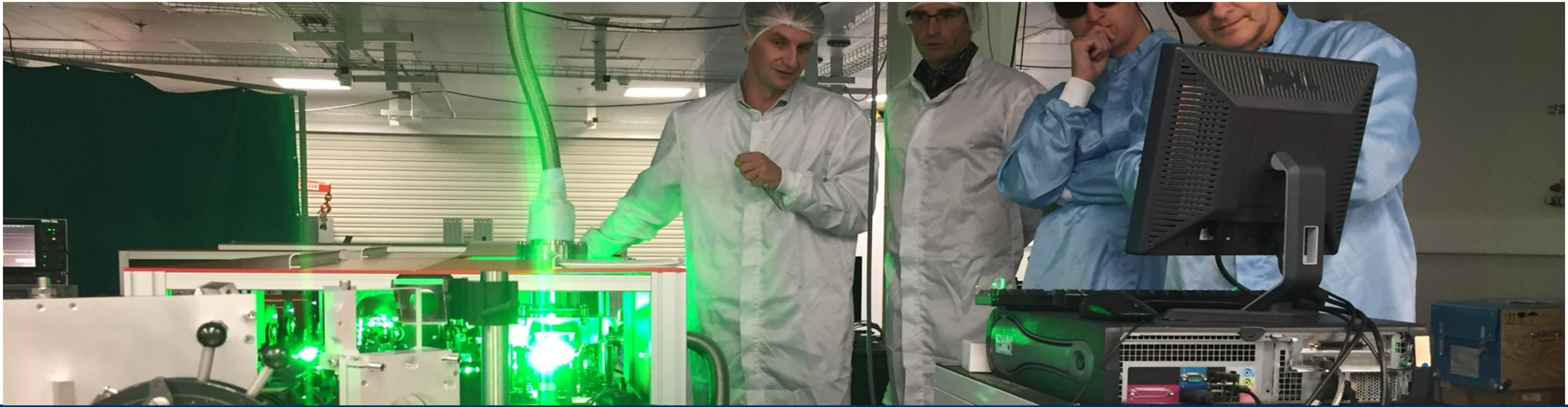


POLARIZED PROTON BEAMS FROM LASER-INDUCED PLASMAS

Talk at: ICAP18, Key West, Florida, USA

21 OCTOBER 2018 | MARKUS BÜSCHER

HOW ARE POLARIZED BEAMS PRODUCED?

Conventional accelerators:
Cooler Synchrotron COSY-Jülich

Reach fundamental & technological limits

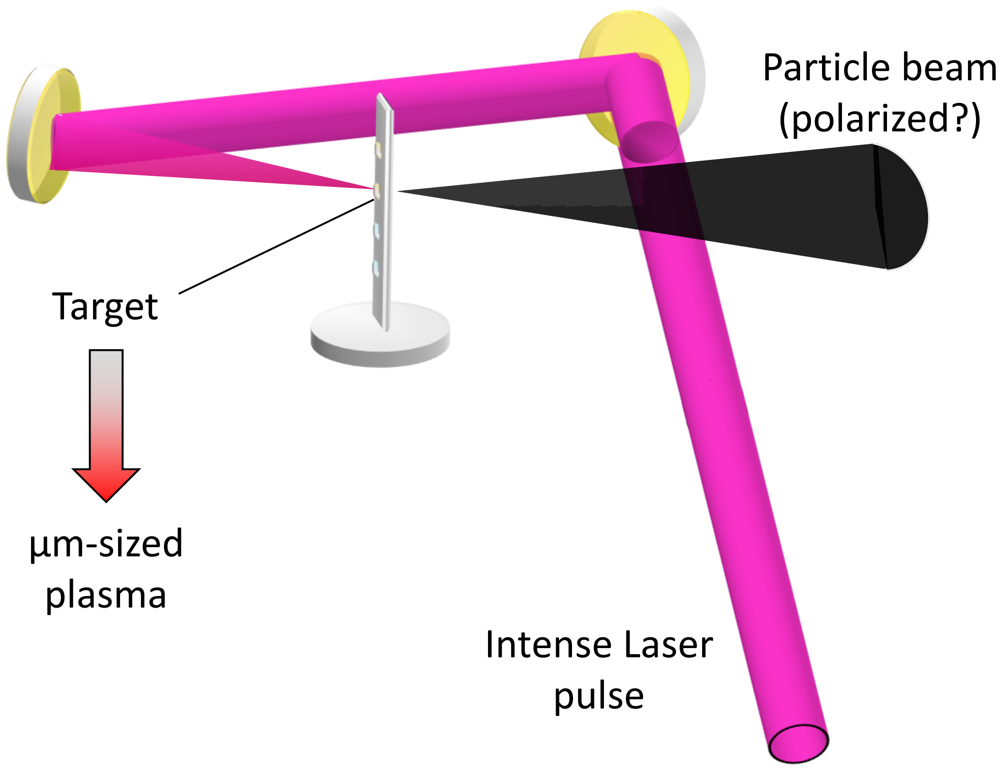
Laser-plasma particle acceleration:
***e.g.* the Jülich Short-pulsed Particle and Radiation Center**

Polarized particle beams?

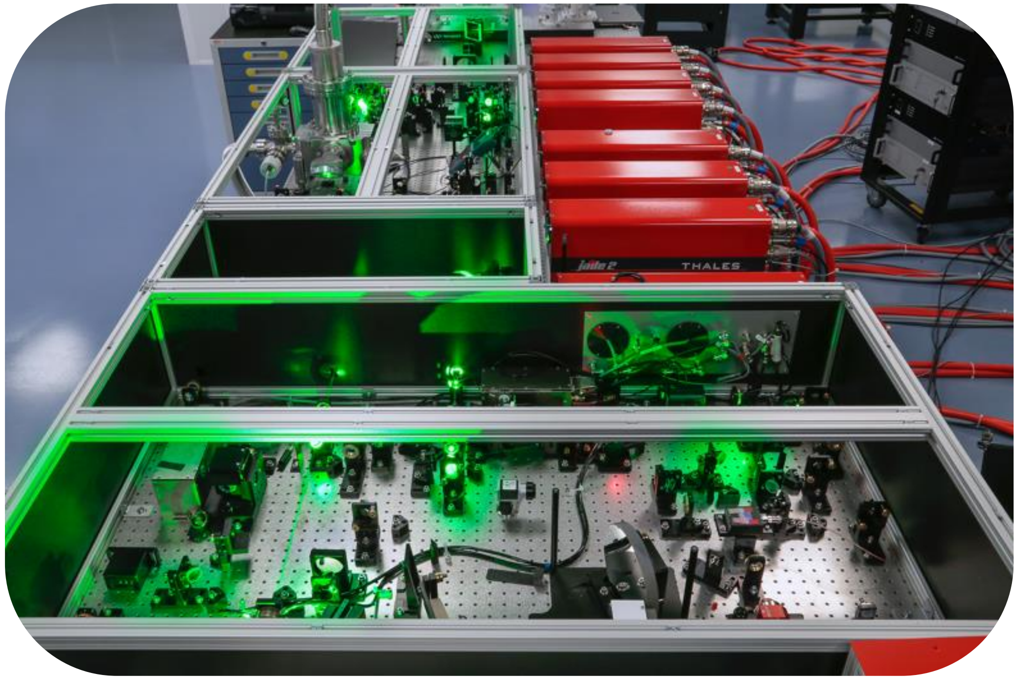
JÜLICH Forschungszentrum

HOW ARE POLARIZED BEAMS PRODUCED?

”Table-top” particle acceleration



Laser-plasma particle acceleration: e.g. the Jülich Short-pulsed Particle and Radiation Center



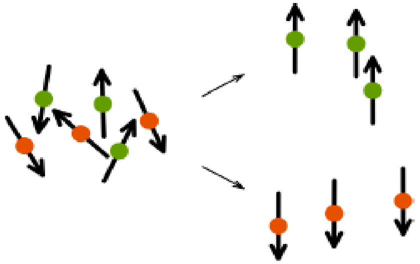
Polarized particle beams?

HOW ARE POLARIZED BEAMS PRODUCED?

Possible scenarios in laser-induced plasmas

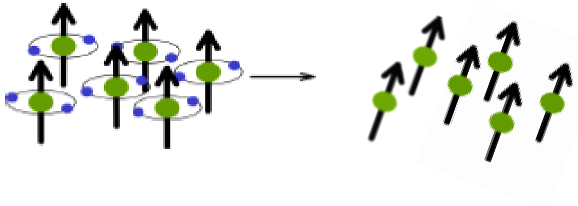
Polarization is <u>generated</u>

spin flip
Sokolov-Ternov effect



Stern-Gerlach effect

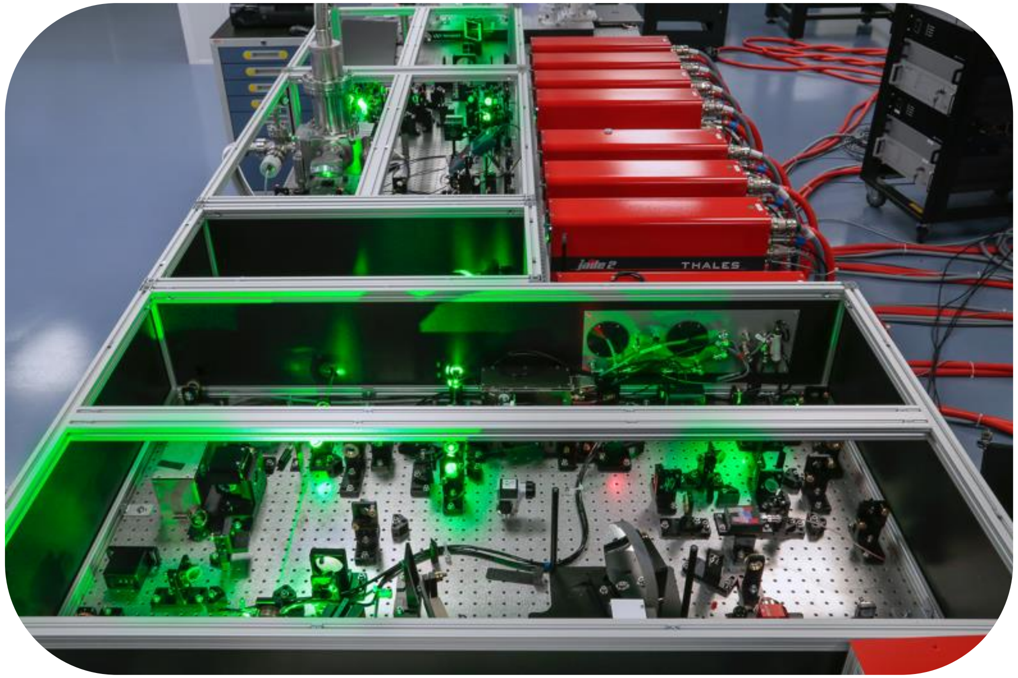
Polarization is <u>preserved</u>



Thomas-BMT equation

☞ Relevant mechanisms?

<u>Laser-plasma</u> particle acceleration: *e.g.* the Jülich Short-pulsed Particle and Radiation Center



Polarized particle beams?

HISTORY: FIRST POLARIZATION EXPERIMENT

HEINRICH HEINE
UNIVERSITÄT DÜSSELDORF

PHYSICS OF PLASMAS **21**, 023104 (2014)

Polarization measurement of laser-accelerated protons

Natascha Raab,[1,a)] Markus Büscher,[1,2,3,b)] Mirela Cerchez,[3] Ralf Engels,[1] Ilhan Engin,[1] Paul Gibbon,[4] Patrick Greven,[1] Astrid Holler,[1] Anupam Karmakar,[4,c)] Andreas Lehrach,[1] Rudolf Maier,[1] Marco Swantusch,[3] Monika Toncian,[3] Toma Toncian,[3] and Oswald Willi[3]

[1]*Institut für Kernphysik and Jülich Center for Hadron Physics, Forschungszentrum Jülich, 52425 Jülich, Germany*
[2]*Peter Grünberg Institut (PGI-6), Forschungszentrum Jülich, 52425 Jülich, Germany*
[3]*Institute for Laser- and Plasma Physics, Heinrich-Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany*
[4]*Institute for Advanced Simulation, Jülich Supercomputing Centre, Forschungszentrum Jülich, 52425 Jülich, Germany*

