The PREFER collaboration/projects

Giuseppe Ciullo & University of Ferrara
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
A. A. Vasilyev et al.	PNPI – NRC KI @ Gatchina
D. Toporkov	BINP @ Novosibirsk
T.P. Rakitzis et al.	IESL-FORTH & University @ Crete
M. La Cognata	INFN-LNS

1

Outlook of the presentation

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

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3

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.

Its use is still far away, mainly due to open questions:

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

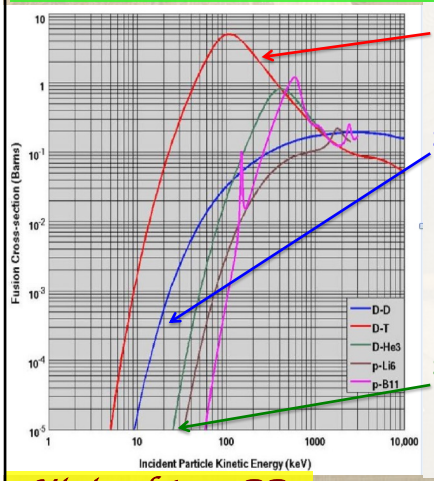
It's a ***challenging deal*** providing ***polarized fuel*** for the purposes of testing it in ***FUSION*** environments, but ***by product we'll gain in "better" targets.***

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

4

Nuclear Fusion with Polarized Fuel

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



1. **Generation: D + T → ^{4}He + n**
   - 1.a) Increase of total cross section!
   - 1.b) differential cross section: angular distrib. $f(\theta)$ 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 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 → ^{3}He + n suppressed

Missing data on DD spin dependent reactions.

Challenge objectives for PREFER

Missing polarized fuel for fusion tests.

5

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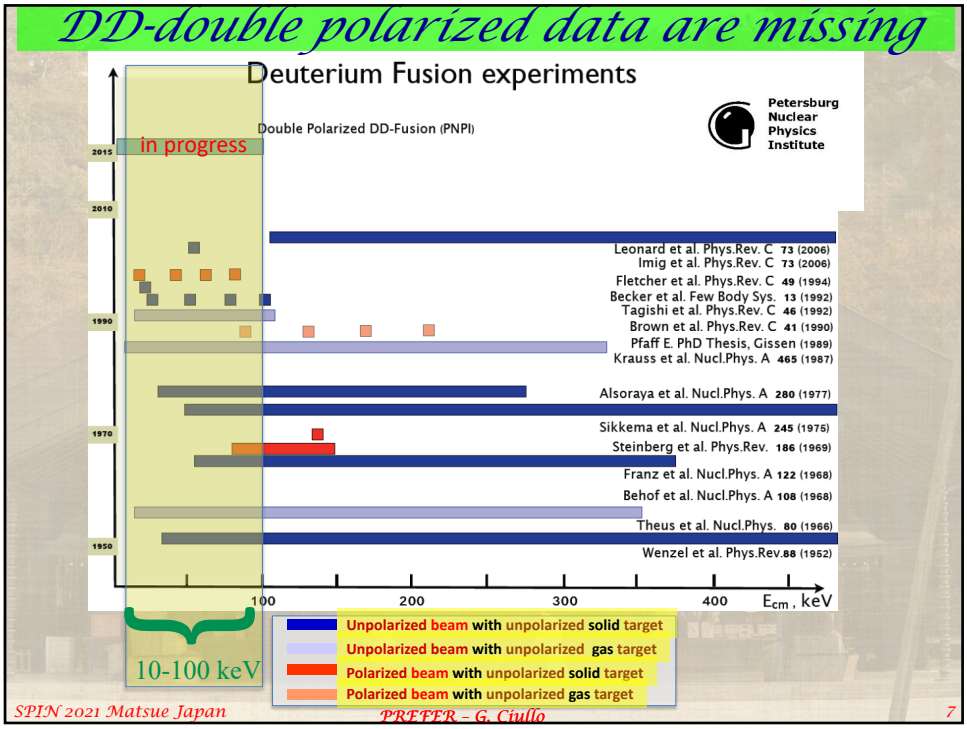
- References more than conclusions.

