JÜLICH
FORSCHUNGSZENTRUM

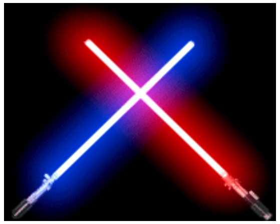
Polarized Ion Beams Generated by Means of Laser-Induced Plasmas

October 02, 2013

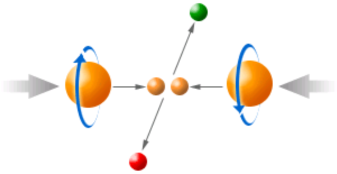
A. Holler, M. Büscher, P. Burgmer and I. Engin

HEINRICH HEINE
UNIVERSITÄT
DÜSSELDORF

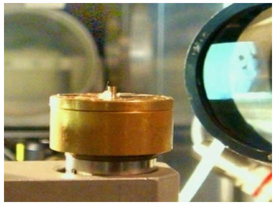
Outline



Short Excursion in Laser-Plasma Acceleration



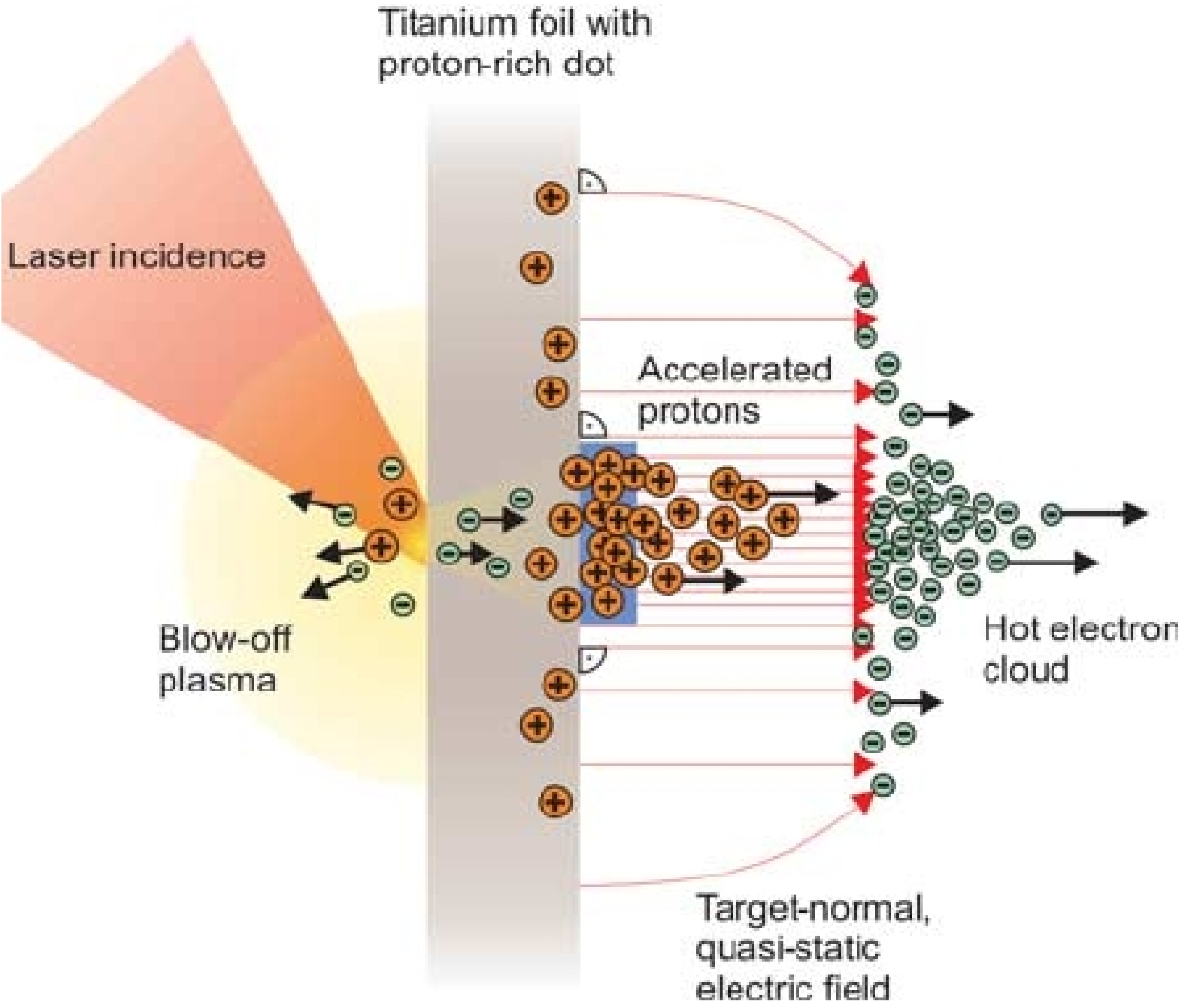
Spin Polarization Induced by a Laser Interaction

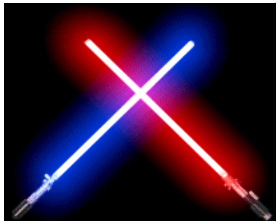


Planned Experiment

Mile Stones on the Way to a Polarized Ion Source

Mechanism of Laser Acceleration





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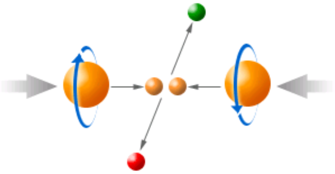

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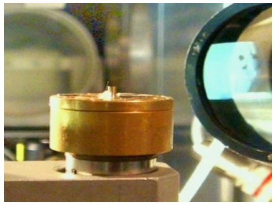
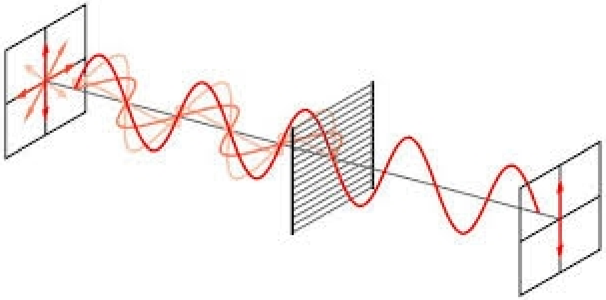


Planned Experiment

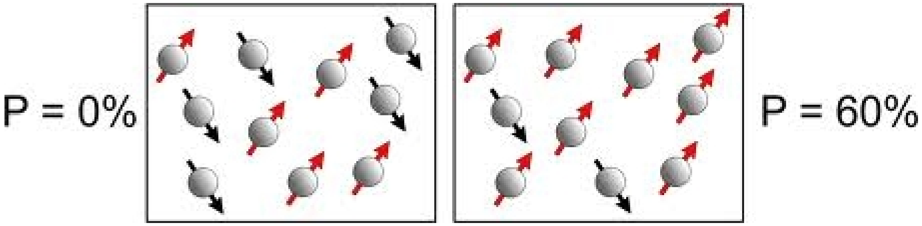
Mile Stones on the Way to a Polarized Ion Source

Polarization

Laser-Plasma Physics:

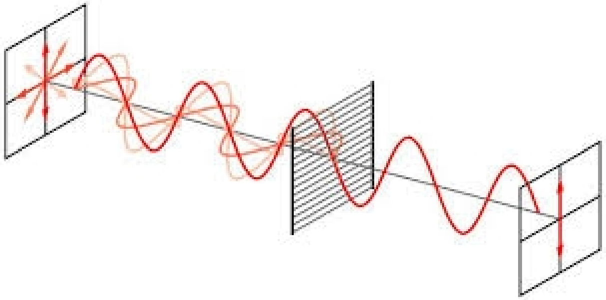


Nuclear Physics:



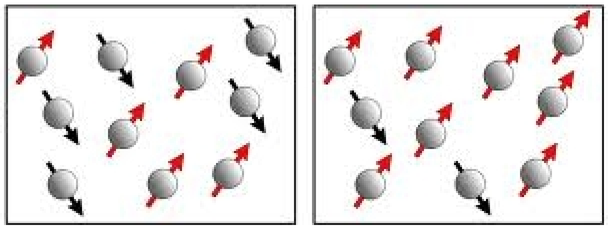
Polarization

Laser-Plasma Physics:



Nuclear Physics:

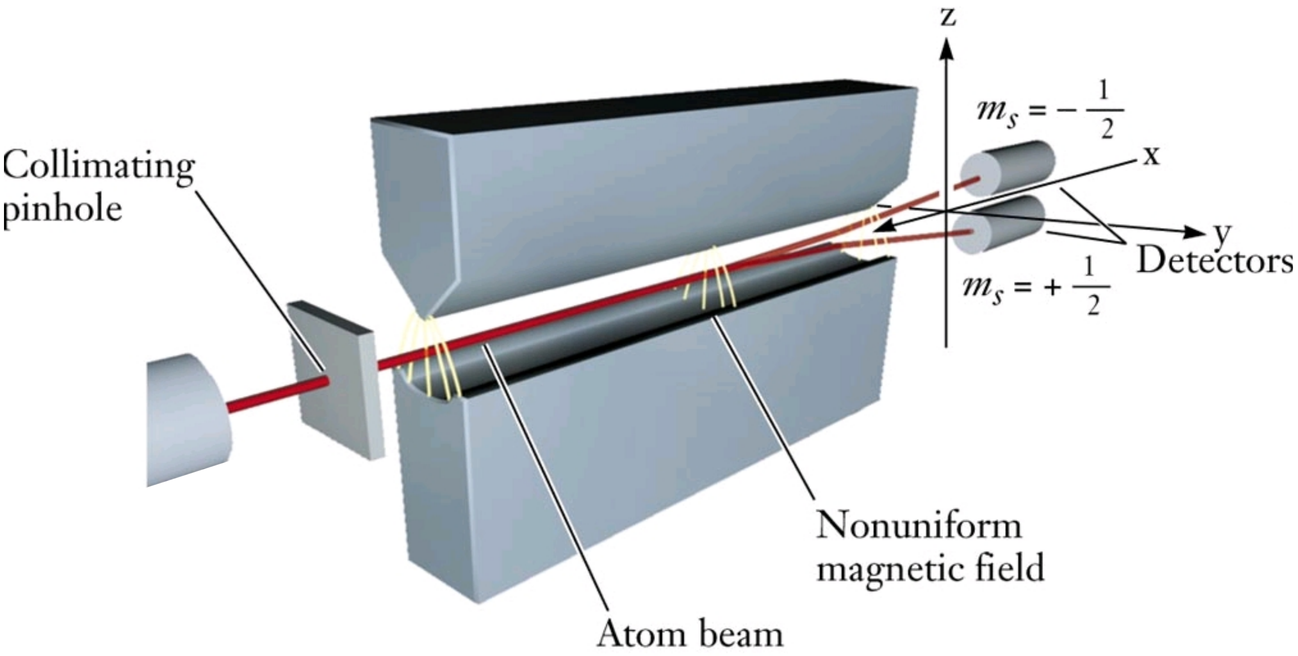
P = 0%



P = 60%

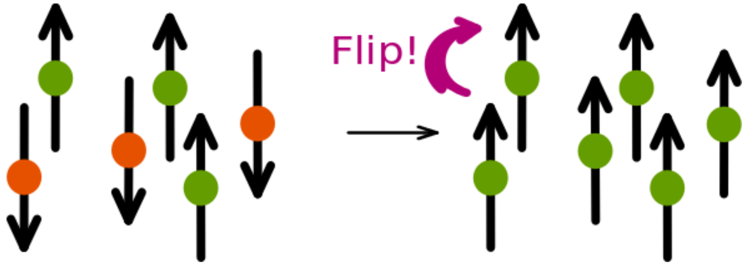
Spin Polarization

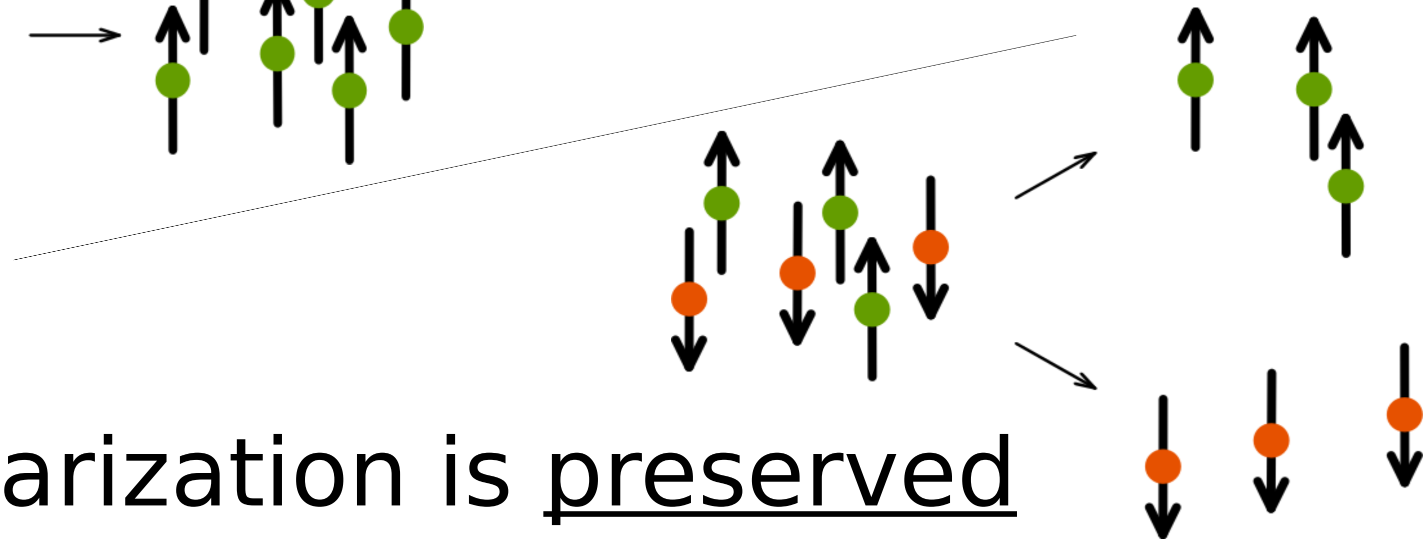
$S = 1/2$



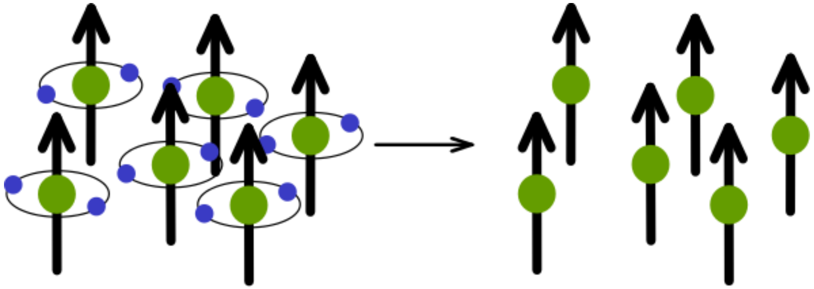
Polarized Ions: Possible Scenarios

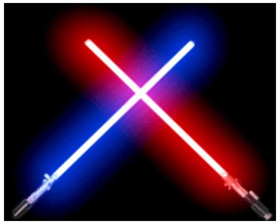
1) Polarization is <u>generated</u>





2) Polarization is <u>preserved</u>





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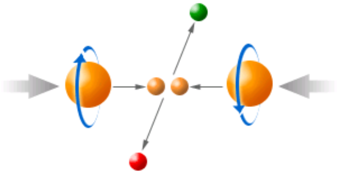
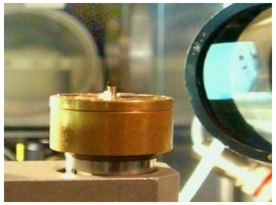


