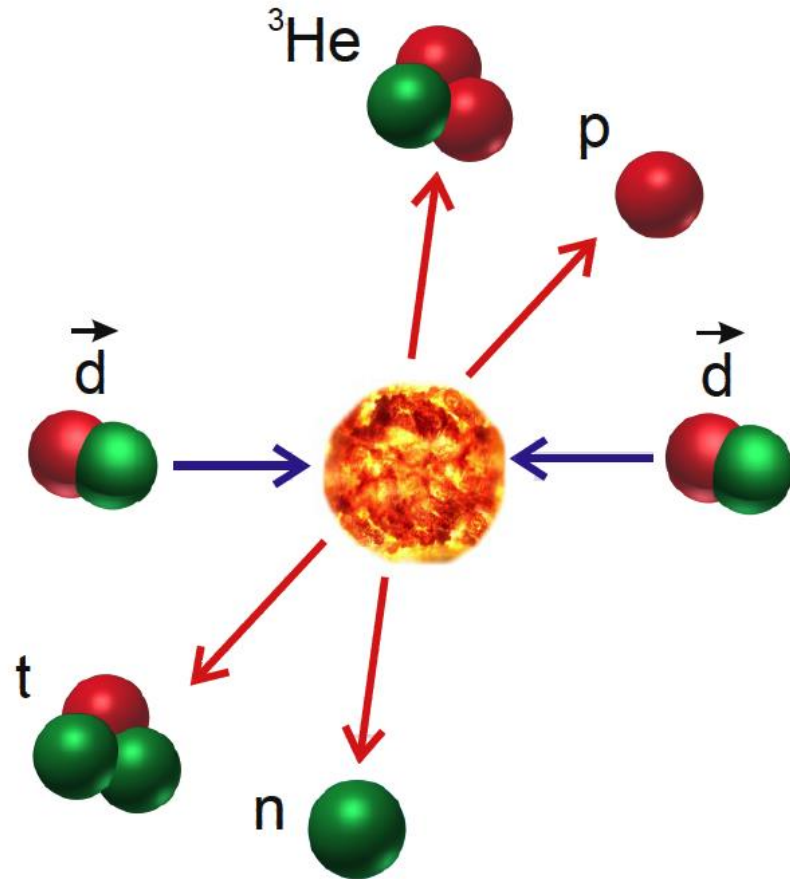
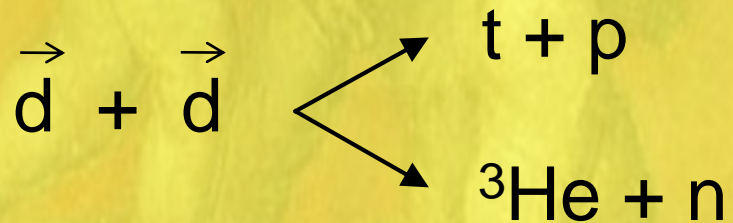


PolFusion Project

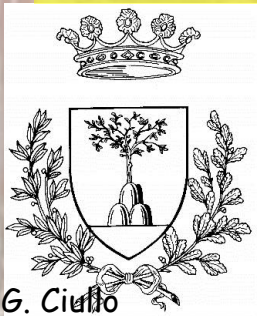
G.Ciullo *

on behalf of the
PolFusion Collaboration
(I'll show it later)

*Ferrara University and INFN
44122 – Ferrara – ITALY

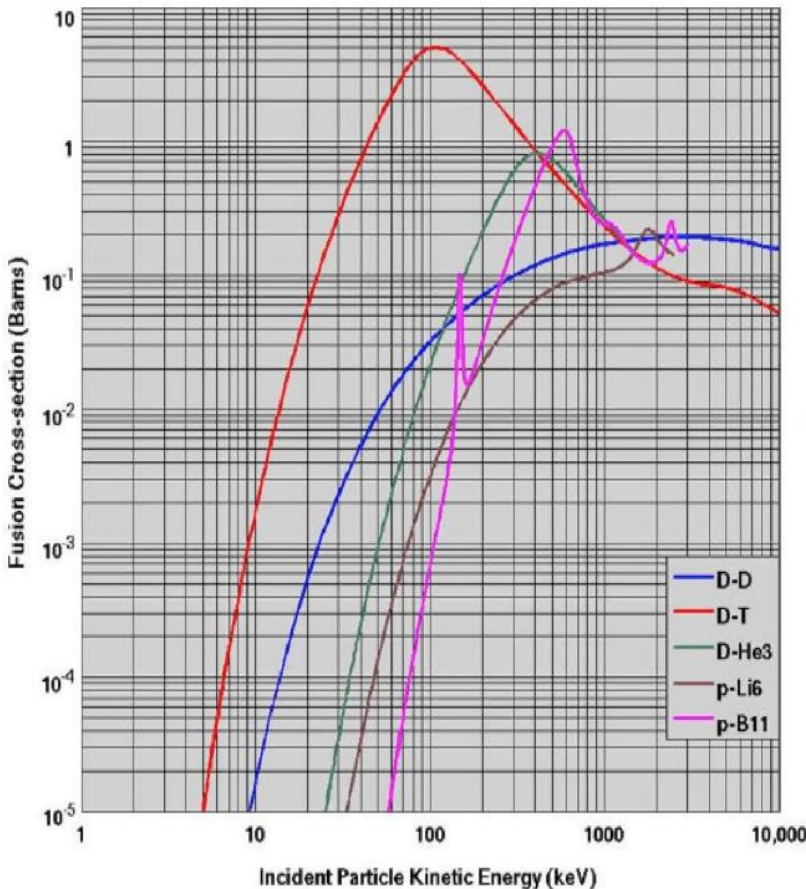


SPIN 2016 Champaign-Urbana, 2016 september 28



Fusion with polarized fuel? Why?

For the first three reaction generations, sorted according to relative energy (temperature) required for fusion.



1. Generation: $D + T \rightarrow {}^4\text{He} + n$

Polarized fuel

- 1.a) Increase of total cross section
- 1.b) differential cross section: angular distrib. $f(\theta)$ therefore better control

2. Generation: $D + D \rightarrow T + p$ or ${}^3\text{He} + n$

Fuel available (30 g m⁻³ in ocean water)

- 2.a) Increase of total cross section?
- 2.b) Like previous one? Still missing data for a complete description.

2.c) Possibility to suppress the reaction (QSF Quintet Suppression Factor)

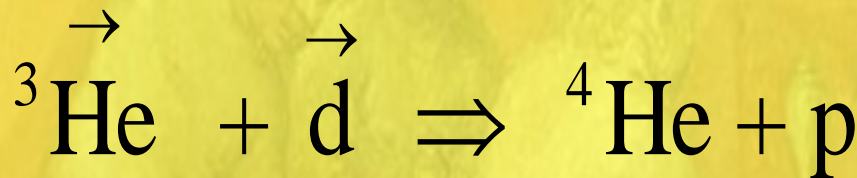
3. Generation: ${}^3\text{He} + D \rightarrow {}^4\text{He} + p$

- 3.a) and 3.b) like 1.a) and 1.b)
- 3.c) Possibility of Neutron lean reactor if $D+D \rightarrow {}^3\text{He} + n$ suppressed

D + T fuel for ITER , D + D in research tokamaks

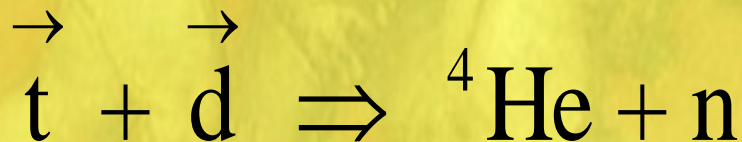
Polarized fusion: tested reaction ${}^3\text{He} + \text{d}$

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



Factor: ~ 1.5 at 430 keV

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



Factor: ~ 1.5 at 107 keV

Reactions through the spin channel
 $J^\pi = 3/2^+ /$ s-wave dominated ($\sim 96\%$)

➤ More information in the recent publication and its references:

H. Paetz gen. Schieck *Spin Physics and Polarized Fusion: Where We Stand in Nuclear Fusion with Polarized Fuel* (Springer Intern. Publ., 2016, Switzerland) eds.: G. Ciullo R. Engels, M. Büscher, A. Vasilyev)

Enhancement factor 1.5 (simple deduction)

Unpolarized cross section = weighted sum of all spin channels

$$S_{unpol} = \frac{\sum_s \hat{a}_s (2s+1) \sigma_s}{\sum_s \hat{a}_s (2s+1)} \quad S_{unpol} = \frac{2\sigma_{1/2} + 4\sigma_{3/2}}{6} = \frac{1}{3}\sigma_{1/2} + \frac{2}{3}\sigma_{3/2}$$

For both reactions channel spins can be 3/2 and 1/2.

From experiments: both reactions proceed via the $J^\pi = 3/2^+$ ($^5\text{He}^*$ and $^5\text{Li}^*$).

