PNPI - NRC KI

Development of a system of scintillation detectors for space radiation suppression in the experiment aims to study dd-fusion reactions with the low beam energy (PolFusion)

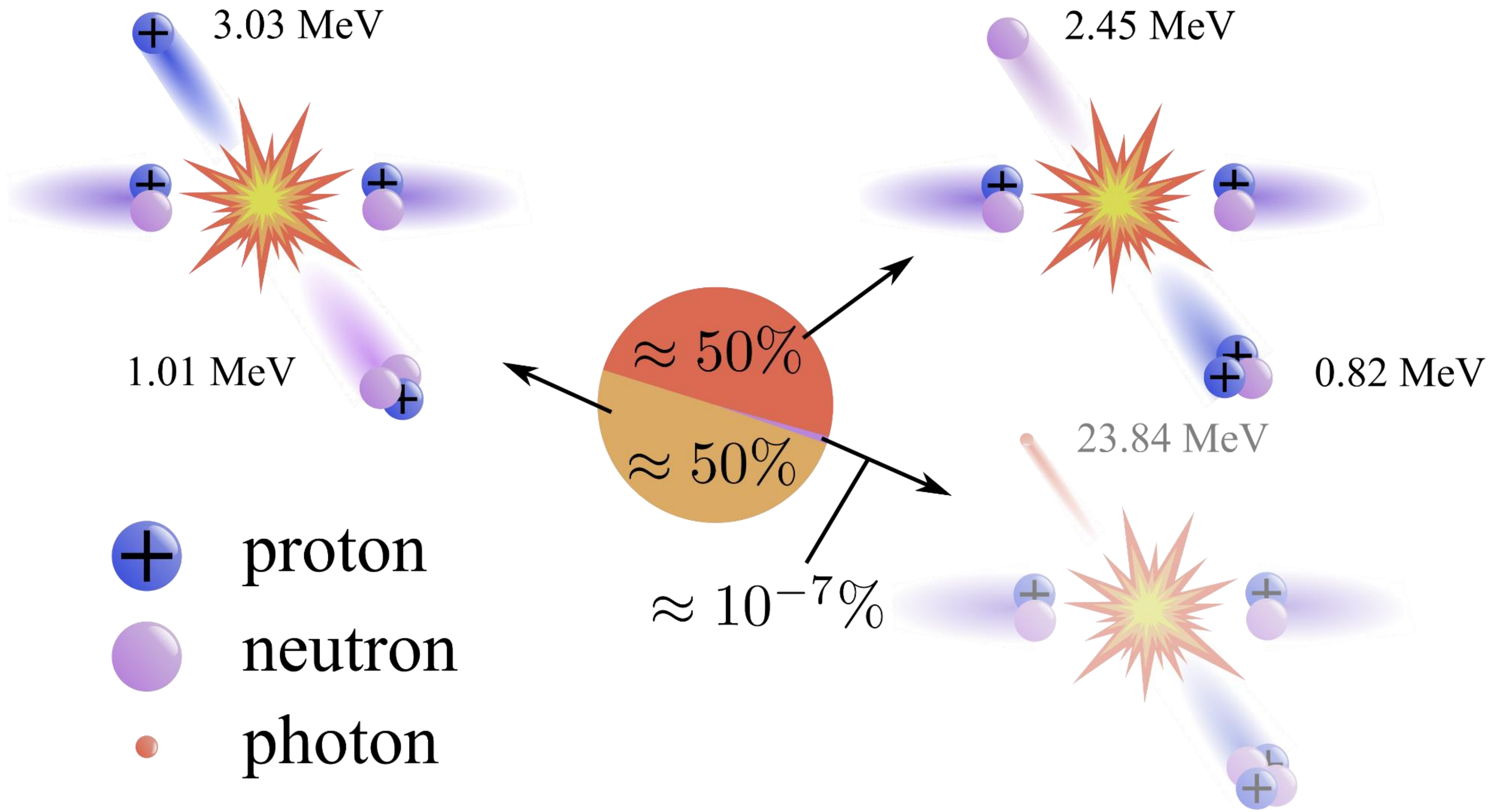
A. Rozhdestvenskij,
A. Vasilyev, M. Vznuzdaev, K. Ivshin, L. Kochenda, P. Kravtsov,
P. Kravchenko, V. Larionov, A. Solovev, V. Trofimov, V. Fotyev

Petersburg Nuclear Physics Institute
Gatchina, Russia

DD-fusion reactions

$$^2H + \, ^2H \rightarrow \, ^3H + p + 4.04 \; MeV$$

$$^2H + \, ^2H \rightarrow \, ^3He + n + 3.27 \; MeV$$



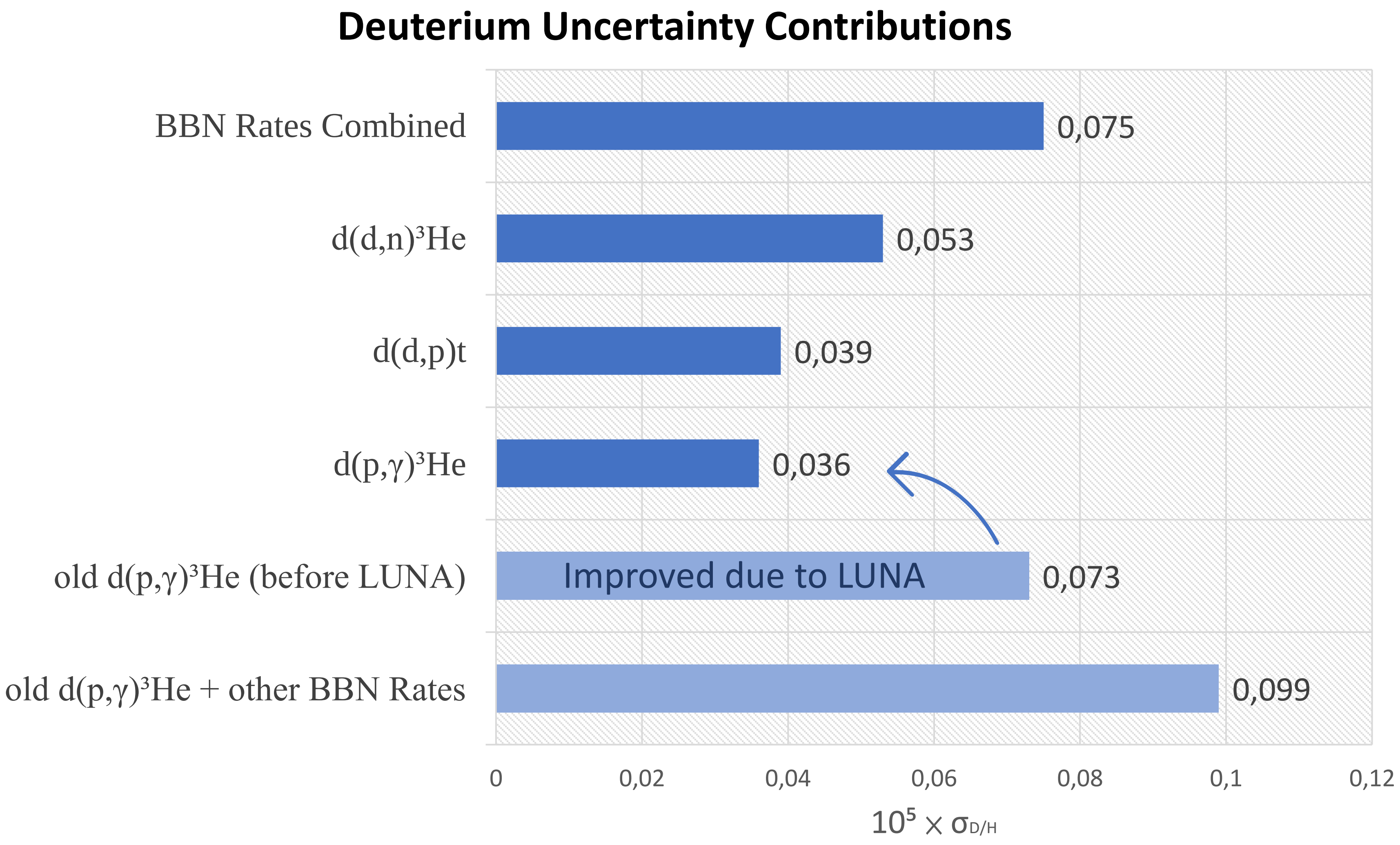
$$^2H + \, ^2H \rightarrow \, ^4He + \gamma + 23.84 \; MeV$$

Applied and fundamental physics

Astrophysics	Theory of nuclear interaction	Thermonuclear energy	Applied physics
• Big Bang • Hydrogen burning • Helium burning • Advanced burning • (carbon/neon/ oxygen/silicon) • s-process (neutron sources) • p-process	• Wide range of models • Difficulties in describing direct/indirect measurements	• Use of polarized fuel • Cross section increase • Controlling the Angular Distribution of Escape of Reaction Products • Reactors with low neutron yield	• Tritium and helium-3 production • 3He-oriented technology of gas-discharge detectors • Neutron source to produce medical isotopes 100Mo(n,2n)99Mo

Astrophysics

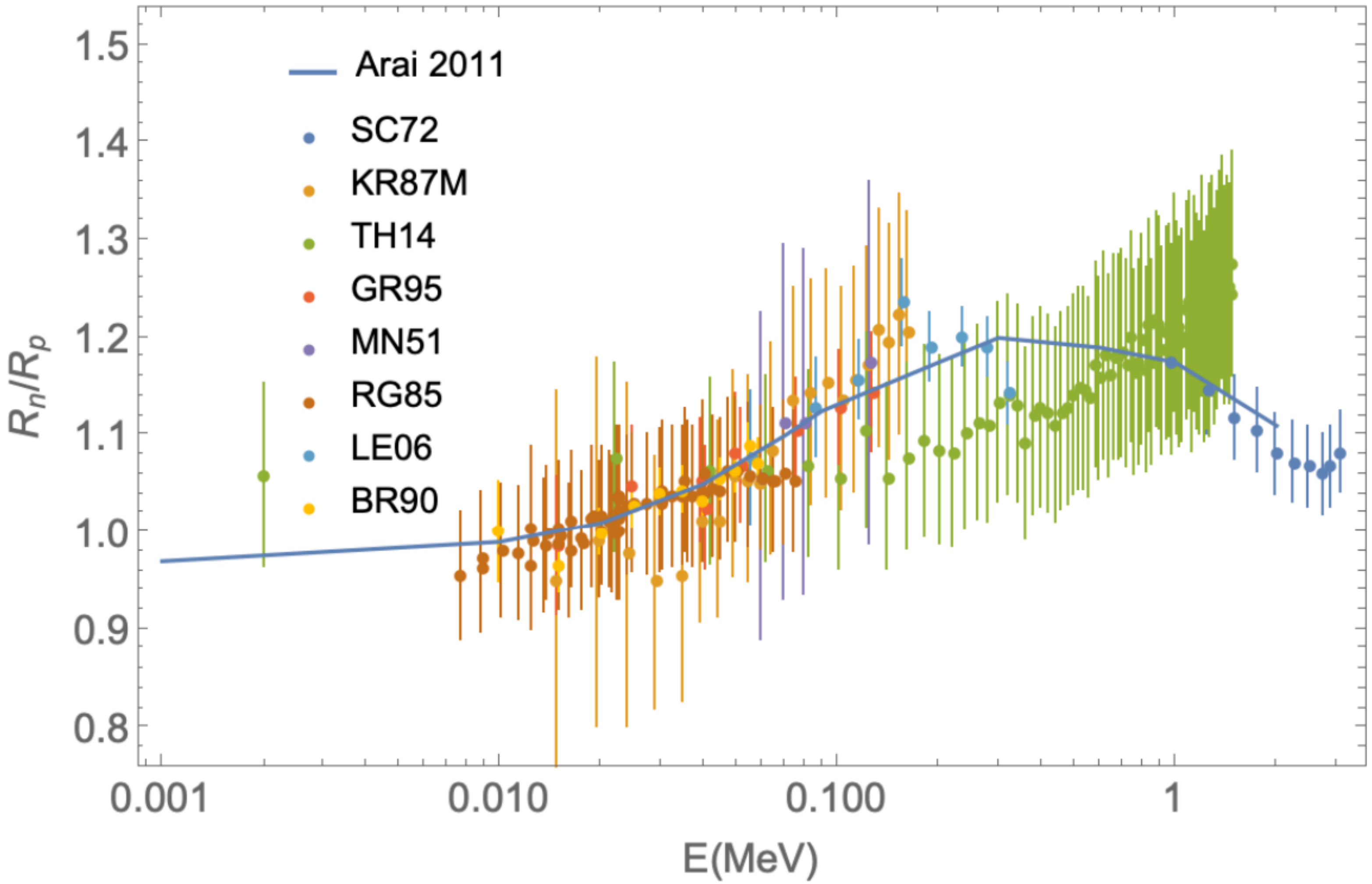
Big Bang nucleosynthesis ⟶ Primordial isotope ratio D/H



Better dd-data needed!

Global BBN Analysis: Tsung-Han Yeh, Keith Olive, Brian Fields (2021)

Astrophysics



Ofelia Pisanti, Gianpiero Mangano, Gennaro Miele, and Pierpaolo Mazzella Primordial Deuterium after LUNA: concordances and error budget (2020)

Ratios of processes $d(d, n)^3He$ to $d(d, p)^3H$ S-factors from experiments (dots) and theory (solid line). The Trojan Horse points from with their 1-σ errors are shown in green (TH).

New dd (both channels) measurements needed!

Theory prediction: K. Arai, S. Aoyama, Y. Suzuki, P. Descouvemont, and D. Baye Phys. Rev. Lett. 107, 132502 (2011)

Theoretical methods

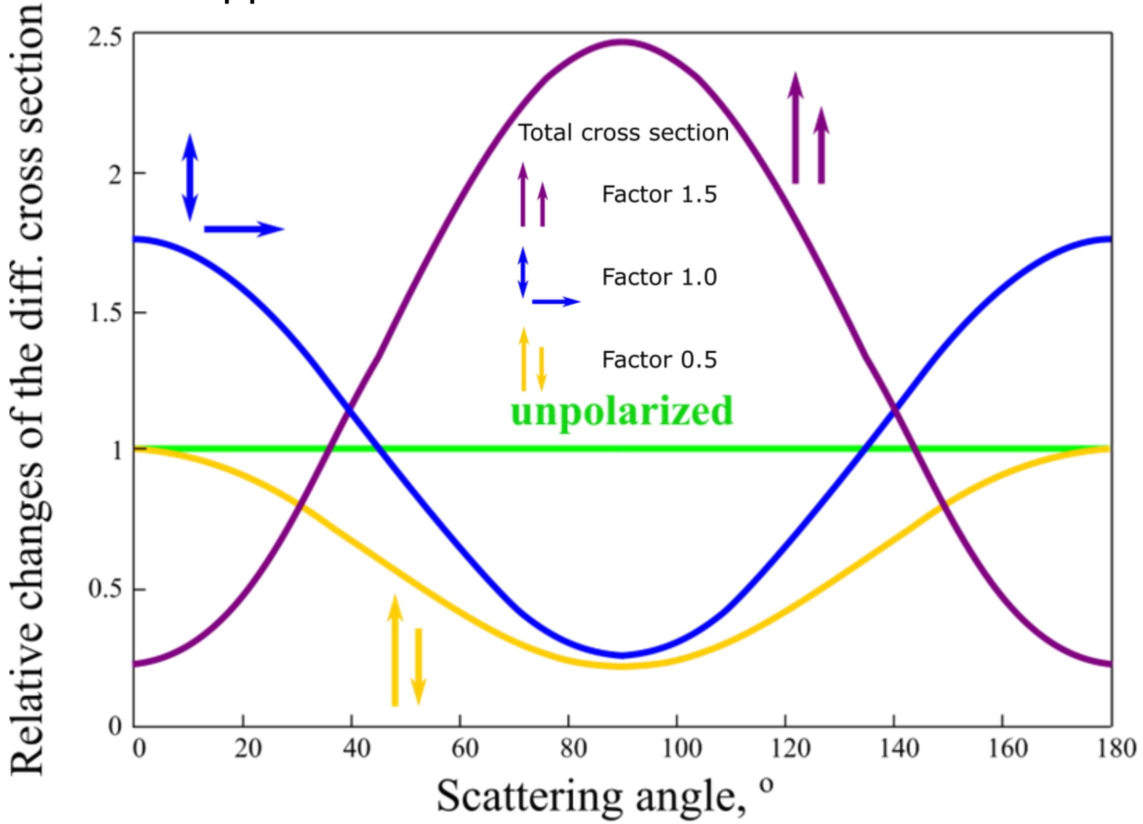
Many different cases ⟶ No “unique” model

Model	Applicable to	Comments
Potential/optical model	Capture Fusion	• Internal structure neglected • Antisymetrization approximated
R-matrix	Capture Transfer	• No explicit wave function • Physics simulated by some parameters
DWBA	Transfer	• Perturbation method • Wave function in the entrance and exit channels
Microscopic models	Capture Transfer	• Based on a nucleon-nucleon interaction • A-nucleon problems • Predictive power

