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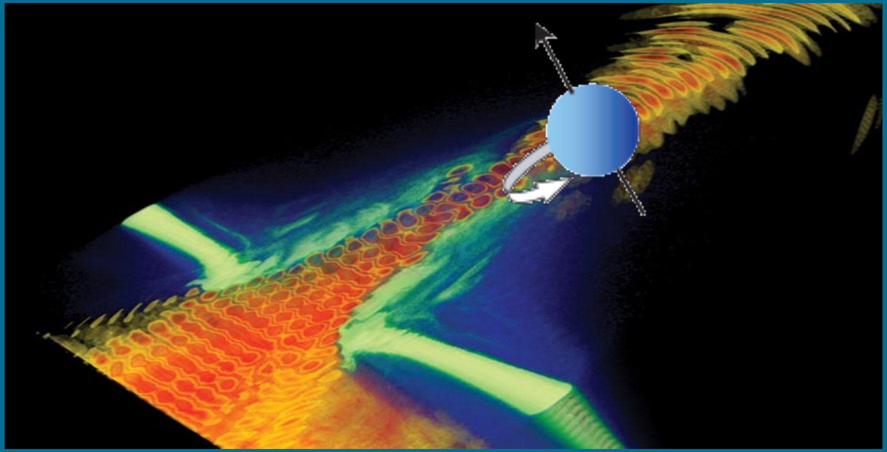
Autumn Lectures / Tbilisi / 2013

Laser-induced particle acceleration

22 October 2013 | Markus Büscher



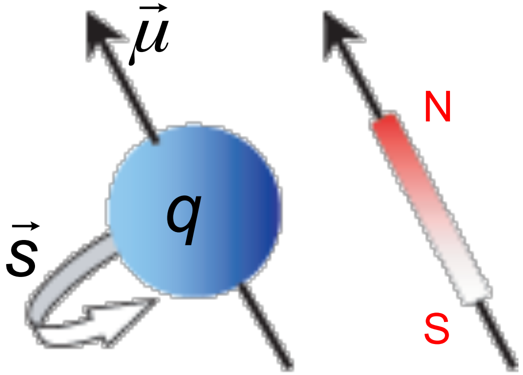
Magnetic fields

Electric fields → change particle energies → acceleration

Magnetic fields → ?

Spin / magnetic fields

Charged spinning particle ➔ magnetic moment μ



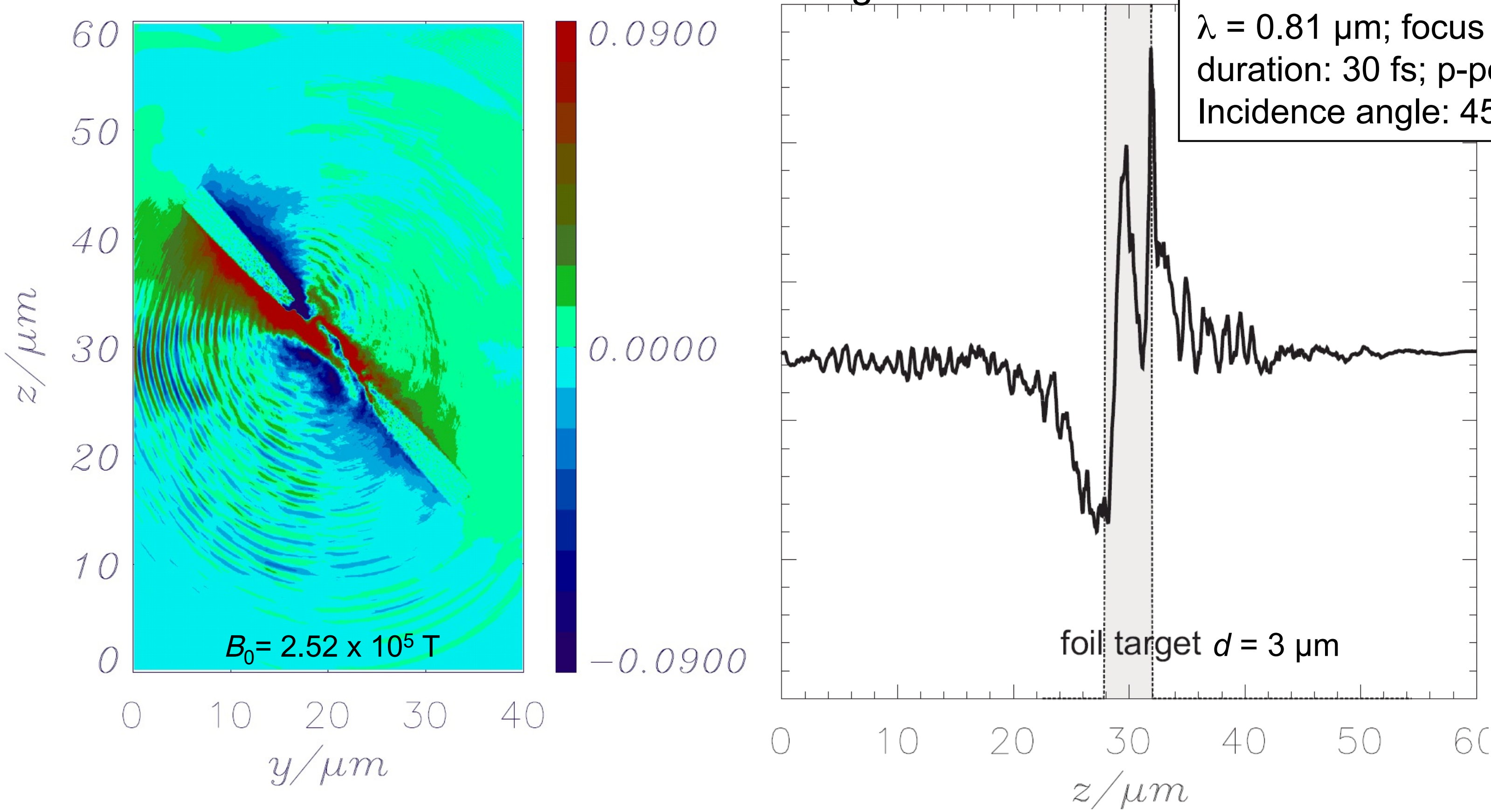
$$\vec{\mu} = g \frac{q}{2m} \vec{s}$$

$$g_e = 2.00\ldots \ (+\varepsilon)$$
$$g_p = 5.586$$
$$g_n = -3.826$$

μ can be manipulated by <u>magnetic fields</u>

Strong magnetic fields (simulation)

B field distribution 140 fs after laser hits foil target



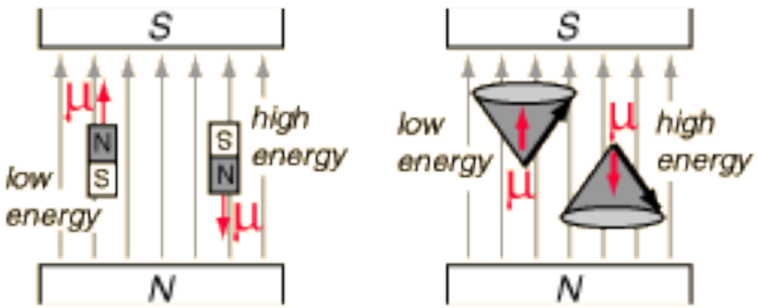
5 · 10^{20} W/cm²
λ = 0.81 μm; focus Ø = 5 μm
duration: 30 fs; p-polarized
Incidence angle: 45°

