GENERATION OF POLARIZED PARTICLE BEAMS AT RELATIVISTIC LASER INTENSITIES

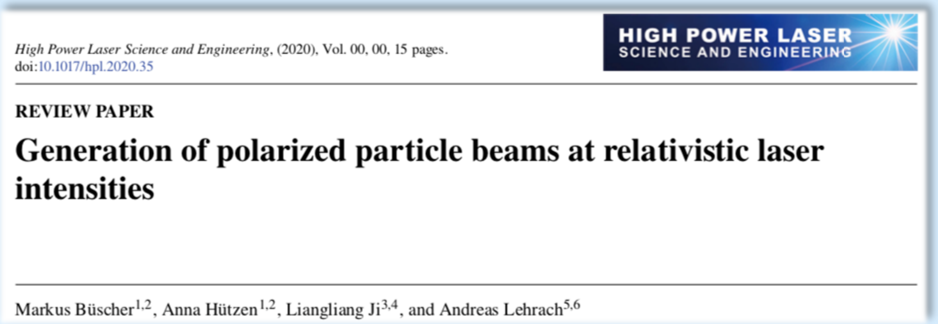
LPA Seminar [*Ju*SPARC Seminar]

ANNA HÜTZEN | 25 NOVEMBER 2020

JuSPARC ATHENA hhu Heinrich Heine Universität Düsseldorf SIOM JÜLICH Forschungszentrum

PARTICLES, SPINS & PLASMA PHYSICS: GOALS

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

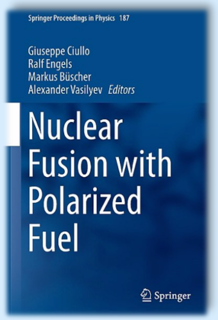

High Power Laser Science and Engineering, (2020), Vol. 00, 00, 15 pages.
doi:10.1017/hpl.2020.35

REVIEW PAPER

Generation of polarized particle beams at relativistic laser intensities

Markus Büscher[1,2], Anna Hützen[1,2], Liangliang Ji[3,4], and Andreas Lehrach[5,6]

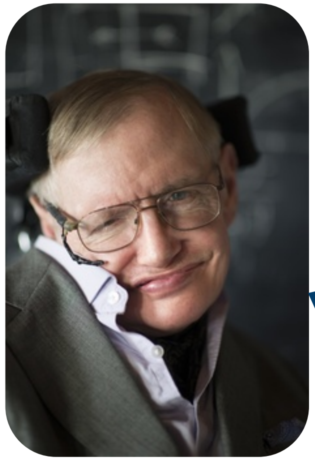
II. Polarized nuclear fusion
   ➡ Enhanced yield of fusion reactors



SPIN AS A PARTICLE PROPERTY

mass

charge

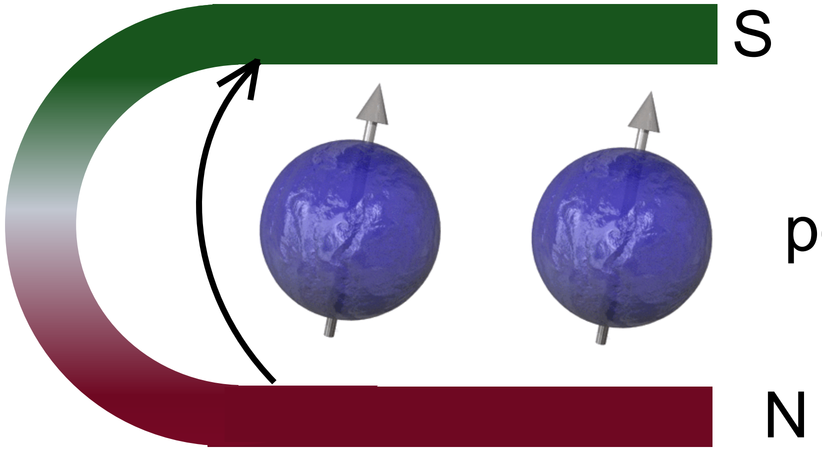


spin

“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

POLARIZATION BUILD-UP?

- Typical energy of spin states:

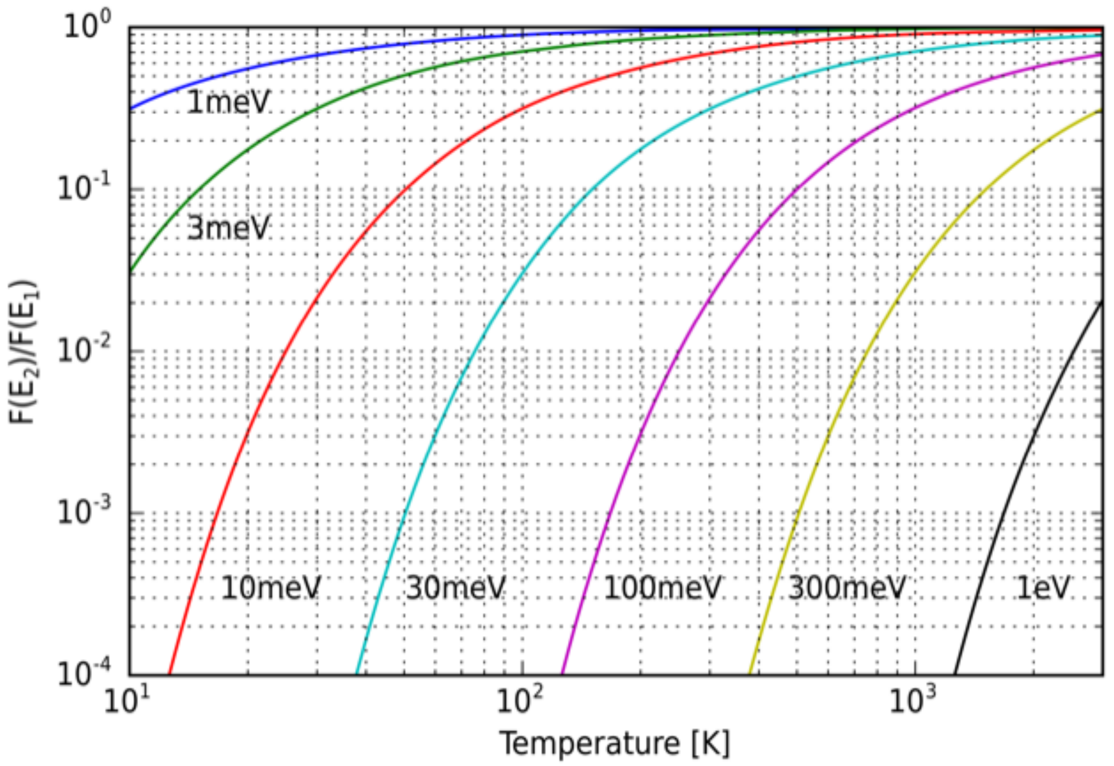
$$E_{\text{spin,p}} = \mu \cdot B = 6 \cdot 10^{-8}\,\frac{\text{eV}}{\text{T}} \cdot 1000\ \text{T}\ \approx 1\ \text{meV}$$

- Typical temperature of the plasma:

  10^8 K ≈ 10 keV

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

➡ no polarization (in thermal equilibrium)

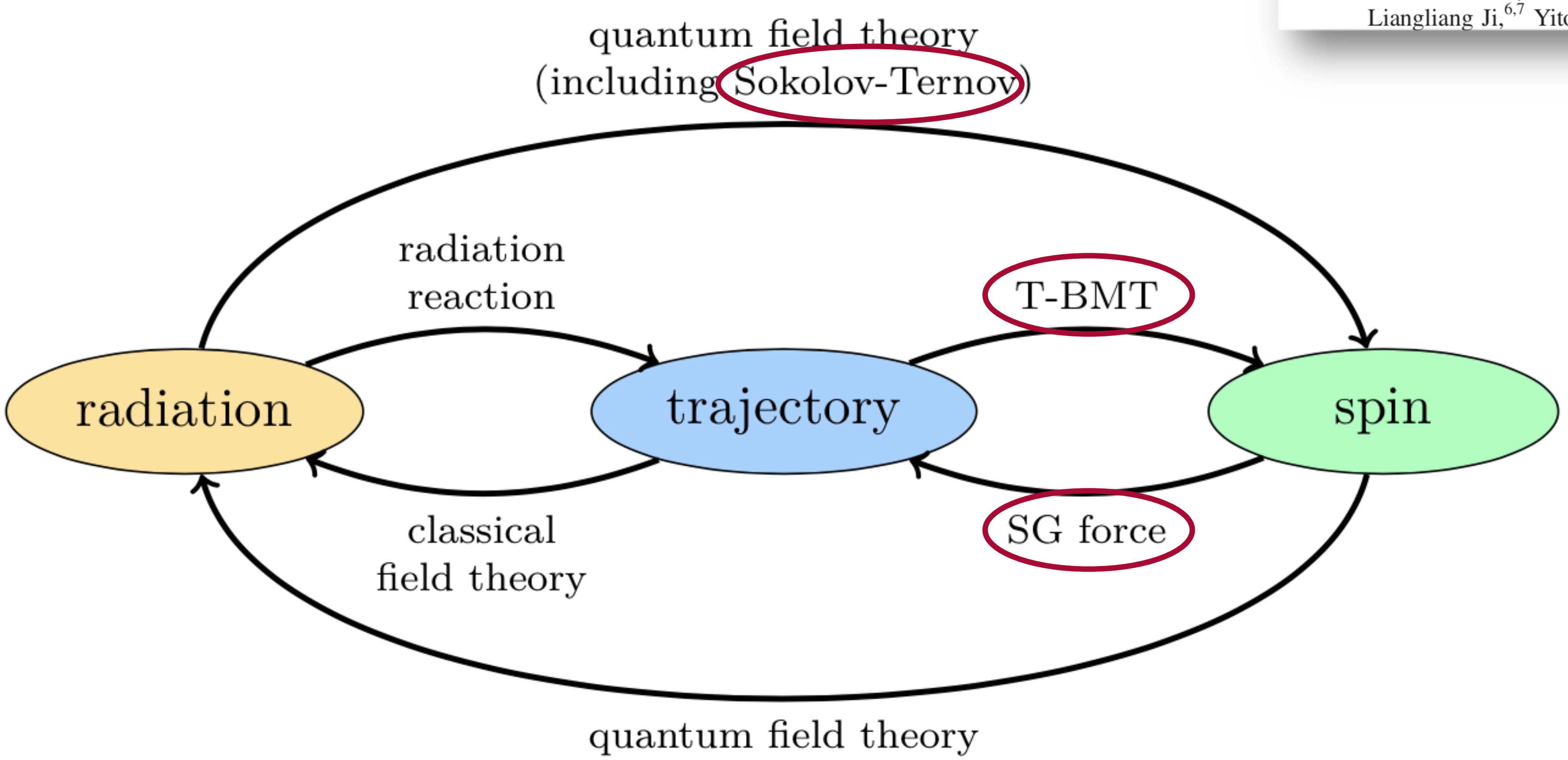


INTERACTIONS INVOLVING SPINS

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]



3 relevant processes (for e^-, protons, ions):