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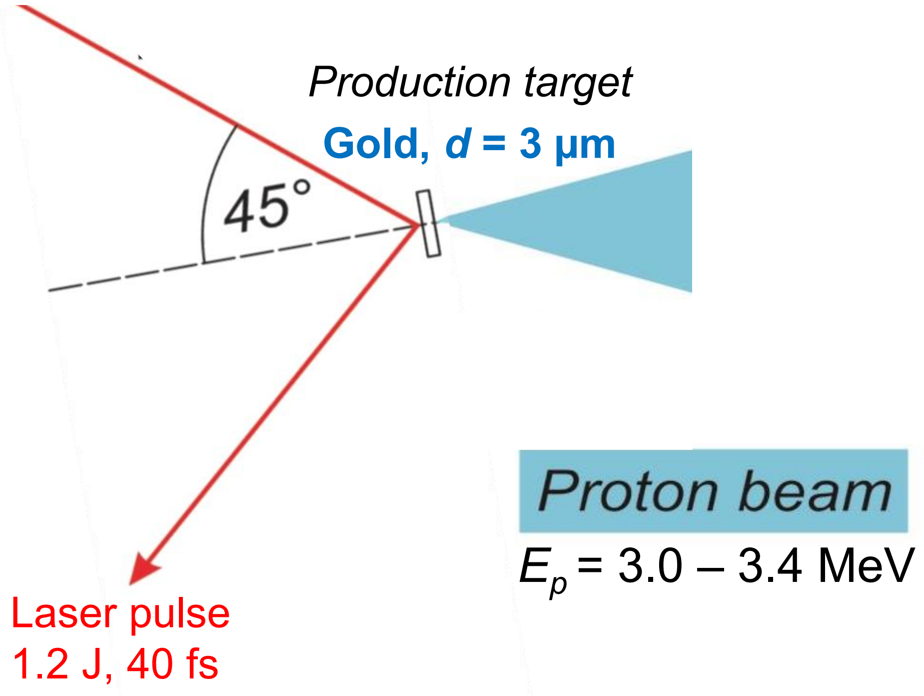
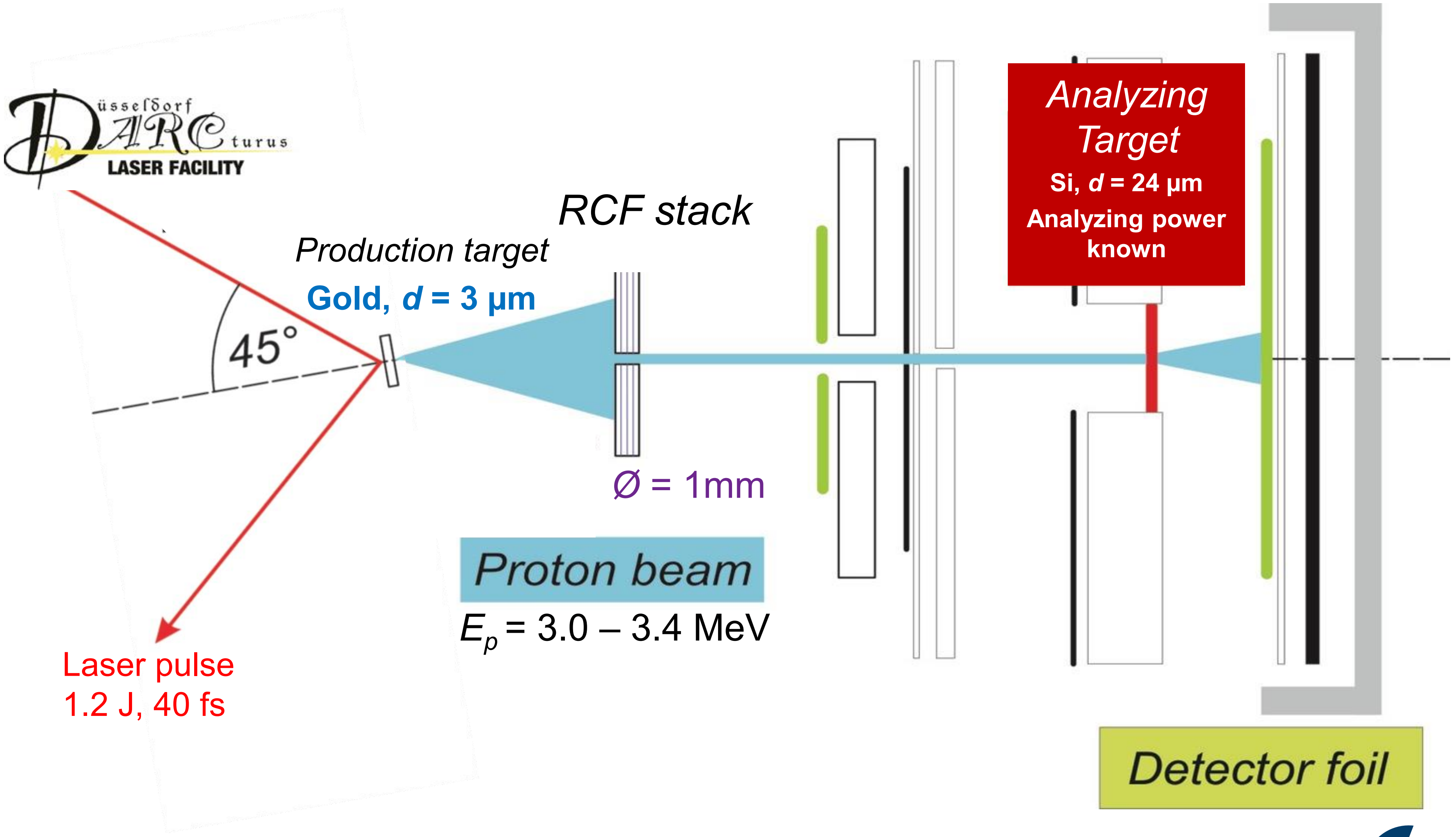
HISTORY: FIRST POLARIZATION EXPERIMENT



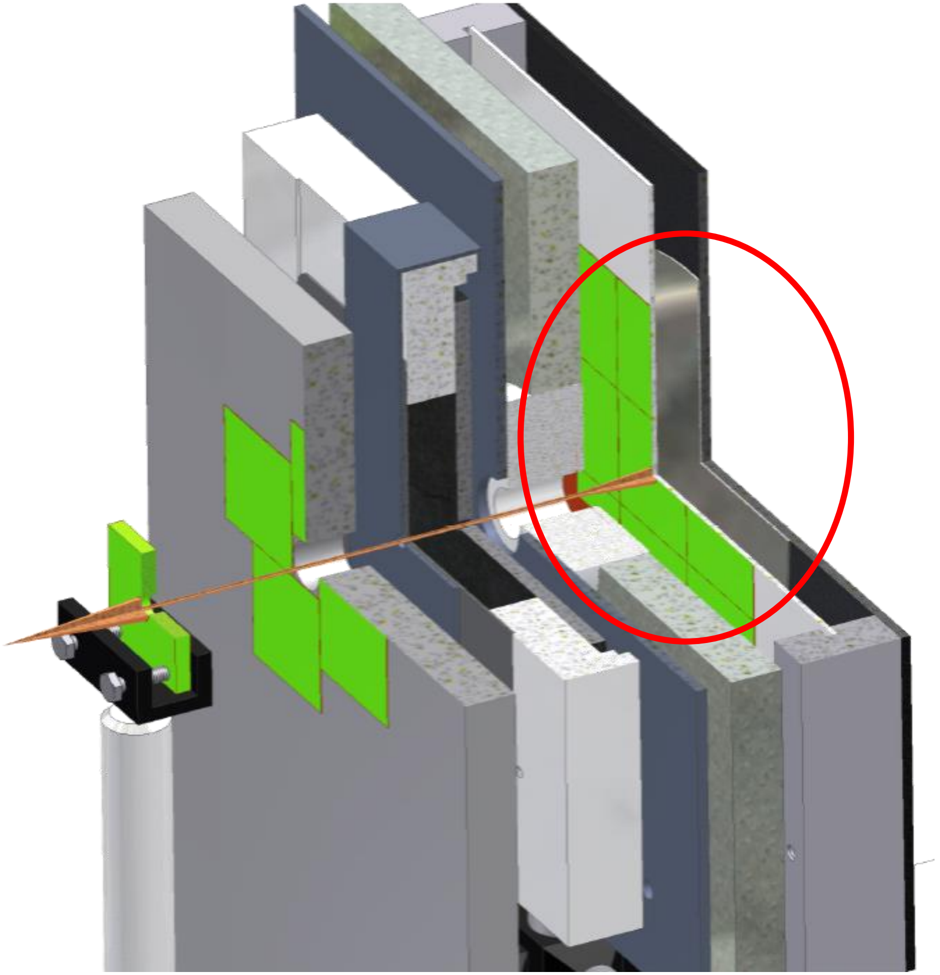
HISTORY: FIRST POLARIZATION EXPERIMENT



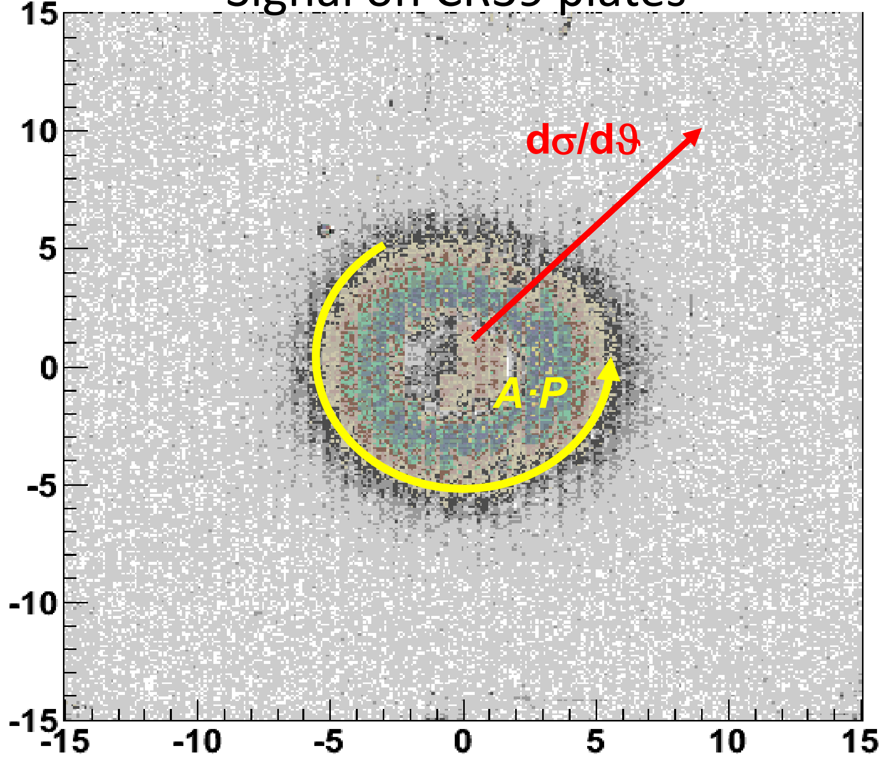
POLARIMETRY FOR MEV "LASER" PROTONS

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

Proton scattering in Si target (for proton energies of a few MeV)



Signal on CR39 plates



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

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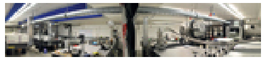
HISTORY: FIRST POLARIZATION EXPERIMENT

CERN COURIER

CERN COURIER

Mar 28, 2014

New results mark progress towards polarized ion beams in laser-induced acceleration



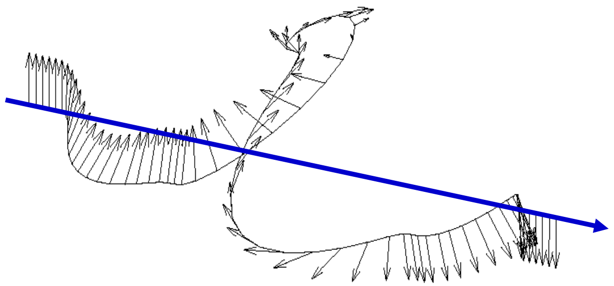
The Arcturus Laser

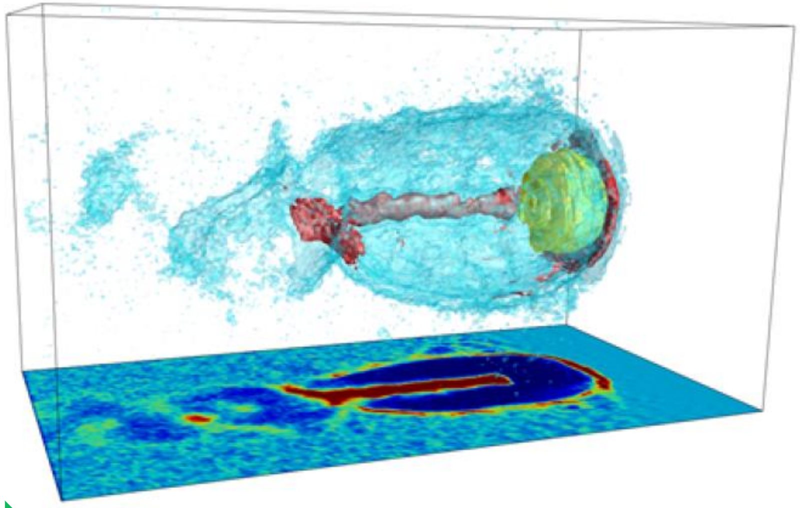
The field of laser-induced relativistic plasmas and, in particular, laser-driven particle acceleration, has undergone impressive progress in recent years. Despite many advances in understanding fundamental physical phenomena, one unexplored issue is how the particle spins are influenced by the huge magnetic fields inherently present in the plasmas.

Laser-induced generation of polarized-ion beams would without doubt be important in research at particle accelerators. In this context, $^3He^{2+}$ ions have been discussed widely. They can serve as a substitute for polarized neutron beams, because in a ^3He nucleus the two protons have opposite spin directions, so the spin of the nucleus is carried by the neutron. However, such beams are currently not available owing to a lack of corresponding ion sources. A promising approach for a laser-based ion source would be to use pre-polarized ^3He gas as the target material. Polarization conservation of ^3He ions in plasmas is also crucial for the feasibility of proposals aiming at an increase in efficiency of fusion reactors by using polarized fuel, because this efficiency depends strongly on the cross-section of the fusion reactions.

