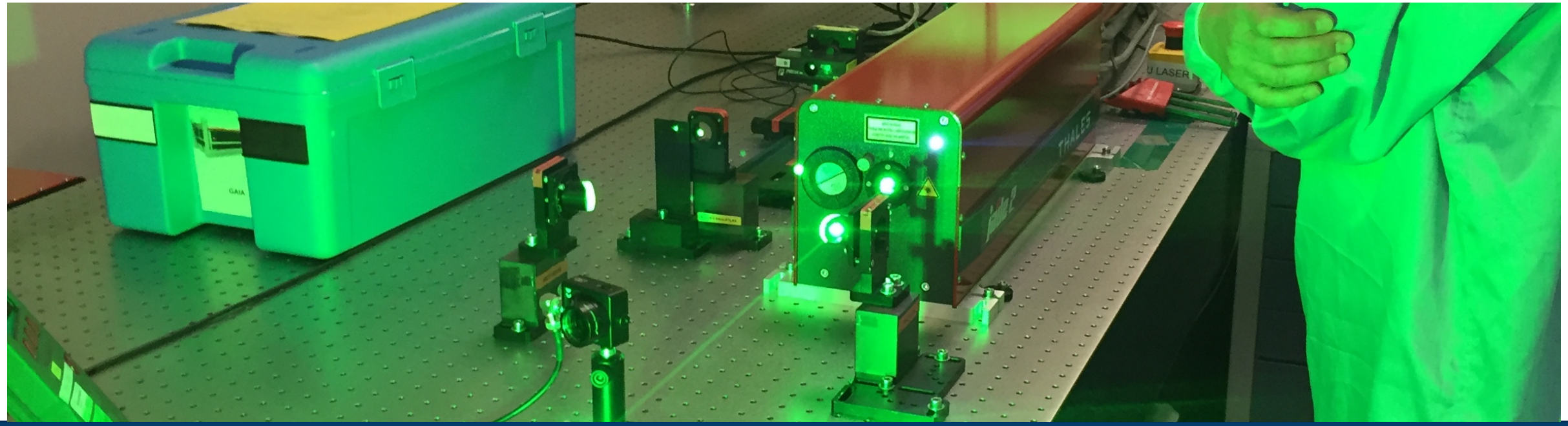


NUCLEAR POLARIZATION IN LASER-INDUCED PLASMAS

(one step towards polarized fusion)

12 SEPTEMBER 2018 | MARKUS BÜSCHER

Mitglied der Helmholtz-Gemeinschaft

JuSPARC

Polarization REsearch for Fusion Experiments and Reactors

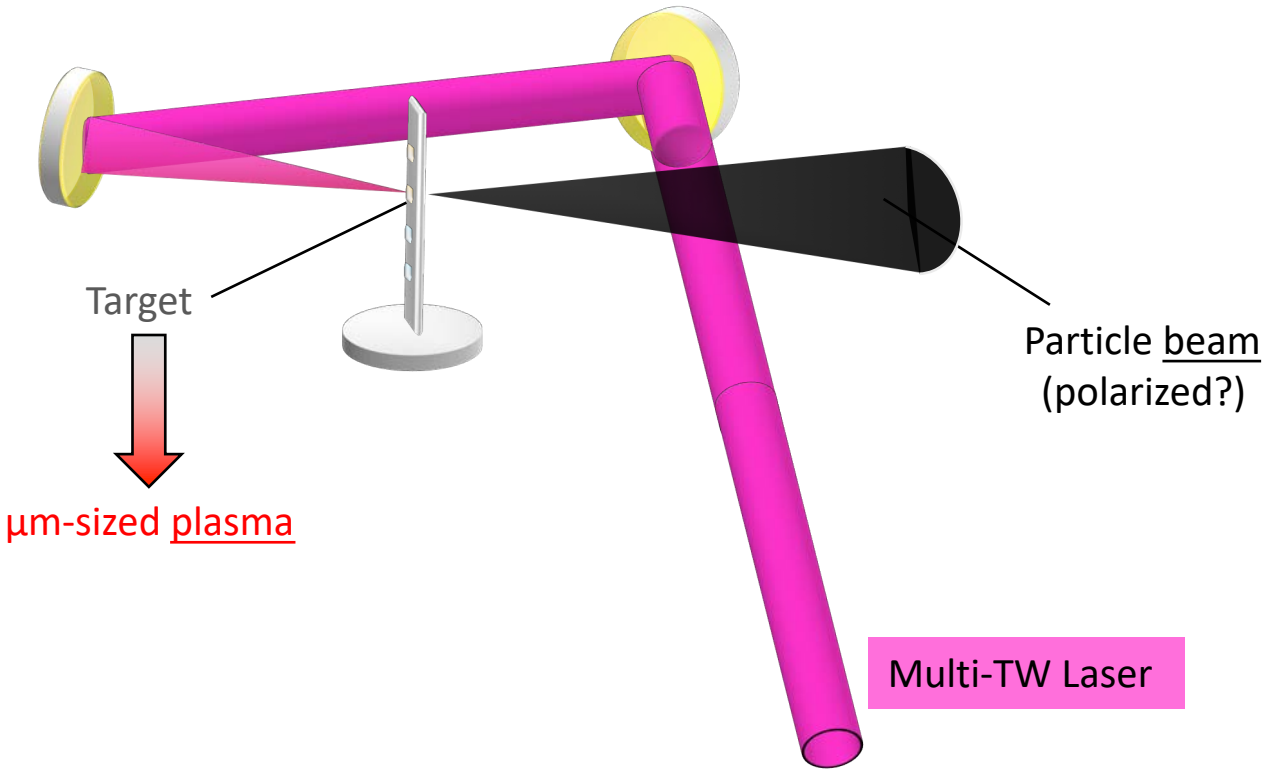
HELMHOLTZ GEMEINSCHAFT | ATHENA Accelerator Technology HElmholtz iNfrAstructure

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

JÜLICH Forschungszentrum

OUR TYPICAL EXPERIMENTS ...

Laser-induced Laser-plasma acceleration



Typical peak power

JuSPARC — 1 TW

Düsseldorf DARC turus LASER FACILITY — 100 TW

PHELIX — 1 PW

SIOM — 10 PW

FUSION REACTIONS IN LASER-INDUCED PLASMAS

Here: D + D → ^{3}He + *n* / Experiment @ Max-Planck-Institut für Quantenoptik (CD_2 foil target)

PHYSICAL REVIEW E VOLUME 58, NUMBER 1 JULY 1998

Neutron production by 200 mJ ultrashort laser pulses

G. Pretzler,[1] A. Saemann,[1] A. Pukhov,[1] D. Rudolph,[2] T. Schätz,[2] U. Schramm,[2] P. Thirolf,[2] D. Habs,[2] K. Eidmann,[1] G. D. Tsakiris,[1] J. Meyer-ter-Vehn,[1] and K. J. Witte[1]

[1]*Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*

[2]*Sektion Physik, LMU München, Am Coulombwall 1, D-85748 Garching, Germany*

(Received 27 October 1997; revised manuscript received 30 January 1998)

1.25 TW

We report the observation of neutrons released from $d(d,n)^3$He fusion reactions in the focus of 200 mJ, 160 fs Ti:sapphire laser pulses on a deuterated polyethylene target. Optimizing the fast electron and ion generation by applying a well-defined prepulse led to an average rate of 140 neutrons per shot. Furthermore, the production of a substantial number of MeV γ rays could be observed. The occurrence of neutrons and γ rays is attributed to the formation and explosion of a relativistic plasma channel in the laser focus, which is confirmed by numerical calculations. [S1063-651X(98)08507-9]