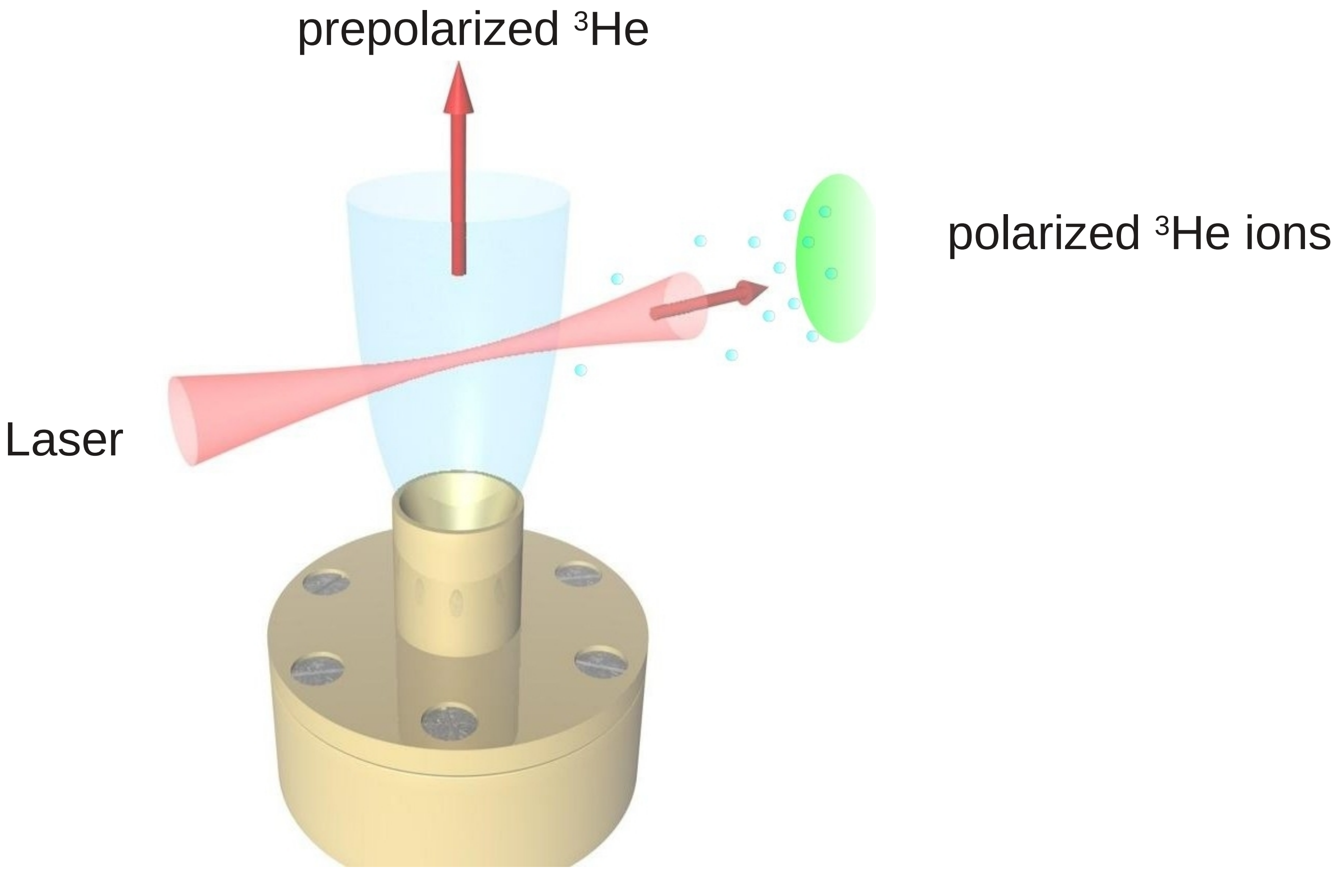
Spin Polarization Induced by a Laser Interaction

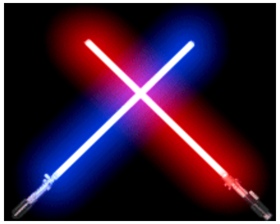


Planned Experiment

Mile Stones on the Way to a Polarized Ion Source

Planed Experiment





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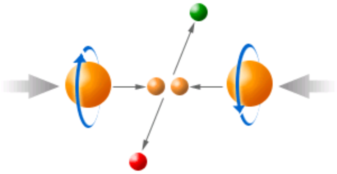

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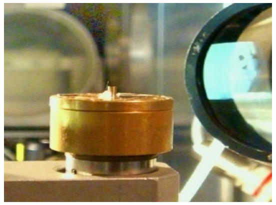
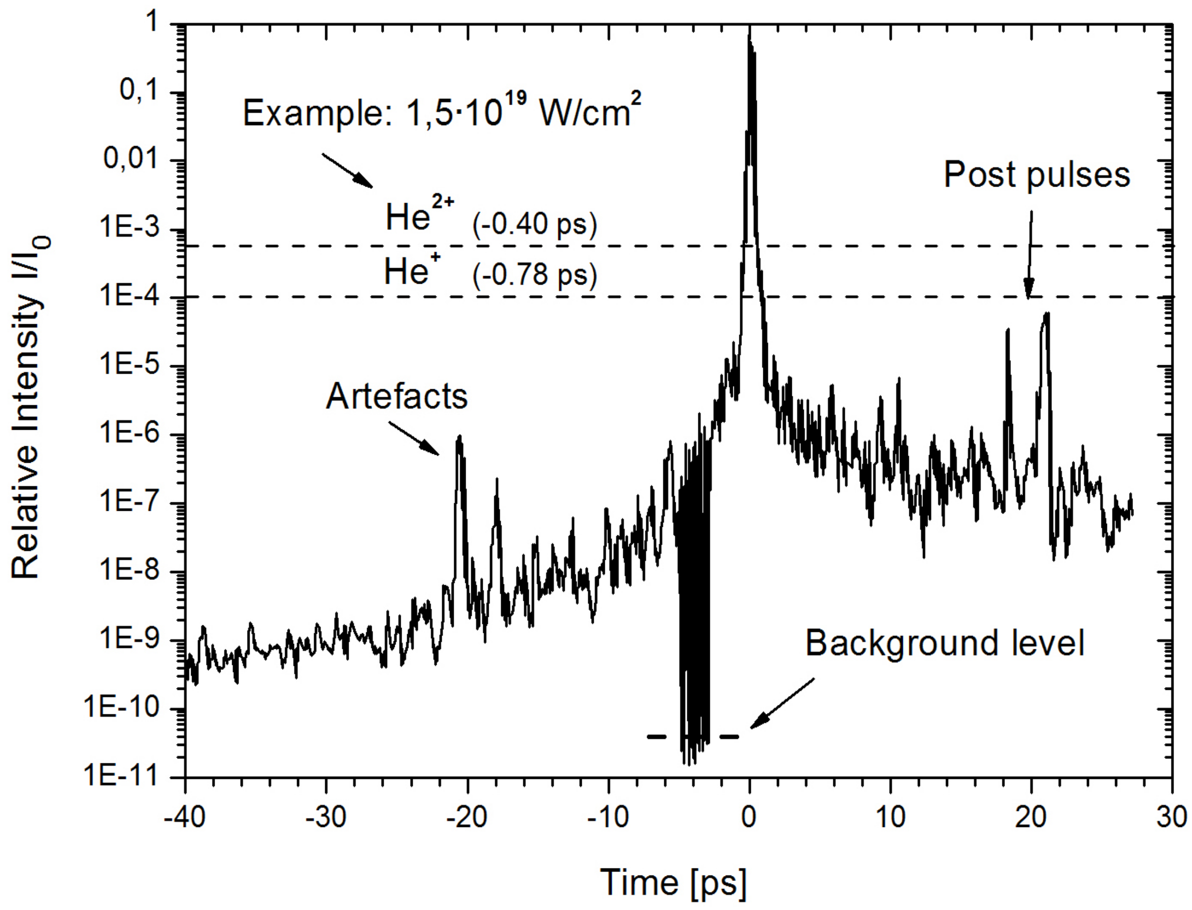


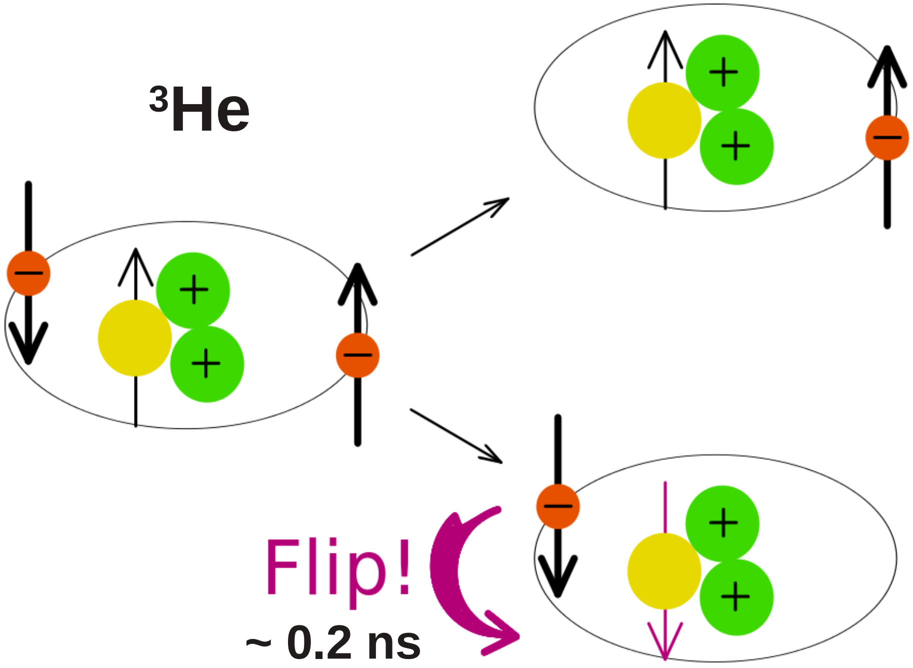
Planned Experiment

Mile Stones on the Way to a Polarized Ion Source

Ionization with a Pulsed Laser



Will the Polarization be Preserved?



^{3}He

Flip!

~ 0.2 ns

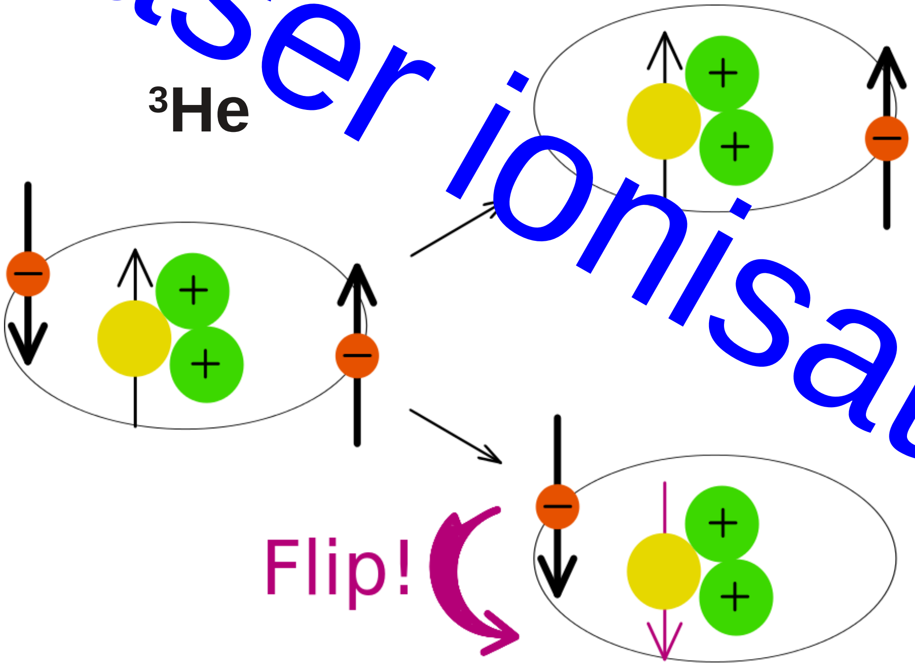
50 %

Polarization is gone!

50 %

1st Ionization

Fast Ionization



50 %

Polarization is gone!

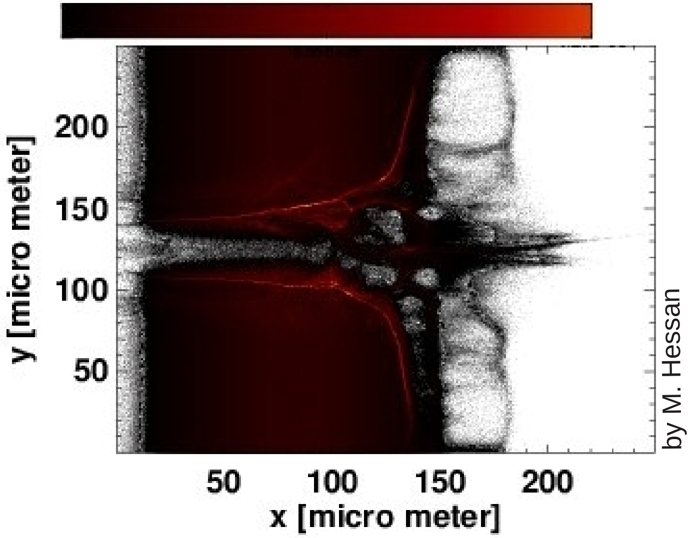
50 %

~ 0.2 ns **1st Ionization**

Laser ionisation is faster

Is it Possible to Generate Ions from a Gas Jet?

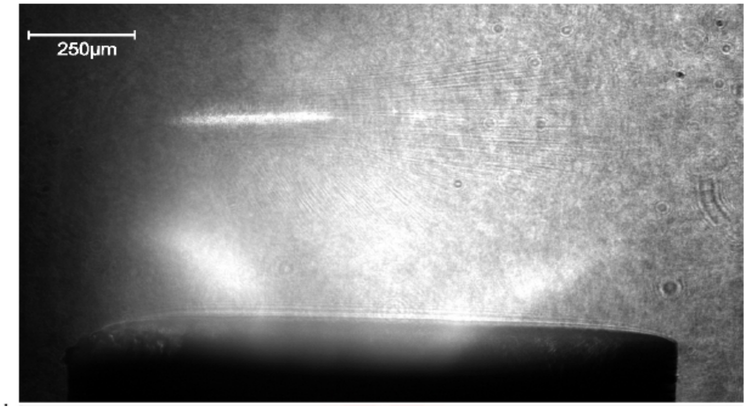
Ion density of ^{4}He

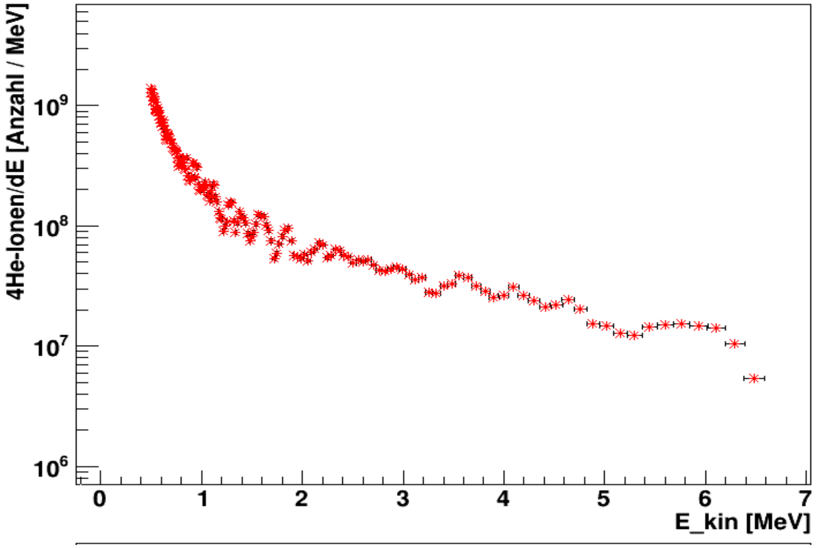


by M. Hessan

Simulation on JUROPA , JSC (P. Gibbon) with EPOCH ✓

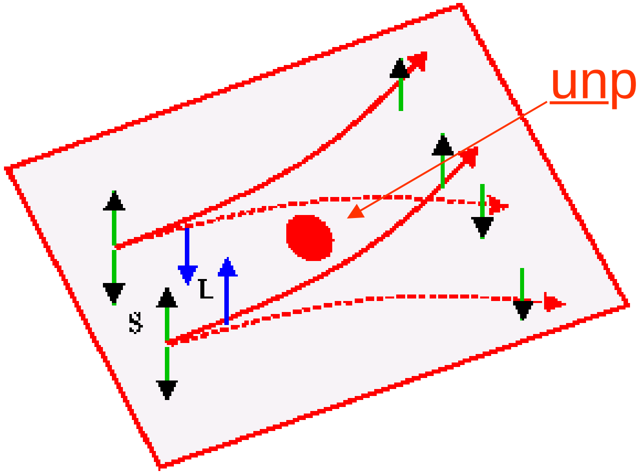
and Experiment with ^{4}He at Arcturus ✓





How to Measure Polarization?