MODELLING OF SPINS IN LASER-INDUCED PLASMAS

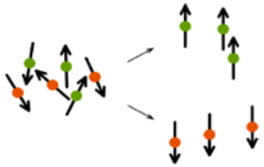
Implementation of particle spins into simulation code (in collaboration with A. Pukhov, HEINRICH HEINE UNIVERSITÄT DÜSSELDORF)





Sokolov-Ternov effect → PIC Code (VLPL)

➡ Characteristic time for spin flips too short

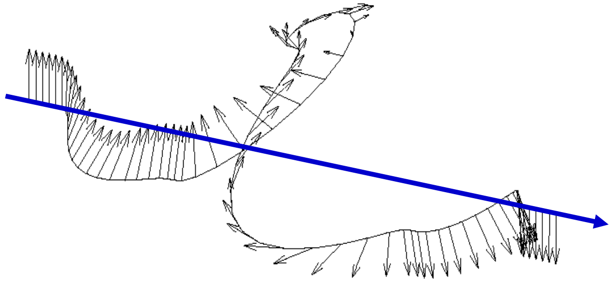


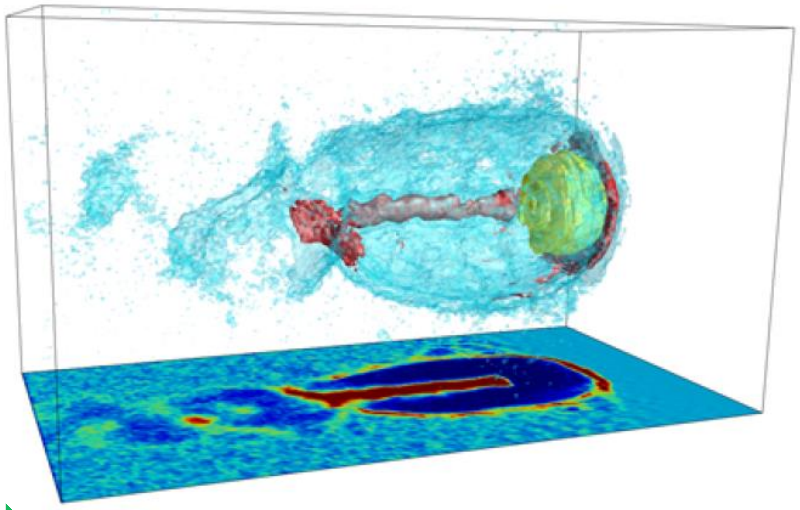
Stern-Gerlach effect → PIC Code (VLPL)

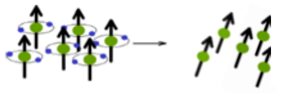
➡ Force for spatial separation on the given length scale too weak

MODELLING OF SPINS IN LASER-INDUCED PLASMAS

Implementation of particle spins into a simulation code (in collaboration with A. Pukhov, HEINRICH HEINE UNIVERSITÄT DÜSSELDORF)







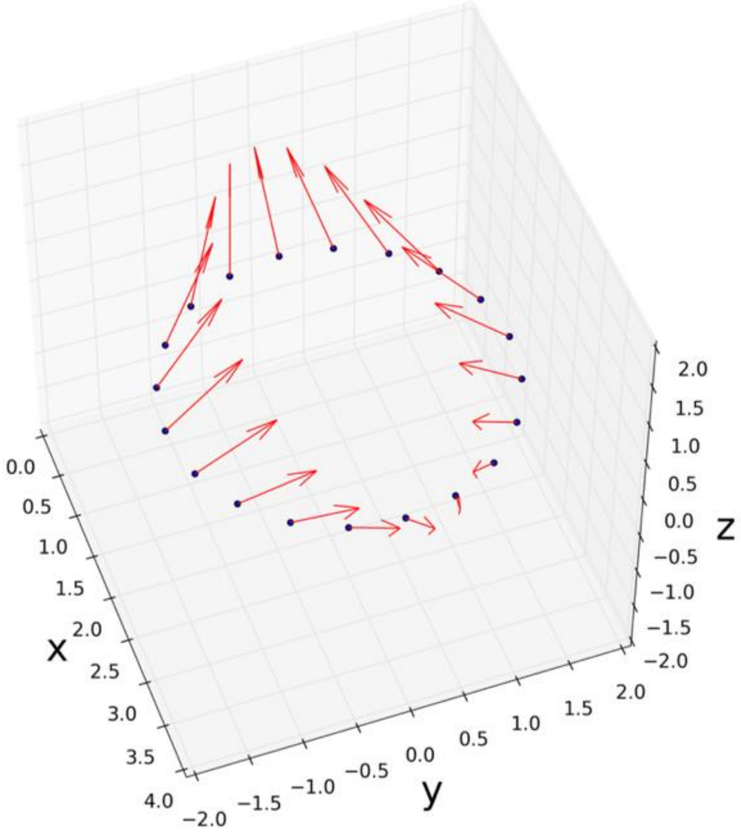
Thomas-BMT equation

PIC Code (VLPL)

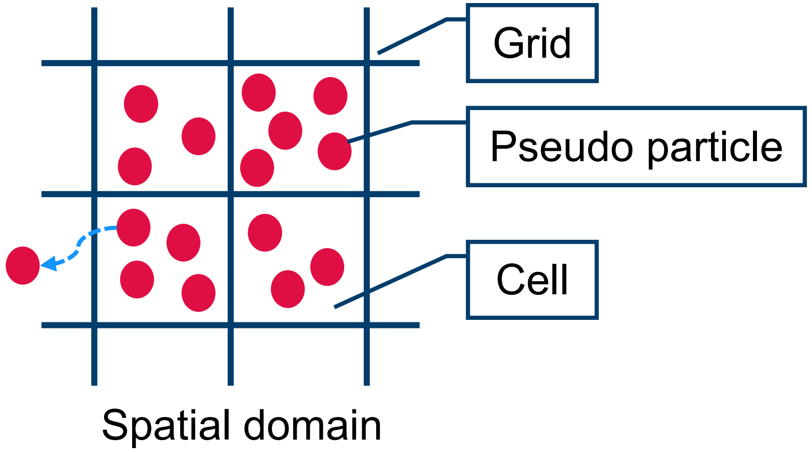
Description of spin motion in arbitrary electric and magnetic fields for the semi-classical approach

$$\frac{d\mathbf{s}}{dt} = -\frac{e}{m_{\mathrm{p}}c}\left[\left(a_{\mathrm{p}} + \frac{1}{\gamma}\right)\mathbf{B}_{\perp} - \frac{a_{\mathrm{p}}\gamma}{\gamma+1}\left(\frac{\mathbf{v}}{c}\cdot\mathbf{B}_{\parallel}\right)\frac{\mathbf{v}}{c} - \left(a_{\mathrm{p}} + \frac{1}{1+\gamma}\right)\frac{\mathbf{v}}{c}\times\mathbf{E}\right]\times\mathbf{s}$$

POLARIZATION IN PIC CODE VLPL



One PIC particle with spin moving in a homogeneous *B*-field



Polarization P : $P = \dfrac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

P. Farago, *Electron spin polarization*, Rep. Prog. Phys. **34,** 1055 (1971)

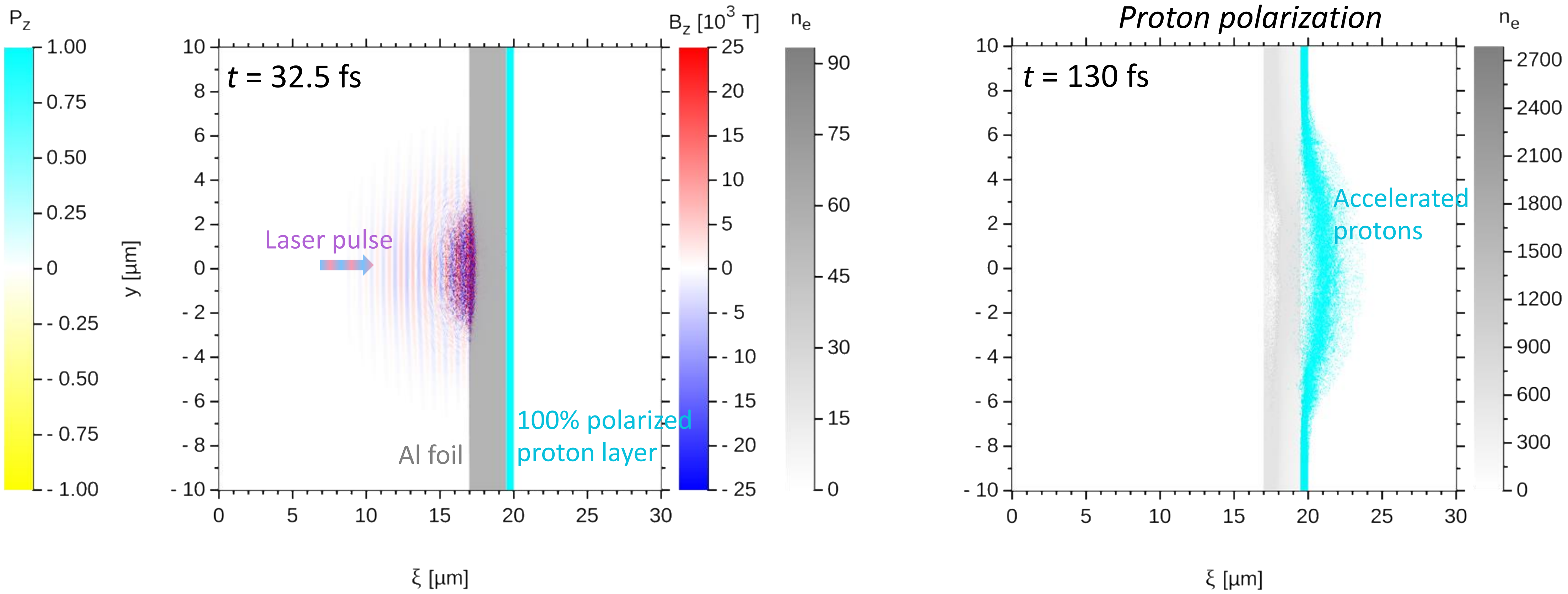
The continuous spin vector of a PIC particle represents the mean value of single particles, depending on the PIC weight.

J. Thomas et al., publication in preparation

A FIRST PIC SIMULATION W/ PARTICLE SPINS

3D VLPL simulation (λ = 800 nm, normalized laser amplitude a_0 = 12, 25 fs duration, 5 µm focal spot size)

Simulations by: Anna Hützen & Johannes Thomas



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A FIRST PIC SIMULATION W/ PARTICLE SPINS

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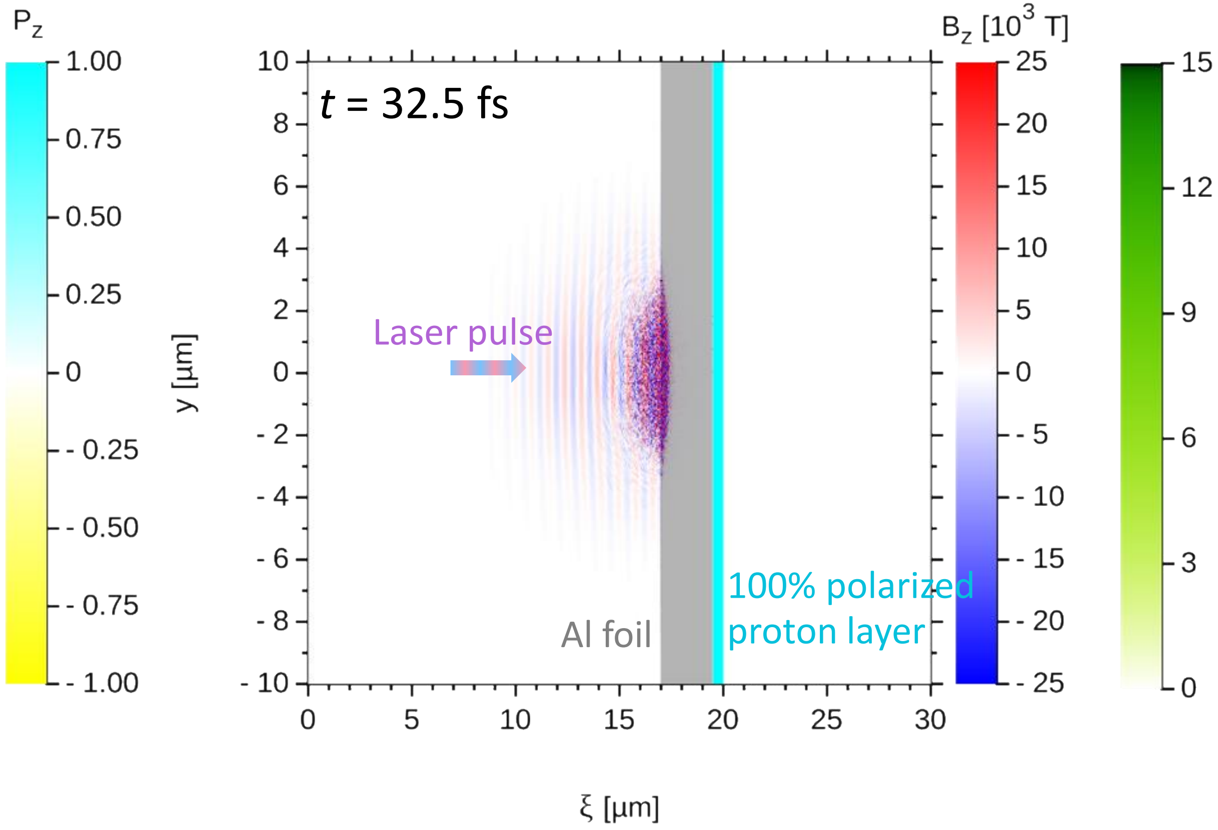
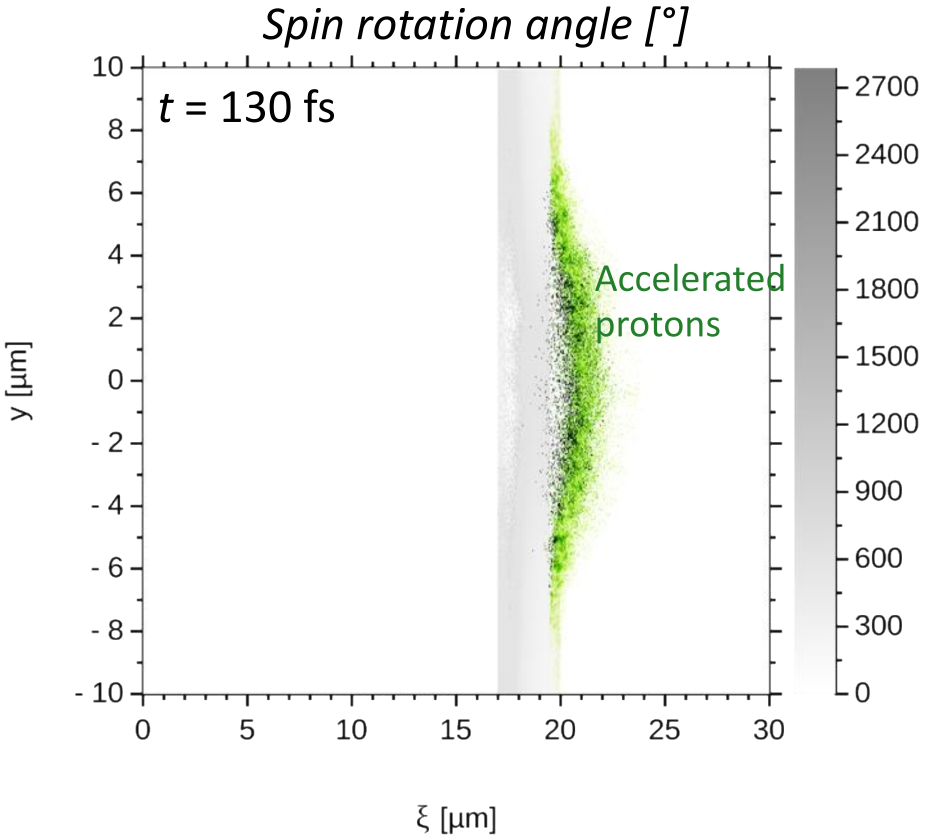


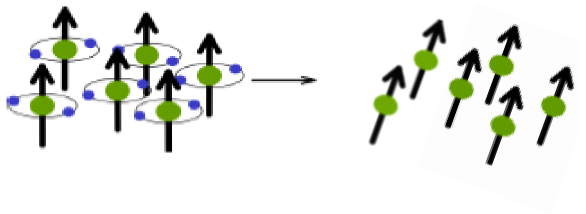


☞ Proton polarization is conserved during acceleration

NEED FOR POLARIZED GAS TARGETS

What have we learned?