At low energy the incoming $l=0$, S-wave dominates:
only the 3/2 contributes to the σ_{unpol} ,
if the incoming particles are both polarized:

$$gain = \frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\sigma_{3/2}}{2/3\sigma_{3/2}} = 1.5$$

Angular distribution of reaction products

In a pure S-wave approx, B along z, (θ) respect to B (z)

$$\frac{dS(q)}{dW} = \left(1 + \frac{1}{2} P_{zz}^D A_{zz} + \frac{3}{2} P_z^D P_z^T C_{zz} \right) \frac{dS(q)}{dW}_{unpol}$$

- 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

$$S_{tot} = 1.5 S_{unpol}$$

$$\frac{dS(q)}{dW} = \frac{9}{4} \sin^2 q \frac{dS(q)}{dW}_{unpol}$$

In the case if only d is polarized perpendicular to B

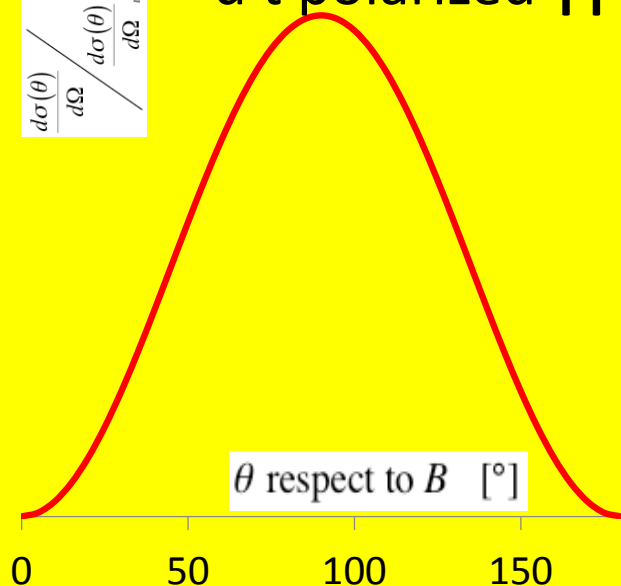
$$S_{tot} = S_{unpol}$$

$$\frac{dS(q)}{dW} = \frac{1}{2} (1 + 3 \cos^2 q) \frac{dS(q)}{dW}_{unpol}$$

Theory

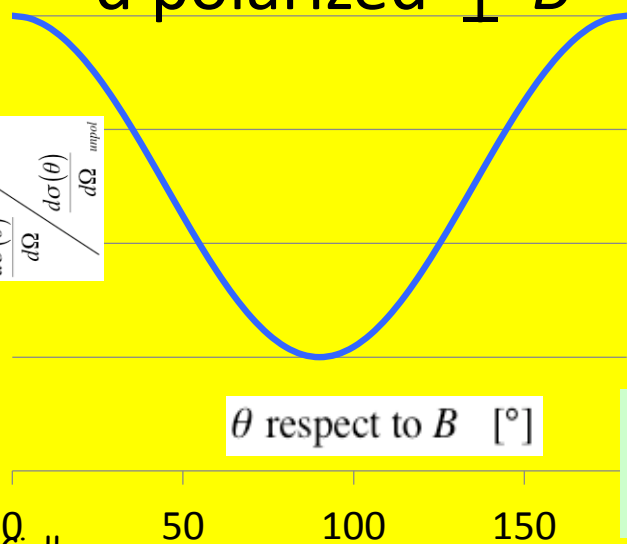
d t polarized || B

$$\frac{d\sigma(\theta)}{d\Omega} \bigg/ \frac{d\sigma(\theta)}{d\Omega}_{unpol}$$



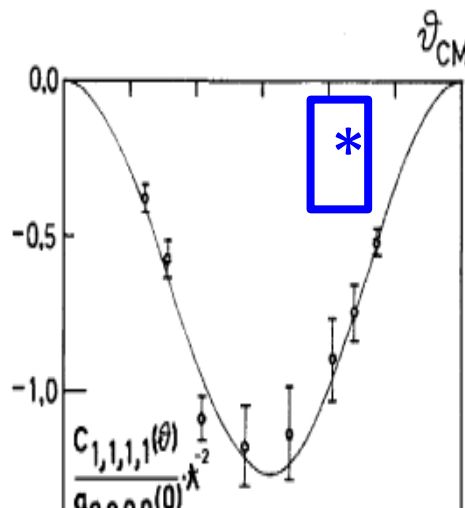
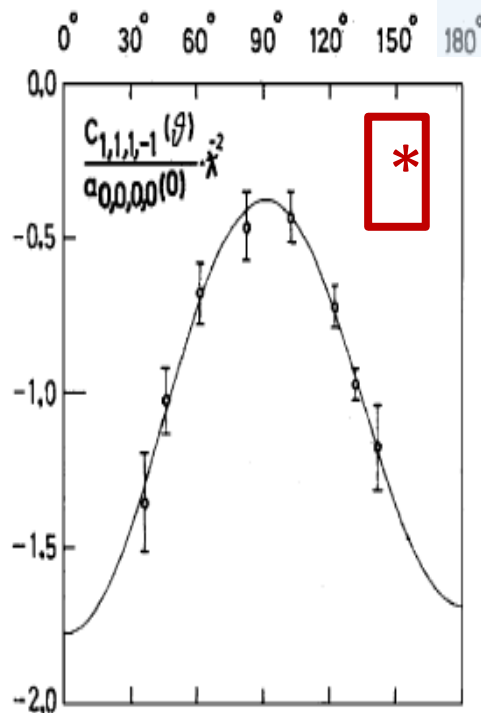
d polarized $\perp B$

$$\frac{d\sigma(\theta)}{d\Omega} \bigg/ \frac{d\sigma(\theta)}{d\Omega}_{unpol}$$



Experiments

* D and T spin || to the confinement field: α and n emitted as $\sin^2 \theta$ respect to B



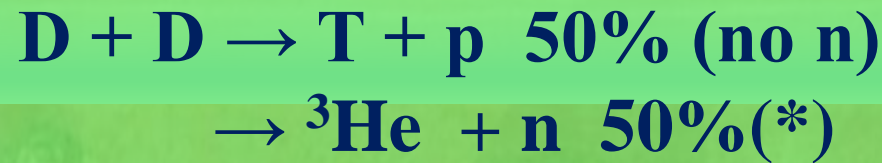
* D spin \perp to the confinement field and T unpolarized: no influence on cross section, but the reaction products follow $(1+3\cos^2 \theta)$.

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

Nuclear Fusion with Polarized Fuel

- R.M. Kulsrud *et al.* Phys. Rev. Lett. **49** (1982) 1248 **polarized fusion reactor plasmas.**
- E. Bittoni *et al.* Nucl. Fus. **23** (1983) 830, **perpendicular spin: reduction of factor two on alpha load** on the walls.
- B. Coppi Phys. Scripta T2B (1982) 590 address to **neutronless fusion reacting plasmas**, using **polarized fuel.**
- M.R. More Phys. Rev. Lett. **51** (1983) 396 study for **ICF.**
- B.J. Micklich *et al.* Nucl. Techn./Fus **5** (1984) 162: **relaxed fusion condition** $n\tau_E$ and T_i for ignition and breakeven, more 20 % ~ 30 % of **neutron flux localized** in the **inboard** first wall (D polarized perpendicular to B).
- D.A. Noever Fus. Tech. **27** (1995) 86: simple **mirror fusion reactors** with **polarized fuel**, $Q = P_{fusion}/P_{input} = 1.63$: **new design optimization.**

2nd



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

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

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

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

**D_↑ + D_↑ spin dependent cross section (data set very poor),
and still worse at lower energy (electron screening ?)**

Neutron lean fusion reactor

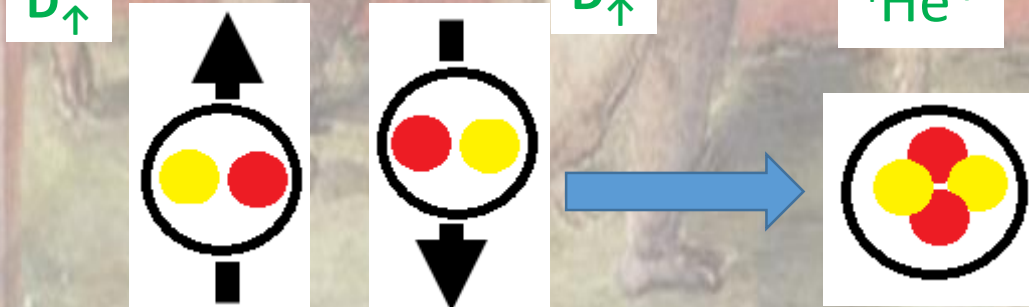
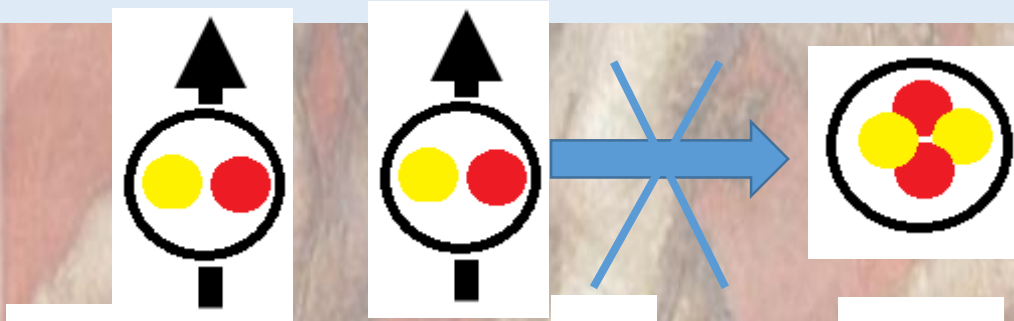
QSF (Quintet Suppression Factor)

Spin alignments allows to enhance or suppress reaction channels? 2.5 -3 ?