Nuclear scattering with known analyzing powers



unpolarized nucleus

Scattering of a Polarized Beam

Simplest case: beam particle with spin ½ on unpolarized target

$$\frac{d\sigma}{d\Omega}(E,\theta,\phi)=\left.\frac{d\sigma}{d\Omega}\right|_{\text{unpol}}(E,\theta)\left[1+A\cdot P\cdot\cos\phi\right]$$

Cross section
(unpolarized!)

Analyzing power

$A(E, \theta, \text{target}, \ldots)$
$-1 \leq A \leq +1$

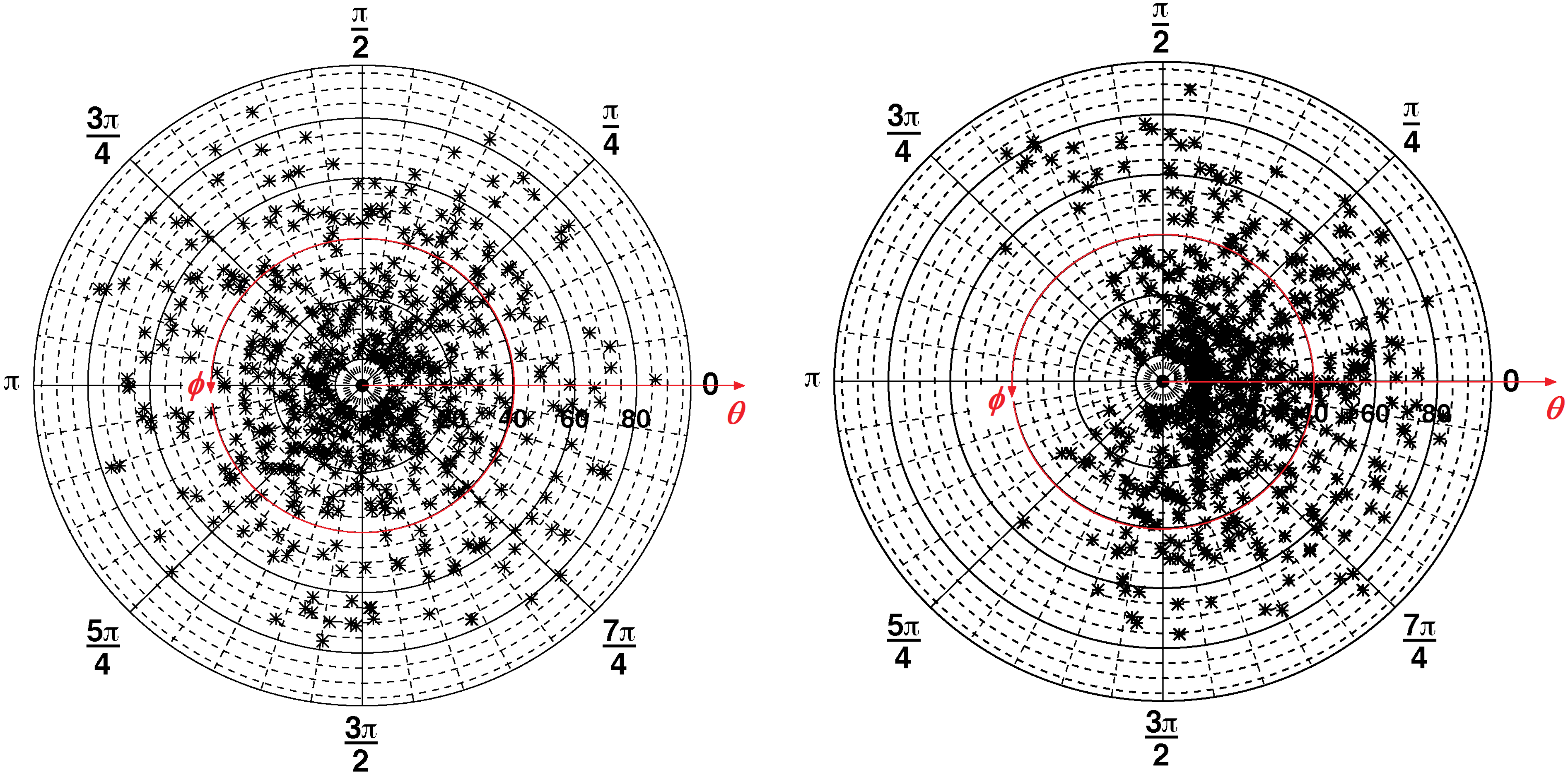
Beam polarization

P
$-1 \leq P \leq 1$

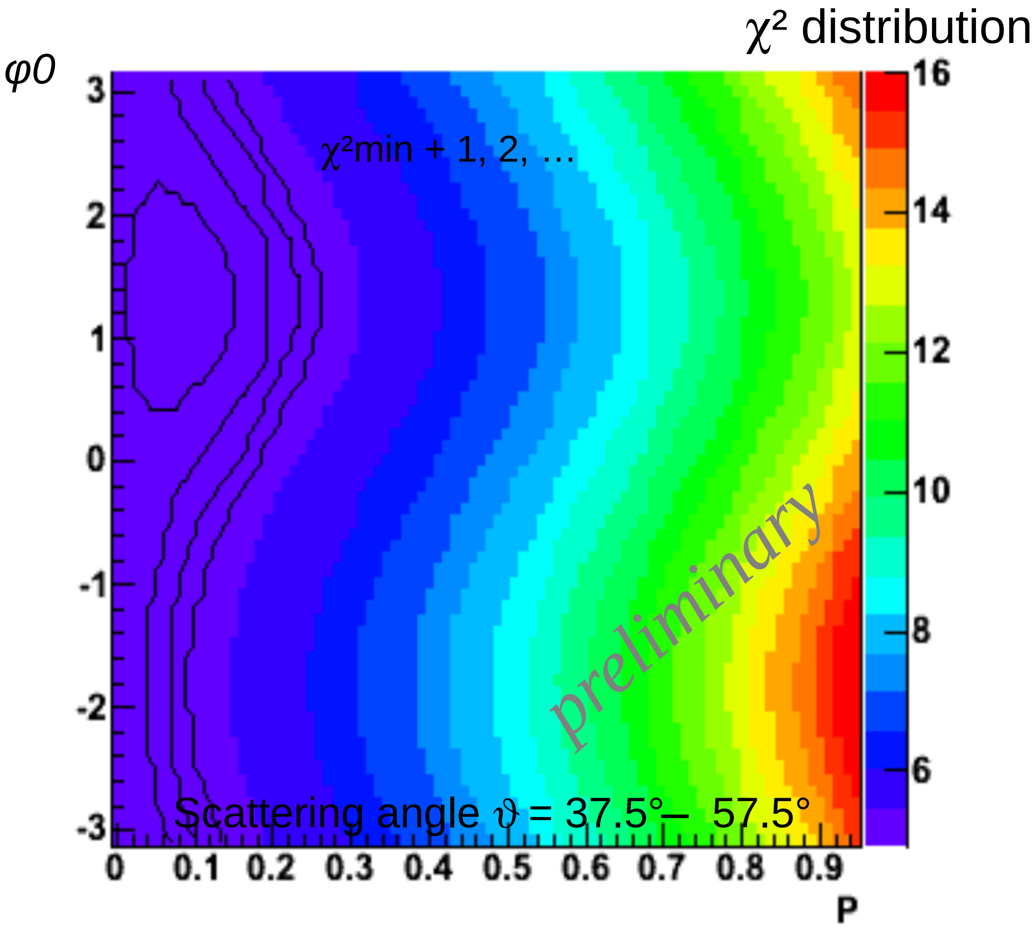
Scattering of a Polarized Beam

Simulation for

P = 0 or A = 0 *P* = 1 and A = 1



Proton polarization: first result



$P \approx 0.08 \pm 0.08$ stat, $2\sigma \pm 0.08$ syst

Conclusion

Laser-plasma induced acceleration might be a good way to produce polarized ions

Challenges on the way to the polarized ion source are solved

Next step: Doing the experiment!

Mitglied der Helmholtz-Gemeinschaft

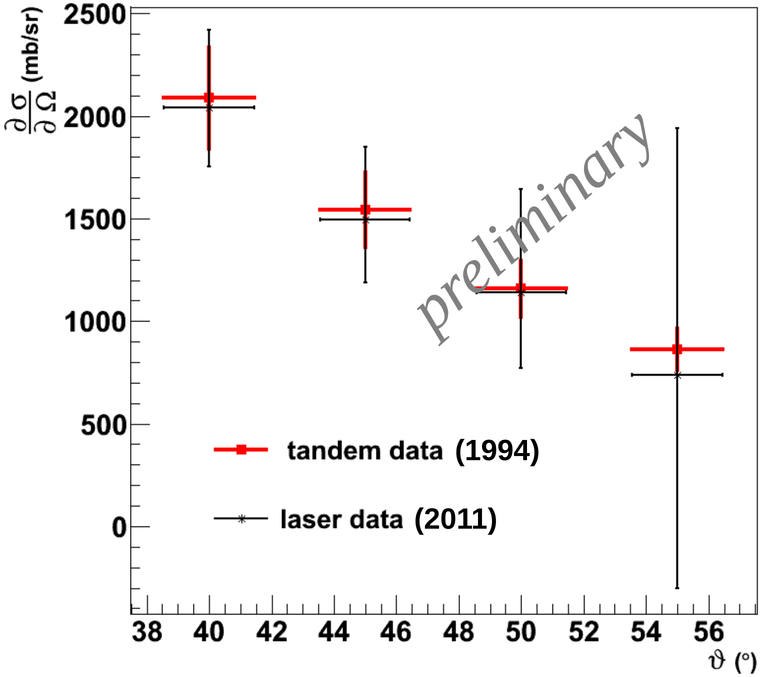
Thank you!

Scattering-angle distribution

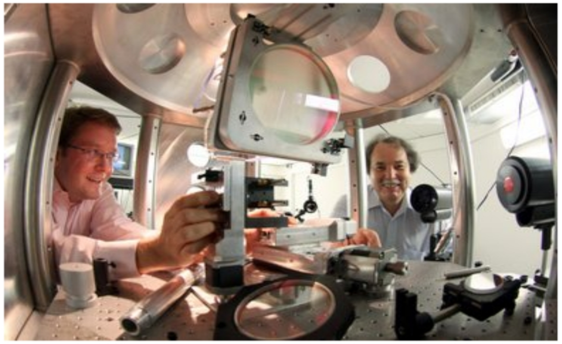
Si(*p*, *p*')Si, *Tp* = (3.2±0.2) MeV

Cologne tandem accelerator

Measurement time: ***O*(days)**



ARCturus laser



Measurement time: ***O*(100 fs)**

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

** average over 10 shots*

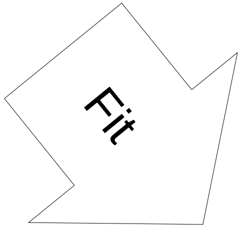
Measurement of Polarization

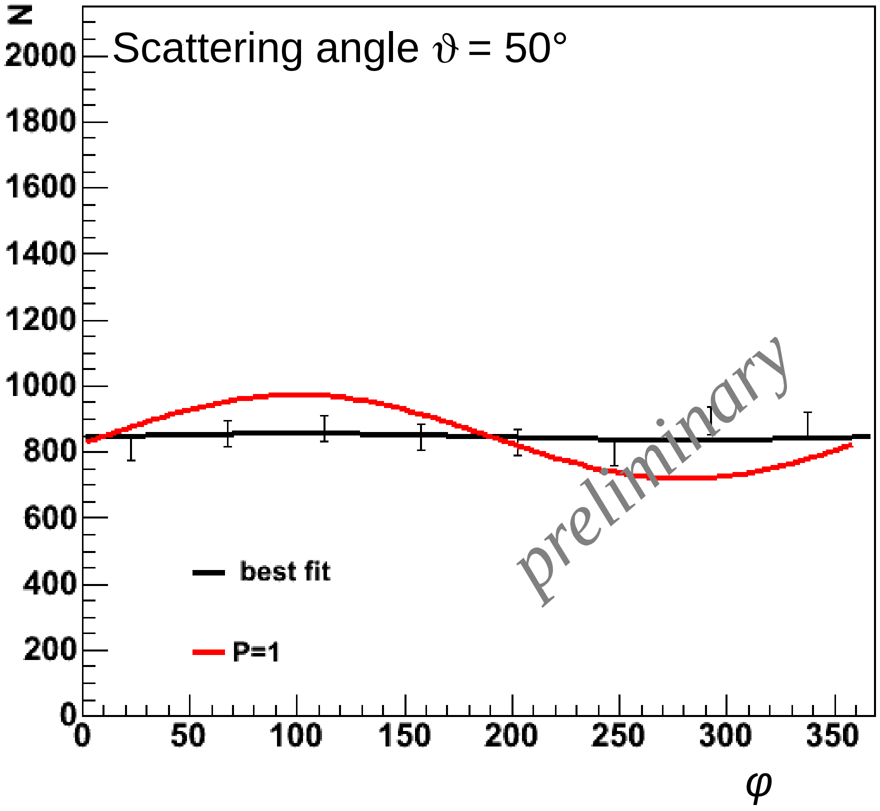
Laser incidence angle:
Φ = 90°, Θ = 45°

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

Relative to production target normal

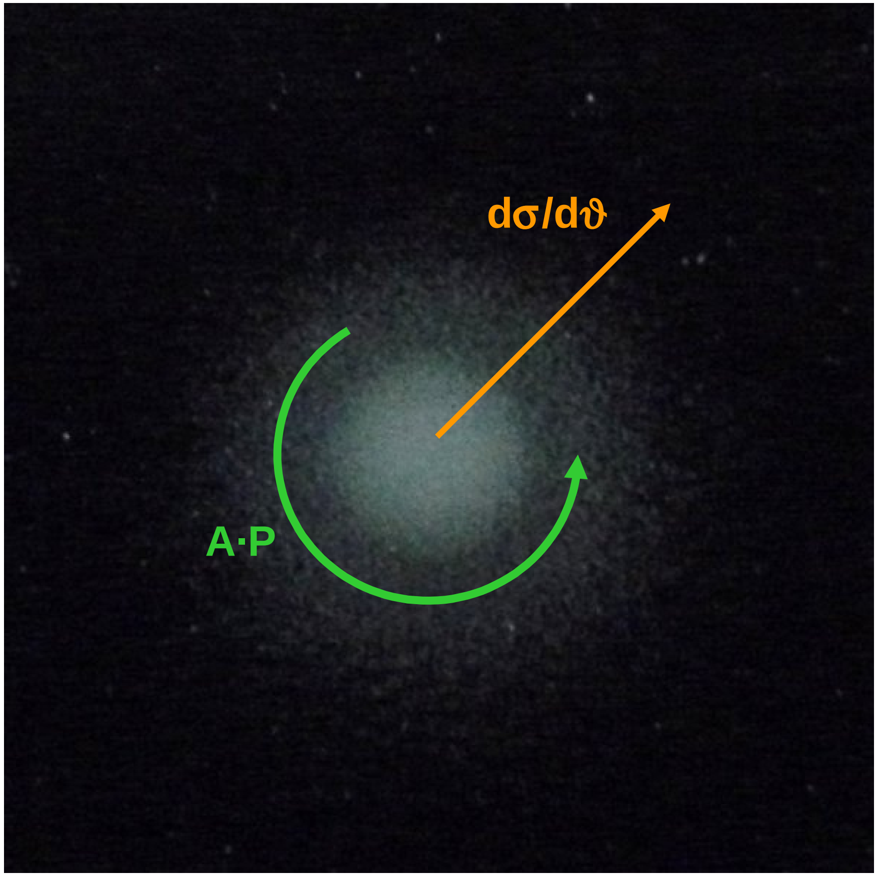
$$\frac{d\sigma}{d\Omega}(E,\vartheta,\varphi) \propto [1 + A \cdot P \cdot \cos(\varphi - \varphi_0)]$$