Polarization is <u>preserved</u>

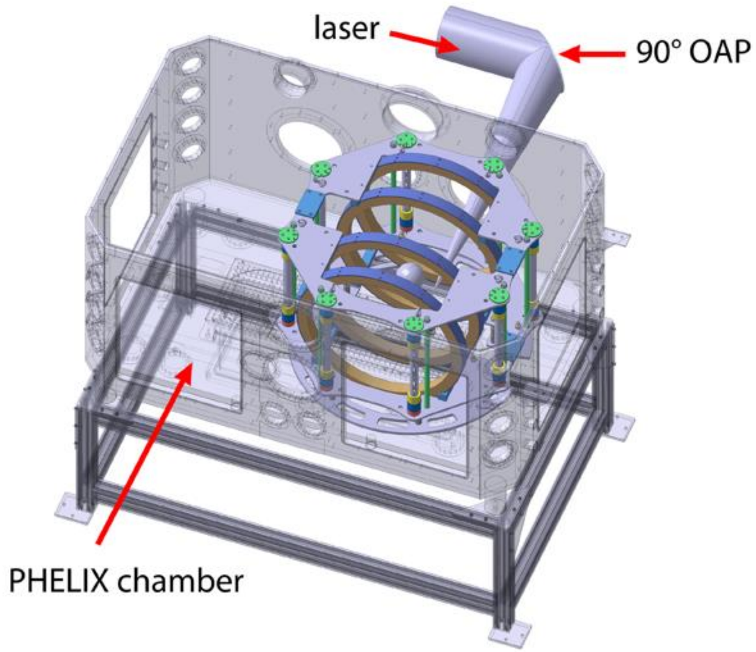


Thomas-BMT equation

- Spins only precess during the acceleration process but they do not flip
- <u>Pre-polarized gas target</u> (density $\gtrsim 10^{20}\ \mathrm{cm}^{-3}$) promises to give rise to a highly polarized relativistic beams

Possible experimental realization:
<u>Polarized ^{3}He</u> target

Measurements @ PHELIX GSI: 2019



But: no suitable Hydrogen targets

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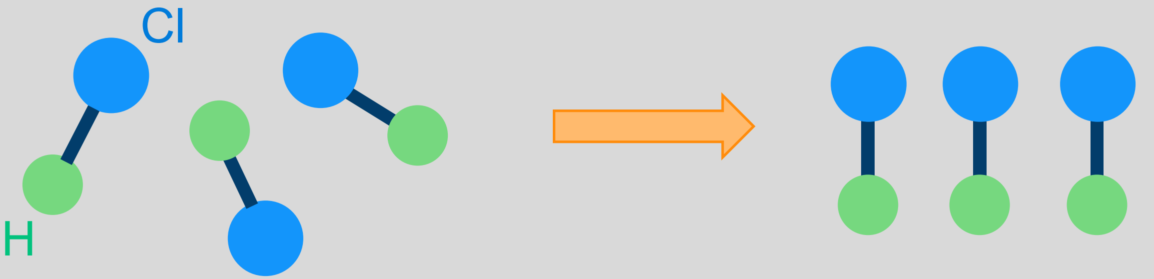
PRODUCTION OF POLARIZED PROTON BEAMS

100 mJ @ 1064 nm



Alignment of HCl bonds

20 mJ @ 213 nm

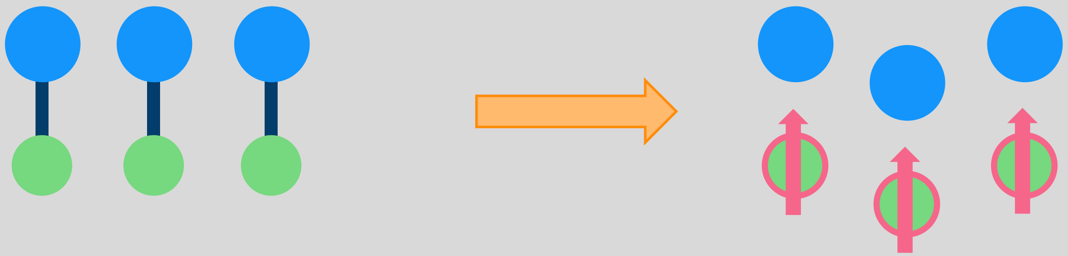
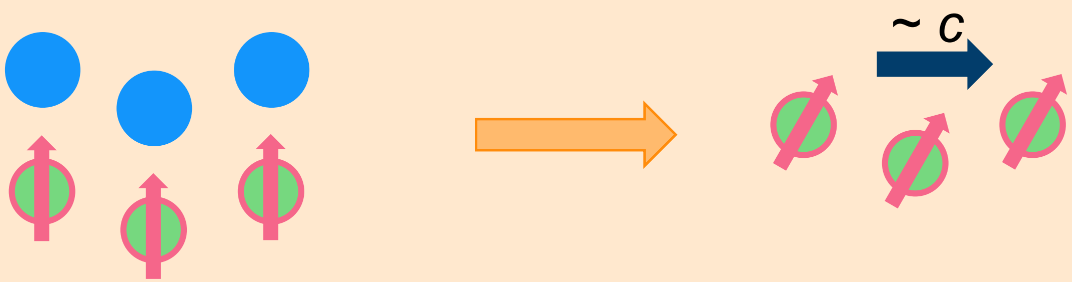


Photo-dissociation & polarization transfer to H nuclei (Δt = 350 ps)

SIOM

300 J @ 800 nm



Acceleration of the protons in gas jet

A. Hützen et al., arXiv:1810.02247 and proceedings of this conference

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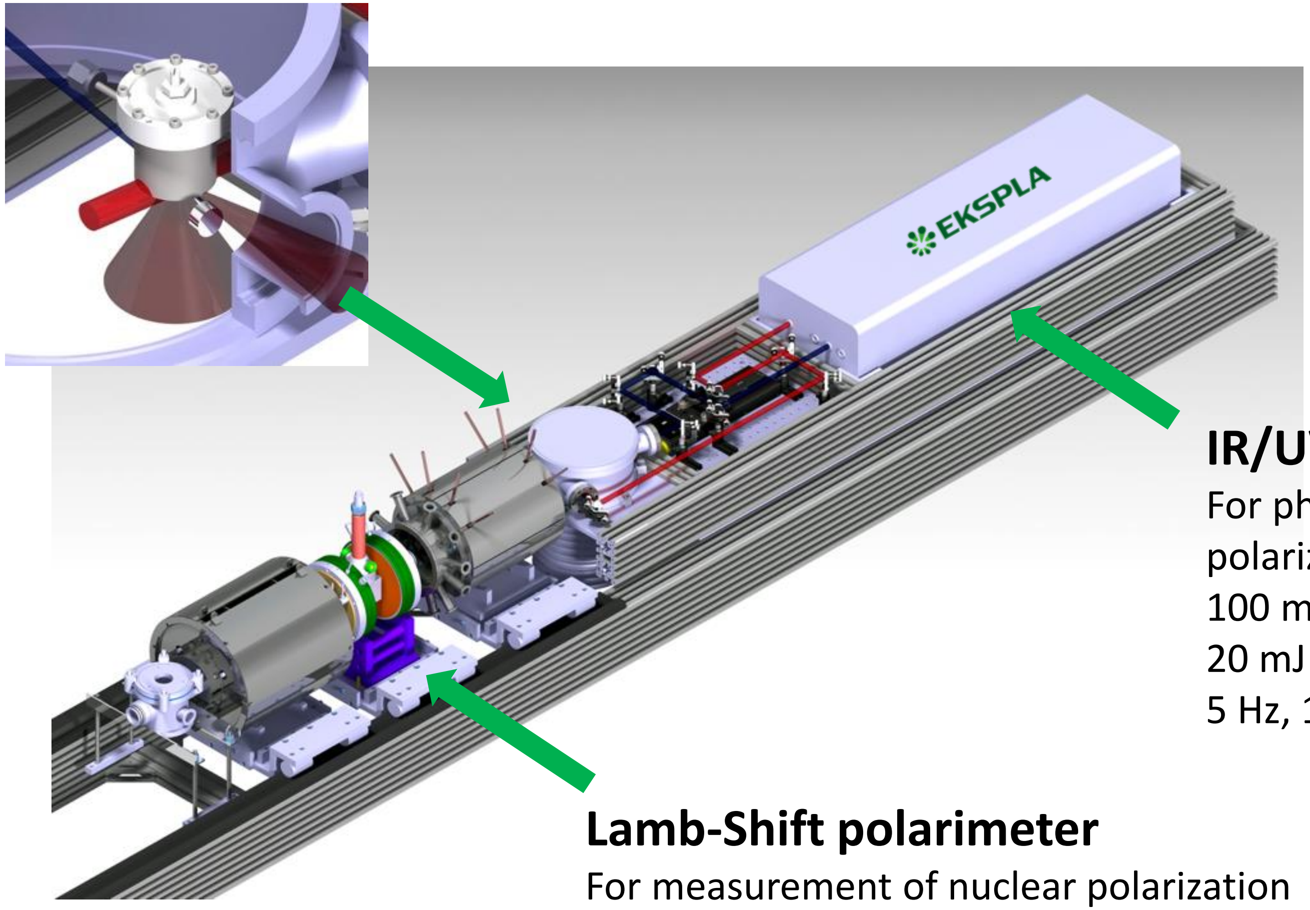
POLARIZED HYDROGEN GAS TARGET

Collaboration with IKP/FZJ & Univ. Crete

Nozzle
For HCl gas jet



Method described in:
T. P. Rakitzis,
Chem.Phys.Chem. **5**, 1489 (2004)

IR/UV Laser
For photo-dissociation & polarization of H atoms,
100 mJ @ 1064 nm,
20 mJ @ 213 nm,
5 Hz, 170 ps

Lamb-Shift polarimeter
For measurement of nuclear polarization
R. Engels et al., Rev.Sci.Instrum. **74**, 4607 (2003)

