POLARIZED BEAMS FROM PLASMA ACCELERATORS

HKIAS mini workshop on plasma acceleration

MARKUS BÜSCHER | 14 JANUARY 2021

JuSPARC ATHENA hhu Heinrich Heine Universität Düsseldorf SIOM JÜLICH Forschungszentrum

POLARIZATION IN PLASMAS???

- Typical energy of (proton) spin states:

$$E_{\mathrm{spin,p}} = \mu \cdot B = 6 \cdot 10^{-8} \frac{\mathrm{eV}}{\mathrm{T}} \cdot 1000\ \mathrm{T} \approx 1\ \mathrm{meV}$$

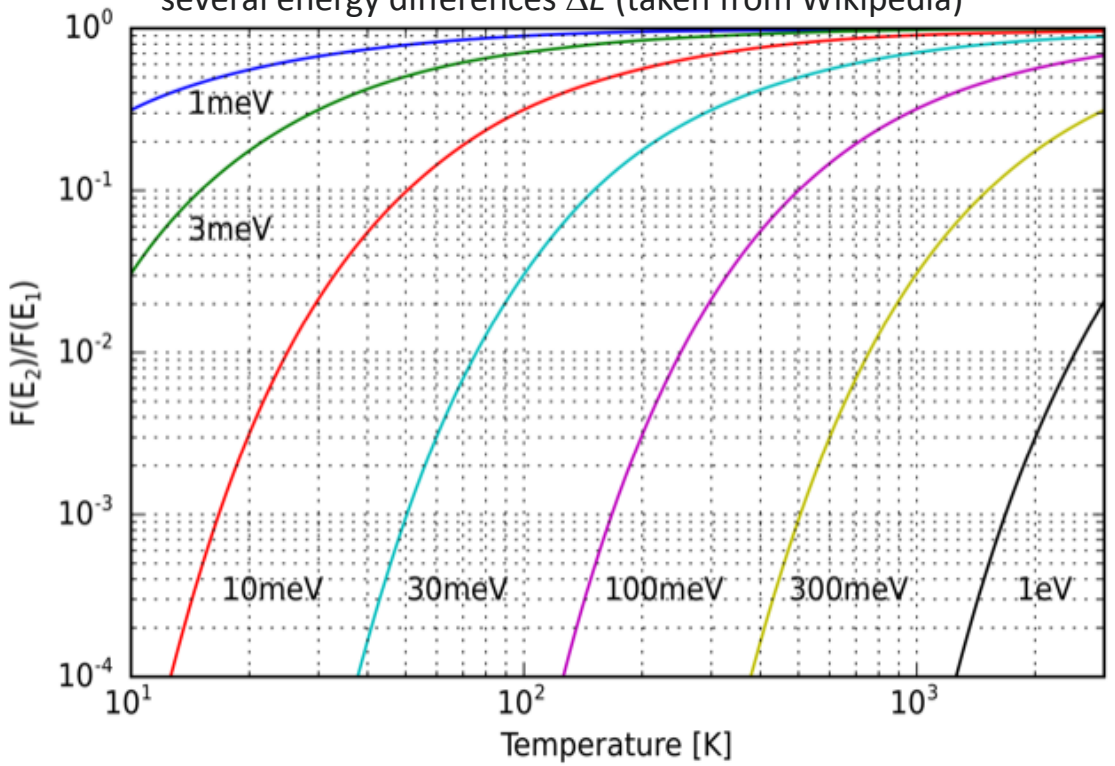
- Typical temperature of the plasma:

  10^8 K ≈ 10 keV

➡ occupation probability of both spin states (almost) equal in thermal equilibrium

➡ no polarization (in thermal equilibrium)

Boltzmann factor as a function of temperature for several energy differences ΔE (taken from Wikipedia)



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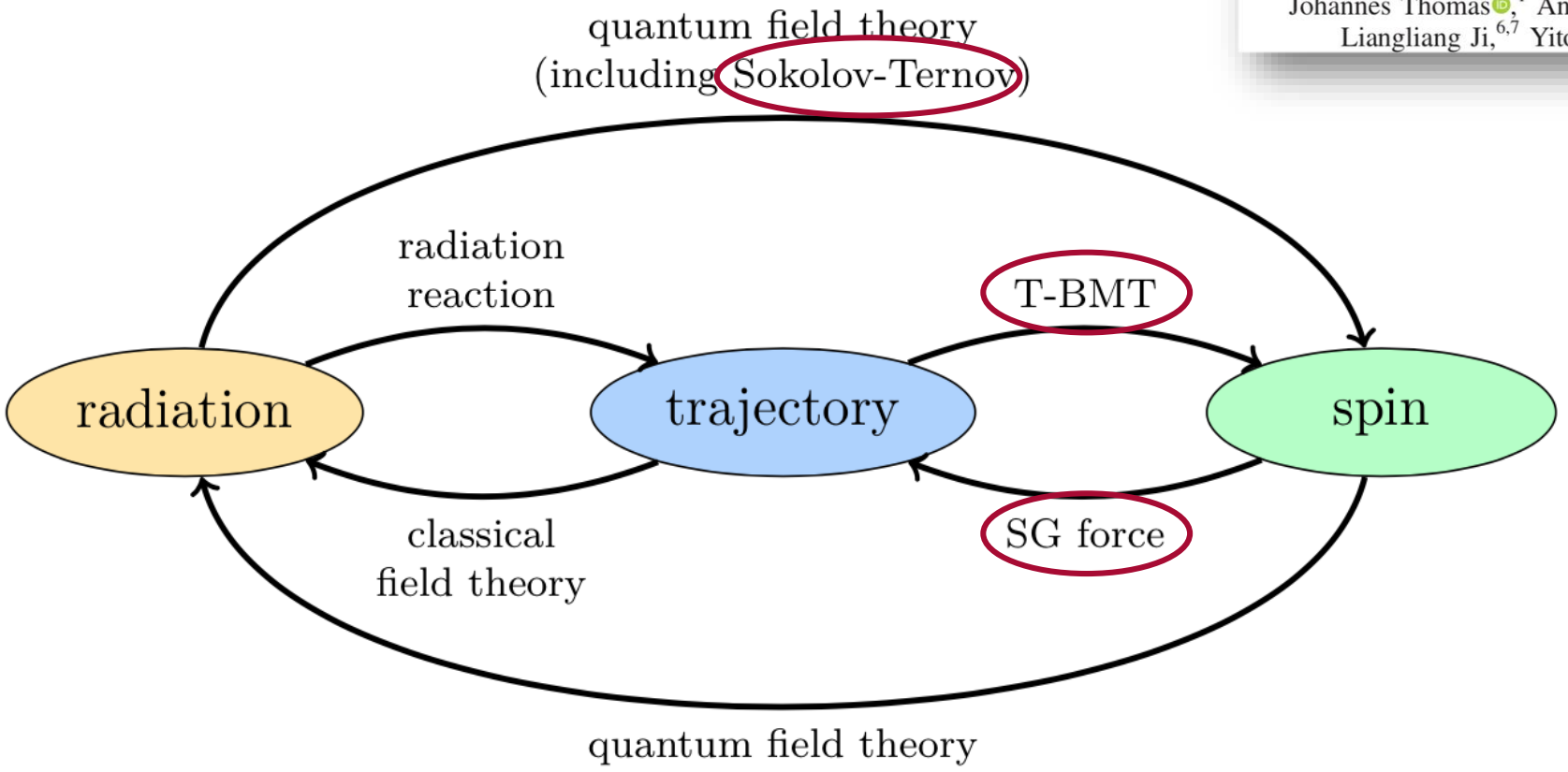
INTERACTIONS INVOLVING SPINS

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 064401 (2020)

Scaling laws for the depolarization time of relativistic particle beams in strong fields

Johannes Thomas,[1] Anna Hützen,[2,3] Andreas Lehrach,[4,5] Alexander Pukhov,[1] Liangliang Ji,[6,7] Yitong Wu,[6,8] Xuesong Geng,[6,8] and Markus Büscher[2,3]



Relevant processes for e^-, p, ions:

- T-BMT
- Sokolov-Ternov
- Stern-Gerlach

- (Radiation reaction only for ultra-relativistic particles)

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POSSIBLE (DE-)POLARIZATION EFFECTS

Conservation of polarization for times < 1 ps in a 10^3 T field
→ Dominant effect

Polarization time ~ 5 ms for a 100 GeV proton beam in a 1000 T field
→ Time scale too long

Separation distances are in the nm-range for e^- & sub pm-range for protons
→ Spatial separation too small

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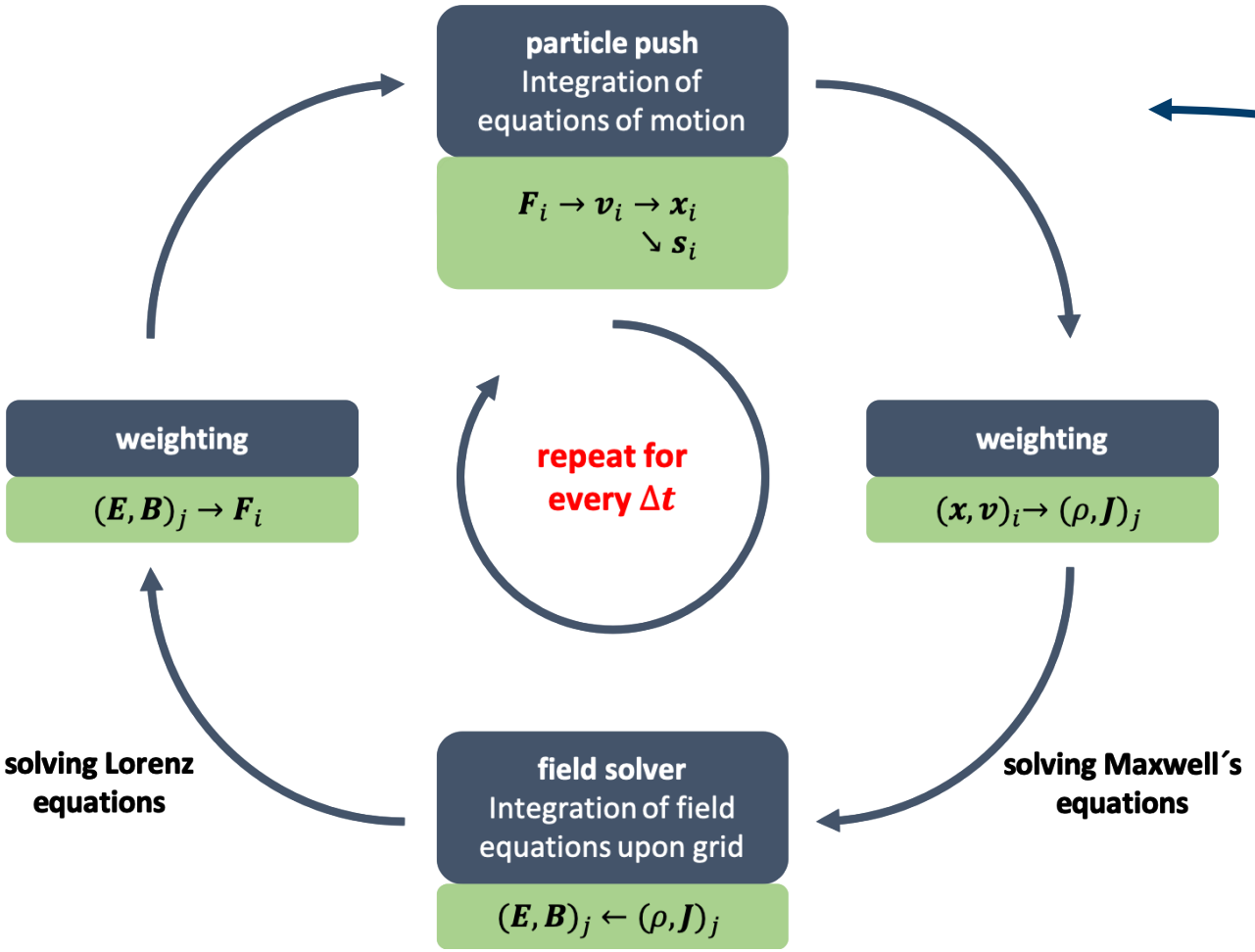
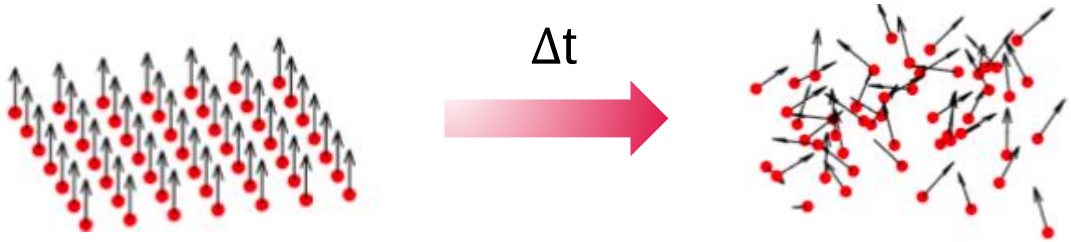
SPIN DYNAMICS IN THE VLPL CODE