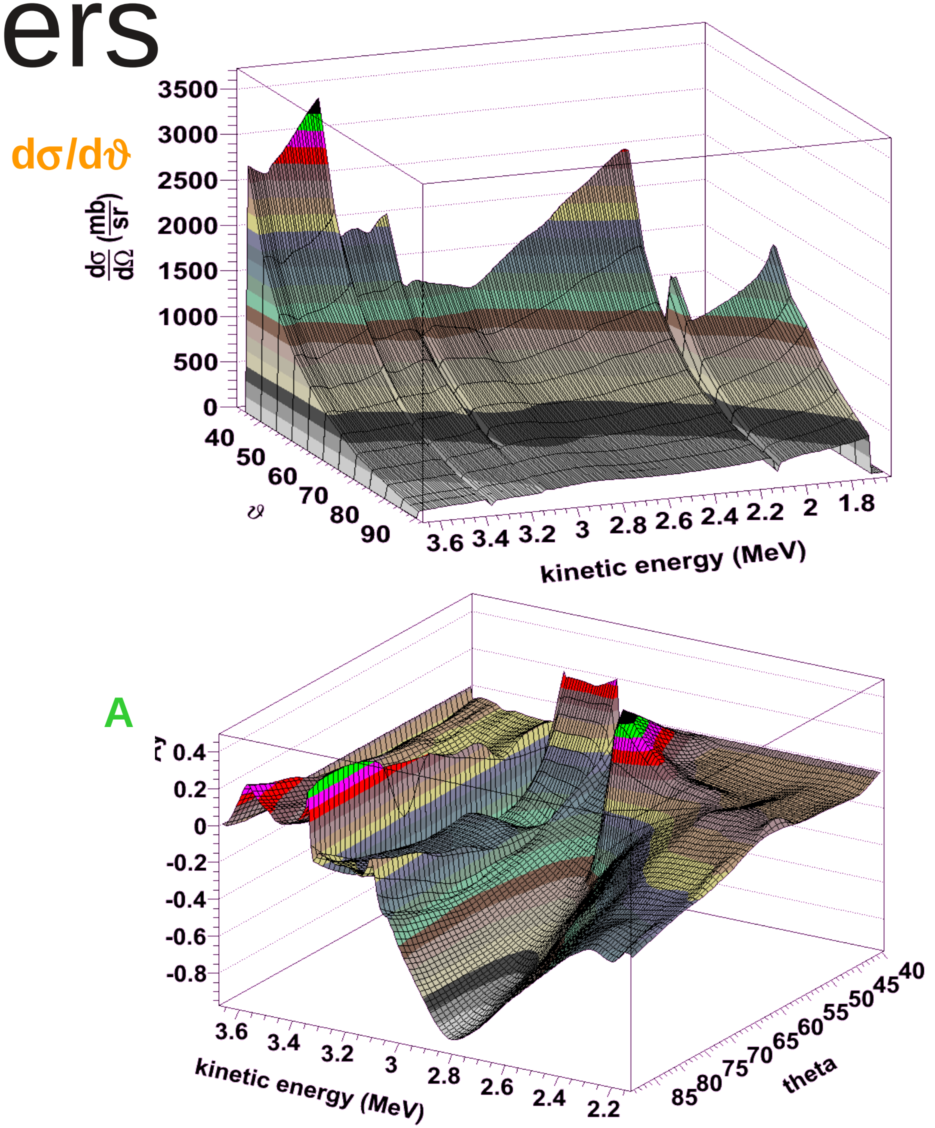




Cross sections & analyzing powers

Example: Si(*p*, *p*‘)Si

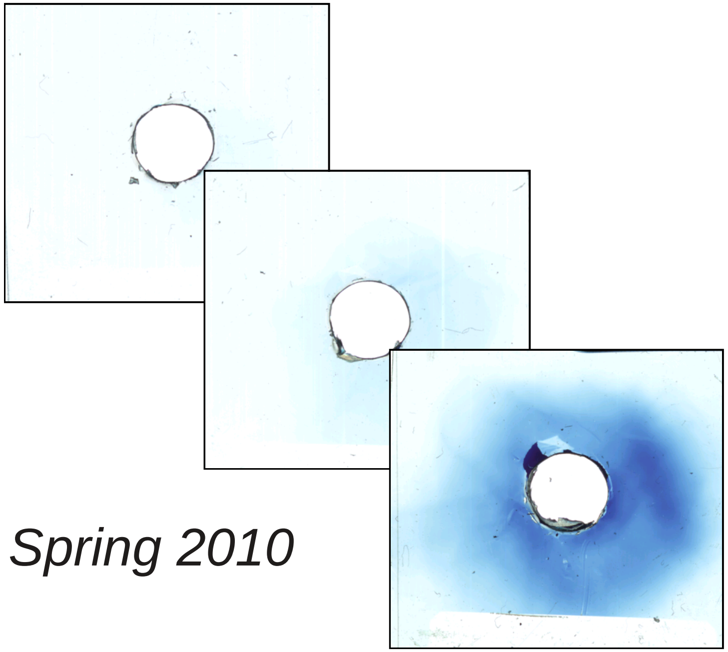




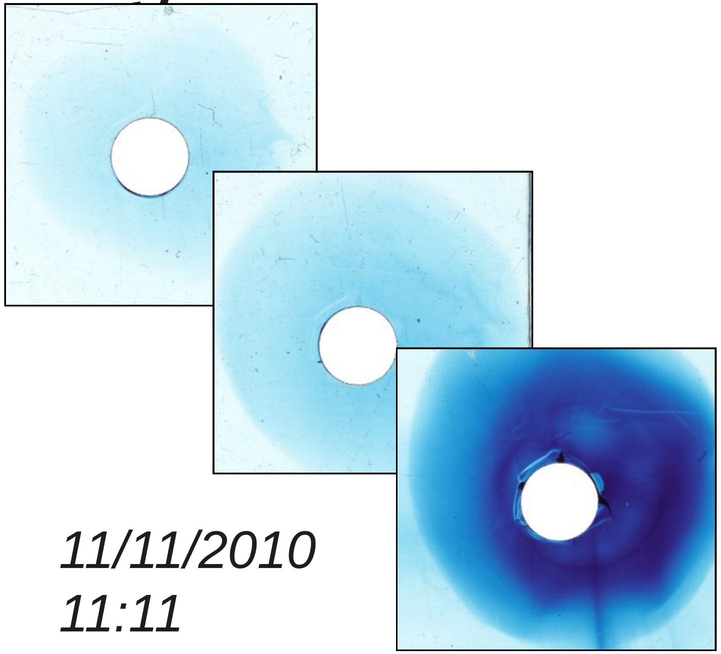
B.Becker, Universität zu Köln (1994)

Angular distribution on rate monitor

Fall 2010: data with ~10 times higher statistics



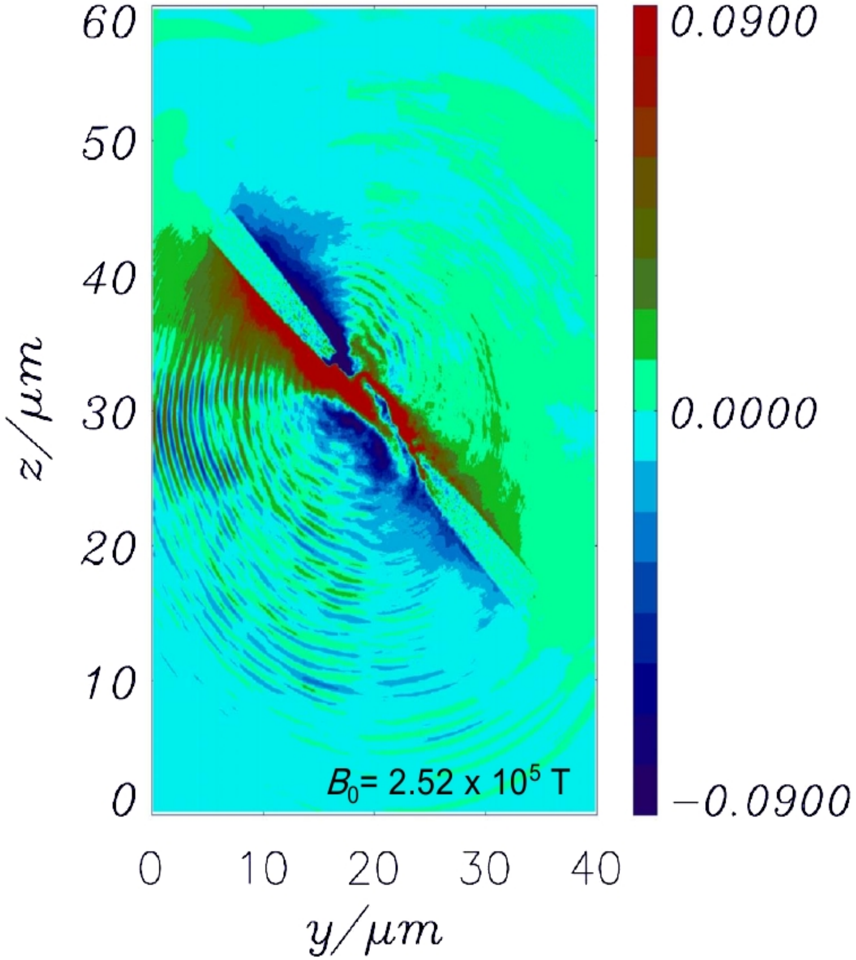
Spring 2010

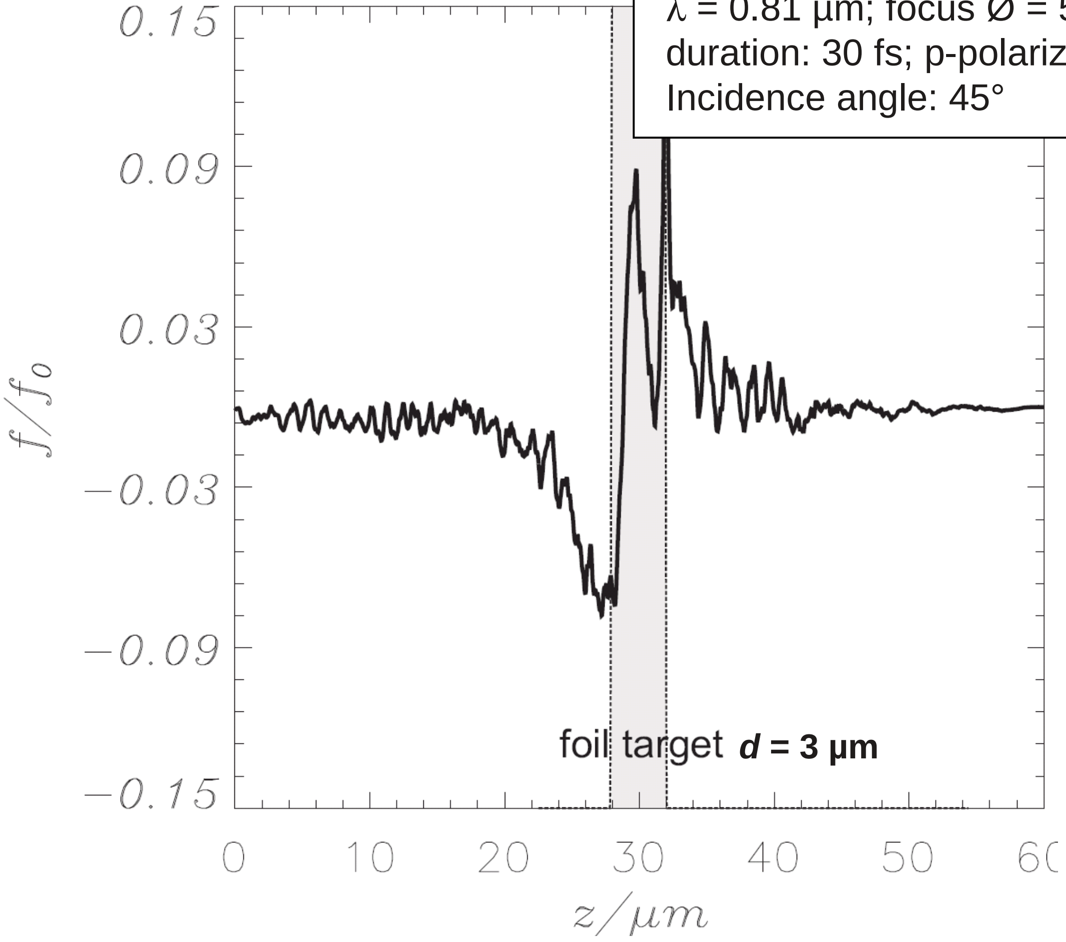


11/11/2010
11:11

Strong magnetic fields (simulation)

