PolFusion: investigating fully polarized thermonuclear fusion in PNPI

Ivan Solovyev

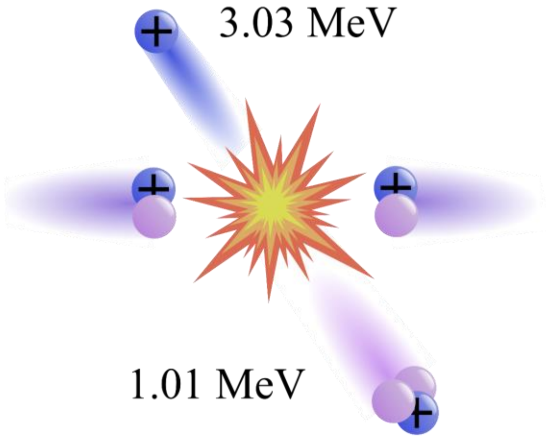
research scientist

PNPI - NRC KI

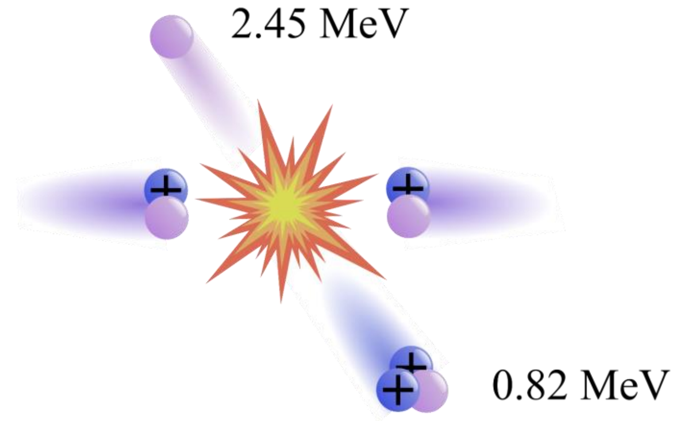
Thermonuclear reactions

PolFusion

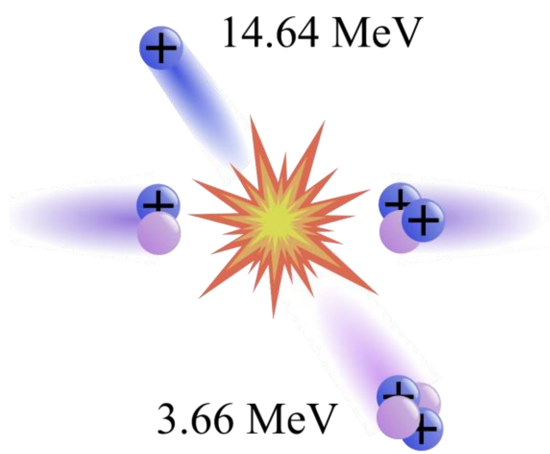
$$d + d \rightarrow t + p + 4.04\ MeV$$

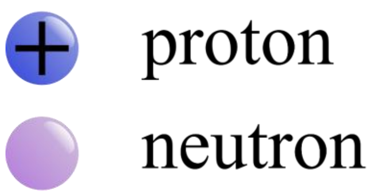


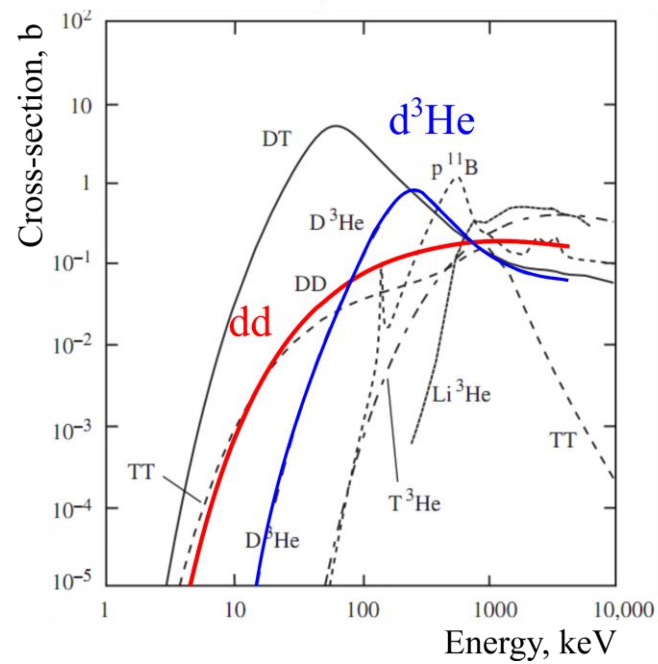
$$d + d \rightarrow {}^{3}He^{2+} + p + 3.27\ MeV$$



$$d + {}^{3}He^{2+} \rightarrow {}^{4}He^{2+} + p + 18.3\ MeV$$

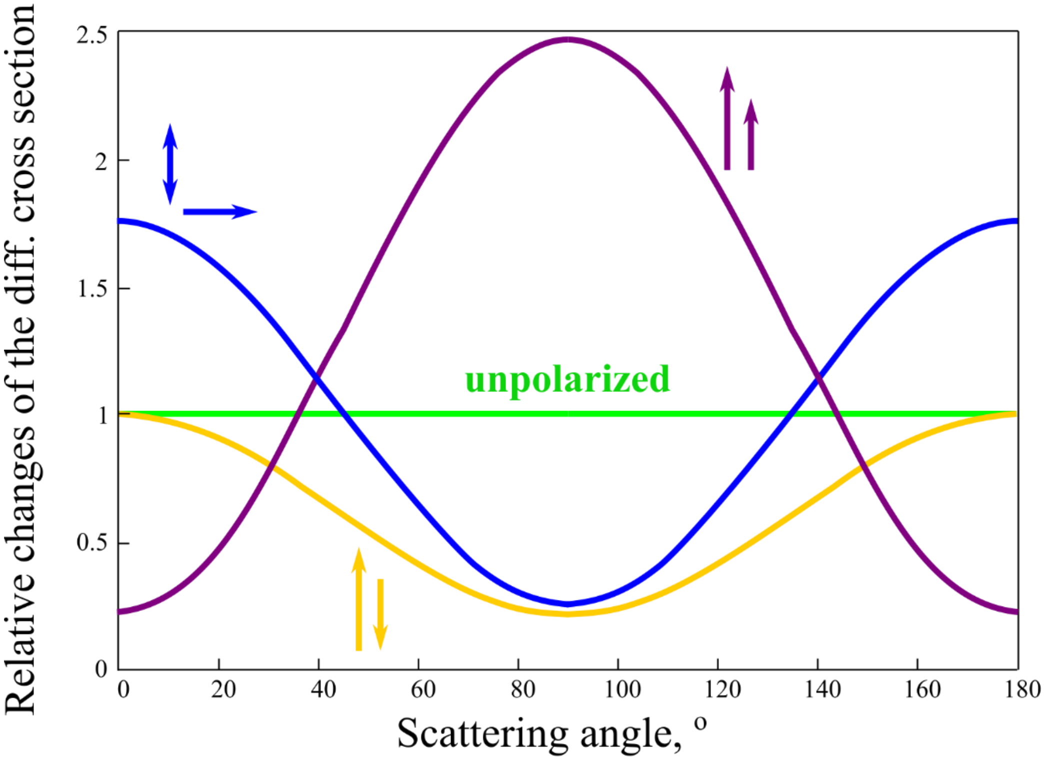




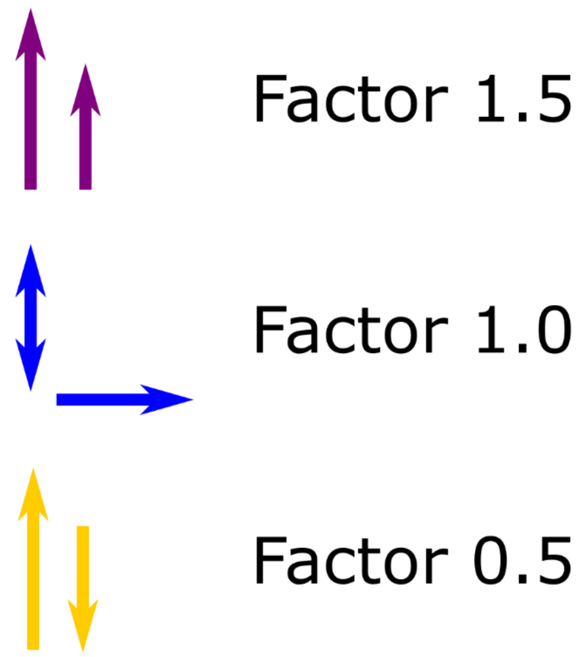


Polarization advantages

1. Cross sections increasement
2. Focussing of the neutrons
3. Suppresion of the neutron channel



Total cross section



$^3He(d,p)\alpha$ Exp.: Ch. Leemann et al., Helv. Phys. Acta **44**, 141 (1971)

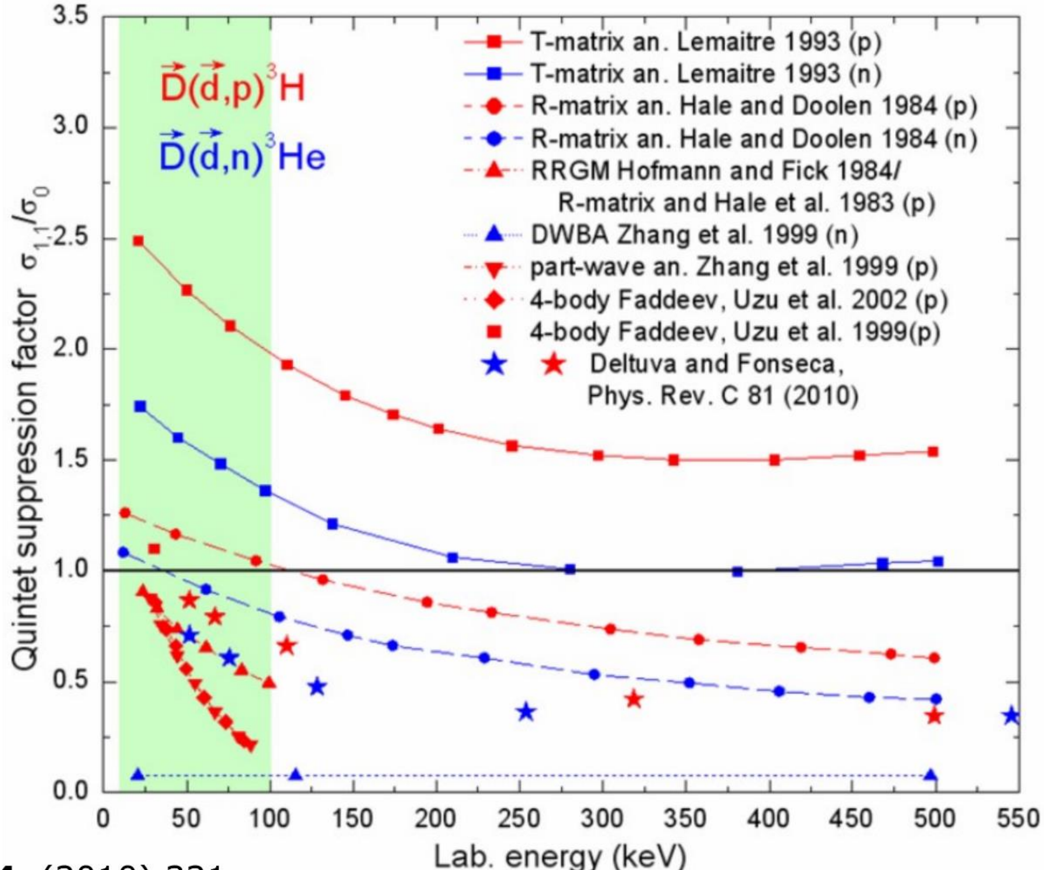
$t(d,n)\alpha$ Theor.: G. Hupin et al., Nature Com. **10**, 321(2019)

Quintet Suppression Factor (QSF)

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

$$\sigma_0 = \frac{1}{9}\left(\underbrace{2\sigma_{1,1}}_{\text{Quintet}} + \underbrace{4\sigma_{1,0}}_{\text{Triplet}} + \underbrace{\sigma_{0,0} + 2\sigma_{1,-1}}_{\text{Singlet}}\right)$$

$$QSF = \frac{33}{16} + \frac{1}{8}A_{zz} + \frac{9}{4}C_{z,z} + \frac{1}{16}C_{zz,zz}$$



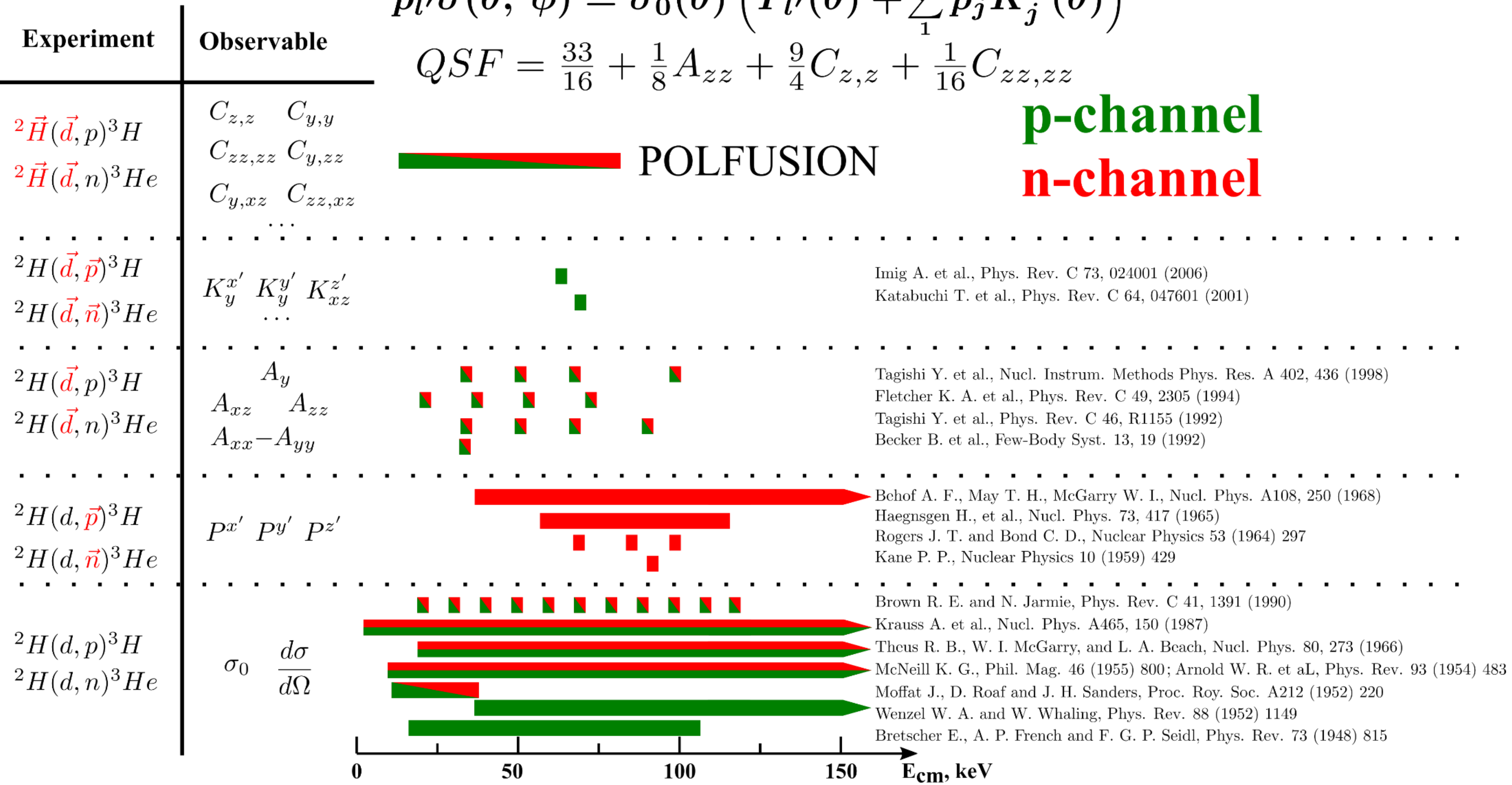
H. Paetz gen. Schieck Eur. Phys. J. A **44**, (2010) 321;
H. Paetz gen. Schieck Nuclear physics with polarized particles (Springer Verlag, Berlin, 2012);
H. Paetz gen. Schieck Few-Body Syst. **54** (2013) 2159;
Gerald G. Ohlsen, Rep. Prog. Phys. **35**, 717 (1972)