Implementation into already existing code

Spin precession described by the Thomas-BMT equation



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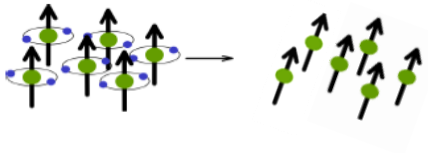
MODELLING OF SPINS IN LASER-INDUCED PLASMAS

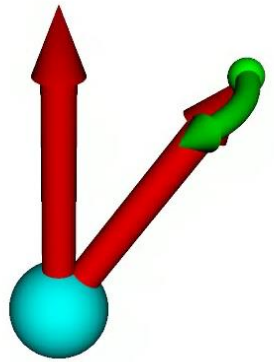
Implementation of particle spins into a simulation code (in collaboration with A. Pukhov, hhu Heinrich Heine Universität Düsseldorf)



Thomas-BMT equation → PIC Code (VLPL, recently EPOCH)

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

$$\frac{d\mathbf{s}}{dt} = -\Omega \times \mathbf{s}$$



Rotation frequency in cgs units

$$\Omega = -\frac{q}{mc}\left[\Omega_{\mathrm{B}}\mathbf{B} - \Omega_{\mathrm{v}}\left(\frac{\mathbf{v}}{c}\cdot\mathbf{B}\right)\frac{\mathbf{v}}{c} - \Omega_{\mathrm{E}}\frac{\mathbf{v}}{c}\times\mathbf{E}\right]$$

with $\Omega_{\mathrm{B}} = a + \frac{1}{\gamma}$ $\Omega_{\mathrm{v}} = \frac{a\gamma}{\gamma+1}$ $\Omega_{\mathrm{E}} = a + \frac{1}{1+\gamma}$

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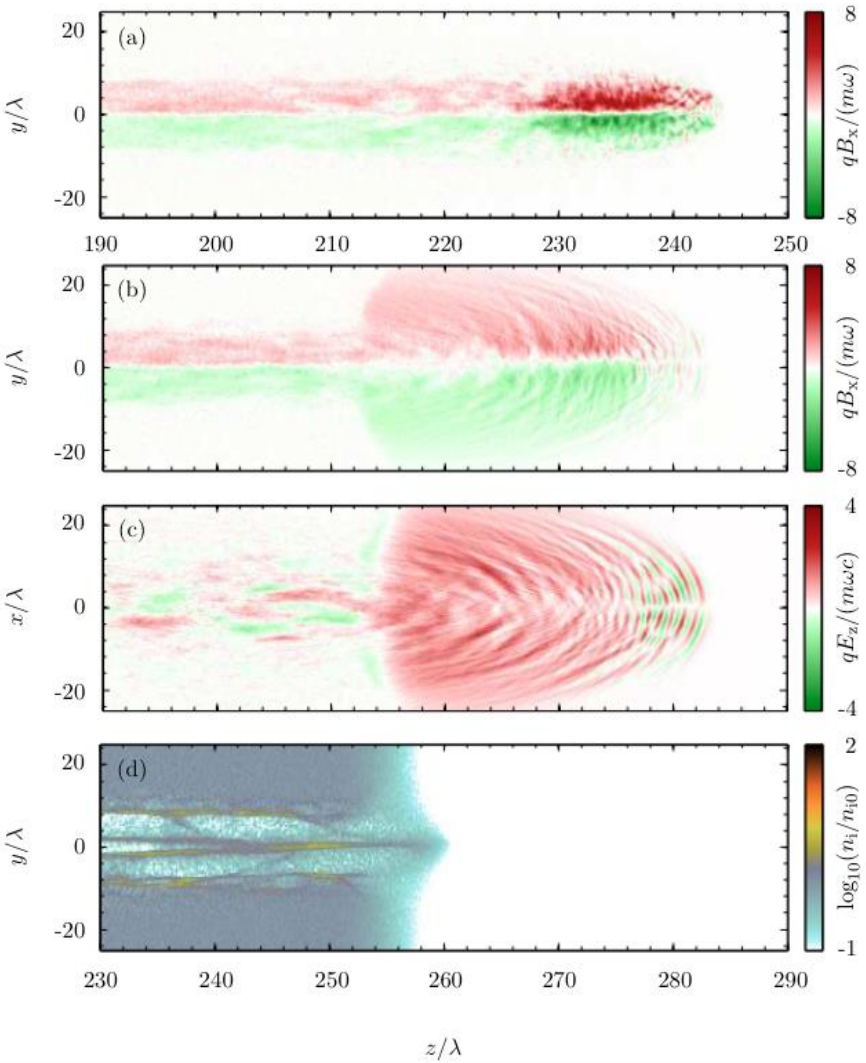
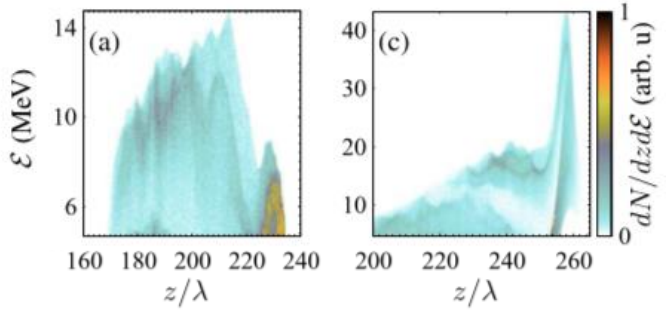
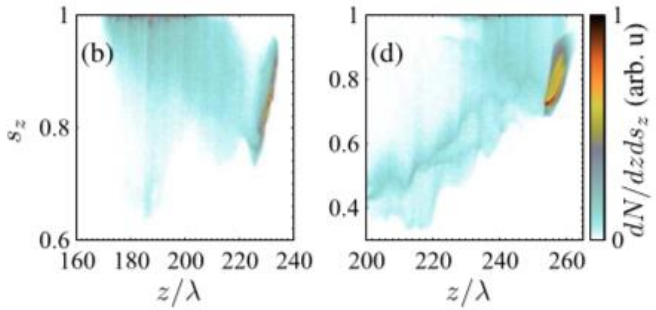
SPIN-POLARIZED PROTON BEAMS FROM HCL GAS





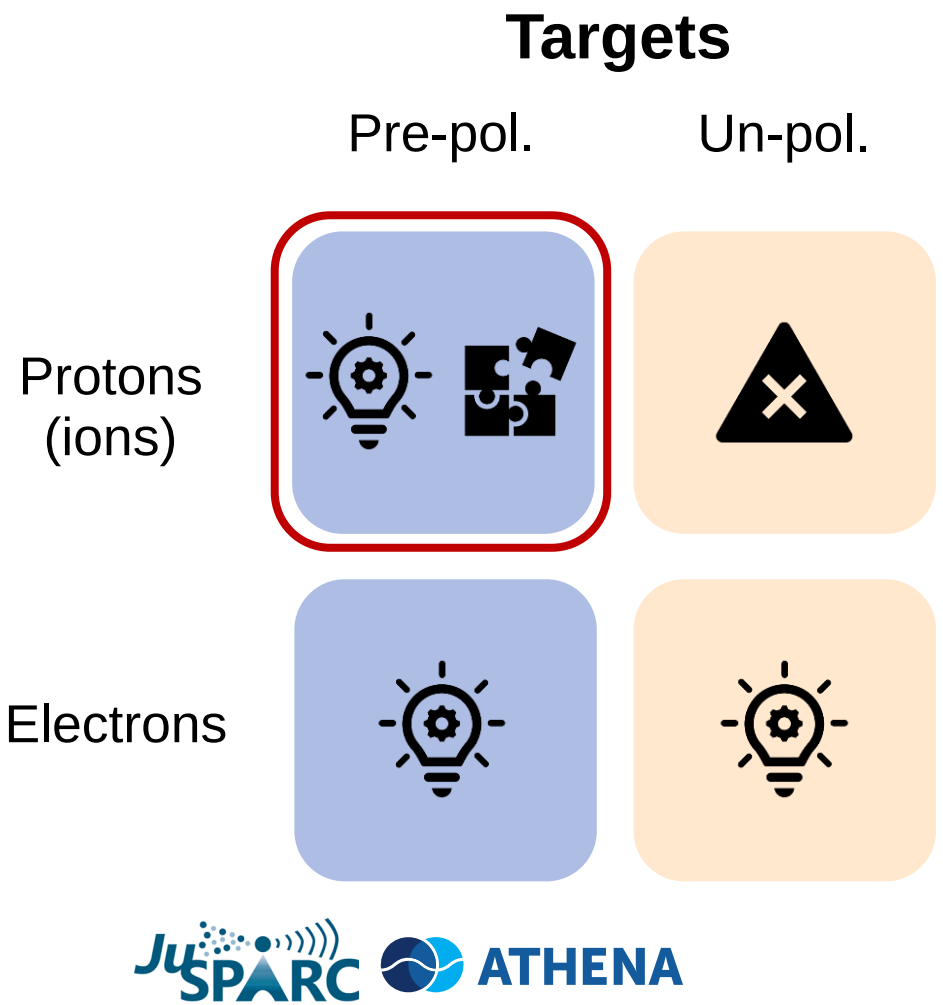


a_0	P_L [PW]	E_p [MeV]	P [%]
25	1.34	53	82
50	5.37	105	65
75	12.1	133	57
100	21.5	152	56

➡ Proton beam polarization driven by PW lasers is mostly maintained

L. Jin et al., Phys. Rev. E **102,** 011201(R) (2020)

POLARIZATION OF ELECTRONS VS PROTONS

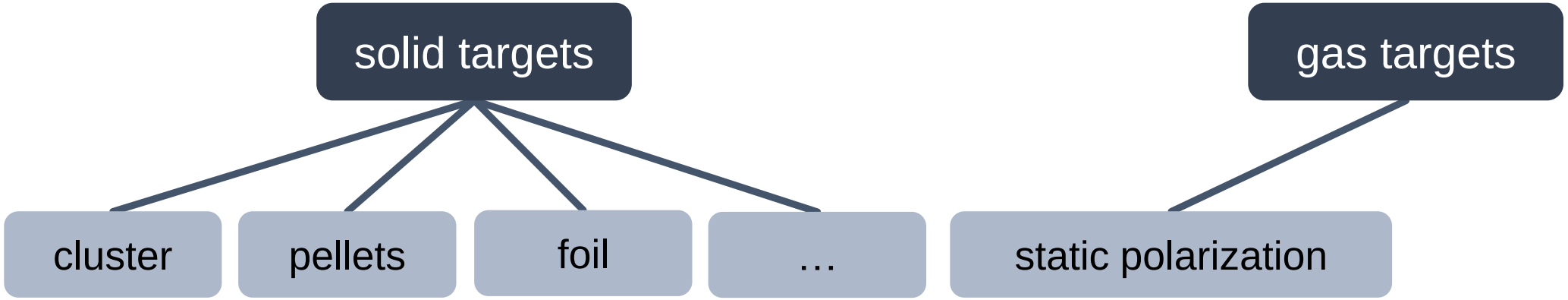


Theoretically studied

Experiments ongoing

not feasible

POLARIZED TARGET OPTIONS FOR PROTONS



- Targets suitable for laser acceleration not available yet
- Experimental realization extremely challenging