B field distribution 140 fs after laser hits foil target





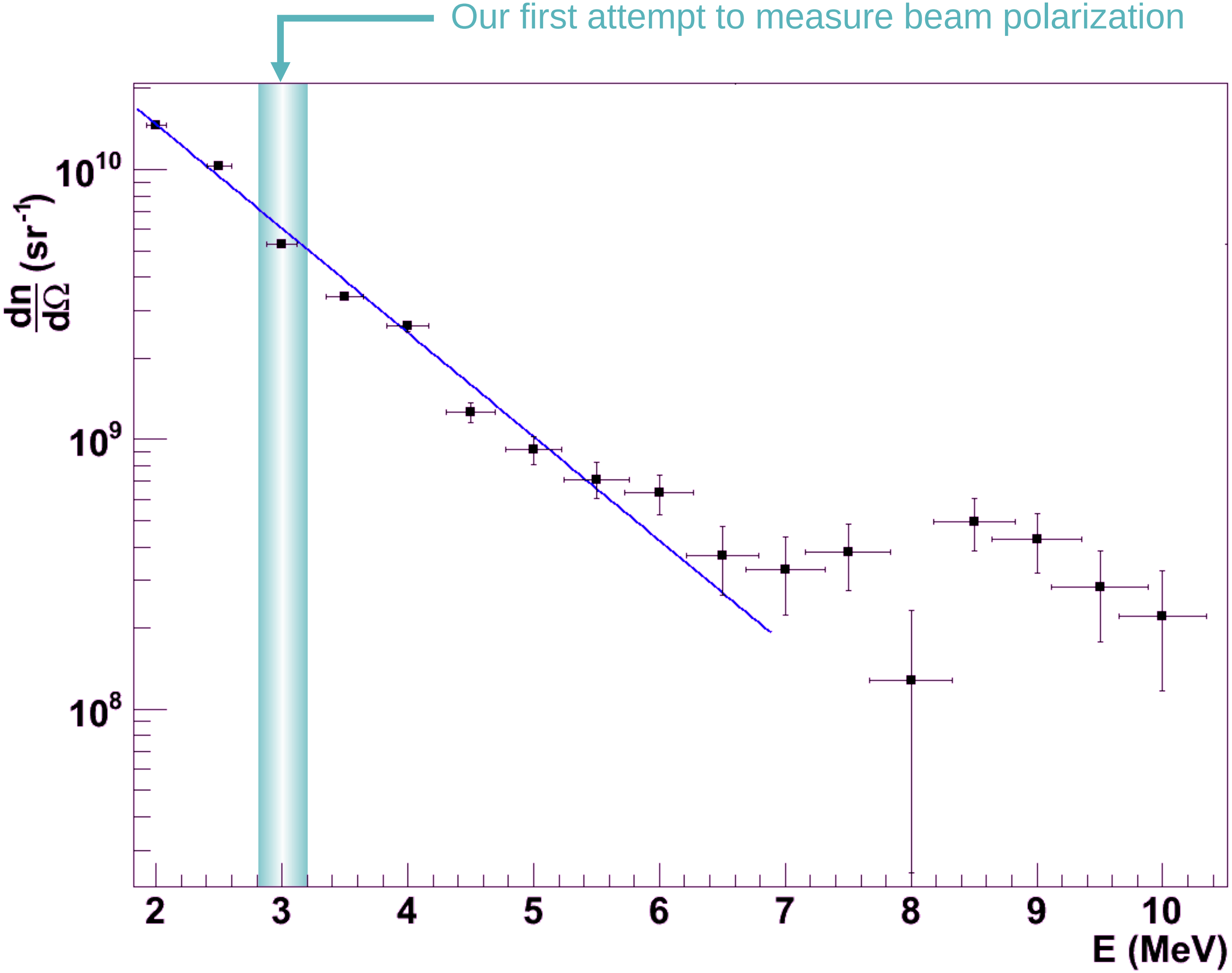
5 · 10^{20} W/cm²
λ = 0.81 μm; focus Ø = 5 μm
duration: 30 fs; p-polarized
Incidence angle: 45°

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

Simulations: A.Karmakar, P.Gibbon (JSC, FZJ)

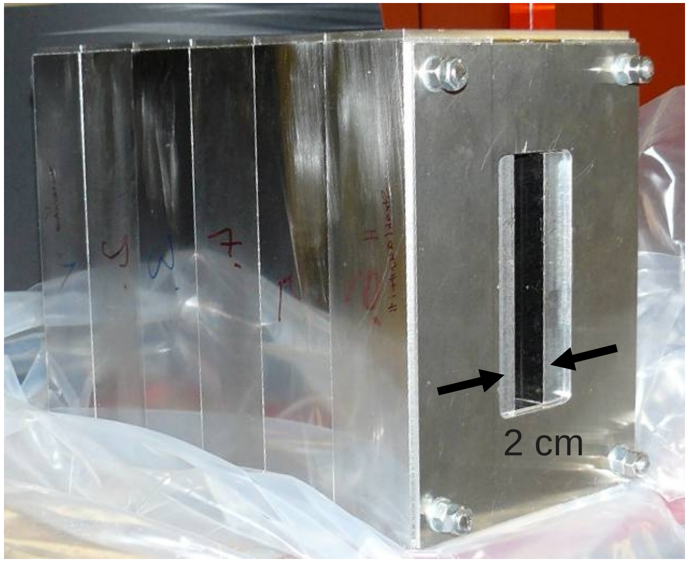
Proton energy spectrum from foil targets

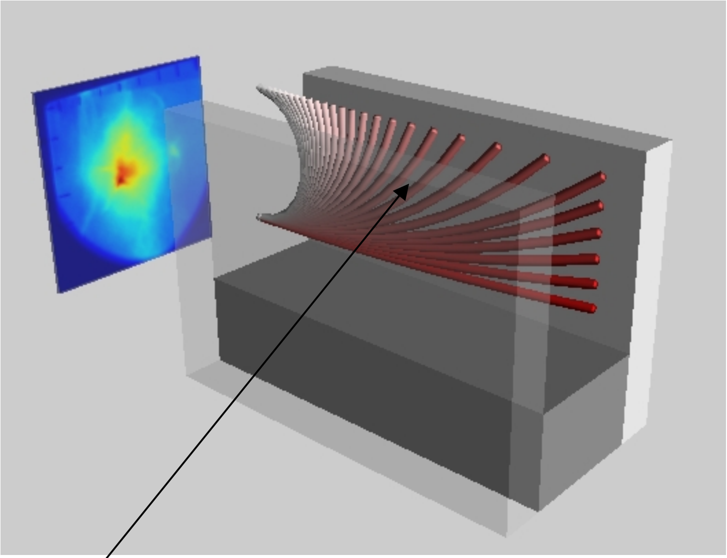
Our first attempt to measure beam polarization

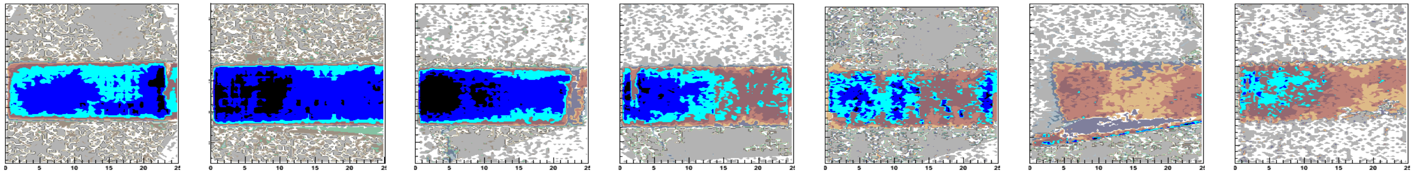


Measurement of proton momenta

Permanent dipole magnet, $B = 0.5$ T



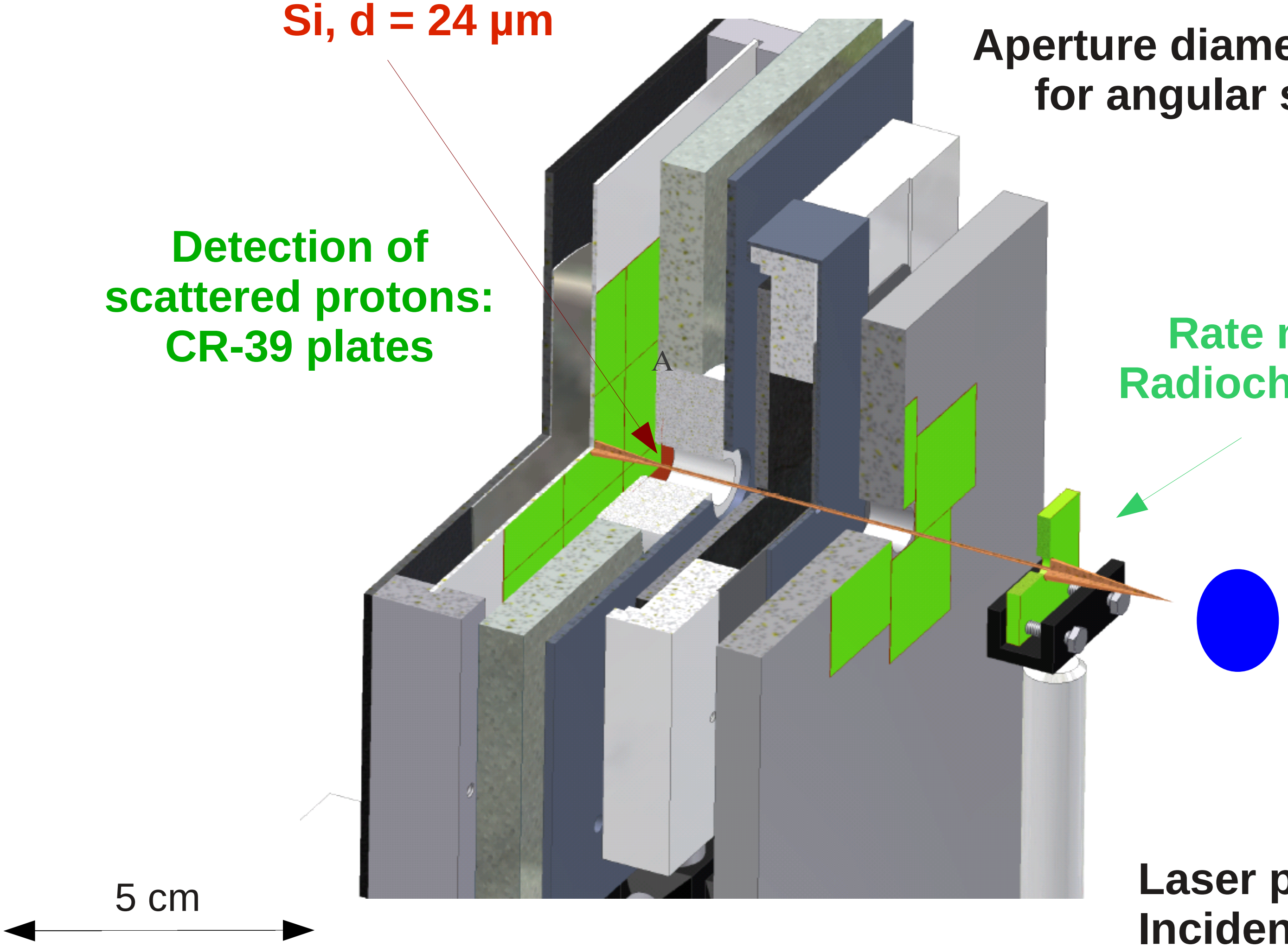




CR-39 plates

proton momentum

Polarization measurement: setup



Secondary scattering target
Si, d = 24 µm

Aperture diameters = 1 mm
for angular selection

Detection of
scattered protons:
CR-39 plates

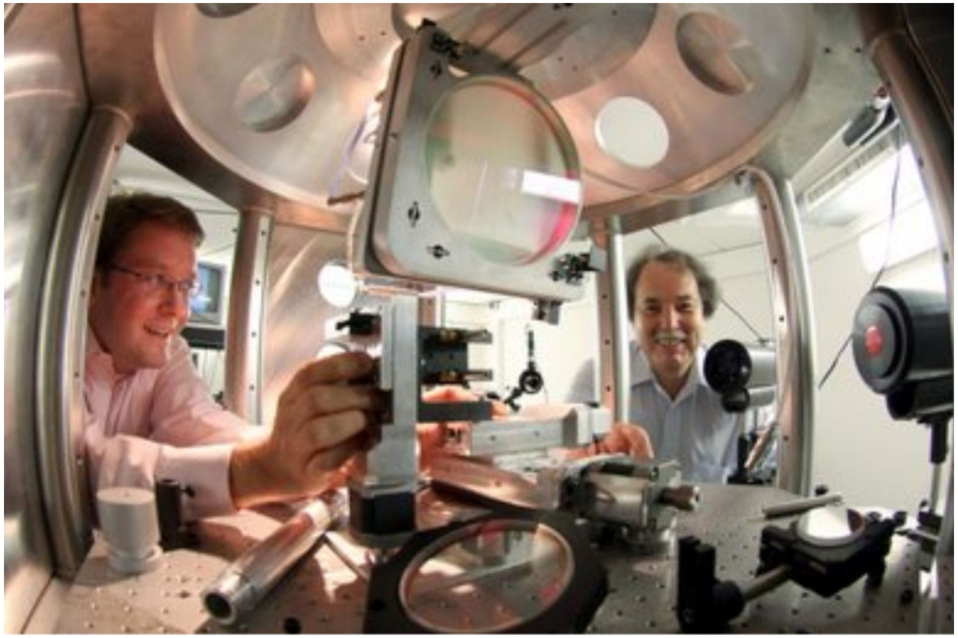
Rate monitor:
Radiochromic film

Production Target
Gold, d = 3 µm

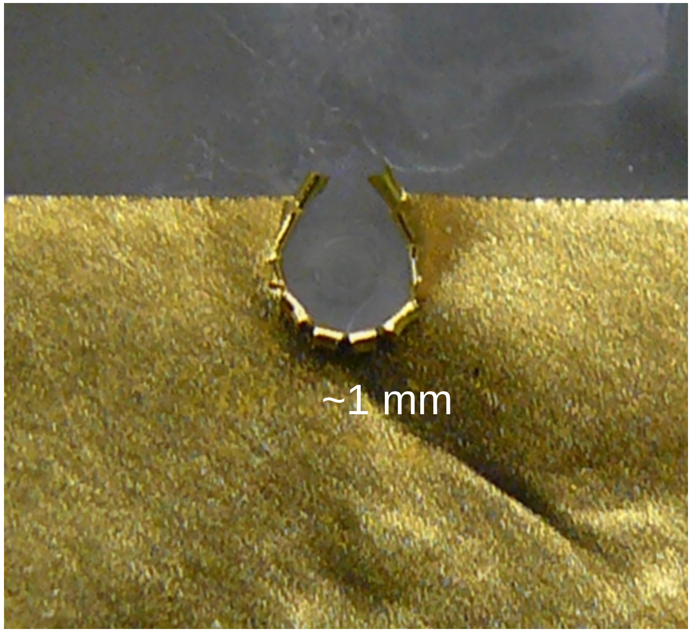
Laser pulse: 1.2 J, 40 fs
Incidence angle: 45°

Foil targets

First measurements / Spring 2010



R.Jung & O.Willi at the target chamber

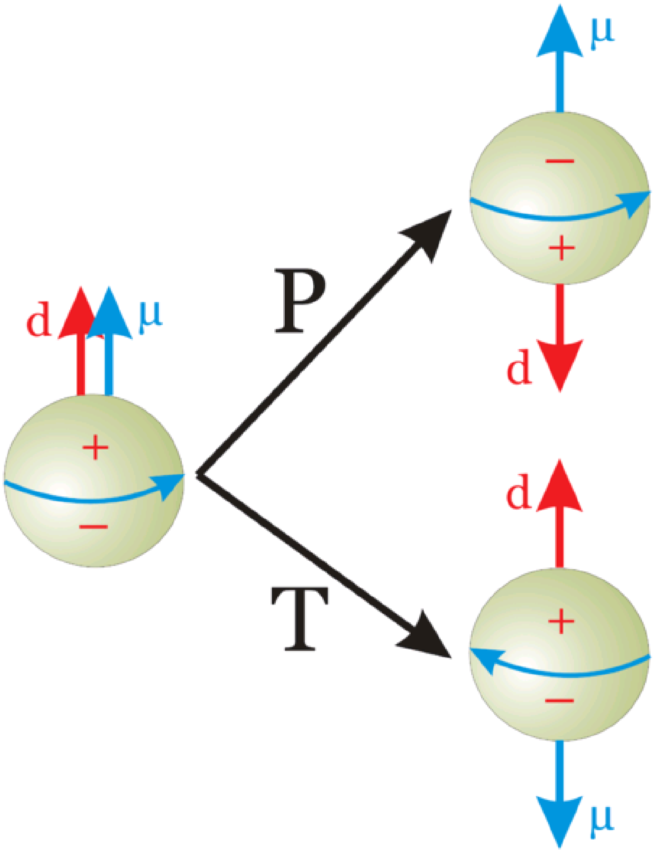


Gold foil

typical thickness 3 µm

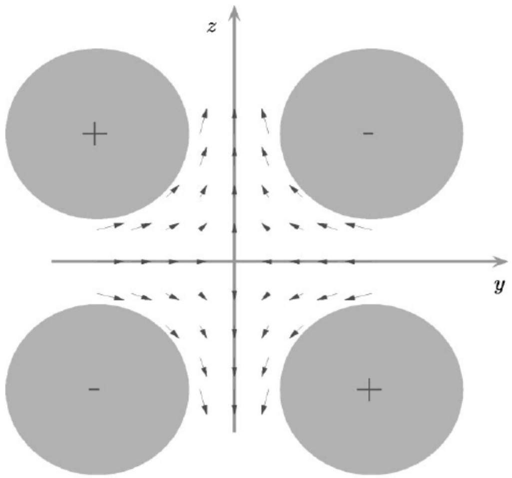
Polarization: Why and how?

