Mitglied der Helmholtz-Gemeinschaft

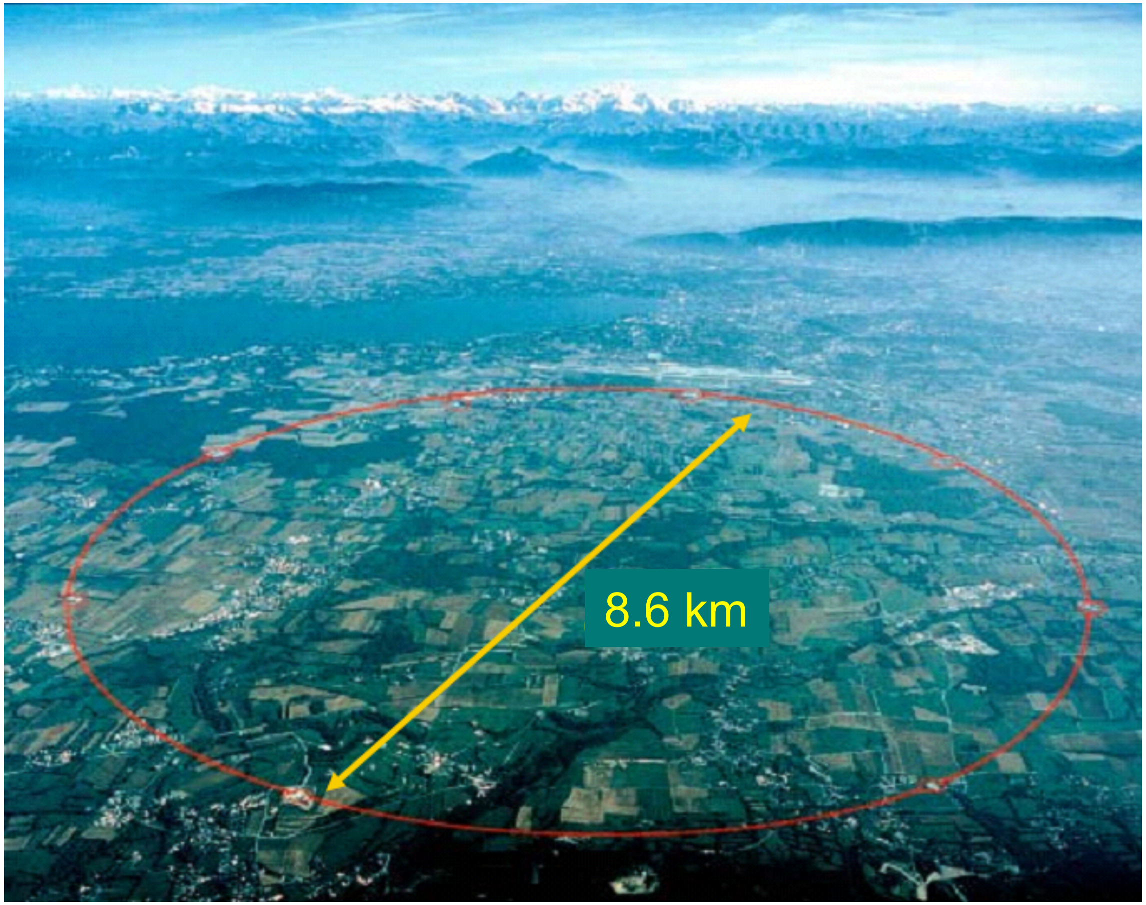
JÜLICH FORSCHUNGSZENTRUM

High-intensity Lasers & Particle Physics

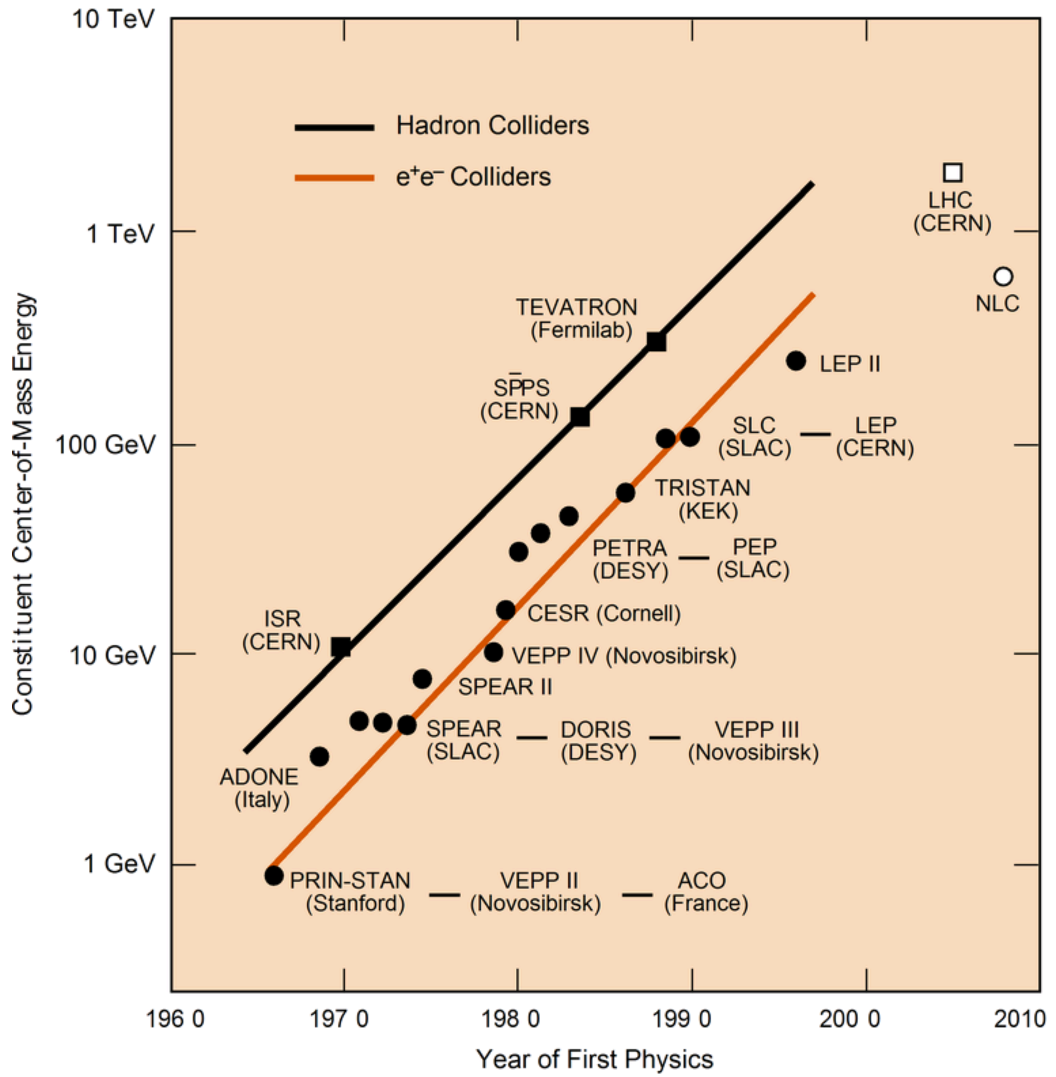
May 4, 2010 | Tbilisi State University | Markus Büscher

Conventional particle accelerators

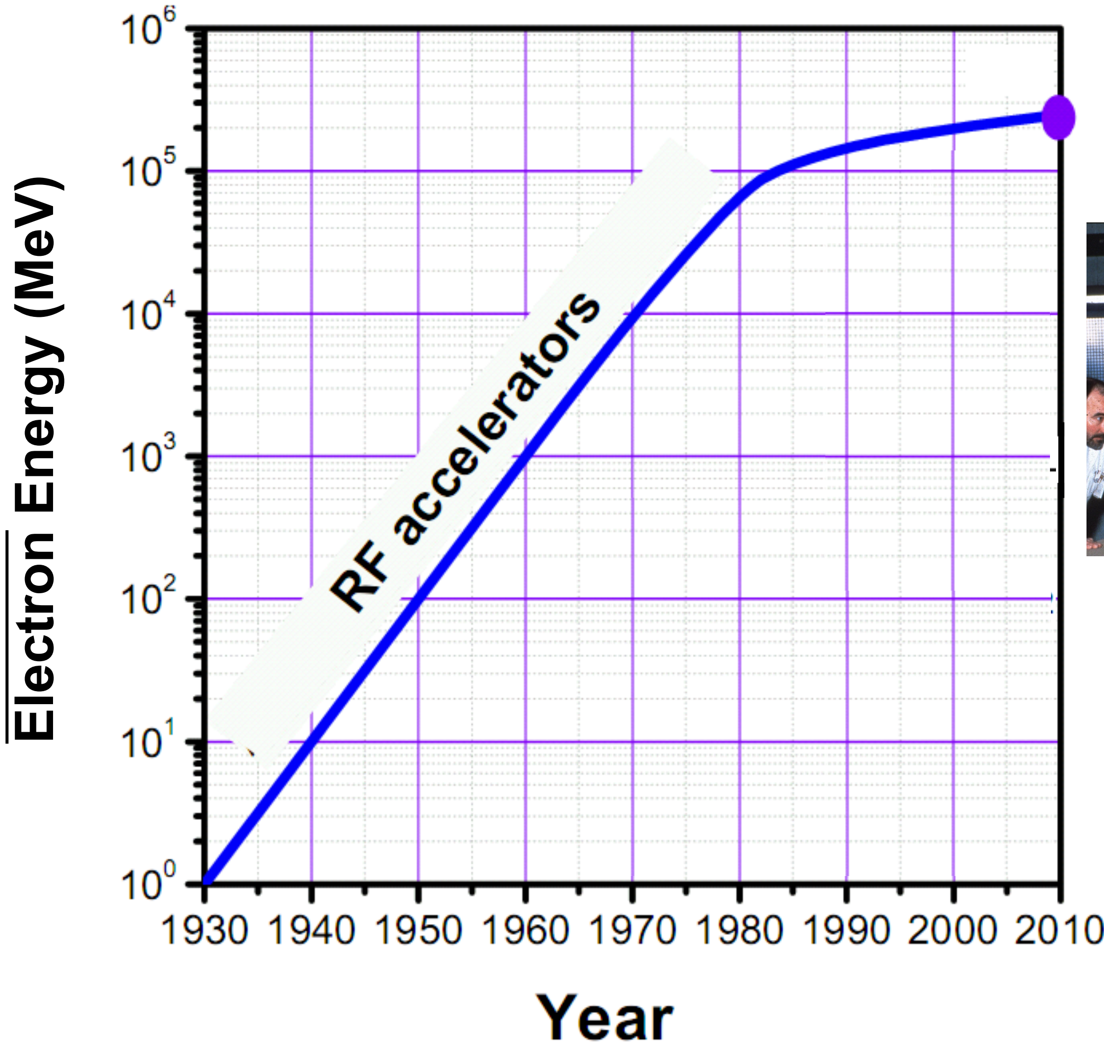
Example: LHC/CERN



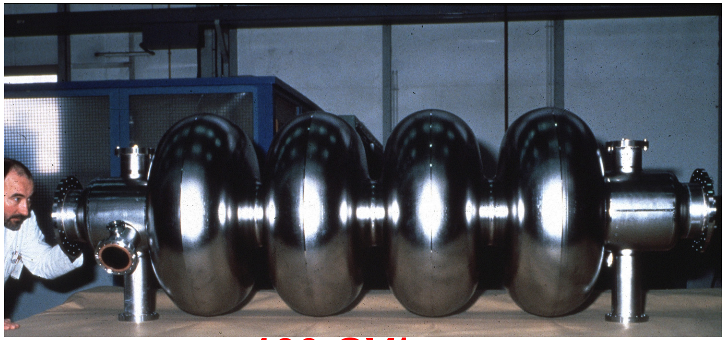
Conventional (RF) accelerators



Need for novel approaches



→Accelerating fields ~ 1 MV/m



~ 100 GV/m

Laser particle acceleration

… some fundamental facts

Lasers … in everyday life

Information technology
Signal transport, data storage,
laser printer, barcode scanner…

