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Nuclear Fusion with Polarized Fuel

Polarized Fusion

13.07.2017

by Ralf Engels

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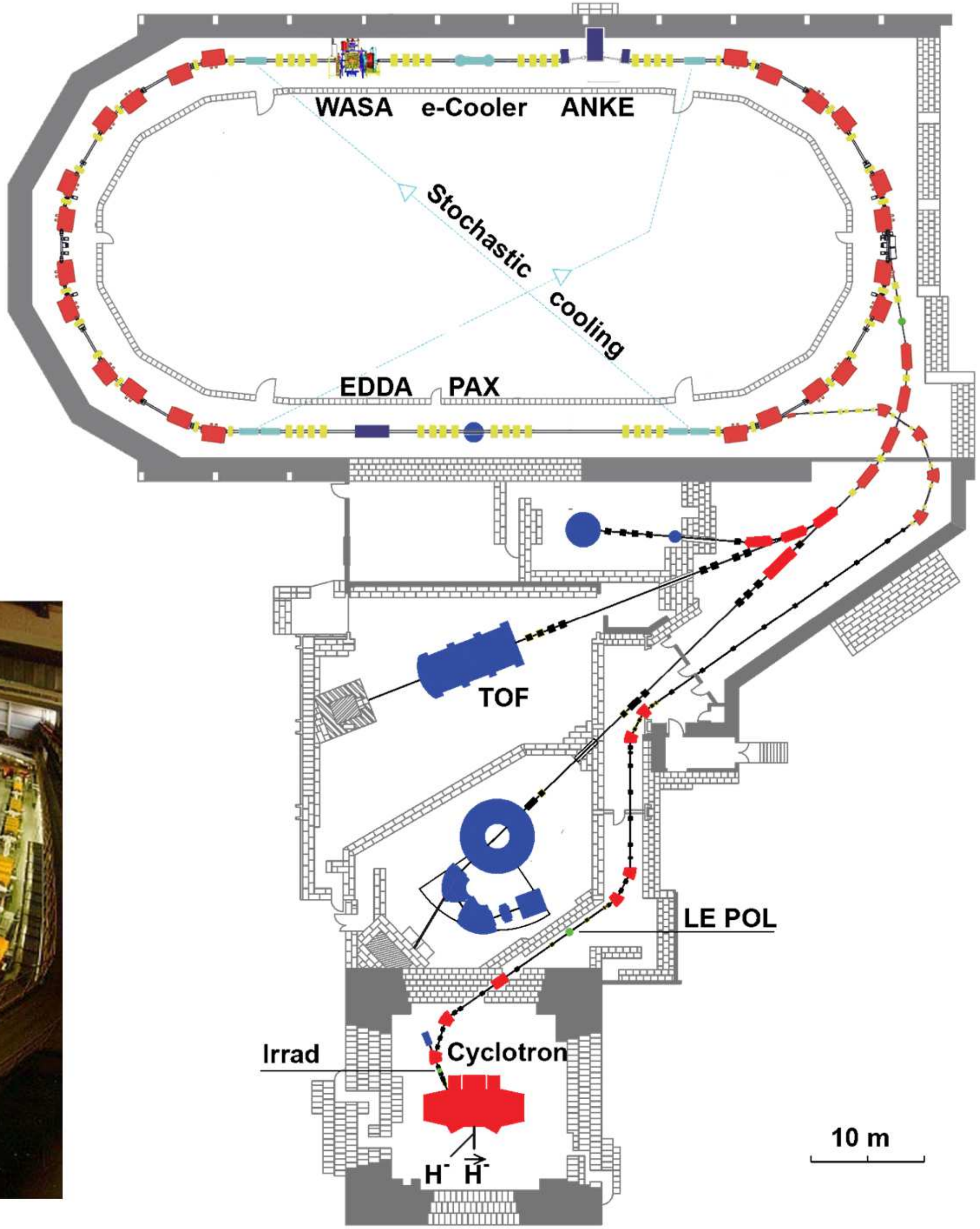
PIT@ANKE

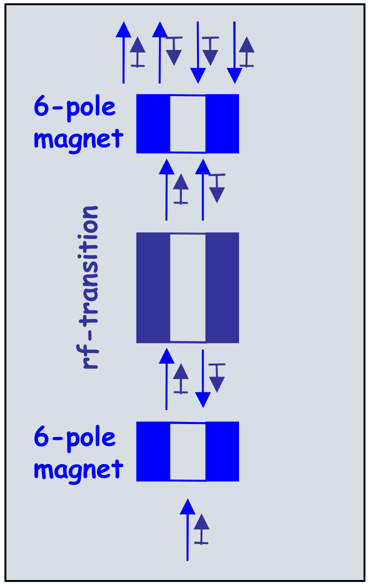
$p, \vec{p}, d, \vec{d}$

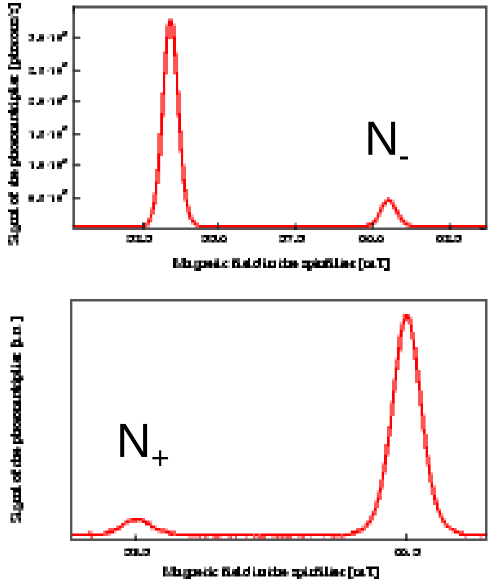
with momenta up to 3.7 GeV/c

- **internal experiments** – with the circulating beam
- **external experiments** – with the extracted beam

