Spin-correlation experiment for investigating dd reactions in PNPI

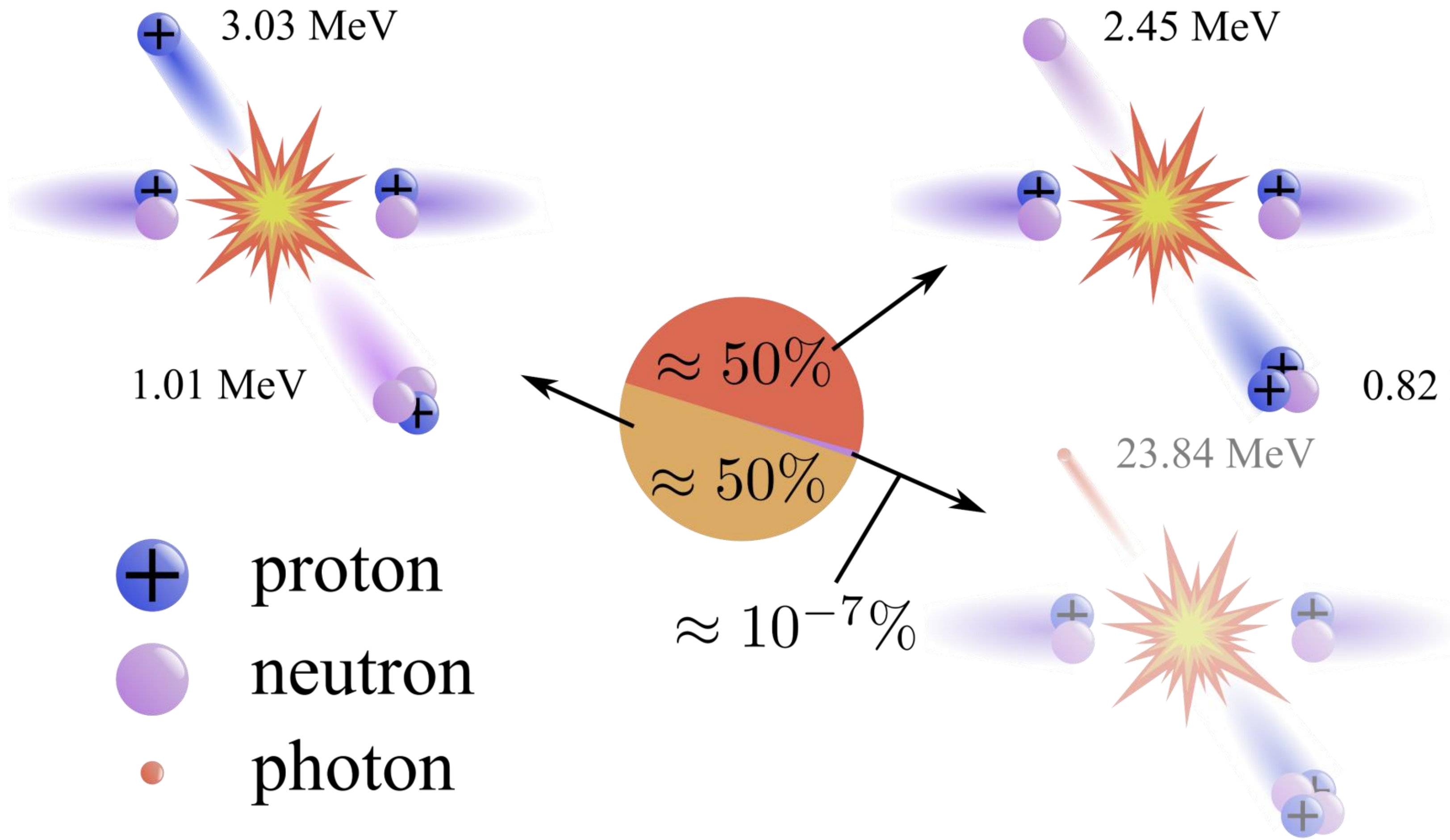
PolFusion

Ivan Solovyev

research scientist

dd fusion reactions

$^2H + {}^2H \rightarrow {}^3H + p + 4.04\ MeV$ $\quad$ $^2H + {}^2H \rightarrow {}^3He + n + 3.27\ MeV$



$^2H + {}^2H \rightarrow {}^4He + \gamma + 23.84\ MeV$

Applied physics

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)

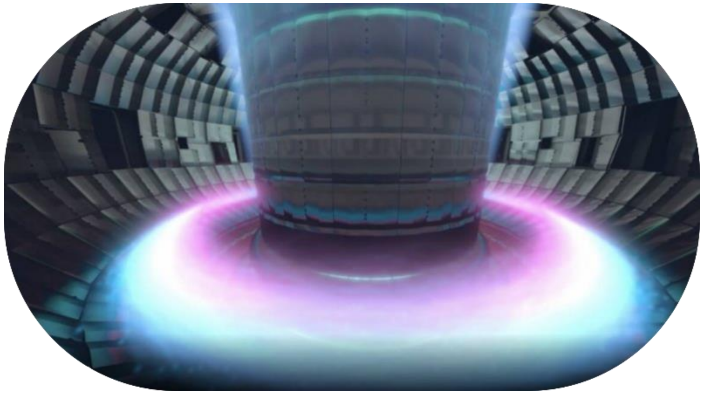
+

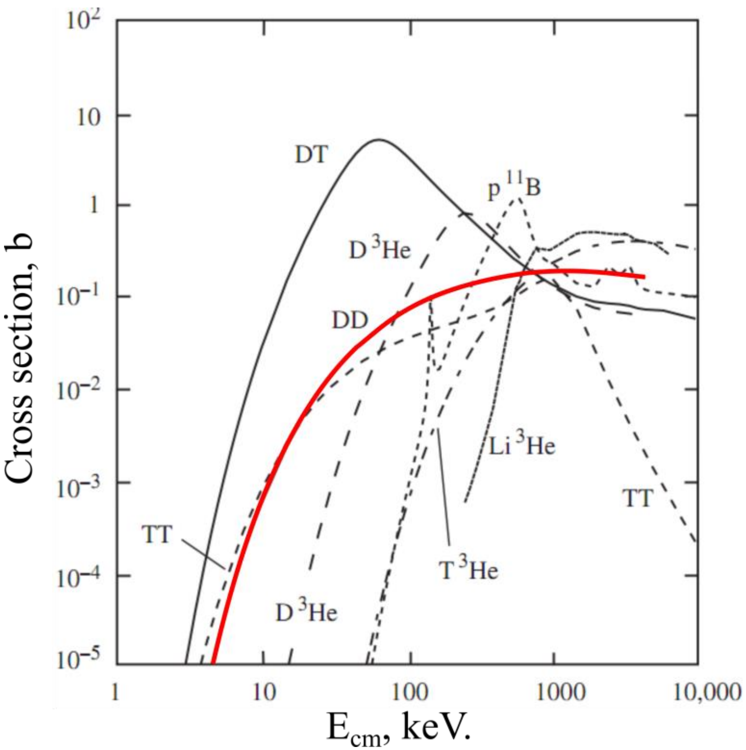
d + t ⟶ ^{4}He + n (17.6 MeV / 107 keV)

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

3rd generation:

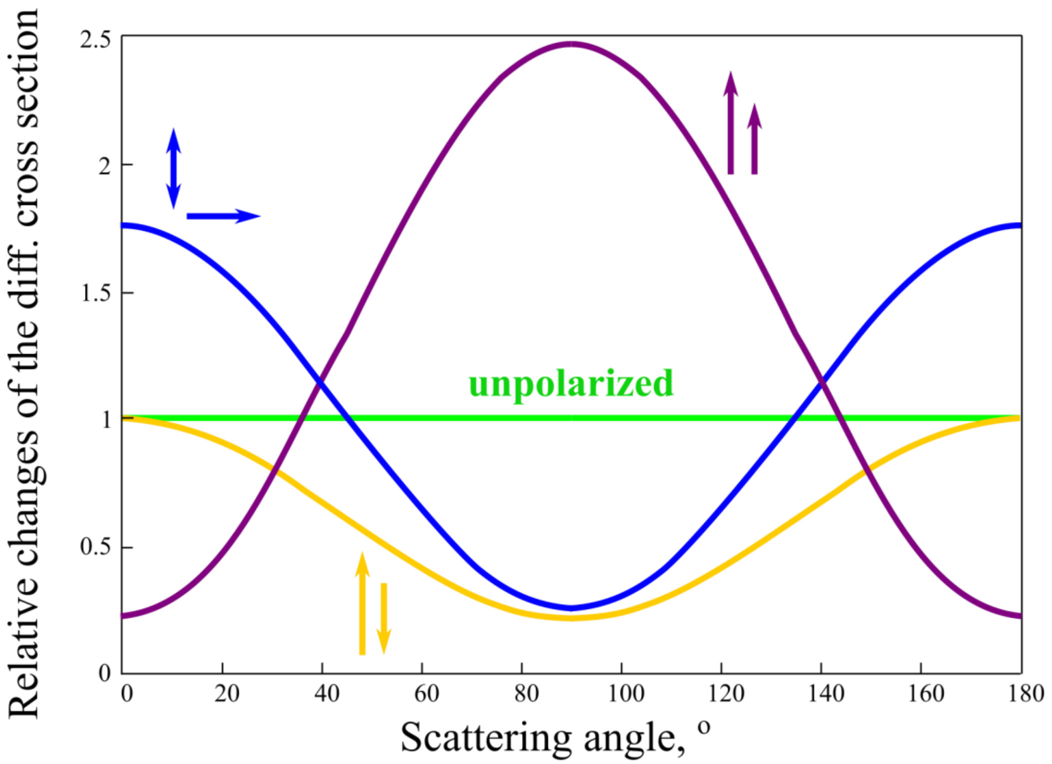
d + ^{3}He ⟶ ^{4}He + p (18.3 MeV / 430 keV)

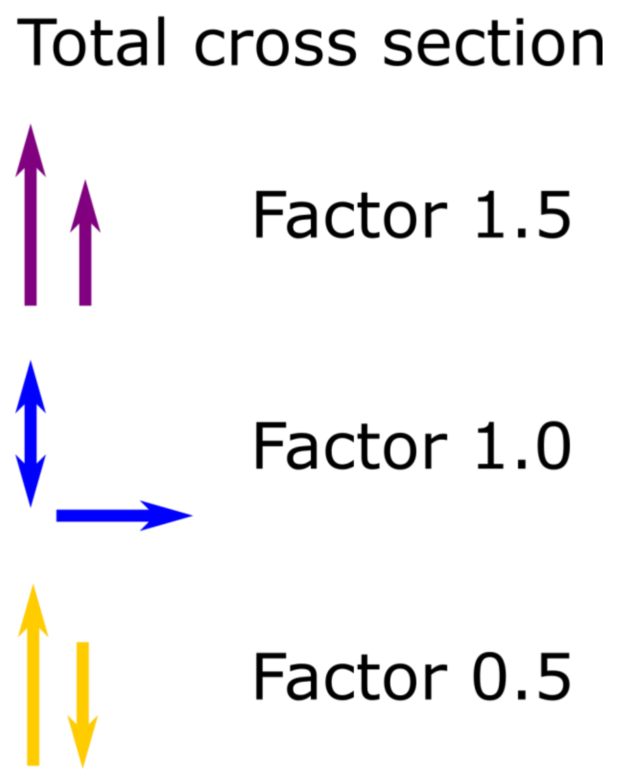




Polarization advantages

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





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

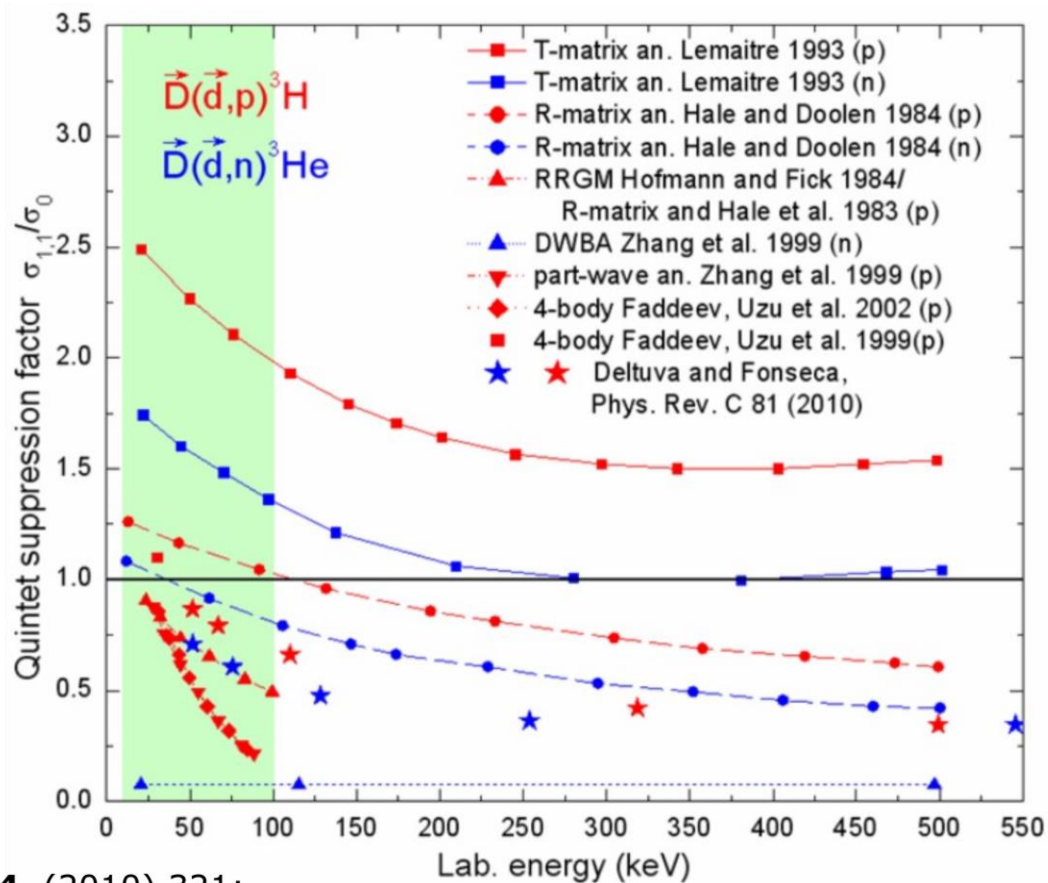
$t(d,n)\alpha$ Theor.: G. Hupin et al., Nature Com. **10**, 321(2019)

