The PREFER collaboration

Giuseppe Ciullo INFN & University of Ferrara

on behalf of the

PREFER
Polarization Research for Fusion Experiments and Reactors

COLLABORATION
at present time.

Group (Responsible)	Institute
R. Engels et al.	IKP - FZJ @ Jülich & GSI- Darmstadt, Germany
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

Polarized fuel for fusion: benefits and open questions

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* on the *angular distributions* of the *reaction products*,
- possible *neutron lean* reactors.

Open questions need still answers:

- *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*, *manipulating*, and *testing* *polarized fuel* in order to gain from the benefits of it in *FUSION environments*, and answer to the *open questions*.

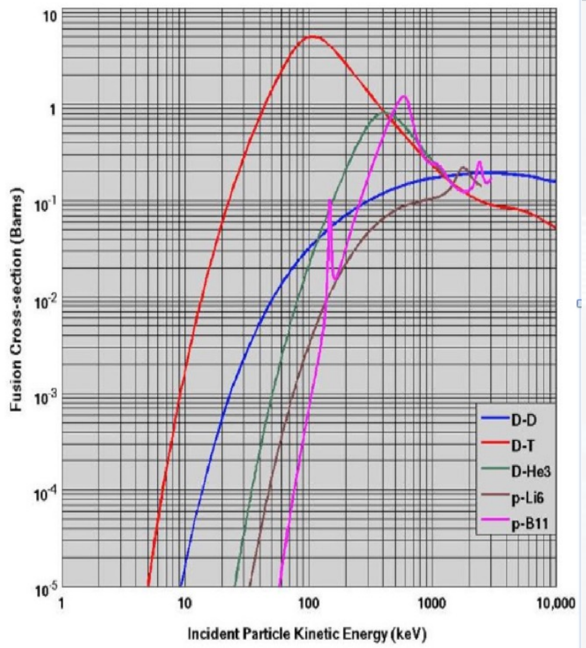
We'll gain deeper insights on knowledge for still "better and better" polarized sources, targets and polarimetry.

Polarized fuel: Benefits and open questions

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

*!! proven in scattering experiments and theoretically models are available, but still **to be proven** in fusion environments*

?? Data not available in order to constrain theoretical models.



1. Generation: D + T → ^{4}He + n

1.a) Enhancement of total cross section !!

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

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

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

2.a) Enhancement 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 ?? This is conditioned by 2.c):

D+D → ^{4}He* → ^{3}He + n suppressed (QSF) ?

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

Challenge objectives for PREFER

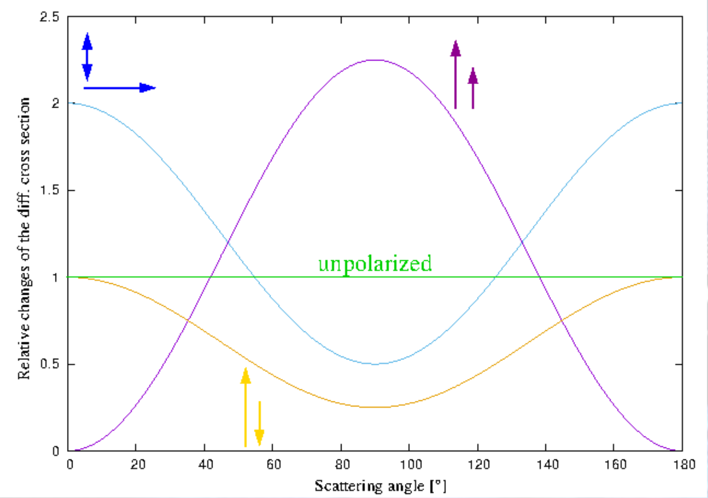
Missing polarized fuel for fusion tests.

Fusion of spin ½ + spin 1 - polarized fuel

T + D → ⁴He + n and ³He + D → ⁴He + p

May 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

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

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

Experimental confirmatio from 1972

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

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... from 1972 many experiments and pubblications on measuments and theoretical models

Theoretical transposition to DT

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

Fusion of spin 1+ spin 1 – polarized fueld

$\mathcal{D} + \mathcal{D} \rightarrow \mathcal{T} + p \,/\, {}^3\mathcal{H}e + n$

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:

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

In the case of D+D 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 less data at lower energy (electron screening ?)

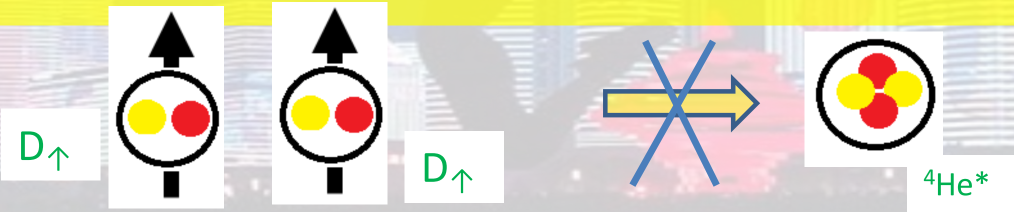
Fusion of spin 1 + spin 1 – polarized fuel

Neutron lean fusion: QSF (Quintet Suppression Factor)

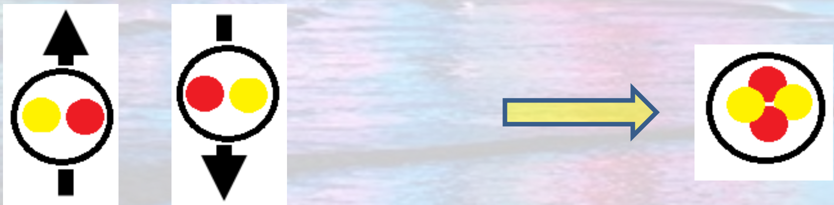
Question: spin alignements allows to enhance, or suppress, reaction channels?

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

S 1 1 = 0 $^5S_2$ Quintet State Suppressed



$$\frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{quintet}}{2/9\,\sigma_{quintet}} = 0$$

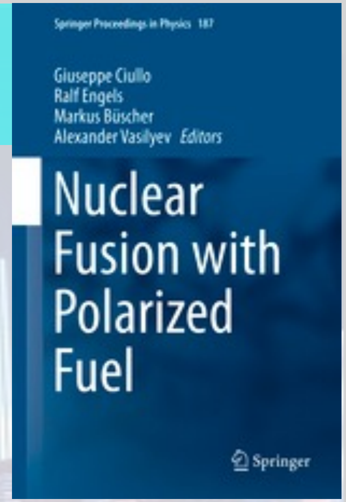


$$\frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{singlet}}{3/9\sigma_{singlet}} = 3$$

S 1 -1 0 $^1S_0$ Singlet state allowed

PSTP people trys to involve fusion community

Contributions of the Workshops held in 2013 at Trento, and in 2015 at 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 - 2016 - Switzerland)

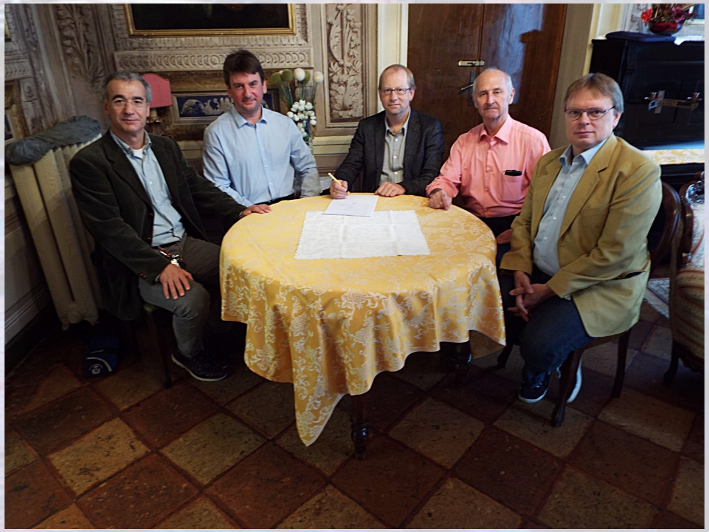


The PREFER collaboration (early stages)

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 collaborations and official contacts with the russian colleagues.