B. Ad'jasevich, V. Antonenko PREPRINT IEA-2704 Moscow(1976)

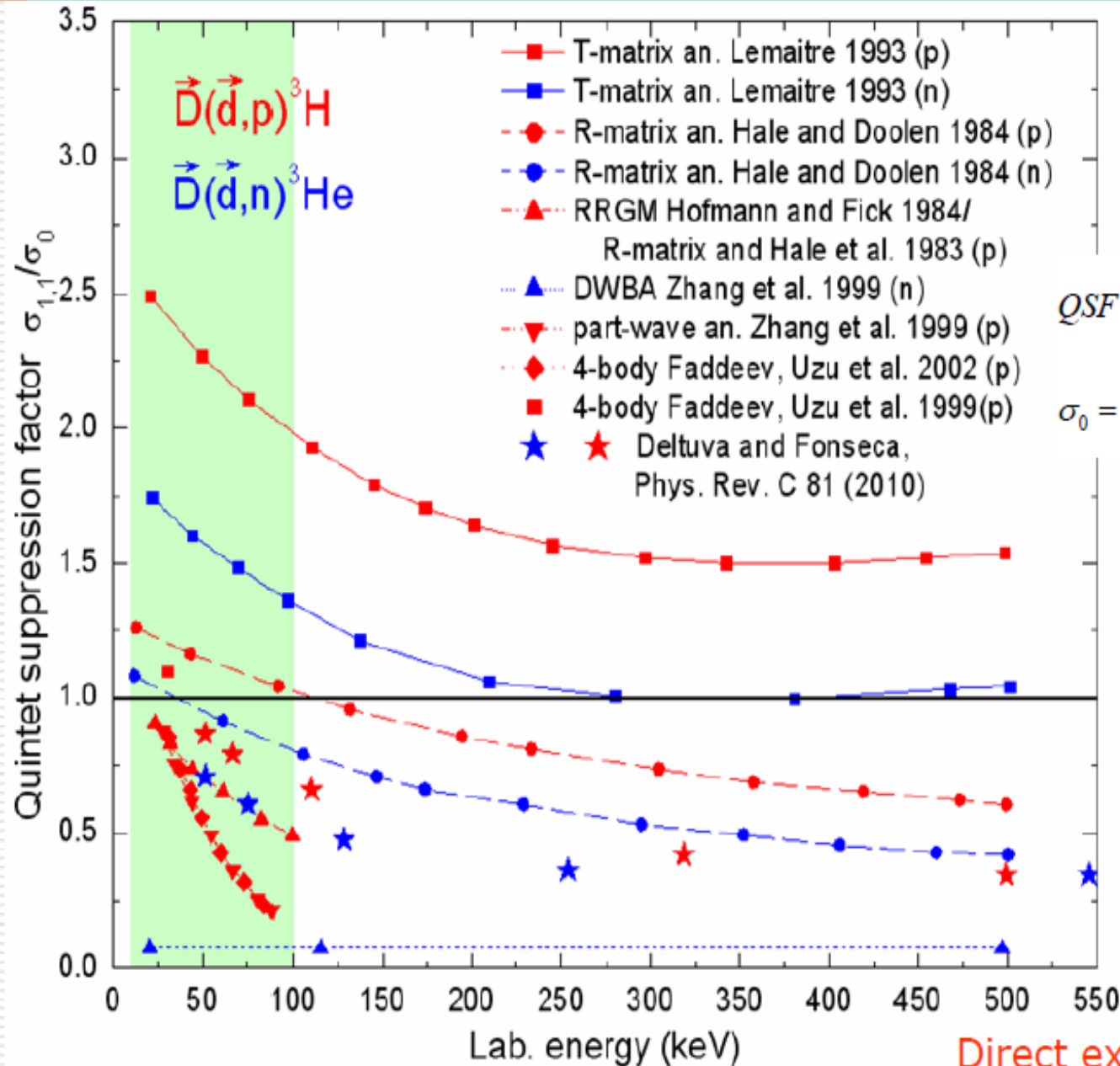
$D_{\uparrow} (d_{\uparrow} p) T$ and $D_{\uparrow} (d_{\uparrow} n) {}^3\text{He}$ suppressed
by choosing deuteron spin parallel each others

S 1 1 0 5S_2 Quintet State Suppressed



S 1 -1 0 1S_0 Singlet state allowed

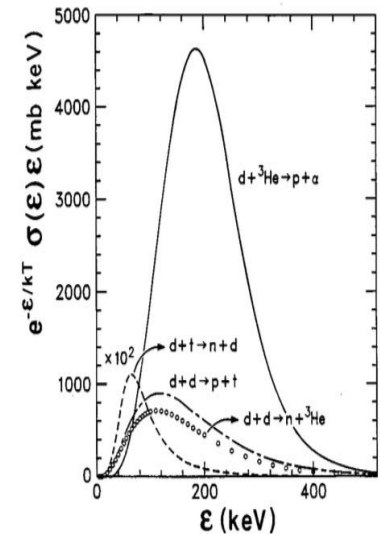
QSF: experimental challenge for testing theories



R. Engels and
H. Paetz gen. Schieck in
Nuclear fusion with
polarized nucleons
Trento 14-15 Nov 2013

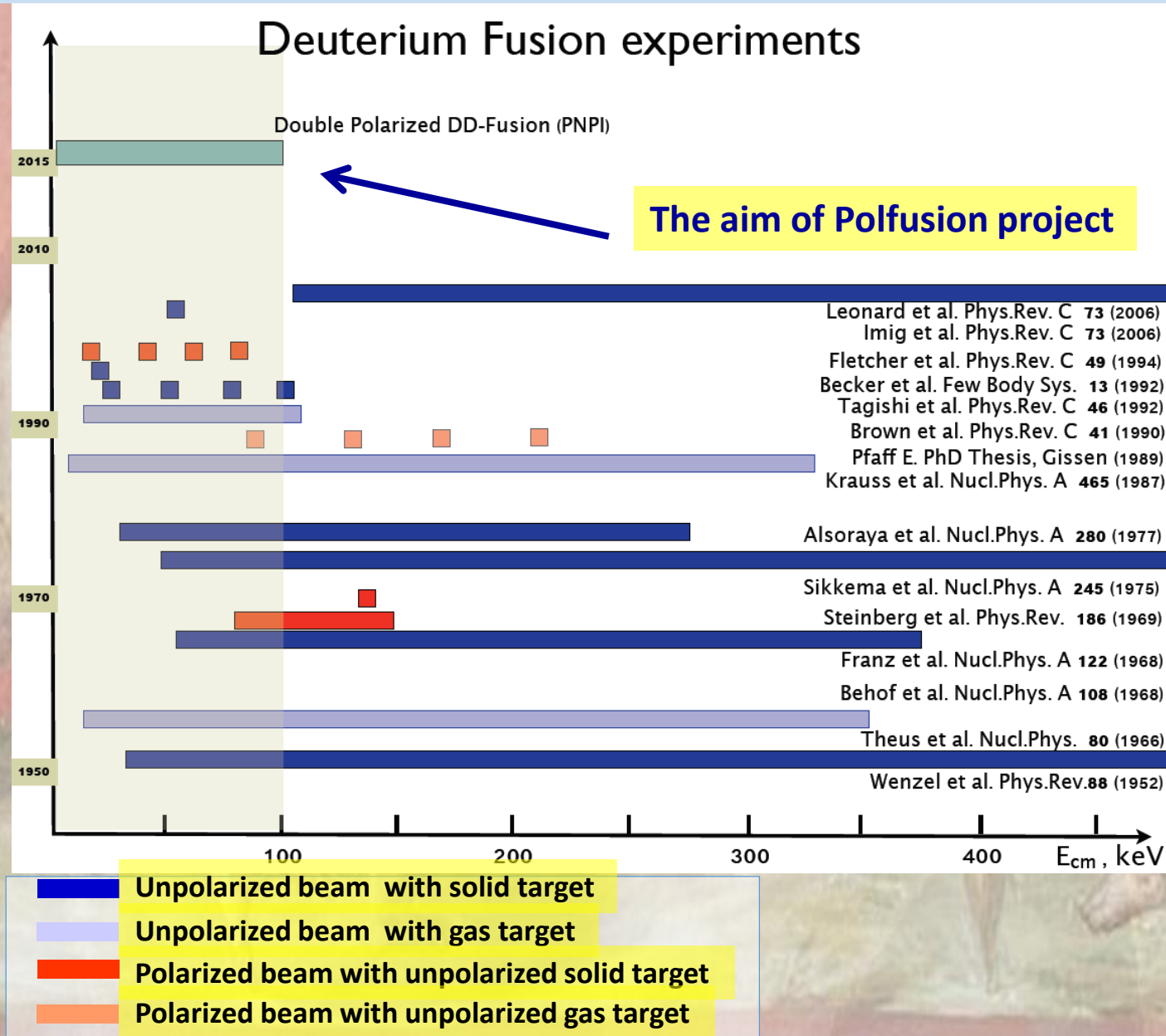
$$QSF = \frac{\sigma_{1,1}}{\sigma_0}$$

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



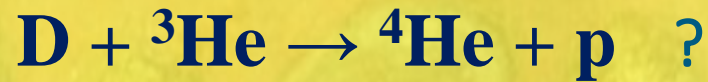
Direct experiment required!

Double polarized D + D data is missing



3rd

Neutron lean fusion



Can we have neutron free reactor?