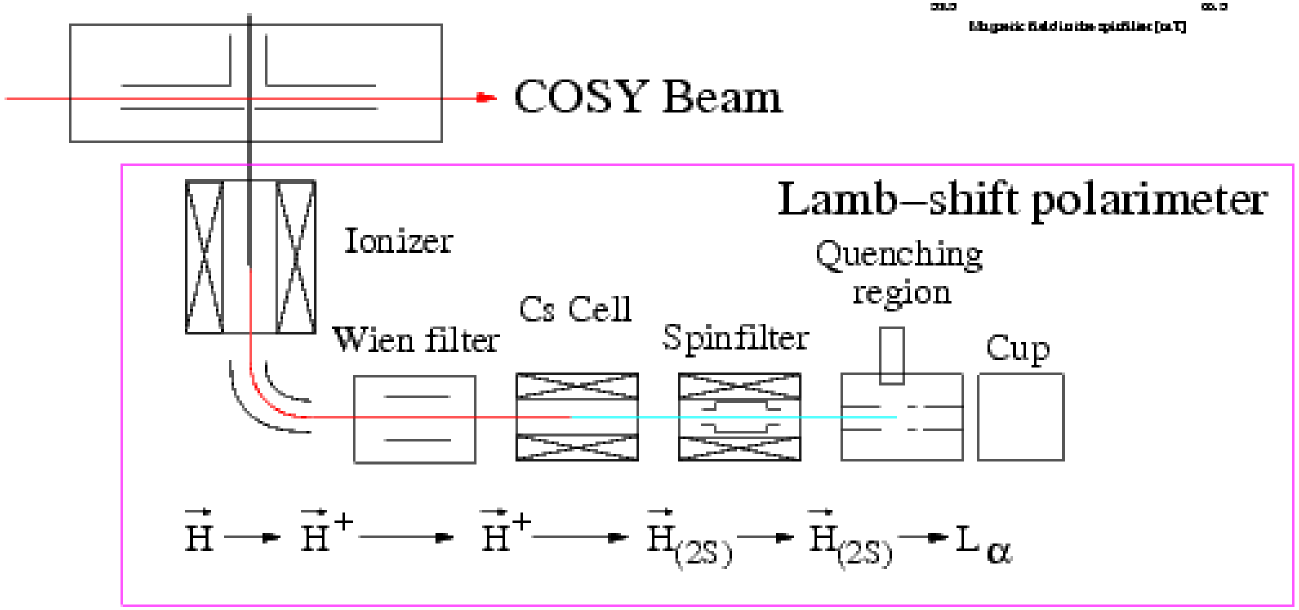


ABS and Lamb-shift polarimeter





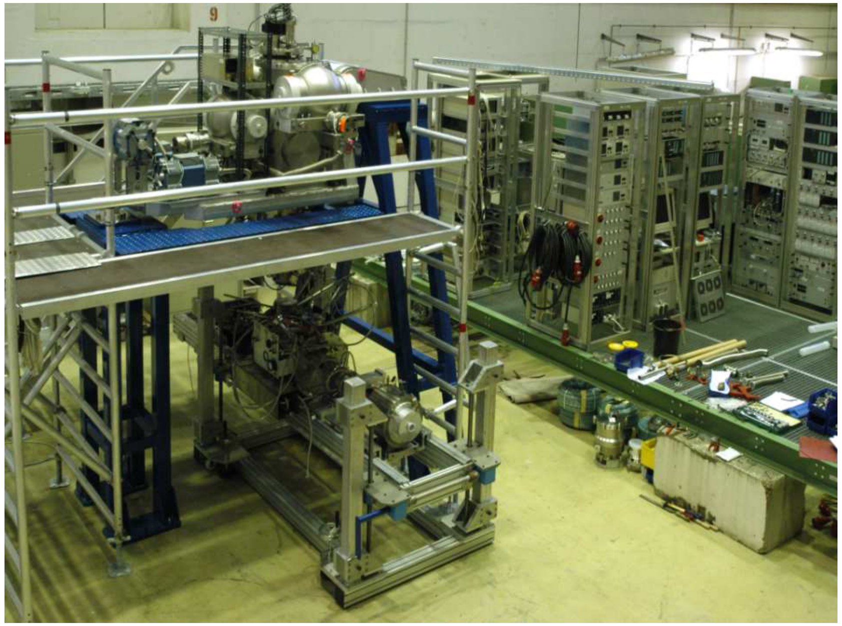
$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

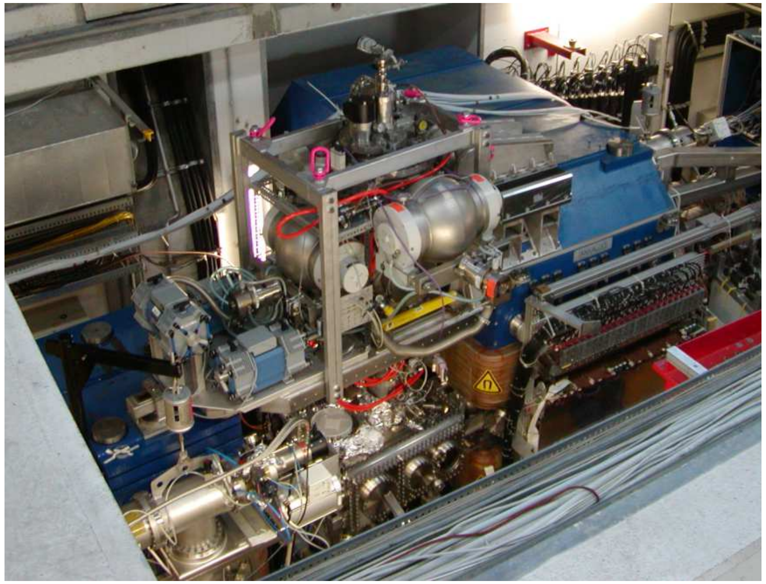


PIT @ ANKE/COSY

Main parts of a PIT:

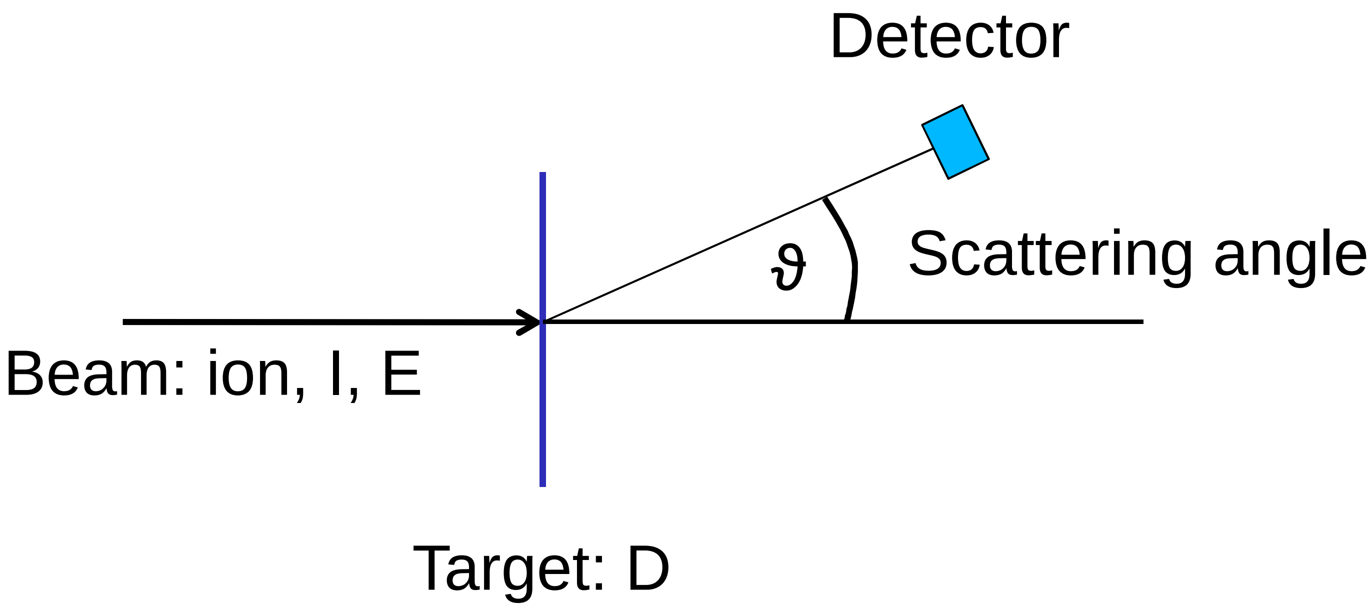
- Atomic Beam Source
  - Target gas
    hydrogen or **deuterium**
  - H beam intensity (2 hyperfine states)
    $\mathbf{8.2 \cdot 10^{16}}$ **atoms / s**
  - Beam size at the interaction point
    $\boldsymbol{\sigma = 2.85 \pm 0.42}$ **mm**
  - Polarization for hydrogen atoms
    $\mathbf{P_Z = 0.89 \pm 0.01}$ **(HFS 1)**
    $\mathbf{P_Z = -0.96 \pm 0.01}$ **(HFS 3)**
- Lamb-Shift Polarimeter
- Storage Cell