Currently no sources for polarized ^{3}He ions



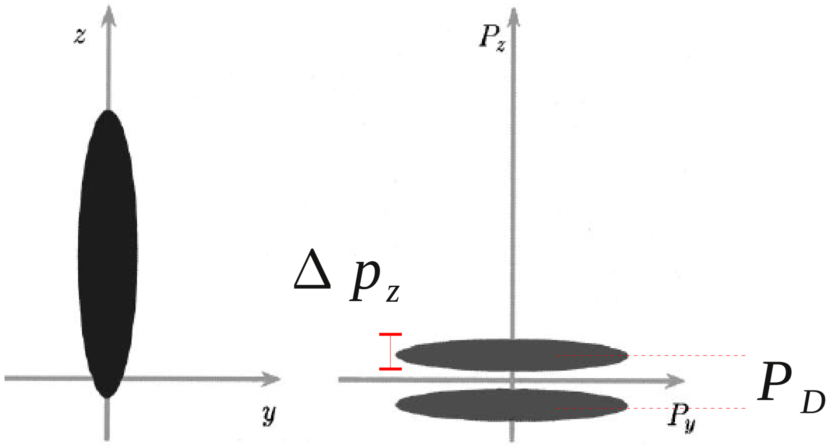
e.g. Search for nuclear EDMs

Stern Gerlach – Momentum space



$$\Delta \frac{p_z}{P_D} \ll 1$$

$$P_D = 2 F_z t_0$$



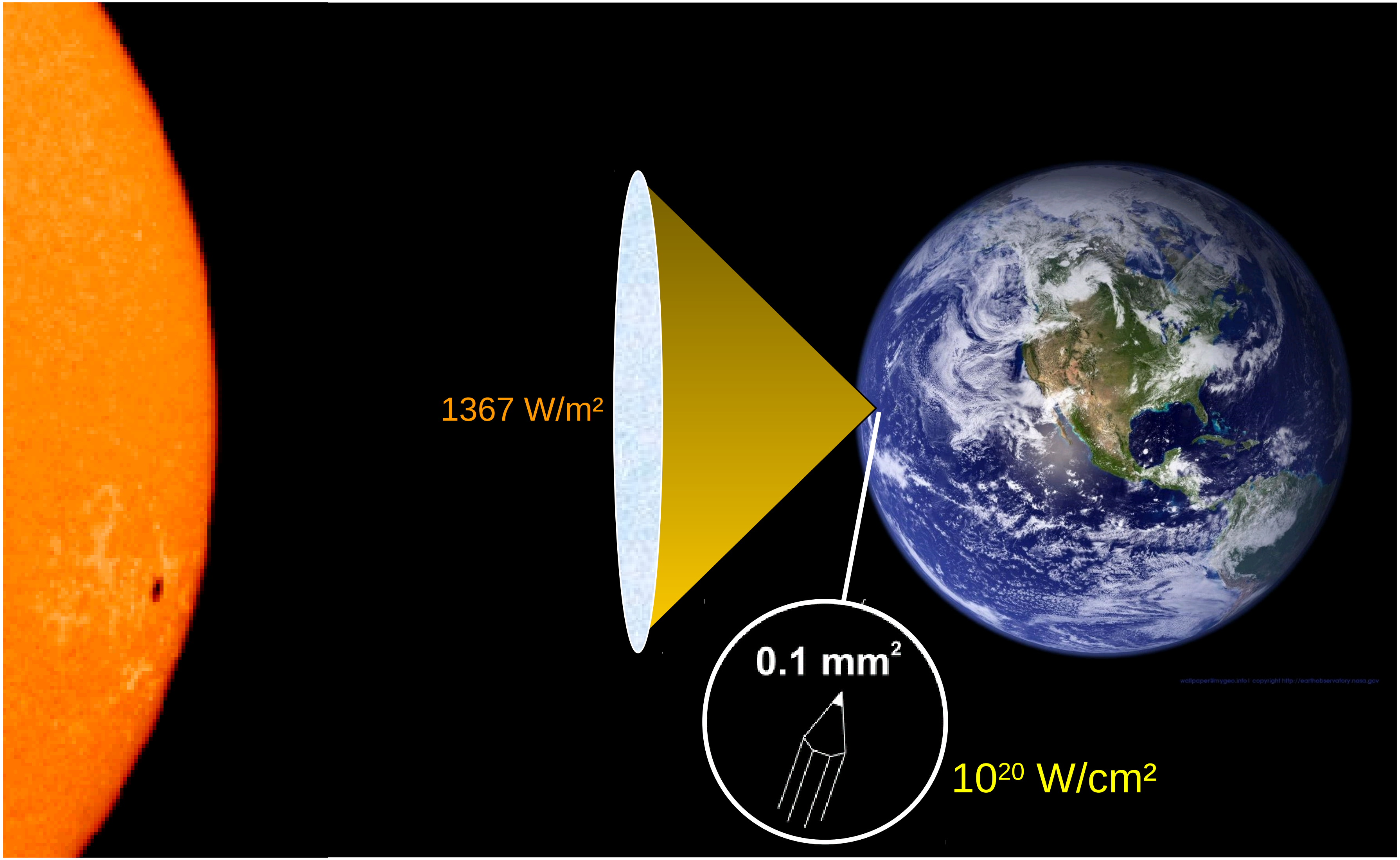
„Nevertheless, this becomes an issue of practice rather than principle.“

Necessary conditions:

- Small beam diameter
- Huge gradients
- Short distance of interaction

see: B.M.Garraway and S.Stenholm, Contemporary Physics 43, p.147 (2002)
and B.M.Garraway and S.Stenholm, Phys. Rev. A, 60(1):63–79, Jul 1999.

Extreme Conditions



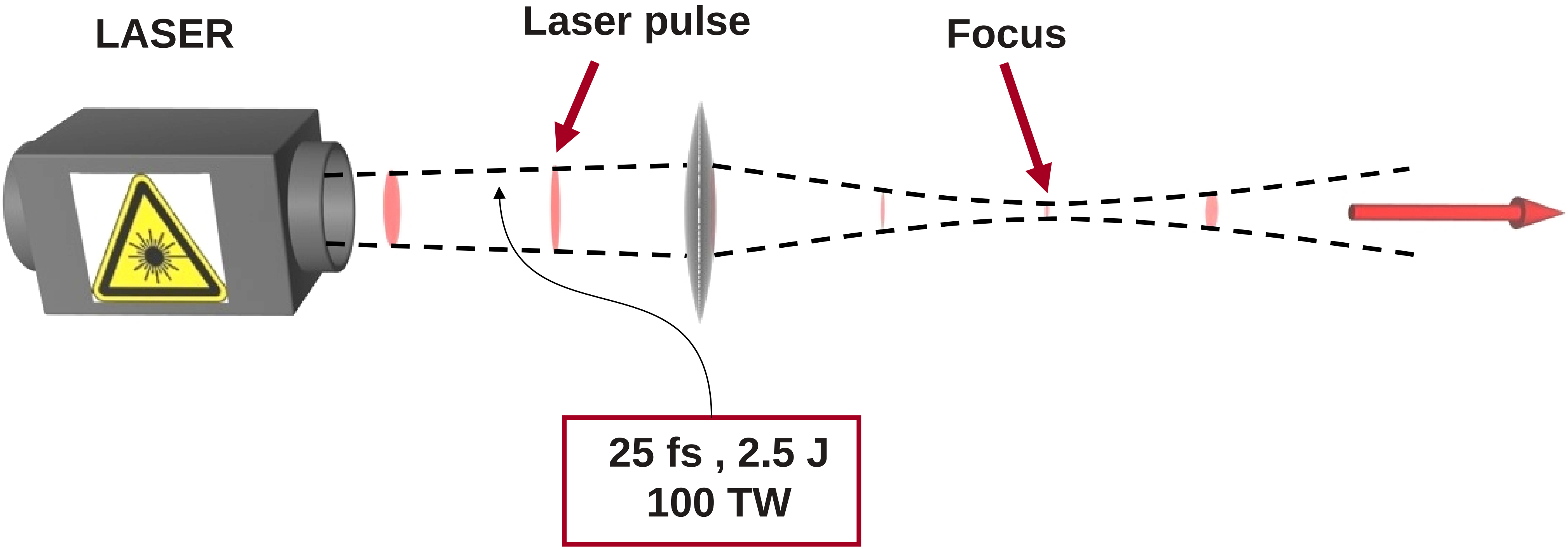
1367 W/m^2

10^{20} W/cm^2

wallpaper@mygeo.info | copyright http://earthobservatory.nasa.gov

Laser: high power through short pulses

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



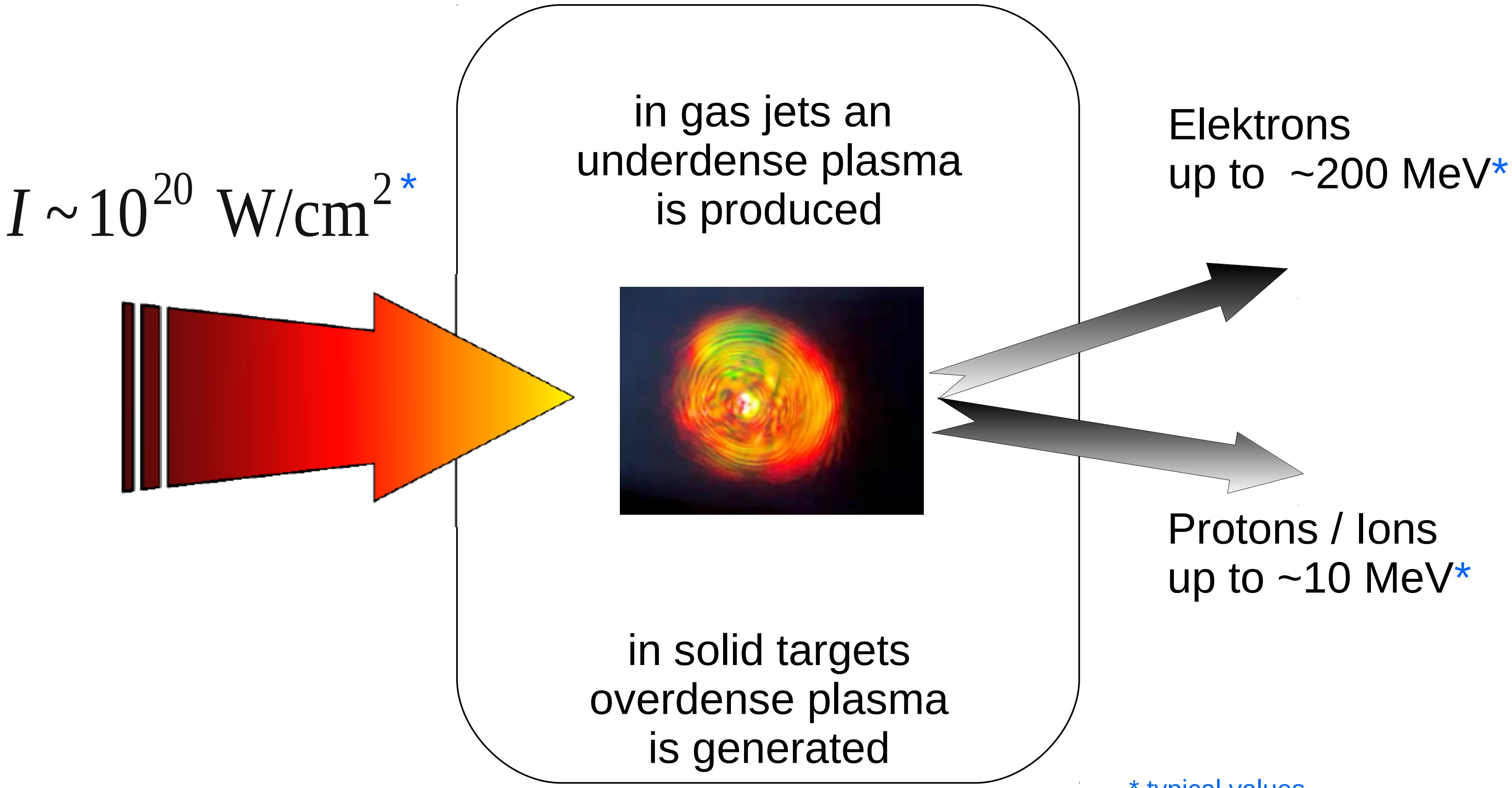
LASER

Laser pulse

Focus

25 fs , 2.5 J
100 TW

Laser induced acceleration of particles



Target

Particles

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

in gas jets an underdense plasma is produced

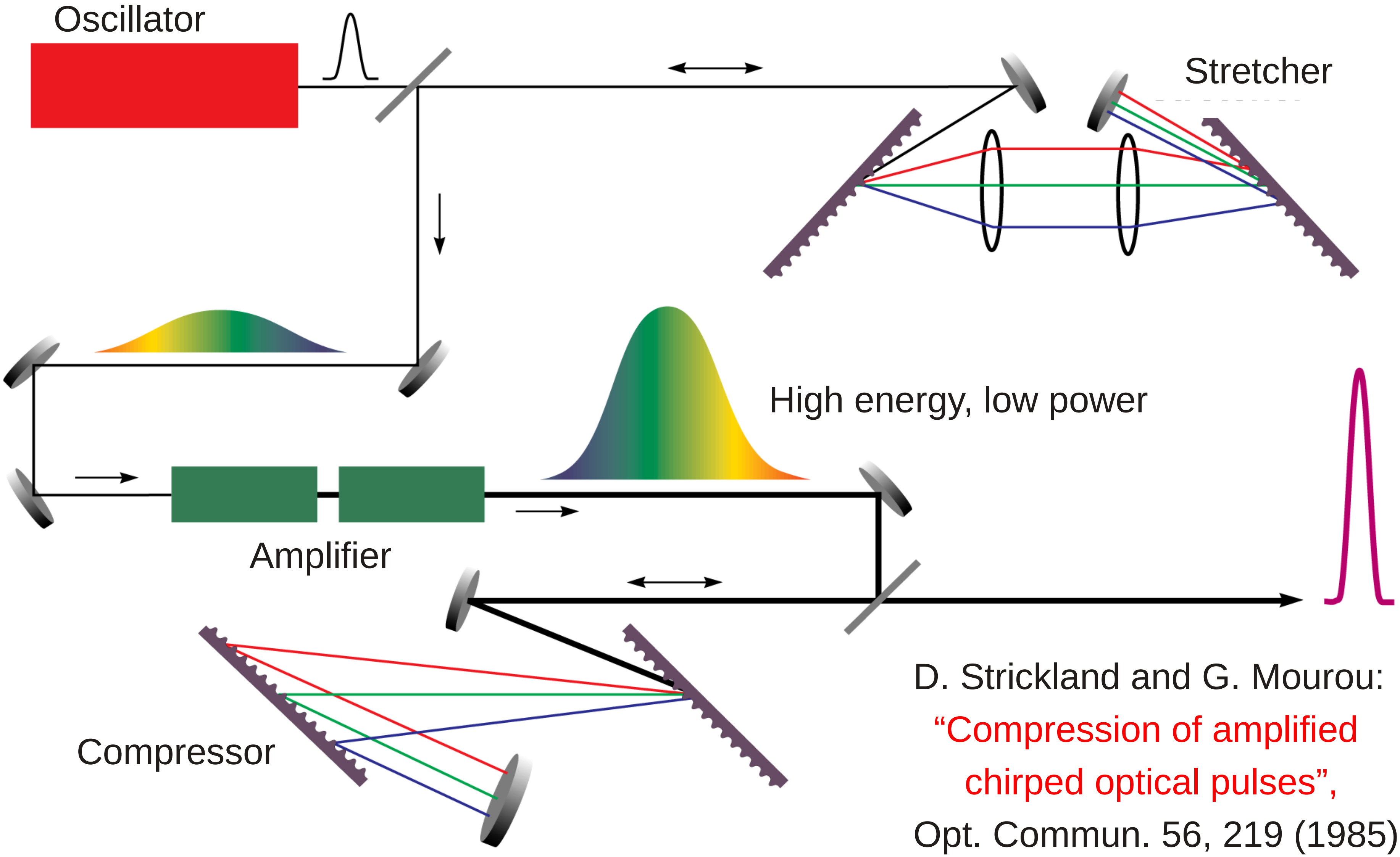
in solid targets overdense plasma is generated