- Established technique and easy in handling
- E.g. ^{3}He

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HYPERPOLARIZED ^{3}HE GAS-JET

PREFER Polarization Research for Fusion Experiments and Reactors

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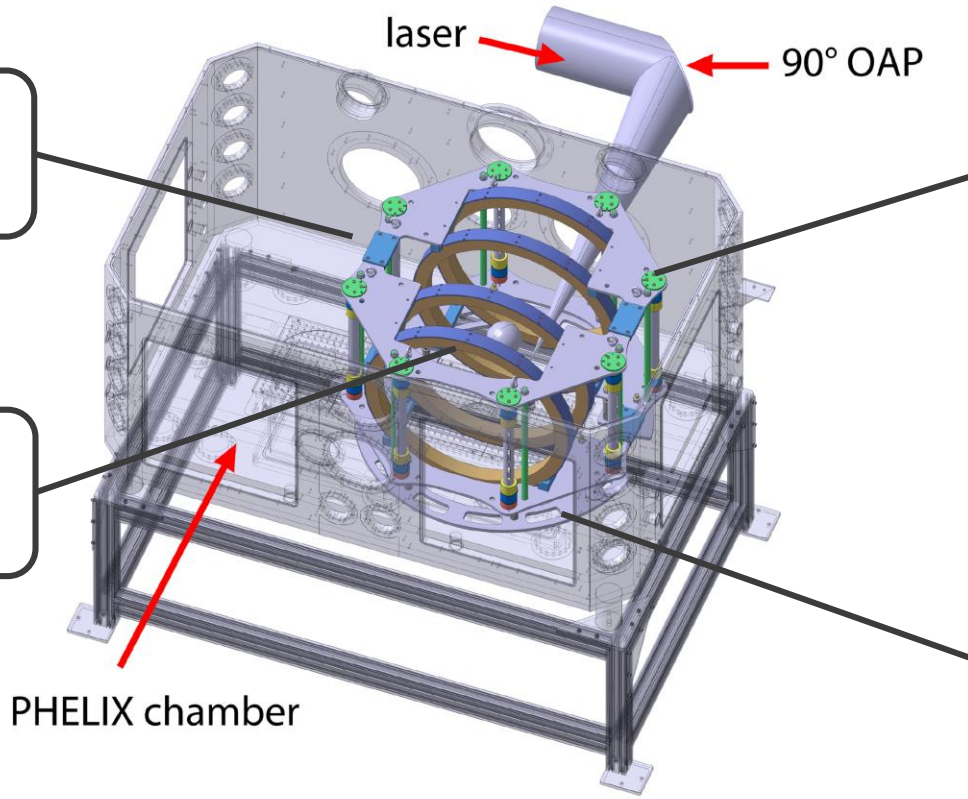
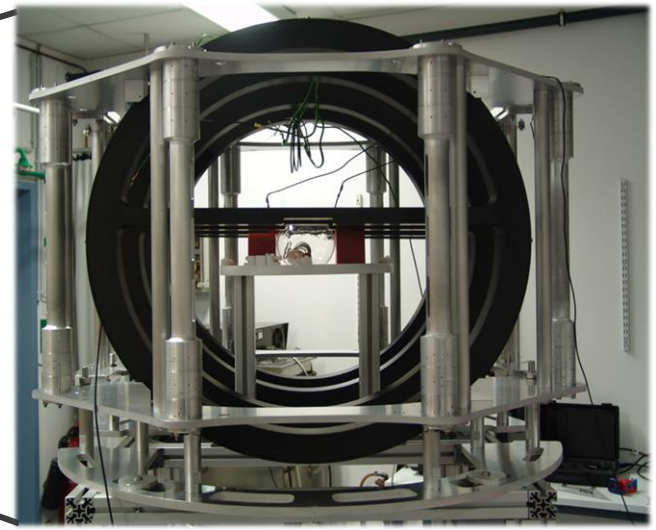
magnetic holding field for storing pre-polarized ^{3}He gas

non-magnetic nozzle for providing the desired gas-jet target





P. Fedorets, C. Zheng

Measurements @ PHELIX GSI : 2021

I. Engin et al., Plasma Physics and Controlled Fusion 61(11) (2019)

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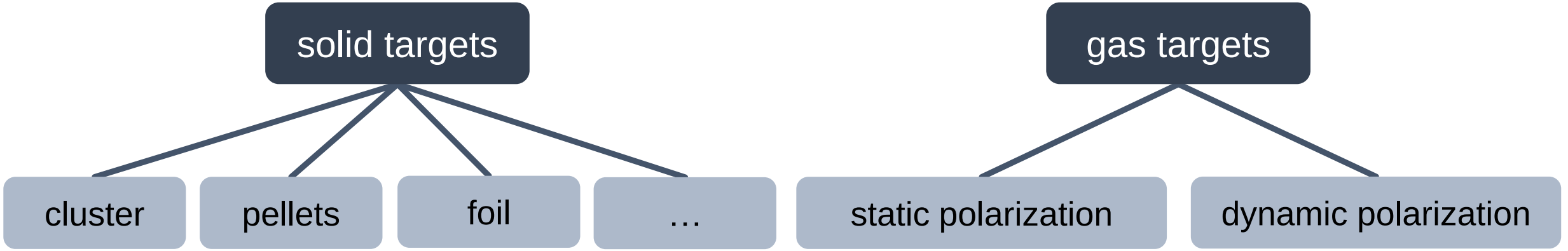
POLARIZED TARGET OPTIONS FOR PROTONS



- Targets suitable for laser acceleration not available yet
- Experimental realization extremely challenging

- Established technique and easy in handling
- E.g. ^{3}He

- Novel approach & synchronization with accelerating laser needed
- E.g. HCl, HBr, HI, …

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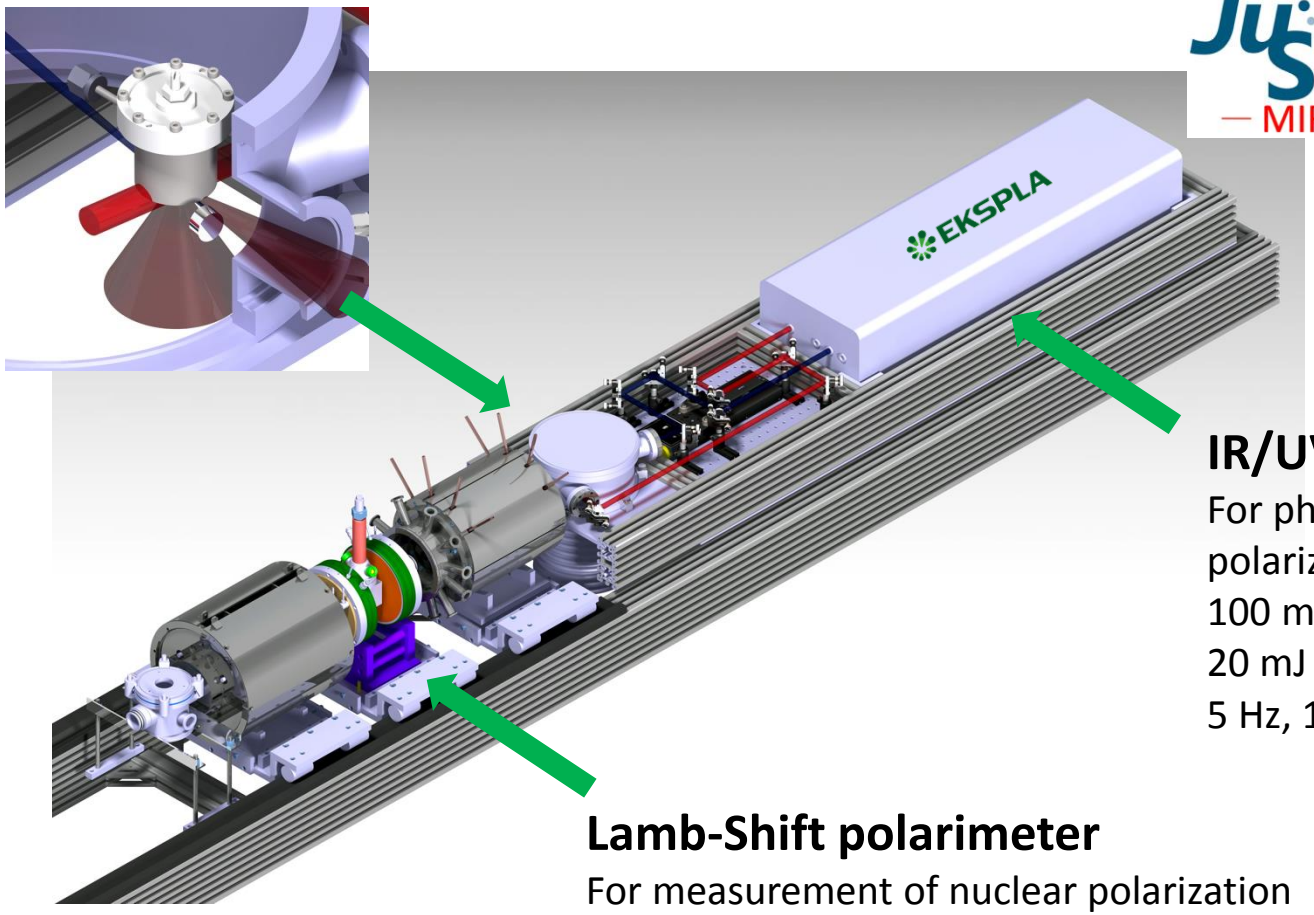
POLARIZED HYDROGEN GAS TARGET @ FZJ

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)

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ATHENA
The Helmholtz-Project for Laser-Plasma-Acceleration

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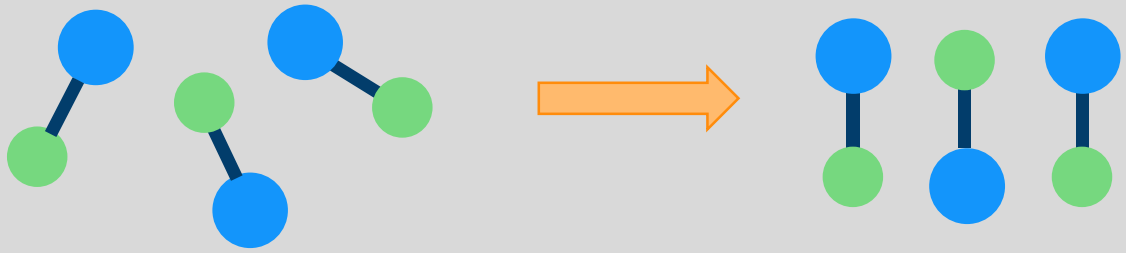
PRODUCTION OF NUCLEAR POLARIZED HYDROGEN

