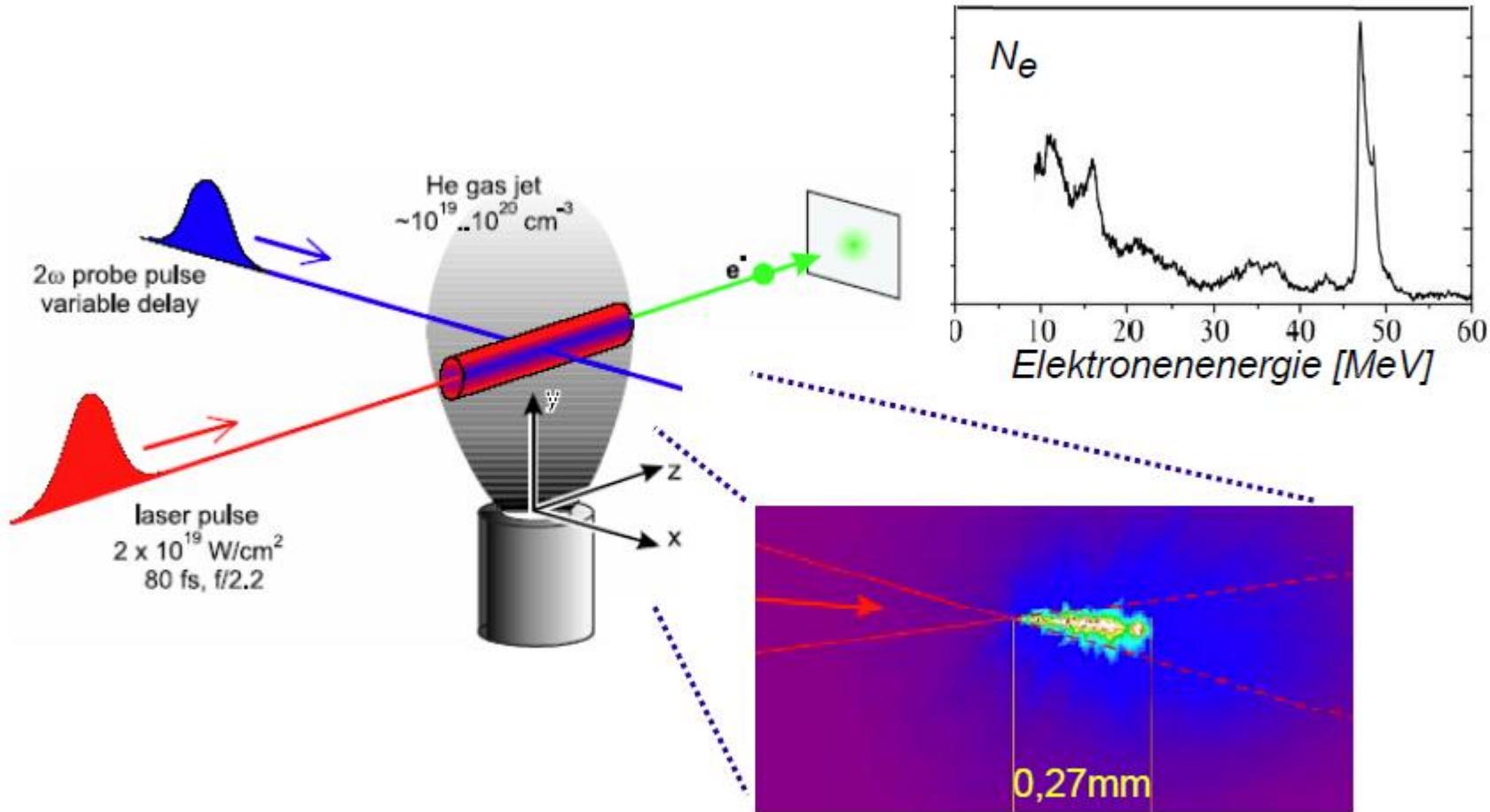
“Bubble“ acceleration (gas targets)

simulation: P.Gibbon, FZ Jülich



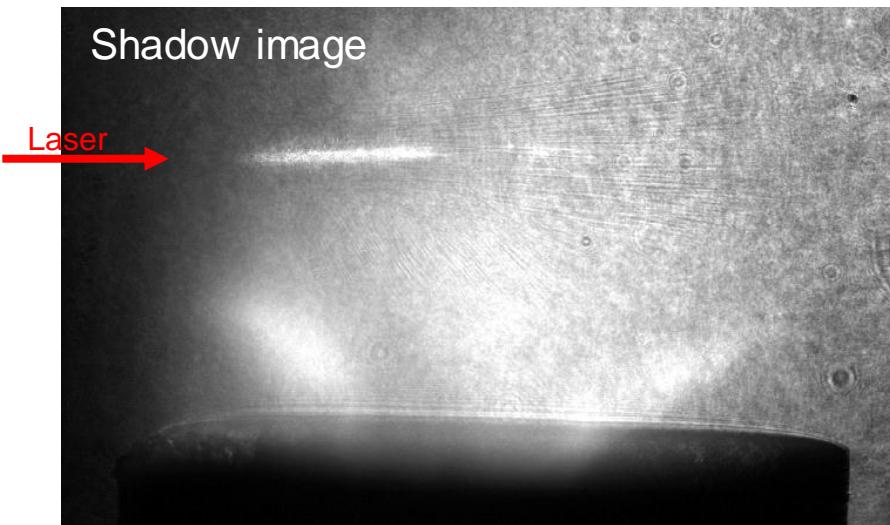
accelerates
electrons

Observation of plasma channel



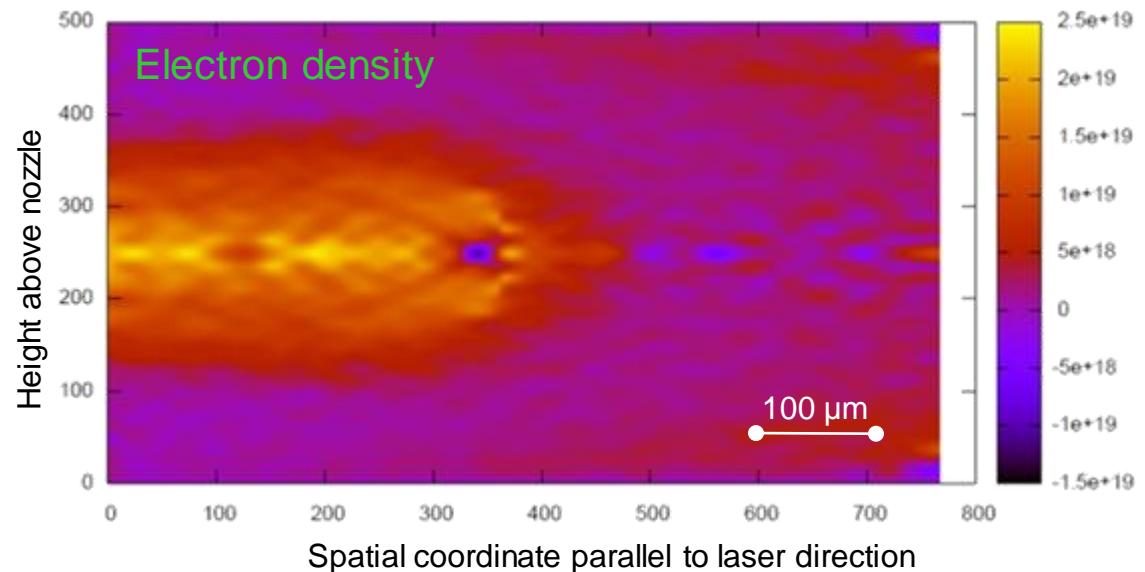
J.Hein, R.Sauerbrey, *Generation of ultrahigh light intensities and relativistic laser-matter interaction*,
 in Springer Handbook of Lasers and Optics (2007), ISBN 978-0-387-95579-7

Observation of plasma channel (2)

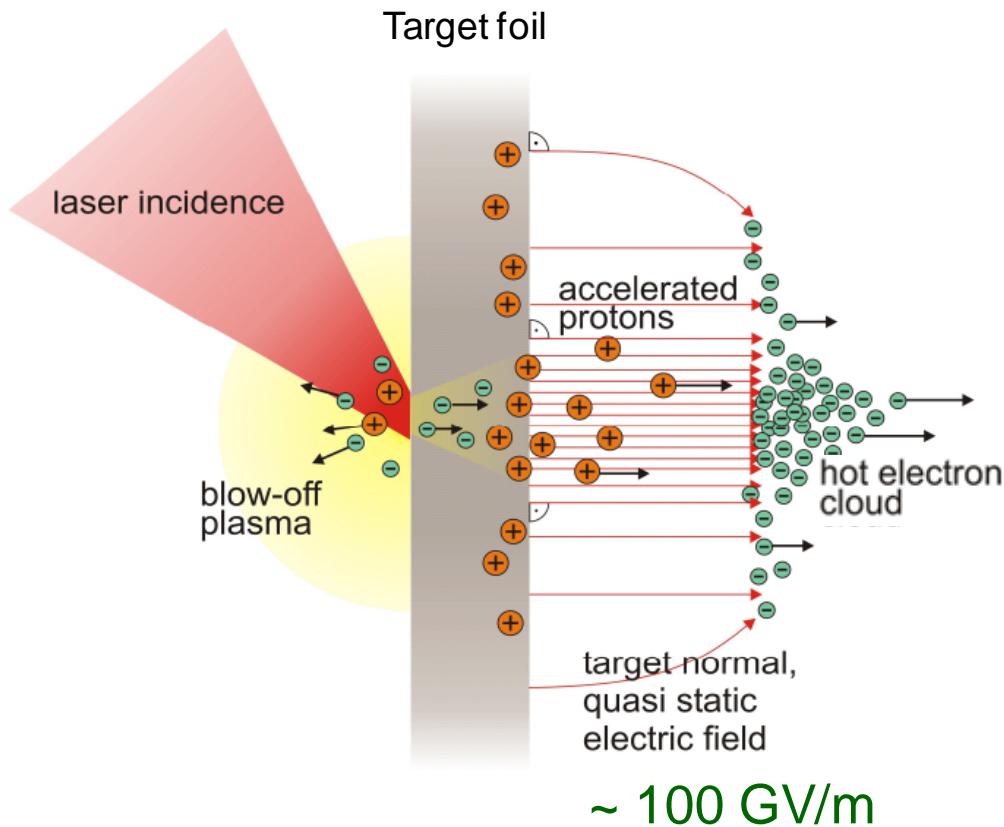


60 TW, 7.8 bar He

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



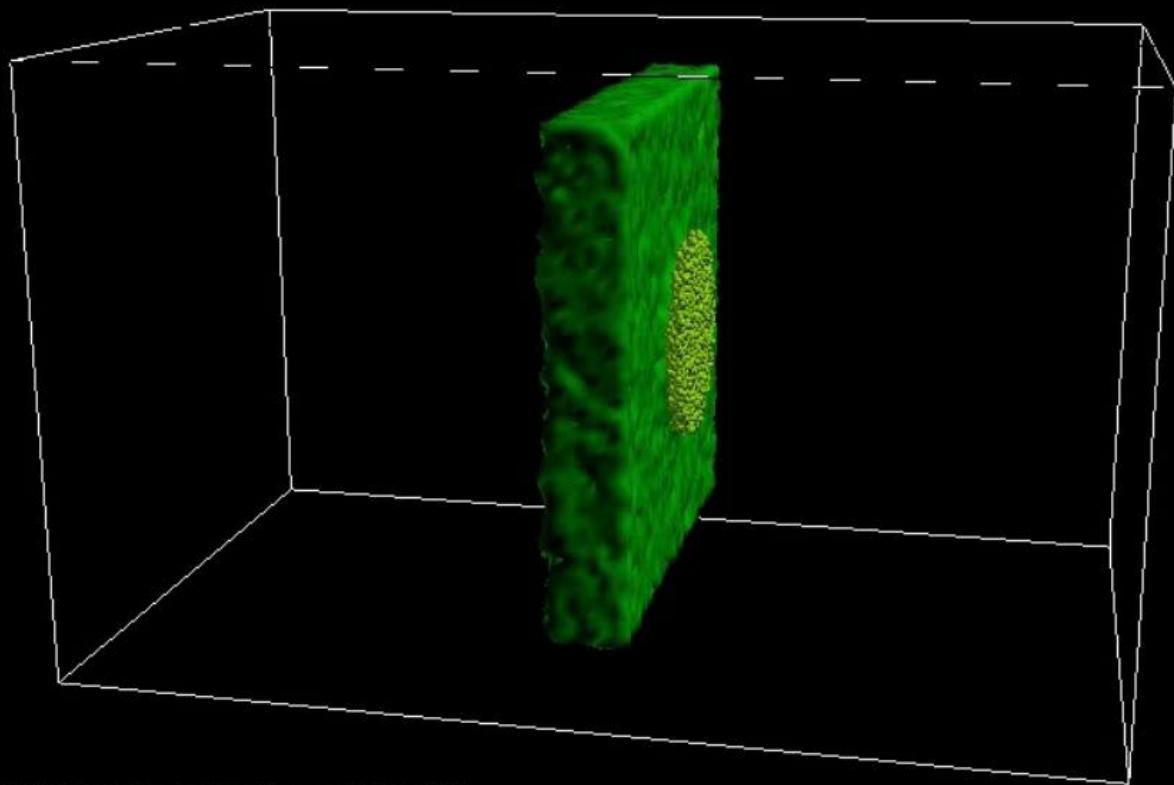
Target Normal Sheath Acceleration (TNSA)



TNSA (foil targets)

simulation: P.Gibbon, JSC, FZ Jülich

Field 0: Ion density
Field 1: Electron temperature
Field 2: Laser intensity



→
accelerates
protons/ions

RF vs. laser acceleration

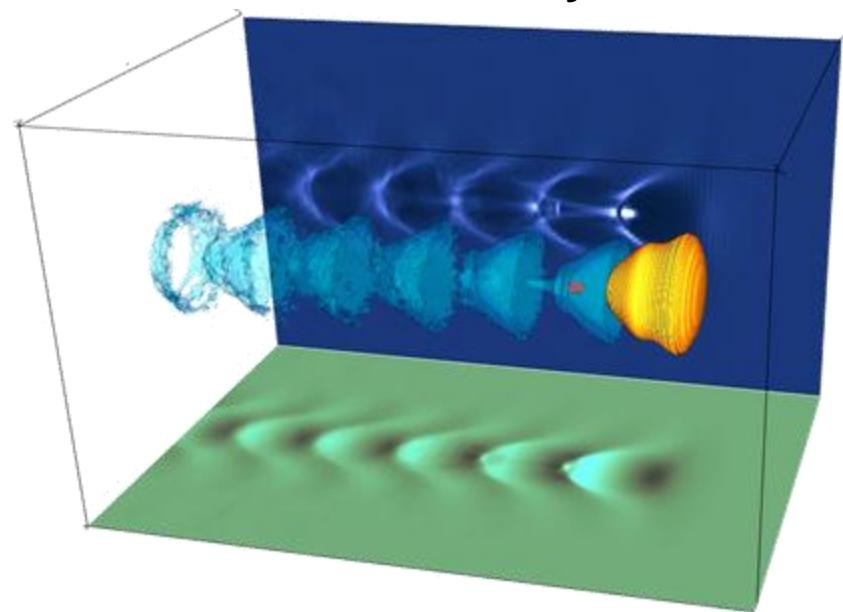
RF cavity



1 m
 1 MV/m

$\}$ 1 MeV

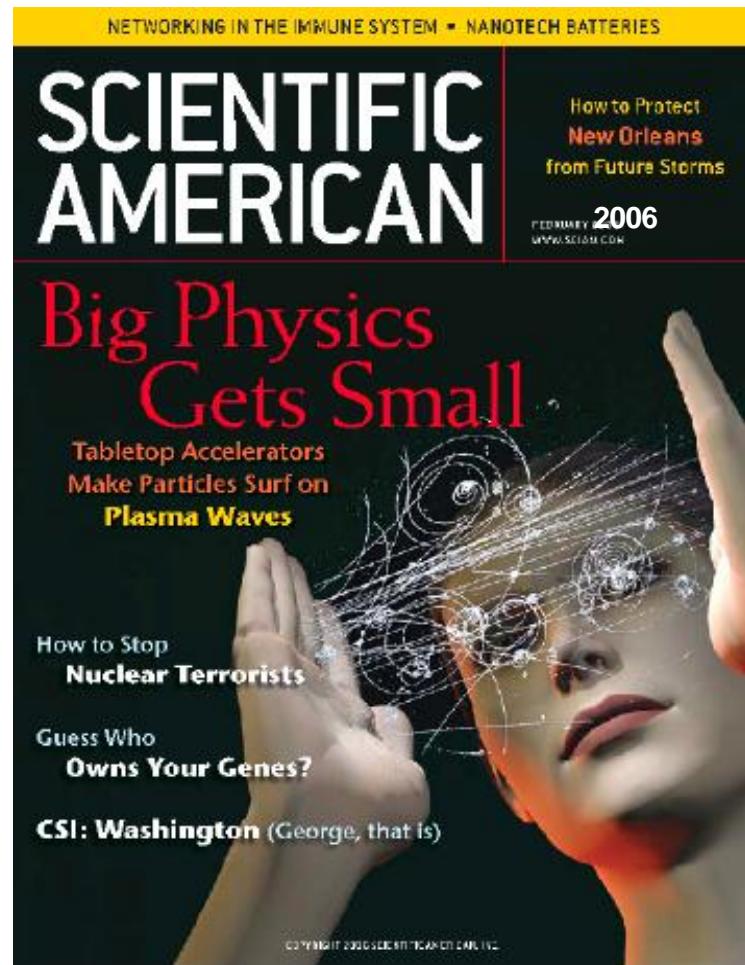
Plasma "cavity"