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

PNPI - NRC KI

PolFusion

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

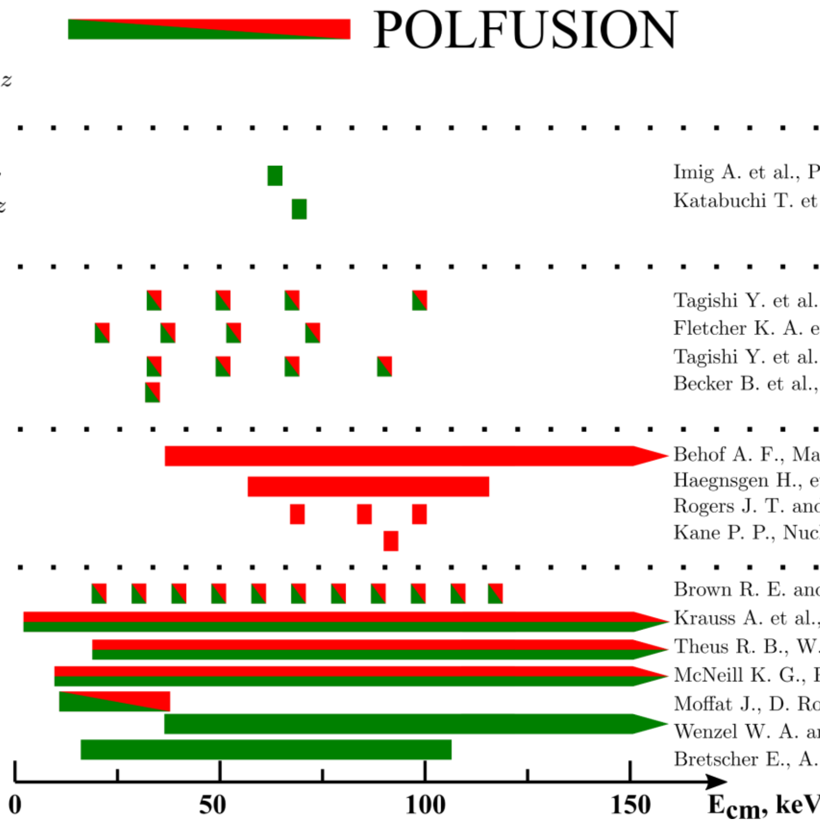
$$p_{l'}\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(P_{l'}(\theta) + \sum_1^9 p_j K_j^{l'}(\theta)\right)$$

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

p-channel

n-channel

Experiment	Observable	References
$^2\vec{H}(\vec{d},p)^3H$, $^2\vec{H}(\vec{d},n)^3He$	$C_{z,z}$ $C_{y,y}$ $C_{zz,zz}$ $C_{y,zz}$ $C_{y,xz}$ $C_{zz,xz}$ …	POLFUSION
$^2H(\vec{d},\vec{p})^3H$, $^2H(\vec{d},\vec{n})^3He$	$K_y^{x'}$ $K_y^{y'}$ $K_{xz}^{z'}$ …	Imig A. et al., Phys. Rev. C 73, 024001 (2006) Katabuchi T. et al., Phys. Rev. C 64, 047601 (2001)
$^2H(\vec{d},p)^3H$, $^2H(\vec{d},n)^3He$	A_y A_{xz} A_{zz} $A_{xx}-A_{yy}$	Tagishi Y. et al., Nucl. Instrum. Methods Phys. Res. A 402, 436 (1998) Fletcher K. A. et al., Phys. Rev. C 49, 2305 (1994) Tagishi Y. et al., Phys. Rev. C 46, R1155 (1992) Becker B. et al., Few-Body Syst. 13, 19 (1992)
$^2H(d,\vec{p})^3H$, $^2H(d,\vec{n})^3He$	$P^{x'}$ $P^{y'}$ $P^{z'}$	Behof A. F., May T. H., McGarry W. I., Nucl. Phys. A108, 250 (1968) Haegnsgen H., et al., Nucl. Phys. 73, 417 (1965) Rogers J. T. and Bond C. D., Nuclear Physics 53 (1964) 297 Kane P. P., Nuclear Physics 10 (1959) 429
$^2H(d,p)^3H$, $^2H(d,n)^3He$	σ_0 $\frac{d\sigma}{d\Omega}$	Brown R. E. and N. Jarmie, Phys. Rev. C 41, 1391 (1990) Krauss A. et al., Nucl. Phys. A465, 150 (1987) Theus R. B., W. I. McGarry, and L. A. Beach, Nucl. Phys. 80, 273 (1966) McNeill K. G., Phil. Mag. 46 (1955) 800; Arnold W. R. et aL, Phys. Rev. 93 (1954) 483 Moffat J., D. Roaf and J. H. Sanders, Proc. Roy. Soc. A212 (1952) 220 Wenzel W. A. and W. Whaling, Phys. Rev. 88 (1952) 1149 Bretscher E., A. P. French and F. G. P. Seidl, Phys. Rev. 73 (1948) 815



POLFUSION

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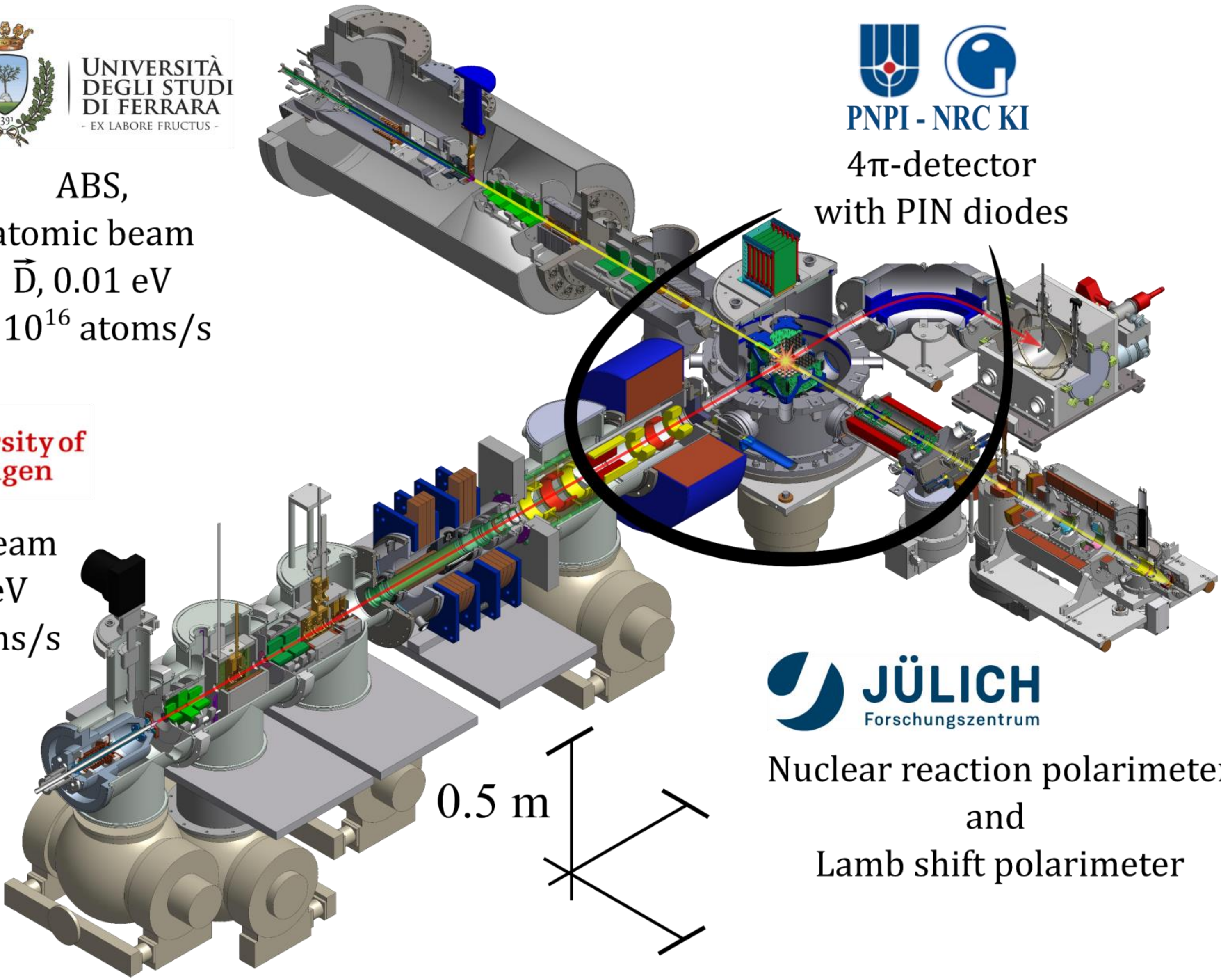
- EX LABORE FRUCTUS -