6


DD-double polarized data are missing
Deuterium Fusion experiments
Double Polarized DD-Fusion (PNPI)
Petersburg Nuclear Physics Institute
in progress
2015
2010
1990
1970
1950
Leonard et al. Phys.Rev. C 73 (2006)
Imig et al. Phys.Rev. C 73 (2006)
Fletcher et al. Phys.Rev. C 49 (1994)
Becker et al. Few Body Sys. 13 (1992)
Tagishi et al. Phys.Rev. C 46 (1992)
Brown et al. Phys.Rev. C 41 (1990)
Pfaff E. PhD Thesis, Gissen (1989)
Krauss et al. Nucl.Phys. A 465 (1987)
Alsoraya et al. Nucl.Phys. A 280 (1977)
Sikkema et al. Nucl.Phys. A 245 (1975)
Steinberg et al. Phys.Rev. 186 (1969)
Franz et al. Nucl.Phys. A 122 (1968)
Behof et al. Nucl.Phys. A 108 (1968)
Theus et al. Nucl.Phys. 80 (1966)
Wenzel et al. Phys.Rev.88 (1952)
100
200
300
400
Ecm , keV
10-100 keV
Unpolarized beam with unpolarized solid target
Unpolarized beam with unpolarized gas target
Polarized beam with unpolarized solid target
Polarized beam with unpolarized gas target
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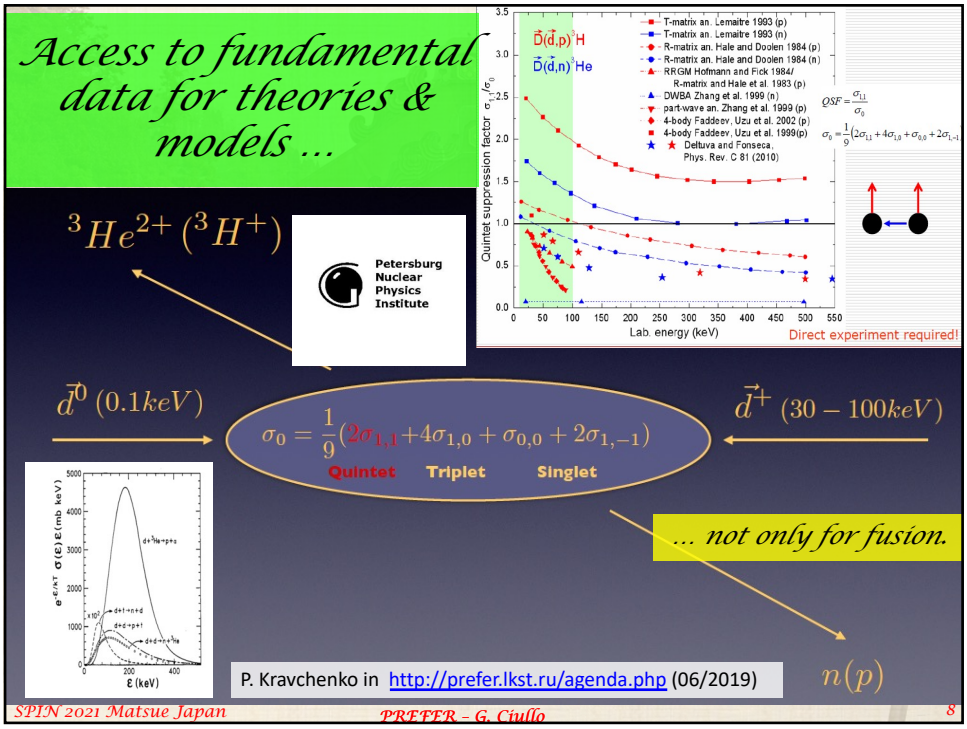
7

7


Access to fundamental data for theories & models …
$^3He^{2+}$ ($^3H^+$)
Petersburg Nuclear Physics Institute
$\vec{d}^0$ (0.1keV)
$\vec{d}^+$ (30 – 100keV)
$\sigma_0 = \frac{1}{9}(2\sigma_{1,1}+4\sigma_{1,0}+\sigma_{0,0}+2\sigma_{1,-1})$
Quintet Triplet Singlet
… not only for fusion.
n(p)
D(d,p)3H
D(d,n)3He
Quintet suppression factor
Lab. energy (keV)
Direct experiment required!
P. Kravchenko in http://prefer.lkst.ru/agenda.php (06/2019)
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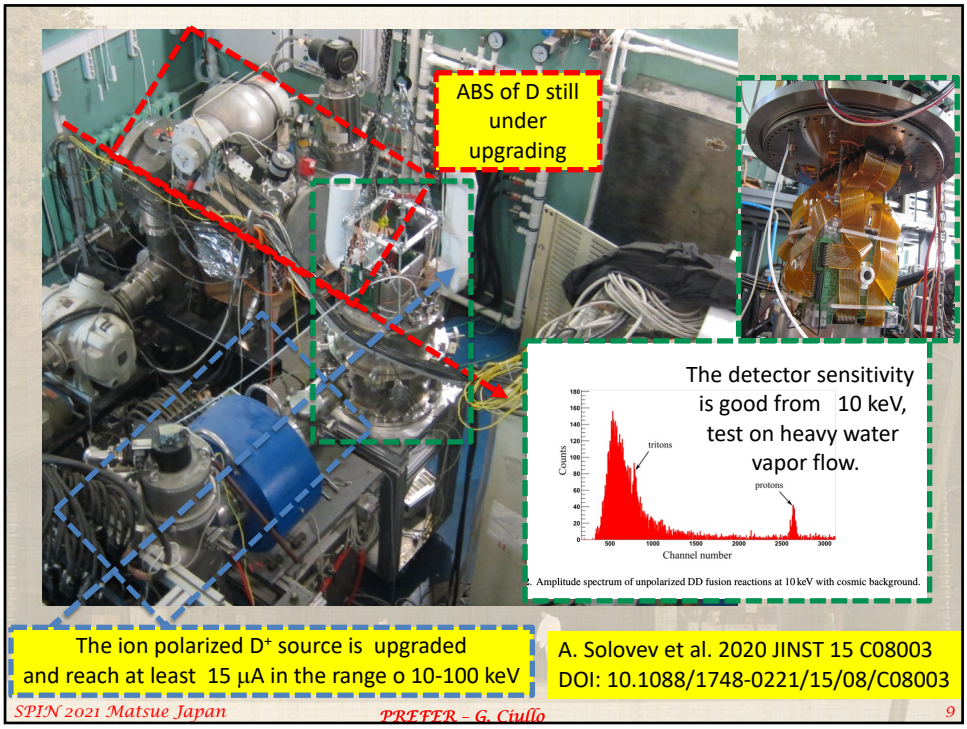
8