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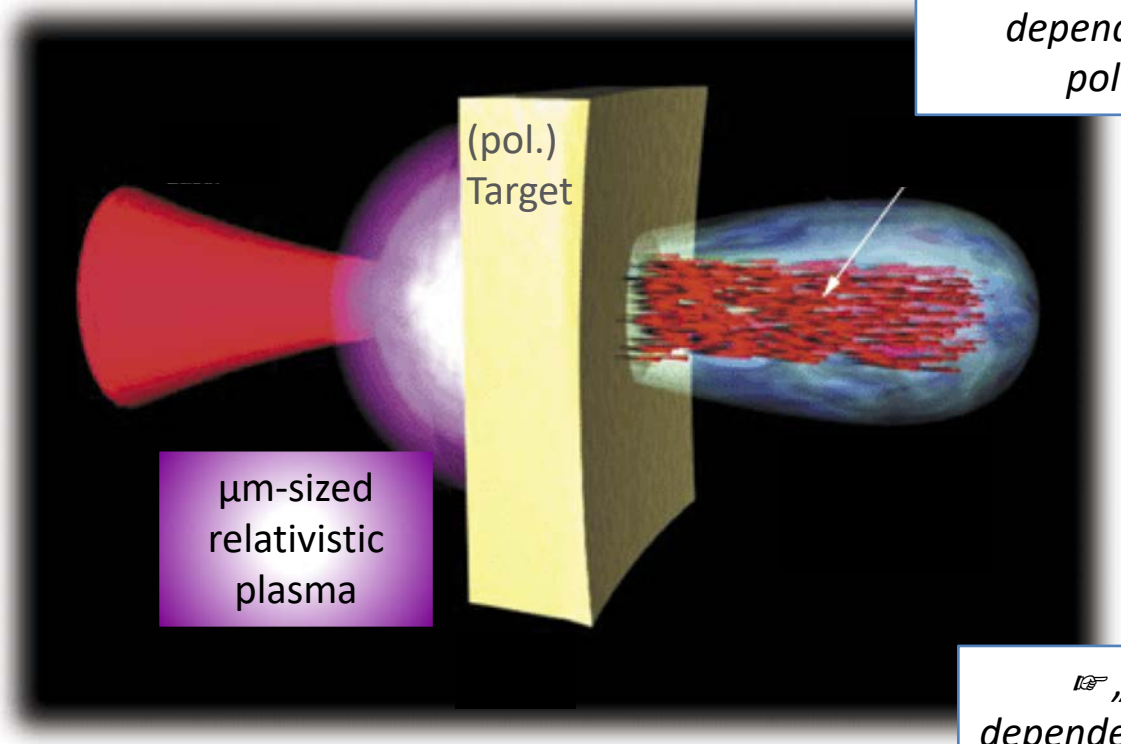
OUR TYPICAL EXPERIMENTS ...

Laser-induced Laser-plasma acceleration

Fusion reactions

☞ „*Does the fusion rate depend on the target polarization?*“



Multi-TW laser beam

Accelerated Ions

☞ „*Are the accelerated ions polarized?*“

☞ „*Angular dependence of fusion products?*“

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HOW ARE POLARIZED BEAMS PRODUCED?

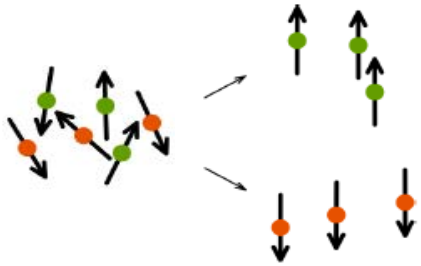
Conventional accelerators:
Cooler Synchrotron COSY-Jülich

Reach fundamental & technological limits

Possible scenarios in laser-induced plasmas

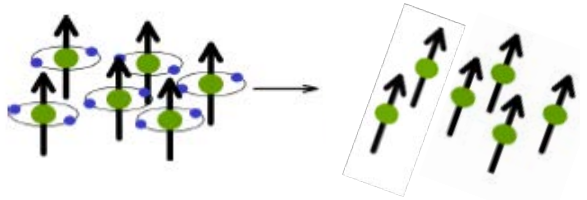
Polarization is generated

spin flip
Sokolov-Ternov effect



Stern-Gerlach effect

Polarization is preserved

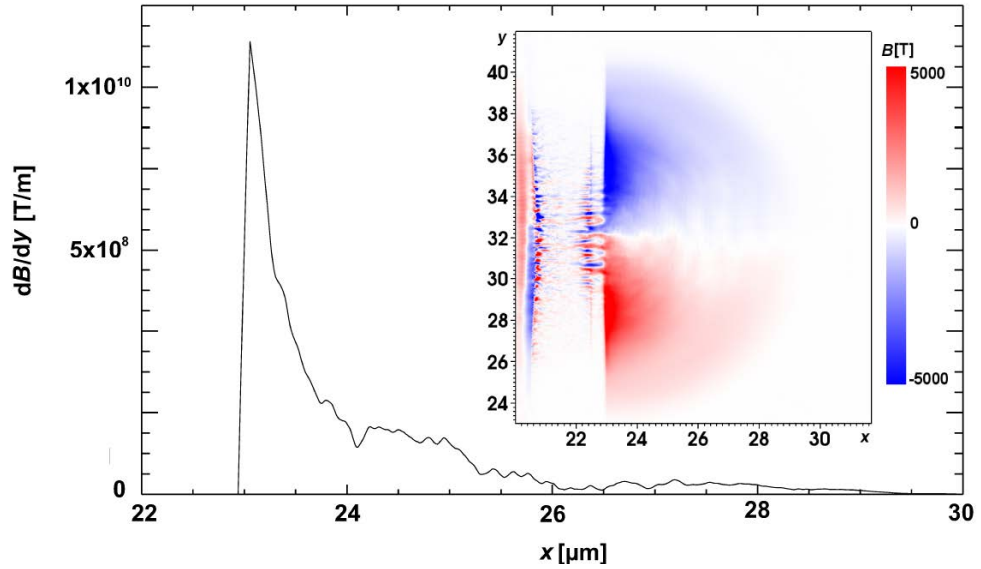


Thomas-BMT equation

New applications for table-top experiments

INFLUENCE OF PLASMA FIELDS ON NUCLEAR SPINS?

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

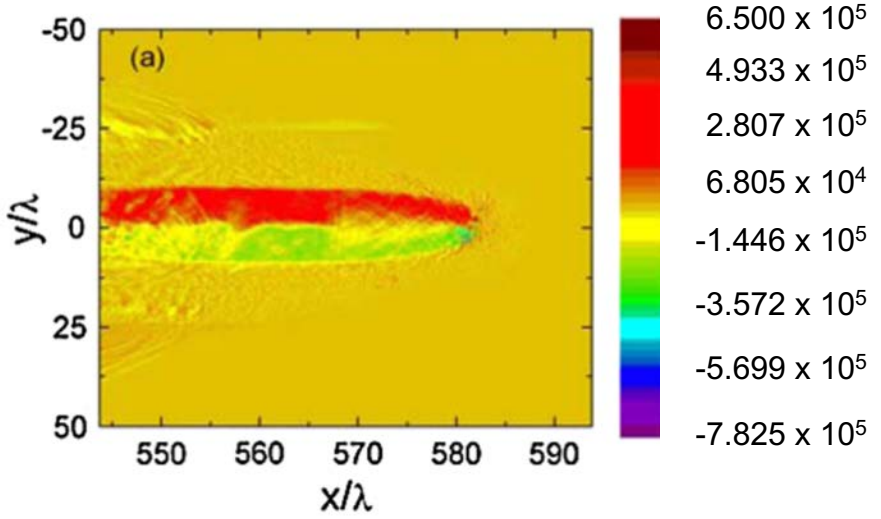


N. Raab et al., Phys. Plasmas **21**, 023104 (2014)

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

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HISTORY: FIRST POLARIZATION EXPERIMENT