Challenging objectives of PREFER

still now & officially before 02/2022

- @PNPI - D-D spin dependent cross-section measurements officially before 02/2022.
- @IKP-FZJ - Production of polarized fuel: from pABS and new proposals.
- @BINP - Production of polarized fuel: from MBS officially before 02/2022.
- @ IESL-FORTH - Production polarized fuel: by Laser IR-Quantum Beat (QB) excitation and Ultra Violet (UV) dissociation, joined the collaboration a little bit later.
- @PGI-FZJ/HHDU - Laser Induced Plasma LIP: production, acceleration and reaction studies.
- @FE - Magnets for holding, manipulating and transporting polarized fuel .

D↑ - D↑ spin dependent cross-sections

➢ **@PNPI** – *D-D spin dependent cross-section measurements,* *officialy before 02/2022.*

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

$\vec{d}$
10^{11} atom/s

- **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.

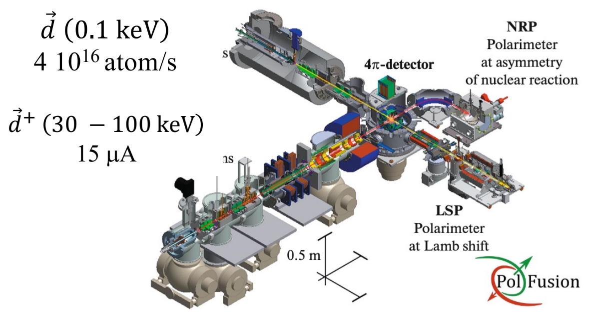
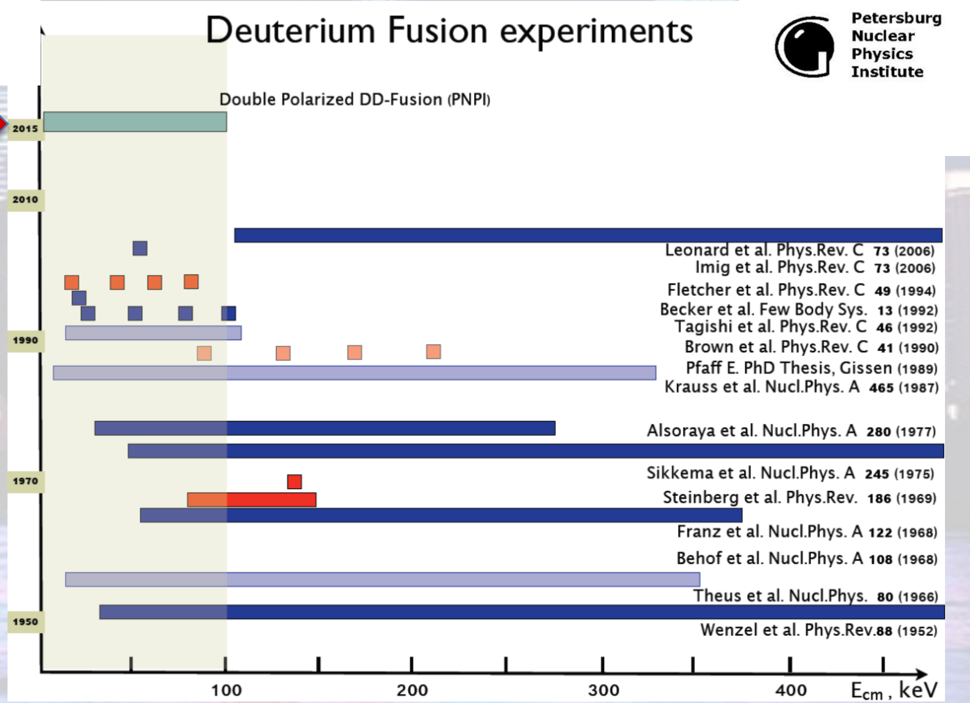


Fig. 2. Experimental facility.



Theoretical models 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).

$D_\uparrow$ - $D_\uparrow$ demanding of measurements

$$\frac{\sigma_{quintet}}{\sigma_{uunpol}} = \frac{\sigma_{11}}{\sigma_0}$$

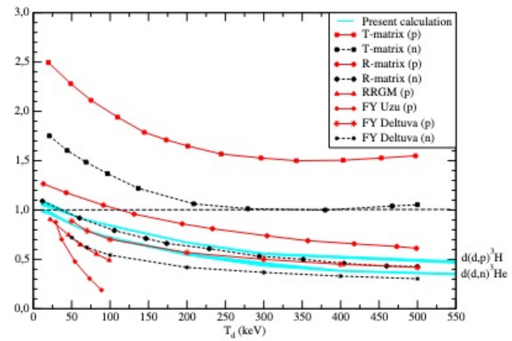


FIG. 2. The QSF for the processes $d(d,n)^3$He and $d(d,p)^3$H shown as bands, in analogy of Fig. 1. We report also the results obtained with other theoretical approaches: T matrix [51]; R matrix [27]; RRGM [32,33]; FY Uzu [35]; FY Deltuva [7]. The red solid [black dashed] lines connecting the red [black]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

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]
[1]Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy

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

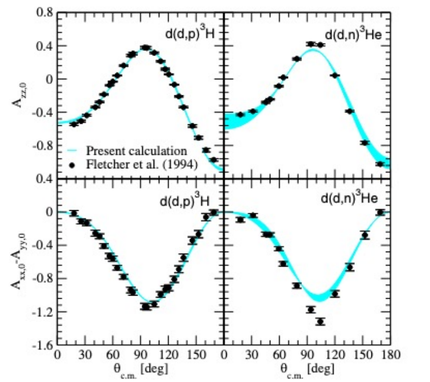


FIG. 3. The observables $A_{zz,0}$ and $A_{xx,0} - A_{yy,0}$ for the $\vec{d}(d,p)^3$H and $\vec{d}(d,n)^3$He processes at $T_d = 21$ keV. The (cyan) bands show the results of the present calculations. The experimental values are taken from Ref. [27].