Review of experiments

$$\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(1 + \sum_1^9 p_j^b A_j^b(\theta) + \sum_1^9 p_j^t A_j^t(\theta) + \sum_1^9\sum_1^9 p_j^b p_k^t C_{j,k}(\theta)\right)$$

$$p_{l'}\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(P_{l'}(\theta) + \sum_1^9 p_j K_j^{l'}(\theta)\right)$$

$$QSF = \frac{33}{16} + \frac{1}{8}A_{zz} + \frac{9}{4}C_{z,z} + \frac{1}{16}C_{zz,zz}$$

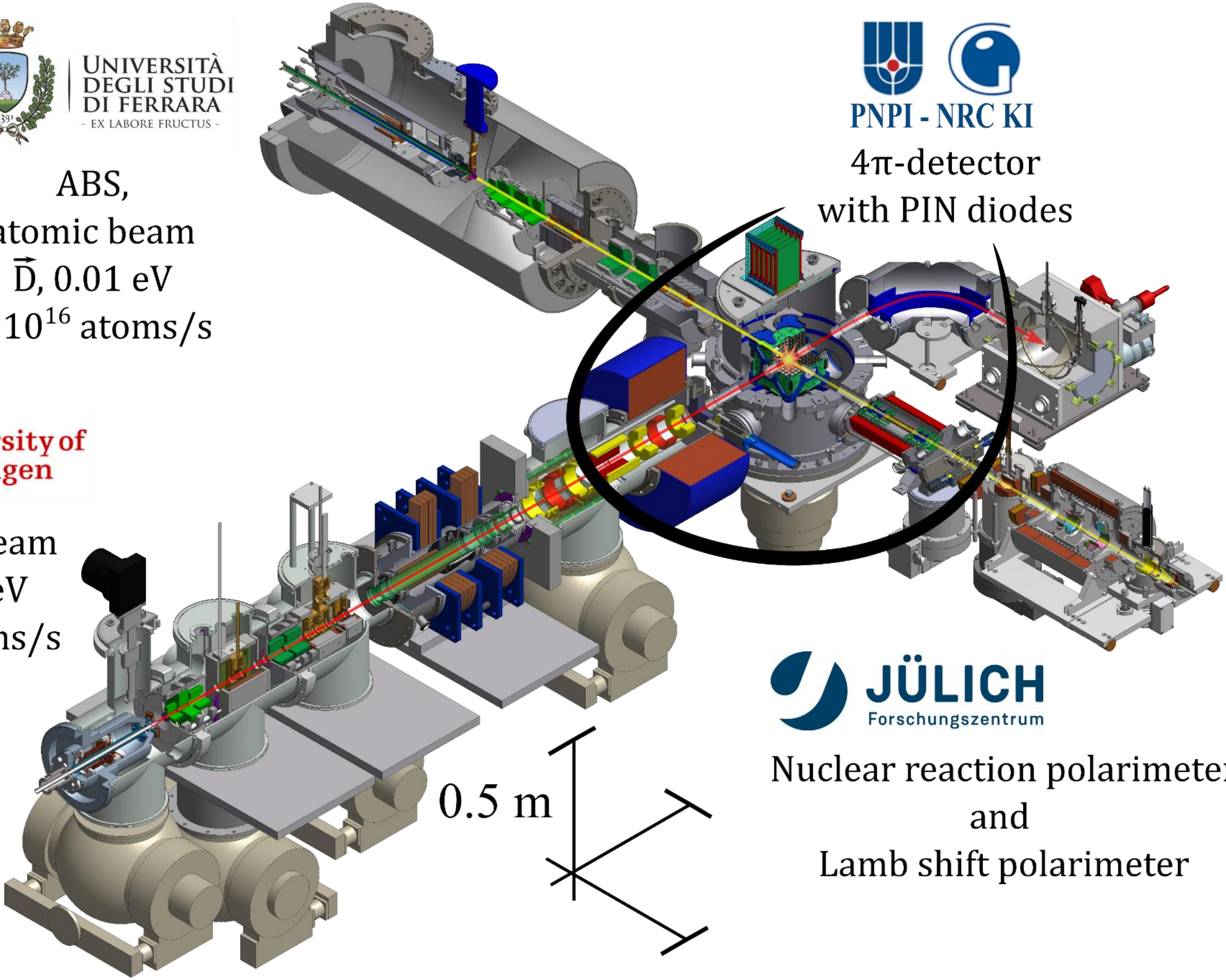


POLFUSION

Università degli Studi di Ferrara
- EX LABORE FRUCTUS -

ABS,
atomic beam
$\vec{D}$, 0.01 eV
$4{\cdot}10^{16}$ atoms/s

PNPI - NRC KI
4π-detector
with PIN diodes



university of groningen

POLIS, ion beam
$\vec{d}$, 10-75 keV
$1.2{\cdot}10^{16}$ atoms/s
>15 μA

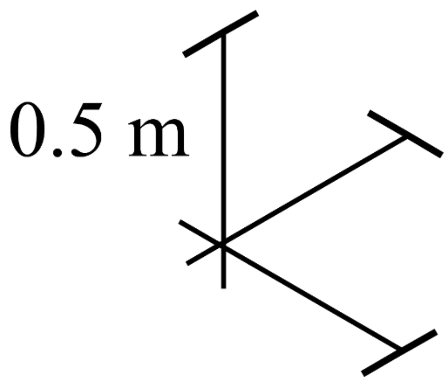
JÜLICH
Forschungszentrum

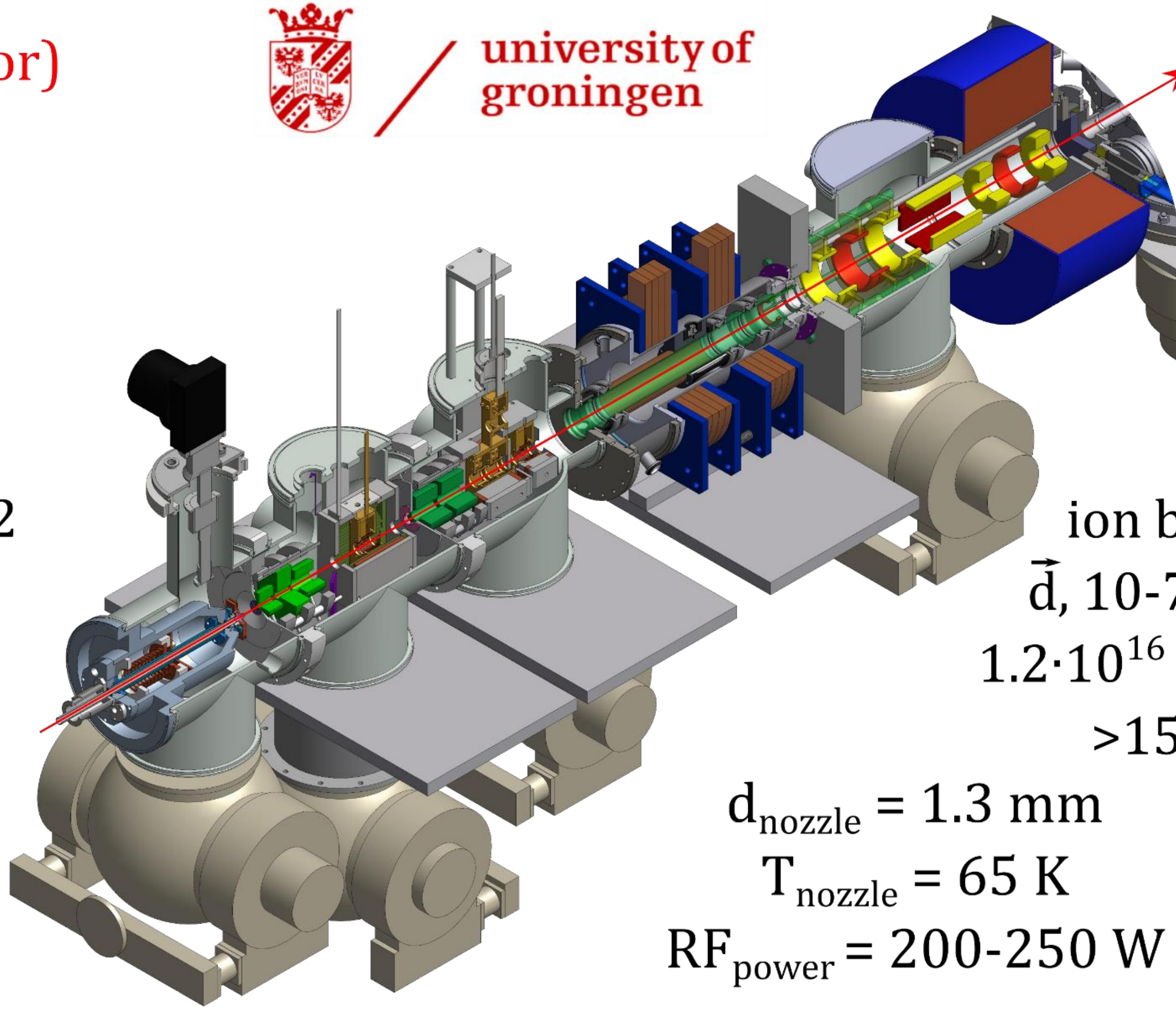
Nuclear reaction polarimeter
and
Lamb shift polarimeter

POLarized Ion Source (POLIS)

p_z (vector)	p_{zz} (tensor)
±2/3	0
0	+1
0	-2
-1/3	±1
+1/3	±1
±1/3	-1/2

university of groningen





ion beam
$\vec{d}$, 10-75 keV
$1.2\cdot10^{16}$ atoms/s
>15 μA

d_{nozzle} = 1.3 mm
T_{nozzle} = 65 K
RF_{power} = 200-250 W

Polarizer:

Sextupoles + WFT + Sextupoles + WFT + SFT1 (460 MHz) +SFT2 (350 MHz)

Atomic Beam Source (ABS)

p_z (vector)	p_{zz} (tensor)
-2/3	0
0	+1
-1/3	+1
-1	+1
±1/2	-1/2

UNIVERSITÀ DEGLI STUDI DI FERRARA
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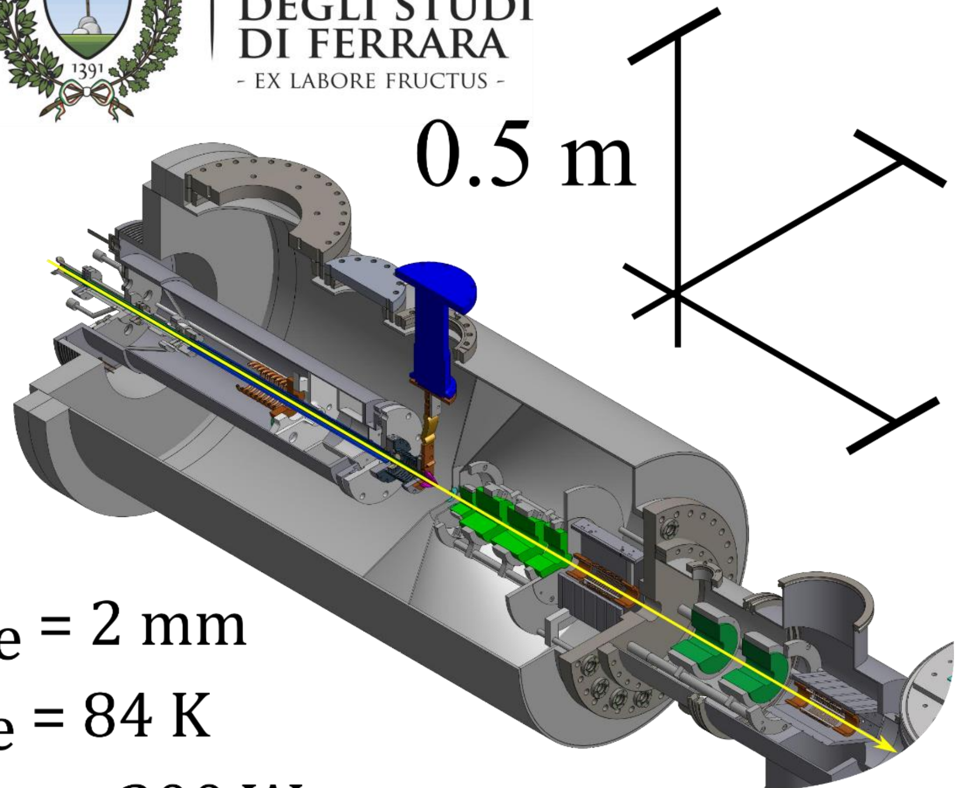