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

Peak power: 2 x 200 TW
Pulse energy: up to 4 J
Pulse duration: 25 fs

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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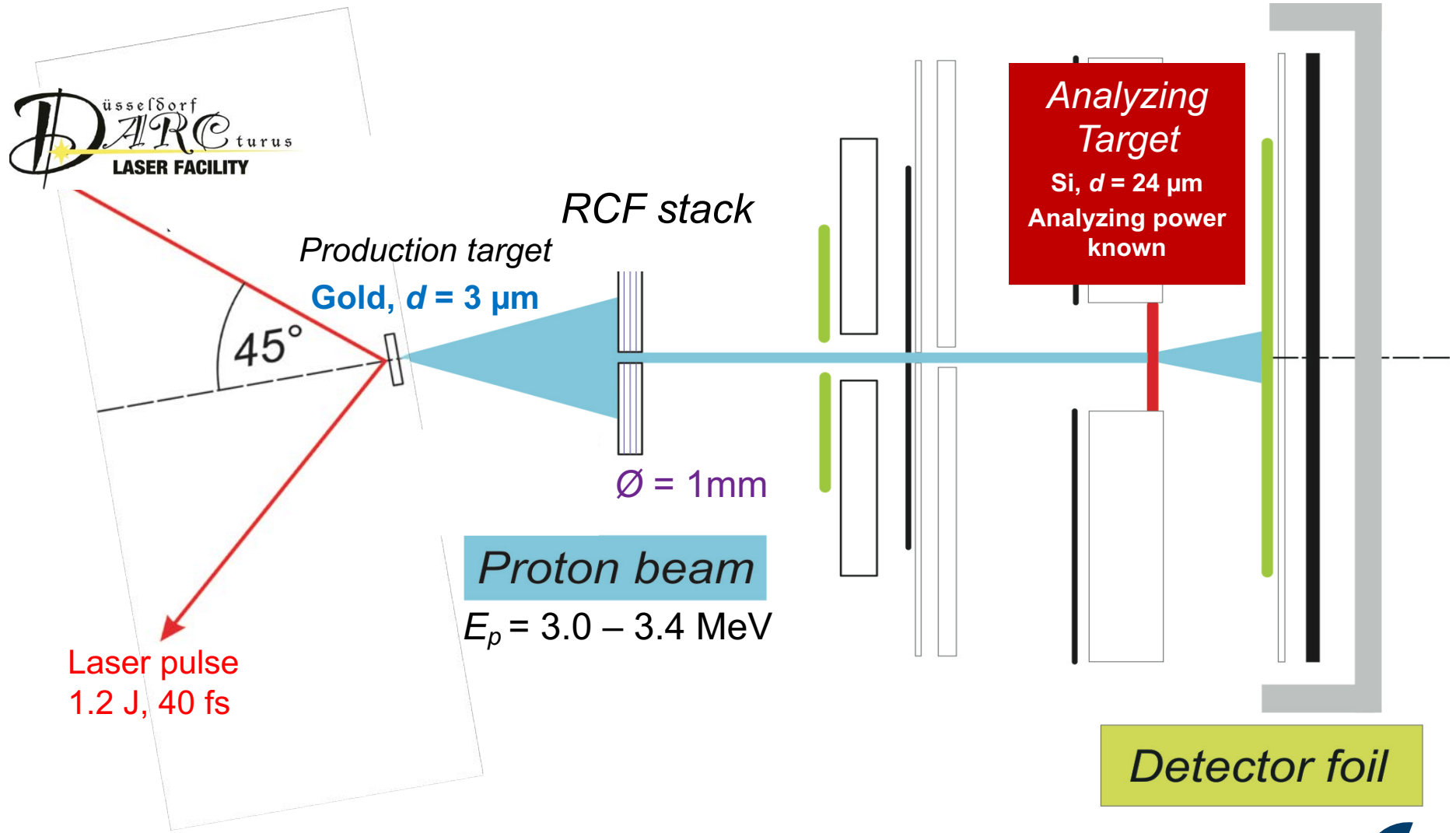
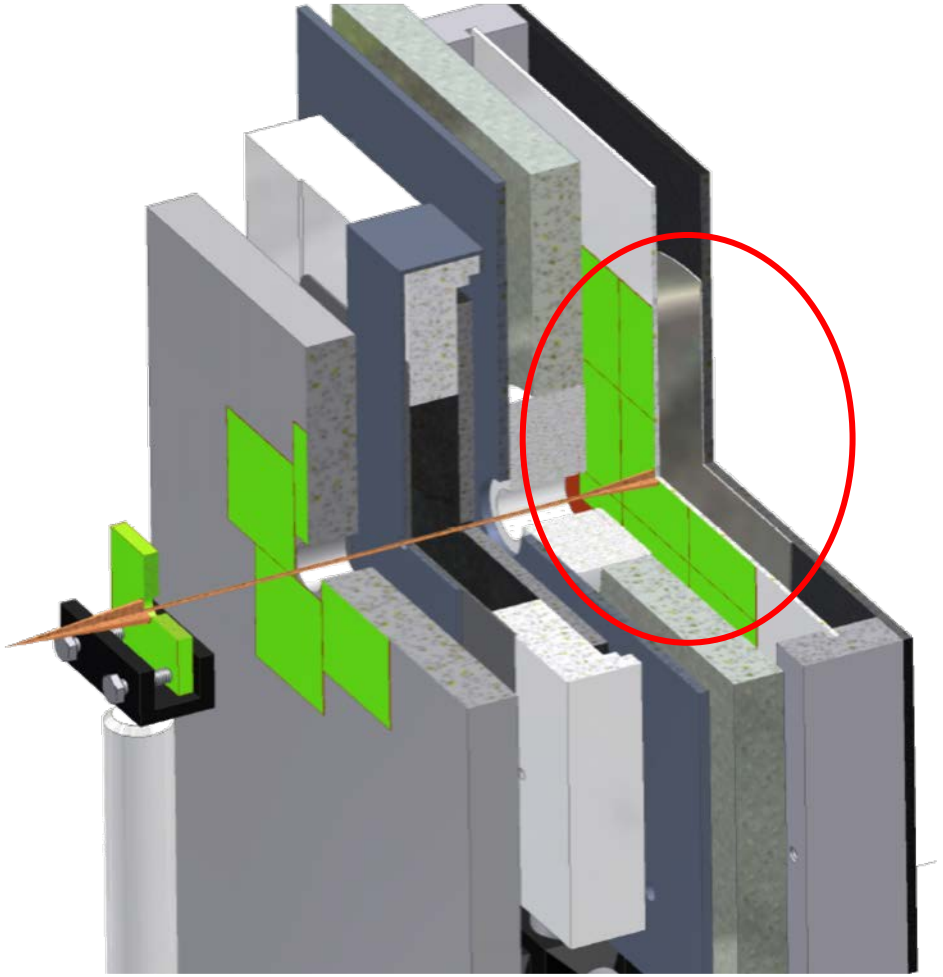
HISTORY: FIRST POLARIZATION EXPERIMENT

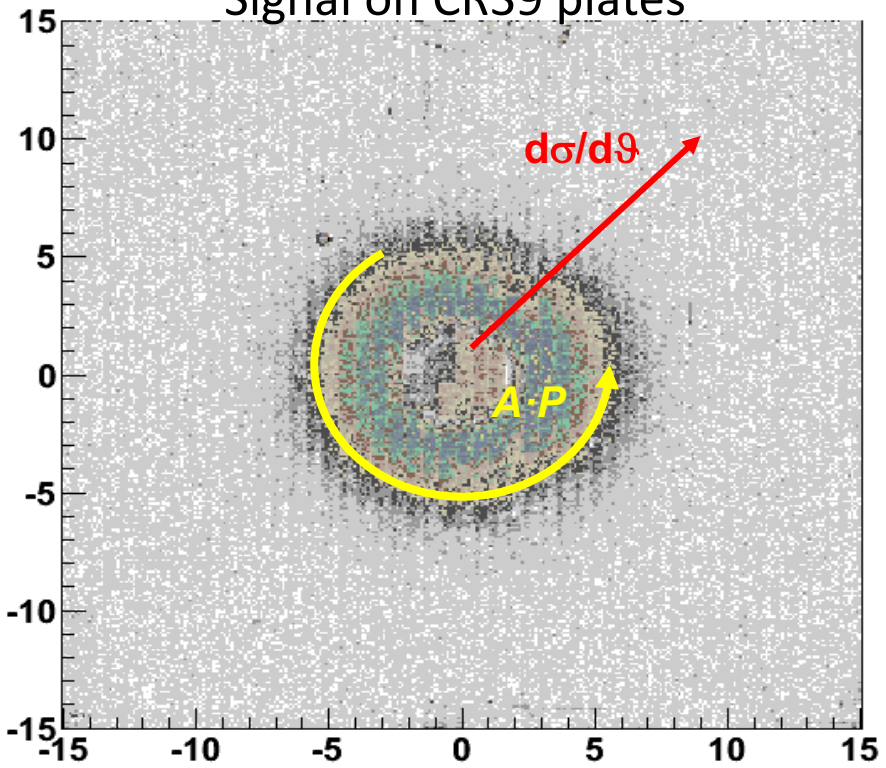


POLARIMETRY FOR MEV PROTONS

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



Signal on CR39 plates



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

HISTORY: FIRST POLARIZATION EXPERIMENT

International Journal of High-Energy Physics

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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.

