The PREFER collaboration/projects

Giuseppe Ciullo INFN & University of Ferrara
on behalf of the collaboration

PREFER
Polarization Research for Fusion Experiments and Reactors

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
A. A. Vasilyev et al.	PNPI – NRC KI @ Gatchina
D. Toporkov	BINP @ Novosibirsk
T.P. Rakitzis et al.	IESL-FORTH & University @ Crete

Outlook of the presentation

- Fusion with polarized fuel.
- The PREFER collaboration/projects:
  - DD spin dependent studies (PNPI/FZJ/FE).
  - Production of polarized fuel from pABS, and its handling (FZJ / PNPI/ FE).
  - Filtering of hyperpolarized molecules from MBS (BINP/HHUD).
  - A new method of Laser QB excitation and UV dissociation (IESL/FZJ/HHUD).
  - Laser Induced Plasma: production, acceleration and fusion (PGI- FZJ/HHUD).
- References more than conclusions.

Fusion of Nuclear Polarized Fuel

From the point of view of the nuclear physics, the use of **polarized fuel** seems the viable way in order to fulfill nuclear fusion for energy production thanks to:

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

But practical use is still far away, mainly due to still open questions and requirements:

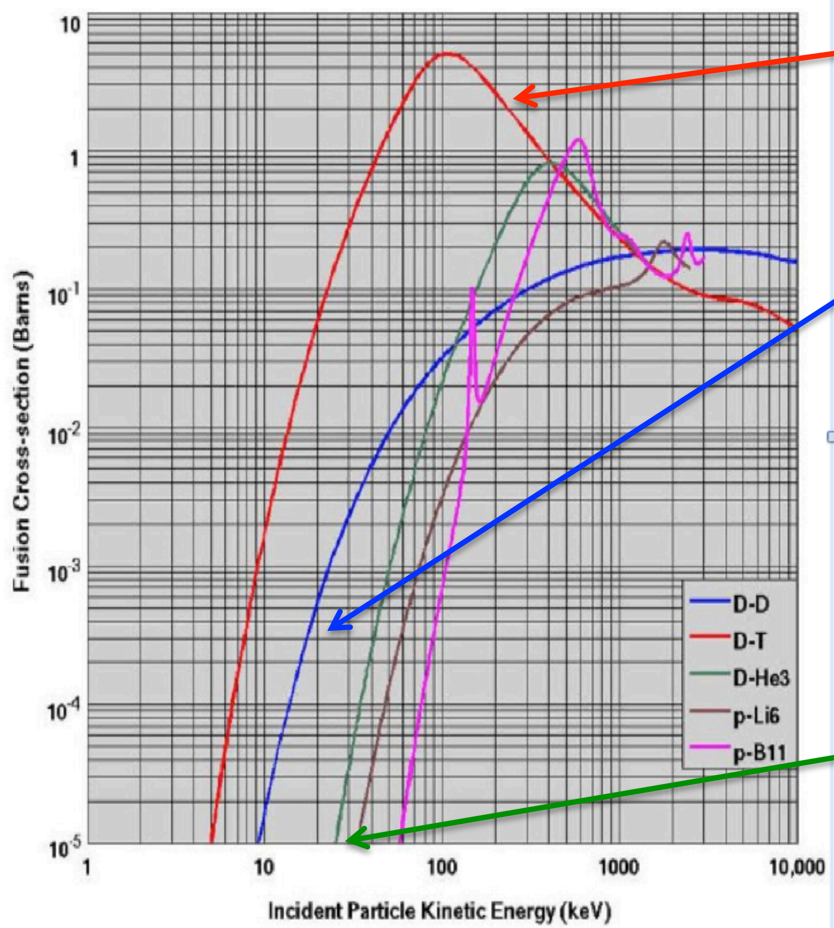
- polarized fuel, high polarization and high density (few orders of magnitude **higher than available** as nuclear polarized targets).
- **Preparation** of fuel for magnetic confinement or inertial confinement.
- **Survival** of polarized fuel in the fusion reactors or in inertial confinement.

It's a **challenging** deal providing **useful polarized fuel** for the purpose of testing in present (… future) **FUSION** environments and **by product gain in "better" targets**.

G. Ciullo et al. *Nuclear Fusion with Polarized Fuel* - Springer Proc. in Phys. **187** (2016)

Nuclear Fusion with Polarized Fuel

Reaction generations sorted according to the relative energy (temperature) required for nuclear fusion.



1. Generation: D + T → ^{4}He + n

1.a) Increase of total cross section!

1.b) differential cross section: angular distrib. *f(θ)* therefore better control!!

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.?

Still missing data for a complete description.

2.c) Possibility to suppress the reactio ^{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 → ^{3}He + n suppressed

Missing data on **DD spin dependent** reactions.

Missing polarized fuel for fusion tests.

Challenging objectives of PREFER

Orbiting projects sorted by labs/inst.s

PGI-FZJ & HH UD
LIP acc., prod., fusion

PNPI Gatchina
DD pol fusion σ

INFN-UniFe
Handling Pol. Fuel

IESL-FORTH Crete
Polarized Beam
From laser prep and diss.

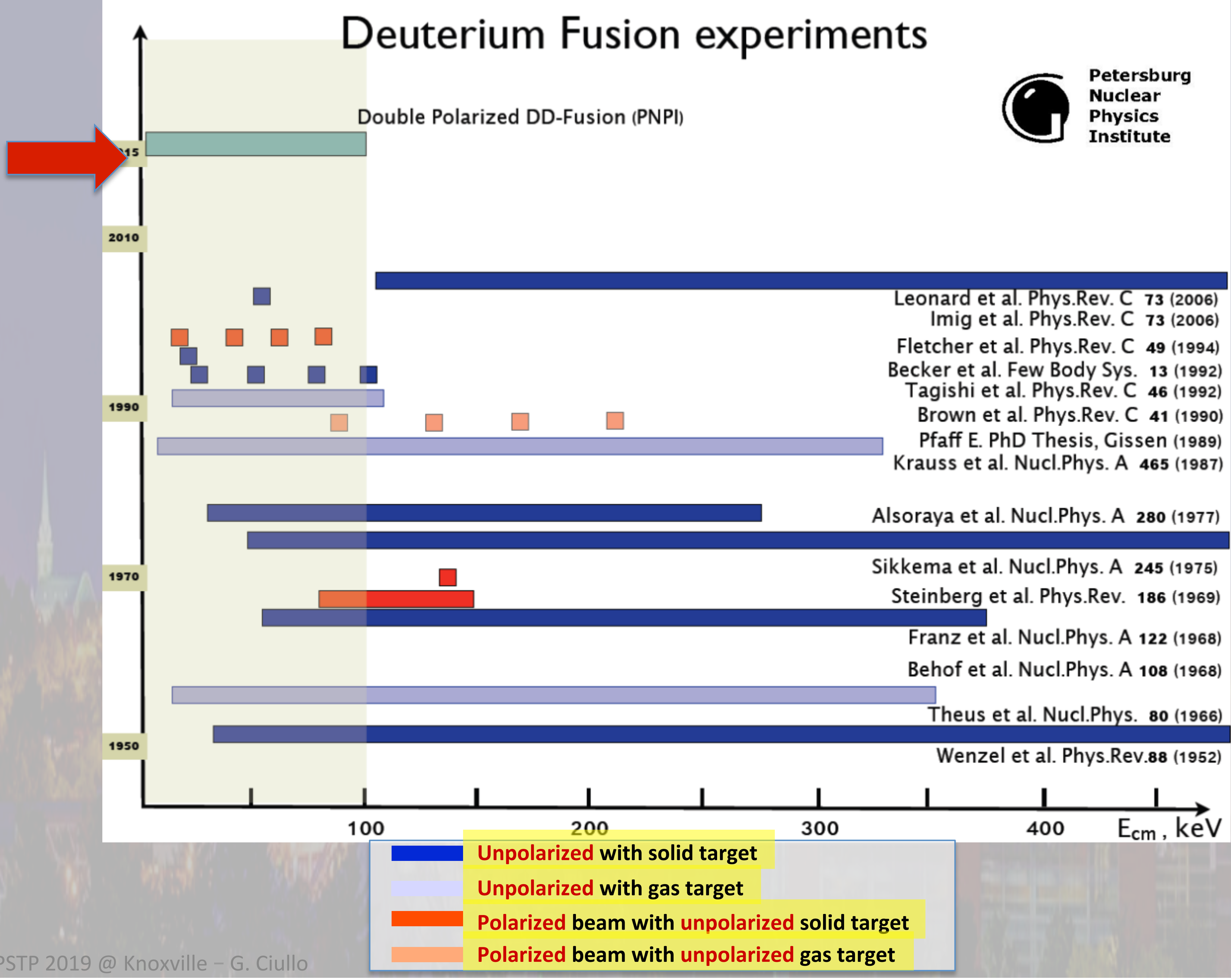
IKP-FZJ
hyperPol. Molecules from ABS.