➔ Field strength / gradient: ~10^4 T / 10^{10} Tm^{-1}

Simulations: A.Karmakar & P.Gibbon, FZJ

Spin alignment in magnetic fields

$\mu = g_p \mu_N$

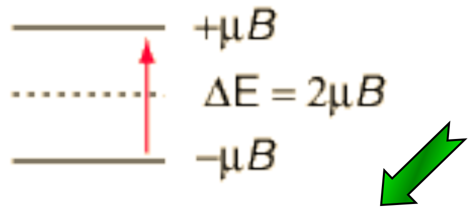


Bar magnet magnetic moment

Proton spin magnetic moment

$g = 2.79$

$\mu_N = 3.15\mathrm{x}10^{-8}\,eV/T$

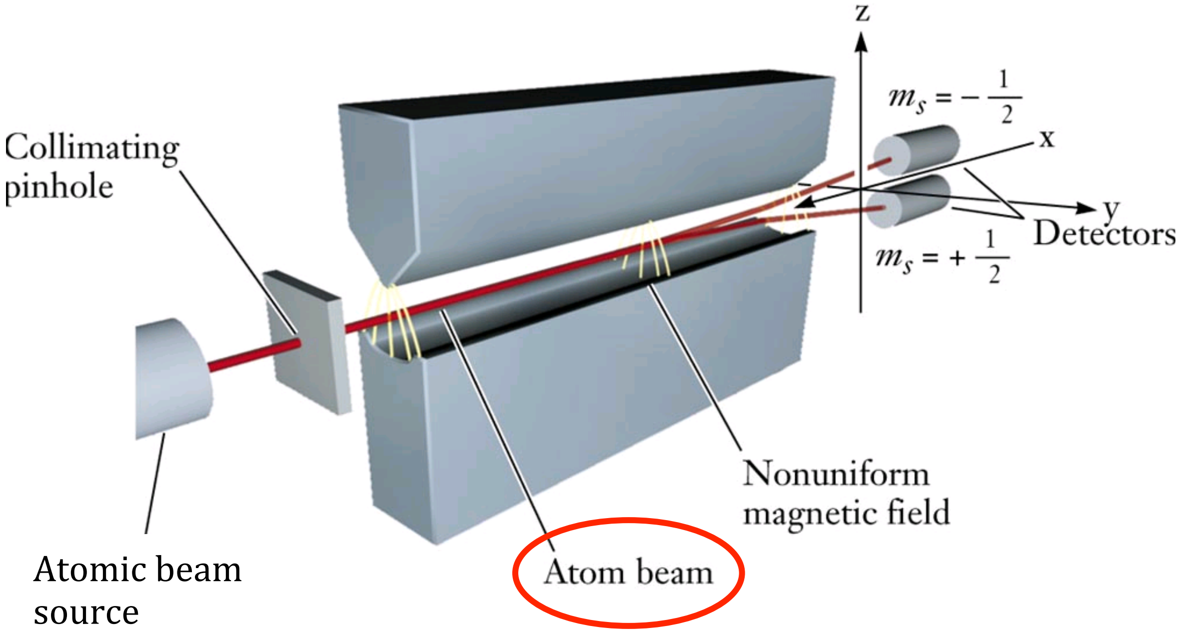


$\Delta E = 2\mu B = 2 g_p \mu_N B$

$\Delta E = 2 \cdot 2.79 \cdot 3.15\mathrm{x}10^{-8}\,eV/T \cdot 1T$

$\Delta E = 1.76\mathrm{x}10^{-7}\,eV$

Stern-Gerlach effect

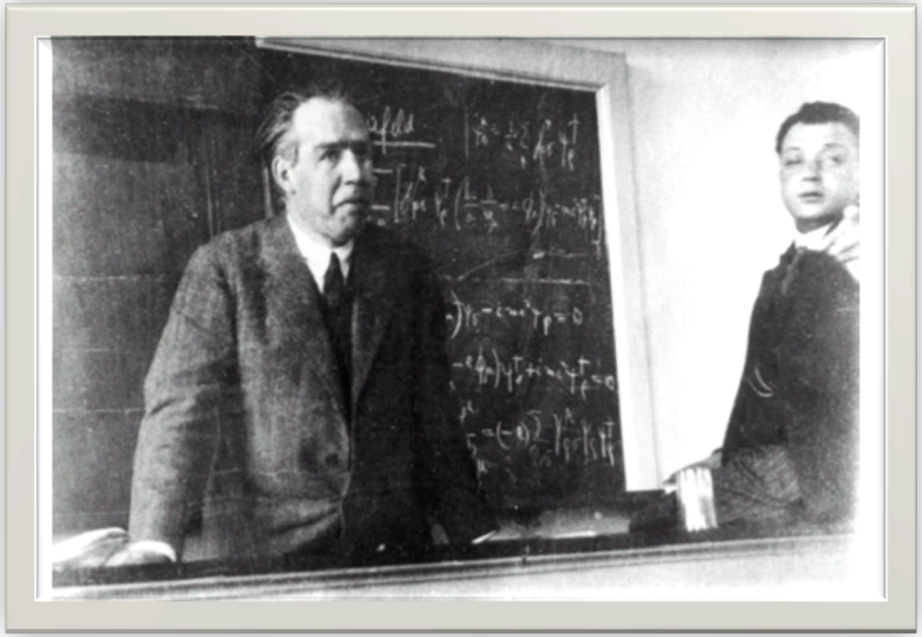


$$\vec{F} = \nabla(\vec{\mu} \cdot \vec{B}) = \begin{pmatrix} 0 \\ 0 \\ \mu_z \cdot \frac{\partial B}{\partial z} \end{pmatrix}$$

Never observed for charged particles!

Stern-Gerlach effect … revisited

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



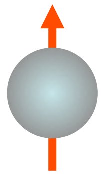
Niels Bohr and Wolfgang Pauli during the Copenhagen conference April 1929 (Niels Bohr Archive, Copenhagen)

"Does a flying electron spin?"

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

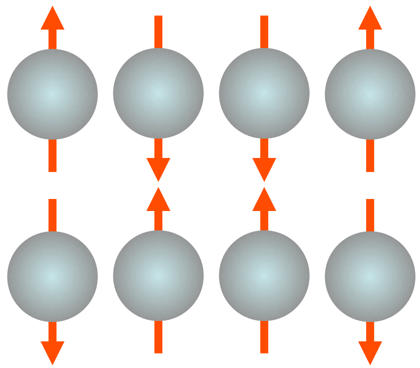
Polarization of a particle beam

1 particle → 1 spin direction

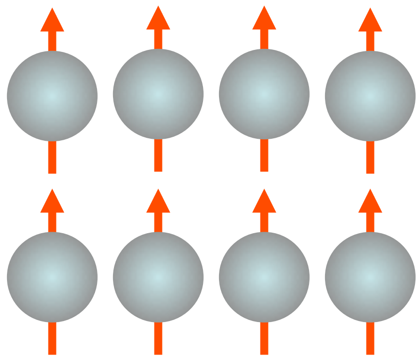


<u>Ensemble of particles</u>

disordered spins
no polarization
$P = 0$



all spins show into same direction
fully polarized beam
$P = 1 = 100\%$



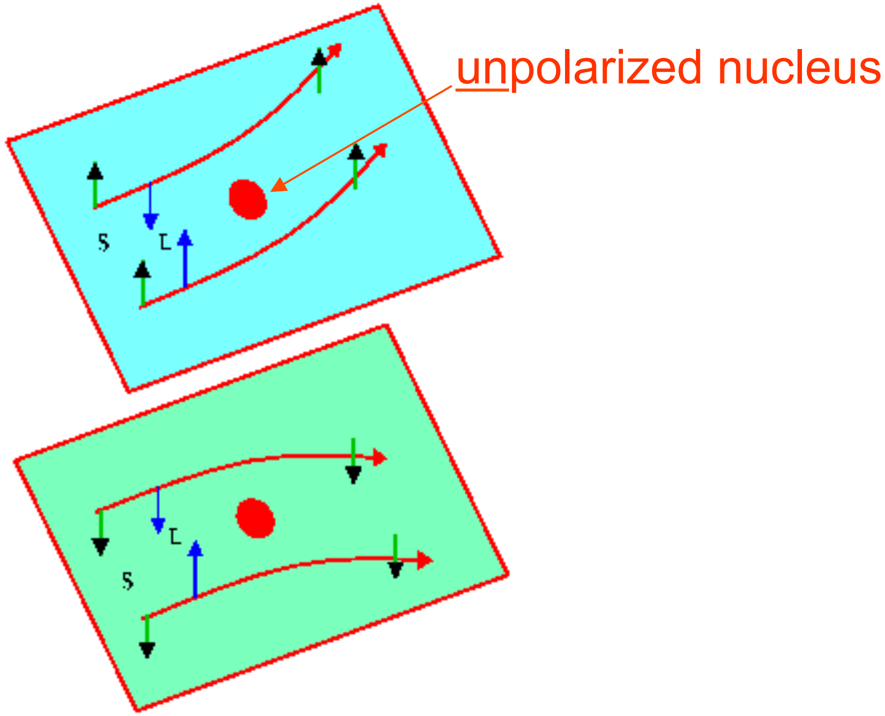
Polarization P

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

N = occupation number of up/down state

How to measure polarization

Nuclear scattering with known analyzing powers



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

Scattering of a polarized beam

Simplest case: beam particle with spin ½ on unpolarized target

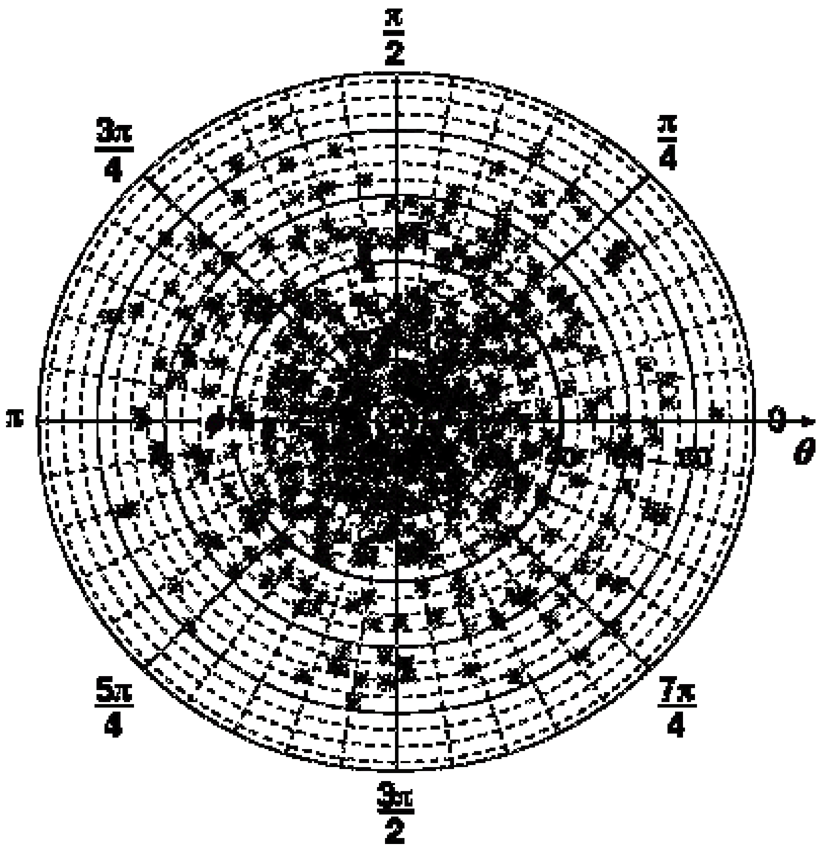
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(E,\vartheta,\varphi)=\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}_{\mathrm{unpol}}(E,\vartheta)\left[1+A\cdot P\cdot\cos\varphi\right]$$