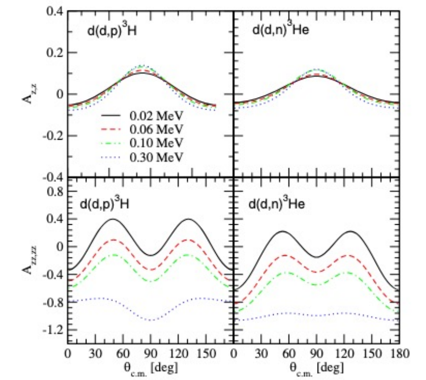


FIG. 4. The polarization observables $A_{z,z}$ and $A_{zz,zz}$ calculated for the $\vec{d}(\vec{d},p)^3$H and $\vec{d}(\vec{d},n)^3$He processes at various laboratory energies. The calculations have been performed for the N3LO500/N2LO500 interaction. The associated theoretical error is of the order of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

226 ROZHDESTVENSKIJ et al.

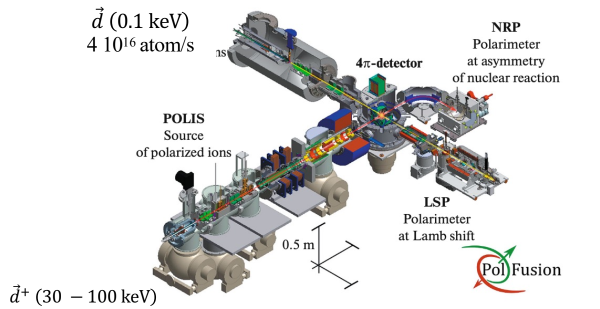


Fig. 2. Experimental facility.

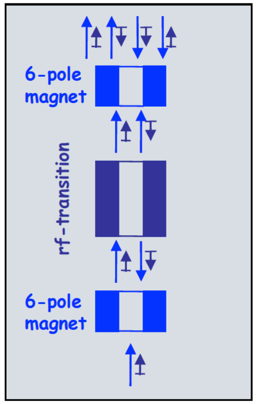
A. Yu. Rozhdestvenskij et. al
Phys. Atom. Nucl. **87** (2024) 224.

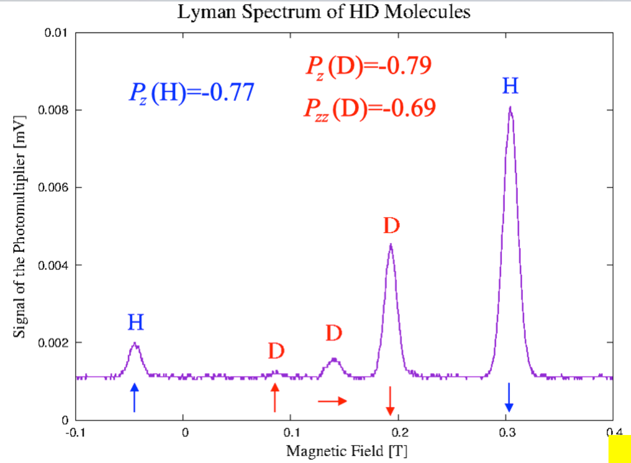
➤ **@PNPI**

Production of polarized fuel by pABS

➤ @IKP-FZJ - Production of polarized fuel: from pABS, and new proposals.

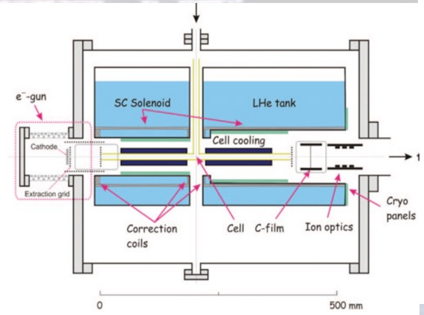
P r o d u c t i o n

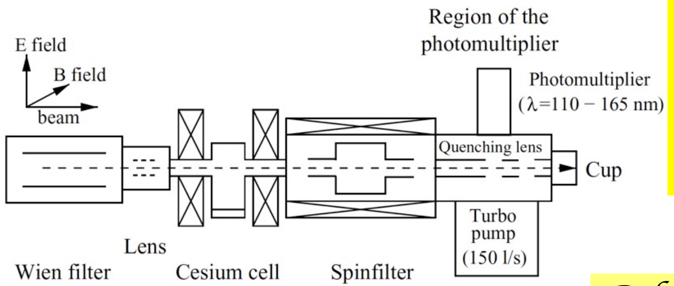




and new proposals.

R. Engels - *Current developments of polarized sources and polarimeter at FZ Jülich and further applications,* this symposium.





S. J. Pütz - *Polarimetry of pulsed H⁻/D⁻ ion beams: extended applicability of the Lamb-shift polarimeter,* in this symposium.

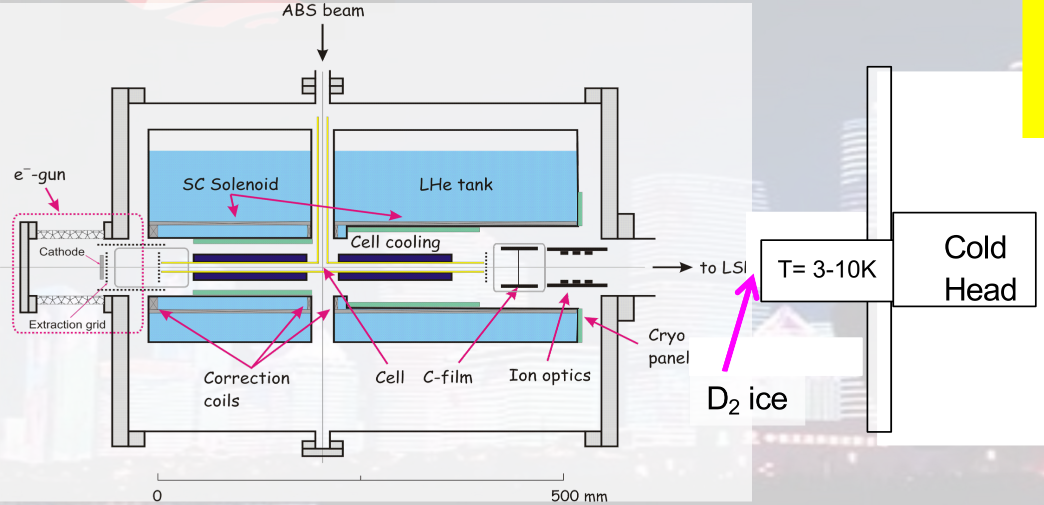
Polarimetry

recombination

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

Production of polarized fuel

Condensation & transp. of pol. fuel



A holding magnetic field is required, for its transportation: superconducting MgB2 hollow Bulk material under investigation @ Fe.

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

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

H_2, D_2, and *HD* hyperpolarized molecules can be produced with polarization of P ~ 0.8 ! For *HD* any spin combination is possible !