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

university of groningen

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

PNPI - NRC KI
4π-detector
with PIN diodes



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Forschungszentrum

Nuclear reaction polarimeter
and
Lamb shift polarimeter

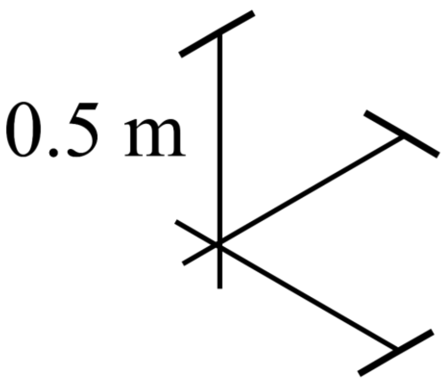
PNPI - NRC KI

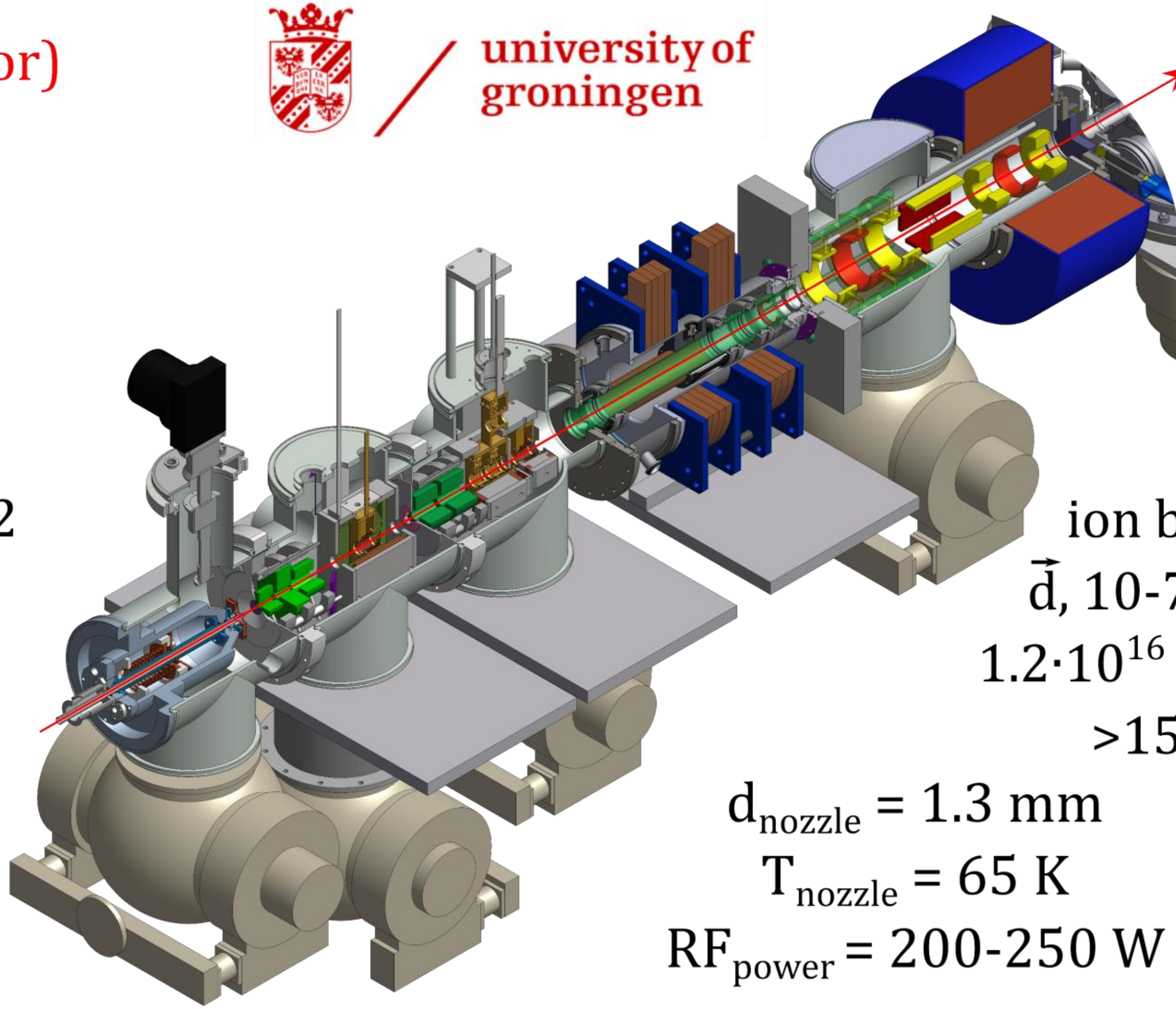
POLarized Ion Source (POLIS)

PolFusion

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

$1.2 \cdot 10^{16}$ 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

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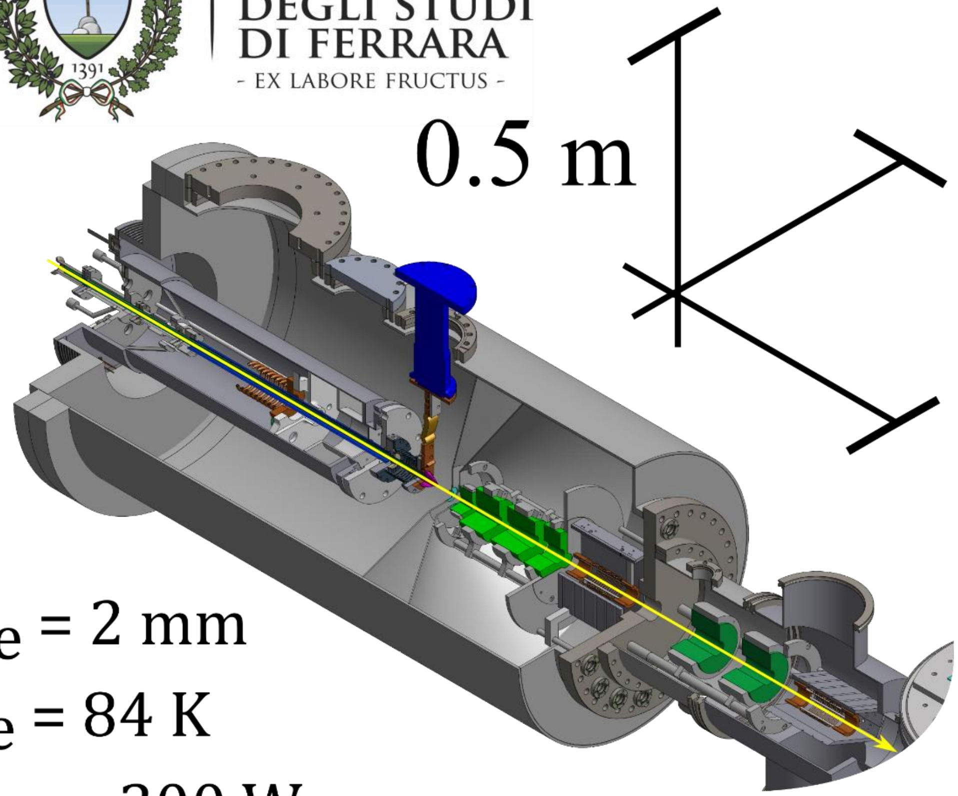
- EX LABORE FRUCTUS -



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

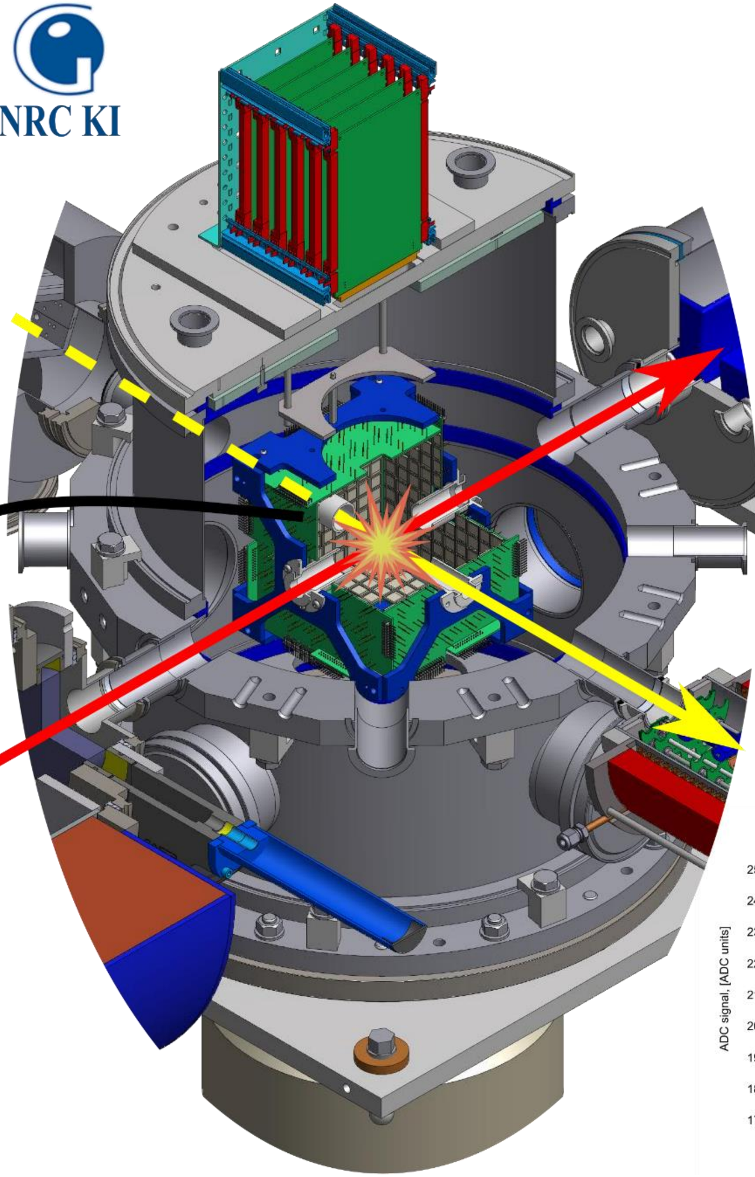
d_{nozzle} = 2 mm
T_{nozzle} = 84 K
RF_{power} = 300 W

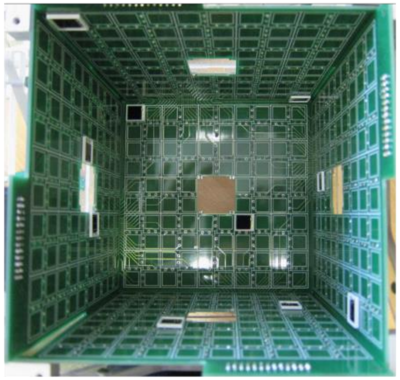
Polarizing system:

Sextupoles + Quadrupoles + MFT + Sextupoles + MFT

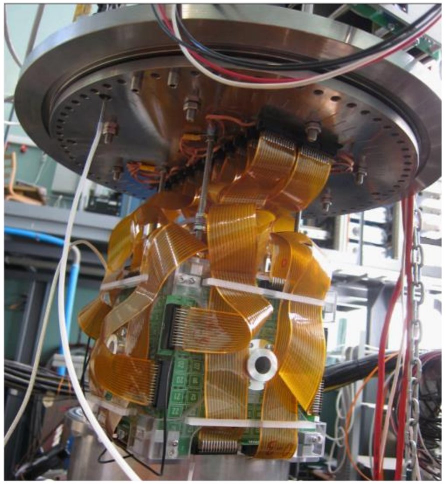
4π-detector

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



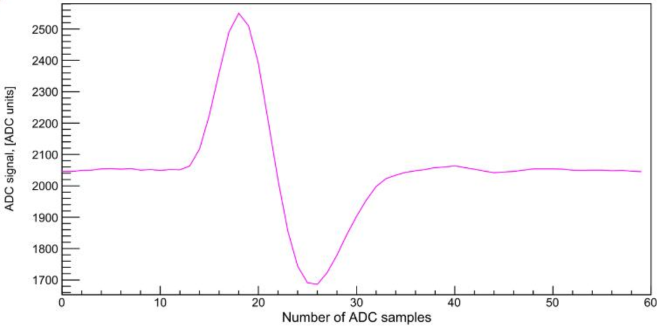


51% effective coverage



10 ns accuracy of recording
the time of signal

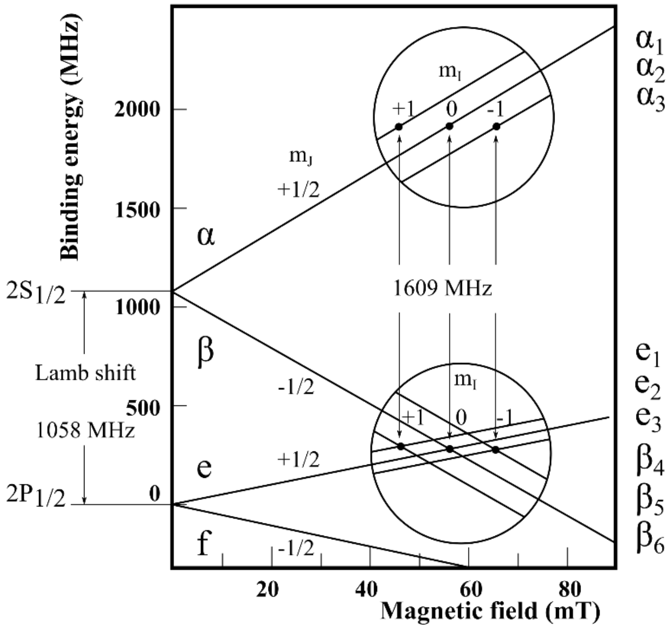
typical signal:



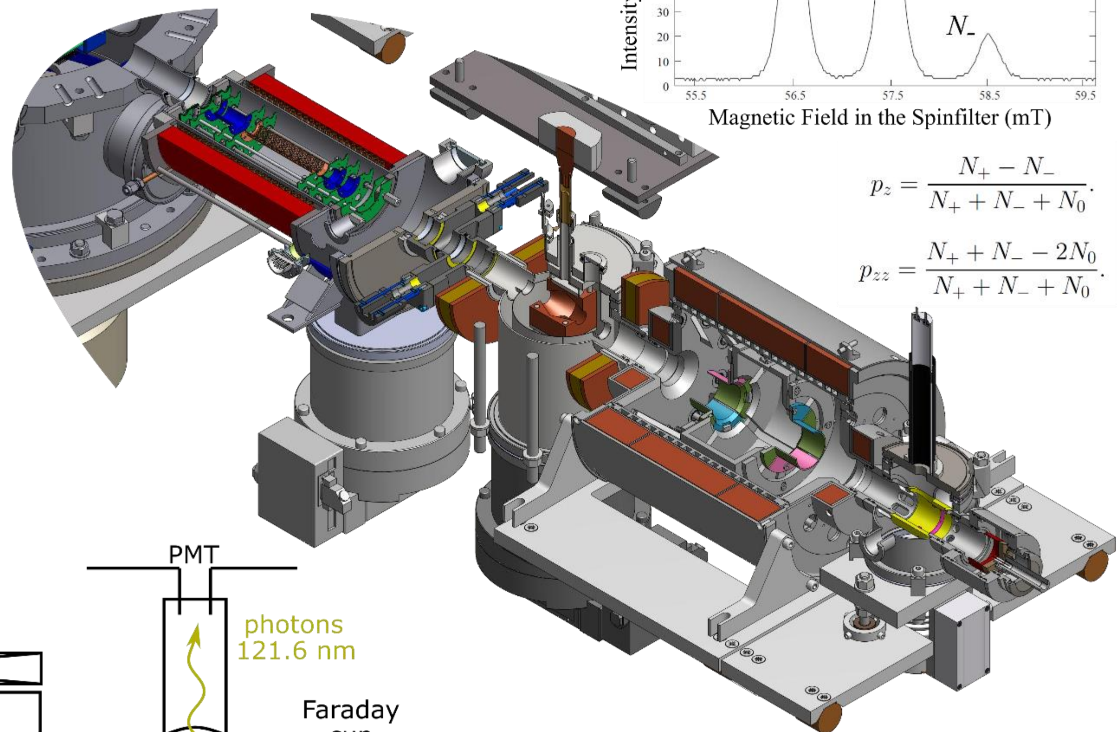
Lamb Shift Polarimeter (LSP)