BINP
hyperPol. Molecules From MBS

Outlook of the presentation

- ❖ *DD spin dependent studies (PNPI/FZJ/FE).*

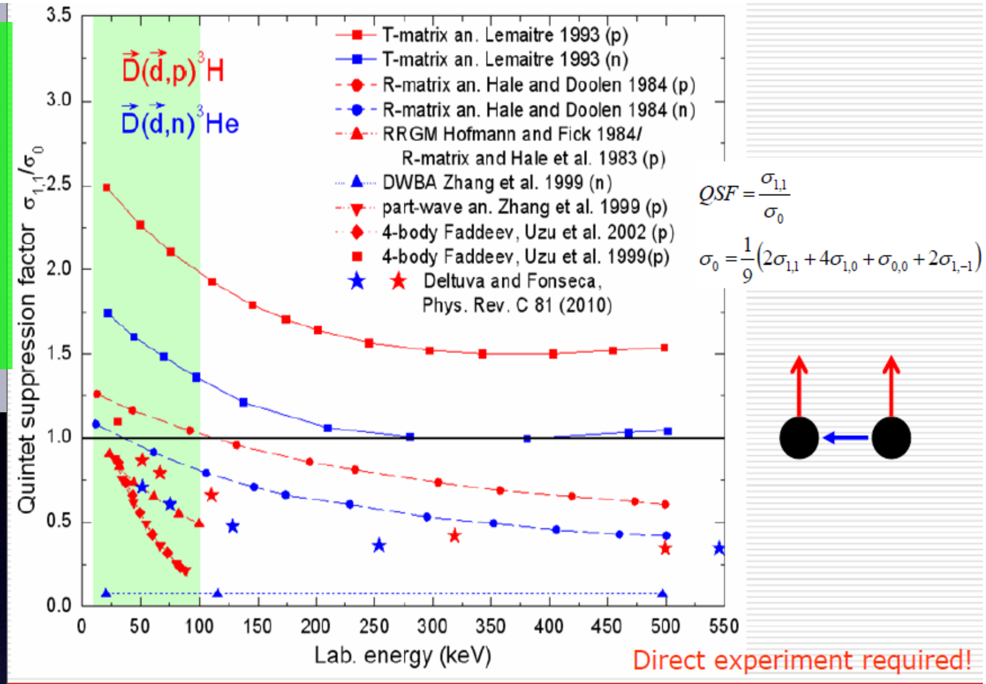
DD-double polarized data are missing



Direct access to basic data for theories & models …

$^3He^{2+}$ ($^3H^+$)

Petersburg Nuclear Physics Institute



$$QSF = \frac{\sigma_{1,1}}{\sigma_0}$$

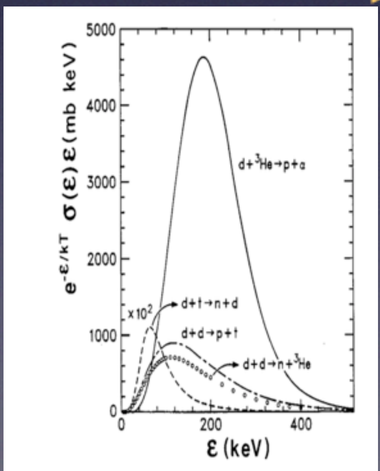
$$\sigma_0 = \frac{1}{9}\left(2\sigma_{1,1} + 4\sigma_{1,0} + \sigma_{0,0} + 2\sigma_{1,-1}\right)$$

Direct experiment required!

$\vec{d}^0$ (0.1 keV) → $\sigma_0 = \frac{1}{9}(2\sigma_{1,1} + 4\sigma_{1,0} + \sigma_{0,0} + 2\sigma_{1,-1})$ ← $\vec{d}^+$ (30 – 100 keV)

Quintet **Triplet** **Singlet**

… not only for fusion.



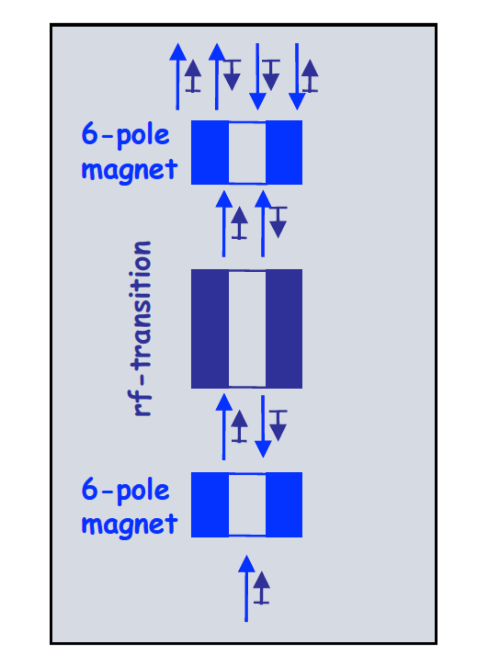
P. Kravchenko in http://prefer.lkst.ru/agenda.php (06/2019)

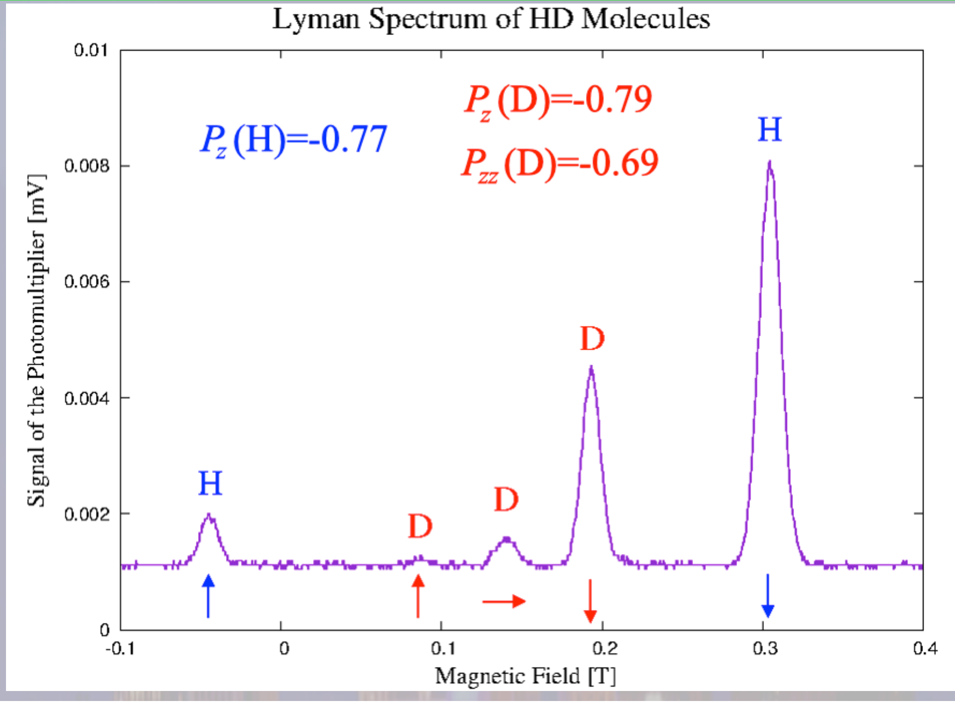
$n(p)$

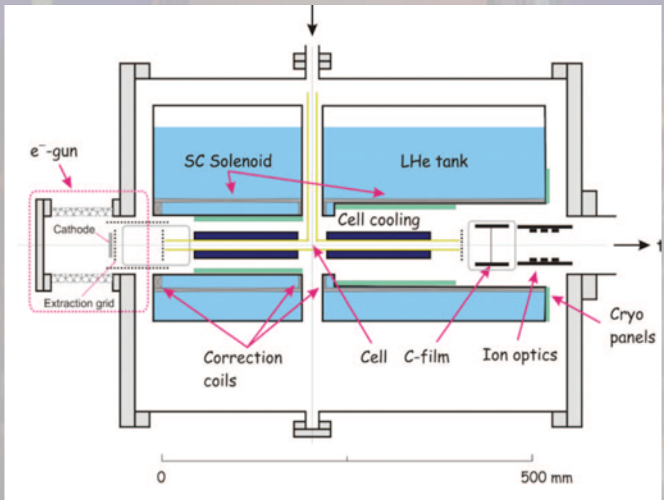
Outlook of the presentation

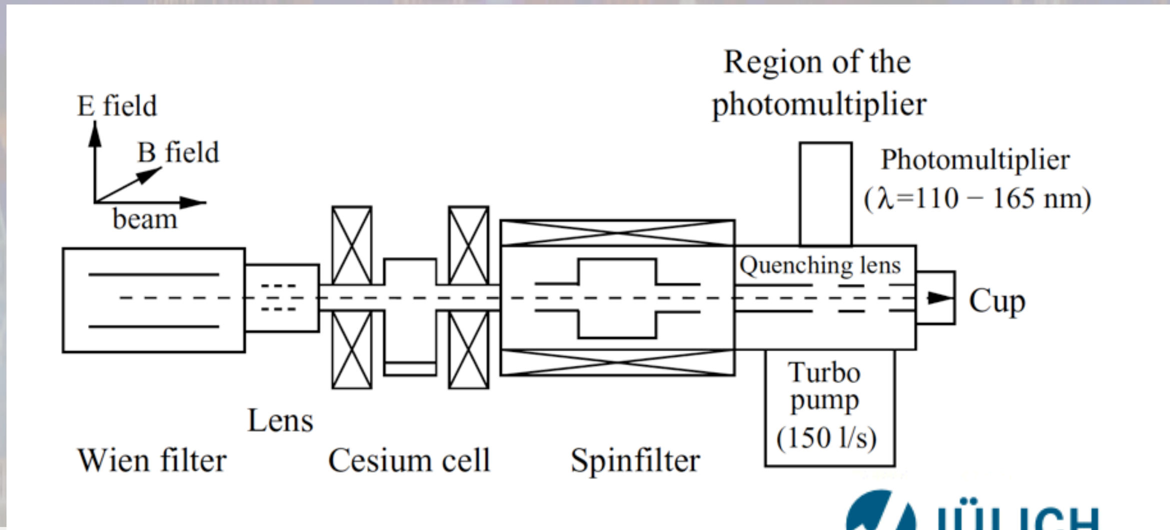
- ❖ *Production of polarized fuel from pABS, and its handling (FZJ / PNPI/ FE).*