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

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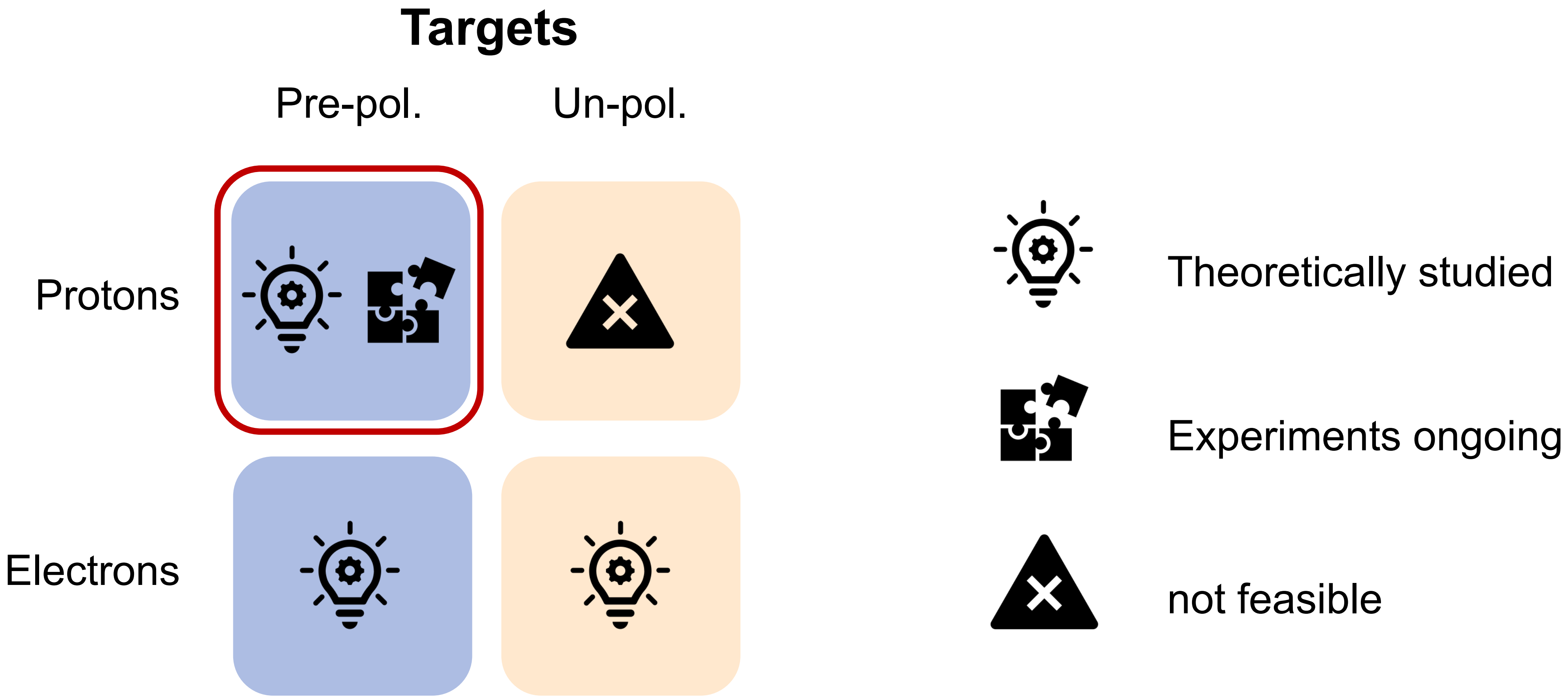
POSSIBLE (DE-)POLARIZATION EFFECTS

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

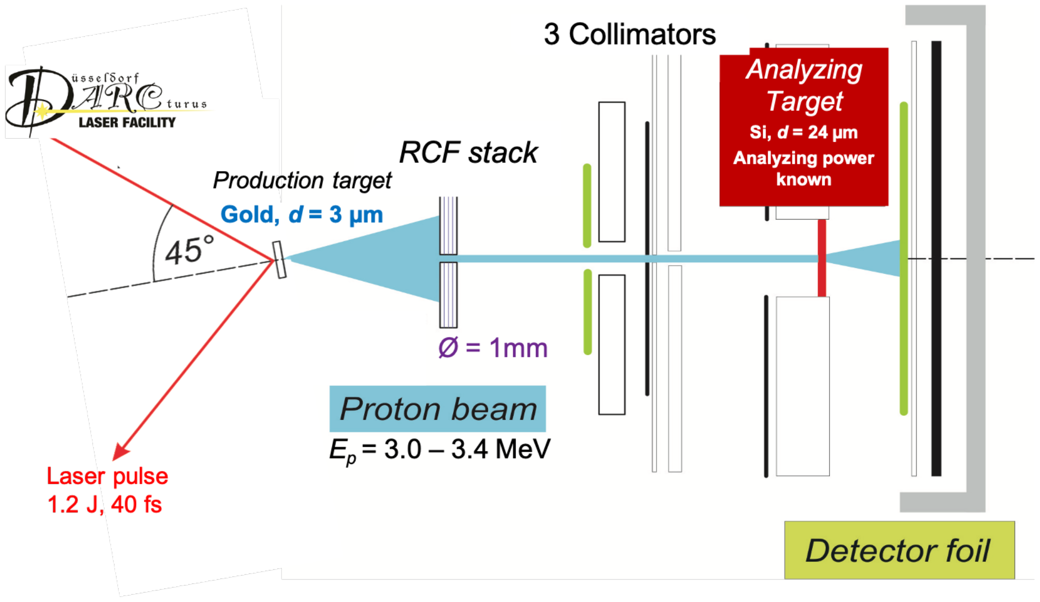
Separation distances are in the nm-range for e^- & sub pm-range for protons
→ Spatial separation too small

POLARIZATION OF ELECTRONS VS PROTONS



WHY POLARIZATION OF PROTONS?

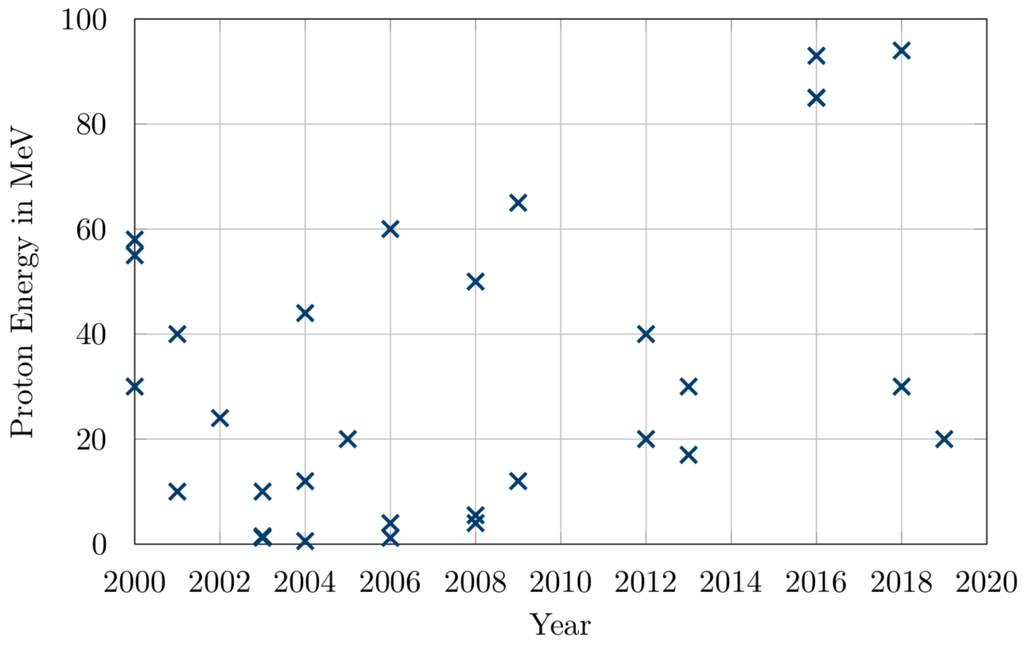
Our group already has expertise in polarized proton acceleration



➡ Polarimetry developed

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

Stagnation in the (unpolarized) proton acceleration



➡ New target concepts needed

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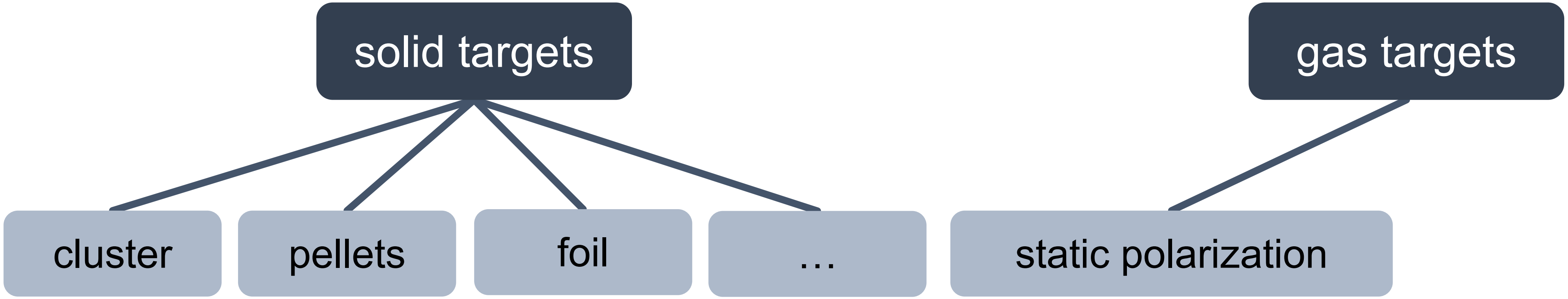
POLARIZED TARGET GEOMETRIES FOR PROTONS



- 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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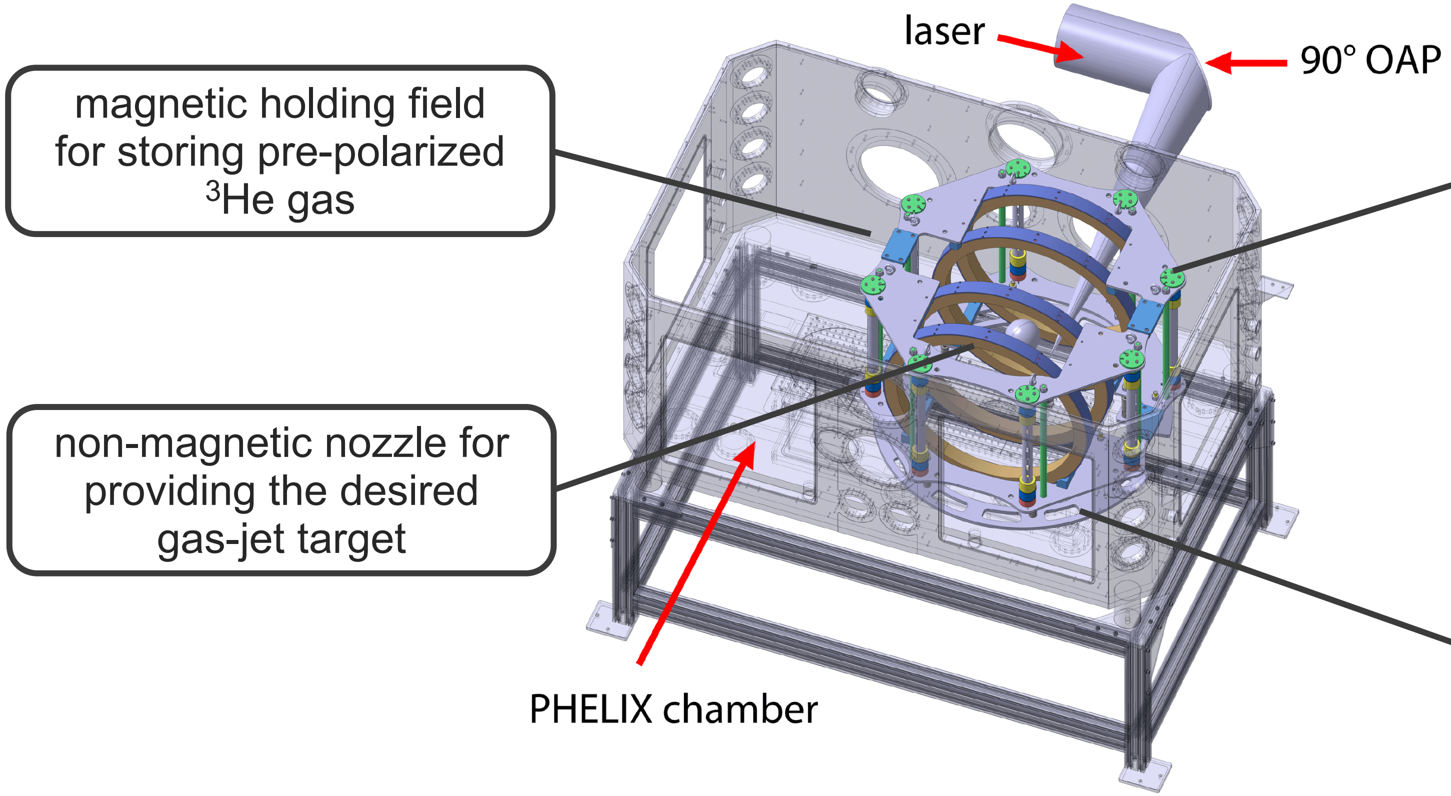
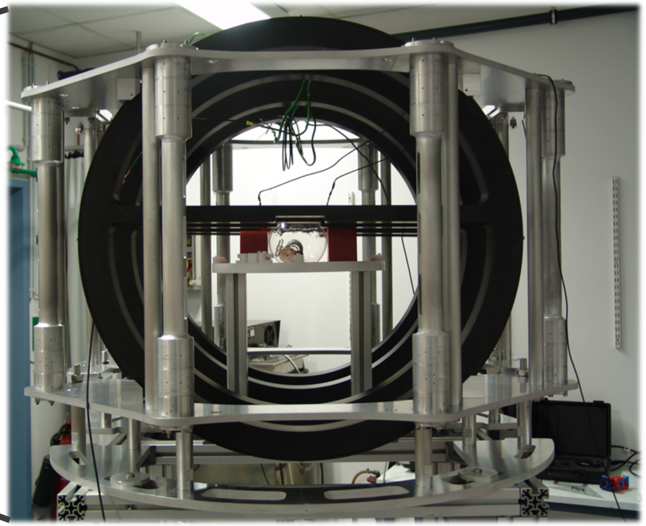
HYPERPOLARIZED ^{3}HE GAS-JET