Pierre Descouvemont: Reaction models in nuclear astrophysics

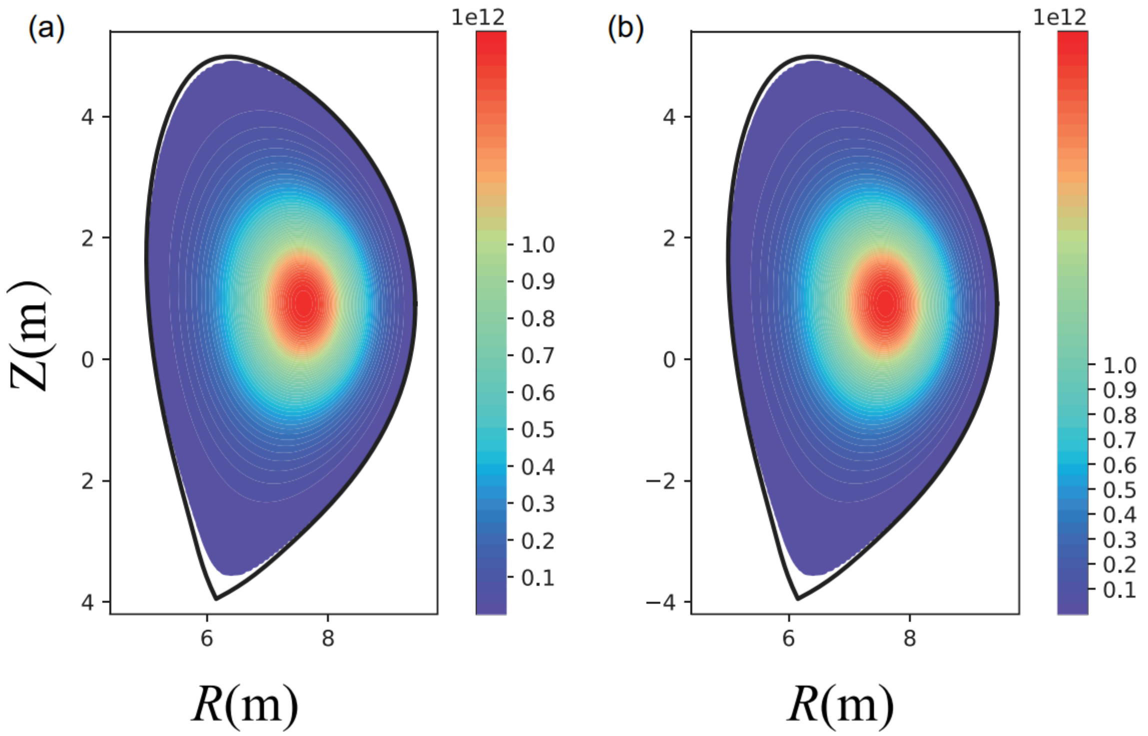
Thermonuclear fusion and applied physics

- Cross section increasement
- Control over the direction of expansion of reaction products
- Suppression of the neutron channel



Exp.: Ch. Leemann et al., Helv. Phys. Acta **44**, 141 (1971)
Theor.: G. Hupin et al. Nature Com. **10**, 321 (2019)

Distributions of neutron sources in coordinates (R, Z) for (a) non-polarized case and (b) case of full parallel polarization

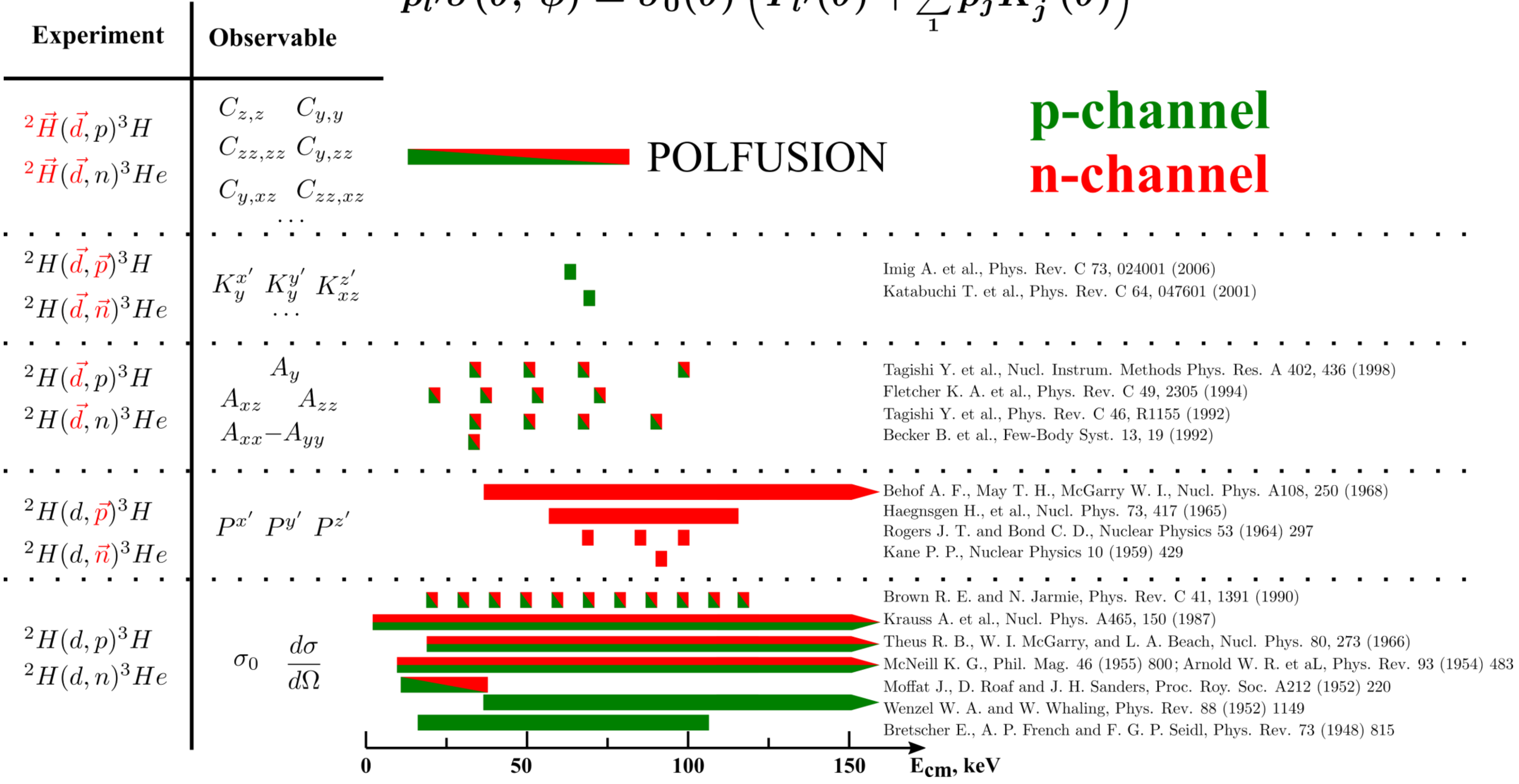


W.Yang, G.Li, X.Gong, X.Gao, X.Li, H.Li… Effect of the Fusion Fuels' Polarization on Neutron Wall Loading Distribution in CFETR (2021) https://doi.org/10.1080/15361055.2021.1969064 (China Fusion Engineering Test Reactor (CFETR))

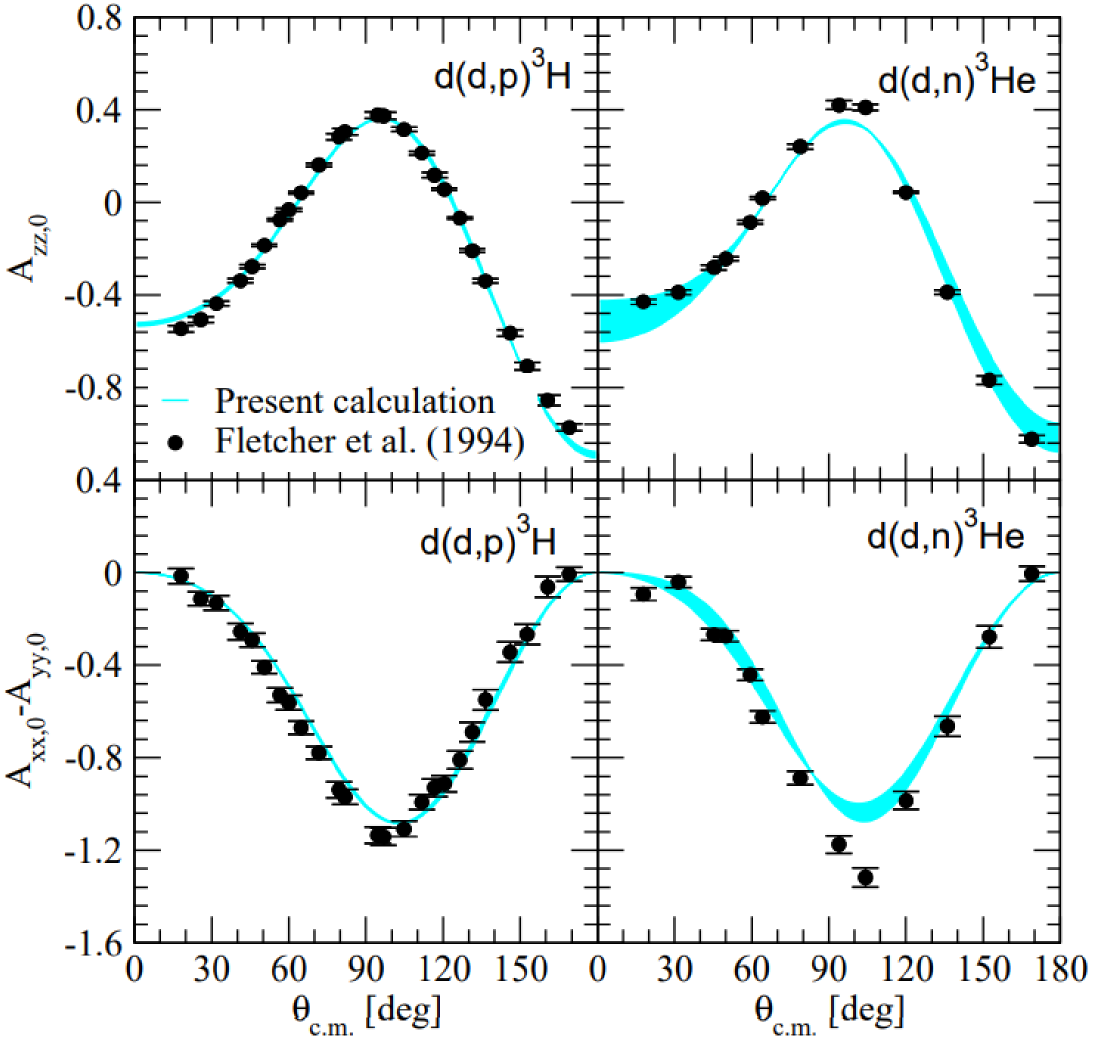
Review of experiments

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

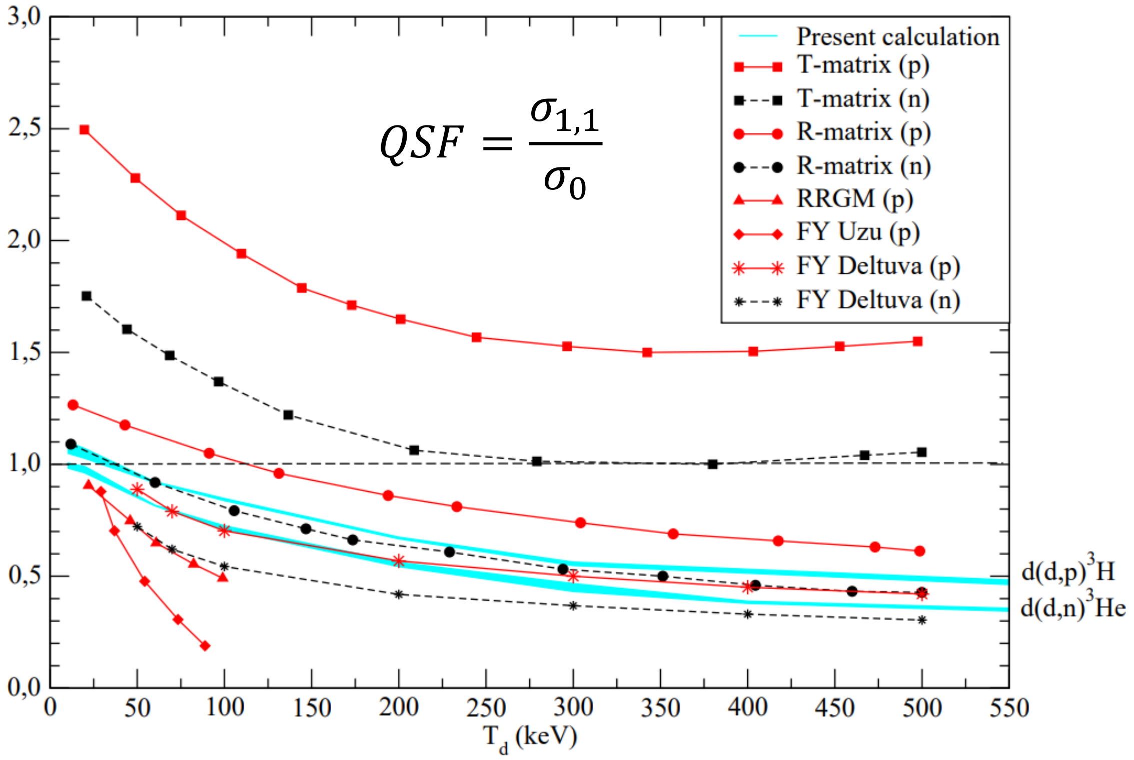
$$p_{l'}\sigma(\theta,\ \phi) = \sigma_0(\theta)\left(P_{l'}(\theta) + \sum_1^9 p_j K_j^{l'}(\theta)\right)$$



Latest research



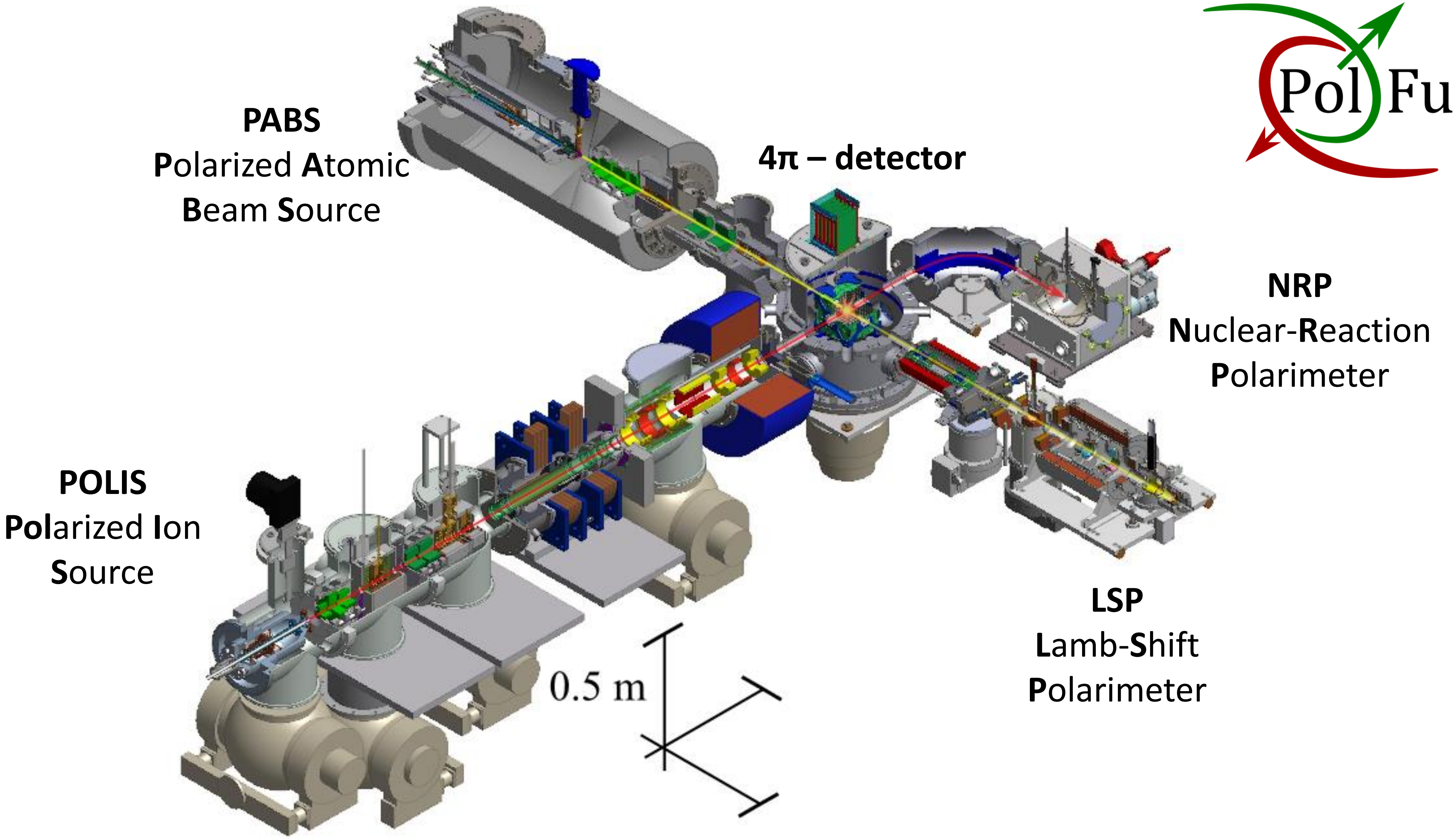
The observables $A_{zz,0}$ and $A_{xx,0} - A_{yy,0}$ for the $\vec{d}$ (d, p) ^{3}H and $\vec{d}$ (d, n) ^{3}He processes at Td = 21 keV. The (cyan) bands show the results of the present calculations.