8



9

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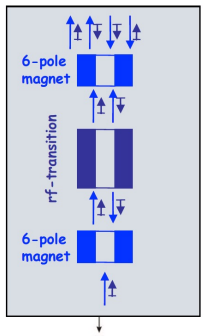
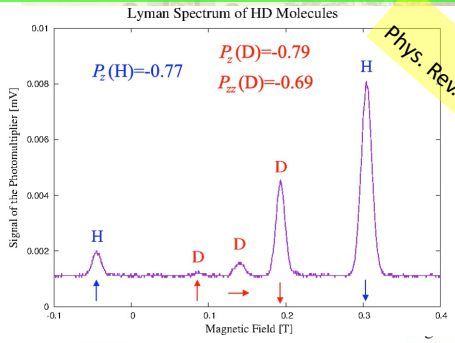
- References more than conclusions.

10

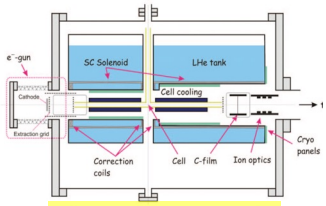
Hyperpolarized molecules from pABS

Production

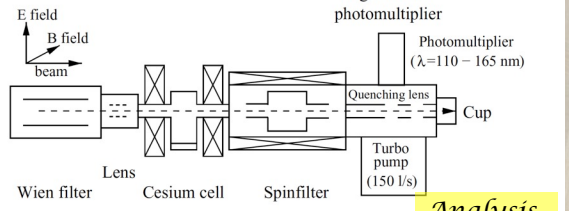




Phys. Rev. Lett. **124** (2020) 113003 R. Engels et al.



recombination



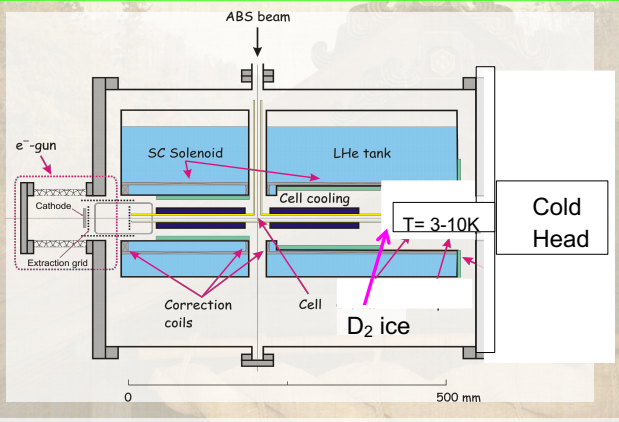
Analysis

R. Engels talk in this conference yesterday 18/10/21

JÜLICH FORSCHUNGSZENTRUM

11

Condensation & transp. of pol. fuel



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

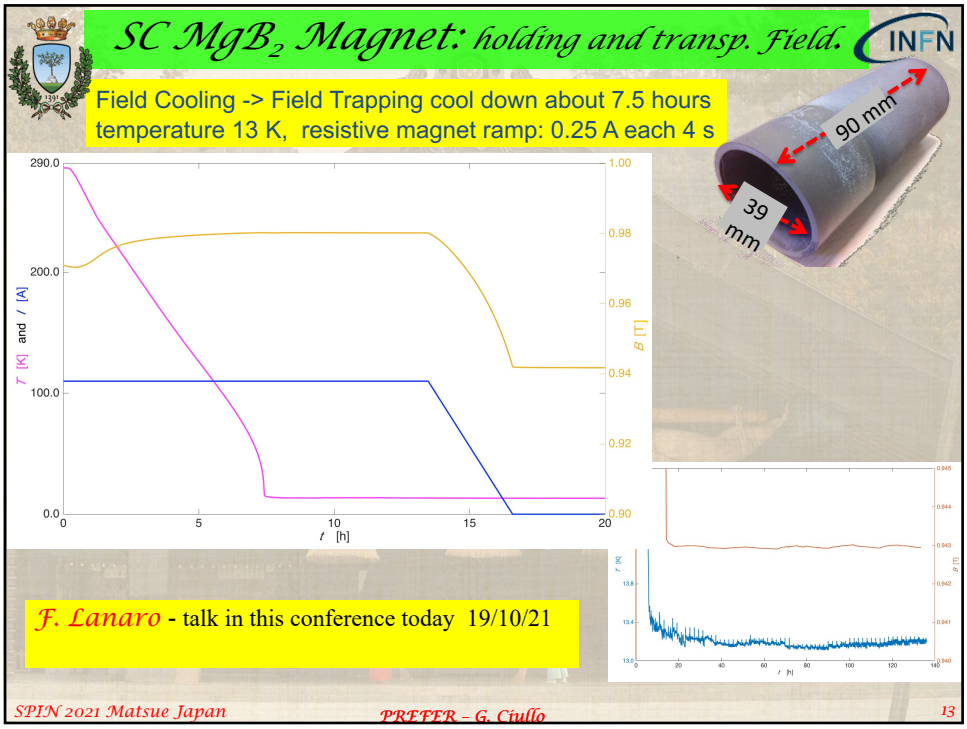
Target useful for LIP fusion

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 is surrounded by a SC MgB_2 cylinder, which provides the holding field during transportation.