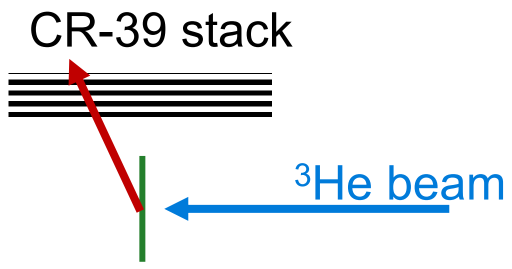




P. Fedorets, C. Zheng

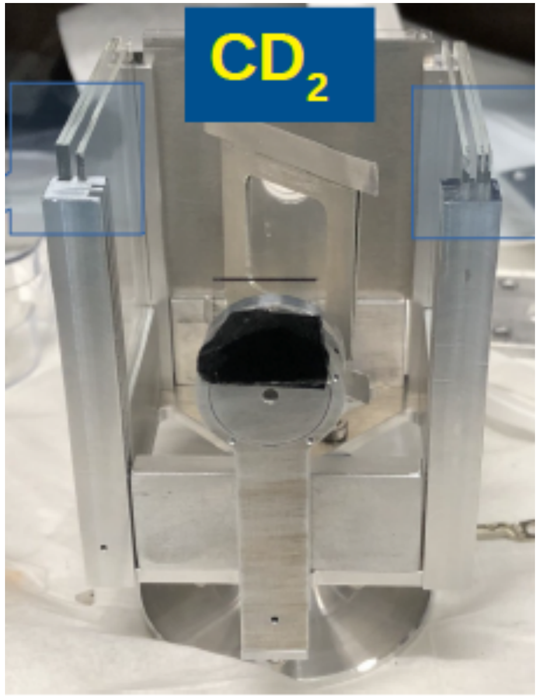
Start of measurements @ PHELIX GSI: 2021

POLARIMETRY FOR ^{3}HE IONS WITH CR-39 PLATES

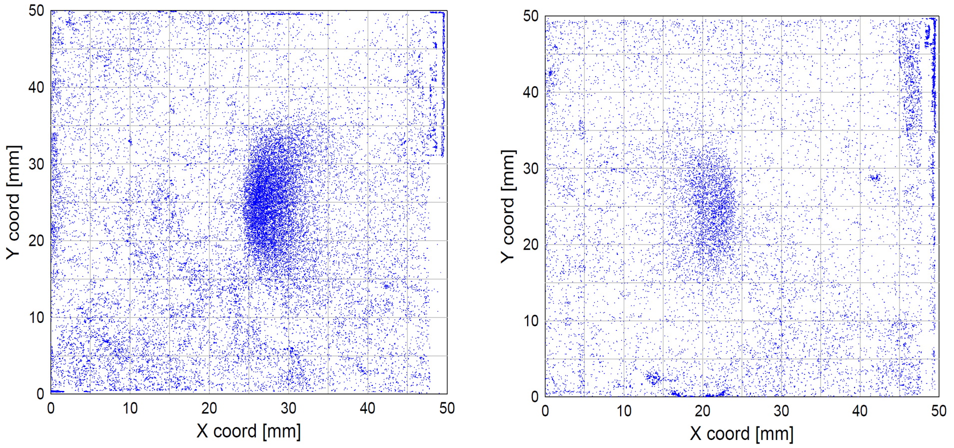


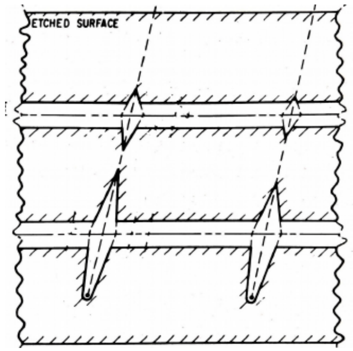
CD_2 foil:

$D(^3He, p)^4He$



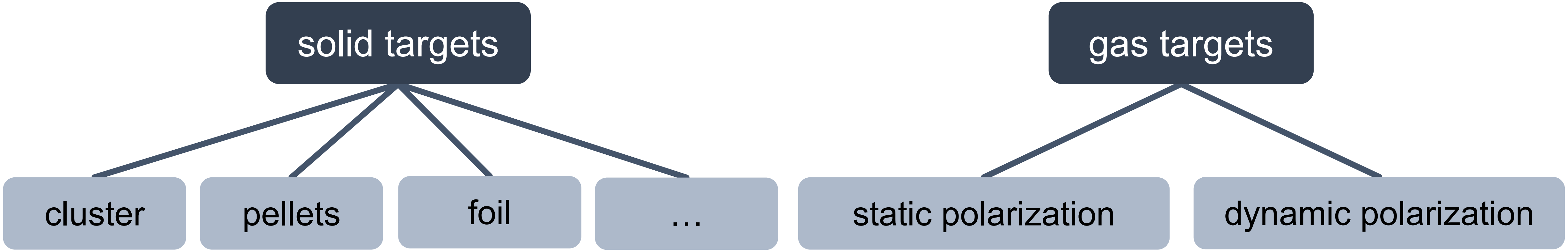
Test beam time at Jülich Tandetron
with unpolarized ^{3}He beam





Analysis by: C. Zheng

POLARIZED TARGET GEOMETRIES FOR PROTONS



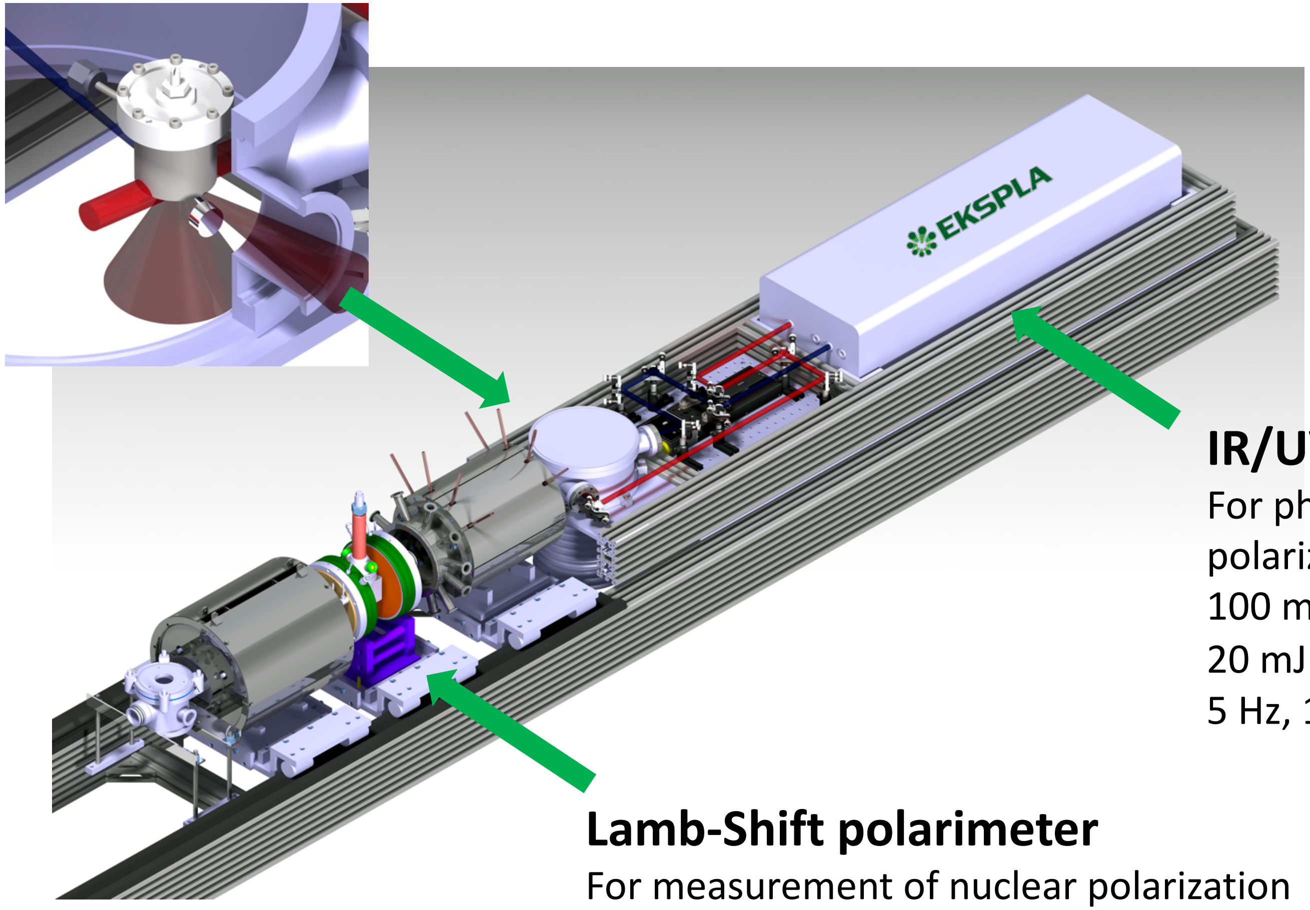
- Targets suitable for laser acceleration not available yet
- Experimental realization extremely challenging

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

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

DYNAMICALLY POLARIZED HCL 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)