Analytics
Length and time measurement,
spectroscopy…

Industrial applications
Manufacturing, cleaning…

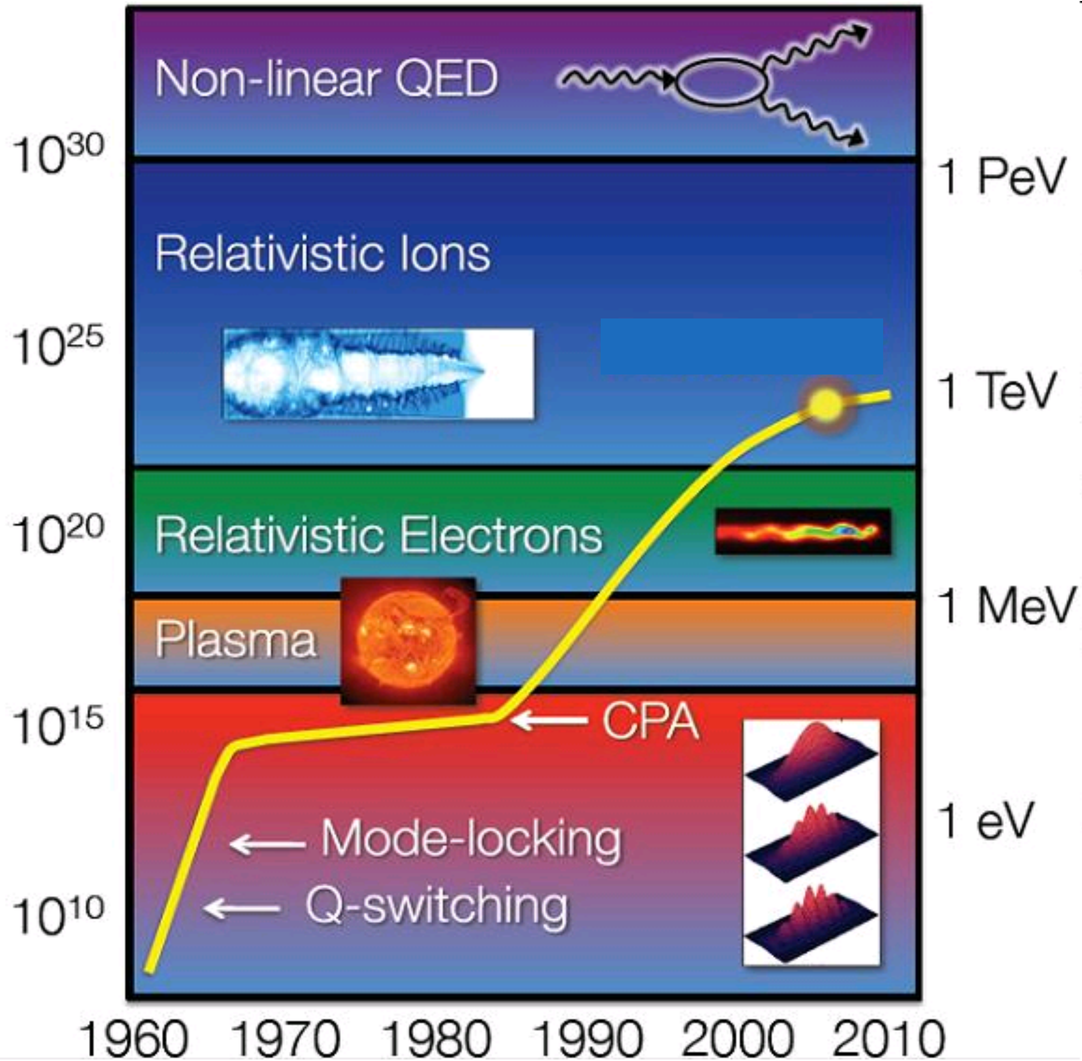
Medicine
Surgery, cicatricial therapy…

Laser in industry *

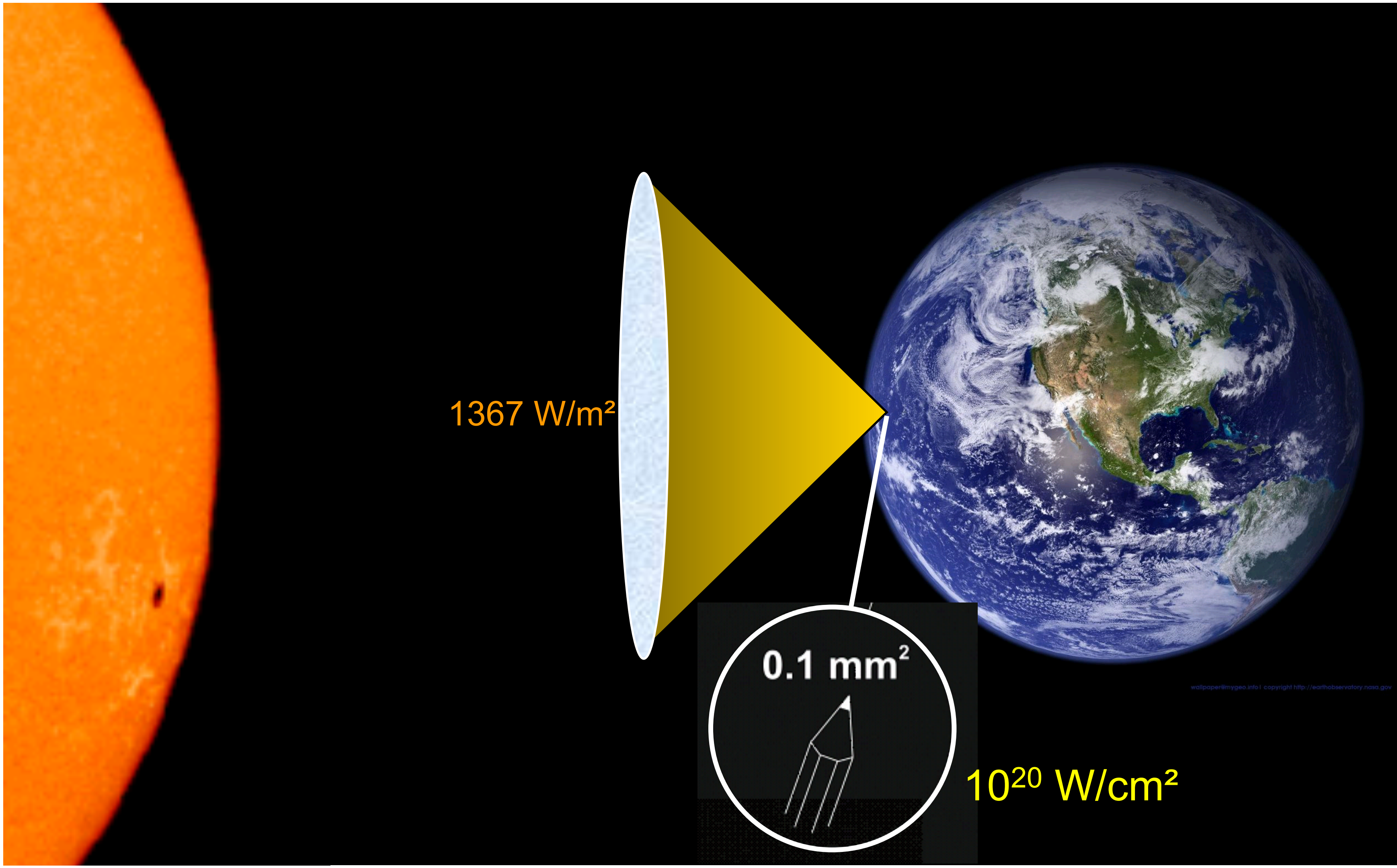
*) Image: Fraunhofer-Institut für Lasertechnik ILT Aachen

Development of Laser intensities

Focussed intensity (W/cm²)

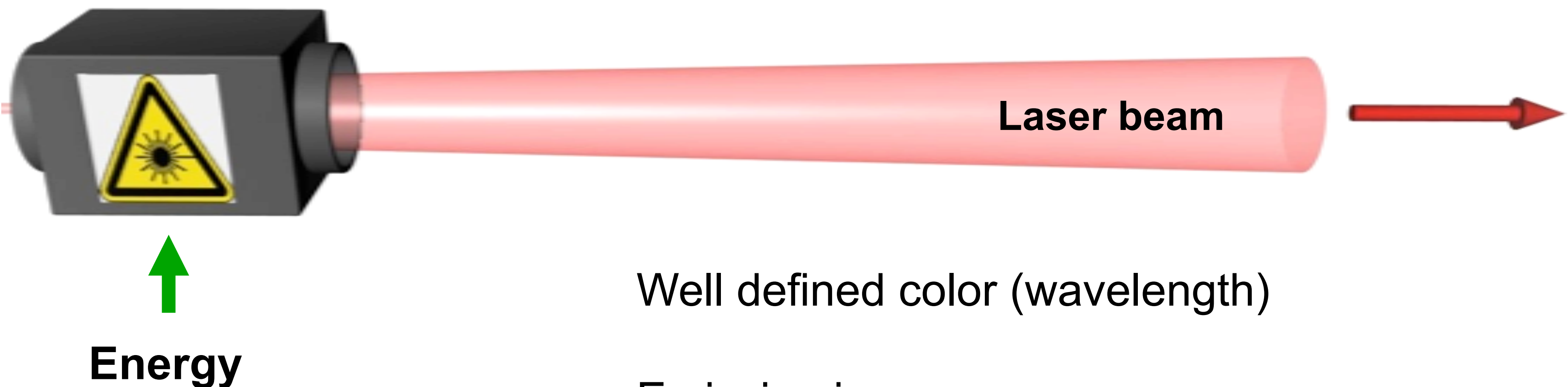


Characteristic electron energy


1367 W/m²
0.1 mm²
10^{20} W/cm²

Laser: basic properties

LASER = „Light Amplification by Stimulated Emission of Radiation“



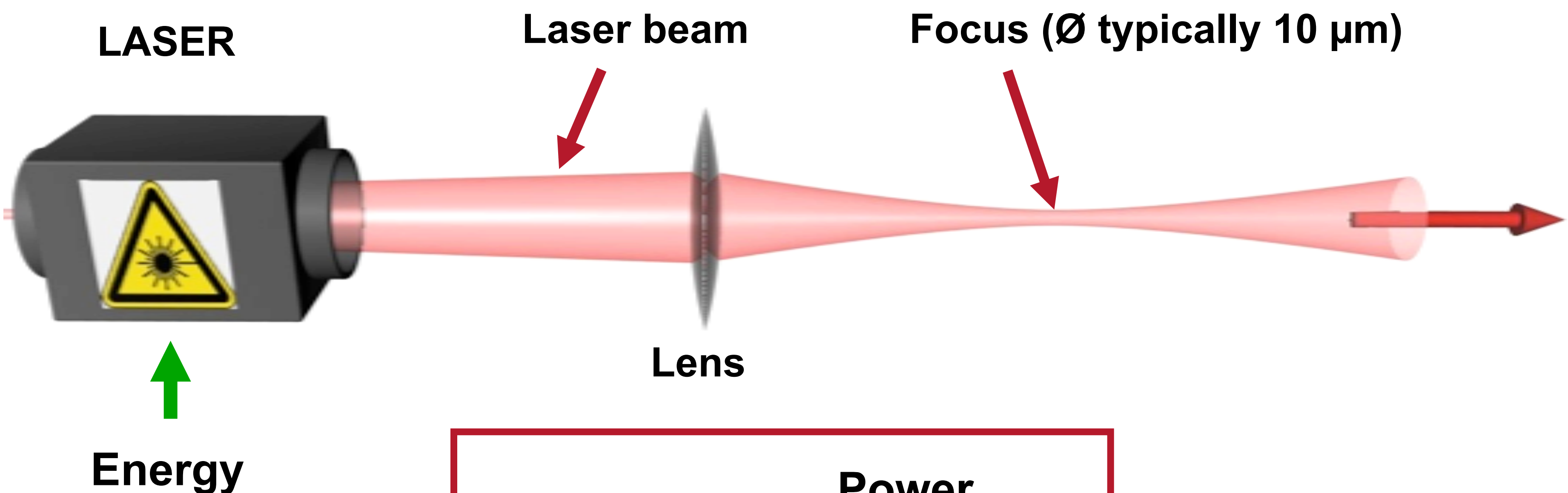
Well defined color (wavelength)

Emission in narrow cone

Coherent oscillations

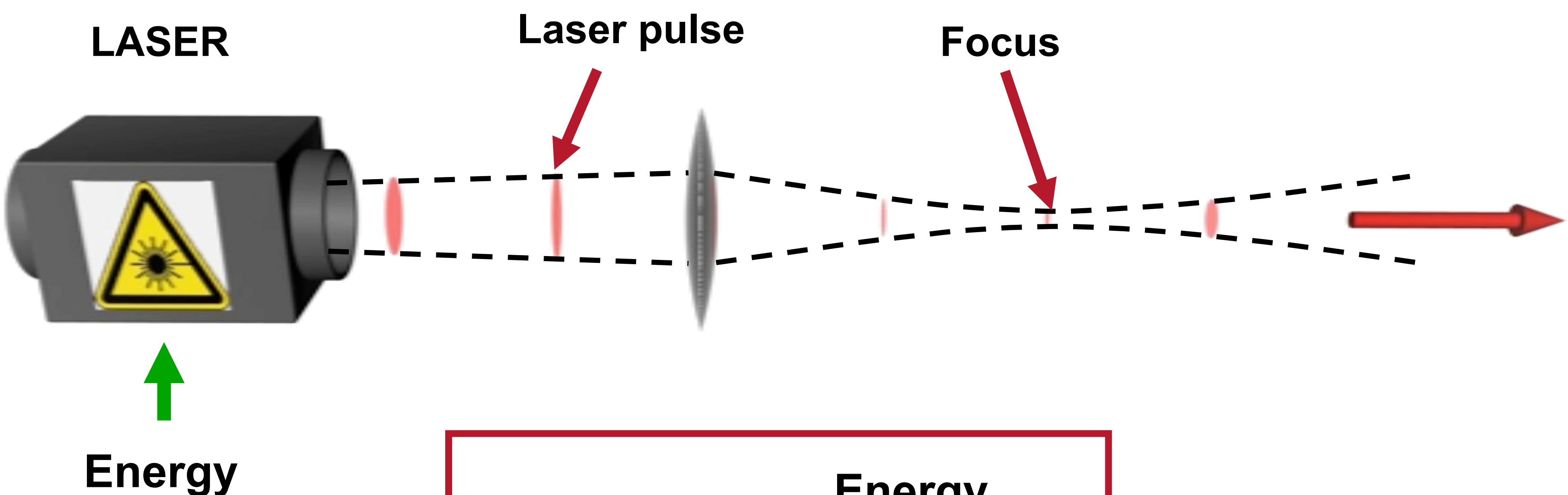
Very high intensities available

Laser: basic properties



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

Laser: basic properties



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

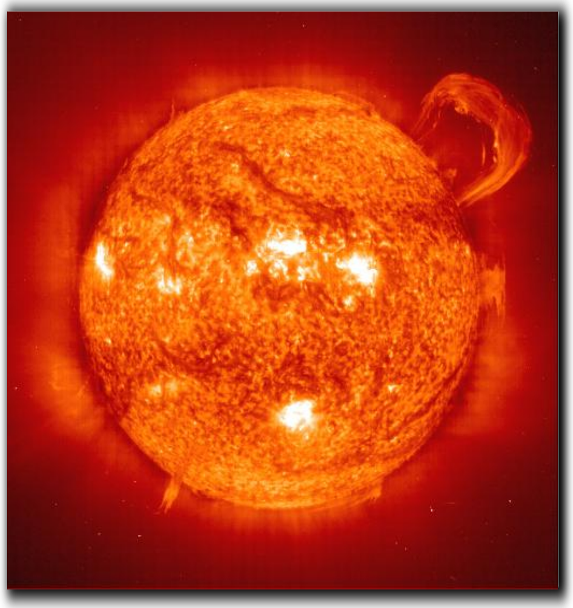
Nowadays peak powers up to Petawatt = 10^{15} Watt are available (*e.g.* 1 Joule in 1 fs)

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

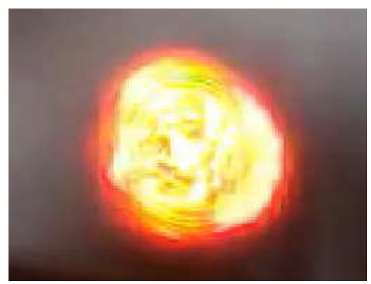
Laser-induced particle acceleration

ultra-short
high-intense
Laser puls

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

target

gas jets to produce
underdense plasma
electron density:



solid targets to produce
overdense plasma

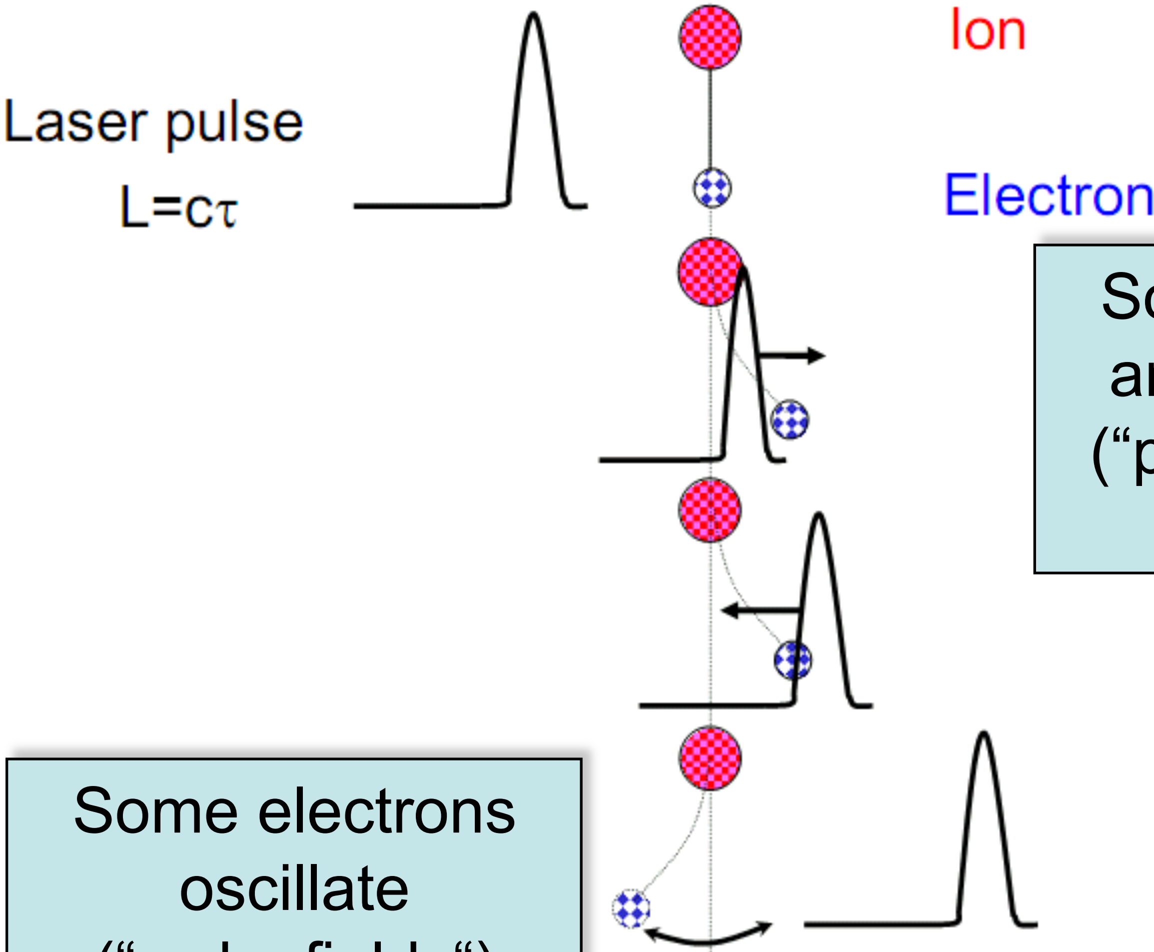
particles

electrons
up to ~100 MeV*

protons / ions
up to ~10 MeV*

* typical values in our experiments

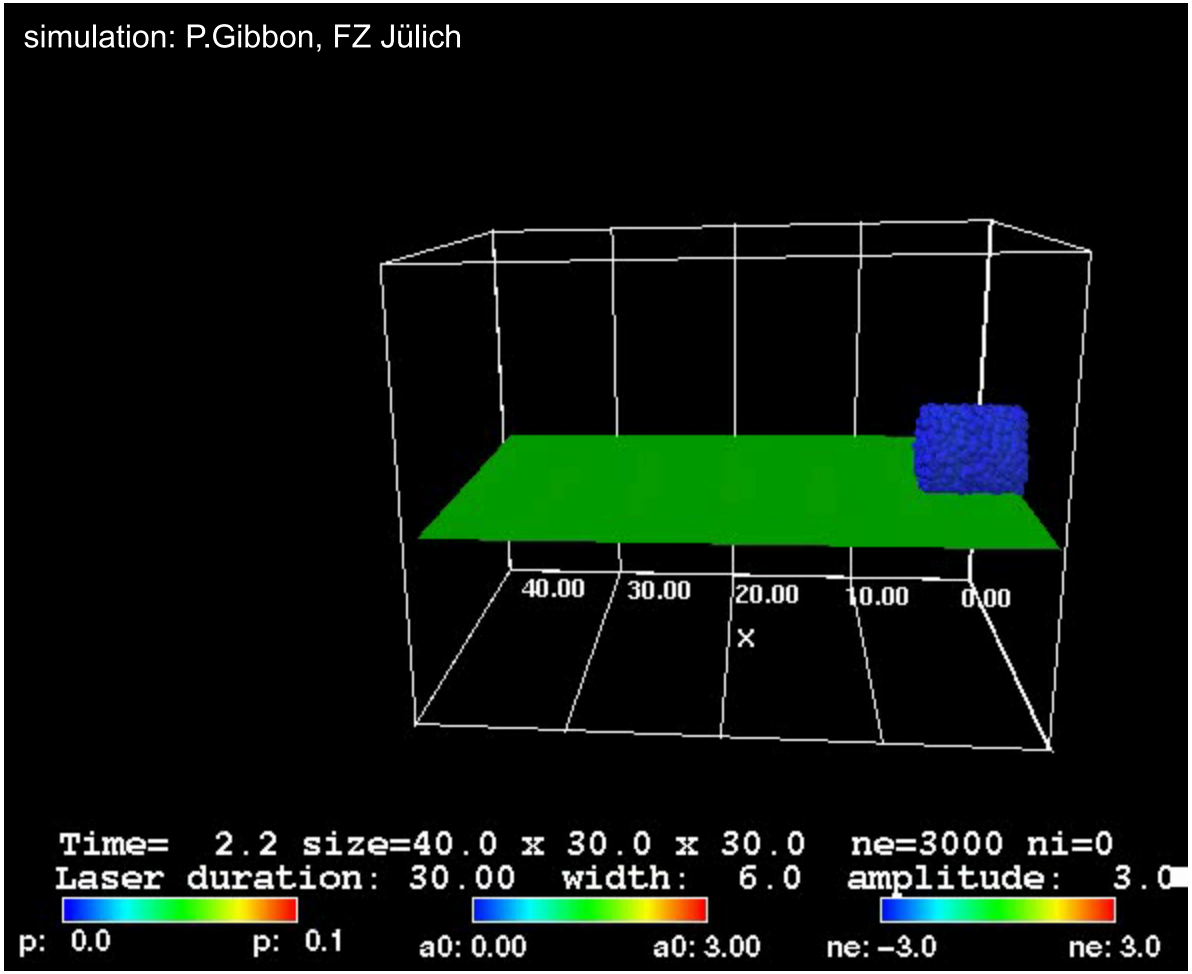
Laser-plasma interaction



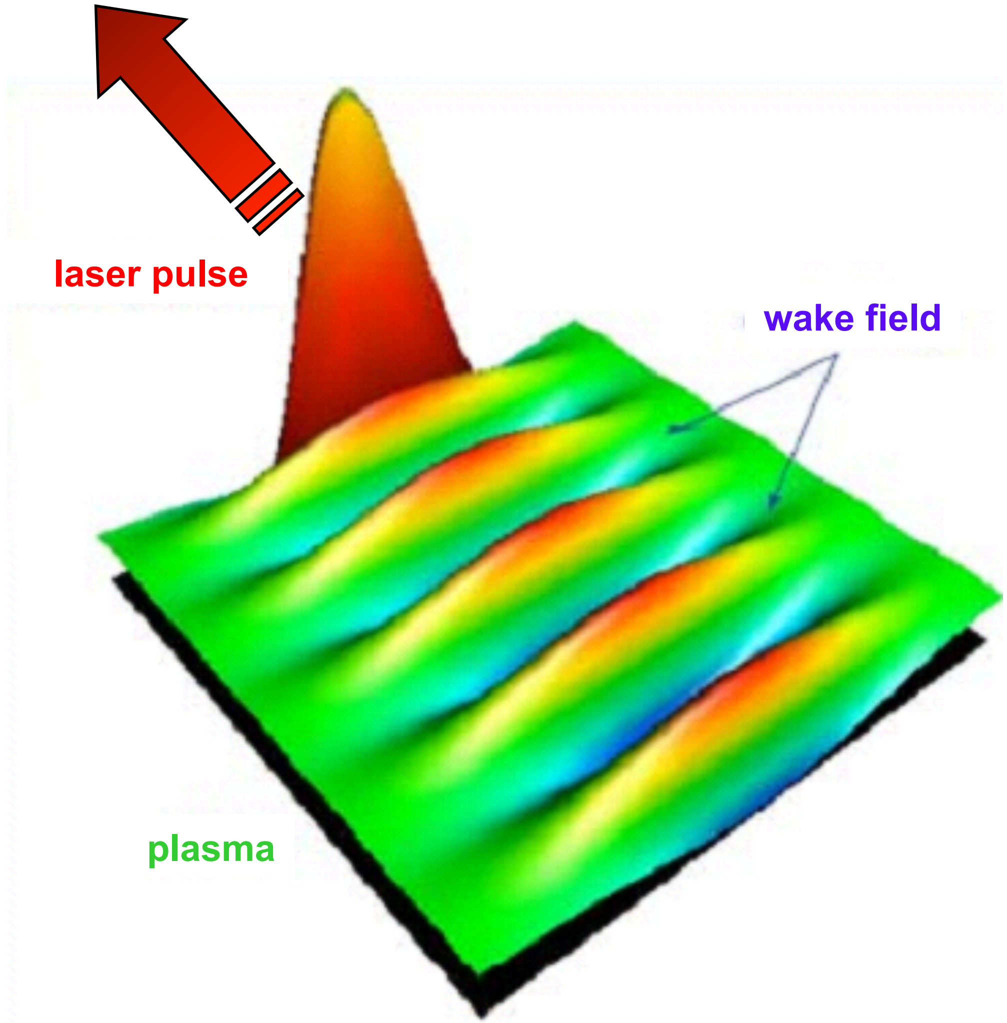
Some electrons are pushed out ("ponderomotive force")

Some electrons oscillate ("wake fields")

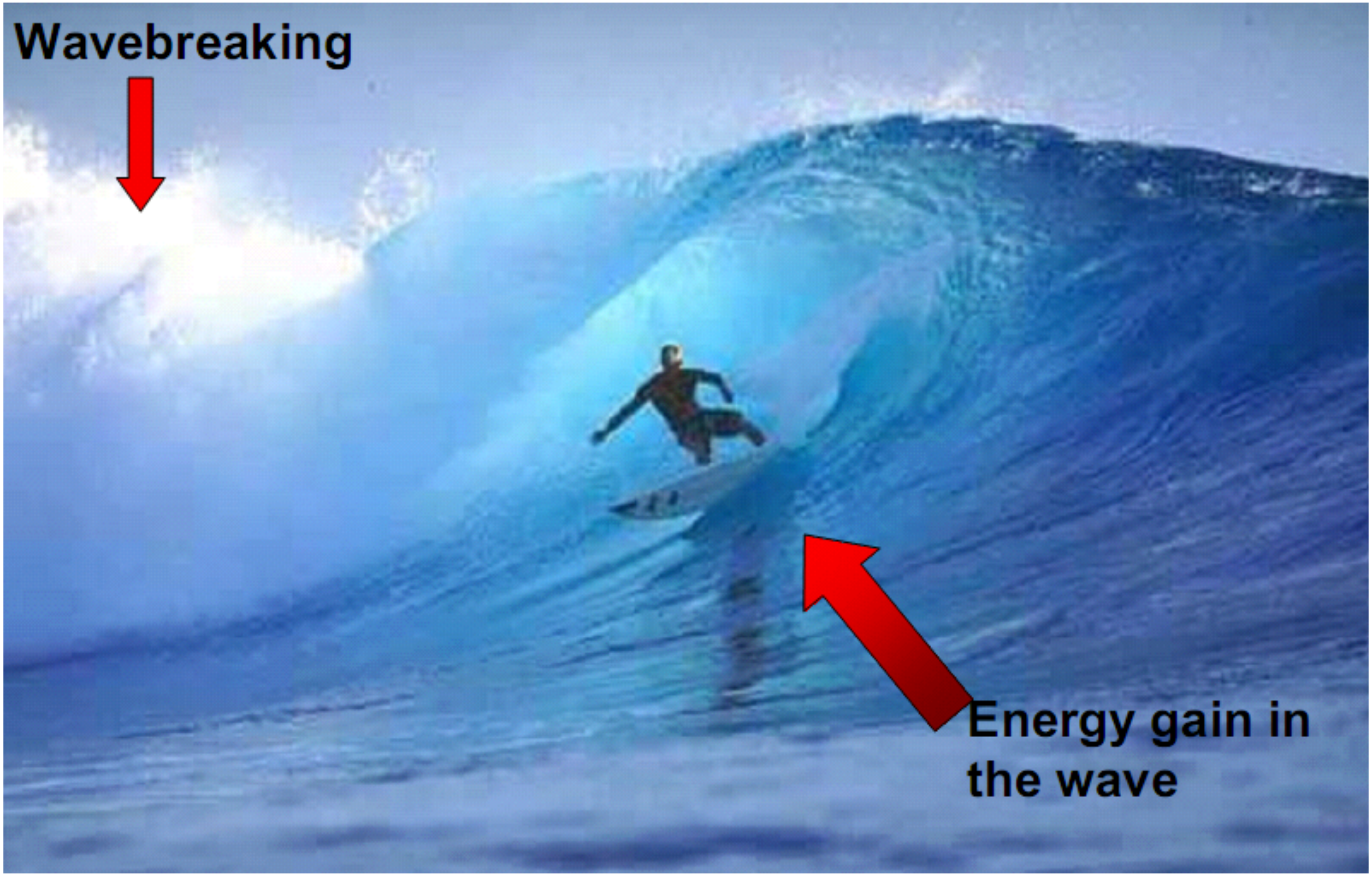
Laser-plasma interaction (simulation)



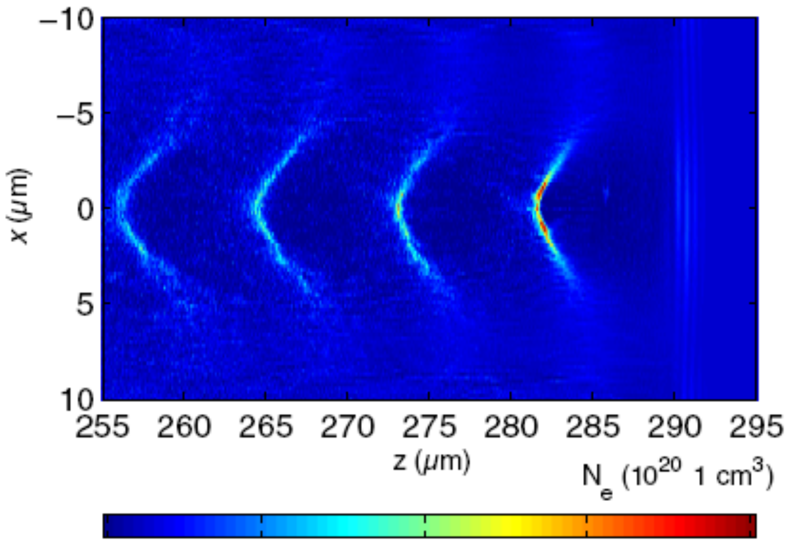
Wake fields

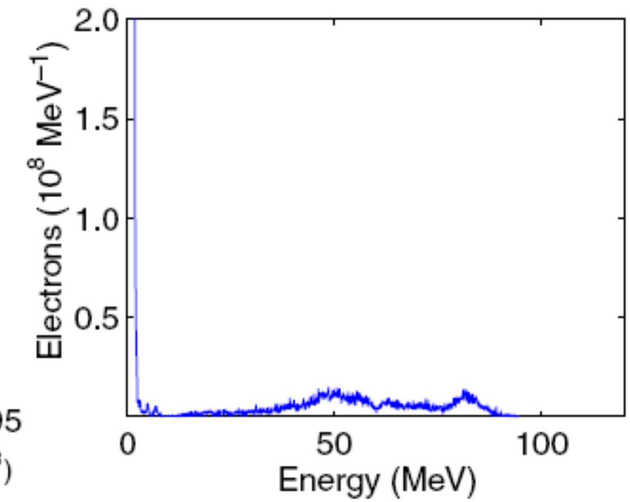


Wakefield acceleration



“Bubble“ acceleration

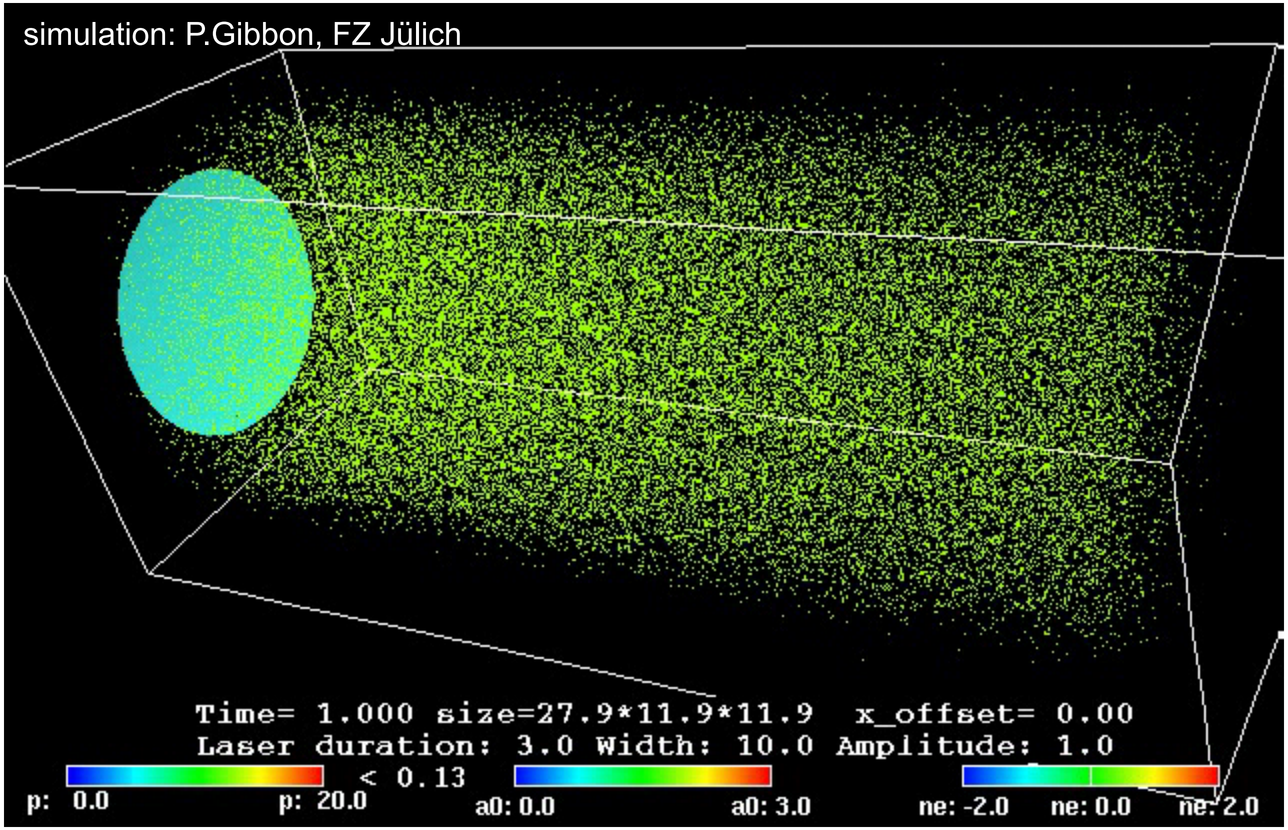




“low” intensity

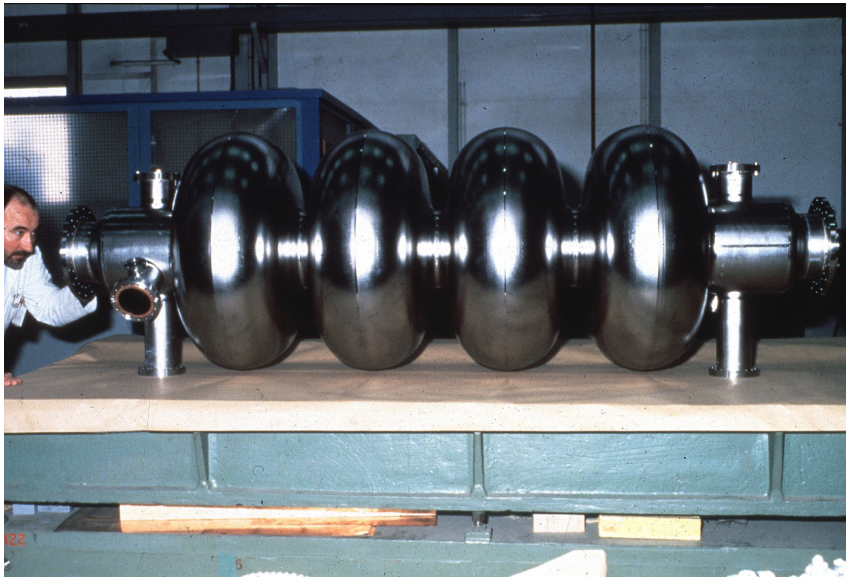
M. Geissler et al., New J. of Phys. 8, 186, (2006)