The spin configuration is $1 + \frac{1}{2}$, like the $\text{T} + \text{D}$, and was confirmed already in 1971

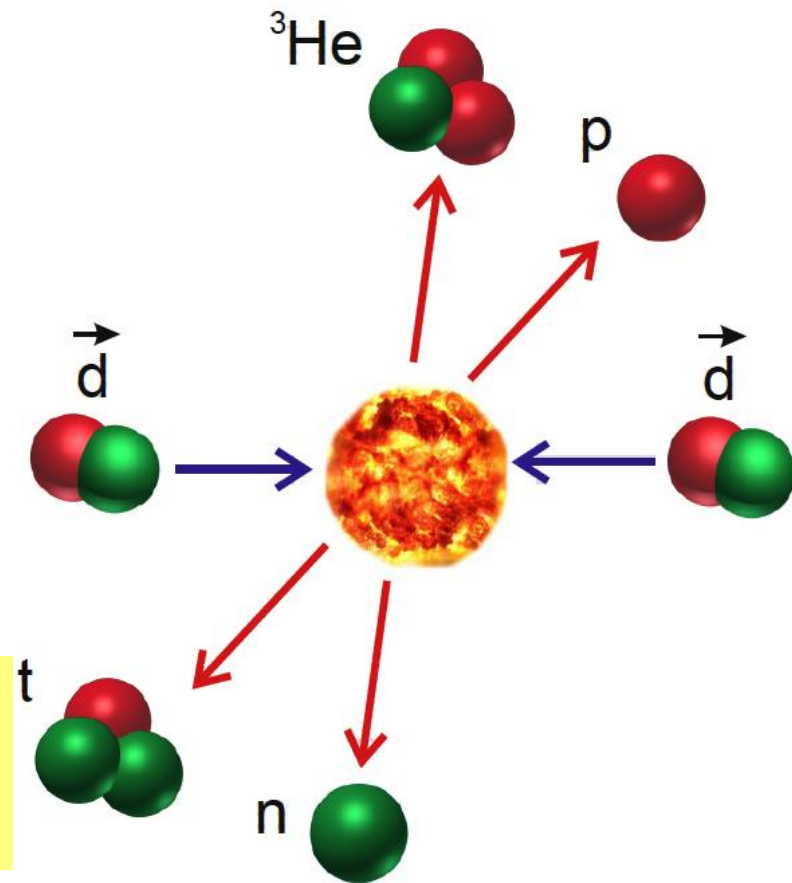
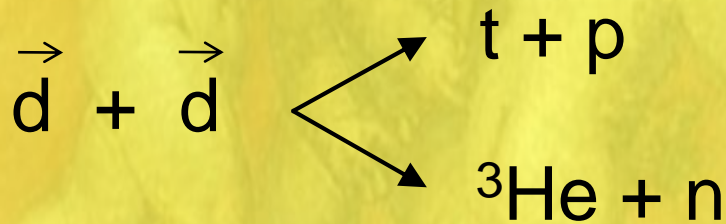
If we **suppress** or **reduce** D-D fusion,
we could have neutron **free** or **lean** reactors

We say “lean”, because we’ll still have n from $\text{D} + \text{D}$,
and $\text{D} + \text{T}$, T is produced in $\text{D} + \text{D}$ reaction.

To understand the fusion process of D polarized fuel, we need to know the cross section of the whole set of orientations of the spins produced in $\text{D} + \text{D}$ reaction.

The most interesting reaction with still missing data

Investigation of 4-nucleons reaction
With both initial particles polarization
at the energy range between 10-100 keV



Possible experimental configuration:
a **polarized ion beam**
Impinging on a **polarized gaseous target.**

D + D cross section: a zoo of analysing powers and spin correlation coefficients

$$\begin{aligned} \sigma(\Theta, \Phi) = \sigma_0(\Theta) \{ & 1 + \frac{3}{2} [A_y^{(b)}(\Theta)p_y + A_y^{(t)}(\Theta)q_y] + \frac{1}{2} [A_{zz}^{(b)}(\Theta)p_{zz} + A_{zz}^{(t)}(\Theta)q_{zz}] \\ & + \frac{1}{6} [A_{xx-yy}^{(b)}(\Theta)p_{xx-yy} + A_{xx-yy}^{(t)}(\Theta)q_{xx-yy}] \\ & + \frac{2}{3} [A_{xz}^{(b)}(\Theta)p_{xz} + A_{xz}^{(t)}(\Theta)q_{xz}] \\ & + \frac{9}{4} [C_{y,y}(\Theta)p_yq_y + C_{x,x}(\Theta)p_xq_x + C_{x,z}(\Theta)p_xq_z \\ & + C_{z,x}(\Theta)p_zq_x + C_{z,z}(\Theta)p_zq_z] \\ & + \frac{3}{4} [C_{y,zz}(\Theta)p_yq_{zz} + C_{zz,y}(\Theta)p_{zz}q_y] \\ & + C_{y,xz}(\Theta)p_yq_{xz} + C_{xz,y}(\Theta)p_{xz}q_y + C_{x,yz}(\Theta)p_xq_{yz} \\ & + C_{yz,x}(\Theta)p_{yz}q_x + C_{z,yz}(\Theta)p_zq_{yz} + C_{yz,z}(\Theta)p_{yz}q_z \\ & + \frac{1}{4} [C_{y,xx-yy}(\Theta)p_yq_{xx-yy} + C_{xx-yy,y}(\Theta)p_{xx-yy}q_y \\ & + C_{zz,zz}(\Theta)p_{zz}q_{zz}] \\ & + \frac{1}{3} [C_{zz,xz}(\Theta)p_{zz}q_{xz} + C_{xz,zz}(\Theta)p_{xz}q_{zz}] \\ & + \frac{1}{12} [C_{zz,xx-yy}(\Theta)p_{zz}q_{xx-yy} + C_{xx-yy,zz}(\Theta)p_{xx-yy}q_{zz}] \\ & + \frac{4}{9} [C_{xz,xz}(\Theta)p_{xz}q_{xz} + C_{yz,yz}(\Theta)p_{yz}q_{yz}] \\ & + \frac{8}{9} [C_{xy,yz}(\Theta)p_{xy}q_{yz} + C_{yz,xy}(\Theta)p_{yz}q_{xy}] \\ & + \frac{16}{9} C_{xy,xy}(\Theta)p_{xy}q_{xy} \\ & + \frac{1}{9} [C_{xz,xx-yy}(\Theta)p_{xz}q_{xx-yy} + C_{xx-yy,xz}(\Theta)p_{xx-yy}q_{xz}] \\ & + \frac{1}{36} C_{xx-yy,xx-yy}(\Theta)p_{xx-yy}q_{xx-yy} \\ & + \frac{1}{2} [C_{x,xy}(\Theta)p_xq_{xy} + C_{xy,x}(\Theta)p_{xy}q_x + C_{z,xy}(\Theta)p_zq_{xy} \\ & + C_{xy,z}(\Theta)p_{xy}q_z] \} \end{aligned}$$

Deuteron spin aligned: only $p_z(q_z)$ and $p_{zz}(q_{zz}) \neq 0$

$$\sigma(\Theta, \Phi) = \sigma_0(\Theta) \left\{ 1 + \frac{3}{2} [A_{zz}^{(b)}(\Theta)p_{zz} + A_{zz}^{(t)}(\Theta)q_{zz}] + \frac{9}{4} C_{z,z}(\Theta)p_zq_z + \frac{1}{4} C_{zz,zz}(\Theta)p_{zz}q_{zz} \right\}$$

This will provide data on QSF

Only beam is polarized:
($p_{i,j} \neq 0, q_{i,j} = 0$)

$$\begin{aligned} \sigma(\Theta, \Phi) = \sigma_0(\Theta) \cdot \{ & 1 + 3/2 A_y(\Theta) p_y \\ & + 1/2 A_{xz}(\Theta) p_{xz} \\ & + 1/6 A_{xx-yy}(\Theta) p_{xx-yy} \\ & + 2/3 A_{zz}(\Theta) p_{zz} \} \end{aligned}$$

Useful for enhancement and angular distribution studies

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

Scheme of the d-d spin dependent cross section measurements

$^3\text{He}^{2+}$ (0.8 MeV),
 $^3\text{H}^+$ (1.0 MeV)

ABS

Ferrara (IUCF) ABS

$I \sim 4 \cdot 10^{16} \text{ atoms s}^{-1}$

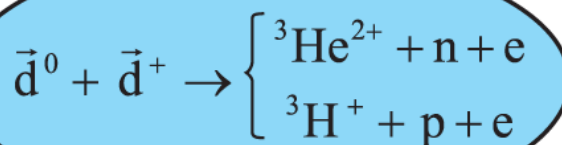
Target density $\sim 2.7 \cdot 10^{11} \text{ atoms cm}^{-2}$

Vector polarization: ± 0.7

\vec{d}^0 (0.1 eV)

dd-polarimeter
or LSP

\vec{d}^+



\vec{d}^+ (1-32 keV)

Ion
source

Polarized Ion Source

Ion beam: $I \leq 20 \mu\text{A}$

$(1.3 \cdot 10^{14} \text{ ions s}^{-1})$

$E_{\text{beam}} \leq 32 \text{ keV}$

Vector polarization: ± 0.7

\vec{d}^0 (0.1 eV)

Luminosity: $3.3 \cdot 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$

count rate at 30 keV:

$\sim 120 \text{ counts h}^{-1}$

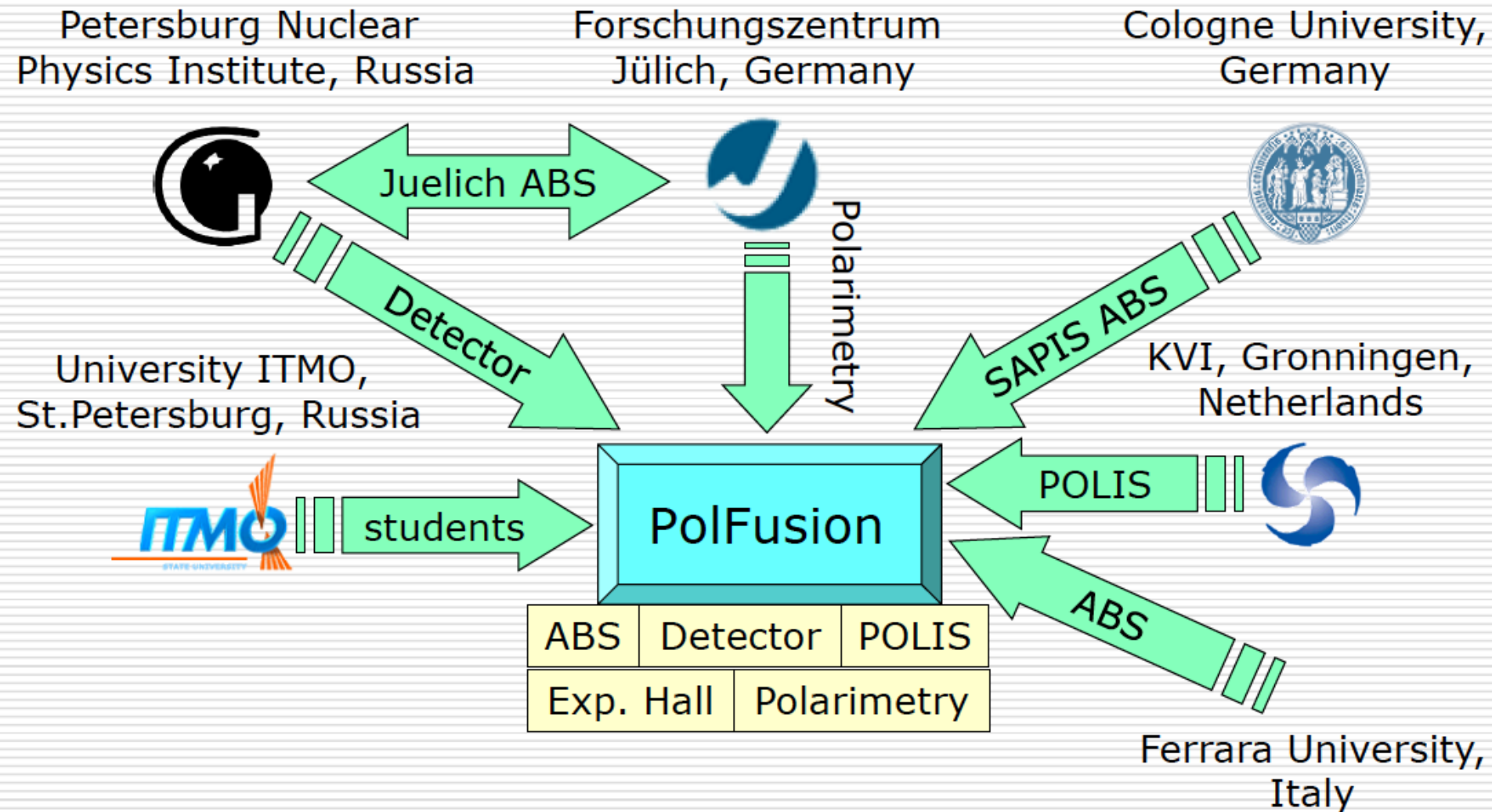
3 week beam time

Lamb-Shift
Polarimeter

LSP

n (2.4 MeV),
 p (3.0 MeV)

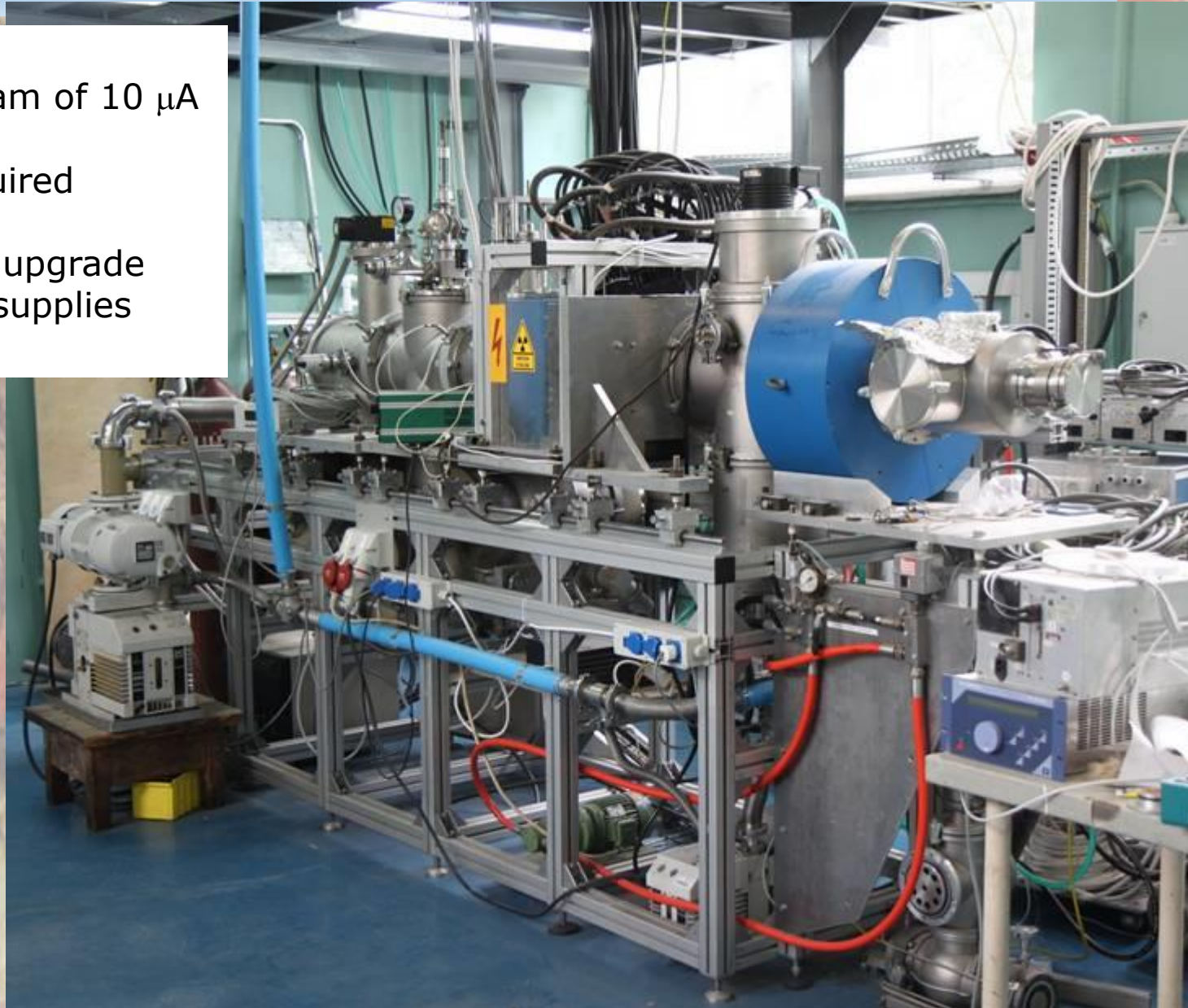
To fulfill this missing knowledge: PolFusion Collaboration



Polarized Ion Source - POLIS status

POLIS

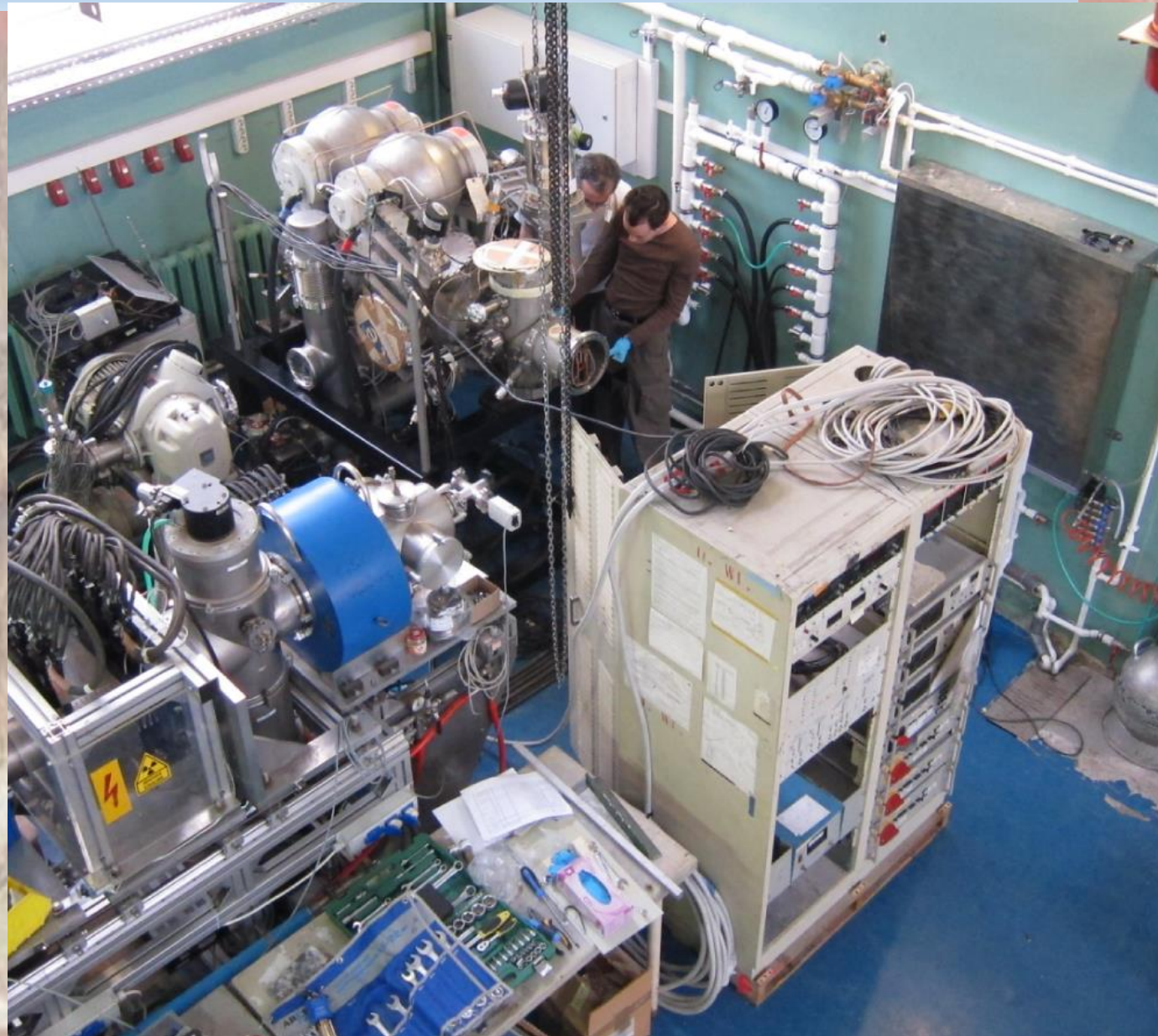
- ✓ Obtained ion beam of 10 μA
- ❑ Unstable beam
- ❑ New ionizer required (100kV)
- ❑ Vacuum system upgrade
- ❑ Magnets power supplies upgrade