Analyzing power	Beam polarization
$A(E, \vartheta, \text{target}, \ldots)$ $-1 \le A \le +1$	P $-1 \le P \le 1$

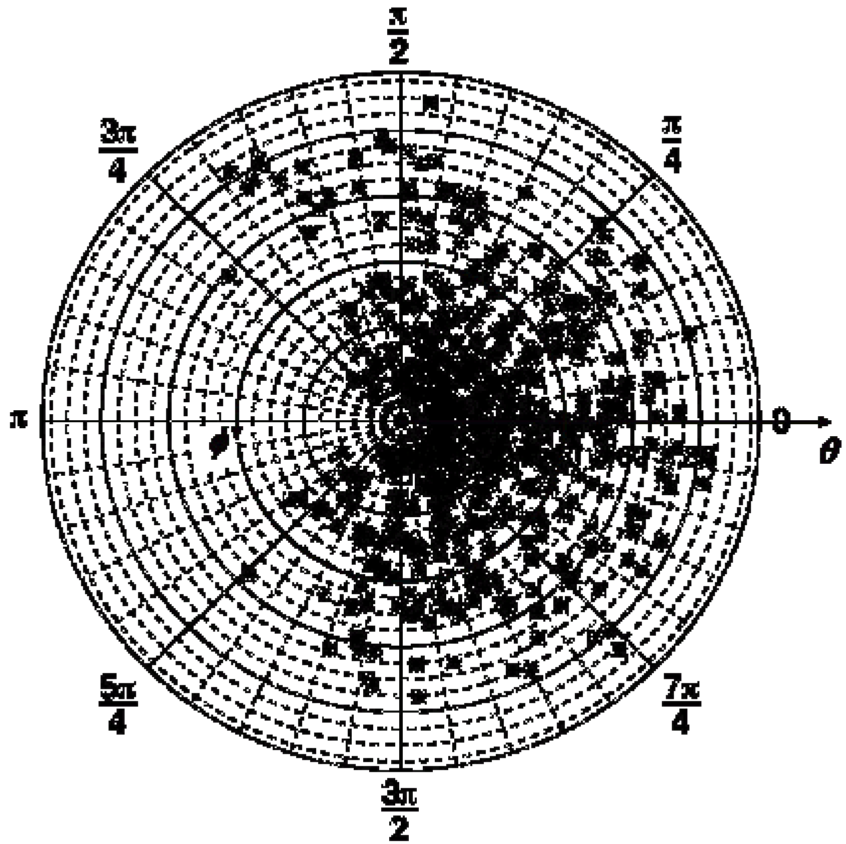
Scattering of a polarized beam (2)

Simulation for

$P = 0$ or $A = 0$

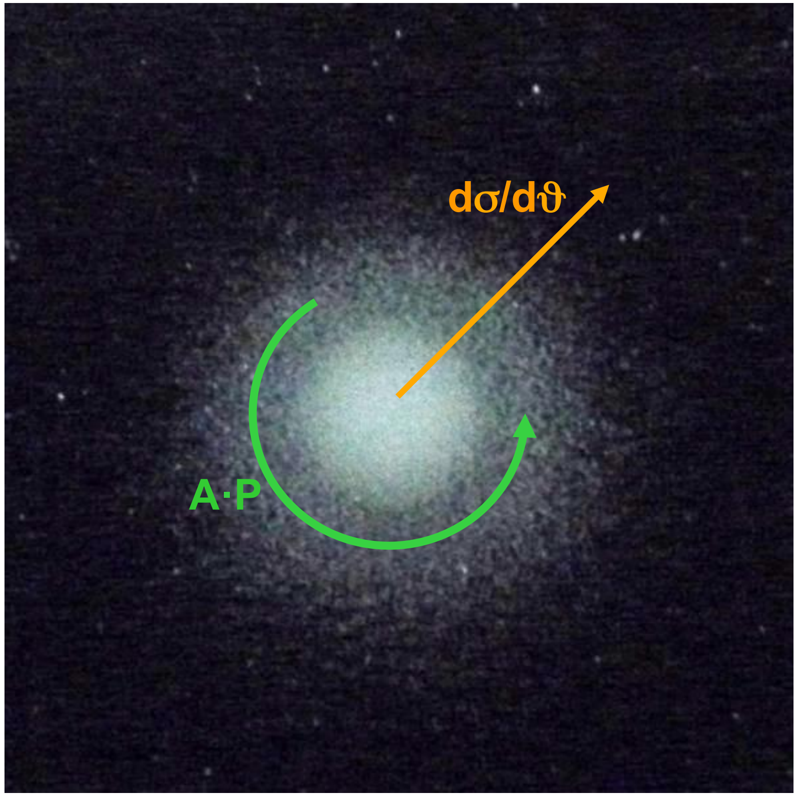


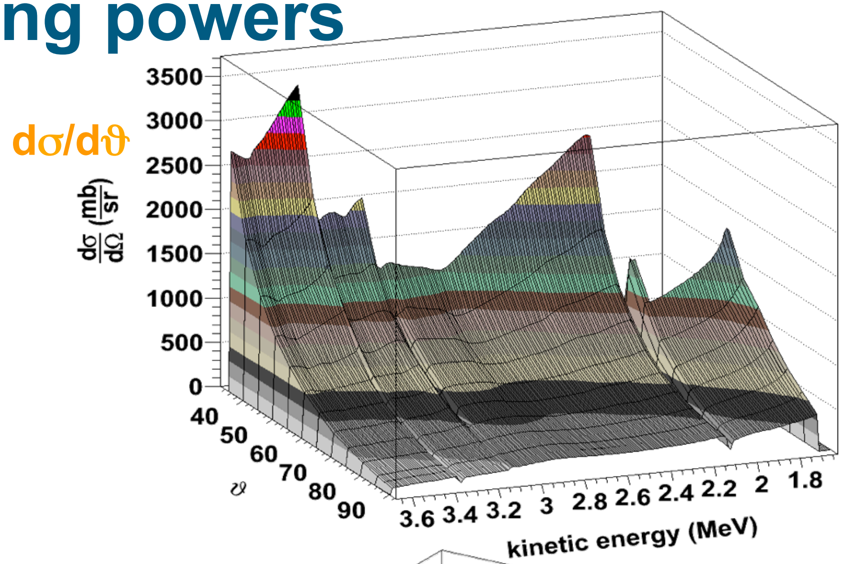
$P = A = +1$

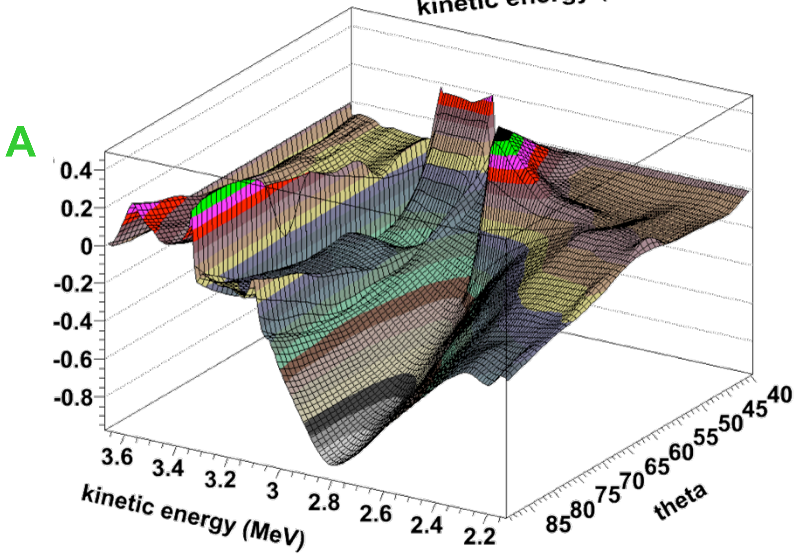


Cross sections & analyzing powers

Example: Si(*p*, *p*‘)Si



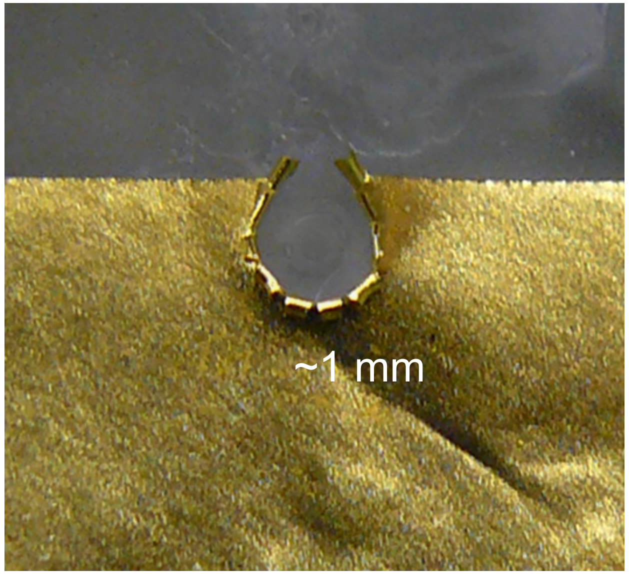




B.Becker, Universität zu Köln (1994)