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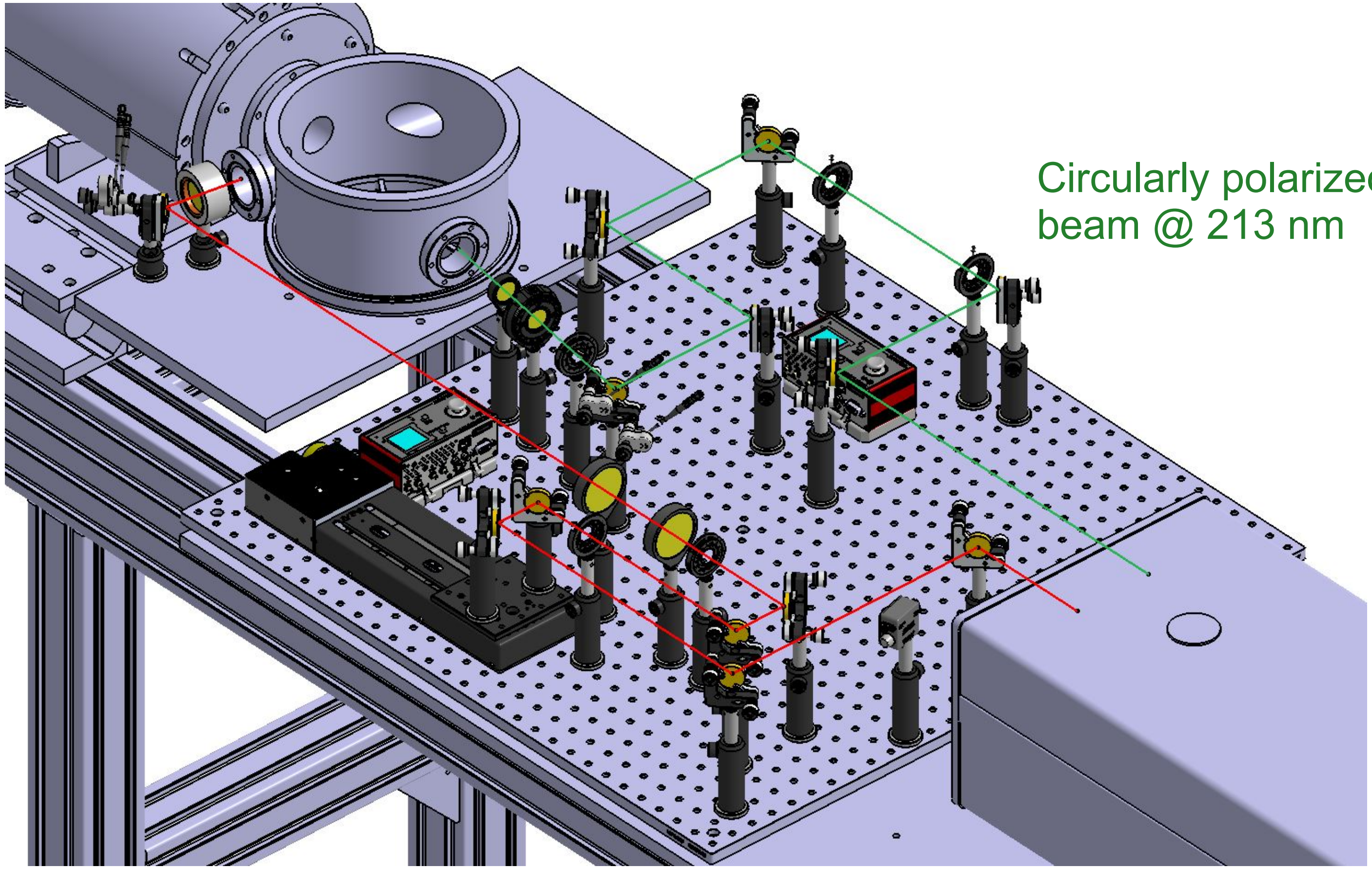
SETUP OF OPTICAL ELEMENTS

Linearly polarized beam @ 1064 nm



Circularly polarized beam @ 213 nm

PRODUCTION OF POLARIZED PROTON BEAMS

100 mJ @ 1064 nm

Alignment of
HCl bonds

ATHENA

20 mJ @ 213 nm

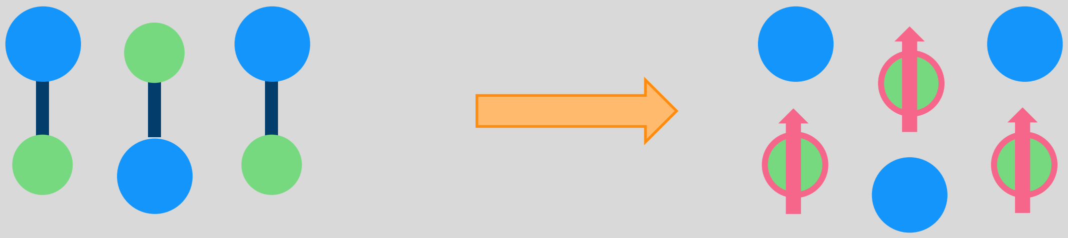
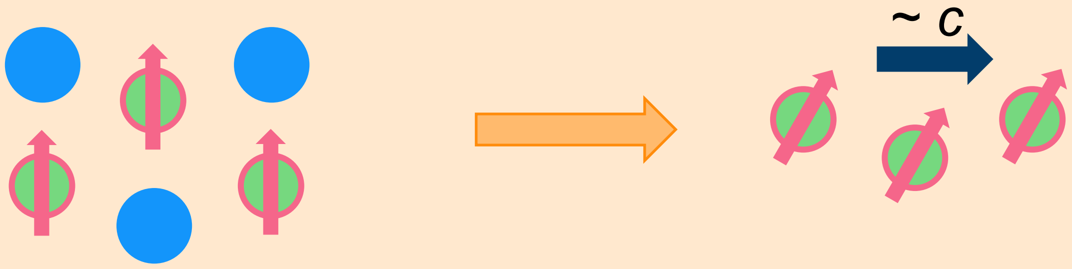


Photo-dissociation &
polarization transfer to
H nuclei (Δt = 350 ps)

SIOM

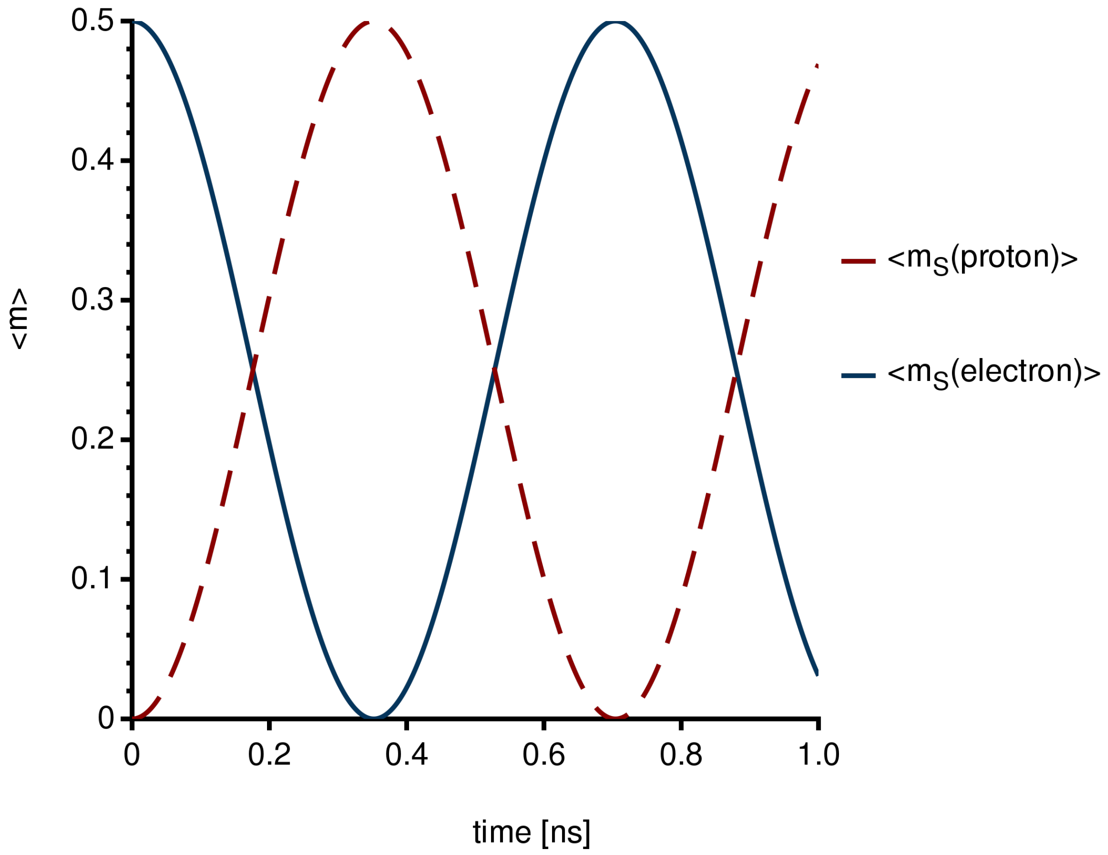
300 J @ 800 nm



Acceleration of the
protons in gas jet

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

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)

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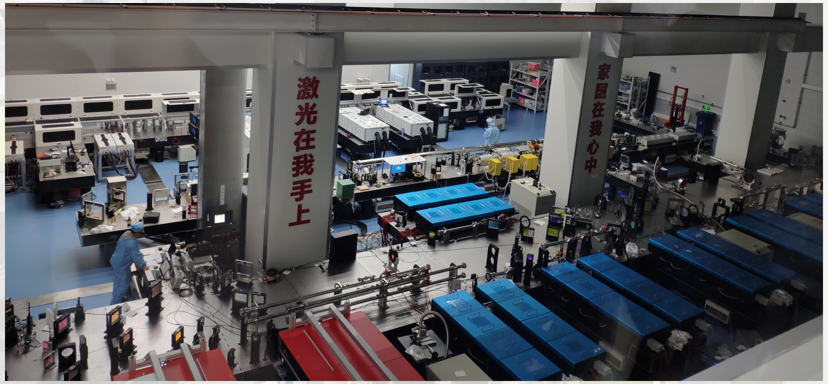
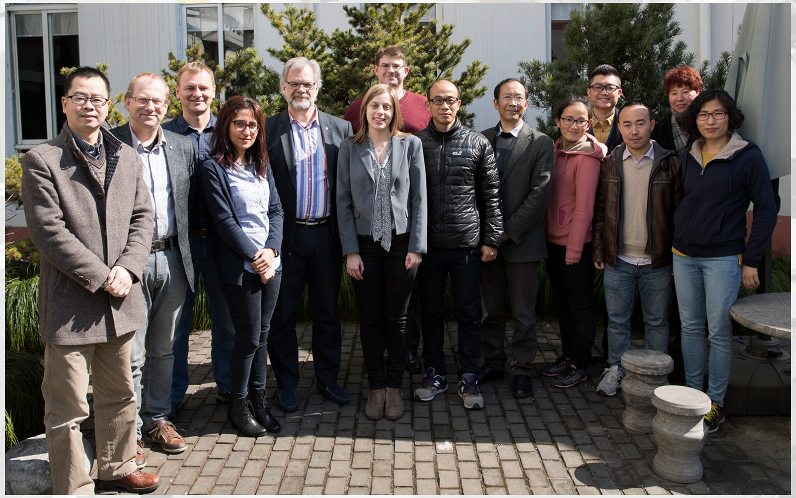
SUPERINTENSE ULTRAFAST LASER FACILITY @ SHANGHAI

SIOM

- Common simulation work and publications on polarized particle beams
- First common experiments on proton acceleration in 2021
- Application of joint Sino-German Research Project





