The PREFER collaboration/projects

Giuseppe Ciullo INFN & *University of Ferrara*

FERRARIAE UNIVERSITAS 13 91 EX LABORE FRUCTUS

on behalf of the

PREFER
Polarization Research for Fusion Experiments and Reactors

COLLABORATION

Group (Responsible)	Institute
R. Engels et al.	IKP - FZJ @ Jülich
M. Büscher et al.	PGI - FZJ @ Jülich ILPP- HH University @ Düsseldorf
G. Ciullo et al.	INFN & University @ Ferrara
T.P. Rakitzis et al.	IESL-FORTH & University @ Crete

Fusion of Nuclear Polarized Fuel

From the point of view of the nuclear physics, the use of ***polarized fuel*** can help fusion reactions thanks to:

- ***enhancement*** of ***cross sections***,
- ***control*** of angular distributions of the ***reaction products***,
- possible ***neutron lean*** reactors.

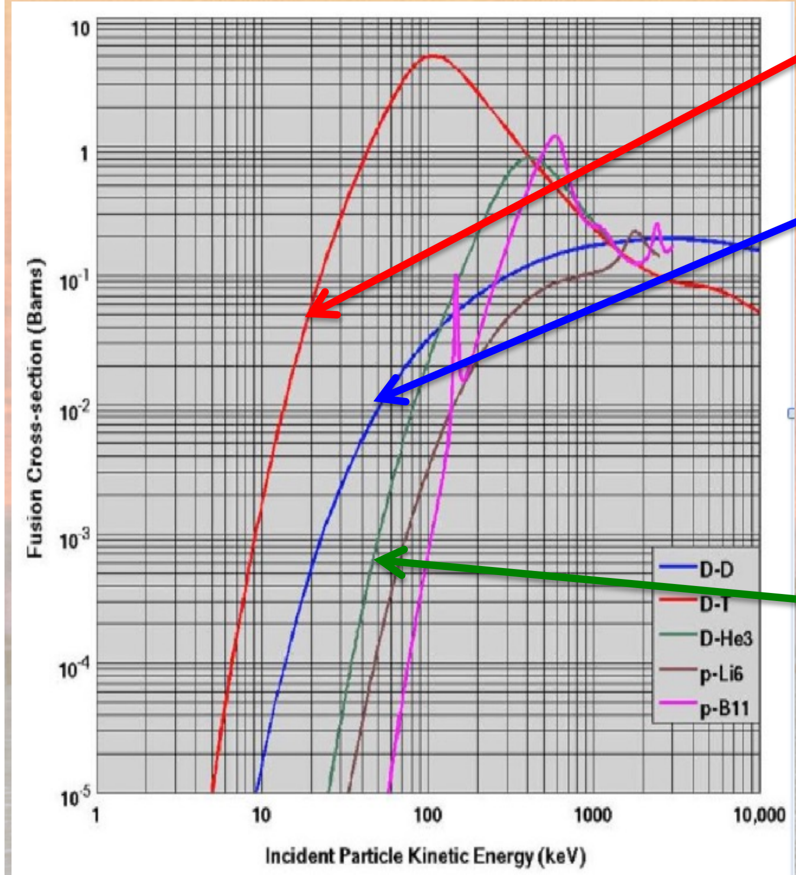
Its use is now under test in order to overcome open questions:

- higher polarization and higher density (orders of magnitude ***more than available*** in nuclear polarized targets).
- ***Preparation*** and ***Manipulation*** of fuel for fusion environments.
- ***Survival*** of polarization in fusion environments.

It's a ***challenging deal*** providing ***polarized fuel*** for the purposes of testing it in ***FUSION*** environments : *by product we'll gain in "better and better" targets*.

Nuclear Fusion with Polarized Fuel

Reaction generations sorted vs the relative energy (temperature) of reactants.



1. Generation: D + T → ^{4}He + n

1.a) Increase of total cross section!!

1.b) differential cross section: control on angular distribution!!

2. Generation: D + D → T + p or ^{3}He + n

Fuel available (30 g m^{-3} in ocean water) !!

2.a) Increase of total cross section ?

2.b) differential cross-section and angular distrib. control?

Still missing data for a complete description.

2.c) Possibility to suppress the reaction ^{3}He + n (QSF Quintet Suppression Factor)?

3. Generation: ^{3}He + D → ^{4}He + p

3.a) and 3.b) expected like 1.a) and 1.b)!!

3.c) Possibility of Neutron lean reactor if D+D → ^{4}He* → ^{3}He + n suppressed (QSF)?

Missing data on D-D spin-dependent cross-sections.

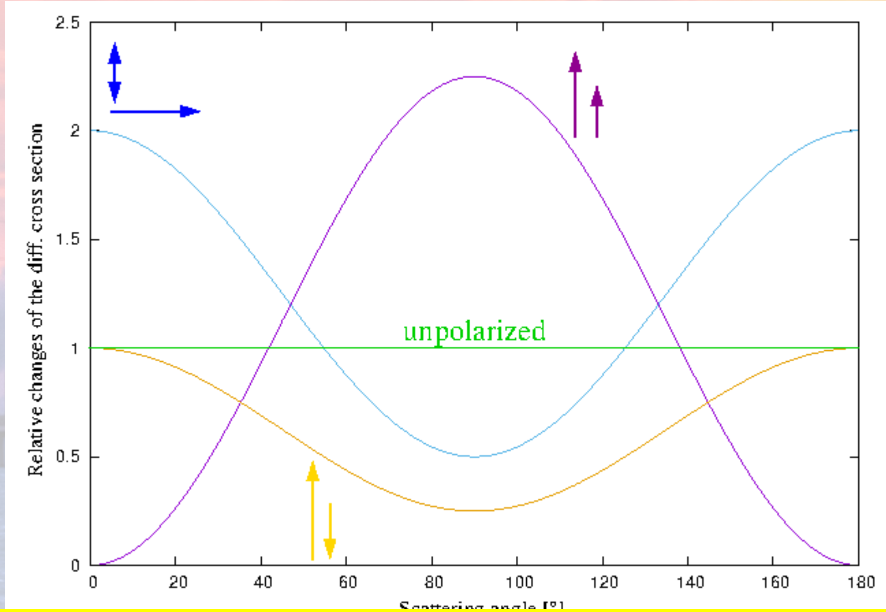
Challenge objectives for PREFER

Missing polarized fuel for fusion tests.

Polarized Fusion Spin ½ and 1

1.) Can the differential cross section of the fusion reactions be controlled by polarized particles ?

$$d\sigma/d\Omega\,(\vartheta) = \sigma_0/4\pi\,(1 - (\tfrac{1}{2}\,P_D^V P_T) + (3/2\,P_D^V P_T \sin^2\vartheta) + \tfrac{1}{4}\,P_D^T\,(1 - 3\cos^2\vartheta)$$



Total cross section

Factor 0.5

Factor 1.5

Factor 1

^{3}He(d, p)^{4}He Reaction

Leeman et al.
ANN. PHYS. **66** (1971) 810.

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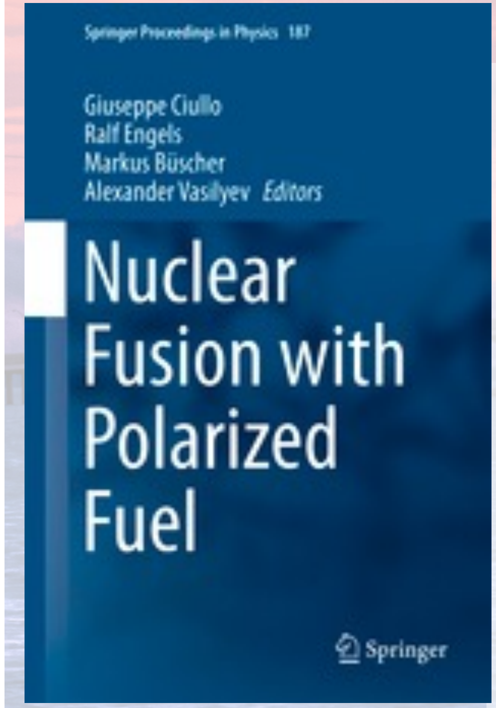
R.Engels et al. *Advantages of Nuclear Fusion with Polarized Fuel* in PoS **423** (SPIN2018) 176.

G. Hupin «Ab initio prediction for polarized deuterium-tritium fusion reaction»
Nat. Comm. **10** (2019) 351.

PSTP people try to involve fusion community

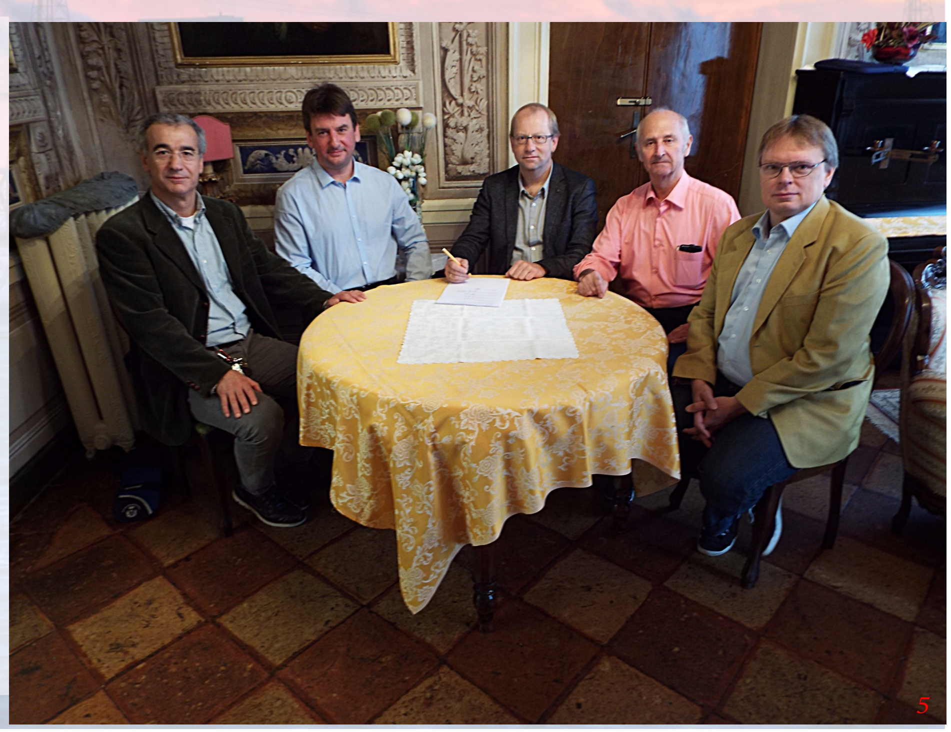
Contributions of the Workshops 2013 (Trento) 2015 (Ferrara)
collected in "Nuclear Fusion with Polarized Fuel"
(ed.s G. Ciullo, R. Engels, M. Büscher and A. Vasyliev)
Springer Proceedings in Physics **187**
(Springer Verlag 2016 Switzerland)



The PREFER collaboration was signed in 2017 in Ferrara during a Workshop on Polarized Fuel for Nuclear Fusion

COVID ended our meetings.