The QSF for the processes d(d, n) ^{3}He and d(d, p) ^{3}H.

M. Viviani: arXiv:2207.01433v1 [nucl-th] 4 Jul 2022

Experimental setup



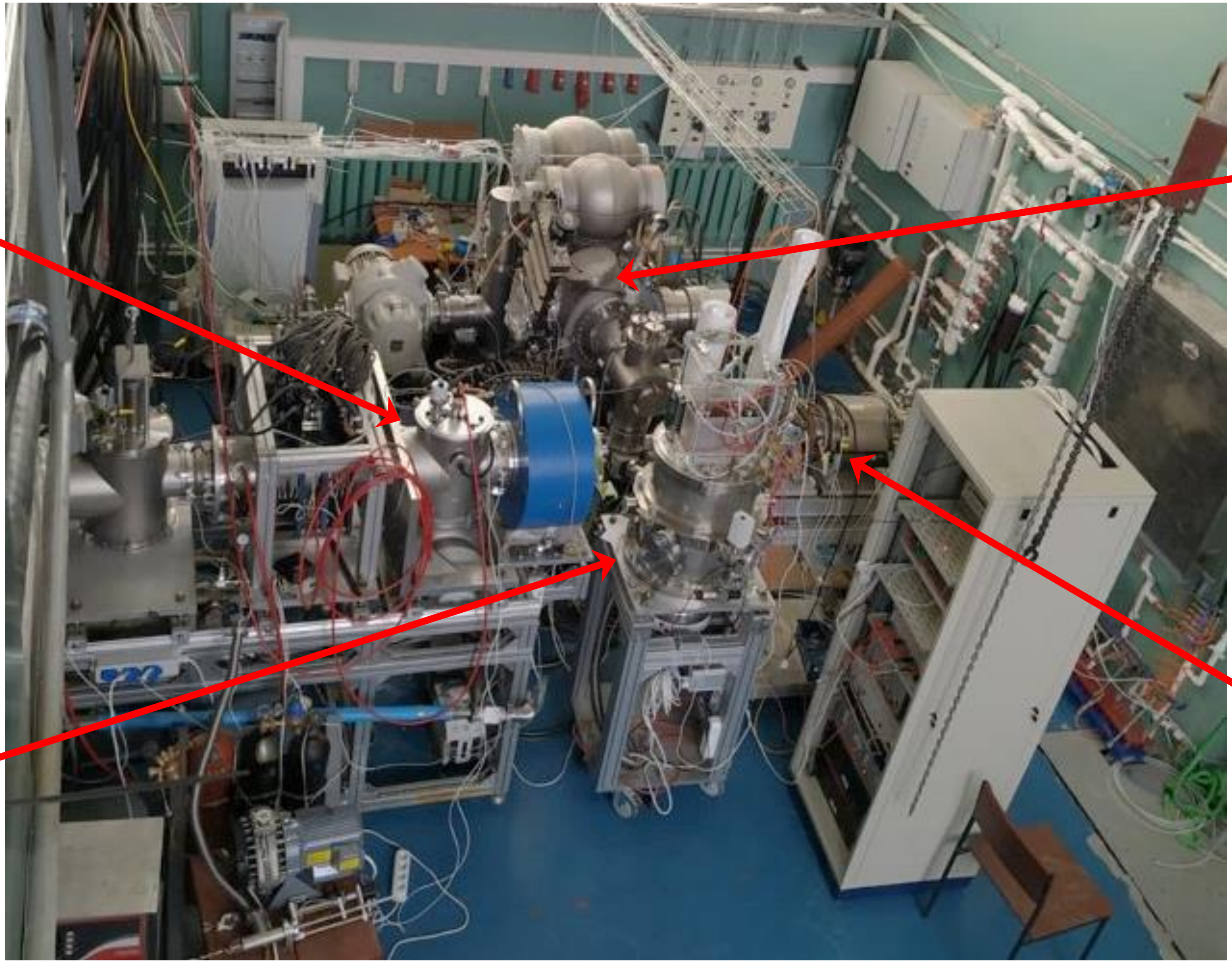
Experimental setup

POLIS
Polarized **I**on **S**ource

Ion beam
10-50 keV
$1.2 \cdot 10^{16}$ ions/s

Nozzle:
d = 1.3 mm
T = 65 K

4π – detector



PABS
Polarized **A**tomic **B**eam **S**ource

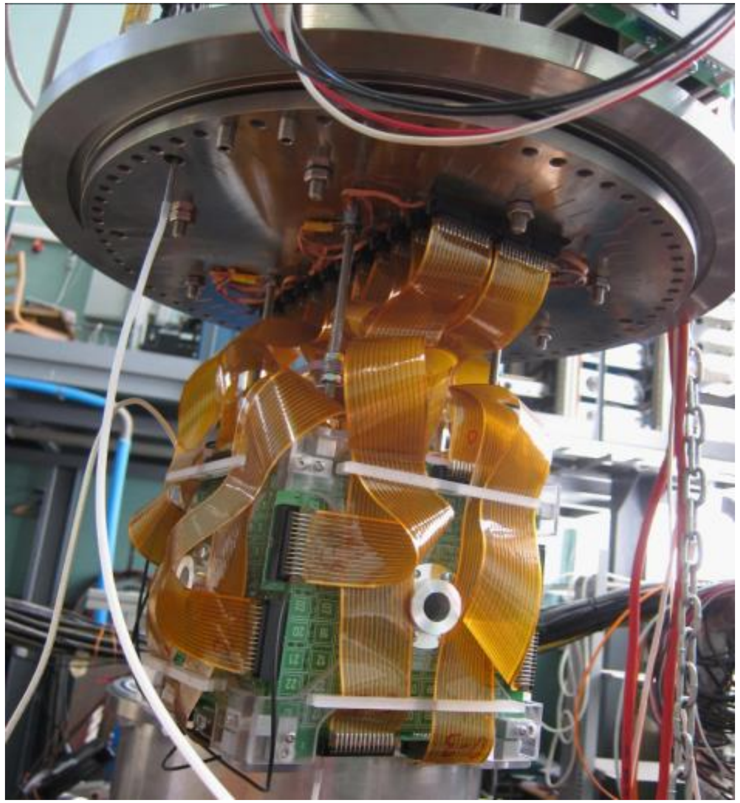
Atomic beam
0.01 eV
$4 \cdot 10^{16}$ atoms/s

Nozzle:
d = 2 mm
T = 65-85 K

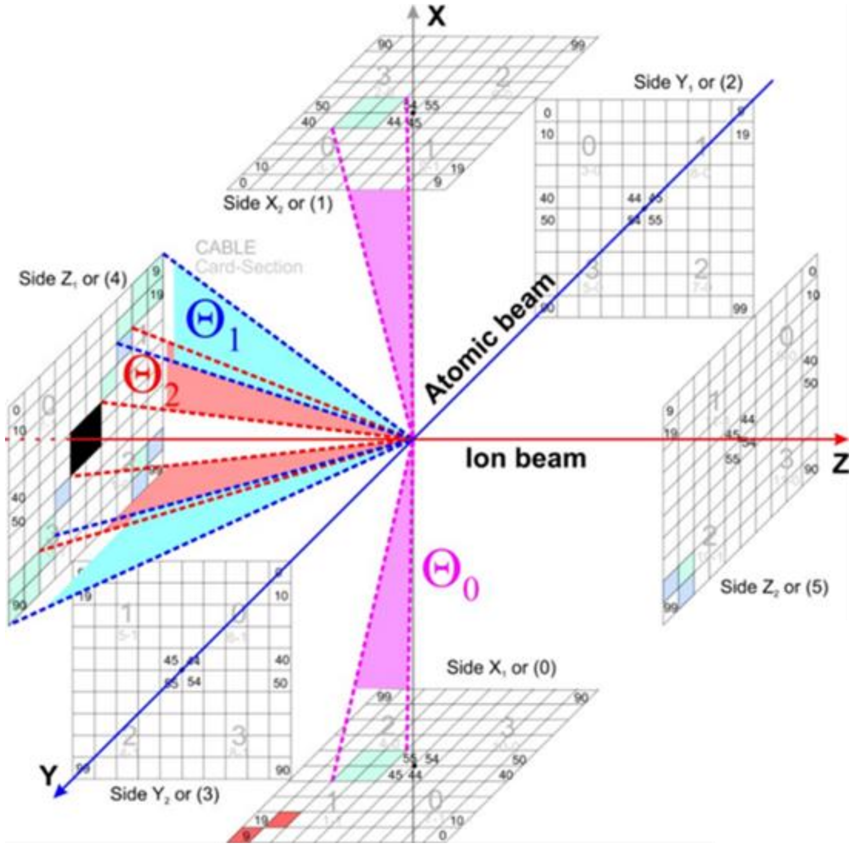
NRP
Nuclear-**R**eaction **P**olarimeter