12


SC MgB_2 Magnet: holding and transp. Field.
INFN
Field Cooling -> Field Trapping cool down about 7.5 hours
temperature 13 K, resistive magnet ramp: 0.25 A each 4 s
90 mm
39 mm
T [K] and I [A]
B [T]
t [h]
F. Lanaro - talk in this conference today 19/10/21
SPIN 2021 Matsue Japan
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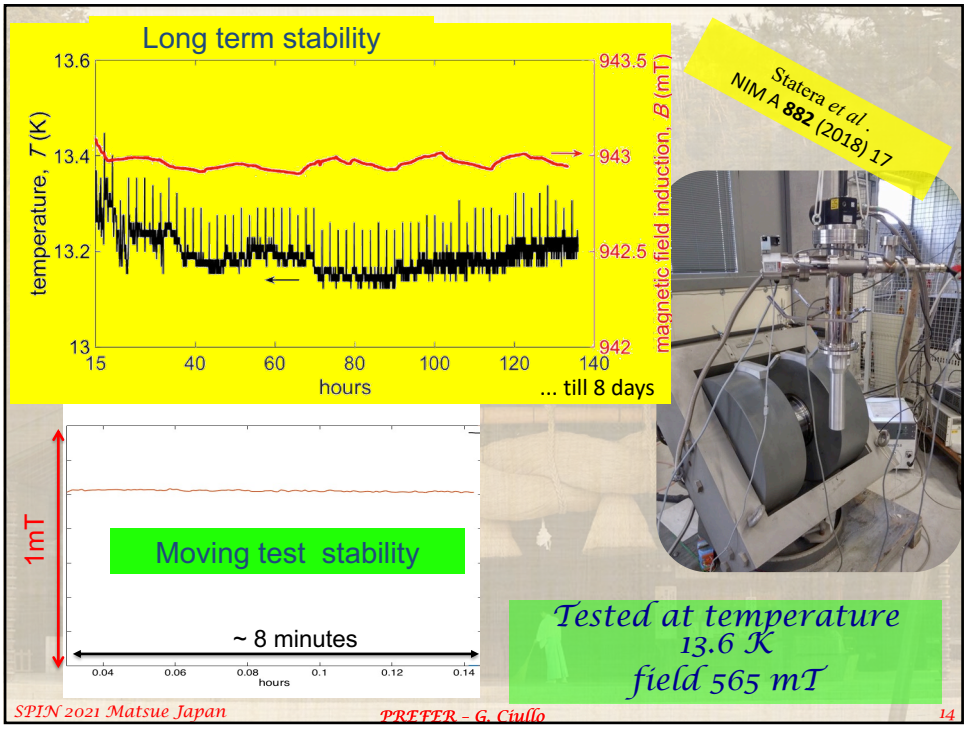
13

13


Long term stability
temperature, T (K)
magnetic field induction, B (mT)
hours
... till 8 days
Statera et al. NIM A 882 (2018) 17
1mT
Moving test stability
~ 8 minutes
hours
Tested at temperature
13.6 K
field 565 mT
SPIN 2021 Matsue Japan
PREFER - G. Ciullo
14

14

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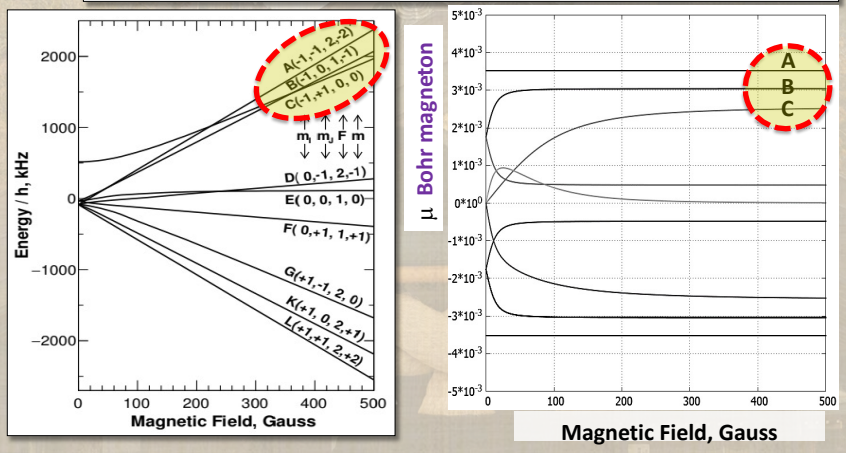
15