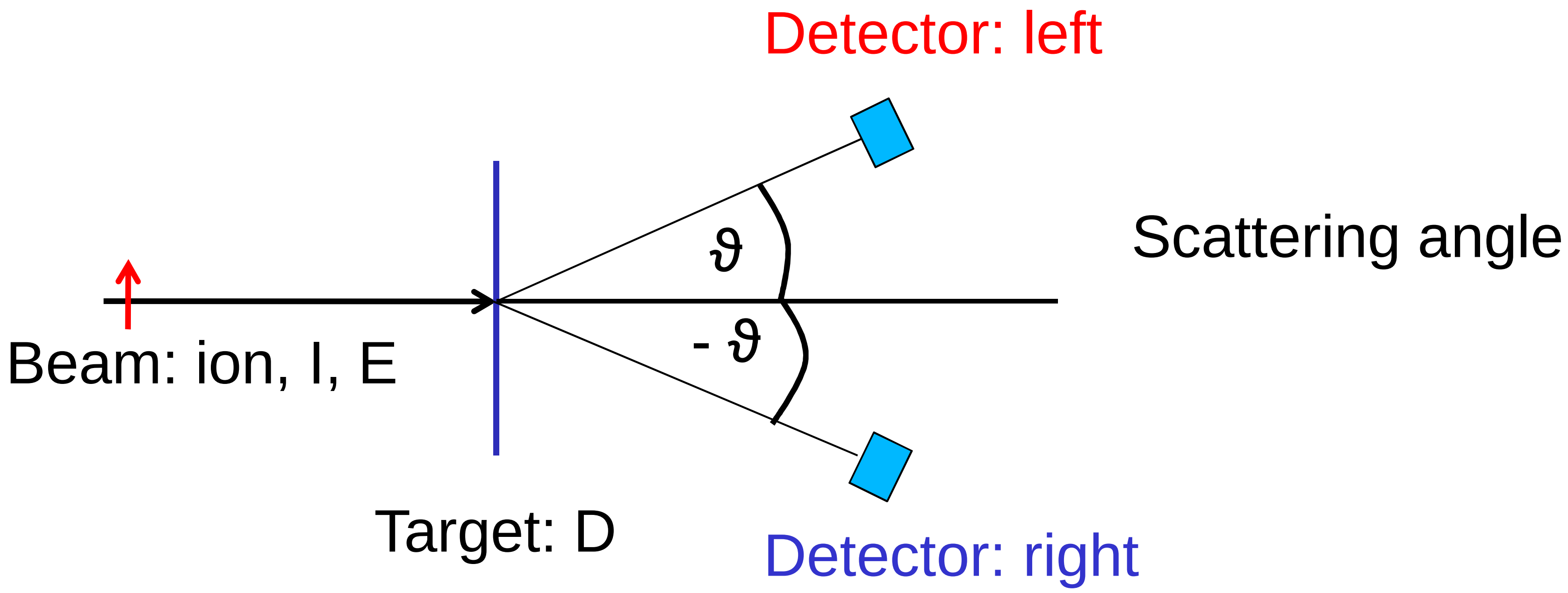
M. Mikirtychyants et al.; NIM A **721** (0) 83 (2013)

Introduction



Only Observable: dσ/dΩ (E,ϑ)

Introduction



$\Rightarrow$ $N_{left} \neq N_{right}$

Introduction

Why is polarization important?

$$V_{\text{nuclear reaction}} = V_{\text{Coulomb}} + V_{\text{Weak}} + V_{\text{Strong}}$$

$$= V_{....} + V_{....} + \boxed{V_{\text{Spin}}} + V_{....}$$

→ Polarization Observables

Simple case: Particle with Spin = ½ on unpolarized particle

$$d\sigma/d\Omega_{\text{pol}}\,(E,\vartheta) = d\sigma/d\Omega_{\text{unpol}}\,(E,\vartheta) \cdot [1 + A_y(E,\vartheta) \cdot \sin\varphi \cdot p_y]$$

→ Analyzing Power: $-1 \leq A_y(E,\vartheta) \leq +1$

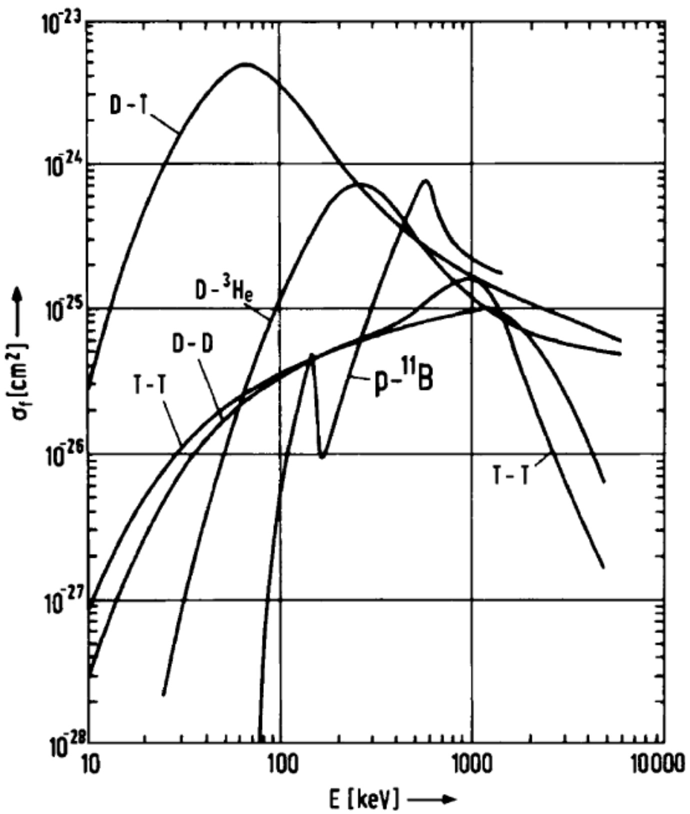
Introduction

$$
\begin{aligned}
\sigma(\Theta,\Phi) = \sigma_0(\Theta)\,\{1 \; & + \; \frac{3}{2}\left[A_y^{(b)}(\Theta)p_y + A_y^{(t)}q_y\right] + \frac{1}{2}\left[A_{zz}^{(b)}(\Theta)p_{zz} + A_{zz}^{(t)}(\Theta)q_{zz}\right] \\
& + \; \frac{1}{6}\left[A_{xx-yy}^{(b)}(\Theta)p_{xx-yy} + A_{xx-yy}^{(t)}(\Theta)q_{xx-yy}\right] \\
& + \; \frac{2}{3}\left[A_{xz}^{(b)}(\Theta)p_{xz} + A_{xz}^{(t)}(\Theta)q_{xz}\right] \\
& + \; \frac{9}{4}\left[C_{y,y}(\Theta)p_y q_y + C_{x,x}(\Theta)p_x q_x + C_{x,z}(\Theta)p_x q_z\right. \\
& \quad \left. + C_{z,x}(\Theta)p_z q_x + C_{z,z}(\Theta)p_z q_z\right] \\
& + \; \frac{3}{4}\left[C_{y,zz}(\Theta)p_y q_{zz} + C_{zz,y}(\Theta)p_{zz} q_y\right] \\
& + \; C_{y,xz}(\Theta)p_y q_{xz} + C_{xz,y}(\Theta)p_{xz} q_y + C_{x,yz}(\Theta)p_x q_{yz} \\
& + \; C_{yz,x}(\Theta)p_{yz} q_x + C_{z,yz}(\Theta)p_z q_{yz} + C_{yz,z}(\Theta)p_{yz} q_z \\
& + \; \frac{1}{4}\left[C_{y,xx-yy}(\Theta)p_y q_{xx-yy} + C_{xx-yy,y}(\Theta)p_{xx-yy} q_y\right. \\
& \quad \left. + C_{zz,zz}(\Theta)p_{zz} q_{zz}\right] \\
& + \; \frac{1}{3}\left[C_{zz,xz}(\Theta)p_{zz} q_{xz} + C_{xz,zz}(\Theta)p_{xz} q_{zz}\right] \\
& + \; \frac{1}{12}\left[C_{zz,xx-yy}(\Theta)p_{zz} q_{xx-yy} + C_{xx-yy,zz}(\Theta)p_{xx-yy} q_{zz}\right] \\
& + \; \frac{4}{9}\left[C_{xz,xz}(\Theta)p_{xz} q_{xz} + C_{yz,yz}(\Theta)p_{yz} q_{yz}\right] \\
& + \; \frac{8}{9}\left[C_{xy,yz}(\Theta)p_{xy} q_{yz} + C_{yz,xy}(\Theta)p_{yz} q_{xy}\right] \\
& + \; \frac{16}{9} C_{xy,xy}(\Theta)p_{xy} q_{xy} \\
& + \; \frac{1}{9}\left[C_{xz,xx-yy}(\Theta)p_{xz} q_{xx-yy} + C_{xx-yy,xz}(\Theta)p_{xx-yy} q_{xz}\right] \\
& + \; \frac{1}{36} C_{xx-yy,xx-yy}(\Theta)p_{xx-yy} q_{xx-yy} \\
& + \; \frac{1}{2}\left[C_{x,xy}(\Theta)p_x q_{xy} + C_{xy,x}(\Theta)p_{xy} q_x + C_{z,xy}(\Theta)p_z q_{xy}\right. \\
& \quad \left. + C_{xy,z}(\Theta)p_{xy} q_z\right]\,\}
\end{aligned}
$$

Polarized Fusion

1.) Can the total cross section of the fusion reactions be increased by using polarized particles?