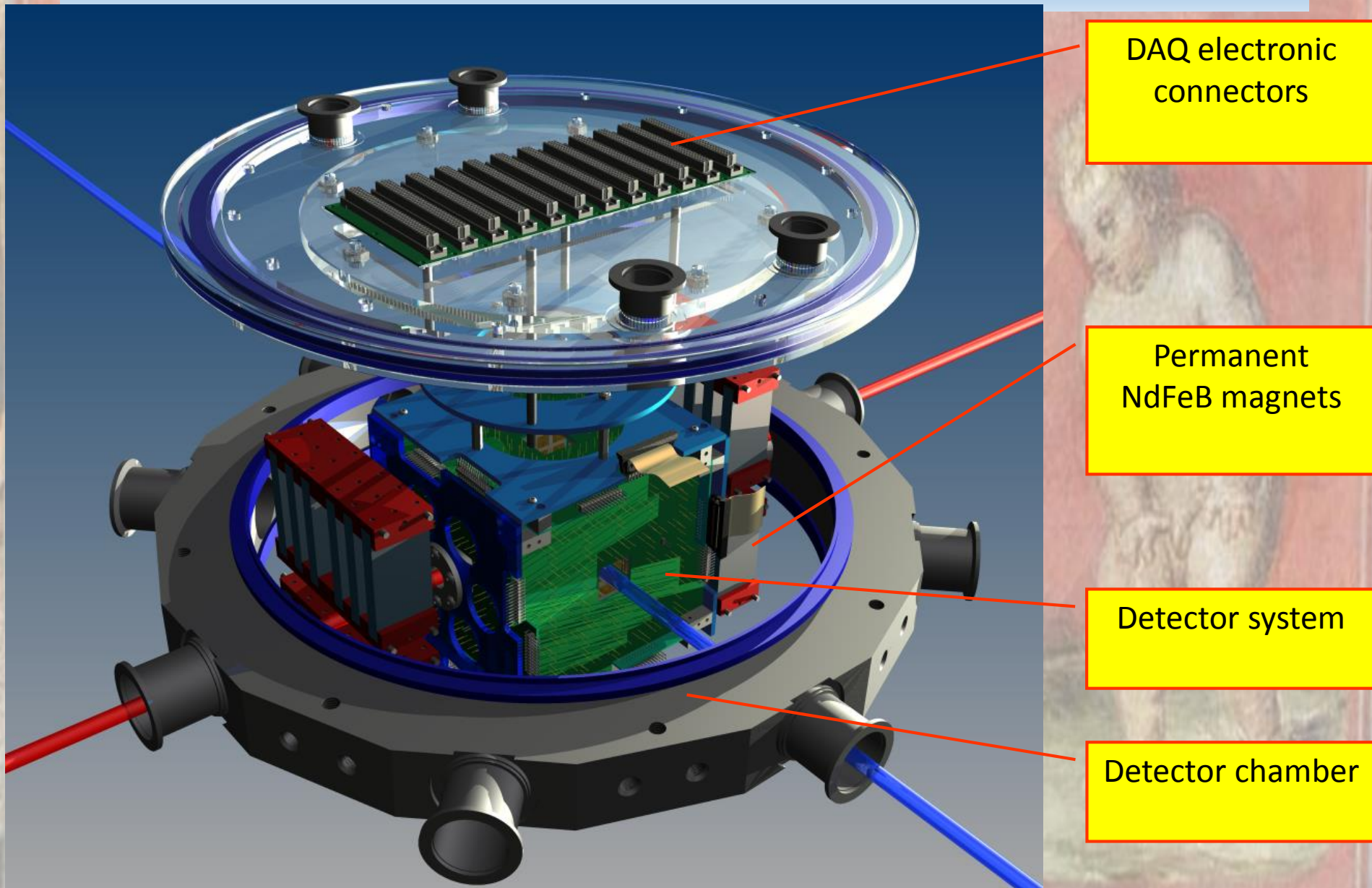
Polarized Atomic Beam Source

Ferrara ABS

- ✓ New generator for dissociator
- ✓ New nozzle cooling
- ✓ New control system
- RF transition units
- Vacuum system upgrade

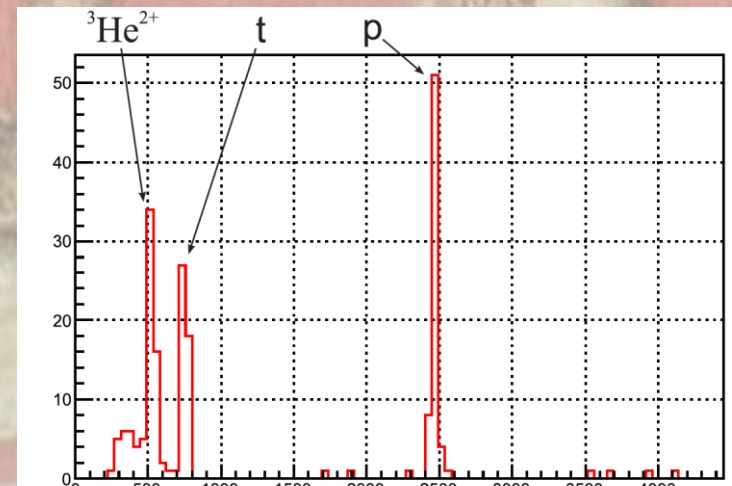
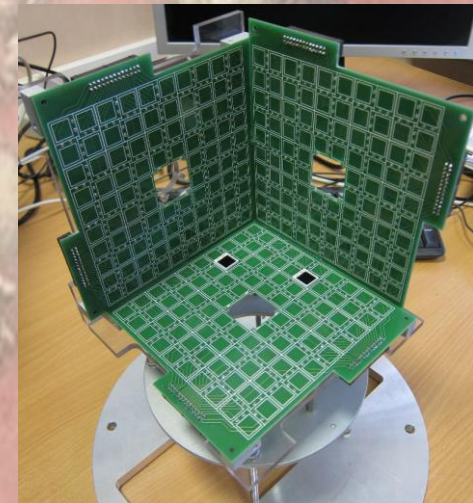
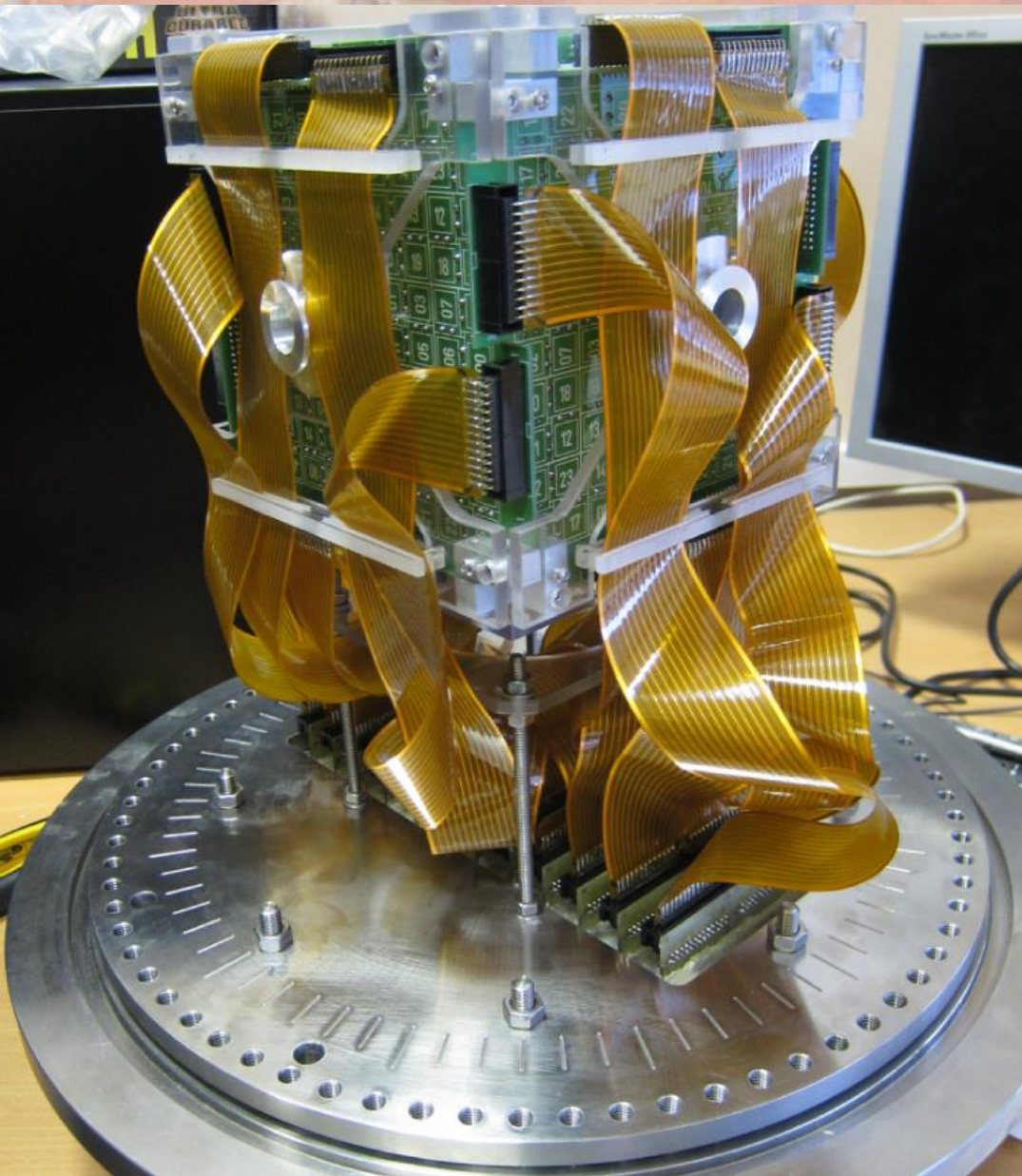