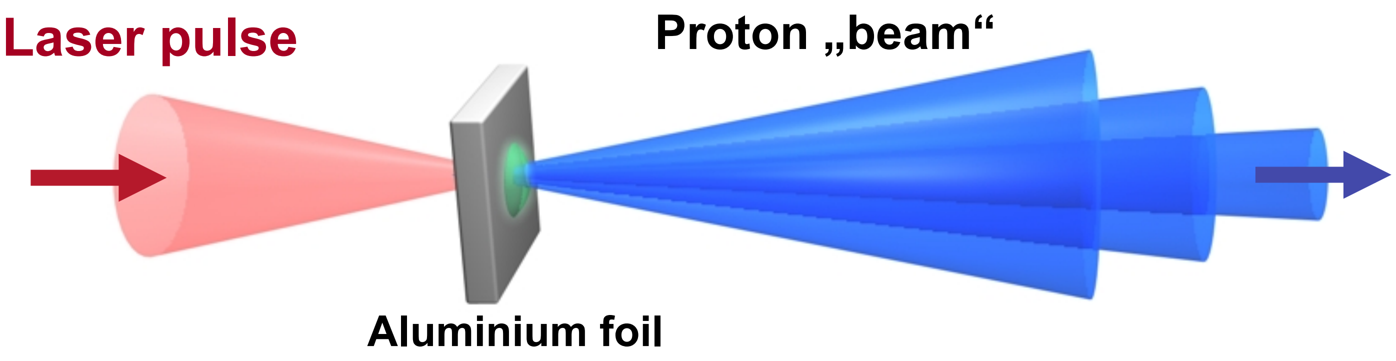
Proton acceleration → Foil targets

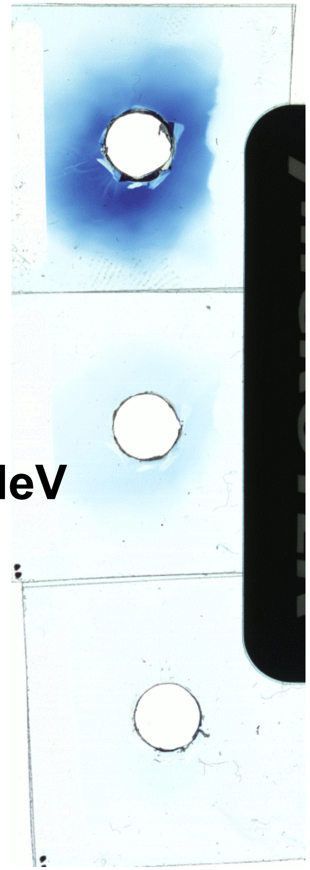
Experiment at ARCturus / Düsseldorf Univ.



Gold foil
typical thickness 3 µm

Proton acceleration





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

Particle detection

bunches of many particles,
extremly high particle rates

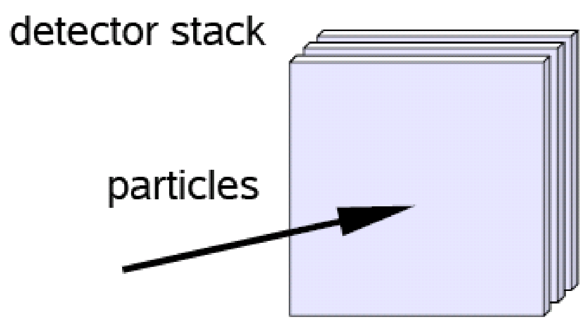
→ use detectors without dead time

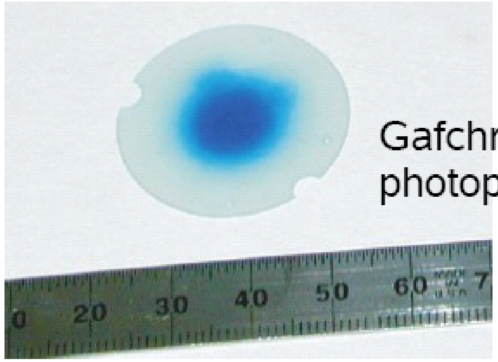
photofilms: calibrated, usable only once

image plates: usable several times
not calibrated

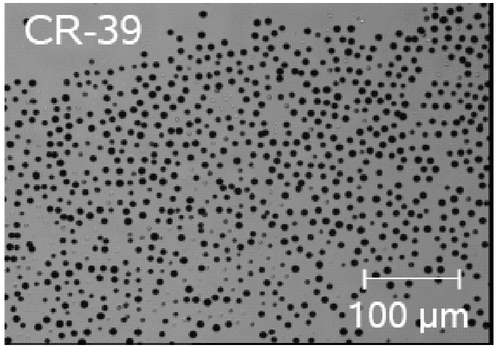
CR-39: usable only once
insensitive to xrays and photons
etching with NaOH and scanning
reveals crates produced by particles

none of the detectors can be read out online

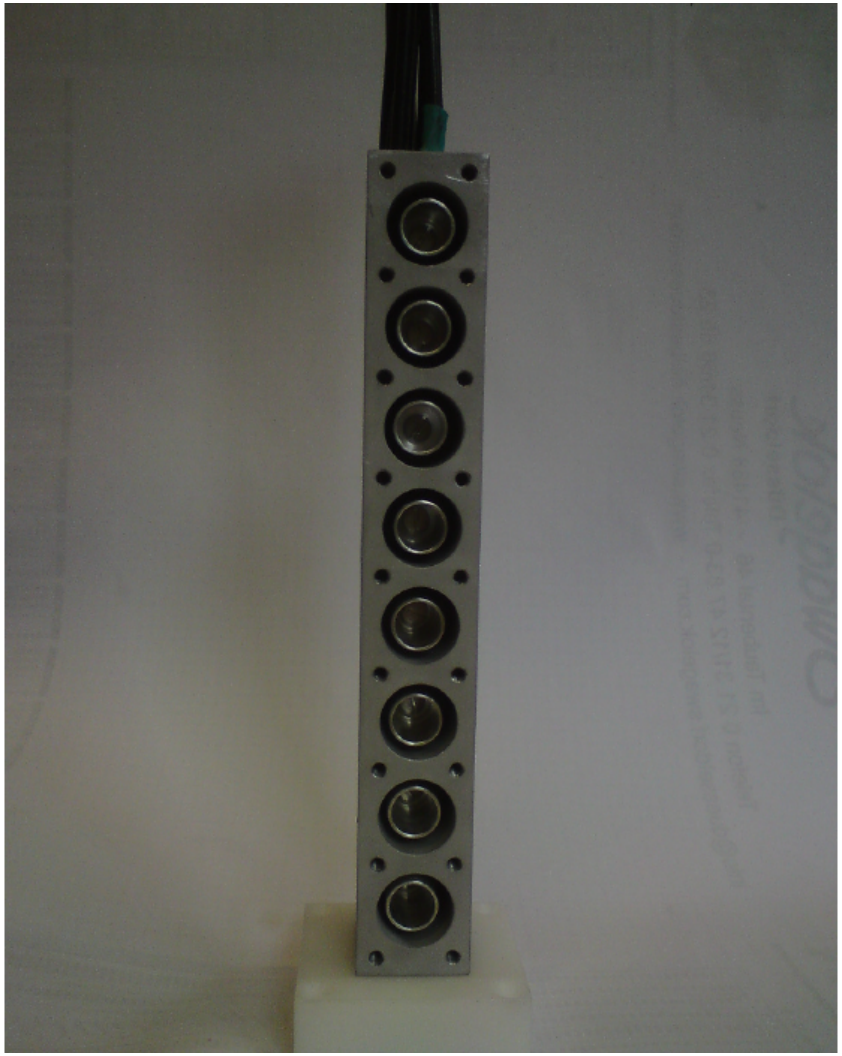




Gafchromic
photoplate



Particle detection (2)



Faraday cups (here: array of 8)