Hyperpolarized molecules from pABS







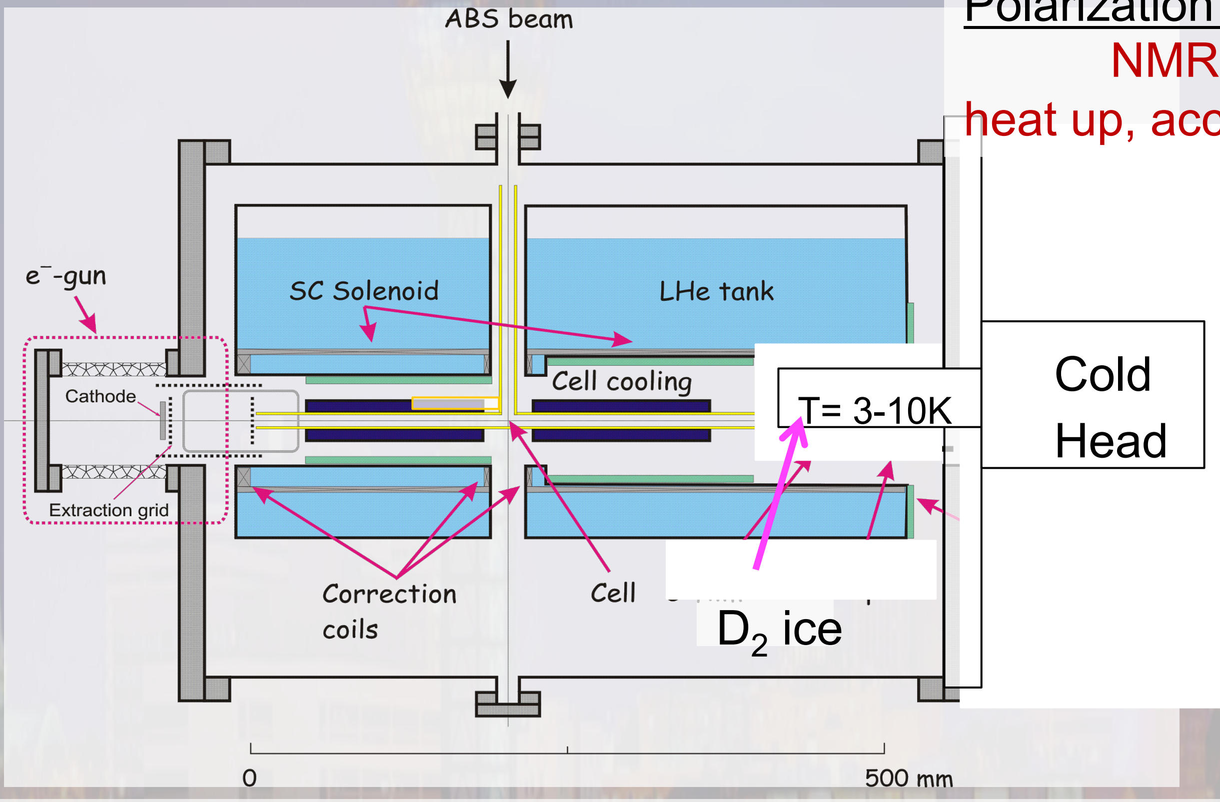


k. Grigoryev in http://prefer.lkst.ru/agenda.php (06/2019)

JÜLICH FORSCHUNGSZENTRUM

Condensation & transp. of pol. fuel

Polarization Measurement:
NMR – Sensor?
heat up, accel., measure with LSP?



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

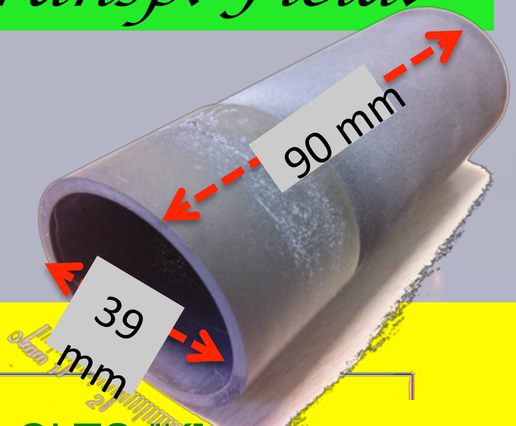
We can produce $\mathcal{H}_2$, $\mathcal{D}_2$, and $\mathcal{HD}$ molecules with a large polarization of P ~ 0.8 ! For $\mathcal{HD}$ any spin combination is possible !

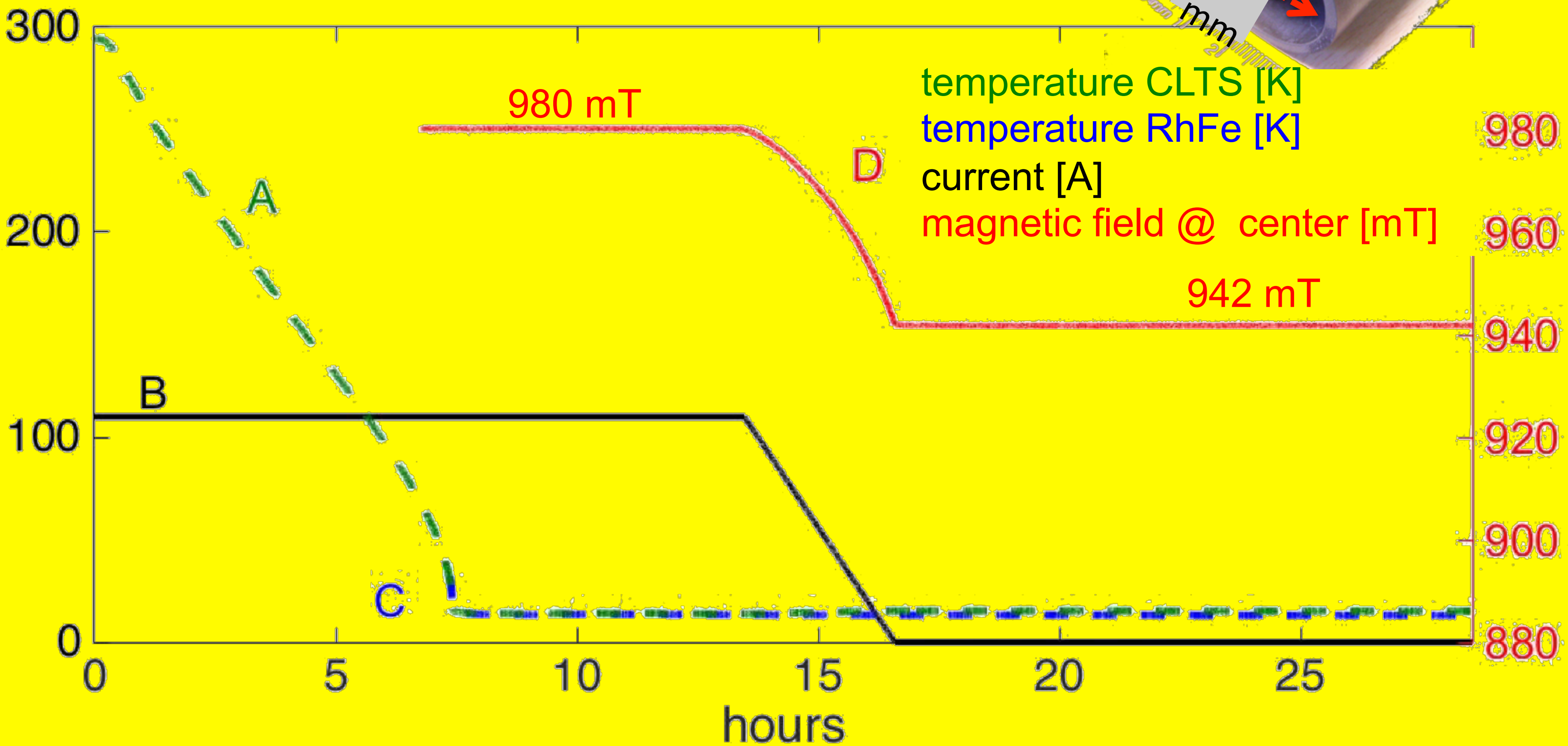
$\mathcal{HD}$ is a perfect training ground for the handling of TD !

The condenser will be surrounded by a SC MgB_2 cylinder, which allows to provide the holding field during transportation.

SC MgB_2 Magnet: holding and transp. Field.