The detector System

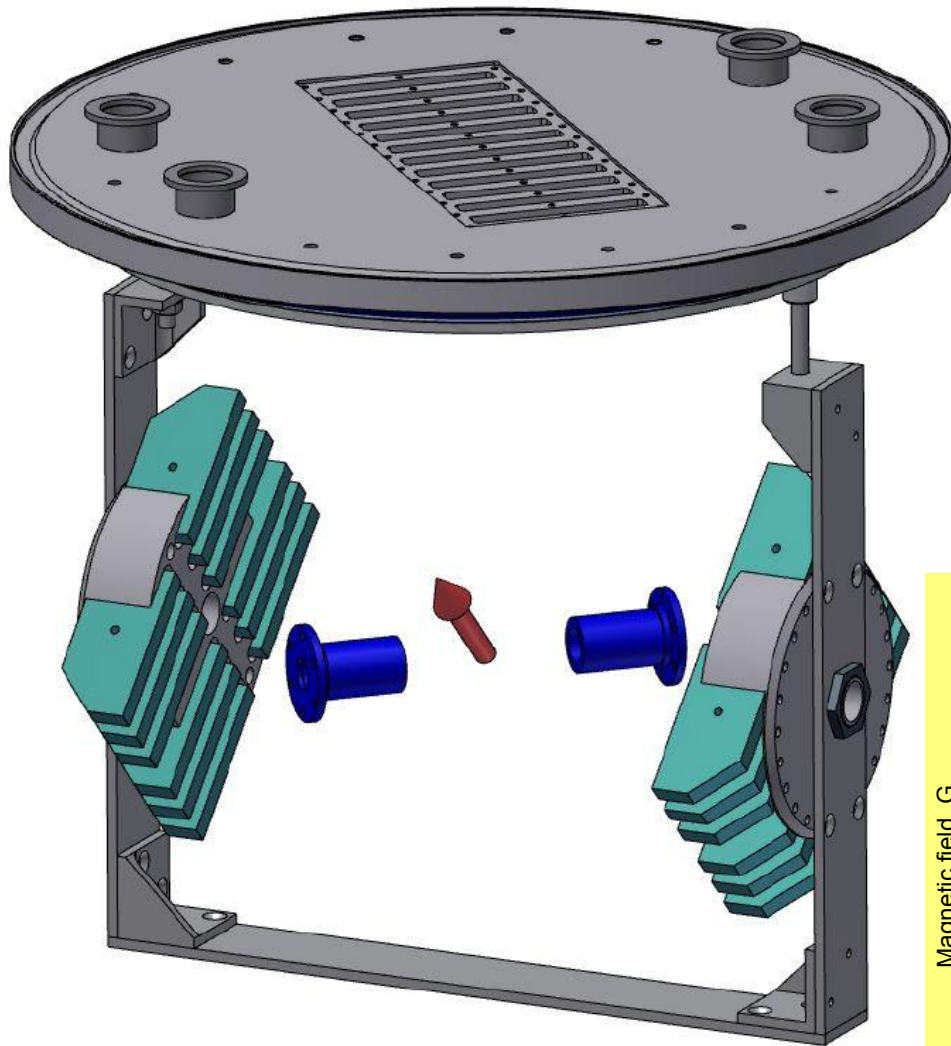


The detector System

- 4- π detector with 51% filling
- 576 Hamamatsu PIN-diodes (S3590-09)
- Diode active area: 1 cm²
- depleted layer: ~ 300 μ m
- good energy resolution (< 50 keV)
- low back voltage (< 50 V)

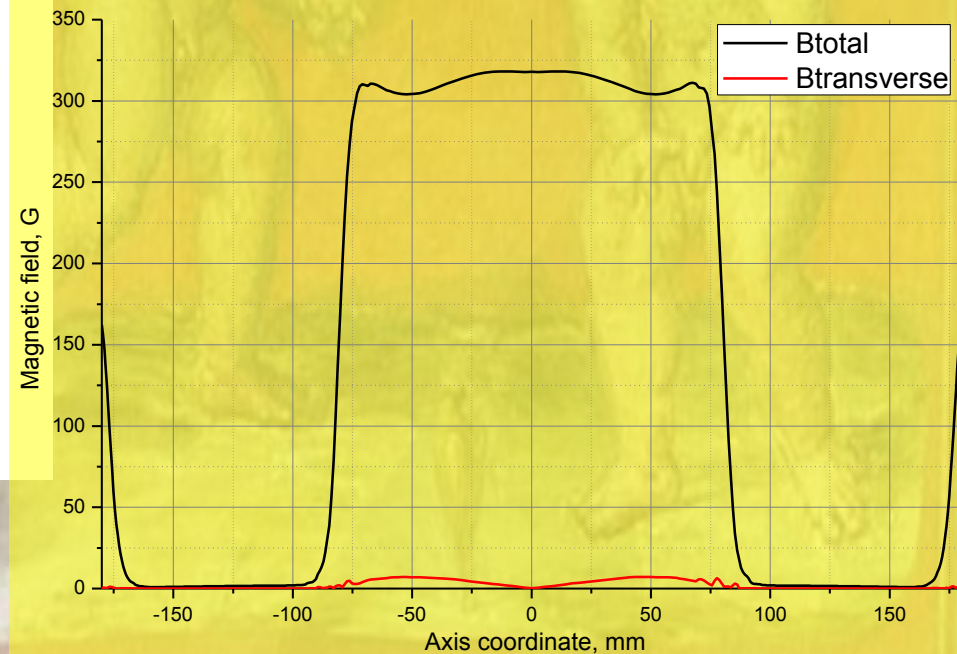


The magnet for the holding field

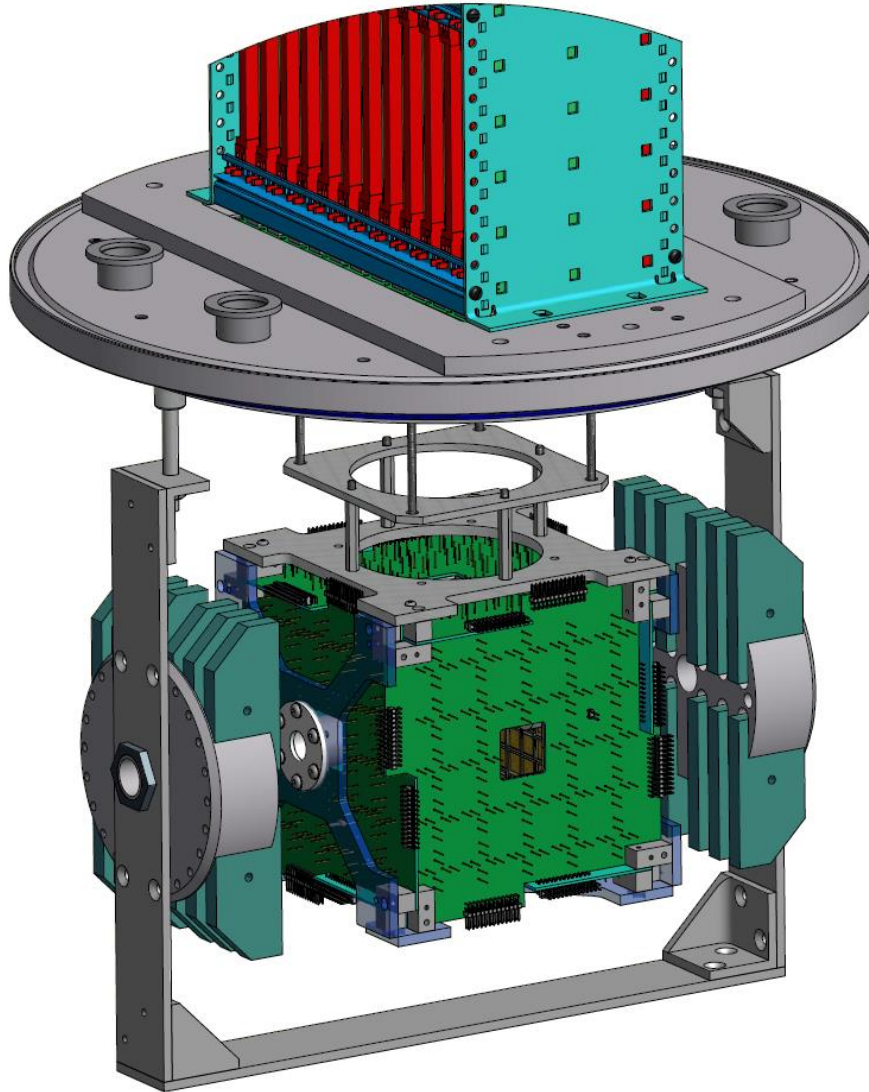
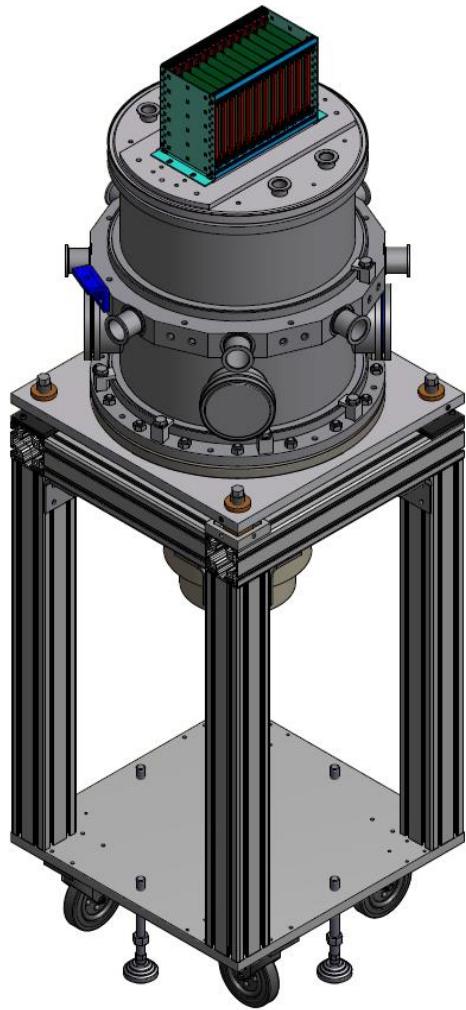