Readout online

Measures collected charge

Good time resolution

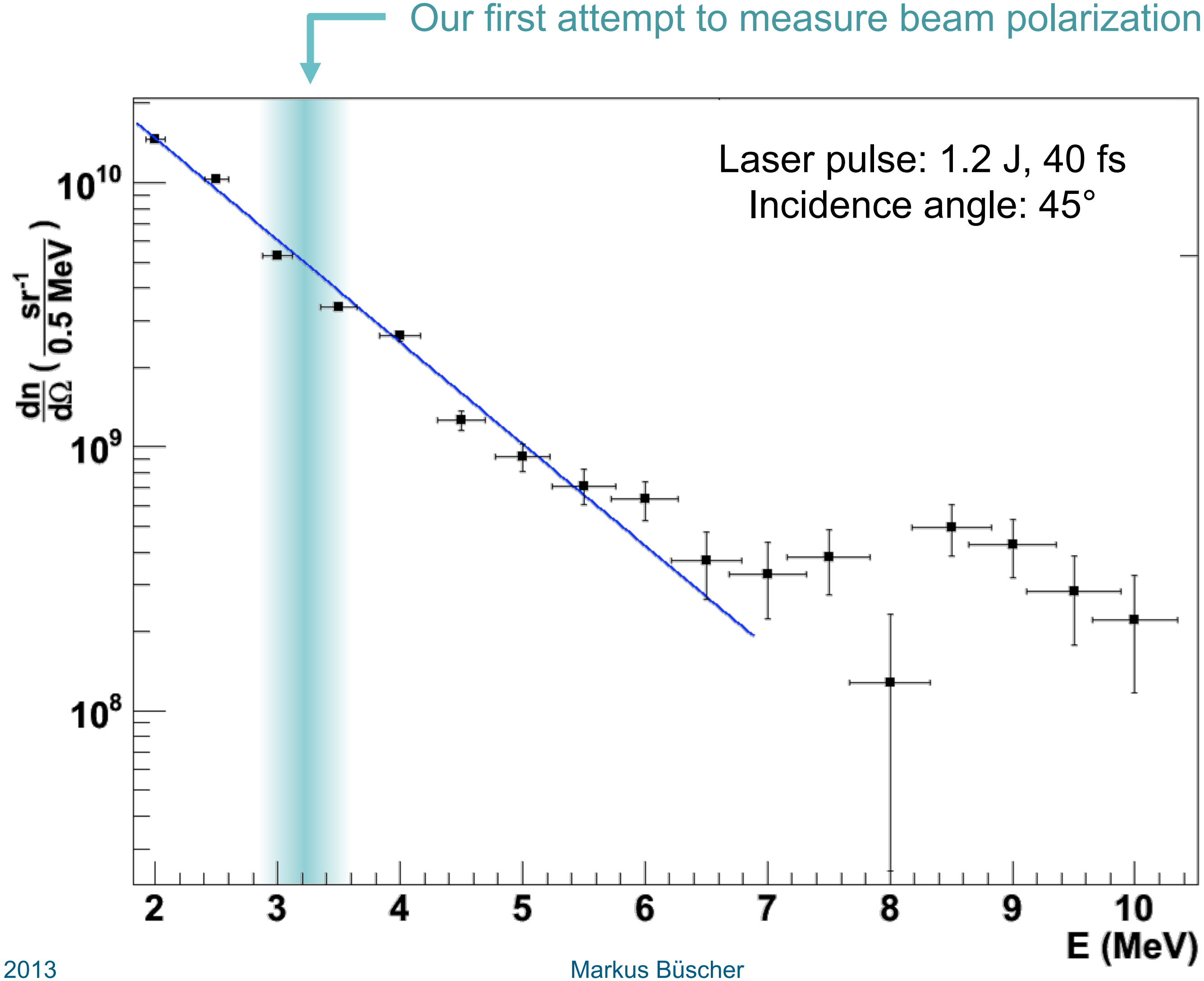
Time stability (here: electron beams)

Measured with LANEX screen

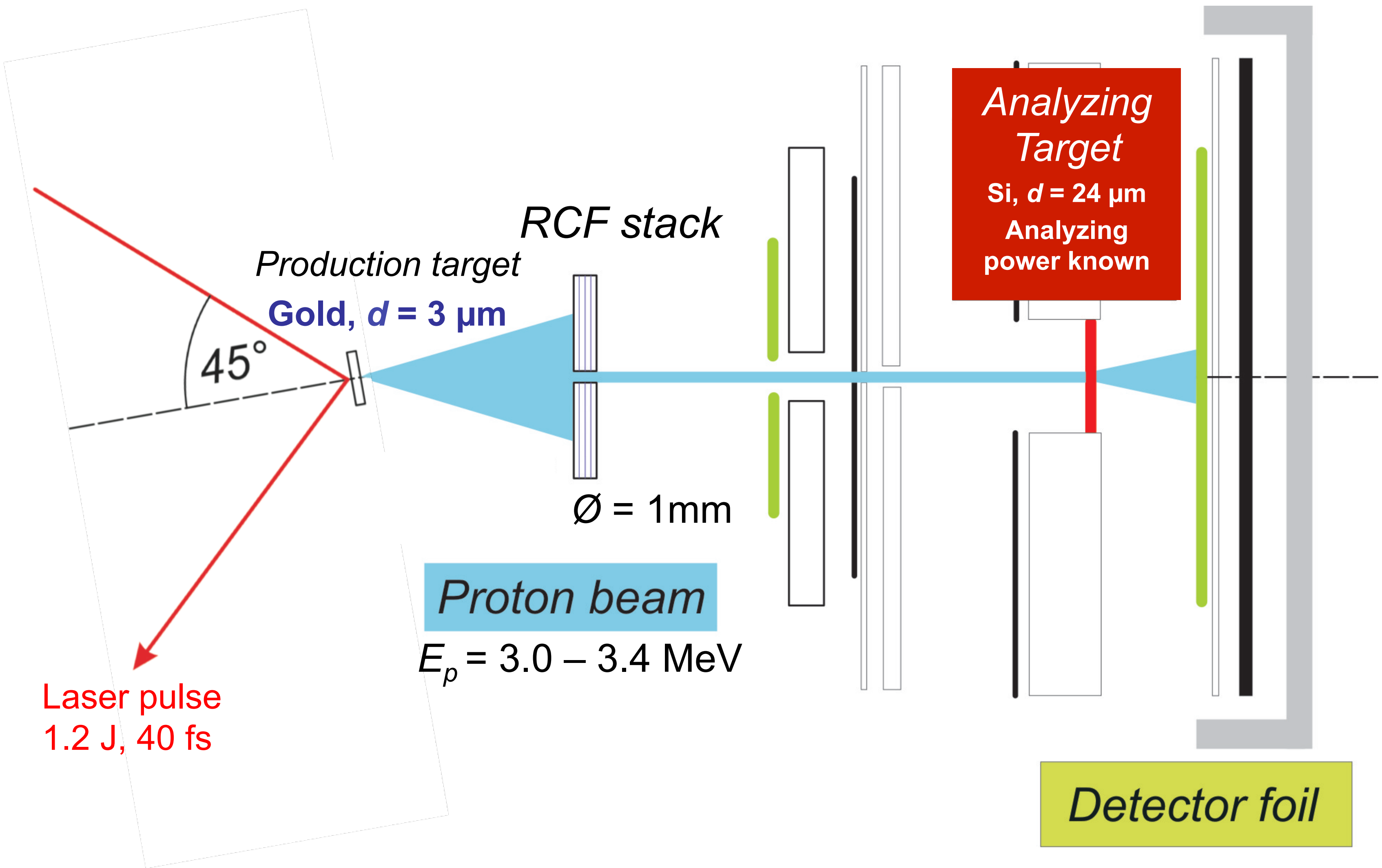
40 fs
23 bar He

Proton energy spectrum

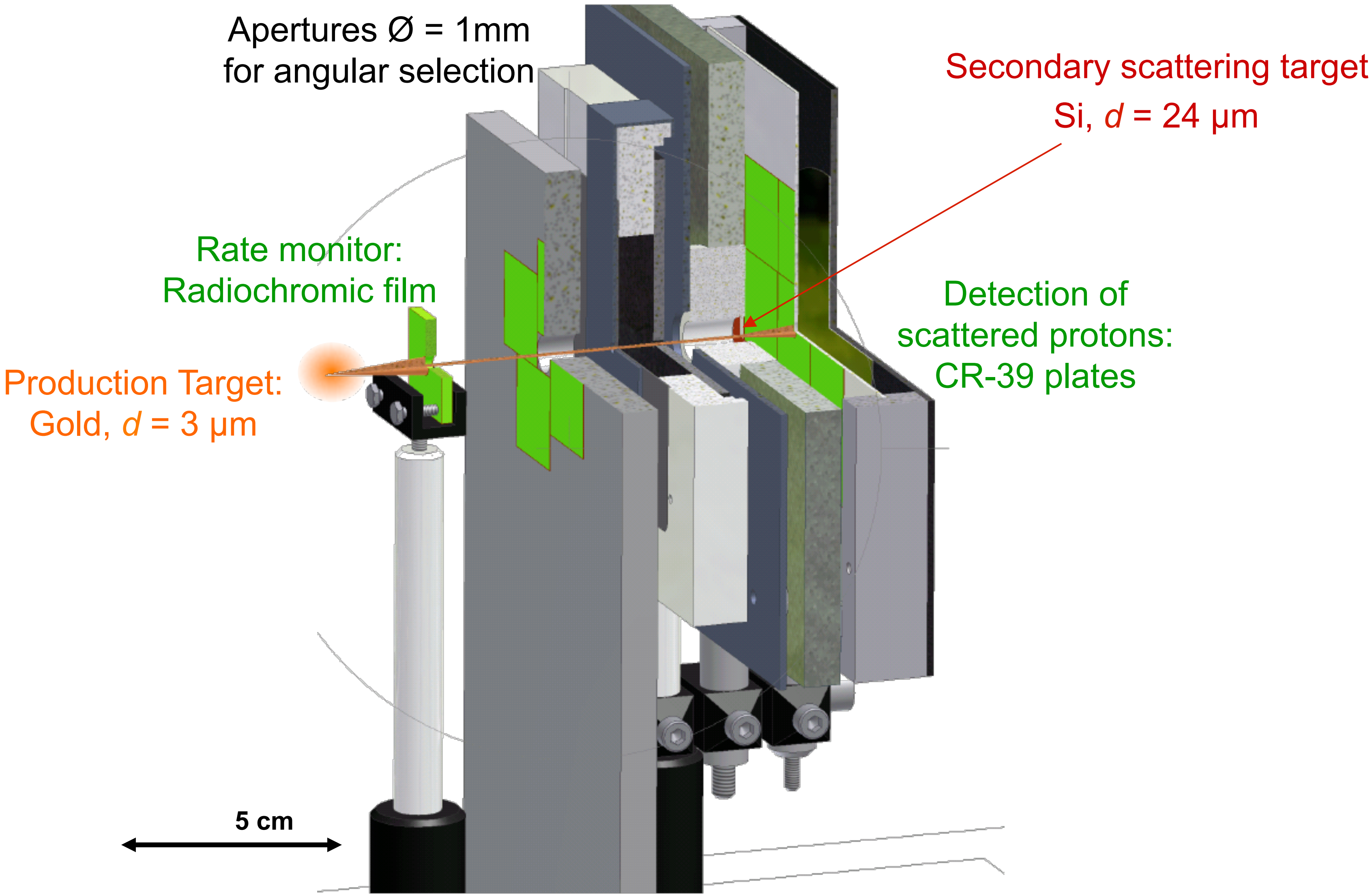
Our first attempt to measure beam polarization