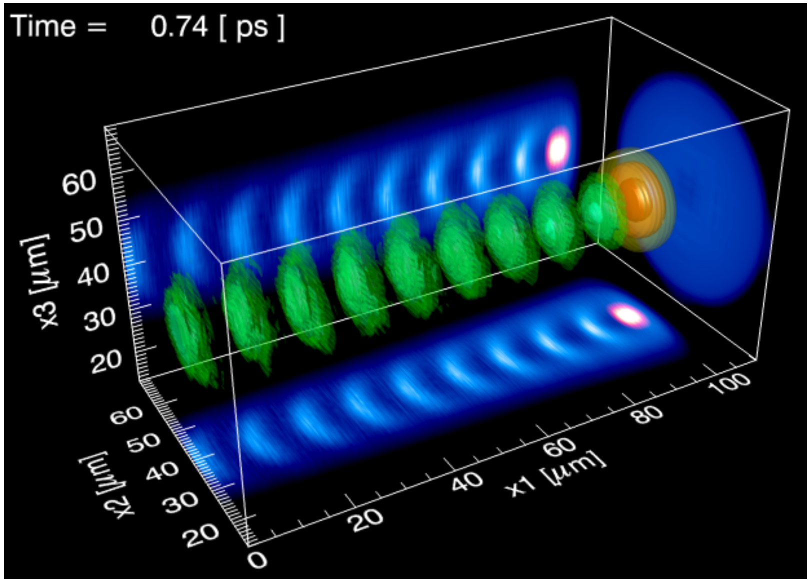
“Bubble“ acceleration



RF vs. Laser acceleration

RF cavity | **Plasma "cavity"**





1 m
1 MV/m } **1 MeV**

100 µm
100 GV/m } **10 MeV**

Our experiments

Institut für Kernphysik, FZ Jülich

Jülich Supercomputing Centre

Fachhochschule Aachen/Jülich

Technical University Cologne

RWTH Aachen

Hochschule Merseburg (FH)

Institut für Laser- und Plasmaphysik, Univ. Düsseldorf

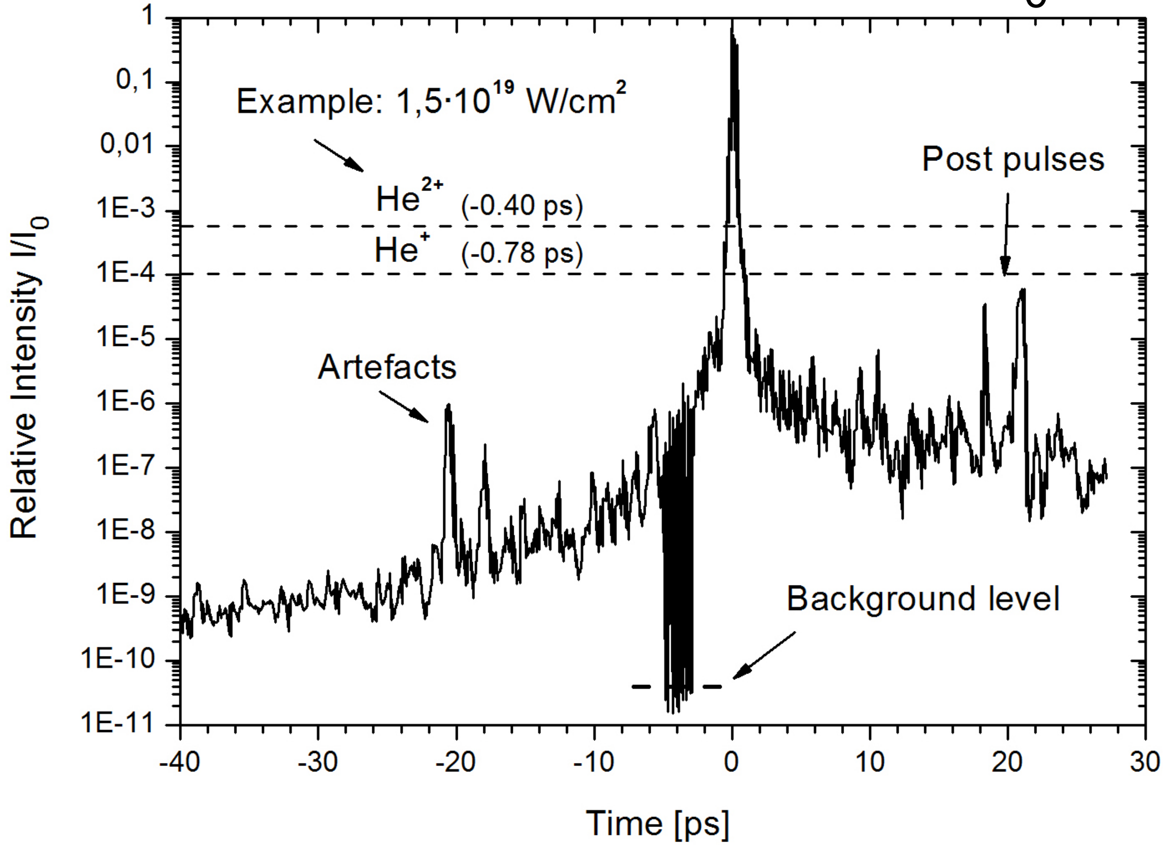
Düsseldorf ARCturus LASER FACILITY

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

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

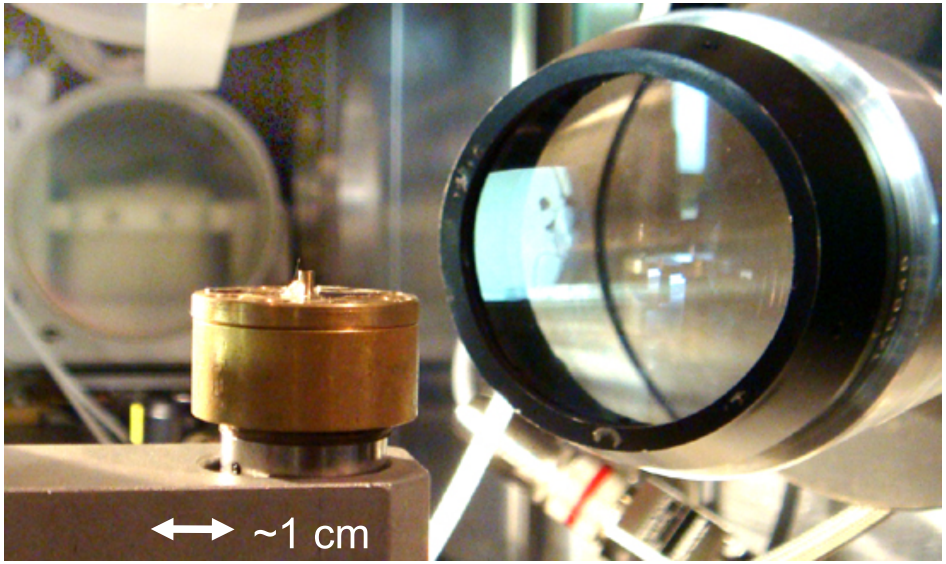
DARCturus: powerful & high contrast

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

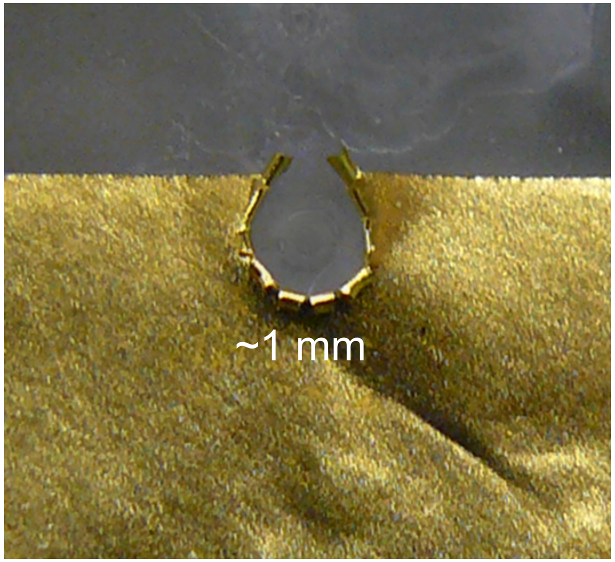


Target chambers

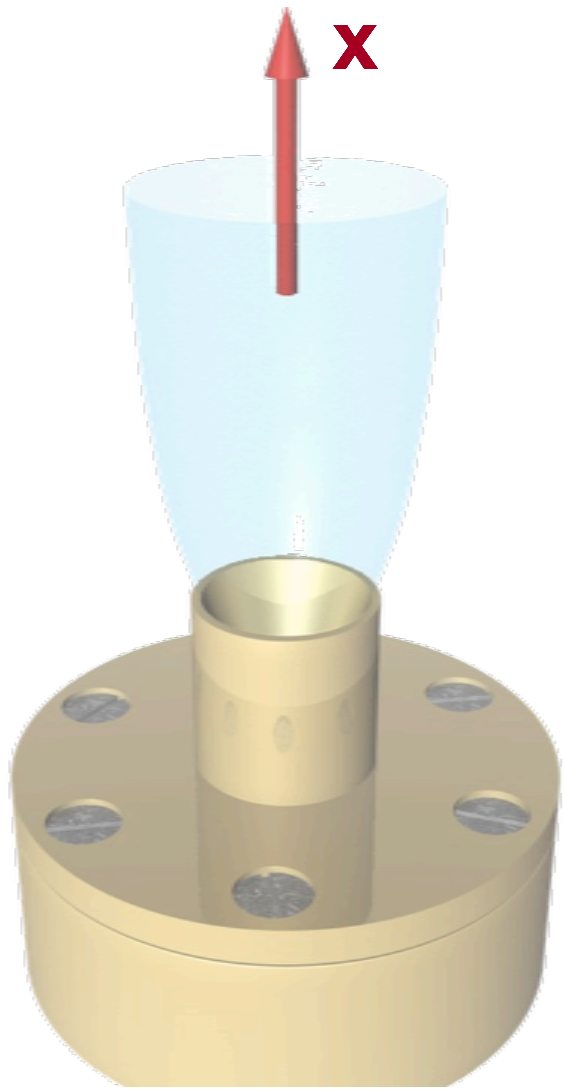
target in chamber T2: gas jets



target in chamber T2: foils



Measurements: He Gas Target

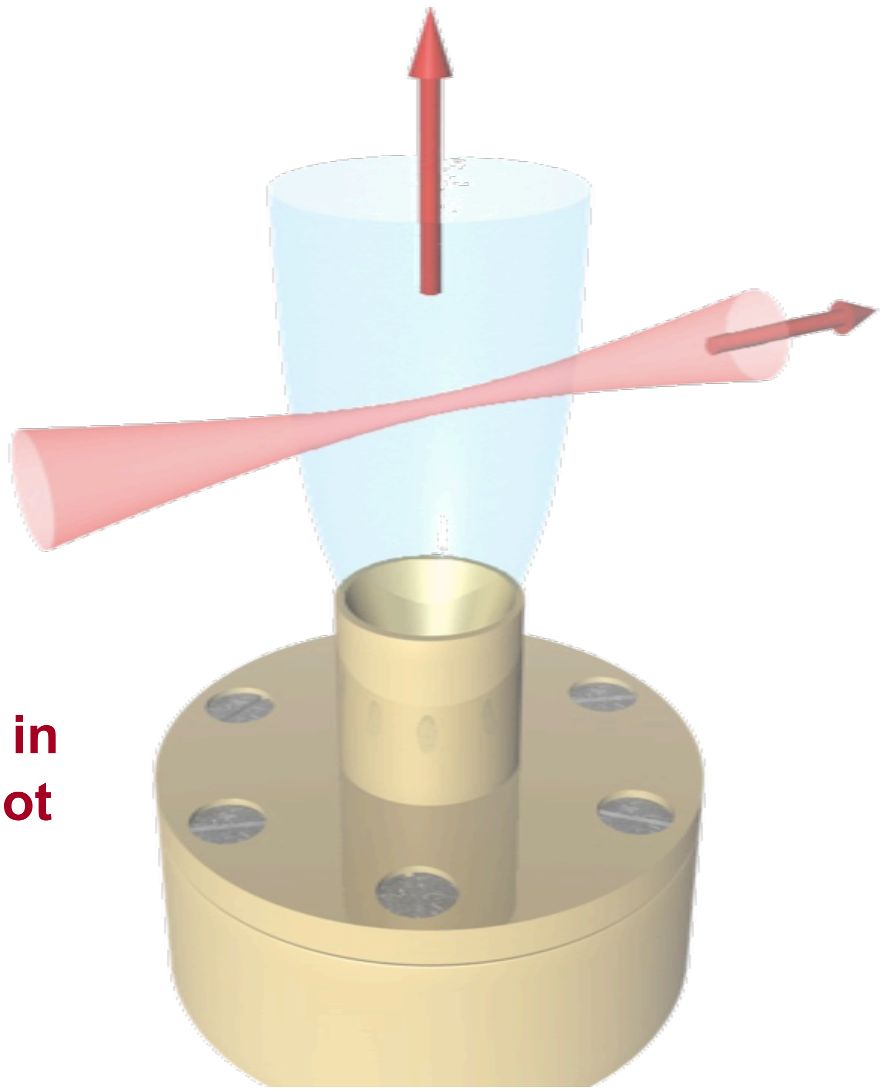


Pulsed gas jet:

Supersonic expansion

up to $3{\cdot}10^{20}$ particles/cm^3 (~10 bar)

Measurements: He Gas Target



Pulsed gas jet:

Supersonic expansion

up to $3 \cdot 10^{20}$ particles/cm^3 (~10 bar)