$$B = 300 \text{ G} = 2.5 B_c$$

Magnetic field
generated by 24
permanent magnets
80x40x10 mm with
magnetic field at the surface
1.25 T (N40) - NdFeB



The chamber hosting the detector and the magnet



Conclusion

- Data on **d-d spin dependent cross sections** will provide useful and expected information in many fields: **few body systems, nuclear fusion** with polarized fuel and **astrophysics**.
- The **experimental setup** in Gatchina is under **construction**.
- We are looking forward for financial supports for hardware and Phd students.

Meanwhile we are exchanging **information, ideas, and opinions** on **Nuclear Fusion with Polarized Fuel**.

As a result we published a collection of **contributions** in this fields in which it's possible to find **more details** and **correlated arguments**.

Springer Proceedings in Physics 187

Giuseppe Ciullo
Ralf Engels
Markus Büscher
Alexander Vasilyev *Editors*

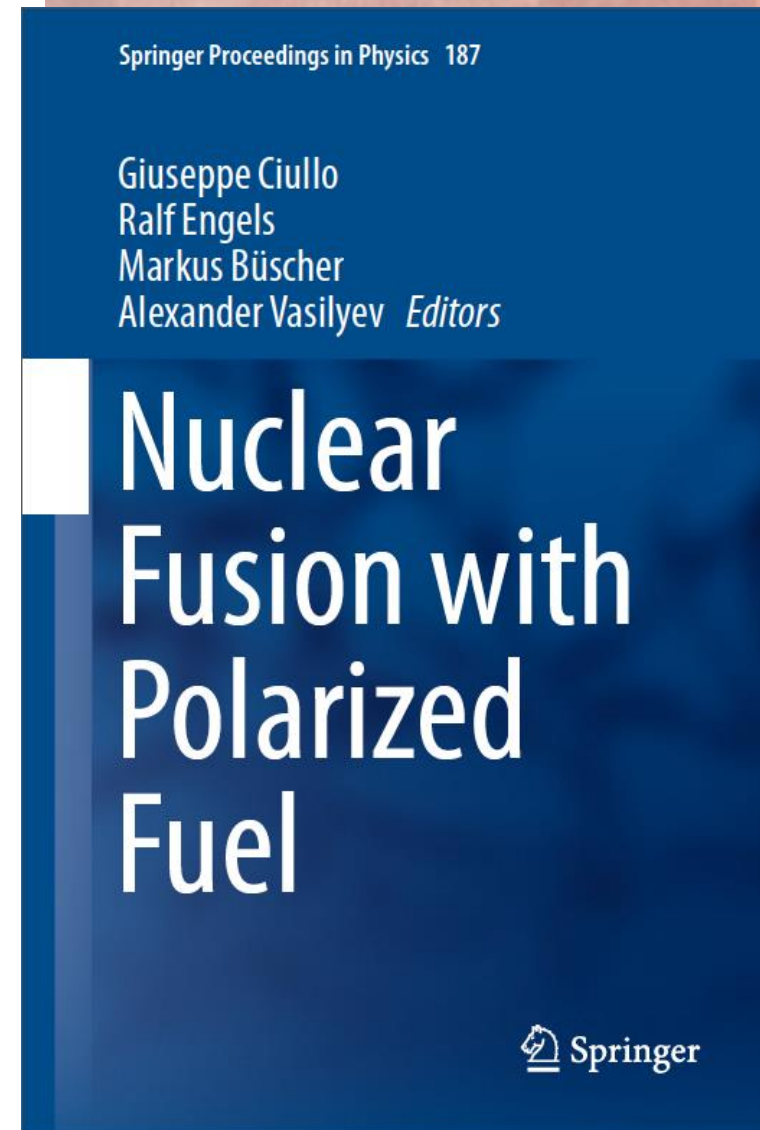
Nuclear Fusion with Polarized Fuel

 Springer

2016 Springer international Publishing

Spare slide

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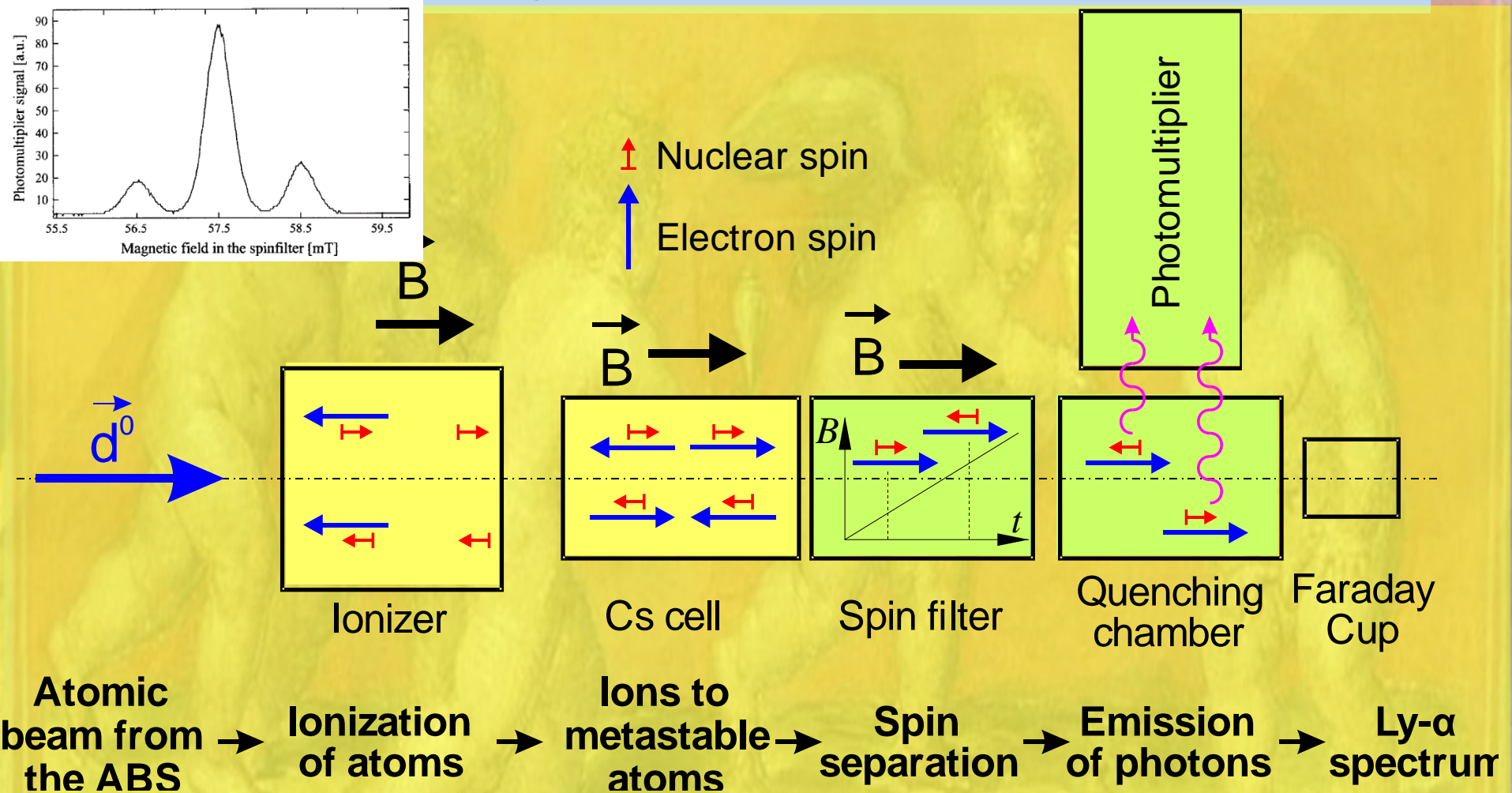
Giuseppe Ciullo
Ralf Engels
Markus Büscher
Alexander Vasilyev *Editors*

Nuclear Fusion with Polarized Fuel

 Springer

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Polarimetry for atomic and ion beam



R.Engels et al.
Precision Lamb-shift polarimeter for polarized atomic and ion beams
Rev. Sci. Instrum., Vol. 74, No. 11, 4607 (2003)