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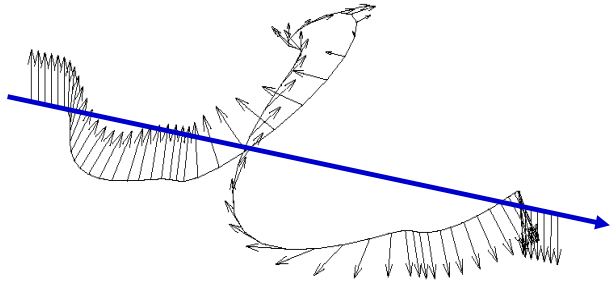
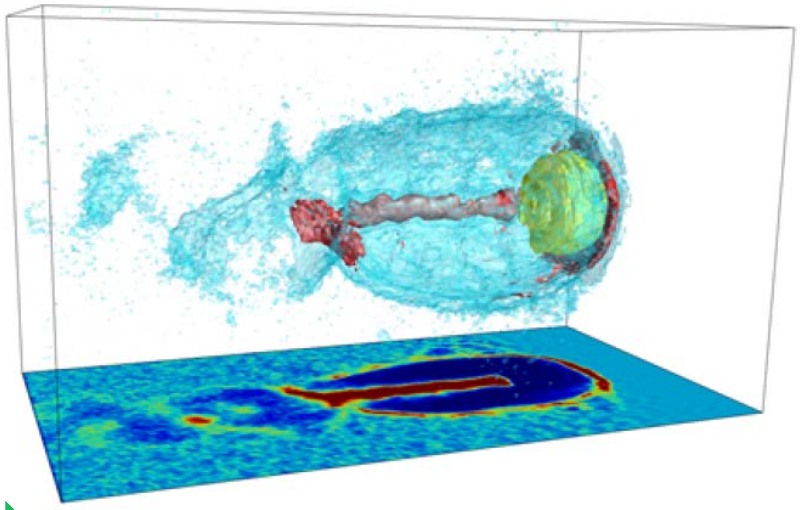
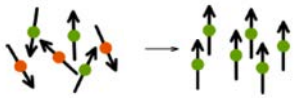
FEATURED COMPANIES

MODELLING OF SPINS IN LASER-INDUCED PLASMAS

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

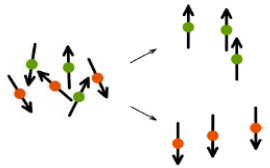






Sokolov-Ternov effect → PIC Code (VLPL)

→ Characteristic time for spin flips too short

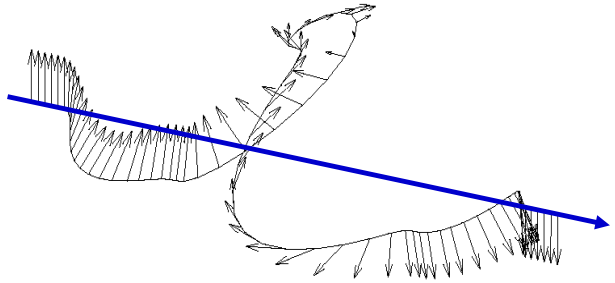


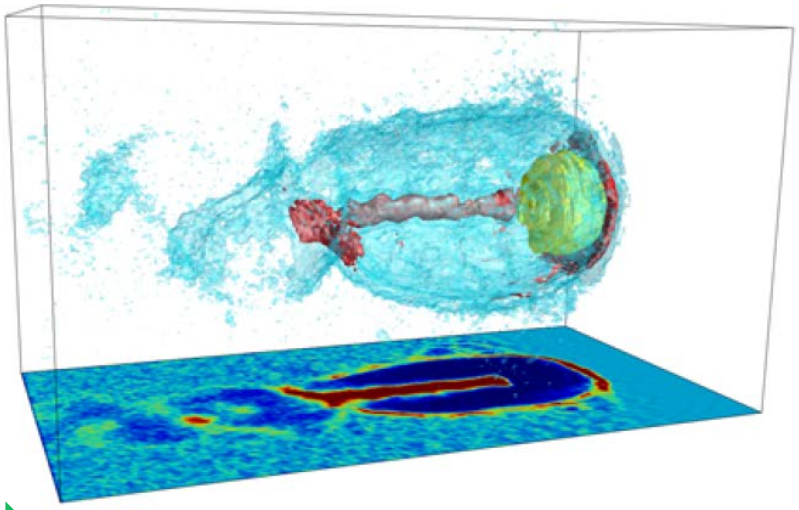
Stern-Gerlach effect → PIC Code (VLPL)

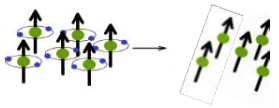
→ Force for spatial separation on the given length scale too weak

MODELLING OF SPINS IN LASER-INDUCED PLASMAS

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





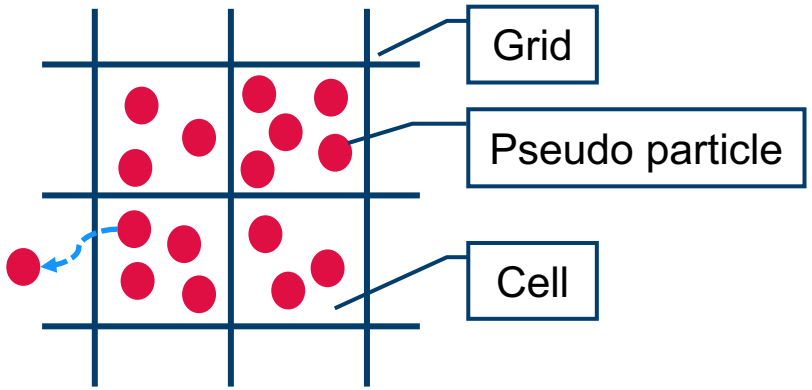


Thomas-BMT equation → PIC Code (VLPL)

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

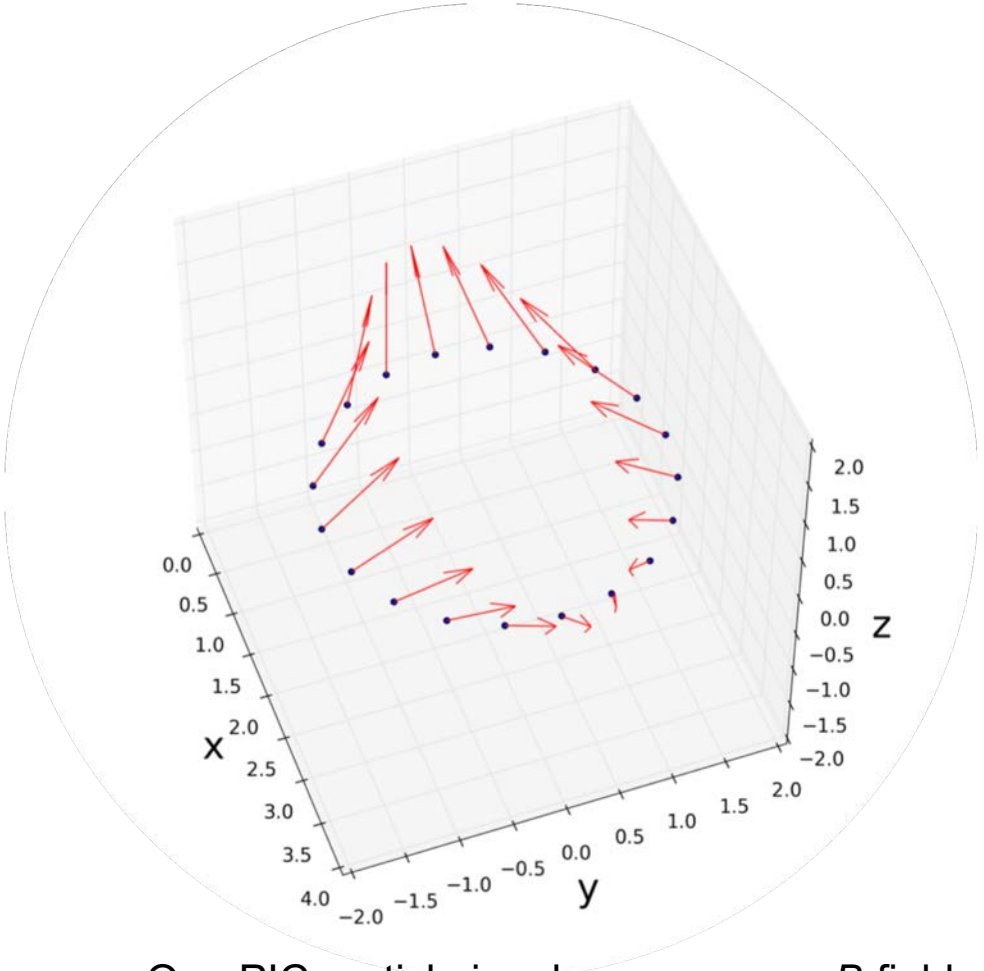


Spatial domain

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 temporal mean value of one single particle, depending on the PIC weight.