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

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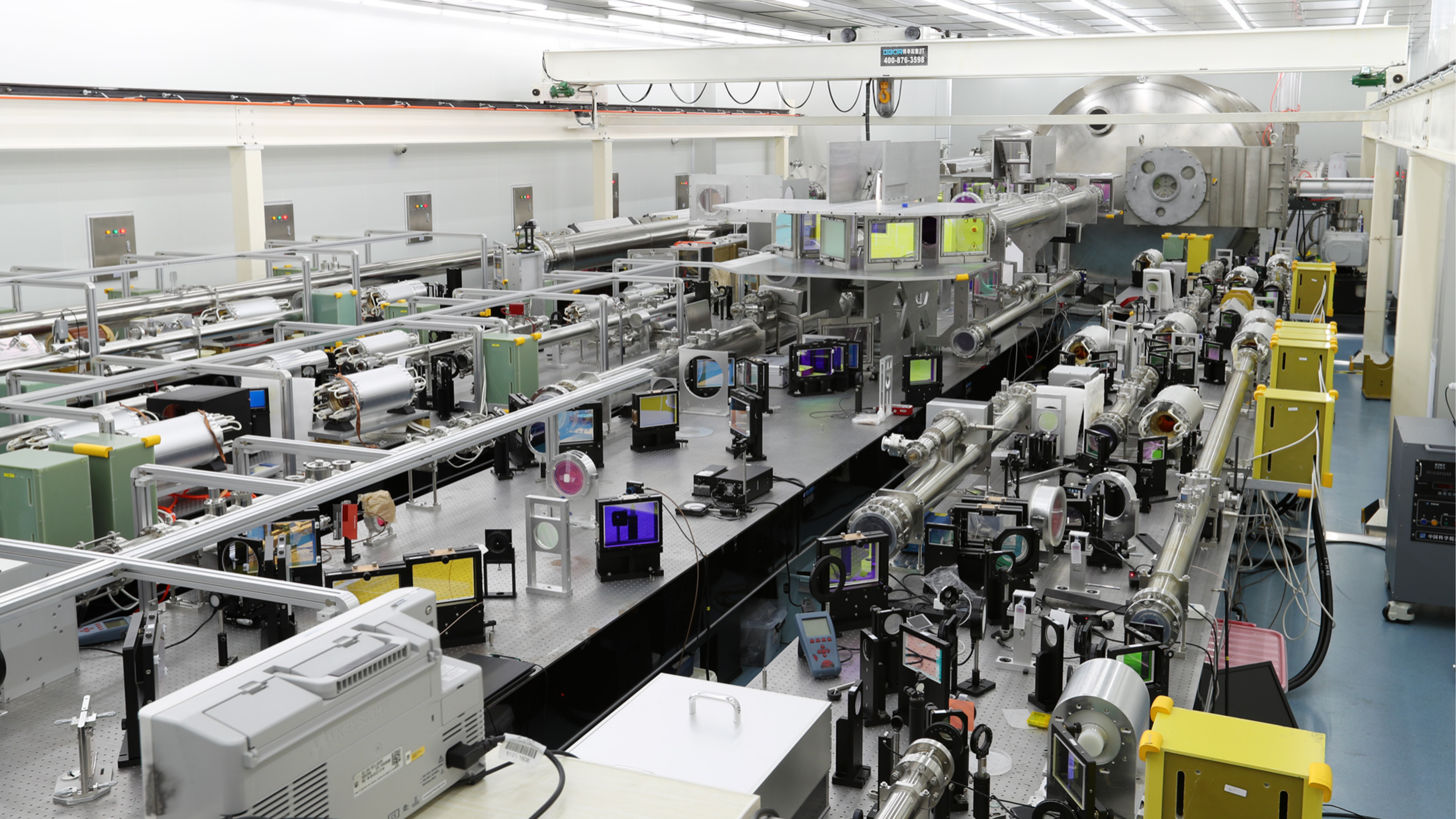
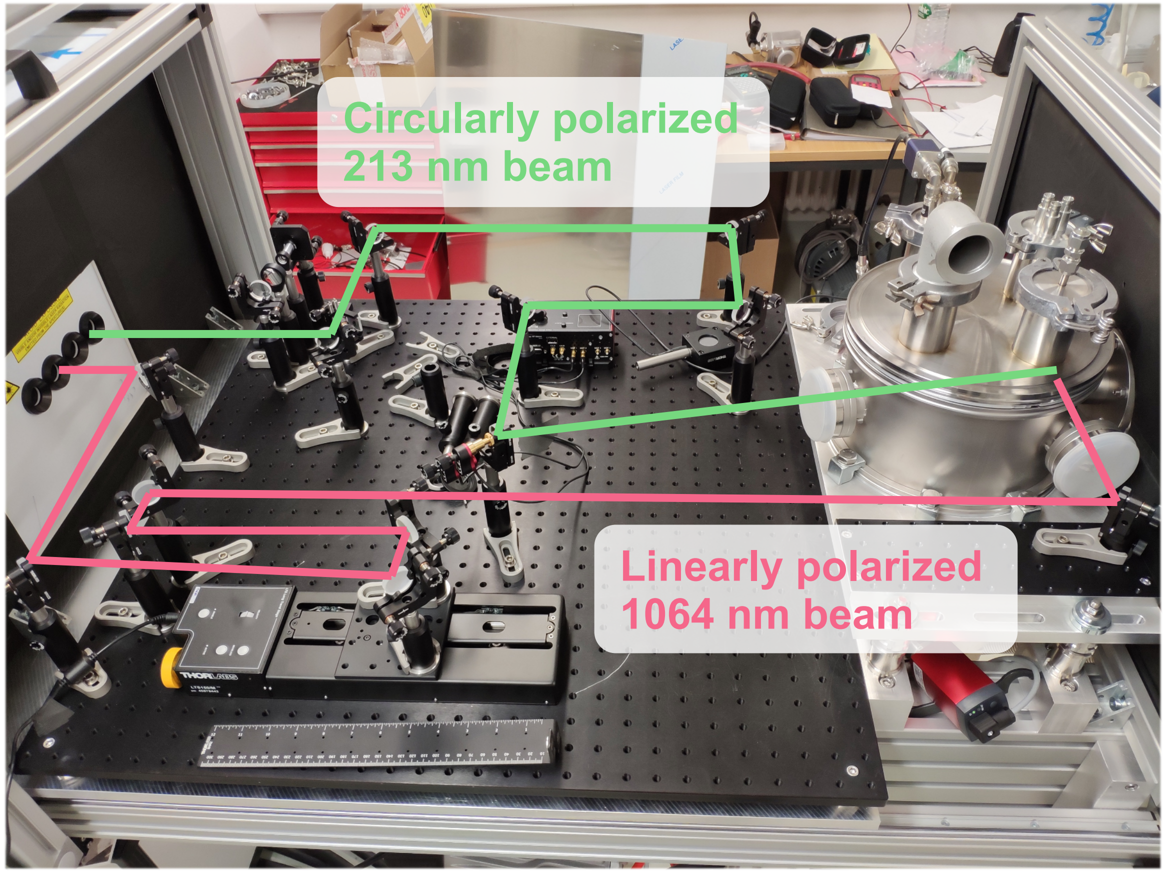
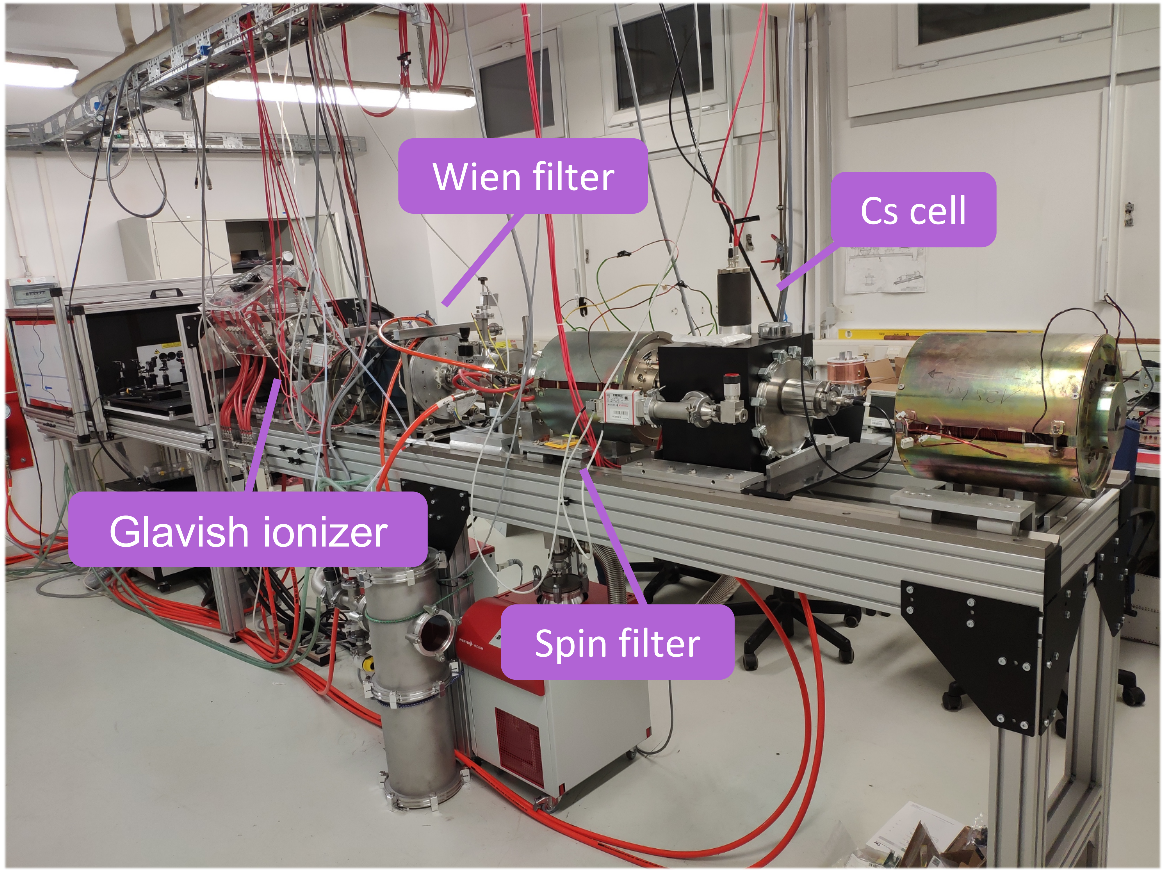

400-876-3598

CURRENT STATUS OF THE EXPERIMENT





COMMISSIONING OF POLARIZED HCL TARGET

Additional signal from nuclear polarized Hydrogen expected

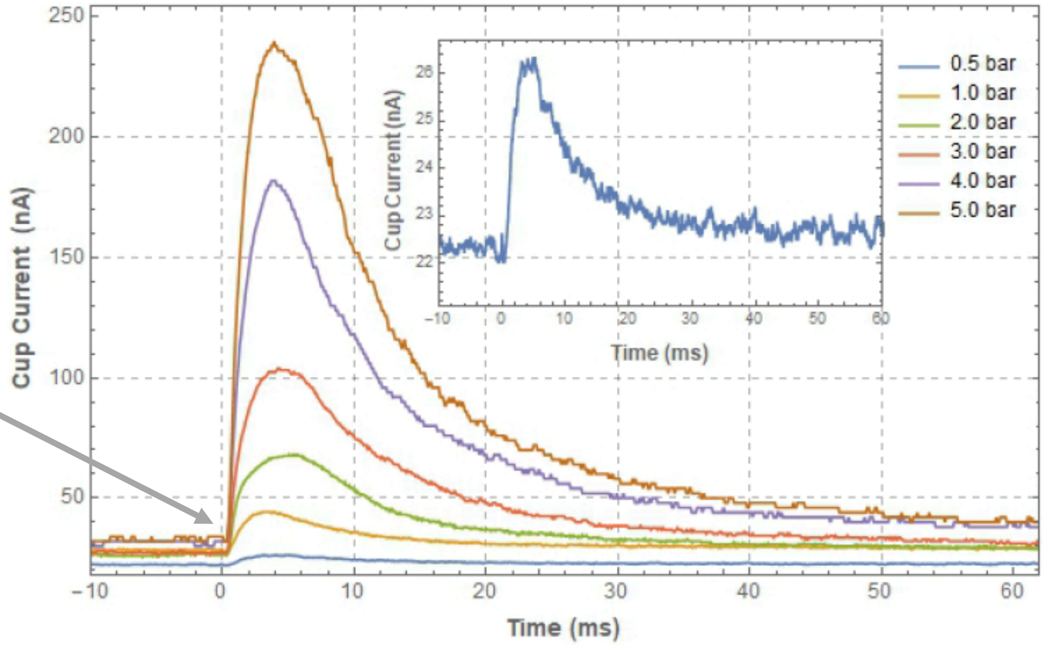
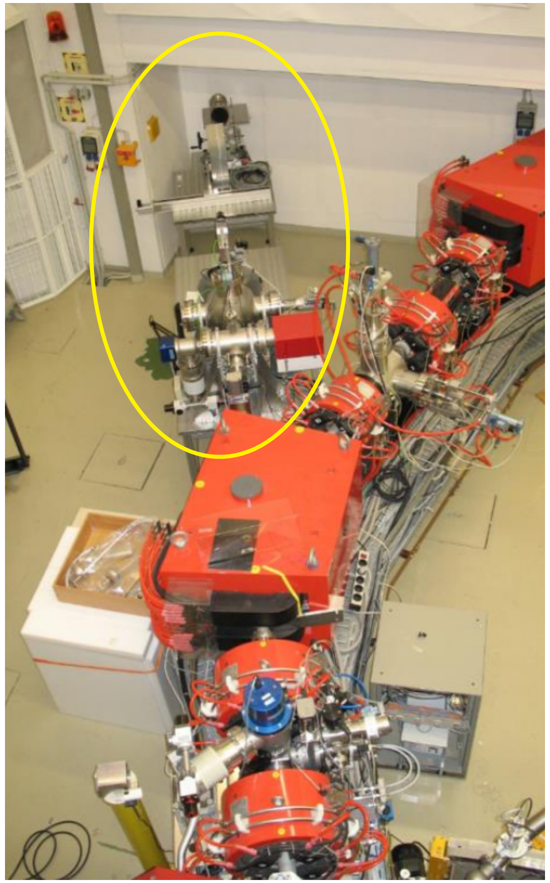