100 mJ @ 1064 nm



Alignment of HCl bonds

20 mJ @ 213 nm

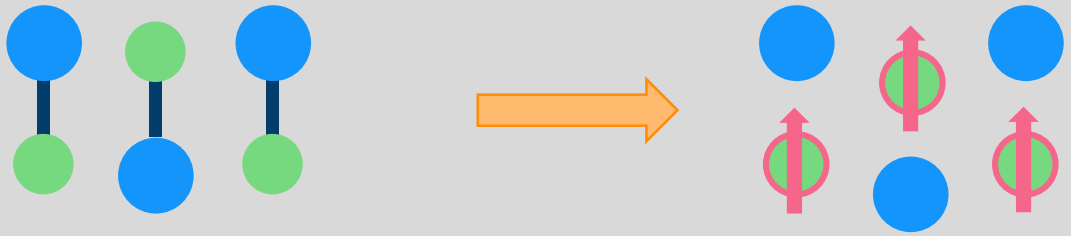
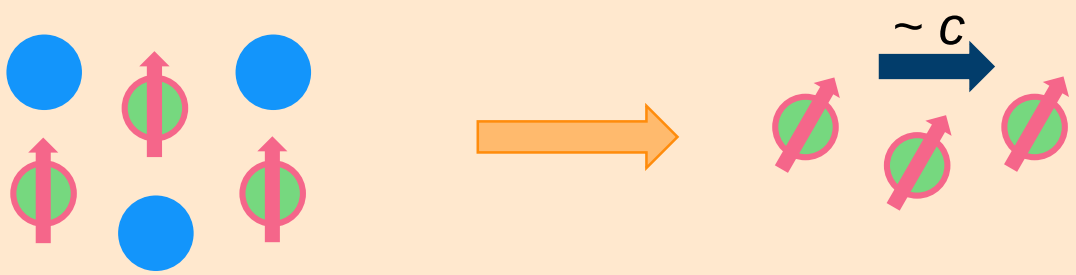


Photo-dissociation & polarization transfer to H nuclei (Δt = 350 ps)

SIOM

300 J @ 800 nm

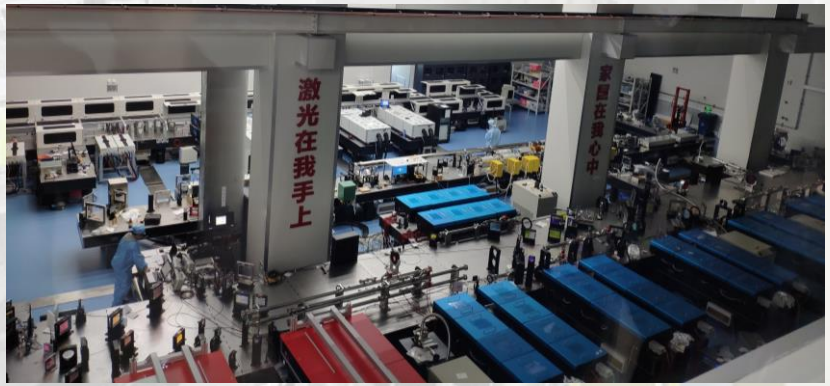


Acceleration of the protons in gas jet

A. Hützen et al., High Power Laser Sci. Eng. **7,** E16 (2019)

SUPERINTENSE ULTRAFAST LASER FACILITY @ SHANGHAI

- Common simulation work and publications on polarized particle beams
- First common experiments on proton acceleration in 2021 (@1 PW)



Laser parameter 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

NEW IDEA: HYPERPOLARIZED CRYOGENIC TARGETS EW

IDEA: HYPERPOLARIZED CRYOGENIC TARGETS

Production of selected nuclear and electron spin orientations

Generation of strong magnetic field focussing the e^- beam

Freezing of molecules while maintaining their polarization

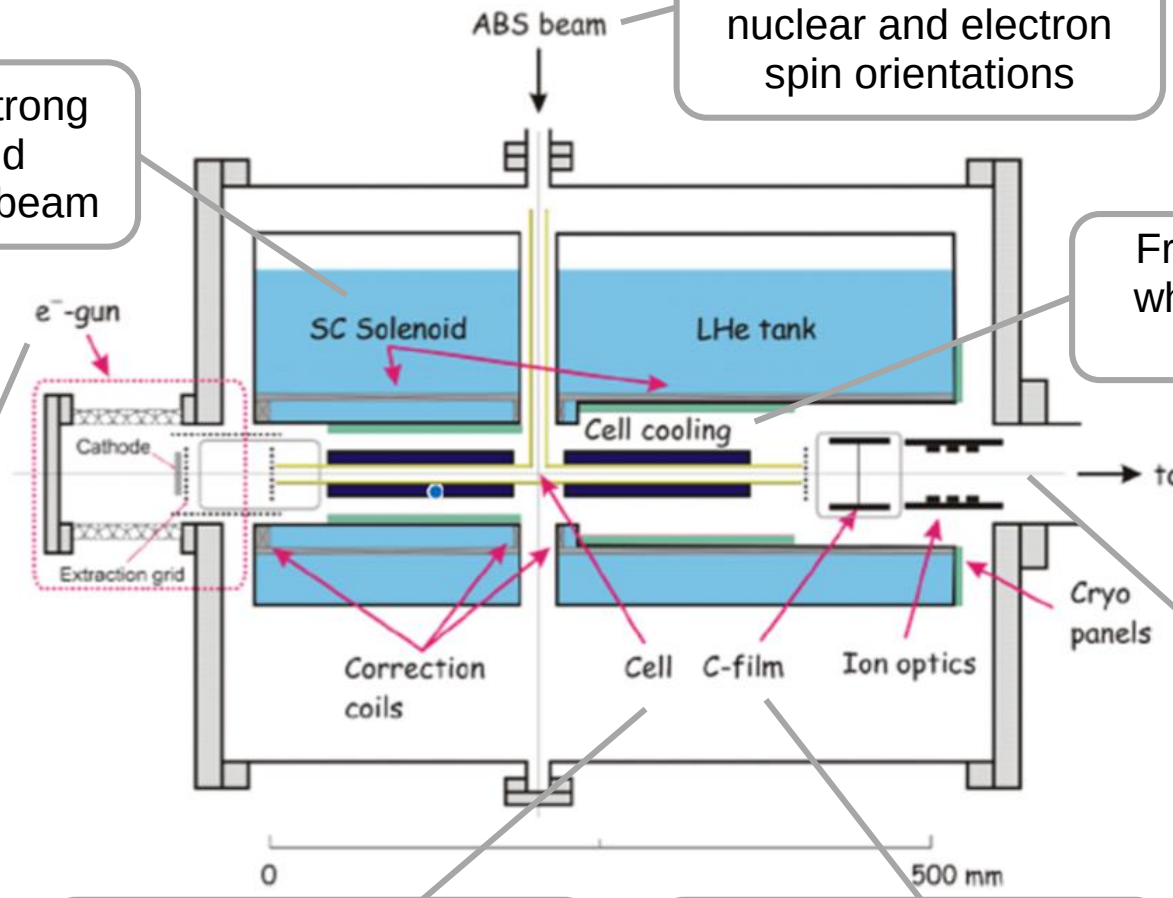
Production of e^- beam at energies of a few 100 eV

Measurement of nuclear polarization

Interaction of polarized atoms and evaporated molecules with e^- beam leads to ionization process

Recombination of atoms into molecules on the surface of the cell

Freezing the molecules to polarized foil target



R. Engels et al.,
Production of HD Molecules in Definite Hyperfine Substates,
PRL 124, 113003 (2020)

ATHENA
The Helmholtz-Project for Laser-Plasma-Acceleration

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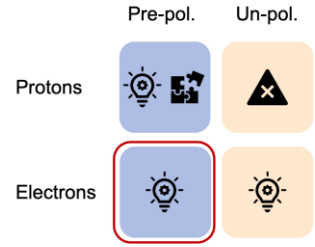
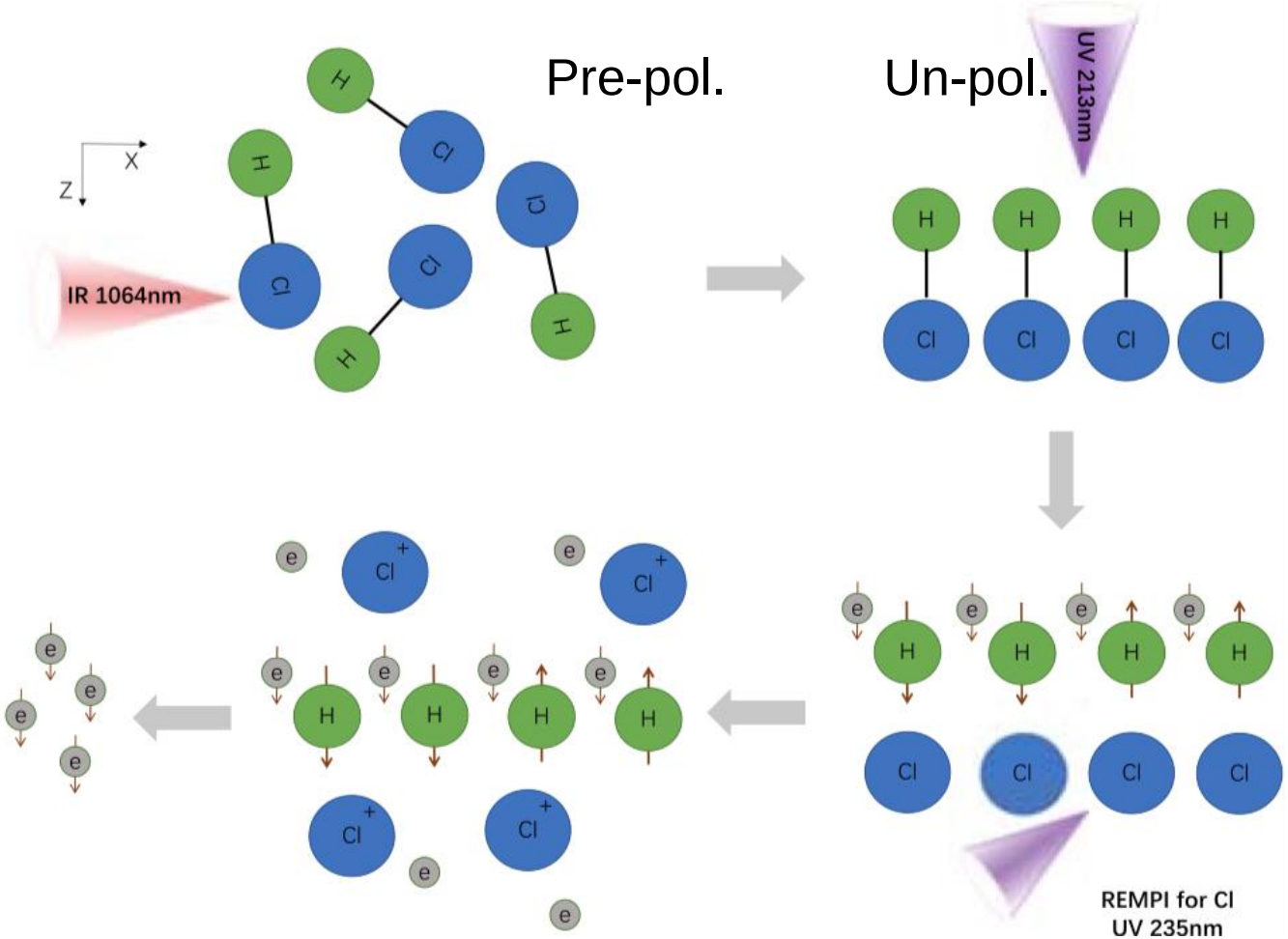
GENERATION OF POLARIZED ELECTRONS

Polarized electron target: Based on the pre-polarized HCl gas target





1st beam at 1064 nm:
Alignment of HCl bonds

2nd beam at 213 nm:
Photo-dissociation &
polarization transfer to H nuclei

3rd beam at 235 nm:
Ionization of Cl atoms &
Expulsion of Cl ions

Wu et al., New J. Phys. **21,** 073052 (2019)

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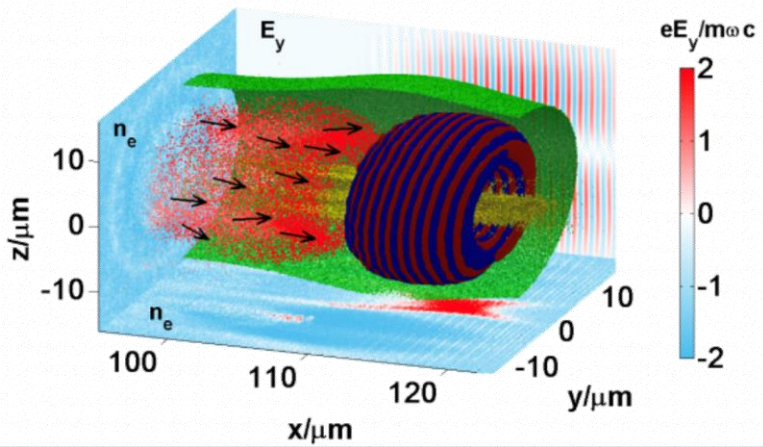
PRE-POLARIZED ELECTRON BEAMS