Russia-Ucraina conflict interrupted official collaboration and connection with the russian colleagues.



Challenge objectives of PREFER now & before 02/2022

- @PNPI – D-D spin dependent cross-section measurements! Not anymore in the collaboration from 02/2022: just literature rumors.

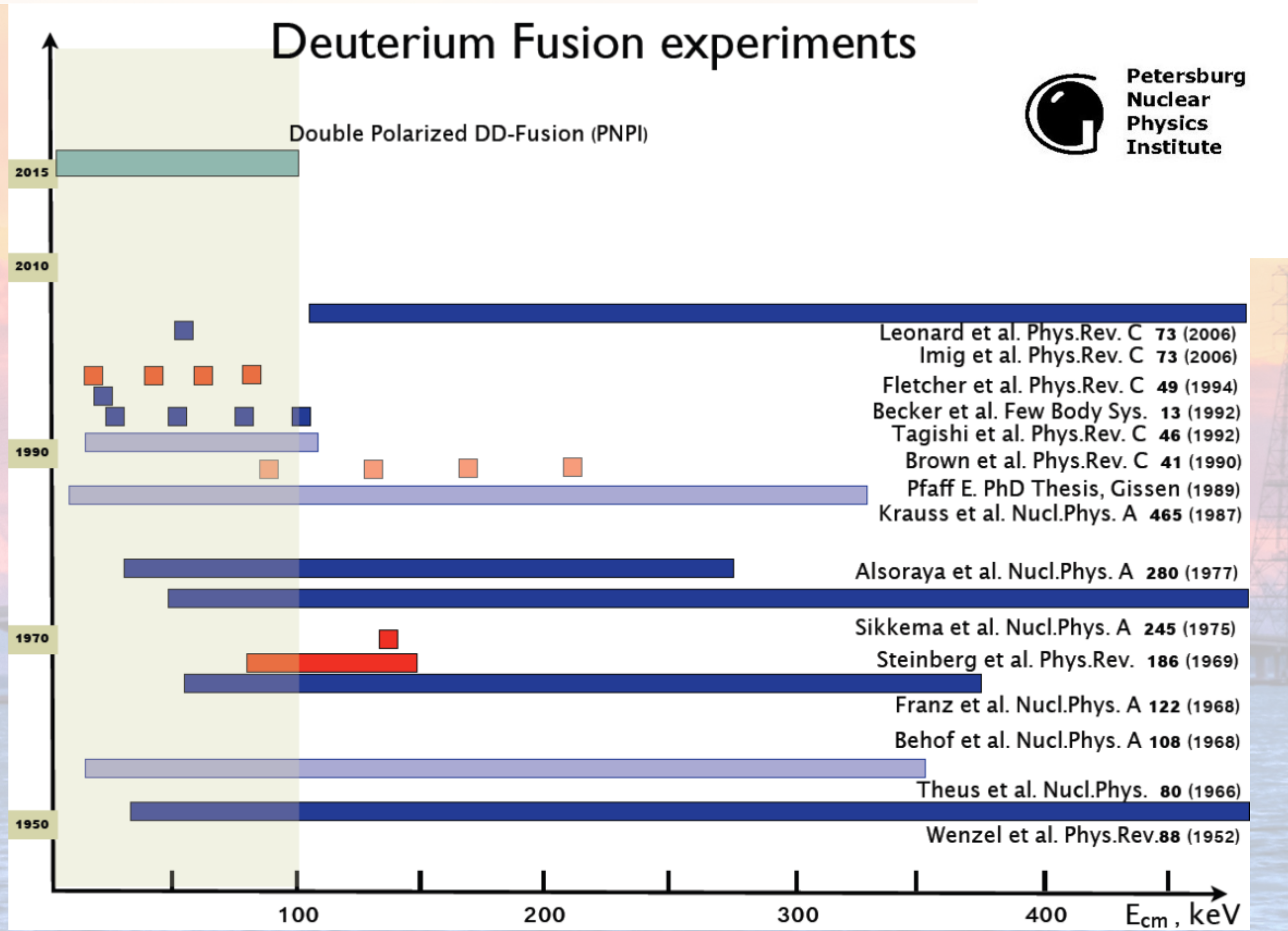
- @IKP-FZJ - Production of polarized fuel: from pABS, and new proposals (Sona transitions).

- @BINP - Production of polarized fuel: from MBS Not anymore in the collaboration from 02/2022: just literature rumors.

- @ IESL-FORTH – Production polarized fuel by Laser IR-Quantum Beat (QB) excitation and Ultra Violet (UV) dissociation.
- @PGI-FZJ/HHDU - Laser Induced Plasma LIP: production, acceleration and reaction studies.
- @FE Magnets for holding, manipulating and transporting polarized fuel .

➢ *@PNPI – D-D spin dependent cross-section measurements! Not anymore in the collaboration from 02/2022: just licterature rumors.*

B. P. Ad'yasevich Czech. J. Phys. B **32** (1982) 1349.
P. Kozma et al. Czech. J. Phys. B **35** (1985) 1118.



Unpolarized with solid target
Unpolarized with gas target
Polarized beam with **unpolarized** solid target
Polarized beam with **unpolarized** gas target

A. Yu. Rozhdestvenskij et. al Phys. Atom. Nucl. **87** (2024) 224.

226 ROZHDESTVENSKIJ et al.

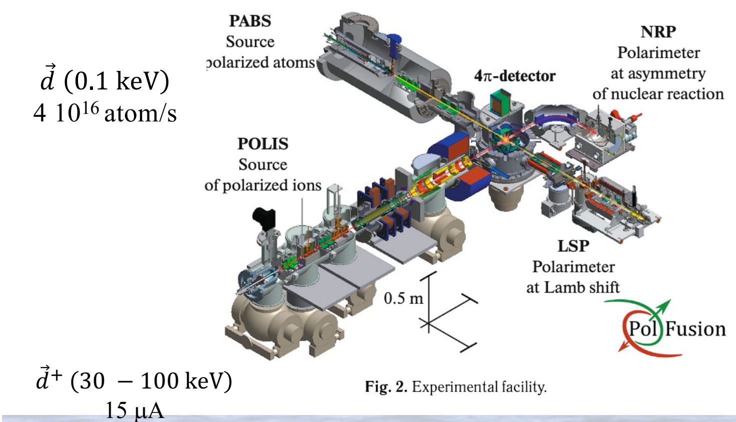


Fig. 2. Experimental facility.

PSTP 24 Newport News

Theoretical model and experiment settings: H. Paez gen Schieck
«*Spin Physics and Polarized Fusion: where we stand*» in Nuclear Fusion with Polarized fuel Ed.s. G. Ciullo et al. Spr. Proc. Phys. **187** (2016).

2° Generation

$$D+D \rightarrow T + p \,/\, {}^3He + n$$

Fusing D + D, then D + T can fuses (n)
^{3}He does not contribute at the ignition energy of D-D

The total cross section D + D in respect to the incoming polarization of the fusing particles:

$$\sigma_{tot} = \frac{1}{9}\left(2\underbrace{\sigma_{1,1}}_{\text{Quintet}} + 4\underbrace{\sigma_{1,0}}_{\text{Triplet}} + \underbrace{\sigma_{0,0}}_{\text{Singlet}} + 2\underbrace{\sigma_{1,-1}}_{\text{Singlet}}\right)$$

Higher energy for fusion involves also P-, D-wave, togheter with S-wave and their interferences

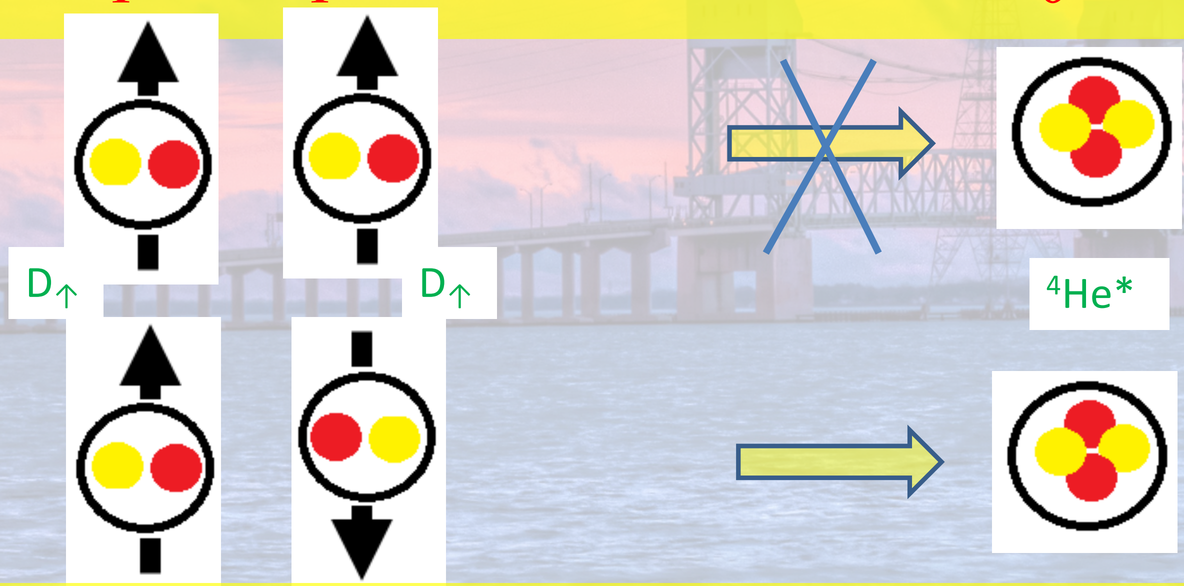
$D_{\uparrow} + D_{\uparrow}$ spin dependent cross section (data set very poor), and stilll worse at lower energy (electron screening ?)