Field Cooling -> Field Trapping
cool down about 7.5 hours
temperature 13 K
resistive magnet ramp: 0.25 A each 4 s

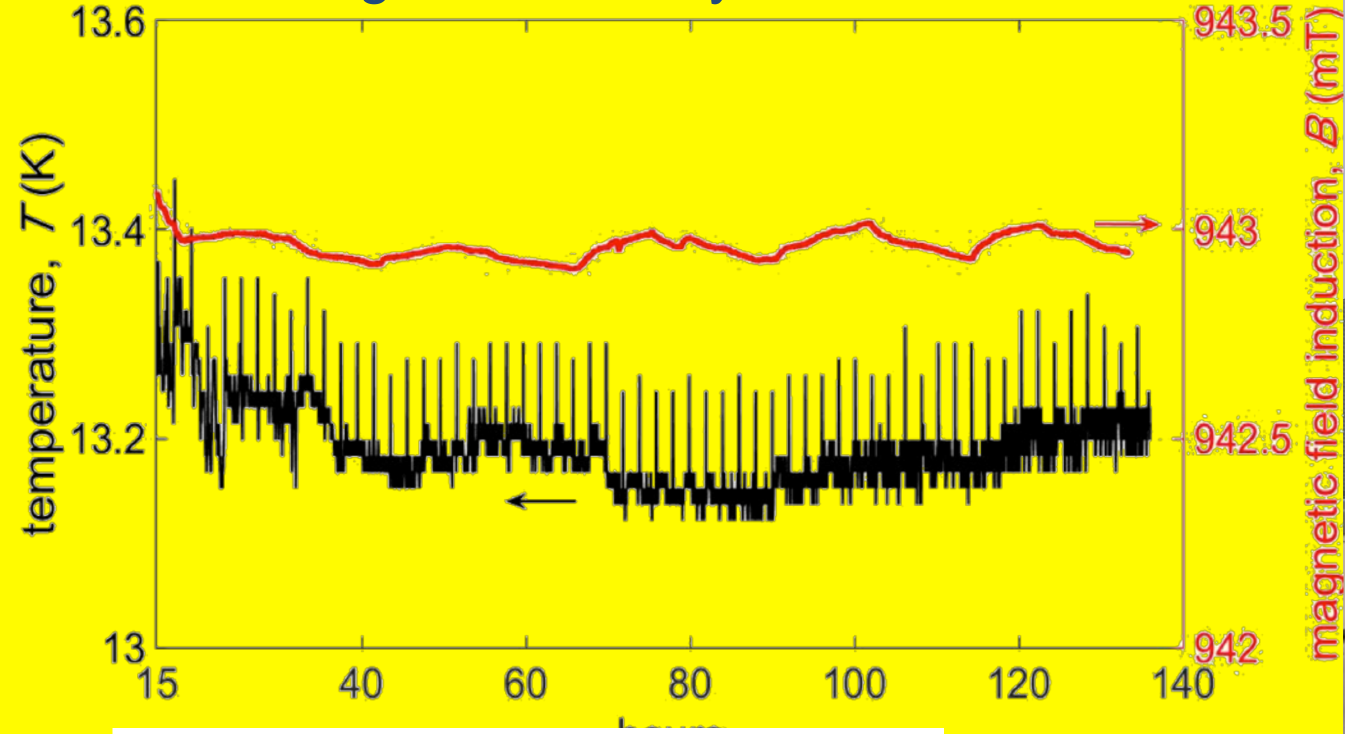


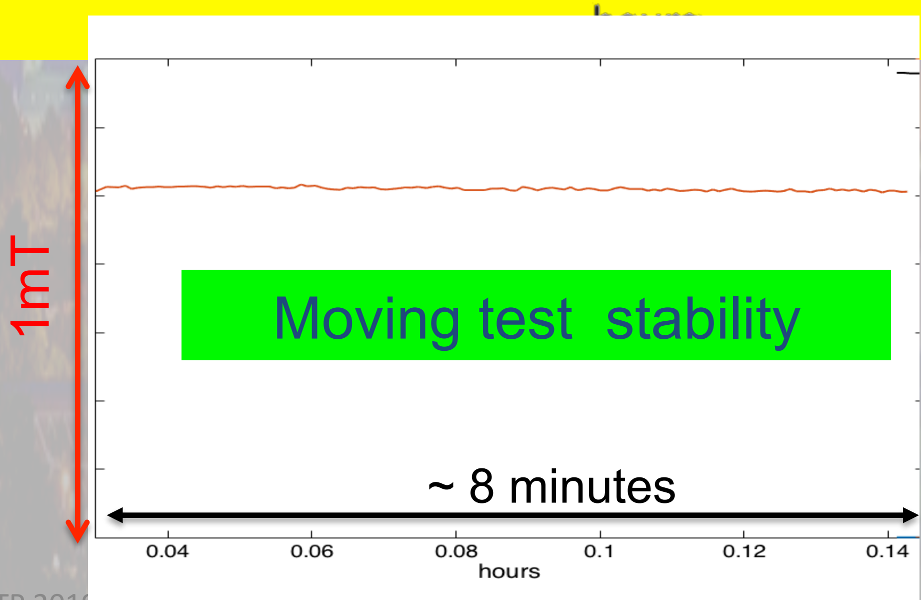


G. Ciullo in http://prefer.lkst.ru/agenda.php (6/2019)

Statera et al . NIM A **882** (2018) 17

Long term stability





Moving test stability

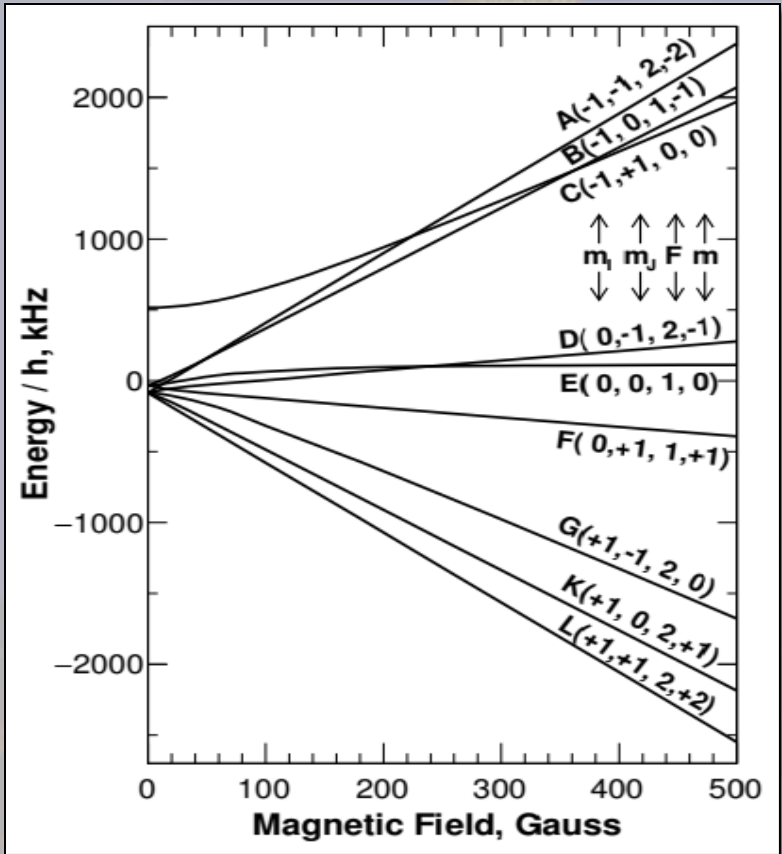
Tested at temperature 13.6 K
field 565 mT

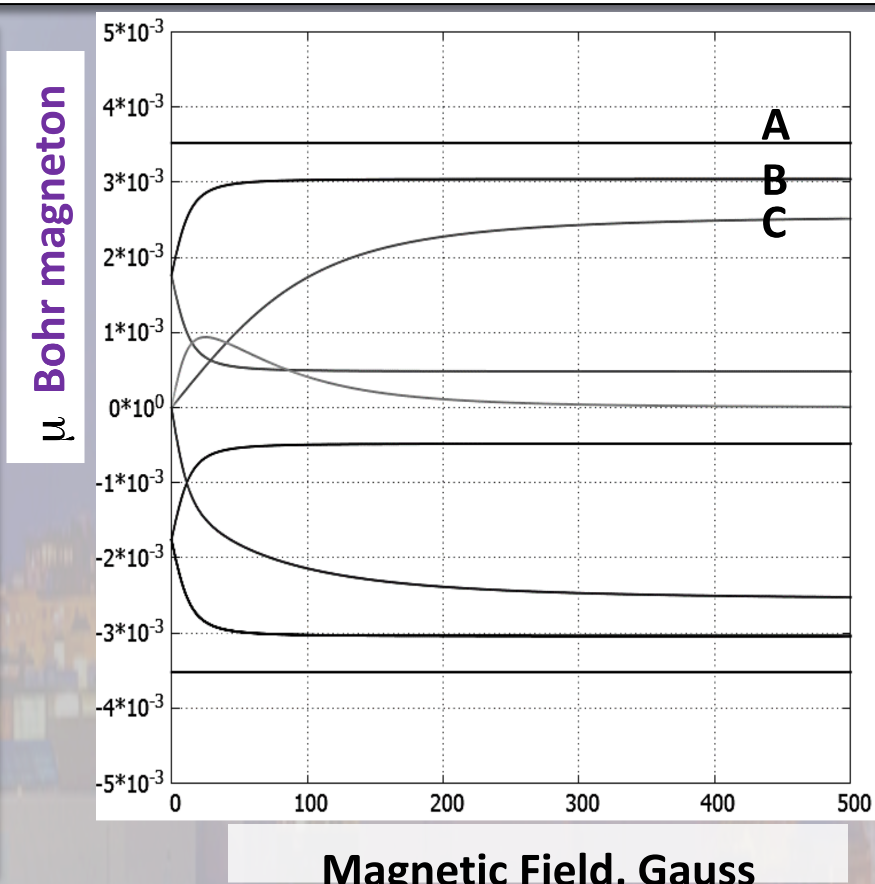
Outlook of the presentation

❖ *Filtering of hyperpolarized molecules from MBS (BINP/HHUD).*

SC ABS → MBS for filtering hyp-pol. mol.