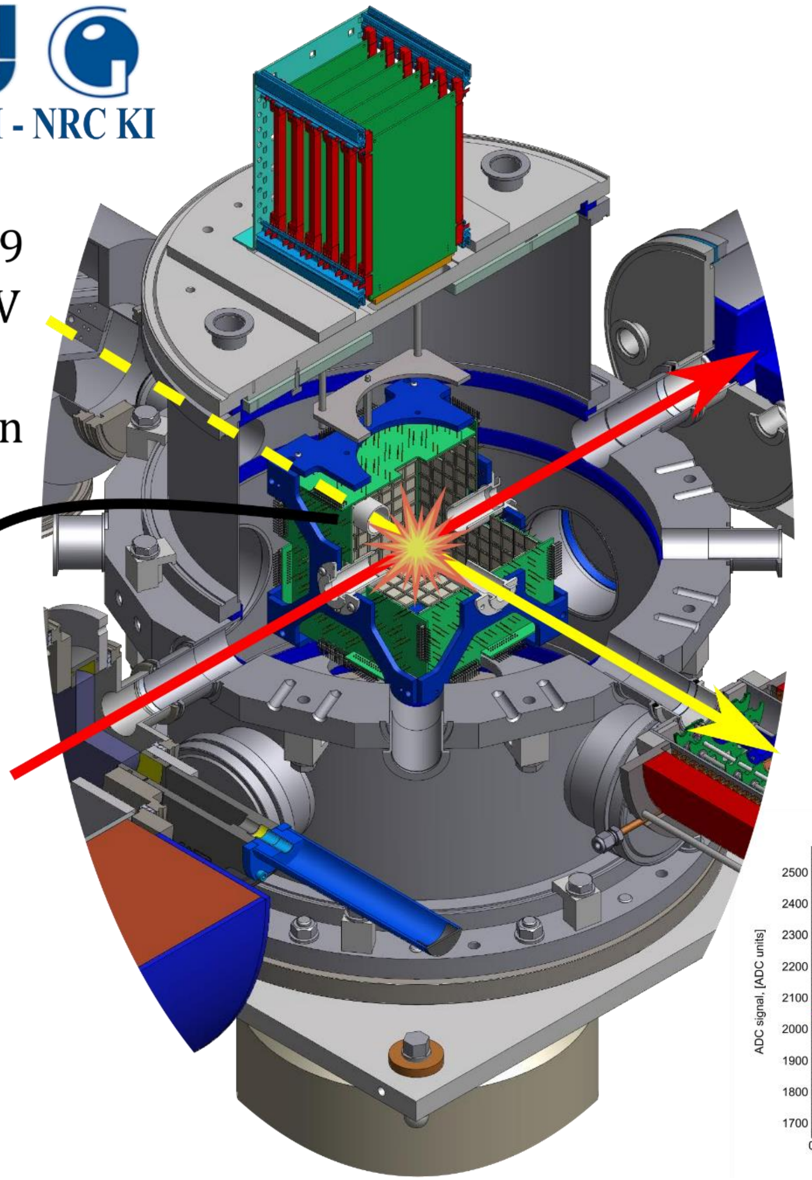
atomic beam $\vec{D}$, 0.01 eV
$2 \cdot 10^{16}$ atoms/s

d_{nozzle} = 2 mm
T_{nozzle} = 84 K
RF_{power} = 300 W

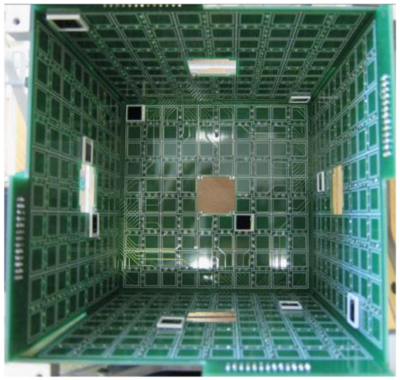
Polarizing system:

Sextupoles + Quadrupoles + MFT + Sextupoles + MFT

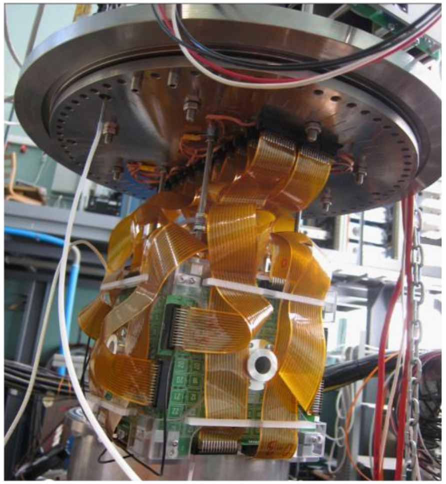
4π-detector



576 PIN diodes
Hamamatsu S3508-09
can detect 0.2 - 4 MeV
charged particles
with energy resolution
< 50 keV

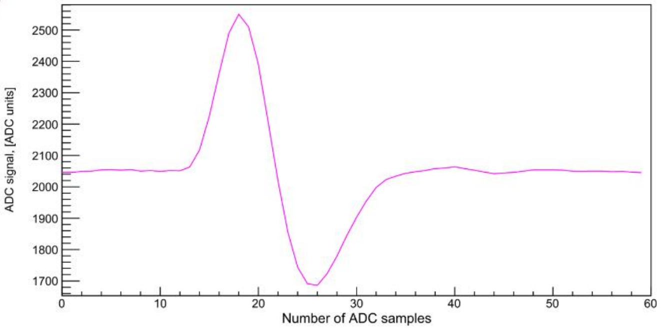


51% effective coverage

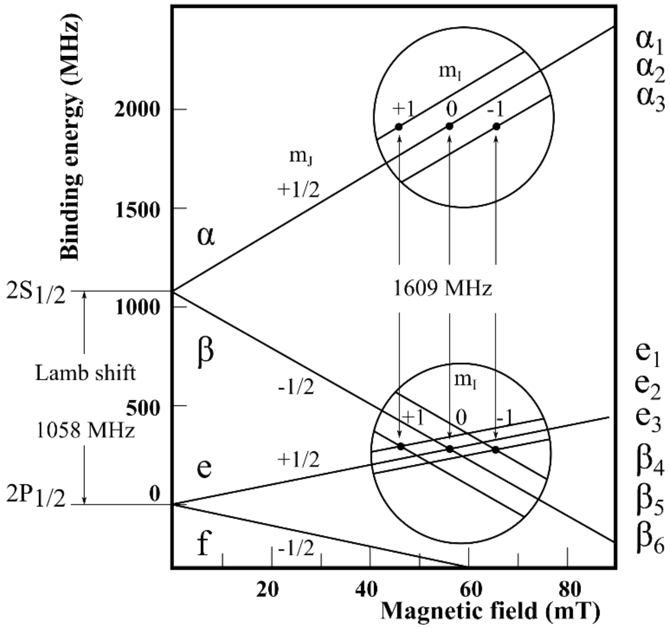


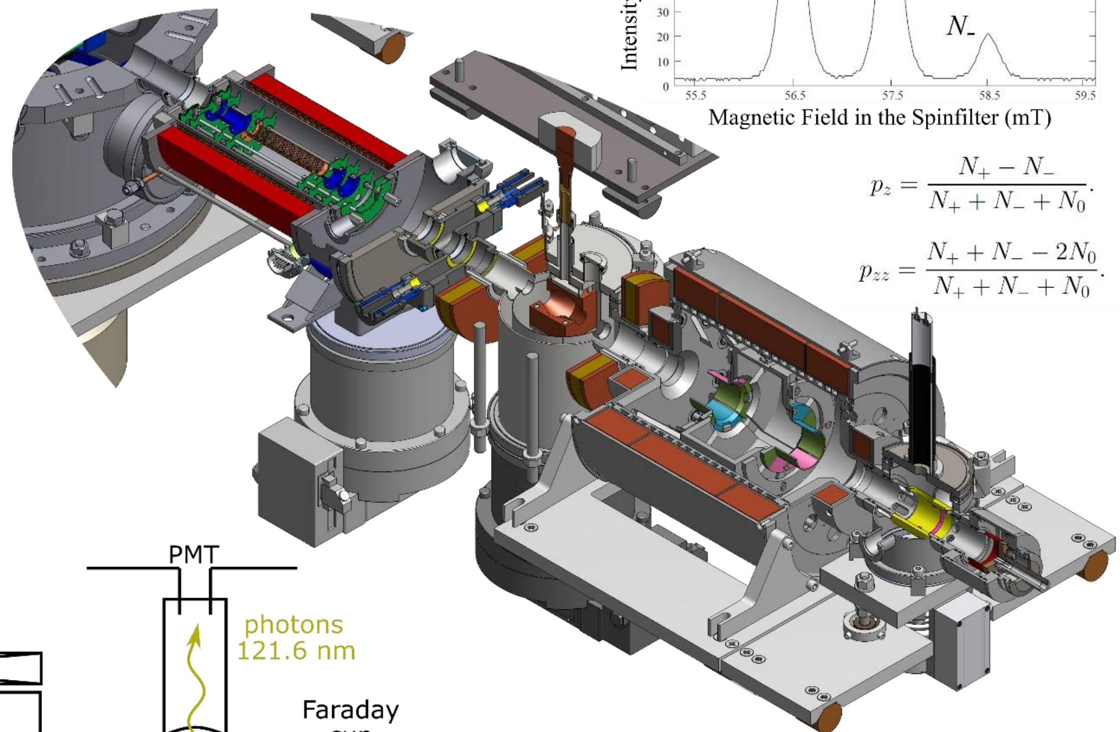
10 ns accuracy of recording
the time of signal

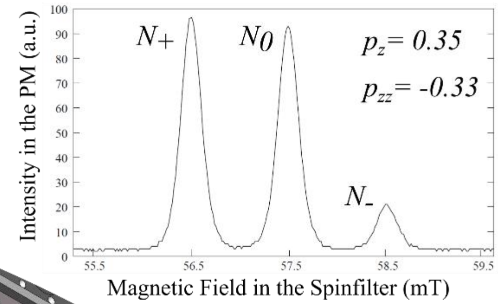
typical signal:



Lamb Shift Polarimeter (LSP)

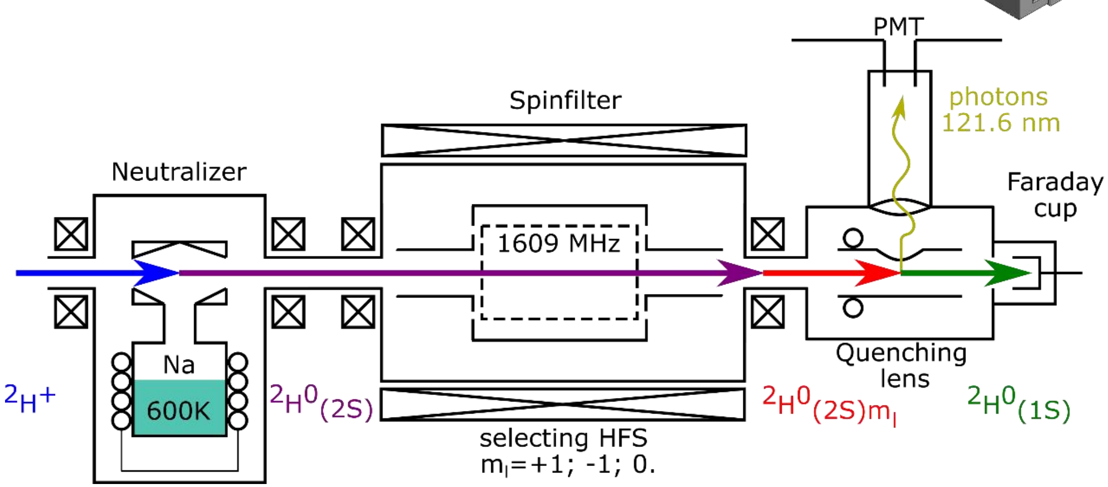






$$p_z = \frac{N_+ - N_-}{N_+ + N_- + N_0}.$$

$$p_{zz} = \frac{N_+ + N_- - 2N_0}{N_+ + N_- + N_0}.$$



Nuclear Reaction Polarimeter (NRP)

$$\frac{L-R}{L+R} = \frac{\frac{3}{2}P_Z \sin\beta\, A_y}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{yy} + \cos^2\beta A_{zz}]}$$

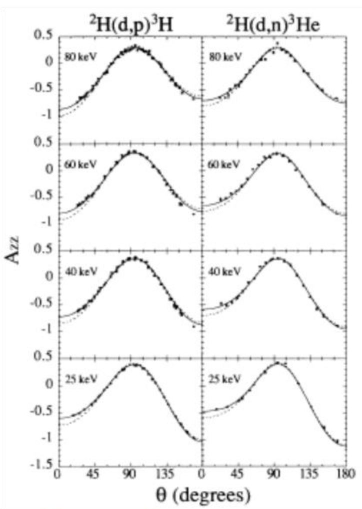
$$\frac{U-D}{U+D} = \frac{P_{ZZ}\sin\beta\,\cos\beta\, A_{xz}}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{xx} + \cos^2\beta A_{zz}]}$$

$$\frac{2(L-R)}{L+R+U+D} = \frac{\frac{3}{2}P_Z \sin\beta\, A_y}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]}$$

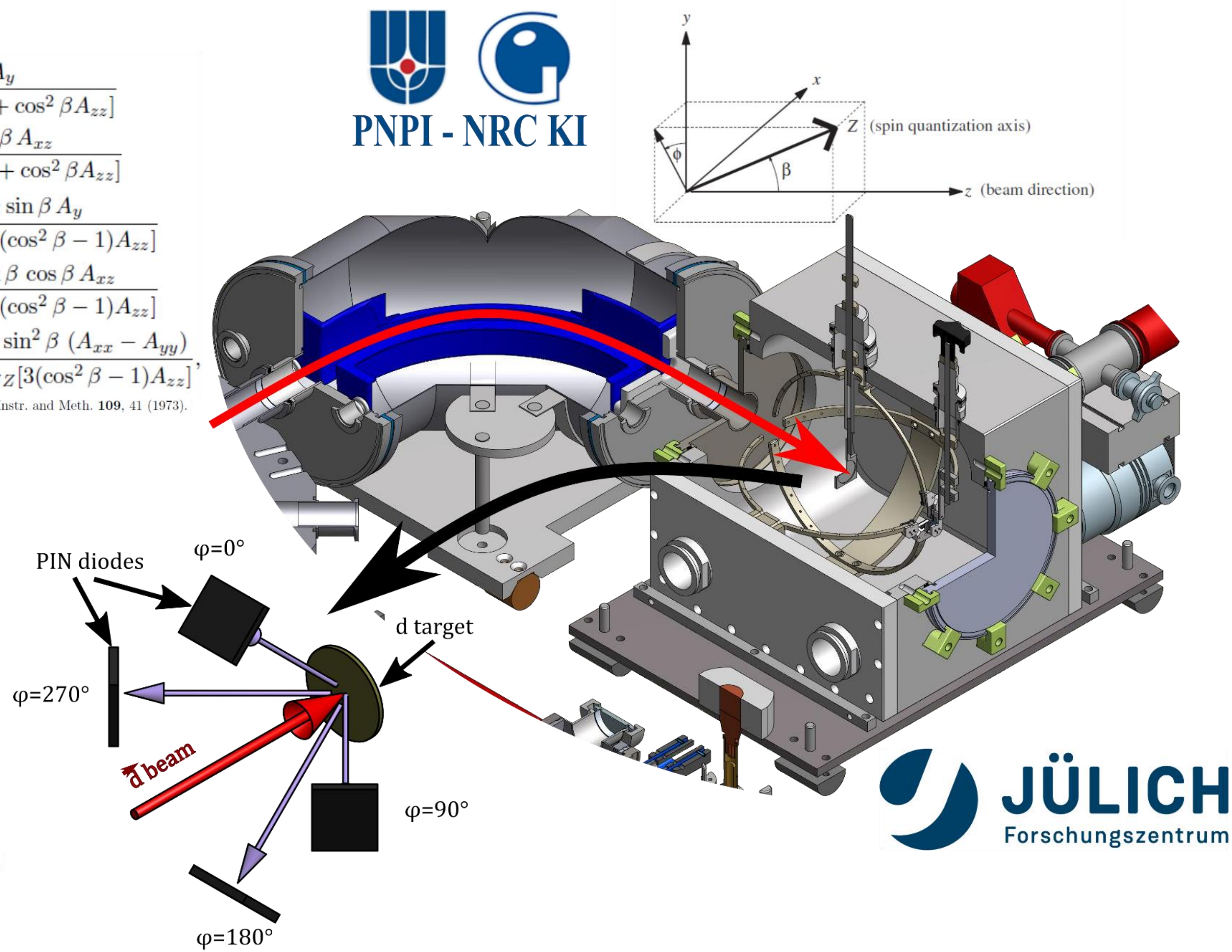
$$\frac{2(U-D)}{L+R+U+D} = \frac{P_{ZZ}\sin\beta\,\cos\beta\, A_{xz}}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]}$$

$$\frac{(L+R)-(U+D)}{L+R+U+D} = \frac{-\frac{1}{4}P_{ZZ}\sin^2\beta\,(A_{xx}-A_{yy})}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]},$$