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

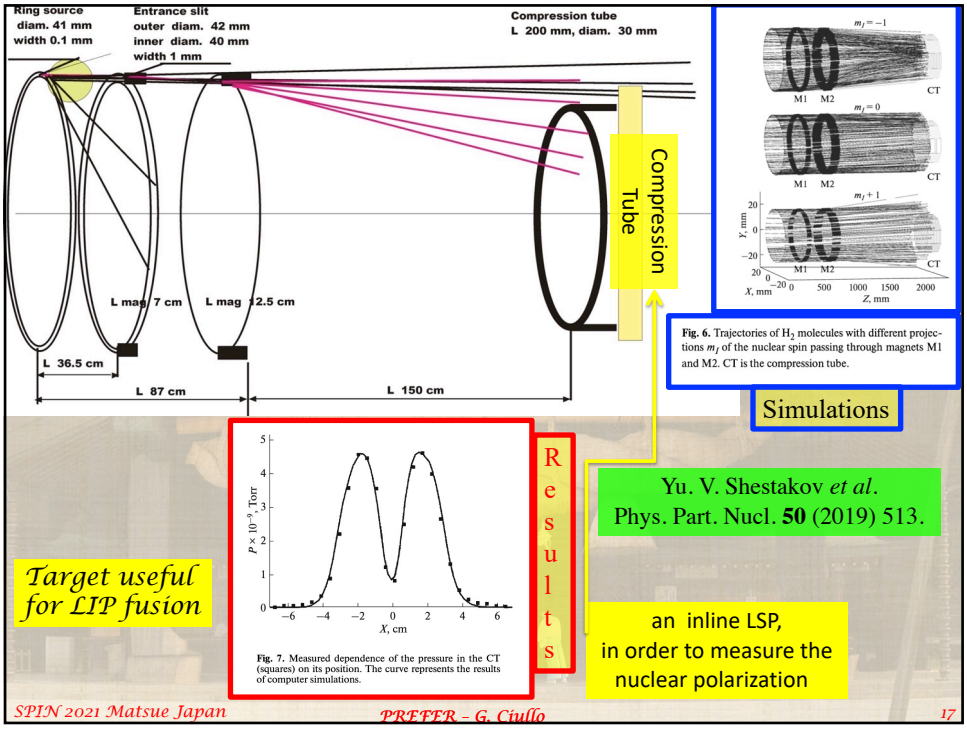
Energies of H_2 states as a function of magnetic field.



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

16



17

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18

Excite QB and dissociate with UV

FORTH Foundation for Research & Technology - Hellas

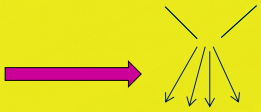
JÜLICH FORSCHUNGSZENTRUM

The 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 (Univ. of Crete/FORTH, IKP/PGI in FZJ/HHUD).

19

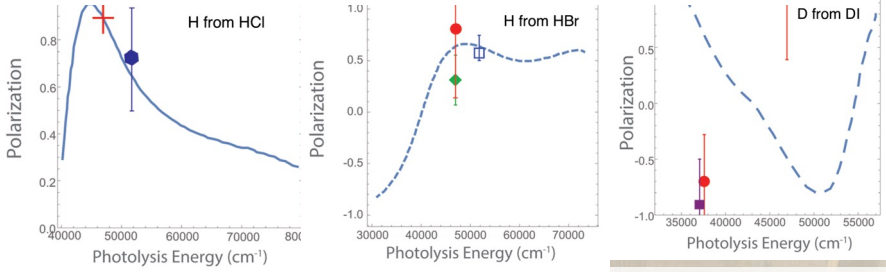
Comparison: ABS and UVD

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 attainable)

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

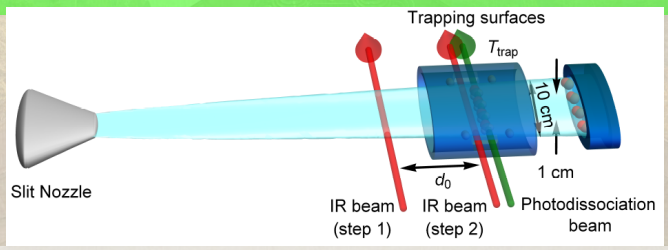
a Excitation by 1026 nm 10^{14} W cm^{-2}, Ionization by 5th harmonic (213 nm) 10^{12} W cm^{-2}



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

20

Macroscopic production of highly nuclear-spin-polarized molecules from IR-excitation and photodissociation of molecular beams



Investigations on the IR excitation and polarization of molecular beams, followed by photodissociation and trapping of polarized products, to see how close polarized-molecule production rates can approach the laser production rates of 10^{21} photons/s of existing table-top commercial lasers.

C. S. Kannis, J. Suárez & T. P. Rakitzis, *Mol. Phys.* (2021).
C. S. Kannis and T. Peter Rakitzis, *Chem. Phys. Lett.* **XX**, 139092 (2021)

21

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22

LIP production, diagnosis and fusion test

Fusion reactions

☞„Does the fusion rate depend on the target polarization?"

Multi-TW laser beam

(pol.) Target

μm-sized relativistic plasma

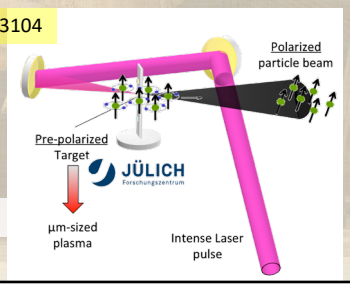
Accelerated Ions

☞„Are the accelerated ions polarized?"

☞„Angular dependence of fusion products?"

hhu Heinrich Heine Universität Düsseldorf

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

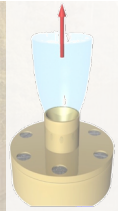


M. Büscher in http://prefer.lkst.ru/agenda.php (6/2019)

23

Polarized beams from LIP

Polarized He beams
From compresse polarized ^{3}He

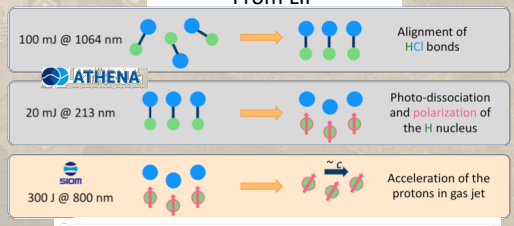


Output pressure: 50 bar

Input pressure: 3 bar

compressor

polarized proton beams
From LIP



Polarized proton beams from laser-induced plasmas

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

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

LIP techniques can be applied to polarized molecules
From MBS OR from recombined molecules from ABS