One PIC particle in a homogeneous *B*-field

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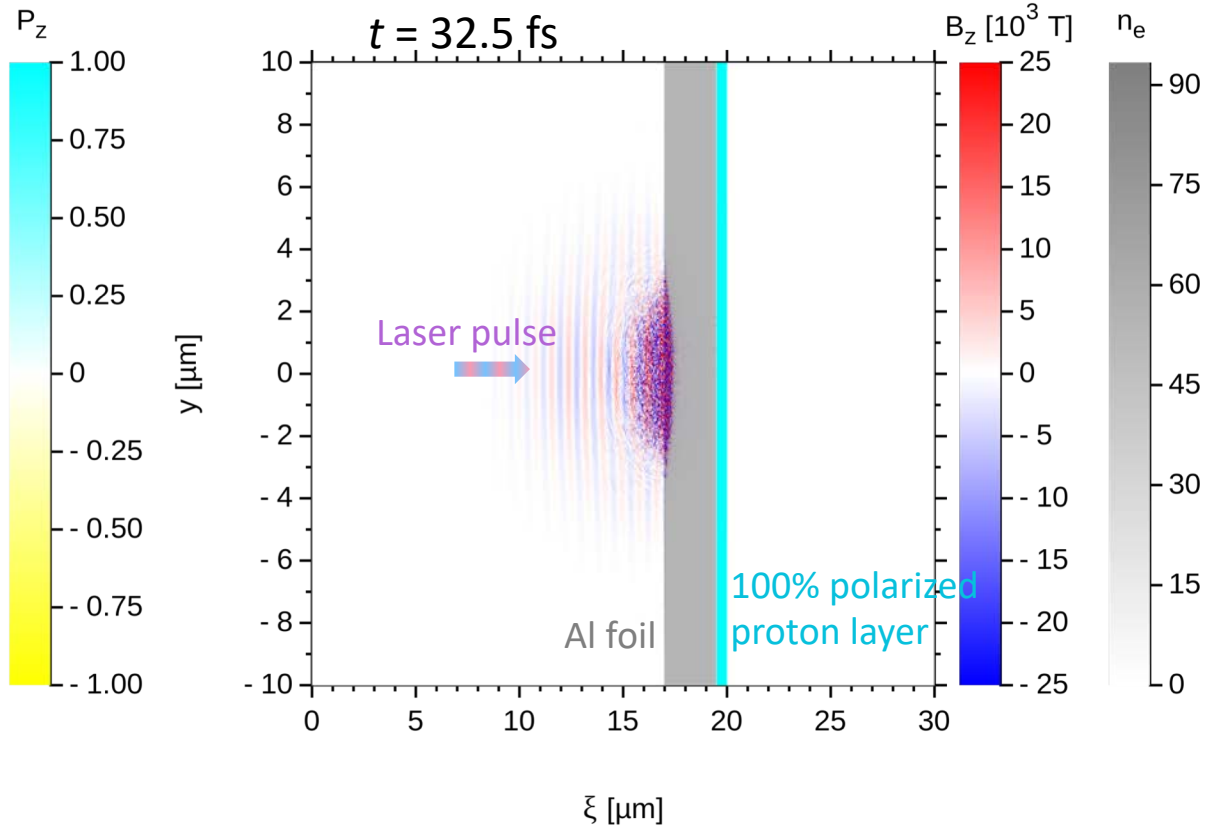
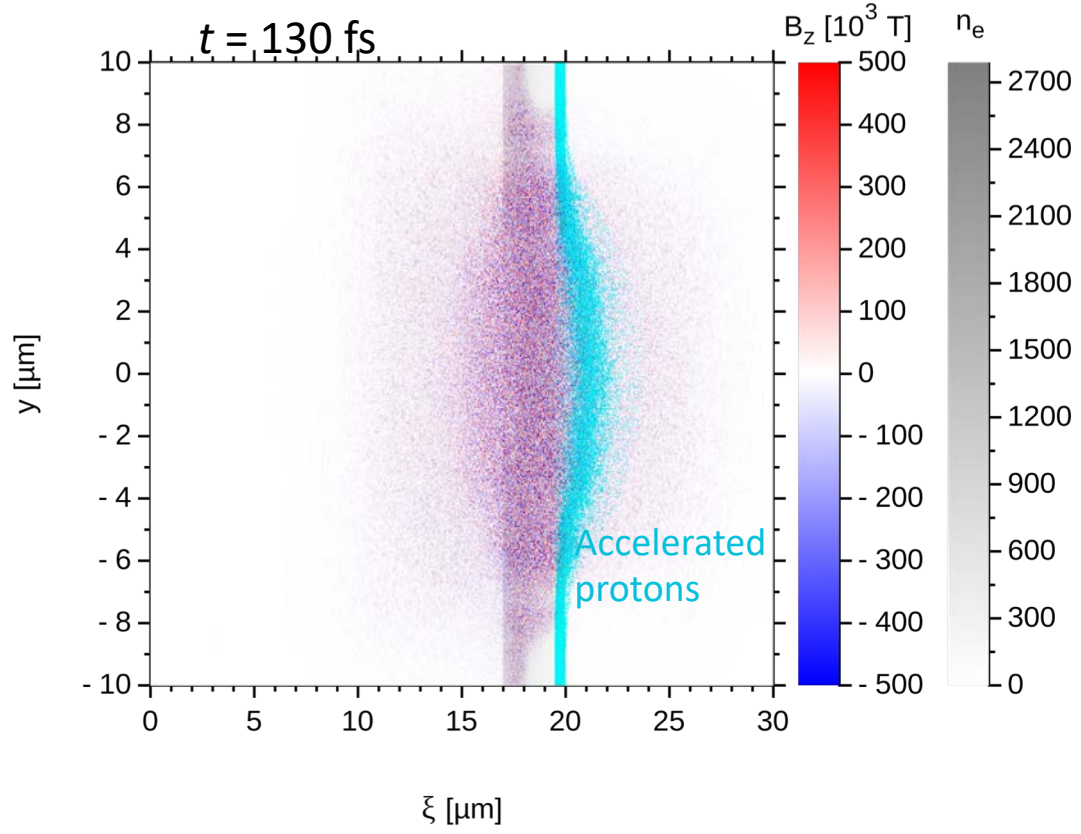
A FIRST PIC SIMULATION W/ PARTICLE SPINS

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





☞ Proton polarization is conserved during acceleration

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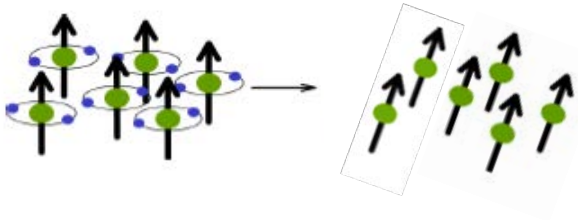
NEED FOR A POLARIZED GAS TARGET

What have we learned?