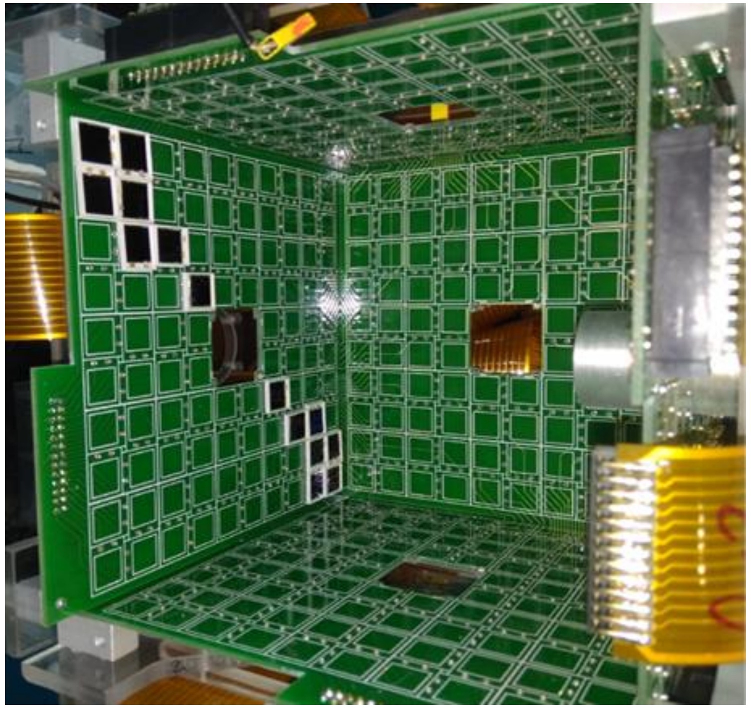
Detector system

Detector coordinate system



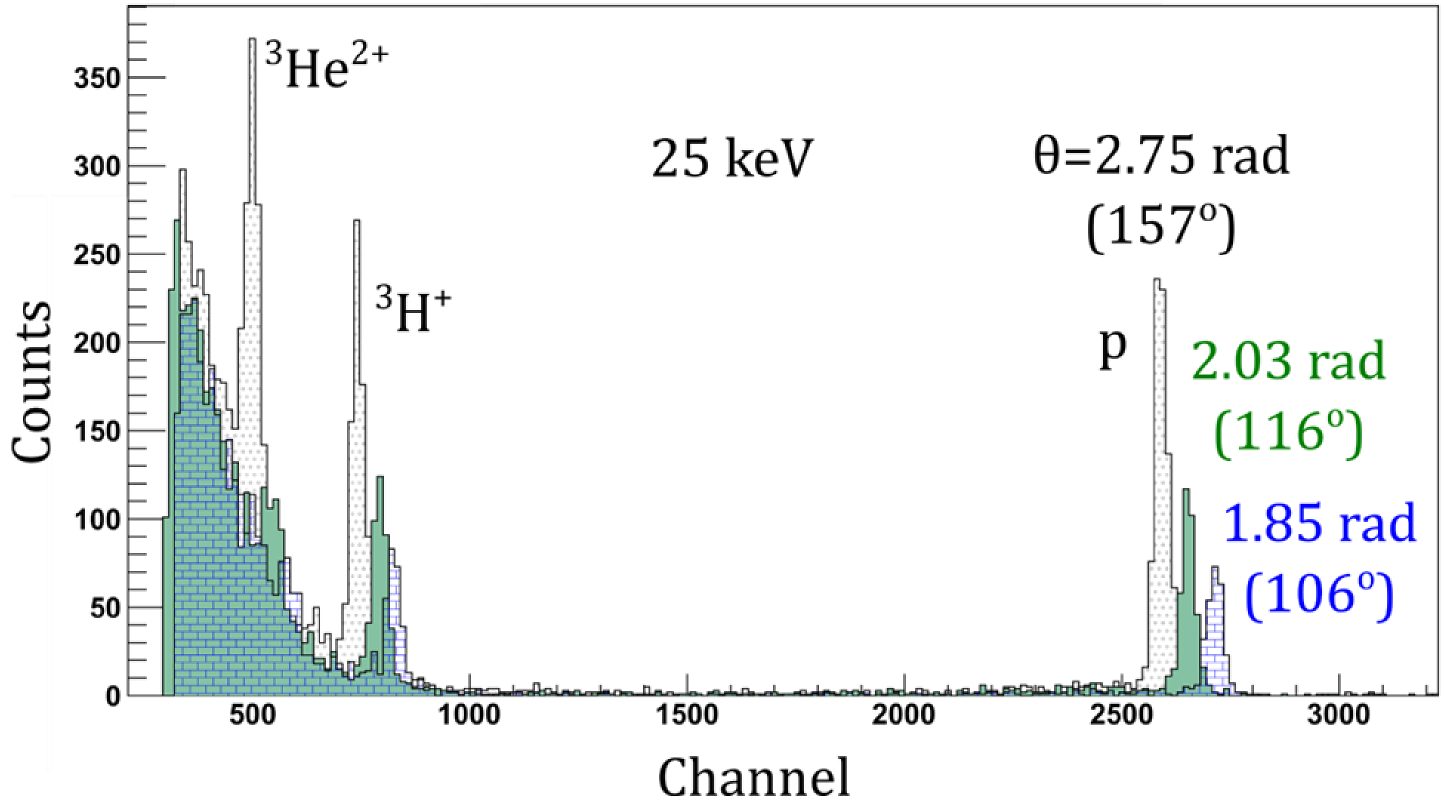
Outside view

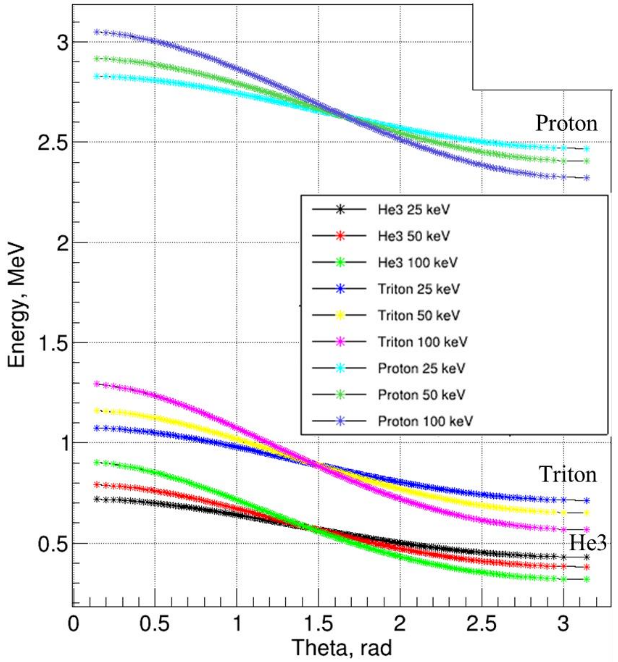


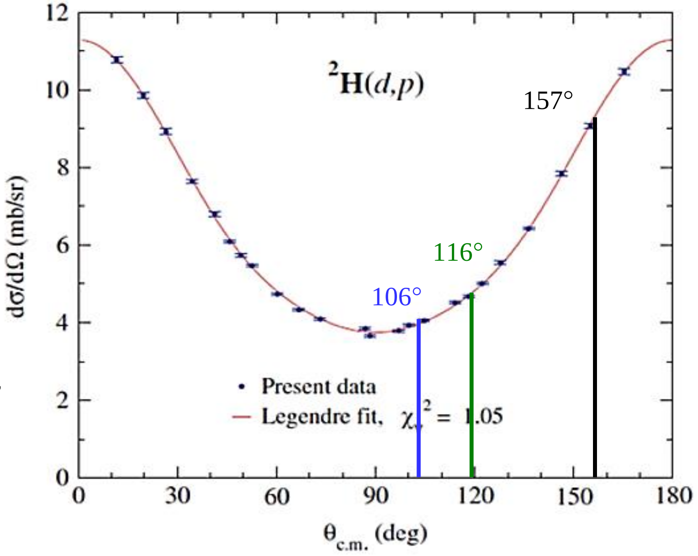


Inside view

Test run 2020

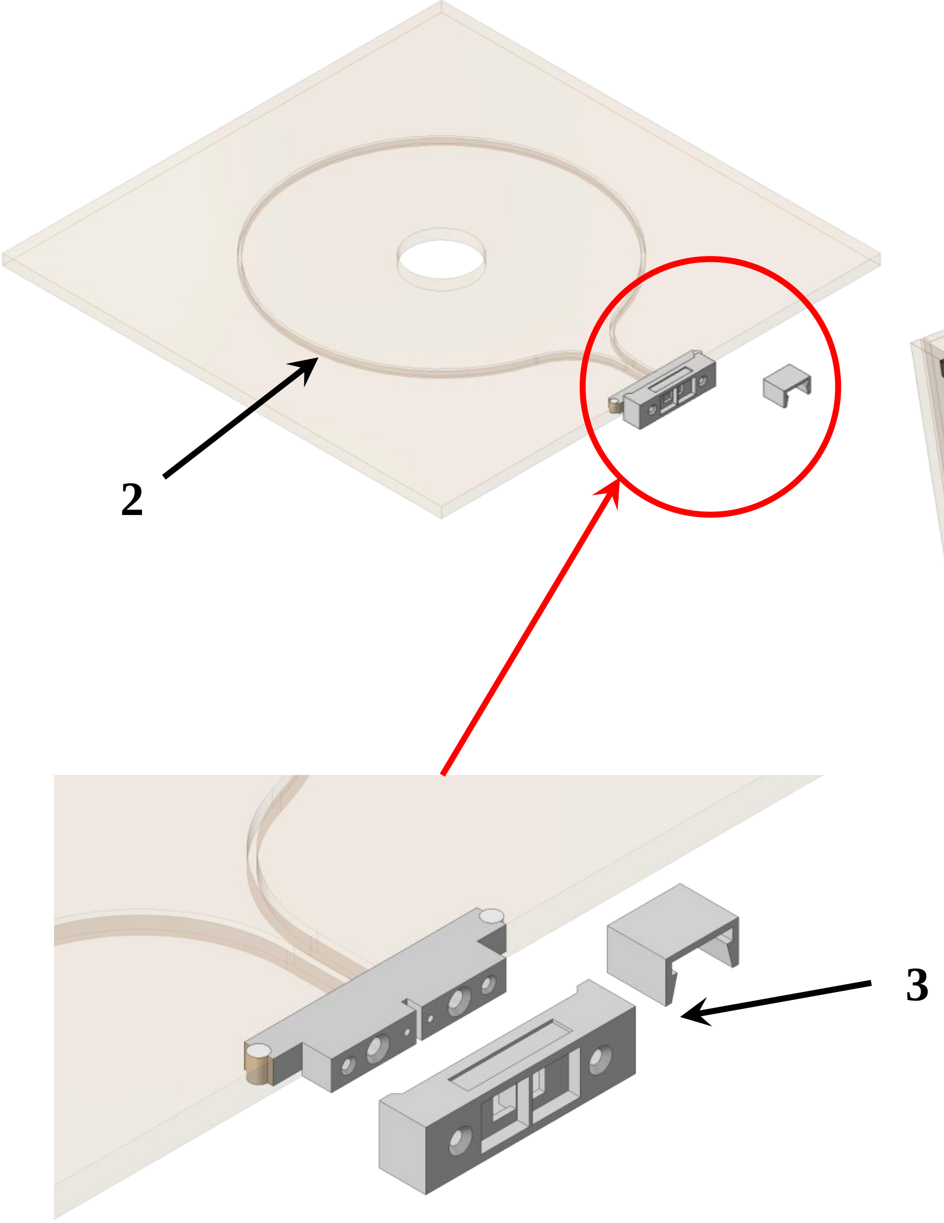


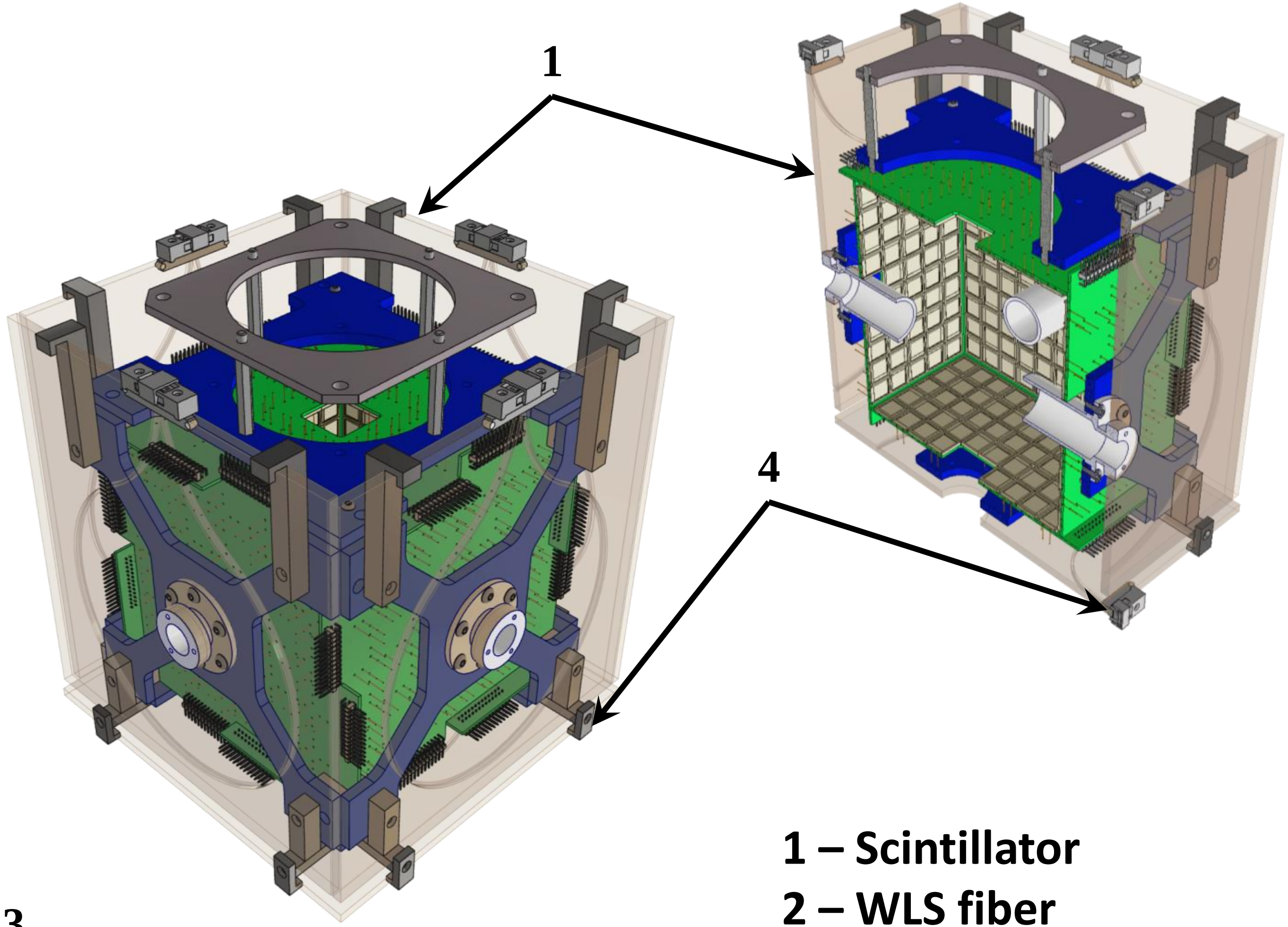




D.S. Leonard at el., Phys. Rev. C 73, 0045801 (2006)

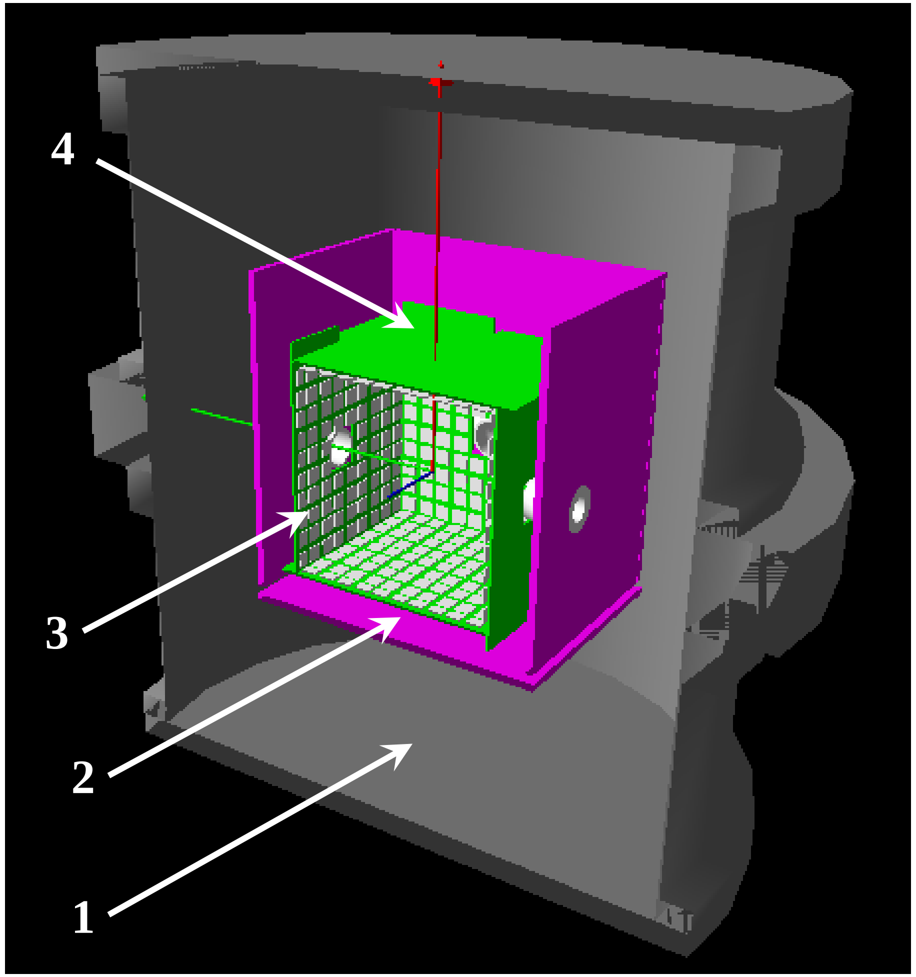
Scintillation detector



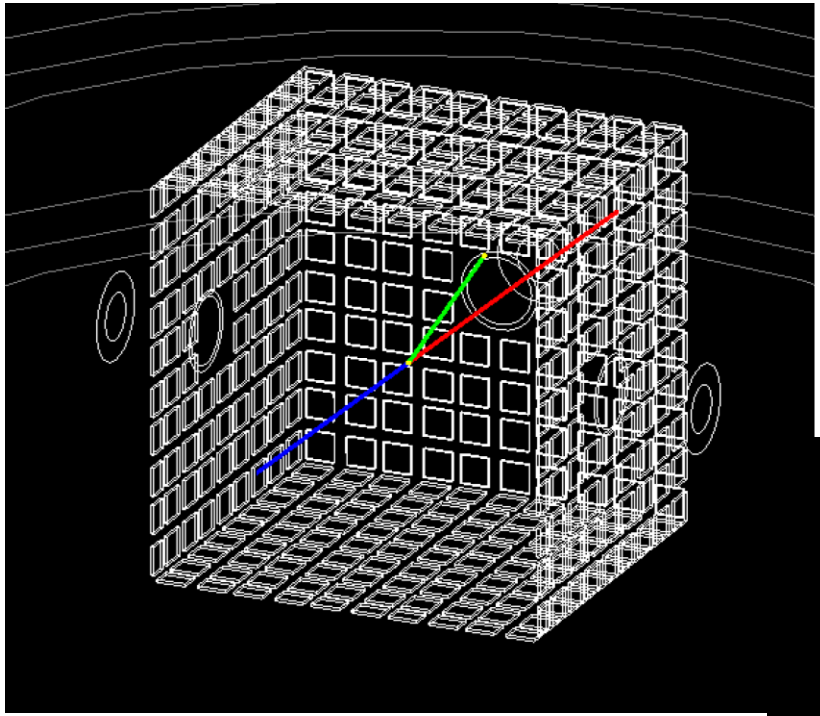


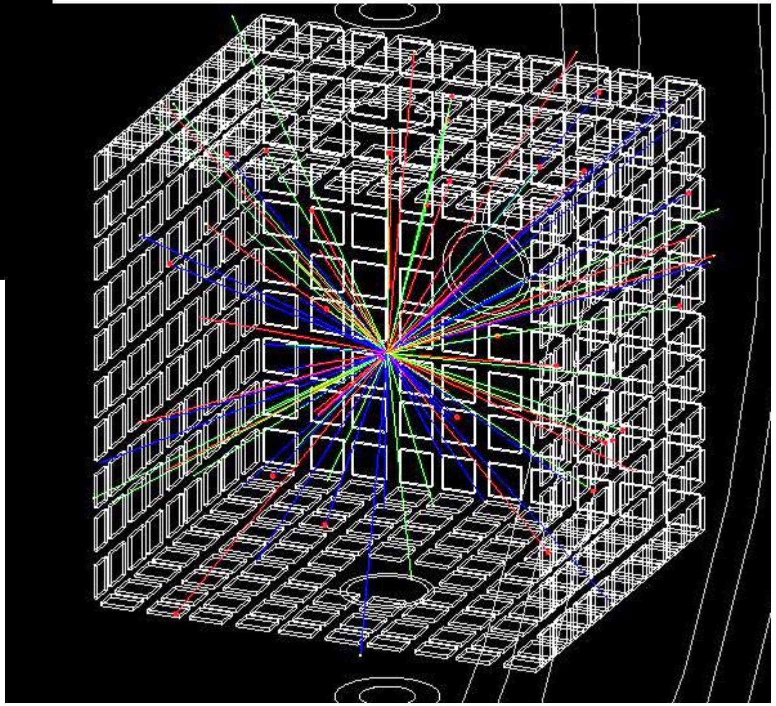
1 – Scintillator
2 – WLS fiber
3 – SiPM-connector
4 – Scintillator mount