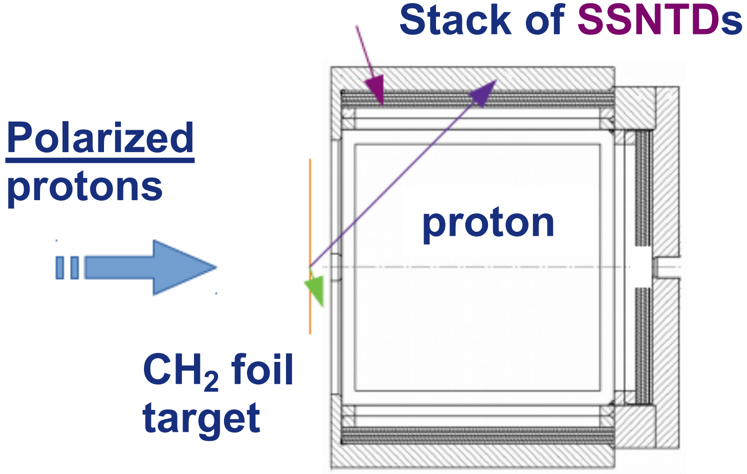
Fig. 2: HCl diffusion signal for various values of backing pressure measured by a Faraday cup. Inset: A zoom into the signal at 0.5 backing pressure.

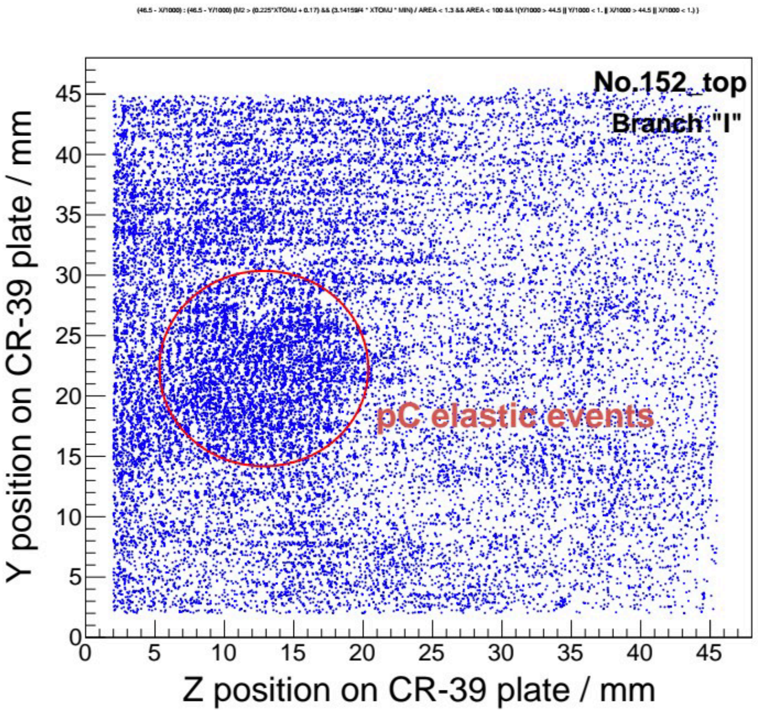
https://www.researchgate.net/publication/340460224

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

POLARIMETER FOR PROTONS WITH CR-39 PLATES



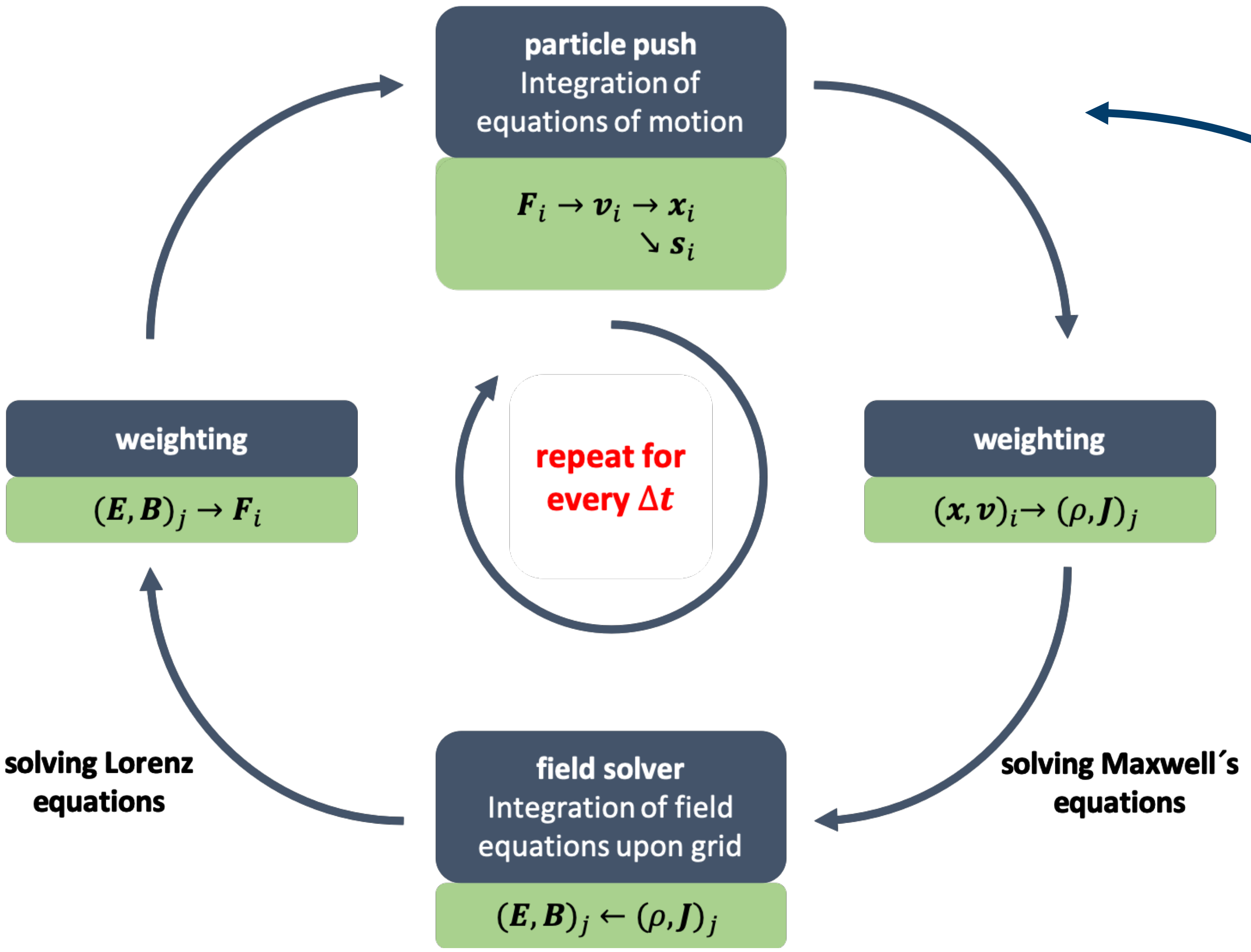




Based on elastic pp and pC scattering
Test beam time @COSY: Feb. 2020
Data under analysis

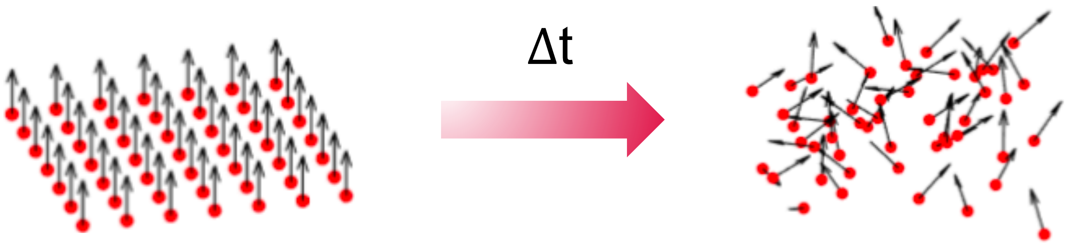
Analysis by: C. Zheng

SPIN DYNAMICS IN THE VLPL CODE



Implementation into already existing code

Spin precession described by the Thomas-BMT equation



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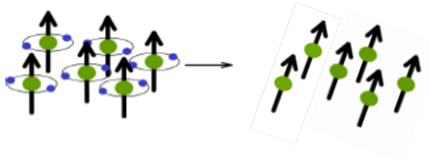
MODELLING OF SPINS IN LASER-INDUCED PLASMAS

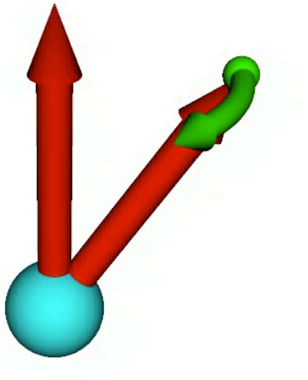
Implementation of particle spins into a simulation code (in collaboration with A. Pukhov, hhu Heinrich Heine Universität Düsseldorf)