$100 \mu\text{m}$
 100 GV/m

$\}$ 10 MeV

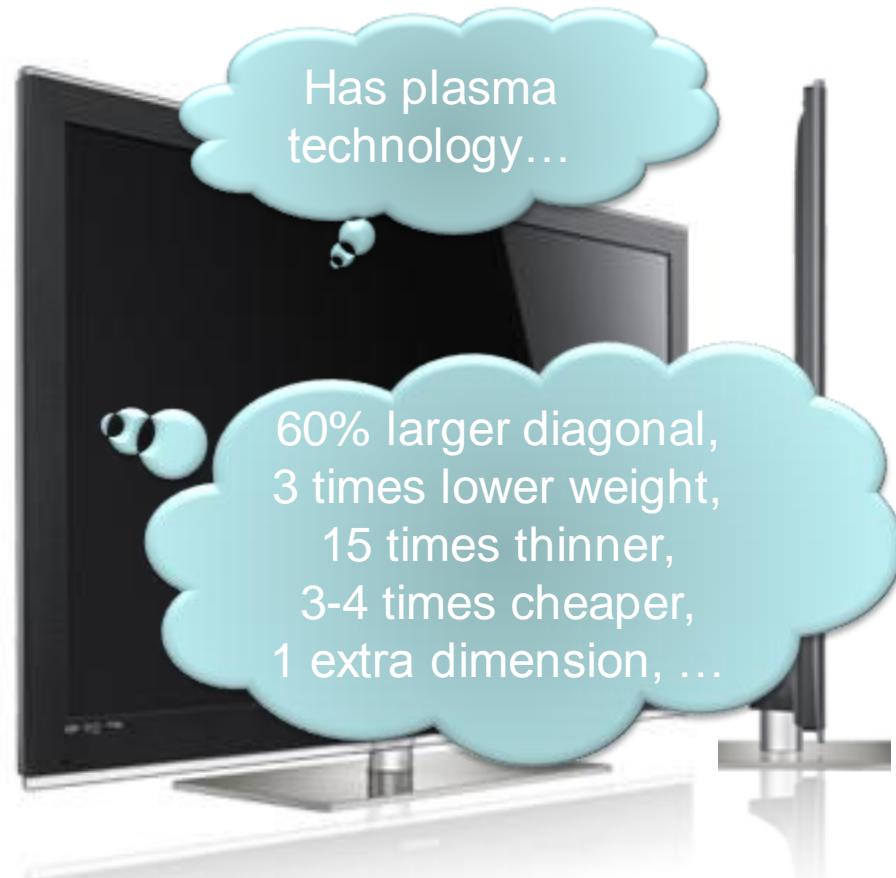
An up-and-coming technology ...



Technological revolutions do happen!

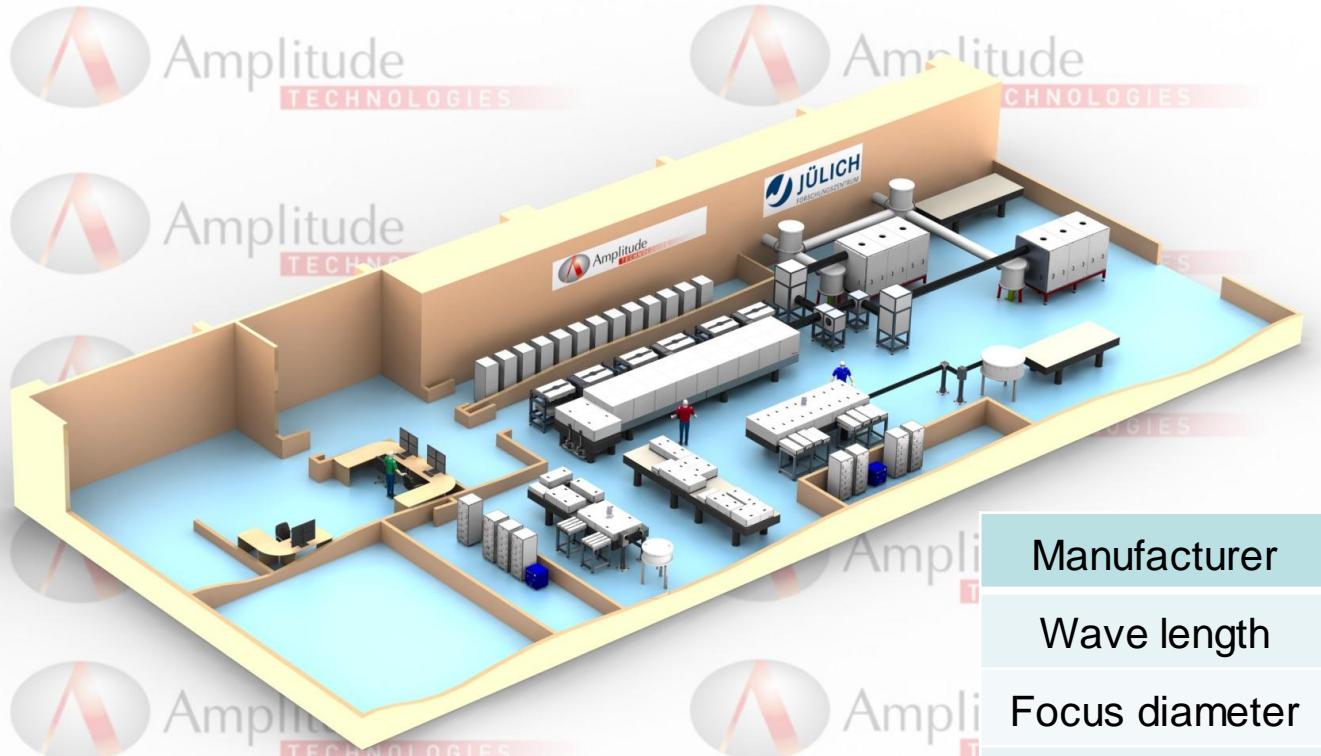


Oct 2002: largest CRT display,
102cm diagonal,
\$15,000, 63cm deep, 92kg



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

JuSPARC = Jülich short-pulse particle and radiation centre



Manufacturer	Amplitude Technologies
Wave length	800 nm
Focus diameter	20 µm
Peak power	10 TW / 200 TW /1.5 PW
Repetition rate	100 Hz / 1 Hz / 1 Hz
Pulse length	25 – 40 fs

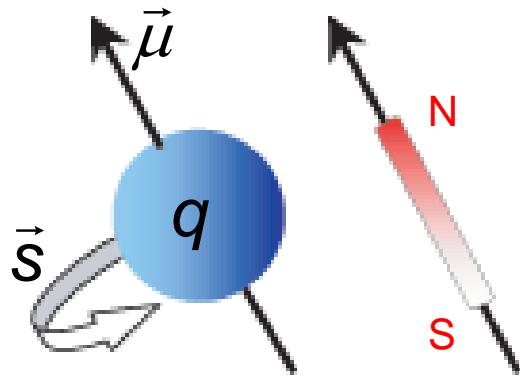
Part 2

Electric fields → change particle energies → acceleration

Magnetic fields → ?

Magnetic fields / spin

Charged spinning particle → magnetic moment μ



$$\vec{\mu} = g \frac{q}{2m} \vec{s}$$

$$g_e = 2.00\dots (+\varepsilon)$$

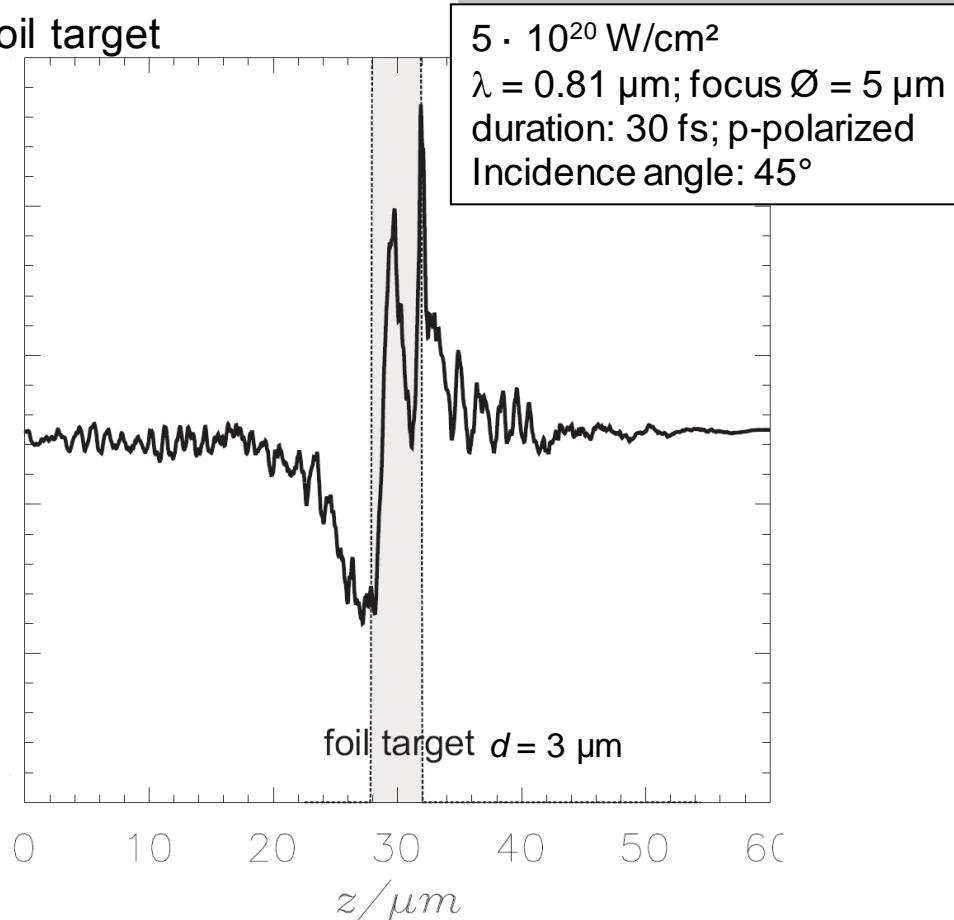
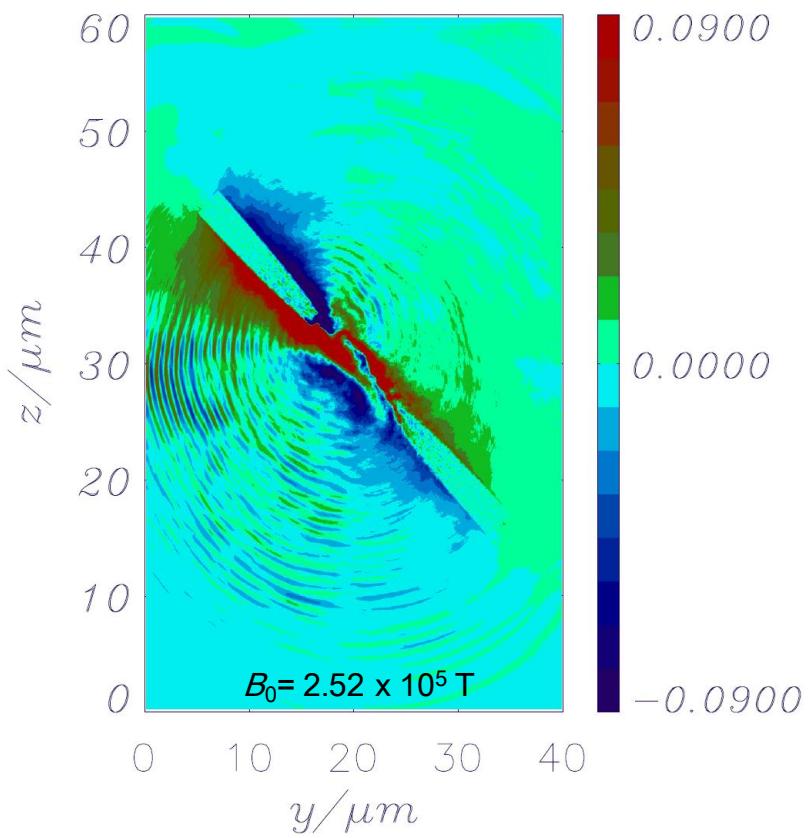
$$g_p = 5.586$$

$$g_n = -3.826$$

μ can be manipulated by magnetic fields

Strong magnetic fields (simulation)

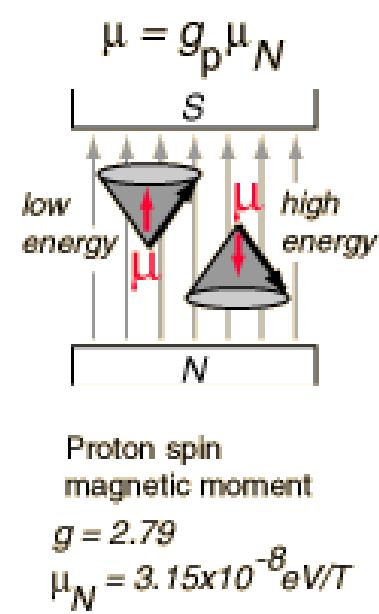
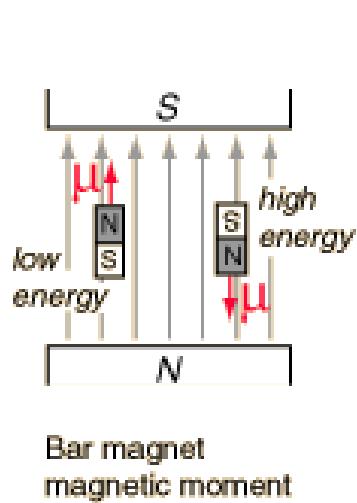
B field distribution 140 fs after laser hits foil target