Polarization is preserved

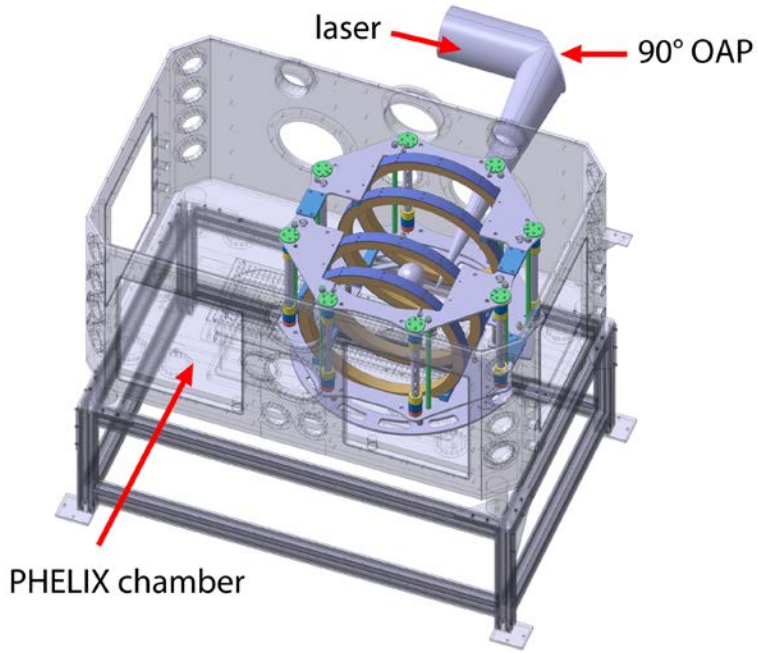


Thomas-BMT equation

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

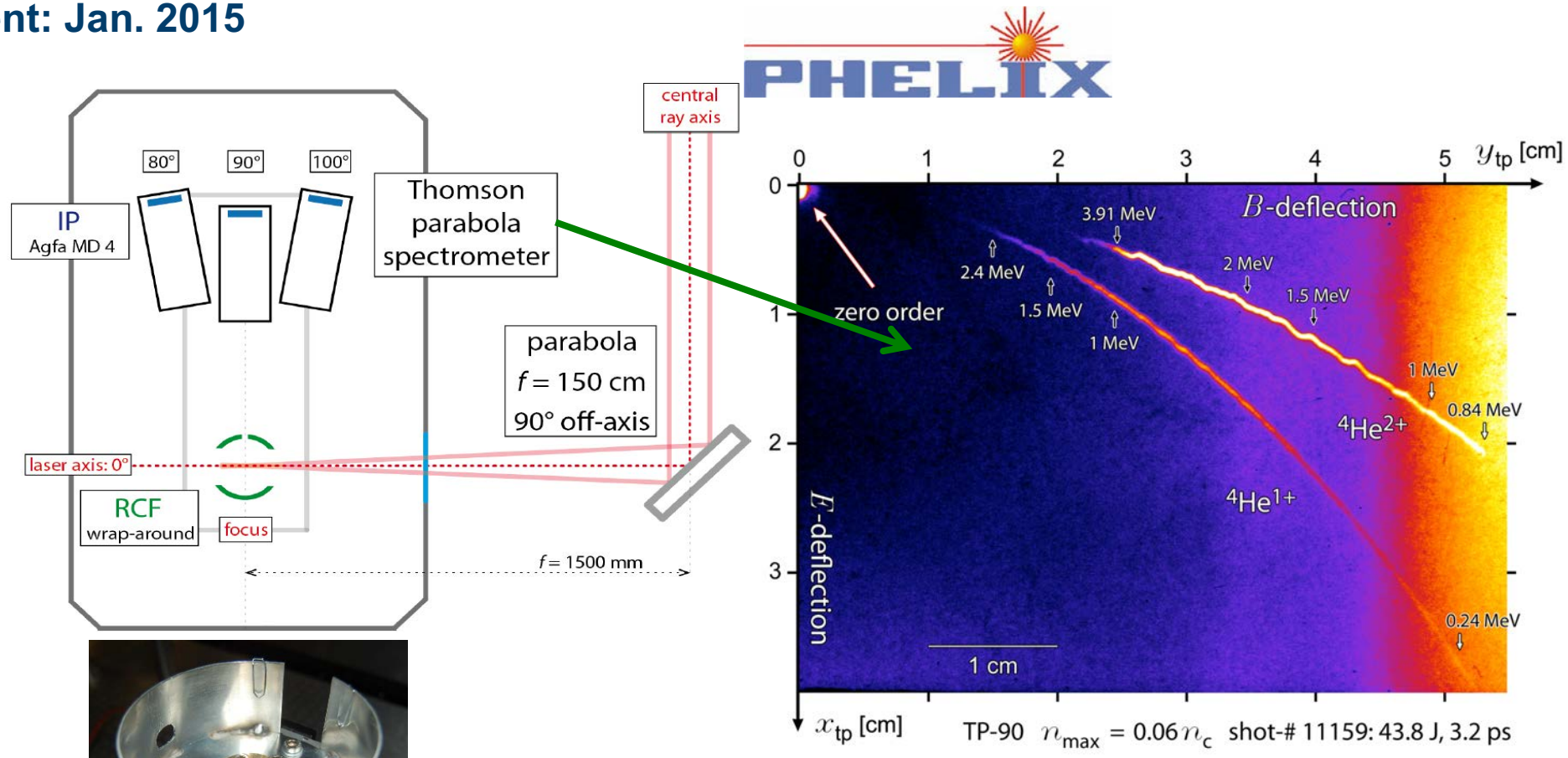
Possible experimental realization: Polarized ^{3}He target

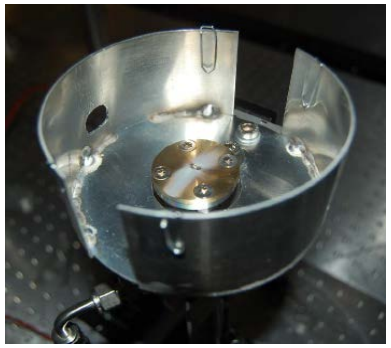
Measurements @ PHELIX GSI: Jan. 2019



ION ACCELERATION FROM GAS TARGETS

Experiment: Jan. 2015





☞ *requires approx. 30 bar gas pressure*

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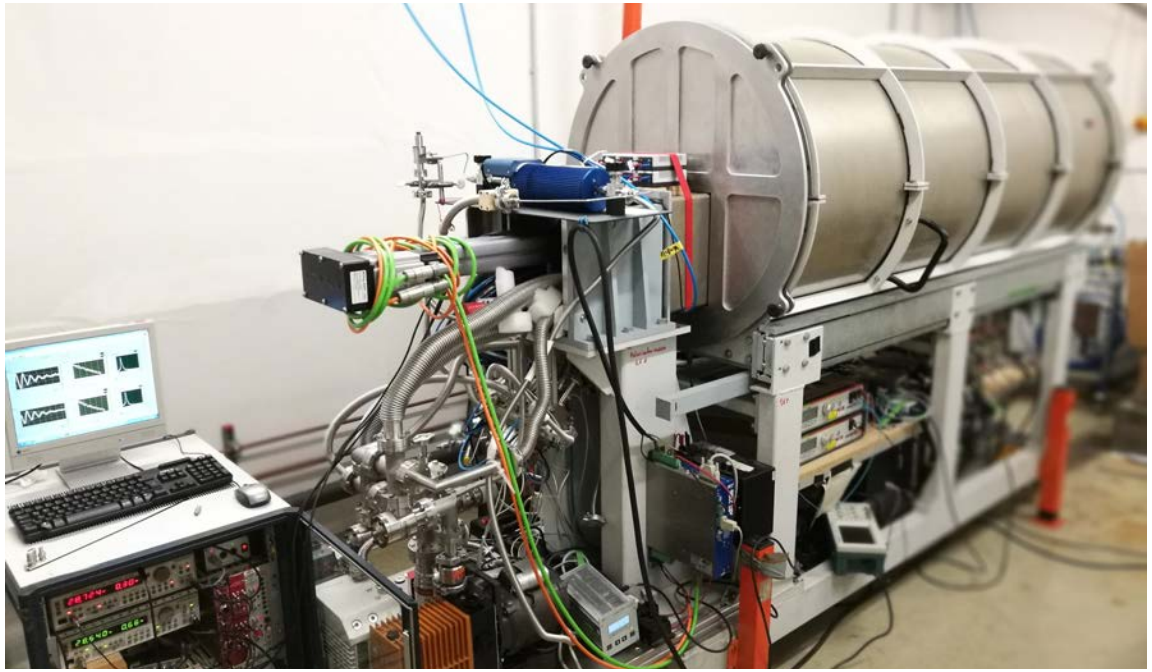
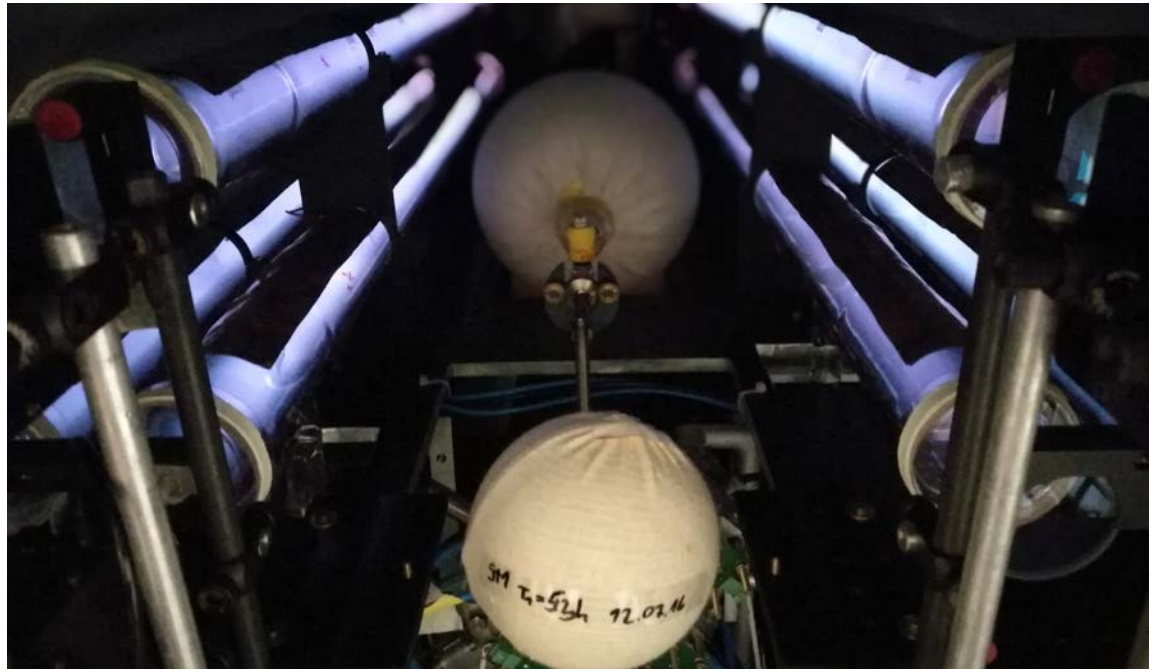
^{3}HE POLARISER