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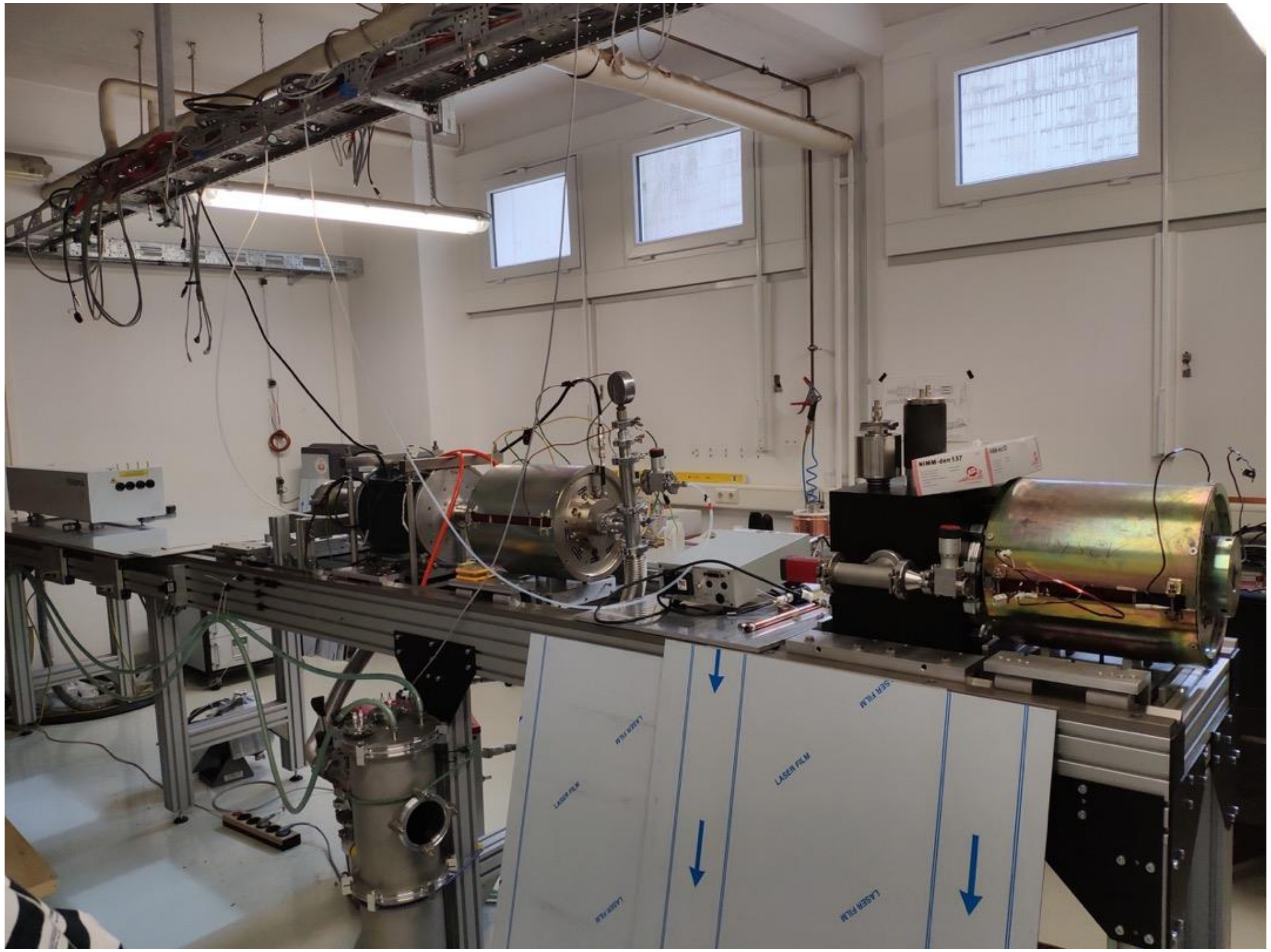
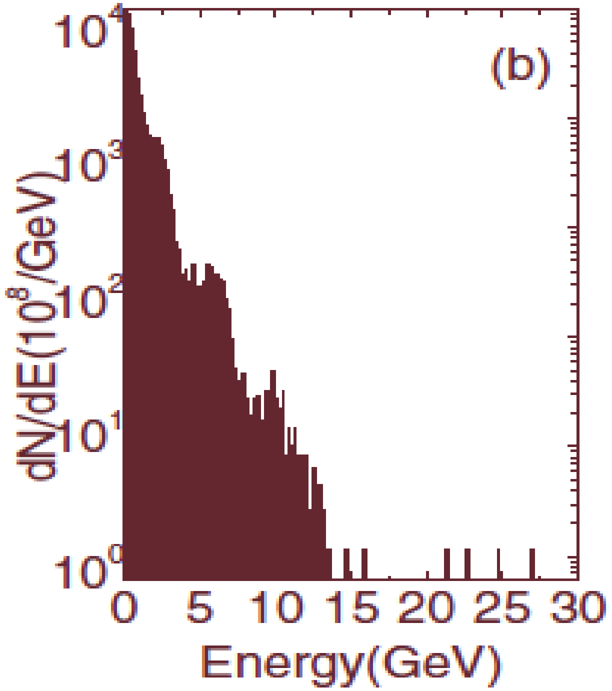
POLARIZED HYDROGEN GAS TARGET

Start of measurements: November 2018



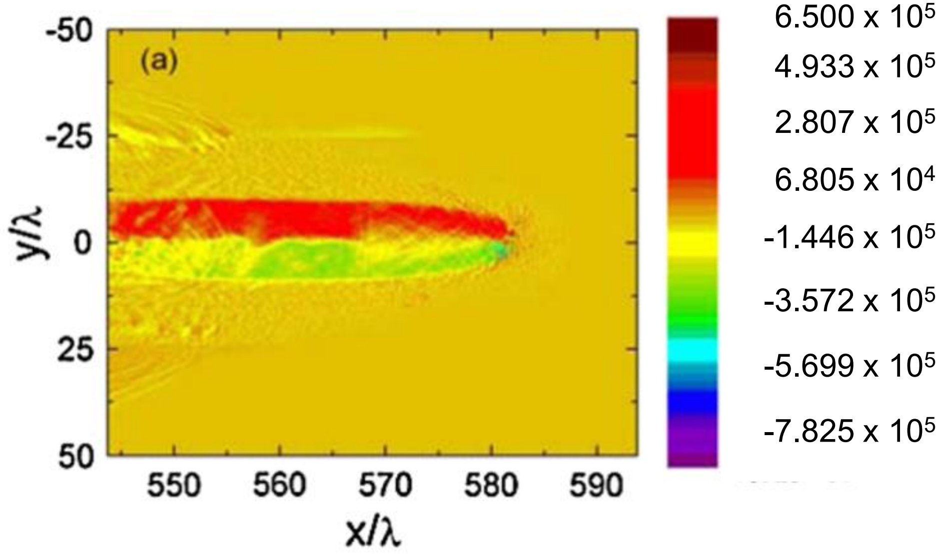
PROTON ACCELERATION IN GAS TARGETS

Proton acceleration into the GeV-regime (here: simulation for H/T gas mixture)



☞ requires Laser powers ≳1 PW!

Long interaction time of protons with huge *B*-field



☞ Spin rotation in plasma likely

B. Shen et al., Phys. Rev. ST Accel. Beams **12**, 121301 (2009) and Phys. Rev. E **76**, 055402R (2007)

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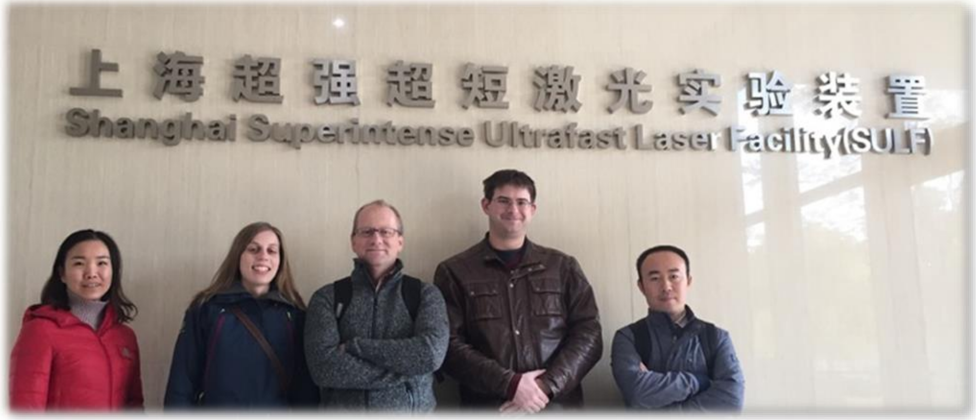
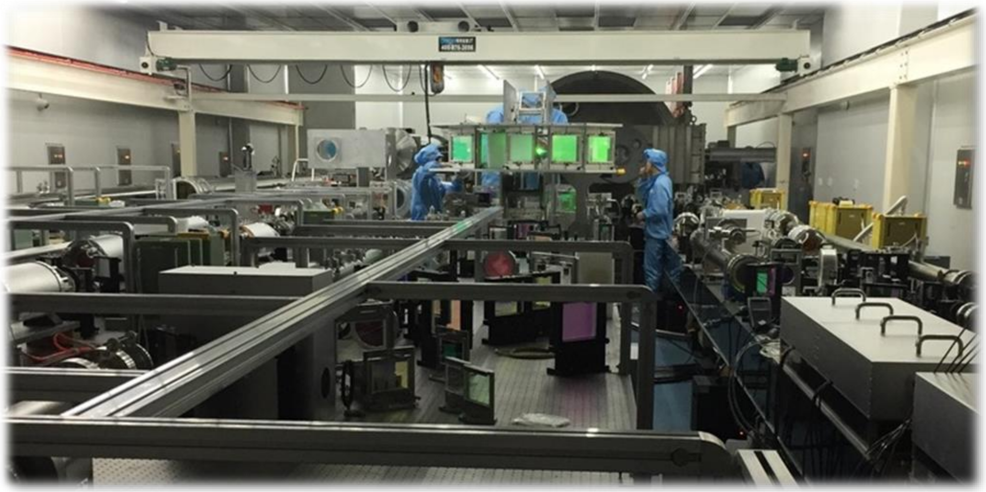
10 PW LASER IN SHANGHAI @ SULF

First experiments on proton acceleration in gas-jet target: Spring 2019





Laser parameters for SULF

- Central wavelength: ~ 800 nm
- Pulse energy: ~ 300 J
- Pulse duration: ~ 30 fs
- Contrast ratio: ~ 10^{11}
- Focused intensity: > 10^{22} W/cm^2

ACKNOWLEDGEMENT

Organizers of

JuSPARC Group at JÜLICH Forschungszentrum

- Markus Büscher
- Andreas Lehrach
- Claus M. Schneider
- Paul Gibbon
- Anna Hützen
- Jürgen Böker
- Ralf Engels
- Ilhan Engin

Shanghai Institute of Optics and Fine Mechanics

- Baifei Shen
- Liangliang Ji
- Lingang Zhang

University of Crete

- T. Peter Rakitzis
- Dimitrios Sofikitis

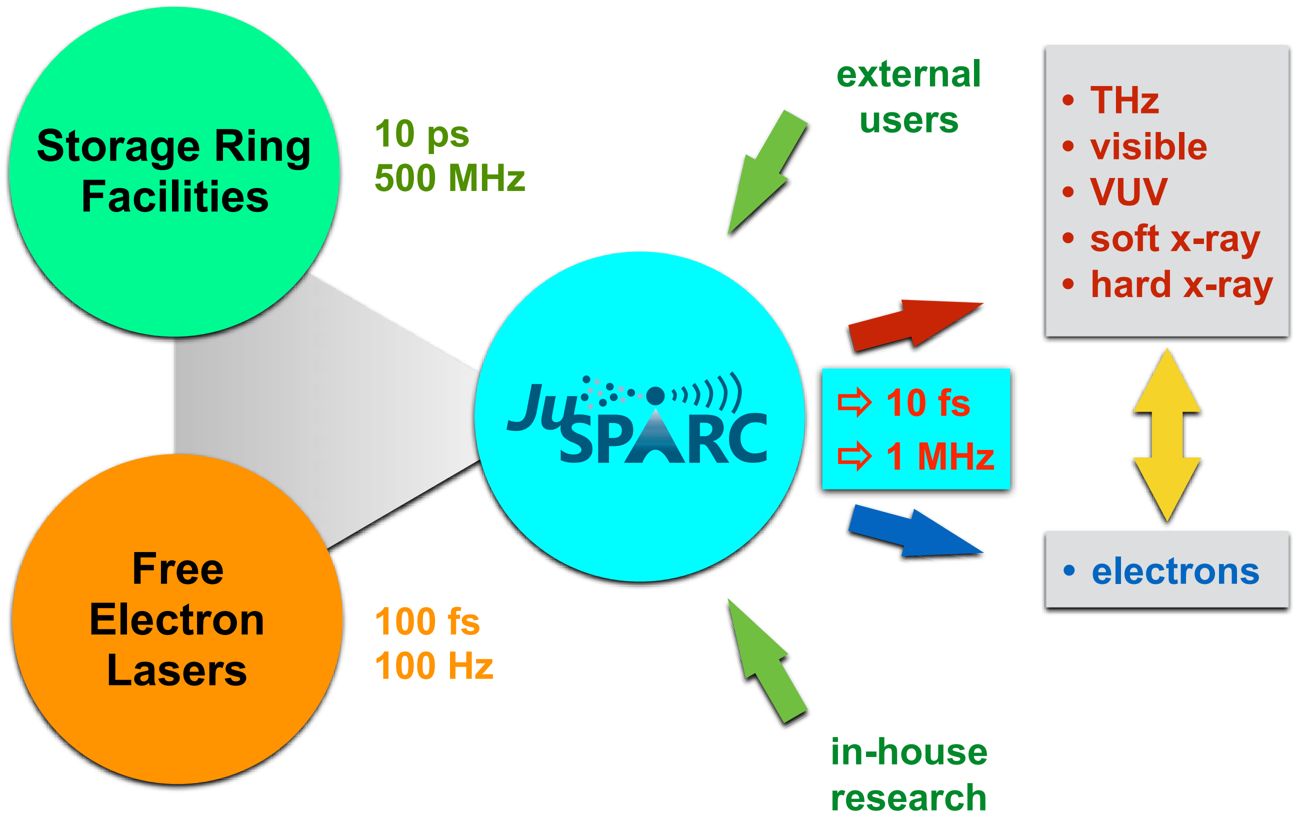
Institut für Theoretische Physik I

- Alexander Pukhov
- Johannes Thomas

QUESTIONS?