New J. Phys. **21** (2019) 073052 https://doi.org/10.1088/1367-2630/ab2fd7

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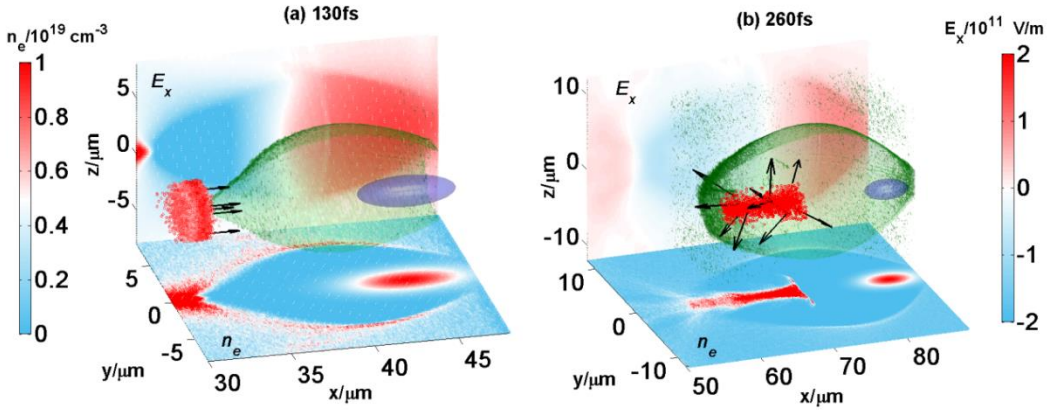
PAPER

Polarized electron-beam acceleration driven by vortex laser pulses

Yitong Wu[1,2], Liangliang Ji[1,3], Xuesong Geng[1], Qin Yu[1], Nengwen Wang[1], Bo Feng[1], Zhao Guo[1], Weiqing Wang[1], Chengyu Qin[1], Xue Yan[1], Lingang Zhang[1], Johannes Thomas[4], Anna Hützen[5,6], Markus Büscher[5,6], T Peter Rakitzis[7,8], Alexander Pukhov[4], Baifei Shen[1,3,9] and Ruxin Li[1,3,10]

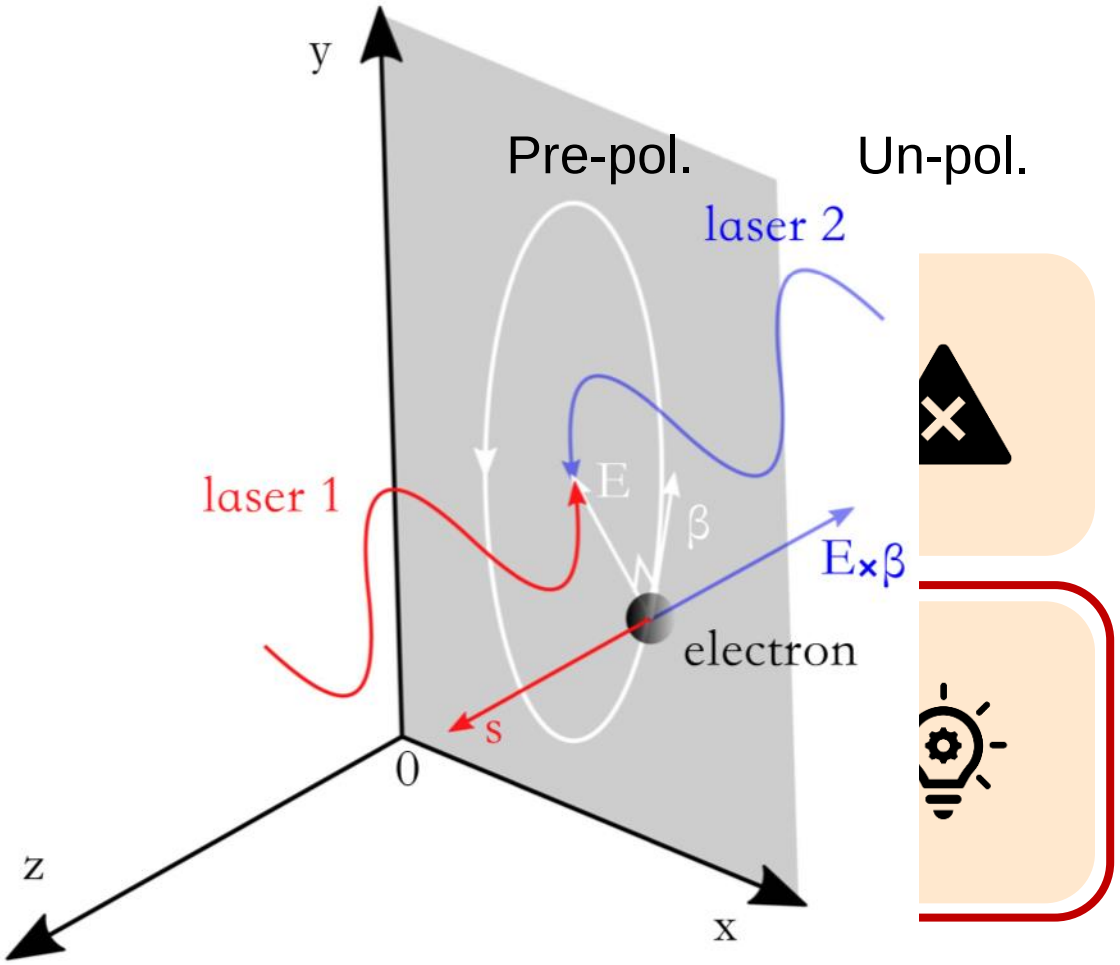


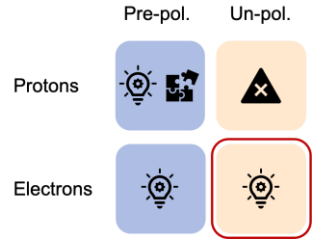
PHYSICAL REVIEW E **100**, 043202 (2019)

Polarized electron acceleration in beam-driven plasma wakefield based on density down-ramp injection

Yitong Wu,[1,2] Liangliang Ji,[1,3,*] Xuesong Geng,[1] Qin Yu,[1] Nengwen Wang,[1] Bo Feng,[1] Zhao Guo,[1] Weiqing Wang,[1] Chengyu Qin,[1] Xue Yan,[1] Lingang Zhang,[1] Johannes Thomas,[5] Anna Hützen,[6,7] Alexander Pukhov,[5] Markus Büscher,[6,7] Baifei Shen,[1,3,4,†] and Ruxin Li[1,3,8,‡]

POLARIZED ELECTRONS BY LASERS





- two counter-propagating circularly polarized lasers produce a standing wave
- ***E*** rotates with constant amplitude at $z=0$, inducing the rotation of any e^-
- e^- tend to align its spin *s* antiparallel to vector ***E* x *β***

Del Sorbo et al., Plasma Phys. Control. Fusion **60,** 064003 (2018)

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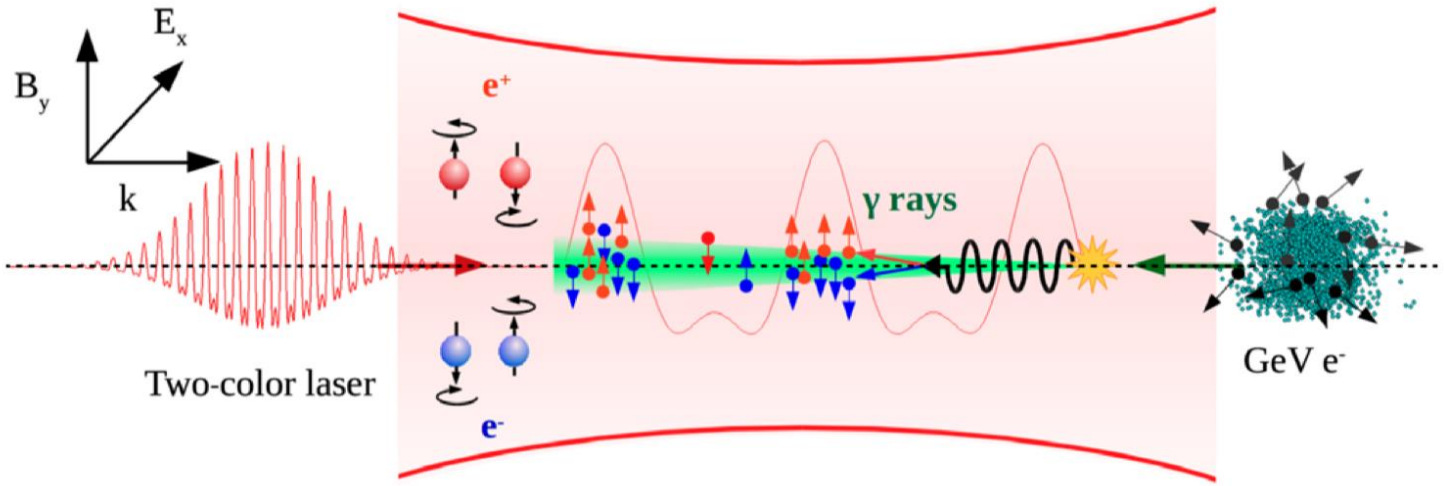
POLARIZED POSITRONS BY LASERS



Chen et al., Phys. Phys. Rev. Lett. **123,** 174801 (2019)

- intense linearly polarized two-color laser pulse collides head-on with unpolarized relativistic e^- beam
- emission of photons in the forward direction decaying into polarized e^+/e^- pairs
- spins parallel & antiparallel to laser's magnetic field direction
- small divergence angle in propagation direction

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JuSPARC Group at JÜLICH Forschungszentrum

- Markus Büscher
- Anna Hützen
- Andreas Lehrach
- Claus M. Schneider
- Paul Gibbon
- Ralf Engels
- Pavel Fedorets
- Chuan Zheng
- Chrysovalantis Kannis

Shanghai Institute of Optics and Fine Mechanics

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- Baifei Shen
- Jiancai Xu
- Liangliang Ji
- Lingang Zhang
- Yitong Wu
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- Dimitrios Sofikitis

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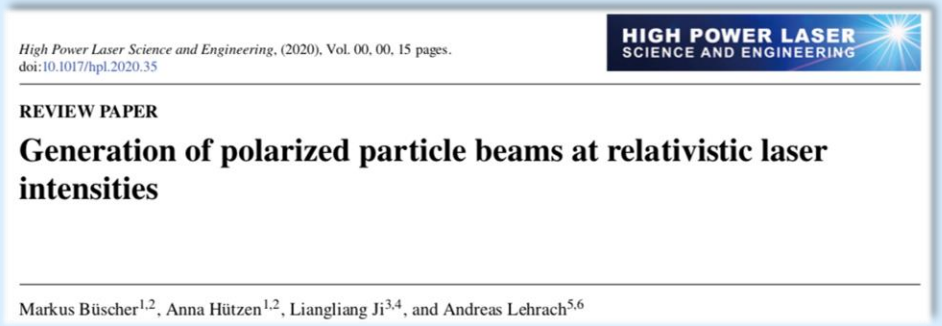
hhu Heinrich Heine Universität Düsseldorf

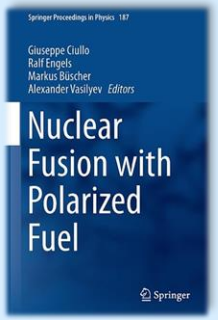
- Alexander Pukhov
- Johannes Thomas
- Lars Reichwein