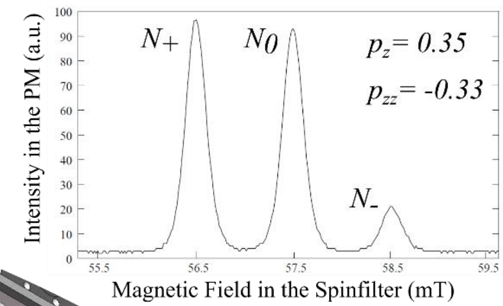
PNPI - NRC KI

Pol Fusion



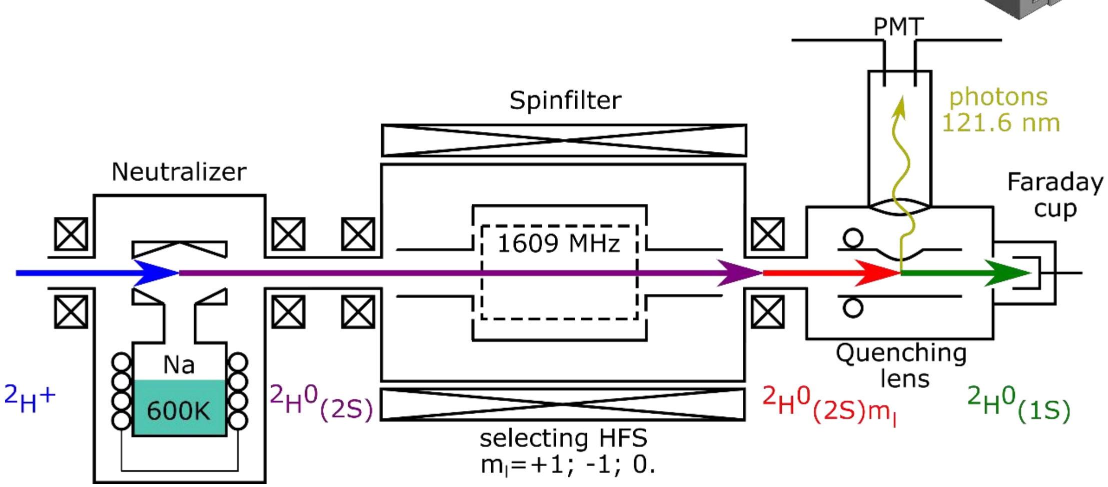
PNPI - NRC KI





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

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



JÜLICH Forschungszentrum

Nuclear Reaction Polarimeter (NRP)

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

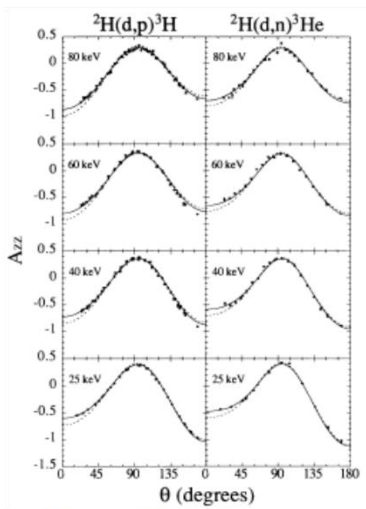
$$\frac{U-D}{U+D} = \frac{P_{ZZ} \sin\beta \, \cos\beta \, A_{xz}}{1 + \frac{1}{2} P_{ZZ} [\sin^2\beta A_{xx} + \cos^2\beta A_{zz}]}$$

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

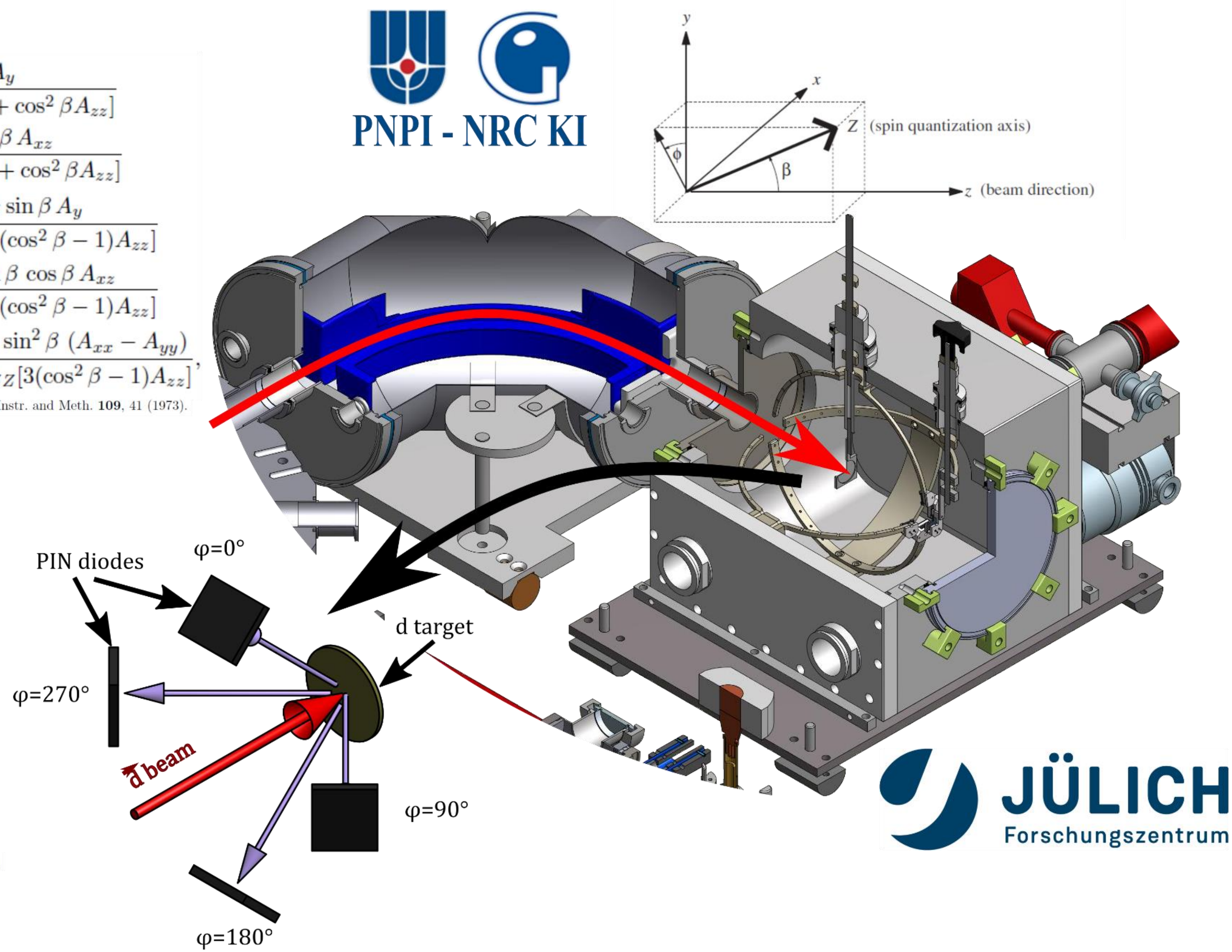
$$\frac{2(U-D)}{L+R+U+D} = \frac{P_{ZZ} \sin\beta \, \cos\beta \, A_{xz}}{1 + \frac{1}{4} P_{ZZ} [3(\cos^2\beta - 1) A_{zz}]}$$

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

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



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



Asymmetries

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

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

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 $C_{zz,zz}$

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

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

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

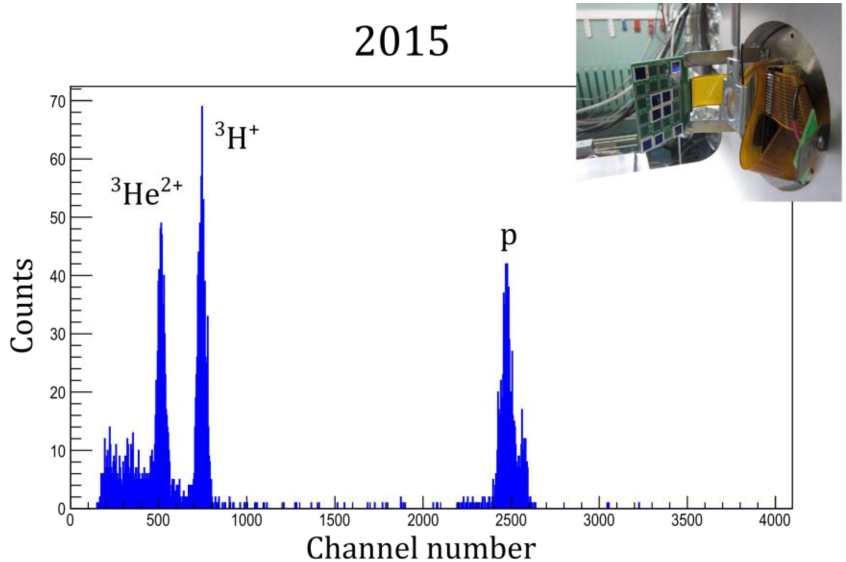
$$\mathcal{A}^{b,t}_Z(\theta,\ \phi) = \frac{9|p^b_Z||p^t_Z|C_{z,z}(\theta)}{4+2p^b_{ZZ}A^b_{zz}(\theta)+2p^t_{ZZ}A^t_{zz}(\theta)+p^b_{ZZ}p^t_{ZZ}C_{zz,zz}(\theta)}$$

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

$p^b_Z = p^t_Z = \pm\frac{2}{3}$	$p^b_Z = p^t_Z = +\frac{1}{3}$
$p^b_{ZZ} = p^t_{ZZ} = 0$	$p^b_{ZZ} = p^t_{ZZ} = \pm 1$
$\mathcal{A}^{b,t}_Z(\theta,\ \phi) = C_{z,z}$	$\mathcal{A}^{b,t}_{ZZ}(\theta,\ \phi) = \frac{C_{zz,zz}}{4+C_{z,z}}$
	$\mathcal{A}^b_{ZZ}(\theta,\ \phi) = \frac{2A^b_{zz}(\theta)}{4+9C_{z,z}}$
	$\mathcal{A}^t_{ZZ}(\theta,\ \phi) = \frac{2A^t_{zz}(\theta)}{4+9C_{z,z}}$