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

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

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

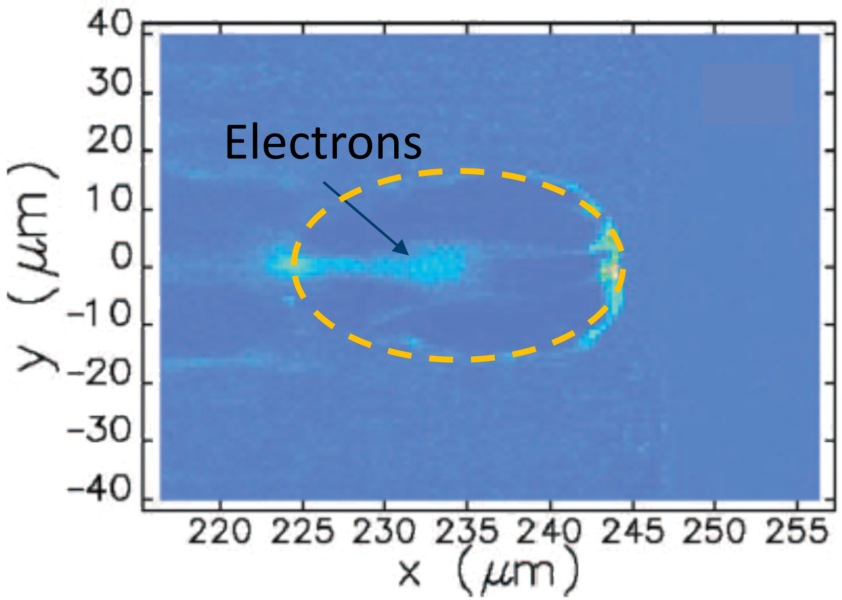


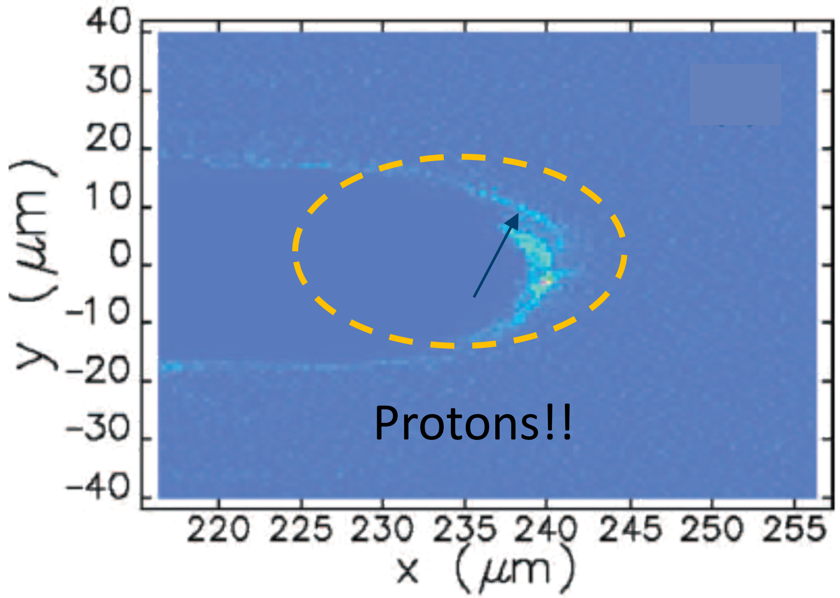
Rotation frequency in cgs units

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

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

PREDICTED ACCELERATION SCHEME FOR PROTONS





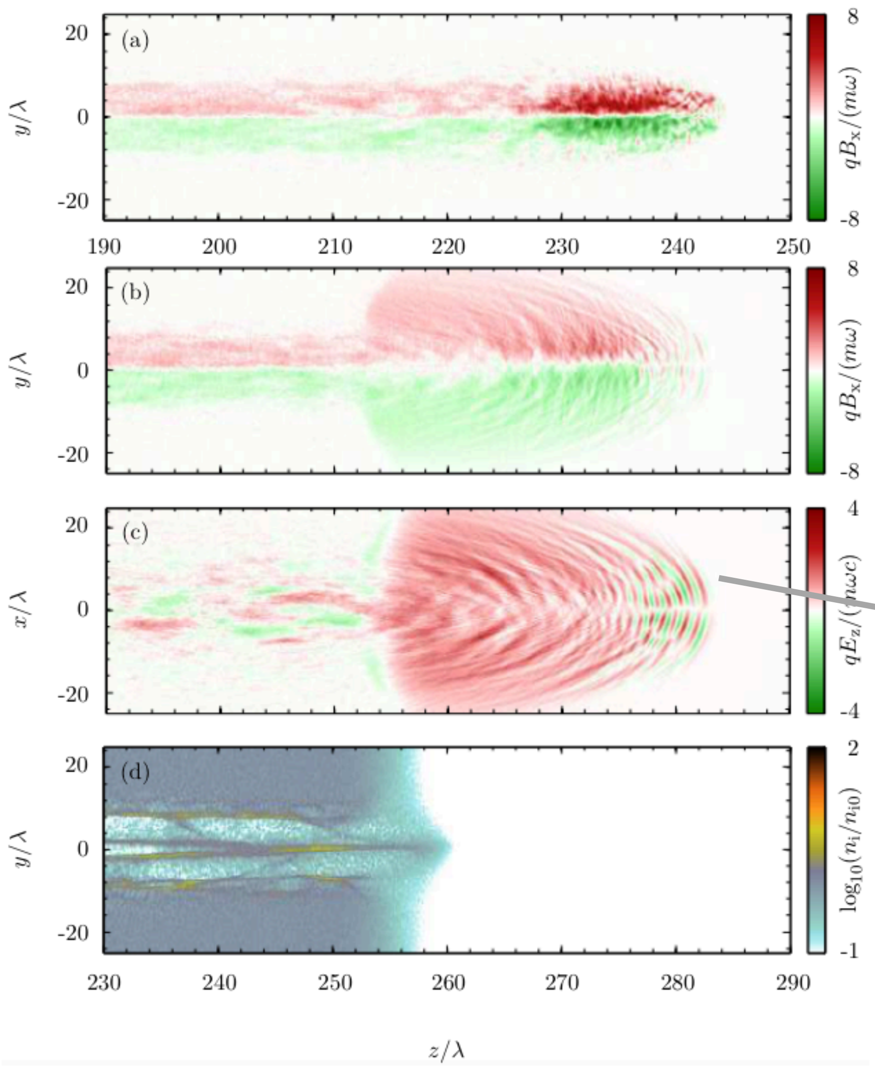
λ_L= 800 nm,
a_0= $316/\sqrt{2}$,
Δx= 10 μm,
ρ_H= 10^{20} cm^{-3},
ρ_T= $1.4*10^{21}$ cm^{-3},
t= 320 fs

- 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)

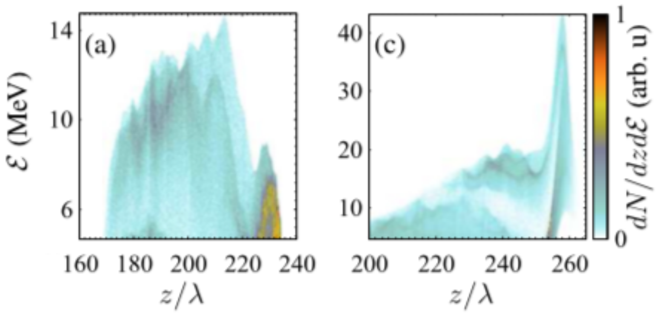
➡ Observation of a up to GeV polarized proton beam.

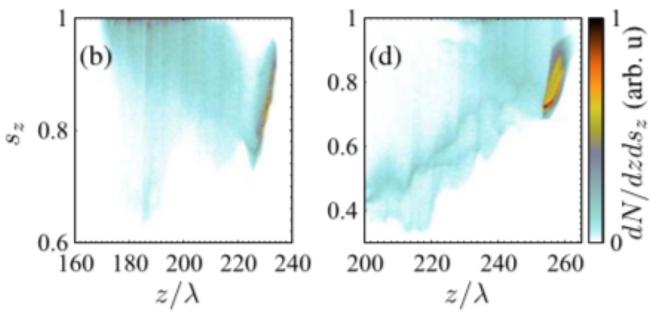
B. Shen et al., Phys. Rev. E **76**, 055402 (2007)

SPIN-POLARIZED PROTON BEAMS FROM HCL GAS



strong accelerating field behind the target (MVA)





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 … , AH, et al., Phys. Rev. E **102,** 011201(R) (2020)

NEW IDEA: HYPERPOLARIZED CRYOGENIC TARGETS

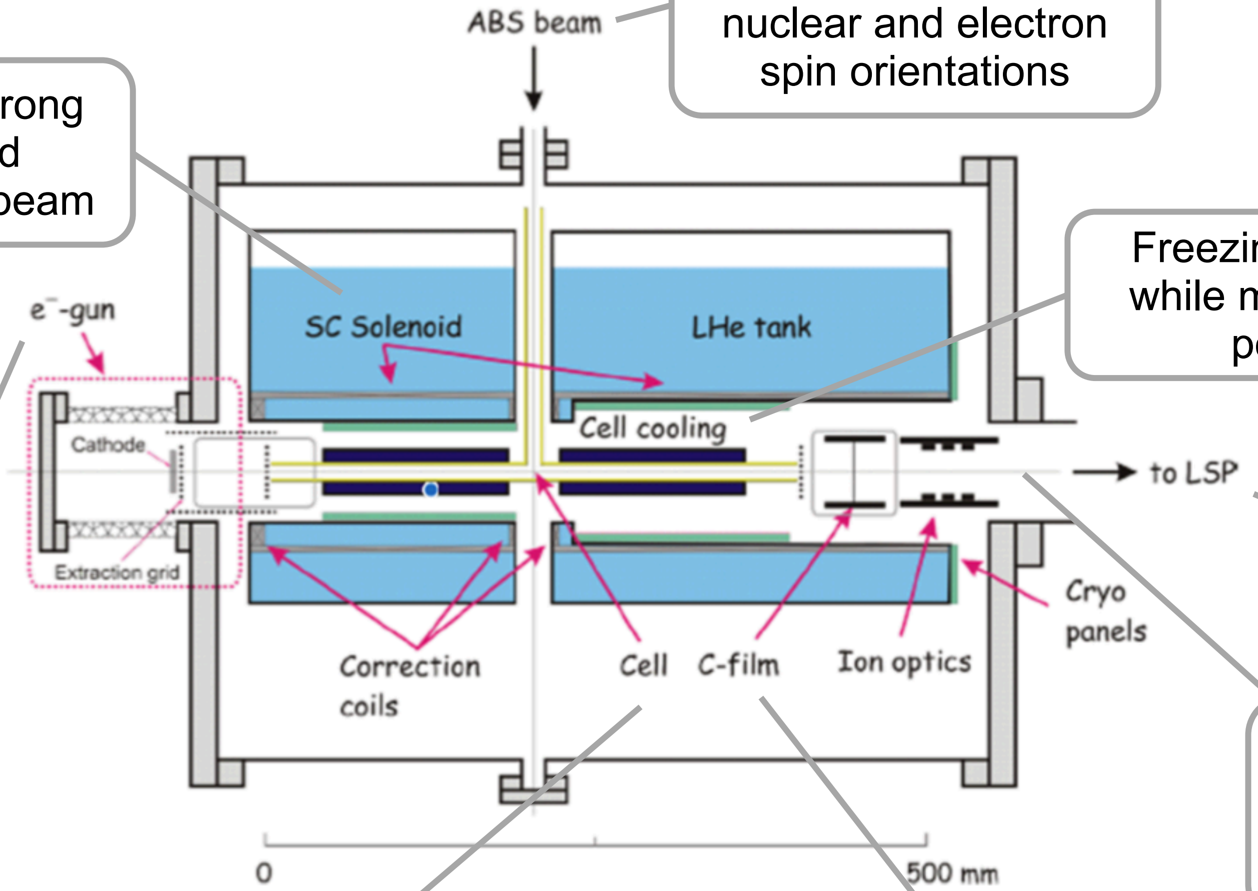
Production of selected nuclear and electron spin orientations

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



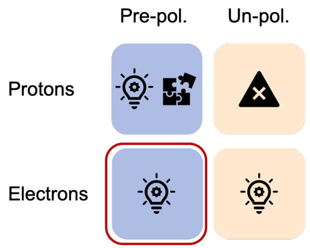
Interaction of polarized atoms and evaporated molecules with e^- beam leads to ionization process