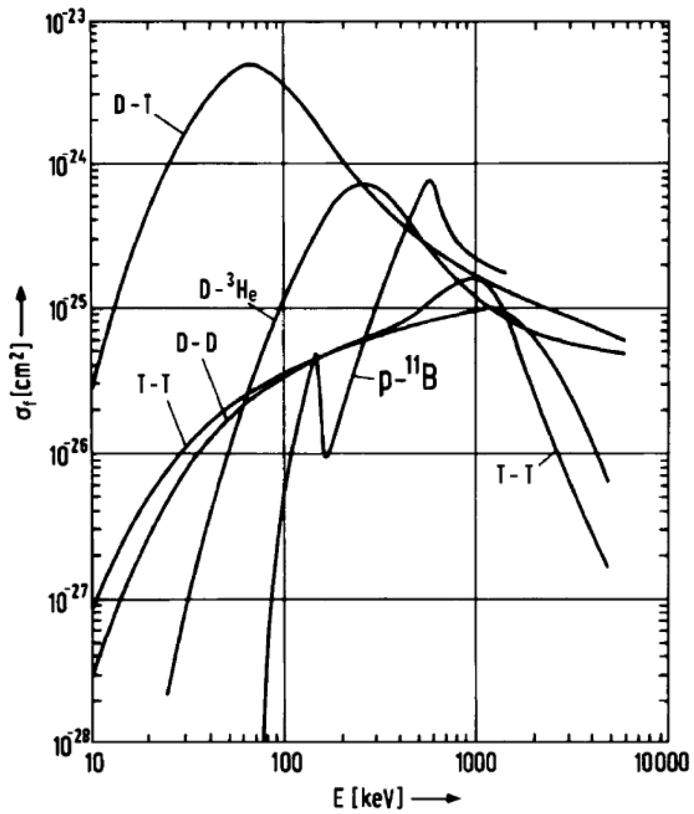
Total cross section



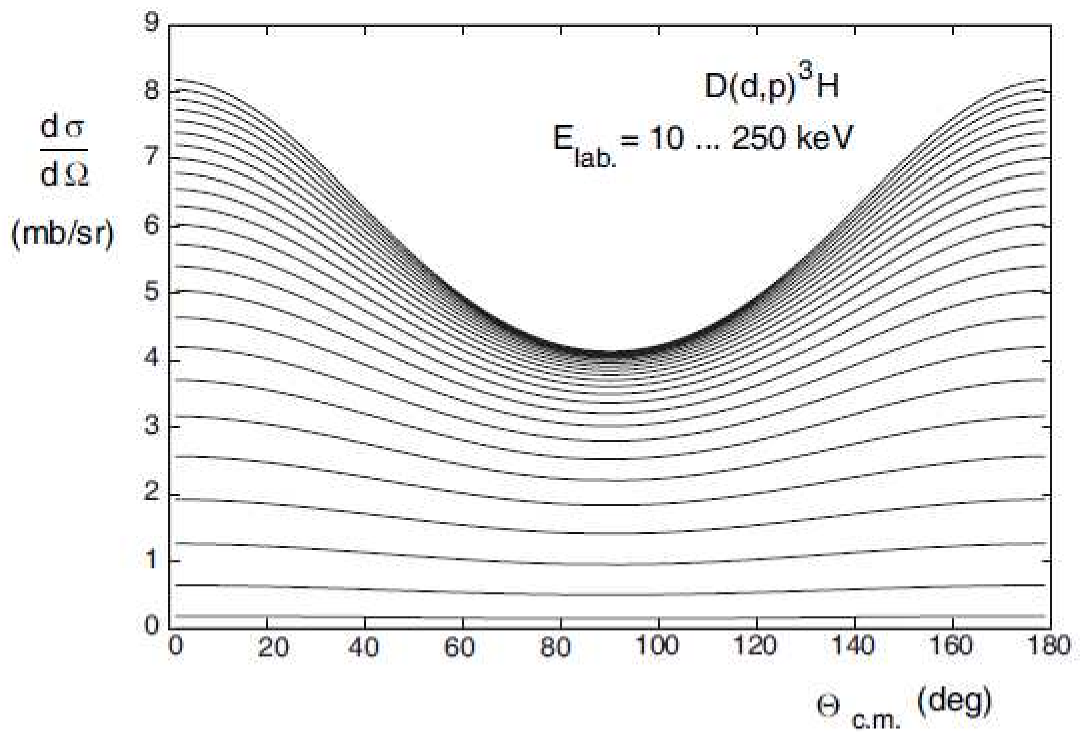
Polarized Fusion

1.) Can the trajectories of the ejectiles be controlled by use of polarized particles ?

Total cross section



Differential cross section



Polarized Fusion

1.) Can the total cross section of the fusion reactions be increased by using polarized particles?

$$t + d \longrightarrow {}^4He + n$$

J = 3/2 $^+$ / s-wave dominated (> 96%)

$$\vec{{}^3He} + \vec{d} \longrightarrow {}^4He + p$$

Factor: ~1.5 at 430 keV

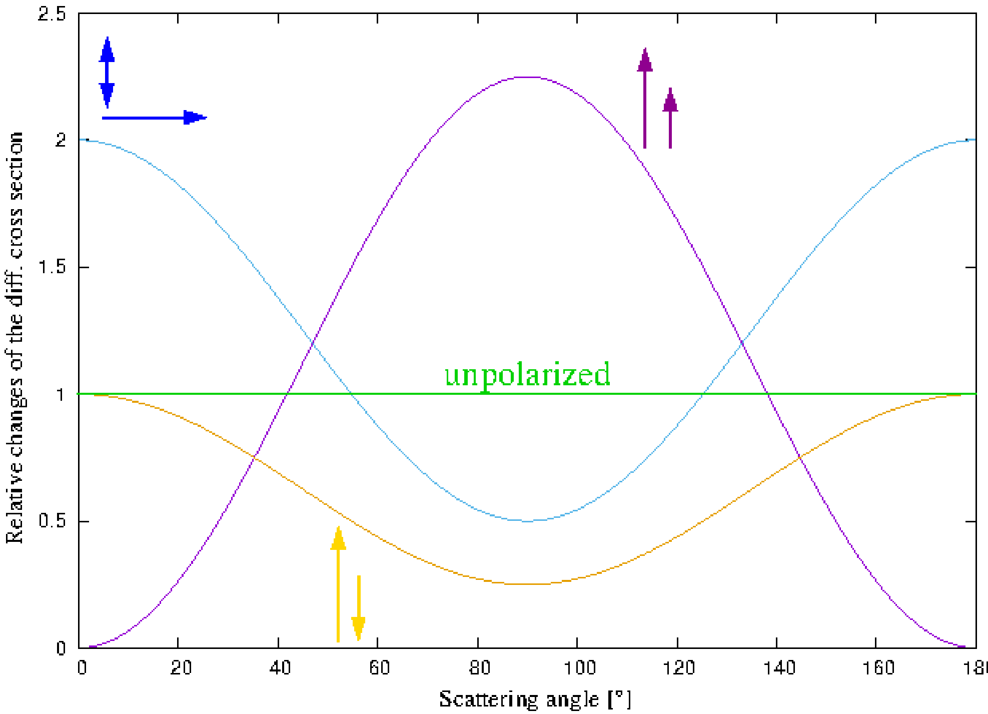
[Ch. Leemann et al., Helv. Phys. Acta **44**, 141 (1971)]

(H. Paetz gen. Schieck, Eur. Phys. J. A **44**, 321-354 (2010))

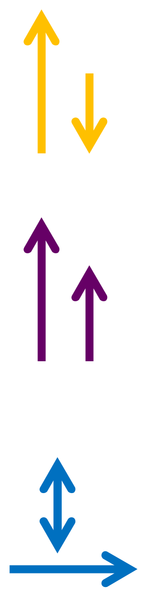
Polarized Fusion

1.) Can the total cross section of the fusion reactions be increased by using 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

Polarized Fusion

1.) Can the total cross section of the fusion reactions be increased by using polarized particles ?