Test runs

2015



Target: deuterated polymethyl methacrylate

Density: ~10^{17} atom/cm^2

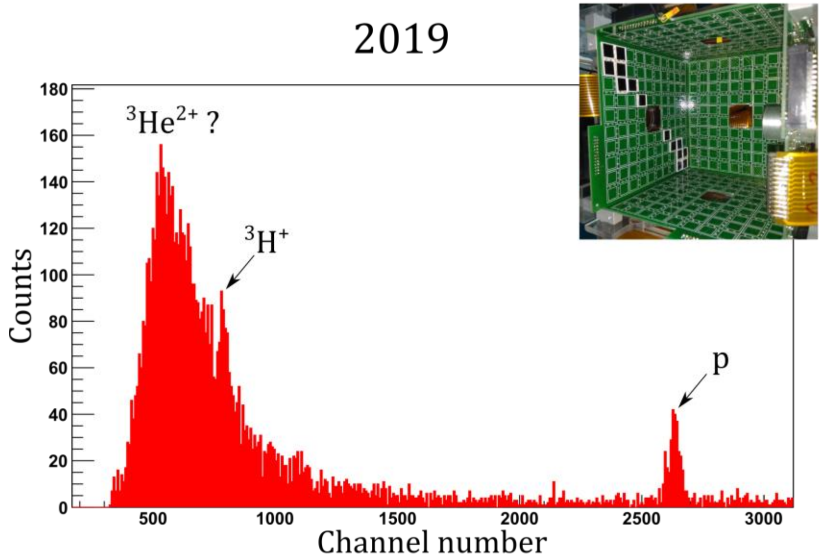
Beam: 15 keV ~5μA

Period: ~3 h

Purpose: evaluating the signal quality

ADC calibration

2019



Target: heavy water vapor

Density: ~10^{12} atom/cm^2

Beam: 10 keV ~10μA

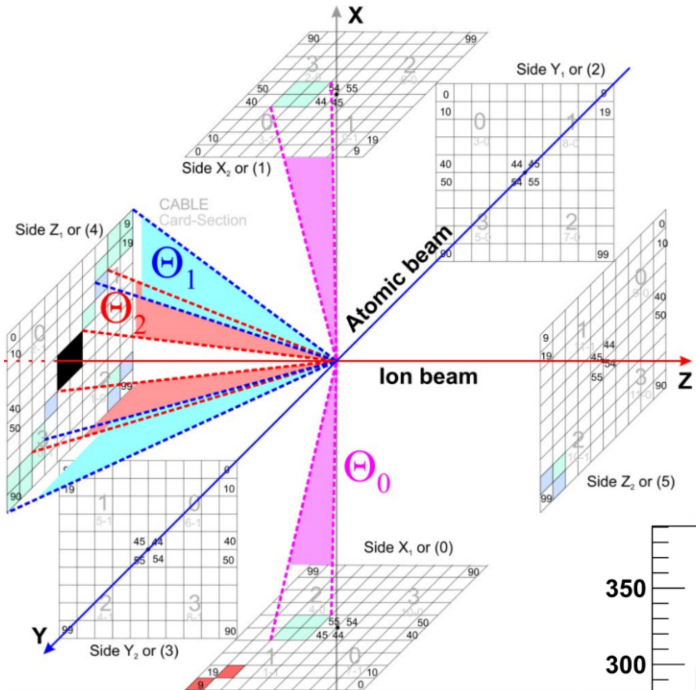
Period: ~200 h

Purpose: simulation of the ABS

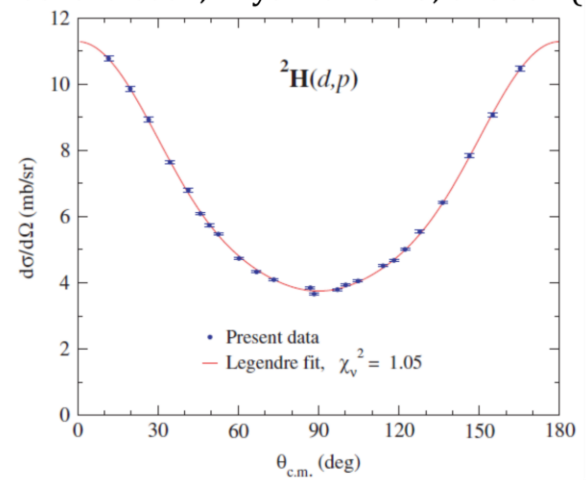
evaluation of cosmic background, form and sources of electronic background

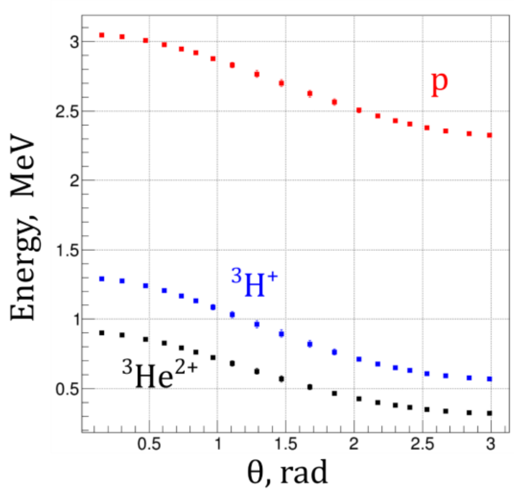
ABS beam density: $2.7 \cdot 10^{11}$ atom/cm^2 at $4 \cdot 10^{16}$ atom/s

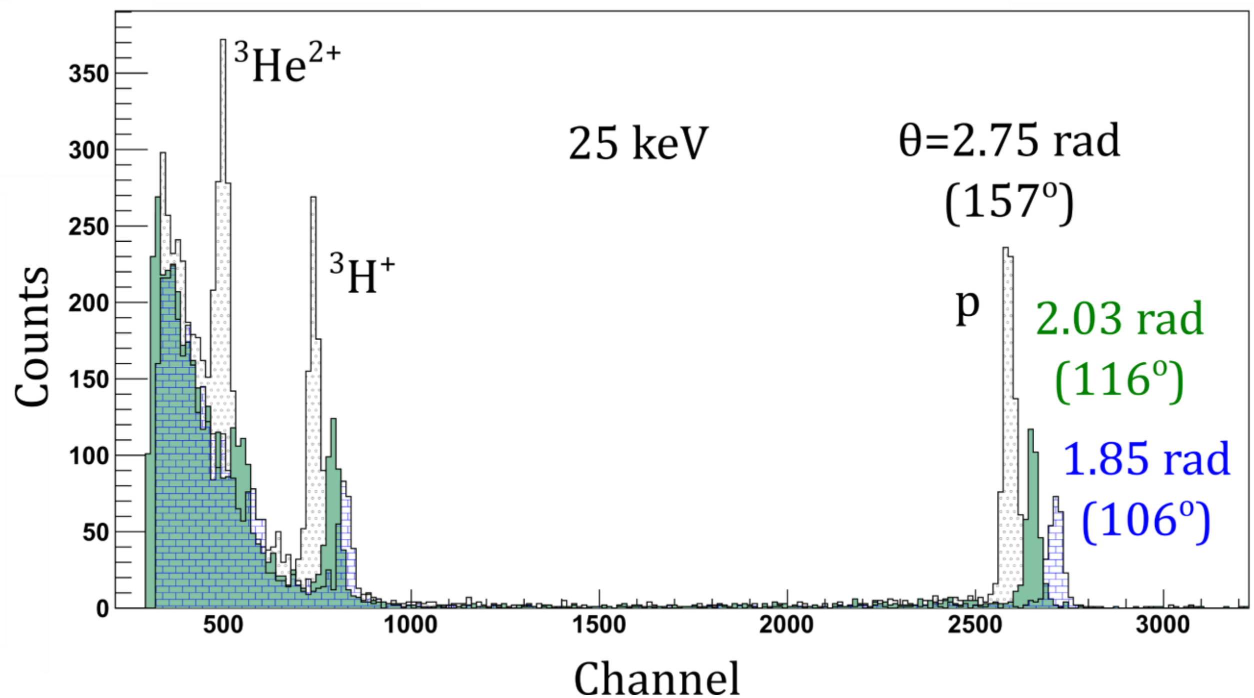
Test run 2020



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







Plans

2022

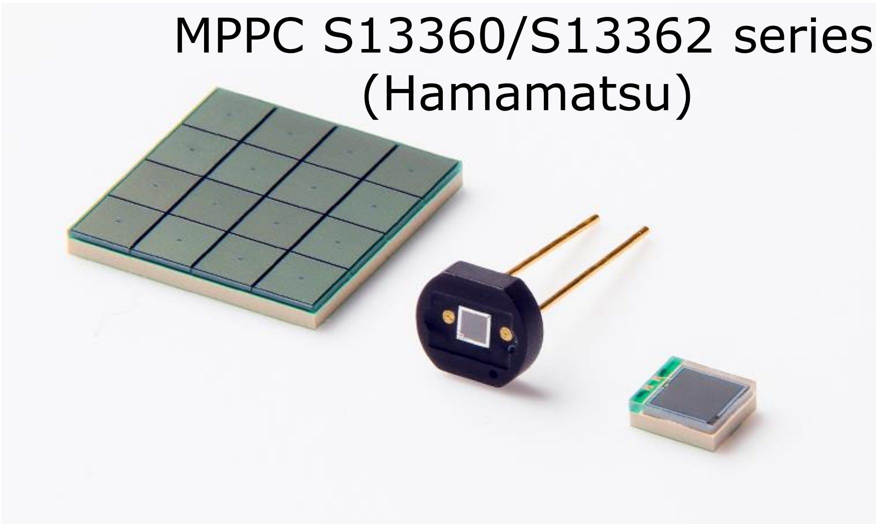
- Commissioning LSP
- Tuning POLIS RF units
- Test run with a polarized ion beam from POLIS and the vapor target
- Run with a polarized ion beam from POLIS and unpolarized atomic beam from the ABS

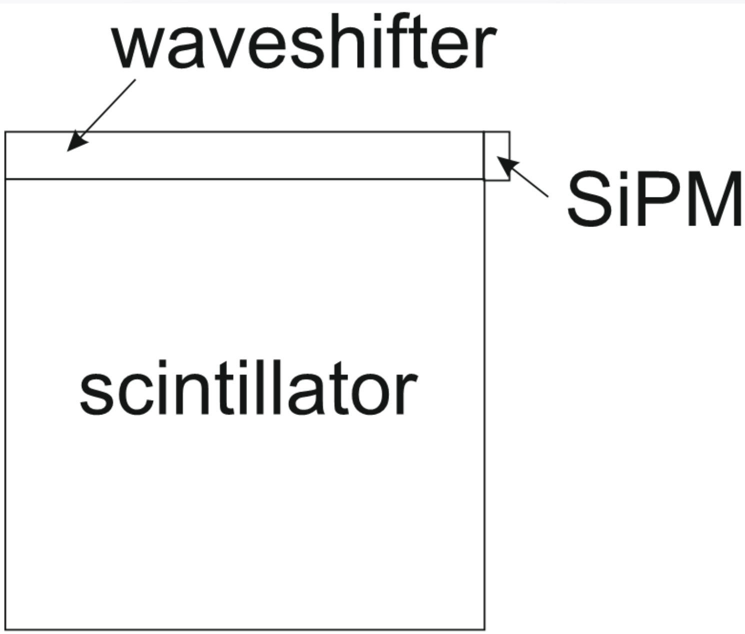
2023-...

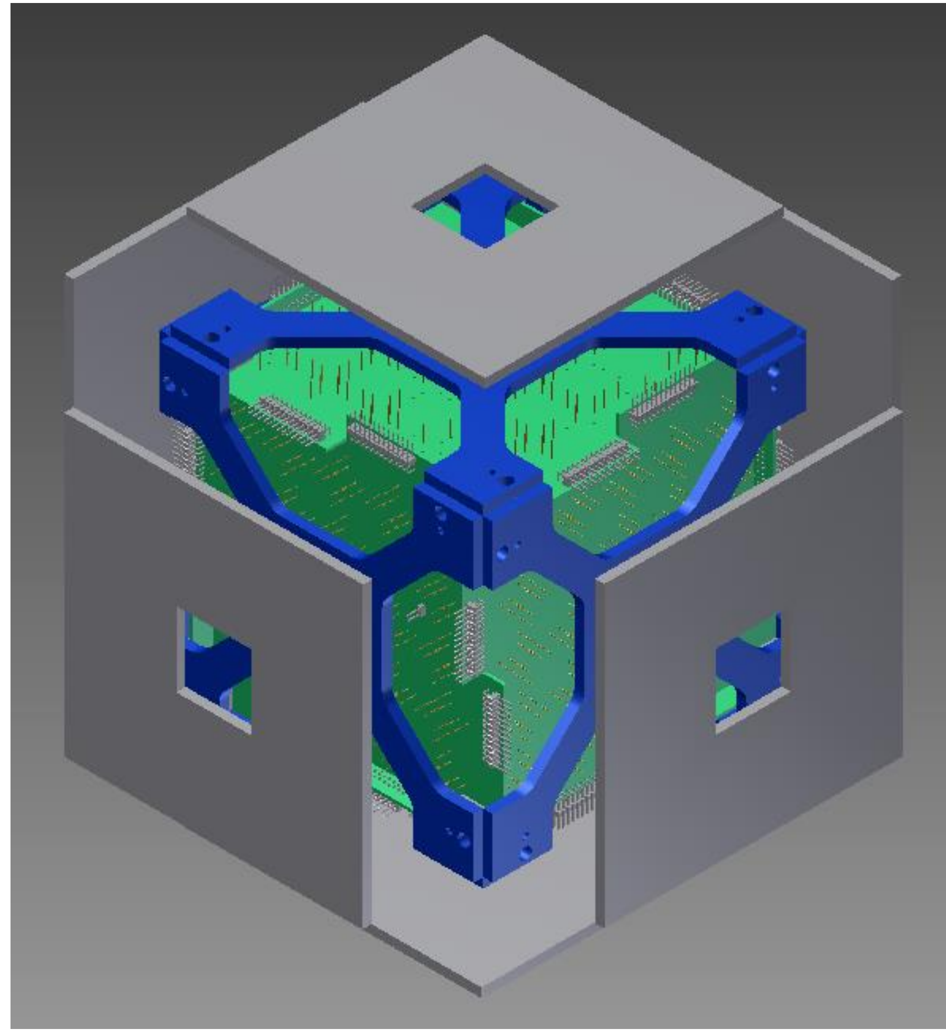
- Manufacturing and assembling the cosmic ray detection system
- Commissioning Glavish ionizer
- Tuning ABS RF units
- Commissioning NRP
- Run with a polarized ion beam from POLIS and polarized atomic beam from the ABS

Thank you for attention!