Monte-Carlo simulation in Geant 4



Detector geometry

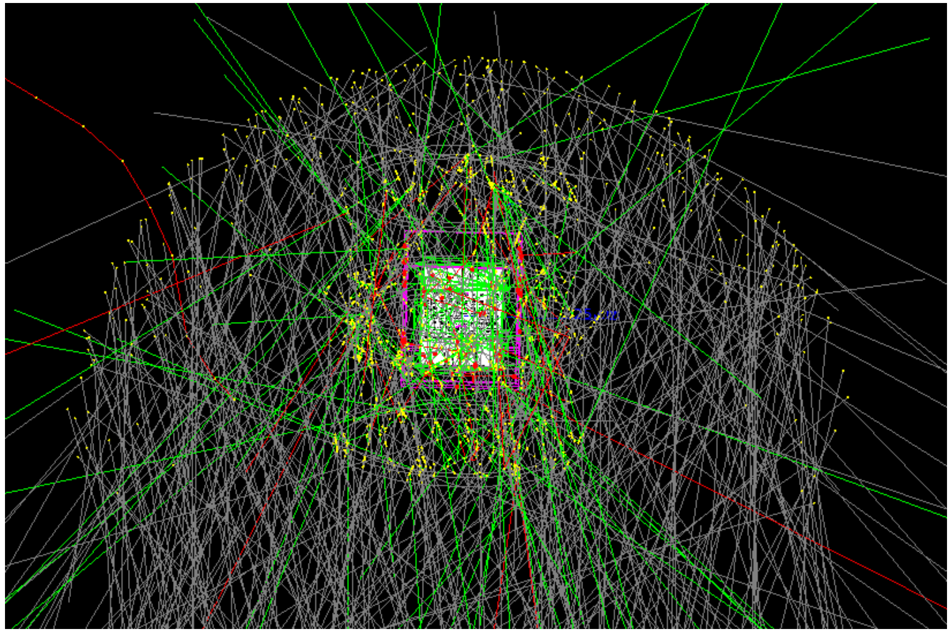


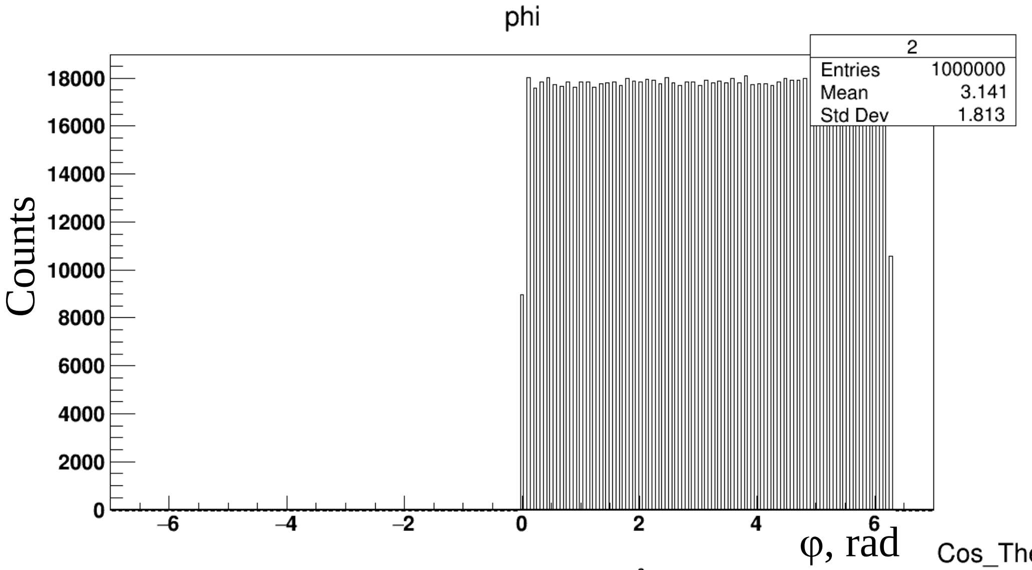


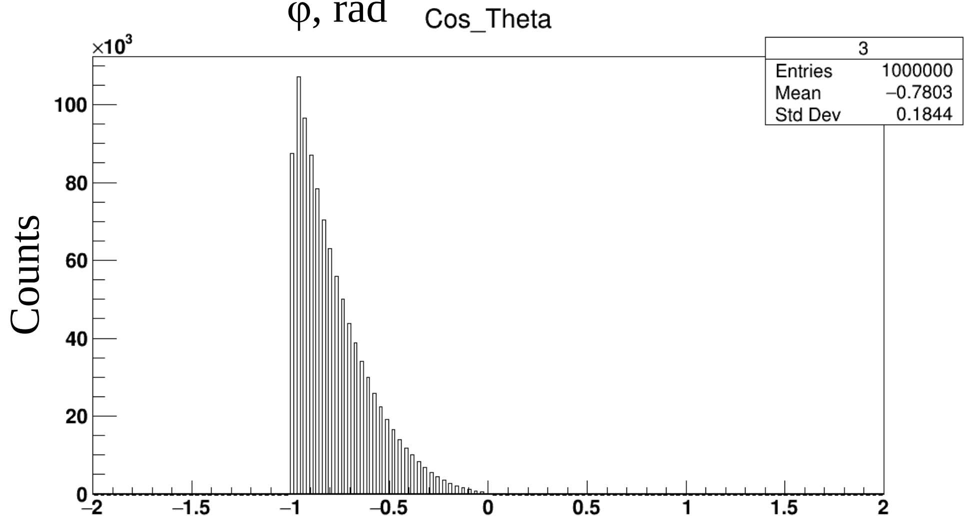
Red - p
Blue – t
Green – He3

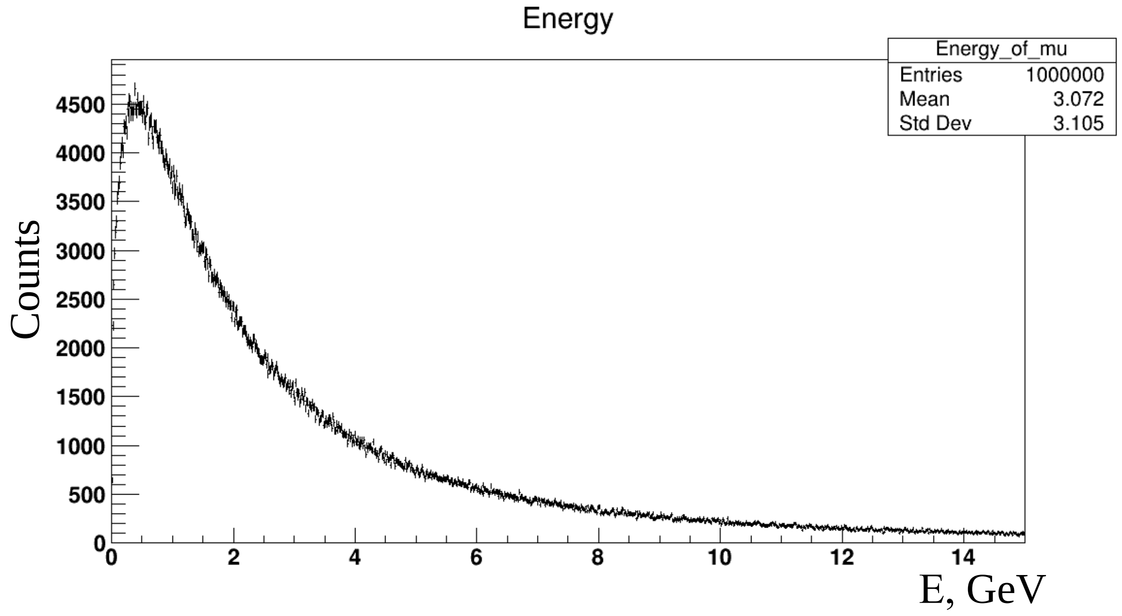
1 – Vacuum chamber
2 – Scintillators
3 – PIN - diodes
4 – Printed circuit boards

Cosmic muon generator



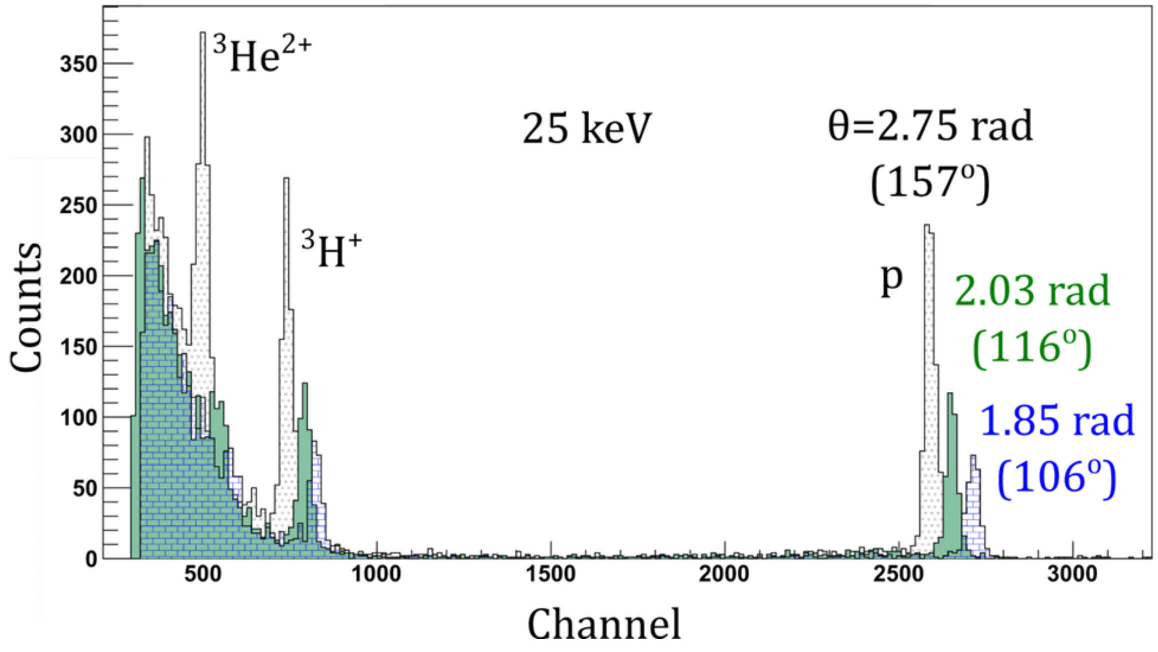


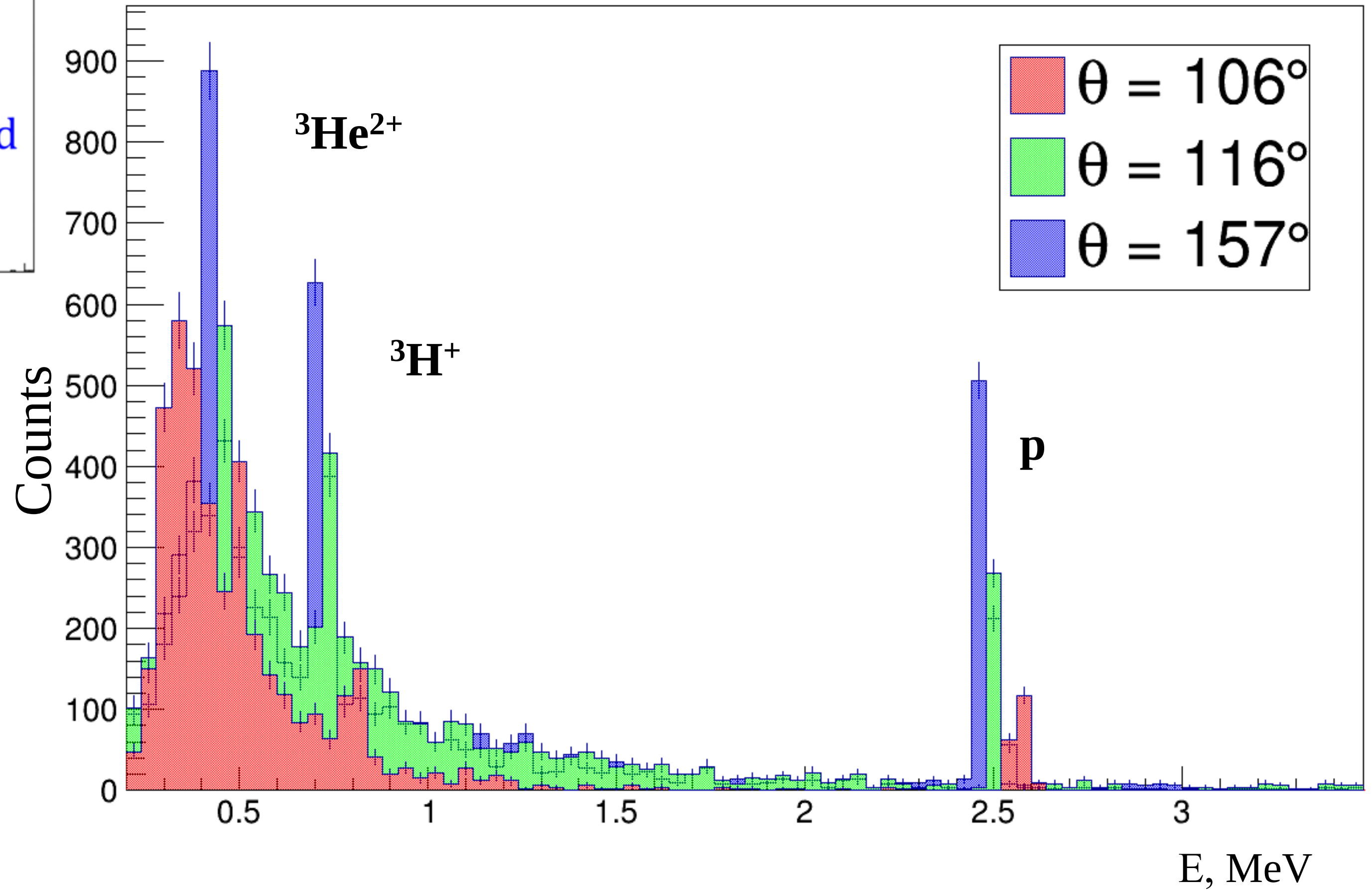




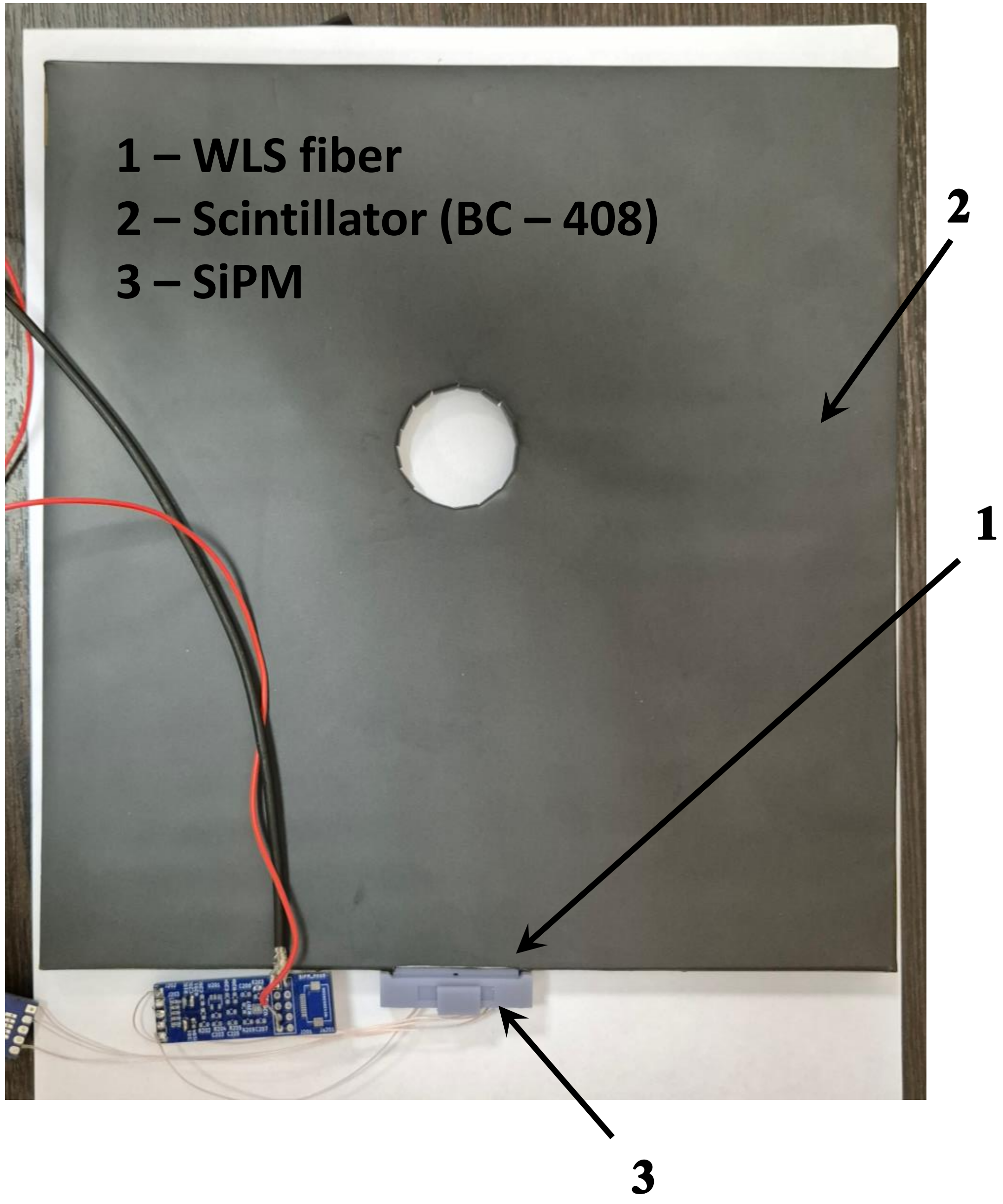
D. Pagano, et al.,
EcoMug: An Efficient COsmic MUon Generator for cosmic-ray muon applications, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1014, 2021, 165732, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2021.165732.