Yes

Energy Production:

Calculations for ITER:
(Magnetic confinement)
....

Factor 2

Calculation for MEGAJOULE:
(Laser-induced intertial fusion)

Factor 1.5, but the necessary laser power can be reduced by 25 %

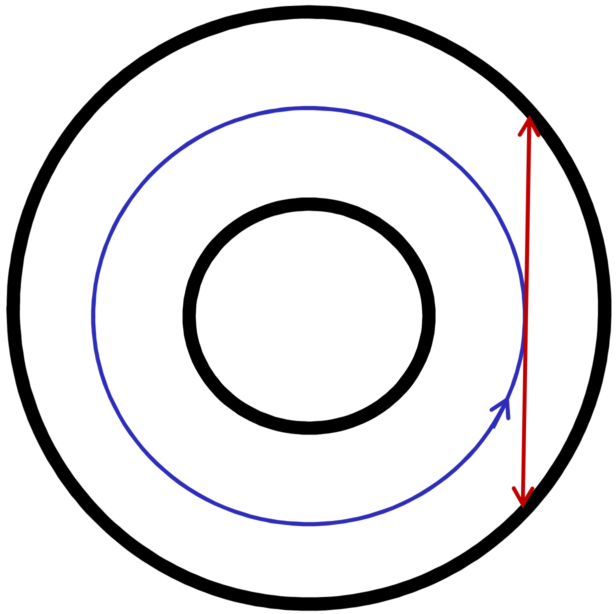
M. Temporal et al.; Nucl. Fusion **52** (2012) 103011

Polarized Fusion

1.) Can the trajectories of the ejectiles be controlled by use of polarized particles ?

Deuterium: $m_s = 0$

Focussing of the Neutrons !



1.) Helps for breeding of the tritium !

2.) Less neutrons on the inner wall -> less cooling needed -> coils can come closer to the plasma -> $E \sim B^{7.81}$

Polarized Fusion

Can the total cross sections of the DD reactions be increased ?

$$\vec{d} + \vec{d} \rightarrow \begin{cases} t + p \\ {}^{3}He + n \end{cases}$$

Can cross sections be increased ?
Can the trajectories of the neutrons be controlled?
Can neutrons be suppressed ?
→ „Quintet suppression factor“

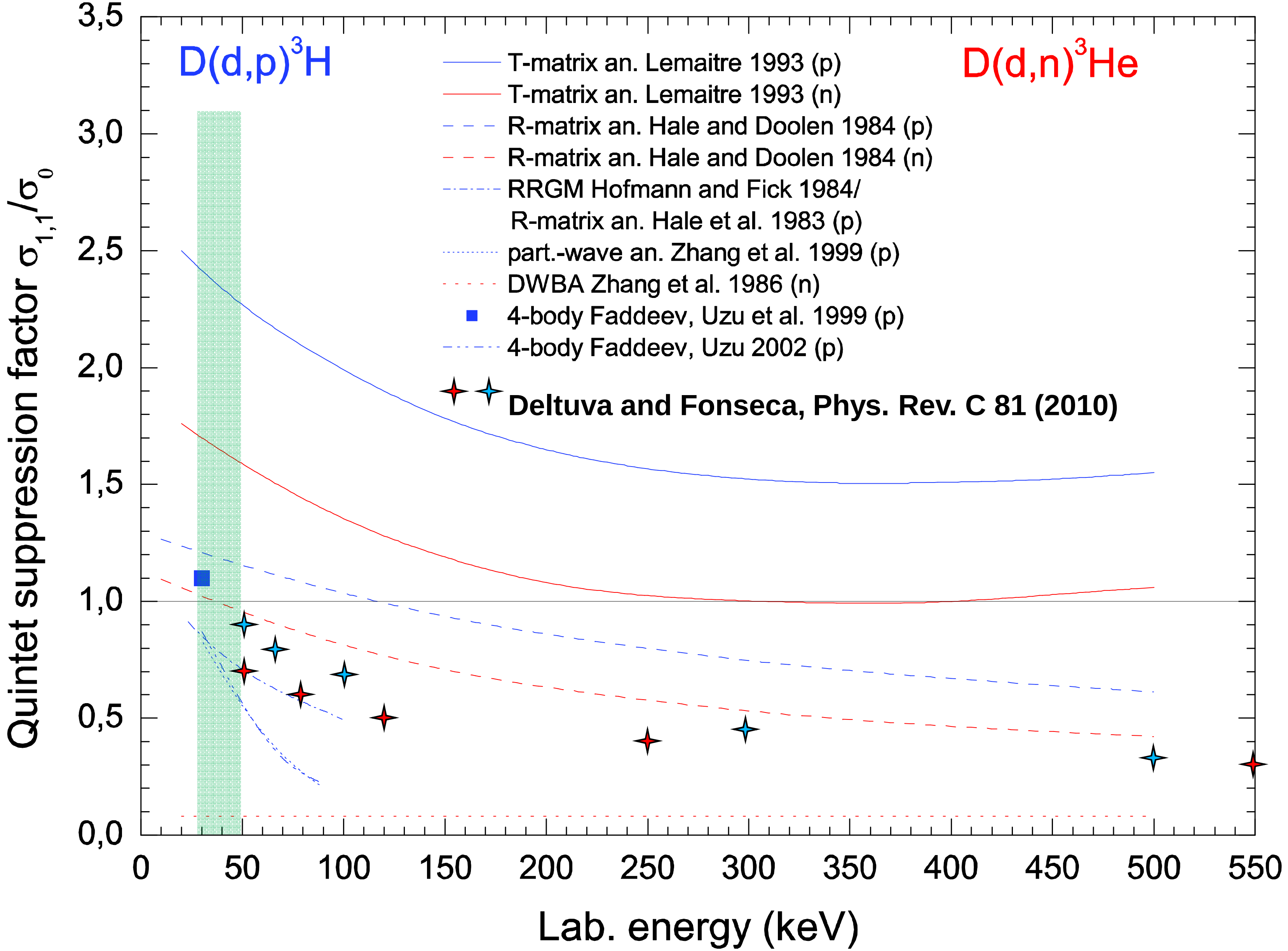
Spin 1 on Spin 1:

In general:
8 Analyzing Powers $A_{i(i)}$ and 32 Spin-Correlation Coeffizients $C_{i(i),i(i)}$

beam and target same particles:
4 Analyzing Powers $A_{i(i)}$ and 16 Spin-Correlation Coeffizients $C_{i(i),i(i)}$

Both spins are aligned:
$A_{zz}(\vartheta)$, $C_{z,z}(\vartheta)$, $C_{zz,zz}(\vartheta)$ are necessary

The Quintet suppression factor



The Experimental Setup in St. Petersburg

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Petersburg Nuclear Physics Institute (PNPI) of the Kurchatov Center in Gatchina
(A. Vasiliev et al.)