*Ju*SPARC: 3RD PILLAR IN THE PHOTON LANDSCAPE

*Ju*SPARC: third pillar in photon landscape



- unique setting due to combination of parameters

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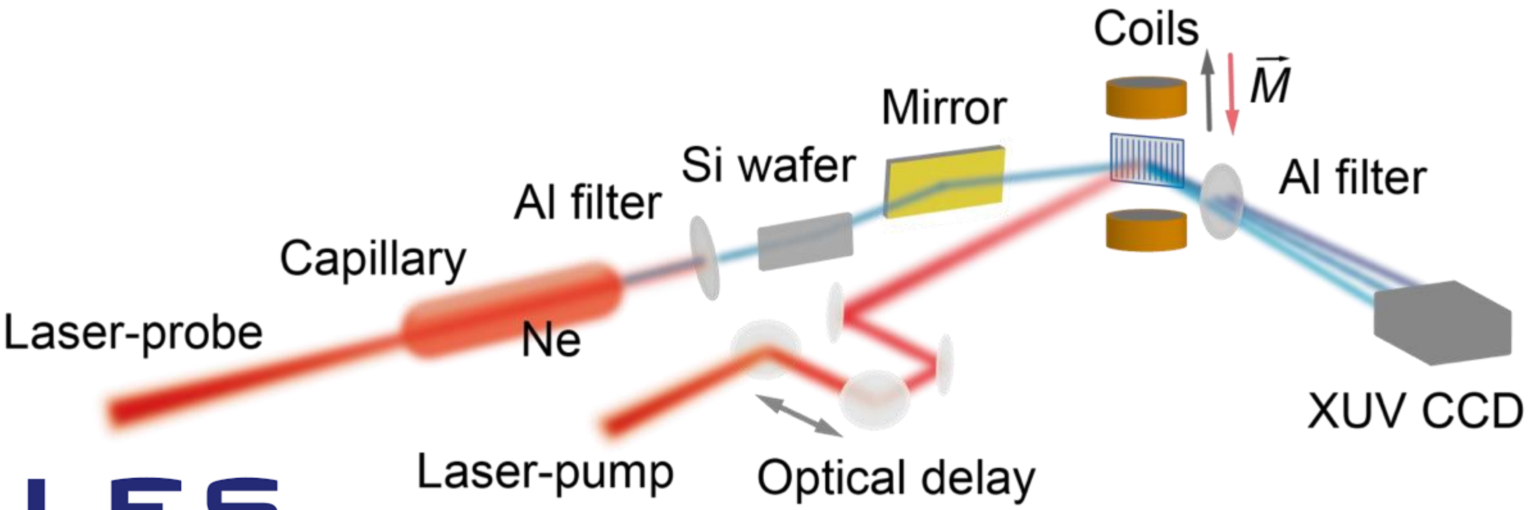
LASER POWERS

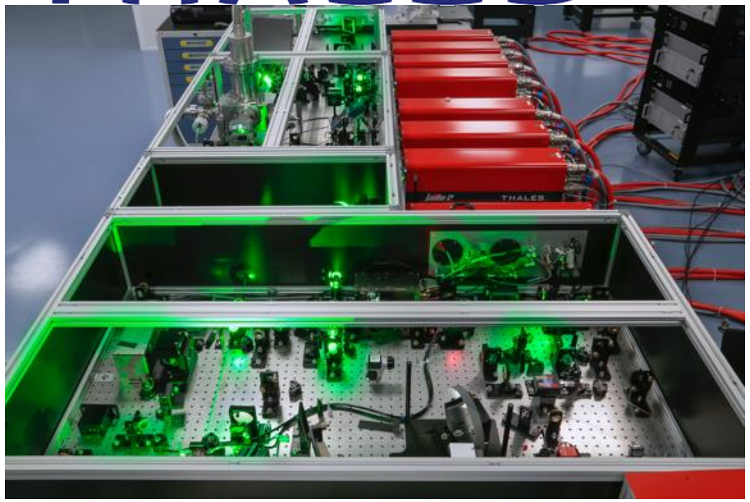
	Typical peak power	Secondary beams
JuSPARC	1 TW	*Photons (x ray), Electrons (?)*
IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES	10 TW	*Electrons*
Düsseldorf ARCturus LASER FACILITY	100 TW	*Electrons, Protons (MeV)*
PHELIX	1 PW	*Protons (10 MeV)*
SIOM	10 PW	*Protons (GeV)*

*Ju*SPARC-1: SOFT X-RAY MAGNETO OPTICS



"Photon in / Photon out"

THALES



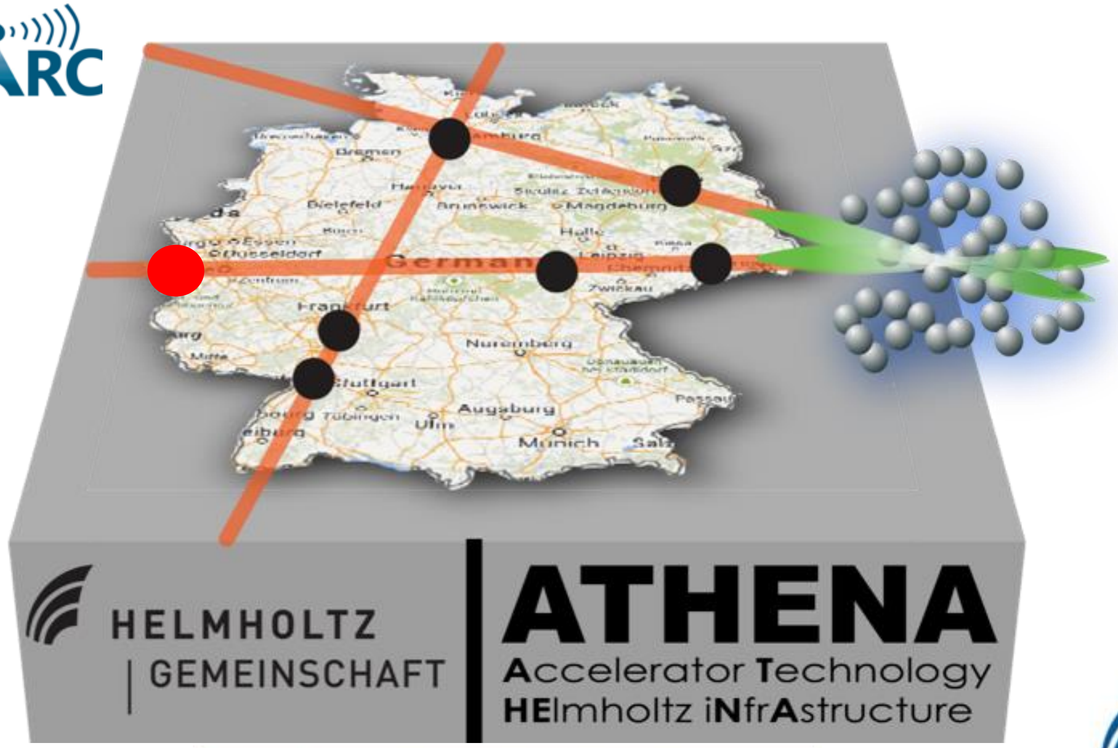
40 mJ / 30 fs / 1 kHz

Goals:

- element-selective magneto optics
- photon energies up to 200 eV
- fs pump-probe studies

TOWARDS *Ju*SPARC-2

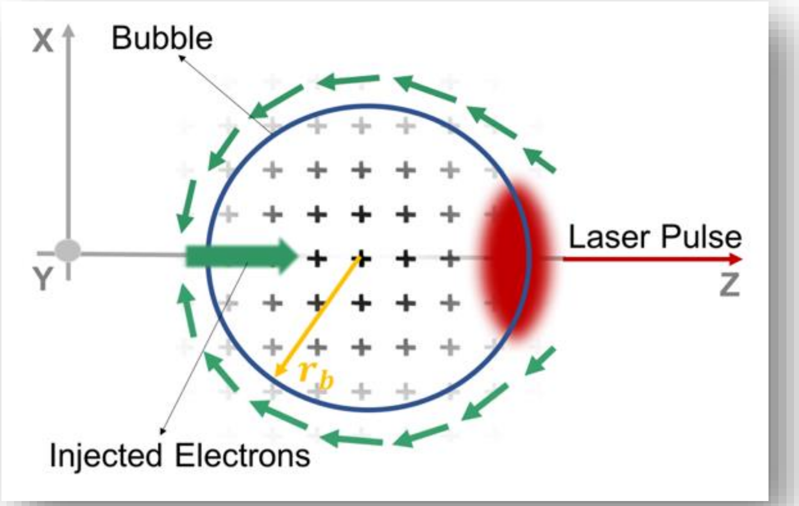
ATHENA: 3.2 M€ for experiments @*Ju*SPARC-1 (2018-2021)

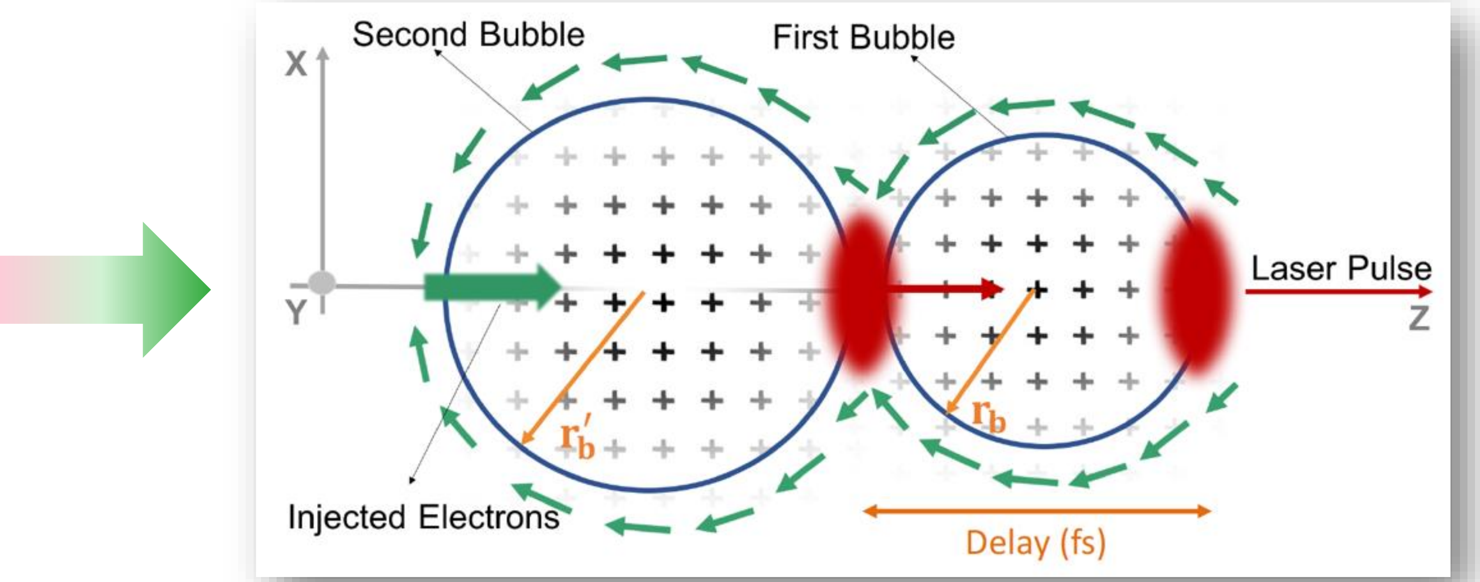


Accelerator Research and Development
ARD
A program by the Helmholtz association

*Ju*SPARC-2: ELECTRON ACCELERATION

Optimization of acceleration processes





Idea: Zahra Chitgar (and IPP Prague) / Publication in prep.

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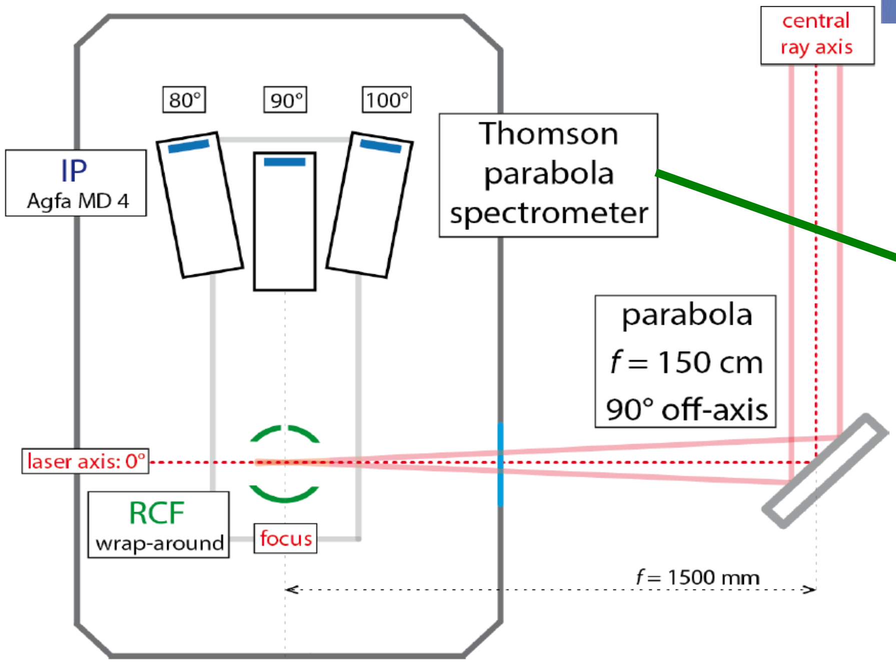
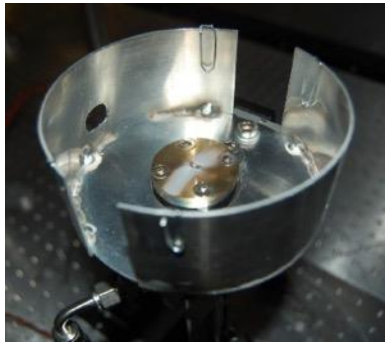
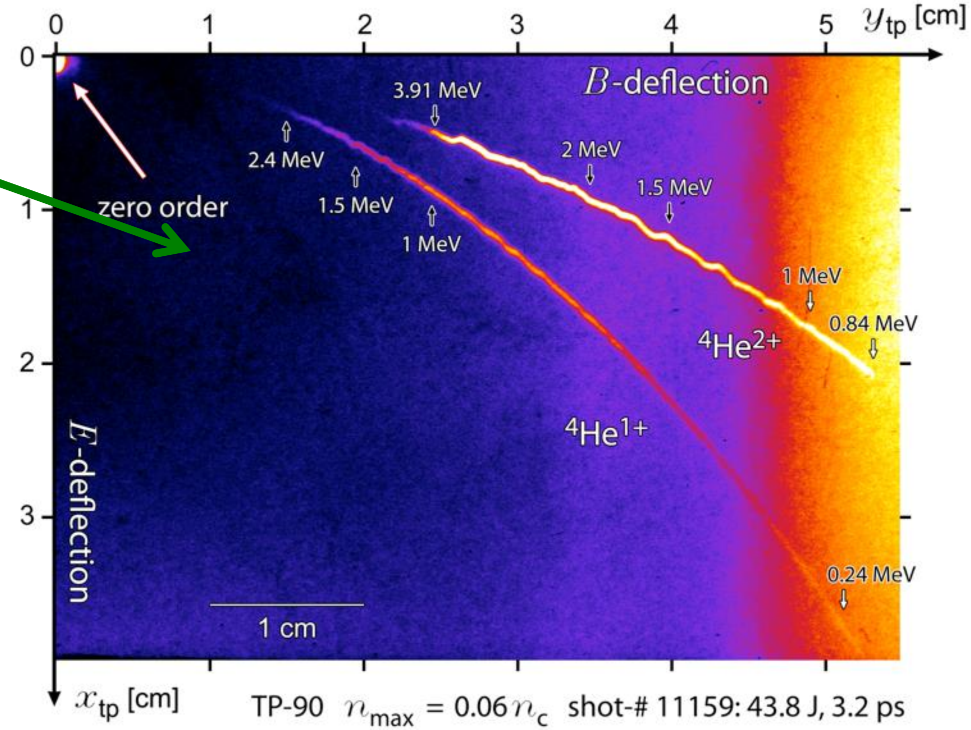
ION ACCELERATION FROM GAS TARGETS