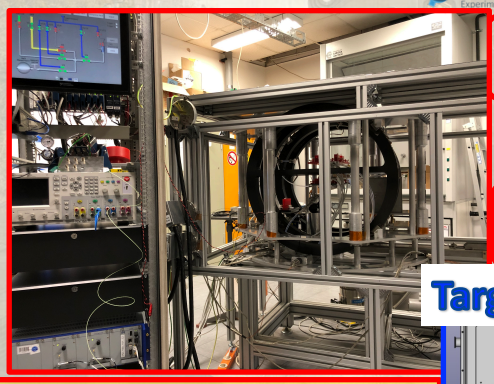
24

Polarized 3He gas-jet

Up to 80% nuclear polarization

PREFER Polarization Research for Fusion Experiments and Reactors

ATHENA



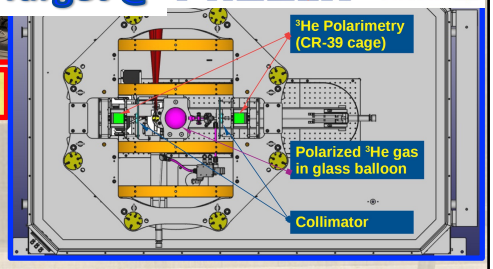
magnetic holding field for storing pre-polarized ^{3}He gas @3 bar

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

non-magnetic nozzle provides the desired gas-jet target

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

Target @ PHELIX GSI



Firts test of fusion reaction at PHELIX – GSI, completed in recent summer, data are under analysis.

25

Outlook of the presentation

- References more than conclusions.

26

PREFER Workshop in Gatchina, 04-06 June 2019

Some reading: *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"

27

One year ago references:

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

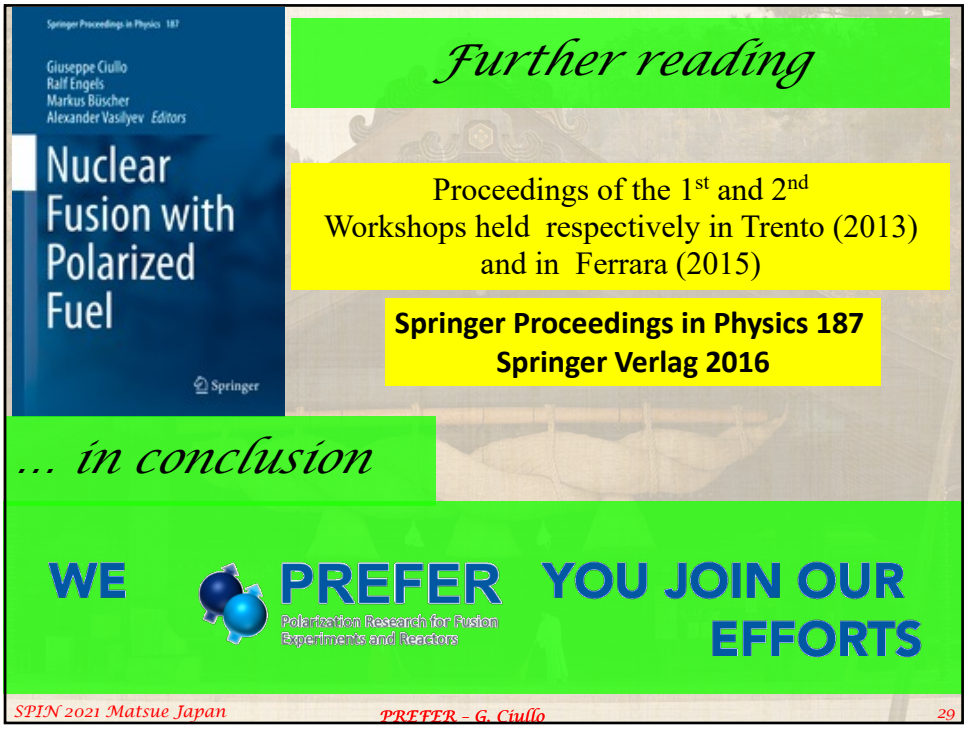
15:00	Advantages of Nuclear Fusion with Polarized Fuel — Dr Ralf Engels — A11, Polo degli Adelardi - Via Adelardi, 33 — 14:30 - 15:05	
	THE STATUS OF THE DOUBLE POLARIZED DD-FUSION EXPERIMENT — Dr Polina Kravchenko — A11, Polo degli Adelardi - Via Adelardi, 33 — 15:05 - 15:30	
	Status of polarized molecular source — Prof. Dmitriy Toporkov — A11, Polo degli Adelardi - Via Adelardi, 33 — 15:30 - 15:45	
	End of Session — A11, Polo degli Adelardi - Via Adelardi, 33 — 15:45 - 16:10	
16:00	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