Elektrons
up to ~200 MeV*

Protons / Ions
up to ~10 MeV*

* typical values

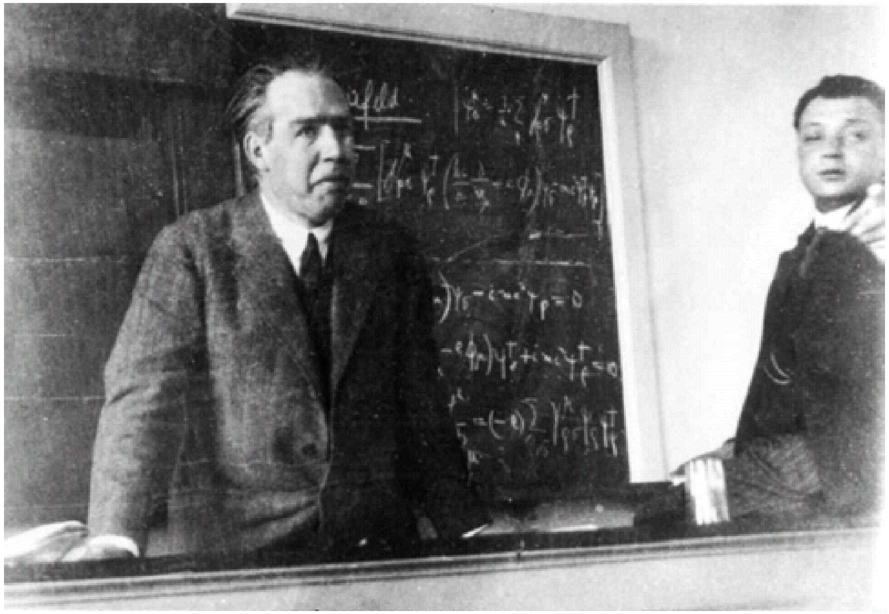
Principe of Chirped Pulse Amplification



D. Strickland and G. Mourou:
“Compression of amplified
chirped optical pulses”,
Opt. Commun. 56, 219 (1985)

Polarization: Why and how?

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



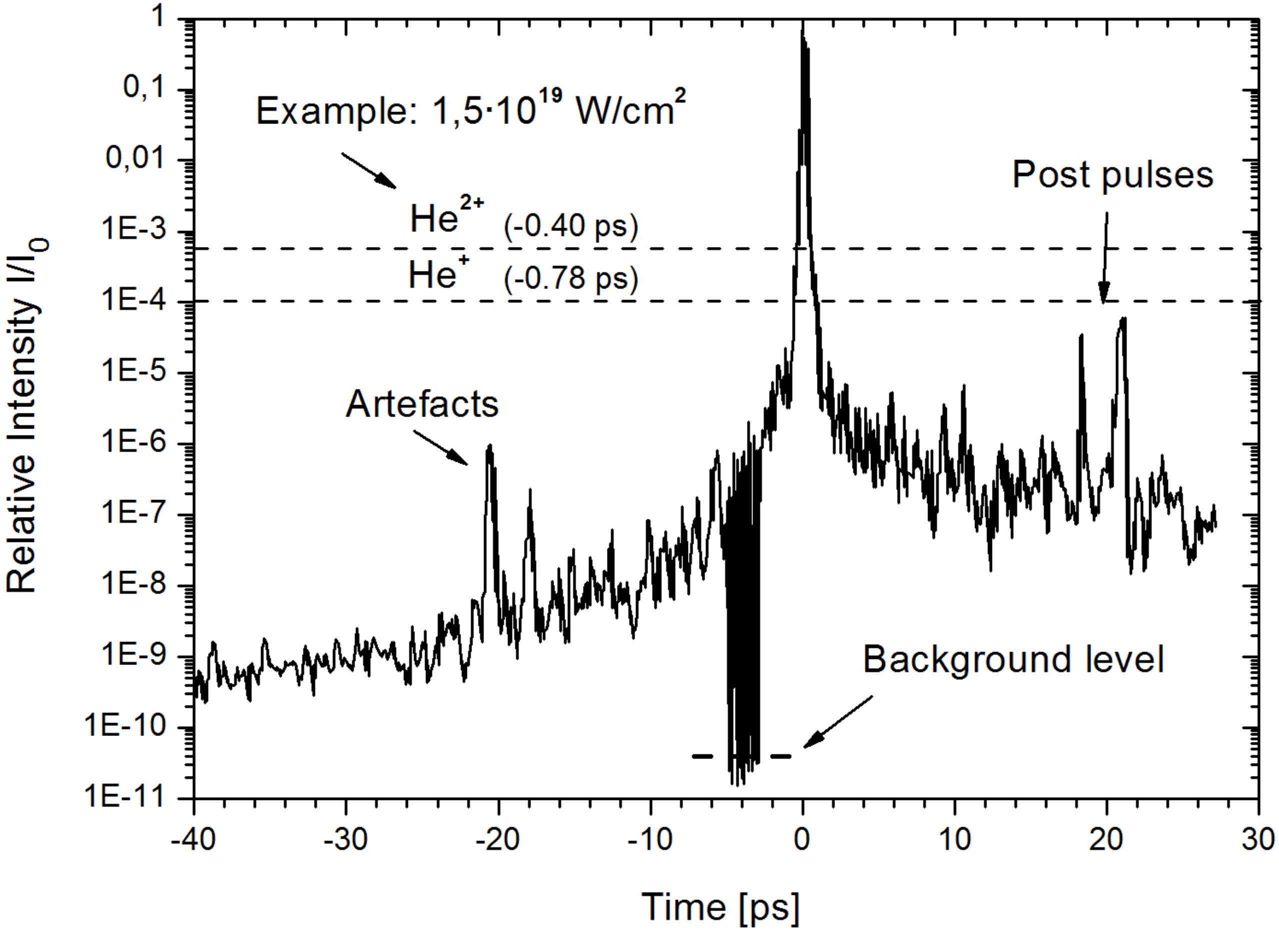
Niels Bohr and Wolfgang Pauli. Taken during the Copenhagen conference of April 1929 (Niels Bohr Archive, Copenhagen)

“Does a flying electron spin?”

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

DARCturus: powerful & high contrast

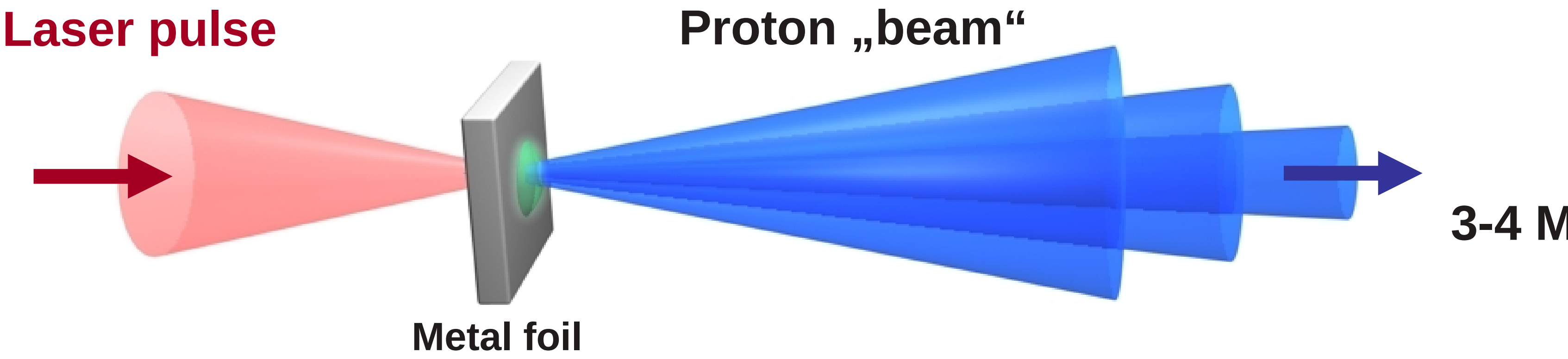
$I_0 \approx 10^{20}$ W/cm²

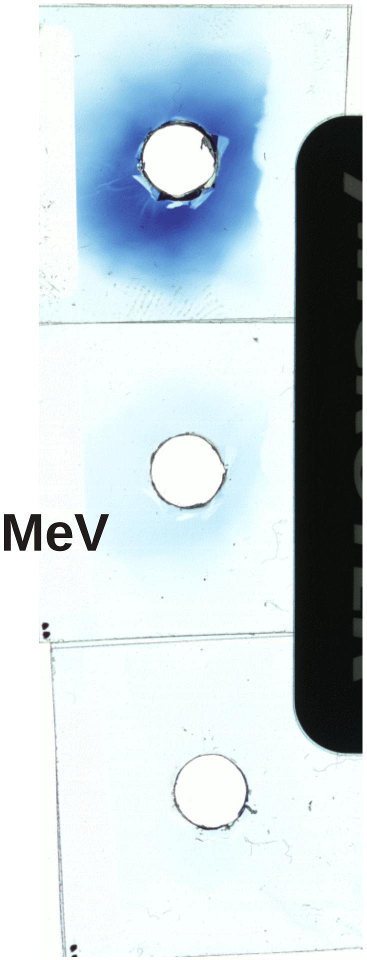


„Handling“ of accelerated beams

Energy spread	~ 10%	**small longitudinal emittance**
Short pulses	sub-ps	
Point-like source	< 10 µm	**small transverse emittance**
Emission angle	~ 30°	
Number of particles	10^8 to 10^{10}	

Angular distributions



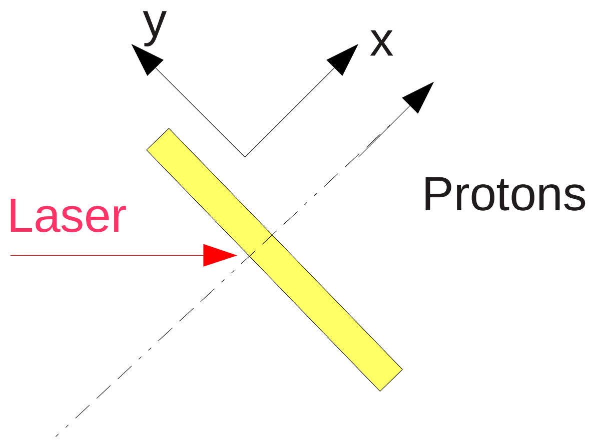


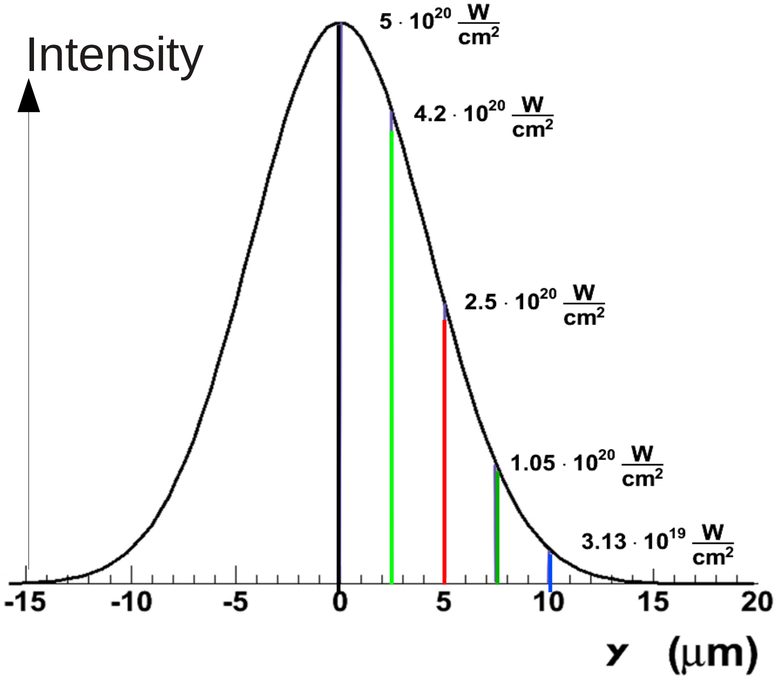
Conversion efficiency ~ 5%
Point-like source < 10 μm
Emission angle ~ 30°
Broad, exponential energy spectra
Short duration (sub-ps pulses)