Experiment: Jan. 2015

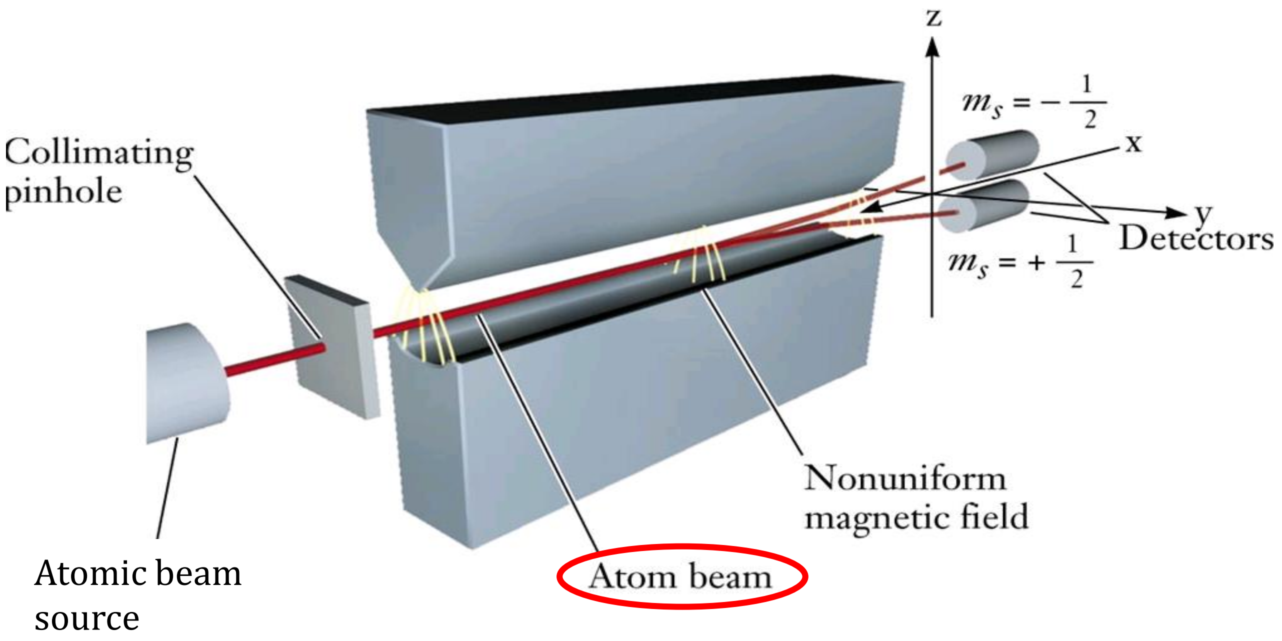






☞ *requires approx. 30 bar gas pressure*

STERN-GERLACH EFFECT

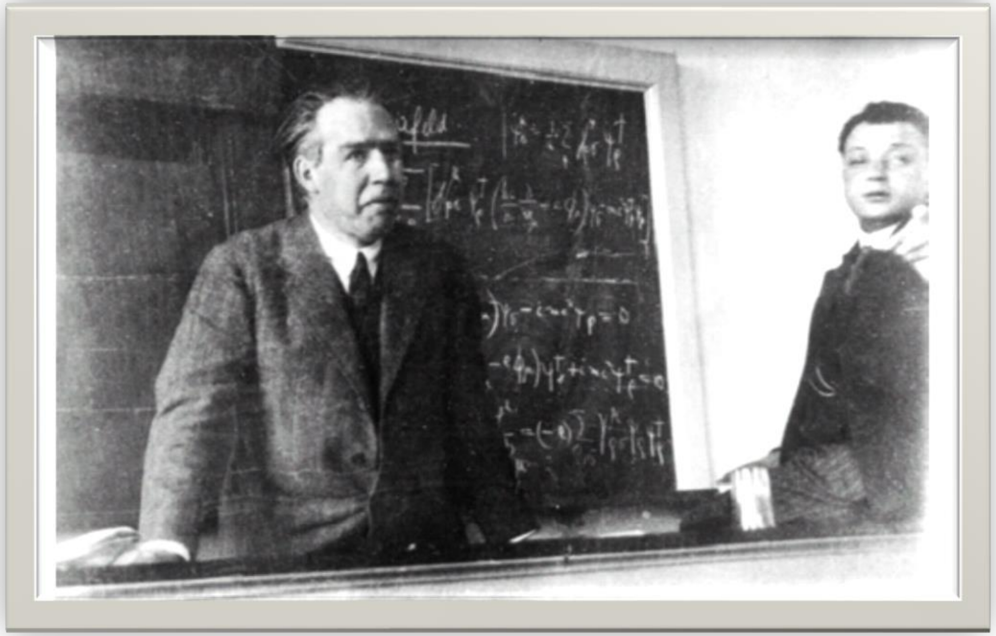


$$\vec{F} = \nabla\left(\vec{\mu}\cdot\vec{B}\right) = \begin{pmatrix} 0 \\ 0 \\ \mu_z \cdot \frac{\partial B}{\partial z} \end{pmatrix}$$

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)

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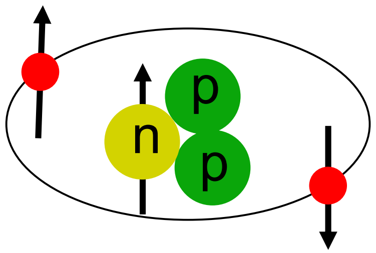
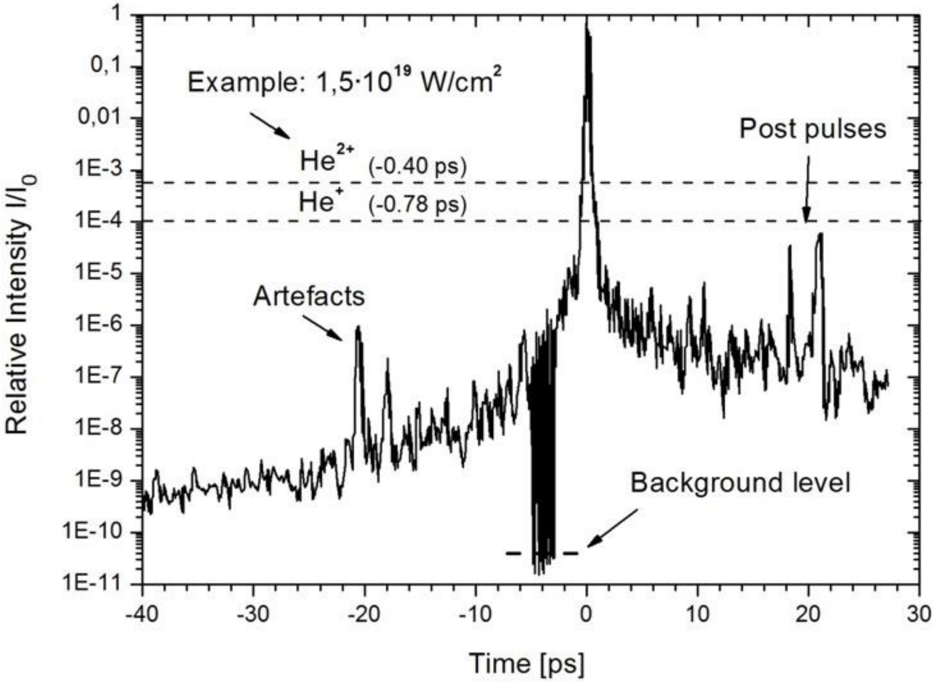
POLARIZATION LOSS DURING IONIZATION?