Neutron lean fusion: QSF (Quintet Suppression Factor)

Spin alignements allows to enhance or suppress reaction channels?
Ad’yasevich 2.5 -3 (? Cited by Russian)

$D_{\uparrow}$ ($d_{\uparrow}$ p) T and $D_{\uparrow}$ ($d_{\uparrow}$ n) ^{3}He suppressed
by choosing deuteron spin parallel each others

S 1 1 = 0 $^{5}S_{2}$ Quintet State Suppressed



$$\frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{singlet}}{3/9\sigma_{singlet}} = 3$$

S 1 -1 0 $^{1}S_{0}$ Singlet state allowed

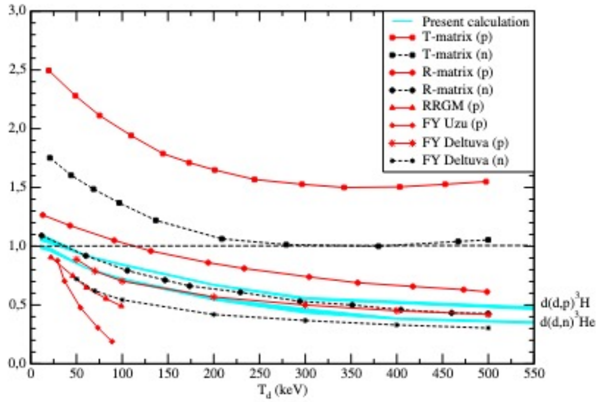
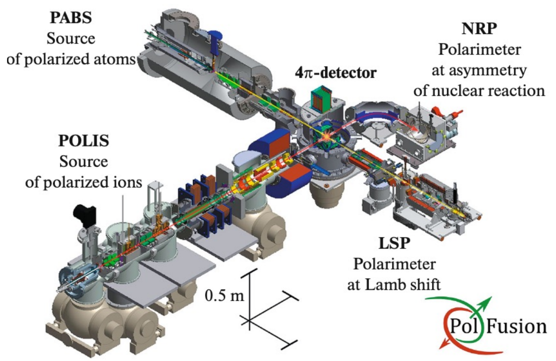


FIG. 2. The QSF for the processes $d(d,n)^3$He and $d(d,p)^3$H shown as bands, in analogy of Fig. 1. We report also the results obtained with other theoretical approaches: T matrix [51]; R matrix [27]; RRGM [32,33]; FY Uzu [35]; FY Deltuva [7]. The red solid [black dashed] lines connecting the red [black] symbols denote the QSF calculated in the literature for the $d(d,p)^3$H [$d(d,n)^3$He] reaction.

A. Yu. Rozhdestvenskij et. al Phys. Atom. Nucl. **87** (2024) 224.

226 ROZHDESTVENSKIJ et al.

$\vec{d}$ (0.1 keV)
4 10^{16} atom/s



$\vec{d}^+$ (30 – 100 keV)
15 μA

Fig. 2. Experimental facility.

PHYSICAL REVIEW LETTERS **130,** 122501 (2023)

Theoretical Study of the $d(d,p)^3$H and $d(d,n)^3$He Processes at Low Energies

M. Viviani,[1] L. Girlanda,[2,3] A. Kievsky,[1] D. Logoteta,[4] and L. E. Marcucci[1,4]

PHYSICAL REVIEW LETTERS **130,** 122501 (2023)

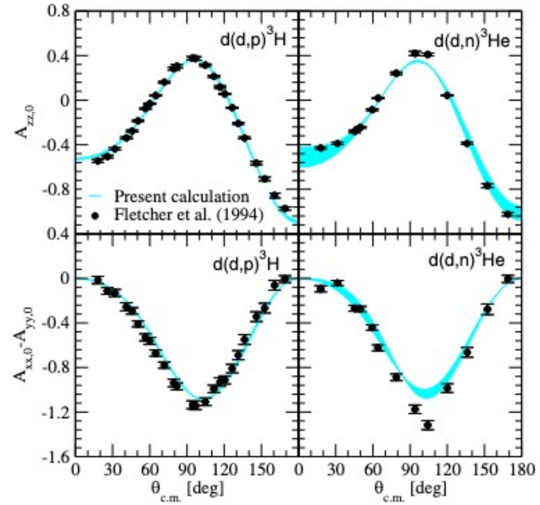


FIG. 3. The observables $A_{zz,0}$ and $A_{xx,0} - A_{yy,0}$ for the $\vec{d}(d,p)^3$H and $\vec{d}(d,n)^3$He processes at $T_d = 21$ keV. The (cyan) bands show the results of the present calculations. The experimental values are taken from Ref. [27].

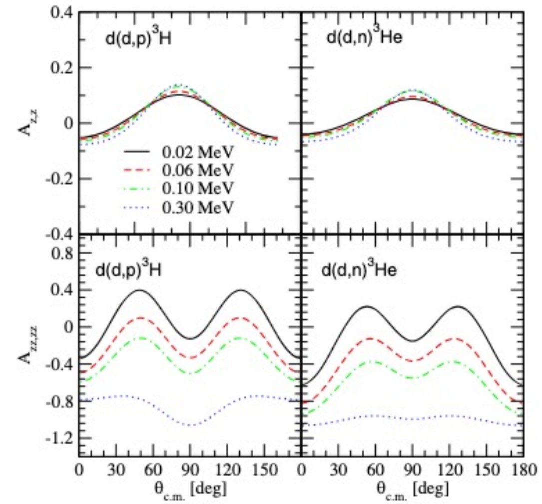


FIG. 4. The polarization observables $A_{z,z}$ and $A_{zz,zz}$ calculated for the $\vec{d}(\vec{d},p)^3$H and $\vec{d}(\vec{d},n)^3$He processes at various laboratory energies. The calculations have been performed for the N3LO500/N2LO500 interaction. The associated theoretical error is of the order of 5%.

other observables. For example, in Fig. 4, we show the prediction for the observables $A_{z,z}$ and $A_{zz,zz}$, which will be studied in the near future by the experiment PolFusion [9].

[9] A. Solovev et al., J. Instrum. 15, C08003 (2020)

Challenge objectives of PREFER now & before 02/2022

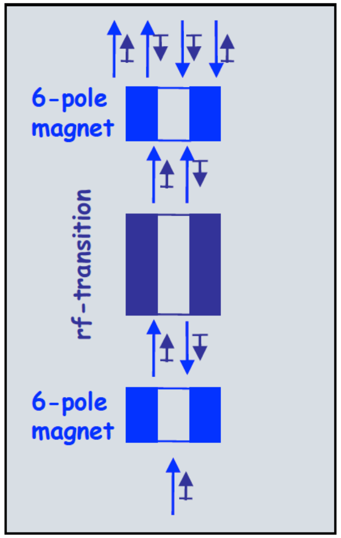
- @PNPI - D-D spin dependent cross-section measurements! Not anymore in the collaboration from 02/2022: just literature rumors.

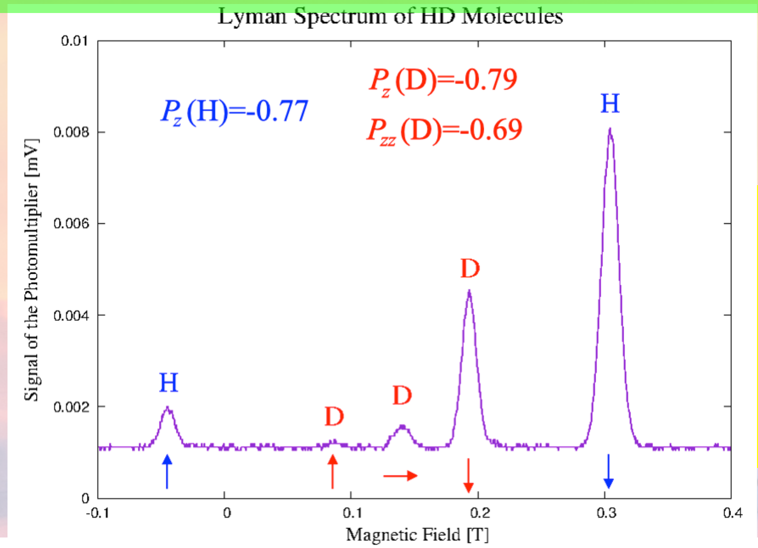
- @IKP-FZJ - Production of polarized fuel: from pABS, and new proposals (Sona transitions).

- @BINP - Production of polarized fuel: from MBS Not anymore the collaboration from 02/2022: just literature rumors.

@IKP-FZJ - Production of polarized fuel: from pABS

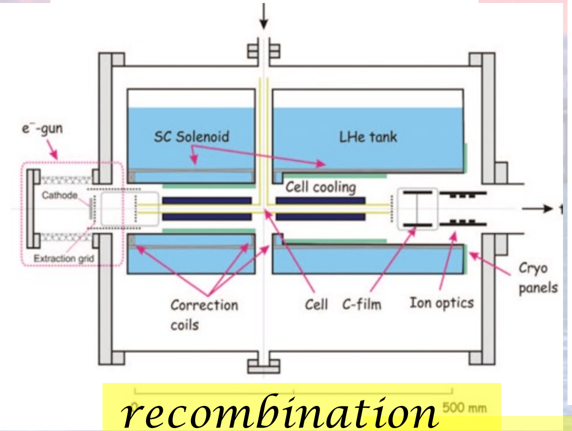
Production



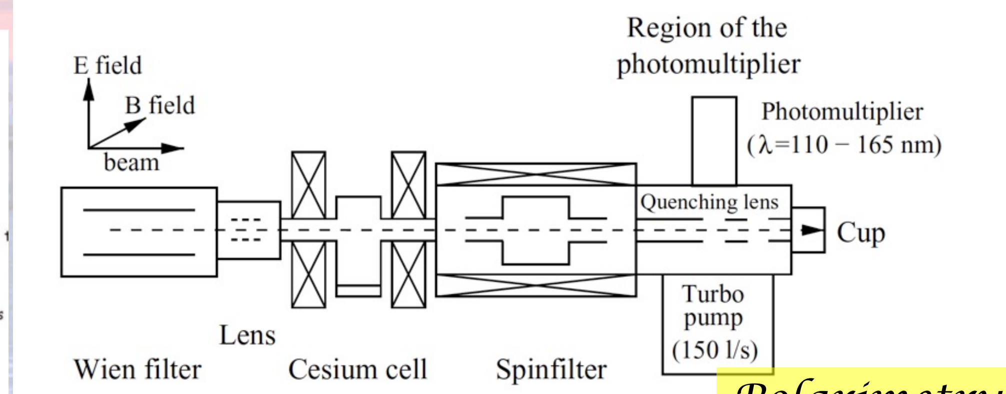


and new proposals.