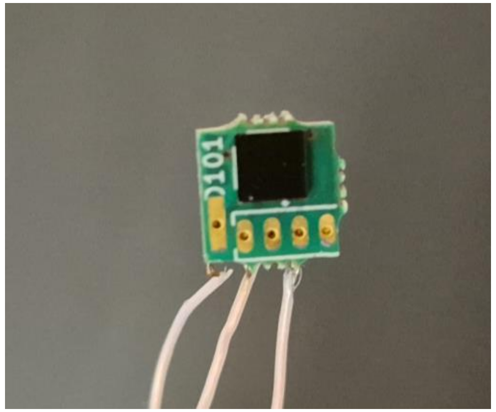
Simulation results

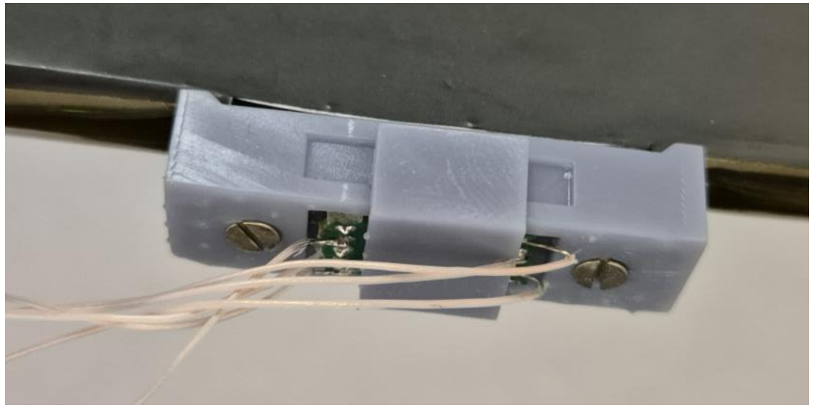




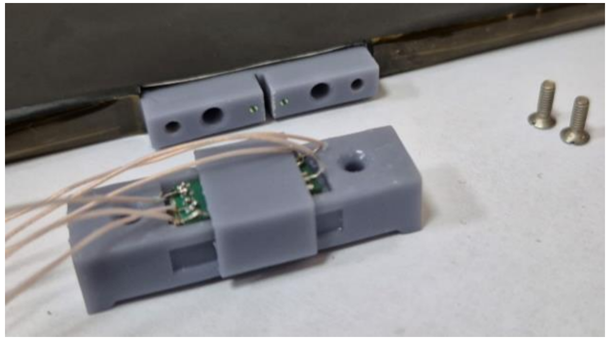
Test system





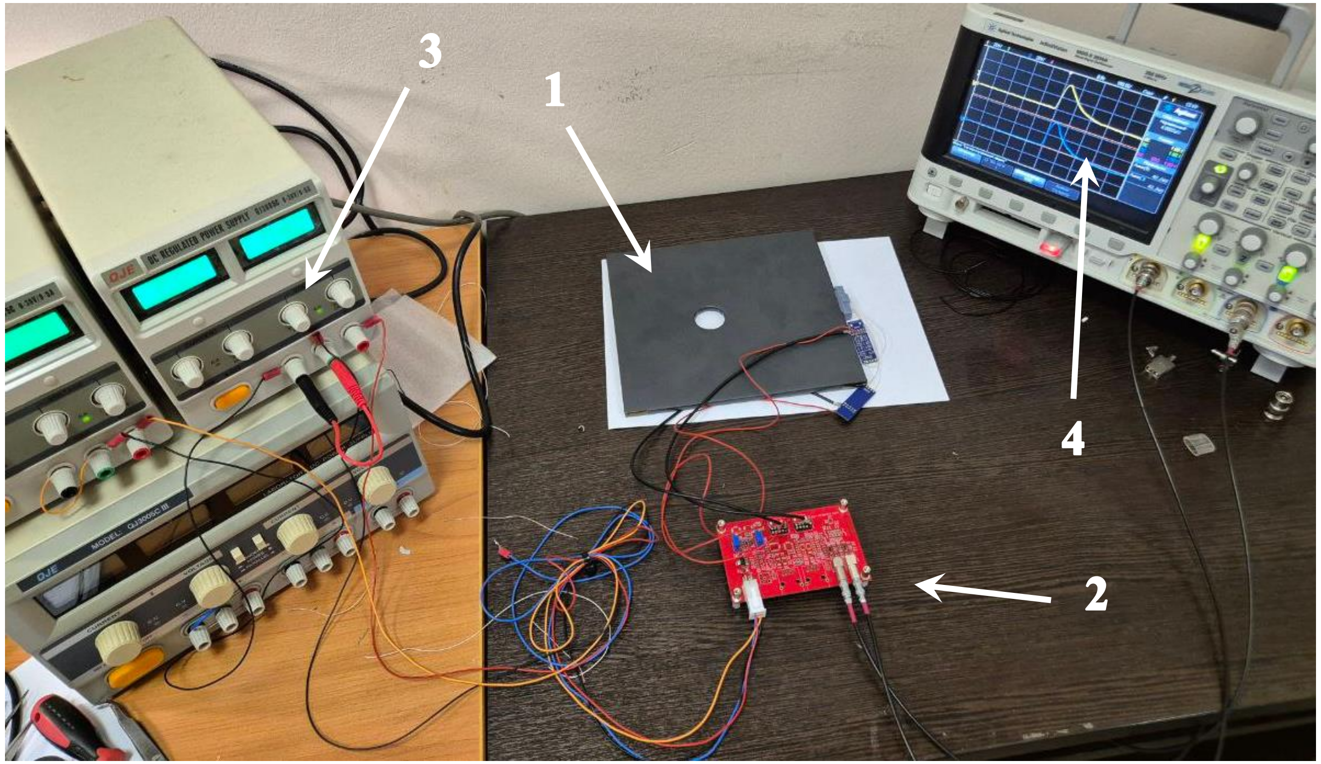


SiPM Onsemi MicroFJ-30035-TSV



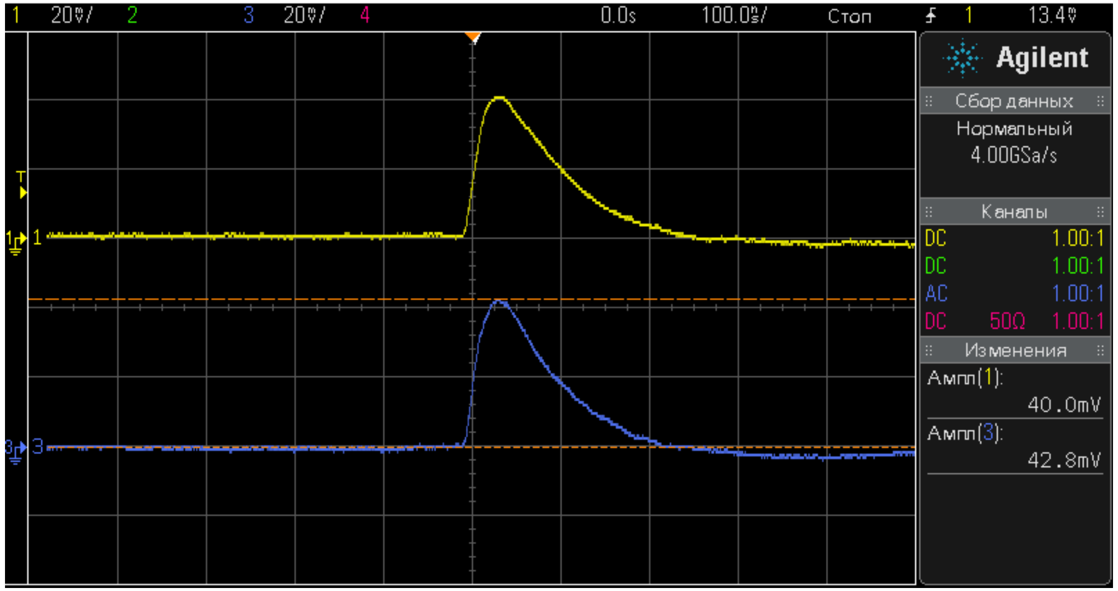
WLS fiber holders and SiPM mounts

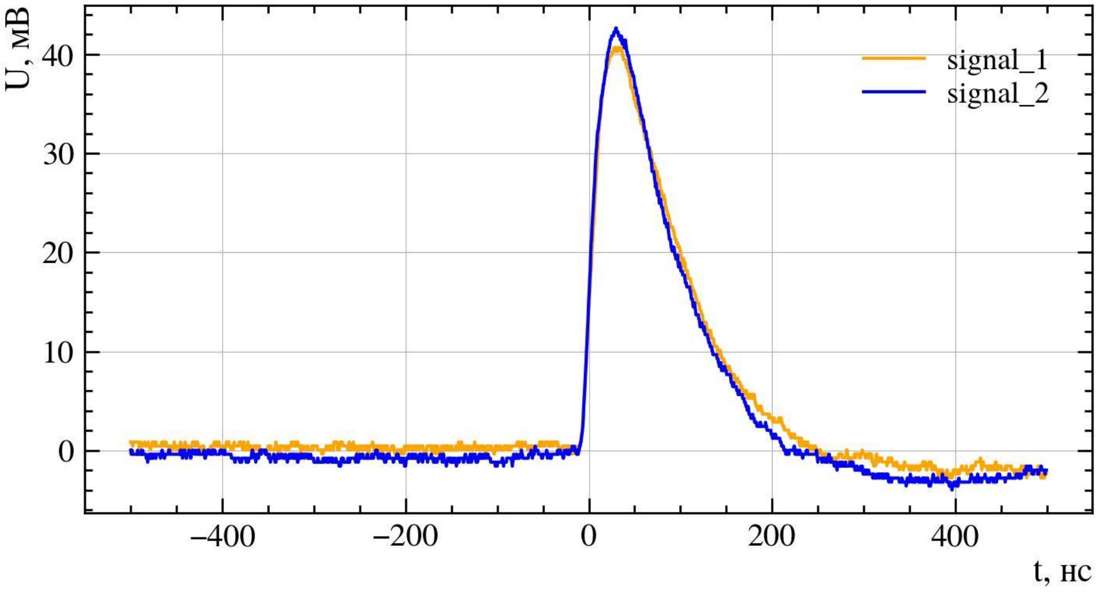
Cosmic muons registration



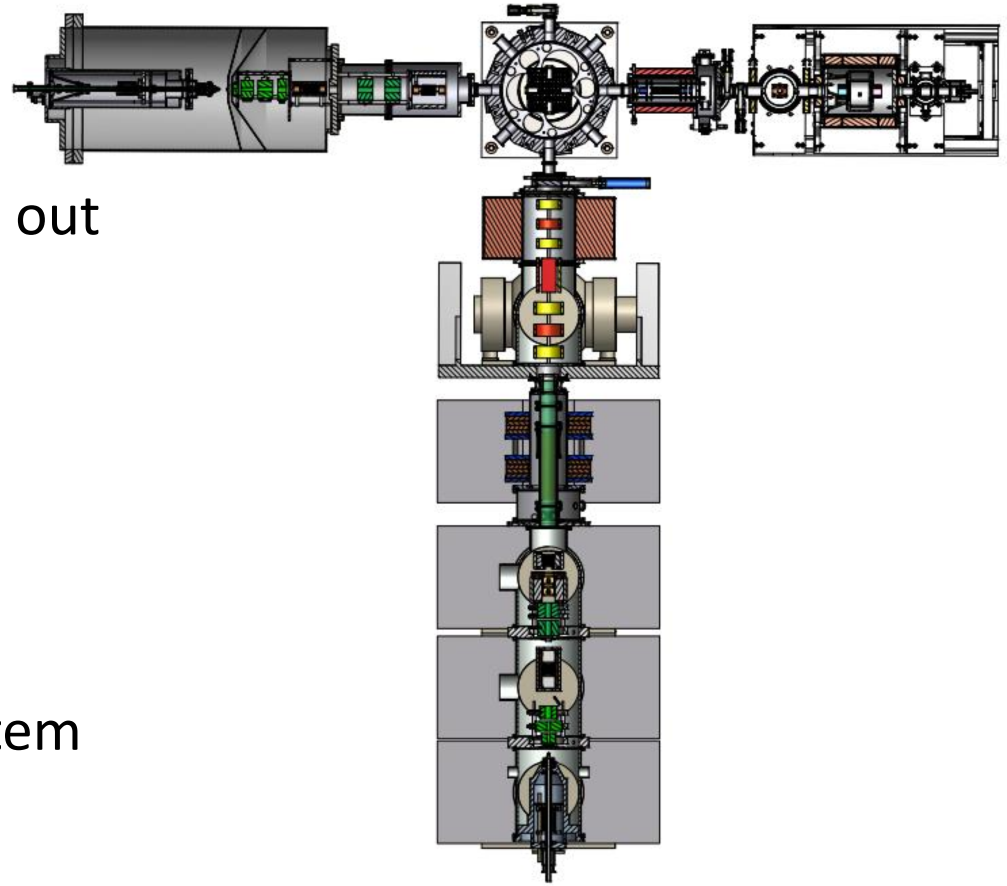
Test assembly for registration of cosmic radiation

1 – Scintillator
2 – Amplifier and power supply PCB
3 – DC voltage sources
4 – Oscilloscope





Development strategy



Performed:

- ✓ Modelling of the scintillation detector system was carried out
- ✓ Optimal cosmic ray generator was selected
- ✓ Designed electronics for SiPM
- ✓ A test system was assembled

Work Plan:

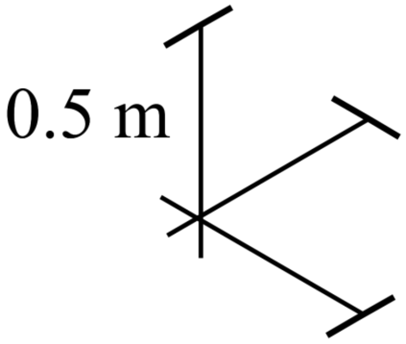
- ❑ Assembly of the system outside the vacuum chamber
- ❑ Connecting the system to a common data acquisition system
- ❑ Recruitment of cosmic ray statistics
- ❑ Placing the system in the vacuum chamber of the main detector
- ❑ Obtaining experimental data

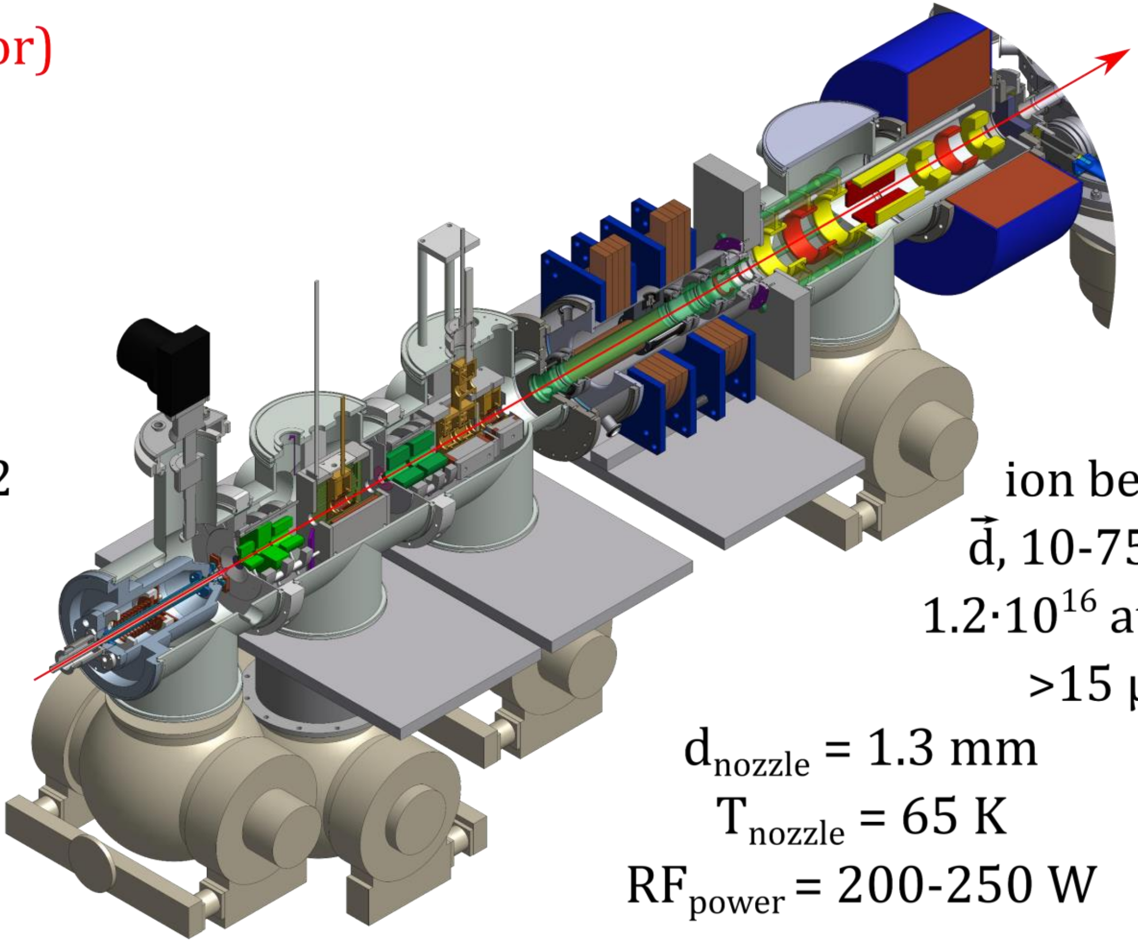
Pol Fusion

Thank you for your attention!