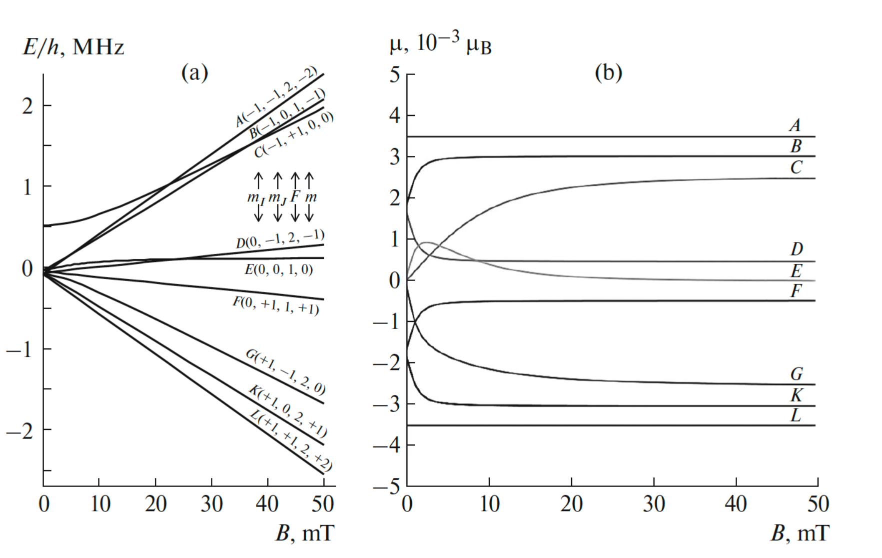
HD is a perfect training ground for the handling of TD !

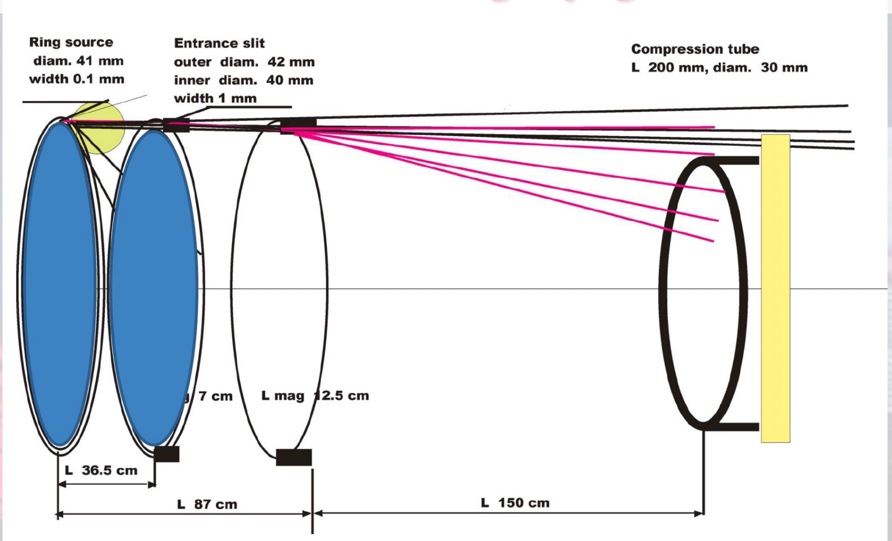
The condenser is surrounded by a S.C. MgB_2 cylinder, which provides the holding field also for transportation.

The super-conducting hollow bulk material is also useful for other techniques under R&D for polarized fuel production, like the ones propose by the colleagues of @ IESL-FORTH .

Production of polarized fuel from pMBS

- **@BINP** - *Production of polarized fuel: from MBS* officially before 02/2022.





An Experimental Setup for Production of Polarized H_2 and D_2 Molecules
D. K. Toporkov[a,b,*], S. A. Zevakov[a], D. M. Nikolenko[a], I. A. Rachek[a], Yu. V. Shestakov[a,b], and A. V. Yurchenko[b]

Instrum. Exper. Tecn. **62** (2019) 56-61.

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]

Instrum. Exper. Tecniques **66** (2024) 531-537.

Simulation of Motion of H_2 and D_2 Molecules in Sextupole Magnets
A. V. Yurchenko[a,*], D. M. Nikolenko[b], I. A. Rachek[b], D. K. Toporkov[a,b], and Yu. V. Shestakov[a,b]

Instrum. Exper. Tecn. **62** (2019) 56-61.

D. Toporkov Status of experiments with polarized deuteron target at VEPP-3 electron storage ring, this symposium.

Production of polarized fuel by laser manipulation

➤ *@ IESL-FORTH – Production polarized fuel: by Laser IR-Quantum Beat (QB) excitation and Ultra Violet (UV) dissociation, joined the collaboration later.*

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

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).

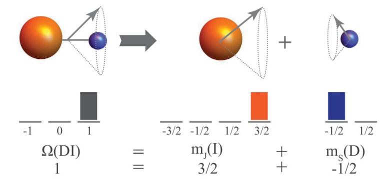


FIG. 2. The angular momentum projection $\Omega_A = +1$ is prepared from the DI ($\Omega = 0$) ground state, using σ^+ circularly polarized photolysis light, and is distributed to the angular momentum projections of the photofragments after photodissociation.

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

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

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

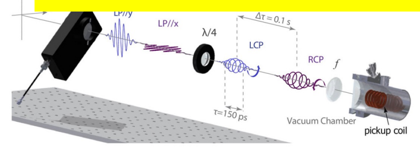
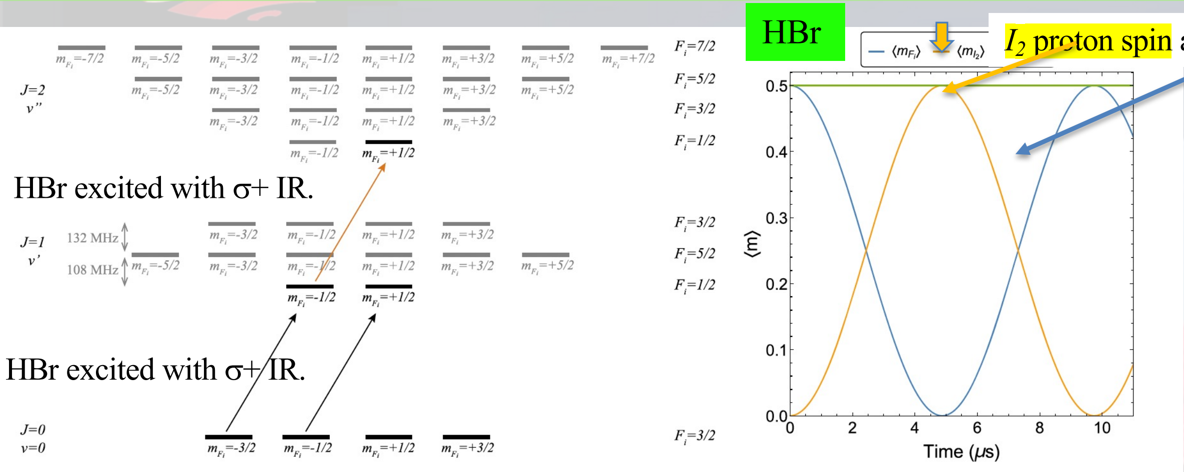


FIG. 1. Experimental setup: The photoelastic modulator (PEM) and quarter-wave plate ($\lambda/4$) alternate laser polarization between right circularly polarized (RCP) and left circularly polarized (LCP) on a shot-to-shot basis at a 10 Hz repetition rate. The laser is focused through the pickup coil, 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.