Energies of H_2 states as a function of magnetic field.

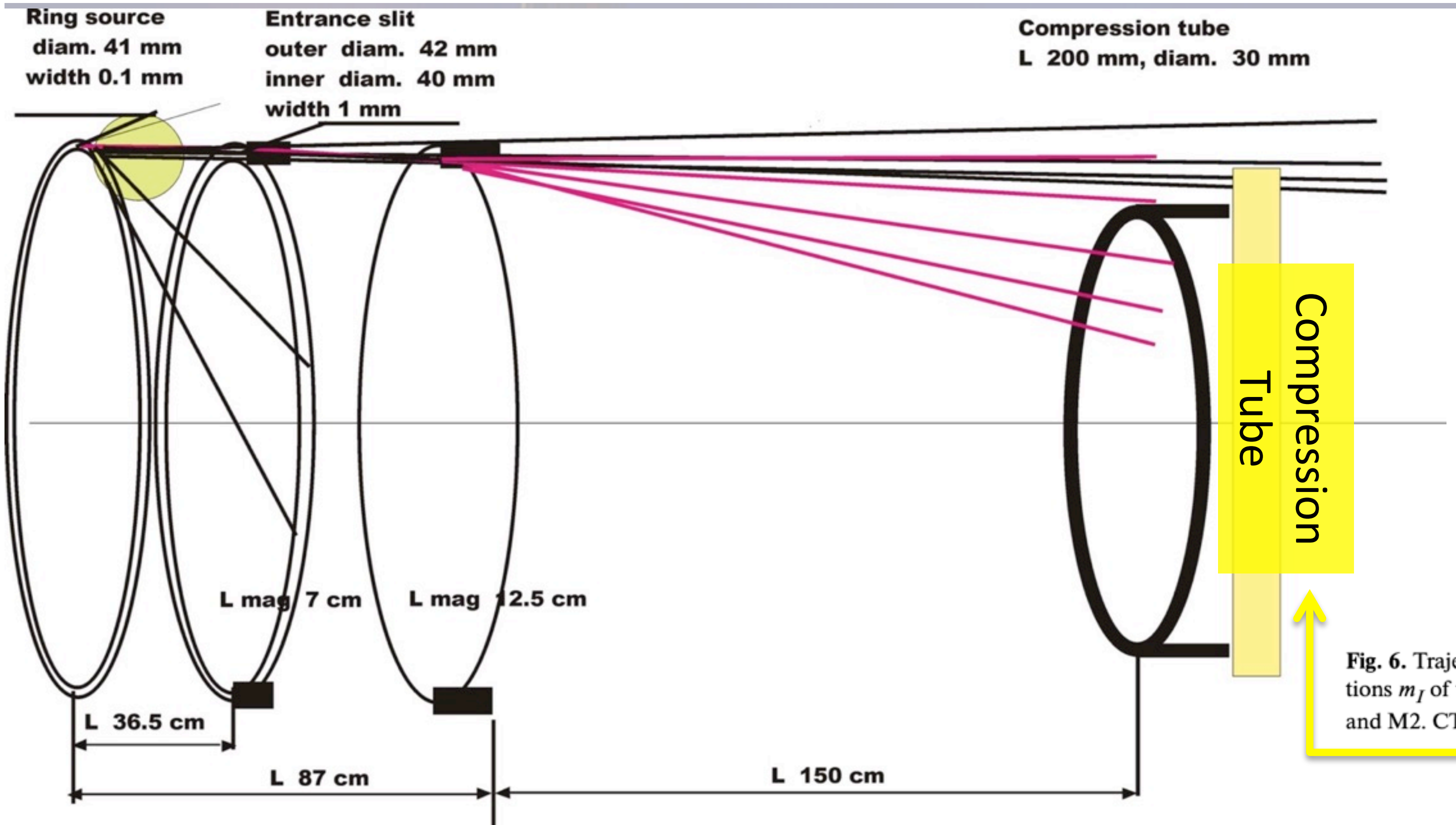




Only molecules in the states A, B, C with m_I=-1, focused by the field can enter the Compression tube (CT).

Budker Institute of Nuclear Physics

D. Toporkov in http://prefer.lkst.ru/agenda.php (6/2019)



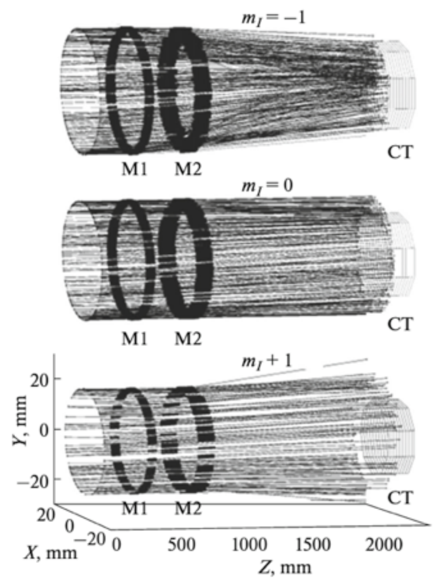


Fig. 6. Trajectories of H_2 molecules with different projections m_I of the nuclear spin passing through magnets M1 and M2. CT is the compression tube.

an inline LSP,
is in operation
to measure the
nuclear polarization

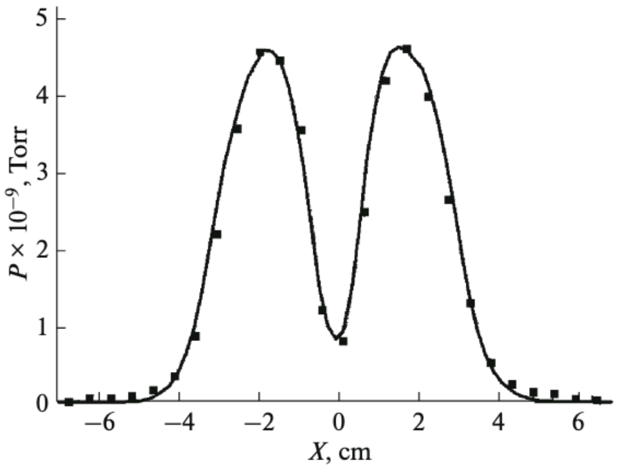


Fig. 7. Measured dependence of the pressure in the CT (squares) on its position. The curve represents the results of computer simulations.

Yu. V. Shestakov *et al*.
Phys. Part. Nucl. **50** (2019) 513.

Outlook of the presentation

- *A new method of Laser QB excitation and UV dissociation (IESL/FZJ/HHUD).*

Excite QB and dissociate with UV

FORTH Foundation for Research & Technology - Hellas

JÜLICH FORSCHUNGSZENTRUM

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

Sofikitis et a.; Phys. Rev. Lett. **118** (2017) 233401.

Pulsed Nozzle

DI

D atoms → LSP of Jülich Type

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

↓

Deuteron-Polarization ~ 2/3

(Proton-Polarization = 1)

Proof-of-principle experiment under study (Uni. of Crete/FORTH, IKP/PGI in FZJ/HHUD).

C. Kannis in http://prefer.lkst.ru/agenda.php (6/2019)

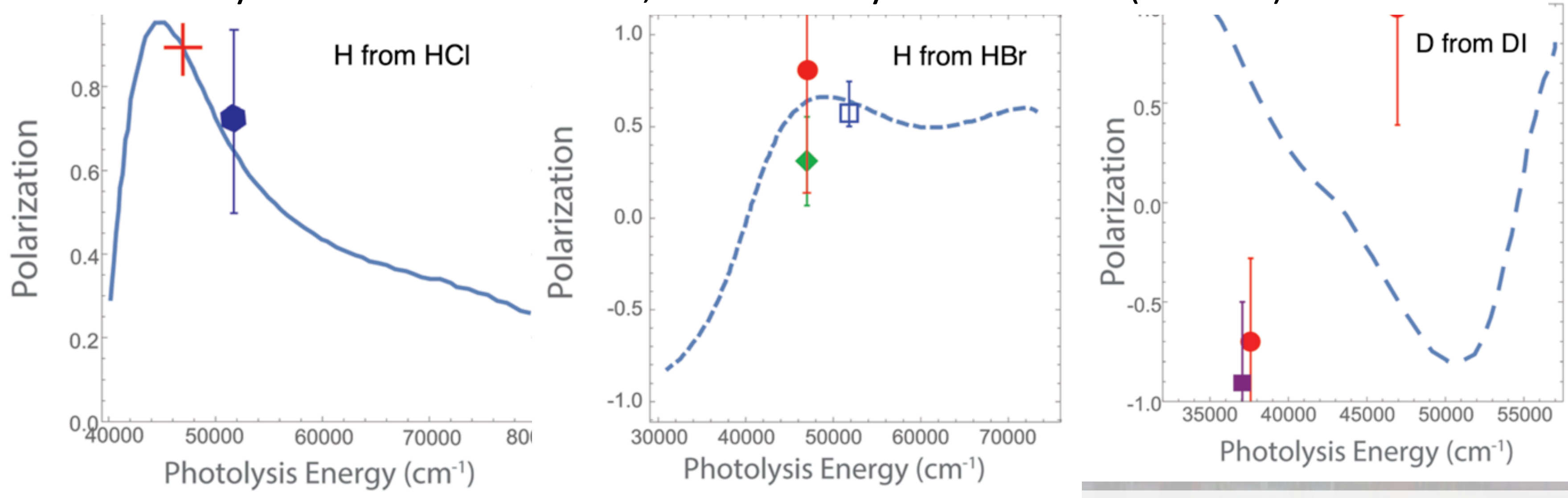
Comparison: ABS and UVD

Comparison of spin polarized hydrogen obtained from atomic beam source (the most intense) and UV dissociation