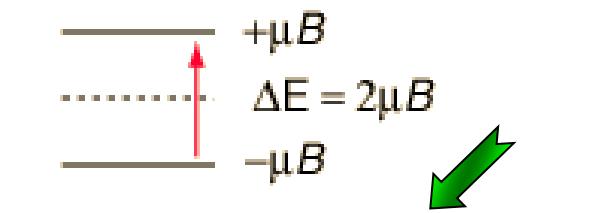


→ Field strength / gradient: $\sim 10^4 \text{ T} / 10^{10} \text{ Tm}^{-1}$

Simulations: A.Karmakar & P.Gibbon, FZJ

Spin alignment in magnetic fields

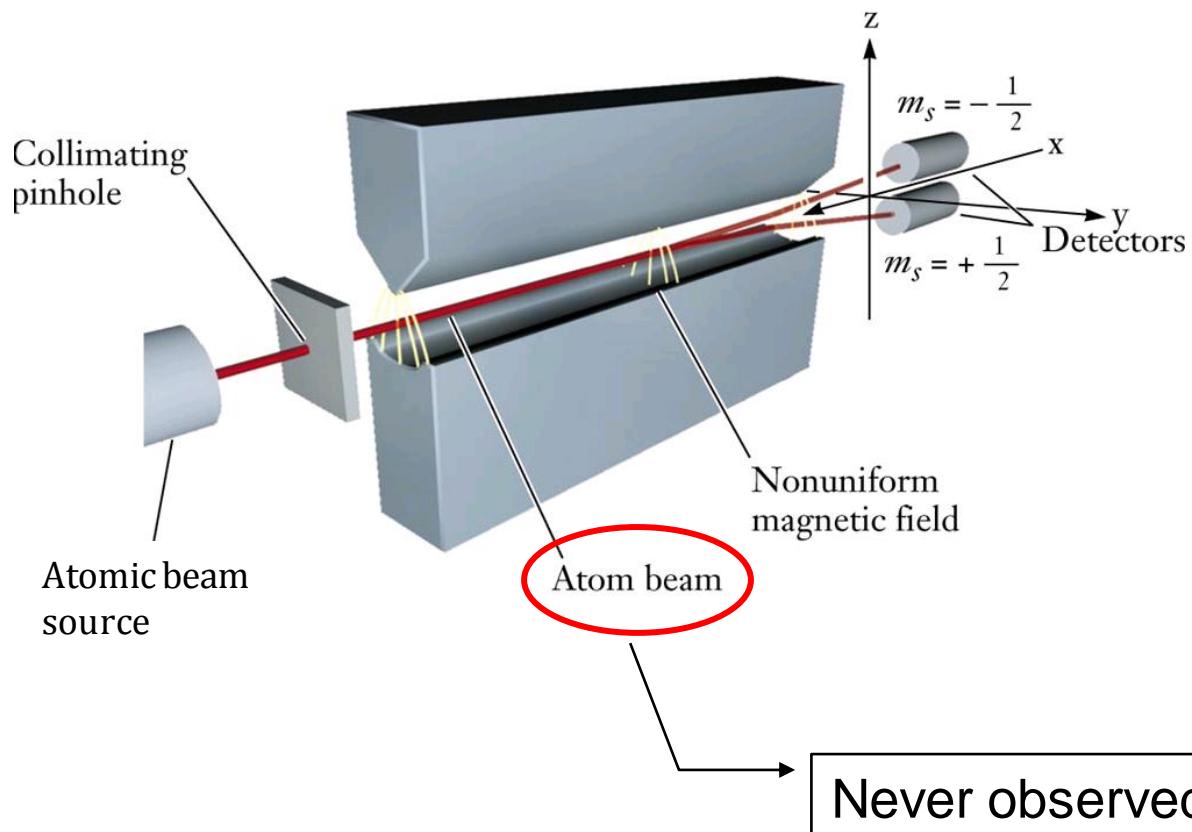




A vertical energy level diagram with three horizontal lines. The top line is labeled $+ \mu B$, the middle line is dashed and labeled $\Delta E = 2\mu B$, and the bottom line is labeled $- \mu B$. A green arrow points from the text below to the middle dashed line.

$\Delta E = 2\mu B = 2 g_p \mu_N B$
 $\Delta E = 2 \cdot 2.79 \cdot 3.15 \times 10^{-8} \text{ eV/T} \cdot 1 T$
 $\Delta E = 1.76 \times 10^{-7} \text{ eV}$

Spin separation: Stern-Gerlach effect

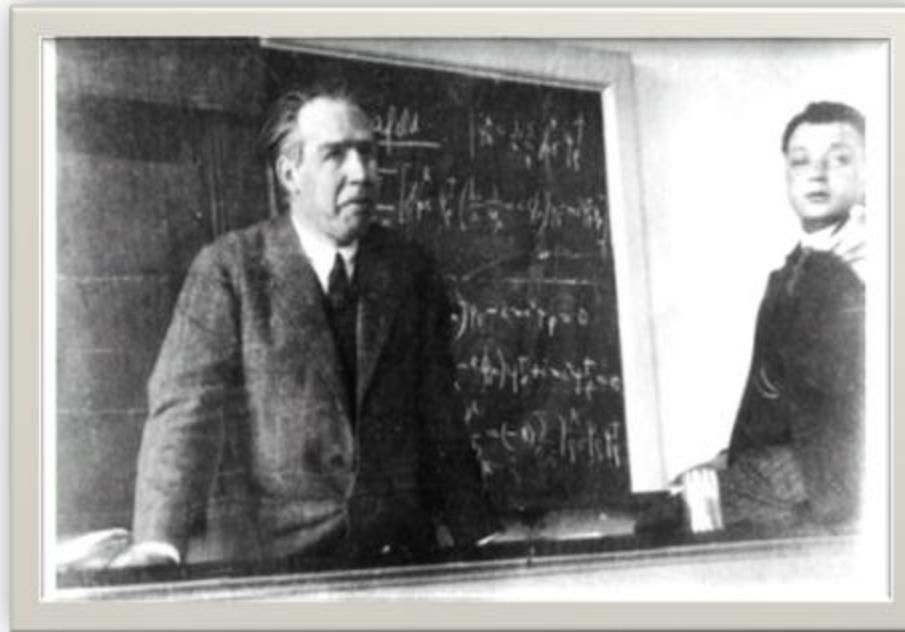


$$\vec{F} = \nabla(\vec{\mu} \cdot \vec{B}) = \begin{pmatrix} 0 \\ 0 \\ \mu_z \cdot \frac{\partial B}{\partial z} \end{pmatrix}$$

Never observed for charged particles!

Stern-Gerlach effect ... revisited

Stern-Gerlach effect for charged particles (e^- , p , ...)?



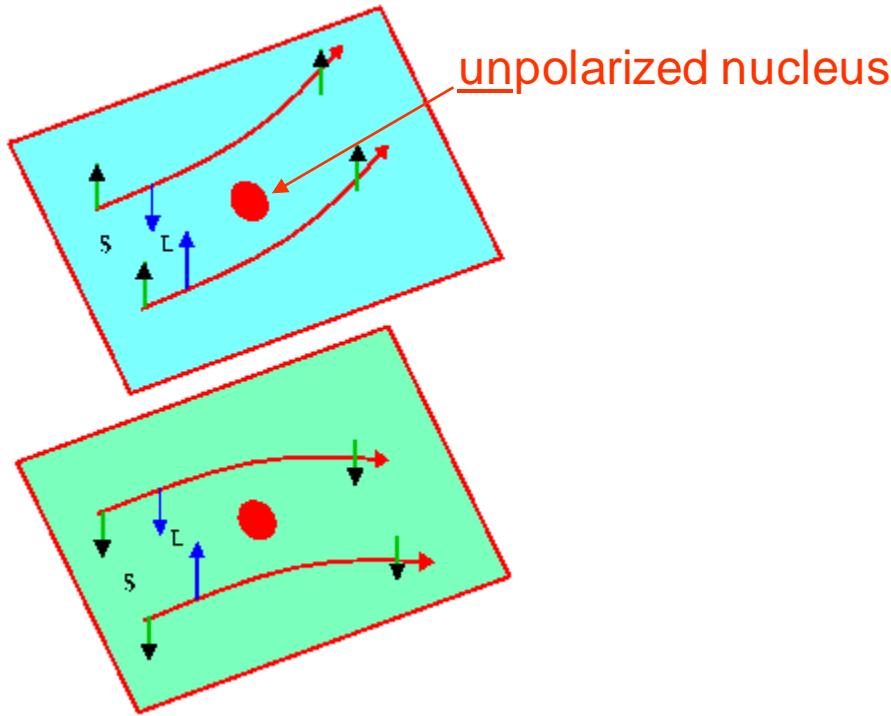
Niels Bohr and Wolfgang Pauli during the Copenhagen conference April 1929
(Niels Bohr Archive, Copenhagen)

“Does a flying electron spin?”

see e.g.: B.M.Garraway and S.Stenholm, Contemporary Physics 43, p.147 (2002)

How to measure beam polarization

Nuclear scattering with known analyzing powers



$$H = V(r) + V_{SO}(r, E, \dots) \cdot (\vec{S} \bullet \vec{L}) + \dots$$

Scattering of a polarized beam

Simplest case: beam particle with spin $\frac{1}{2}$ on unpolarized target

$$\frac{d\sigma}{d\Omega}(E, \vartheta, \varphi) = \frac{d\sigma}{d\Omega_{\text{unpol}}}(E, \vartheta)[1 + A \cdot P \cdot \cos \varphi]$$

Analyzing power

$A(E, \vartheta, \text{target}, \dots)$
 $-1 \leq A \leq +1$

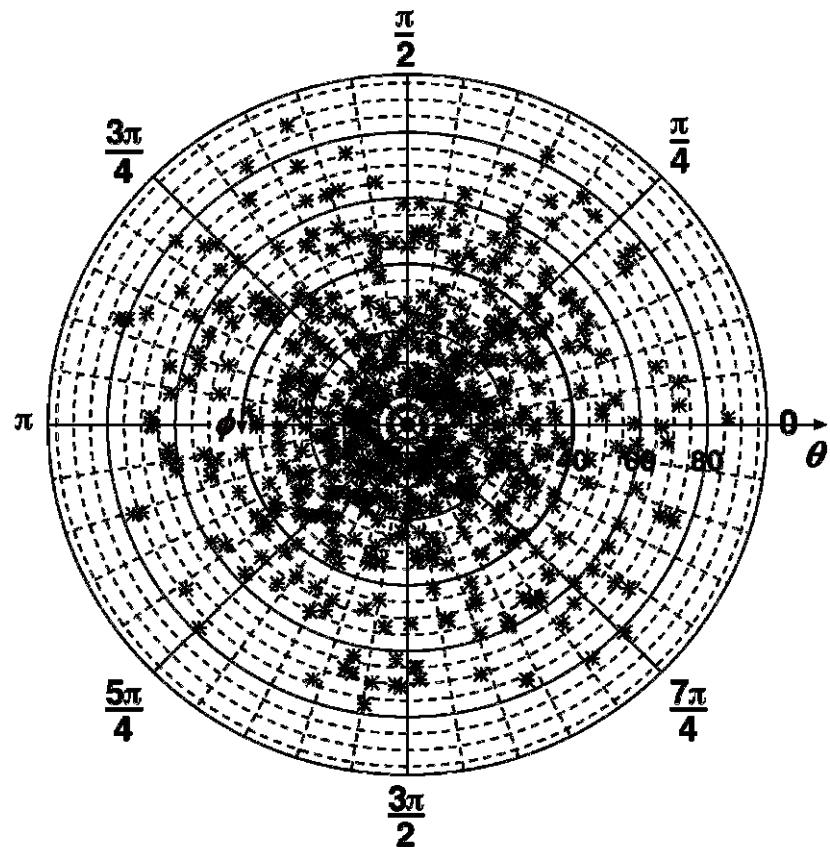
Beam polarization

P
 $-1 \leq P \leq 1$

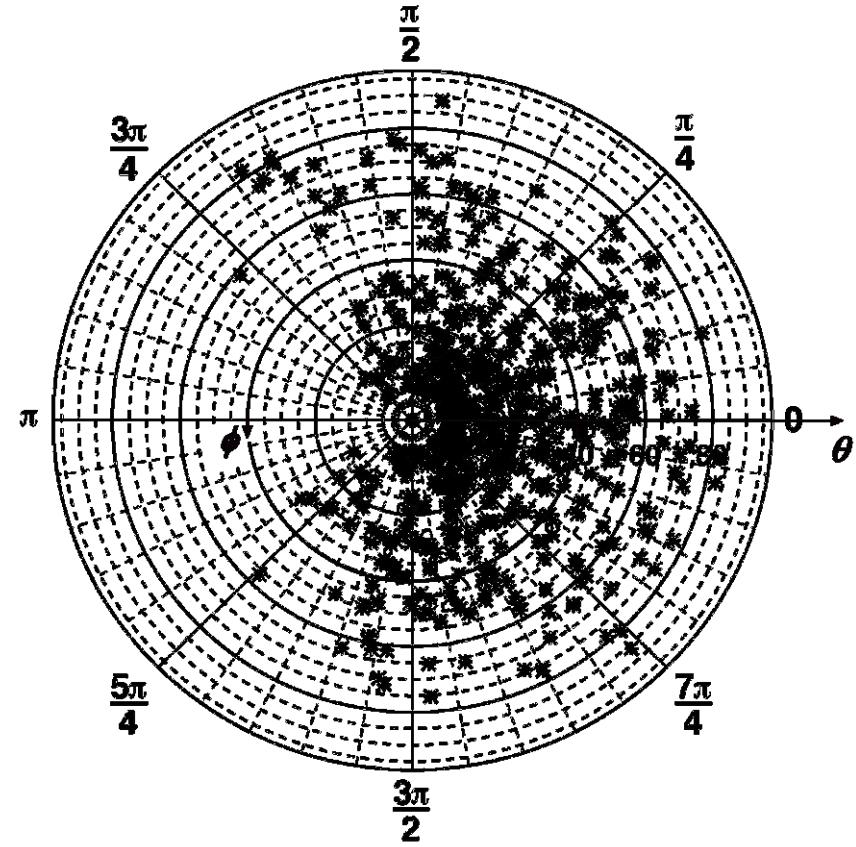
Scattering of a polarized beam (2)