Cosmic ray detection system







Координатные системы

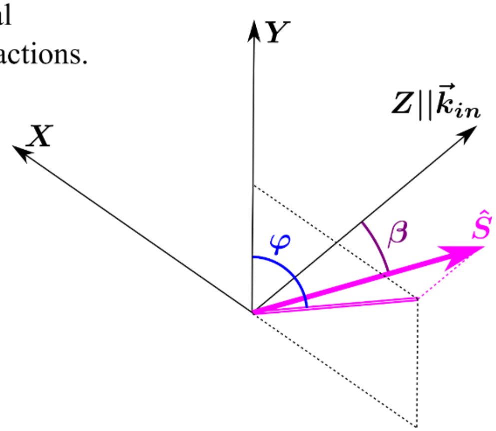
Basel convention (1961): Huber, P., Meyer, K.P. (eds.): Proceedings of the International Symposium on Polarization Phenomena of Nucleons. Helv. Phys. Acta Suppl. VI. Birkhäuser

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

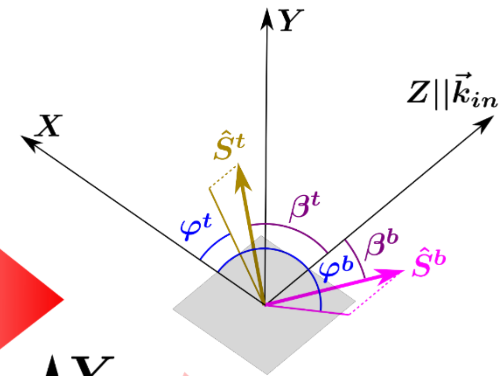
$\vec{k}_{in}$ - момент импульса налетающей частицы

$\vec{k}_{out}$ - момент импульса вылетающей частицы

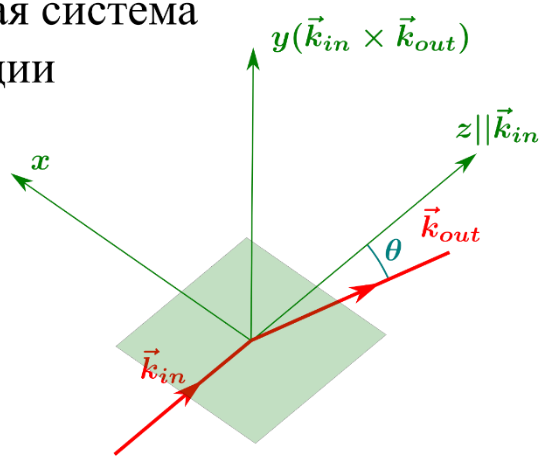
$\hat{S}^b$, $\hat{S}^t$ - оси квантования пучка и мишени

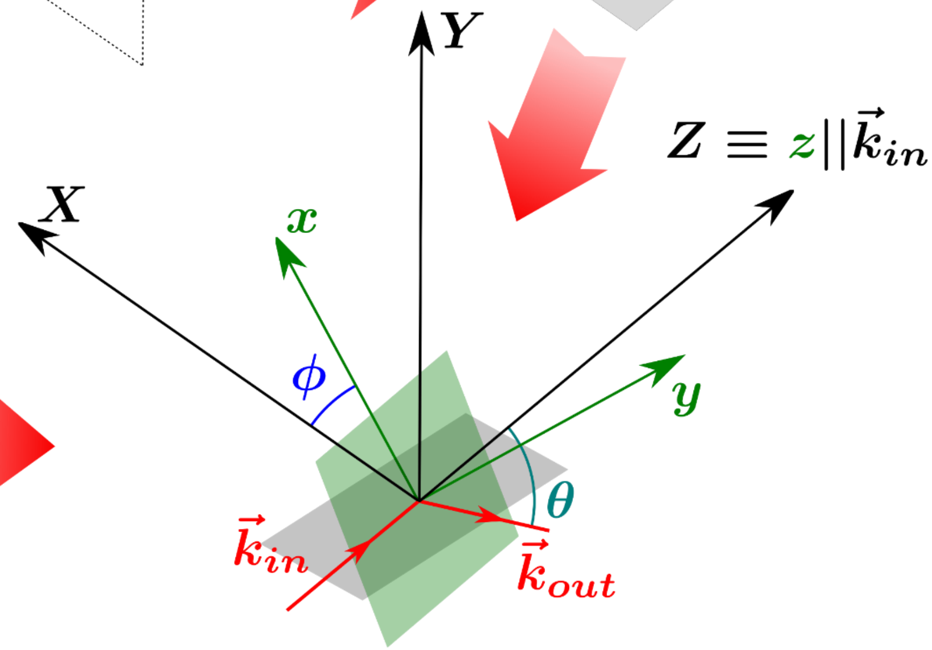


Описание поляризации (фиксированная в пространстве координатная система)



Координатная система реакции





Дифференциальное сечение

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

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

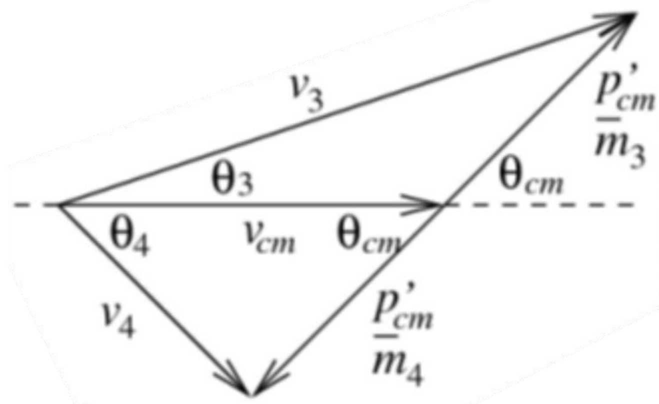
$$\bar{p}_1 = \frac{3}{2}p_x \qquad \bar{p}_6 = \frac{2}{3}p_{yz}$$

$$\bar{p}_2 = \frac{3}{2}p_y \qquad \bar{p}_7 = \frac{1}{3}p_{xx}$$

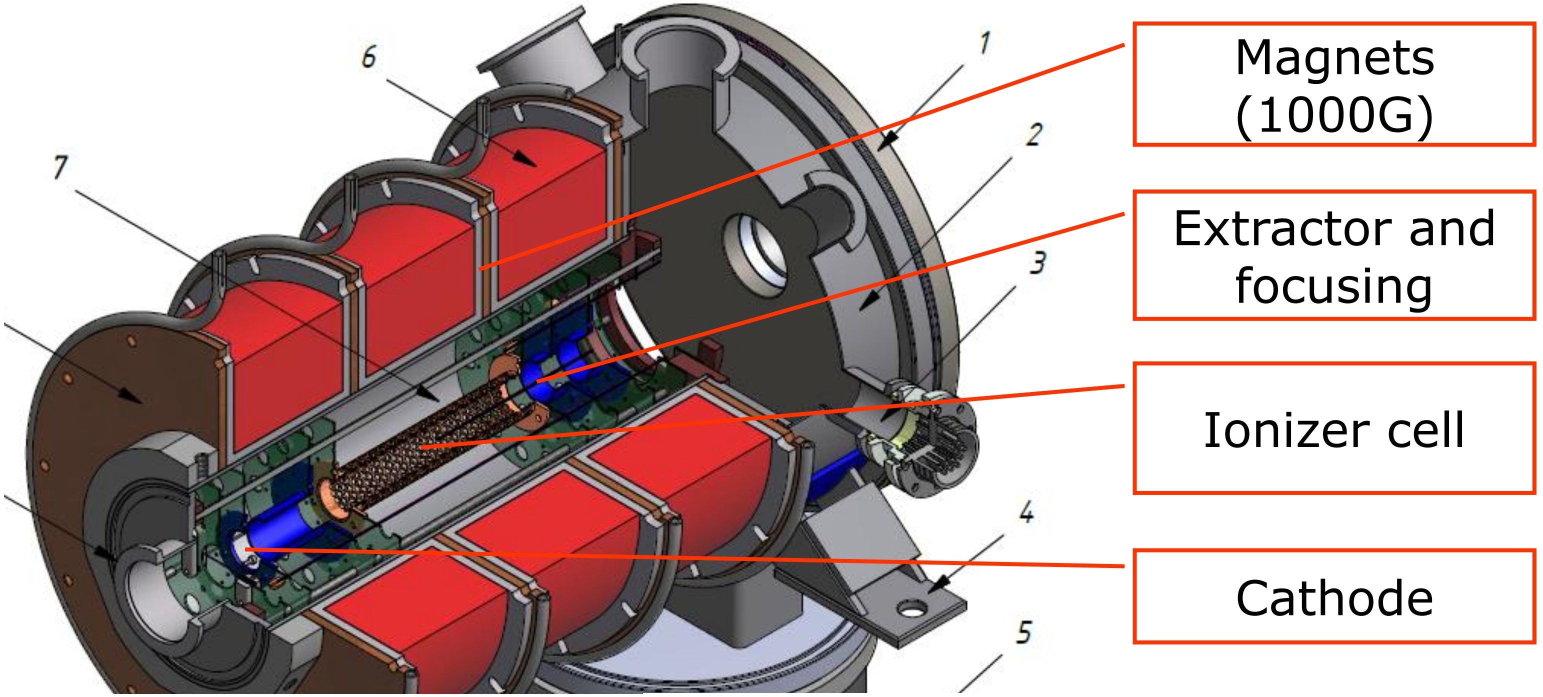
$$\bar{p}_3 = \frac{3}{2}p_z \qquad \bar{p}_8 = \frac{1}{3}p_{yy}$$

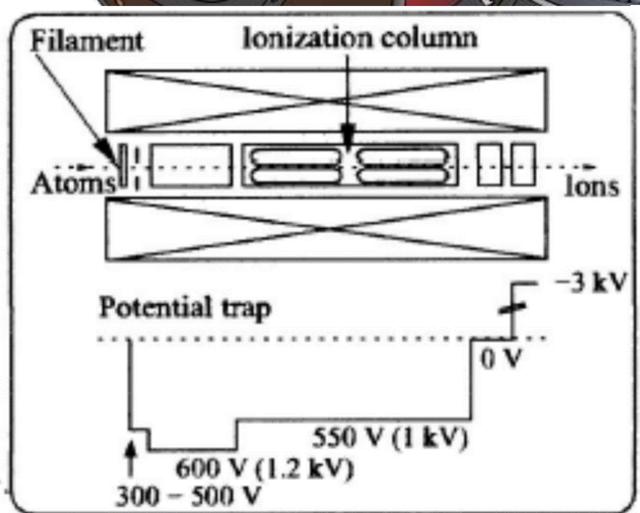
$$\bar{p}_4 = \frac{2}{3}p_{xy} \qquad \bar{p}_9 = \frac{1}{3}p_{zz}$$