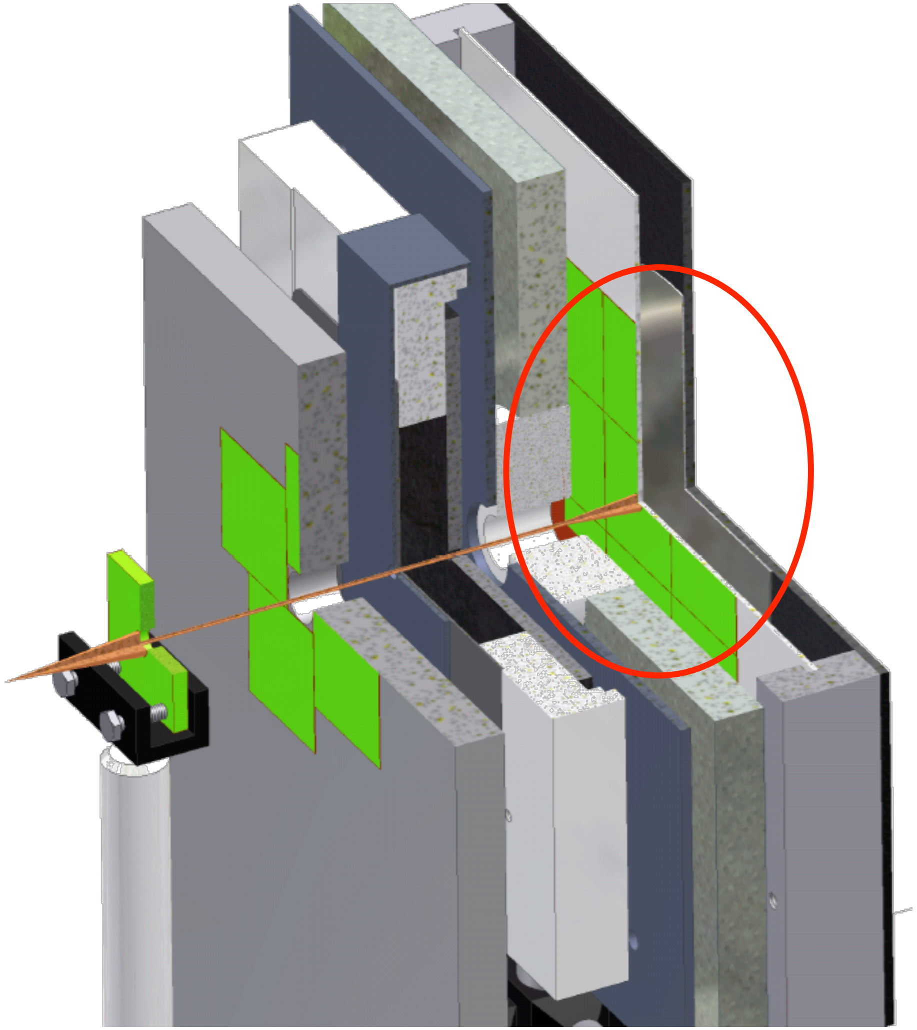
Polarization measurement: setup



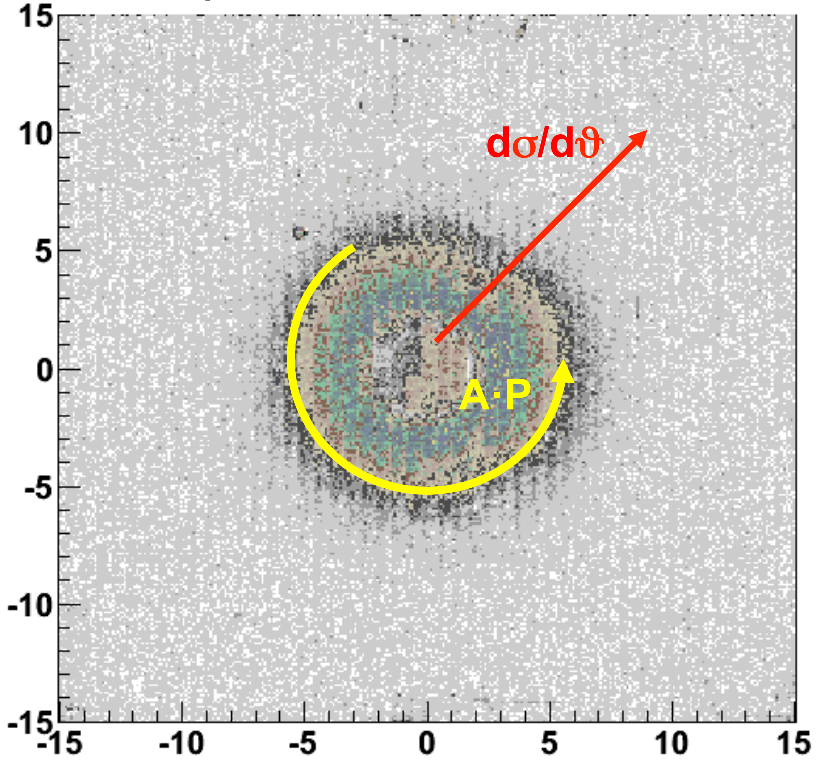
Polarization measurement: setup



Proton scattering in Si target



CR39 plates

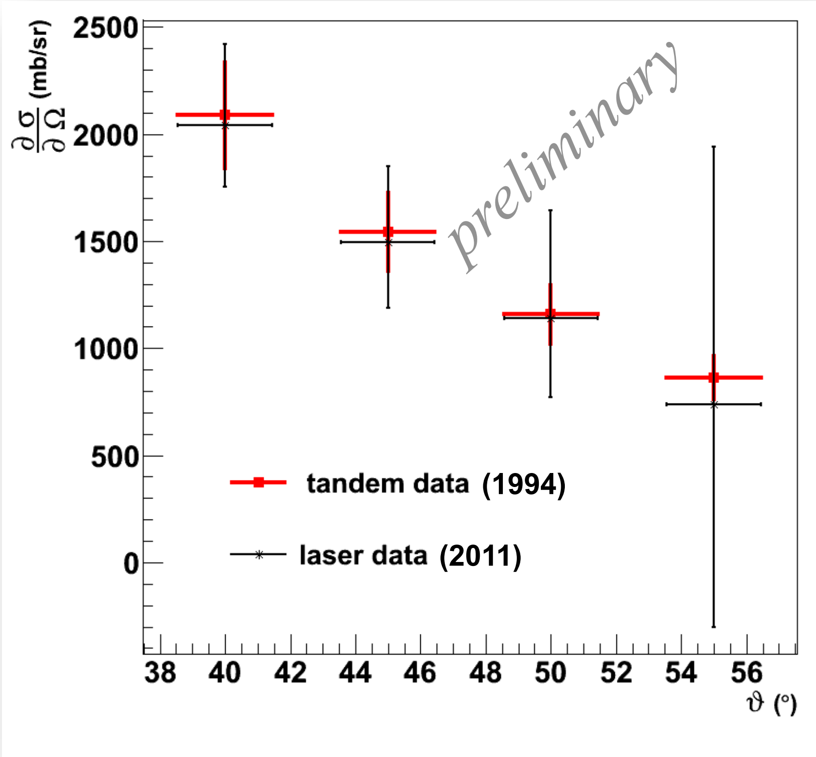


Scattering-angle distribution

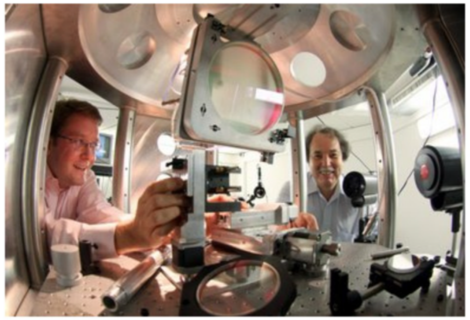
Si(*p*, *p*')Si, T_p = (3.2±0.2) MeV

Cologne Tandem

Beam time = O(days)