28


Springer Proceedings in Physics 187
Giuseppe Ciullo
Ralf Engels
Markus Büscher
Alexander Vasilyev Editors
Nuclear Fusion with Polarized Fuel
Springer
Further reading
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
SPIN 2021 Matsue Japan
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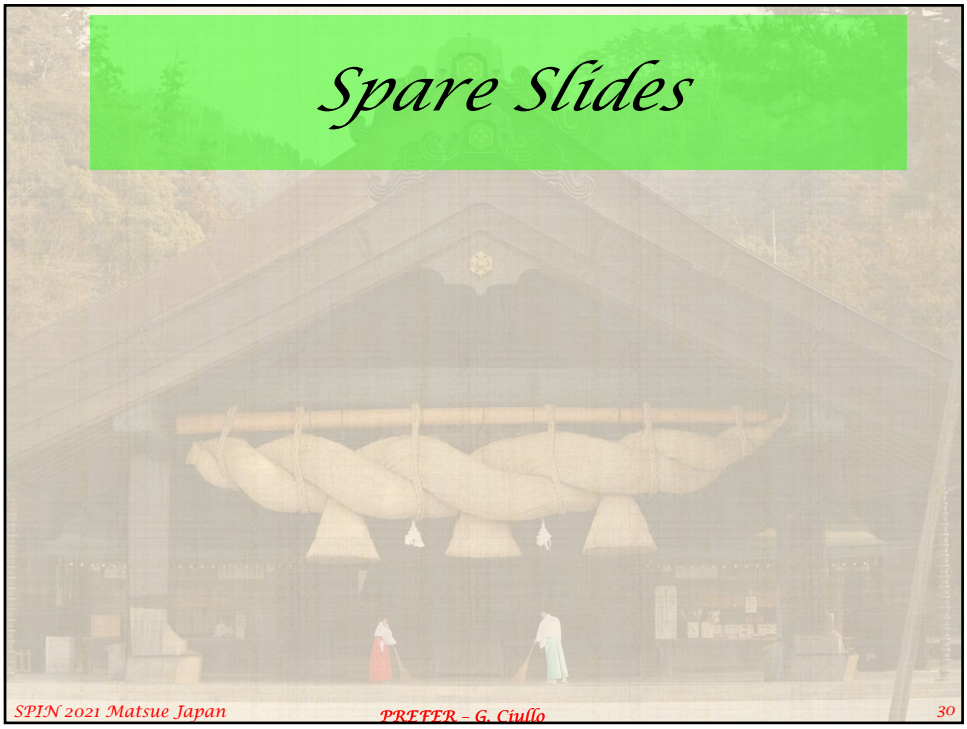
29

29


Spare Slides
SPIN 2021 Matsue Japan
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30

30

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 ($\cos^2(\theta)$ -1]/2
- C_{zz} spin correlation coefficient C_{zz}= - 3 [$\cos^2(\theta)$ -2]/2

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

$$\sigma_{tot} = 1.5\,\sigma_{unpol} \qquad \frac{d\sigma(\theta)}{d\Omega} = \frac{9}{4}\sin^2\theta \frac{d\sigma(\theta)}{d\Omega}_{unpol}$$

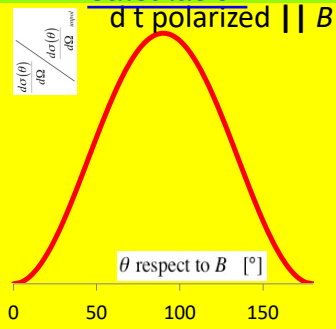
In the case of only d polarized perpendicular to B

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

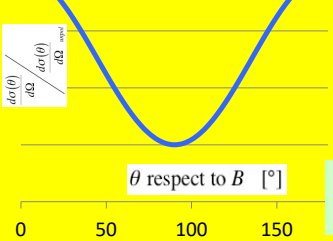
31

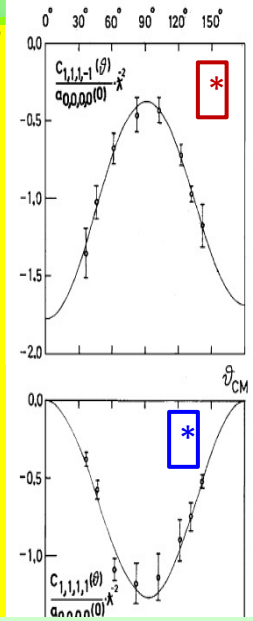
Calculation

d t polarized || *B*



d polarized ⊥ *B*





Experiments

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

α and *n* emitted as $\sin^2$ θ 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 ^{3}He(d,p)^{4}He
[Ch. Leeman et al Helv. Phys. Acta **44** (1971) 141]

32

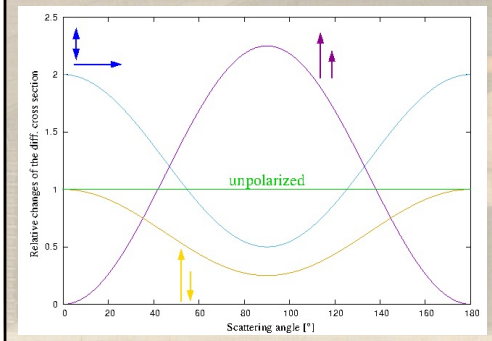
For spin 1/2 & 1 proved experimentally

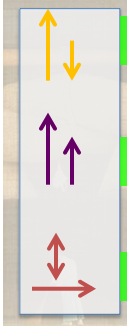
$^3\vec{He} + \vec{d} \longrightarrow {}^4He + p$ Factor: ~1.5 at 430 keV

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

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

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





Factor 0.5

Factor 1.5

Gain in σ

Factor 1

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33

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:

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

Higher 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 ?)