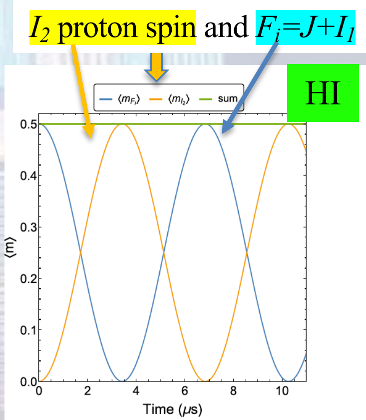
Production of polarized fuel by laser

➤ **@ IESL-FORTH** – *Production polarized fuel: by Laser* IR-Quantum Beat (QB) excitation and Ultra Violet (UV) dissociation, joined the collaboration a little bit later.



(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.

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.

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

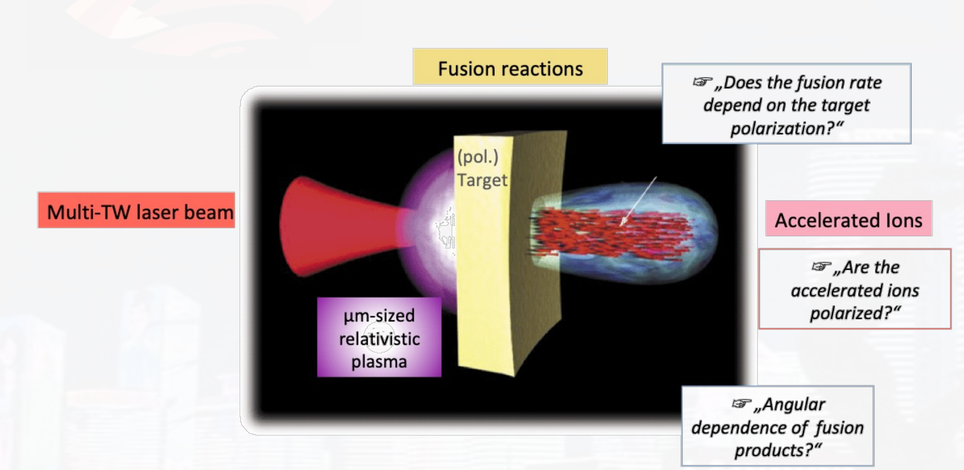
C. S. Kannis et al. *Chem. Phys. Lett.* **784**, 139092 (2021)

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

C.S. Kannis *Spin manipulation in atomic and molecular systems for nuclear spin applications.* This Symposium

Laser Induced plasma (LIP)

@PGI-FZJ/HHDU - Laser Induced Plasma LIP: production, acceleration and reaction studies.



There are various proposal to produce high intense and pure polarized fuel for fusion, but ...

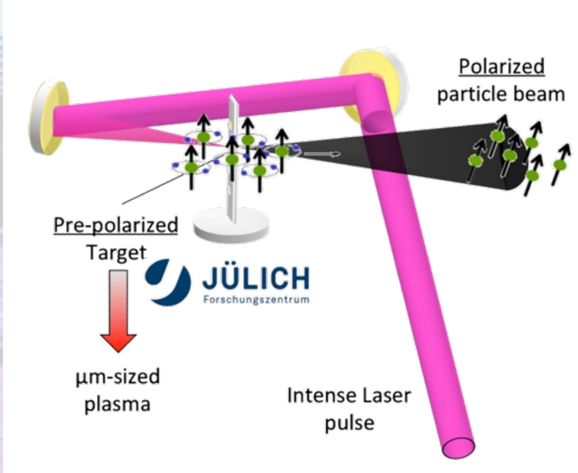
... still an question is pending:

... the polarization will survive 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*

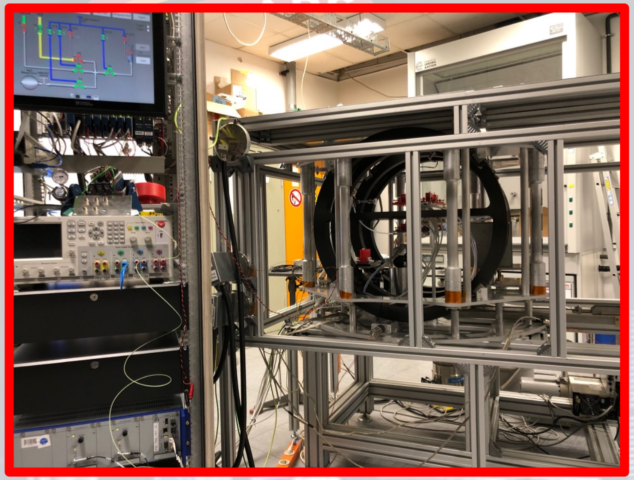


... then let's jump a step and start from polarized beam and test its survival in PW laser. As a result this will be a goal on providing polarized ion sources too.

Polarized ³He gas-jet for LIP acceleration

PREFER
Polarization Research for Fusion Experiments and Reactors

ATHENA



^{3}He polarized @Jülich

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

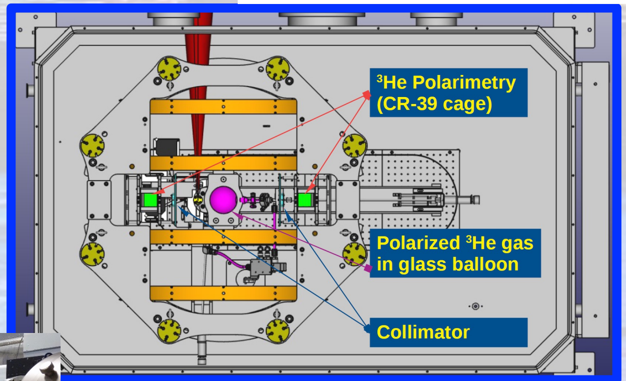
Up to 80% nuclear polarization

^{3}He polarized jet beam at @GSI

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

non-magnetic nozzle provides the desired gas-jet target

Target @ PHELIX GSI



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

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

Best Working points: ± 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}

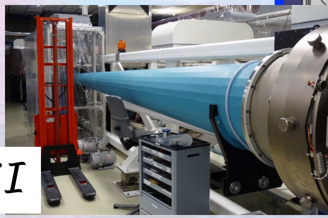
High density polarized ^{3}He Gas-Jet Target 3/4 10^{19} cm^{-3}