ABS from the SAPIS project:
(after upgrade)
~ 4 · 10^{16} a/s
→ ≈ 3 · 10^{11} a/cm^2

ABS from Ferrara:
6 · 10^{16} a/s
→ ≈ 2 · 10^{11} a/cm^2

Detector Setup:
4π covered by
- large pos. sens. Detectors
- (~400 single PIN diodes ?)

POLIS (KVI, Groningen)
Ion beam: I ≤ 20 μA

→ 1.5 · 10^{14} d/s
(E_{beam} ≤ 32 keV)

dd-fusion polarimeter (FZJ)

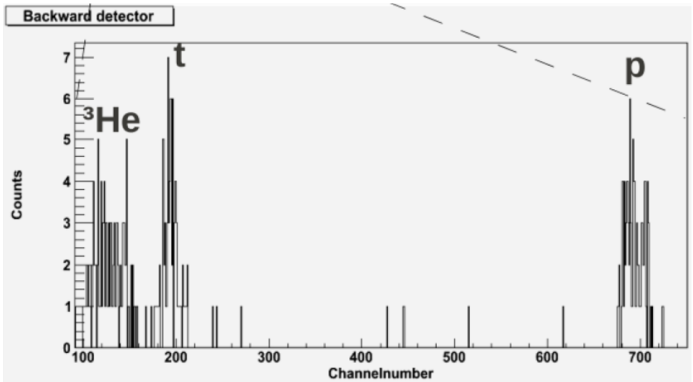
LSP from POLIS

Luminosity: 3.5 · 10^{25} /cm^2 s
Luminosity: 4 · 10^{25} /cm^2 s

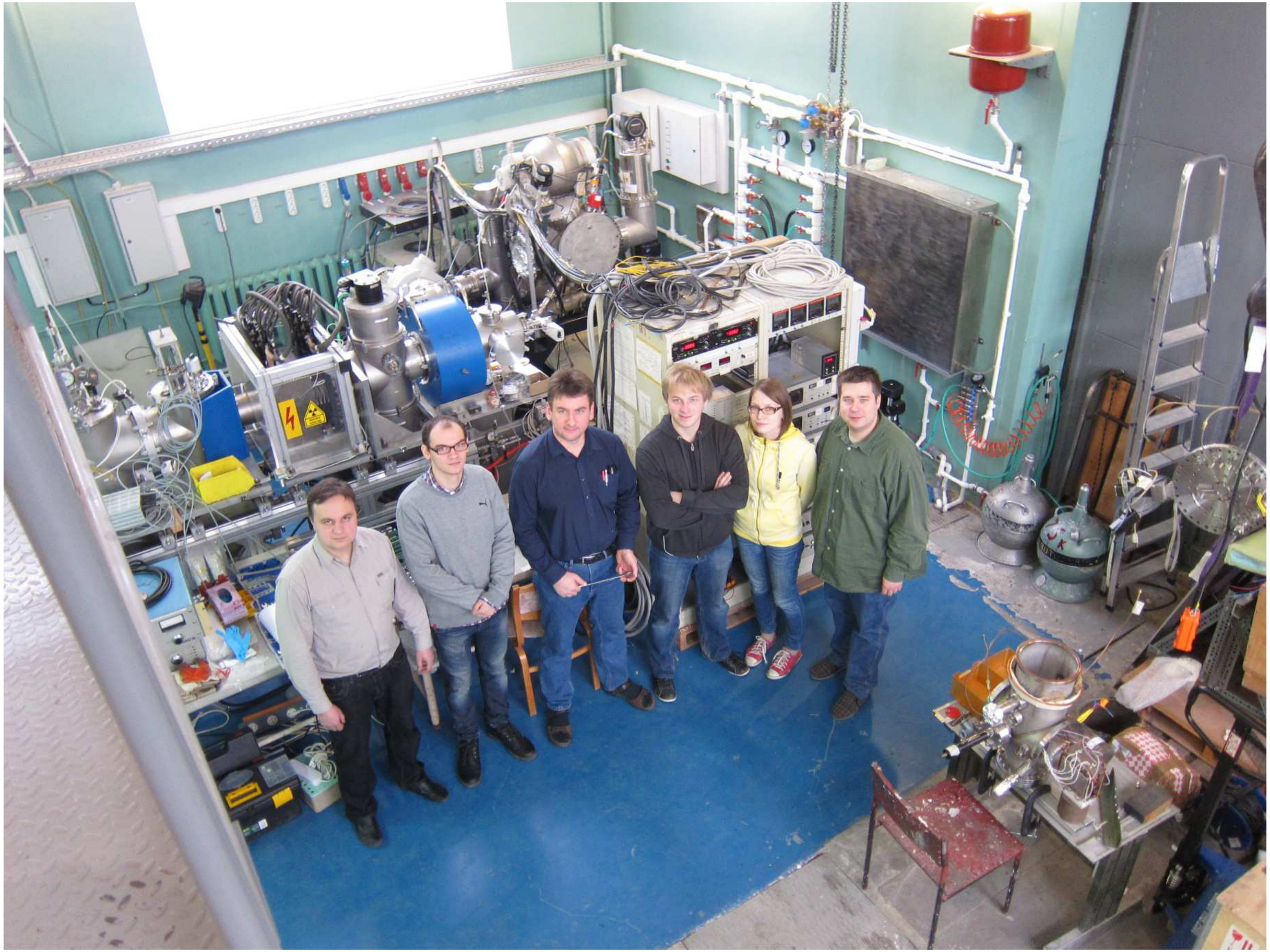
→ count rate: ~ 40 /h
→ count rate: ~ 60 /h

→ 1 month of beam time
→ 2 month of beam time

LSP from FZJ



The dd-Project at PNPI



Important Questions for Polarized Fusion

1.) Can the total cross sections of the fusion reactions be increased by use of polarized particles?

(TD and ^{3}HeD fusion: gain factor f: ~ 1.5 ↔ DD fusion: ????)

2.) Will polarization survive in a fusion plasma?

2. Will the polarization survive in a fusion plasma

Many Publications:

1.) Kulsrud, Goldhaber, et al.; Phys. Rev. Lett. **49**, 1248 (1982).
(-> Polarization should survive long enough in a Tokamak!)

2.) Greenside, et al.; J. Vac. Sci. Technol. A **2**(2), 619 (1984).
(-> Polarization losses during wall interaction
-> Patent on surface coating !!!!)

3.) Coppi et al.; Phys. Fluids **29**, 4060 (1986).
(Possible resonanzes with some plasma modes will destroy the nuclear polarization -> Polarization lifetime as analyser for these plasma modes !!!)

4.) S. Bartalucci, Contribution to „Nuclear Fusion with Polarized Fuel“, Springer Proceedings in Physics **187**, 2016. **(IGNITOR !!!)**

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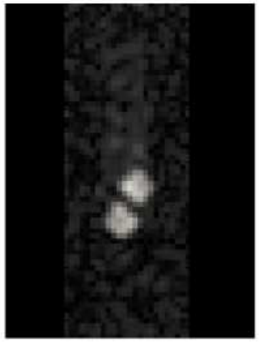
Actual Projects (Magnetic confinement):

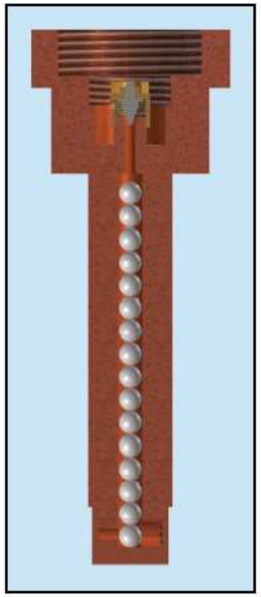
1.) Sandorfi et al.: Collaboration between Jlab, University of Virgina, Oak Ridge Lab. and the DIII-Tokamak

Idea: Fill the DIII tokamak with polarized ^{3}He and HD ice and measure the lifetime of the polarization in situ.