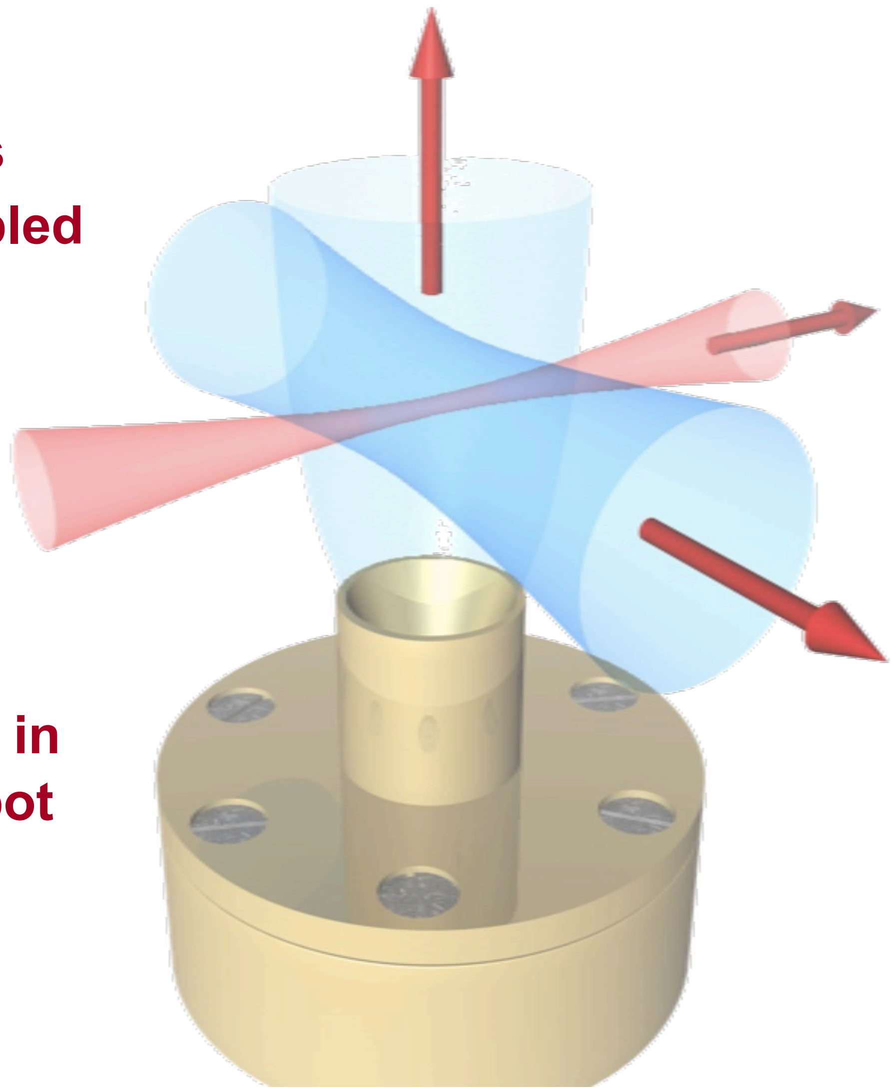
Main pulse:

Up to 2 J in 25 fs focused in 15 μm in diameter focal spot

Measurements: He Gas Target

Probe pulse:

Few mJ @ 25 fs
frequency doubled



Pulsed gasjet:

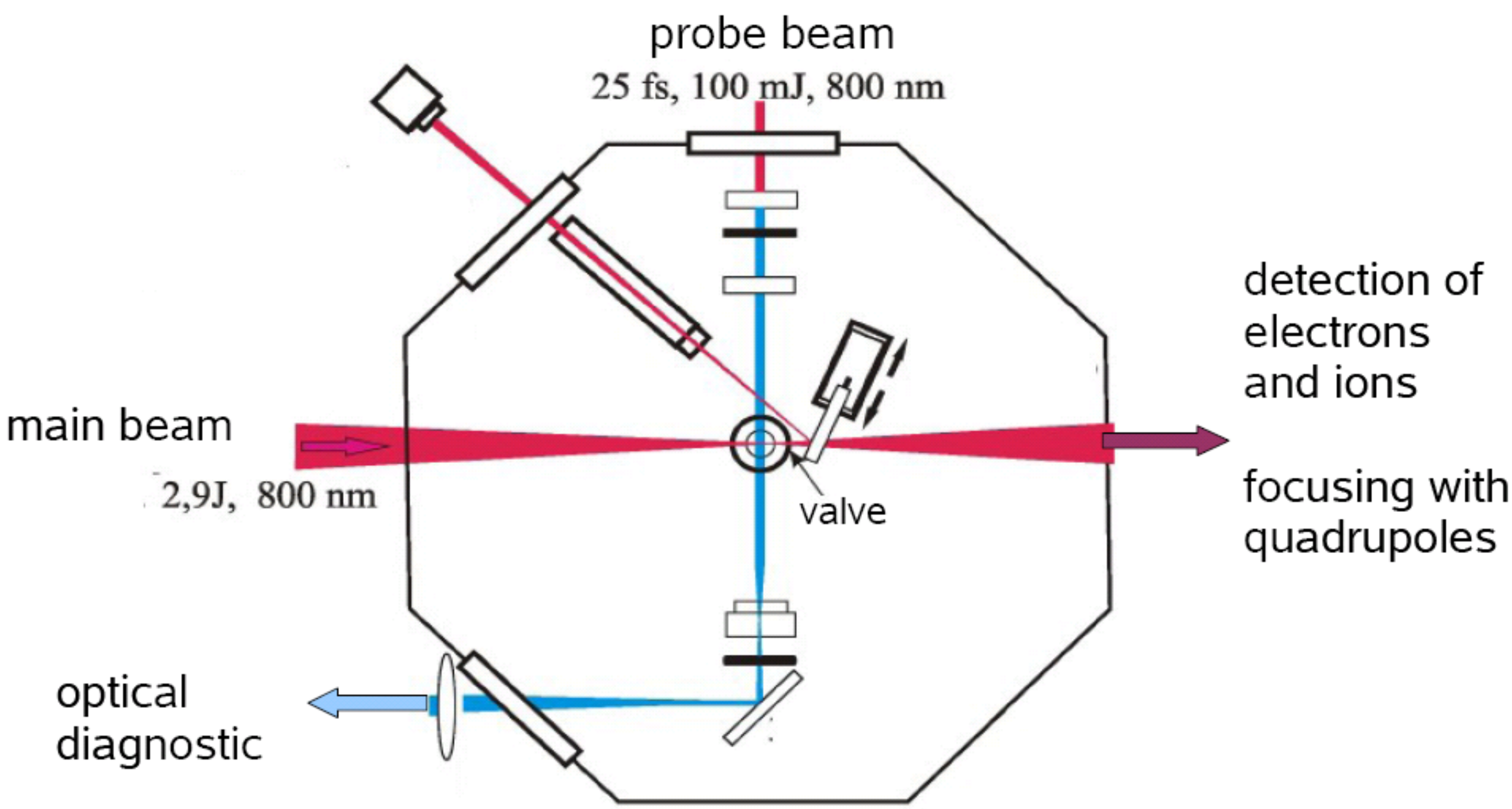
Supersonic expansion

up to $3{\cdot}10^{20}$ particles/cm^3 (~10 bar)

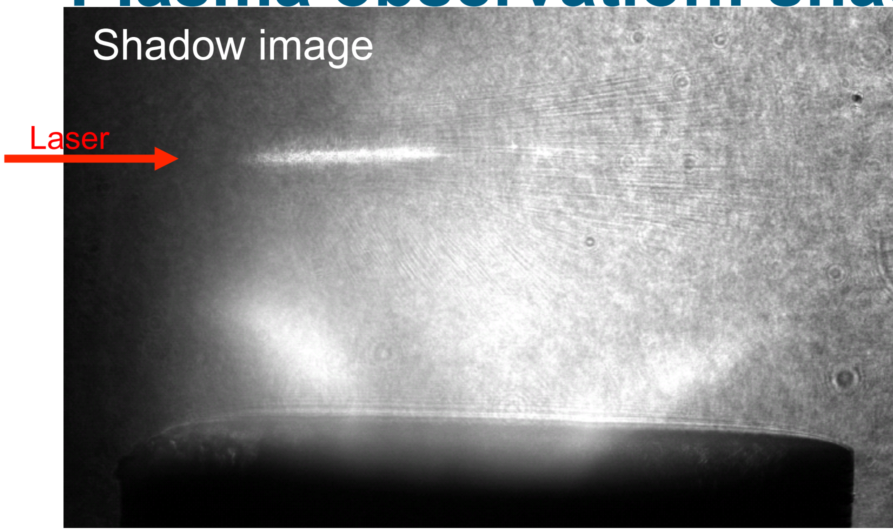
Main pulse:

Up to 2 J in 25 fs focused in 15 µm in diameter focal spot

Gas target: schematic layout

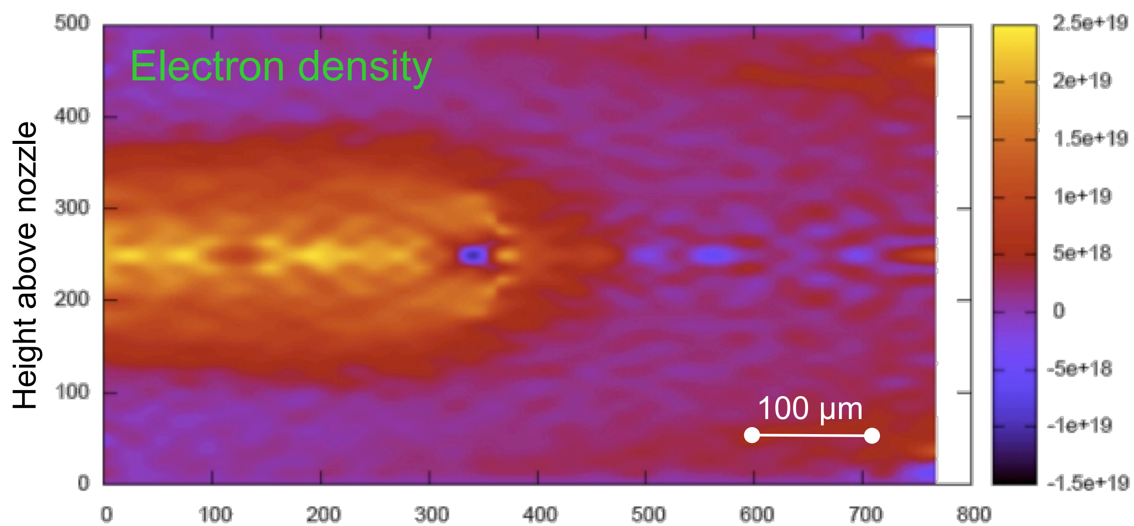


Plasma observation: shadow images



60 TW, 7.8 bar He

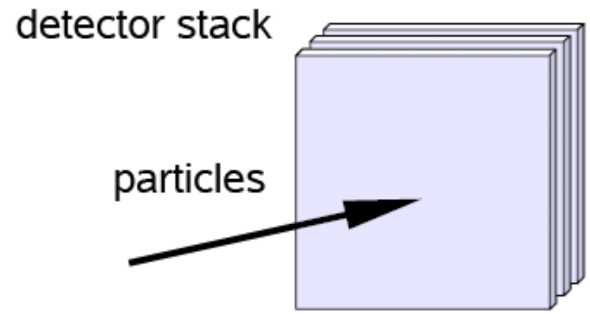
Images reveal plasma development and rapid filamentation
Time resolution: few 10 fs (!)



Particle detection

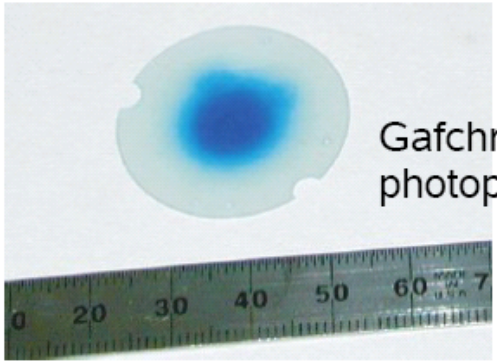
bunches of many particles,
extremly high particle rates

→ use detectors without dead time



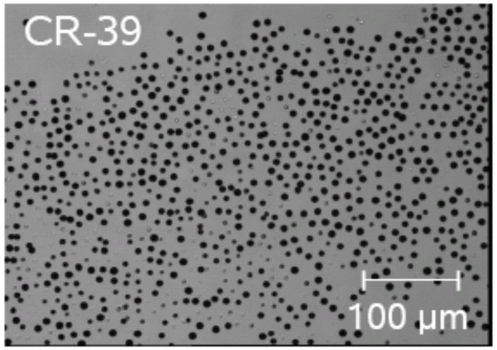
photofilms: calibrated, usable only once

image plates: usable several times
not calibrated



Gafchromic photoplate

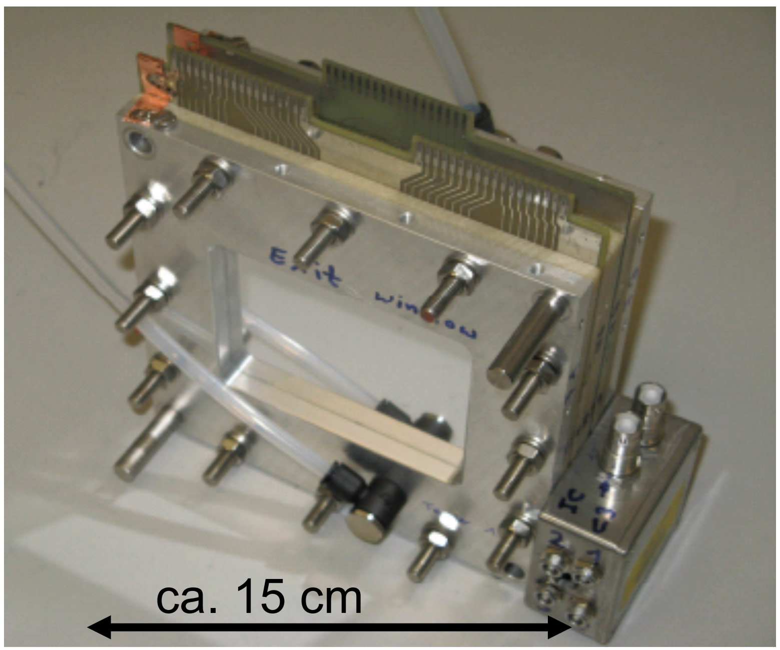
CR-39: usable only once
insensitive to xrays and photons
etching with NaOH and scanning
reveals crates produced by particles

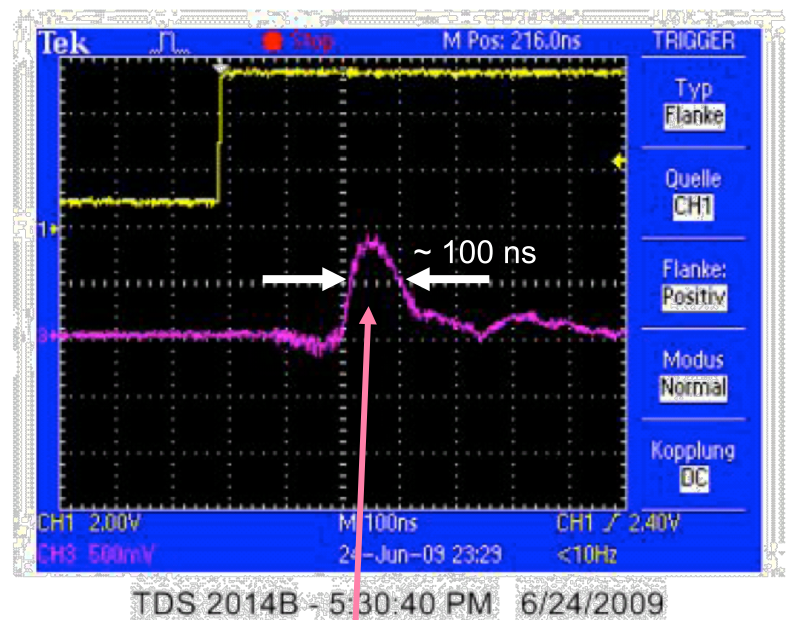


none of the detectors can be read out online

Real-time detectors

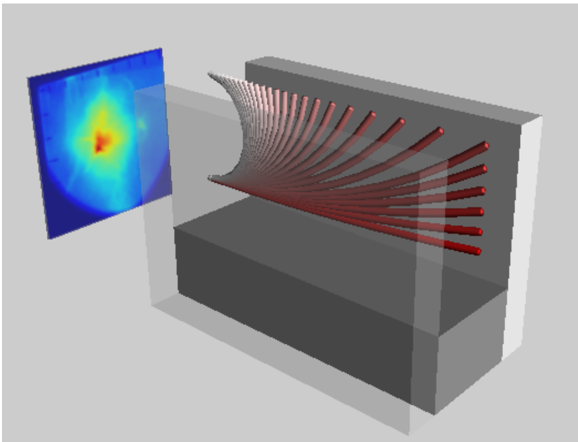
Test chamber for electron and proton detection