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

FZJ

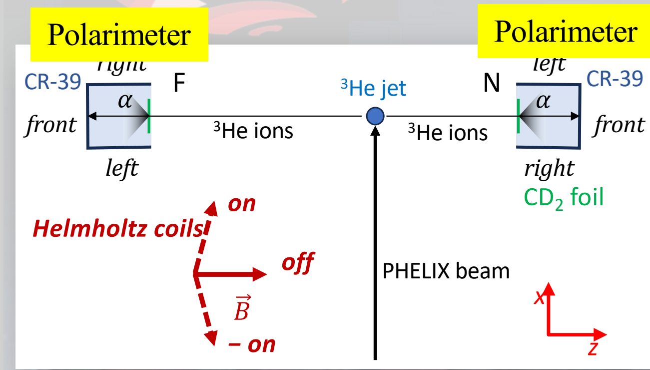
~ 250 km

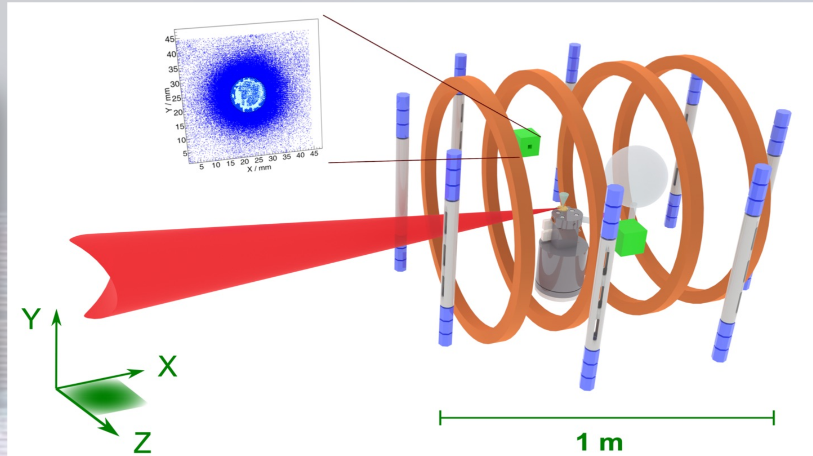
GSI

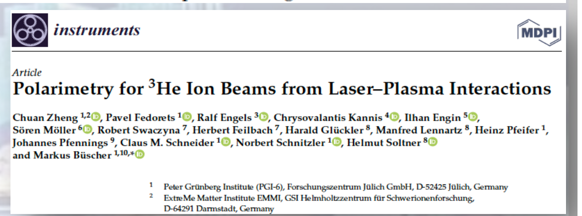


Polarimetry for ³He ions for LIP

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







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instruments

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,*]

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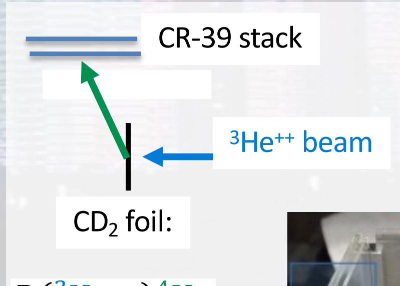
2 ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany



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

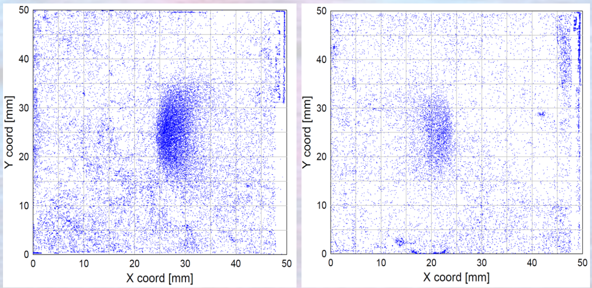
³He polarization along z mantained with $B \sim 1.3$ mT (——), Helmoltz coils (10 A and 5 mT max) hallow to rotate the polarization along the x axis ($\pm$ 75.5°) relative to the ³He ion momenta (- - -).

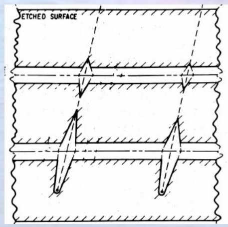
Transverse polarization ($\vec{s} \perp \vec{p}$) of the $\overrightarrow{^3He}$ ions

⇕

Measurable left/right & up/down rate :

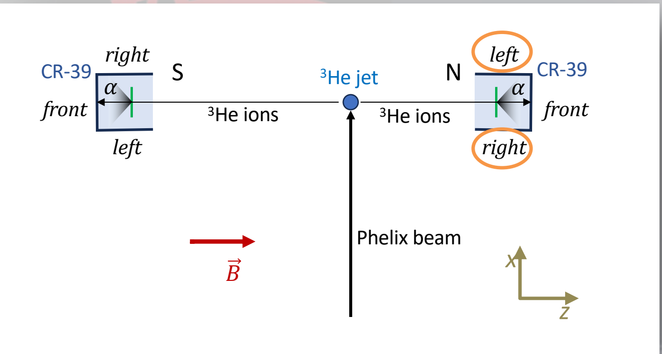
asymmetry of α particles

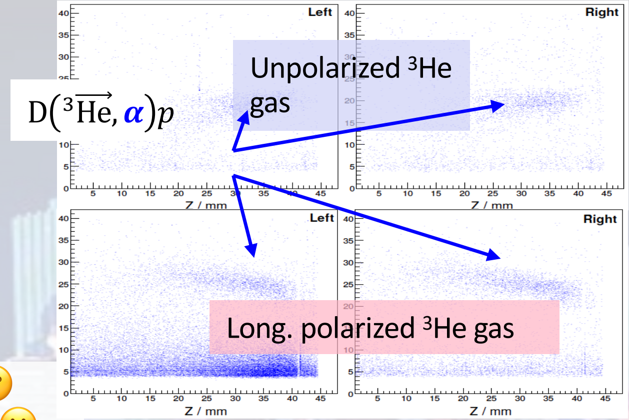




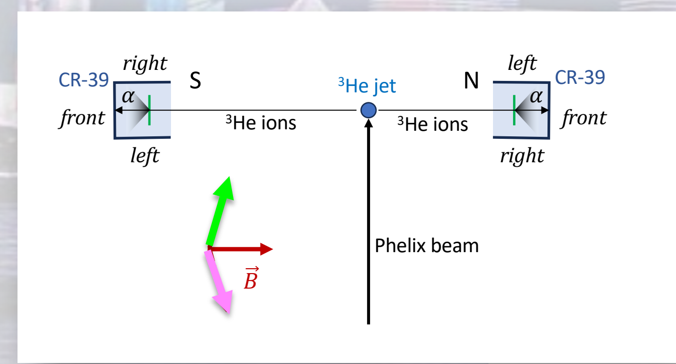
CR-39 stack

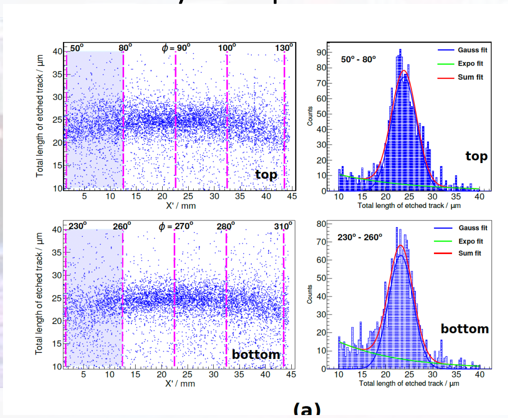
Observed (a-)symmetry for LIP

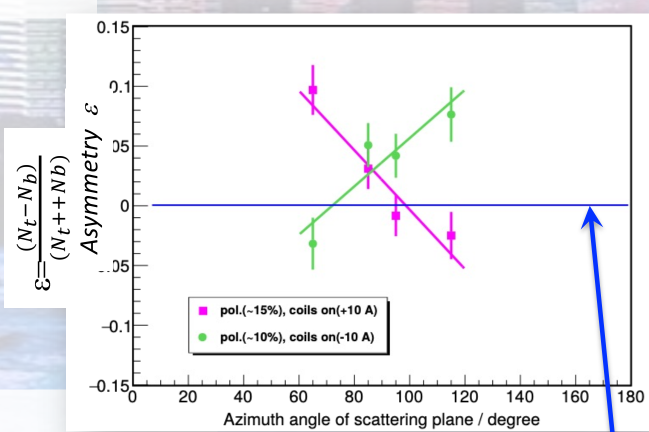




- Change of α-distribution: modified kinematics for polarized ^{3}He gas 😮
- In both cases no L/R (U/D) asymmetry ➔ polarimeter works as expected 😀
- Higher sensitivity on α particle.