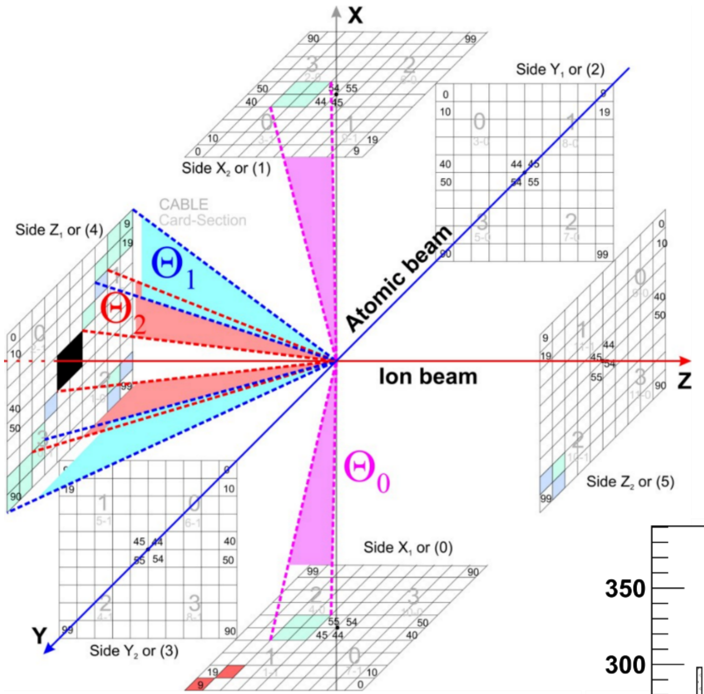
G.G Ohlsen, P.W. Keaton, Jr., Nucl. Instr. and Meth. **109**, 41 (1973).



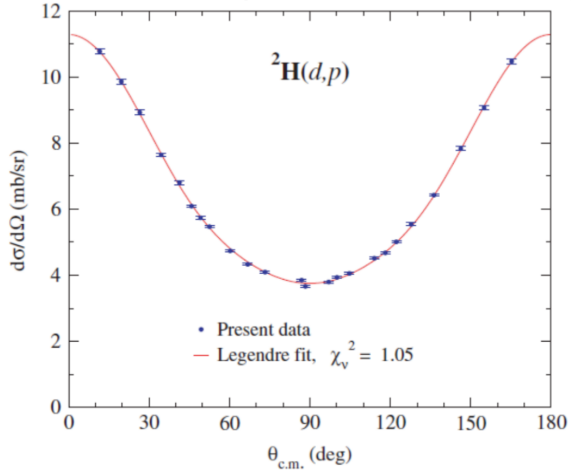
K. Fletcher, *et al.*, Phys. Rev. C **49**, 2305 (1994).

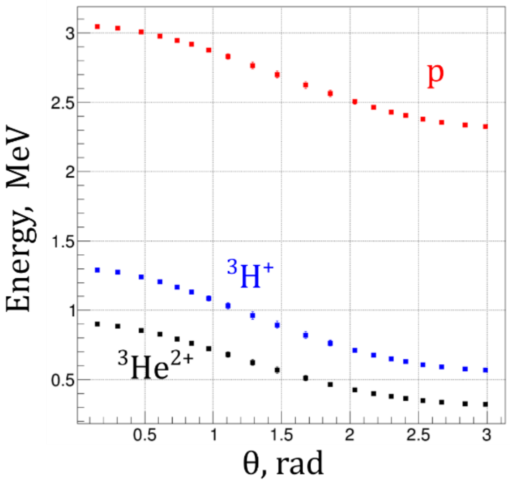


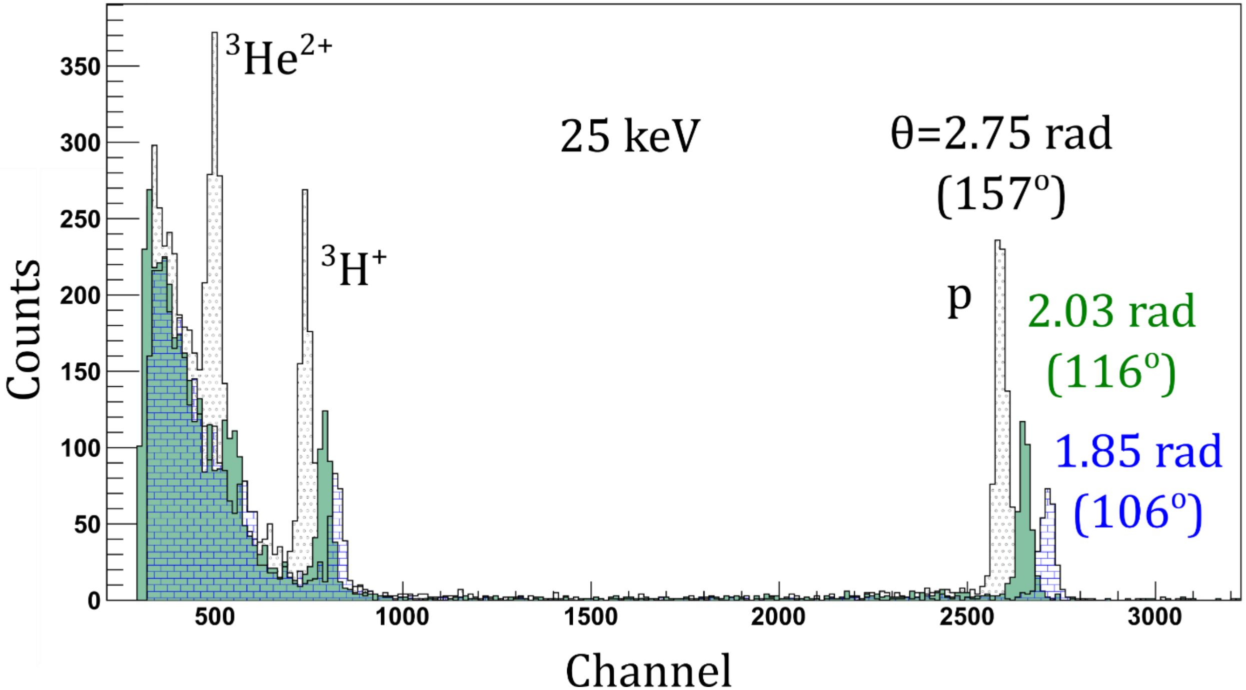
Test run 2020



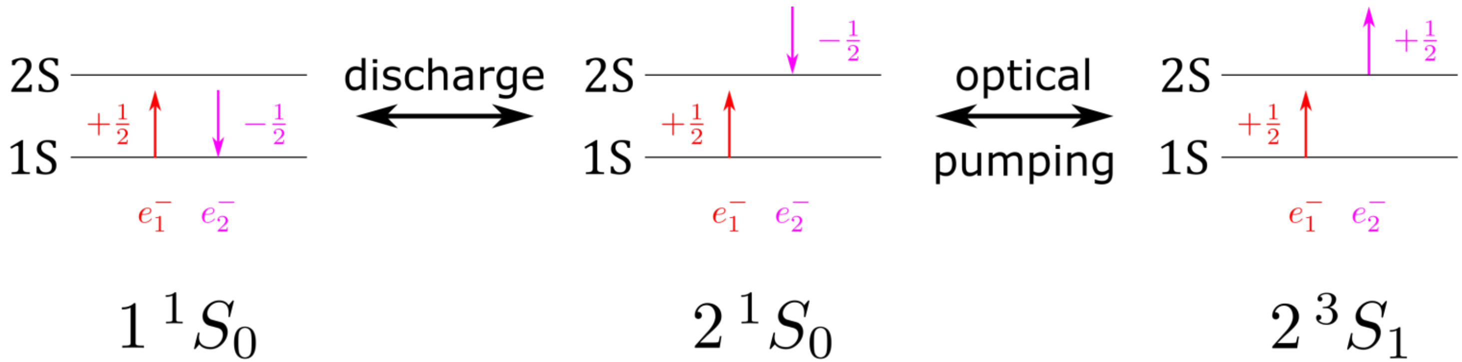
D.S. Leonard et al., Phys. Rev. C **73**, 045801 (2006).

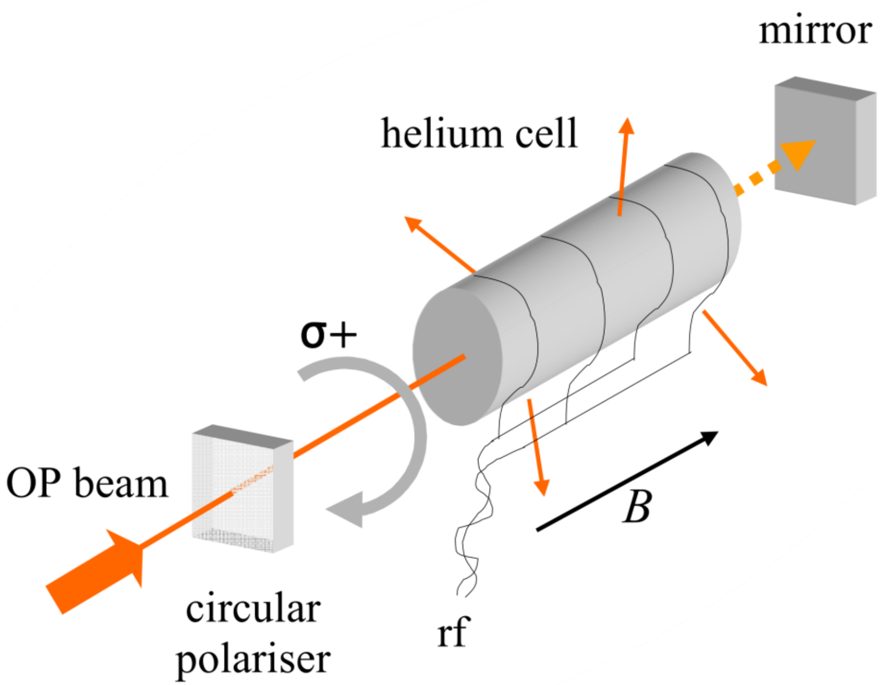


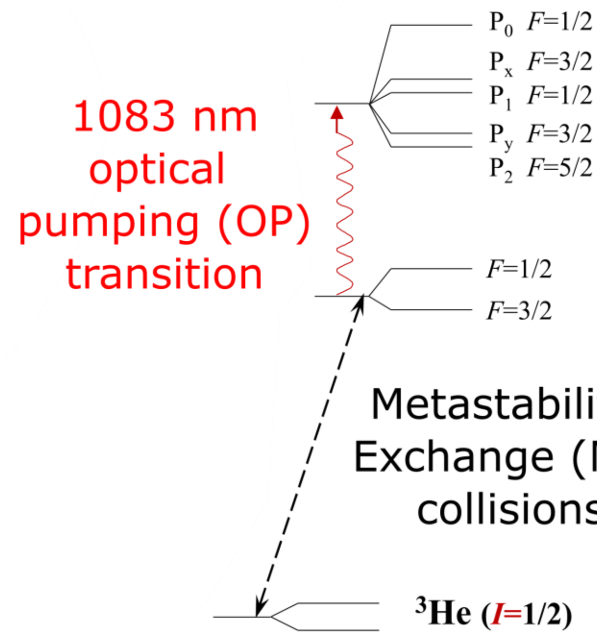




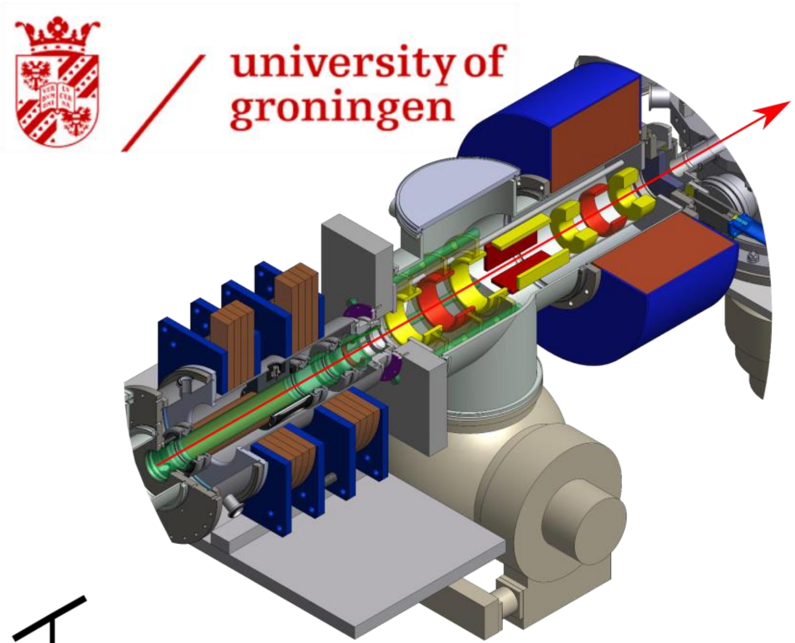
^{3}He polarizer (MEOP type)

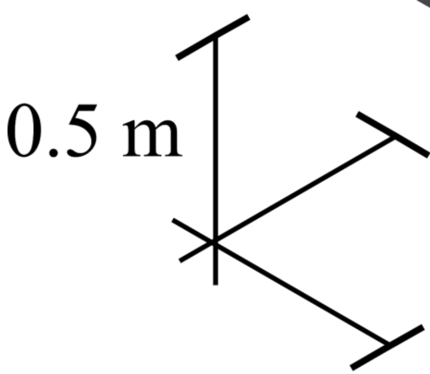






ionizing ^{3}He



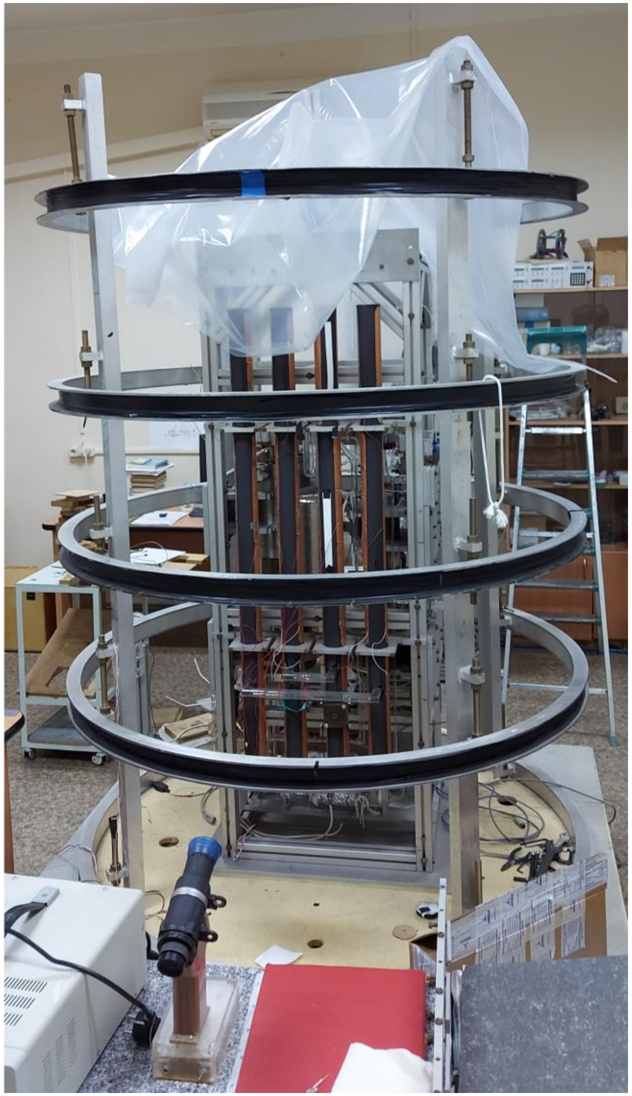


ion beam

$^3\vec{He}^{2+}$, 10-75 keV

polarization ~20%

ionization efficiency ~10^{-3}



Thank you for attention!