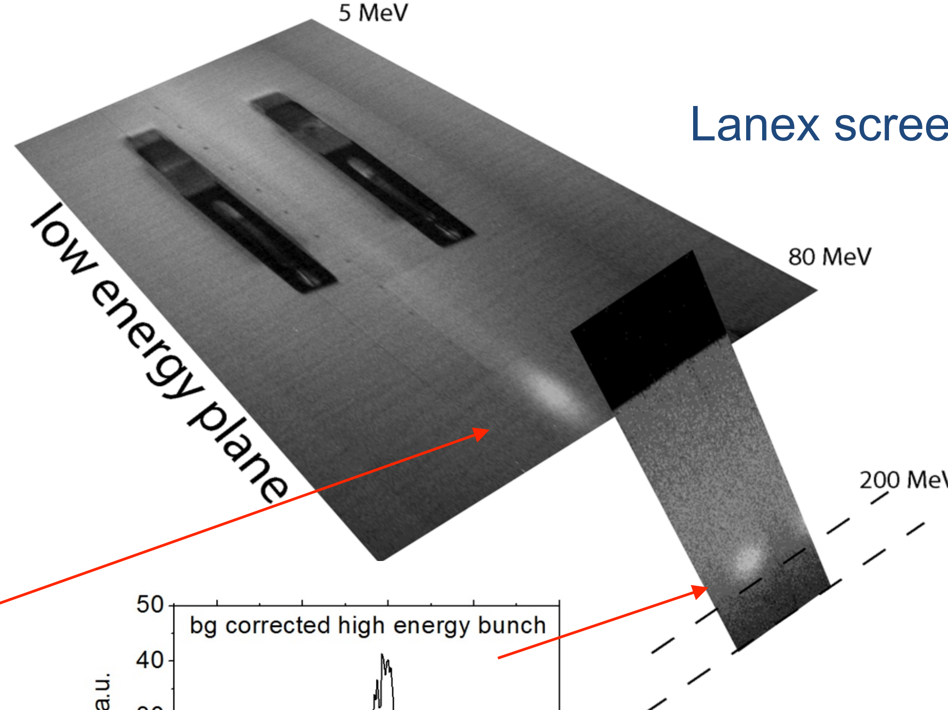


few 10^9 electrons

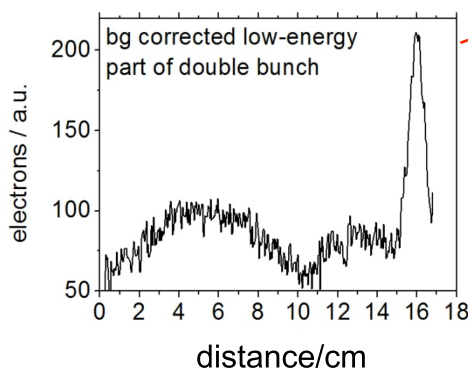
Electron acceleration in gas target



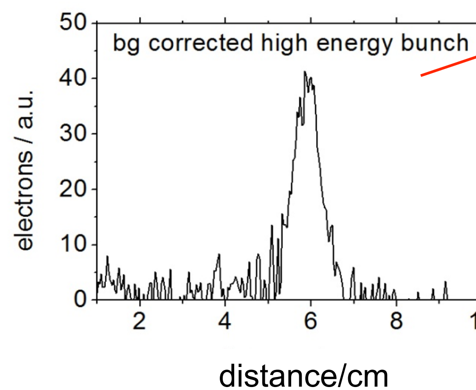
Spectrometer dipole



Lanex screens



5MeV ⟷ 80MeV



80MeV ⟷ 200MeV

60 TW on Helium at 6.2 bar

B. Hidding, T. Königstein
2008

Time stability of electron beams

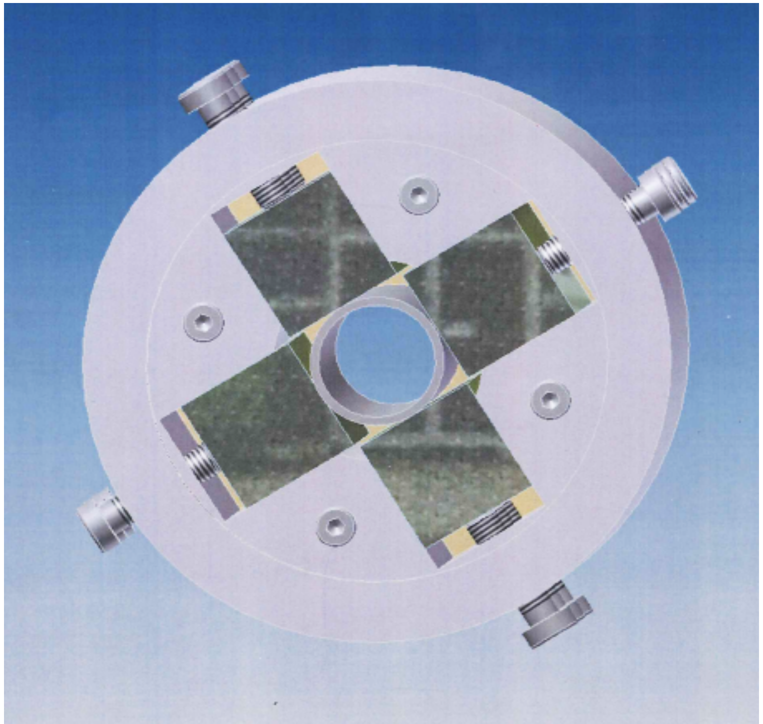
40 fs
23 bar He

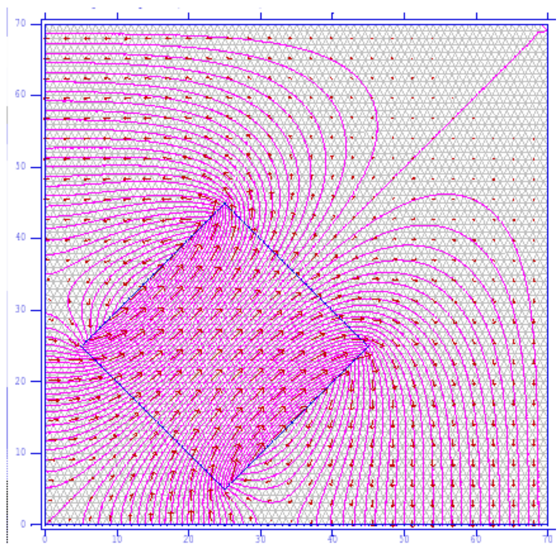
Permanent quadrupole magnets

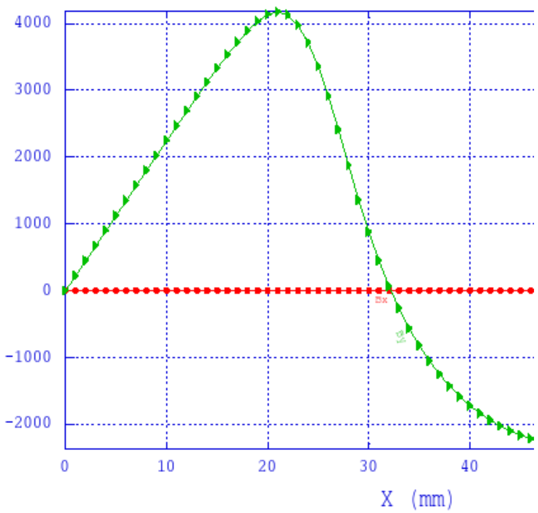
4 neodym magnets in an aluminium housing

20-40 mm distance
from beam-axis
to pole

->
according to
calculations
7.5 – 20 T/m







readjustable between measurements

Capture of accelerated particles

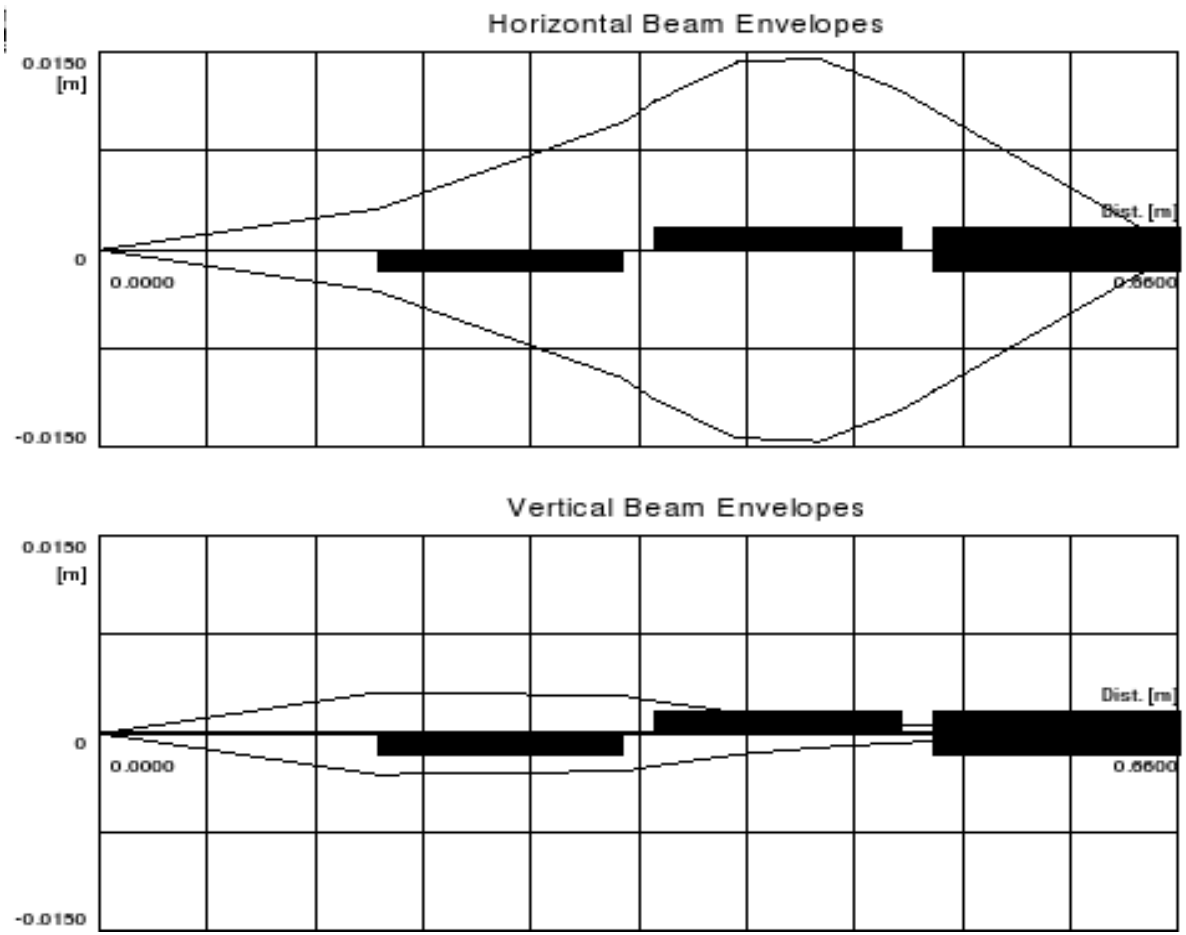
Quadrupole doublet

for 40 MeV/c

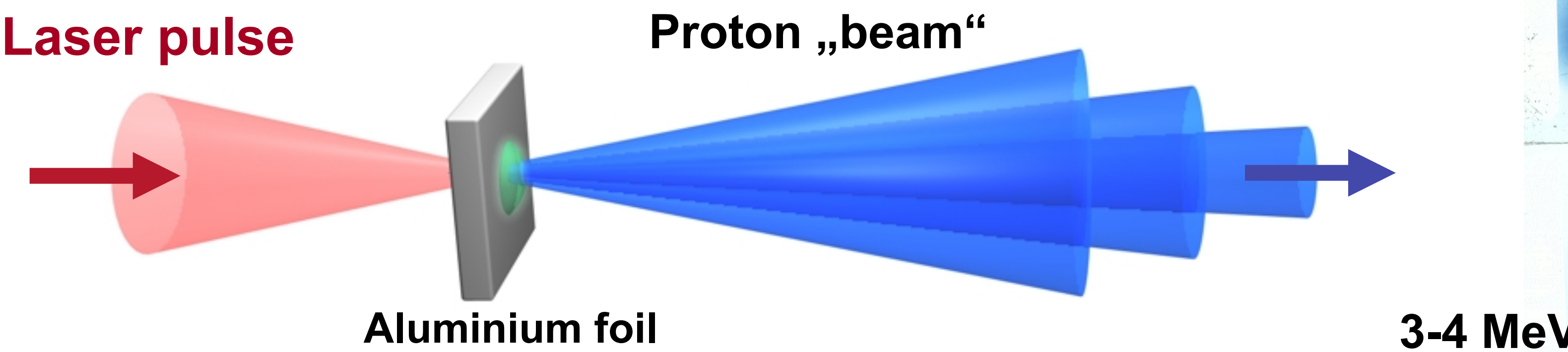
quadrupole strength
10 T/m

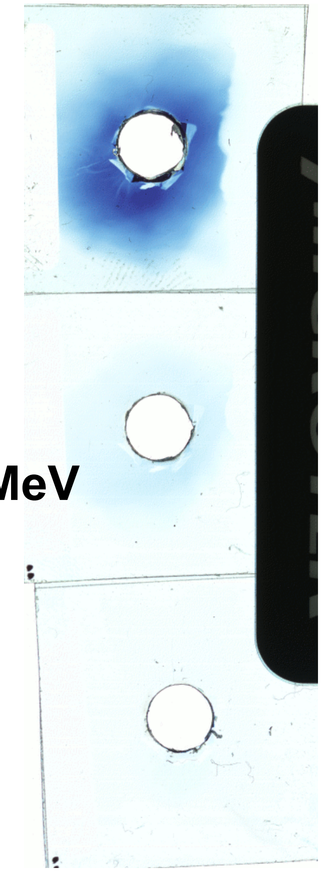
due to the wide
beam spread
the setup must be
very close to the
particle source
(here 17cm)

→ permanent
quadrupoles



Proton acceleration → foil targets

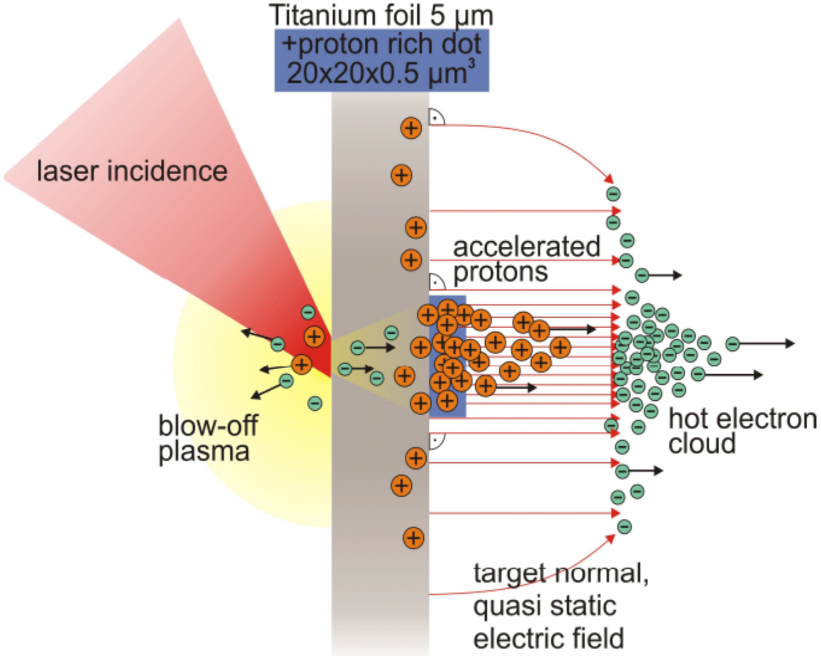




Conversion efficiency ~ 5%
Point-like source (< 10 μm)
Emission angle ~ 30° (15 MeV)
} small vertical emittance

Broad, exponential energy spectra
Short duration (sub-ps pulses)
} small longitudinal emittance

Target Normal Sheath Acceleration (TNSA)

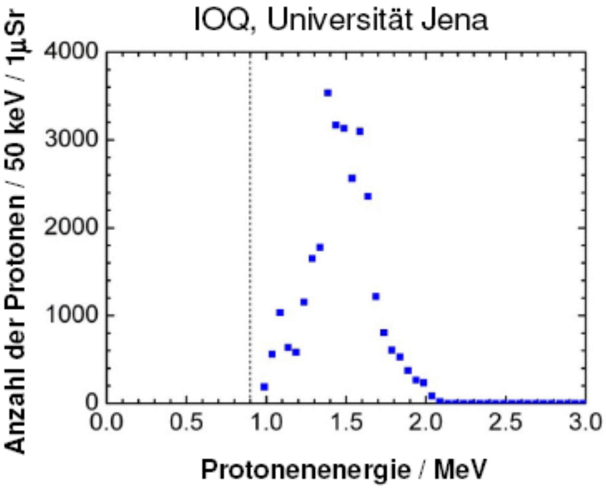


Laserparameter:

E = 600 mJ, τ = 80 fs, P = 7.5 TW

$I = 3 \cdot 10^{19}$ W/cm²

IOQ, Universität Jena

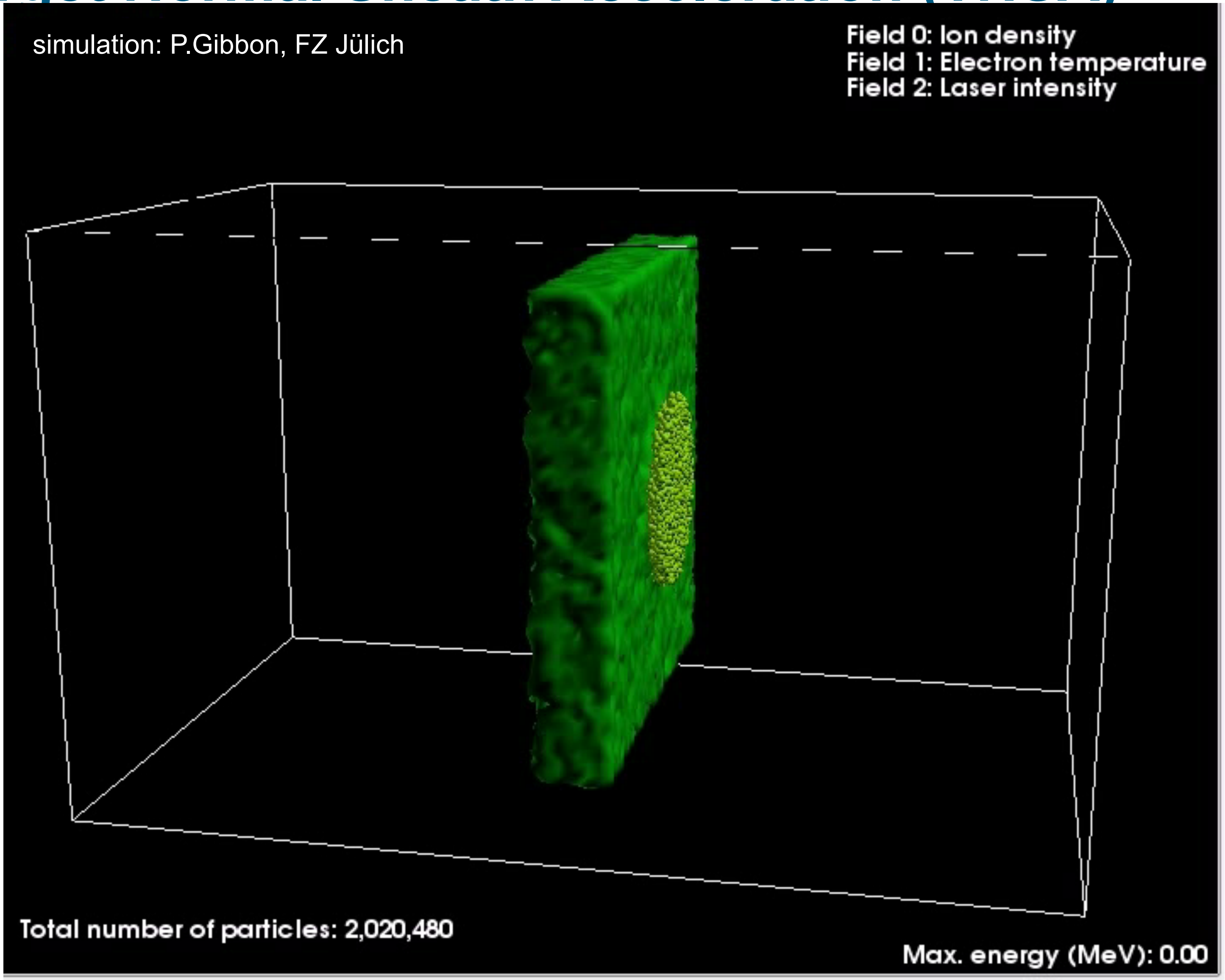


E_p=1.5 MeV ± 10%

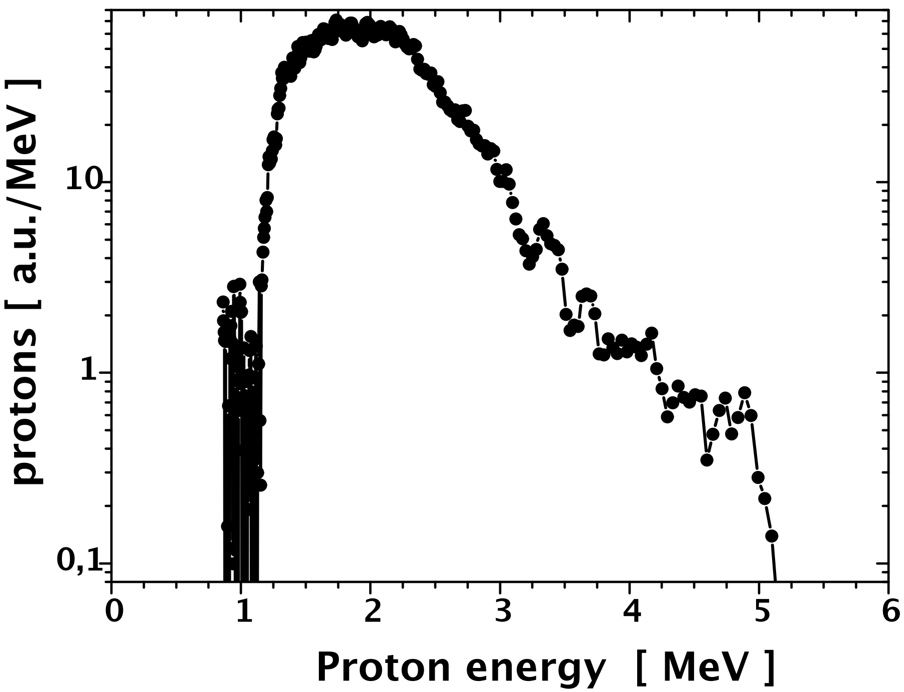
Anzahl der Teilchen: n_p= 10^8 in 24mSr

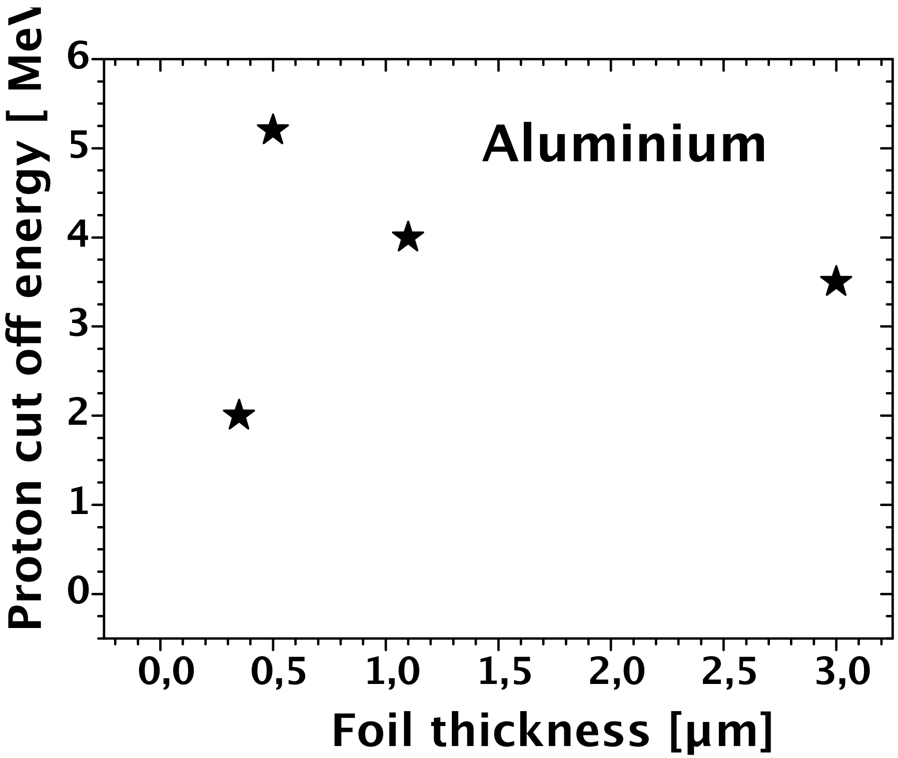
H. Schwörer et al., Nature 439, 445 (2006)

Target Normal Sheath Acceleration (TNSA)



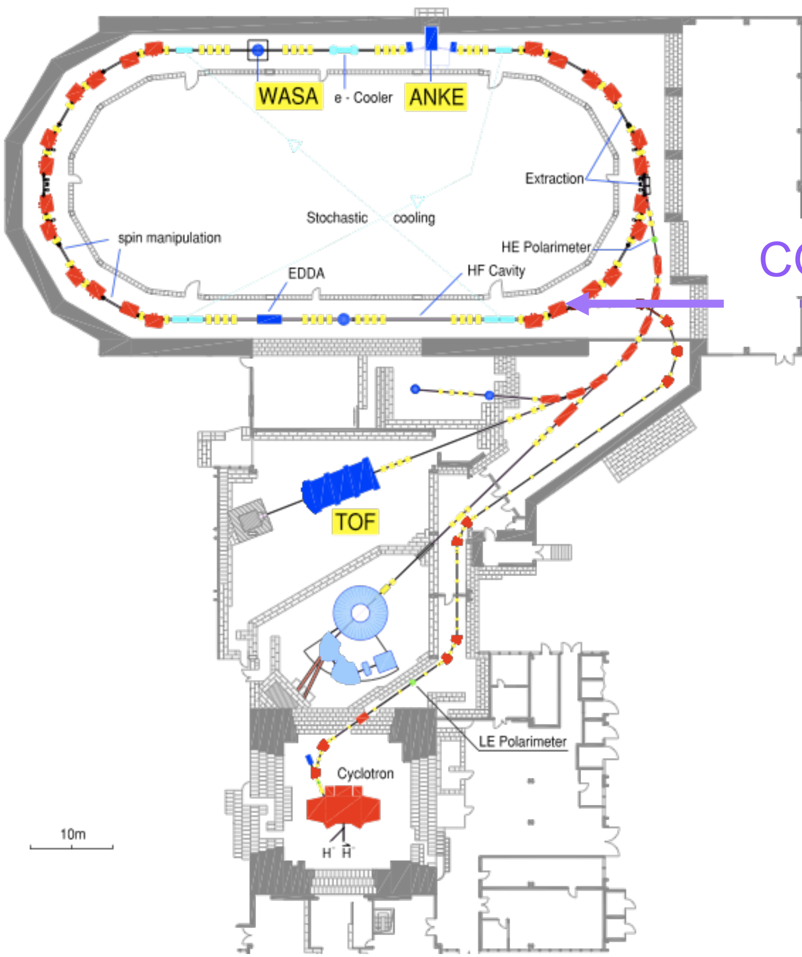
Measured proton spectra from foil targets



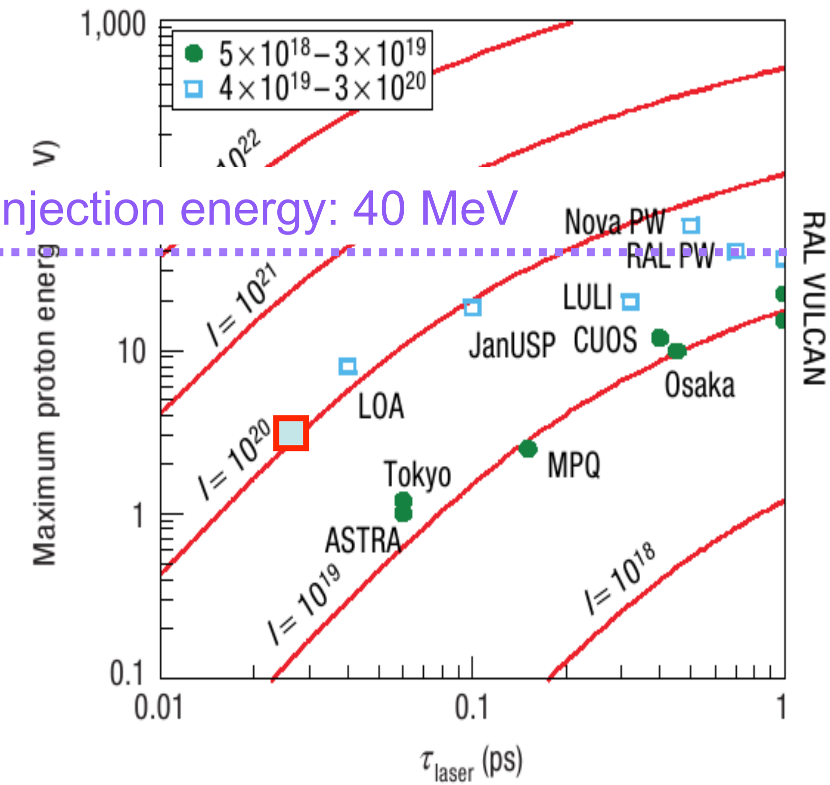


Data: T. Toncian

Maximum proton energy



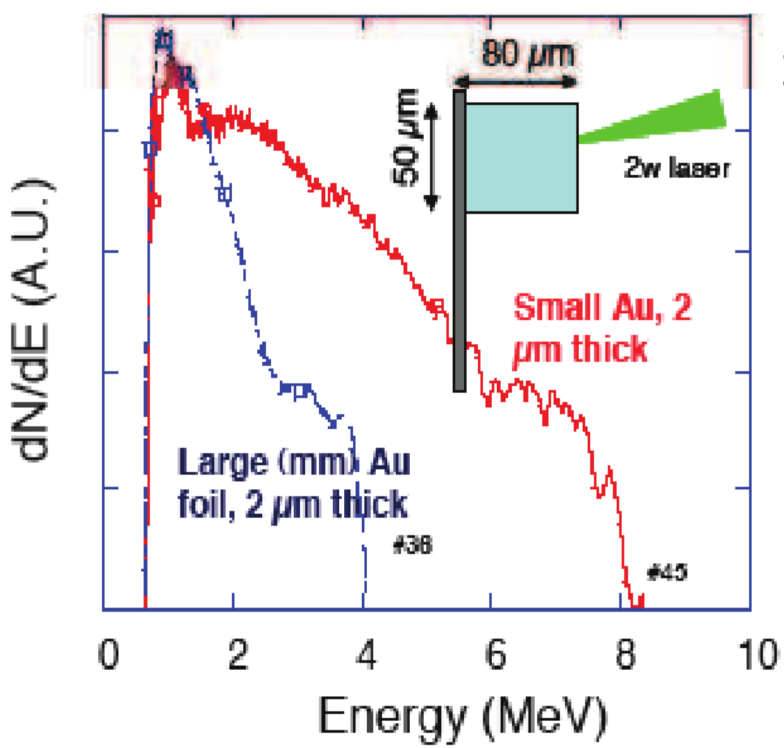
COSY injection energy: 40 MeV



Limited mass targets

Accumulation of protons in regions with high field strength

Reduced reflux of electrons from the target

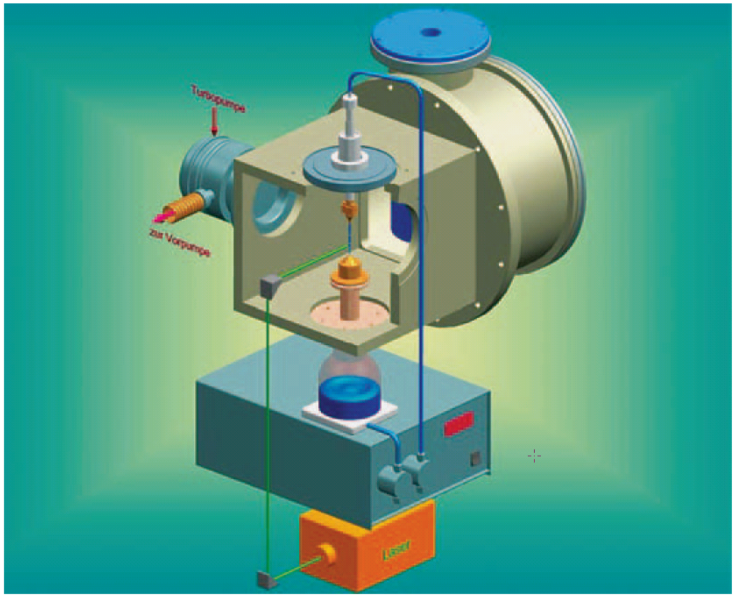


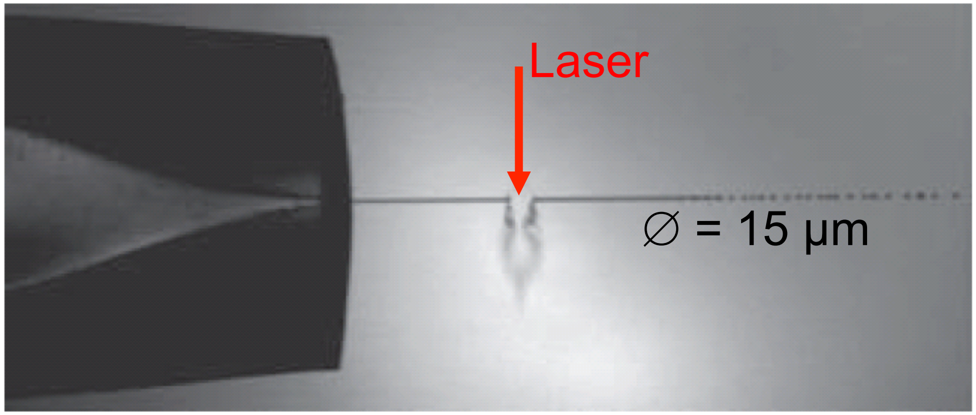
J.Fuchs, M. Borghesi, T. Cowan, O. Willi et. al.