FURTHER READING …

I. Polarized particle beams
   ➡ Polarized e^+/e^- collider

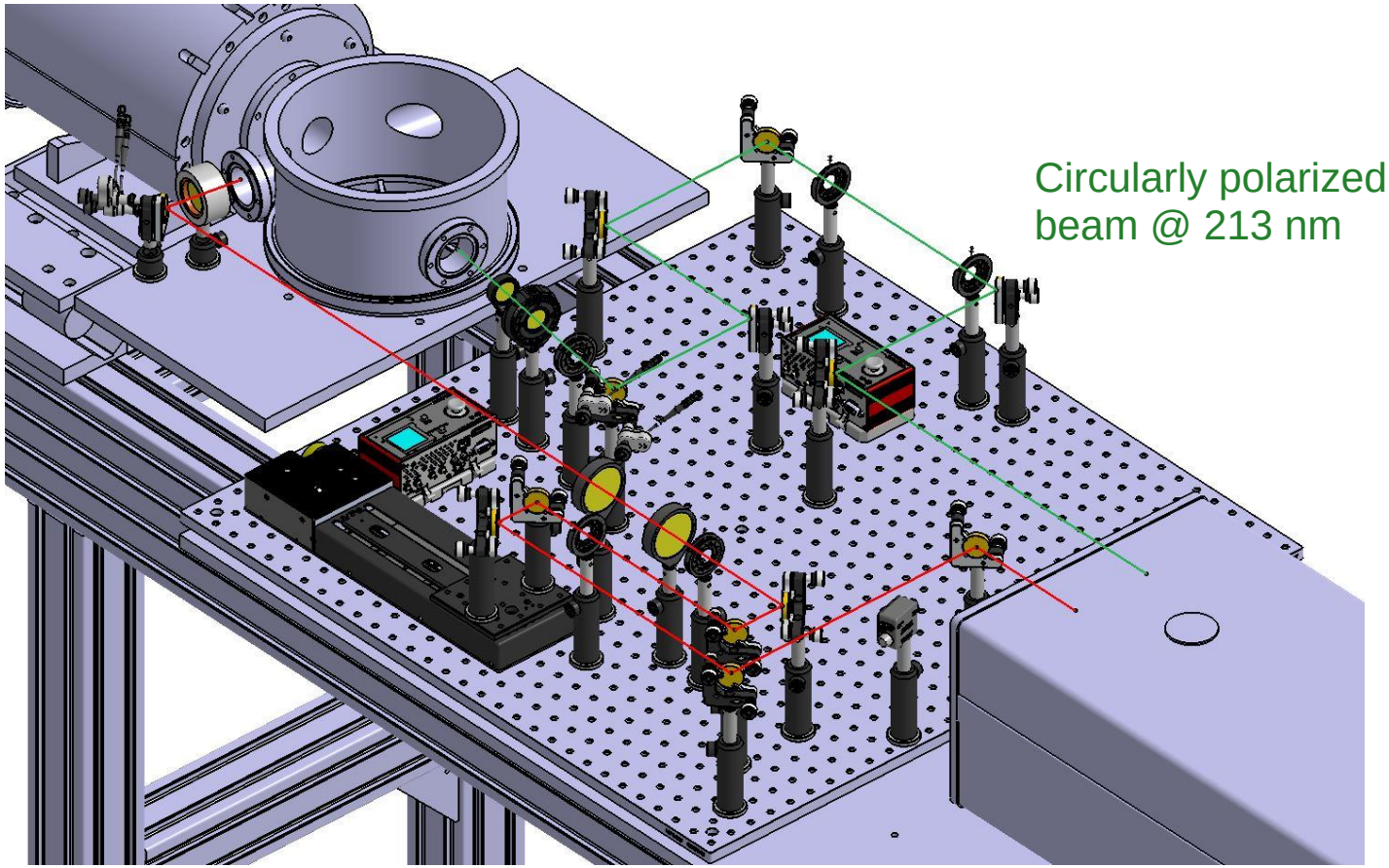


II. Polarized nuclear fusion
   ➡ Enhanced yield of fusion reactors



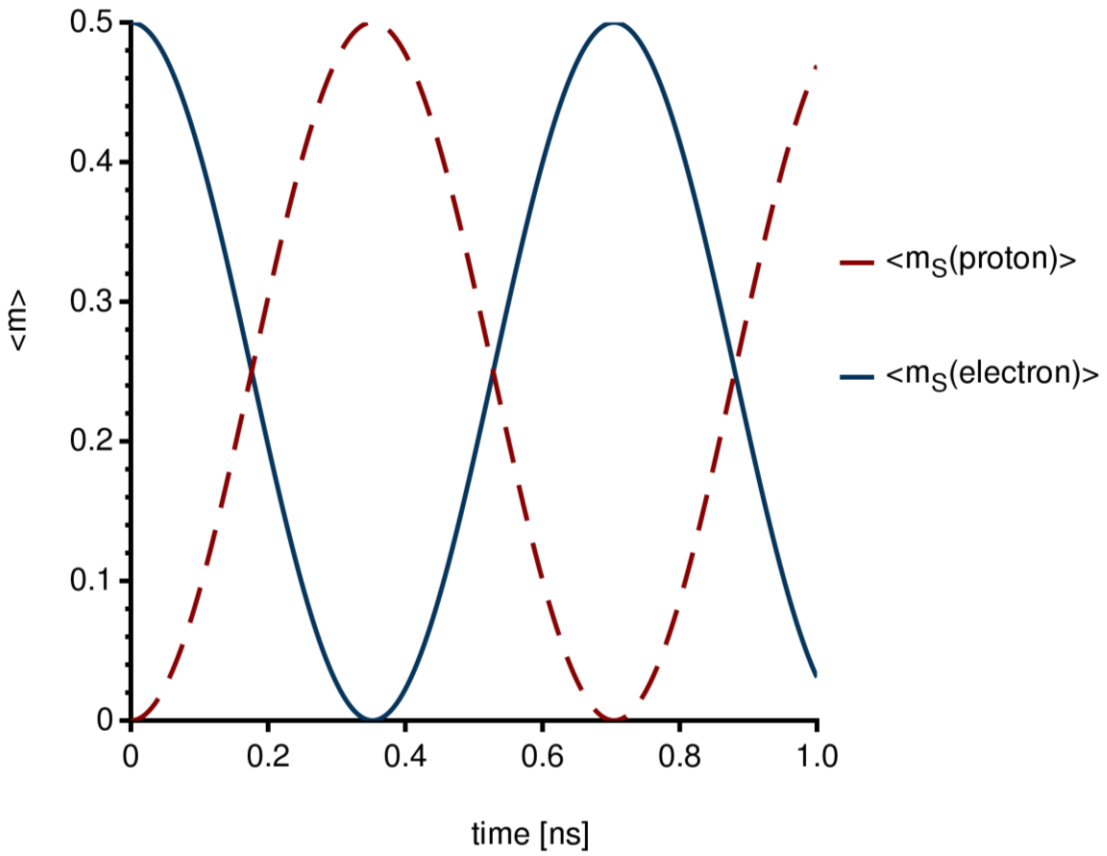
SETUP OF OPTICAL ELEMENTS

Linearly polarized
beam @ 1064 nm



Circularly polarized
beam @ 213 nm

POLARIZATION OF THE H NUCLEUS

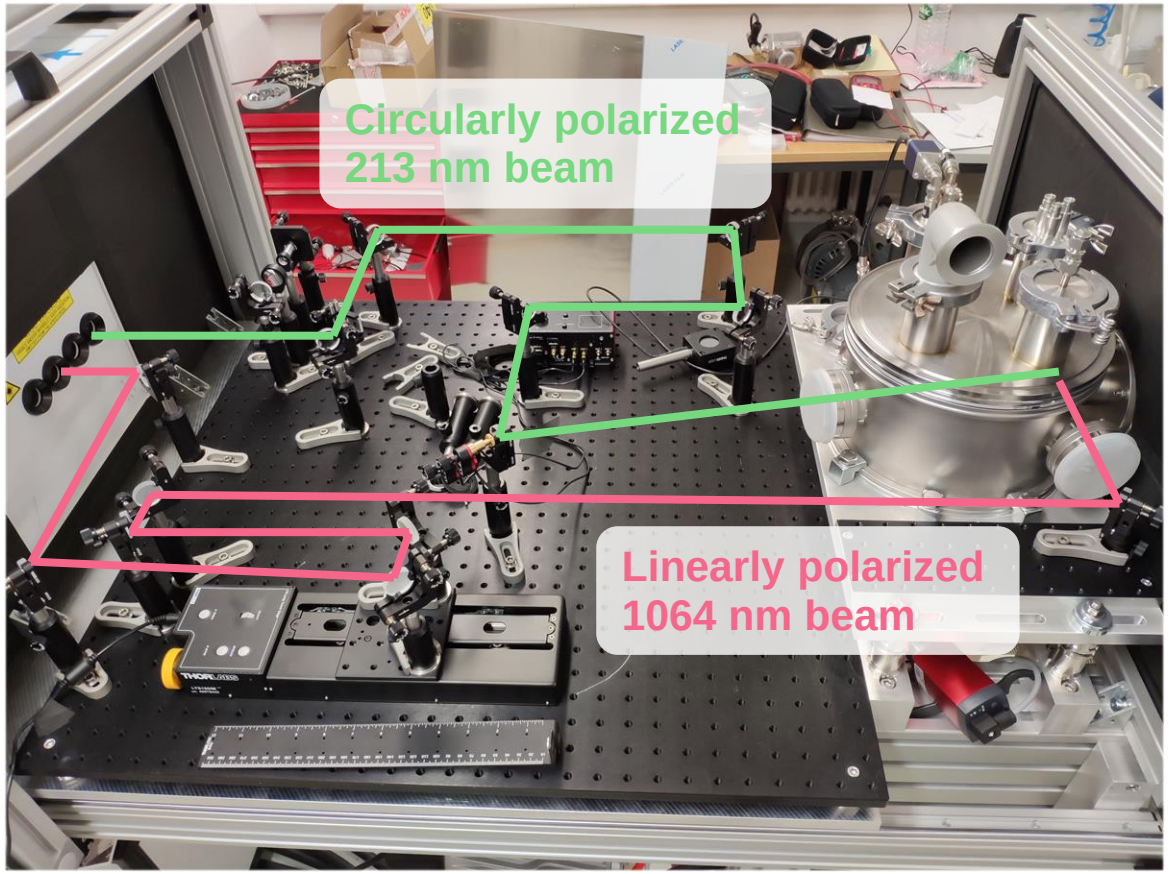


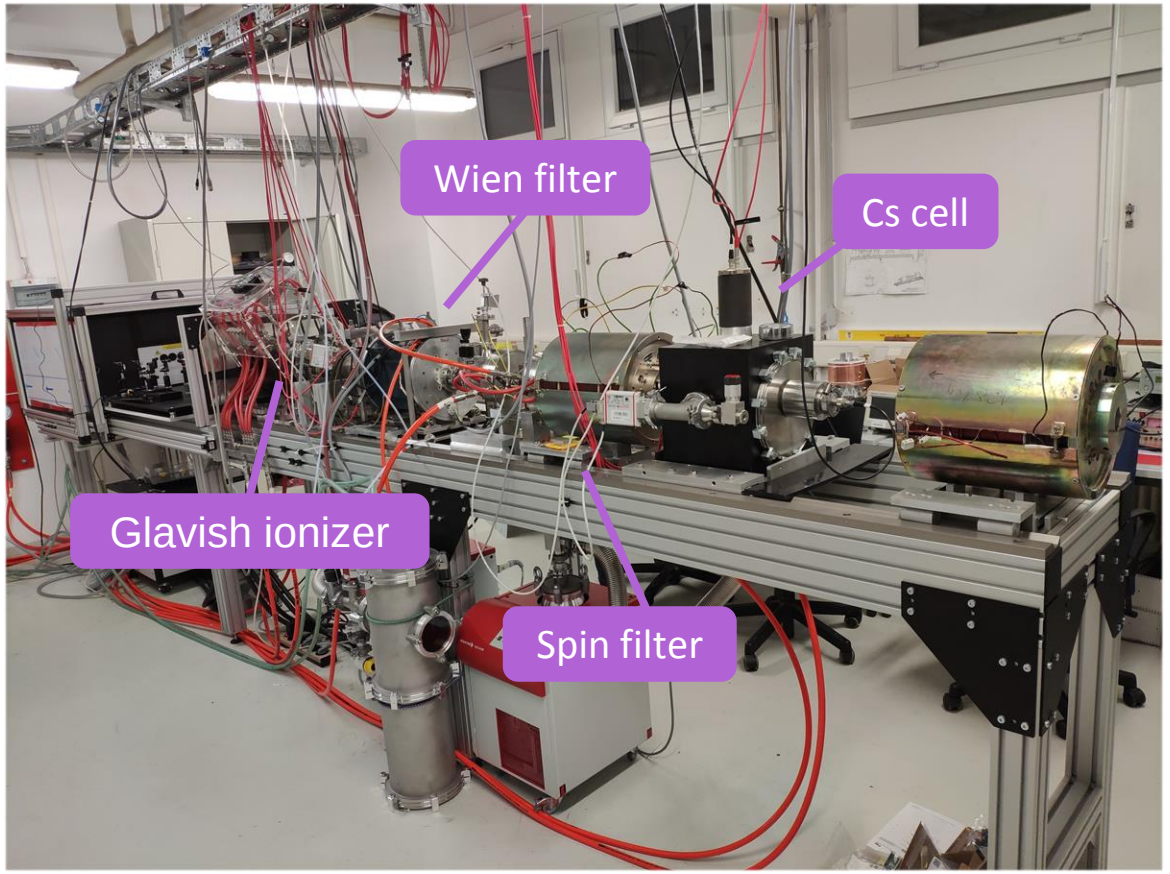
- Maximal theoretical polarization *P*

$$P = \frac{m}{m_{\max}} = 100\%, \text{ with } m_{\max} = 0.5$$

- After 0.35 ns the e^- polarization of the H atoms is transferred into a nuclear polarization
- Out-coming protons will remain polarized, even if they undergo spin precession (T-BMT equation)

CURRENT STATUS OF THE EXPERIMENT





COMMISSIONING OF POLARIZED HCL TARGET

Additional signal from nuclear polarized Hydrogen expected

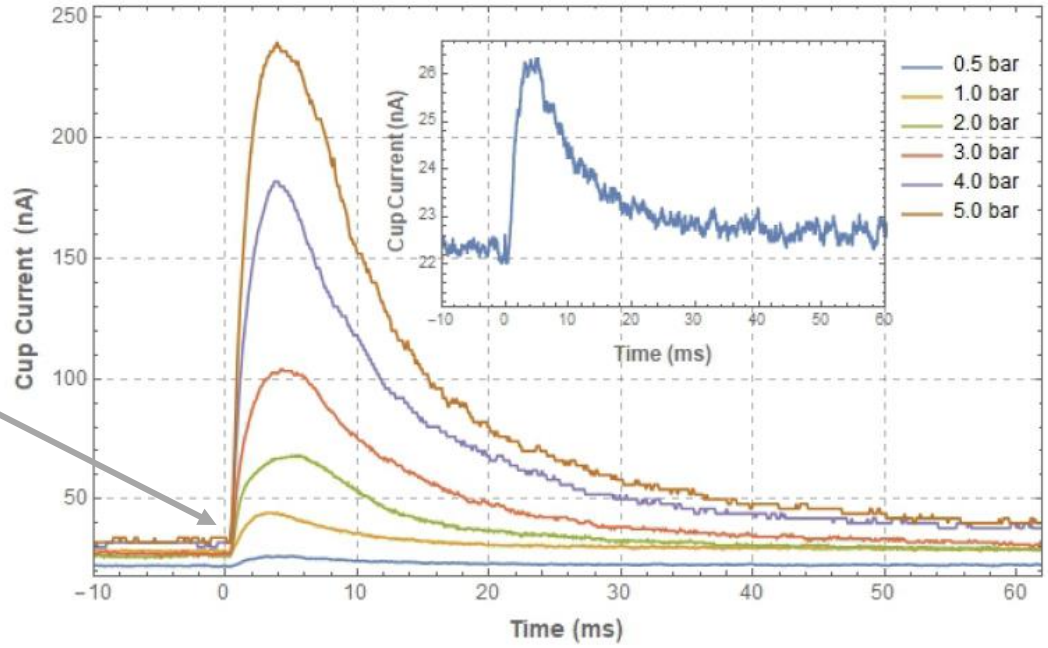


Fig. 2: HCl diffusion signal for various values of backing pressure measured by a Faraday cup. Inset: A zoom into the signal at 0.5 backing pressure.

https://www.researchgate.net/publication/340460224

- Clear detection of proton signal from diffusive HCl into ionizer after ~ 4 ms.
- Laser-generated atoms should produce additional proton signal
  → not yet detected