Transfer Univ. Mainz ➜ Jülich: Summer 2018

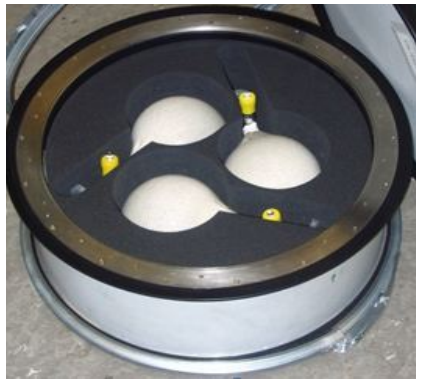


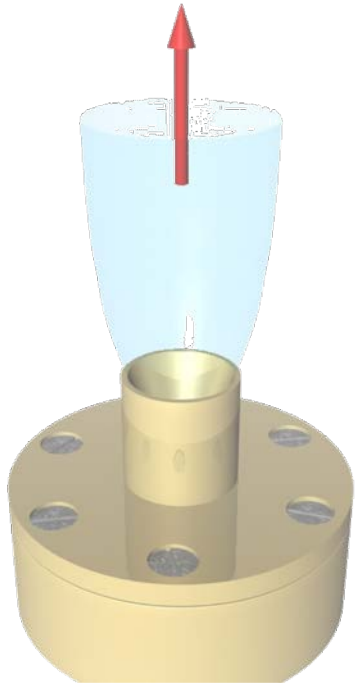


Photos: Ilhan Engin

POLARIZED ^{3}HE GAS: PRESSURE BOOSTER

Input pressure: 3 bar

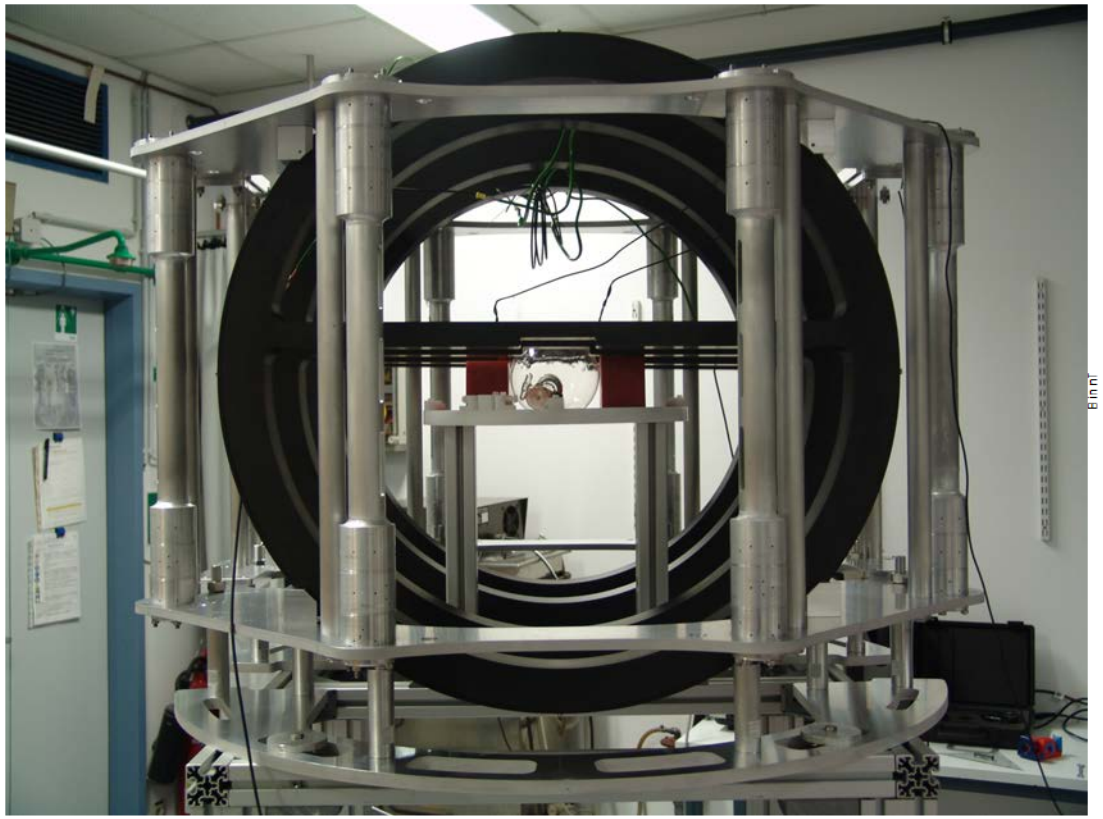




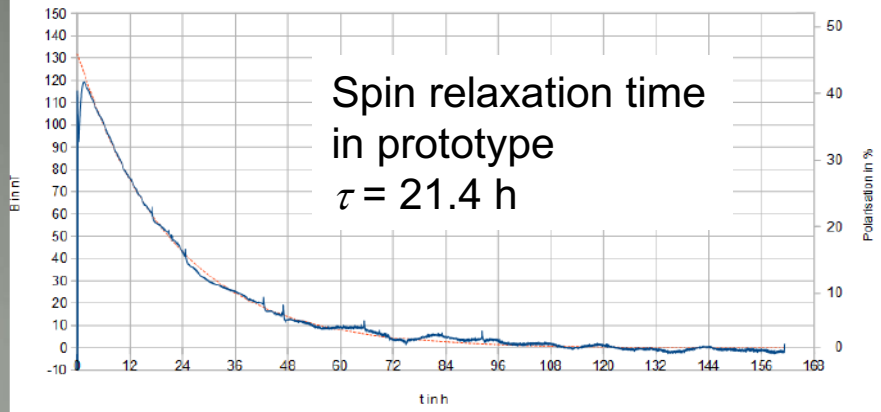
Output pressure: 50 bar

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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PRODUCTION OF POLARIZED PROTON BEAMS

100 mJ @ 1064 nm

Alignment of HCl bonds

20 mJ @ 213 nm

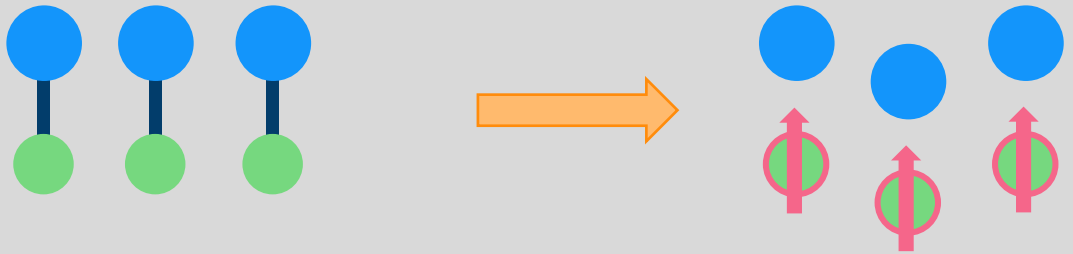
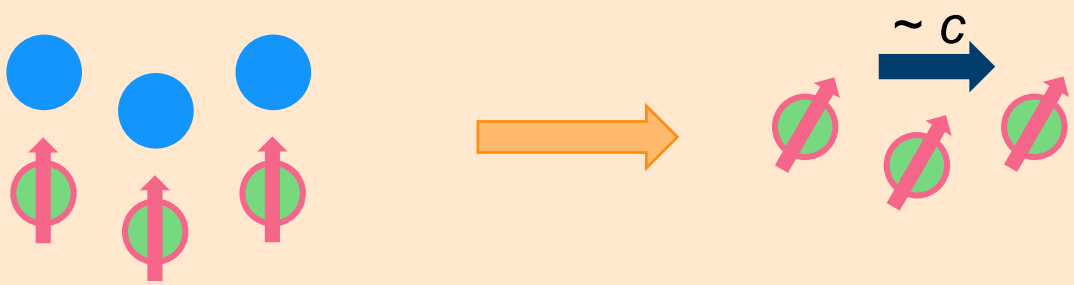