See
R. Engels et al.
N. Faatz et al.
presentations in this workshop!



recombination

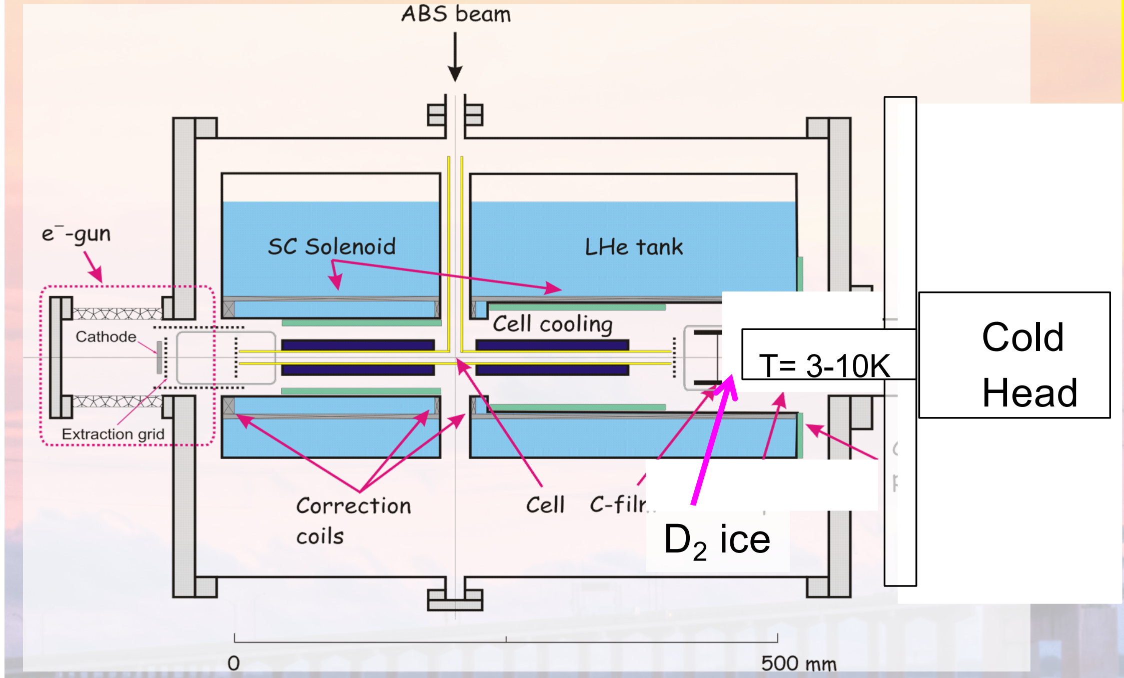


Polarimetry

R. Engels *et al.* «*Production of HD molecules in definite hyperfine substates*» Phys. Rev. Lett. **124** (2020) 113003

Condensation & transp. of pol. fuel

A holding magnetic field is required, for its transportation MgB_2 S.C. Bulk material @ FE



Production of 1 day ($>10^{21}$ molecules) is enough to feed a Tokamak for seconds, in pellets or test in ICF !!

The Target can be used for LIP fusion test and esperiments @PGI-FZJ/HHDU

$\mathcal{H}_2$, $\mathcal{D}_2$, and $\mathcal{HD}$ hyperpolarized molecules can be produced with polarization of P ~ 0.8 ! For $\mathcal{HD}$ any spin combination is possible !

$\mathcal{HD}$ is a perfect training ground for the handling of $\mathcal{TD}$!

The condenser is surrounded by a S.C. MgB_2 cylinder, which provides the holding field also for transportation.

Challenge objectives of PREFER before 02/2022

- @PNPI - D-D spin dependent cross-section measurements! Not anymore in the collaboration from 02/2022: just literature rumors.

- @BINP - Production of polarized fuel: from MBS Not anymore in the collaboration from 02/2022: just literature rumors: recent publication on LSP operation.

ISSN 0020-4412, Instruments and Experimental Techniques, 2023, Vol. 66, No. 4, pp. 531–537. © Pleiades Publishing, Ltd., 2023.
Russian Text © The Author(s), 2023, published in Pribory i Tekhnika Eksperimenta, 2023, No. 4, pp. 13–20.

Measurement of the Polarization of a Deuterium Atomic Beam Using a Lamb Shift Polarimeter

D. K. Toporkov[a,b,*], S. Yu. Glukhovchenko[a], D. M. Nikolenko[a], I. A. Rachek[a], A. M. Semeonov[a,c], and Yu. V. Shestakov[a,b]

[a] *Budker Institute of Nuclear Physics (BINP), Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*

[b] *Novosibirsk State University, Novosibirsk, 630090 Russia*

[c] *Novosibirsk State Technical University, Novosibirsk, 630073 Russia*

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Challenge objectives of PREFER now

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- @BINP - Production of polarized fuel: from MBS Not anymore the collaboration from 02/2022: just literature rumors.

- @ IESL-FORTH - Production polarized fuel by Laser IR-Quantum Beat (QB) excitation and Ultra Violet (UV) dissociation.

@ IESL-FORTH QB excitation and UV dissociation

The idea: **"Highly nuclear-spin polarized deuterium atoms from the UV dissociation of Deuterium Iodide"**

10^{18} cm^{-3} SPD from DI

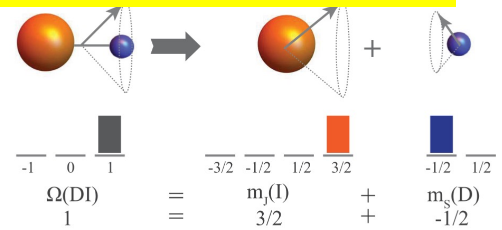


FIG. 2. The angular momentum projection $\Omega_A = +1$ is prepared from the DI ($\Omega = 0$) ground state, using σ^+ circularly polarized photolysis light, and is distributed to the angular momentum projections of the photofragments after photodissociation.

Sofikitis et a.; PRL. **118** (2017) 233401.

Pulsed Nozzle

DI

D atoms → LSP of Jülich Type

Laser Excitation → Laser Dissociation → Electron-Polarization = 1

↓

Deuteron-Polarization ~ 2/3

HI

(Proton-Polarization = 1)

Proof-of-principle
(Univ. of Crete/FORTH, IKP/PGI in FZJ/HHUD).

> 10^{19} cm^{-3} SPH & SPD

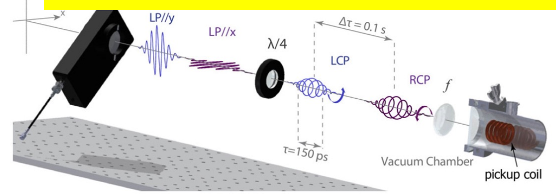
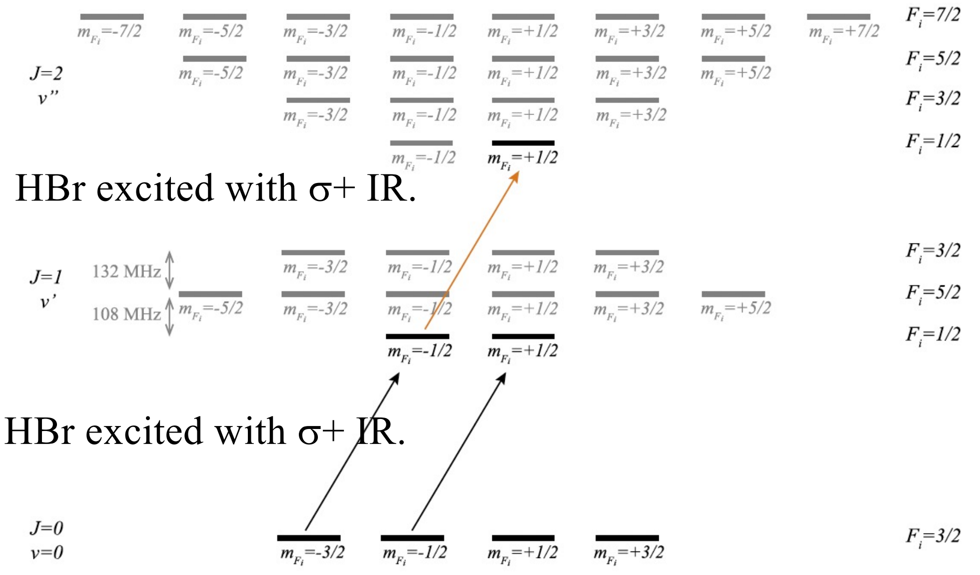


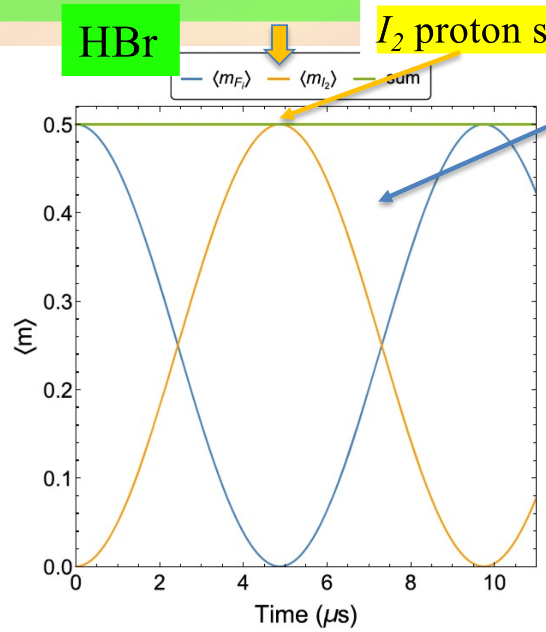
FIG. 1. Experimental setup: The photoelastic modulator (PEM) and quarter-wave plate ($\lambda/4$) alternate laser polarization between right circularly polarized (RCP) and left circularly polarized (LCP) on a shot-to-shot basis at a 10 Hz repetition rate. The laser is focused through the pickup coil, producing an ~2 mm diameter beam (f_1= 50 mm) or a focused beam (f_2= 25 mm, $4 < r < 200$ μm).