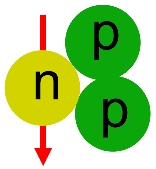
$^3He^{1+}$

$^3He^{2+}$

^3He



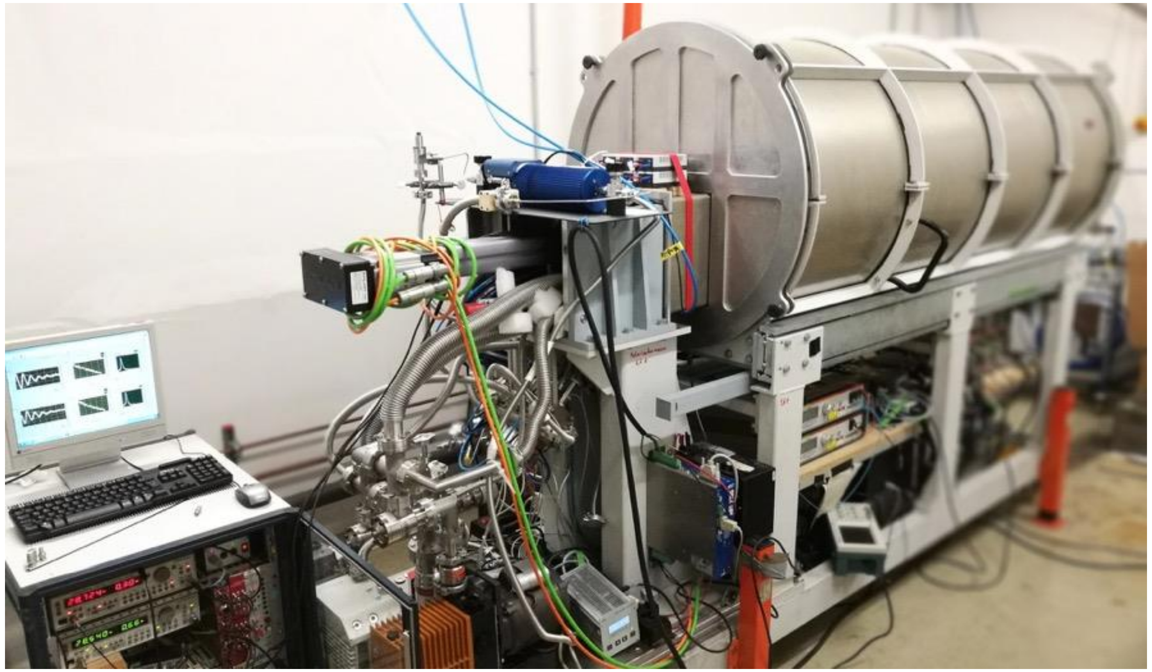


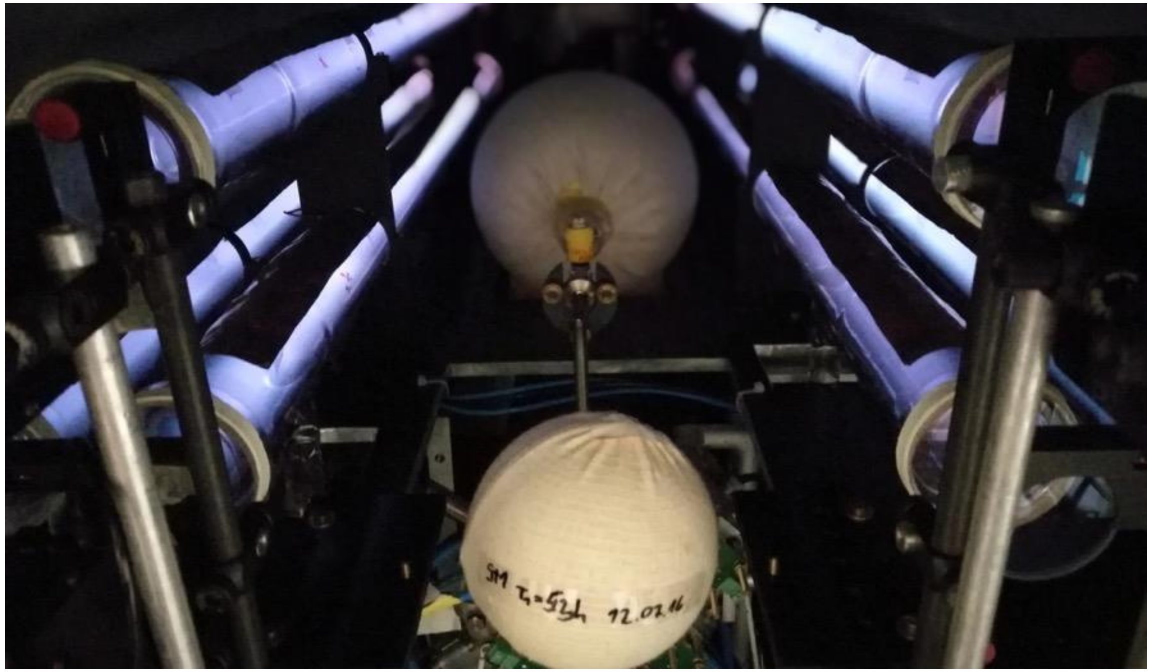


2nd ionization

^{3}HE POLARISER

Transfer Univ. Mainz ➜ Jülich: Summer 2018

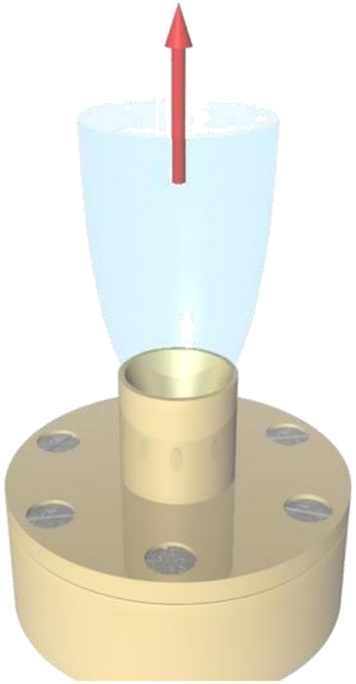




Photos: Ilhan Engin

POLARIZED ^{3}HE GAS: PRESSURE BOOSTER

Input pressure: 3 bar



Output pressure: 50 bar

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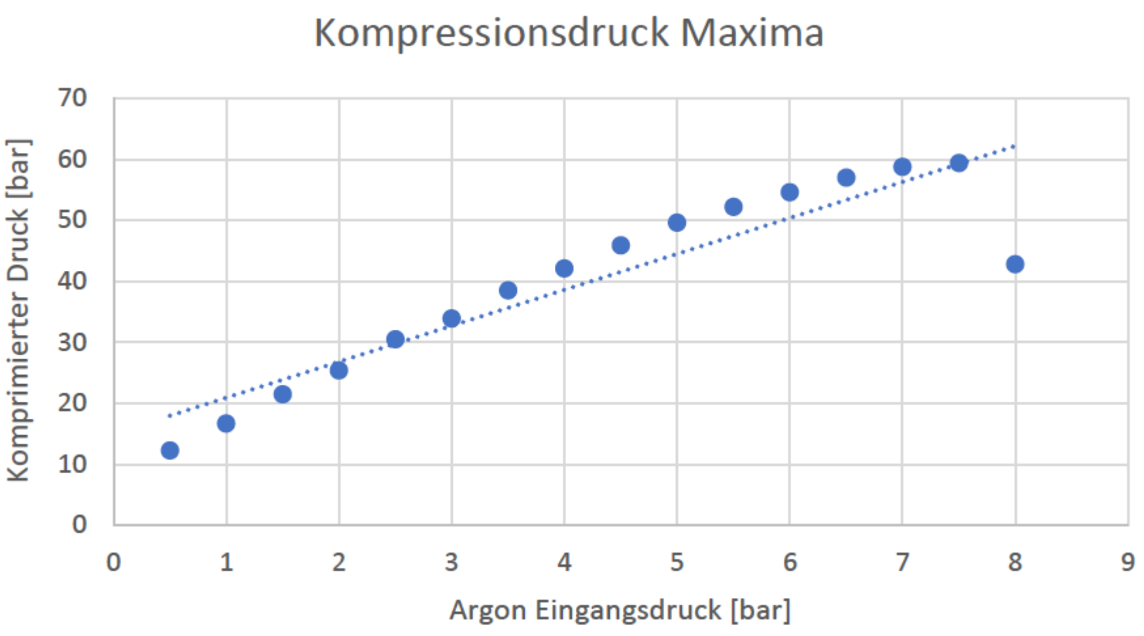
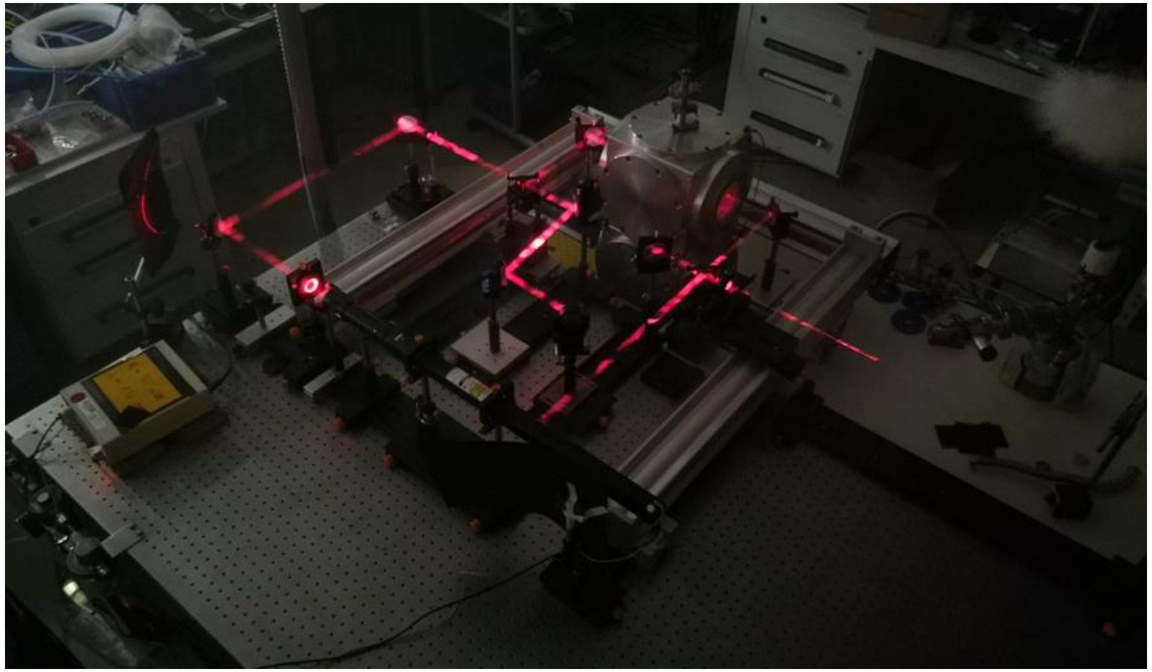
CHARACTERIZATION OF ^{3}HE GAS JET



^{3}He Pressure in compressor

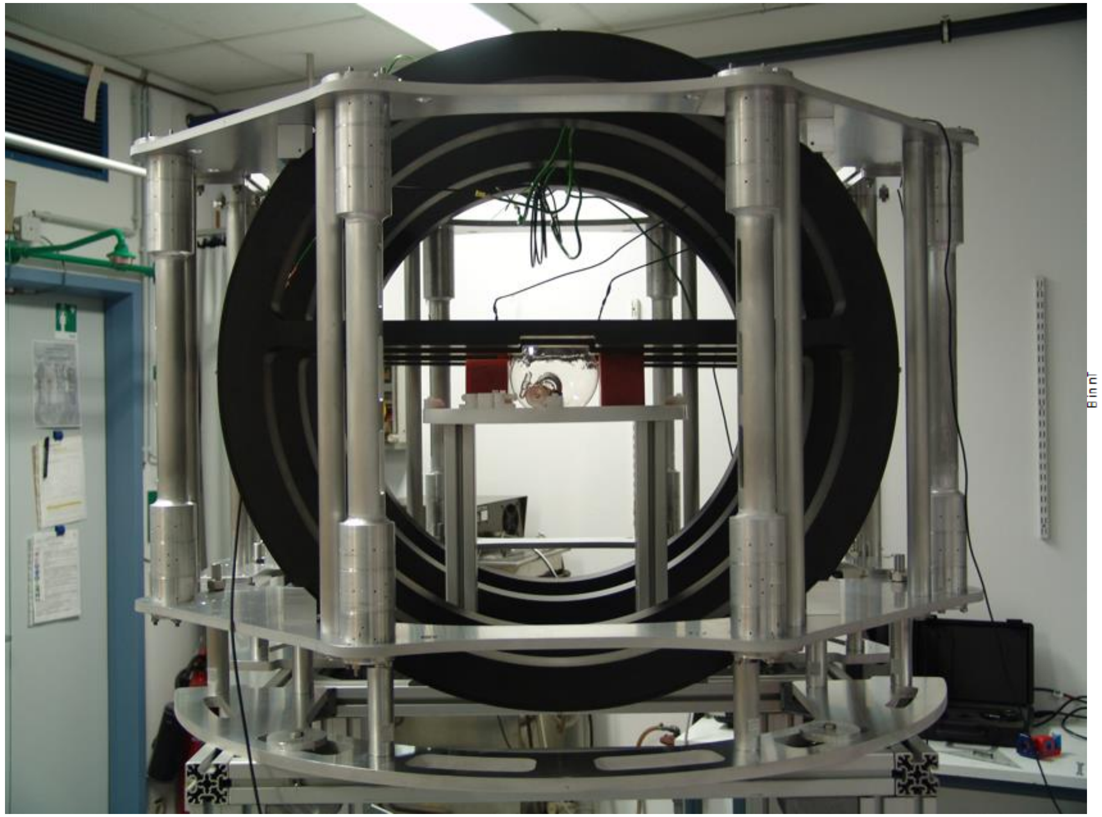


Mach-Zehnder-Interferometer for characterization of gas jet

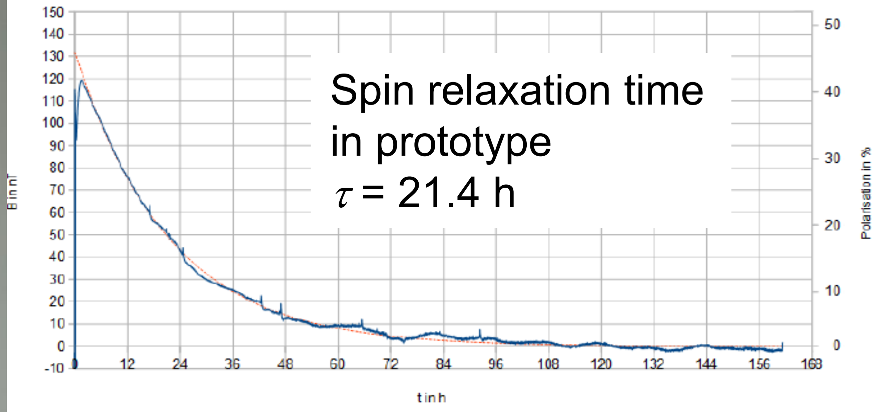
Images: Patrick Spiller

POLARIZED ^{3}HE GAS: MAGNETIC HOLDING FIELD

Permanent magnets (Halbach array) + Helmholtz coils



Jan. 2017



B.Nauschütt,
Bachelor thesis FH Aachen (Aug. 2014)

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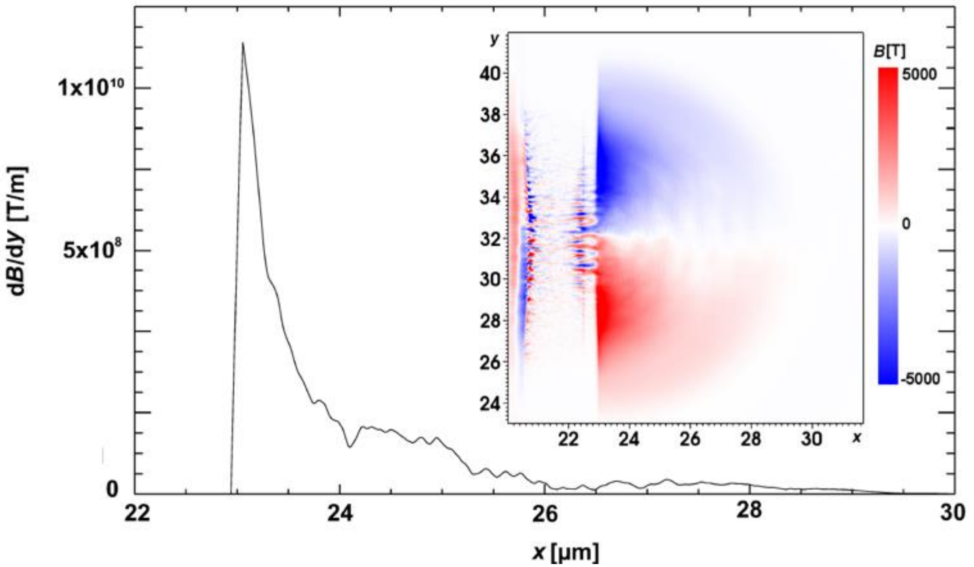
INFLUENCE OF PLASMA FIELDS ON NUCLEAR SPINS?

Simulated *B*-field distribution behind a (unpolarized) foil target

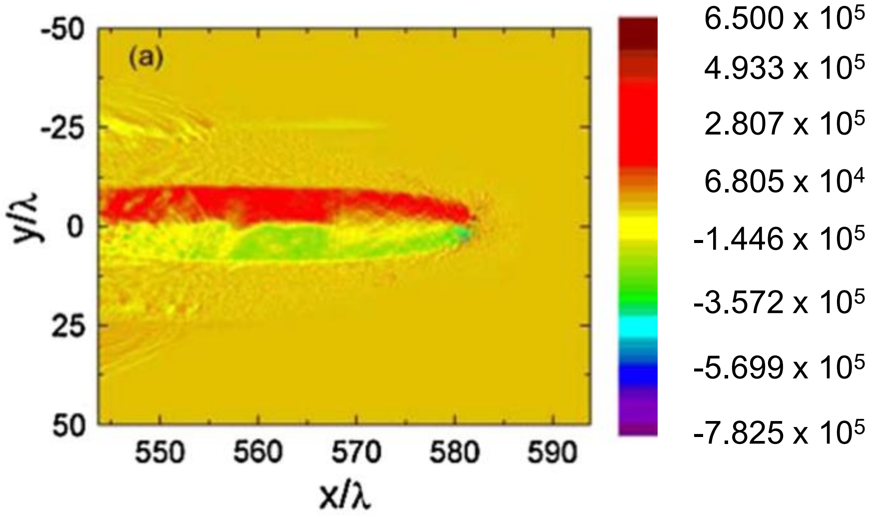


N. Raab et al., Phys. Plasmas **21**, 023104 (2014)

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

Yet too small for polarization to build-up

Spin alignment in gas target w/ multi-PW laser?



B. Shen et al., Phys. Rev. ST Accel. Beams **12**, 121301 (2009)

Long interaction time of protons with *B*-field

➡ Spin rotation very likely

☞ Proton (Hadron) acceleration requires Lasers powers ≳1 PW!