Simulation for

$$P = 0 \text{ or } A = 0$$

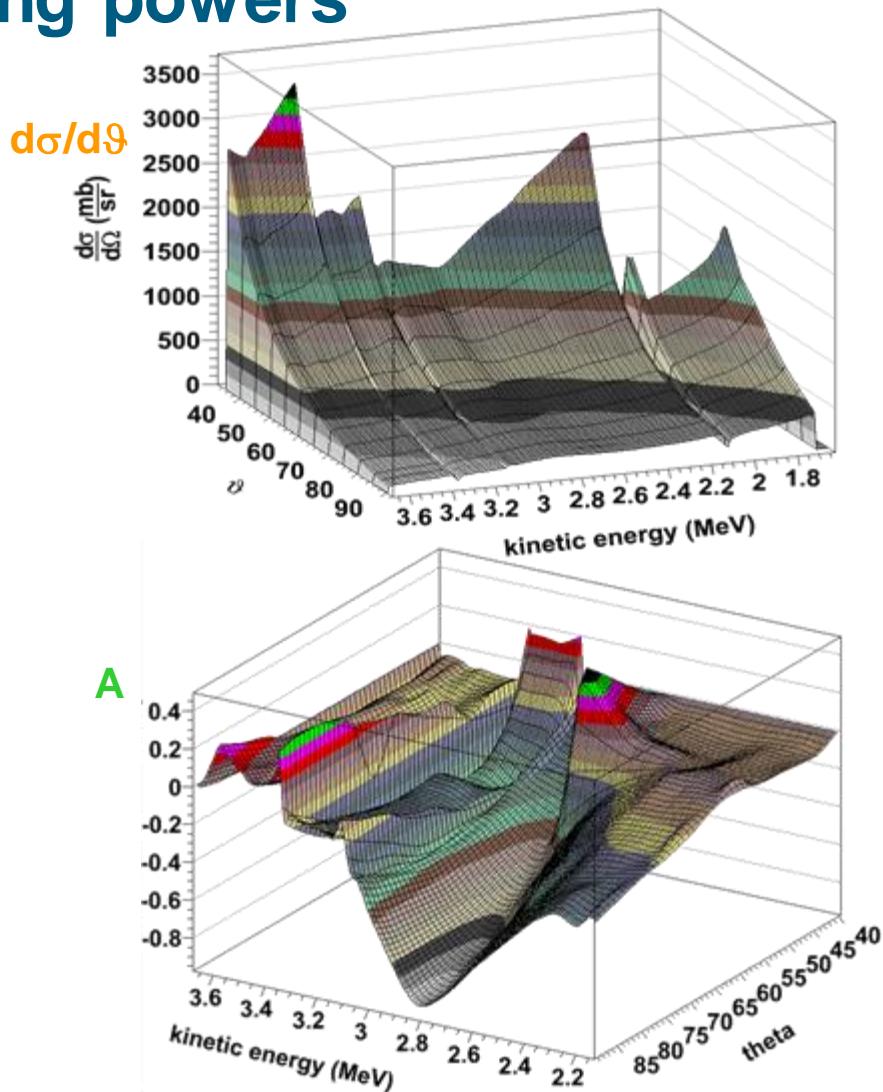
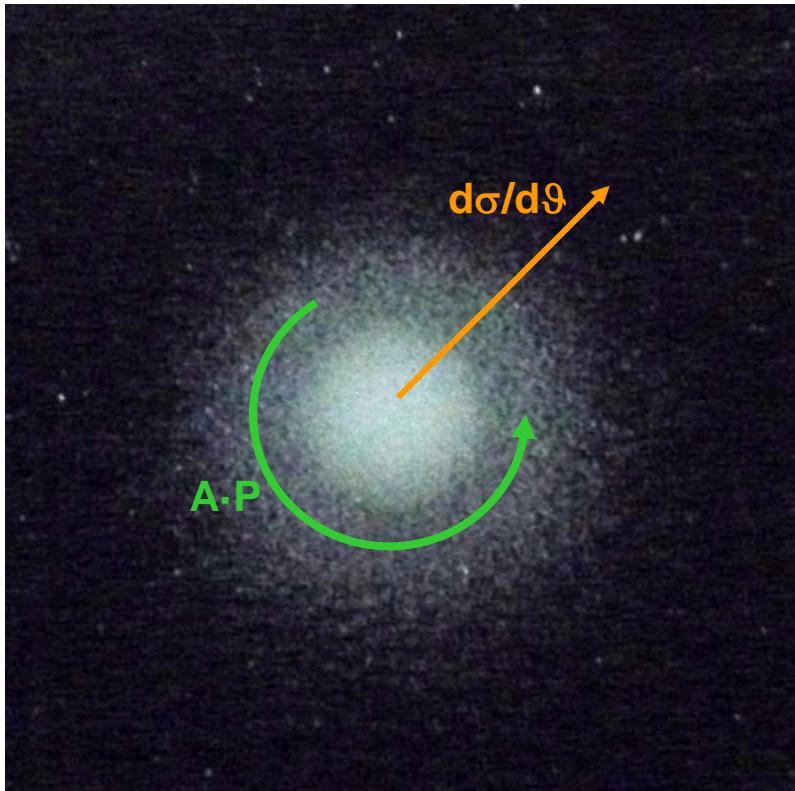


$$P = A = +1$$



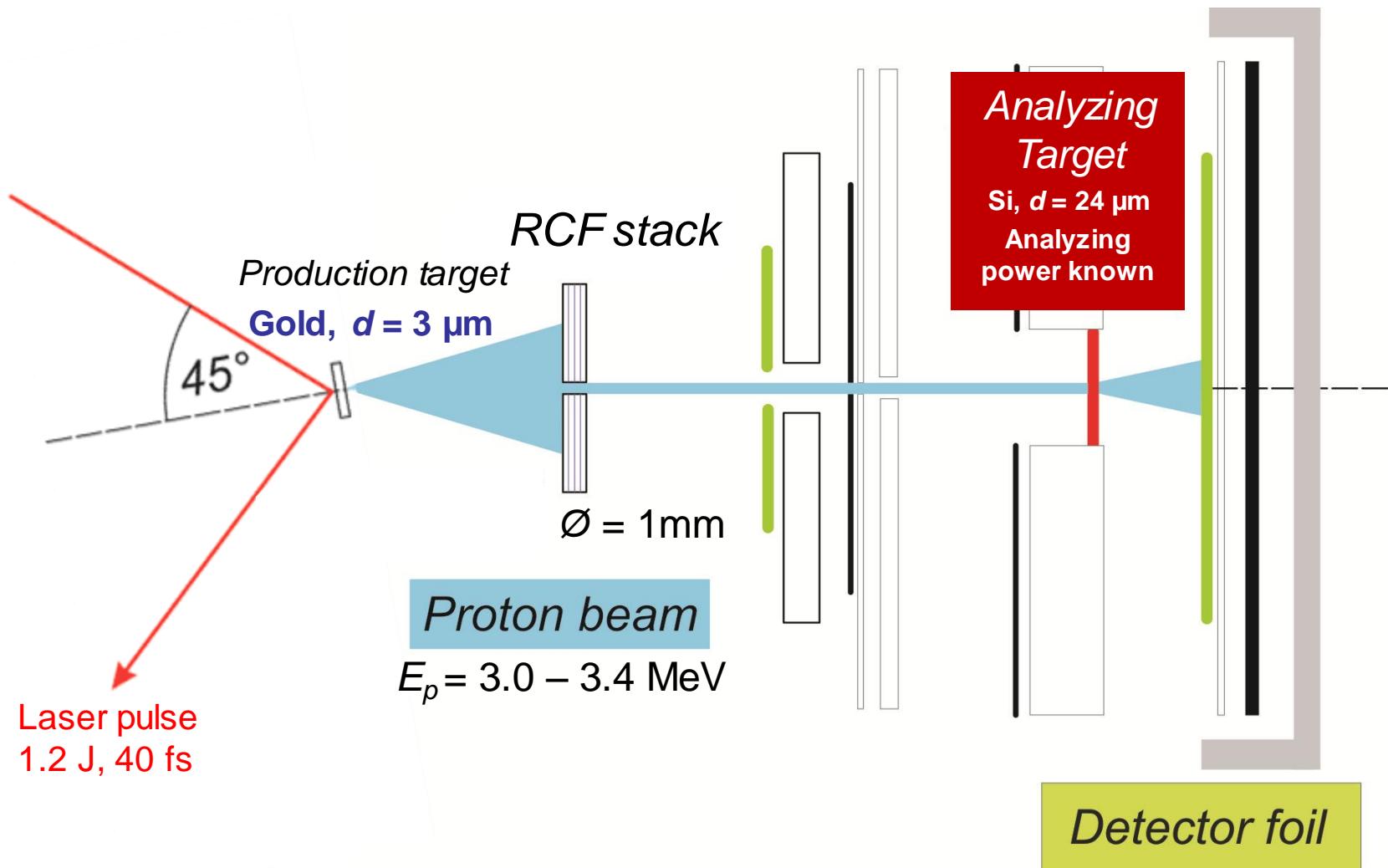
Cross sections & analyzing powers

Example: $\text{Si}(p, p')\text{Si}$

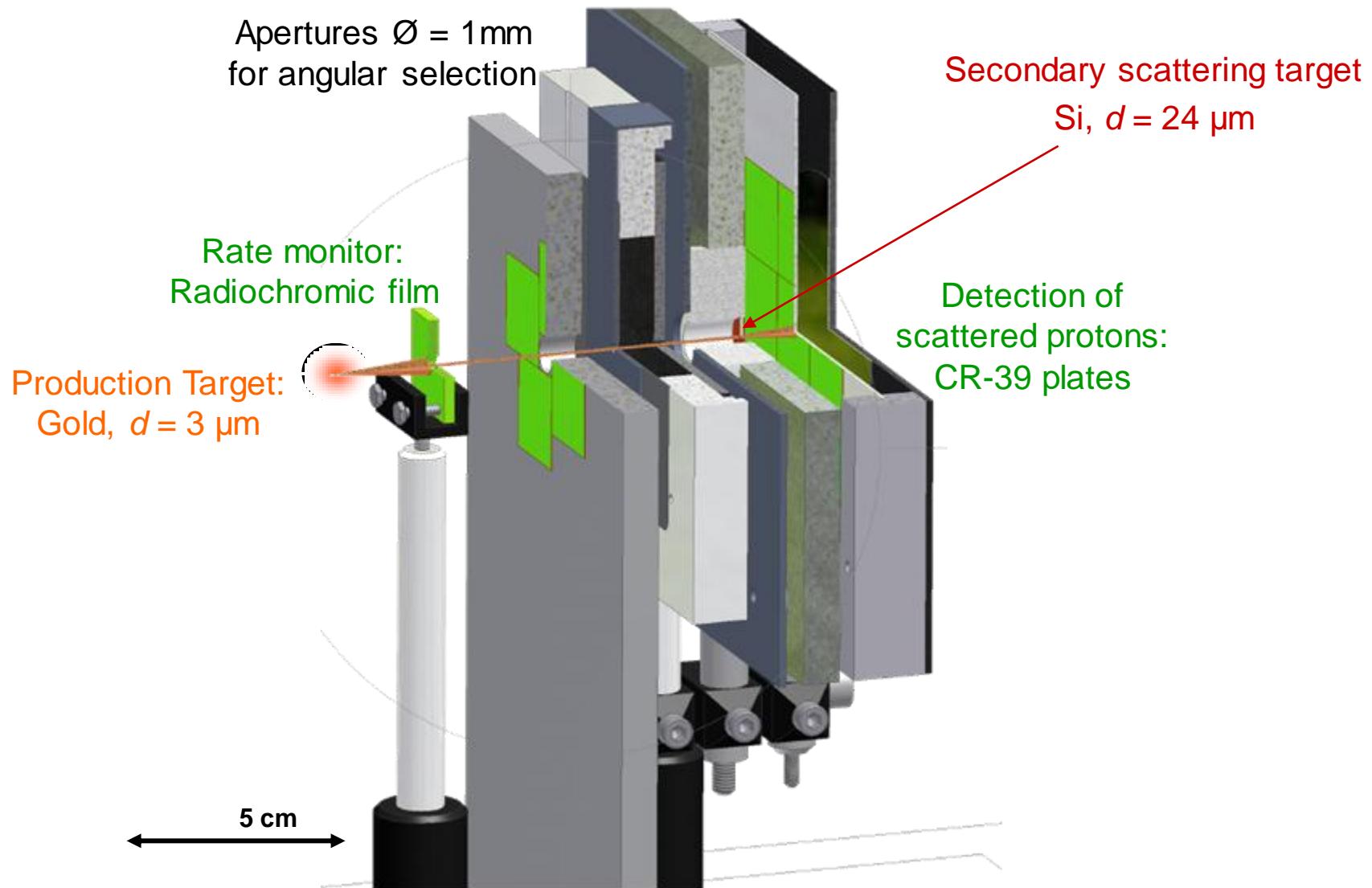


B.Becker, Universität zu Köln (1994)

Polarization measurement: setup

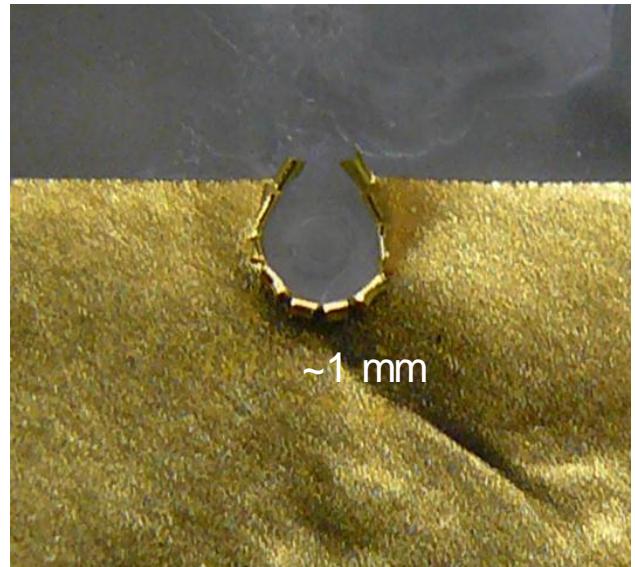


Polarization measurement: setup



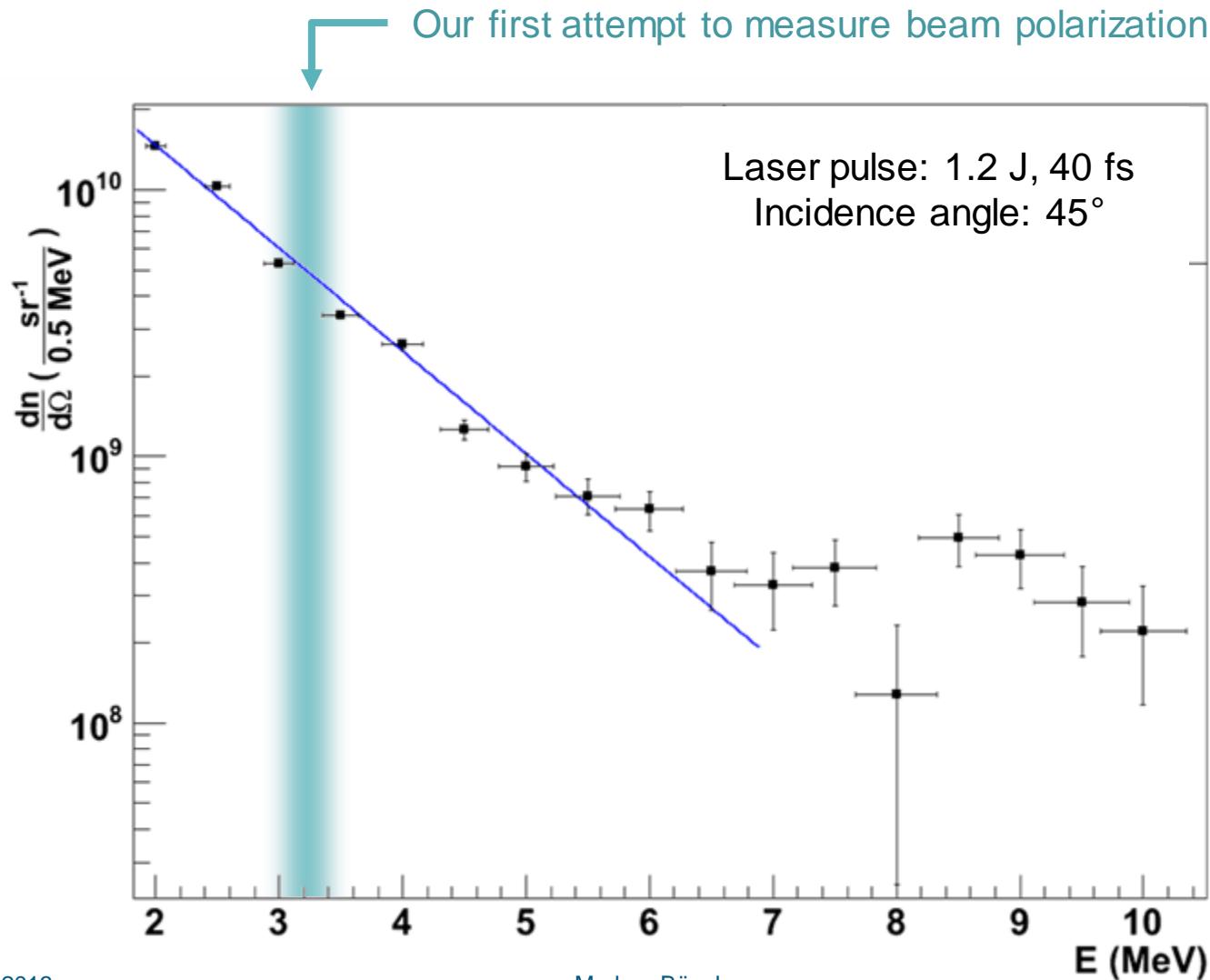
Foil targets: proton acceleration

Target chamber at ARCTurus / Düsseldorf Univ.