POLIS

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





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

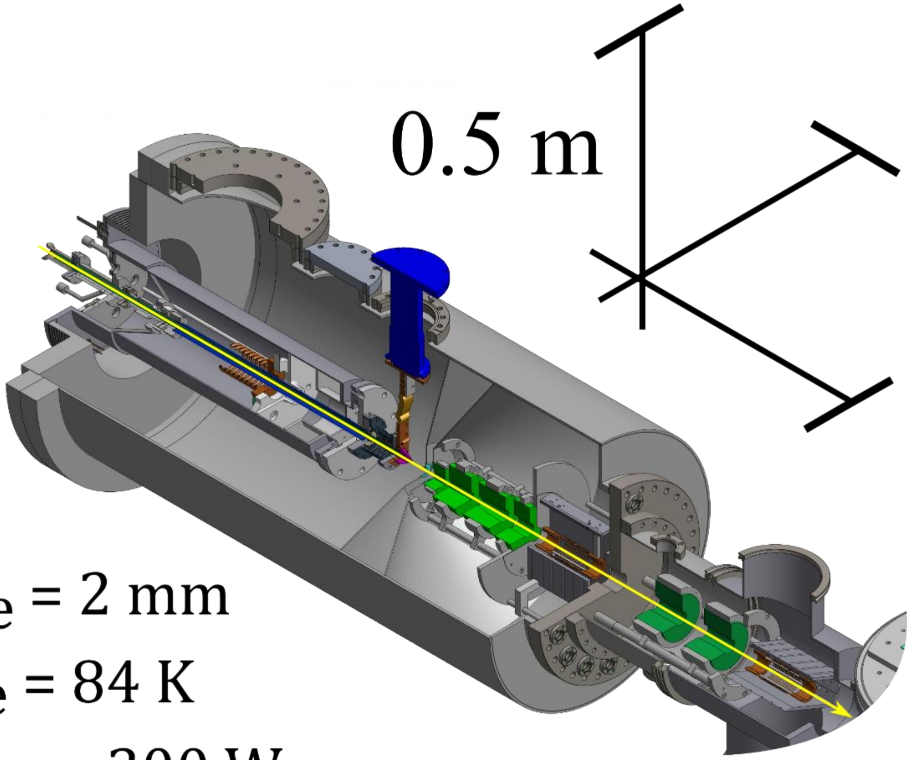
d_{nozzle} = 1.3 mm
T_{nozzle} = 65 K
RF_{power} = 200-250 W

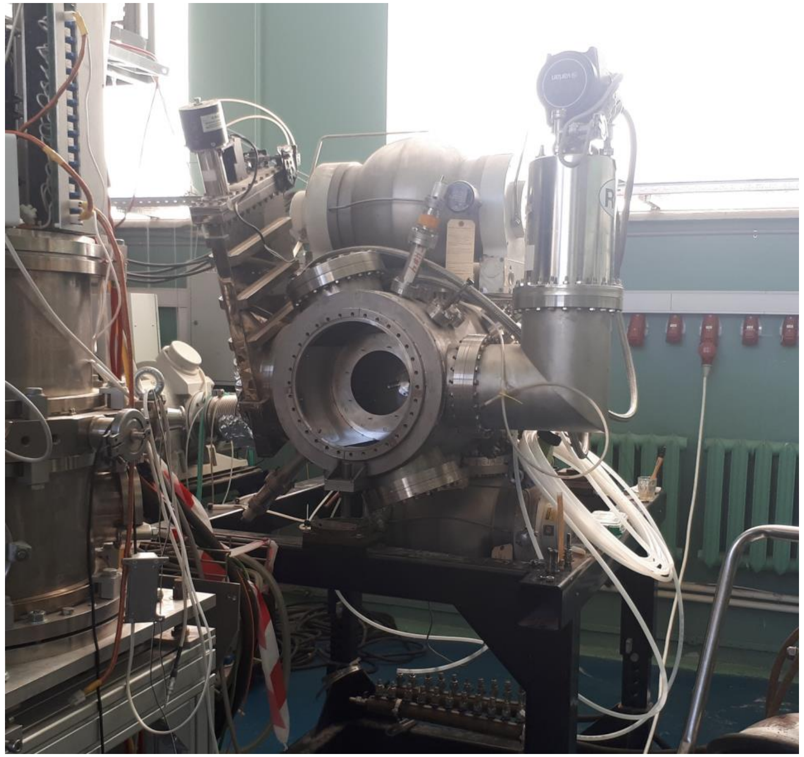
Polarizer:

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

PABS

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





atomic beam d_{nozzle} = 2 mm

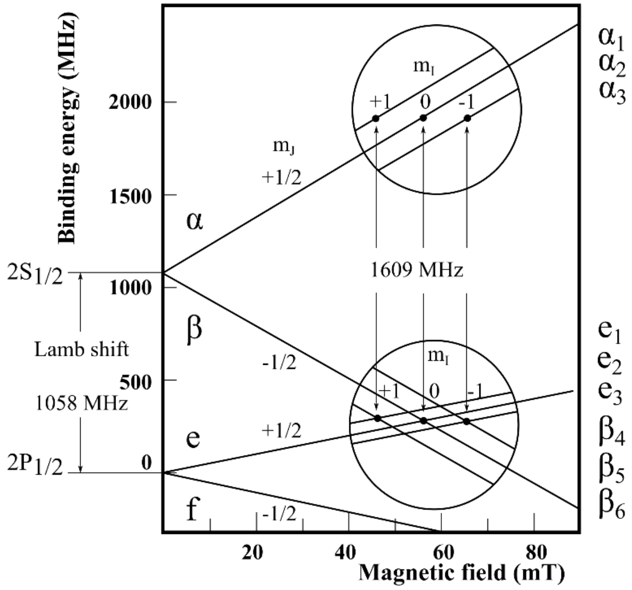
$\vec{D}$, 0.01 eV T_{nozzle} = 84 K

$2 \cdot 10^{16}$ atoms/s RF_{power} = 300 W

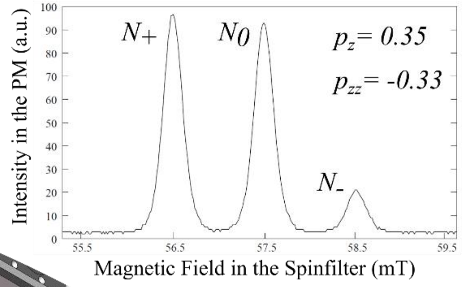
Polarizing system:

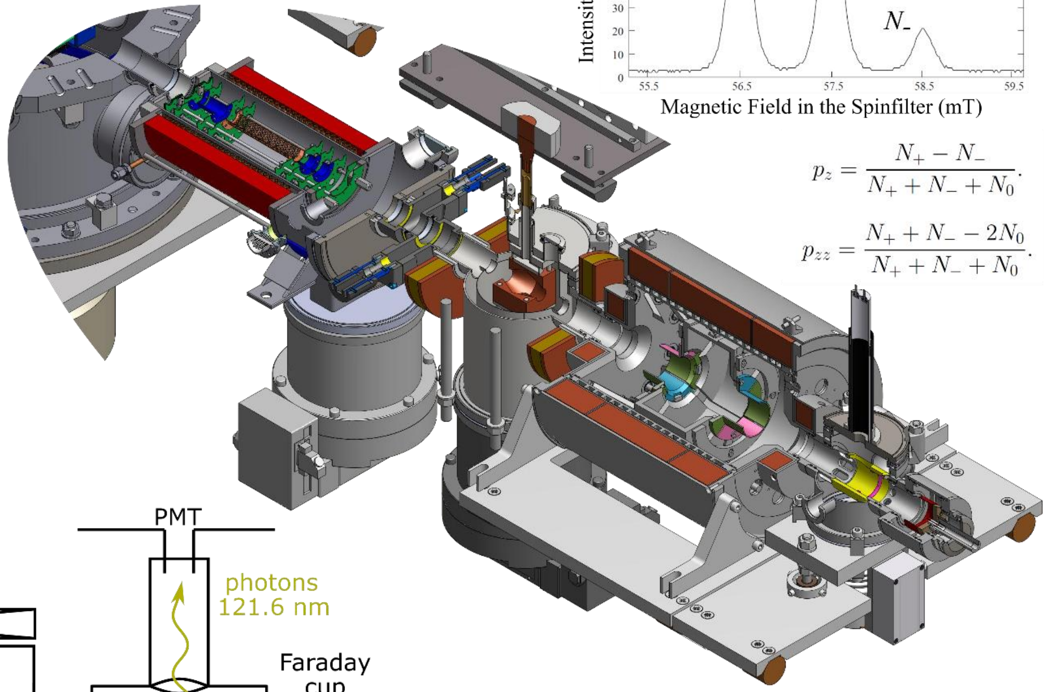
Sextupoles + Quadrupoles + MFT + Sextupoles + MFT

LSP



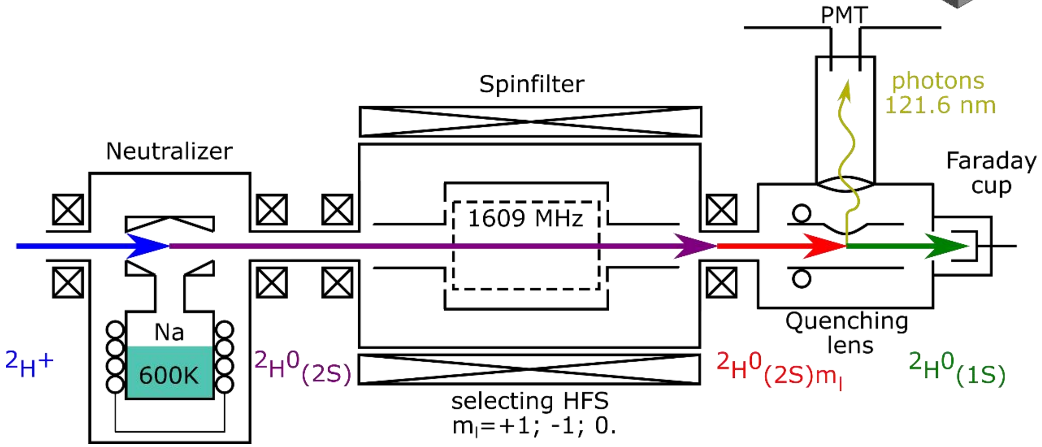
PNPI - NRC KI





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

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



NRP

PNPI - NRC KI

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

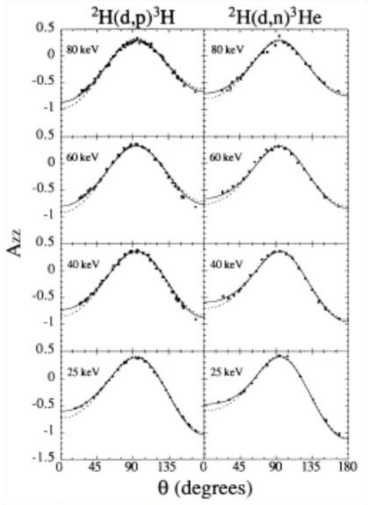
$$\frac{U-D}{U+D} = \frac{P_{ZZ}\sin\beta\,\cos\beta\, A_{xz}}{1+\frac{1}{2}P_{ZZ}[\sin^2\beta A_{xx} + \cos^2\beta A_{zz}]}$$

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

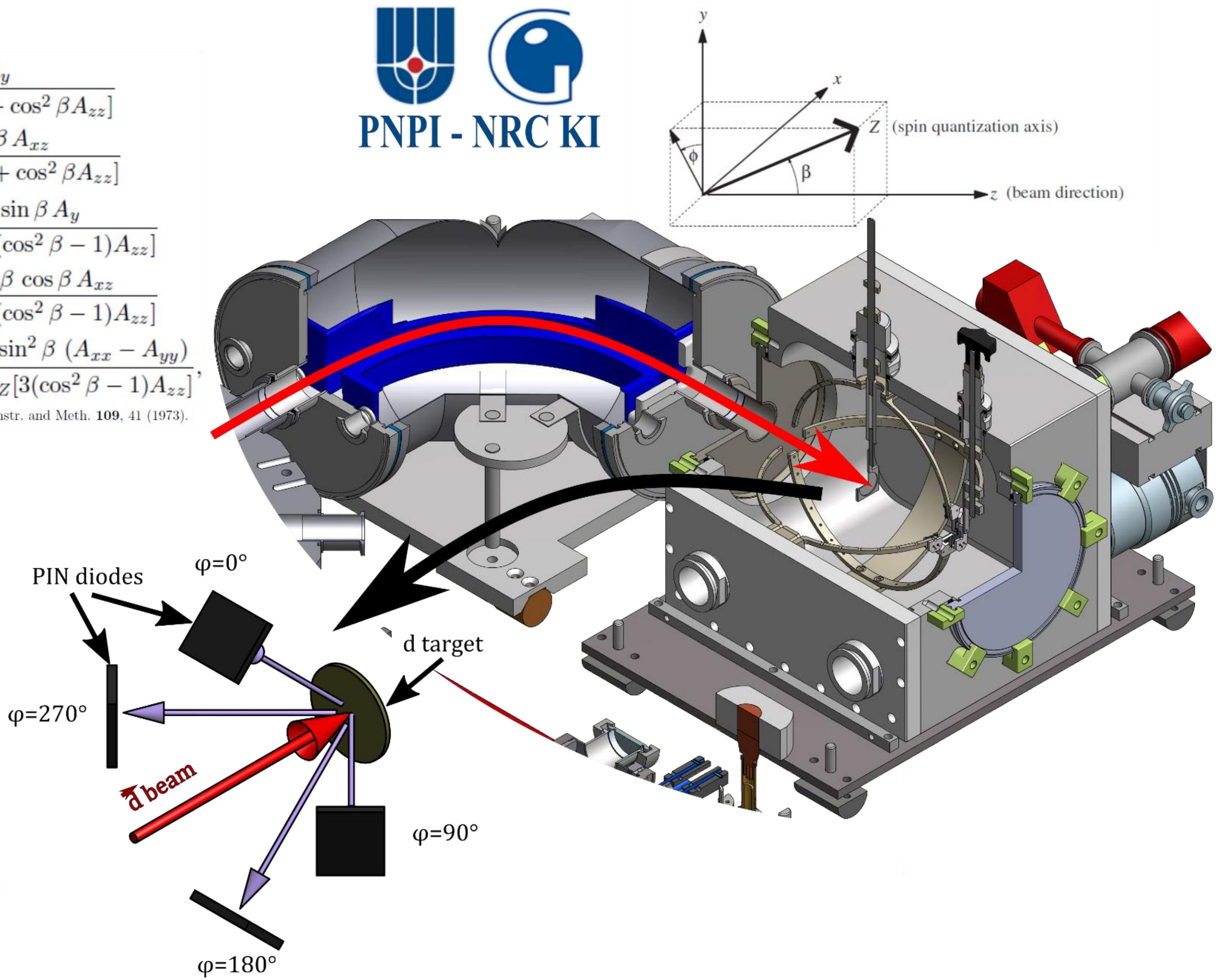
$$\frac{2(U-D)}{L+R+U+D} = \frac{P_{ZZ}\sin\beta\,\cos\beta\, A_{xz}}{1+\frac{1}{4}P_{ZZ}[3(\cos^2\beta - 1)A_{zz}]}$$

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

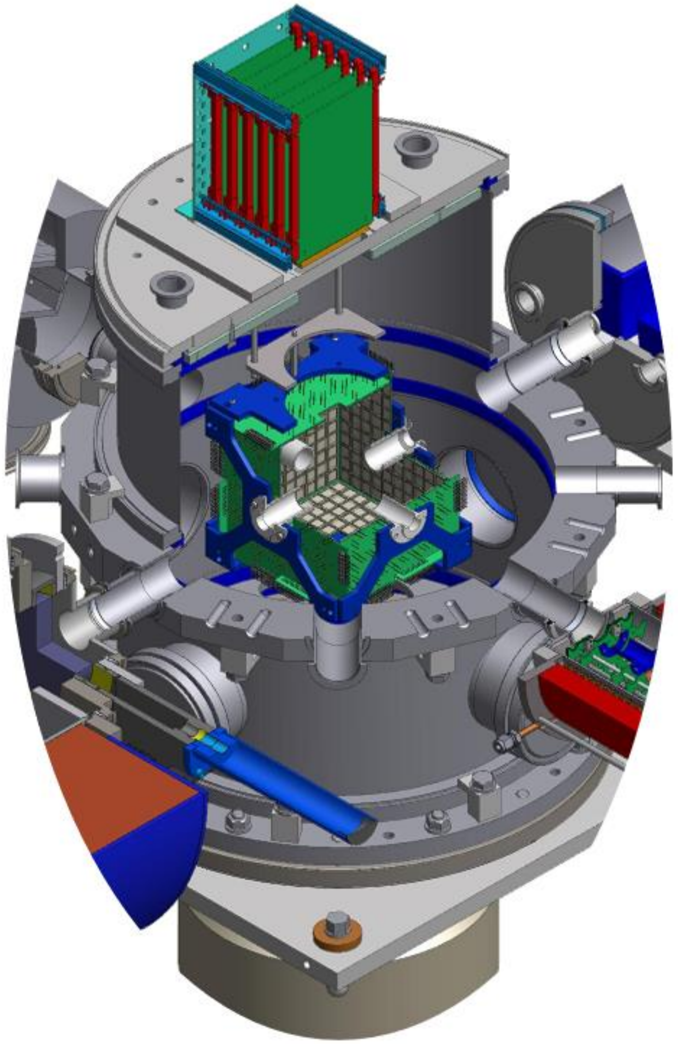
G.G Ohlsen, P.W. Keaton, Jr., Nucl. Instr. and Meth. **109**, 41 (1973).