Sofikitis et a.; Phys. Rev. Lett. **121** (2018) 083001.

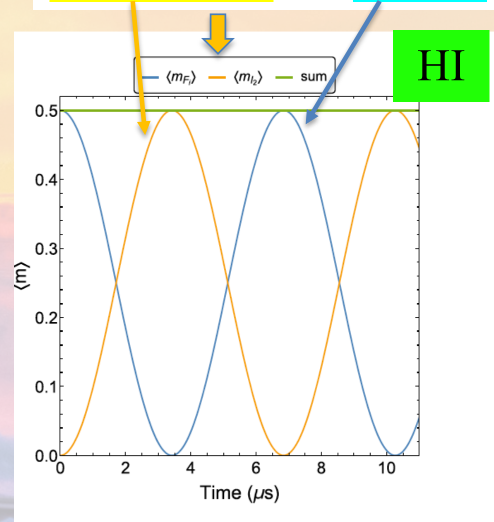
Accurate rotational state preparation and timing of shooting



(a) IR-excitation steps of $H^{79}Br$ presented in the partial hyperfine resolution. At $t = 0$, the $|\nu'', J = 2, F_i = 1/2\rangle$ state is populated and the molecule is prepared in the $m_{F_i} = +1/2$ substate.



(b) Polarization beating of $\langle m_{F_i}\rangle$ and $\langle m_{I_2}\rangle$. The hydrogen nucleus is 100% polarized at t_0=4.87 μs.



(b) Polarization beating of $\langle m_{F_i}\rangle$ and $\langle m_{I_2}\rangle$. The hydrogen nucleus is 100% polarized at t_0=3.42 μs.

17

SPH and SPD $> 10^{19}$ /cm^3 *vs* SEOP and S-G $\sim 10^{13}$ /cm^3

H isotope -Y diatomic molecules

Notation: I_1 (Y nuclear spin) I_2 (H isotope nuclear spin) J (rotational angular momentum, $F_i = J + I_1$ and $F = F_i + I_2$.

C. S. Kannis et al. *Chem. Phys. Lett.* **784**, 139092 (2021)

After the IR excitation the UV shooting after the trasfer of polarization to p, which can be «frozen» by a magnetic field.

C. S. Kannis et al. *Mol. Phys.* **120** (2022) e1975053.

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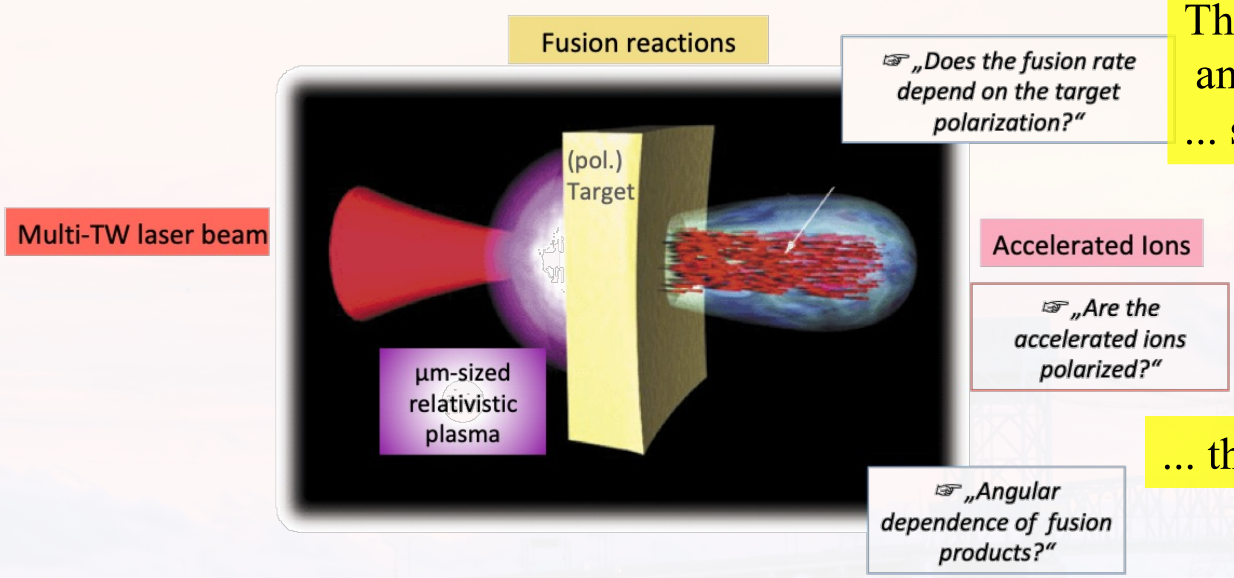


There are various proposal to produce high intense and pure polarized fuel for fusion, but ...
... still an question is pending:

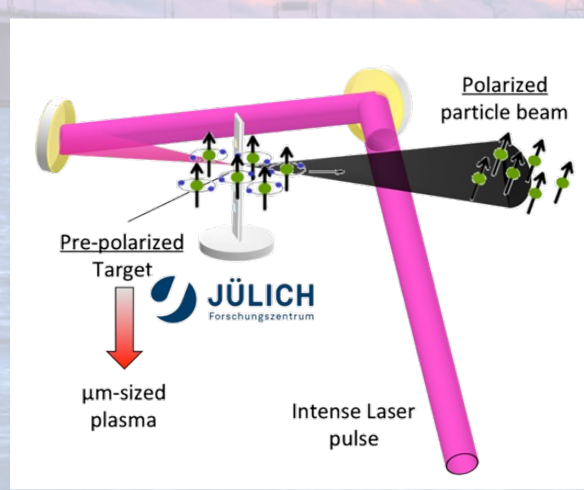
... the polarization survives in fusion environments?

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

Polarization measurement of laser-accelerated protons

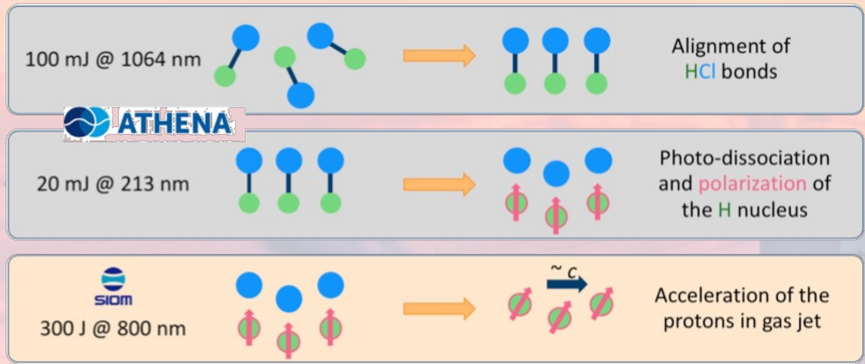
Natascha Raab,[1,a)] Markus Büscher,[1,2,3,b)] Mirela Cerchez,[3] Ralf Engels,[1] Ilhan Engin,[1] Paul Gibbon,[4] Patrick Greven,[1] Astrid Holler,[1] Anupam Karmakar,[4,c)] Andreas Lehrach,[1] Rudolf Maier,[1] Marco Swantusch,[3] Monika Toncian,[3] Toma Toncian,[3] and Oswald Willi[3]

[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*



@ PGI-FZJ Polarized beams from LIP

Polarized proton beams on IR-polarization and post UV dissociation



High Power Laser Science and Engineering, (2019), Vol. 7, e16, 6 pages.

doi:10.1017/hpl.2018.73

Polarized proton beams from laser-induced plasmas

Anna Hützen[1,2], Johannes Thomas[3], Jürgen Böker[4], Ralf Engels[5], Ralf Gebel[4], Andreas Lehrach[4,6], Alexander Pukhov[3], T. Peter Rakitzis[7,8], Dimitris Sofikitis[7,8], and Markus Büscher[1,2]
[1]*Peter Grünberg Institut (PGI-6), Forschungszentrum Jülich, Wilhelm-Johnen-Str. 1, 52425 Jülich, Germany*
[2]*Institut für Laser-und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany*