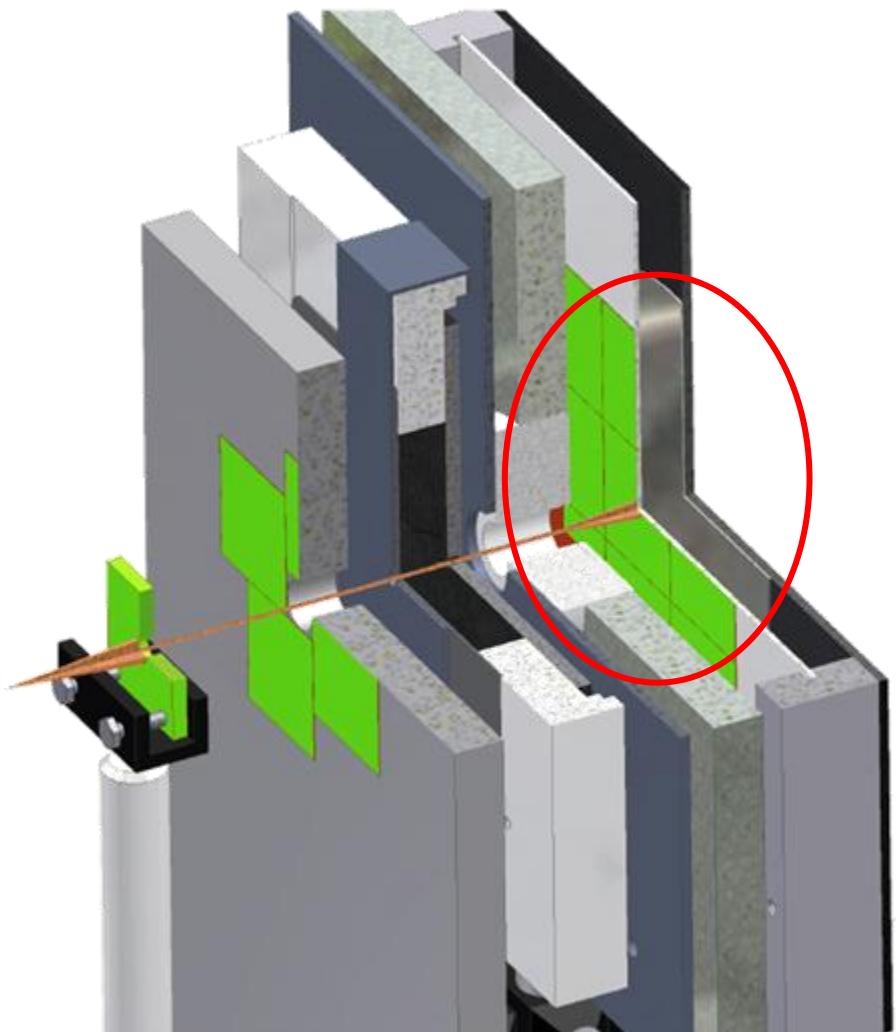


Gold foil
typical thickness 3 μm

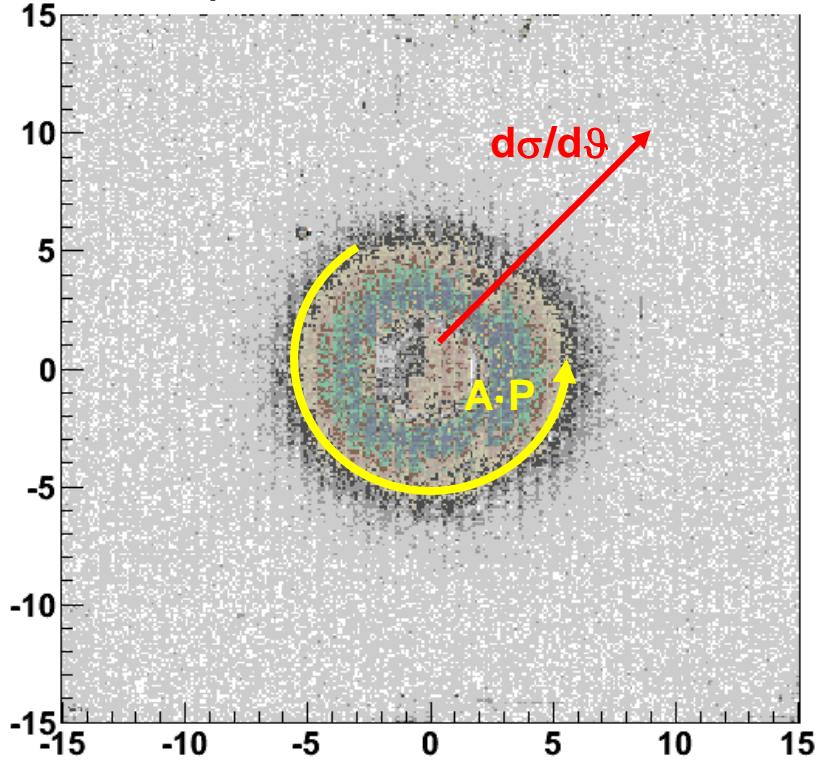
Proton energy spectrum



Proton scattering in Si target



CR39 plates



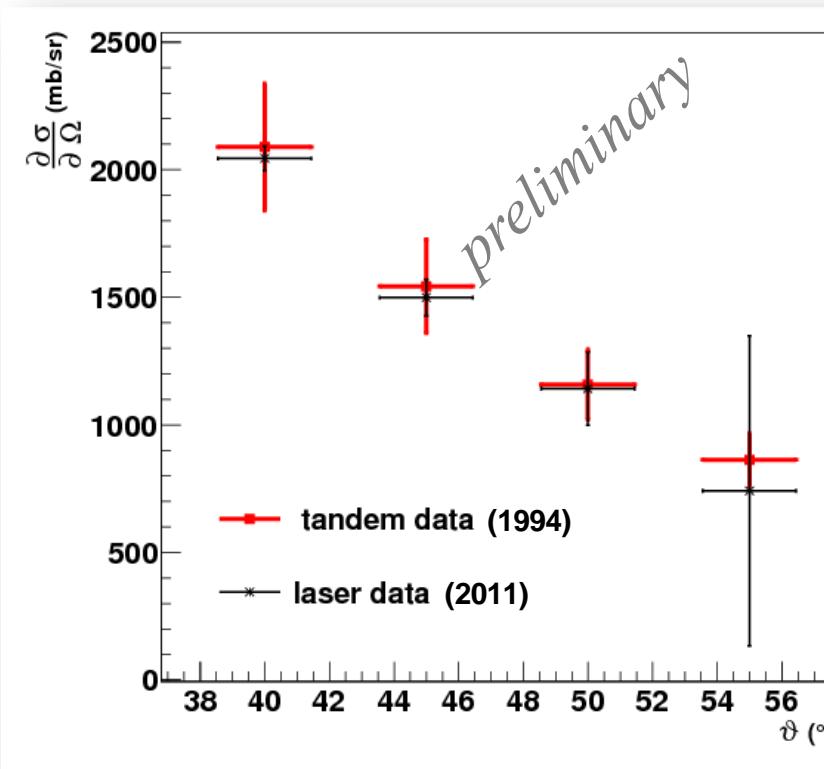
Scattering-angle distribution

$\text{Si}(p, p')\text{Si}, \quad T_p = (3.2 \pm 0.2) \text{ MeV}$

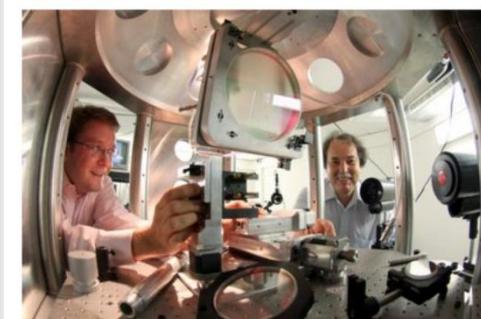
Cologne Tandem



Beam time = $\mathcal{O}(\text{days})$



ARCturus Laser

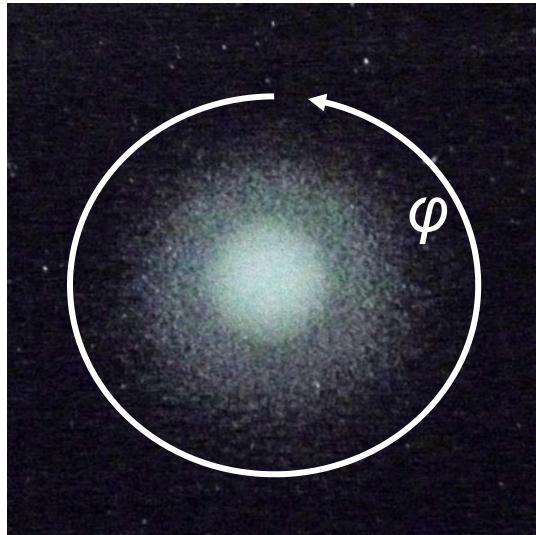


Beam time = $\mathcal{O}(100 \text{ fs})^*$

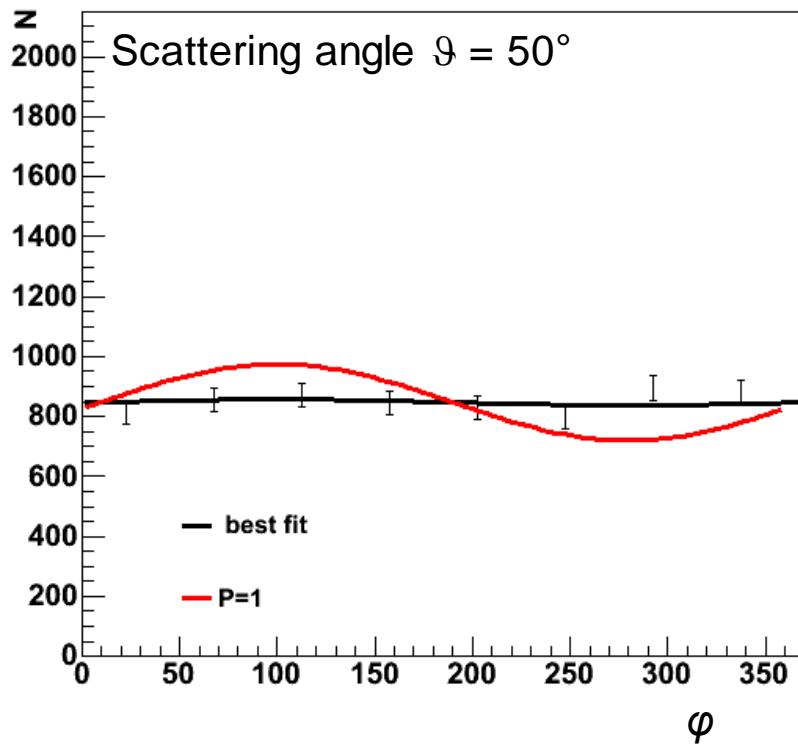
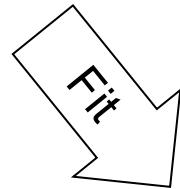
* average over 10 shots

Data analysis: N.Raab, Ph.D. thesis, Univ. zu Köln (Jan. 2011)

Azimuthal-angle distribution



$$\frac{d\sigma}{d\Omega}(E, \vartheta, \varphi) \propto [1 + A \cdot P \cdot \cos(\varphi - \varphi_0)]$$



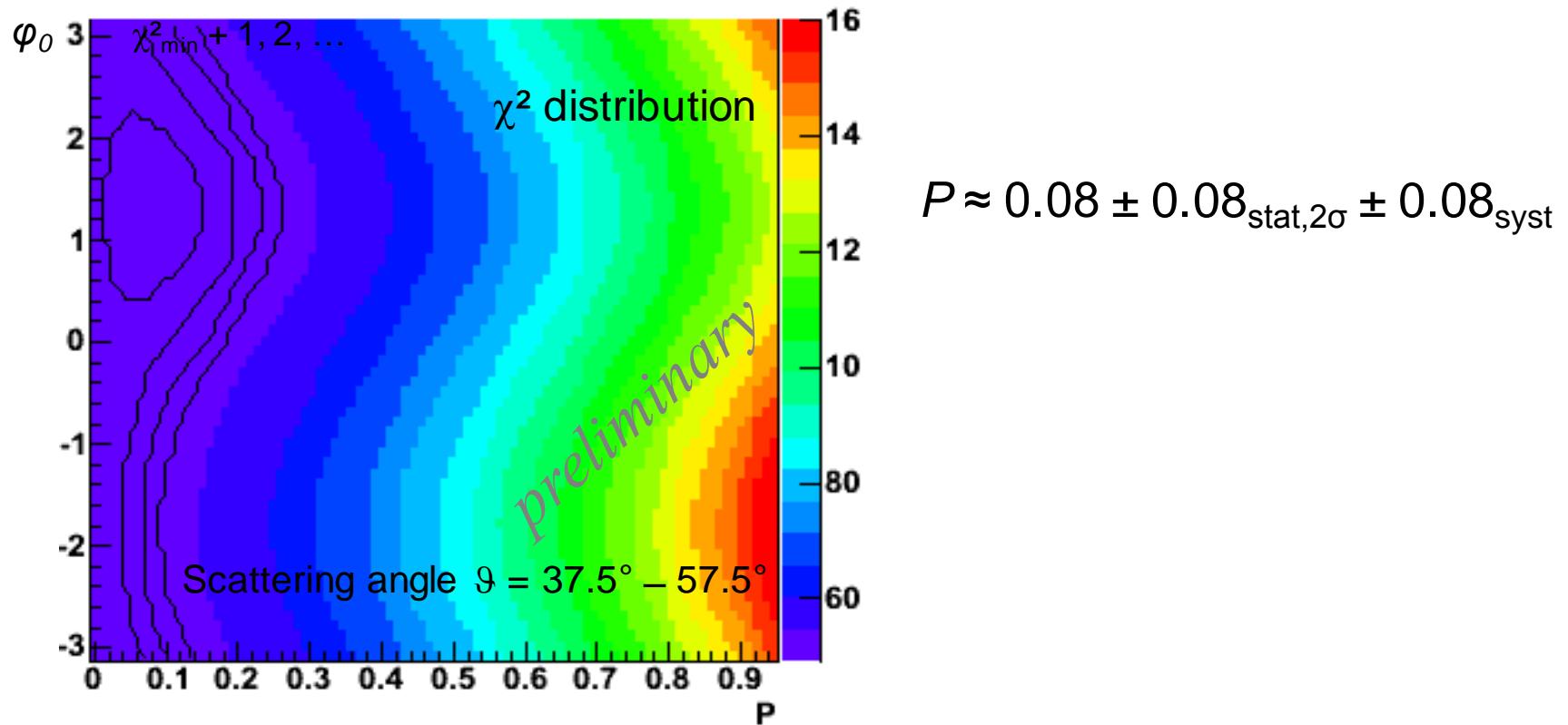
Laser incidence angle:
 $\Phi = 90^\circ, \Theta = 45^\circ$