signal for unpolarized or longitudinally pol. ions

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

➔ Our concept (polarized target @ PW laser) works

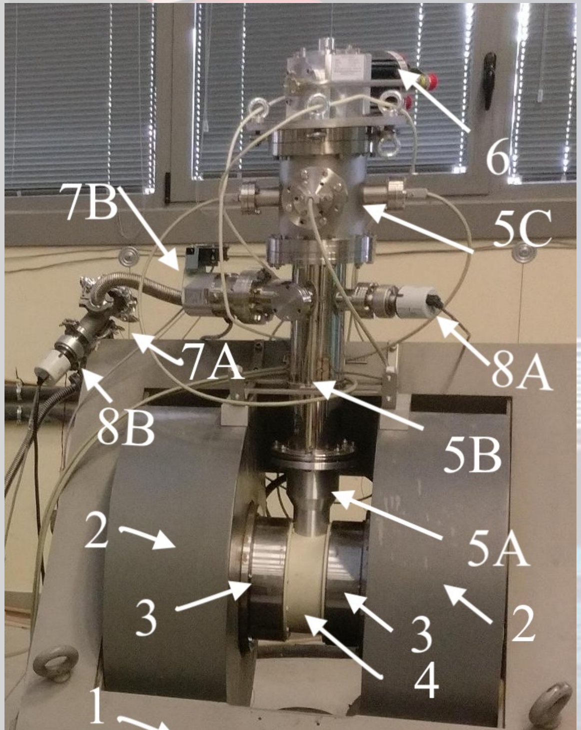
➔ Plasma acceleration of polarized beams (e^-, p, ions) feasible

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

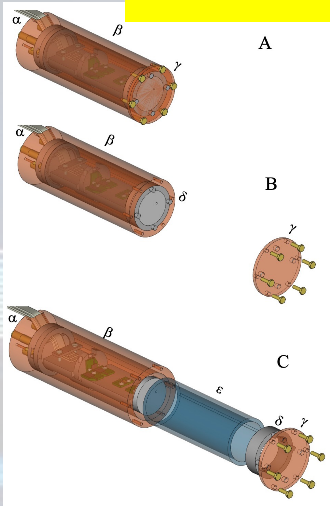
Superconducting Bulk magnets

➤ **@FE** - *Magnets for holding, manipulating and transporting polarized fuel .*

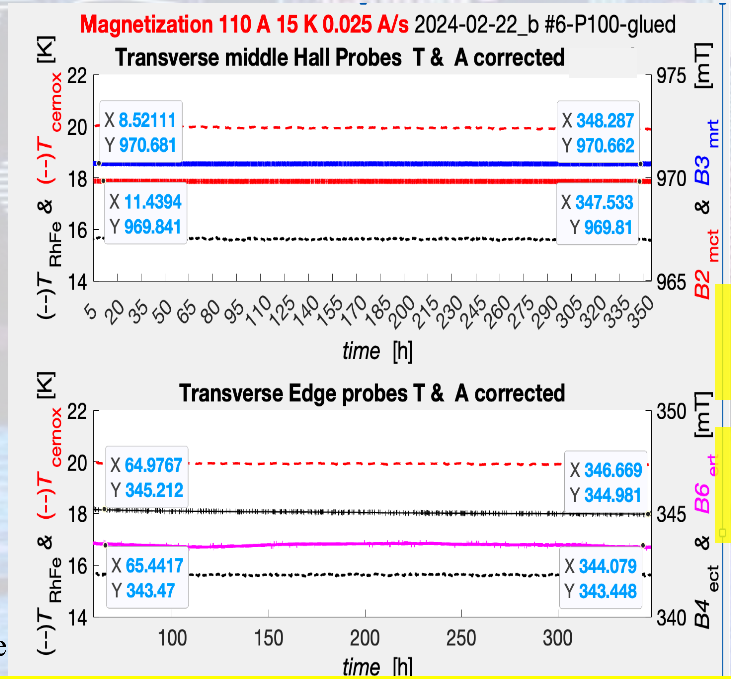
We found the optimal MgB_2 bulk tube and tested it in the so called FC (Field Cooling) condition and keep useful fields for a long time more than the requirements for transportation.



1- iron yoke, 2 –coils, 3-iron poles, 4-nylon support, 5A –Al Chamber, 5B-5C SS chambers, 6-cold-head, 7B -7A TM pumps, 8A-8B Penning gauges



A- Cu-can hosting sensors and MgB_2 tube.
B – Opening Cu-cover.
C- Extracting MgB_2 tube from the Cu-can.



$\Delta B \sim 0.02$ mT on 970 mT in 15 days

M. Statera et al. NIM A 882 (2018) 17-21.

G. Ciullo et al. Front. Phys. 12 (2024) 1358369

We tested the tube in the so called ZFC (Zero Field Cooling) condition and it shielded 970 mT for more than 1480 h ~ 61.5 days.

Estending framework and collaboration

SPINPOL: Novel Methods for Hyperpolarized electron and nuclear spin production for: hyperolarized magnetic resonance (MRI/NMR/ESR) and Polarized Laser Fusion.

(1) *in vivo medical imaging*, and (2) *atmospheric chemistry* (3) *polarized nuclear fusion*

Spin-polarized HD trapped at a surface is done in the following steps:

(1) production of cold HD beam, with all molecules in the J=0 rotational state. (2) IR excitation of all molecules in the ground J=0 state using STIRAP [42], producing polarization of HD bond rotation ; (3) transfer of rotational polarization to HD nuclear spin through hyperfine beating; (4) trapping of HD at a cold surface; (5) transport of trapped HD to measurement facility; (6a) (polarized) laser fusion at the PALS in IPP, which possesses the intensity to produce collision energies high enough to trigger fusion reactions, such as D-D fusion (and D-^{3}He fusion, in the presence of both hyperpolarized D and ^{3}He; the latter supplied by UDUS); 6b) Hyperpolarized MRI on animals using hyperpolarized hydrocarbons (instead of HD), at Aarhus.

(*The main novelty of SPINPOL is to combine all 6 steps*, and *to produce spin-polarized molecules* at a scaled up level (at least mmol quantities of SPMs). Given that *each of these 6 steps has been demonstrated individually* (references given in each case), the *likelihood of success for SPINPOL is very high.*

Foundation of Research Technology- FORTH-Hellas; University of Düsseldorf - UDUS ; University of Münster- UMU; Quamtum Diamonds - QD – Münich; Aarhus University – AU; Institute of Plasma Physics - IPP – Prague; SpinFlex Ashkelon; University of Creta-UOC-Hellas, University of Ferrara – UNIFE.

The ARPA-E ad hoc workshop

ARPA_E involved the PREFER in a very workshop on polarized fuel for the improvement of fusion facilities.