1d-targets: micro-filaments

Target material: H_2O, N_2, Ar, Xe …

T.Spangenberg, B.Abel (Microliquids GmbH)
Photonik 6/2004





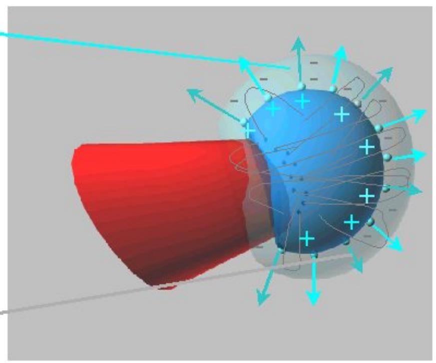
Small distance nozzle ↔ plasma (max. few mm)
➔radiation damage, limited space

Not for pure Hydrogen

Point-like targets

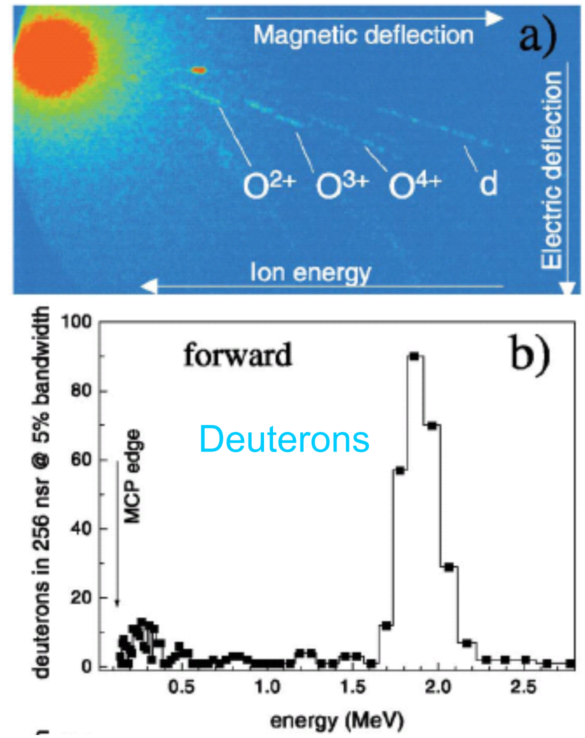
Drops from H_2O, D_2O, Ethanol, …

Protons,
Deuterons



Electron cloud

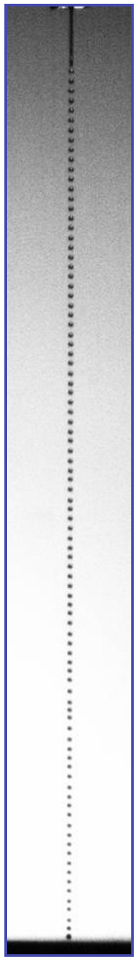
S. Ter-Avetisyan et al., PRL 96, 145006 (2006)

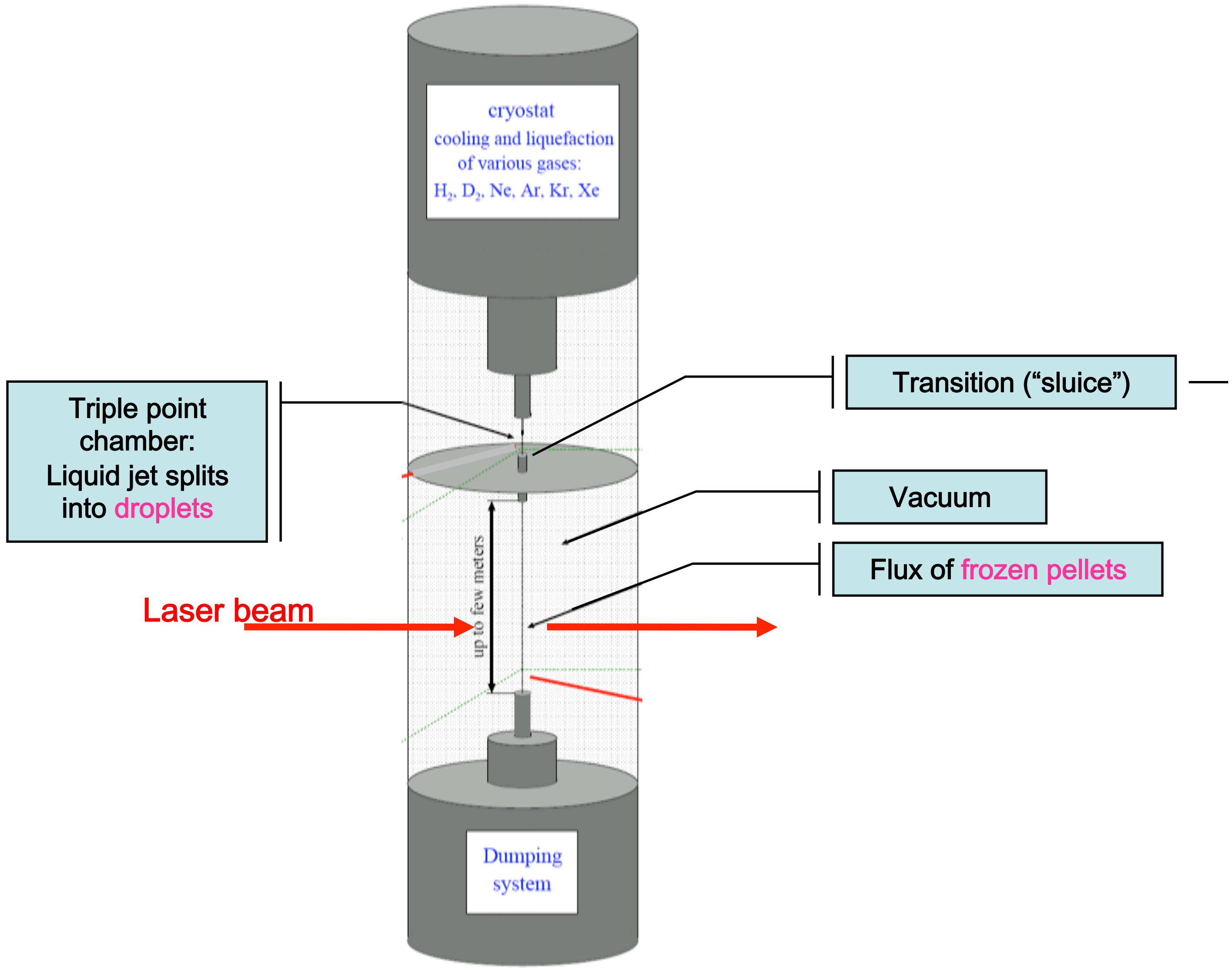


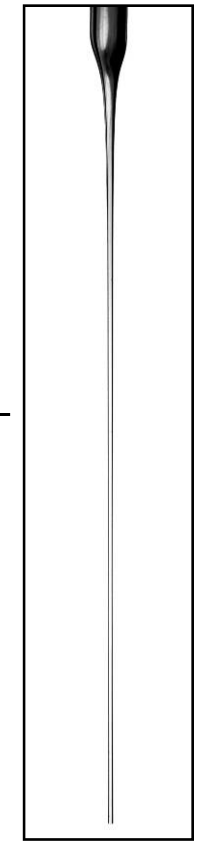
Small distance nozzle ↔ plasma (max. few mm)
➔radiation damage, limited space

Not for pure Hydrogen
➔No pure Target for Proton acceleration

Pellet Target: Principle







Frozen Pellet Target (FZJ, ITEP, MPEI)

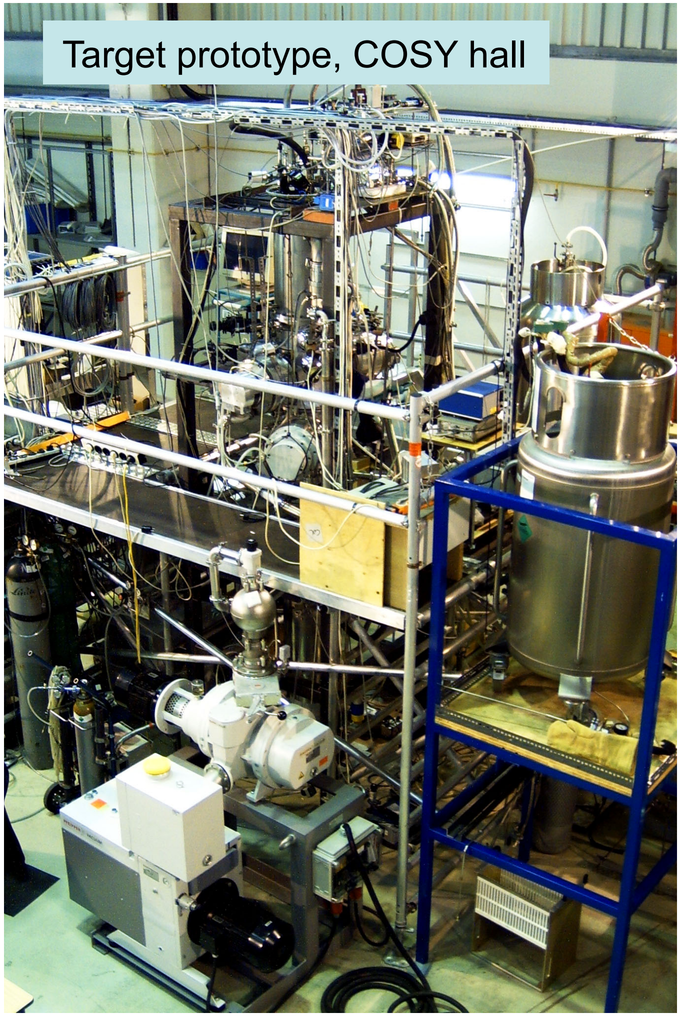
Frozen pellets ∅ ~ 20 µm

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

Pellet rate ~10 kHz

Pellet velocity ~80 m/s

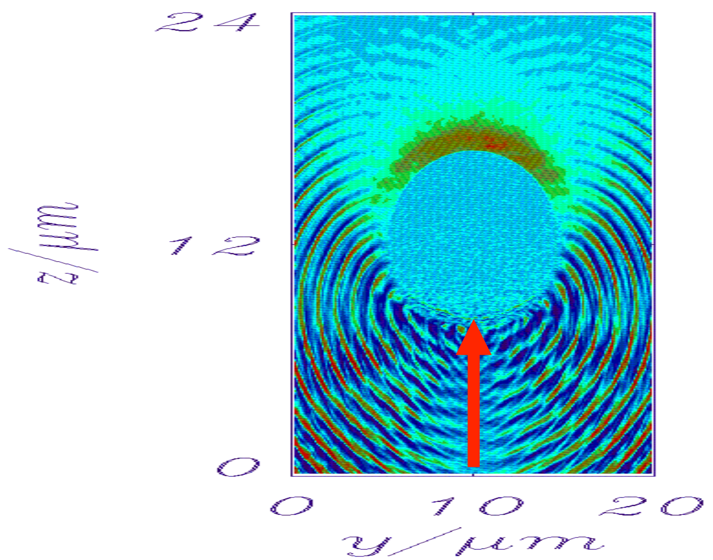
Pellet beam Ø < 1 mm

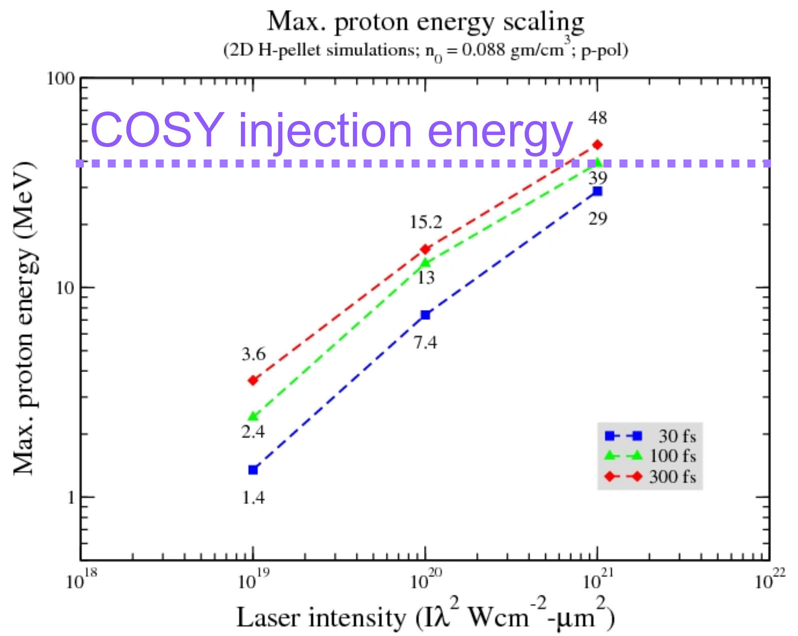


Hydrogen pellets as target

2-D Simulations from the JSC Jülich

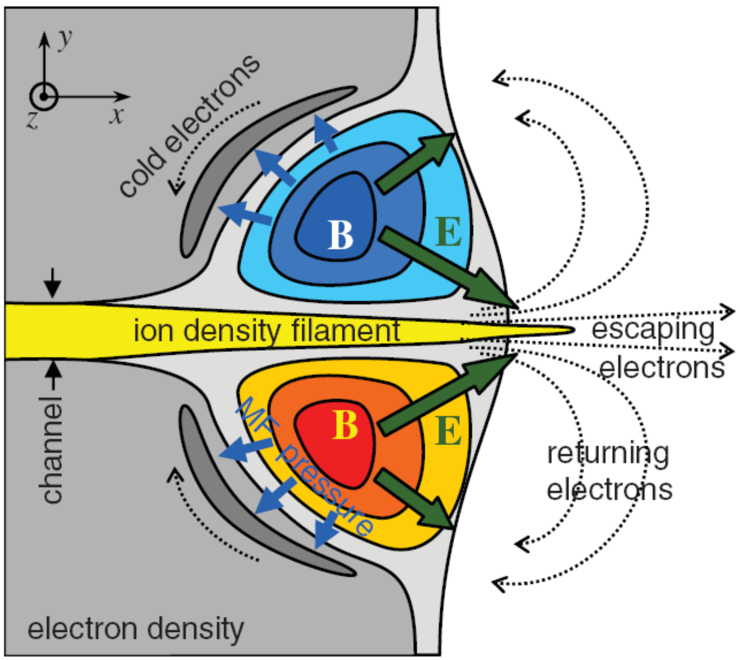
Laser pulse with λ=1 µm and fokus Ø =10 µm hits a 10 µm frozen H_2 pellet





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

Polarized Beams?



Field strengths: ~1000 T

Field gradients: ~10^8 T/m
(typical Stern-Gerlach exp.: 100 T/m)

Figure: Bulanov *et al* ., Phys. Rev. Lett. 98, 049503 (2007)

The end …