Proton emission angle:
 $\Phi = 180^\circ, \Theta = 8^\circ$

Relative to production target normal

Proton polarization: first result

For 3.2 MeV protons from foil target



Polarized beams from laser plasmas: possible scenarios

1) Polarization is generated

Laser-acceleration process polarizes particles from unpolarized targets (plasmas) due to large magnetic fields and/or gradients

→ foil targets $\mathcal{P} = 0$

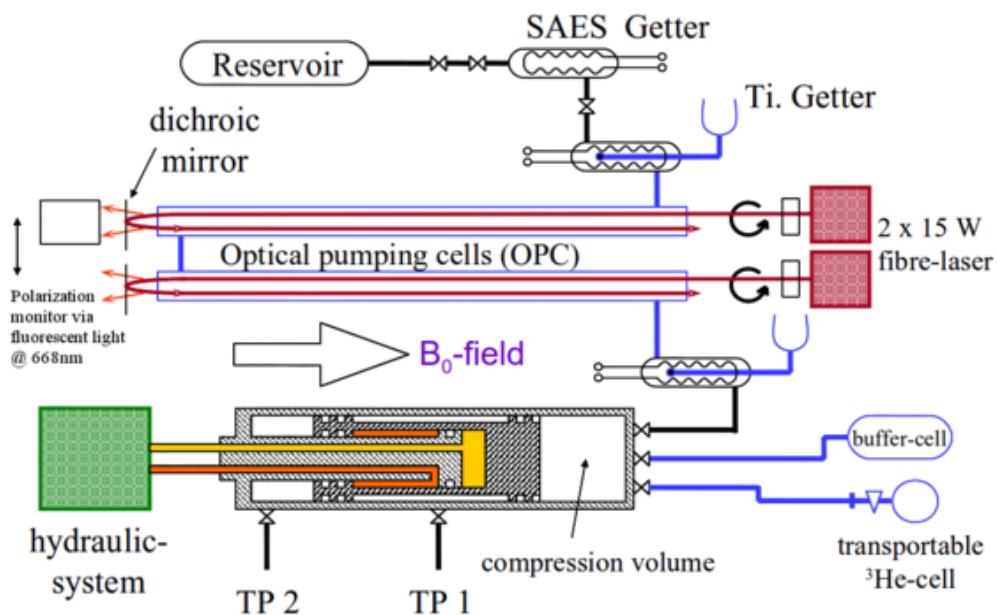
2) Polarization is preserved

Spin direction is invariant in strong laser & plasma fields

→ polarized ^3He gas

Polarized ^3He

Stable (days) nuclear polarization @ room temperature
 Available from Univ. Mainz



Production

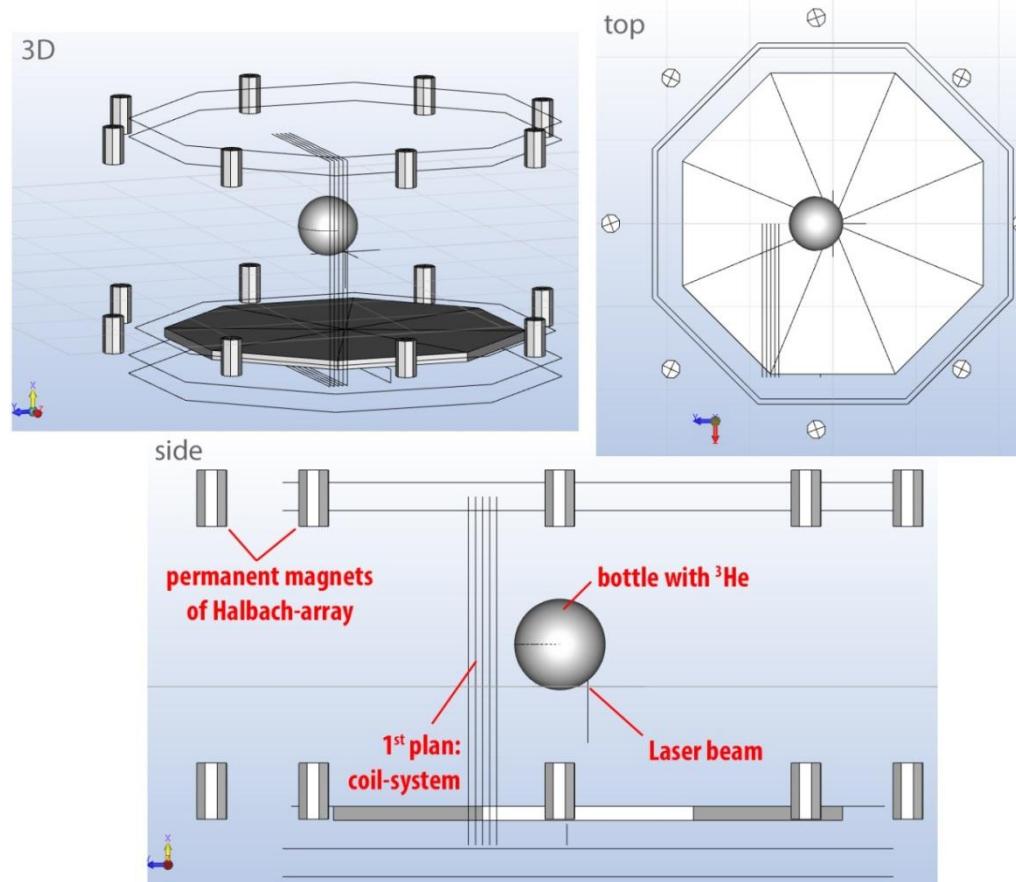


Transport

Polarized ^3He : Magnetic holding fields

Halbach array of permanent magnets

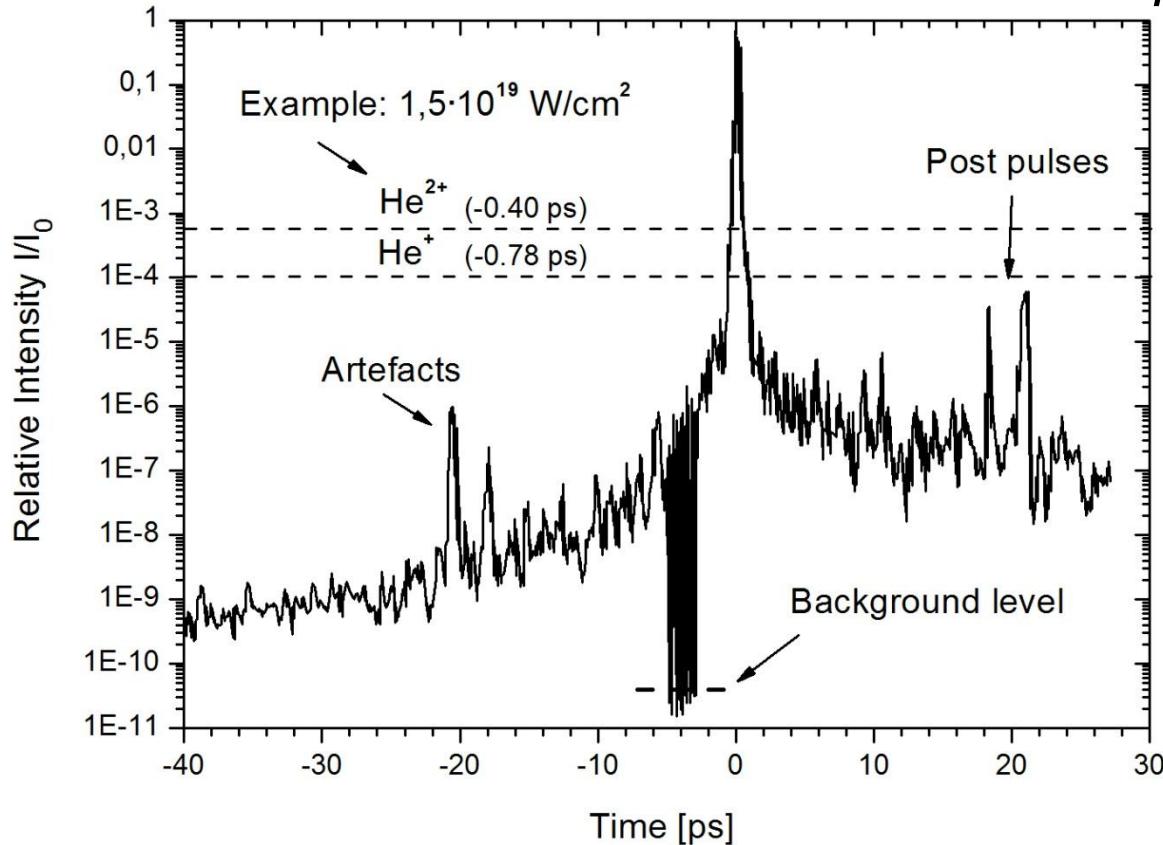
Homogeneous field distribution at target location



CPA: Rapid ionization

Measured at ARCTurus / Düsseldorf Univ.

$$I_0 \approx 10^{20} \text{ W/cm}^2$$



Conclusion

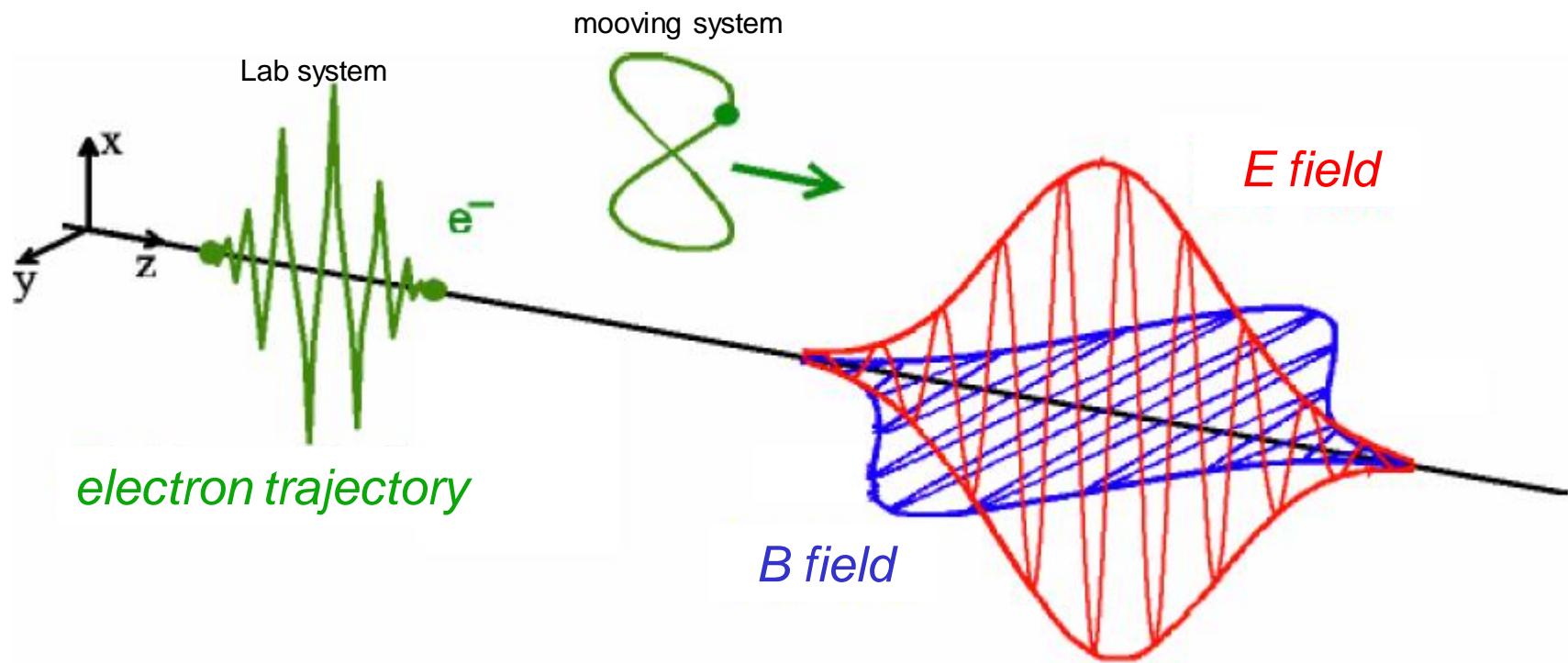
Laser-particle acceleration:
on the verge of a technological revolution

Laser-based radiation facilities (e.g. JuSPARC)

First steps towards polarized ion sources

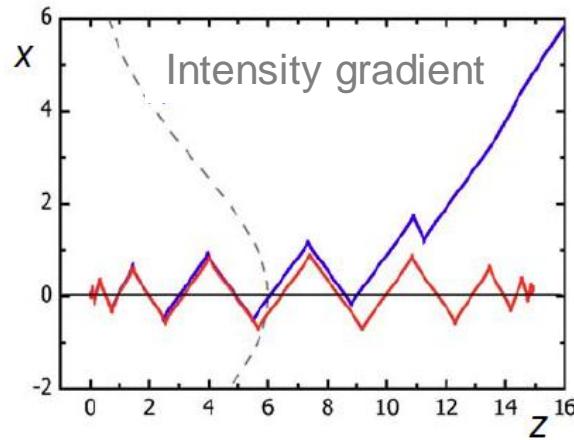


Response of electrons to plane waves

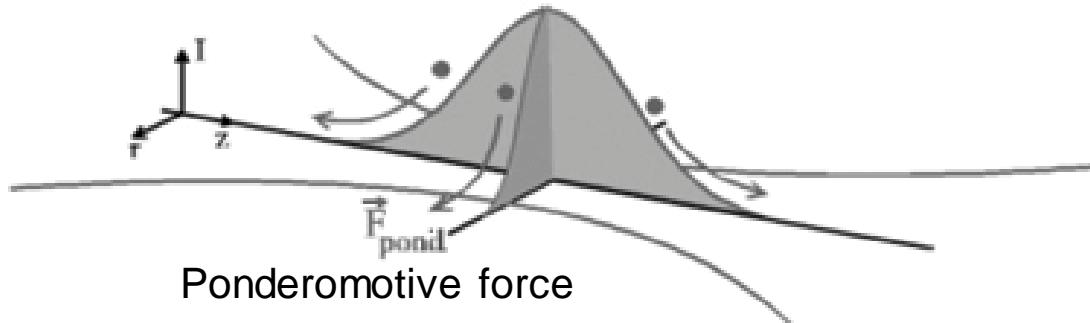


Electron is at rest again when laser pulse is gone!