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

It will be easier to start from a prepolarized beam

Input pressure: 3 bar

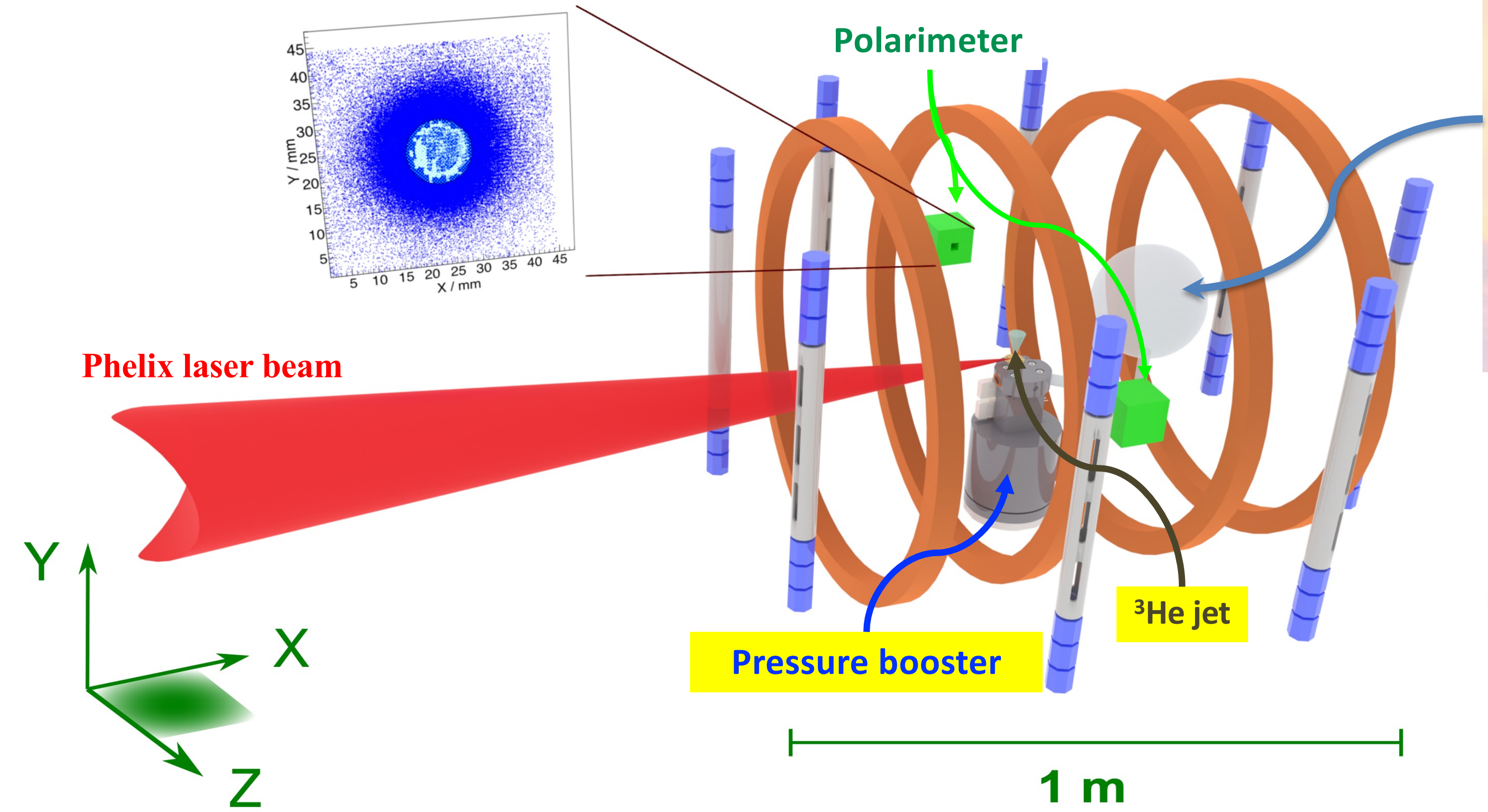
c o m p r e s s o r

Output pressure: 50 bar

Polarized He beams
From compressed polarized ^3He

coming back to our dilemma: polarization will survive?

Experimental setup scheme @Phelix



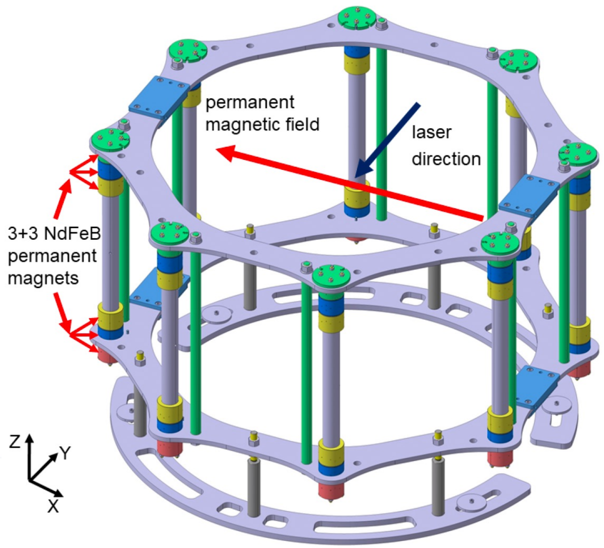
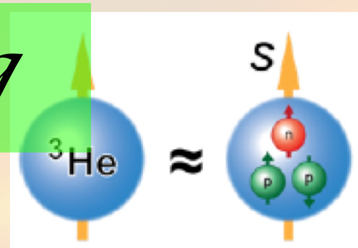


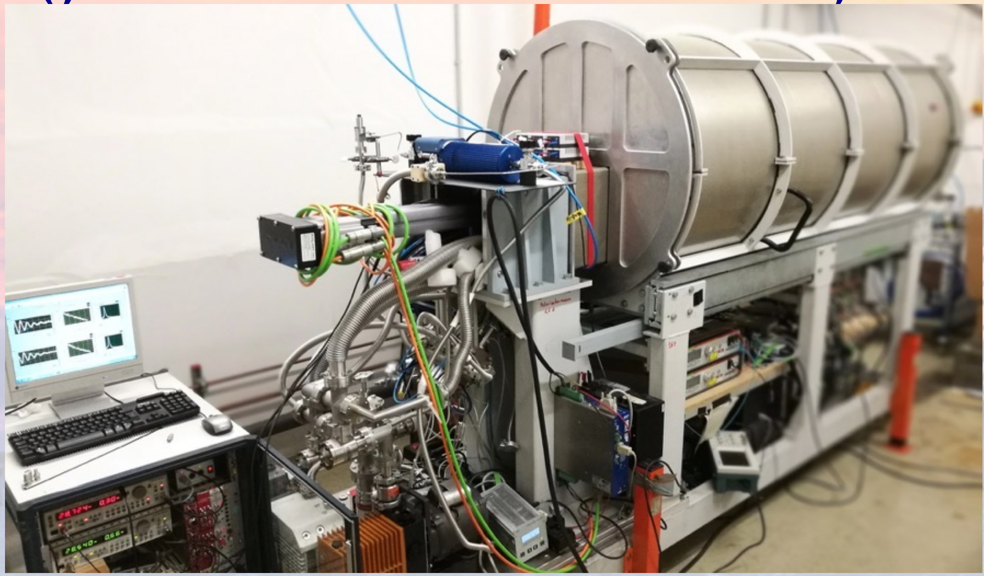
Figure 1. Layout of the permanent magnet system.

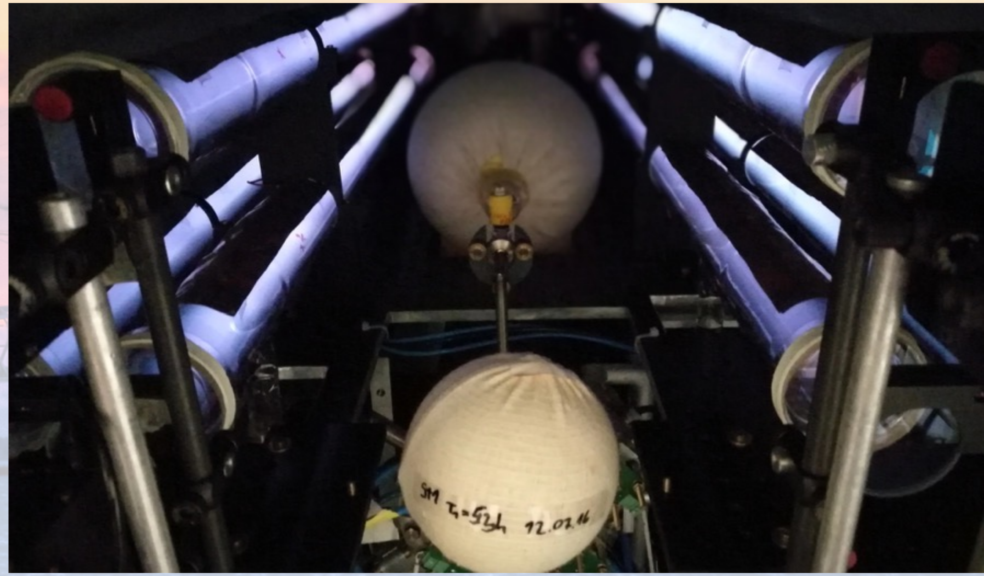
^{3}He polarizer with recovering



- Metastability-Exchange Optical Pumping

(polarizer borrowed from Univ. Mainz)





Max. ^{3}He polarization: ~75%
Relaxation times: hundreds of hours (up to 3 bar in transport vessels)

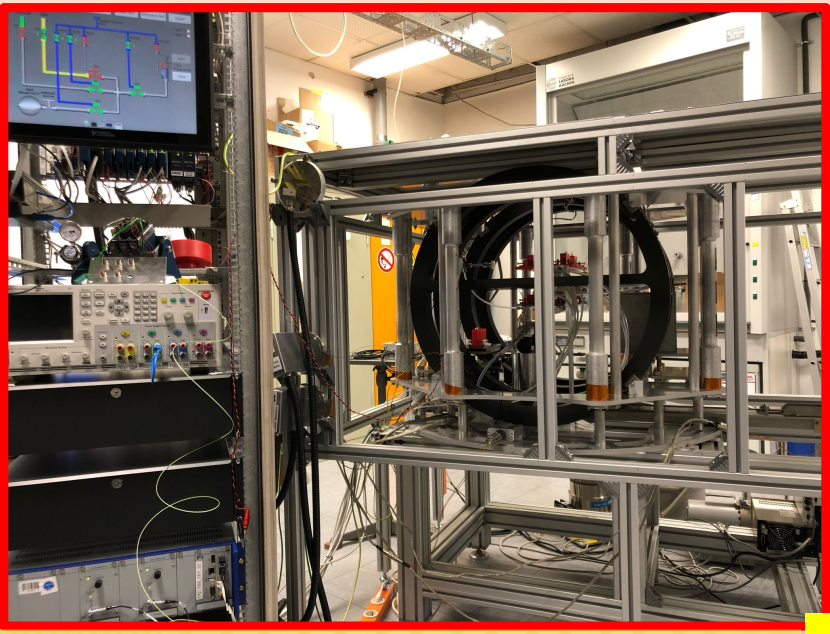
C. Mrozik et al., Construction of a compact ^{3}He polarizing facility, J. Phys. Conf. Ser. 2011, 294, 012007

Polarized ³He gas-jet

Up to 80% nuclear polarization

PREFER
Polarization Research for Fusion Experiments and Reactors

ATHENA



Feasibility studies of laser induced acceleration on ^{4}He

I. Engin et al.,
Plasma Physics and Controlled Fusion **61** (2019) 115012

High density polarized ^{3}He Gas-Jet Target 3/4 10^{19} cm^{-3}

P. Fedorets *et al*.
Instruments **6** (2022) art.n. 18

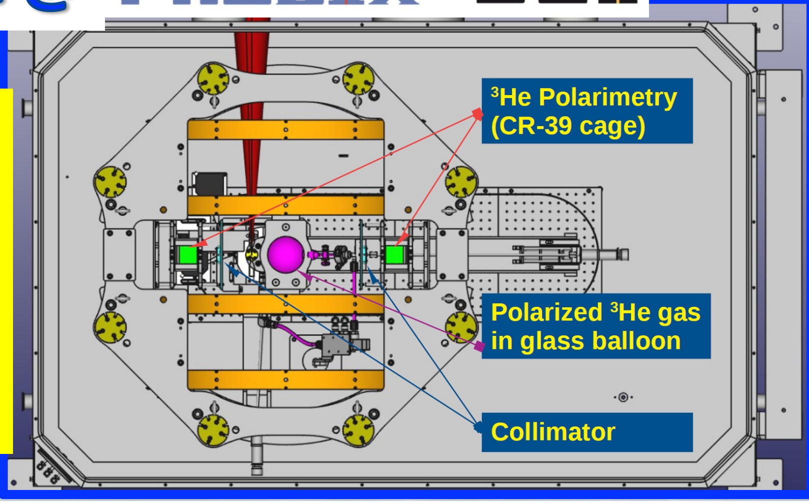
magnetic holding field for storing pre-polarized ^{3}He gas @3 bar

compressor increases pressure of ^{3}He gas to ~30 bar

non-magnetic nozzle provides the desired gas-jet target

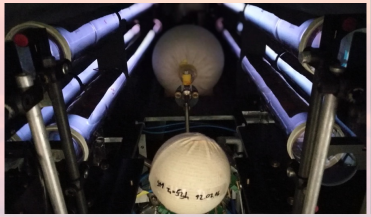
Best Working points:
$\pm$ 90° Laser dir.
^{4}He^{++} 4.65 MeV
^{4}He^{+} 3.27 MeV.
Gas Backing *p*= 30 bar
40-60 J & 1.6-3.2 ps
jet of 4 10^{19} cm^{-3}