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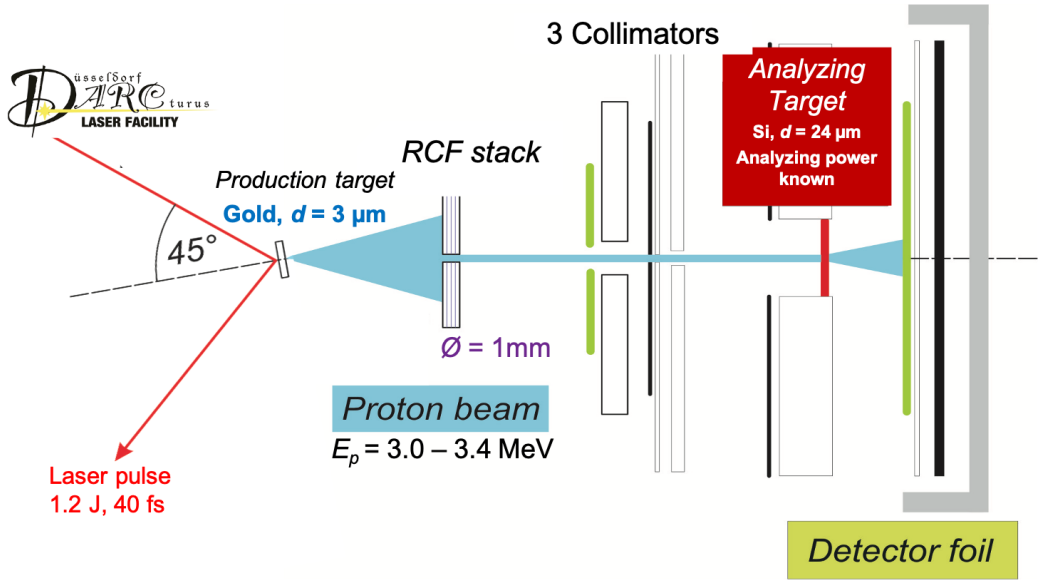
WHY POLARIZATION OF PROTONS?

Our group already has expertise in polarized proton acceleration



➡ Polarimetry developed

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

Stagnation in the (unpolarized) proton acceleration

➡ New target concepts needed

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SPIN AS A PARTICLE PROPERTY

mass

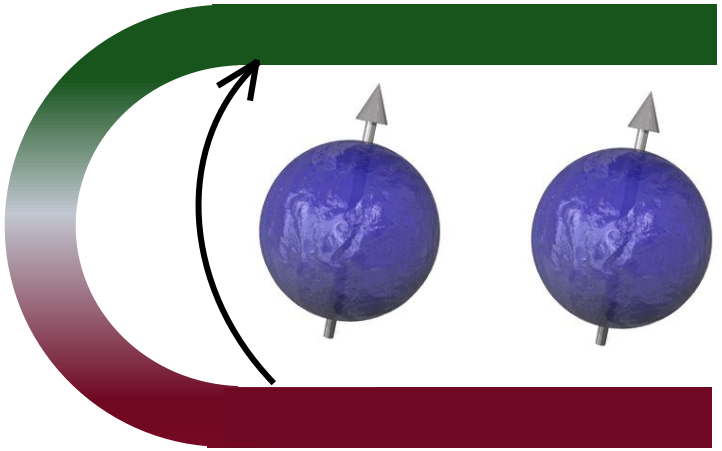
charge

spin

"Everything in the universe, including light and gravity, can be described in terms of particles. These particles have a property called spin. [...] What the spin of a particle really tells us is what the particle looks like from different directions."

A Brief History of Time – Stephen Hawking - Chapter 5

spin = intrinsic angular momentum



polarization

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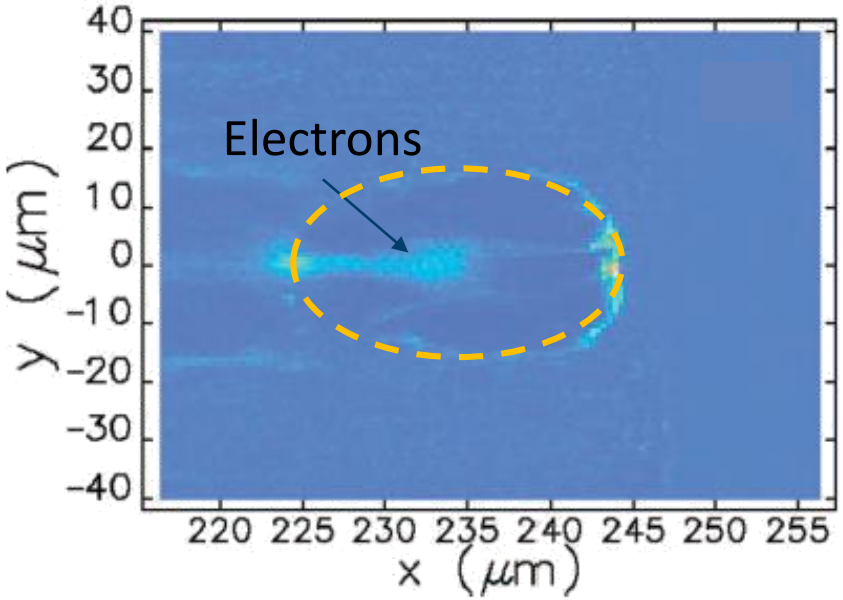
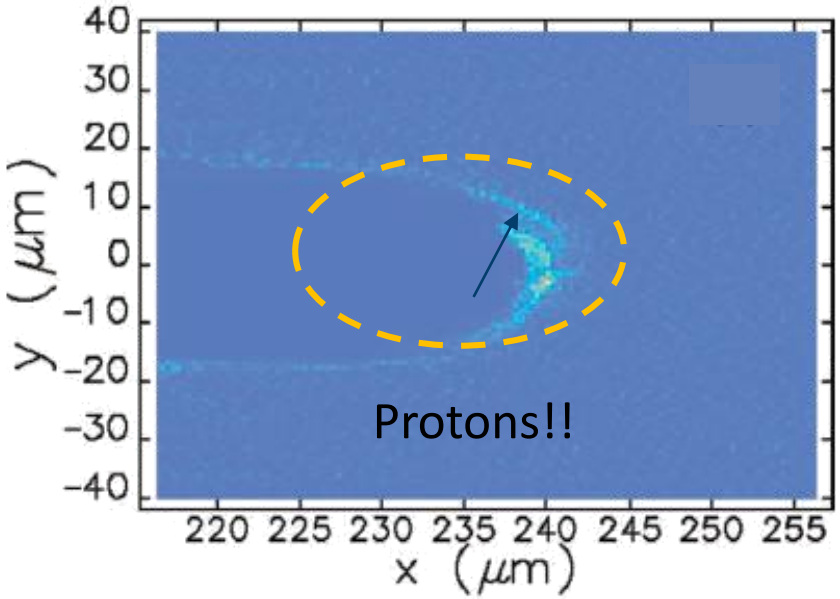
PREDICTED ACCELERATION SCHEME FOR PROTONS





λ_L= 800 nm,
a_0= 316/$\sqrt{2}$,
Δx= 10 µm,
ρ_H= 10^{20} cm^{-3},
ρ_T= 1.4*10^{21} cm^{-3},
t= 320 fs

- Acceleration in electron bubble-channel structure: e^- at the rear of the bubble, ions at the front
- Gas mixtures required (protons & heavier nuclei)
- High Laser powers required (>10 PW)

➡ Observation of a up to GeV polarized proton beam.