Response to finite wave packet



Response to
focused light pulse
plane wave



Ponderomotive force

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

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

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

Plasma oscillation

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

Frequency only depends weakly on the wavelength

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

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

n_e = electron density
 e = electron charge

m_e = electron mass
 ϵ_0 = permittivity of vacuum

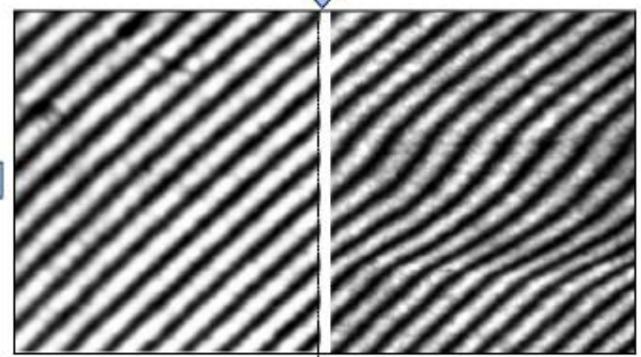
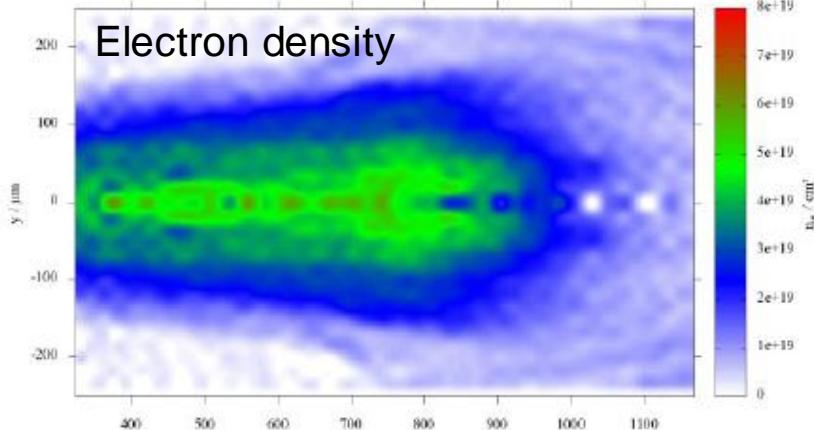
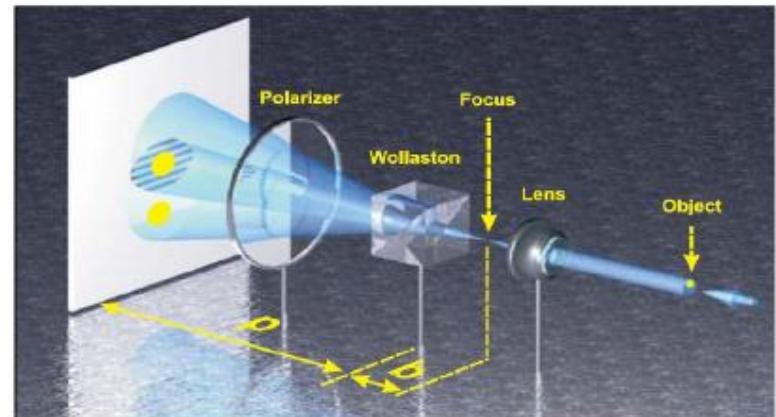
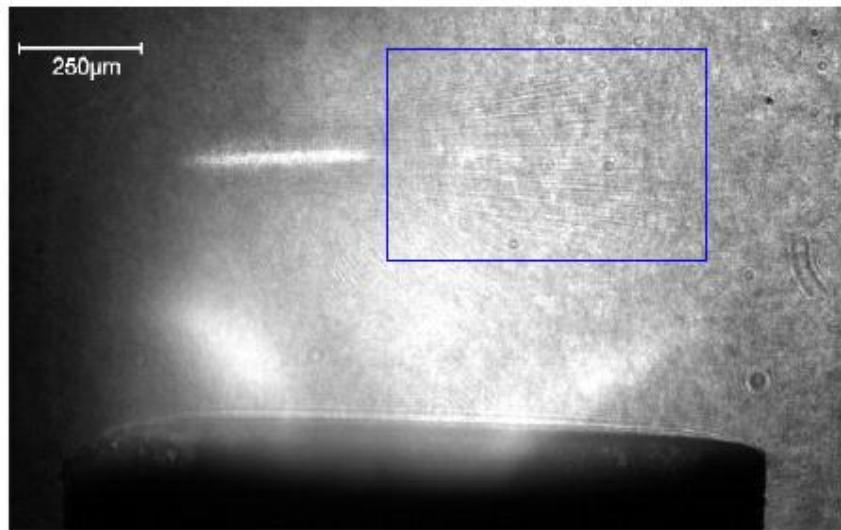
Critical plasma density

$$n_{\text{cr}}[\text{cm}^{-3}] \approx 1.1 \cdot 10^{21} / (\lambda_L[\mu\text{m}])^2$$

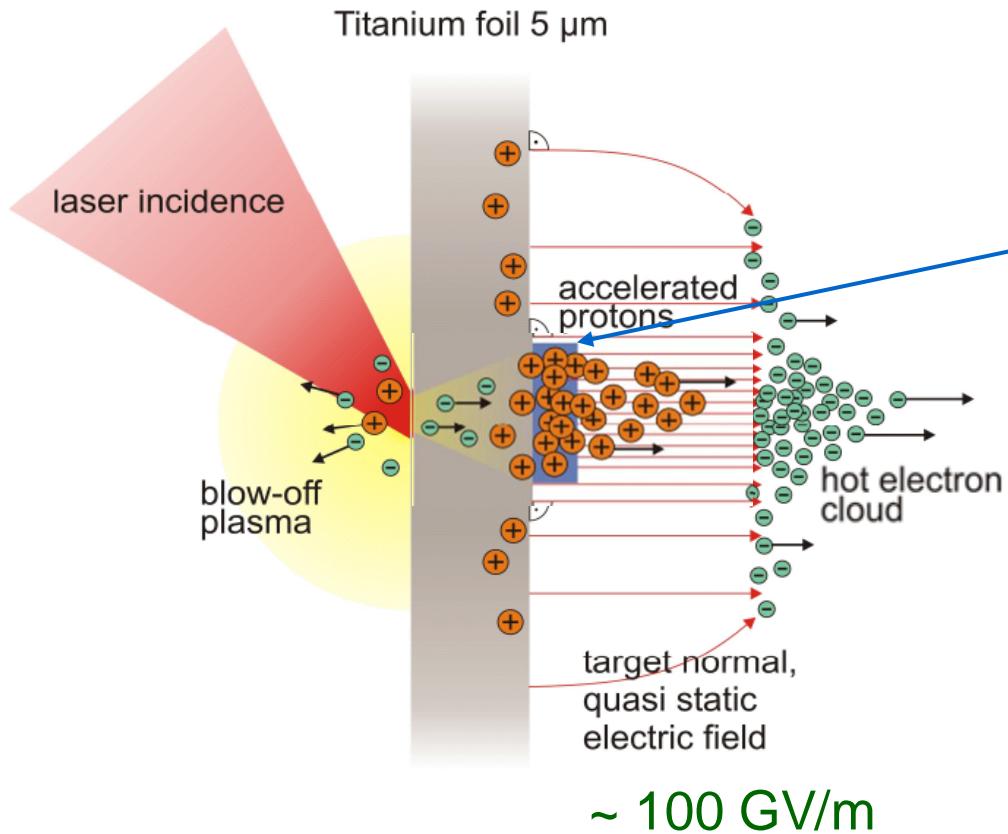
- $n_e \ll n_{\text{cr}}$
 - wave speed = speed of light
 - plasma transparent, “under-dense plasma”
 - gas targets

- $n_e > n_{\text{cr}}$
 - plasma electrons “short-circuit” Laser E-field
 - wave is damped & reflected, “over-dense plasma”
 - solid (foil) targets

Plasma observation: interferometry

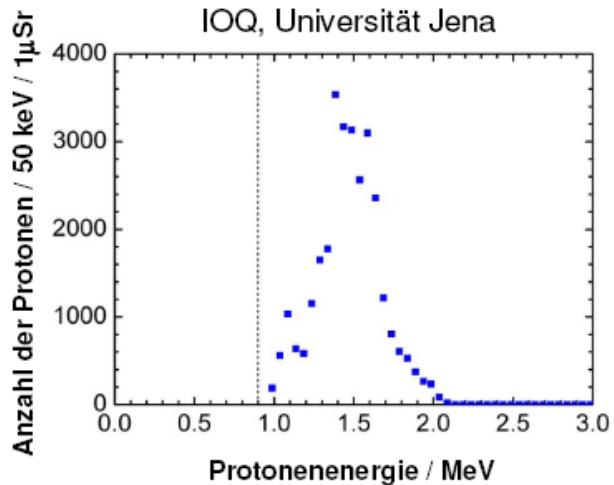


Target Normal Sheath Acceleration (TNSA)



Proton rich dot
20x20x0.5 μm

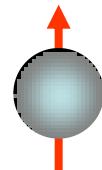
Laserparameter:
 $E = 600 \text{ mJ}, \tau = 80 \text{ fs}, P = 7.5 \text{ TW}$
 $I = 3 \cdot 10^{19} \text{ W/cm}^2$
 IOQ, Universität Jena



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

Polarization of a particle beam

1 particle → 1 spin direction

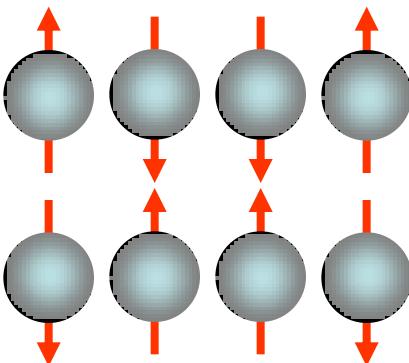


Ensemble of particles

disordered spins

no polarization

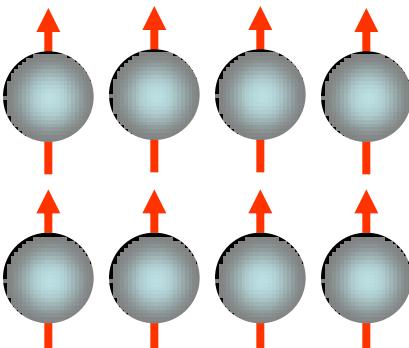
$$P = 0$$



all spins show into same direction

fully polarized beam

$$P = 1 = 100\%$$



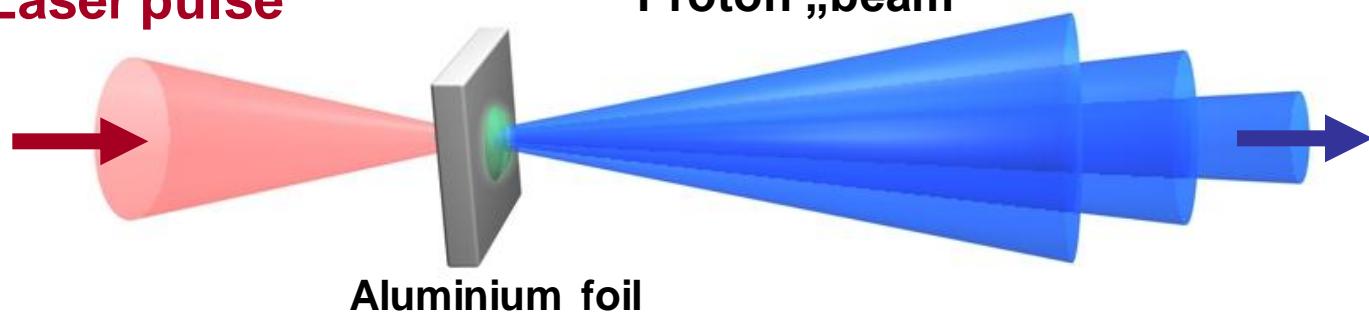
Polarization P

$$P = \frac{N^{\text{up}} - N^{\text{down}}}{N^{\text{up}} + N^{\text{down}}}$$

N = occupation number
of up/down state

Proton acceleration → foil targets

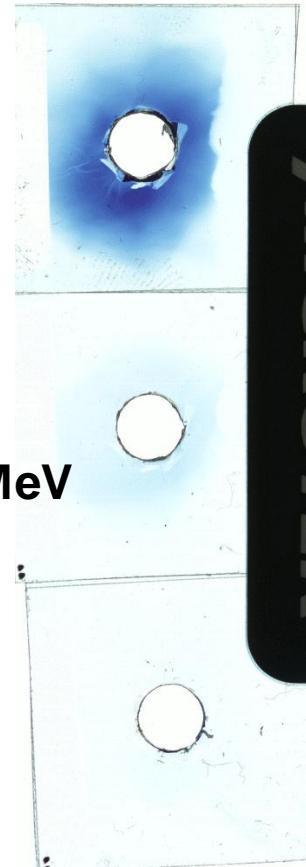
Laser pulse



Proton „beam“

Aluminium foil

3-4 MeV



Conversion efficiency ~ 5%

Point-like source (< 10 µm)

Emission angle ~ 30° (15 MeV)

Broad, exponential energy spectra

Short duration (sub-ps pulses)

} small vertical emittance

} small longitudinal emittance

Particle detection

bunches of many particles,
extremely high particle rates

→ use detectors without dead time

photofilms: calibrated, usable only once

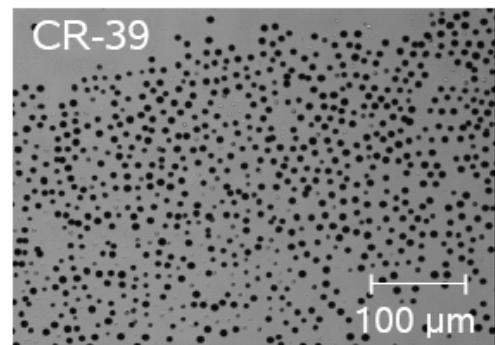
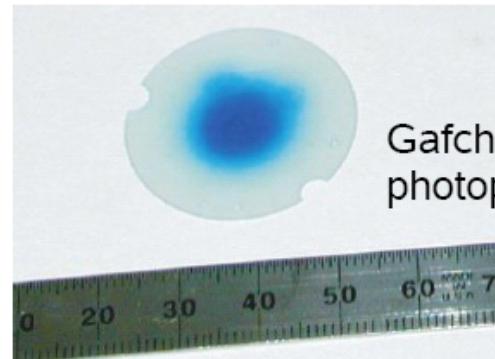
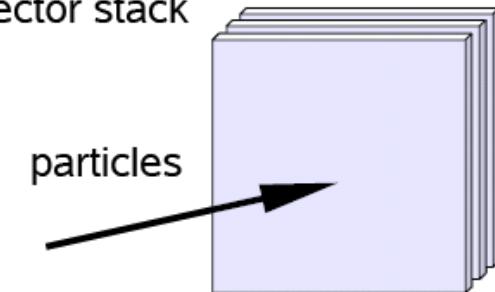
image plates: usable several times
not calibrated

CR-39: usable only once
insensitive to x-rays and photons
etching with NaOH and scanning
reveals tracks produced by particles