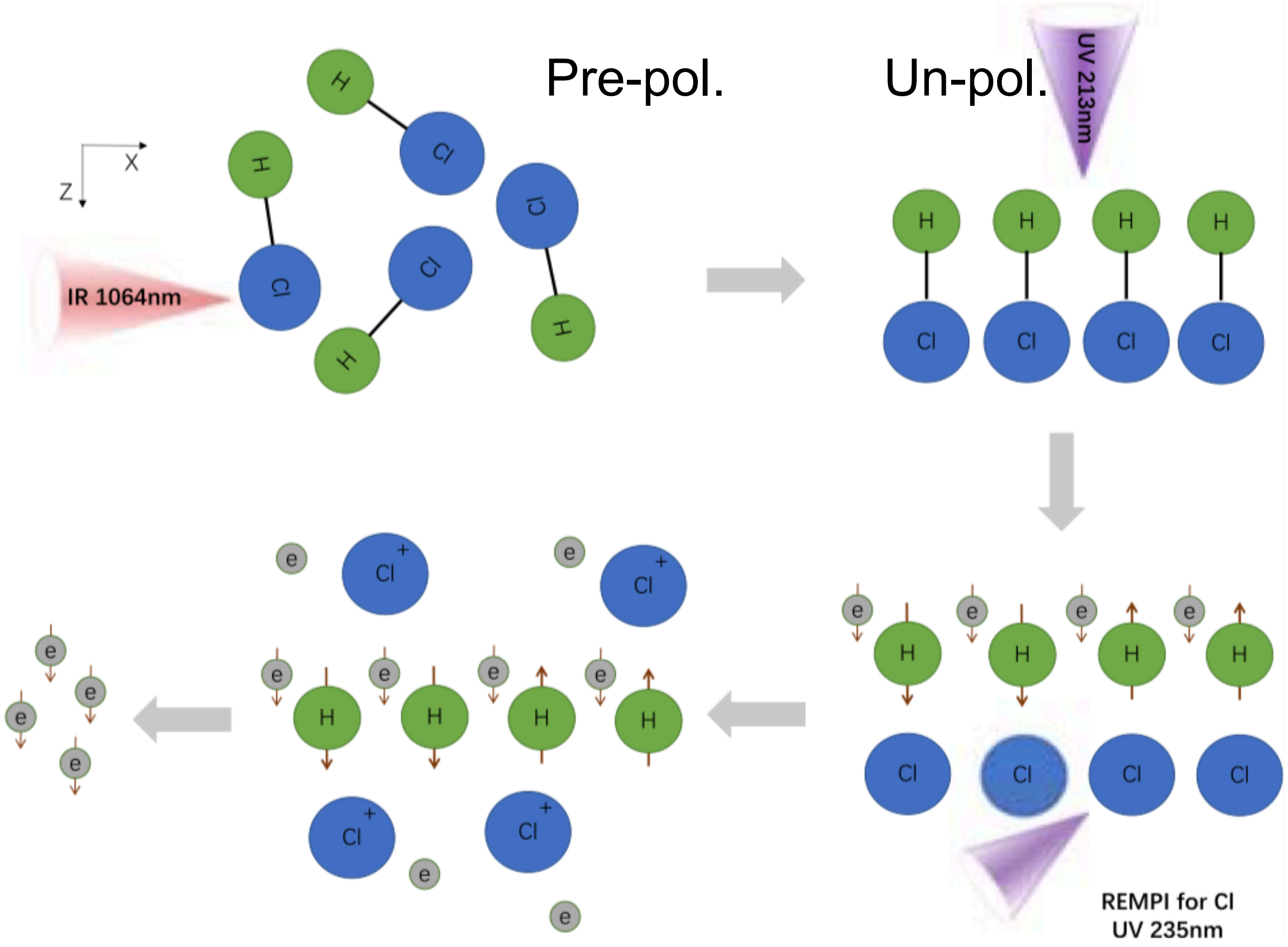
Recombination of atoms into molecules on the surface of the cell

Freezing the molecules to polarized foil target

GENERATION OF POLARIZED ELECTRONS

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





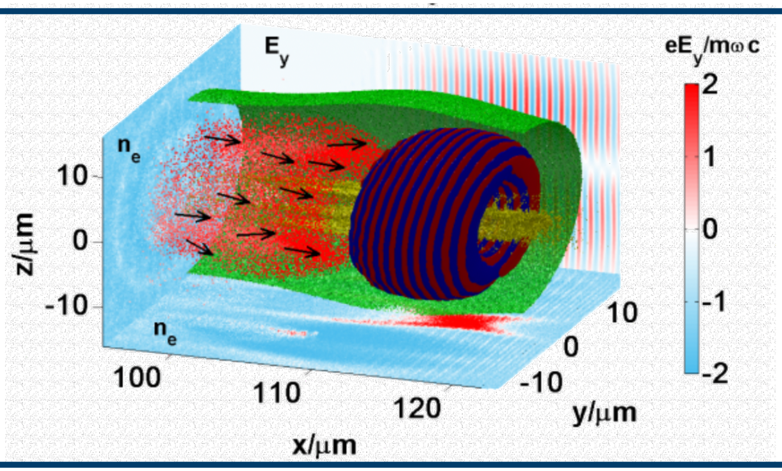
Wu et al., New J. Phys. **21,** 073052 (2019)

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

PRE-POLARIZED ELECTRON BEAMS



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

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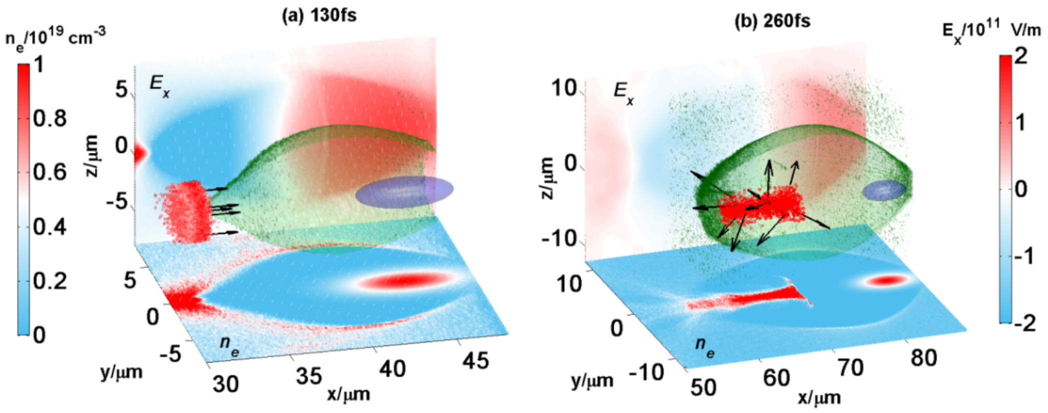
PAPER

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]

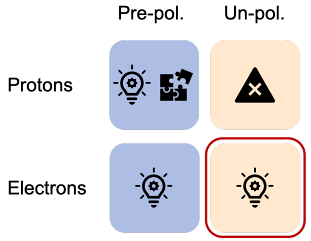


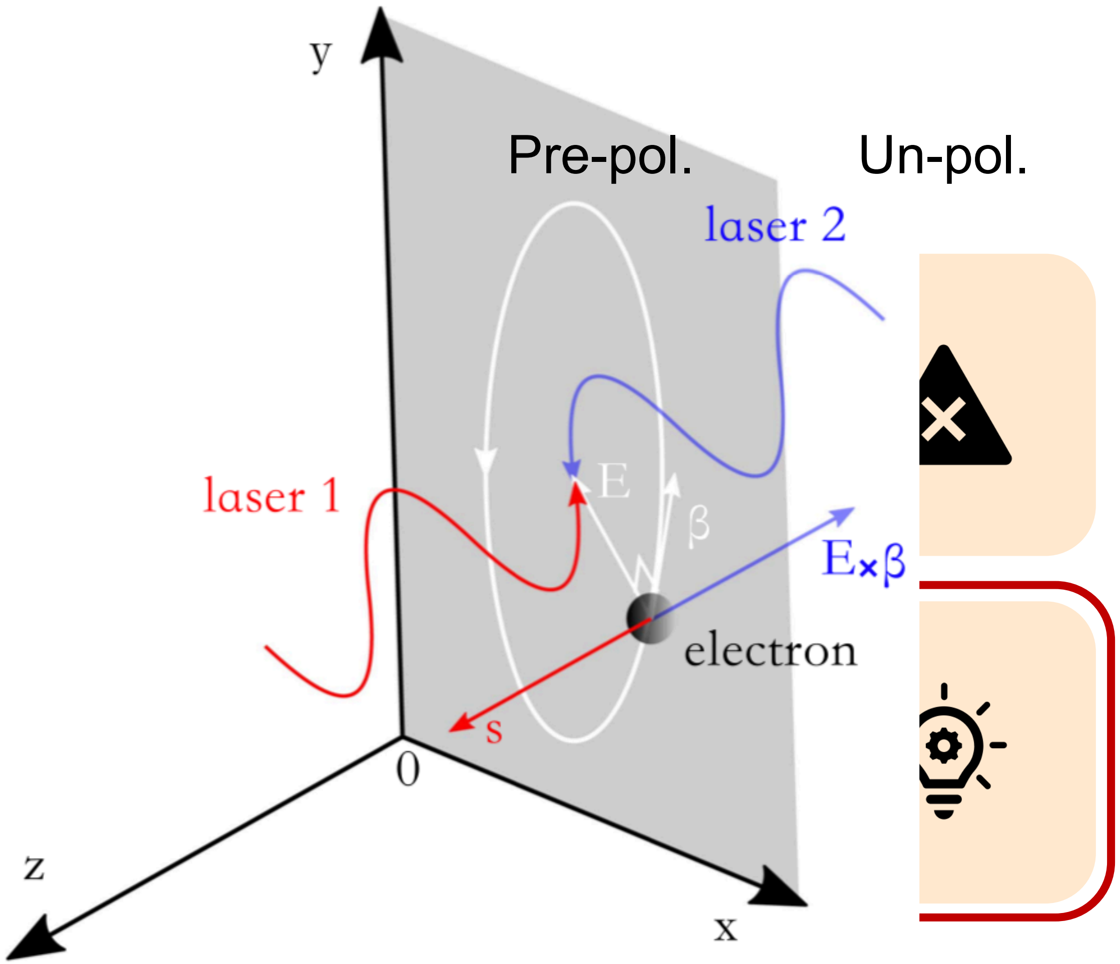
PHYSICAL REVIEW E **100**, 043202 (2019)

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

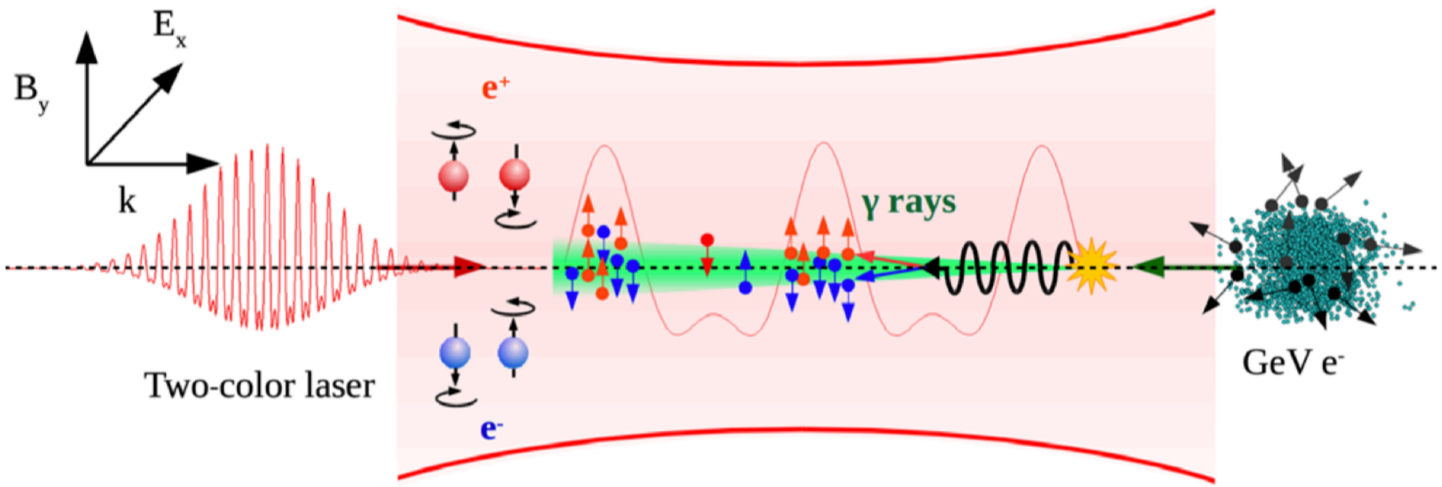




- two counter-propagating circularly polarized lasers produce a standing wave
- ***E*** rotates with constant amplitude at z=0, inducing the rotation of any e^-
- e^- tend to align its spin *s* antiparallel to vector ***E* x *β***

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

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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