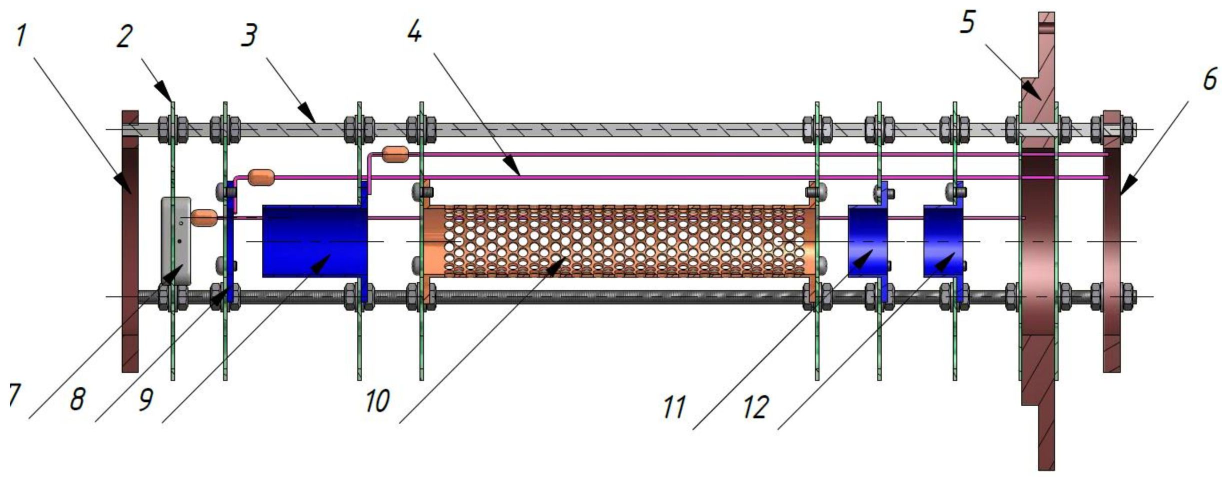
$$\bar{p}_5 = \frac{2}{3}p_{xz}$$



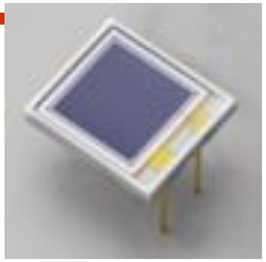
Glavish ionizer



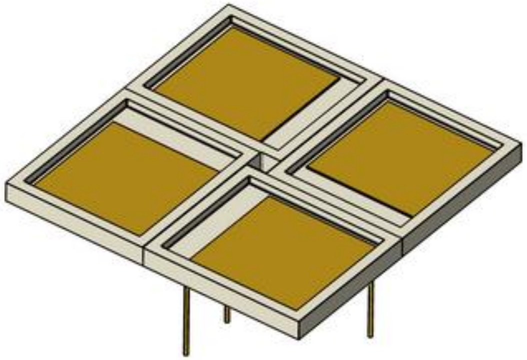


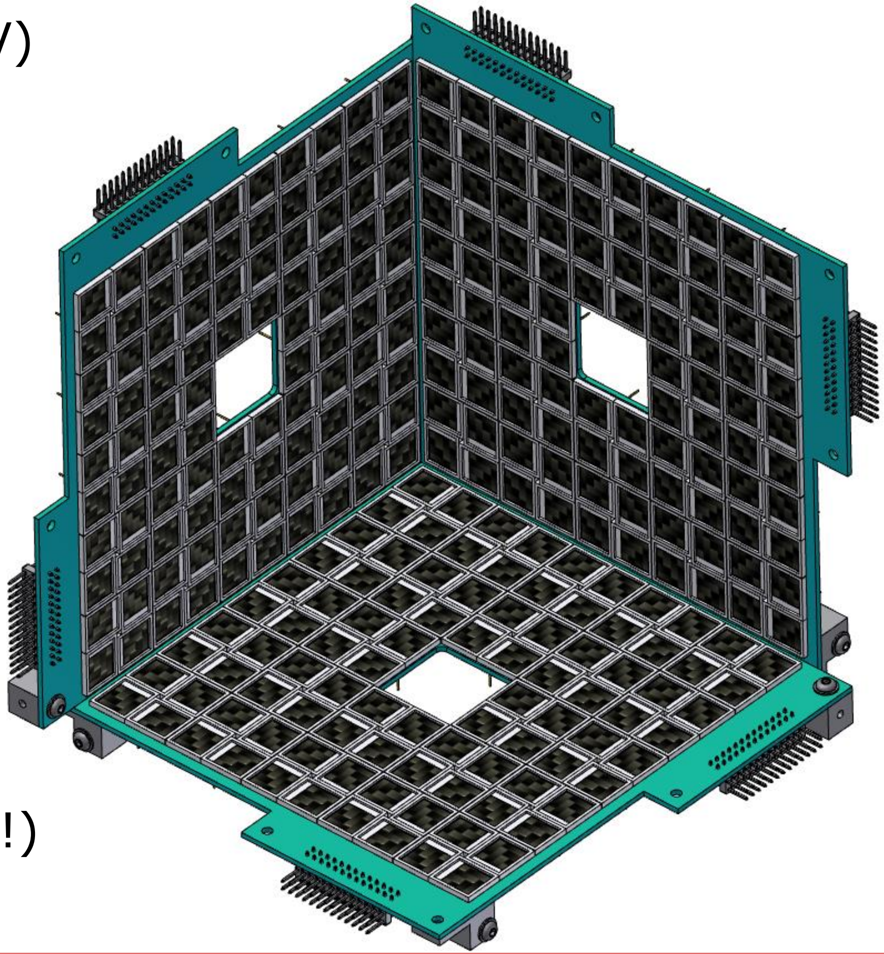


Detector system. PIN diodes version



- 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!)

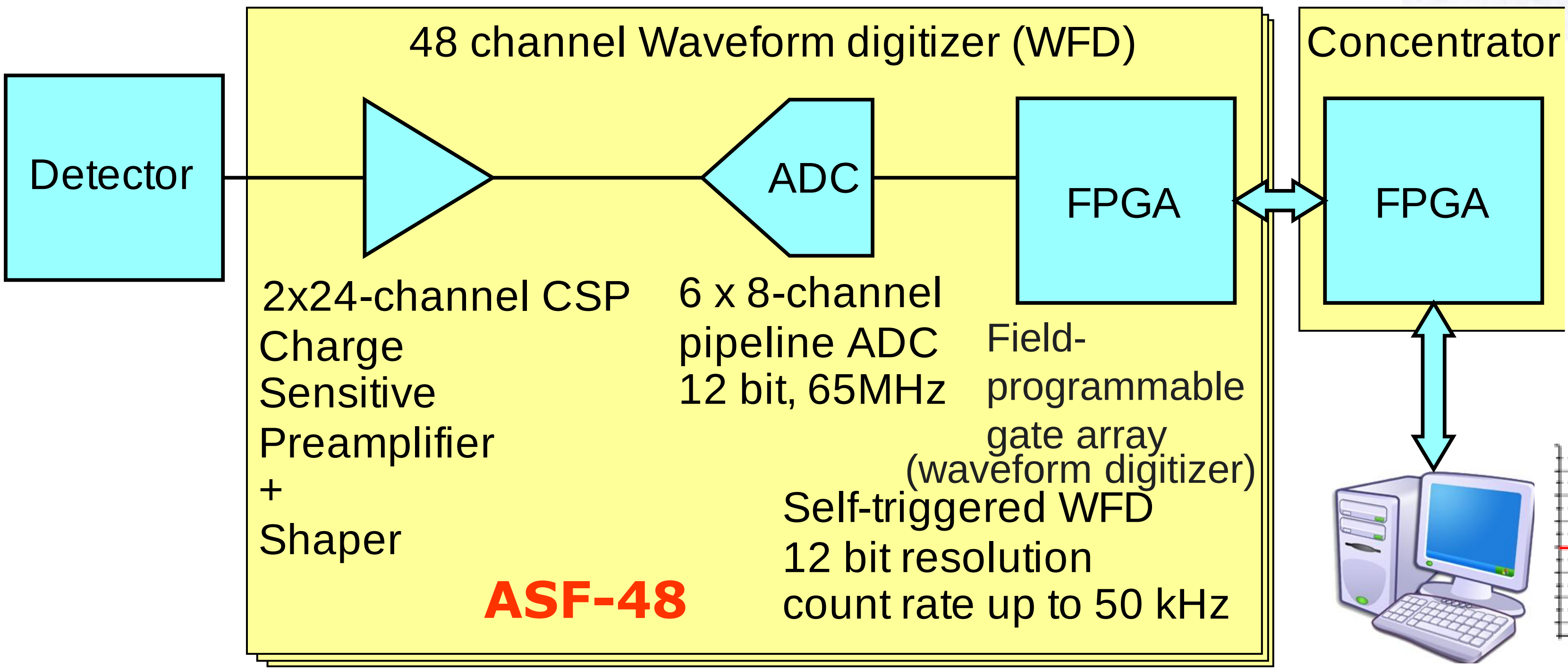
Readout electronics

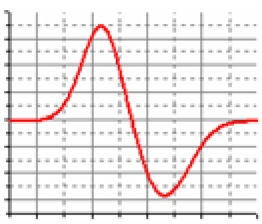
Readout requirements:

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

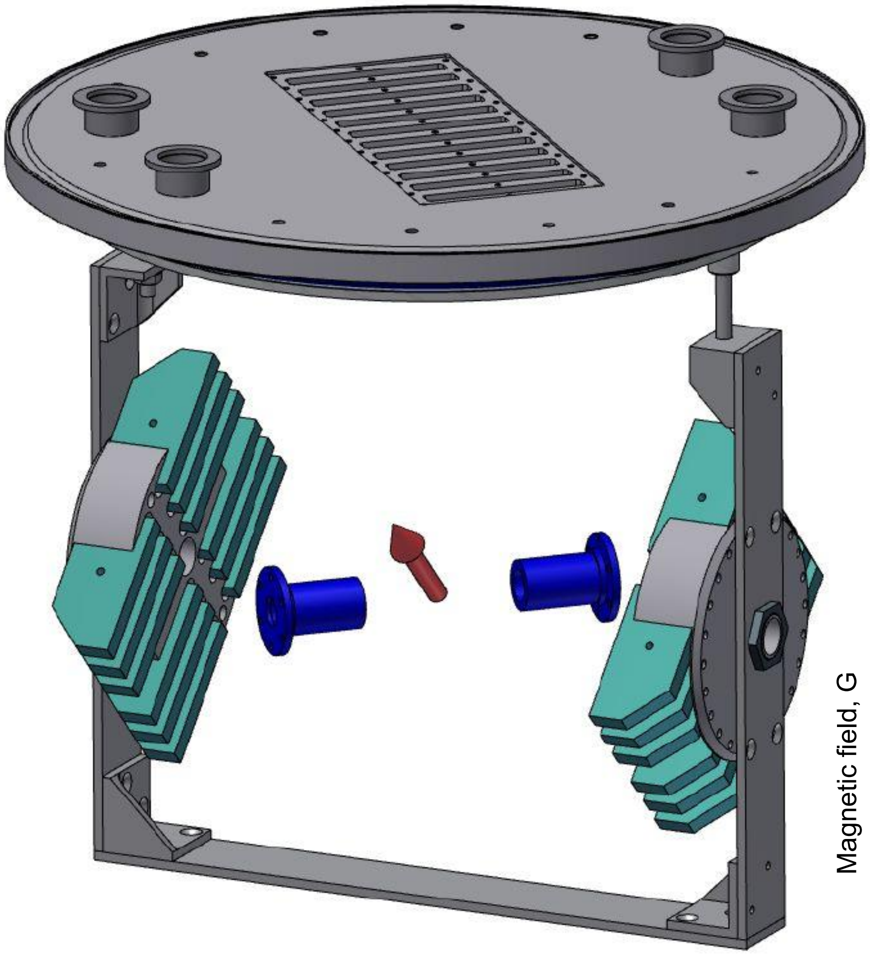
CSP from ATLAS CSC [BNL]