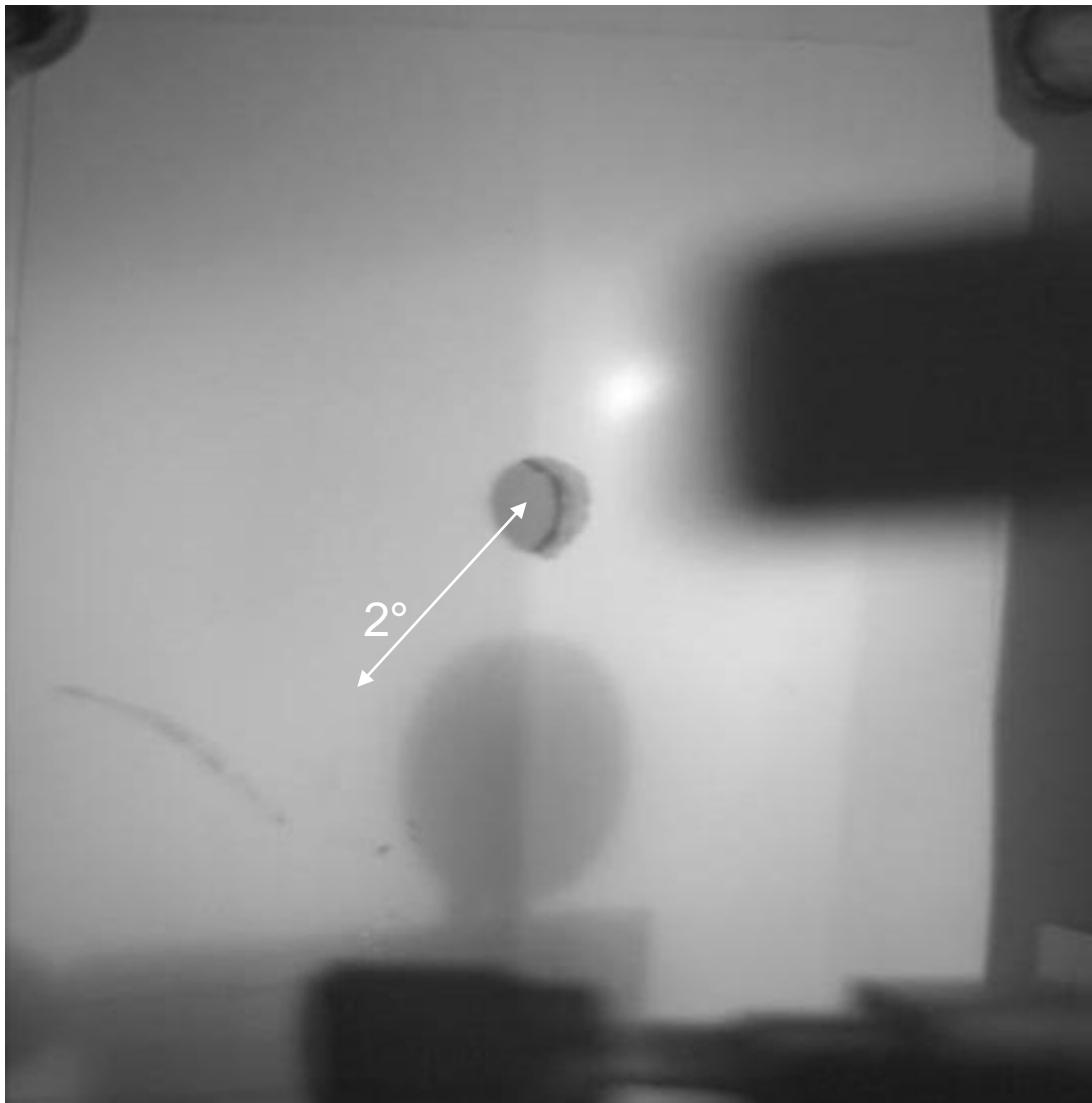
none of the detectors can be read out online

detector stack

particles



Time stability of electron beams



Frozen Pellet Target (FZJ, ITEP, MPEI)

Frozen pellets $\varnothing \sim 20 \mu\text{m}$

H_2 , N_2 , Ar (D_2 , Kr, Xe)

Pellet rate $\sim 10 \text{ kHz}$

Pellet velocity $\sim 80 \text{ m/s}$

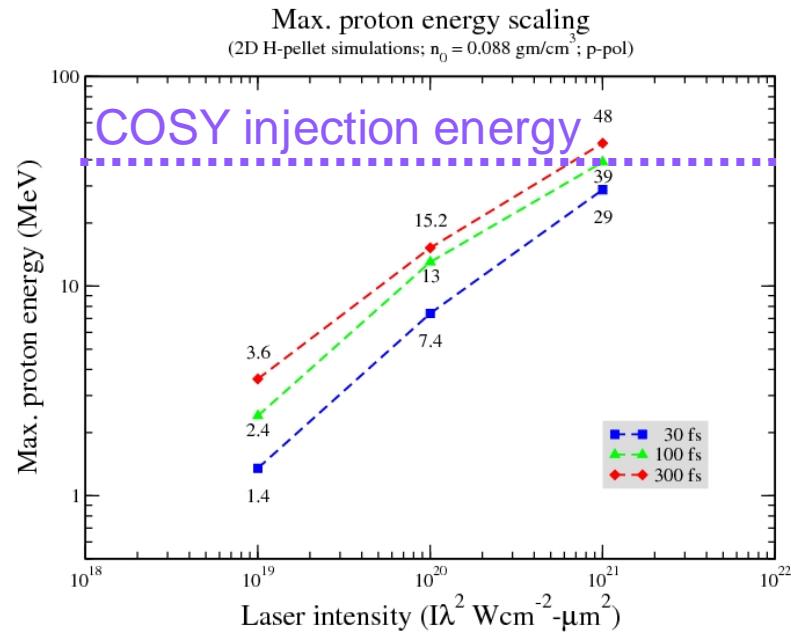
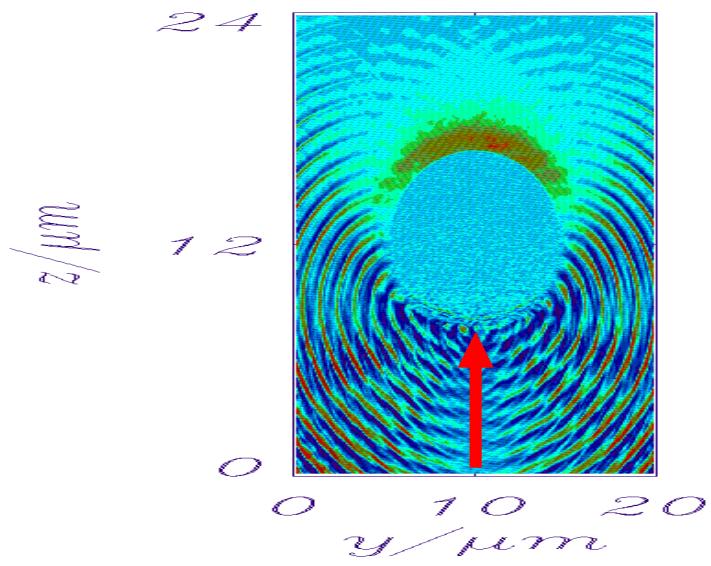
Pellet beam $\varnothing < 1 \text{ mm}$



Hydrogen pellets as target

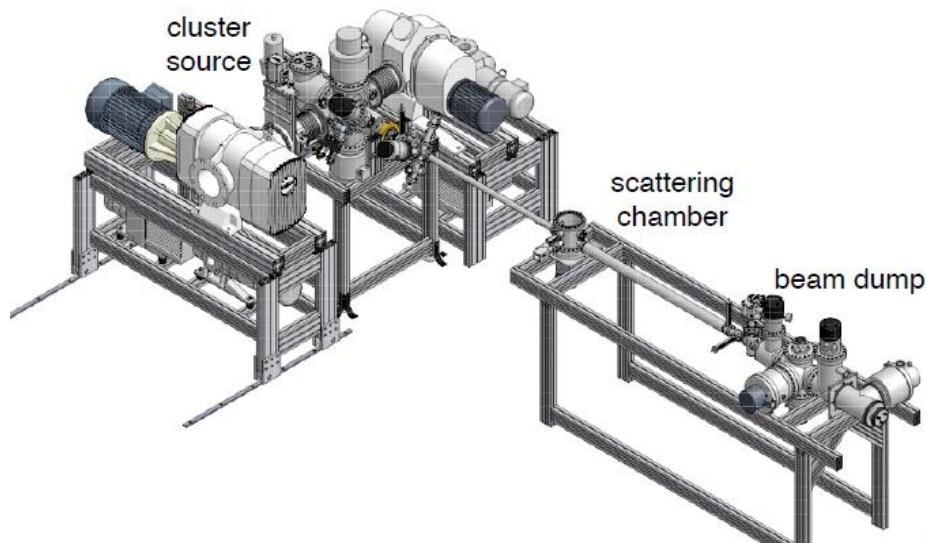
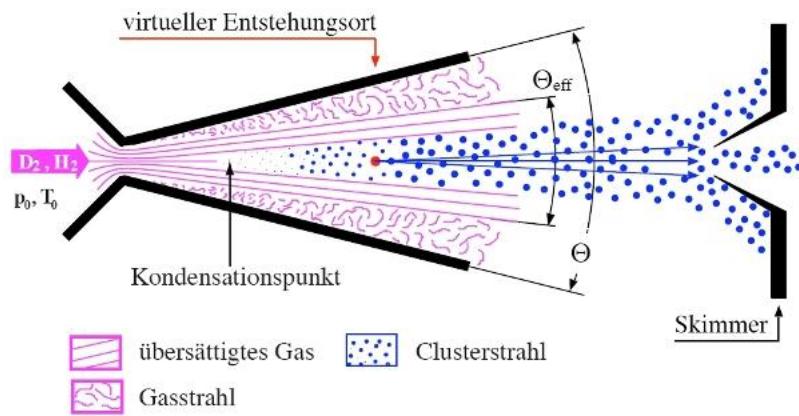
2-D Simulations from the JSC Jülich

Laser pulse with $\lambda=1 \mu\text{m}$ and fokus $\varnothing = 10 \mu\text{m}$ hits a $10 \mu\text{m}$ frozen H_2 pellet



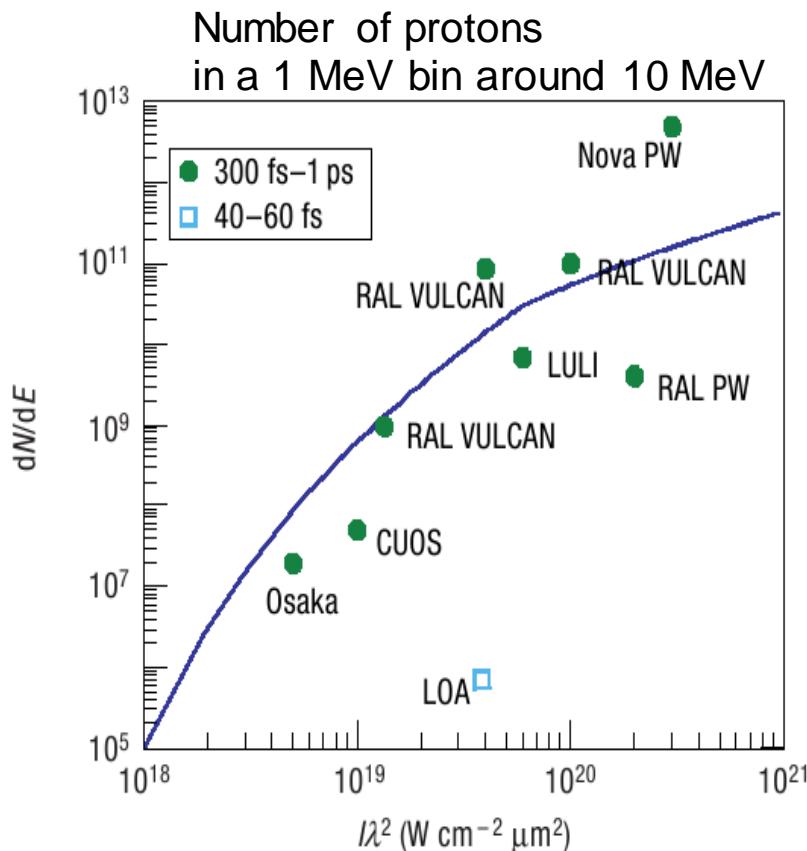
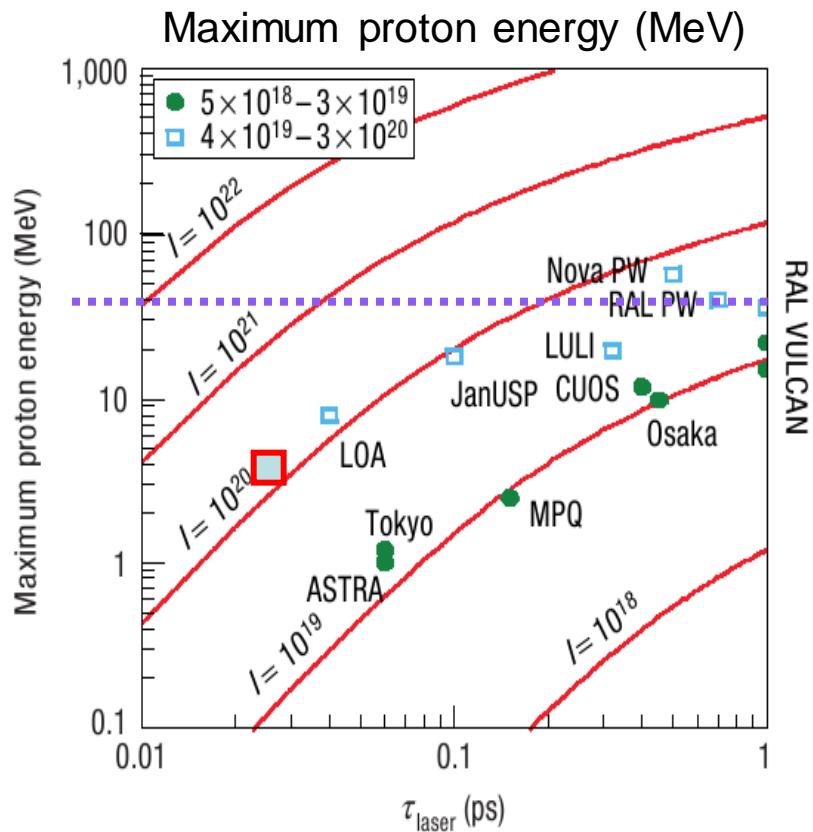
maximum proton energy can further be increased (factor 4)
 by optimization of the focus size

Cluster-Jet Target (Univ. Münster)



Proton energy and intensity

a



COSY injection energy: 40 MeV

Helmholtz Association HGF



Research Centers: 18

Total staff: ~ 33 000

Total budget ~ 3.4 billion €

Research Fields:

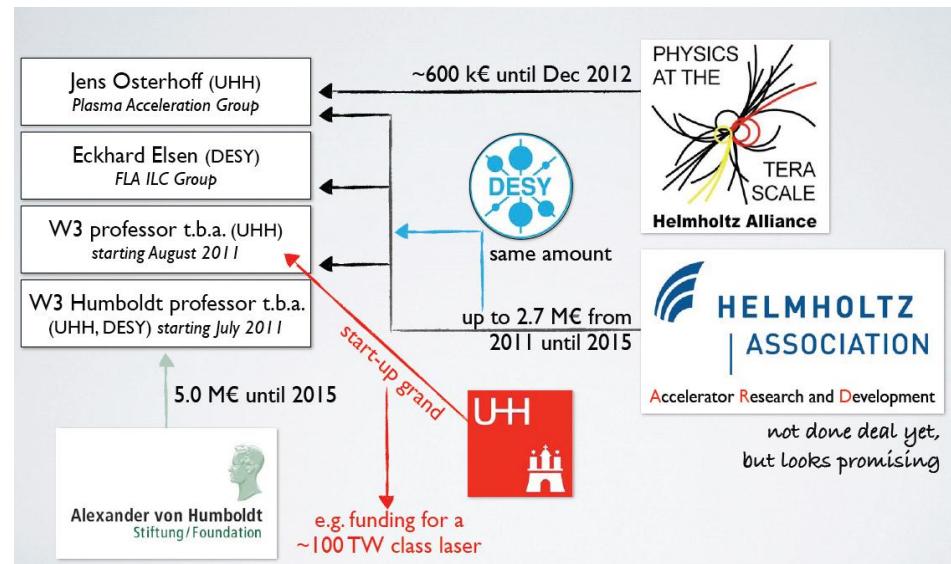
Energy
 Earth and Environment
 Health
 Key Technologies
Structure of Matter
 Aeronautics, Space and Transport



“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

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



2008:

PHELIX (Petawatt Hoch- Energie Laser
für SchwerioneneXperimente)
500 TW



→ Ion-laser interactions
→ X-ray laser

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



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

2012:
 PW Laser



→ Laser particle acceleration
 → Cancer research