Photo-dissociation and polarization of the H nucleus

SIOM

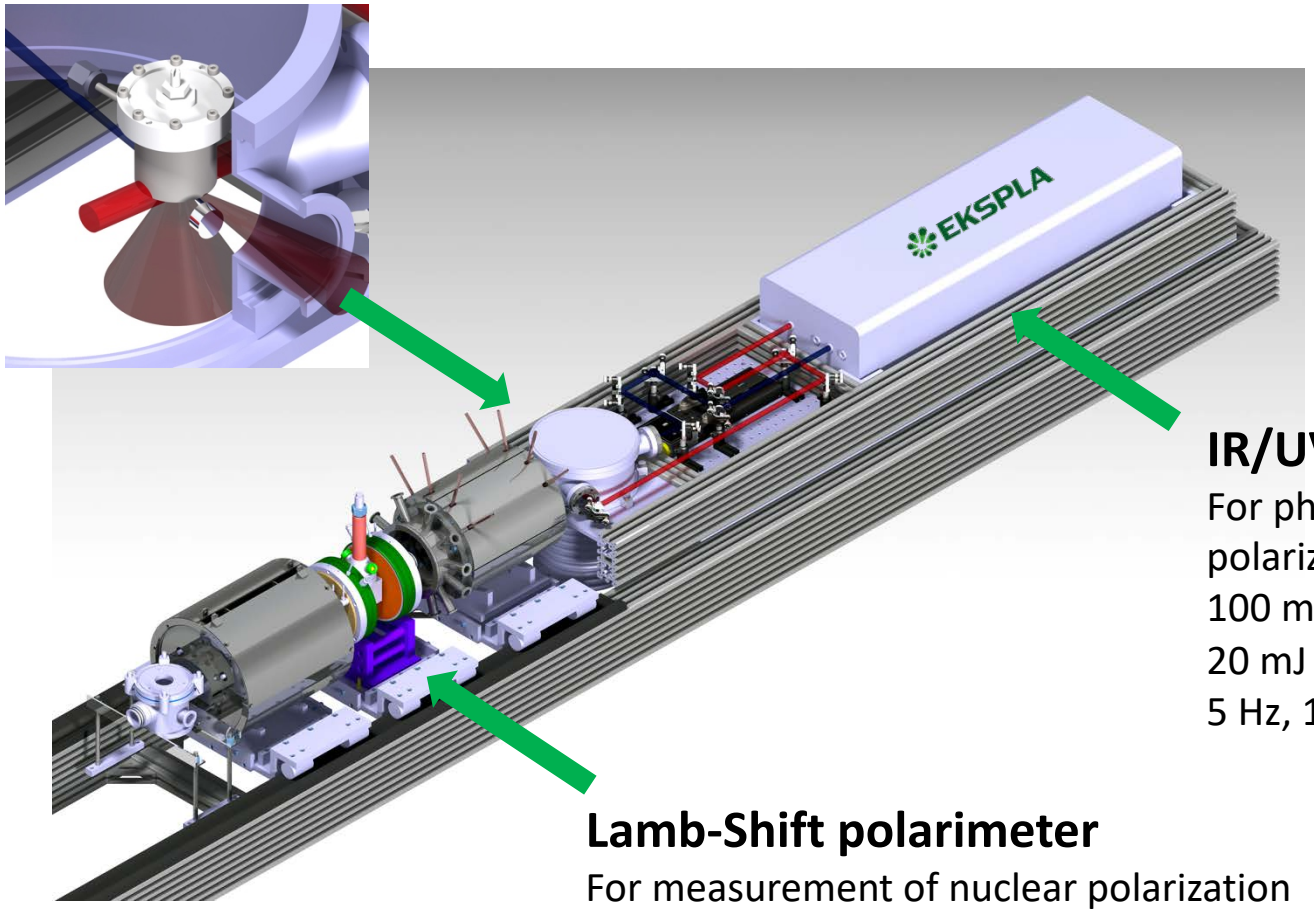
300 J @ 800 nm



Acceleration of the protons in gas jet

POLARIZED HYDROGEN GAS TARGET

Nozzle
For HCl gas jet



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

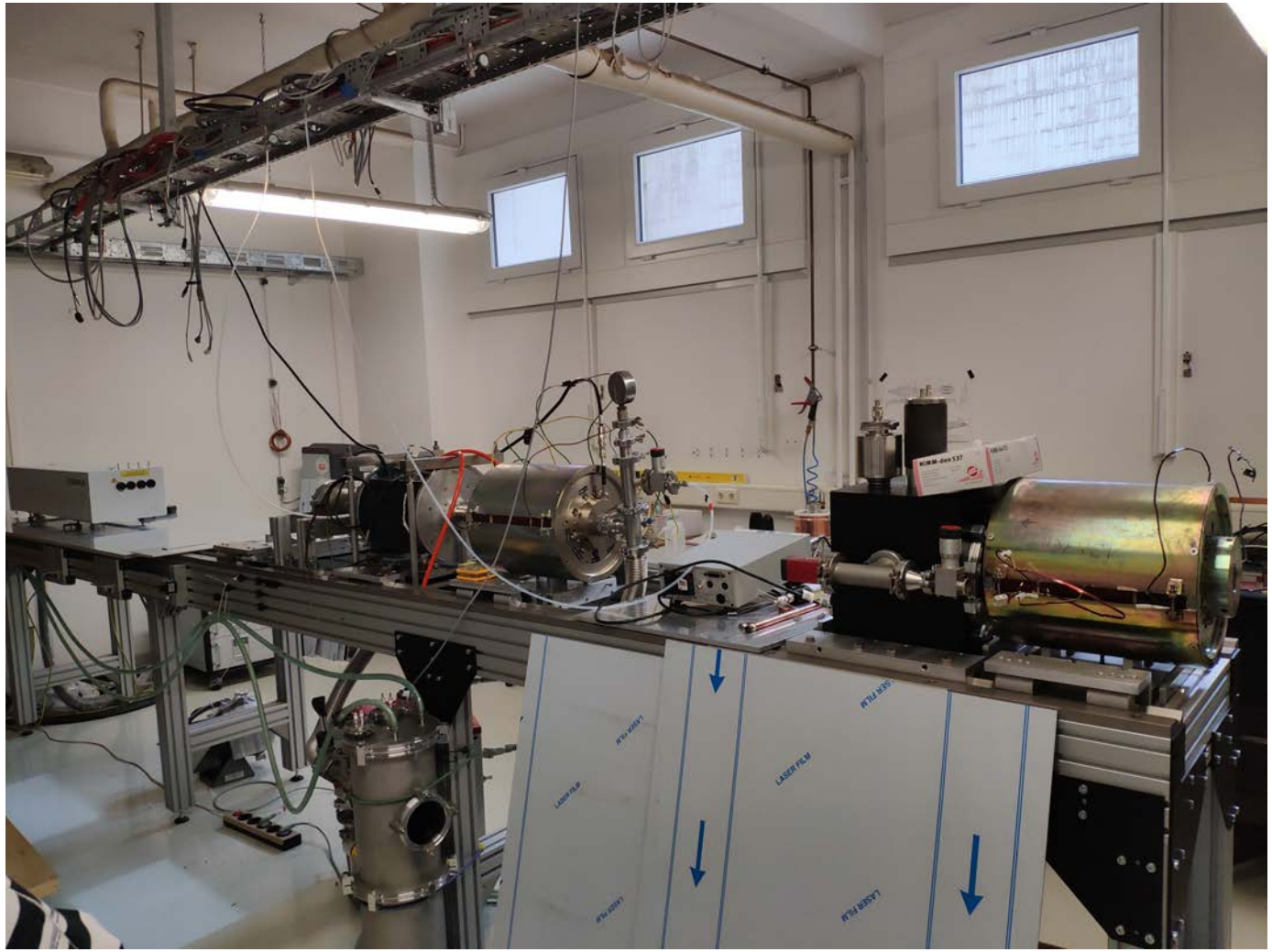
Lamb-Shift polarimeter
For measurement of nuclear polarization
R. Engels et al., Rev.Sci.Instrum. **74**, 4607 (2003)

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

UNIVERSITY OF CRETE

POLARIZED HYDROGEN GAS TARGET

Start of measurements: October 2018



10 PW LASER IN SHANGHAI @ SULF

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

Visit in Dec. 2017

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 SPIN2018

JuSPARC Group at JÜLICH Forschungszentrum

- Markus Büscher
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- Claus M. Schneider
- Paul Gibbon
- Jürgen Böker
- Ralf Engels
- Ilhan Engin

Shanghai Institute of Optics and Fine Mechanics

- Baifei Shen
- Liangliang Ji
- Lingang Zhang

SIOM

University of Crete

UNIVERSITY OF CRETE

- T. Peter Rakitzis

Institut für Theoretische Physik I

- Alexander Pukhov
- Johannes Thomas

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

THANK YOU!