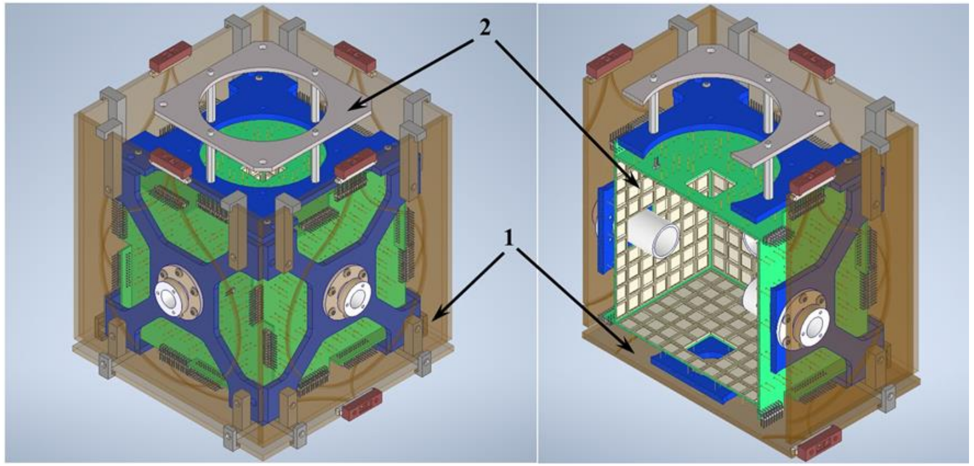


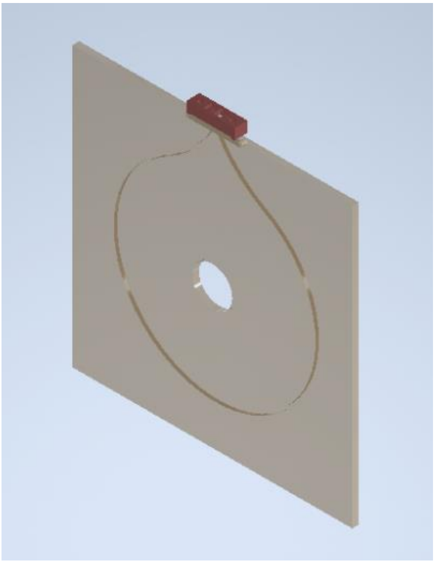
K. Fletcher, *et al.*, Phys. Rev. C **49**, 2305 (1994).

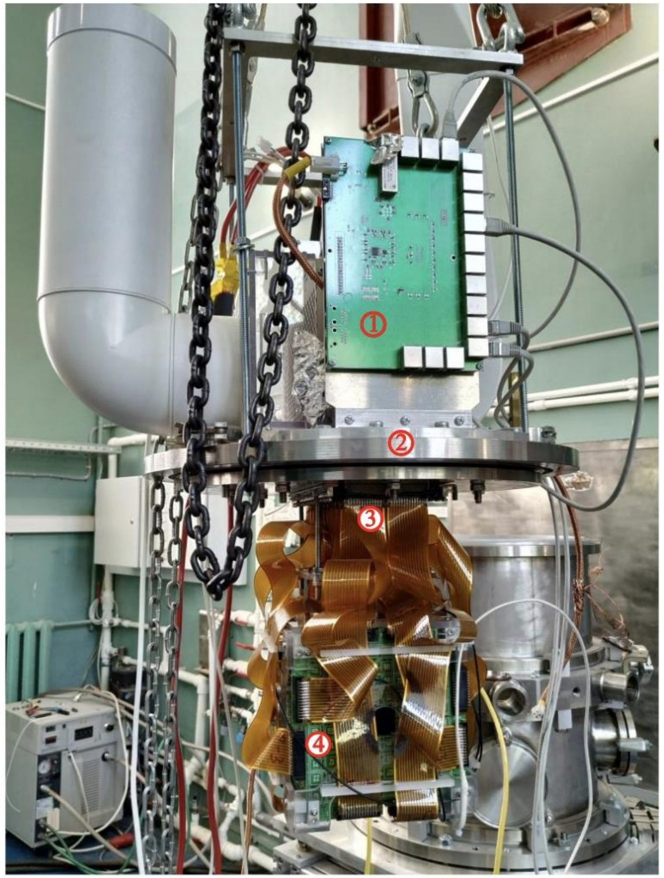


Detector system



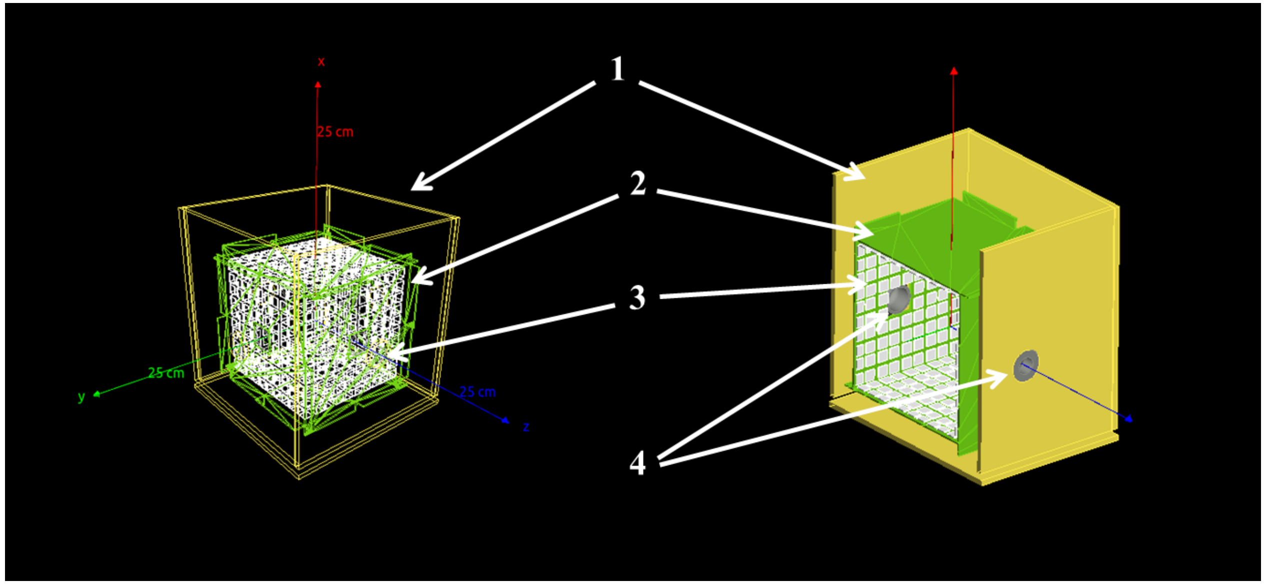




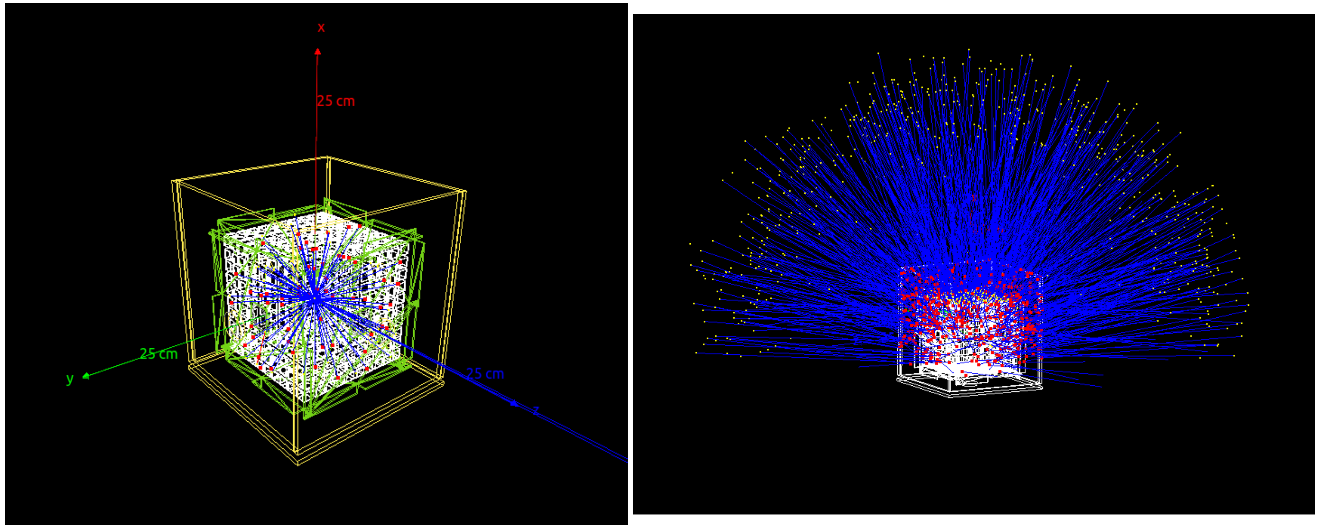


① concentrator
② top flange
③ signal cables
④ detector cube

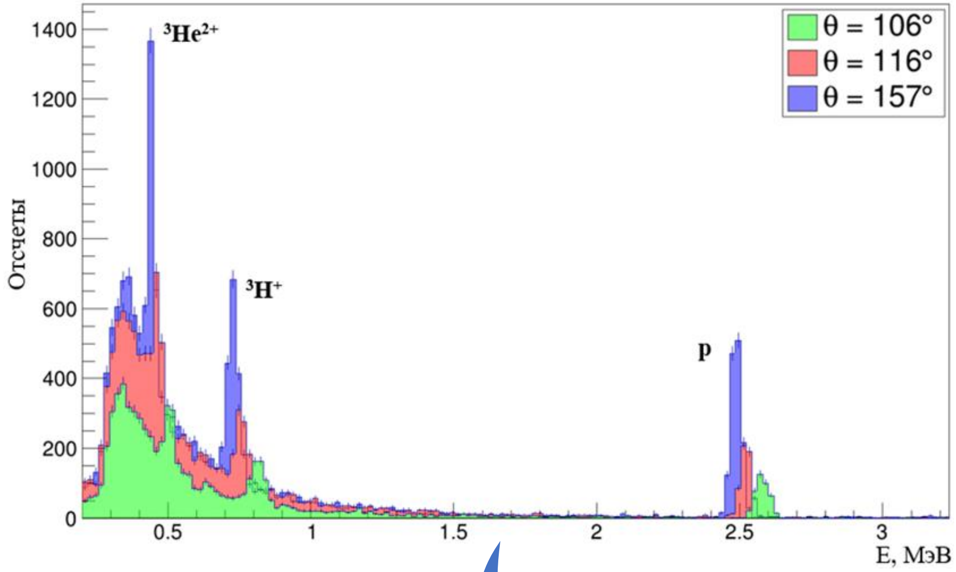
Geant 4



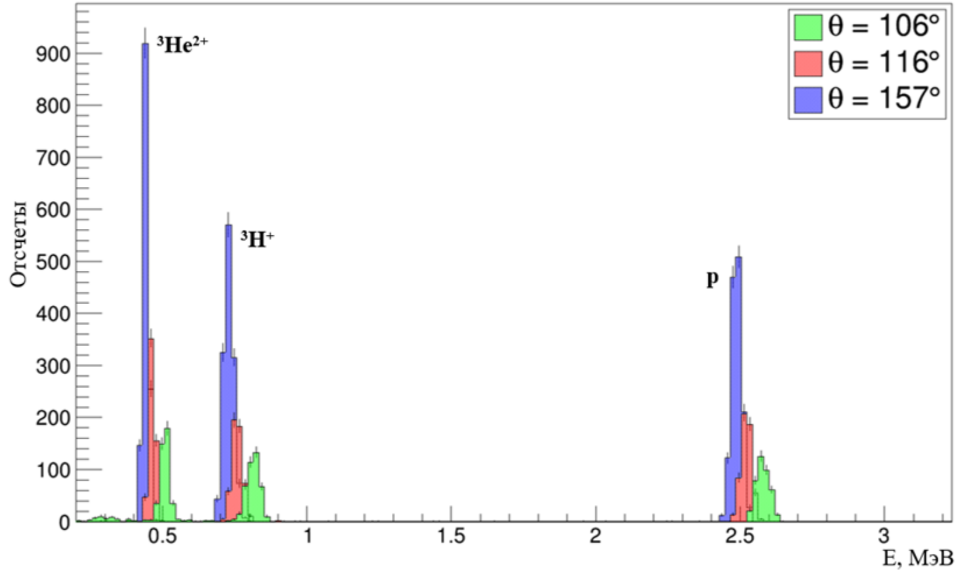
x
25 cm
25 cm
y
25 cm
z
1
2
3
4



x
25 cm
25 cm
y
25 cm
z

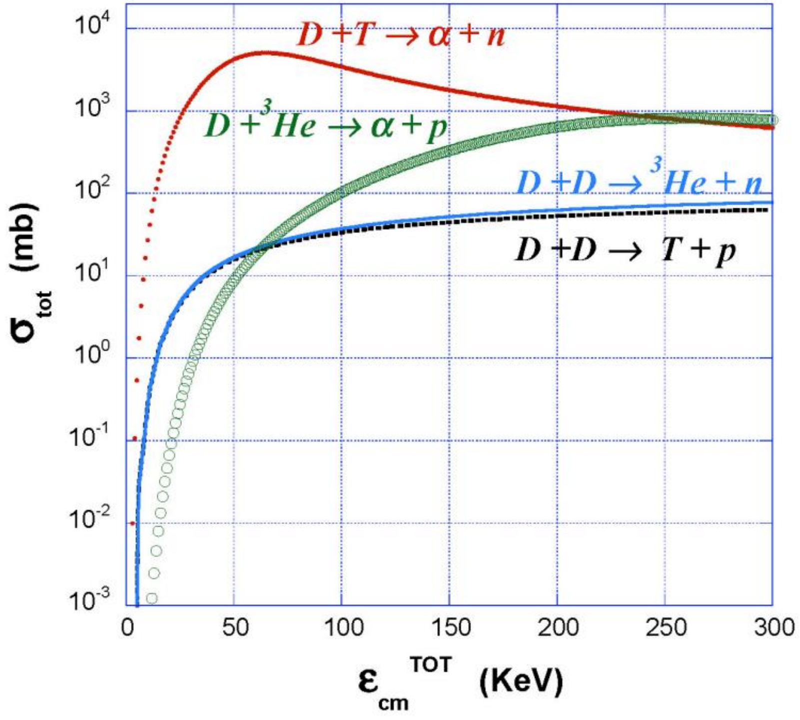


1400
1200
1000
800
600
400
200
0
Отсчеты
^{3}He^{2+}
^{3}H$^+$
p
θ = 106°
θ = 116°
θ = 157°
0.5
1
1.5
2
2.5
3
E, МэВ



900
800
700
600
500
400
300
200
100
0
Отсчеты
^{3}He^{2+}
^{3}H$^+$
p
θ = 106°
θ = 116°
θ = 157°
0.5
1
1.5
2
2.5
3
E, МэВ

Optical polarization ³He



$D + T \to {}^4He + n$ Q=17.58MeV $\sigma_{max}(E \sim 70keV)$

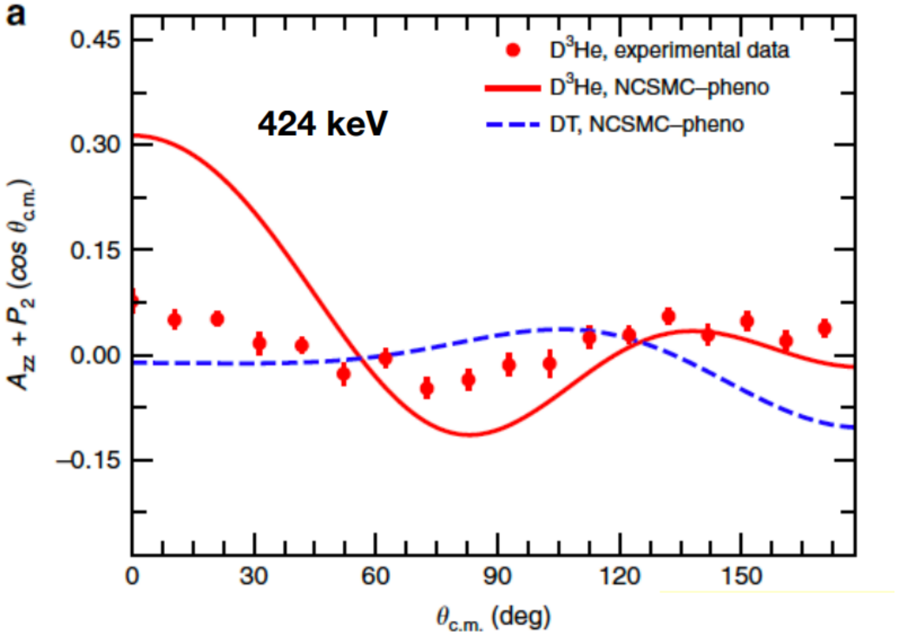
$D + {}^3He \to {}^4He + p$ Q=18.35MeV $\sigma_{max}(E \geq 250keV)$

$D + D \to {}^3He + n$ Q=3.27MeV

$D + D \to T + p$ Q=4.04MeV

$\sigma_{max}(E \sim 1000keV)$

Data: Geist 1999



G.Hupin, S.Quaglioni, P.Navratil (2019)
https://doi.org/10.1038/s41467-018-08052-6

Cross section

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

The spins of both deuterons are the same:
Only $p_z(q_z)$ and $p_{zz}(q_{zz}) \neq 0$

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

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

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