	BNL ABS	UV dissociation (Crete)
Density of SPH (cm^{-3})	10^{12}	10^{19}
Intensity (s^{-1})	10^{16} (continuous)	10^{22} (pulsed)
Polarization	0.92	0.42 (0.90 attaiinable)

The intensity is correlated to the number of impinging photons, one photon -one proton the for laser source of 10^{22} photons! s^{-1}.

a Excitation by 1026 nm 10^{14} W cm-^{2}, Ionization by 5th harmonic (213 nm) 10^{12} W cm^{-2}

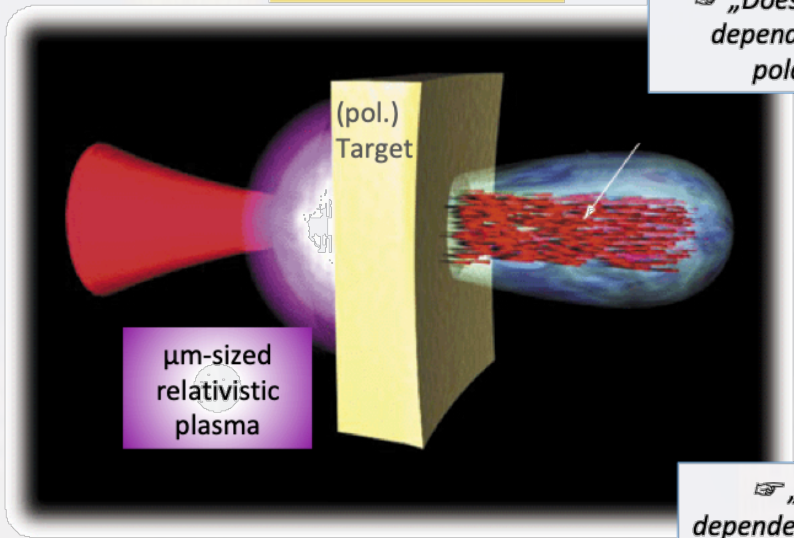


D. Sofikitis et al. Phys. Chem. Chem. Phys. **21** (2019) 14000.

Outlook of the presentation

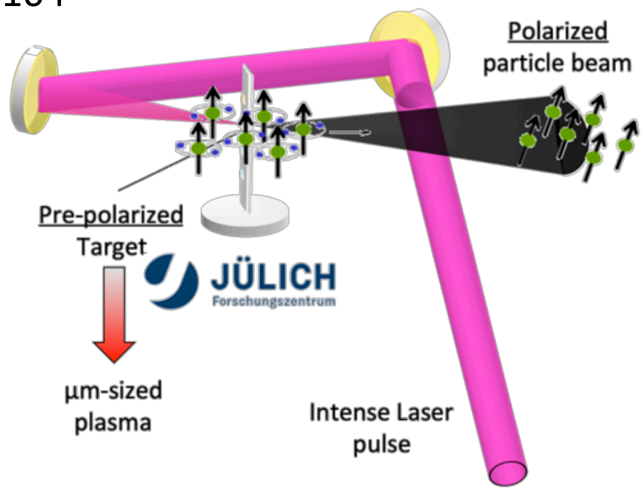
- ❖ *Laser Induced Plasma: production, acceleration and fusion (PGI- FZJ/HHUD).*

LIP production, diagnosis and fusion test



Heinrich Heine Universität Düsseldorf

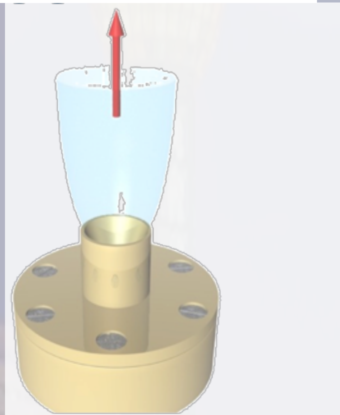
Polarimetry available: N. Rab et al. Phyisics of Plasma **21** (2014) 023104



M. Büscher in http://prefer.lkst.ru/agenda.php (6/2019)

Polarized beams from LIP

Polarized He beams
From compresse polarized ^{3}He



Output pressure: 50 bar

Input pressure: 3 bar

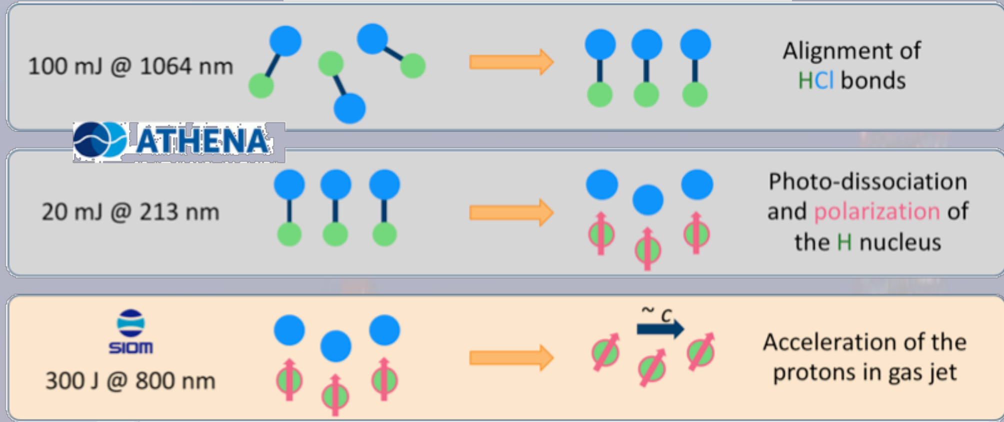
c o m p r e s s o r

Laser-induced Acceleration of ^{4,3}He Ions for a spin-polarized Ion Source

Ilhan Engin,[1,a)] Markus Büscher,[1,2,b)] Oliver Deppert,[3,c)] Laura Di Lucchio,[4] Ralf Engels,[5] Pavel Fedorets,[1] Simon Frydrych,[3] Paul Gibbon,[6] Annika Kleinschmidt,[3] Andreas Lehrach,[5,7,8] Rudolf Maier,[5] Dieter Prasuhn,[5] Markus Roth,[3] Friederike Schlüter,[1,c)] Claus M. Schneider,[1] Thomas Stöhlker,[9,10,11] and Katharina Strathmann[1,c)]

in preparation.

polarized proton beams
From LIP



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.

Deuterium Polarized Molecules
From MBS
or
From recombined molecules
from ABS: HD too.

Outlook of the presentation

- Fusion with polarized fuel.
- The PREFER collaboration/projects:
  - DD spin dependent studies (PNPI/FZJ/FE)
  - Production of polarized fuel from pABS, and

- References more than conclusions.

PREFER Workshop in Gatchina, 04-06 June 2019

Most recent References:

http://prefer.lkst.ru/agenda.php

10:30 Ralf Engels
"Advantages of nuclear fusion with polarized fuel"

11:00 Markus Buesher
"Nuclear polarization in Laser-induced plasmas"

12:00 Giuseppe Ciullo
"A movable magnetic holding field for HD-ice targets, easily implementable for hyper-polarized molecular targets for fusion research"

12:30 Polina Kravchenko
"Experimental studies of nuclear fusion reactions at PNPI"

14:00 Ivan Solov'ev
"Improvement and optimization of the Atomic Beam Source as part of the Polarized Ion Source in the experiment PolFusion"

14:30 Guillaume Hupin
"Ab Initio Description of Thermonuclear Fusion Reactions"

10:30 Dmitriy Toporkov
"Test of Lamb Shift polarimeter for molecular source"

11:00 Erhard Steffens
"Design considerations of a polarized gas target for the LHC"

12:00 Kannis Chrysovalantis
"High-density spin-polarized H and D atoms for studies of polarized laser-fusion"

12:30 Kirill Grigoryev
"Production and storage of polarized H2, D2 and HD molecules"

14:00 Feodor Karpeshin
"Preparation of polarized targets through radiationless excitation of the nuclei by negative muons"

14:30 Valery Tyukin
"Status of the polarized atomic hydrogen target at MAMI & MESA"

One year ago references:

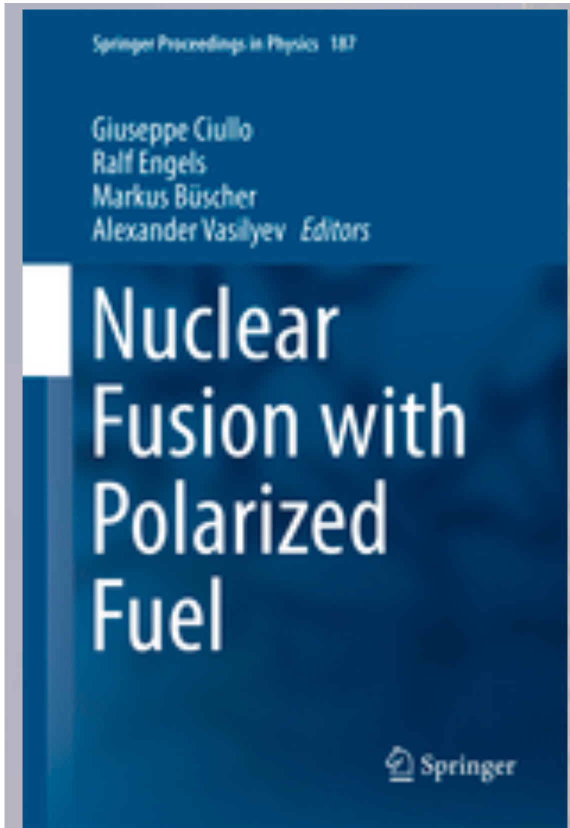
Presentations @ https://agenda.infn.it/event/12464/

	Advantages of Nuclear Fusion with Polarized Fuel	Dr Ralf Engels	A11, Polo degli Adelardi - Via Adelardi, 33	14:30 - 15:05
15:00	THE STATUS OF THE DOUBLE POLARIZED DD-FUSION EXPERIMENT	Dr Polina Kravchenko	A11, Polo degli Adelardi - Via Adelardi, 33	15:05 - 15:30
	Status of polarized molecular source	Prof. Dmitriy Toporkov	A11, Polo degli Adelardi - Via Adelardi, 33	15:30 - 15:45
16:00	End of Session		A11, Polo degli Adelardi - Via Adelardi, 33	15:45 - 16:10
	Optical excitation of molecules for Spin-Polarized Nuclear Fusion	Prof. T. Peter Rakitzis	A11, Polo degli Adelardi - Via Adelardi, 33	16:40 - 17:05
17:00	Nuclear Polarization in Laser-induced Relativistic Plasmas	Prof. Markus Büscher	A11, Polo degli Adelardi - Via Adelardi, 33	17:05 - 17:30
	Progress toward spin-polarized fusion: Performance of laser-polarized He-3 during permeation into tokamak pellets	Mr Sina Tafti		
18:00	General relativity experiment with frozen spin rings	Andras Laszlo	A11, Polo degli Adelardi - Via Adelardi, 33	17:55 - 18:20

Proceedings available online @
https://pos.sissa.it/346/

PROCEEDINGS OF SCIENCE

23rd International Spin Physics Symposium



Detailed references (fusion people involved).

Proceedings of the 1st and 2nd Workshops held respectively in Trento (2013) and in Ferrara (2015)

Springer Proceedings in Physics 187
Springer Verlag 2016

… in conclusion

WE PREFER YOU JOIN OUR EFFORTS

Polarization Research for Fusion Experiments and Reactors

Integral and differentiaal cross-section for spin 1 and 1/2 (angular distribution of reaction products)

In purely S-wave approx *f* =1, *B* along *z*, *(θ) respect to B (z)*

$$\frac{d\sigma(\theta)}{d\Omega}=\left(1+\frac{1}{2}P_{zz}^{D}A_{zz}+\frac{3}{2}P_{z}^{D}P_{z}^{T}C_{zz}\right)\frac{d\sigma(\theta)}{d\Omega}_{unpol}$$

- A_{zz} *tensor* analysing power A_{zz}= - [3 (cos^2 (θ) -1]/2
- C_{zz} spin correlation coefficient C_{zz}= - 3 [cos^2 (θ) -2]/2

In the d t reaction with d and t polarized parallel to B

$$\sigma_{tot}=1.5\sigma_{unpol}$$

$$\frac{d\sigma(\theta)}{d\Omega}=\frac{9}{4}\sin^2\theta\,\frac{d\sigma(\theta)}{d\Omega}_{unpol}$$

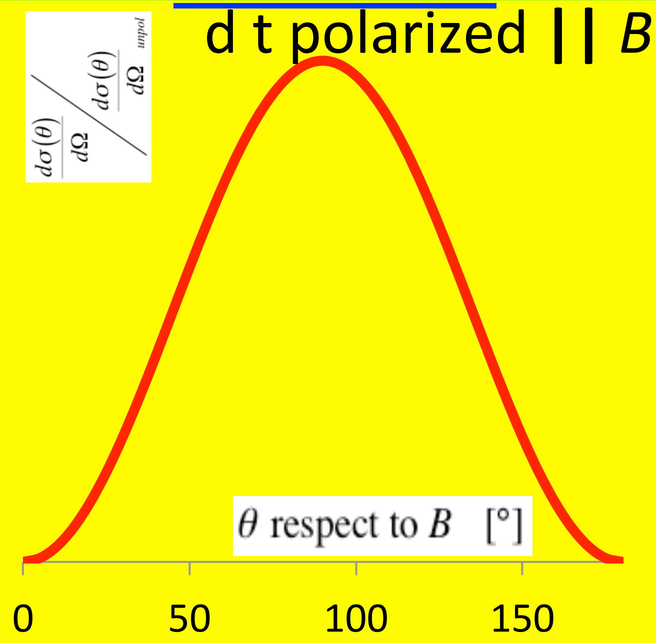
In the case of only d polarized perpendicular to B

$$\sigma_{tot}=\sigma_{unpol}$$

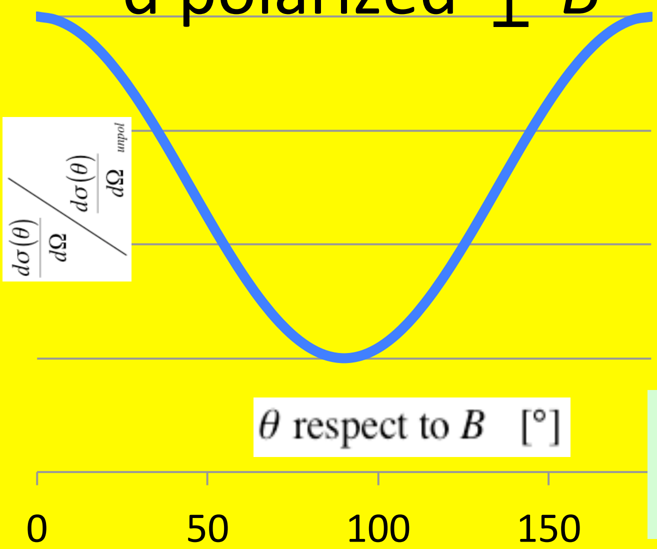
$$\frac{d\sigma(\theta)}{d\Omega}=\frac{1}{2}(1+3\cos^3\theta)\frac{d\sigma(\theta)}{d\Omega}_{unpol}$$

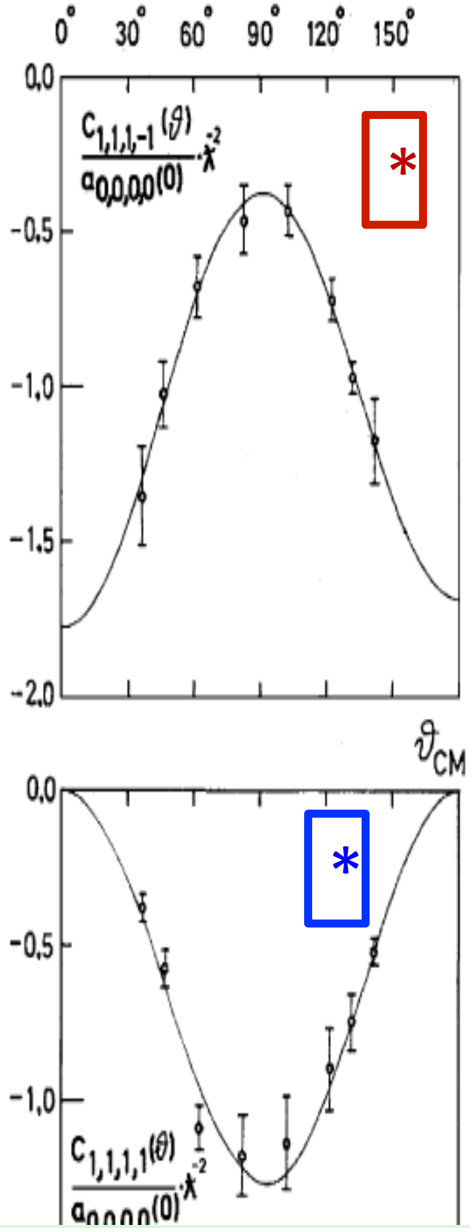
Calculation

d t polarized || *B*



d polarized ⊥ *B*





Experiments

- D and T spin || to the confinement field:

  α and *n* emitted as $\sin^2 \theta$ respect to *B*

* D spin ⊥ to the confinement field and T unpolarized: no influence on cross section, but the reaction products follow $(1+3\cos^2 \theta)$.