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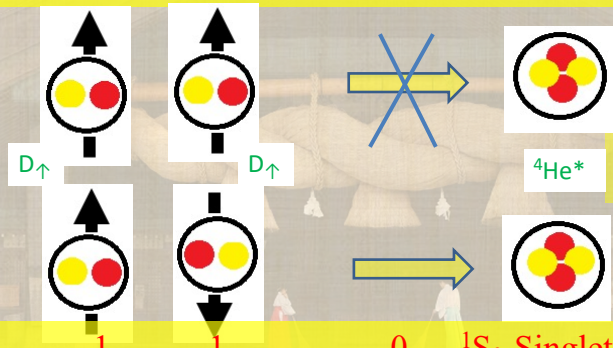
34

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 $^5S_2$ Quintet State Suppressed



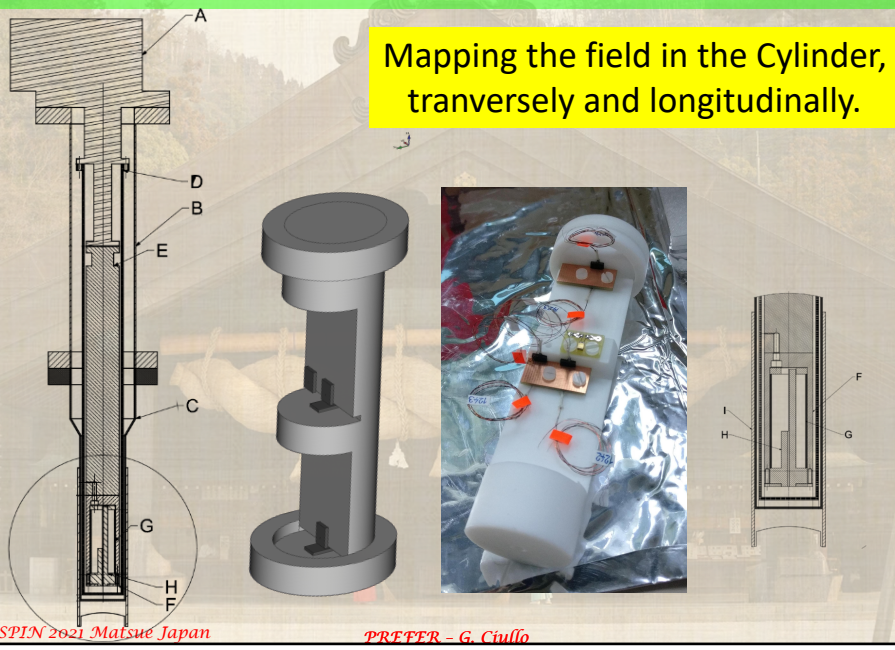
$$\frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{singlet}}{3/9\sigma_{singlet}} = 3$$

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

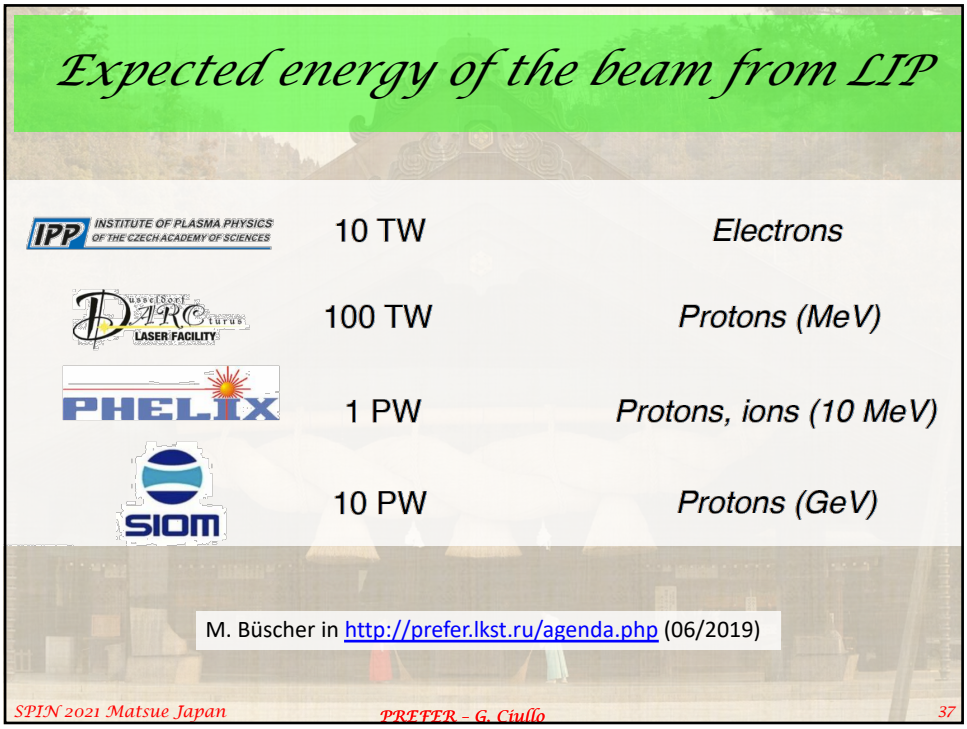
35

Upgrading MgB_2 magnet measurements

Mapping the field in the Cylinder, tranversely and longitudinally.



36


Expected energy of the beam from LIP
INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES
10 TW
Electrons
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)
SPIN 2021 Matsue Japan
PREFER - G. Ciullo
37

37