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



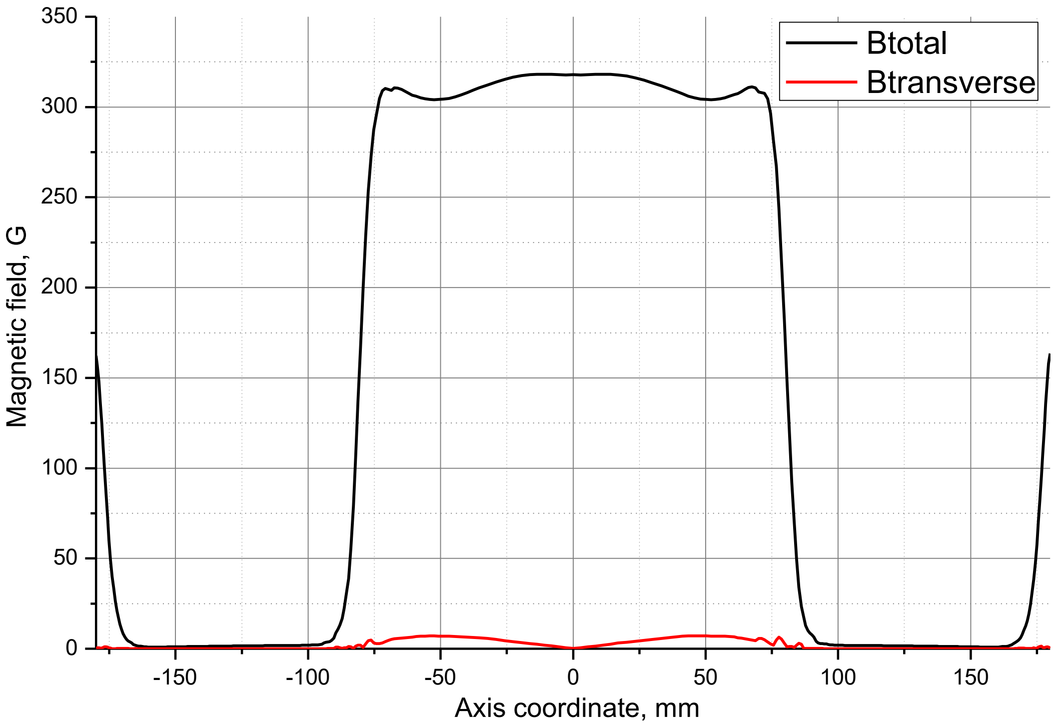


Magnet system

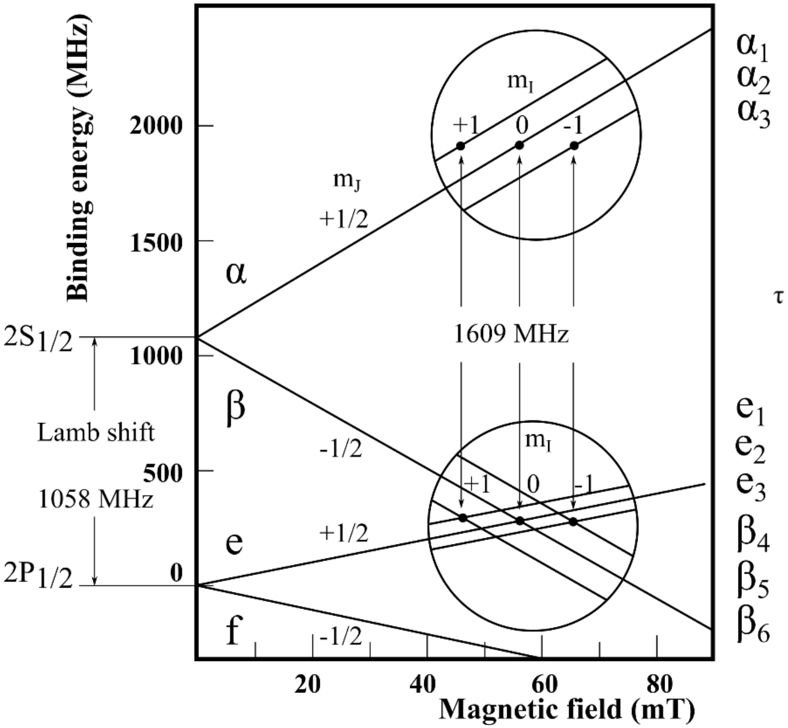


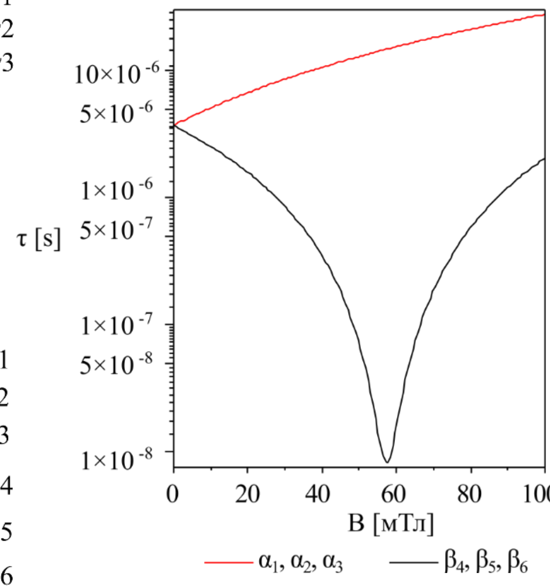
B =300 G = 2.5 B_c

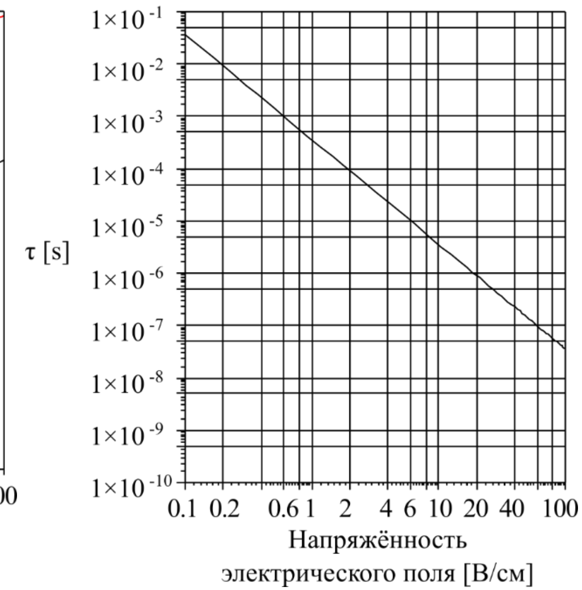
Magnet field is generated by 24 permanent magnets with dimensions 80x40x10 mm^3 with pole tip field of 1.25 T at the surface (NdFeB N40)

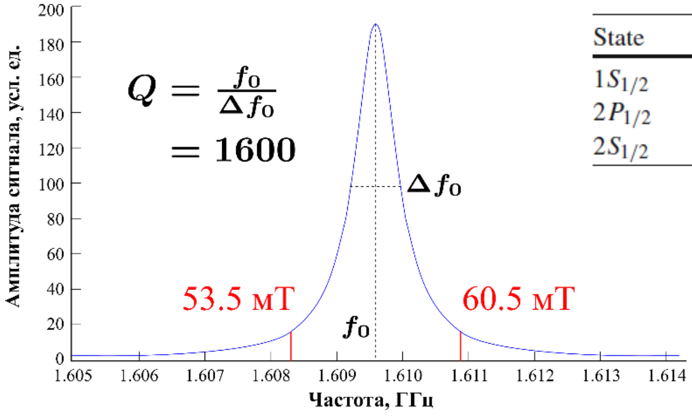


LSP principle

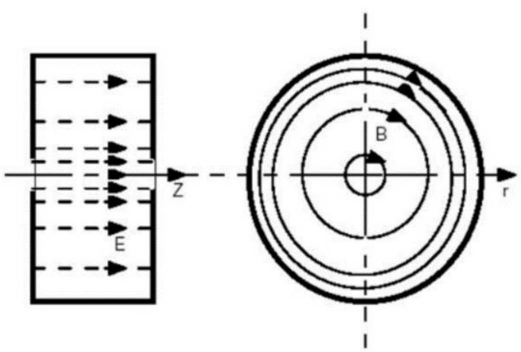








State	B_{crit} (mT)	ΔW (MHz)
$1S_{1/2}$	11.7	327
$2P_{1/2}$	0.5	14
$2S_{1/2}$	1.5	41



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).

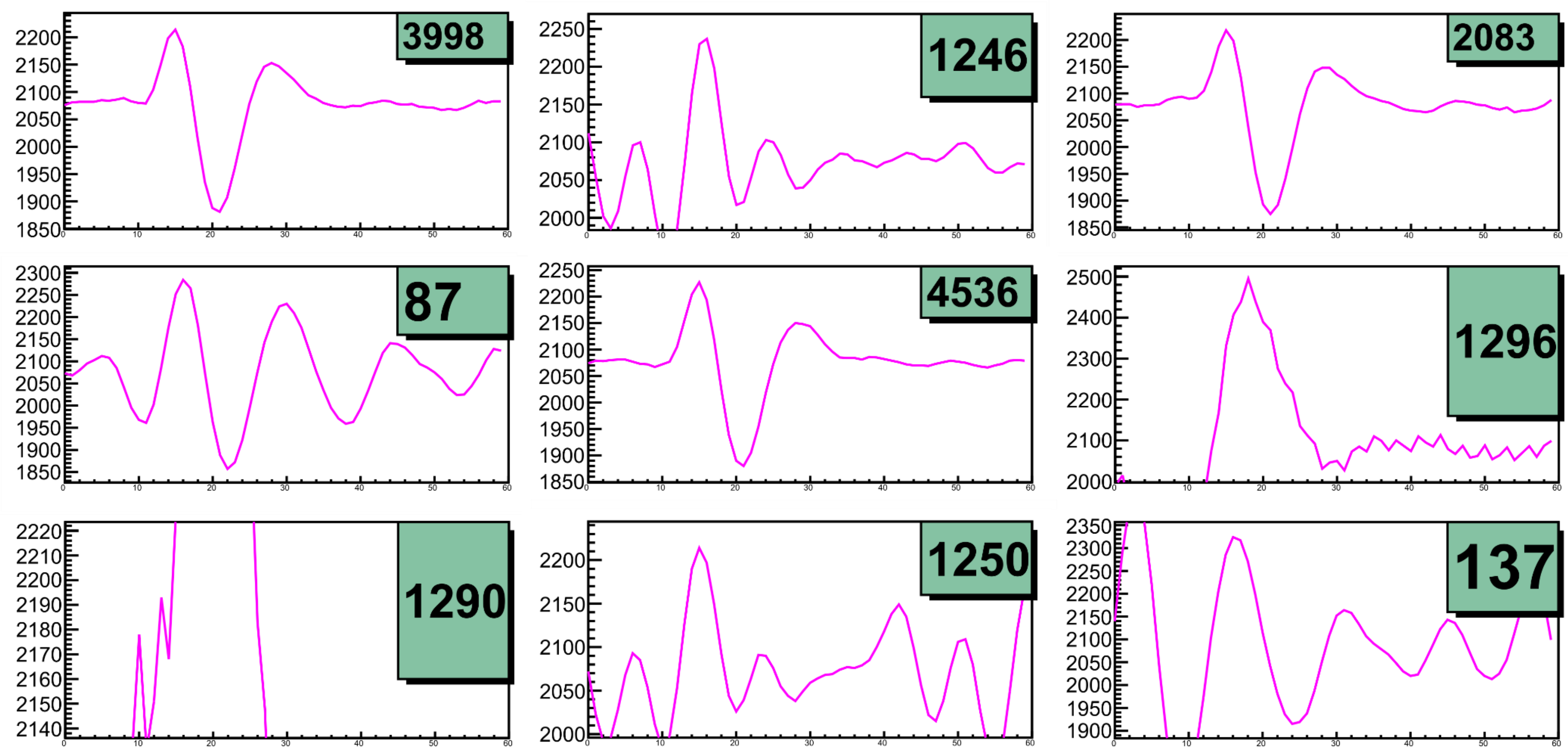
$$\begin{aligned}
\sigma_L &= \sigma_0(1 + \frac{3}{2}P_Z A_y(\theta)\sin\beta + \frac{1}{2}P_{ZZ}(A_{yy}(\theta)\ \sin^2\beta + A_{zz}\ \cos^2\beta)),\\
\sigma_R &= \sigma_0(1 - \frac{3}{2}P_Z A_y(\theta)\sin\beta + \frac{1}{2}P_{ZZ}(A_{yy}(\theta)\ \sin^2\beta + A_{zz}\ \cos^2\beta)),\\
\sigma_U &=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

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

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

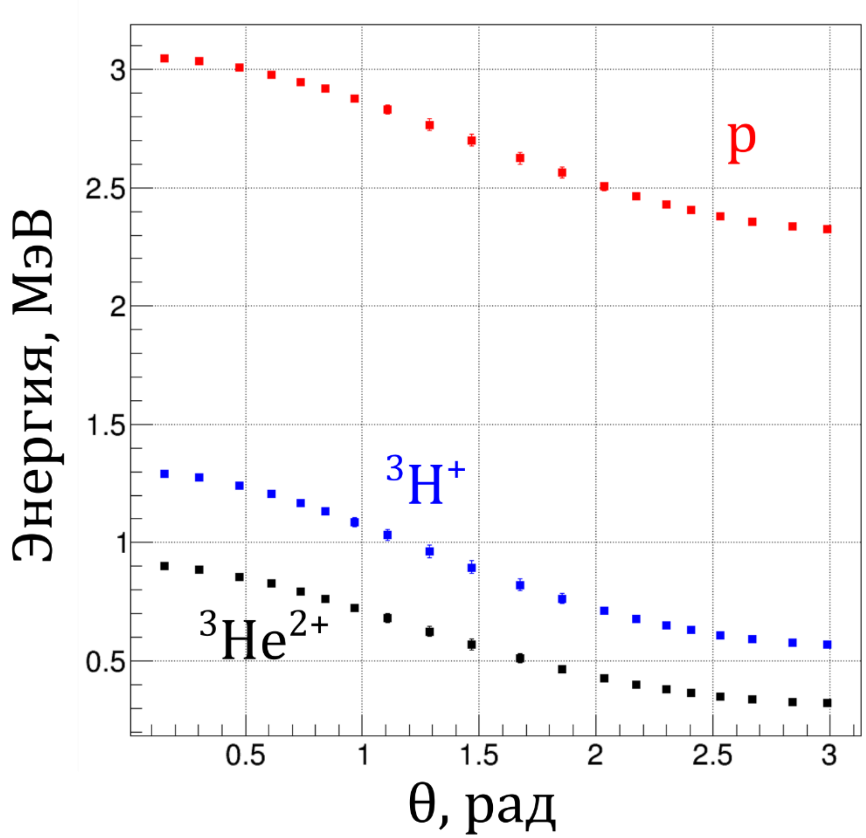
$$\begin{aligned}
\epsilon_1 &\equiv \frac{L-R}{L+R} = \frac{\frac{3}{2}P_Z\sin\beta\, A_y}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{yy} + \cos^2\beta A_{zz}]}\\
\epsilon_2 &\equiv \frac{U-D}{U+D} = \frac{P_{ZZ}\sin\beta\ \cos\beta\, A_{xz}}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{xx} + \cos^2\beta A_{zz}]}\\
\epsilon_3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

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]