3He polarizer

PNPI - NRC KI

Applied physics

Pol Fusion

1st generation:

d + t ⟶ ^{4}He + n (17.6 MeV / 107 keV)

2nd generation:

d + d ⟶ t + p (4 MeV)

d + d ⟶ ^{3}He + n (3.3 MeV)

+

n + ^{6}Li ⟶ ^{4}He + t (4.8 MeV)

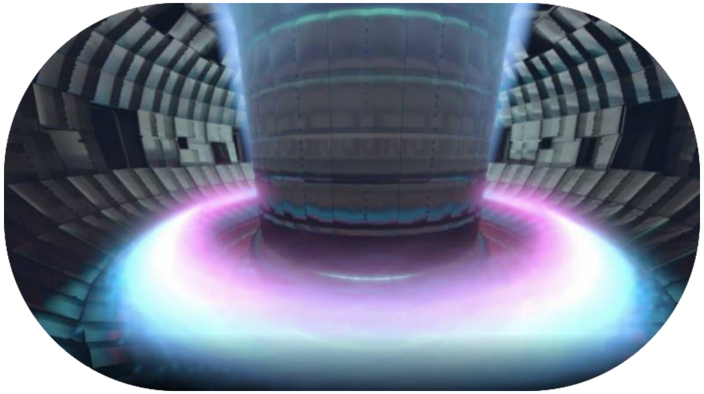
+

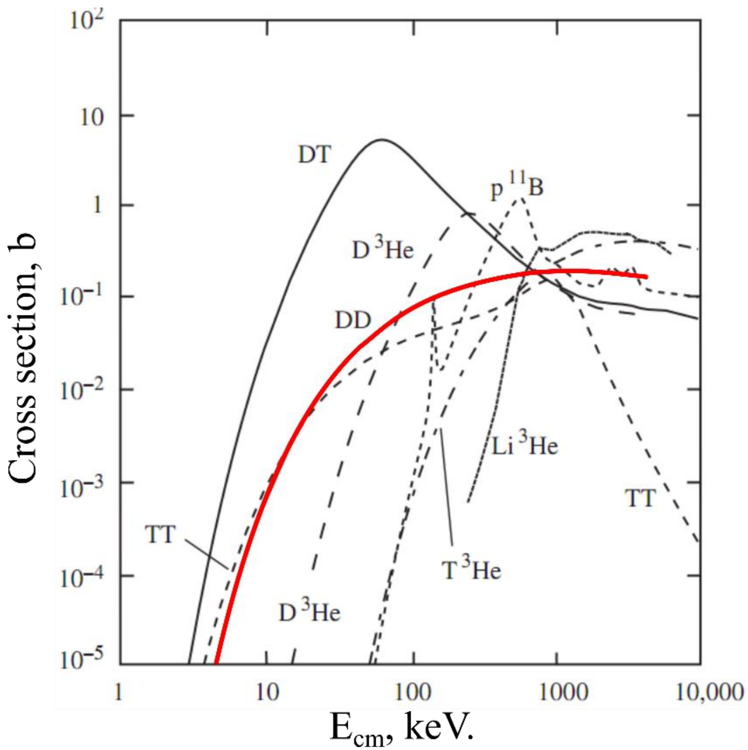
d + t ⟶ ^{4}He + n (17.6 MeV / 107 keV)

d + ^{3}He ⟶ ^{4}He + p (18.3 MeV / 430 keV)

3rd generation:

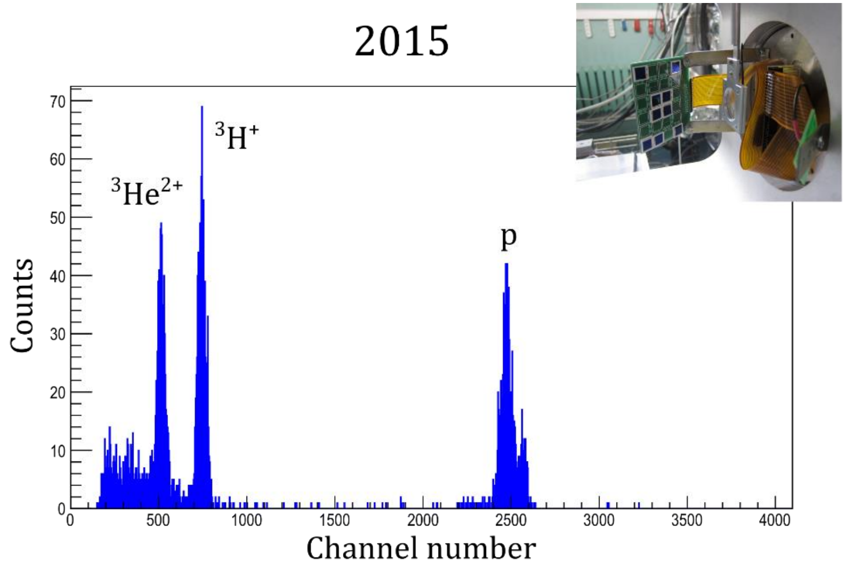
d + ^{3}He ⟶ ^{4}He + p (18.3 MeV / 430 keV)





Test runs

2015



Target: deuterated polymethyl methacrylate

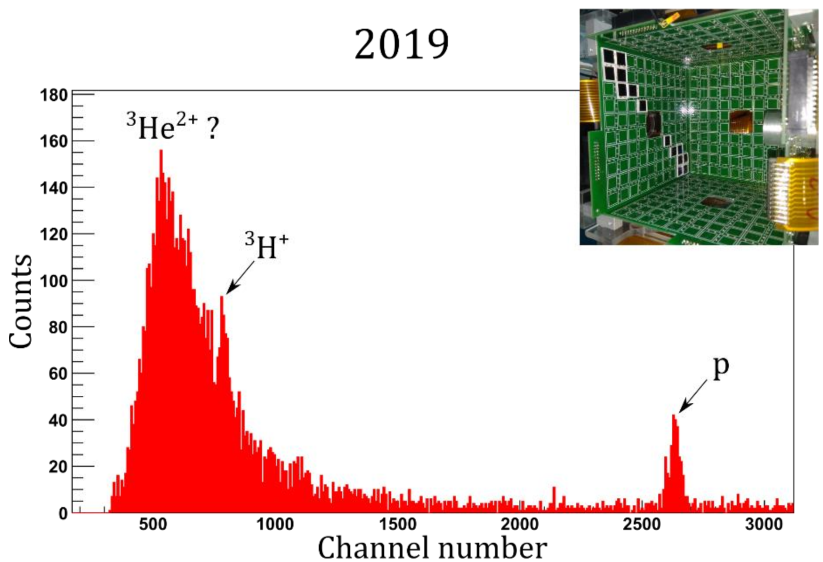
Density: $\sim 10^{17}$ atom/cm^2

Beam: 15 keV ~5μA

Period: ~3 h

Purpose: evaluating the signal quality
ADC calibration

2019



Target: heavy water vapor

Density: $\sim 10^{12}$ atom/cm^2

Beam: 10 keV ~10μA

Period: ~200 h

Purpose: simulation of the ABS
evaluation of cosmic background, form and sources of electronic background

ABS beam density: $2.7 \cdot 10^{11}$ atom/cm^2 at $4 \cdot 10^{16}$ atom/s

Asymmetries

PNPI - NRC KI

PolFusion

$$Y(\theta,\ \phi) = L \cdot \sigma(\theta,\ \phi)$$

$$\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(1 + \sum_1^9 p_j^b A_j^b(\theta) + \sum_1^9 p_j^t A_j^t(\theta) + \sum_1^9 \sum_1^9 p_j^b p_k^t C_{j,k}(\theta)\right)$$

Gerald G. Ohlsen, Rep. Prog. Phys. **35,** 717 (1972)

polarization sign as subscript: $(L_{POLIS,\ ABS})$

$$L_{++} = L_{-+} = L_{+-} = L_{--}$$

$$\mathcal{A}^b(\theta,\ \phi) = \frac{(Y_{++}+Y_{+-})-(Y_{-+}+Y_{--})}{Y_{++}+Y_{+-}+Y_{-+}+Y_{--}}$$

$$\mathcal{A}^t(\theta,\ \phi) = \frac{(Y_{++}+Y_{-+})-(Y_{+-}+Y_{--})}{Y_{++}+Y_{+-}+Y_{-+}+Y_{--}}$$

$$\mathcal{A}^{b,t}(\theta,\ \phi) = \frac{(Y_{++}+Y_{--})-(Y_{-+}+Y_{+-})}{Y_{++}+Y_{+-}+Y_{-+}+Y_{--}}$$

$C_{z,z}$ and $C_{zz,zz}$

$$\beta^b = \beta^t = 0^\circ :$$

$$\sigma(\theta,\ \phi) = \sigma_0(\theta)\left[1 + \tfrac{1}{2}p^b_{ZZ}A^b_{zz}(\theta) + \tfrac{1}{2}p^t_{ZZ}A^t_{zz}(\theta) + \tfrac{9}{4}p^b_Z p^t_Z C_{z,z}(\theta) + \tfrac{1}{4}p^b_{ZZ}p^t_{ZZ}C_{zz,zz}(\theta)\right]$$

$$\mathcal{A}^b(\theta,\ \phi) = \frac{2|p^b_{ZZ}|A^b_{zz}(\theta)}{4+9C_{z,z}} \qquad \mathcal{A}^t(\theta,\ \phi) = \frac{2|p^t_{ZZ}|A^t_{zz}(\theta)}{4+9C_{z,z}}$$

$$\mathcal{A}^{b,t}_Z(\theta,\ \phi) = \frac{9|p^b_Z||p^t_Z|C_{z,z}(\theta)}{4+2p^b_{ZZ}A^b_{zz}(\theta)+2p^t_{ZZ}A^t_{zz}(\theta)+p^b_{ZZ}p^t_{ZZ}C_{zz,zz}(\theta)}$$

$$\mathcal{A}^{b,t}_{ZZ}(\theta,\ \phi) = \frac{|p^b_{ZZ}||p^t_{ZZ}|C_{zz,zz}}{4+9|p^b_Z||p^t_Z|C_{z,z}}$$

$$p^b_Z = p^t_Z = \pm\tfrac{2}{3}$$

$$p^b_{ZZ} = p^t_{ZZ} = 0$$

$$\mathcal{A}^{b,t}_Z(\theta,\ \phi) = C_{z,z}$$

$$p^b_Z = p^t_Z = +\tfrac{1}{3}$$

$$p^b_{ZZ} = p^t_{ZZ} = \pm 1$$

$$\mathcal{A}^{b,t}_{ZZ}(\theta,\ \phi) = \frac{C_{zz,zz}}{4+C_{z,z}}$$

$$\mathcal{A}^b_{ZZ}(\theta,\ \phi) = \frac{2A^b_{zz}(\theta)}{4+9C_{z,z}}$$

$$\mathcal{A}^t_{ZZ}(\theta,\ \phi) = \frac{2A^t_{zz}(\theta)}{4+9C_{z,z}}$$

Plans

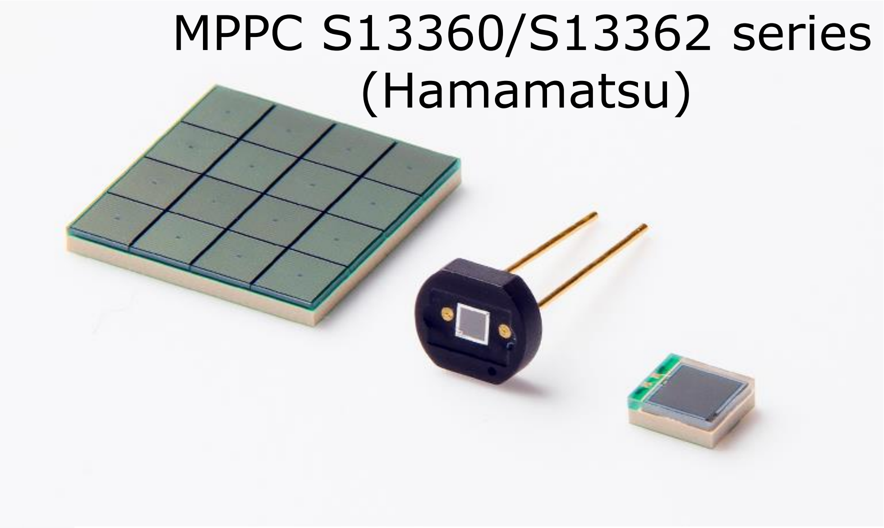
2022

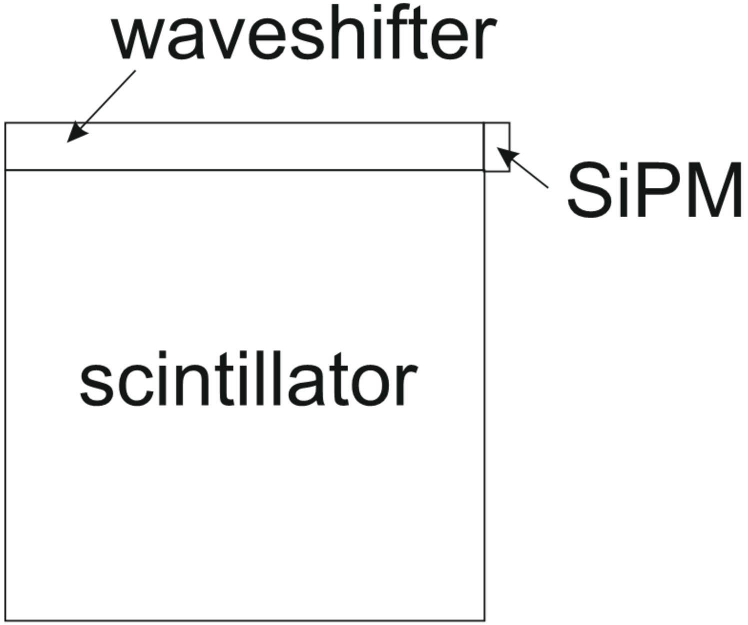
- Commissioning LSP
- Tuning POLIS RF units
- Test run with a polarized ion beam from POLIS and the vapor target
- Run with a polarized ion beam from POLIS and unpolarized atomic beam from the ABS