Target @ PHELIX GSI

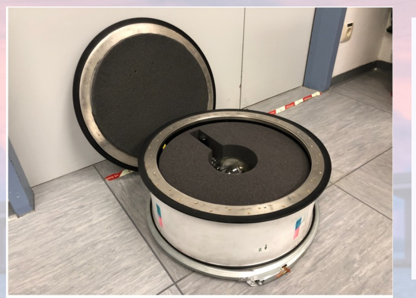


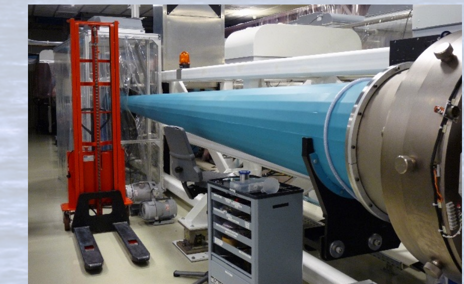
Transport of Polarized ^{3}He gas

Every morning: Transfer of 3 bar-liter ^{3}He from FZJ to GSI (250 km)



JÜLICH
Forschungszentrum

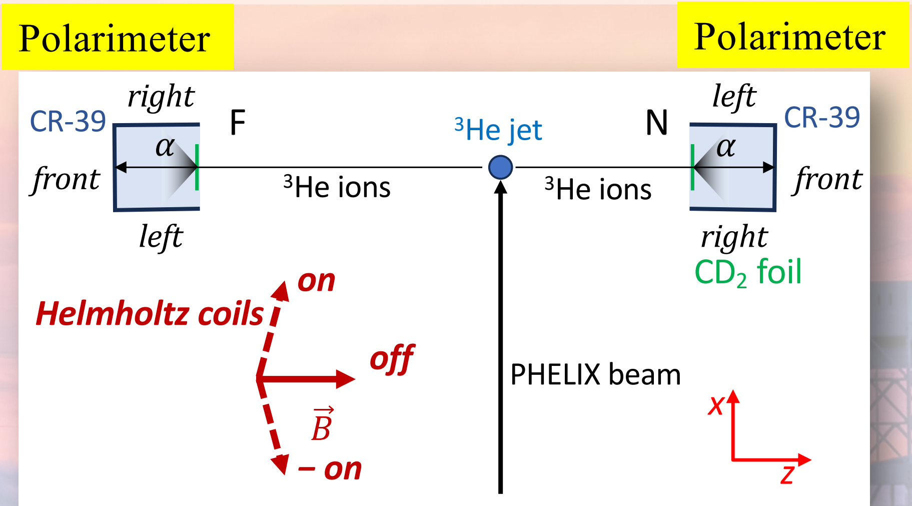




FAIR GSI

Polarimetry for ³He ions

Employing analyzing power of the $\mathrm{D}(^3\overrightarrow{\mathrm{He}},\alpha)p$ reaction



Instruments **2022**, *6*, 61. https://doi.org/10.3390/instruments6040061 MDPI

Article

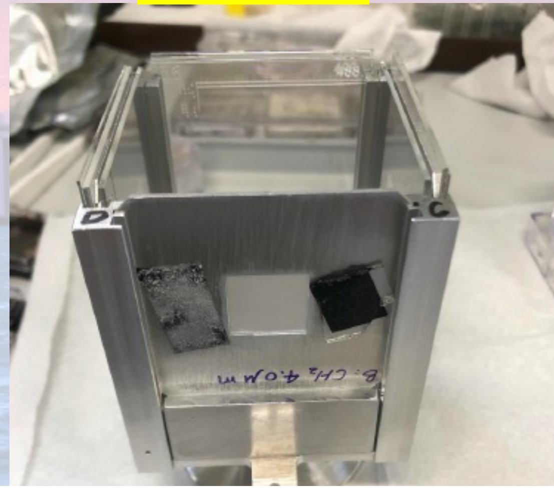
Polarimetry for ³He Ion Beams from Laser–Plasma Interactions

Chuan Zheng [1,2], Pavel Fedorets [1], Ralf Engels [3], Chrysovalantis Kannis [4], Ilhan Engin [5], Sören Möller [6], Robert Swaczyna [7], Herbert Feilbach [7], Harald Glückler [8], Manfred Lennartz [8], Heinz Pfeifer [1], Johannes Pfennings [9], Claus M. Schneider [1], Norbert Schnitzler [1], Helmut Soltner [8] and Markus Büscher [1,10,*]

[1] Peter Grünberg Institute (PGI-6), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
[2] ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany

^{3}He polarization along z mantained with (1.3 mT), Helmoltz coils (10 A and 5 mT max) hallow to rotate the polarization along the x axis ($\pm$75.5°) relative to the ^{3}He ion momenta.

Polarimeter



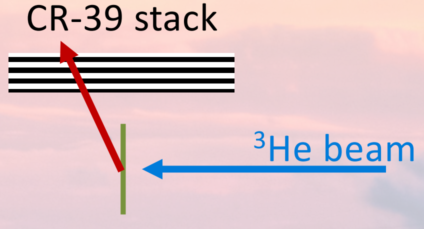
Contains CD_2/CH_2 foil and 5 CR-39, front, left, right, bottom and top.

Transverse polarization ($\vec{s} \perp \vec{p}$) of the $^3\overrightarrow{\mathrm{He}}$ ions

$\Updownarrow$

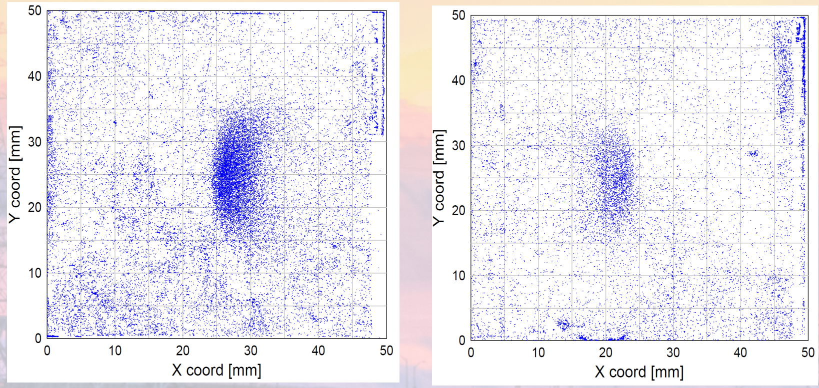
Measurable left/right up/down rate : asymmetry of α particles

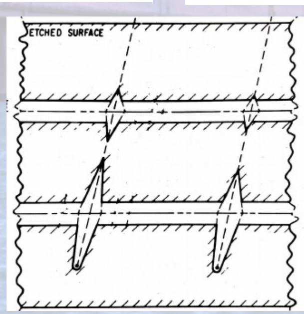
Polarimetry for ³He ions



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

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

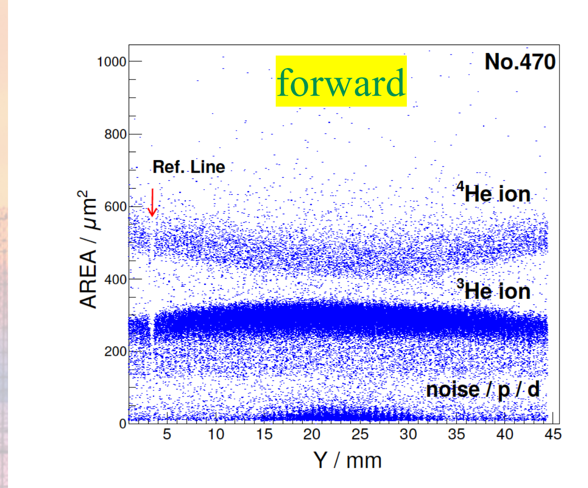


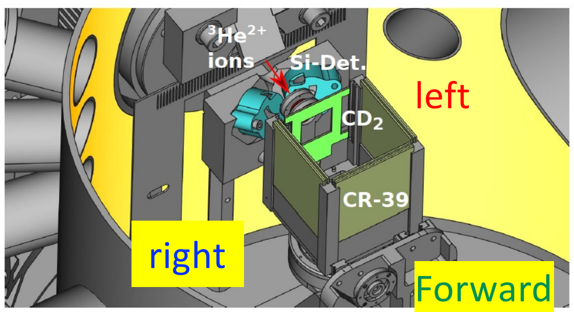


Analysis by: C. Zheng et al. Instruments **6** (2022) 61

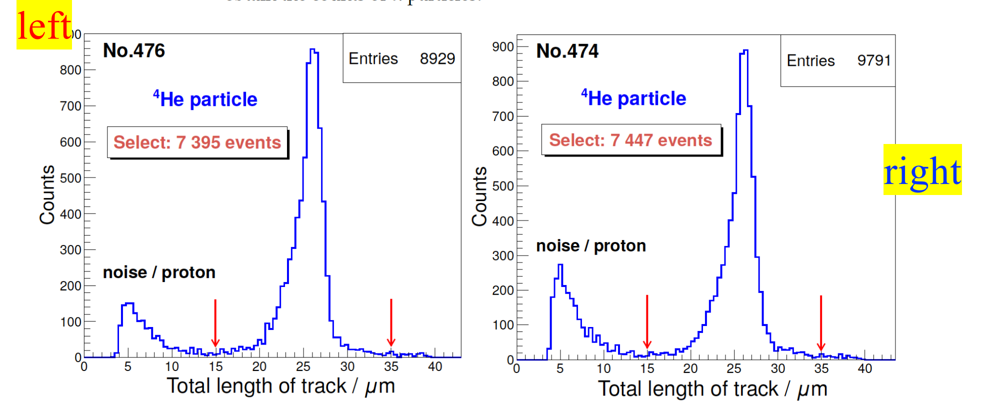
Polarimetry for ^3He from LIP

Identification of the products of reaction of $^3He^{++}$ beam on CD_2, at lower energy till 0.64 MeV (fusion reaction resonance) on **left**, **right** CR-39 (SSNTD detectors) and **forward** (beam detection). Minimal detectable polarization 21 % at 10^9 ^3He ions entering the polarimeter.