B. Shen et al., Phys. Rev. E **76**, 055402 (2007)

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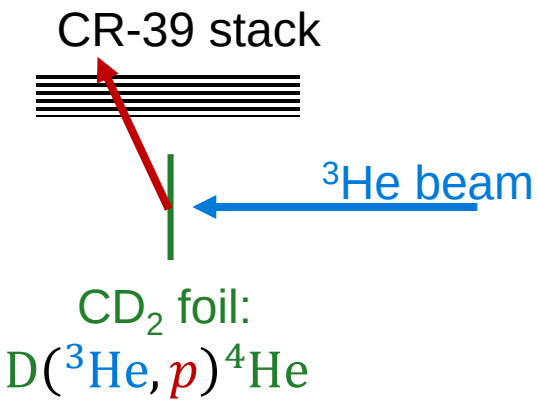
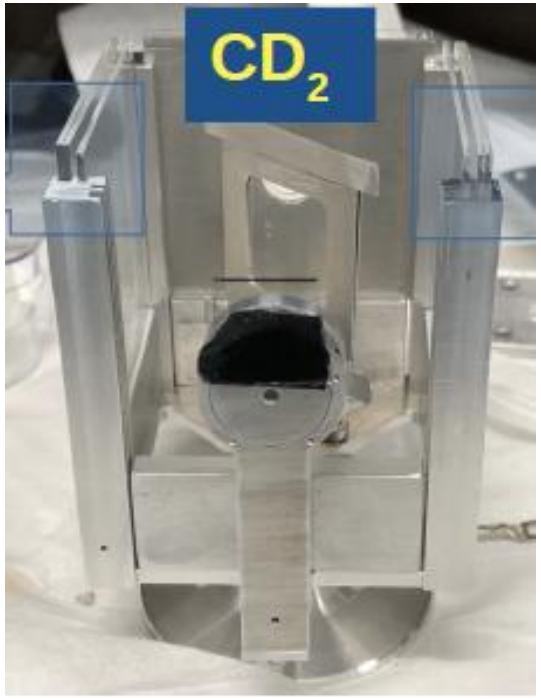
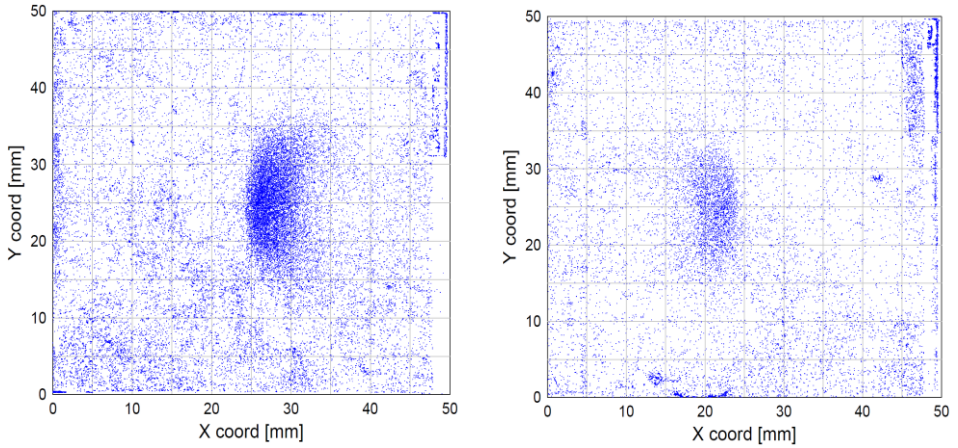
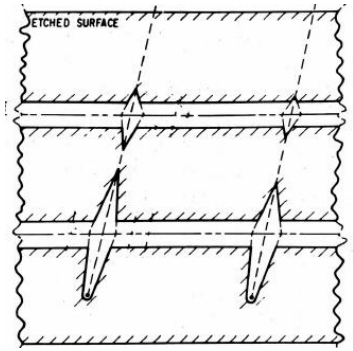
POLARIMETRY FOR ^{3}HE IONS





Test beam time at Jülich Tandetron with unpolarized ^{3}He beam





Analysis by: C. Zheng

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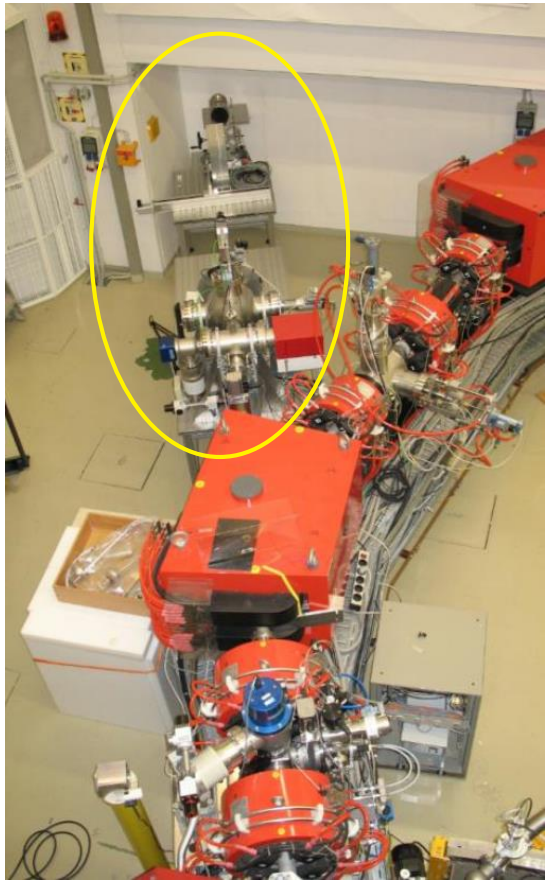
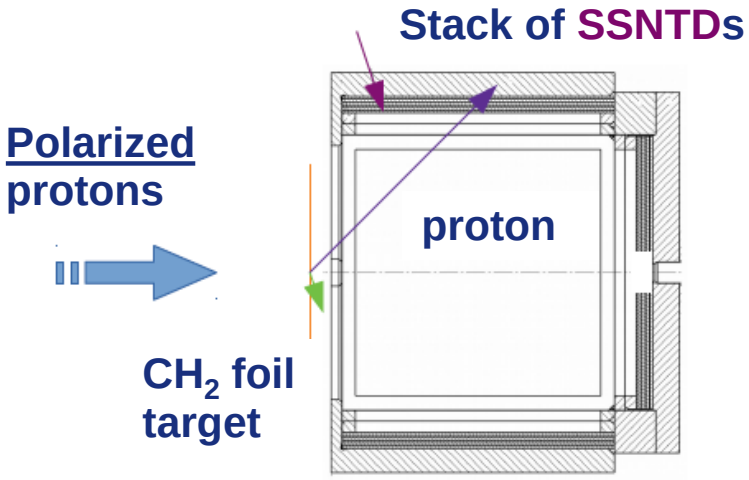
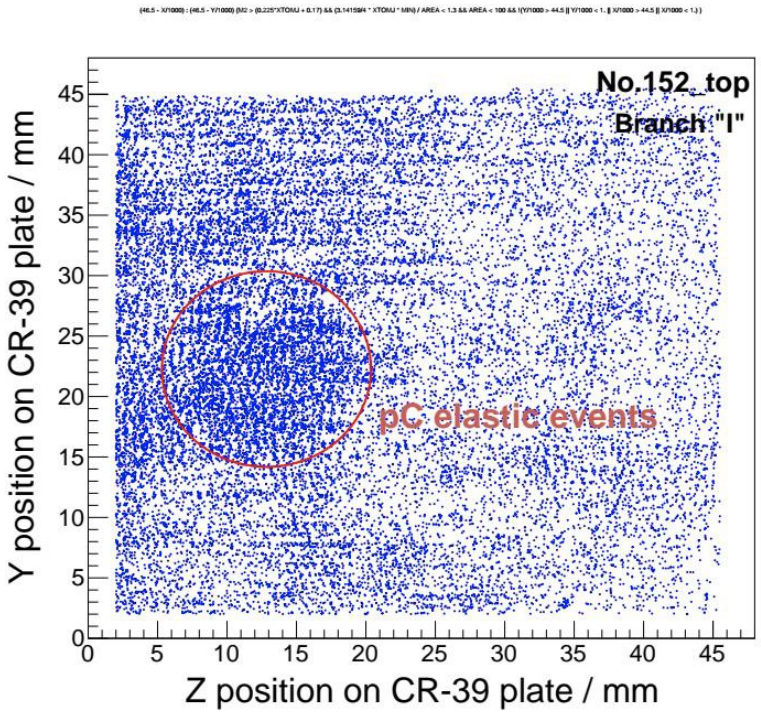
POLARIMETRY FOR PROTONS





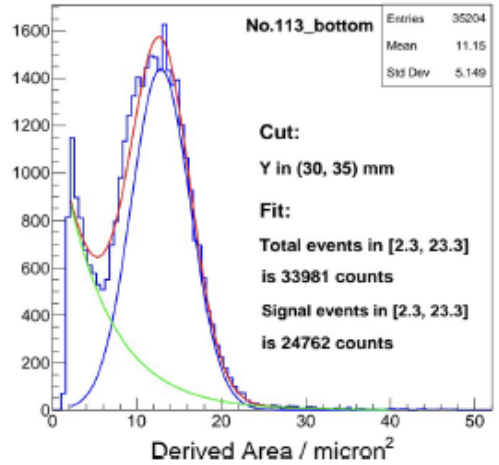


Based on elastic pp and pC scattering
Test beam time @COSY: Feb. 2020
Data under analysis

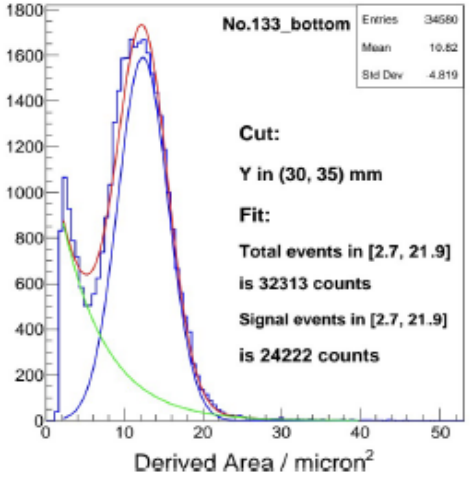
Analysis by: C. Zheng

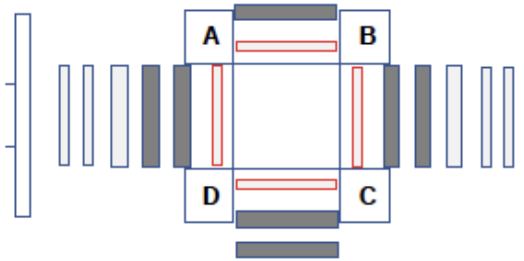
Events selection: Shot No. 3 (unpol., 6hrs)

Up: 24 762 evts

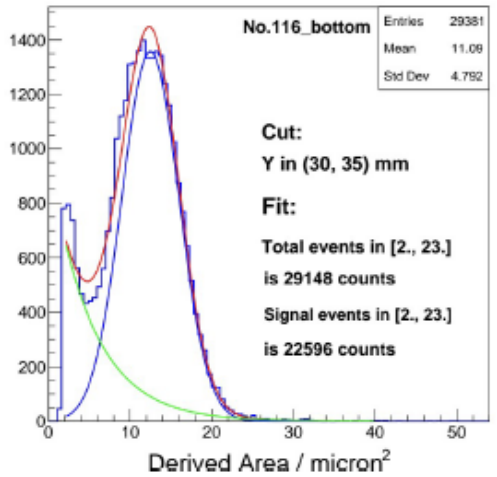


Left: 24 222 evts





Right: 22 596 evts



Down: 19 750 evts