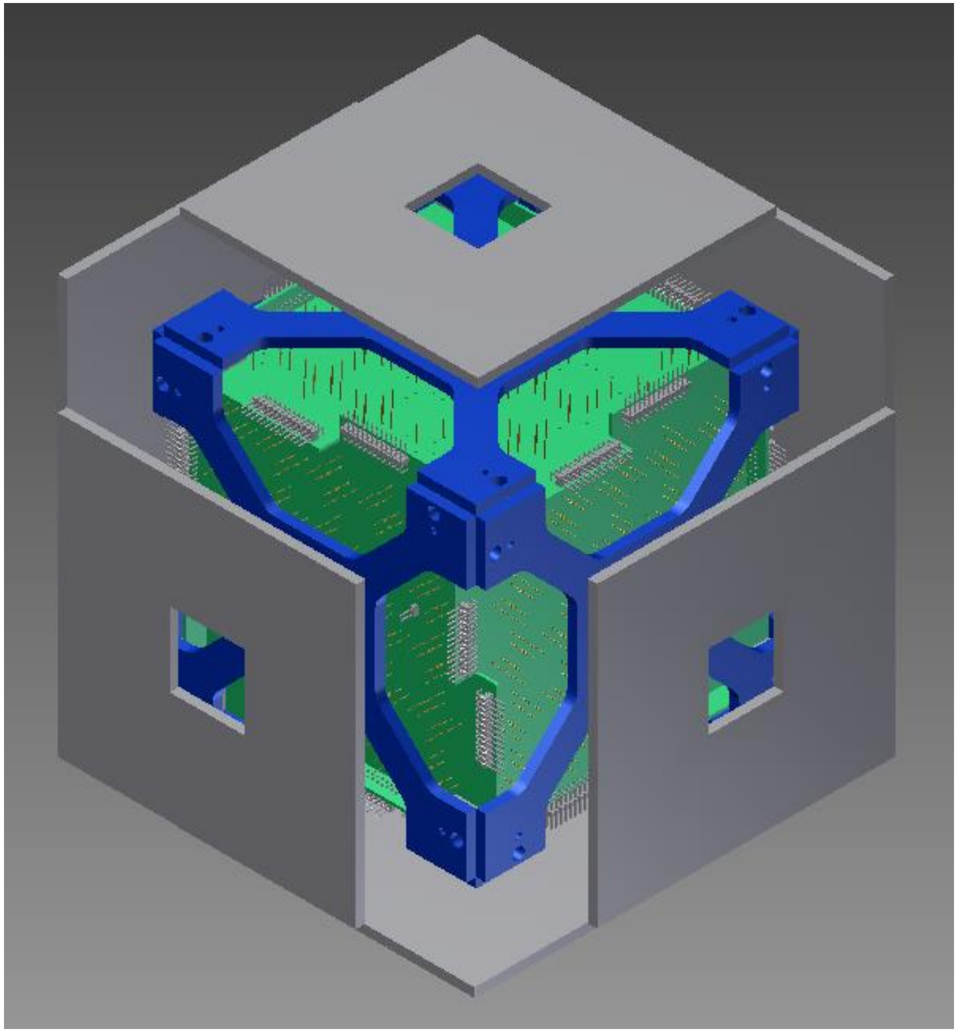
2023-...

- Manufacturing and assembling the cosmic ray detection system
- Commissioning Glavish ionizer
- Tuning ABS RF units
- Commissioning NRP
- Run with a polarized ion beam from POLIS and polarized atomic beam from the ABS

Cosmic ray detection system







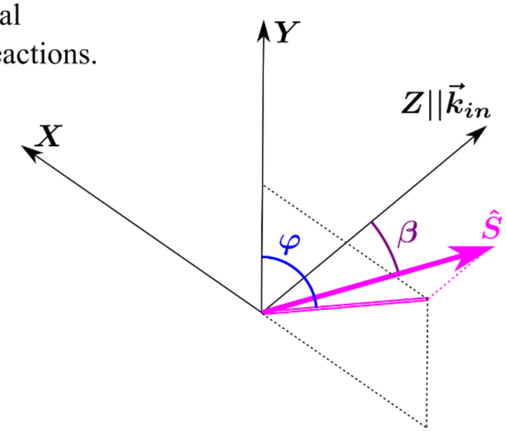
Координатные системы

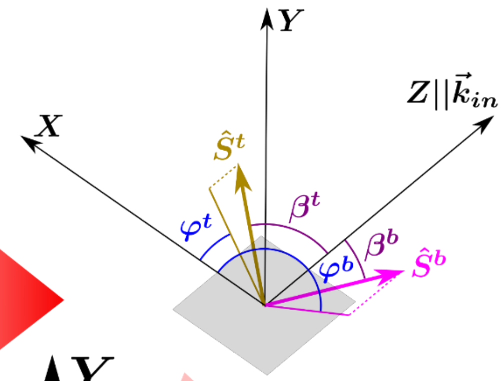
Basel convention (1961): Huber, P., Meyer, K.P. (eds.): Proceedings of the International Symposium on Polarization Phenomena of Nucleons. Helv. Phys. Acta Suppl. VI. Birkhäuser

Madison convention (1971): Barschall, H.H., Haeberli, W. (eds.): Proceedings of the 3rd International Symposium on Polarization Phenomena in Nuclear Reactions. University of Wisconsin Press

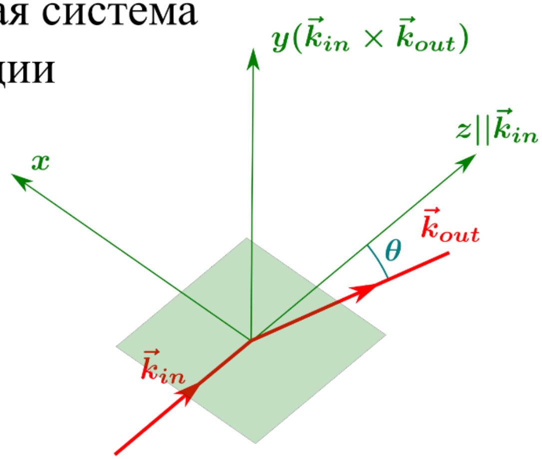
Описание поляризации (фиксированная в пространстве координатная система)

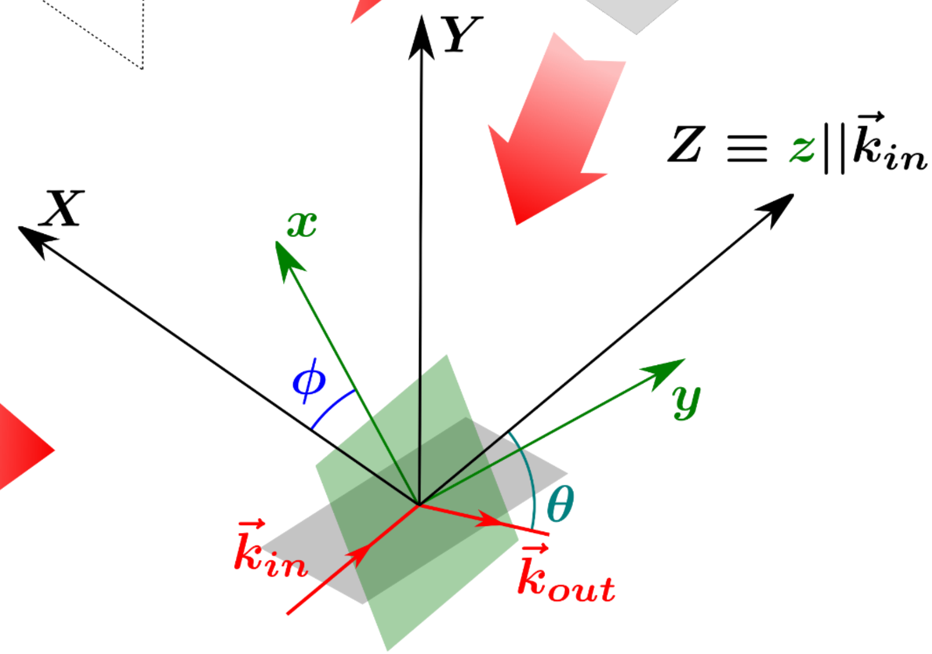
- $\vec{k}_{in}$ - момент импульса налетающей частицы
- $\vec{k}_{out}$ - момент импульса вылетающей частицы
- $\hat{S}^b$, $\hat{S}^t$ - оси квантования пучка и мишени





Координатная система реакции





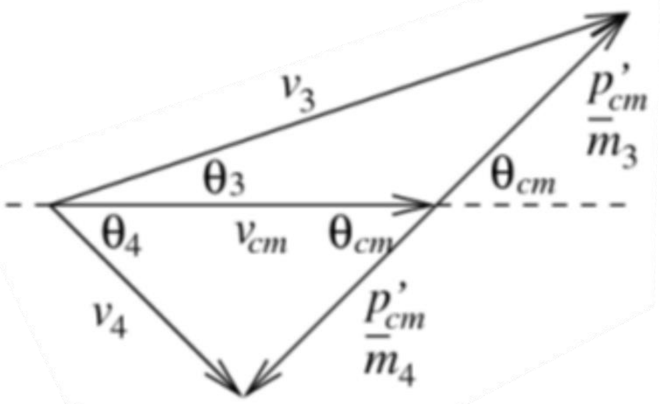
Дифференциальное сечение

$$\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(1 + \sum_{j=1}^{9} \bar{p}_j^b A_j^b(\theta) + \sum_{j=1}^{9} \bar{p}_j^t A_j^t(\theta) + \sum_{j=1}^{9}\sum_{k=1}^{9} \bar{p}_j^b \bar{p}_k^t C_{j,k}(\theta)\right)$$

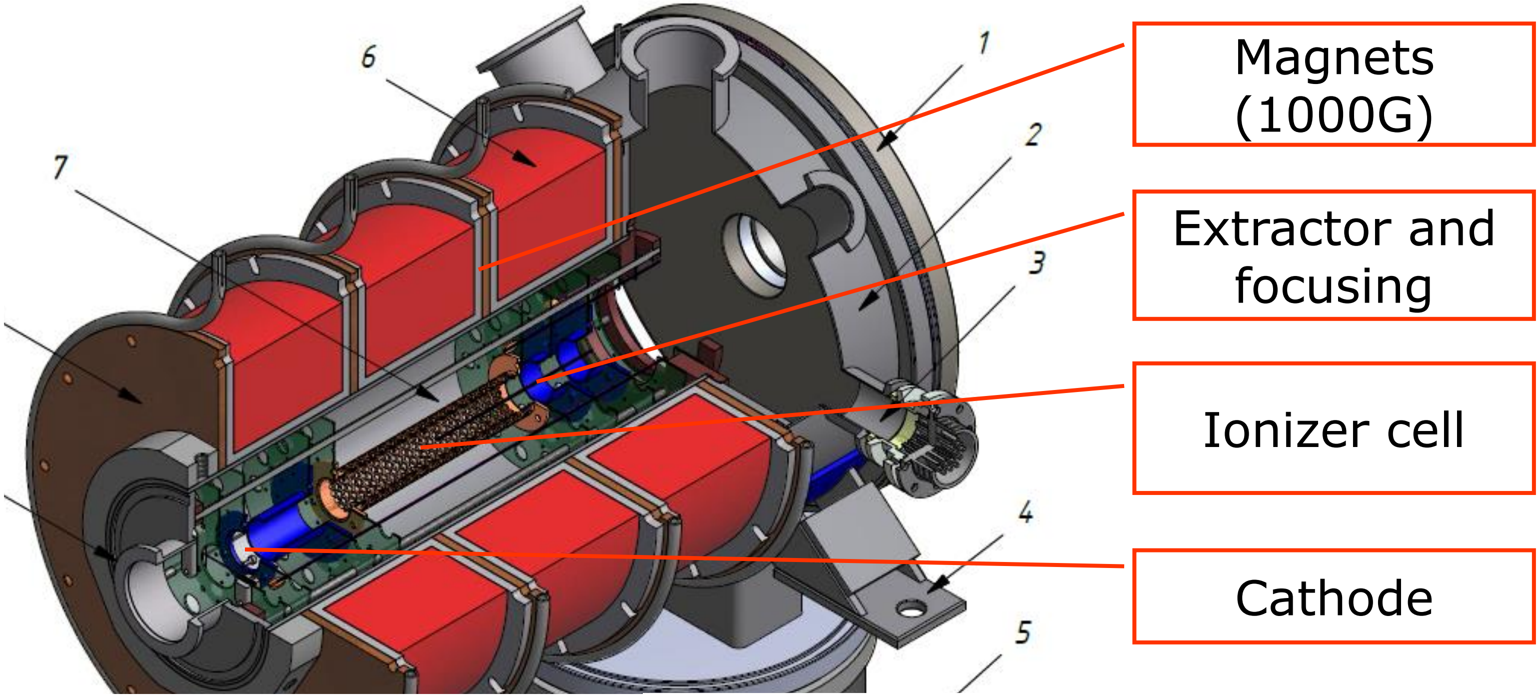
$$p_{l'}\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(P_{l'}(\theta) + \sum_{j=1}^{9} \bar{p}_j K_j^{l'}(\theta)\right)$$

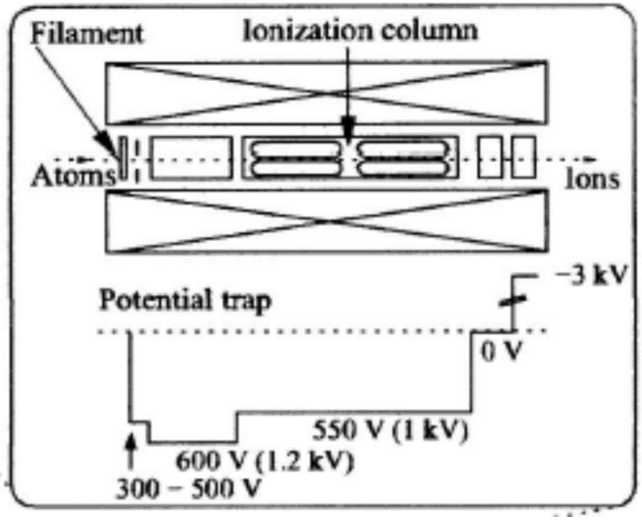
$$\bar{p}_1 = \frac{3}{2}p_x \qquad \bar{p}_2 = \frac{3}{2}p_y \qquad \bar{p}_3 = \frac{3}{2}p_z \qquad \bar{p}_4 = \frac{2}{3}p_{xy} \qquad \bar{p}_5 = \frac{2}{3}p_{xz}$$