Spin Polarized Fusion Activities in DOE Office of Science
Matthew Lanctot, DOE SC Fusion Energy Sciences (FES)

Overview of the Spin Polarized Fusion Landscape
Andrew Sandorfi, University of Virginia

Status of the Planned DIII-D Experiments and Lifetime Measurement of Spin Polarized D-He3
Xiangdong Wei, Jefferson Lab

Polarization Lifetime Measurements in DIII-D and Other Magnetic Fusion Experiments
Bill Heidbrink, University of California, Irvine

The PREFER (Polarization REsearch for Fusion Experiments and Reactors) Collaboration: Aims, Goals and Present Status
Giuseppe Ciullo, University of Ferrara

First Experience with the Production, Storage and Handling of Polarized D2 and HD Molecules
Ralf Engels, Institut für Kernphysik (IKP) Jülich

Production of Spin-Polarized Molecules via IR or Microwave Rotational Excitation of Molecular Beams
Peter Rakitzis, FORTH Institute for Electronic Structure and Laser (IESL)

Polarized Beams From Plasma Accelerators and Prospects for Polarized Fusion
Markus Büscher, Forschungszentrum Jülich (FZJ)

Concepts for Spin-Qubit Based Polarisation and Negative Ion Detachment of Hydrogen from Diamond Surfaces
Alastair Stacey, Princeton Plasma Physics Laboratory (PPPL)

Challenges of D-T Spin Polarization for ICF
James Sater, Lawrence Livermore National Laboratory (LLNL)

Ab Initio Calculations of Spin Polarized Fusion
Sofia Quaglioni, Lawrence Livermore National Laboratory (LLNL)

Nuclear Lattice Simulations and Plans for Polarized Fusion Calculations
Dean Lee, Facility for Rare Isotope Beams (FRIB), Michigan State University

Neutronics Impact of Source Neutron Direction Anisotropy in Spin Polarized Fusion for Spherical Tokamaks
Katarzyna Borowiec, Oak Ridge National Laboratory (ORNL)

Non-thermonuclear Fusion: Manipulating the Coulomb Barrier
John Perkins, Lawrence Livermore National Laboratory (LLNL)

Conditions for High-Yield Muon Catalyzed Fusion; Preliminary Results from our October 2024 Measurement Campaign
Ara Knaian, Acceleron Fusion

Using Spin-Polarized Fuel To Enhance Tritium Burn Efficiency
Jason Parisi, Princeton Plasma Physics Laboratory (PPPL)

Spin it to Win it: Exploring the Benefits of Spin-Polarized Fusion in a Spherical Tokamak Pilot Plant
Aaron Washington, Tokamak Energy, Inc.

Impact of Spin Polarization on Total Capital Cost and Levelized Cost of Electricity for a Magnetic Fusion Energy Power Plant
Simon Woodruff, Woodruff Scientific

https://arpa-e.energy.gov/news-and-events/events/spin-polarized-fusion-spf-workshop

The SPF (Spin Polarized Fusion) program at DIII--D

A project is funded by the DOE in USA for the test at the DIII-D tokamak for the survival of polarization.

W. W. Heidbrink et. al. *A research program to measure the lifetime of spin polarized fuel* Front. Phys. **12** ((2024) 1355212.

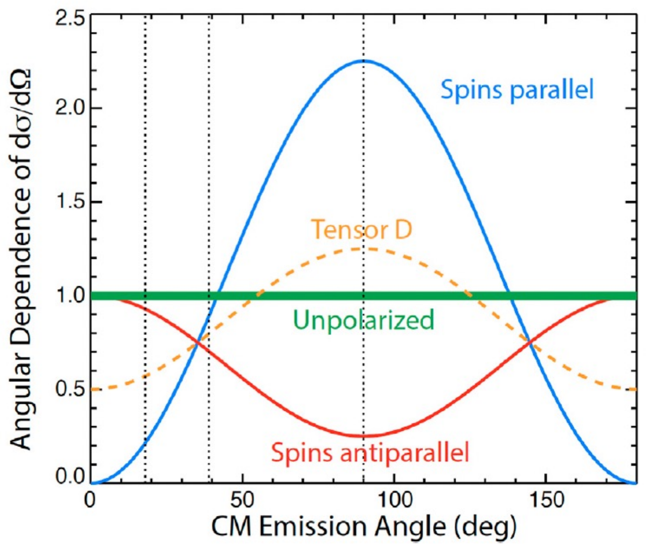


FIGURE 6
Angular dependence of the differential cross section $d\sigma/d\Omega$ for maximally-aligned parallel D and ^{3}He nuclear spins (blue line), anti-parallel spins (red line), and randomly oriented spins (thick green line). The angular dependence for unpolarized ^{3}He and tensor-polarized deuterium $P_D^T = 1$ is also shown (dashed orange line). If one measures fusion-product signals at the emission angles indicated by the vertical lines, the ratios of the signals are quite sensitive to the nuclear polarization.

Feeding pellet of
^{3}He and LiD with spin parallel and antiparallel
with proper diagnostics of the angular
distribution of fusion products,
will provide evidence of the survival of the polarization.

Also the D polarized +
D unpolarized reaction has to be considered, they compared different beam pitch $v_{||}/v$ and with the D+^{3}H spin aligned reaction
and tensor polarized D + ^{3}He unpolarized
reaction.

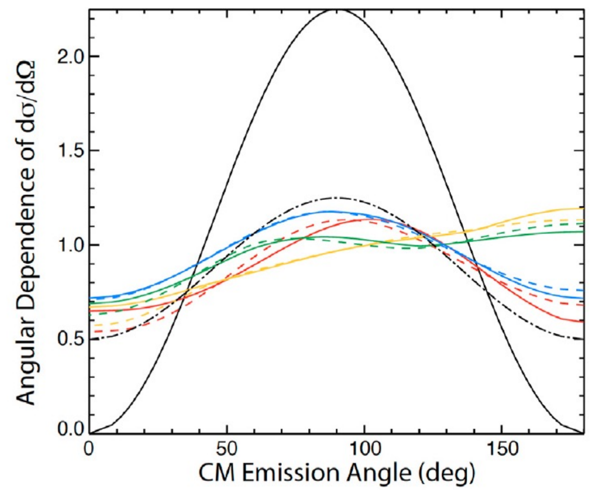


FIGURE 8
Angular dependence of the differential D-D cross section relative to the unpolarized dependence $\langle d\sigma/d\Omega\rangle/(d\sigma/d\Omega)_0$ for maximally-aligned D nuclear spin ($P_D^V = 1.0 = P_D^T$) that collides with an unpolarized D target for various values of incident beam pitch $v_{||}/v$ relative to the magnetic field: ± 0.99 (red), ± 0.75 (yellow), ± 0.5 (green), ± 0.1 (blue). (Solid lines are positive values; dashed lines are negative.) The curves are averaged over randomly oriented incident gyroangles of the beam. In comparison, when both species are polarized, maximally-aligned D-^{3}He reactions between parallel spins (solid black) have much stronger angular sensitivity than the D-D reactions, while reactions between tensor-polarized D and unpolarized ^{3}He (black dash-dot line) have comparable sensitivity.

Conclusions

Interests and activities on fusion with polarized fuel are "boiling" around, involving fusion experts too.
This is another good result, which will be surely fruitful.
The proposal SPINPOL, submitted to the European community, enlarged already our collaboration.
A program in USA has been funded, in which our collaboration was determinant.

The most impelling and determinant result is to provide useful and "easy to handle" polarized fuel,
but we engaged excellent teammates for our spin games.

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