• 2 mm Ø ICF shells in a glass tube



• MRI scan of ICF shells filled with polarized ^{3}He, cooled to 77K to seal, ^{3}He outside removed



A.Sandorfi et al.; JLab-14727, arXiv:1703.06165 Springer Proceedings in Physics **187**, 2016.

^{3}He polarization inside ICF shells can be maintained for ~ 10 hr at 77 K

2. Will the polarization survive in a fusion plasma

Actual Projects (Inertial/laser-induced fusion):

2.) Didelez et al.: Laser on polarized HD ice

(J.P. Didelez, C. Deutsch; Laser Part. Beams **29**, 169 (2011))

3.) Büscher et al.: Collaboration of PGI and IKP at FZJ,
Uni. of Düsseldorf and Darmstadt

Idea: Ionize polarized ^{3}He gas with a laser to produce and to accelerate $^3He^{2+}$ ions (-> January 2018)

(Raab et al.; Phys. Plasmas **21**(2), 023104 (2014)
I. Engin et al.; Contribution to „Nuclear Fusion with Polarized Fuel“, Springer Proceedings in Physics **187**, 2016.)

Important Questions for Polarized Fusion

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1.) Can the total cross sections of the fusion reactions be increased by use of polarized particles?

(TD and ^{3}HeD fusion: gain factor f: ~ 1.5 ↔ DD fusion: ????)

2.) Will polarization survive in a fusion plasma?

(???? ↔ Must be tested for any kind of fusion reactor separately!)

3.) How to produce and how to handle polarized fuel?

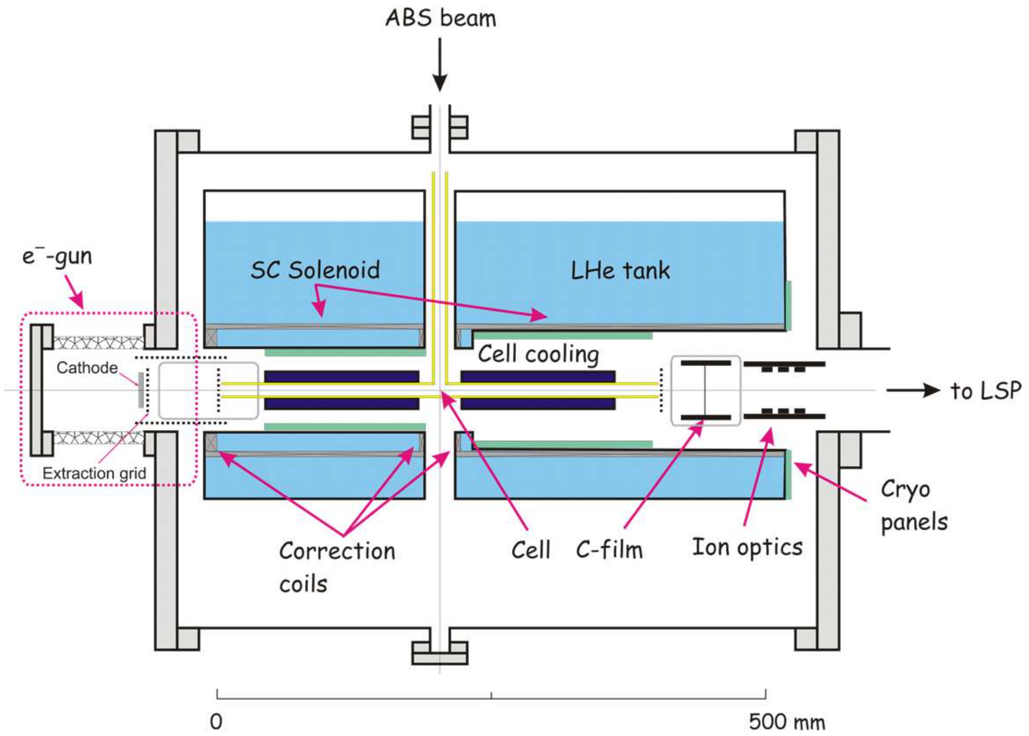
(3He: ☺ / Tritium: Polarization by „laser pumping“ / Deuterium: ???)

3.) How to produce and to handle polarized fuel

Idea: Polarized Deuterium from an ABS: **P > 0.9**

Problem: Intensity $< 10^{17}$ at/s ↔ Tokamak: $> 10^{22}$ at/s

Solution: Recombine the Deuterium atoms into molecules, which might be stored for a reasonable time.