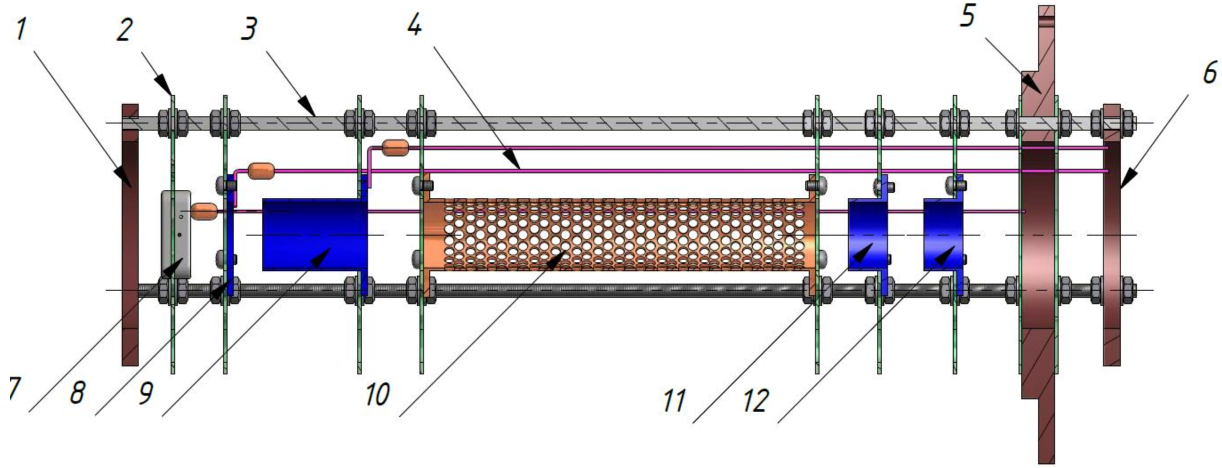
$$\bar{p}_6 = \frac{2}{3}p_{yz} \qquad \bar{p}_7 = \frac{1}{3}p_{xx} \qquad \bar{p}_8 = \frac{1}{3}p_{yy} \qquad \bar{p}_9 = \frac{1}{3}p_{zz}$$



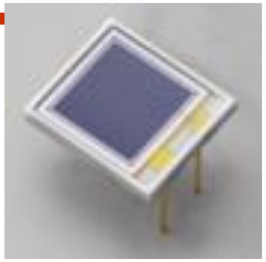
Glavish ionizer



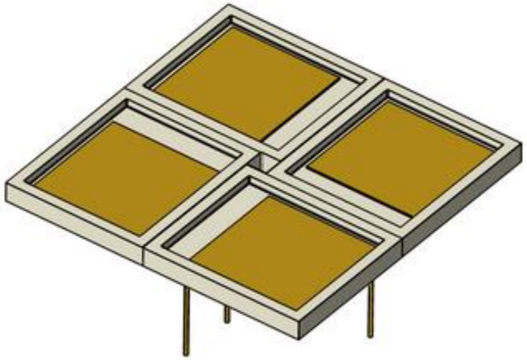


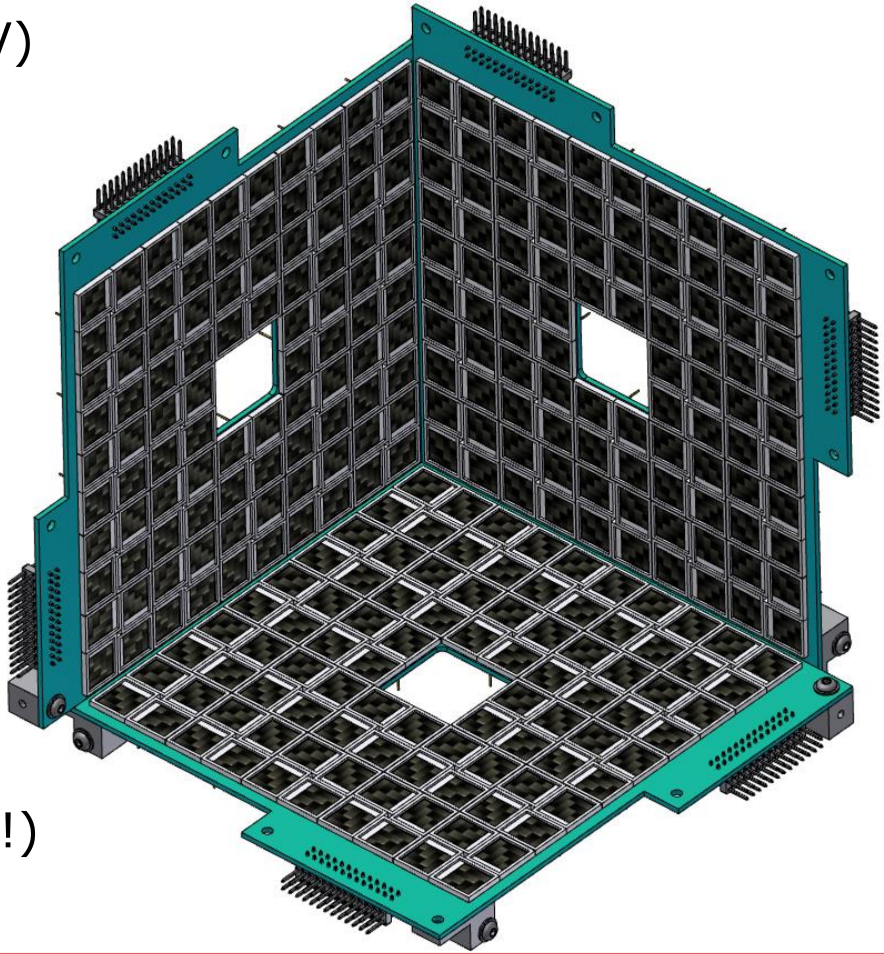


Detector system. PIN diodes version



- 4-π detector with 51% filling
- 576 Hamamatsu PIN-diodes (S3590-09)
- PIN-diode active area: 1 cm^2
- depleted layer: 300 um
- energy resolution: <50keV
- low reverse voltage (<=50V)





Square detector elements (4x4 diodes)
Standard PCB assembly with
spring through-hole mounting (no solder!)

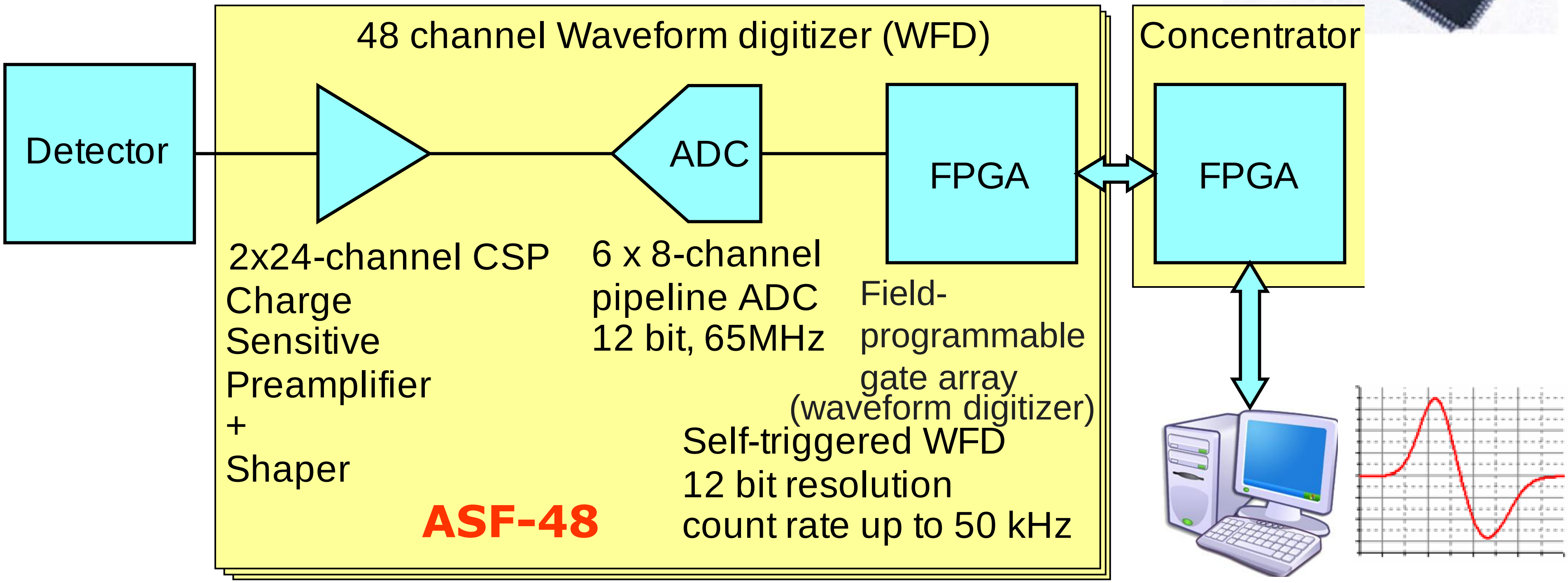
Readout electronics

Readout requirements:

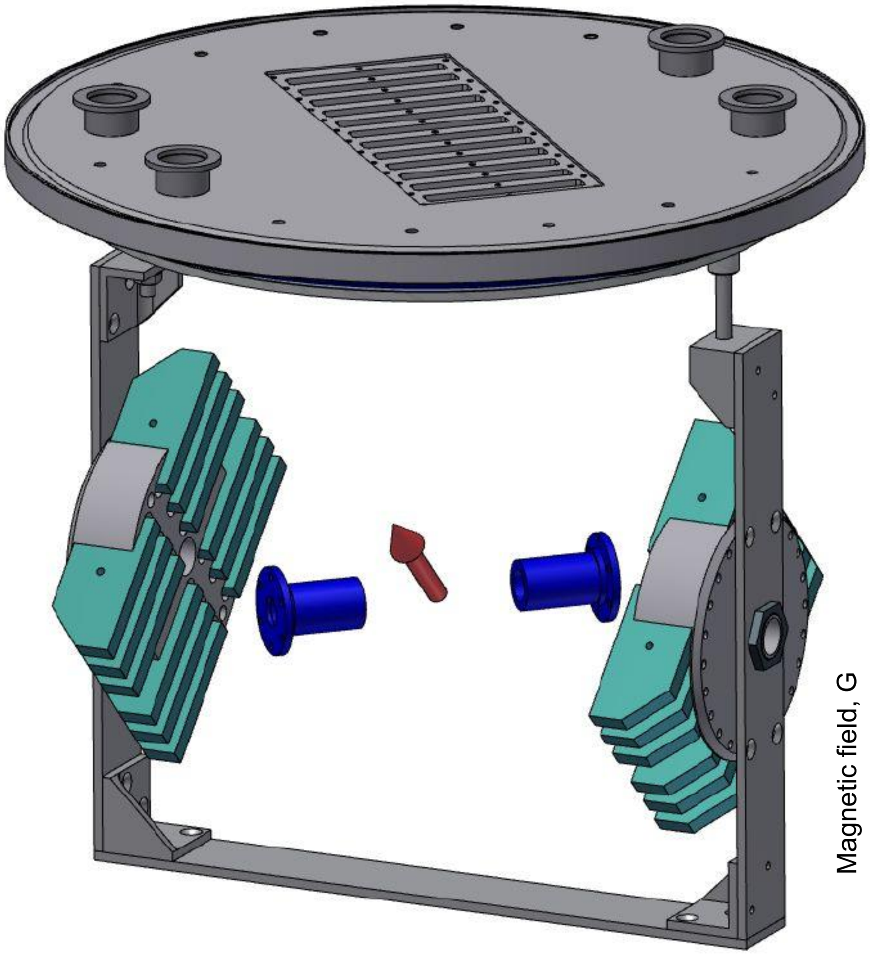
- 600 channels
- Total count rate ≤ 1kHz
- Standard interface (Ethernet?)
- Event synchronization for coincidence trigger

CSP from ATLAS CSC [BNL]

Junnarkar et al. IEEE Nuclear Science Symposium Conference Record (2005)