ARCturus Laser

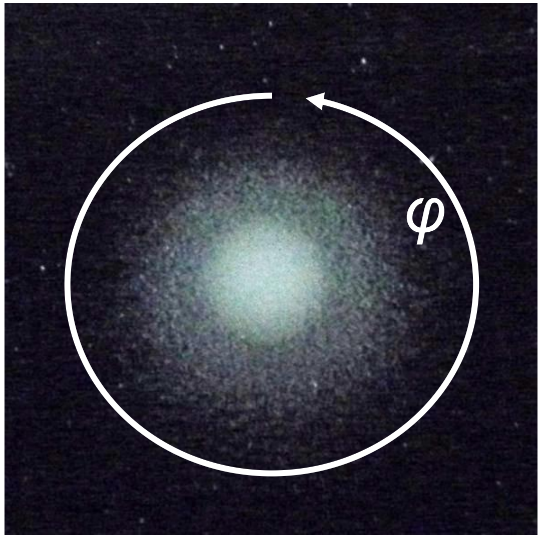


Beam time = O(100 fs)*

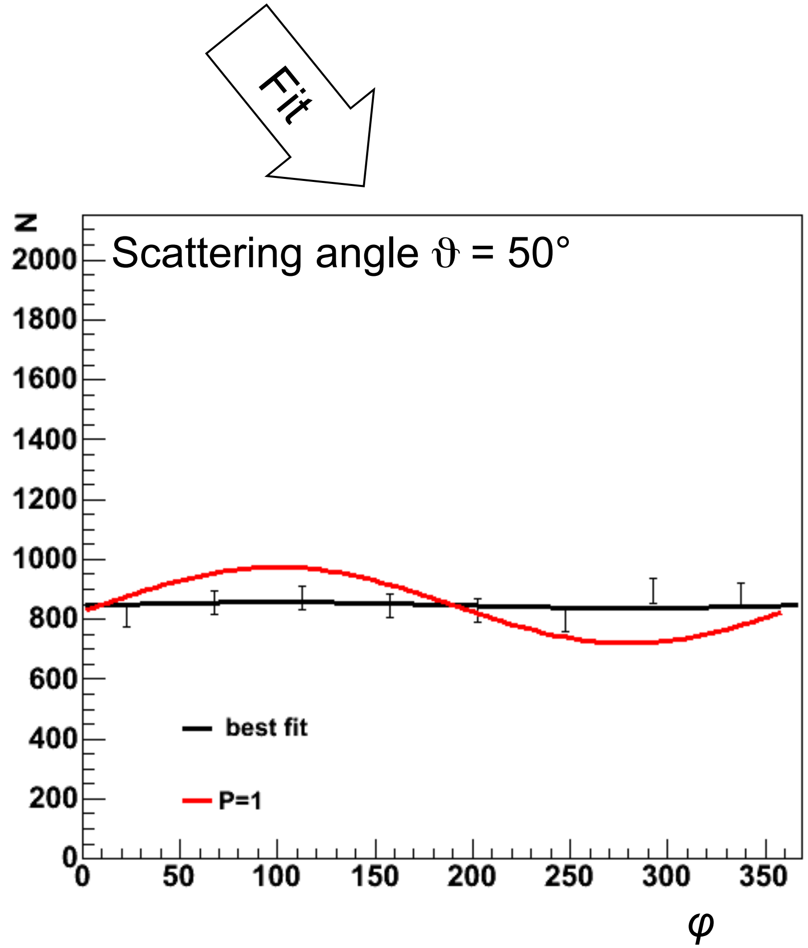
* *average over 10 shots*

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

Proton polarization: angular distribution



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

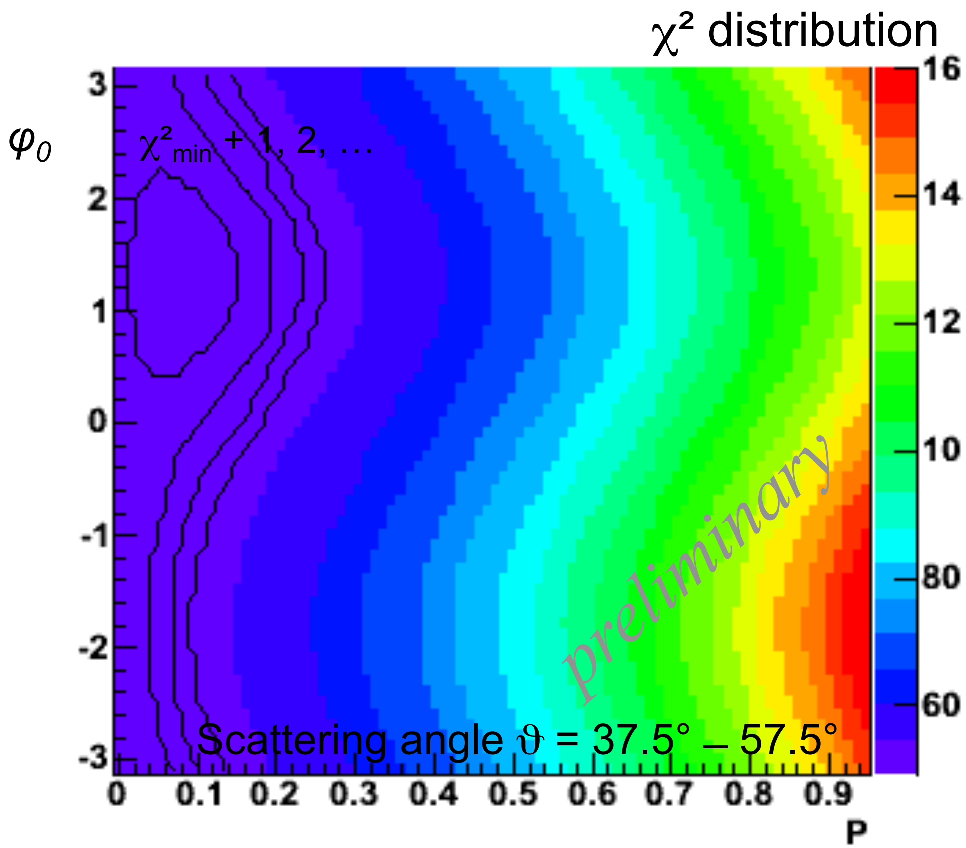


Laser incidence angle:
Φ = 90°, Θ = 45°

Proton emission angle:
Φ = 180°, Θ = 8°

Relative to production target normal

Proton polarization: first result



$P \approx 0.08 \pm 0.08_{stat,2\sigma} \pm 0.08_{syst}$

→ *no polarization build-up*

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

2) Polarization is preserved

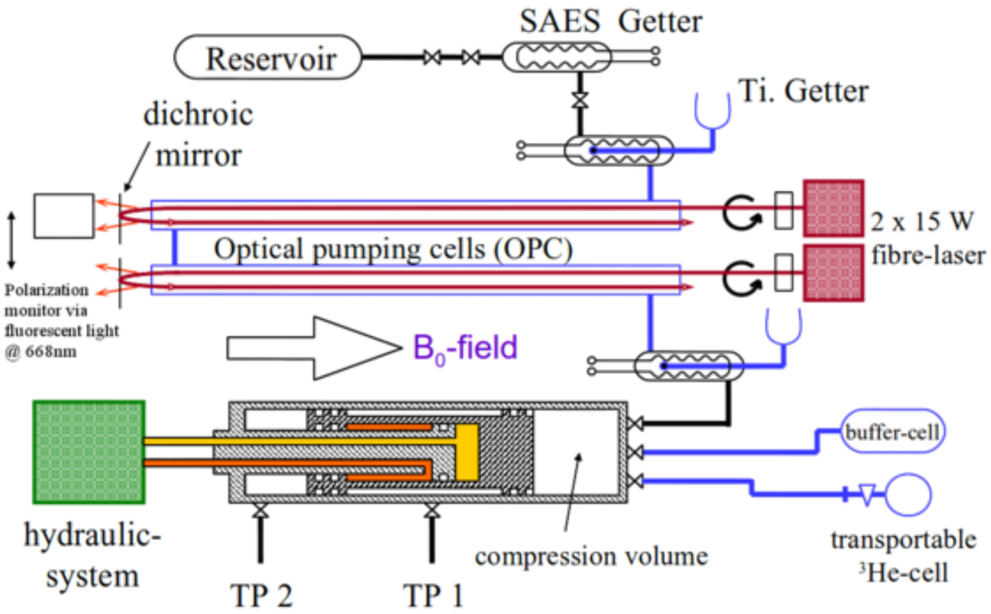
Spin direction is invariant in strong laser & plasma fields