Confirmed on mirror reaction $^3He(d,p)^4He$
[Ch. Leeman et al Helv. Phys. Acta **44** (1971) 141]

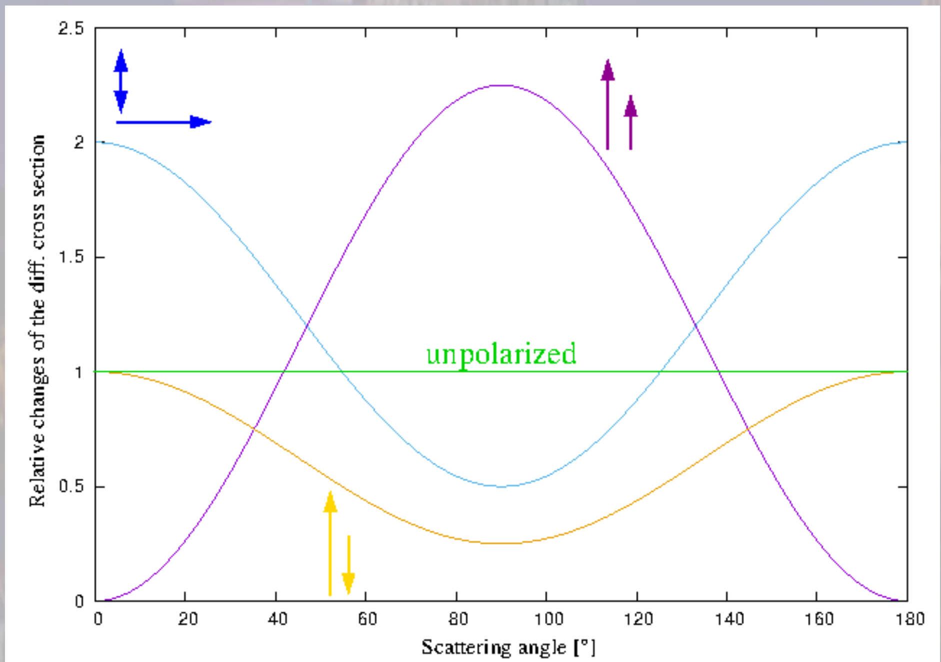
For spin 1/2 & 1 proved experimentally

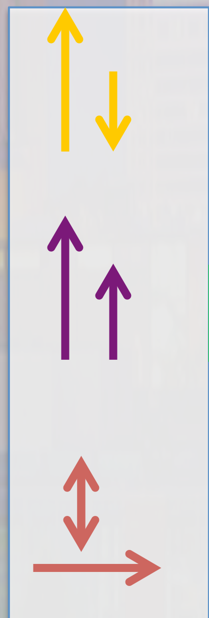
$^{3}\vec{He} + \vec{d} \longrightarrow {^{4}He} + p$ Factor: ~1.5 at 430 keV

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

$\vec{t} + \vec{d} \longrightarrow {^{4}He} + n$ Factor: ~1.5 at 107 keV

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





Factor 0.5

Factor 1.5

Factor 1

Gain in σ

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

2nd

D + D → T + p 50% (no n)
→ ^{3}He + n 50%(*)

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:

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

Hjgher energy for fusion involes also P-, D-wave, togheter with S-wave and their interferences

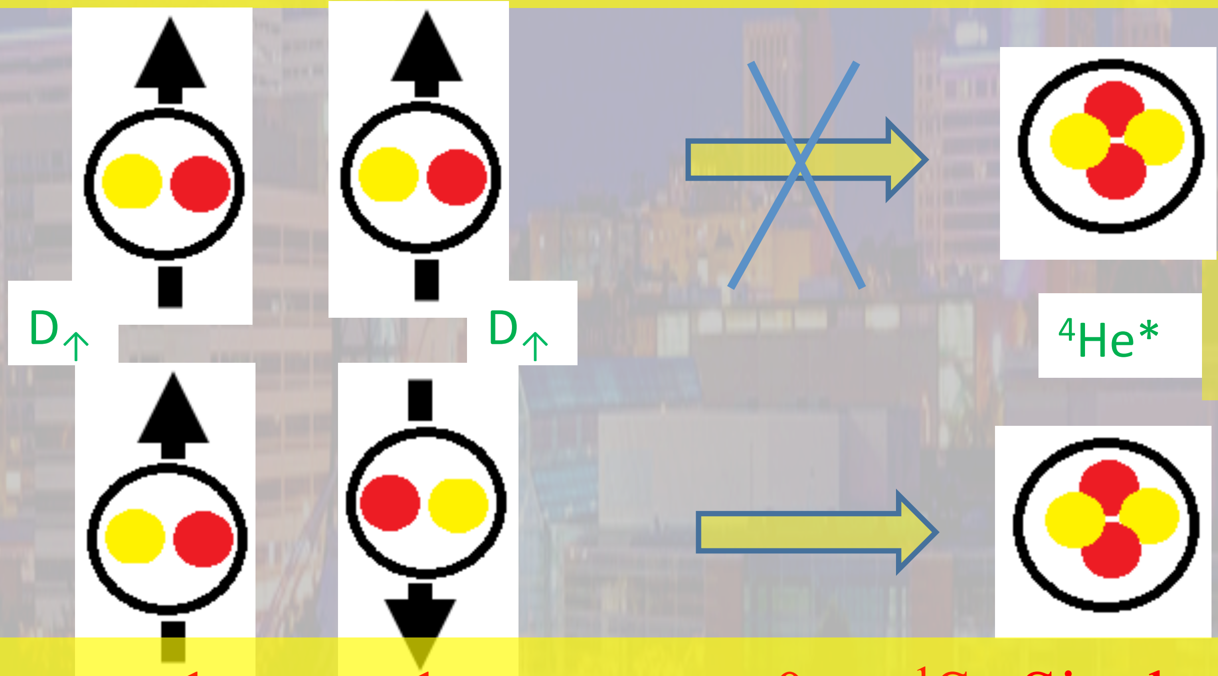
$D_{\uparrow} + D_{\uparrow}$ spin dependent cross section (**data set very poor**), and stilll **worse** at **lower energy** (e^- screening ?)

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

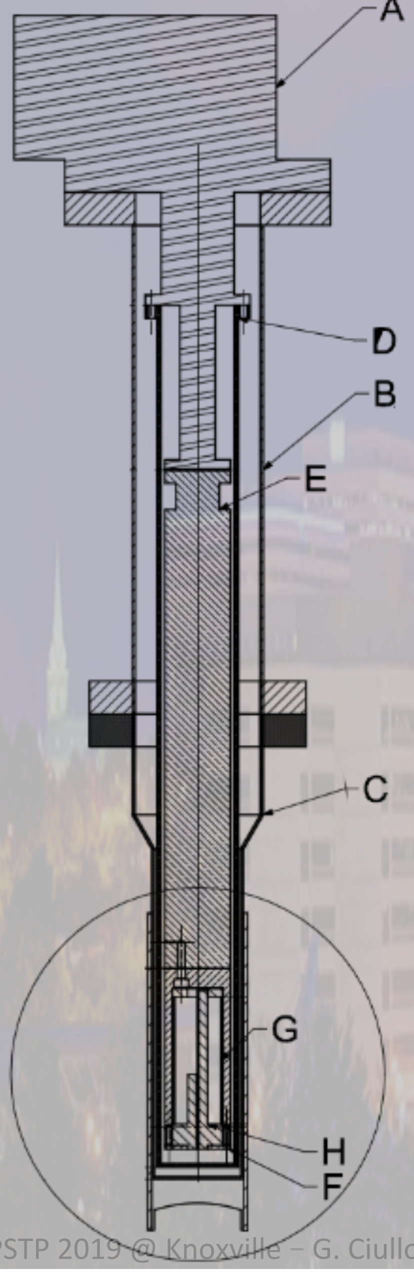
S 1 1 0 $^5S_2$ Quintet State Suppressed



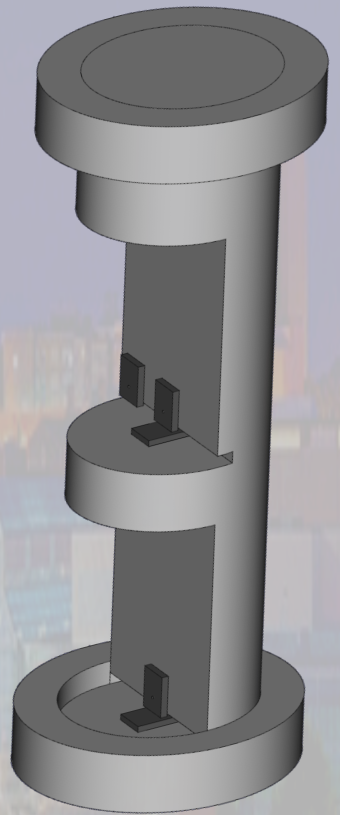
$$\frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{singlet}}{3/9\sigma_{singlet}} = 3$$

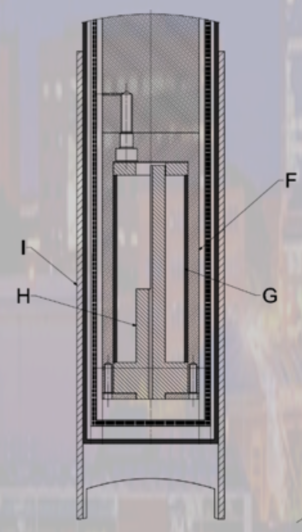
S 1 -1 0 $^1S_0$ Singlet state allowed

Upgrading MgB_2 magnet measurements



Mapping the field in the Cylinder, tranversely and longitudinally.





Expected energy of the beam from LIP

INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES	10 TW	*Electrons*
Dusseldorf ARCturus LASER FACILITY	100 TW	*Protons (MeV)*
PHELIX	1 PW	*Protons, ions (10 MeV)*
SIOM	10 PW	*Protons (GeV)*

M. Büscher in http://prefer.lkst.ru/agenda.php (06/2019)