(**b**) Setup in the μ-NRA chamber



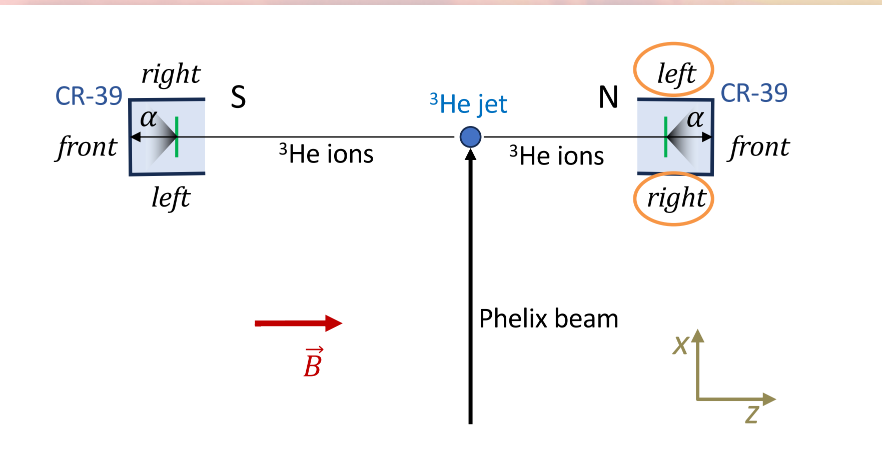
(**a**) on the Left

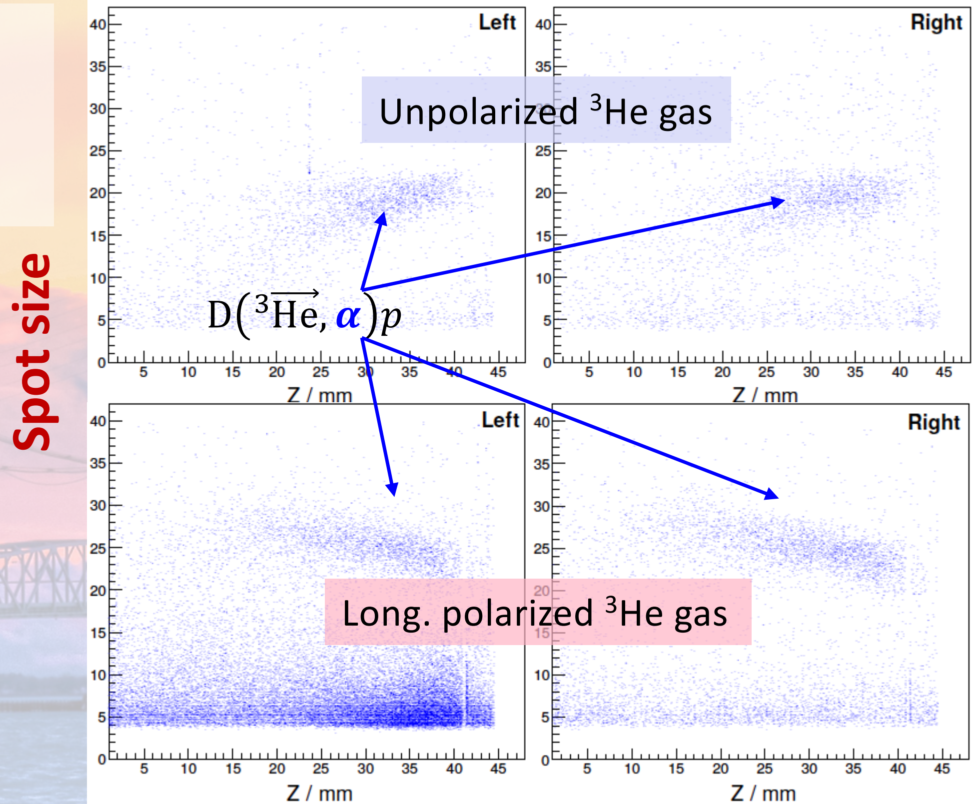
(**b**) on the Right

Figure 10. Comparison of spectra of track profile on the Left and Right of the polarimeter in a range of polar angle between 40° and 75°.

Measured (a-)symmetry

- Unpolarized gas vs
- polarized / Helmholtz coils off



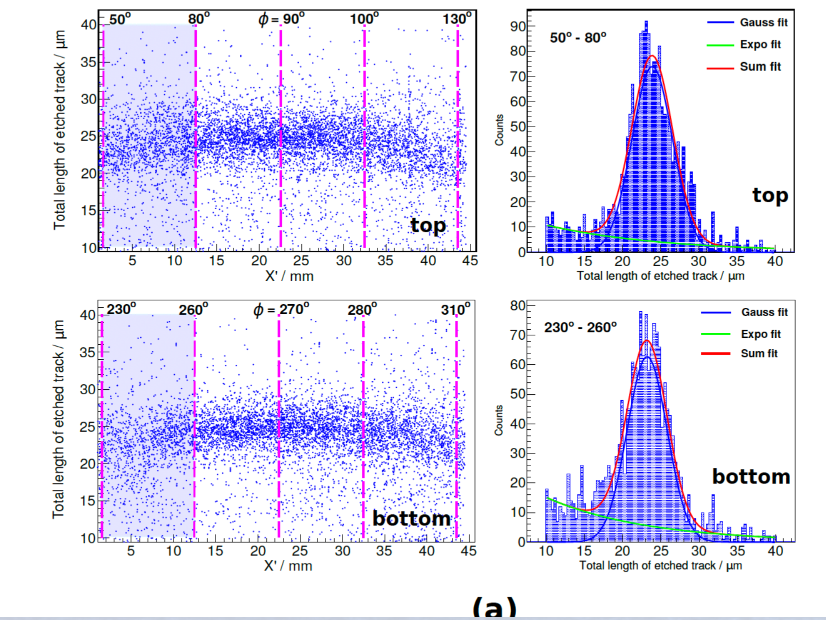


- Change of α-distribution: modified kinematics for polarized ^{3}He gas 😮
- In both cases no left/right (up/down) asymmetry ➔ polarimeter works as expected 😀
- Higher sensitivity on α particle.

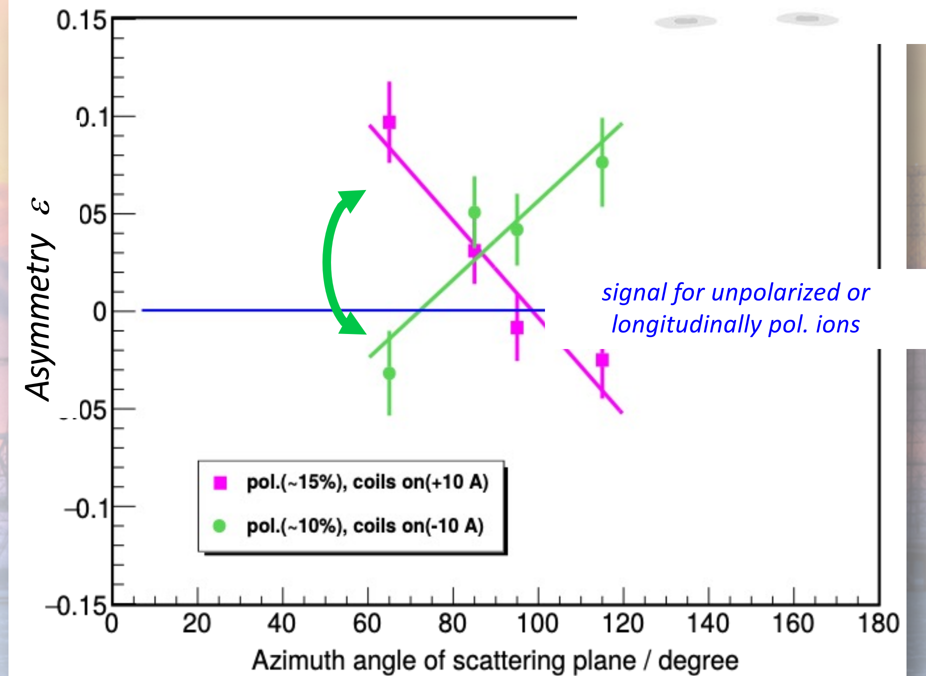
After 2 years of data analysis …

Hit pattern of α

fusion events estraction
for the bin 50°-80° of the 4 bins



$$\varepsilon = \frac{(N_t - N_b)}{(N_t + +Nb)}$$



C. Zheng et al. "First evidence of nuclear polarization effects in a laser-induced ^{3}He fusion plasma" doi: 10.48550/arXiv.2310.04184

- ^{3}He-ion polarization conserved after acceleration
- 2x increased ^{3}He-ion flux from pol. plasma

➔ Our concept (polarized target @ PW laser) works

➔ Plasma acceleration of polarized beams (e^-, p, ions) feasible

➔ Models/simulation codes seem incomplete (spin-dependent ionization?)

Challenge objectives of PREFER now

- @PNPI - D-D spin dependent cross-section measurements! Not anymore in the collaboration from 02/2022: just literature rumors.

- @BINP - Production of polarized fuel: from MBS Not anymore the collaboration from 02/2022: just literature rumors.

- @FE Magnets for holding, manipulating and transporting polarized fuel : Next talk.

Conclusions of PREFER activities

We are still enjoy playing with spin for nuclear fusion, and we are coming closer and closer, and friends and colleagues got the chance to test it soon, see Next talk By Xiangdong Wei

Still a missing information:

Sebastiano Filippi (named Bastianino) "The spin game"
A fresco on the cieling of the Games's Hall – Este Castle – Ferrara
dated after earthquake of 1570.