} small vertical emittance

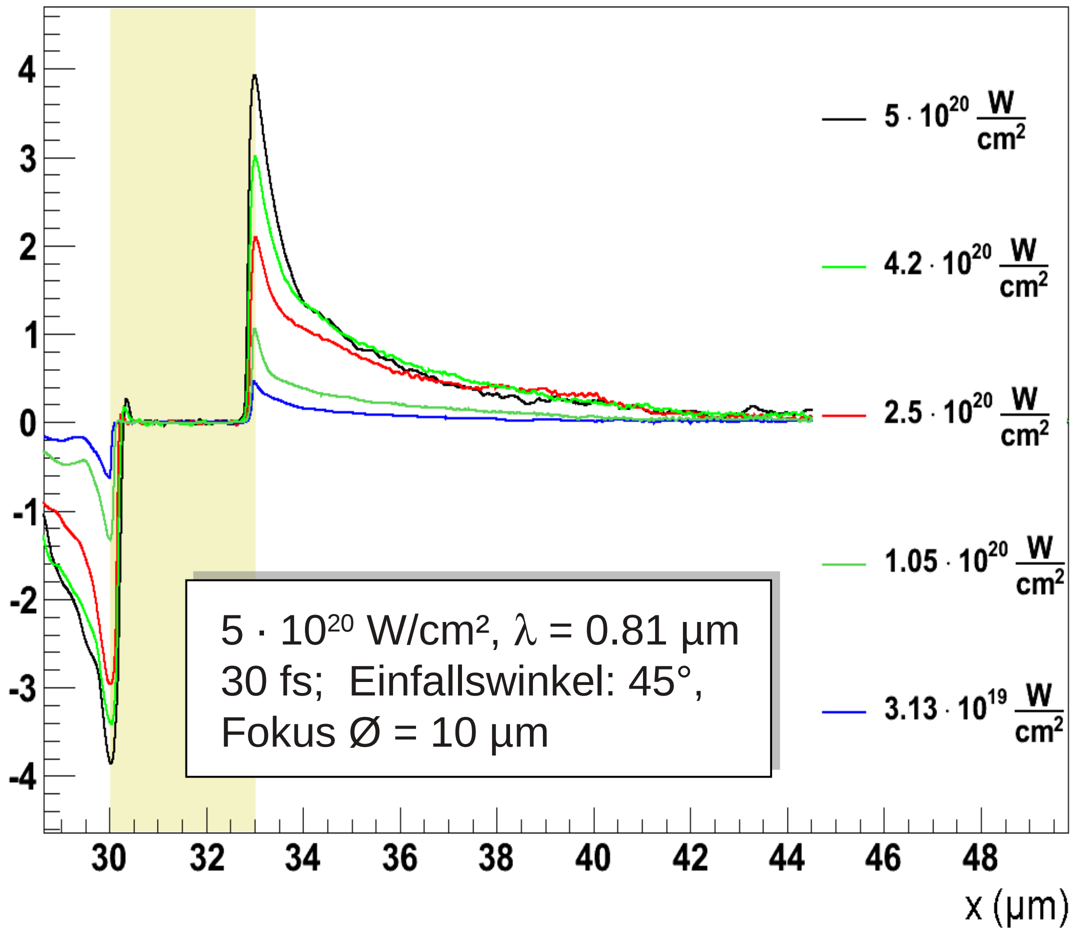
} small longitudinal emittance

Magnetic-field gradient (1D simulation)





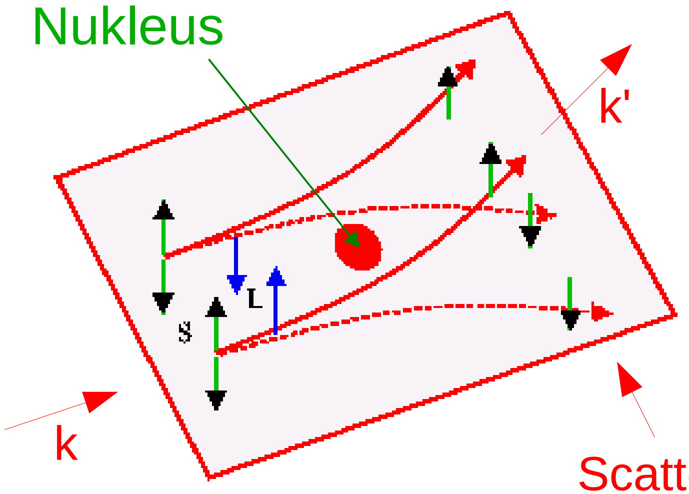
Foli target

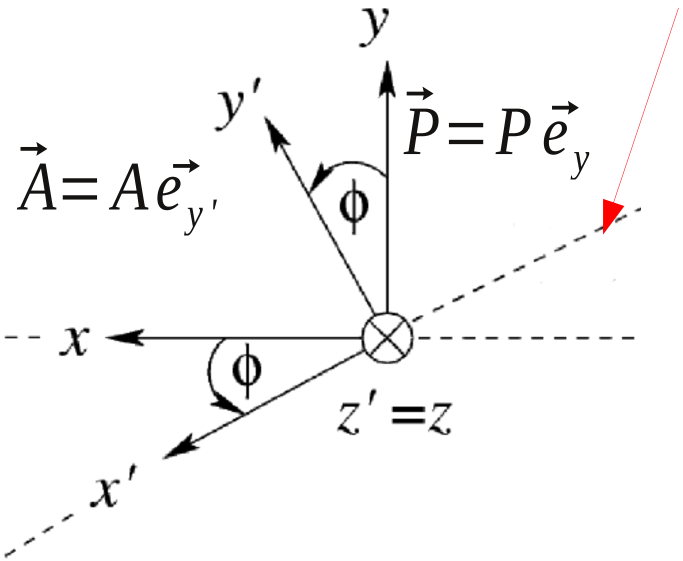


$5 \cdot 10^{20}$ W/cm², $\lambda = 0.81$ µm
30 fs; Einfallswinkel: 45°,
Fokus Ø = 10 µm

Program BOPS3.2 from Gibbon and Bell
(Boosted Oblique Particle Simulation)

Polarization measurement with scattering target





$$H=V_0(r)+V_{SO}(r,E,\ldots)\cdot\left(\vec{S}\cdot\vec{L}\right)+\ldots$$

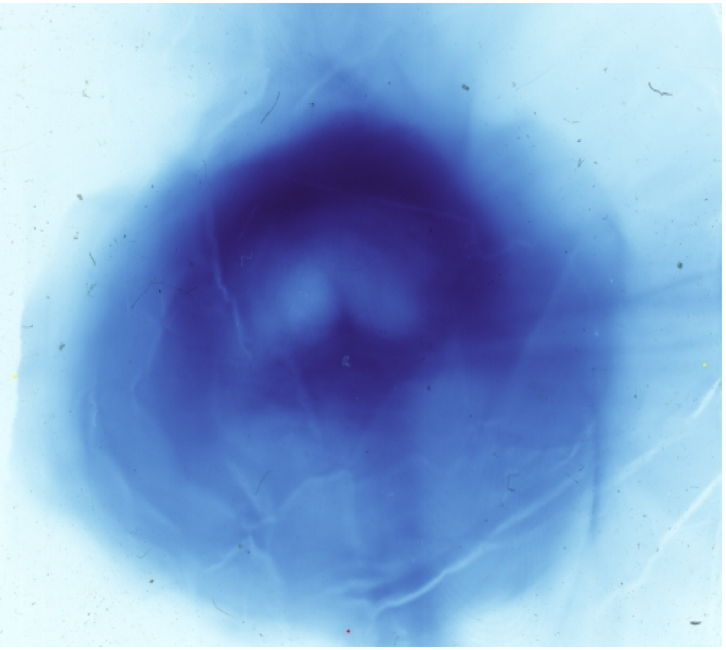
$$\psi\propto e^{i\vec{k}\vec{r}}|n\rangle+\frac{e^{ikr}}{r}M(\vec{k},\vec{k}')|n\rangle$$

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega_0}\left[1+\sum P_i\overset{\mathbf{A_i}}{\boxed{\frac{Sp(M\sigma_i M^t)}{Sp(MM^t)}}}\right]$$

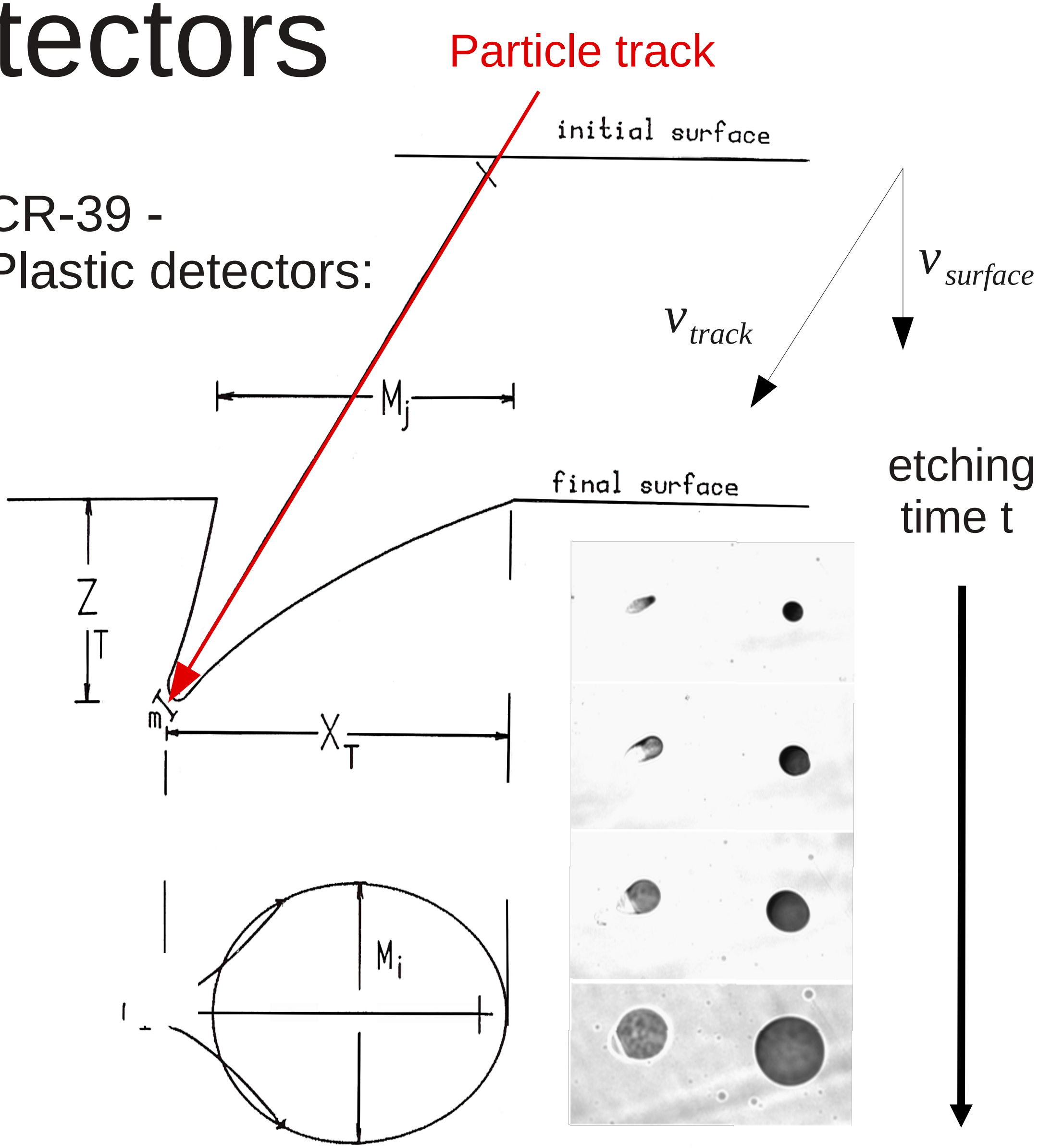
$$\frac{d\sigma}{d\Omega}(E,\theta,\phi)=\frac{d\sigma}{d\Omega_0}(E,\theta)\left[1+A\cdot P\cdot\cos\phi\right]$$

Experimental Methods: Detectors

Radio-chromic film detectors:

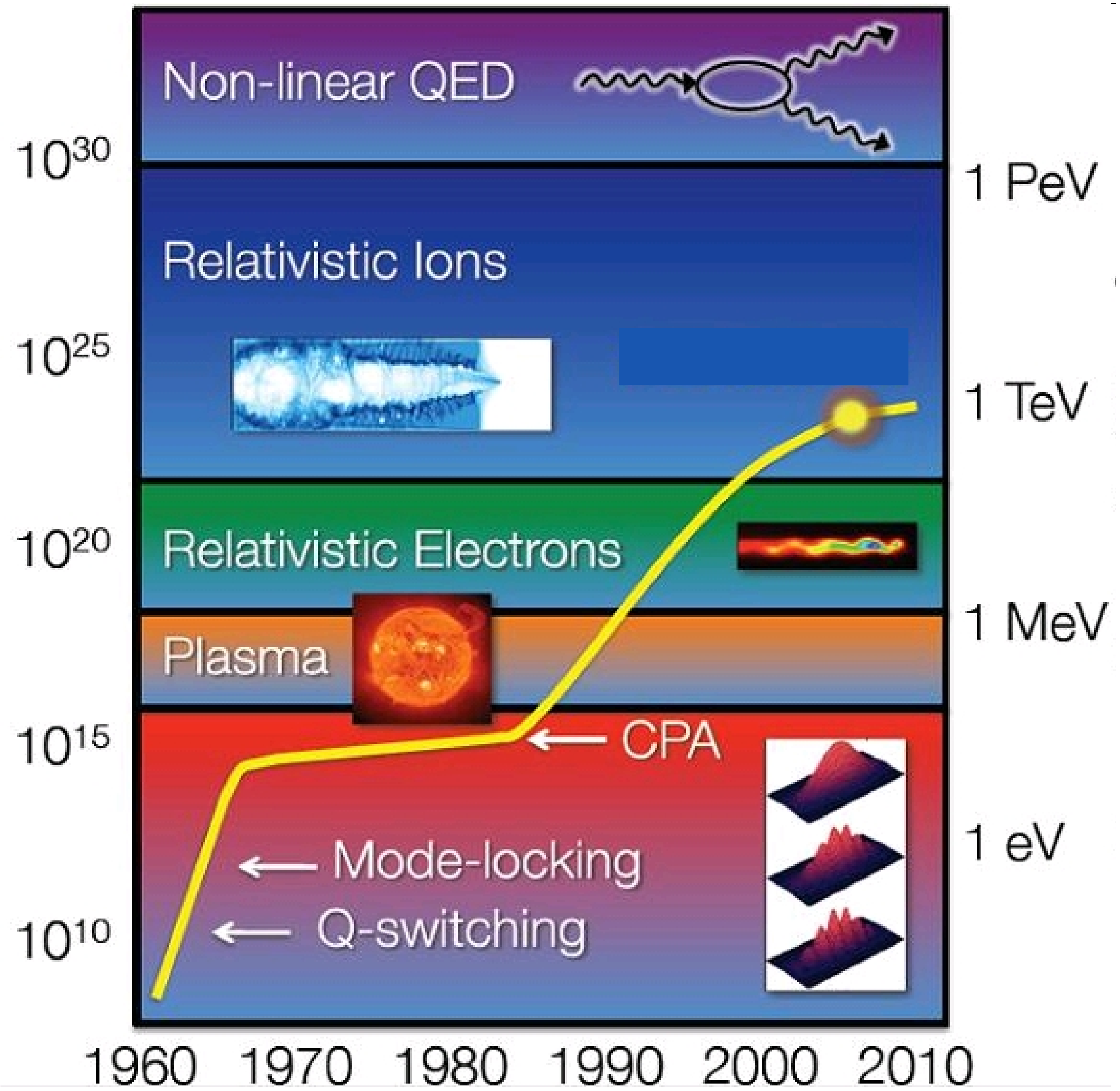


CR-39 -
Plastic detectors:



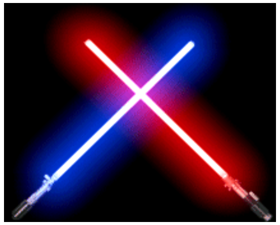
Development of Laser intensities

Focused intensity (W/cm²)

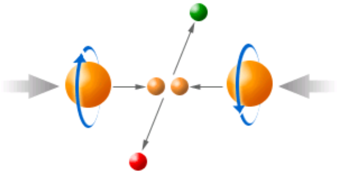


Characteristic electron energy

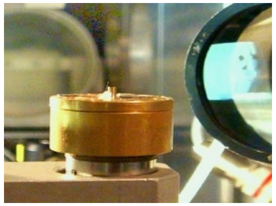
Outline



Short excursion in laser-plasma acceleration



Spin polarization induced by a laser interaction



Planed Experiment

Mile Stones on the way to the polarized Beam Source