3.) How to produce and to handle polarized fuel

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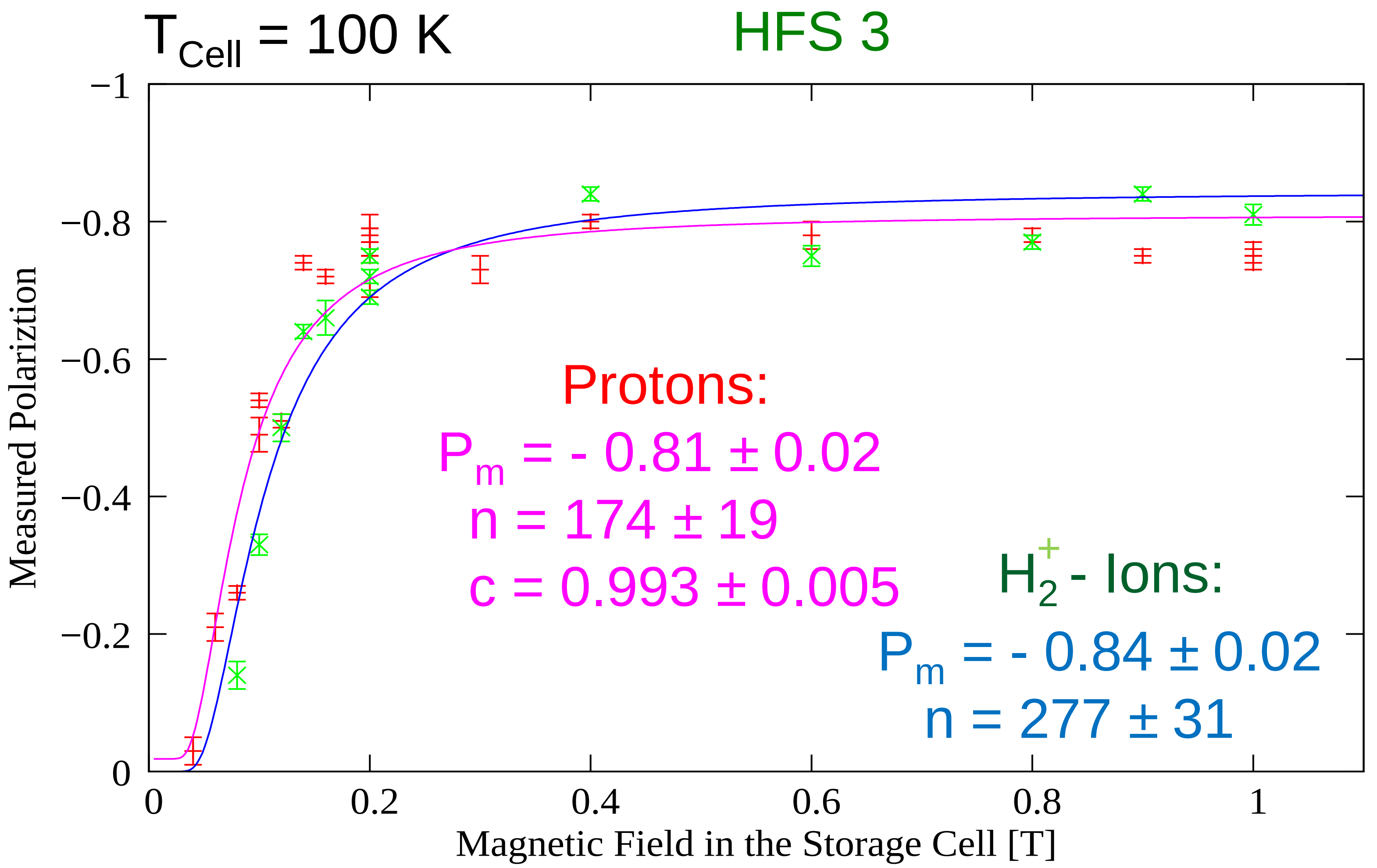
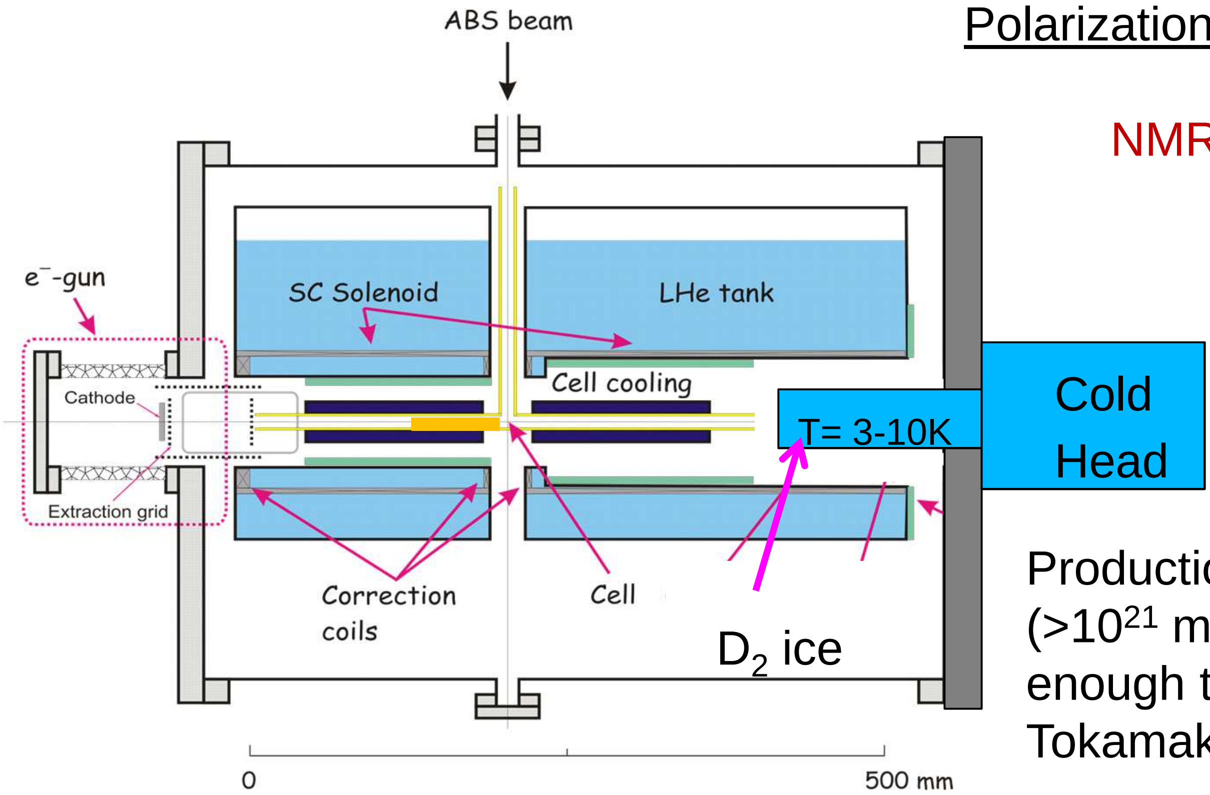
Measurements on Fomblin Oil (Perfluorpolyether PFPE)



R. Engels et al.; Phys. Rev. Lett. **115**(11),113007 (2015)

3.) How to produce and to handle polarized fuel



Polarization Measurement:

NMR – Sensor

Production of 1 day ($>10^{21}$ molecules) is enough to feed a Tokamak for seconds !!

We can produce H_2, D_2, and HD molecules with a large polarization of P > 0.8 !

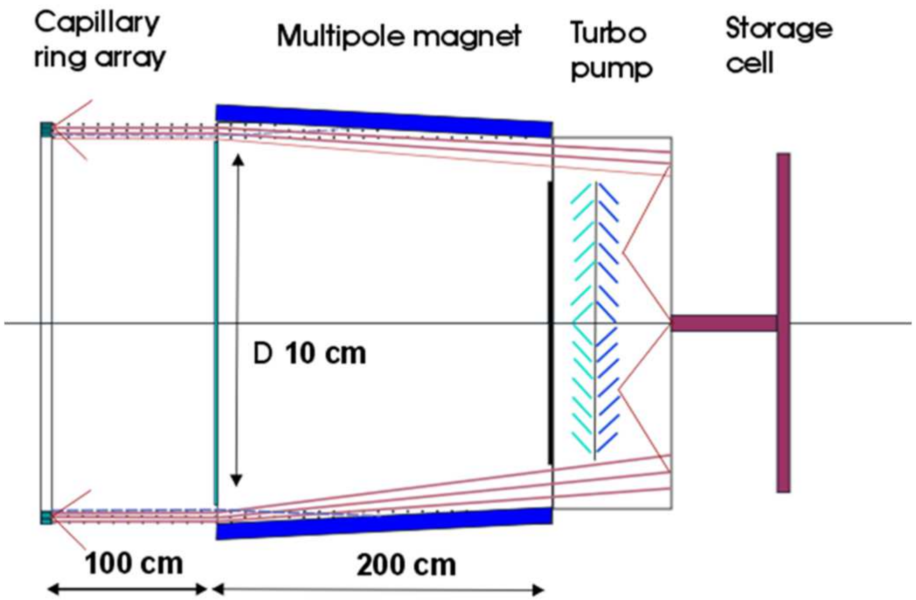
For HD any spin combination is possible !

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

A molecular beam source for polarized H_2 and D_2

Collaboration of the Budker Institut in Novosibirsk, the Uni. of Düsseldorf and the Research Center Jülich

Idea:



Joined Project
DFG <-> RSF

Modified superconducting ABS from BIN in combination with the LSP from FZJ

D. Toporkov et al.; JETP Letters **105**(5):289 (2017)

3.) How to produce and to handle polarized fuel

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

(Sofikitis et a.; Phys. Rev. Lett. **118**(23) (2017))

DI

D atoms → LSP of the Jülich Type

Laser-Excitation → **Dissoziation** → **Electron-Polarization = 1**

↓

Deuteron-Polarization ~ 2/3

Proof-of-prinziple experiment under discussion between the Uni. of Crete, IKP/PGI in FZJ and the MPI in Göttingen.

Polarized Fusion

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Other options:

New Publication: (May 2017)

H. Khanzadeh and M. Mahdavi, Contr. to Plasma Phys. **57**, 209 (2017)
„Investigation of the particle spin properties on the
velocity space instability in high-density plasmas“

Idea: Weibel-like instabilities are suppressed with polarized electrons in the plasma.

Coming:

Electron-screening with polarized electrons and deuterons

Conclusion

Due to technical development of polarized sources and targets in nuclear physics the production of **polarized fuel** for any kind of fusion reactors seems to be in range! This will create new options for coming fusion reactors.

(increased cross section ↔ focusing of the neutrons)

The long-missing spin-dependent cross sections for the **dd reactions** are underway.

What is missing is the measurement of the polarization lifetime for different reactors (mag. confinement ↔ inertial)

(Jlab + DIII are on the run!)

Workshop: Polarized Fuel for Fusion

2./3. October 2017 in Ferrara

(INFN and Unife of Ferrara)

http://www.fe.infn.it/polfusion/2017/