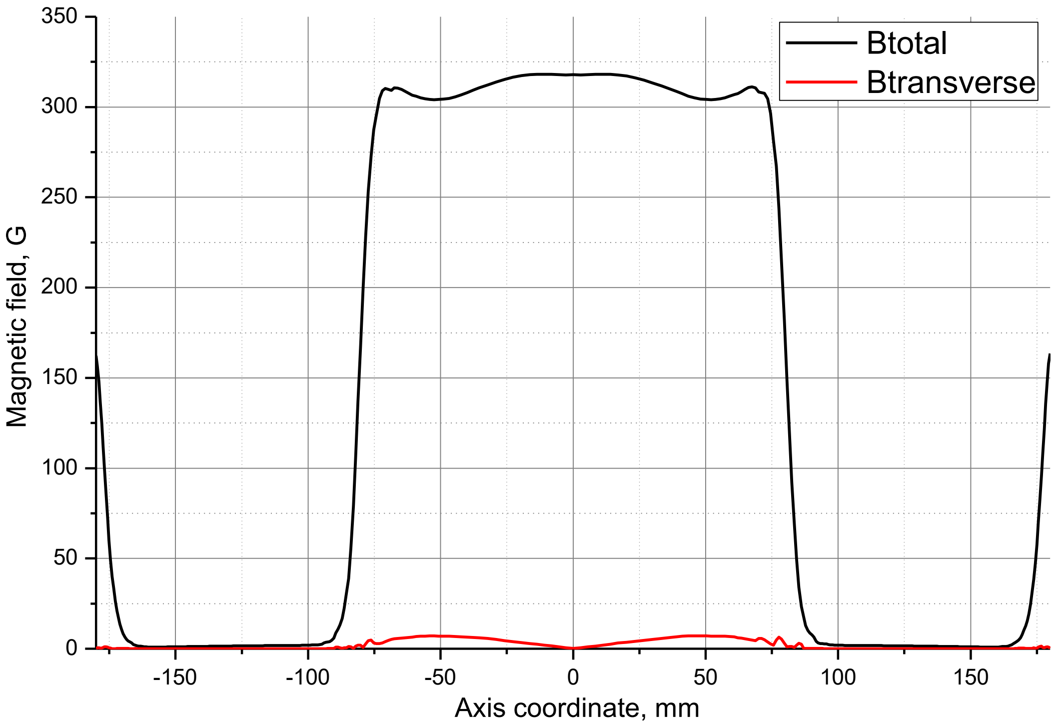


Magnet system

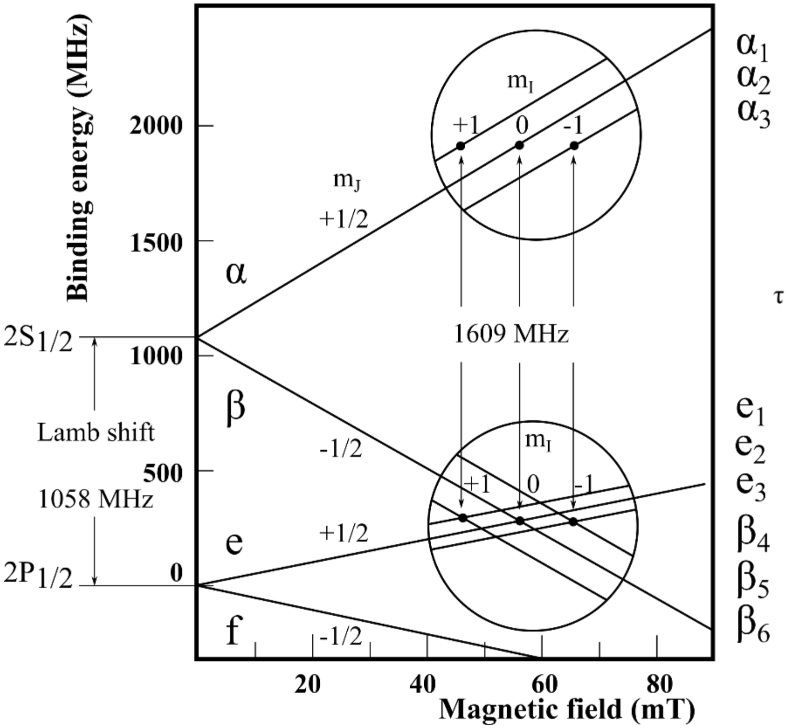


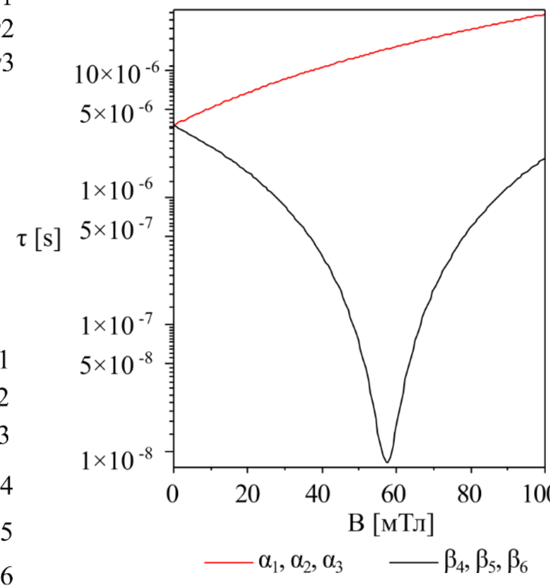
B =300 G = 2.5 B_c

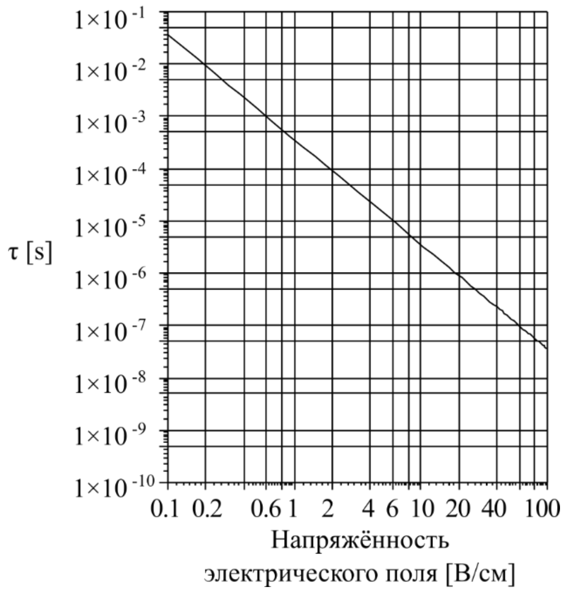
Magnet field is generated by 24 permanent magnets with dimensions 80x40x10 mm^3 with pole tip field of 1.25 T at the surface (NdFeB N40)

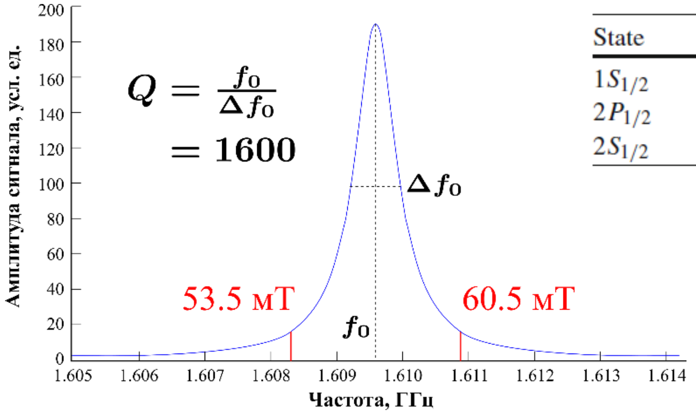


LSP principle

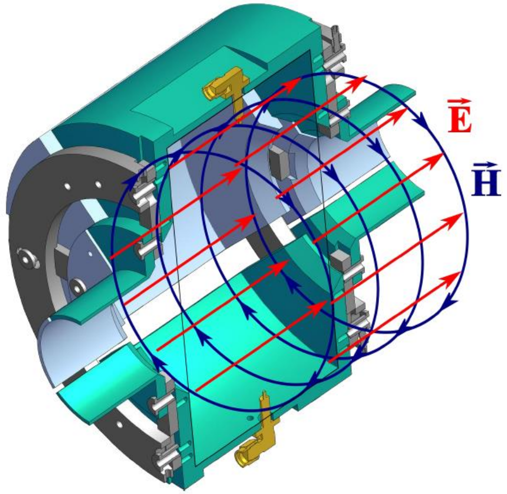








State	B_{crit} (mT)	ΔW (MHz)
$1S_{1/2}$	11.7	327
$2P_{1/2}$	0.5	14
$2S_{1/2}$	1.5	41



Polarization determination by NRP

$$\sigma(\theta,\phi) = \sigma_0\Big(1 + \frac{3}{2}P_Z A_y(\theta)\cos\phi\sin\beta - P_{ZZ}A_{xz}(\theta)\sin\beta\cos\beta\sin\phi - \frac{1}{4}P_{ZZ}\big(A_{xx}(\theta) - A_{yy}(\theta)\big)\sin^2\beta\cos 2\phi + \frac{1}{4}P_{ZZ}A_{zz}(\theta)\big(3\cos^2\beta - 1\big)\Big).$$

G.G Ohlsen, P.W. Keaton, Jr., Nucl. Instr. and Meth. **109**, 41 (1973).

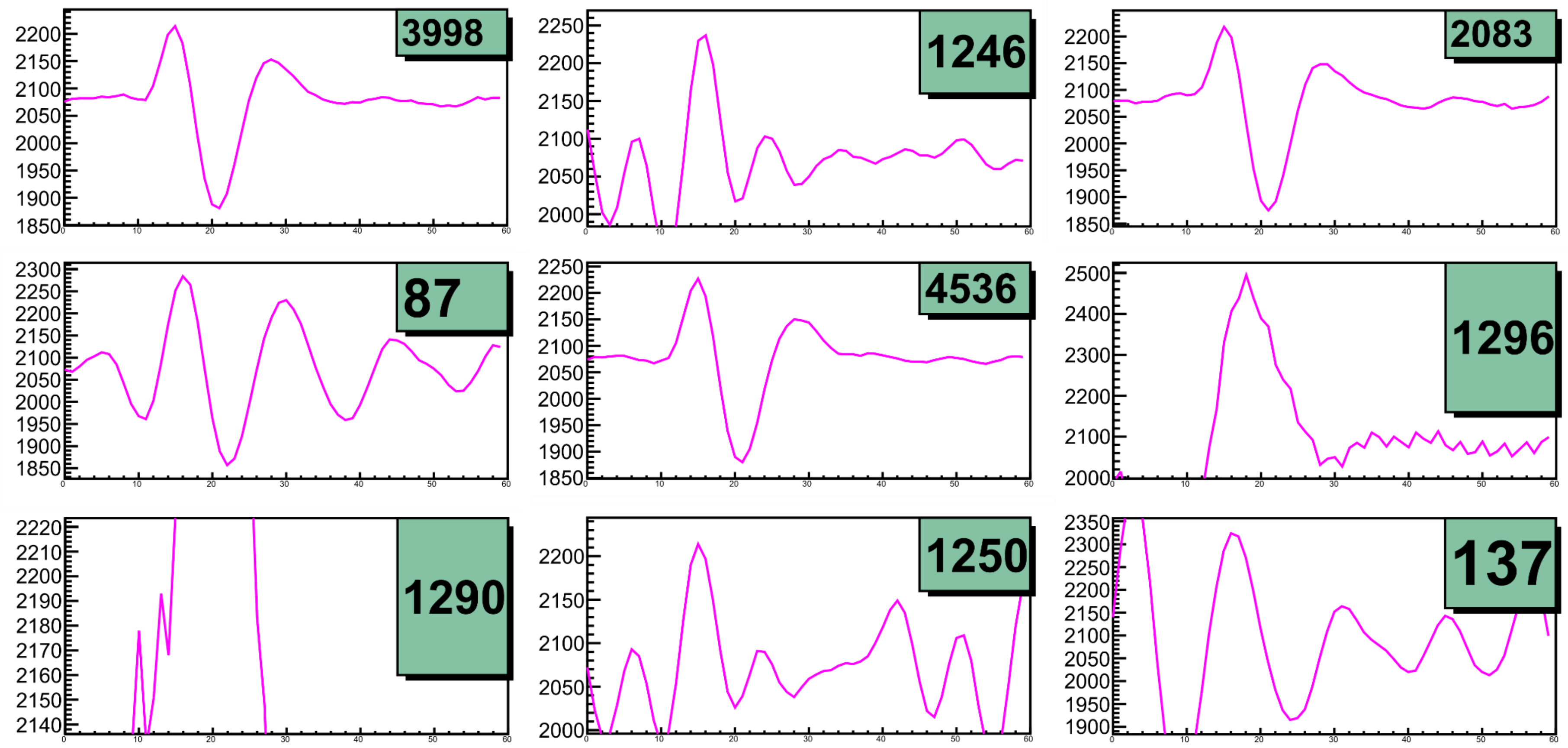
$$\begin{aligned}
\sigma_L &= \sigma_0(1 + \frac{3}{2}P_Z A_y(\theta)\sin\beta + \frac{1}{2}P_{ZZ}(A_{yy}(\theta)\ \sin^2\beta + A_{zz}\ \cos^2\beta)),\\
\sigma_R &= \sigma_0(1 - \frac{3}{2}P_Z A_y(\theta)\sin\beta + \frac{1}{2}P_{ZZ}(A_{yy}(\theta)\ \sin^2\beta + A_{zz}\ \cos^2\beta)),\\
\sigma_U &= \sigma_0(1 + P_{ZZ}A_{xz}(\theta)\sin\beta\cos\beta + \frac{1}{2}P_{ZZ}(A_{xx}(\theta)\ \sin^2\beta + A_{zz}\ \cos^2\beta)),\\
\sigma_D &= \sigma_0(1 + P_{ZZ}A_{xz}(\theta)\sin\beta + \frac{1}{2}P_{ZZ}(A_{yy}(\theta)\ \sin^2\beta\cos\beta + A_{zz}\ \cos^2\beta)).
\end{aligned}$$

$$\begin{aligned}
L &\propto \sigma_L\\
R &\propto \sigma_R\\
U &\propto \sigma_U\\
D &\propto \sigma_D.
\end{aligned}$$

$$R = \frac{R_{polarized}}{R_{unpolarized}}.$$

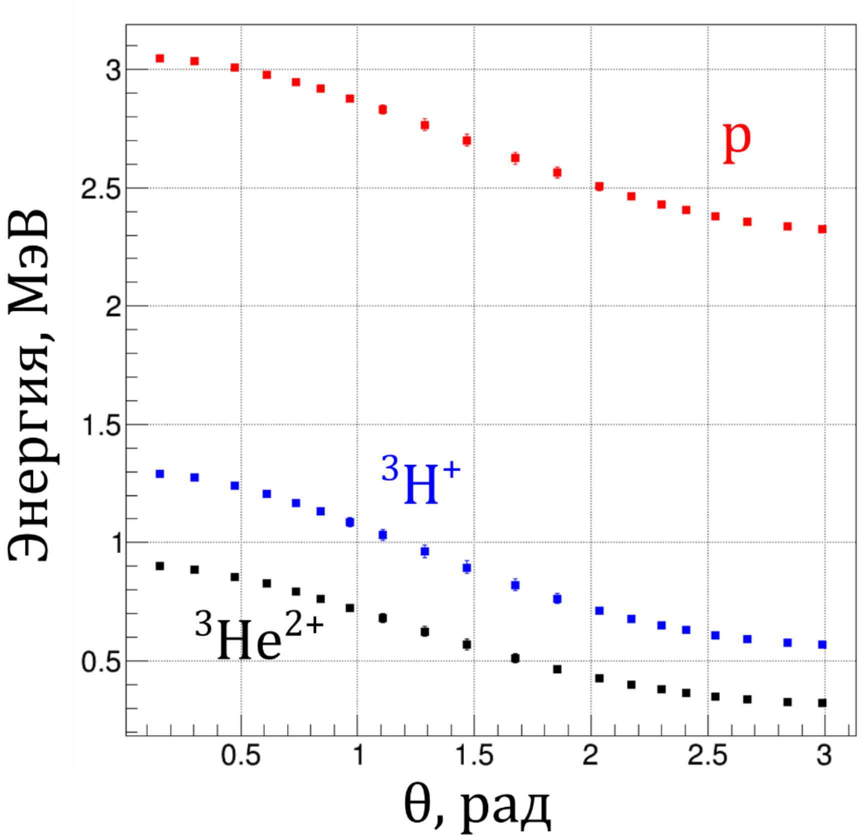
$$\begin{aligned}
\epsilon_1 &\equiv \frac{L-R}{L+R} = \frac{\frac{3}{2}P_Z\sin\beta\,A_y}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{yy} + \cos^2\beta A_{zz}]}\\
\epsilon_2 &\equiv \frac{U-D}{U+D} = \frac{P_{ZZ}\sin\beta\ \cos\beta\,A_{xz}}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{xx} + \cos^2\beta A_{zz}]}\\
\epsilon_3 &\equiv \frac{2(L-R)}{L+R+U+D} = \frac{\frac{3}{2}P_Z\sin\beta\,A_y}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]}\\
\epsilon_4 &\equiv \frac{2(U-D)}{L+R+U+D} = \frac{P_{ZZ}\sin\beta\ \cos\beta\,A_{xz}}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]}\\
\epsilon_5 &\equiv \frac{(L+R)-(U+D)}{L+R+U+D} = \frac{-\frac{1}{4}P_{ZZ}\sin^2\beta\ (A_{xx} - A_{yy})}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]},
\end{aligned}$$

Different signals



Heavy water vapor target

Энергия продуктов реакции от угла рассеяния



На основе формул из [Г.А.Борисов, Р.Д.Васильев, В.Ф.Шевченко Кинематические таблицы ядерных реакций d,n и p,n Издательство стандартов, Москва 1974]