→ polarized ^{3}He gas

Scenario #2: Polarized ^{3}He

Stable (days) nuclear polarization @ room temperature

Available from Univ. Mainz



Production

Transport

Polarized ^{3}He: Applications

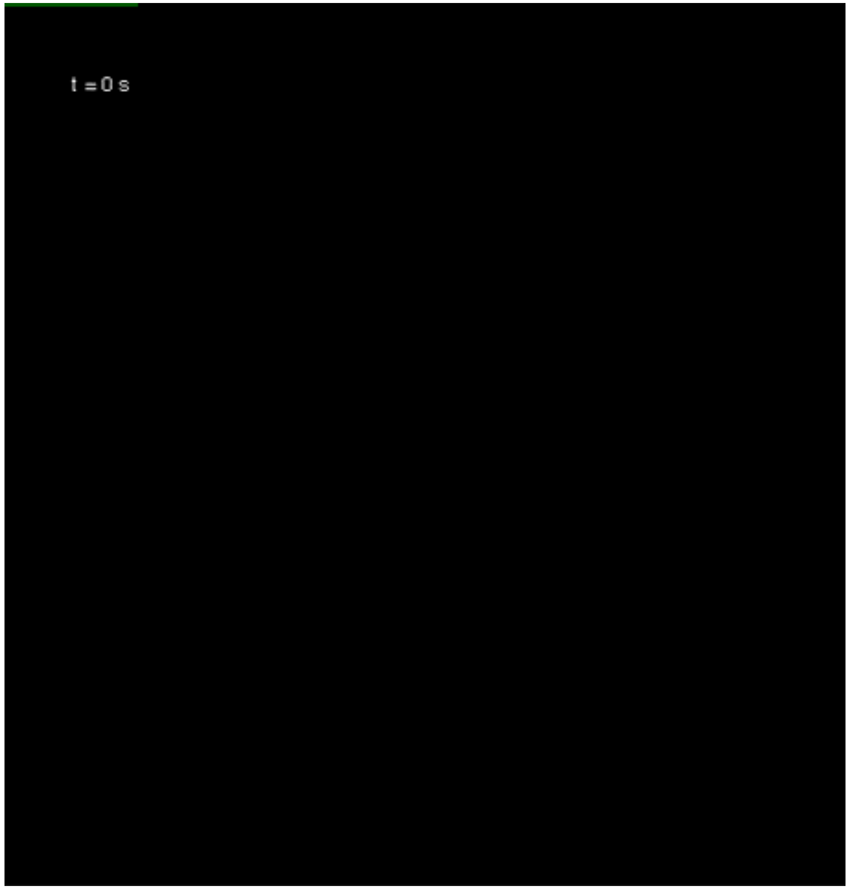
MRI of the lung

^{1}H-MRI of the chest. The black area is the lung, which hardly gives a signal.

Lung after inhalation of HP-^{3}He. Now only the lung is visible.

Polarized ^{3}He: Applications

Healthy



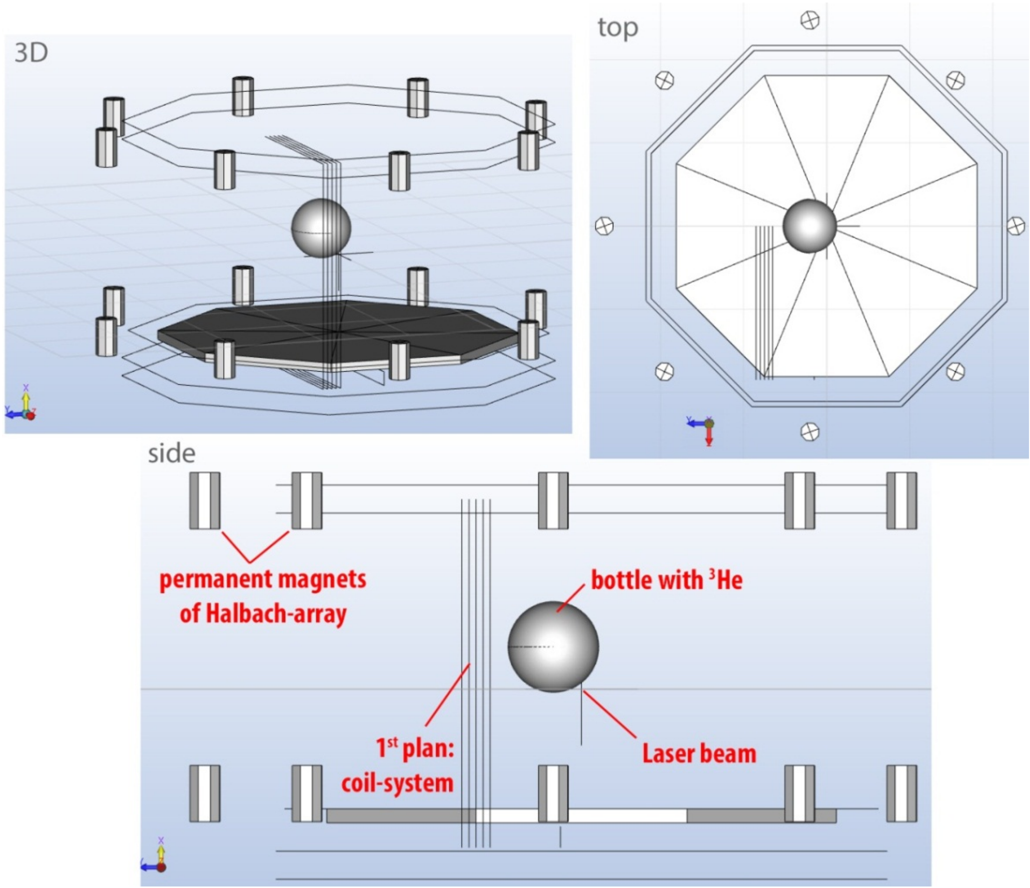
COPD patient

http://www.airprom.european-lung-foundation.org/16590-results.htm

Polarized ^{3}He: Magnetic holding fields

Halbach array of permanent magnets

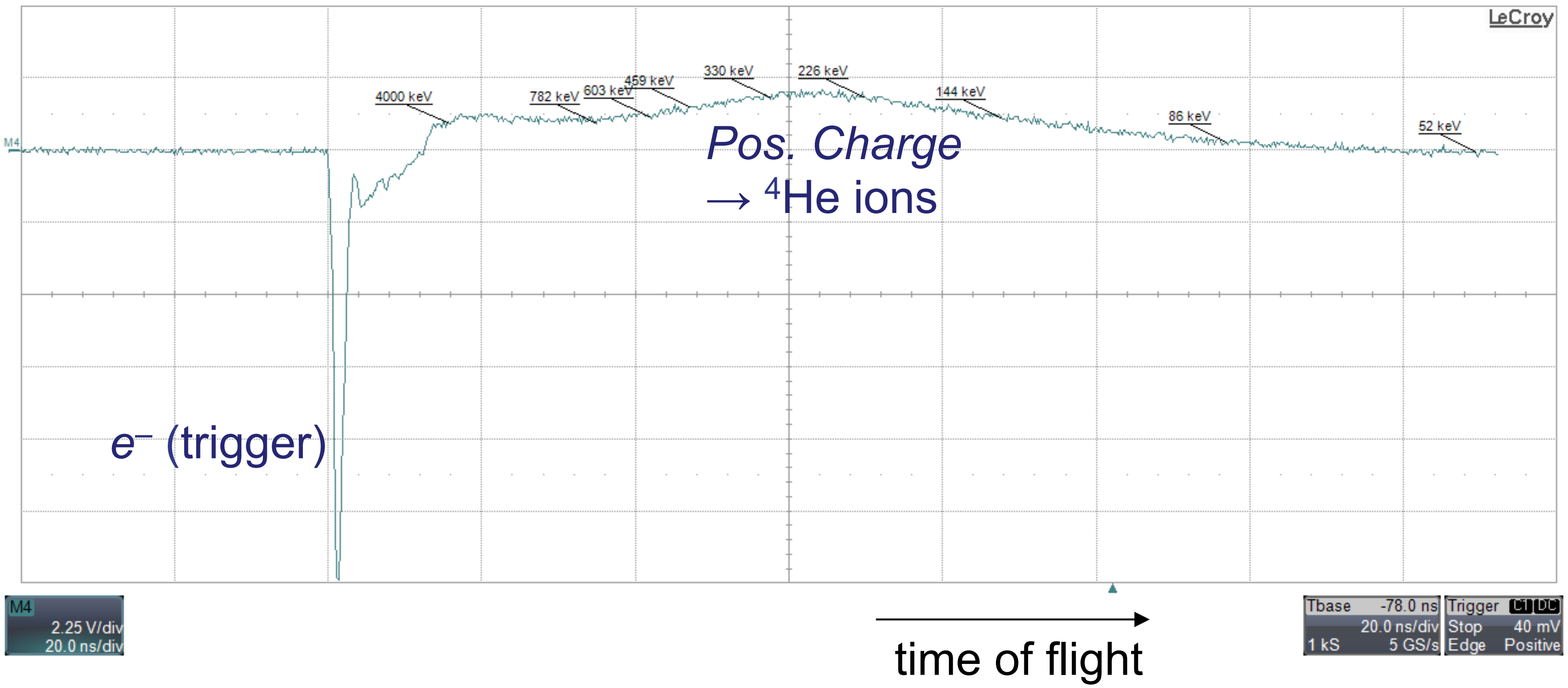
Homogeneous field at target location



Polarized ^{3}He: Ion acceleration in gas target

Data: ARCturus / Düsseldorf Univ. / Jan. 2013

Measured with Faraday cup



CPA: Pulse shape

ARCturus / Düsseldorf Univ.

$I_0 \approx 10^{20}$ W/cm²